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Systematic approach for the development of remote handling system concepts for high energy physics research facilities

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Systematic Approach for the Development of Remote Handling System Concepts for High Energy Physics Research Facilities

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Abstract

Equipment maintenance is one of the most important areas in the life-cycle management of High Energy Physics (HEP) facilities. In HEP facilities (such as CERN, ISOLDE, GSI/FAIR, GANIL, FRIB and ESS), beam intensities are increasing. Ionizing radiation is a significant hazard. The ionizing radiation directly affects the health of radiation workers and therefore it is desirable to reduce human intervention through robotic operations. The Facility of Antiproton and Ion Research (FAIR), a HEP facility under construction in Darmstadt, Germany, will house the world's most powerful Super Fragment Separator (Super-FRS) facility, which will require remote maintenance. One section of the Super-FRS is termed the main tunnel. This is 160m long and has four focal planes. The Super-FRS beamline inserts will require remote maintenance and remote inspection. To carry out these Remote Handling (RH) tasks, a RH system for the Super-FRS main tunnel is essential. RH equipment for HEP facilities are complex systems. They must operate within an intricate environment with multiple interfaces. However, there is very limited literature on how to approach the development and evaluation of RH concepts at HEP facilities even though various facilities have developed RH systems tailored to their individual environments.

This thesis proposes new systematic approach for developing and evaluation of RH concept designs targeted to help maintenance procedures at HEP facilities. The systematic approach is composed of Systems Engineering (SE) State of the Art practices molded to fit HEP facilities needs and requirements. The SE approach for HEP facilities focuses on finding optimum RH solution by exploiting HEP facilities limited resources available compared to nuclear power production industry. The systematic approach is tested to develop the RH maintenance solution for Super-FRS main tunnel scenario for FAIR facility. The practice carried out during this research work resulted in the best possible RH solution for Super-FRS and is currently under development for the Super-FRS facility.

The research work to develop systematic approach for development of RH system was based on a very critical State of the Art study that has not been carried for HEP facilities till now. The State of the Art studies explores the HEP facilities in detail and results in: classification of HEP facilities RH environments, classification of RH equipment currently used at HEP facilities and present status of SE knowledge integration within HEP facilities.

The systematic approach to develop RH system and knowledge attained during State of the Art studies are utilized to develop three RH system concept designs that fulfill the Super-FRS RH requirements. This research work focuses on collaborating between RH experts to conduct reliable and creditable trade-off analysis for RH system concepts evaluation. The aim of collaboration with RH experts is to develop diversify the systematic approach for RH system concept development. The collaboration and the State of the Art studies enable the model to formalize the procedures that will ensure the integration of RH needs into facility's development by classifying (Commercial Off-the–Shelf (COTS)) RH equipment and by identifying key steps in the development of RH concepts.

The developed RH concepts for Super-FRS are evaluated for requirements traceability, functional analysis, radiation dose analysis, possible system failure scenarios, including cost estimates, and task sequence optimization analysis. The result of trade-off analysis is delivered in the form of optimal RH system design that fulfills the RH requirements and will be developed to carry out RH tasks at Super-FRS facility.

This thesis provides details concerning each concept design's merits and demerits, along with suggestions for design changes needed to improve RH system's flexibility and performance. The systematic approach used to develop the RH concepts was used to

identify and address the critical issues with Super-FRS tunnel layout, beamline insert designs, storage / transport of activated parts, and remote maintenance integration at very early stage of HEP facility design.

The research work in this thesis paves the way for the future systematic RH systems concepts design, and development practices; by moving beyond the classical approaches to develop concept designs at the HEP facilities. The conclusion will also present a summary design comparison, relevant technologies, advantages, limitations and future research work opportunities.

Preface

The main focus of this thesis is to develop RH system concept using SE knowledge to carry out remote maintenance at HEP facilities. The work has been carried out within the Preventing hUman inteRvention for increased SAfety in inFra-structurEs (PURESAFE) project, which is an Initial Training Network (ITN) for the training of young researchers, funded under the European Commission's Seventh Framework Programme Marie Curie Actions. ITNs have two fold goals. On one hand, the purpose of ITN is to develop the career of Early Stage Researchers (ESRs) by improving their research skills and integrating the min the research teams. On the other hand, the research which results from these networks is expected to be of great scientific value and have high impact.

The aim of the PURESAFE ITN is to provide solutions for cost-efficient life-cycle management of facilities that generate ionizing radiation. To achieve this, new engineering techniques have been studied, both in hardware and software. Implementation of a SE approach to develop RH solutions has large benefits for maintaining these facilities. Therefore, one of the research packages within PURESAFE has been focused on developing RH solutions for the Super-FRS facility. The main results of the work carried out in said research package are presented in this thesis.

The research work presented in this thesis has been carried out at GSI, Darmstadt. I would like to express my sincere gratitude to my project supervisor Dr. Helmut Weick, who gave me the chance to participate in this experience and for his support and guidance during the whole project. I would also like to thank him for his support, not only in the actual development work, but also in research work and in the doctoral studies. Without his support, this thesis would have never been possible.

I would like also to express my sincere gratitude towards Professor Jouni Mattila, my doctoral thesis supervisor at TUT and coordinator of PURESAFE project for his unfailing guidance and encouragement throughout the preparation of this thesis.

I would also like to give special thanks to all PURESAFE consortium members for providing the inputs that they have provided to make this research work possible. I would also like to specially thank my fellow Early Stage Researchers at PURESAFE project for such a diverse and rich research working experience. This thesis would have not been what it is with help, input and enthusiasm of PURESAFE personnel.

Finally, I would like to thank my whole family especially my wife Nousheen Bibi, father Amjad Ali, and mother Shahnaz Parveen for providing the time, encouragement and support in order to complete my thesis when I need them most.

Darmstadt 02.08.2016

Faraz Amjad

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List of symbols and abbreviations

ACB	Atelier Chantier de Bretagne
AT1	Atelier de Traitement
ALARP/ALARA	As Low As Reasonably Practicable /Achievable
BMUB	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety
CBM	Compressed Baryonic Matter
CEA	French Alternative Energies and Atomic Energy Commission (Commissariat à l'énergie atomique et aux énergies alternatives)
CP5	Chicago Pile 5
CERN	Conseil Europ´een pour la Recherche Nucl´eaire
COTS	Commercial off-the-shelf
CNGS	CERN Neutrinos to Gran Sasso
DEMO	DEMOnstration Power Plant
DAWP	Dual Arm Work Platform
DOF	Degrees Of Freedom
EC	European Commission
ECSS	European Cooperation for Space Standardization
ESA	European Space Agency
ESR	Experimental Storage Ring
ESRs	Early Stage Researchers
ESS	European Spallation Source
EU	European Union
EURATOM	European Atomic Energy Community
FAIR	Facility of Anti-proton and Ion Research
FRIB	Facility for Rare Isotope Beams
FRS	Fragment Separator
GSI	Gesellschaft für Schwerionenforschung Helmholtz Center for Heavy Ion Research
GANIL	Grand Accélérateur National d'Ions Lourds
GPRS	General Packet Radio Service
HEP	High Energy Physics
HESR	Hochenergie-Speicherring
HMI	Human Machine Interface
HIB	High Intensity Beam
ISOL	Isotope Separations Online
ITER	International Thermonuclear Experimental Reactor
ITN	Initial Training Network
IAEA	International Atomic Energy Agency
ILO	International Labour Organization
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
ICRH	Ion Cyclotron Resonance Heating
INEEL	Idaho National Engineering and Environmental Laboratory
INCOSE	International Council on Systems Engineering

ISAC	Isotope Separator and Accelerator
ISIS	Science and Technology Facilities Council
JET	Joint European Torus
J-PARC	Japan Proton Accelerator Complex
JSNS	Japan Spallation Neutron Source
KEK	Japan National Laboratory for High Energy Physics
LWR	Light Water Reactor
LINAC	Linear Accelerator
LHC	Large Hadron Collider
LSS	Long Straight Section
mSv	millisievert
MTRH	Main Tunnel Remote Handling
MUSE	Muon Science Establishment
NASA	National Aeronautics and Space Administration
NuMI	Neutrinos at the Main Injector
NEA	Nuclear Energy Agency
NESR	Neue-Experimentier-Speicherring
Nhelix	Nanosecond High-Energy Laser for Heavy Ion Experiments
NuPECC	Nuclear Physics European Collaboration Committee
NUSTAR	Nuclear Structure, Astrophysics and Reactions
OECD	Organization for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory
PSI	Paul Scherrer Institute
PSB	Proton Synchrotron Booster
PURESAFE	Preventing hUman inteRvention for increased SAfety in inFrastructurEs
RP	Research Package
RAMS	Reliability, Availability, Maintainability and Safety
RESR	Recycled-Experimental-Storage-Ring
RIKEN	Rikagaku Kenkyusho (Institute of Physical and Chemical Research, Japan)
RH	Remote Handling
Phelix	Petawatt High-Energy Laser for Heavy Ion Experiments
RCS	Rapid Cycling Synchrotron
ROV	Remotely Operated Vehicle
RIB	Rare Isotope Beams
Super-FRS	Super Fragment Separator
SE	Systems Engineering
SIS18	Schwerionen-Synchrotron 18
SLAC	Stanford Linear Accelerator Centre
SPS	Super Proton Synchrotron
SNS	Spallation Neutron Source
SSK	German Commission on Radiological Protection
Sv	Sievert
T2K	Tokai-to-Kamioka
TIM	Train Inspection Monorail
TAN	Target Absorber Neutral
TRIUMF	Canada's national laboratory for particle and nuclear physics
UNILAC	Universal Linear Accelerator

UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WP	Work Package
WHO	World Health Organization
WAK-BG	WAK–Betriebsgesellschaft
WAK	Karlsruhe Reprocessing Plant

1 Introduction

1.1 Research context

1.1.1 The importance and challenges of fundamental experimental physics research

High-energy and nuclear physics research communities are pushing the boundaries of knowledge concerning known nuclides in order to understand nature at its most basic level. Modern fragment separator facilities have made it possible to study of the fundamental questions of the universe in the fields of nuclear structure and astrophysics. Fragment separator facilities are designed to deliver beams of rare nuclei via fragmentation and fission reactions caused by high-energy beams hitting targets. Advances in technology have enabled scientists to build powerful facilities for producing high-energy beams of short-lived radioactive nuclei. Rare isotopes are radioactively unstable, and they decay into stable nuclei by emitting radiation. Figure 1 shows a nuclide chart as a function of proton and neutron numbers. The nuclei shown in black are the more stable nuclei; these have very long half-lives and can be found naturally in the universe. The more unstable and discovered nuclei are shown in orange. The green region of the chart shows nuclei that have been theoretically predicted, but that are thus far unknown to mankind[1].

In the current scientific environment, radioactive beams represent the primary way to explore the uncharted regions of the nuclei chart (Figure 1) and to find answers concerning the evolution of the universe [2][3][4]. The main aim of Rare Isotope Beam (RIB) facilities is to study nuclear physics in order to understand the properties of nuclear matter and atomic nuclei in order to answer such fundamental questions such as:

- What is the significance of unstable nuclei in the nuclear processes that shape the visible universe [5]?
- To discover new forms of matter and to study the structure and behavior of matter at extreme conditions, (namely) when a transition from nuclear to quark gluon matter occurs [1]?

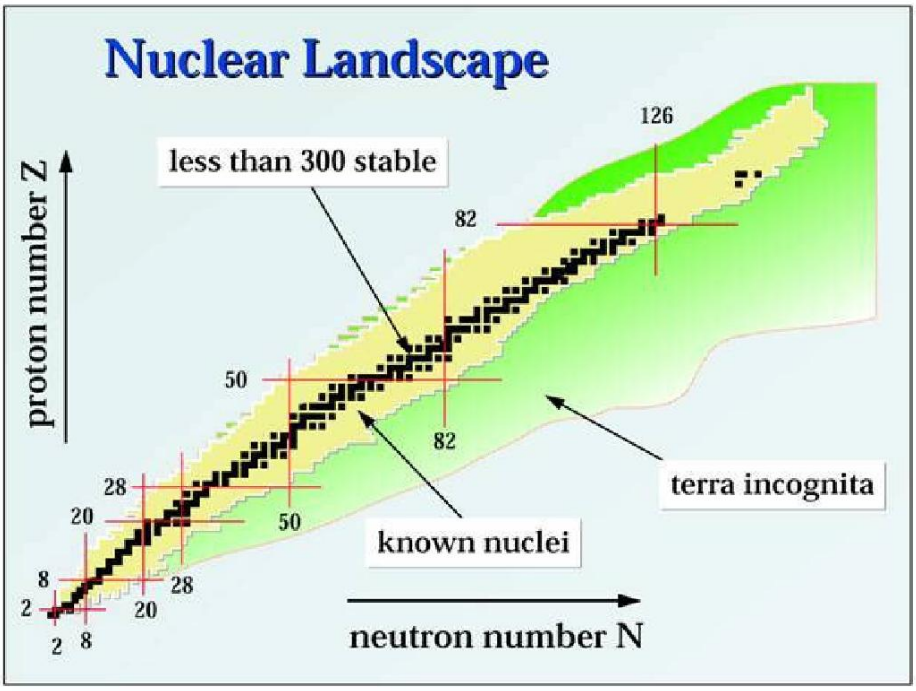

Figure 1. Chart of nuclide: stable, discovered and predicted nuclei. Presented as function of their Proton (Z) and Neutron (N) numbers[1].

The Organization for Economic Co-operation and Development (OECD) Global Science Forum's report [6] shows that RIB facilities are producing the latest and most important research in the field of nuclear physics. The research performed in these facilities has a direct impact on medical imaging, cancer treatment, environmental research, food processing, material sciences, accelerator technology, space technology, space sciences, microchip fabrication, biology and clean energy technologies [6]. Within the last decade, the Nuclear Physics European Collaboration Committee (NuPECC)[7] have reported major progress and discoveries in the field of nuclear physics that have direct applications to society.

1.1.2 Importance of particle accelerators

In 2000, an estimated 15,000 particle accelerators [8] were operational across the globe. This number is increasing as research in various relevant fields is expanding. Existing accelerators are diversifying with the construction of new facilities. According to Amaldi [8], primary and secondary particle beams have undergone an evolution (Figure 2). Currently, they are u-sed for the following three types of activities:

- Beam particles are used in the analysis of physical, chemical and biological samples.
- Beam particles are used for the modification of the physical chemical and biological properties of matter.
- Energetic beam particles are used for the research in study of basic subatomic particles.

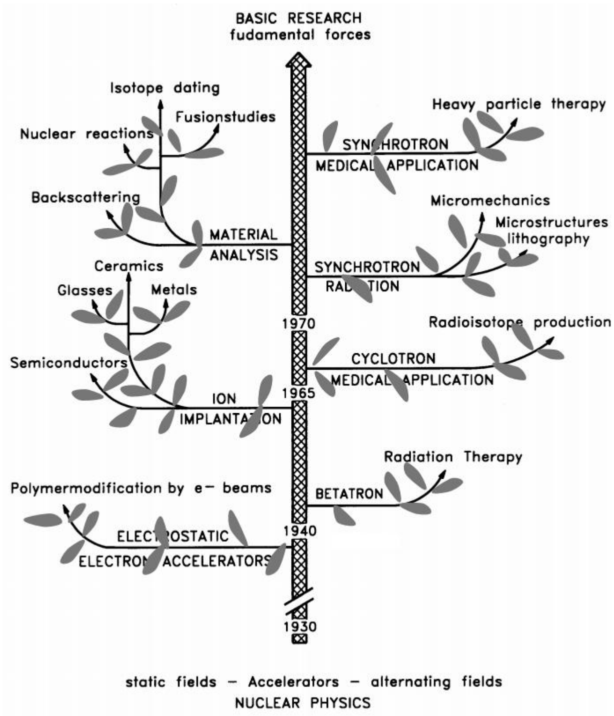

Figure 2: The Time Tree gives a pictorial view of the development of the applications of accelerators in both modification processes and sample analyses [8].

Current research shows accelerator applications in the arts, other sciences, medicine and high-tech industries. Scientific applications include: national security (e.g. cargo inspection), stockpile stewardship and materials characterization. Medical applications include: accelerator-based diagnoses and radiation therapy in hospitals and clinics around the world. High-tech industrial applications include: the modification of material properties, such as the alteration of plastics, for surface treatments and pathogen destruction in medical sterilization and food irradiation; the extensive use of ion-beam accelerators in the semiconductor industry, where they are used for chip manufacturing and for hardening the surfaces of materials, such as those used in artificial joints. Particle accelerators are also crucial for understanding the origin of our universe and for forming heavy nuclei [7][8][9].

1.1.3 PURESAFE

This project work is connected with Preventing hUman inteRvention for increased SAfety in inFrastructurEs (PURESAFE) research project [10]. PURESAFE is an acronym for “Preventing hUman intervention for increased SAfety in inFrastructures Emitting ionizing radiation”. The project’s main scientific objective is to develop models, methods and tools to improve the radiation protection in scientific facilities emitting ionizing radiation, as well as to practically implement these techniques using case studies within PURESAFE project work packages (WPs). PURESAFE focuses particularly on high energy physics accelerator facilities that can generate radioactive nuclei parts and thus require innovative maintenance techniques.

PURESAFE is a multi-disciplinary project that is divided into five WPs, of which three are further divided into research packages (RPs). WP1 addresses processes and modeling. WP2 is concerned with the hardware platforms and applications of WP1 and WP3 in actual RH projects. WP3 addresses software platforms for RH. It is worth noting that input from various research projects from WP1, WP2 and WP3 are applied in this research work and contribute to the research work's results. These concern radiation protection, intervention planning, teleoperation, mobile robotic communication and the integration of RAMS (Reliability, Availability, Maintainability and Safety) into systems design.

1.1.4 General context

The main application of the PURESAFE project concerns High Energy Particle accelerator (HEP) facilities. Such HEP facilities are focused on high energy physics in order to study the smallest known components of matter [11]. These facilities use high-tech equipment (including particle accelerators, vacuum chambers, targets, detectors and magnets) to accelerate, steer, focus and stop particle beams in order to perform experiments [11][12][13]. In order to push the boundaries of physics research , experimental physics is progressing towards the use of higher-energy particle beams to perform experiments [2][6][7]. This has, in turn, caused physicists and engineers to develop more complex machines [13][14][17]. Particle accelerator facilities that consist of multiple complex machines can be termed "super-systems." The complex machines themselves can be termed as "subsystems", which are composed of "equipment". During beam circulations in experiments, these subsystems and pieces of equipment interact directly with high-energy beams, causing beam collisions within accelerators and detectors. These interactions cause the undesirable radiological activation of accelerator facilities and equipments [18].

Due to the ionizing radiation at HEP facilities, the radioactive equipment at such facilities cannot be directly handled or maintained by personnel. Thus, at this stage, there is a significant need to reduce the level of radiation dosage experienced by personnel during the inspection, maintenance, installation, replacement, removal and storage of radioactive elements. Strategies to reduce the radiation dosages experienced by personnel include: improving the design and development of HEP facilities, using telerobotics or RH to conduct maintenance activities, and implementing State Of the Art tools for intervention prediction and planning.

The studies conducted in this research are connected with the Facility of Anti-proton and Ion Research (FAIR), which is currently under construction and development in Darmstadt, Germany. The development of this thesis is focused solely on the FAIR project and it addresses the design needs of the FAIR facility. However, the same approaches, tools and techniques can be implemented in other high-energy particle accelerator facilities. Examples of such facilites are: Conseil Européen pour la Recherche Nucléaire (CERN) [19][20] , Grand Accélérateur National d'Ions Lourds (GANIL) SPIRAL2[21], and Facility for Rare Isotope Beams (FRIB)[22]). Since particle accelerator inception, there are two basic types of modern accelerators for HEP facilities: linear and circular with various components that can become activated due to operation [23][24].The developments can also be useful to other facilities involving ionizing radiation which are not accelerator facilities, for example: Joint European Torus (JET) [96][97], International Thermonuclear Experimental Reactor (ITER) [98], and DEMOnstration Power Plant (DEMO) [98].

1.1.5 Facility for Antiproton and Ion Research (FAIR)

The FAIR facility, in Darmstadt, Germany, was proposed in 2001 by the GSI in collaboration with the wider international science community. The government gave conditional approval for the construction of FAIR in February 2003. The approval was based upon the following conditions [2]: "(i) a scientific-technical plan for a staged construction, and (ii) participation of international partners contributing at least 25% to the construction cost". Thus far, 14 countries (China, Finland, France, Germany, Greece, India, Italy, Poland, Romania, Russia, Slovenia, Spain, Sweden, and the United Kingdom) have signed the Memorandum of Understanding for FAIR, indicating their wish to participate in the FAIR facility [2][5].

The current FAIR facility layout consists of a superconducting double-Synchrotron, the SIS100/300, with a circumference of 1,100 meters. This lies at the heart of the FAIR accelerator facility, as shown in Figure 3. Following an upgrade for high intensities, the existing GSI accelerators Universal Linear Accelerator (UNILAC) and Schwerionen-Synchrotron 18 (SIS18) will serve as an injector. Following a high-intensity upgrade, the existing GSI accelerators, the UNILAC and the SIS18, will serve as injectors. In the resulting double-ringed facility, continuous beams with high average intensities of up to $3x10^{11}$ ions per second will be provided at energies of 1 GeV/u for heavy ions, using primary beam parameters from the SIS100/300 facility for the different research fields, as shown in Figure 4 [5].

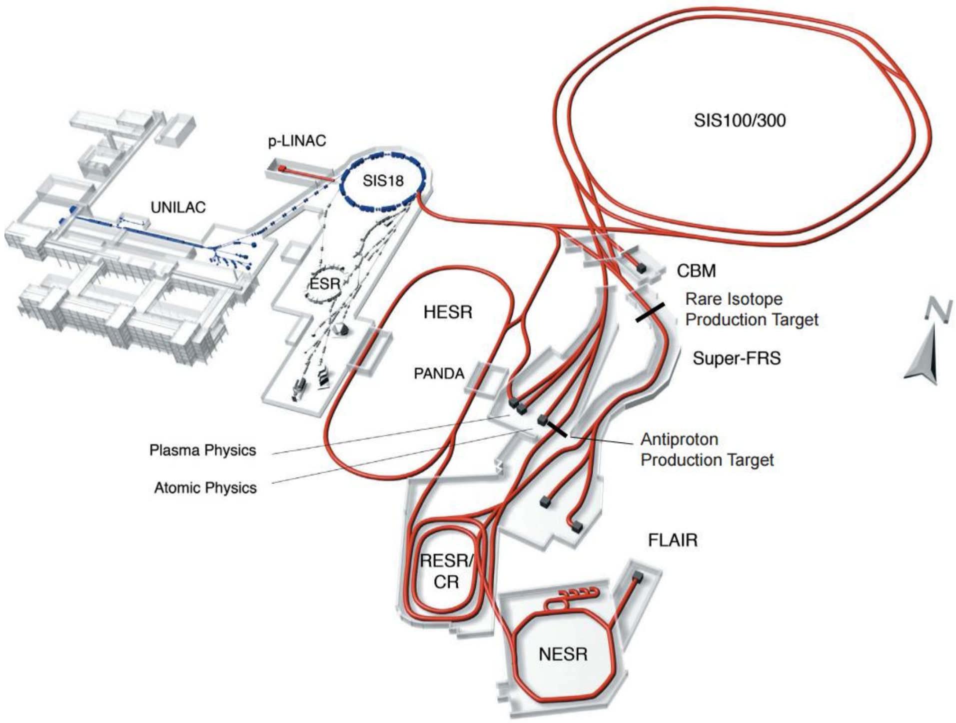

Figure 3: Layout of the existing GSI facility (UNILAC, SIS18, and Experimental Storage Ring (ESR)) are shown in blue on the left and the planned FAIR facility is shown on the right in red. This includes: the superconducting synchrotrons SIS100 and SIS300, the collector ring (CR), the accumulator ring (Recycled-Experimental-Storage-Ring (RESR)), the new experimental storage ring (Neue-Experimentier-Speicherring (NESR)), the rare isotope production target, the superconducting fragment separator (Super-FRS), the proton LINAC, the antiproton production target, and the high energy antiproton storage ring (der Hochenergie-Speicherring (HESR)). Also shown are the experimental stations for plasma physics, relativistic nuclear collisions (Compressed Baryonic Matter (CBM)), radioactive ion beams (Super-FRS), atomic physics, and low-energy antiproton and ion physics [2].

Research Field	Energy	Peak Intensity	Average Intensity	Pulse Structure
Radioactive Ion Beams	0.4 to 1.5 GeV/u for all elements up to uranium	~$5 \cdot 10^{11}$ per pulse for storage ring experiments	~$3 \cdot 10^{11}$ per second high duty cycle for fixed target experiments	~60 ns for injection into the storage ring
Antiprotons	29 GeV protons	$4 \cdot 10^{13}$ per cycle	--	~25 ns
Dense Nuclear Matter	45 GeV/u for A/q=0.5 up to 34 for A/q=2.7	--	$2 \cdot 10^{9}$ per second	--
Plasma Physics	0.4 to 1 GeV/u ions	~10^{12} per pulse	--	50 - 100 ns (fixed target)
Atomic Physics	0.1 to 10 GeV/u ions	--		--

Figure 4: Primary beam parameters (table) from the SIS100/300 facility for the different research fields[2].

The accelerator complex at FAIR will host a large number of experiments, of which the four largest will reside on the Super Fragment Separator (Super-FRS). The Super-FRS is the main application area for FAIR facility. Radiation doses will be present at the Super-FRS facility due to the activation of beamline inserts, which will require remote maintenance. It is in this context of remote maintenance that this thesis focuses on developing a conceptual solution with a systematic framework to fulfill the RH needs of the Super-FRS and FAIR facility in an effective and optimized manner.

1.2 Remote Handling (RH)

Teleoperation and mobile robotics are now frequently used to carry out maintenance tasks in hostile and hazardous environments, where humans cannot perform certain tasks due to safety issues (e.g., high radiation levels or environmental challenges) [25][26][27][28]. Performing tasks with teleoperation equipment, mobile robotics and automated robotic systems enables humans to conduct remote manipulations safely and reliably, without engaging in personal contact with dangerous items [29]. The term “RH” is used in this thesis to refer to remote maintenance tasks performed by robots, whether these tasks are teleoperated, completed under supervisory control or carried out by automatic systems. The use of RH systems is very common in nuclear [30][31][32][33], space [34][26][28], and subsea [29][30][40] industries; however, the term “RH” is most commonly used in relation to the nuclear power industry, where the term refers to the maintenance of power-generating equipment, the processing of fuel assemblies, the inspection of surroundings and the manipulation of activated parts (e.g. through repairs to damaged equipment, exchanges of parts, disposals of activated material and storage). In the nuclear power industry, all tasks are conducted inside hot cell. RH tasks in radiation environments are typically carried out using dedicated, modified equipment that is controlled and operated from a central control room, as shown in Figure 5. RH is also used in hospitals and educational laboratories to conduct surgeries and research activities using high-precision telerobotic equipment.

From the 1960s until the present day, the RH philosophy has followed the “human in the loop” concept, in which a human operator controls machine output by entering commands via a Human-Machine Interface (HMI)[29]. However, progress in the use of industrial robots over the past three decades has enabled RH engineers to use low-cost, high-performance industrial robots for more automated RH applications[41].

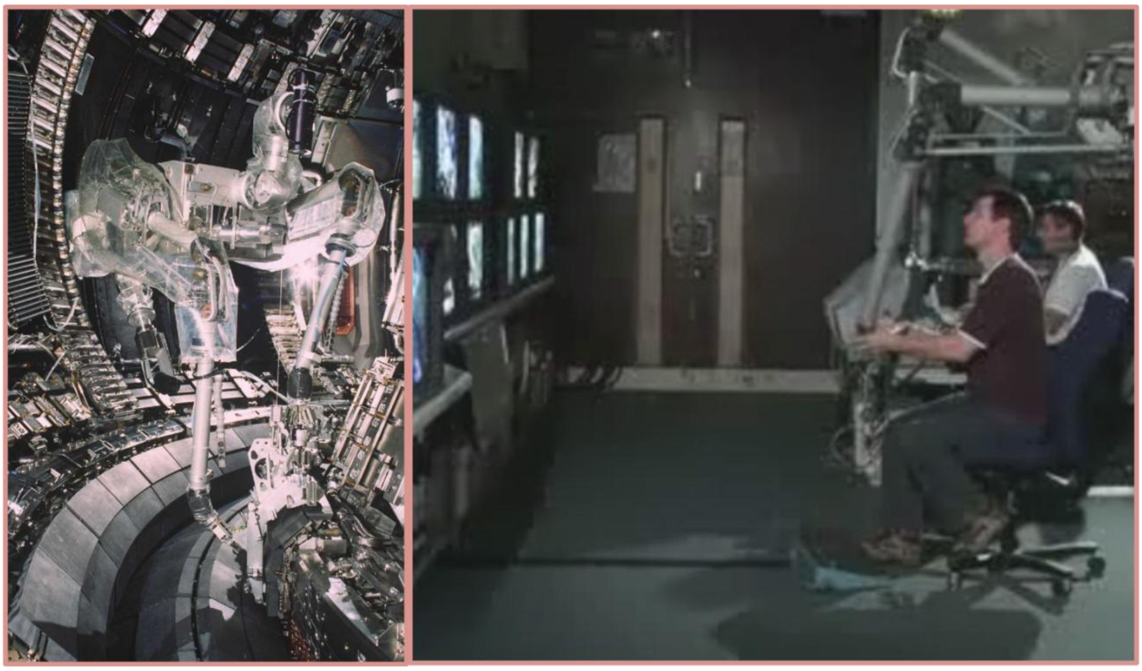

Figure 5. RH at JET facility representing control room (right) and RH equipment (left)

1.3 The need for RH in HEP facilities

1.3.1 Radiation environment

HEP facilities are highly radioactive due to activated material in the beamline equipment. In order to produce a high rate of secondary particles, such as antiprotons, neutrons, neutrinos and rare isotopes, beams are required to be very high-intensity [2][9][47]. When these beams interact with targets, it radioactively activates the material which ultimately degrades the material properties and limits the lifetime of beamline equipment. Degraded targets, collimators and beam dumps also become activated as a result of this beam interaction and, hence, must be shielded to protect humans. This beamline equipment requires constant remote maintenance. Prior to any remote maintenance or upgrade project, HEP facility accelerators are shut down gradually in order to seize the production of neutrons and to prevent the possibility of damaging radioactive effects during the interventions.

The activated products exhibit one or more of a range of radionuclides (atoms with nuclei characterized by excess energy) which is eventually dissipated through the ejection of a particle or electron. The energy state of the activated material undergoes nuclear decay, emitting harmful ionizing radiation in the process [18][42]. A radioactive “source" is said to have an activity of 1 Becquerel[1] when such trans-

[1] In this document, we will use Sievert (Sv) as the basic unit for a radiation dosage. Sv is a derived unit for ionizing radiation dosage in the International System of Units (SI).

formations are occurring at the rate of one per second. The precise relationship of activity radiation intensity depends on the decay scheme of the radionuclide involved. Radiation protection is concerned with the intensity of the radiation emitted by a source, and its main aim is to reduce human exposure to ionizing radiation. Thus, the following measures are typically taken to ensure worker safety:

- *Wait*: Radioactivity decays with time, and this decay is normally exponential. Thus, activation is typically reduced by many orders of magnitude in the first days of shut-down.
- *Shielding*: Gamma radiation can exist for long periods of time; hence, shielding is needed to protect workers from harmful effects. Shields should be developed from appropriate materials, such as concrete or lead.
- *Increased distances between workers and sources*: Workers should be placed as far from sources as possible in order to carry out maintenance. This increased distance is the prime motivator for using RH for activated beamline inserts.

New research facilities [10][12][14][36][40] which are capable of delivering powerful beams will also generate more activated parts. The handling and maintenance of these activated parts must be done remotely, and the design of new facilities should incorporate provisions for RH. Figure 6 shows a typical radioactive environment at a particle accelerator target facility—in this case, the ISOLDE facility at CERN.

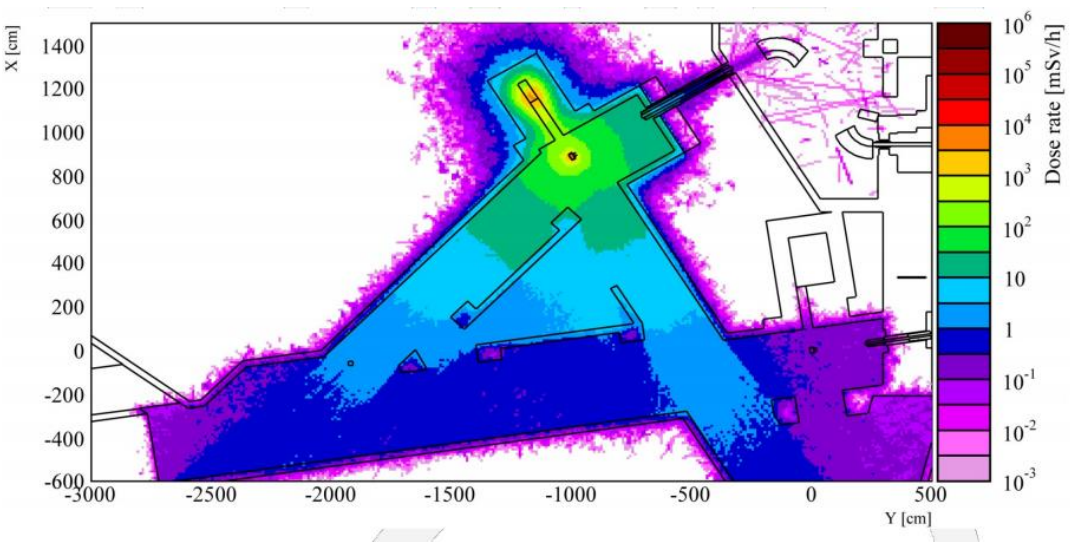

Figure 6. Radiation visualization of radiation levels at ISOLDE facility CERN [45]

1.3.2 Radiation effects on RH equipment

RH equipment typically enables workers to perform maintenance remotely, thus reducing the radiation dosages experienced by workers. However, this approach directly exposes the RH equipment to ionizing radiation. Modern robotic systems include various electronic sub-systems which require protection during RH tasks. Modern robotic systems are composed of various components which are affected by radiation (see Figure 7), including:

- Electronic components, such as microprocessors, RAM/ROM memory, ADC/DAC converters, operational amplifiers, controllers, sensors, diodes, capacitors, motors, etc.

- Mechanical components, such as metal, insulators, glass, camera lenses, fiber optic cables, lead cells, plastics, etc.

The exposure of robotic systems to ionizing radiation causes embrittlement, a loss of ductility, creep, and aging. Hence, equipment selected for use in radioactive facilities must be radiation-hardened, and sensitive systems should be placed far away from radiation. Critical robotic systems also require extensive testing before commissioning in order to estimate their life expectancy and performance parameters. Modifications are also commonly made to commercial off-the-shelf (COTS) equipment in order to reduce external development costs and enhance in-house development capabilities. Such modifications include the removal of on-board electronics and addition of shielding. The target area robots used in the ISOLDE facility are an example of this.

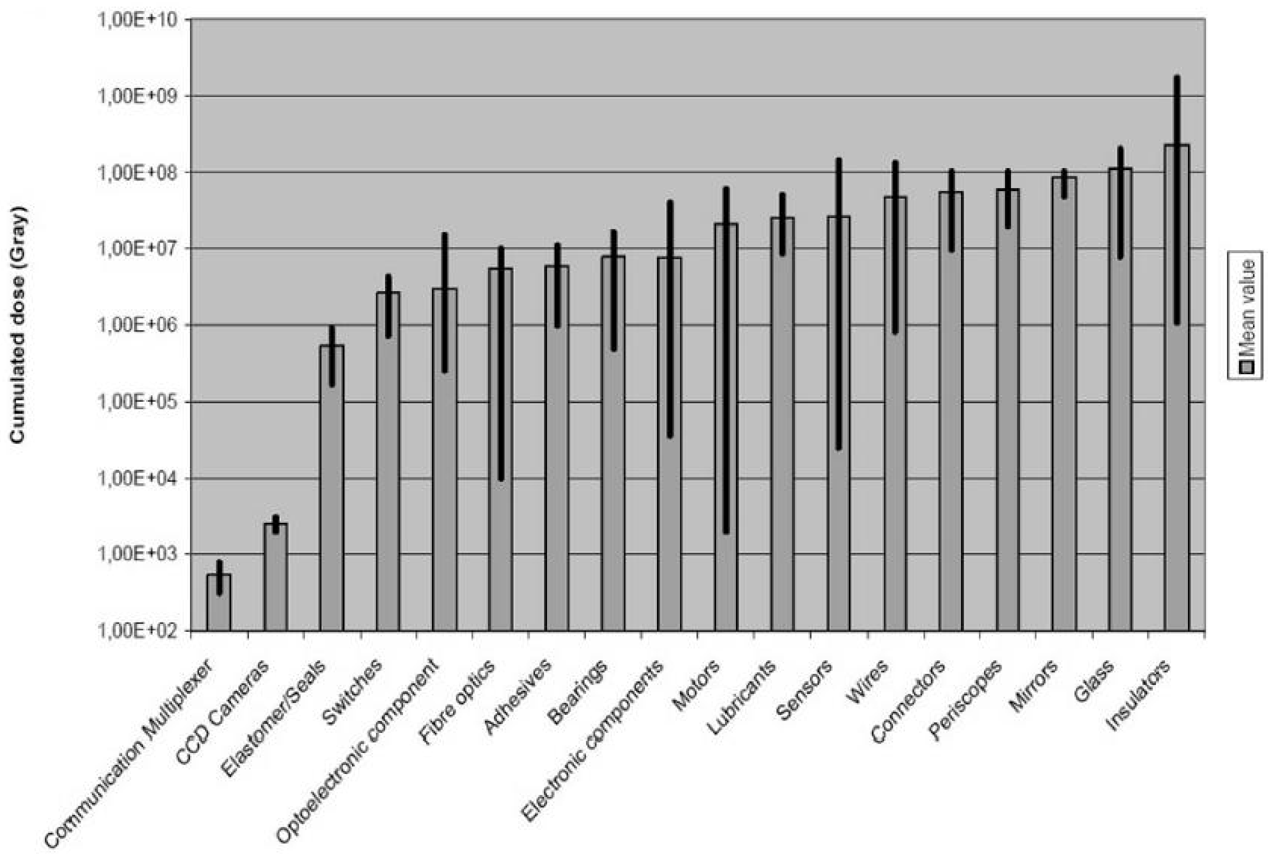

Figure 7. Cumulated permissible dose level for electronic components [42]

1.3.3 Radiation protection

Radiation protection, sometimes termed radiological protection, refers to the science of radiation effects and the practices used to protect people and the surrounding environment from the harmful effects of ionizing radiation[11][18][49][50]. Radiation protection involves measuring radiation doses and ensuring that people are not exposed to levels which are capable of causing damaging biological effects.

1.3.3.1 International legal efforts in radiation protection

Occupational radiation protection is critically important among the international community due to the harmful effects of radiation on workers' health. Legal limits are defined by national and international authorities. Some notable organizations involved in providing recommendations on radiation dose limits are listed below.

- International Atomic Energy Agency (IAEA)
- International Labour Organization (ILO)
- European Commission (EC)
- World Health Organization (WHO)
- Organization for Economic Co-operation and Development's Nuclear Energy Agency (OECD/NEA)
- United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)
- International Commission on Radiological Protection (ICRP)
- International Commission on Radiation Units and Measurements (ICRU)

In 2002, the IAEA and ILO organized an International Conference on Occupational Radiation Protection. The event was co-sponsored by the other listed organizations and was held in Geneva, Switzerland. The conference specified recommendations for occupational radiation protection based on the global progress made over the past few decades in radiation protection.

ICRP [51] recommendations regarding radiation limits serve as the basis for all standards put forward by all of the other organizations listed. The radiation dose limits recommended by the ICRP [50][52] are based on radiation biology, which consider the damaging interactions of ionizing particles with living tissues. The European Union (EU) has adopted the European Atomic Energy Community (EURATOM) directive (Directive 96/29 [53]), which is the basis for radiation protection regulations for EU member states. EURATOM includes the Recommendations of the International Commission on Radiological Protection (ICRP60)[54][55][2].

The work in this thesis follows the occupational radiation doses recommended by the German Federal Office for Radiation Protection, which are in line with those of the EURATOM directive [53] and those of the ICRP103 [55]. Thus, the dose limits used are in line with the basic safety standards outlined by the EU [56] at the time of writing. Dose limits are frequently altered by national and international regulators, as shown in Figure 8[57] This is due to the continued evolution of the field of radiation protection and the persistent lack of a full understanding of the effects of radiation [58]. In Germany, according to European guidelines, the permissible effective dose of occupational radiation exposure is 20 millisievert (mSv) per calendar year [56]. The German Commission on Radiological Protection (SSK) (in German: Strahlenschutzkommission) advises the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) on issues concerning protection from the risks of ionizing and non-ionizing radiation.

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[2] The ICRP updated the recommendation in 2007 that are known as "ICRP103"[55]

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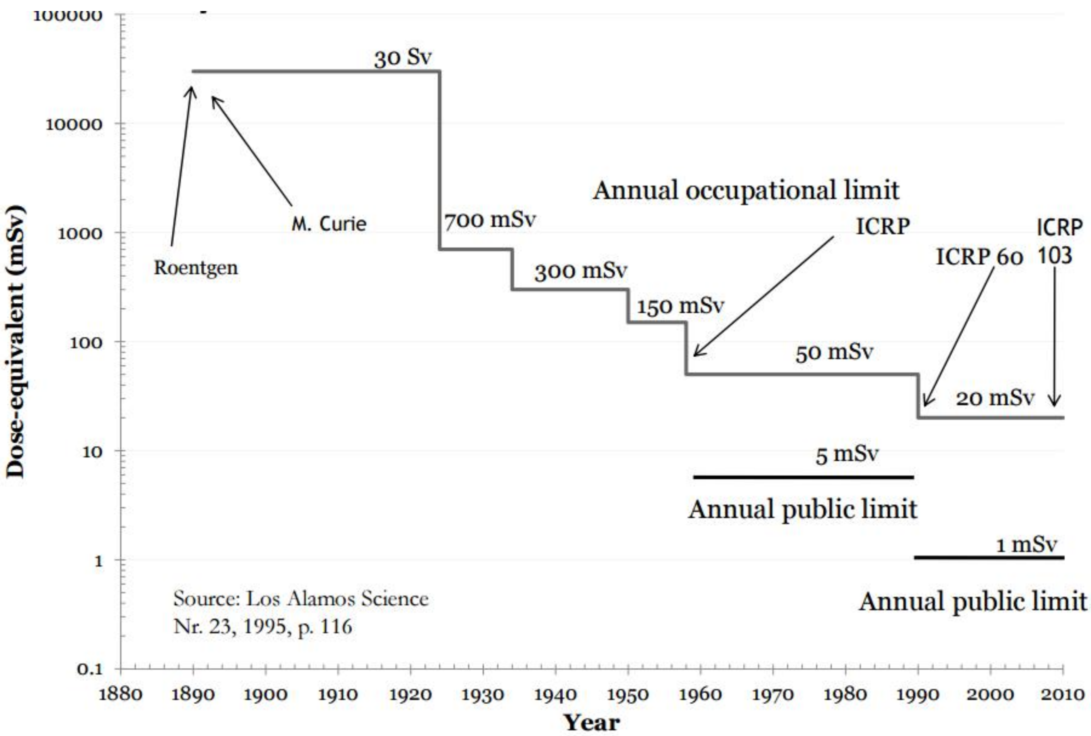

Figure 8: This logarithmic plot of the recommended limits on annual exposures to radiation shows a continual decrease from the beginning of the century to the present [57].

The GSI Helmholtz Center for Heavy Ion Research is a German research organization and, thus, is obliged to abide by German dose limit standards. However, the GSI also imposes stricter regulations on itself to reduce workers' radiation doses to no more than 2mSv/year, [24].

1.3.3.2 Radiation protection principles and philosophy

HEP facilities are complex machines, comprised of various types of scientific equipment, such as particle accelerators and beamline inserts (e.g., detectors/slits, etc.). All of these require maintenance over time. It is during this maintenance that human intervention is needed. To protect human beings in radiation environments, the most common technique is called ALARP or ALARA (As Low As Reasonably Practicable or Achievable) [50][59][66]. This approach is used to limit the radiation doses received by humans. The ALARA approach is based on the philosophic principle of "justifying, optimizing and limiting" the doses received by all who need to work on or near activated parts of the facility.

ICRP60 and ICRP103 recommend that all radiation protection be based on this same philosophy[54][55]. The justification principle requires that an "intervention procedure will benefit the individual and society to balance the radiation dose effects; while there is no alternative solution exists which would not involve radiation exposure". The optimization principle states that any "(1) intervention scenario/s has been assessed in regards to radiation protection, (2) decision making process is traceable to selected intervention scenario/s, (3) possible accidents and disposal of radiation sources are taken into consideration for intervention scenario/s". The limitation principle requires that exposure "comply with the annual dose limit/dose constraint based on recommendations of the ICRP" [61][62].

Based on this philosophy of "justification, optimization and limitation", the ALARA principle has become the most predominant methodology for estimating received doses [59]. In the case of occupational exposure, which is the relevant case for the context of this thesis, the dose received by individually monitored personnel during any consecutive 12-month period must not exceed 20 mSv. The ALARA approach is implemented to prevent any exposures beyond the limit value since "in case of continuing exposure, this exposure is associated with a radiological risk for the individual which cannot be accepted any more under 'normal' circumstances" [59][61][62]).

The ALARA principle has been globally adopted by all radiation protection agencies based on the IAEA's Occupational Radiation Protection recommendations: Protecting Workers against Exposure to Ionizing Radiation[61].

1.3.3.3 Radiation doses

HEP facilities and nuclear power plants are some of the major sources of non-naturally occurring ionizing radiation. The ionization process occurs when an atom becomes excited due to the high energy carried by the radiation and therefore gains (or loses) an electron. In HEP facilities, ionizing radiation includes alpha particles (protons and neutrons), beta particles (electrons and positrons) and photons (gamma rays and X-rays). Ionizing radiation can affect humans both deterministically (through high levels of radiation exposure) and stochastically (through low levels of exposure). The ICRU has laid the scientific-mathematical basis for radiation protection [62][66].

The fundamental protection quantities adopted by the ICRP are based on measures of the energy deposited in the organs and tissues of the human body. The total amount of ionizing radiation absorbed by material or tissues is termed an "absorbed dose". This absorbed dose (aka "energy dose") is the fundamental physical quantity that serves as the basis for all subsequent quantities used in radiation protection [50]. The ICRP states the following: "The ***absorbed dose*** abbreviated as D, is the amount of energy locally deposited at a given location in matter. It is defined as the deposited energy (ΔE) per unit of mass of material (Δm)"[62][66]:

$$D = \frac{\Delta E}{\Delta m} \qquad [\mathrm{Gy} = \mathrm{J.kg^{-1}}] \qquad \text{Eq 1}$$

The unit of an absorbed dose is the gray (Gy)[3]. The absorbed dose depends on both the incident radiation and the absorbing material.

Equivalent dose

Since different types of ionizing radiation cause different amounts of damage to living tissue, the "equivalent dose" (H) was developed as the product of the absorbed dose for ICRU-tissue and the weighting factor W_R (where R stands for the radiation type). This dose is used to determine the dam-

[3] Old units, which are still used in parts of the world are the rad and the rep.
1 rad = 0.01 Gy (2.3)
1 rep = 8.3 or 9.3mGy

age to human tissue for different types of radiation. These weighting factors (shown in Figure 9) are defined by ICRP103 [55]. The "equivalent dose" is defined as:

$$H = \sum_{R} W_R D_R \qquad \text{Eq 2}$$

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	$\begin{cases} 2.5 + 18.2 \cdot e^{-(\ln(E_n))^2/6} & E_n < 1 \text{ MeV} \\ 5.0 + 17.0 \cdot e^{-(\ln(2E_n))^2/6} & 1 \text{ MeV} \leq E_n \leq 50 \text{ MeV} \\ 2.5 + 3.25 \cdot e^{-(\ln(2E_n))^2/6} & E_n > 50 \text{ MeV} \end{cases}$

Figure 9. Radiation weighting factors W_R table as defined in ICRP103 [55]

The "equivalent dose" to a specific organ or tissue T is defined as:

$$H_T = \sum_{R} W_R D_{T,R} \qquad \text{Eq 3}$$

The unit of equivalent dose is J kg^{-1}, which is also known as the Sievert (Sv).

Effective Dose

All human organs are sensitive to ionizing radiation; however, the equivalent dose can harm some organs more than others. To quantify the effects of the equivalent dose on different organs, the "effective dose" (E) was developed. To calculate the effective dose, the equivalent dose is weighted by the tissue weighting factor W_T, which depends on the tissue or organ that the radiation is affecting. W_T values are also defined by ICRP103 (see Figure 10). The effective dose is defined as:

$$E = \sum_{T} W_T H_T \qquad \text{Eq 4}$$

$$= \sum_{T} W_T \sum_{R} W_R D_{T,R} \quad [Sv]$$

In Eq 4 W_T is the tissue weighting factor for tissue T and $\sum_T W_T = 1$.The unit of equivalent dose is also the Sievert. The effective dose is the main quantity that is used in radiation protection, and it is also the main quantity that we will use in this research work.

Tissue	w_T	$\sum w_T$
Bone-marrow (red), Colon, Lung, Stomach, Breast, Remainder tissues[1]	0.12	0.72
Gonads	0.08	0.08
Bladder, Oesophagus, Liver, Thyroid	0.04	0.16
Bone surface, Brain, Salivary glands, Skin	0.01	0.04
	Total	1

[1] Remainder tissues: Adrenals, Extrathoracic (ET) region, Gall Bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate (♂), Small intestine, Spleen, Thymus, Uterus/cervix (♀)

Figure 10. Tissue weighting factor W_T table as defined by ICRP103 [55].

1.3.3.4 Radiation protection in particle accelerator facilities

HEP facilities have a legal obligation to protect the public and any persons working on their sites from exposure to ionizing radiation. The results of these measurements facilitate the preventive assessment of radiological risks and the reduction/elimination of individual and collective doses. Figure 11 provides an example of a GSI beam operation lifecycle and shows the position of an ALARA approach in radiation protection. The following criteria may apply, depending on whether the particle accelerator machines (and, thus, the particle beams) are running:

Beam ON: No access for personnel is possible when particle beams are circulating in the accelerator. This is because of the high levels of radiation will affect both humans and electronics. For the same reason, electronic devices (e.g., RH equipment) cannot be permanently fixed or placed inside the beam facilities.

Beam OFF: Once the beam is turned off and the cool-down period has passed, human intervention is usually possible. The cool-down period is over when the residual activity is below a certain legal and admissible threshold. However, some areas are not accessible to humans even after the beam has been turned off, due to residual radioactivity from activated components. Such areas can only be inspected and maintained with remote maintenance equipment. Radiation tolerances in robot components are generally greater than four orders of magnitude higher than those in humans [20] [51][54][69]. For this reason, RH can be used inside beam facilities during and after the cool-down period when human access is restricted.

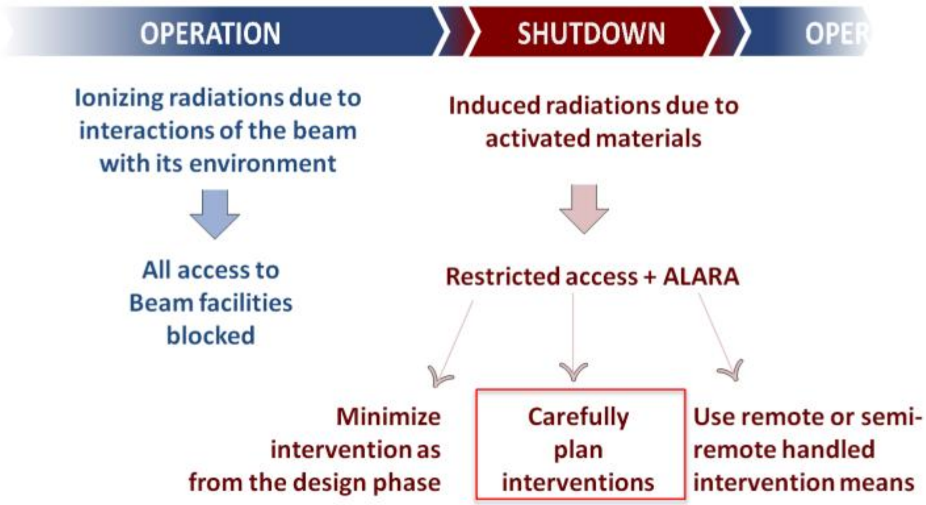

Figure 11. HEP facilities operational cycle with ALARA application.

1.3.3.5 The need for robotic systems for RH

There is a clear need for robotic RH systems in HEP facilities, due to the radioactive environment and effects of radiation as explained above. Electronics can handle a total dosage of 100 Sv, which is far more than 2mSv dose limit for personnel at GSI. In the FAIR facility, the beamline insert will be highly radioactive. Remote maintenance will be obligatory as human workers will be unable to directly handle the beamline inserts. The major benefits of using RH equipment in the FAIR facility are:

- Reducing the exposure of workers to ionizing radiation within FAIR through planning. RH could help in the planning of human maintenance interventions by providing detailed radiation measurements and visual checks of faulty equipment. Moreover, mobile robots may facilitate more accurate measurements and visual inspections, since they eliminate the need for the time limits imposed on humans in places with high-radiation.
- Handling radioactive parts (i.e., removing and installing the beamline insert, transporting radioactive parts to hot cells for storage and maintenance, etc.).
- Optimizing HEP facility maintenance overall (i.e., increasing beam availability by reducing downtime). The cool-down period can be quite long (several days/weeks) before an access is granted for a human to visually check of the equipment, especially in cases of machine failures during beam operation. The use of RH would remove this restriction and so allow maintenance to be carried out more quickly.

1.3.4 Existing RH in HEP facilities

RH is not a new concept within HEP facilities. However, although it has been used frequently in some facilities, the use is limited and very specific. Majority of the RH systems with in HEP facilities were not originally planned for the HEP facilities overtime and one examples of particle accelerator facilities that have gradually added RH capabilities over time are: The Paul Scherrer Institute (PSI) in Switzerland [33][34], the Oak Ridge National Laboratory (ORNL) in USA [35][36], CERN in Switzerland [19][66], and the GSI Helmholtz Centre for Heavy Ion Research (GSI) in Germany [3][24] For all these facilities, RH was not originally planned for. It was only integrated later, as the radioactivity hampered the sequence of maintenance tasks.

There are four main cases in which HEP facilities require maintenance:

- System failure prevents the facility's normal operations (e.g., damage to a beamline insert, including target or instrumentation, leads to a need for replacement).
- Normal degradation of system components (aging) leads to a need for periodic preventive maintenance of the system (e.g., beamline inserts, vacuum pumps, cryogenics, etc.).
- The experimental system requires changes. The Super-FRS setup will require modifications or changes as a routine part of the experiments. For example, the Nuclear Structure, Astrophysics and Reactions (NuSTAR) collaboration at FRS may want to test new ideas to verify theories, which will require the installation of new instruments into the setup.
- Regular inspections during regular annual checks. These are carried out to maintain the operational license for HEP facilities (e.g., cryogenic systems require annual checks of their values).

As a general rule, FAIR components with failure probabilities of greater than 1 in 20 years of facility operation require scheduled preventive maintenance or replacement. For example, the Super-FRS target will interact directly with a beam and, thus, be subjected to a high level of wear and tear. As a result, it will need scheduled replacement after two years. FAIR's lifecycle is 40 years; hence, the equipment that is bound to fail during the FAIR facility's operation duration will require maintenance if its parts are ionized due to beam interactions.

Components with low failure probabilities do not require scheduled maintenance; however, in the case of unexpected failures, they may require unscheduled maintenance. For example, magnets are designed to last throughout a facility's lifecycle. However, a magnet failure would require unscheduled shutdown and maintenance.

In September 2008, a "large helium leak into sector 3-4 of the LHC tunnel [was confirmed to have been caused by] a faulty electrical connection between two of the accelerator's magnets". This was an unexpected event that was unforeseen, and CERN had to conduct necessary repairs to make the facility operational again[67] . If certain failures occur at HEP facilities due to unforeseen incidents, unscheduled repairs must be considered. Any unplanned event will require remote inspection prior to a systematic analysis of the event.

Maintenance operations in HEP facilities are performed by qualified workers in full accordance with the principle of ALARA (see section 1.3.3.4). For example, at GSI, the environmental dose limit for radiation workers is 10μSv/h for hands-on maintenance. As discussed in section 1.3.3.3, the annual total dose limit is 2mSv. Some of the equipment at GSI (as well as in CERN, PSI and other facilities) have higher activation levels than these limits allow and, hence, emit very dangerous levels of radiation. In such cases, RH is the only solution. The need for RH is explained in section 1.3 in more detail.

RH utilizes State of the Art technologies and engineering management techniques to enable operators to handle radioactive components from a safe distance without endangering maintenance workers. Experiences of RH at facilities, like JET, show that remote maintenance operations take more time and effort than normal maintenance[41]. Effective remote maintenance is only possible when [41]:

- RH equipment is carefully designed from an early stage according to system needs.
- RH tasks are planned in advance and in detail.

- The components requiring remote maintenance are compatible with RH.
- Extensive testing is required on mockups before RH tasks are actually performed in a real-world environment.

The role of RH in the maintenance of HEP facilities has increased recently and it is now considered a basic requirement. Provisions for the RH of activated materials is now a major part of proposals for new HEP facilities, such as GANIL SPIRAL2 [21], the Japan Proton Accelerator Research Complex (J-PARC) [43], the FAIR [2] and the FRIB[22].

The details regarding existing RH equipment and capabilities at selected HEP facilities will be explained in more detail in Chapter 2.

1.3.5 Project engineering and Systems Engineering (SE) for HEP facilities RH

The complexity of HEP facilities is increasing and, as a result there is an increasing need for Systems Engineering (SE). Previous studies [68][69] have shown that a standard SE approach to project management can increase chances to success to develop HEP complex systems. However, SE [70][71][72] literature suggest that the "complex technical project success is dependent on the management process and procedure supporting the technical requirements and concept designs that are carefully designed that vividly explains the interfaces within the system". Hence, project management or the technical development of RH at later project stages is a suitable option for HEP project success. RH systems need to be integrated from the start of any HEP project. The technical aspects of the project need to be defined very early on in order to ensure project success and compatibility[73].

Every HEP facility is a complex project composed of complex systems and machines. Normally, HEP facilities are developed by physicists, whose knowledge regarding project management and SE are limited. Early HEP facilities were not as large as they are now, and the resources needed to execute them were locally available. In contrast, modern HEP facilities, like the LHC, the FRIB, SPIRAL 2 and FAIR, are enormous projects. They require funding and resources from both local and international bodies. Effective project management and SE approaches must be introduced if the projects are to be successful. The PURESAFE ITN is one such approach, launched by the EU to introduce SE practices into the development of HEP facilities. PURESAFE brings together engineering students from different fields to train them in the maintenance needs of HEP facilities.

1.4 Research motivation and objectives

1.4.1 Motivation

As outlined above, RH has become an integral part of the design of HEP facilities. It is imperative that designers adopt a systematic approach to develop and evaluate integrated RH concepts during the early stages of the project. However, there is very little literature on how to approach such development in a systematic way.

Up until now, every HEP facility in the world has adopted its own practices to develop their RH systems. Thus, each facility has unique RH equipment and, hence, the information regarding their RH systems is scattered and not available in a unified format. Individual HEP facilities also have RH experts, who are major contributors and pioneers of the equipment and practices used within the facility.

These experts don’t often publish their experiences, which limits our understanding of the existing RH practices in such facilities. All these factors combined mean that RH systems are developed without any systematic approach.

Due to the reasons stated above, RH systems are always based on expert opinions and personal experiences. It is undeniable that expert opinions and experiences are critical to RH development; however expert opinion is not enough on its own. It is also critical to understand the RH systems and approaches that are used in various HEP facilities and to utilize knowledge from SE to design RH concepts at earlier stages to avoid issues with equipment reliability, cost, maintenance and logistics at later stages of the product life cycle. Since HEP facilities are research-oriented and have limited budgets for RH. The budget allocated to the development of HEP RH is fraction of total facility costs, it is important to develop systems that are cost effective and reliable. To develop such systems, it is important to use COTS equipment to reduce the costs of concept development. It is also important to evaluate the concepts developed for RH, including costs, without compromising system functionality.

The Super Fragment Separator (Super-FRS) facility is a new facility at FAIR, with higher beam intensities compared to beam intensities at FRS in GSI. It is of the utmost importance that the RH concepts are developed in such a way that they can be tested and further developed before the RH is implemented in the new facility.

Thus, the motivation for carrying out this research is to develop a concept design for the Super-FRS facility by:

- Reviewing the RH systems of HEP facilities across the globe.
- Classifying RH equipment to develop a guideline for future RH equipment selection in HEP facilities.
- Reviewing the various SE approaches which already exist for developing complex equipment.
- Defining a systematic approach for developing and evaluating RH concept designs based on the findings of this SE review.
- Developing an optimal RH concept for the main Super-FRS tunnel using a SE approach.

1.4.2 Objectives

Complex machines like the Super-FRS are not only expensive to build, but are also costly to maintain due to the fact that they produce activated beamline inserts (e.g., targets, instruments, slits, degrader wedges, etc.). Consequently, due to high levels of radiation, the Super-FRS requires comprehensive RH logistics to address logistical issues in the handling of activated beamline inserts. These RH logistics need to be developed at a conceptual level to make them more reliable. This approach will identify the possible failures of RH systems and negate any causes for possible failures. It will also make it safer, and more cost-effective, to conduct detailed radiation and intervention analysis and maintenance. However, for routine inspections and maintenance tasks, the number and duration of interventions should be minimized and shifted to the use of RH equipment.

The main focus of this thesis is to develop RH system concept using SE knowledge to carry out remote maintenance at HEP facilities. The key objective of this thesis is to propose new systematic approach for developing and evaluation of RH concept designs for HEP facilities. This thesis also focuses on developing a RH logistics concept and select RH equipment for the activated beamline inserts produced in the Super-FRS facility a systematic approach. The work presented in this thesis can then be used as a guideline for the development of RH system and logistic concept studies at other HEP facilities across the globe. The key features of this RH logistics concept and systematic approach will be based on the following:

- Selecting a concept that is safe to operate with minimum failures (due to known causes and consequences) and that will reduce human interventions and accumulated doses for humans and equipment.
- Optimizing and improving the RH logistics in order to optimize individual intervention scenario.
- Optimizing the HEP facilities limited resources to find suitable RH system according to HEP facility's requirements.

1.5 Research questions

Based on the thesis section motivation (Section 1.3.3.5 and Section 1.3.4) and objectives, this research will address the following research questions:

- How the latest RH technologies can be used to reduce the exposure of worker to ionization radiation at HEP facilities?
- How to optimize the HEP facility RH maintenance by increasing beam availability and reducing downtime?
- What are the State of the Art techniques and equipment used in existing HEP facilities to conduct RH and maintenance of radioactive parts?
- How can we develop, classify and categorize the RH equipment used in HEP facilities, to improve HEP facilities and equipment categorization in order optimize technology integration?
- How can we study and understand the approaches and processes related to the development of RH concepts in HEP facilities and in the nuclear industry?
- What do we know about the expert approach to concept development in the earlier design stages of HEP facilities?
- What do experts consider to be the key factors in the development of RH concepts for HEP facilities?
- How can we use current practices to develop a SE approach which improves the development, integration and evaluation of RH concepts in the stages of a project?
- What tools and approaches can be adopted that will contribute to the concept development for RH logistics?
- How can we develop a concept for RH logistics in a cost-effective manner?

1.6 Research approach

This research project is focused on finding a solution to Super-FRS RH problems in a systematic manner. It aims to find an approach to professional design development that can be reused in the future. The research uses a multimethodological approach [74] for systems building within design engineering. The research only focuses on concept development and does not involve prototype development, which is outside the scope of the thesis.

RH system concepts are typically developed at a very early stage of a facility's lifecycle. A system's behavior may subsequently change once it has been deployed, due to changing environmental factors during facility development. This makes the objective evaluation of specific RH concept very difficult, since every situation and case is different. By using a multimethodological approach, the focus is on the construction and extraction of valuable artifacts (e.g., models, knowledge, methods and tools) from existing solutions to other problems in the field. In this way, the research aims to obtain solutions for future problems in an innovative way and to deliver the required results. Multimethodological approaches for systems development uses a constructive approach [132] that fills in conceptual and knowledge gaps by using existing practices and knowledge, which are tailored to support each individual case or situation.

The specific multimethodological approach used in this research is based on that presented by Nunamker et al. [74], which is shown in Figure 12.

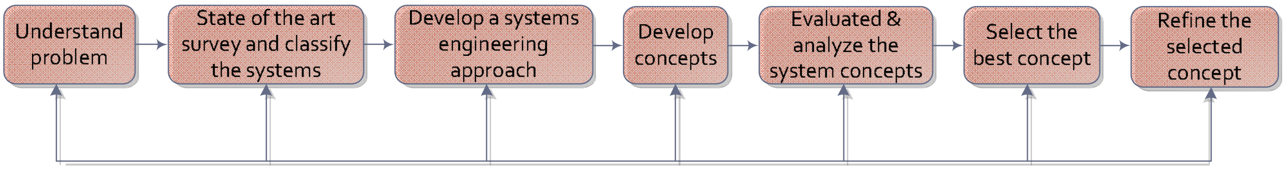

Figure 12. Research approach for development of RH logistic concept [74].

In order to utilize this multimethodological approach, it is important to understand the background of the problem domain in order to establish the environment of the RH system. It is also important to understand the roles of system engineering and system development lifecycles in order to develop a lean, systematic approach for the development of RH system concepts. Based on this analysis, concept designs can then be developed. The various concepts are then evaluated in order to select the best one, which is then refined for architectural and detailed design processes.

1.7 Contribution of the research

The main contributions of this research are as follows:

- Development of systematic approach for designing RH systems concepts for HEP facilities.
- Detailed classification and categorization of HEP facilities hazardous environments, RH practices, RH planning methodologies, RH equipment, and RH technologies to develop RH solutions for development of HEP facilities and research facilities from across the globe.
- Development of RH system and logistics concept for Super/FRS facility utilizing SE approach.
- Planning an effective RH remote maintenance schedule to maximize system flexibility and performance by optimization the RH task sequences.
- Development and selection of RH designs based on SE approach, which can then be generalized for developing RH logistic concepts for scientific facilities.
- Development of criteria for integrating COTS equipment into RH logistics concepts based on the opinions and evaluations of RH experts.
- Detailed information concerning RH systems in scientific facilities (e.g., PSI, CERN, GSI etc.) that have not yet been reported, including logistics practices, methods, equipment and problems faced .
- Use of and contribution to the development of tools to improve and optimize RH logistics, task sequences and intervention scenarios.

- Integrating RH system requirements and needs to HEP facility development process at an early stage of product lifecycle, to influence the facilities equipment and infrastructure design process.

1.8 Thesis structure

This thesis is divided into four chapters. The contents of each chapter are summarized below:

This thesis is divided into four chapters. The contents of each chapter are summarized below:

Chapter 1: Chapter 1 provides a brief overview of the research objectives, contributions and goals. It elaborates on the research context, the importance of particle accelerators, the need for RH in radiation, radiation protection requirements, and the research methodology used to achieve the target goals.

Chapter 2: Chapter 2 examines the current state of the systems and practices in the field of RH engineering, including RH systems and SE practices for them. The chapter is split into two sections. The first section includes a detailed survey of the RH systems currently used in different HEP facilities. Based on the results of this survey, the State of the Art equipment used to conduct remote maintenance are categorized and classified. The second section of this chapter focuses on SE standards and practices in the development of complex equipment. Current SE standards and practices are reviewed by conducting interviews with RH experts from different HEP facilities.

Chapter 3: This chapter presents a SE approach for developing RH logistics concepts at HEP facilities, using the Super-FRS as a test bed. It is split into five sections.

The first section presents the SE approach for developing RH logistics concepts at HEP facilities, which is then refined through discussions and interviews with SE and RH experts at various HEP facilities.

The second section presents how an SE approach can assist in the development of RH logistic concepts using Super-FRS as a test bed.

The third section compares the concepts developed for the RH of the Super-FRS tunnel before the application of SE practices with those following the application of SE. This section presents the Super-FRS RH logistic concepts for the facility developed during the period from 2012 to 2015.

The fourth section presents the tools and techniques which were needed to realize the RH logistic concept for the Super-FRS. The concepts are then evaluated against the developed criteria, following an extensive discussion on the best way to select commercial, off-the-shelf equipment.

In the final section of this chapter, a tradeoff analysis is conducted to select the best conceptual solution for the Super-FRS facility.

Chapter 4: This chapter presents conclusions and future research work.

2 Review of the State of the Art: RH technologies, logistics and concept design practices in HEP facilities

This provides a detailed overview of the State of the Art within HEP facilities with regards to RH requirements and practices, RH equipment and technologies, and system engineering involvement in the development of RH concepts. Section 2.1 discusses State of the Art in RH setups and techniques, which are used to handle the activated parts for remote maintenance in existing HEP facilities. Through this, the key strategic RH scenarios and techniques are identified. Section 2.2 elaborates on the key State of the Art equipment that is currently utilized for remote maintenance and disposal activities both within HEP facilities and the nuclear industry. Section 2.3 attempts to classify RH for the purpose of assisting engineers in their quest to develop concepts for RH requirements. Section 2.4 provides a compact and composite overview of system engineering practices within HEP facilities alongside the State of the Art within the field of SE.

2.1 State of the Art in RH in HEP facilities

This section will discuss existing HEP facilities with activated targets and the State of the Art RH techniques which are used to handle the activated parts.

2.1.1 HEP facilities with proton beams

Table 1 shows a list of large accelerators with high-powered radioactive targets. These HEP facilities accelerate proton beams that are used for the production of secondary particles, such as antiprotons, neutrinos, and muons. Many of these HEP facilities use close shielding around beamlines to avoid the spread of radiation close to the source, thus reducing the overall volume required. To exchange consumable targets into the beam, the vertical plug concept is often used. Following a standard method of radiation shielding against fast neutrons, the inner part consists of iron, which is a high-density material. In contrast, the outer part, which has a large volume, is made of cheaper concrete for neutron moderation and absorption. Significant shielding can be saved by placing the target in a tunnel below ground level, so that the soil can contribute to the shielding. In such an underground tunnel, space is usually limited for extended maintenance setups and additional close shielding with plugs. In these facilities, activated parts must at least be transported from the beamline to a maintenance region built as either a hotcell or a workcell detached from the beamline. In a scenario with enough space and cranes for heavy equipment, the maintenance area can be completely separated from the in-beam position through either a shielded transport tunnel or a mobile shielding flask.

Table 1: List of selected HEP facilities with radioactive targets.

S.No.	Facility Name	Target Type
1.	Antiproton target CERN, Switzerland	Antiproton
2.	Fermilab, USA	
3.	p-bar at FAIR (planned), Germany	
4.	Fermilab NuMI , USA	Neutrino Production
5.	CERN CNGS, Switzerland	
6.	J-PARC T2K , Japan	
7.	Target E at PSI , Switzerland	Muon Production
8.	J-PARC MUSE , Japan	
9.	SNS Oak Ridge, USA	Spallation Neutron Sources (SNS)
10.	JSNS at J-PARC, Japan	
12.	ISIS, STFC Rutherford Appleton Laboratory, UK	
13.	SINQ at PSI, Switzerland	
14	ESS (planned), Sweden	
15.	LHC, Switzerland	Hadron Collider

Figure 13 shows the basic parts of a close shielding with plug inserts. The main purpose of the plug is to limit activation on the side opposite the beam to a level at which hands-on maintenance becomes possible. At the same time, radiation-sensitive materials, such as vacuum seals, are protected. In principle, this solution offers well-protected access, since there is always shielding between the main source of radiation and the operator. Moreover, this approach limits the motions necessary for maintenance to simple, vertical movements. However, at the same time, it drastically increases the weight of the components, since they become directly connected to the heavy shielding blocks. Despite this limitation, it is the method of choice at numerous particle accelerator facilities as explained in the following sub-sections.

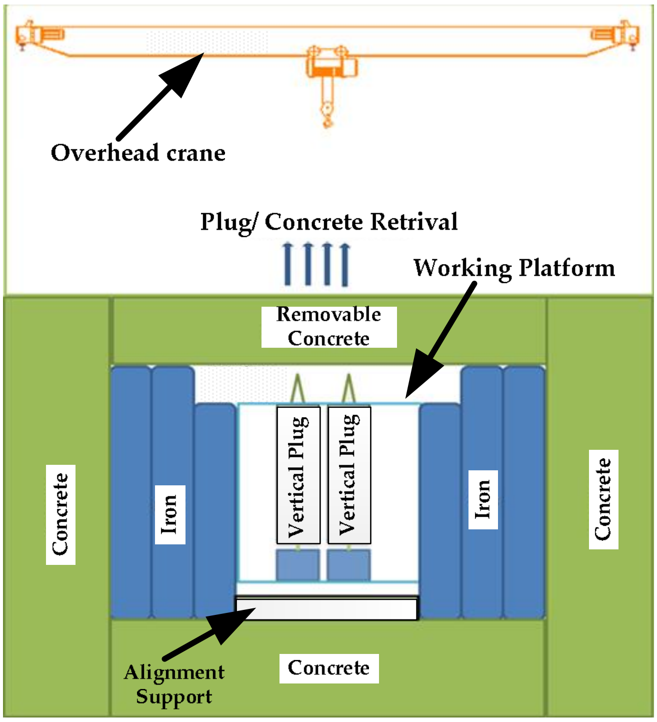

Figure 13. Sample drawing of a closed tunnel with vertical plugs.

2.1.1.1 Remote maintenance systems at PSI

The PSI in Switzerland (Figure 14) operates a proton accelerator and a spallation neutron source which supply particles for experimental scientific and industrial programs. It also has a large facility for canner treatment using protons. The PSI cyclotron delivers a proton beam of 2mA at 590MeV [64][75][76]. Targets and beam dumps are in direct contact with the beam and, hence, doses can range 4 mSv/h or more at a distance of one meter from the target. Thus, hands-on maintenance is not an option. The PSI beamline (Figure 15) is shielded through the use of concrete blocks which provide adequate radiation shielding for hands-on operations on the working platform when the beam is turned off.

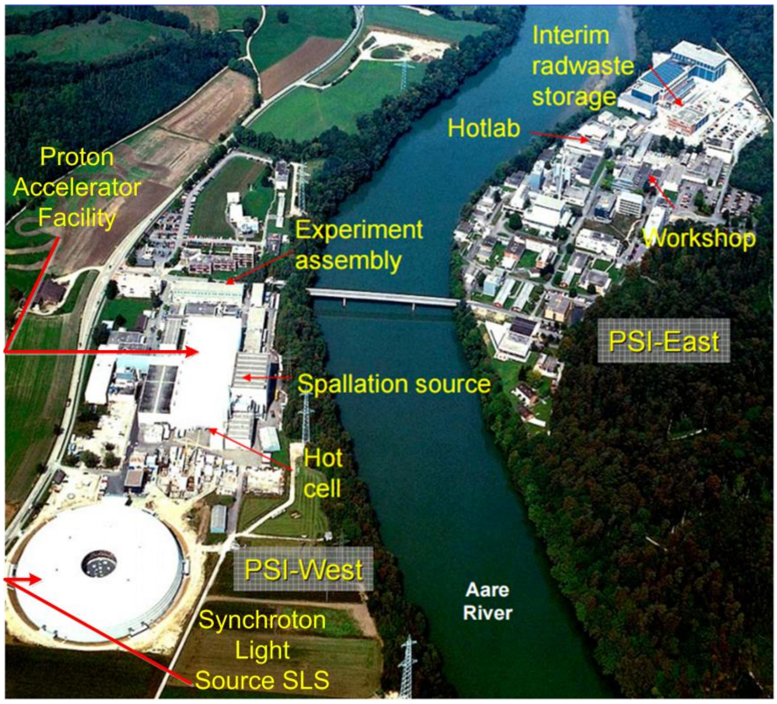

Figure 14: PSI in Switzerland, birds-eye view [77].

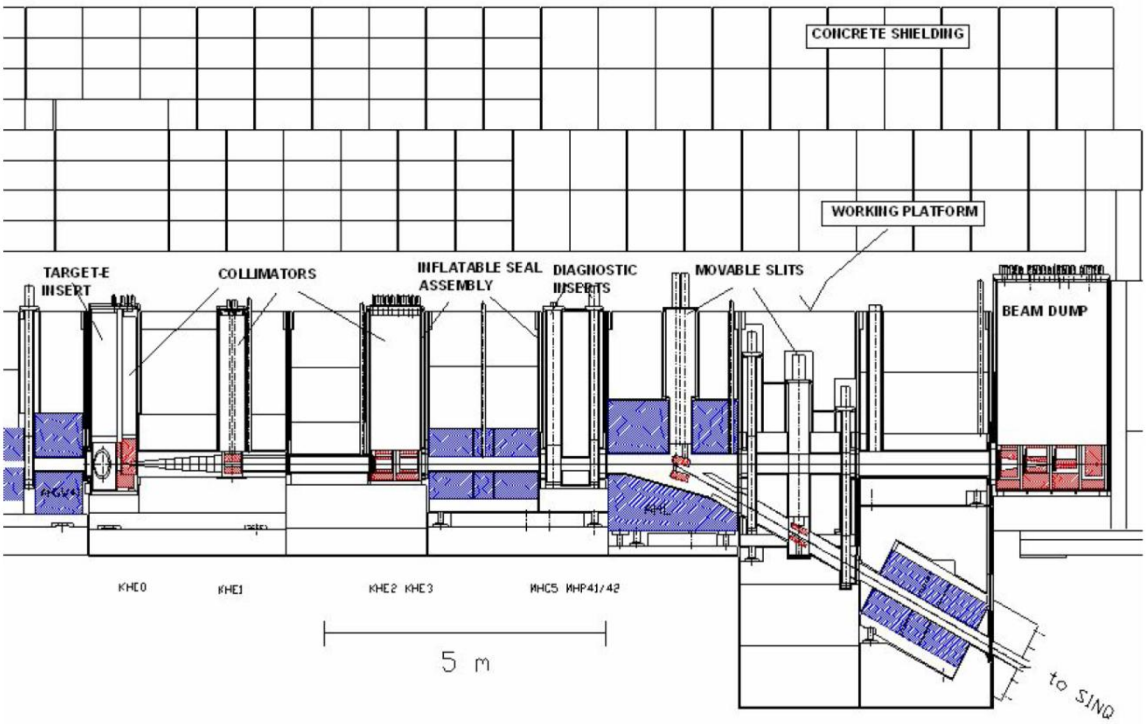

Figure 15. beamline section, showing a multiple beamline inserts (i.e., targets and collimators) that require remote maintenance under concrete shielding [77].

Target M, target E and the SINQ target shown in Figure 15 are three of the most activated beamline inserts in the PSI beamline. The SINQ and E targets are exchanged using the following sequence [77]:

1. Concrete blocks are removed to clear access to working platform (Figure 16).
2. Media cables and other connections (e.g., water, electricity, control signals, vacuum) are disconnected. This is performed by an operator and the dose rates are monitored on top of the beamline.
3. A parking bridge structure is installed and positioned. The bridge is used to position the shielding flask.
4. The shielding flask is moved across the hall using an overhead crane. An operator is involved in monitoring the installation of the bridge.
5. The transfer cask is moved and docked onto the bridge. The operator checks to confirm that the docking of the flask is complete and secure. The operators then depart from the area before the target extraction is carried out using the shielding flask (Figure 16).
6. The shielding flask engages the target and extracts it using an internal lifting mechanism. The doses at the target are extremely high. The shielding flask is designed in such a manner that it protects the environment from radiation doses.
7. The shielding flask is closed down and the beamline insert is transported (Figure 17) to the hotcell for dismantling operations (Figure 18).

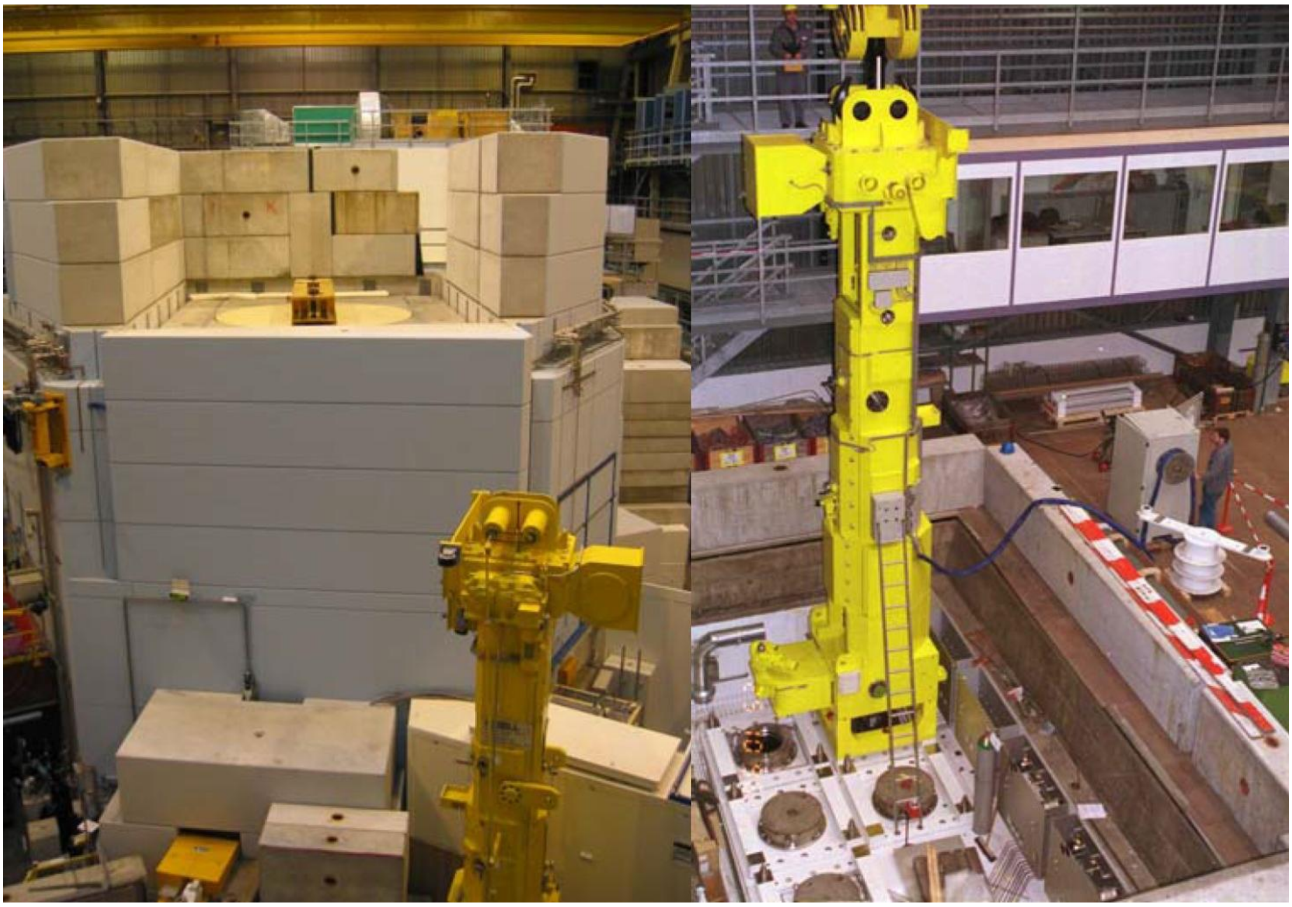

Figure 16. SINQ target concrete shielding (left) and shielding flask installed on top of the storage pit (right) [77].

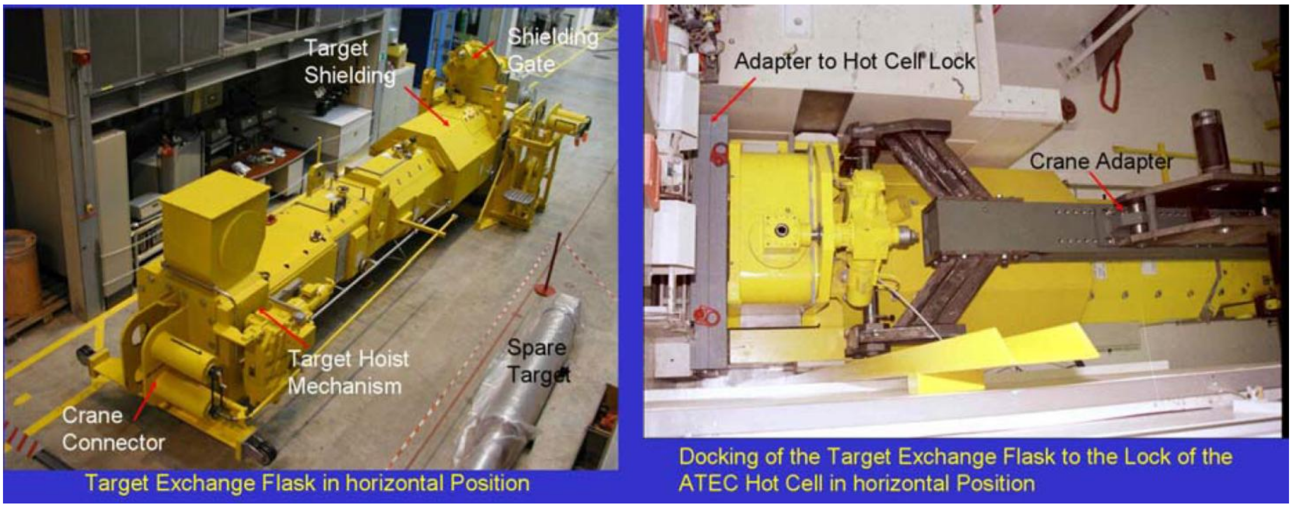

Figure 17. PSI SINQ target is transported (left) and docked with the hotcell (right) [77].

Figure 18. PSI SINQ target is extracted within the hotcell and dismantled using a Master Slave Manipulator and power manipulators [77].

The PSI facility uses different shielding flasks for maintenance of its targets. The RH was built gradually into the facility; hence, the shielding flasks were also built gradually according to changing needs and requirements.

2.1.1.2 Remote maintenance systems at J-PARC

J-PARC is a high-intensity proton accelerator facility. J-PARC includes three main sections (Figure 19): a 400 MeV linear proton accelerator, a 3 GeV Rapid Cycling Synchrotron, and a 50 GeV Main Ring synchrotron. The Materials and Life Science Experimental Facility at J-PARC (Figure 20) uses the beam from the Rapid Cycling Synchrotron on muon and neutron targets [43]. These targets are both highly radioactive and therefore require remote maintenance. Heavy concrete shielding is used on top of the beamline during facility operation. The targets are located inside the target hall, which has an integrated hotcell and storage facility, but are individually transported into the hotcell facility for remote disassembly using separate shielding flasks. The facility currently operates at 0.4 MW, but by 2018, it will be operating at 1 MW—thus generating targets with an even greater level of activation that will also require remote maintenance [43].

The shielding flask for muon targets is composed of a shielding case and a sliding door. Two chains, driven by a motor, are used to move the door. There is also a gripper, which is driven by an individual motor. The transport task sequence for the J-PARC target is identical to that of the PSI target, as shown in Figure 21. The shielding flask is moved by an overhead crane installed on top of the bridge arrangement, which keeps the shielding flask aligned with the beamline insert [78].

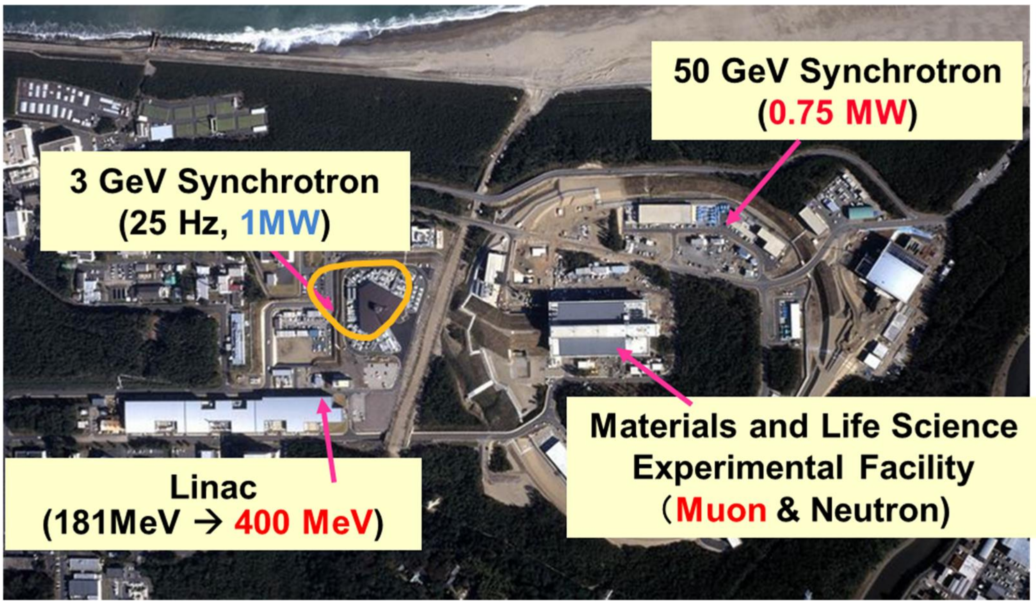

Figure 19. J-PARC facility in Tokai, Japan.

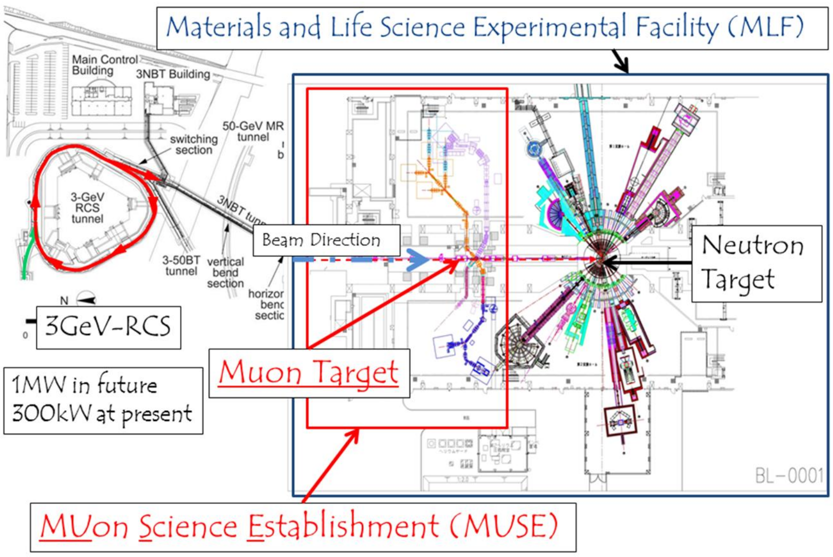

Figure 20. J-PARC Materials and Life Science Experimental Facility with muon and neutron targets requiring remote maintenance.

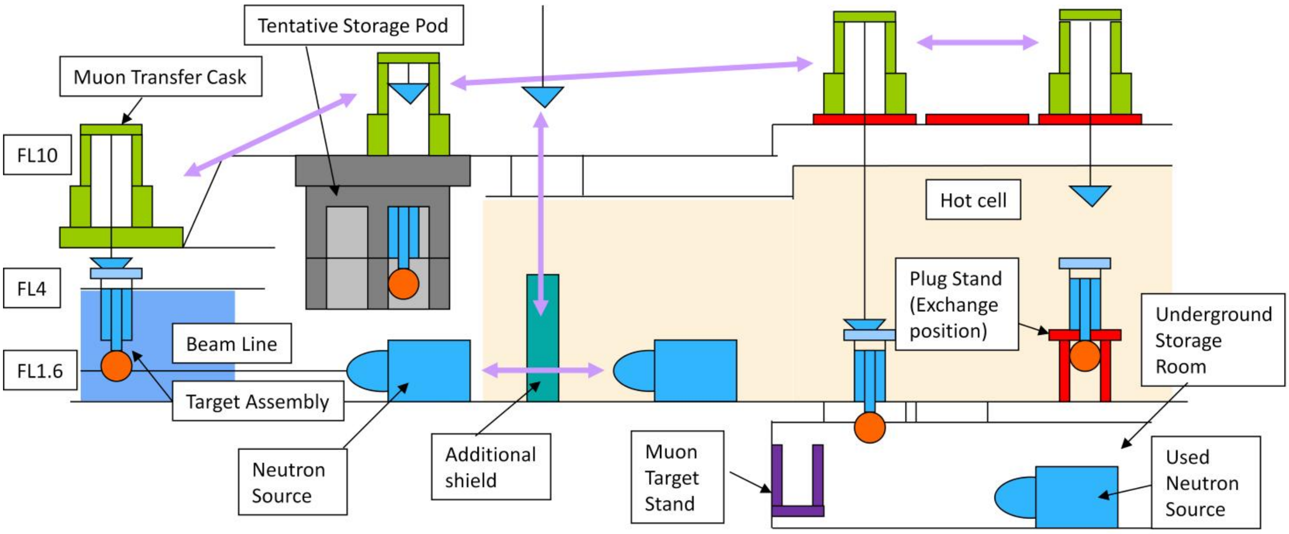

Figure 21. Schematic illustration of the J-PARC muon target and shielding flask, showing critical positions for remote maintenance [78].

The shielding flask uses its internal crane to lower the target plug onto the plug stand, which is situated inside the hotcell (Figure 22). The plug stand has the capability to rotate by 360 degrees and is also compatible with other beamline plugs. The exchange device is used to remove the target rod from its shielding after it is unscrewed from the shielding by a power manipulator using a specially designed tool. The target rod is then transported, via an exchange device, to a cutting device, where it is cut into small pieces and later packed into a disposal barrel. A new target rod is then attached to the target plug shielding using: an exchange device, a power manipulator and a Master Slave Manipulator (Figure 22). During the design stage of this equipment, a misalignment was detected between the target rod and the target plug shielding. This misalignment was caused by the tolerances of the devices between several parts: the plug stand and plug stand attachment; the plug stand attachment and Target assembly; the Target rod and rod attachment; and the rod attachment and exchange device[78]. To tackle this misalignment, during assembly a careful sequence is followed, and the Center of Mass for each element is carefully considered.[4]

Figure 22 shows the current RH setup for the muon target in the J-PARC Materials and Life Science Experimental Facility. The facility includes a target hall, a shielding flask, a bridge for the shielding flask, and a hotcell (which itself includes a power manipulator, an exchange device, a Master Slave Manipulator, an overhead crane and a plug stand). The muon target has been replaced several times, with six replacements occurring since 2014. The timeline of these replacements is given below:

- 2008: Commissioning for replacements of the cold fixed target, the profile monitor and the current transformer.
- 2009: Commissioning for replacements of the hot fixed target. The fixed target was used again (50 mSv/h at surface).
- 2011: Tests of hot fixed target (500 mSv/h at surface).

[4] "In particular, the rod attachment must have two hanging positions, because it has two weight centers, one with a Target rod and another without. The balance of the rod attachment is adjusted by the position of the hanging points and some counter weights" [78].

- 2012: Commissioning for replacements of the cold rotating target.
- 2013: Commissioning for replacements of the cold rotating target and volume reduction of the cold target rod.
- 2014: Commissioning for volume reduction of the cold fixed and rotating mock target rods.

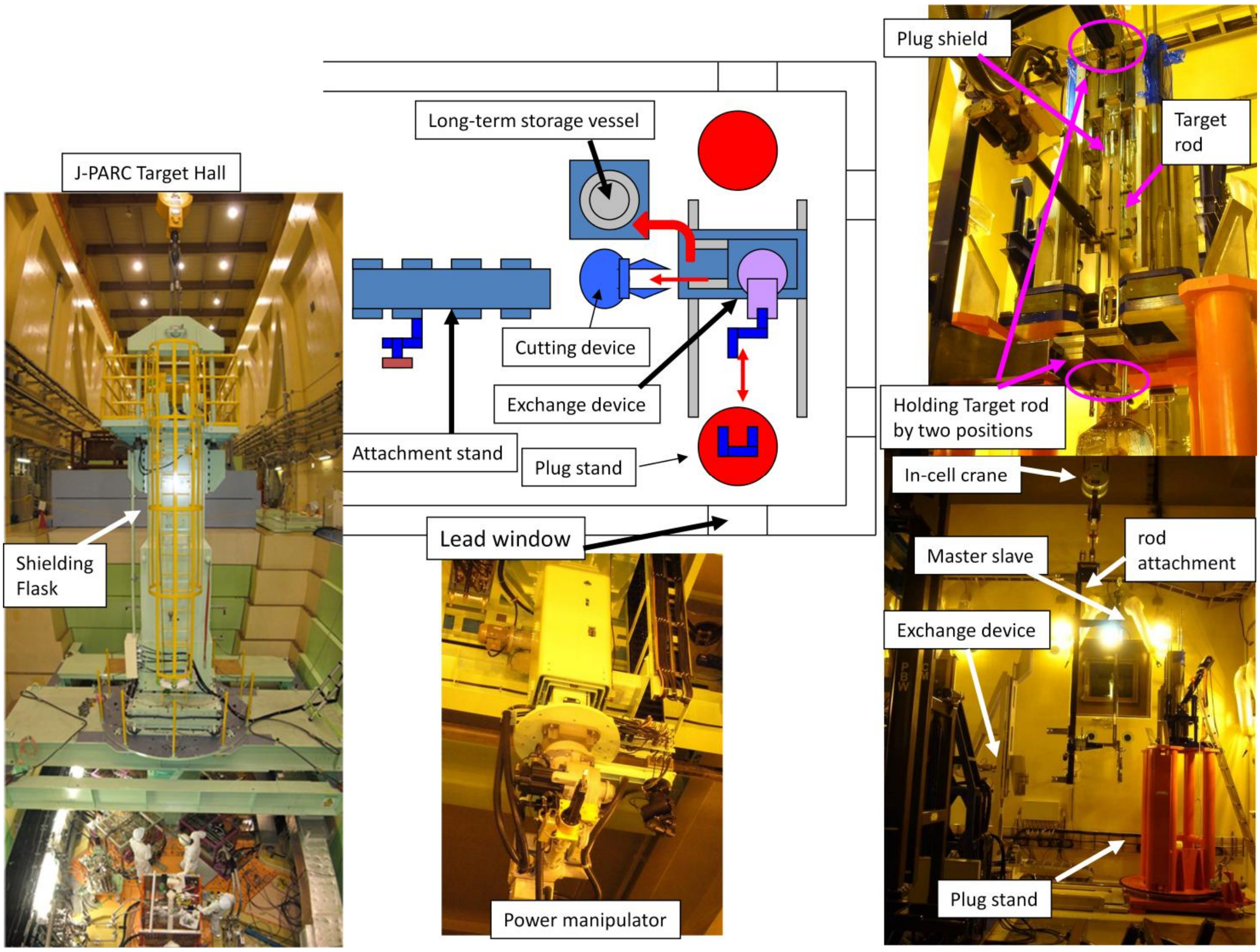

Figure 22. J-PARC remote maintenance setup: Materials and Life Science Experimental Facility target hall with muon target shielding flask; hotcell setup; power manipulator on the roof of the hotcell; muon target handled in the hotcell; hotcell from the inside.

The neutron spallation target at the J-PARC Materials and Life Science Experimental Facility also requires remote maintenance. More details concerning the handling of the Japan Spallation Neutron Source (JSNS) are provided in Section 2.1.1.5 in the context of the Oak Ridge, USA, setup for remote handing of spallation source targets.

2.1.1.3 Targets with vertical plug maintenance

The "Neutrinos at the Main Injector" (NuMI) is a 120 GeV proton beam facility at the Fermilab facility, USA. The neutrino target is mounted on a vertical plug in a closed tunnel that is heavily shielded with iron and concrete[79]. Analysis of the target indicates high levels of radiation; however, the space is confined due to the shielding making it challenging for maintenance by RH. With regard to the layout, the facility design report states: "Most of the components of the primary beam system reside in the Main

Injector enclosure or the NuMI stub. Both regions are covered by an extensive earth shield and built as part of the civil construction." [79] In the facility there are two beamline devices, termed "horns," to focus the beam. They are mounted on top of the vertical plug for retrieval. An overhead crane is used to remotely transfer the target from the beamline to the workcell area, where basic maintenance is carried out [79].

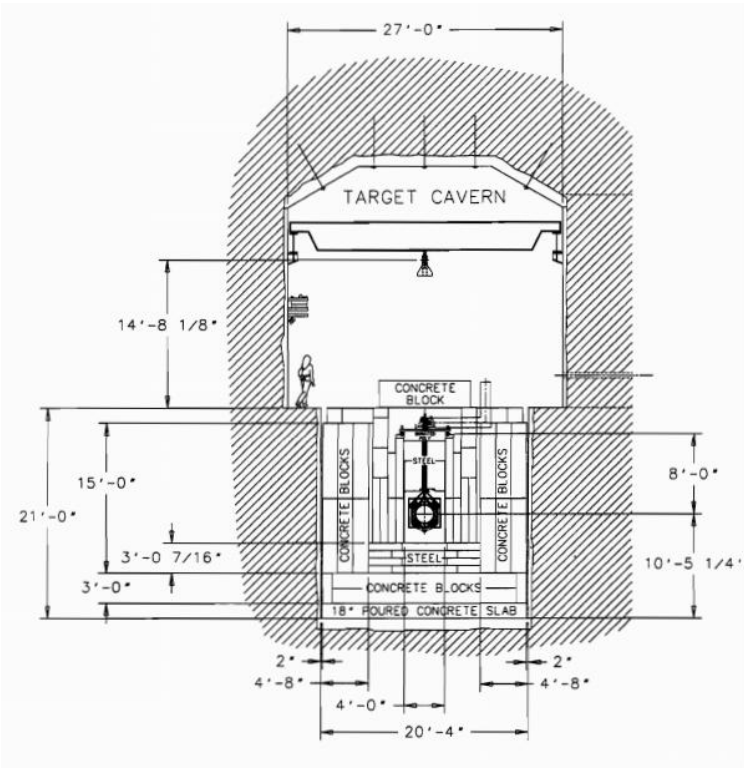

Figure 23. Fermi lab NuMI target area cross-section. The second horn is shown hanging from its alignment module, which rests on alignment rails at the top of the channel [79].

Like the NuMI target, the Tokai-to-Kamioka (T2K) target and horns at J-PARC are also mounted on vertical plugs and are retrieved vertically using an RH crane that can lift up to 40 tons. The T2K target station is covered with a 2.2 m thick iron shielding and concrete blocks. The target station is comprised of: the target, horn 1, horn 2 and horn 3, which are constructed underground to protect the environment from radiation [80][81].

The target is attached to horn 1 on the T2K beamline. Horn 1 is then lifted up using a specially designed, remotely handled crane from the beamline and installed on the remote maintenance area (the hotcell). The spend target is removed from Horn 1, and a new one is installed onto it before it is installed onto the beamline for further operations. The used target is stored after remote maintenance. The target has a specially designed target exchanger, with which the target can be replaced using an master slave manipulators [80]. The target exchanger is equipped with twin jack systems which can be adjusted to the required angle. The exchanger is also equipped with a load cell, gimbals and a spring system to preventing overloading.

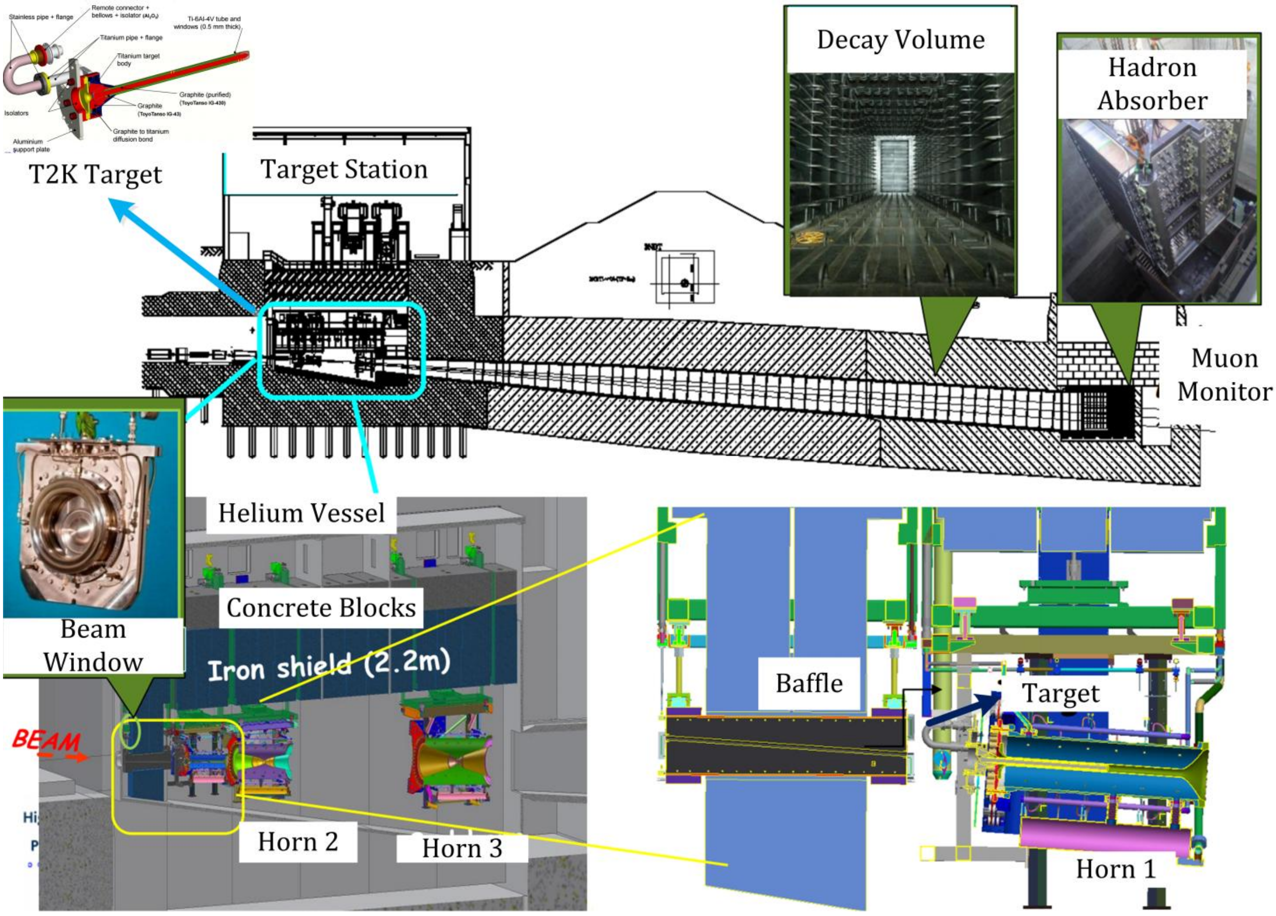

Figure 24. T2K target station setup at J-PARC.

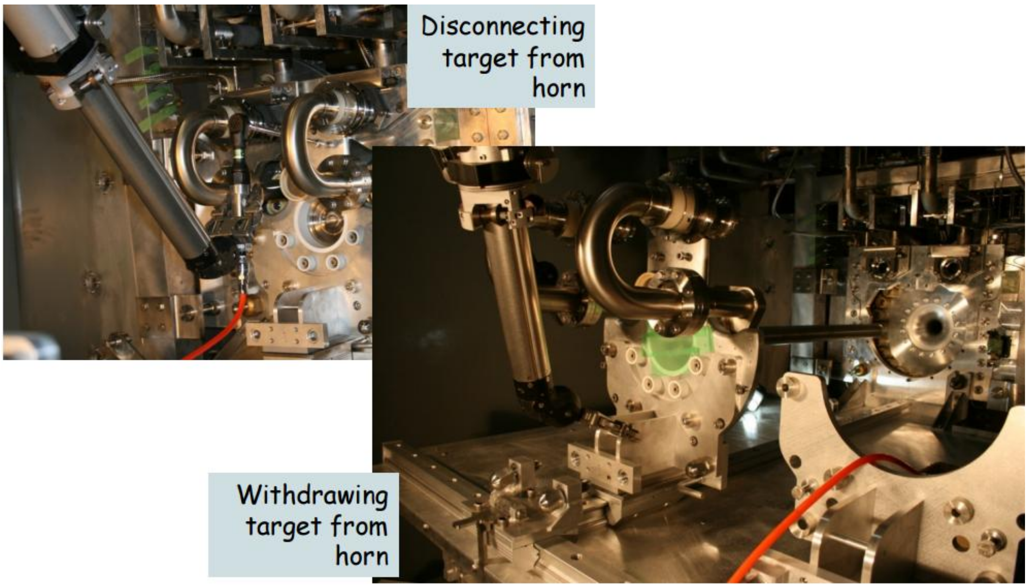

Figure 25. T2K target remote maintenance in the hotcell using a Master Slave Manipulator provided by Canada's national laboratory for particle and nuclear physics (TRIUMF) [80][81].

2.1.1.4 Remote maintenance systems at CERN (excluding ISOLDE)

For High Intensity Beam (HIB) machines with very high beam energies (of hundreds of GeV or TeV) close shielding becomes impractical and can even lead to increased dose rates during maintenance operations. The reason for this is the much higher attenuation distance required for secondary radiation, as well as the potential build-up of radiation, due to the effect whereby from one particle, many more particles are created, leading to an avalanche of radiation. In this case, adding more material close to the beam may make activation even worse. The very long attenuation distance required can only be achieved by placing machinery over a large area and locating it far underground. The most extreme example of this is the Large Hadron Collider (LHC) at CERN. The LHC collides two opposing proton beams at energies of up to 7TeV. Over the whole circumference of 27km, dedicated beam dumps and collimators are installed, which all require maintenance [82]. The CERN accelerator beam lies approximately 50 to 175 meters (164 to 574 ft) underground (Figure 26).The earth above it and the radiation shielding on the sides of the tunnel provide the shielding necessary to protect the outside environment. However, over time, the equipment in the tunnel becomes radioactive to varying degrees.

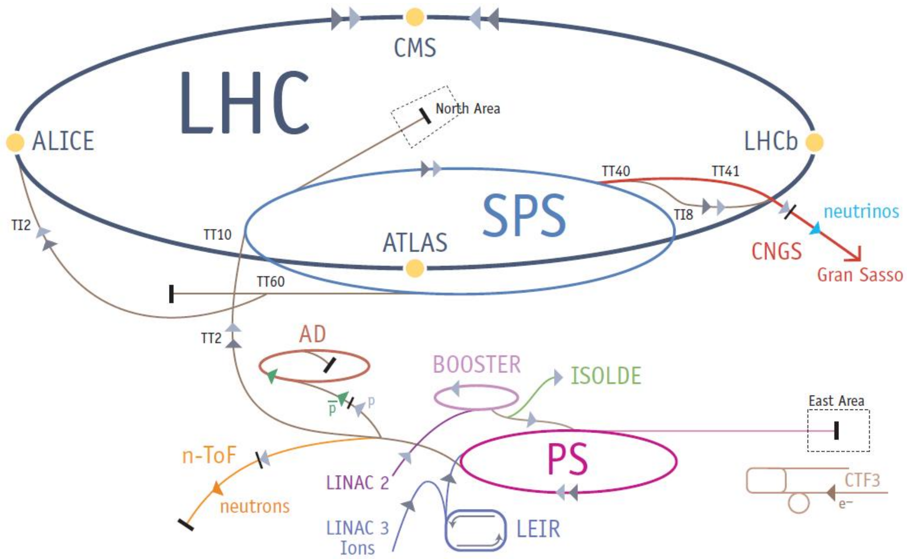

Figure 26. CERN accelerator network [83].

To conduct maintenance within the CERN facility, the maintenance team uses various pieces of remote maintenance and inspection equipment. These are discussed in the following sub-sections.

Collimator exchange using a remotely operated crane

More than 100 collimators of various types are currently installed in the LHC, mainly at Points 3 and 7 (Figure 27). The collimators exist at certain points around the LHC ring in order to stop particles from straying from their desired beam orbits. The collimators become radioactive as a result of collisions with stray particles; thus, repair scenarios need to be developed to minimize personnel access. These regions are among the most radioactive in the LHC, with dose rates in the order of several mSv/h. In the case of a collimator failure, it is necessary to remotely exchange the collimator whilst minimizing direct intervention by people. The various CERN services affected in such a case are: transport, vacuum, water cooling, radiation protection, surveying and the design office [83]. The initial installations of collimators are designed to facilitate remote replacement, as follows: "Vacuum connections are made using special beam pipe vacuum clamps and the collimator sits on supports fitted with guiding pins to ease their installation. Electrical and cooling water connections are established by automatic plug-in devices when the collimator is lowered onto its supports" [83]. Initial installation of the LHC collimators was done using a custom-designed mobile crane (Figure 27), which required hands-on guidance from operators to move the collimators into position (Figure 27).

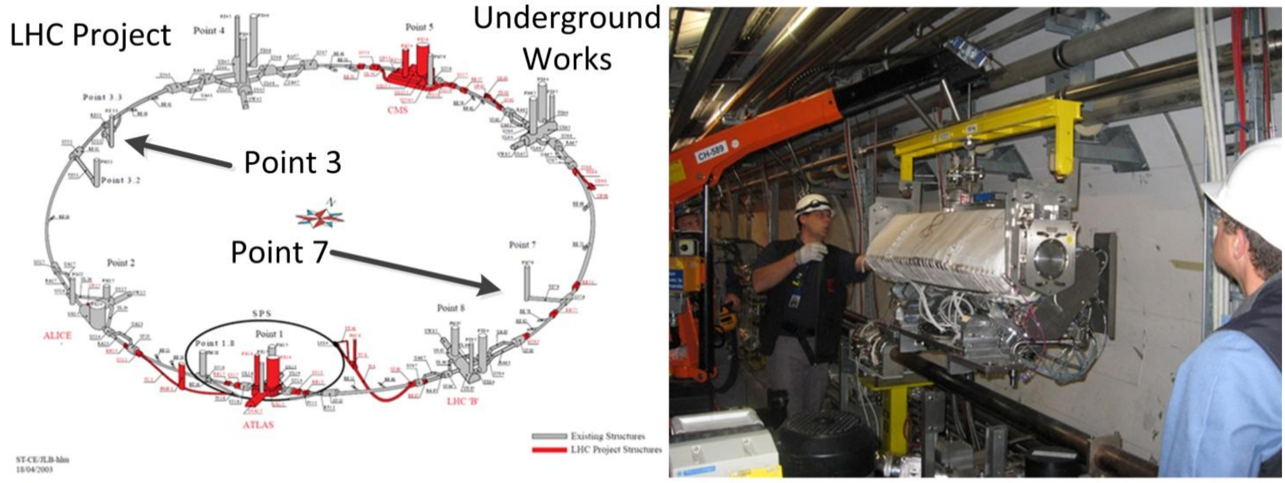

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Figure 27. LHC underground tunnels and caverns, with points 3 and 7 marked (left); the initial installation of an outer collimator passing over an adjacent beam pipe, showing a limited availability of space in the LHC tunnel (right).

A third-generation remotely operated crane (Figure 28) is currently being tested to perform full remote removal and installation of the LHC collimators, based on the same concept as the original mobile crane. The new, remotely operated crane will have a one-ton lifting capacity, a visual system to monitor the extraction and installation of the collimator, a mobile platform capable of accessing the LHC tunnel, a shielding container for the activated collimator, and a control system for remote operation. The remotely operated crane will obtain power from existing installations within the LHC tunnel and from a backup battery, which will drive the system in the event of power failure.

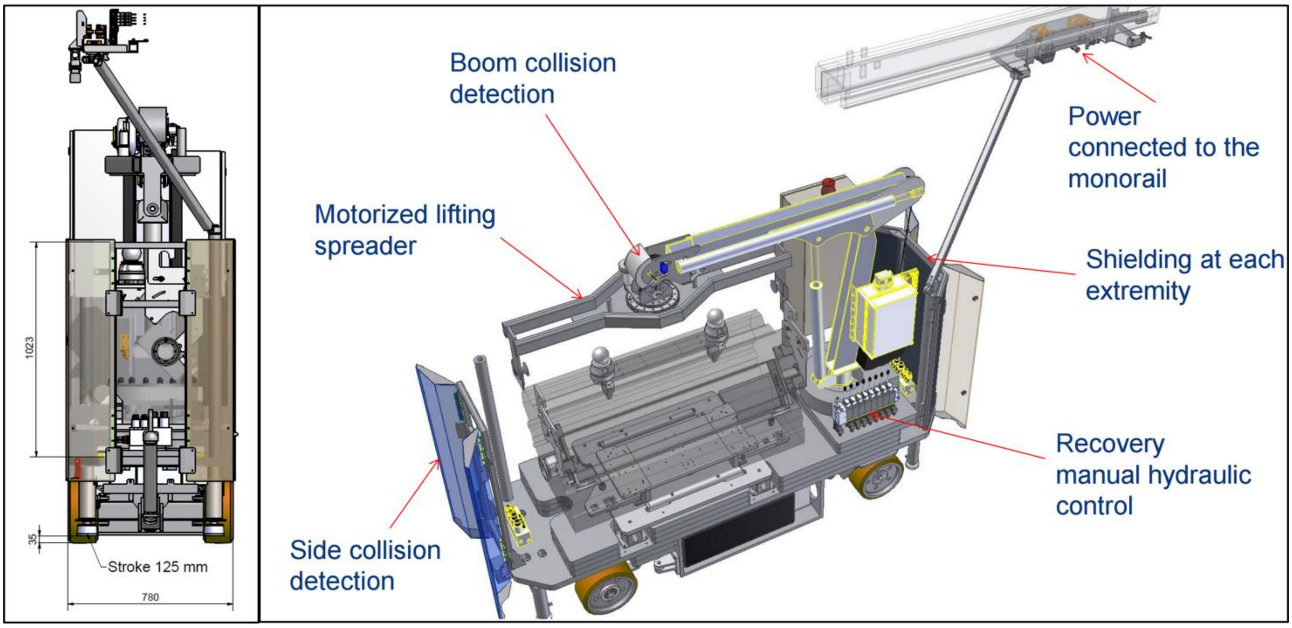


Figure 28. Remotely operated crane for collimator exchange.

Remotely Operated Vehicle (ROV)

According to a review of the RH needs of the CERN accelerator, a RH team identified the need for a general-purpose, Remotely Operated Vehicle (ROV) to carry out:

- Remote visual inspections
- Remote radiation dose measurements
- Remote manipulations of small loads.

Currently, CERN is using a Telemax ROV (Figure 29) equipped with tracks that enable it to climb stairs. The ROV is also fitted with a six-axis manipulator arm (5kg payload). The control station is portable and communication between the control station and the ROV occurs through either an optical fiber or a radio link. The Telemax ROV has programmable movement sequences. It was recently used for the following tasks [84]:

- Disposal of the Antiproton Decelerator target.
- Disconnection of the Super Proton Synchrotron Long Straight Section 1 (LSS1) collimators, including water vacuum, cabling, etc.
- Visual inspection of the Antiproton Decelerator.
- Providing vision assistance for the Proton Synchrotron Booster dump removal.

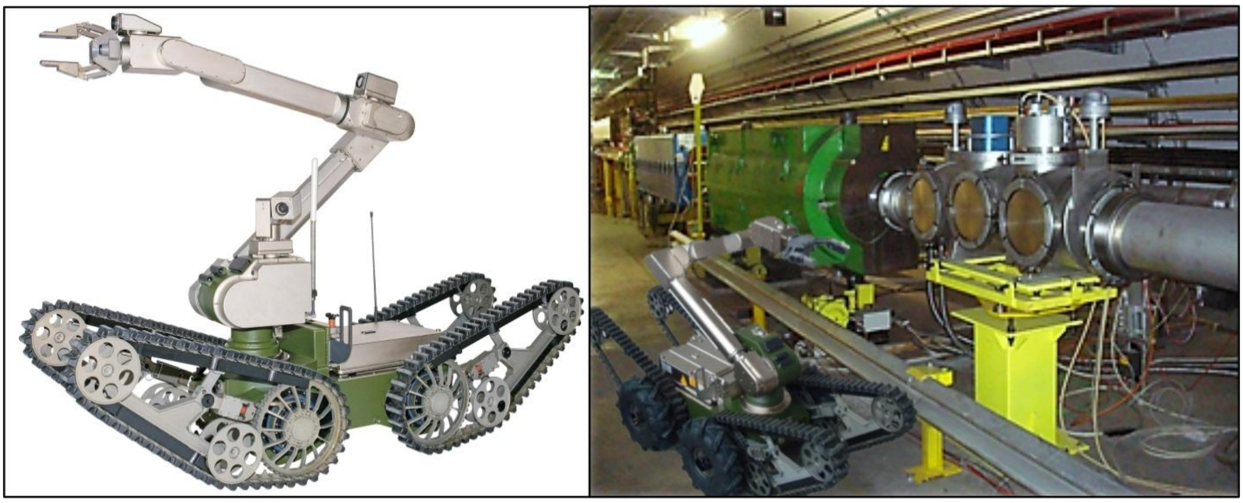


Figure 29. Telemax ROV for RH at CERN.

Remote overhead crane at CERN

The CERN Neutrinos to Gran Sasso (CNGS) target also receives high-energy protons (400GeV) from the CERN Super Proton Synchrotron. These interact with an assembly of five graphite rods mounted on a revolving assembly which is encompassed by iron shielding [85]. Operational problems have made it evident that adequate shielding measures are required to protect the electronics and personnel during operation. The facility tunnel is underground and uses no shielding. The target station can be remotely inspected, but there is only space for a remotely controlled overhead crane and its cameras [85]. The CNGS target is not coupled directly to a maintenance hotcell. Currently, the CERN engineering team has installed a specially-built crane in the CNGS region. This overhead crane can handle up to 7.5 tons, has width of 3.4m and motion range of 123m (Figure 30). The crane also has no onboard electronics; instead, remote control panels and remote cameras are used to assist in the handling of radioactive parts. The remote maintenance at CNGS target has faced various issues and unplanned disruptions. The maintenance of these disruptions revealed some important lessons[85]:

- In the design of the target, brazing must be avoided in compression regions. Ceramics can be used in compression-only regions. Identical bolts/screws must be used with proper positioning. RH procedures must be well documented with a video and photo diary.
- Intervention optimization must be carried out by planning the intervention in detail to minimize the dose received.
- For “consumables items,” optimization of the radioactive waste should be included in the design and designs must be RH compatible. The designs must be home grown to increase the availability of the system, as this will allow optimized replacement and maintenance of the consumable.
- Radiation effect to COTS electronics is important factor for electronics. The CNGS electronics were installed at location with higher radiation doses, which that caused the electronic ventilation system to fail. This was resolved with more shielding.
- It is important to use radiation simulations to understand and evaluate the radiation environment in a facility beforehand.
- Anticipate tooling and procedures to observe the components that fail, before exchanging them with spares.

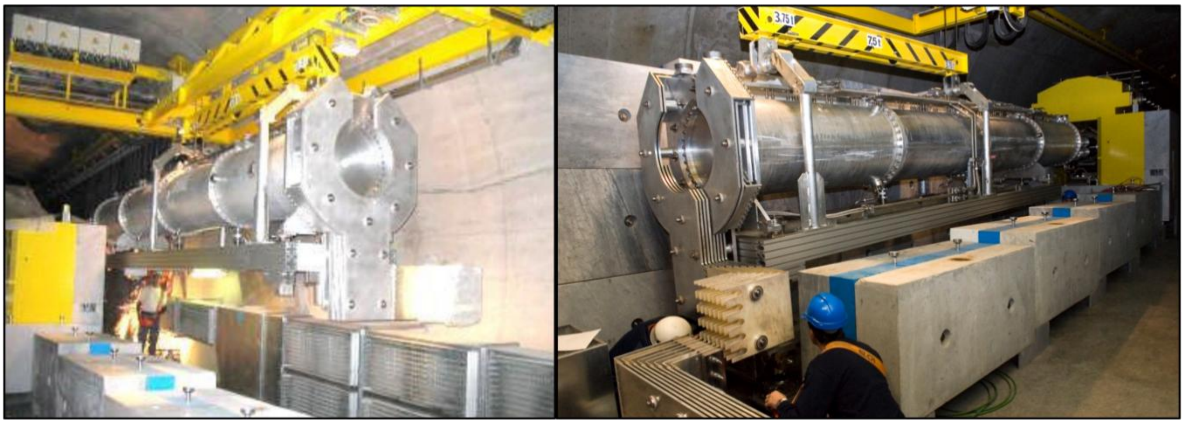


Figure 30. CNGS region with a specially built, remotely controlled crane.

During the 2013-2015 shutdown at CERN, the Target Absorber Neutral (TAN) detector and shielding elements needed to be exchanged in the LHC tunnel on either side of the ATLAS experiment. Remote TAN mini cranes were commissioned to carry out the exchange. The cranes were equipped with on-board cameras and controlled from a remote control station. Separate, free-standing, pan-tilt zoom cameras were also deployed to provide an overview of the operations. The TAN mini-crane setup can be seen in Figure 31. The crane has a very restricted operational space, and it is permanently located inside the tunnel. Due the nature of the tunnel, and the delayed realization of the RH needs, the remote TAN mini crane was custom-designed [86].

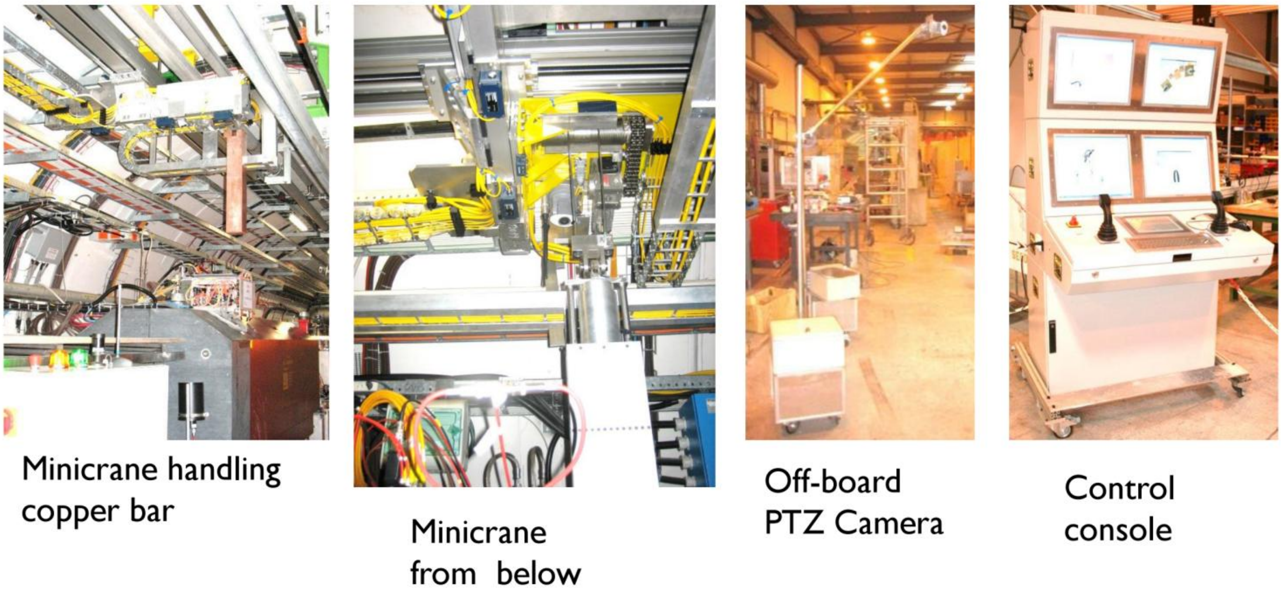


Figure 31. Remote TAN mini-crane setup at CERN a) Minicrane handling copper bar, b) Min-crance from below, c) Off-boad PTZ camera, and d) Control console [86].

RH train for LHC radiation protection surveys and visual inspection

In the event of limited or no personal access to the LHC tunnel, a Train Inspection Monorail (TIM) is used to conduct the inspection and measurements remotely. The TIM is an overhead train mounted on a monorail in the ceiling of the LHC tunnel. The TIM includes cameras to conduct visual inspections, as well as instruments to measure the radiation and oxygen levels within the LHC tunnel. The TIM structure is 10.2m long and it is divided into a motor wagon, a reconnaissance wagon, a radiation protection wagon, a battery wagon and a control wagon.

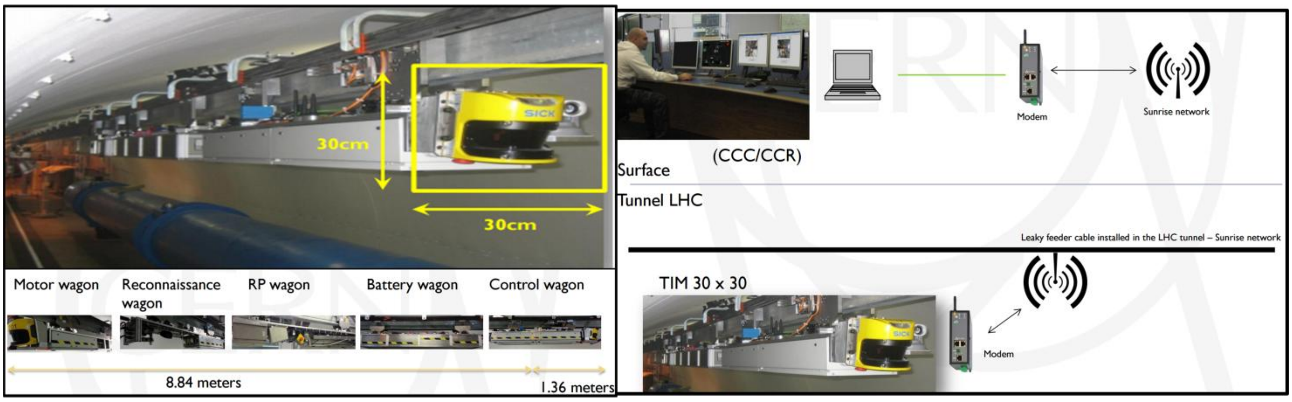


Figure 32. TIM structure (left); TIM remote control setup from the LHC control room (right)

Currently, the TIM infrastructure covers the space between Point 5 and Point 8 in the LHC tunnel. Future plans for the TIM project include developing three more TIM trains that can cover the entire LHC tunnel. The TIM has a maximum speed of 8Km/h. As well as being autonomous, it can also be controlled remotely from the LHC main control room via the General Packet Radio Service (GPRS) network that is available within the LHC tunnel.

2.1.1.5 Remote maintenance system for neutron spallation targets and facilities

Larger and heavier target installations, such as large liquid/solid target assemblies, cannot be transported in overhead shielding containers or mounted on larger shielding plugs that can be extracted vertically, due to the high loads and liquid containment; instead, they have to be maintained on-site. The hotcell in these facilities are built on top of the target regions in order to conduct on-site remote maintenance. The large targets are mounted on horizontal assemblies that use rail mechanism to transport the target in between target station and hotcell Figure 33 shows the general components of a spallation neutron source (SNS) target for RH.

SNS at Oak Ridge National Laboratory

The SNS at Oak Ridge National Laboratory (ORNL) facility is powered by a 2MW, 1GeV proton linear accelerator that is 335m long. Beam pulses are bunched in a ring and then directed towards a flowing liquid mercury target that converts the protons to a pulse of approximately $5x10^{15}$ neutrons [65]. The horizontal RH setup (Figure 34) was established to allow maintenance of the target, since the target is mounted on a moveable platform that retrieves it into the hotcell.

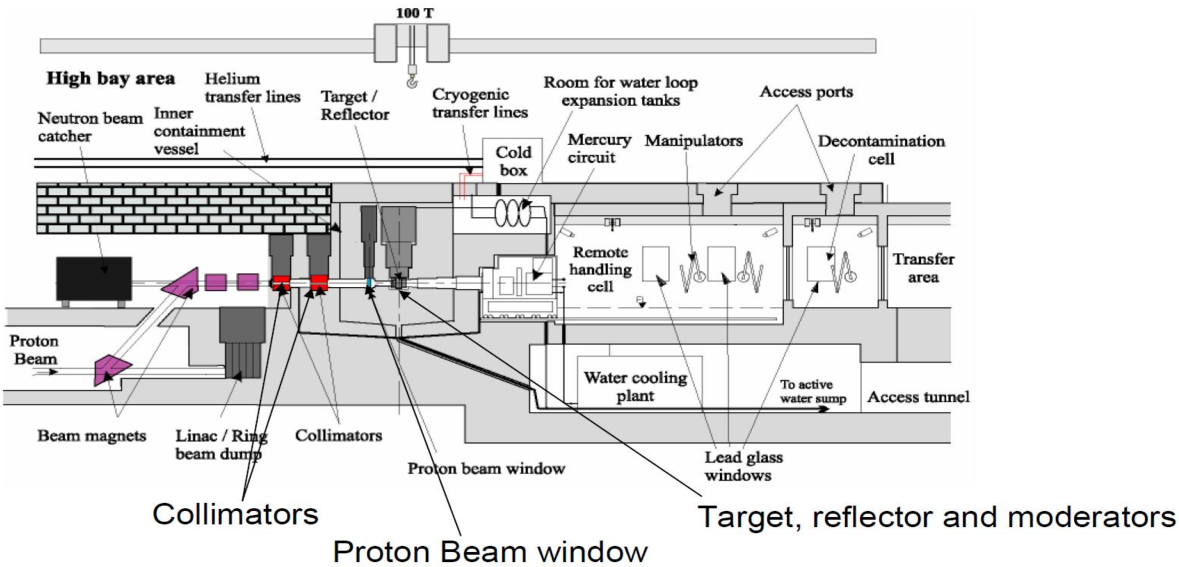


Figure 33. SNS target setup: general overview and components [65].

The SNS ORNL hotcell (Figure 35) is equipped with Telerob EMSM-2B dual servo manipulator arms. Each manipulator has six positioning Degrees Of Freedom (DOF), a gripper axis, a 1.8m reach, a 25Kg continuous capacity and a 45.5Kg peak capacity (Figure 35). The servo manipulator package includes a 227kg auxiliary hoist for assisting in component handling and tool support. The servo manipulator bridge is supplemented by a robotic, 7.5 ton bridge crane, which is mounted on an independent set of rails in the hotcell. With regard to positioning the arms and hoist hook, it has been reported that: *"Precise robotic position control of the bridges allows the arms or hoist hook to be positioned automatically to within less than 3.1mm "* [65]. The hotcell RH equipment is controlled from a safe area using Internet communication. The cell viewing systems can have total absorbed doses of up to 10^6 Gy [65].

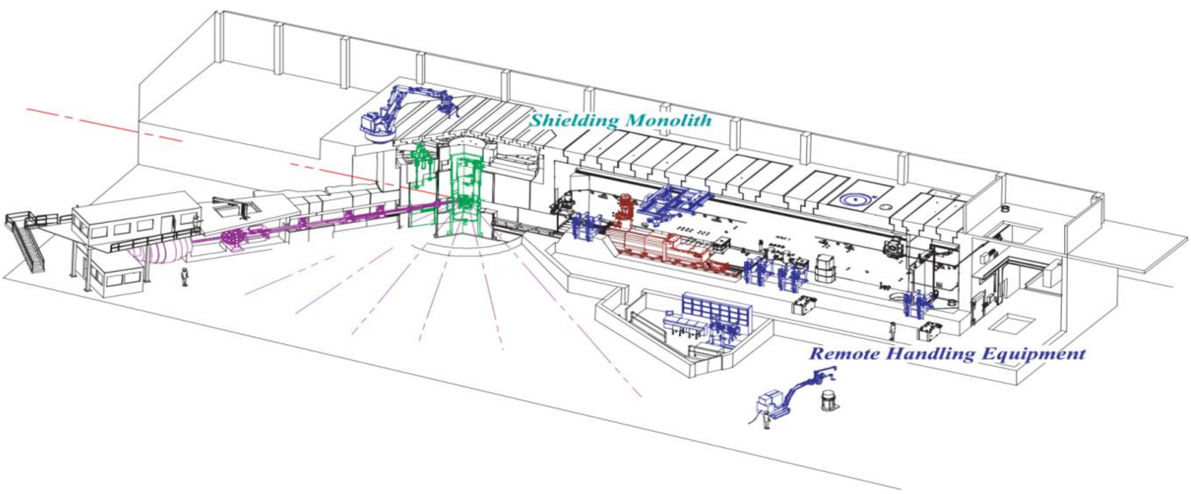


Figure 34. RH system setup at SNS at ORNL [65].

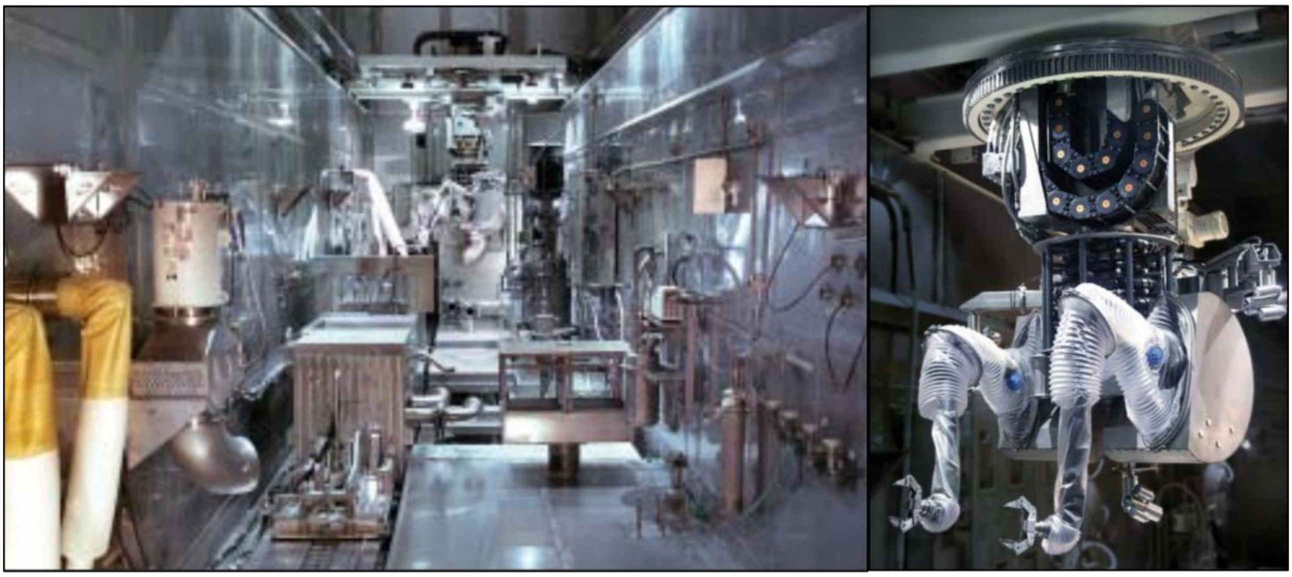


Figure 35. SNS ORNL hotcell setup (left); Telerob EMSM-2B dual servo manipulator arms (right) [65].

The high bay area on top of the target chamber uses a pedestal-mounted hydraulic boom system (Figure 36), which can be equipped either with a 450kg hoist or dual servo manipulator arms to conduct RH on the radioactive waste parts. The boom has a payload capacity of 2948Kg and can reach 9.2m horizontally, 9.7m above the level, and 3.7m below level, giving it access to the pipe fittings and other components located at the top of the shielding plugs. Operations in the high bay area focus on the removal of spent, failed, or obsolete components, such as proton beam windows, rather than on remote maintenance. Thus, the remote equipment in the high bay is "*designed to be disconnected for removal into shielded transfer casks. Removed components may go into long-term storage, be shipped off site, or moved into the hotcell through a top-loading hatch for inspection, breakdown, or packaging*" [65].

In order to carry out RH tasks in the SNS facility, a mobile manipulator vehicle (Figure 36) is used. It is equipped with a Telemate servo manipulator arm which has a 101.6 cm reach, a continuous load capacity of 11.3 kg, and a peak capacity of 15 kg. The mobile platform is based on a commercial mini-excavator that was converted from a diesel engine to electric. The system is mounted on tracks that provide versatile positioning capabilities, such as zero-radius turning and an ability to drive through 99cm doorways. The mobile device is controlled from a remote station that includes a vehicle control panel, a servo manipulator master control arm, and a man-machine interface [65].

Figure 36. SNS ORNL RH system: pedestal-mounted hydraulic boom system (left); mobile manipulator vehicle system (right) [65].

SNS at J-PARC

The SNS source at J-PARC is also a liquid mercury target, making it similar to that at SNS ORNL. However, it has an intense, high-energy proton beam (3GeV, 1MW), compared to the 1GeV at ORNL The lifetime of the JSNS mercury target was estimated based on a fatigue endurance curve, taking into account the degradation due to pitting and irradiation damage [87][88]. The target is mounted on a horizontal trolley that is retracted into the hotcell for remote maintenance. Figure 37 shows the target assembly setup. The hotcell at J-PARC is shared by muon and neutron targets. It is equipped with RH equipment to carry out maintenance and disposal task sequences on the facility's radioactive components. A separate shielding flask is used to transport the neutron target components to a long-term storage facility below the hotcell area (see Figure 38) [89]. Detailed description of this RH task is given in[89].

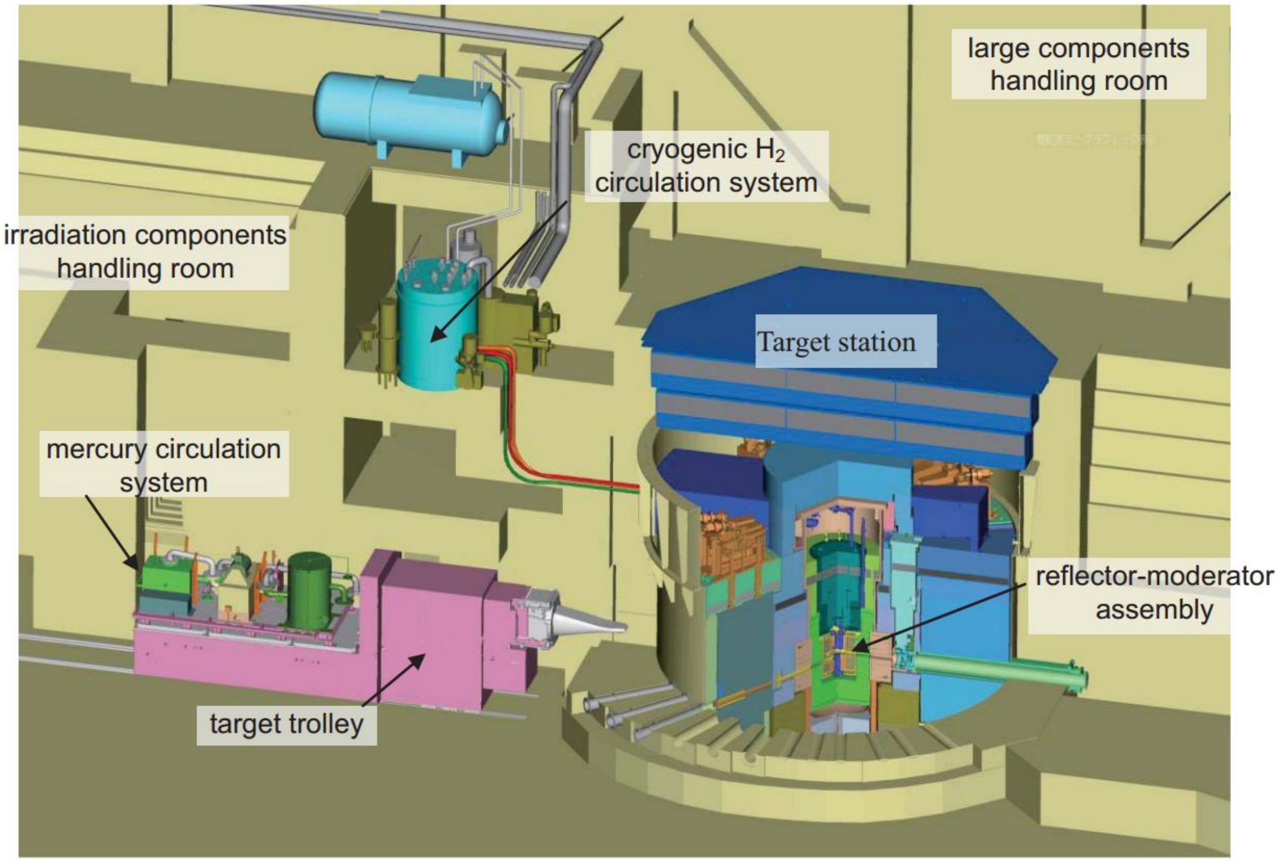


Figure 37. Target assembly setup of the SNS source at J-PARC [89].

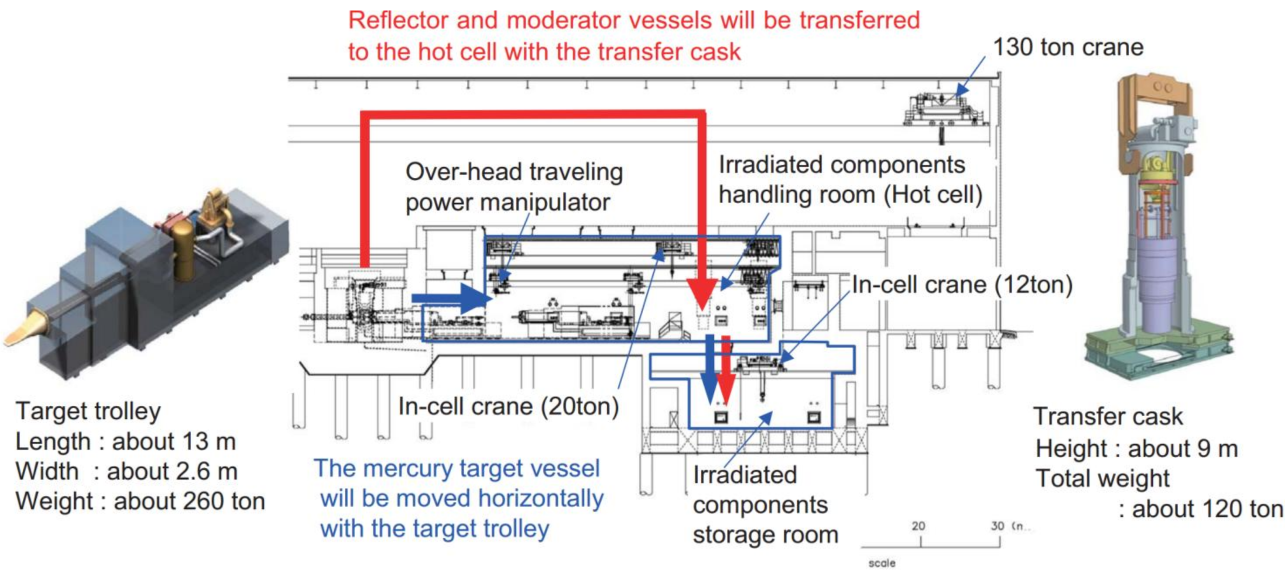


Figure 38. RH task sequence for a target assembly setup of the SNS source at J-PARC [89].

Science and Technology Facilities Council SNS target at Rutherford Appleton Laboratory

The Science and Technology Facilities Council (ISIS) facility at the Rutherford Appleton Laboratory uses proton beams on a solid, tantalum-clad tungsten target (Figure 39). This target is maintained by two Master Slave Manipulators, which are positioned opposite one another, each with a dedicated window for viewing. The cell also has a crane and cameras to provide assistance in remote manipulation. The spent target is stored close by and removed via an underground mechanism using a transport flask. RH at the ISIS facility includes the horizontal removal of target, reflector and moderator systems (as well as all cooling plants). The target replacement normally takes 10 days from beam off to beam on. Certain RH operation can take up to 14 days, with no beam operation possible during this time[133].

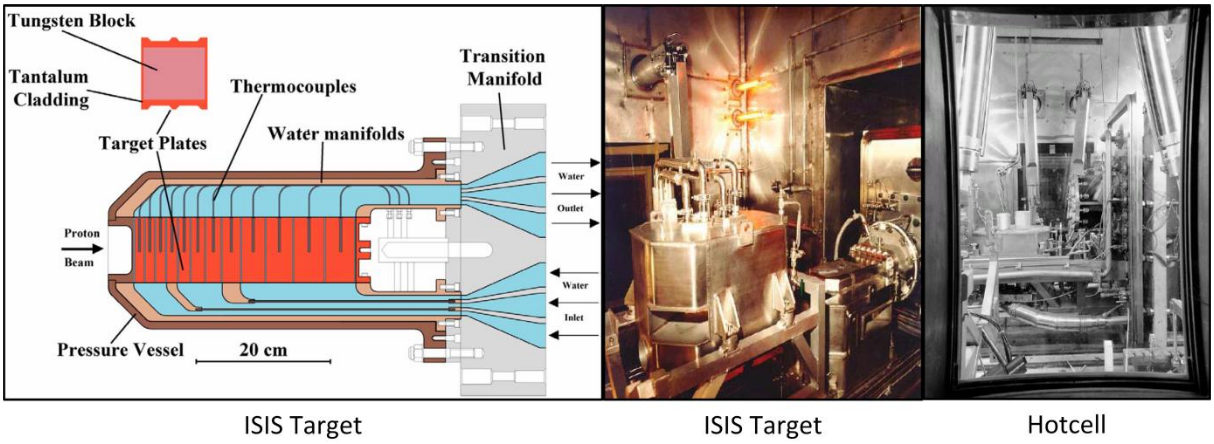


Figure 39. Science and Technology Facilities Council (ISIS) SNS target and hotcell setup for RH.

2.1.2 HEP facilities with Rare Isotope Beams (RIB) targets

Rare Isotope Beams (RIB) are produced using two techniques (Figure 40): in-flight separation and isotope separations online (ISOL) [90][91].

In-flight separations involve the nuclei in heavy ion beams being converted to other nuclides when impinged on the target. Many different fragments are produced, which are then separated in a fragment separator with the application electromagnetic fields. The nuclides can even be separated independently by mass and charge, by using degraders. This method of operation means that there are high levels of radiation due to the beam's interaction with the target and other parts. Parts hit by the intense beam, such as the dedicated beam catchers, become strongly activated. Most of the beam is dumped during the separation process, and the radiation level drops towards the end of the separator.

In ISOL facilities, the nuclei in the target are converted through bombardment with a high-intensity beam consisting mostly of protons. The nuclei produced are then extracted from the target and collected in a low-energy beam. Afterwards, a low-energy but high-resolution mass separator is used to select the nuclides of interest. Due to the lower energy of this process (except in the case of the target) little activation is caused; however, due to the extraction from the target, contamination poses a severe problem.

Figure 40 illustrates the different production schemes. Table 2 shows some of the major RIB in-flight and ISOL facilities.

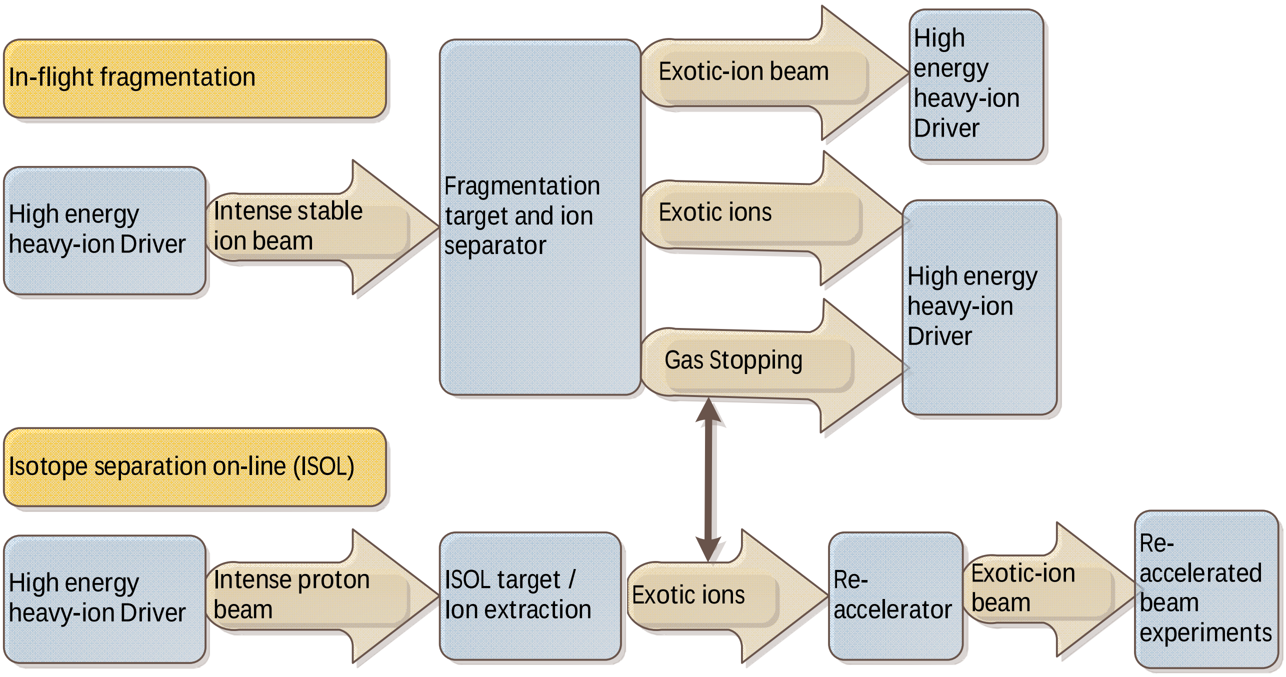


Figure 40: RIB-producing processes.

Table 2. Selected RIB in-flight and ISOL facilities.

S.No.	Facility Name	Target Type
1	RIKEN RIBF Target at BigRIPS, Japan	In-Flight
2	FRIB at MSU (new), USA	
3	FRS at GSI, Germany	
4	Super-FRS at FAIR (new), Germany	
5	SISSI at GANIL, France	
6	SPIRAL 2 at GANIL, France	ISOL
7	ISOLDE at CERN, Switzerland	
8	ISAC at TRIUMF, Canada	
9	SPIRAL 1 at GANIL, France	

As shown in Table 2, the FRIB, Super-FRS and SPIRAL2 are new facilities with higher beam energies and intensities. This means that, in these facilities, more parts will be activated and, ultimately, require maintenance. It is imperative to study the practices of other RIB facilities to effectively design the RH for such new facilities. The FRS facility in GSI and ISOLDE in CERN currently deploy State of the Art RH equipment to maintain the targets and beamlines. In later sections, we will discuss the RH in these facilities in more detail.

2.1.2.1 FRS target remote maintenance systems at GSI

The GSI Helmholtz Centre for Heavy Ion Research (German: GSI Helmholtzzentrum für Schwerionenforschung GmbH) is a federally and state co-funded heavy ion research center. It was founded in 1969 as the Society for Heavy Ion Research (German: Gesellschaft für Schwerionenforschung), abbreviated GSI, to conduct research on and with heavy-ion accelerators. The facility can be divided into the following research sub-facilities [92]:

- A heavy ion LINAC for energies up to 14 MeV/u
- A heavy ion synchrotron for energies up to 1 GeV/u in the case of Uranium beams.
- A fragment separator (FRS), which was built in 1990 and which produces and separates different beams of (usually) radioactive ions. The process involves a stable beam that is accelerated through “Schwer Ionen Synchrotron” (SIS) and that impinges on a production target. From this event, many fragments are produced. The secondary beam is then purified in the FRS. The experiment storage ring (ESR) and additional experiment caves exist for the conducting of experiments.
- Two high-energy lasers: the Nhelix (Nanosecond High-Energy Laser for Heavy Ion Experiments) and the Phelix (Petawatt High-Energy Laser for Heavy Ion Experiments).

Currently, in the GSI FRS, the target area and the first dipole stage are activated areas that have been operational since 1990. The FRS target area is located at the first focal plane, where primary beam interactions with the target cause radiation to the order of mSv/h [3][92]. Radiation at the target area exists even after a month of cool-down; hence, it is not possible for humans to conduct maintenance. The second focal plane also accumulates a substantial amount of beam loss. As a result, RH needs to be performed for both focal planes. The vacuum chambers of the focal planes consist of complex equipment, including beam diagnostic devices, targets, mechanical drives, and vacuum pumps. Each of these need to be remotely replaced (Figure 41). The chamber in target area and first dipole stage, along with its components requires remote maintenance.

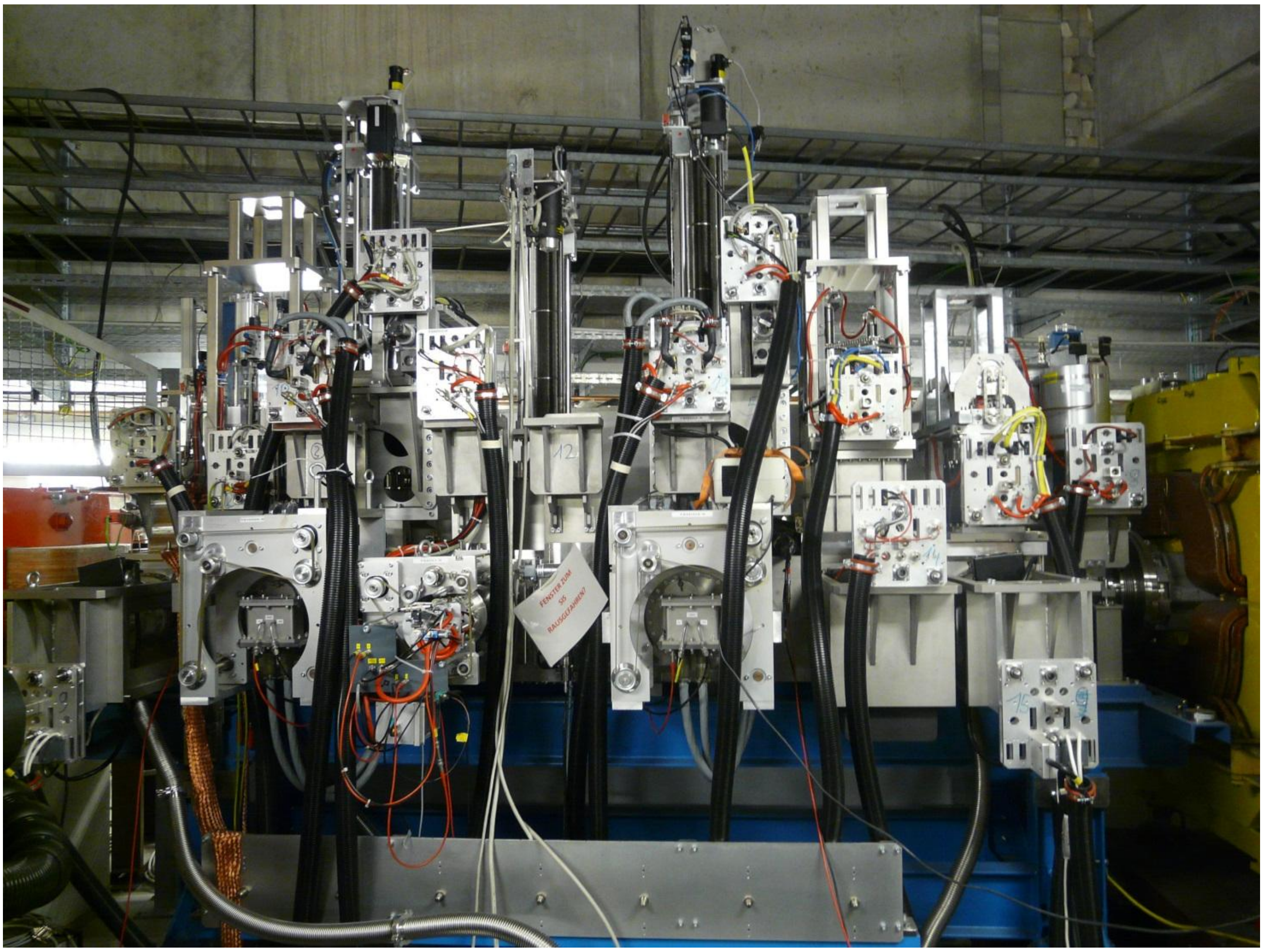
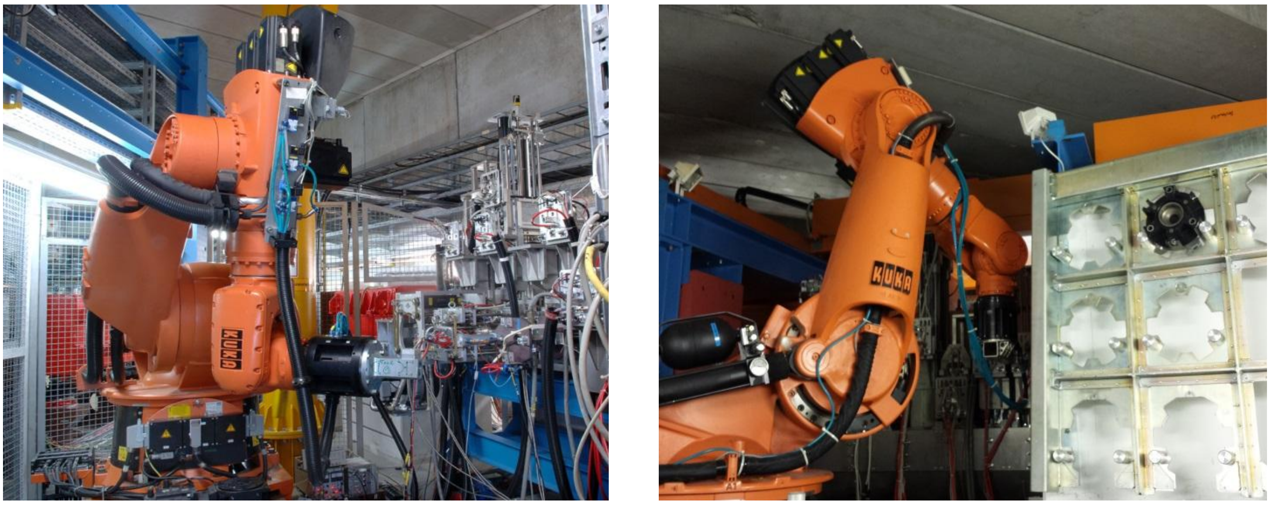


Figure 41. FRS target area.

The two focal FRS planes are remotely handled using two individual KUKA KR350 robots (Figure 42). Each robot can handle loads up to 350 kg and has a working envelope of 25 m². The positioning accuracy and repeatability is better than 0.3 mm. The robot which operates in the target area is mounted on a 5 m long rail system to facilitate access to all necessary components. The robot at the first focal plane is mounted on a fixed concrete base. The levels of radiation at the target area are much greater than those at the focal plane; and hence, the robot at the target area needs protection while the beam is on and until the cool-down time is completed. When the FRS is using a beam for experiments, the robot at the target area is parked behind a lead wall to prevent it from being ionized. Lead shielding containers are provided near the robots to safely store activated beamline parts once they are removed from the vacuum chamber. The lead-shielding containers are later transported to long-term storage facilities. This is done through human intervention, since there is no automated mechanism to transport the activated beamline inserts. The ALARA principle is used to conduct interventions, with time, distance and shielding used as bases for the intervention [3].



(a) (b)

Figure 42: FRS remote maintenance work using KUKA KR 350 robots: (a) target area robot installed on a 5 m long rail to conduct remote maintenance across the target chamber; (b) robot at the first focal plane, installed on a fixed concrete base with a tool rack beside the chamber on the wall [3].

FRS robots carry customized tools (or end effectors), which are required to handle the individual components. FRS robots use two tools—a hook and a grippe (Figure 43)—to conduct RH tasks. The hook is used to lift heavy loads and transport them from the chamber to a lead-shielding container, or vice versa[3].

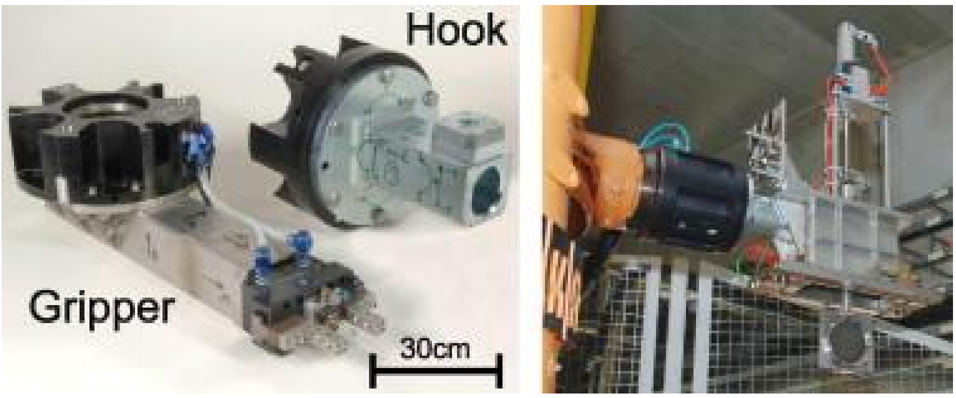


Figure 43: Hook and gripper tools for the Super-FRS (left); KUKA KR350 removing and transporting a vacuum window from a vacuum chamber using a hook tool (right) [3].

The gripper tool, which is operated by a pneumatic actuator, is used to catch and handle smaller parts, such as media supply panels (Figure 44). Media supply panels are specially designed for the FRS beamline inserts. They supply compressed air, electricity (including high- and low-voltage supplies), electronics (detector and control signals, etc.), cooling water, and exhaust air and gases for the detectors. They are also used to vent the vacuum system. The media supply panels are connected via a 20 by

20 cm² media panel. A pneumatically driven lock/unlock mechanism ensures a tight mechanical connection after the robot arm has moved away. All media feeds go through standard commercial pieces. The water and gas feeds are self-locking and open automatically upon disconnection and connection[3].

Figure 44. FRS beamline insert media supply panels (left); KUKA robot arm using a gripper to remove the beamline insert media panel from the detector in the target chamber (right) [3].

Viton O-rings are used to ensure a solid vacuum in the chamber. Due the weight of the beamline inserts the gravitational force to secure the vacuum sealing. Viton O-rings suffer from radiation damage and can withstand integral doses of up to 10^6 Gy [3].

All RH tasks are programmed, simulated and tested using KUKA SIMPRO software, which includes 3D models of the KUKA KR350 and beamline inserts. The software determines, in detail, the robot motion sequences necessary to perform various subtasks. It also ensures that all points are within reach of the robot and that no operation errors or critical robot trajectories occur. Once a task sequence is refined in KUKA SIMPRO, it is carried out using an actual test platform. Finally, the robots are installed in the desired target location (e.g. the target chamber or focal planes) [3].

2.1.2.2 RH at ISOLDE, CERN

The ISOLDE facility is a world-leading laboratory for ISOL production and studies of radioactive nuclei. ISOLDE belongs to CERN's accelerator complex, and the facility has been in operation since CERN opened in 1967. ISOLDE's typical proton beam energies range between 1 and 1.4 GeV. The facility has two target stations (Figure 45): a High-Resolution Separator (HRS) and a general-purpose separator (GPS). The target at ISOLDE has a dose rate of several Sv/h; hence, maintenance is only possible using RH equipment. ISOLDE targets are exchanged 30 times per year, on average. These targets must be exchanged approximately every 10 days, and they have a residual radiation dose of approximately 200 mSv on contact [45][93][94].

In the past, the ISOLDE target stations were remotely maintained with Stäubli RX industrial robots (Figure 45). These robots were installed on the ground and were utilized to: (i) remove and transport the spent target from the (front end) target station to shielded storage shelves and (ii) transport and install a fresh target from the shielded storage shelves to the (front end) target station.

Between 2012 and 2013, the robots experienced various breakdowns during remote maintenance procedures. The Stäubli RX industrial robots were 20 years old, and in the coming year, they will no longer be supported for spare parts and software by their manufacturer. The ISOLDE facility is currently set to be upgraded to Hi-ISOLDE, which will require new types of targets, new target storage locations and new maintenance trajectories. As the robots were installed on the ground, they could only move along a fixed trajectory, which made them unsuitable for this upgrade.

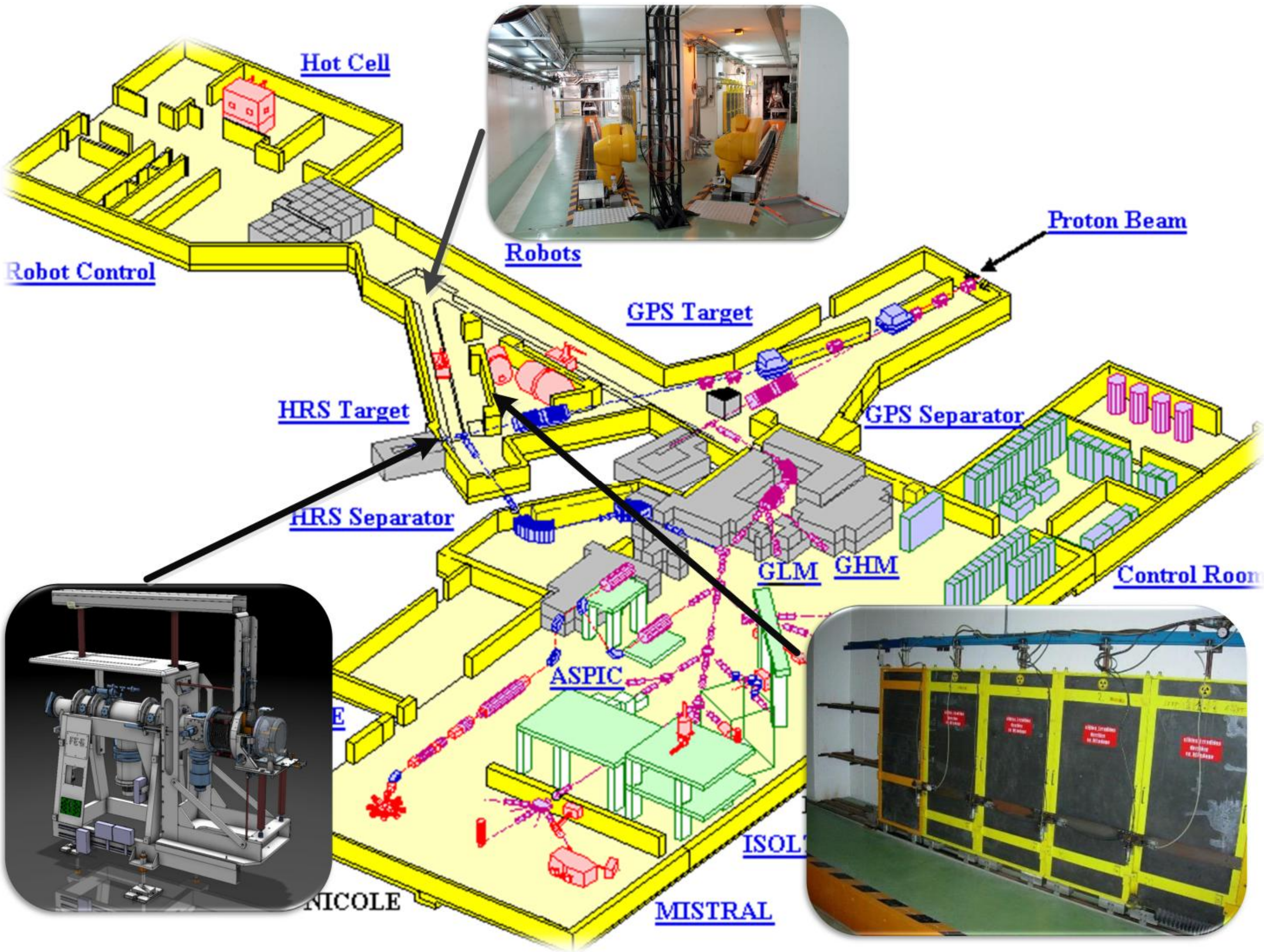


Figure 45. ISOLDE facility with RH setup: Stäubli RX robots; the front end target; and the storage of activated parts in lead-shielded storage racks [93].

In 2013, the Stäubli RX industrial robots were replaced with two new KUKA industrial robots (Figure 46), which were mounted on the roof of the ISOLDE target area. The removal of the Stäubli RX industrial robots and the installation of KUKA arms was executed over a 16-month duration by 90 workers sharing a total dose of 13.4 mSv, with dose rates ranging up to several mSv/h [93].

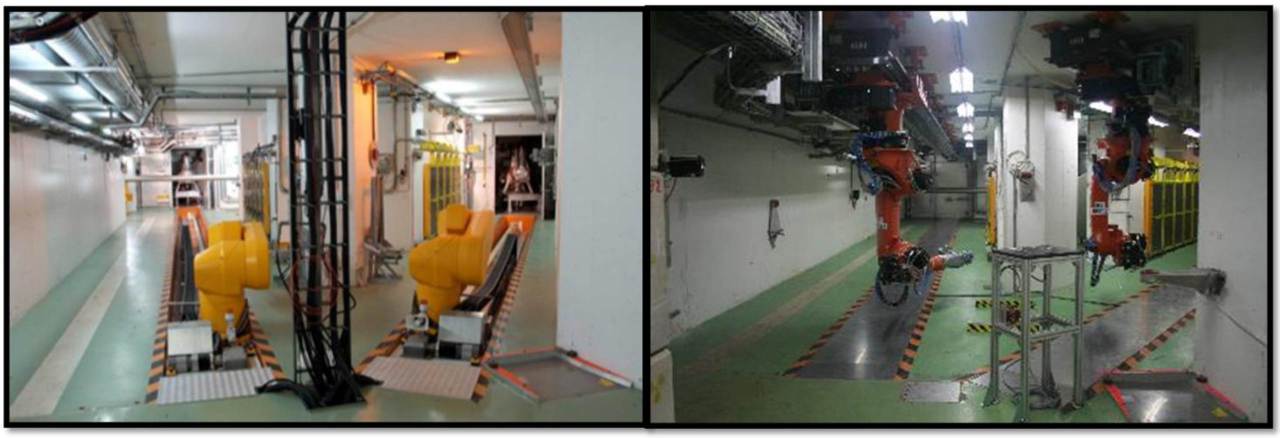
The KUKA robot selected is a foundry robot that can withstand harsh environments. The KUKA robot can lift up to 30 kg and has an arm reach of 2.23 m, with a precision range of 0.5 mm. Due to the radioactive environment, various modifications were made to the robot in-house, as follows [93]:

- Alteration of the robot positioning so that it was based on resolver technology (to promote reliable use in a radiation environment).
- Addition of viton seals to the robot arm to make the robot partially radiation-hardened.
- Removal of on-board electronics.
- Removal of a normal cable on-board the robot and installation of a radiation-hardened cable on-board the robot.

- Replacement of cable support on-board the robot to enable robot movements without obstruction.
- No extra sensors needed for the protection of infrastructure.
- Modification and redesign of the gripper. A recovery method was included, for use in the event that the gripper or target becomes stuck.
- Sensor feedback for each movement.
- Collision detection.

The modifications to the KUKA robot were done in-house at CERN in order to develop in-house expertize related to utilizing industrial robots in a radiation environment. The development took five years, with four full-time workers assigned to the task. The total cost was 10 million euros [93].

The task sequences for the robots were initially optimized using 3D software and later tested on a full-scale mockup of the facility at CERN. This enabled the final installation team to make only minor adjustments in the real environment. The robots became operational within the ISOLDE facility in March 2015.



ISOLDE old robots **ISOLDE new KUKA robots**

Figure 46. Old and new ISOLDE robot setups [93].

2.1.2.3 Target remote maintenance at BigRIPS at Rikagaku Kenkyusho (Institute of Physical and Chemical Research, Japan) (RIKEN)

The BigRIPS (radioactive-isotope beam separator) at Rikagaku Kenkyusho (Institute of Physical and Chemical Research, Japan) (RIKEN) uses a water-cooled, high-power rotating disk target with a ^{238}U primary beam. The rotating target is designed to be an “all-in-one target.” The flange unit is attached to a vacuum chamber. It is constructed in this way to facilitate the RH During remote maintenance, the target flange unit and the vacuum pump unit are dismounted using a remote-handling maintenance cart (Figure 47) [95], which runs on guide rails and is remote-controlled. The complete target assembly, including the pump unit, can be removed from the BigRIPS target station using this maintenance cart. To release the vacuum, the pneumatic locks on the flange are released. When the target chamber is flushed with air, the cart transports the complete assembly through the access tunnel to a temporary storage area [95].

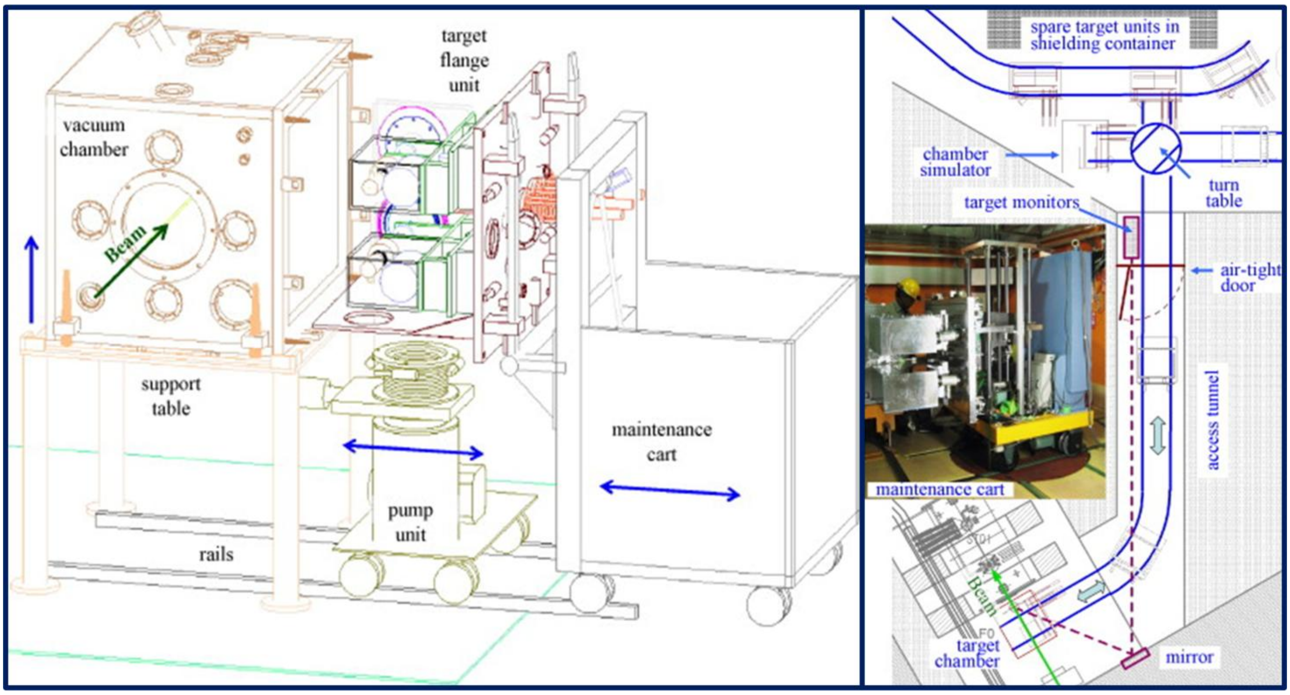


Figure 47. The BigRIPS target RH setup (left); schematics of the target flange unit and the pump unit, with the maintenance cart pictured as an inset and the guideline rails for the maintenance cart outlined from the target chamber to the shielding storage container (right) [95].

2.1.3 Conclusions: State of the Art survey of RH in HEP facilities

The State of the Art survey of described in this section reveals that HEP facilities can be divided into the following categories:

- The first type (closed tunnel) of facility is developed with a closed tunnel design concept and a vertical plug system (Figure 13). In such facilities, the hotcell is located separately from the beamline region. Such facilities require the remote transfer of beamline equipment during maintenance. Normally, a shielding flask is used to transport the beamline insert between the hotcell and the beamline region. This process involves the total shutdown of the facility and can only be performed after a cool-down period. The beamline inserts in such facilities have radiation doses of up to several mSv/h. Examples include PSI, J-PARC MUSE, Fermilab NuMI and T2K at J-PARC.
- The second type (Integrated hotcell and target area)of facility builds the hotcell on top of the target area (Figure 33, Figure 37, Figure 39). SNS, JSNS, ISIS, FRIB and SPIRAL 2 are examples of facilities in which the hotcell is located near the target region. The other important aspect of these facilities is that their liquid targets have pumping equipment that is radioactive due to beam interaction. The hotcell is built on top of the target in order to safely drain and store the radioactive fluid before transportation to a disposal site. At such facilities, the target is mounted on top of a horizontal base, which can be retrieved into the hotcell. The target assembly as a whole is dissembled within the hotcell using Master Slave manipulators, power manipulators and cranes. The waste products are stored in secure containers, which are later transported to long-term storage facilities. New targets are then installed onto the horizontal target assembly and the beamline. The hotcell is equipped RH equipment and waste disposal management systems to conduct maintenance on-site.

- The third type (facilities with very high energy) of facility uses very high-energy beams. Examples of such facilities include LHC and CNGS at CERN. These facilities are built with open underground tunnels to provide natural shielding as shielding of the at such high energies is impractical. To keep these facilities operational, some parts such as the collimators require regular inspection and replacement if damaged. Facilities like the LHC are very large in nature and require mobile equipment to conduct remote inspections and maintenance. The LHC TIM and the remotely operated crane for collimator exchange are very good examples of customized tools that were designed once it was realized that the failure of the LHC collimators could cause facility-wide shutdowns. Aside from collimator replacement, remote maintenance is not typically needed in the LHC tunnel.
- The fourth type (Open tunnel) of facility was developed with an open tunnel that uses localized shielding around the target area. Activated parts are replaced using modified industrial robots or mobile carts. Examples include the target exchange systems of FRS, ISOLDE and the BigRIPS at RIKEN. These facilities develop dedicated systems for target or beamline insert exchange by modifying COTS, since the development of a completely new system is typically impractical from a cost point of view. The remote maintenance space in such facilities is very restricted and is shared with radiation workers.

2.2 State of the Art robotic equipment for RH

2.2.1 Robotics equipment used at HEP facilities

The RH survey of HEP facilities (see Section 2.1) provides a detailed overview of existing particle accelerator facilities and the equipment they use to conduct remote maintenance. This section will provide a summary review of the State of the Art equipment (currently in use for RH in various HEP facilities (some of which was already introduced in Section 2.1).

HEP facilities require that RH equipment can transport radioactive targets and beamline inserts that directly interact with beams. Such objects can have dose rates as high as 5 Sv/h (on the surface). Hence, they require shielding during transportation, which is normally achieved using shielding flasks. Shielding flasks are normally equipped with internal cranes that can handle loads in tons. Self-aligning mechanisms are used to retrieve or install the targets and transfer them to storage units or a hotcell. Shielding flasks provide the necessary protection during the transportation of activated beamline inserts and reduce dose rates to between 10 and 100 µSv/h. The PSI (Figure 16) and J-PARC (Figure 21, Figure 22) facilities, introduced in the previous section, use multiple shielding flasks to transport targets and other beamline inserts. PSI uses individual shielding flasks to handle Target M, Target E and the SNS target during the remote maintenance process (see Section 2.1.1.1 for description of these parts). Similarly, J-PARC successfully achieved the replacement of its Muon target in December 2014 using a shielding flask. It is clear that shielding flasks represent an integral aspect of RH equipment across HEP facilities and are critical to the safe transportation of radioactive components.

The facilities with targets in open tunnels, such as FRS at GSI, ISOLDE at CERN and BigRIPS at RIKEN, use industrial equipment to conduct remote maintenance. The FRS and ISOLDE targets, for example, are handled using industrial robots from KUKA. Their equipment has been modified by removing sensitive, on-board electronic equipment to make the robots more radiation-hardened. These robots perform RH by directly removing and installing targets and beamline components from beamline vacuum chambers. The BigRIPS at RIKEN uses very unique equipment modified from COTS, which transports targets to safety and does not perform any remote manipulation directly on the target. The open tunnel facilities also use localized shielding to protect RH equipment from damage and degradation due to radiation doses in irradiating environments.

The inspection and RH of tunnels and irradiated areas with restricted accessibility are conducted using mobile equipment. The LHC tunnel at CERN is inspected for damage and radiation using TIM and TAN, which are remotely-controlled devices that are mounted on the monorail that runs along the top of the LHC tunnel. The Telemax ROV and the remotely operated crane for collimator exchange are also used at CERN. They are both mobile equipment and are used to retrieve radioactive parts and LHC collimators remotely from the beamline. The SNS ORNL facility also uses a mobile manipulator vehicle system, which can be remotely controlled to perform maintenance tasks.

The post-processing of radioactive beamline inserts is an important step in RH at particle accelerator facilities. It can be divided into two parts: (i) the repair of beamline inserts and (ii) the long-term storage and disposal of radioactive waste material. The post-processing of radioactive beamline inserts is performed within a hotcell. PSI, J-PARC, ORNL, ISIS and Fermilab all use hotcells to repair, dispose of and store radioactive beamline inserts. These hotcells are paired with storage compartments, in which the radioactive waste is securely stored for certain duration before being transported to long-term storage facilities. The hotcells in all HEP facilities utilize Master Slave Manipulators, power manipulators, visual systems, overhead cranes, specialized remote maintenance tools, clamping (table) mechanisms (to hold radioactive components during remote maintenance), and radioactive waste disposal/packing systems.

2.2.2 Robotics equipment in the nuclear power production industry

This section will describe some of the robotic RH equipment that is currently used to conduct remote maintenance in the nuclear industry. Specifically, this section focuses on the utilization of industrial and customized robot arms for RH. Since radiation and radioactive waste levels in nuclear power plants are far higher than those in HEP facilities, it is logical to study the State of the Art equipment used by such plants for RH, in order to utilize the latest technologies to design reliable RH systems for HEP facilities.

2.2.2.1 RH at the Joint European Torus (JET) facility

Increased future energy needs present a challenge for today's society, and fusion energy is seen as one solution to fulfill future requirements. The Joint European Torus (JET) project is currently the world's largest tokamak, and is located in Oxfordshire, UK. This fusion research facility is a joint European project with the main purpose of paving the way to a future of nuclear fusion energy on the electricity grid. In 1997, for first time, the JET project produced 16 megawatts of fusion power and successfully demonstrated the key technologies required for the production of fusion power. Due to the high levels of radiation in the environment, the JET project has had to undergo regular remote maintenance since 1998 [96].

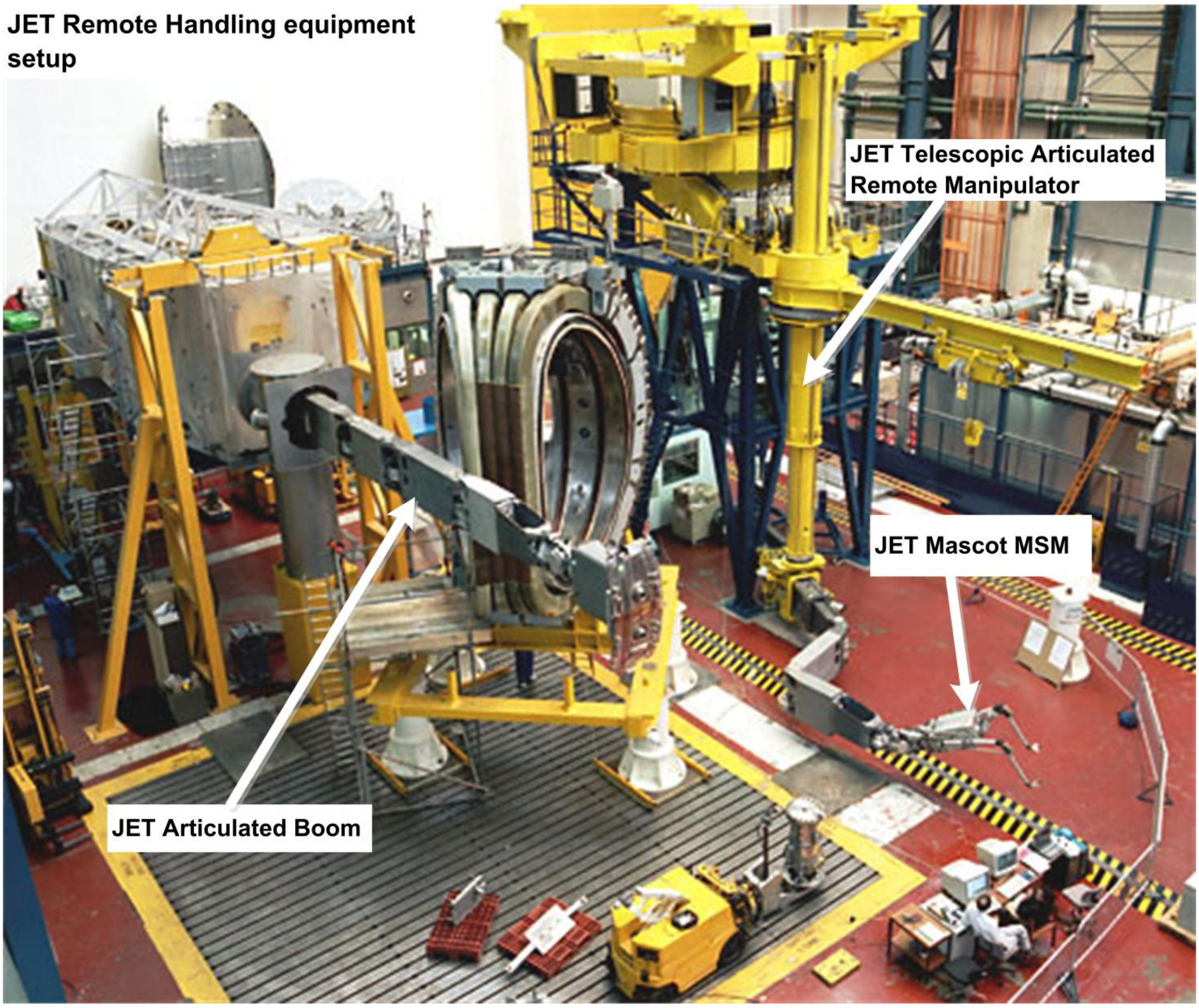


Figure 48. JET RH equipment setup (images courtesy of EFDA-JET).

The JET RH team uses State of the Art equipment specifically designed for fusion reactor maintenance (Figure 48). This equipment is supported by the EU. The RH setup includes the following two pieces of equipment, which are both controlled by operators from a main control room:

Mascot

The Mascot RH system (Figure 49) is the main piece of equipment used to conduct remote maintenance at the JET facility. It consists of two force feedback Master Slave Manipulators to extend an operator's own arms into the radioactive environment [41][96]. Each Mascot slave arm has servo-manipulators with load capacities of 20 kg. The master-slave connections are not mechanical, as in many devices, but instead are connected via computer links. This means that that the slave units can be operated from any distance from the master arms. Mascot is used to perform various tasks, including welding, cutting, bolting, handling and inspection. Many of these tasks are performed using special tools that have been designed and developed at JET. The Mascot manipulator is connected to the JET articulated boom, described below, which provides the maneuverability necessary to perform the required tasks. Mascot operations are directly monitored using a CCTV system.

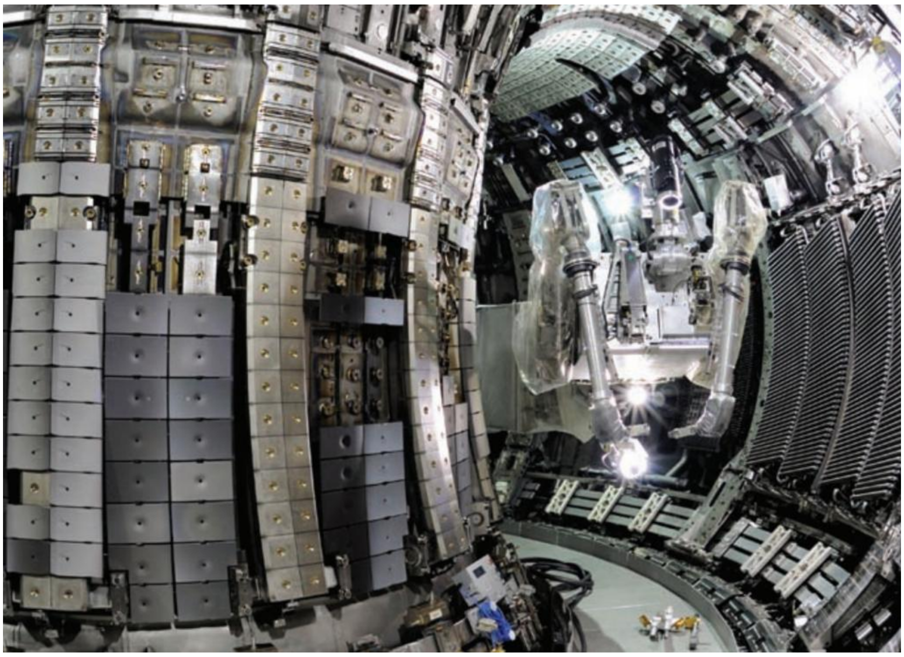
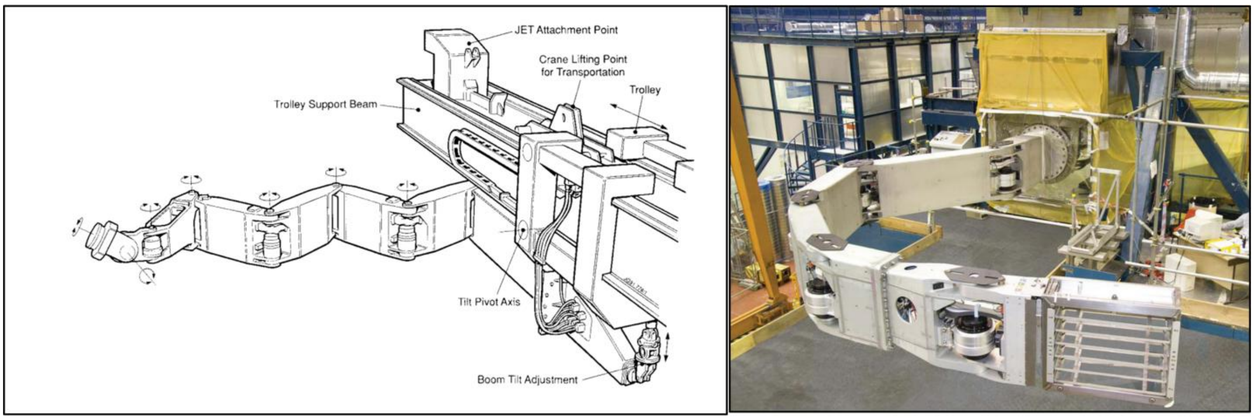


Figure 49. JET Mascot RH system: performing remote maintenance in the JET project (images courtesy of EFDA-JET).

JET articulated boom

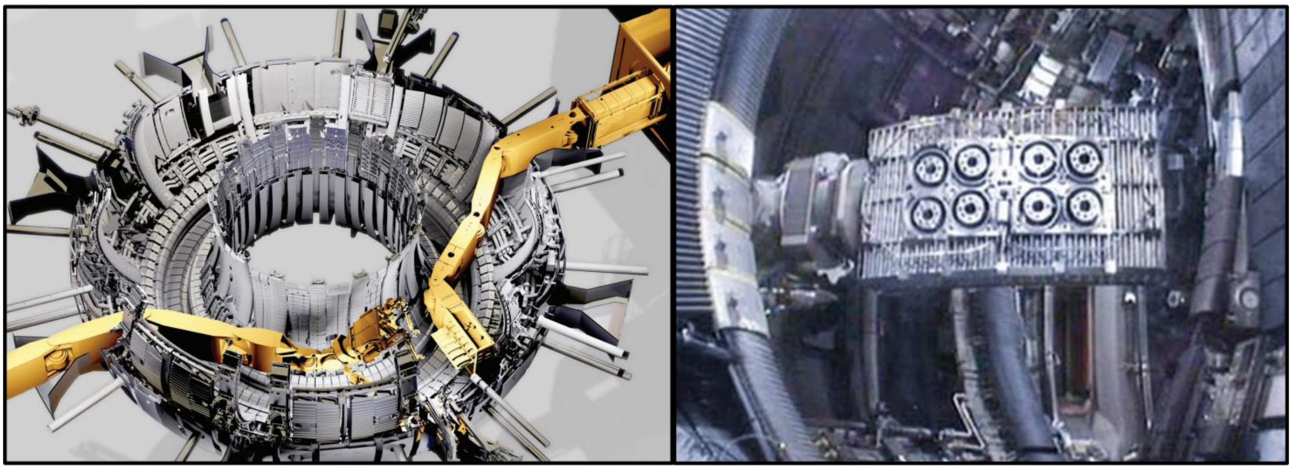
To gain access to the inside of the JET torus, two of entry ports are reserved for remote maintenance only. The JET articulated boom (Figure 50) is a 10 m long articulated robot that is used to transport both material and the Mascot into the torus for maintenance. This device has 19 DOF and is controlled using either a joystick, a keyboard or through pre-taught sequences of motion [97].



(a) (b)

Figure 50. JET articulated boom (images courtesy of EFDA-JET).

Based on success of the JET experiment, the International Thermonuclear Reactor (ITER) is under development in France. The systems for the ITER have been tested at JET. During the operations at ITER operation, plasma temperatures are expected to rise to 100 million degrees Celsius. The Ion Cyclotron Resonance Heating (ICRH) antenna (Figure 51), which is one of the heating systems for the ITER, was first tested with the JET machine. In 2007, the ICRH antenna was installed at the JET facility during a shutdown period. The 300 kg antenna was transported into the torus using the JET articulated boom via a specially designed end-effector. The installation task sequence was carried out using pre-defined smooth trajectories until the final approach. The final stage to install the antenna was performed with "man-in-the-loop" guidance. Feedback was provided using the contact forces exerted on the antenna by its wall-mounted supports, which utilized force and torque sensors installed on the articulated boom end-effector [98].



(a) (b)

Figure 51. Installation of an ITER ICRH-like antenna installation at the JET facility in 2007 (images courtesy of EFDA-JET).

2.2.2.2 RH at nuclear reactor decommissioning

Conventional nuclear power plants that have reached their designed lifetime require an extensive dismantling process, which follows various stages. Due to higher dose rates, of well above several Sv/h, sophisticated RH devices have been developed to carry out these dismantling processes. In this section, we will discuss the various types of RH equipment used in such procedures.

Wiederaufarbeitungsanlage Karlsruhe Rückbau-und Entsorgungs-GmbH (WAK-GmbH)

The Karlsruhe Reprocessing Plant (WAK) was built between 1967 and 1971 by WAK–Betriebsgesellschaft (WAK-BG) in Germany. During its 20 years of operation, the WAK plant processed 208 tons of heavy metal and irradiated oxide fuel from the research and power reactors. On June 30, 1991, the plant was closed. Plant decontamination and dismantling began in 1994. Dismantling activities were conducted variously using hands-on techniques, remote techniques, or a mixture of both, depending on the radiological conditions. Significant upfront planning was conducted on this project, which included the use of a mockup facility for operator training, operations planning, and equipment testing and dose rate analysis. Particular attention was paid to the parallel development of radiation protection measures and an optimal organization structure for ensuring the safety of personnel and the environment. Due to this extensive planning, no serious safety incidents were reported during the cleanup operations, and the project appears to have met its baseline cost and schedule targets [99].

The dismantling of the WAK facility concentrated on the use of RH equipment. The radioactive waste and the decommissioned equipment had very high surface dose rates of up to 100 mSv/h, along with very high levels of human safety risk factors[100].

The dismantling system for the WAK facility consisted of the following equipment [100][101] (Figure 52):

- EMSM3, a Master Slave Manipulator with bilateral force feedback.
- A gantry (crane-like) manipulator, which carried the EMSM3 across the WAK facility for RH tasks.
- Cutting tools and devices for the EMSM3, such as hydraulic shears, compass saws, disc grinders, etc.
- Auxiliary crane and crane-supported auxiliary manipulators for remote-controlled recovery and repair work to manipulator carrier systems and Master Slave Manipulator.
- Radioactive waste processing and packaging systems.
- A control room for managing remote controlled operations.

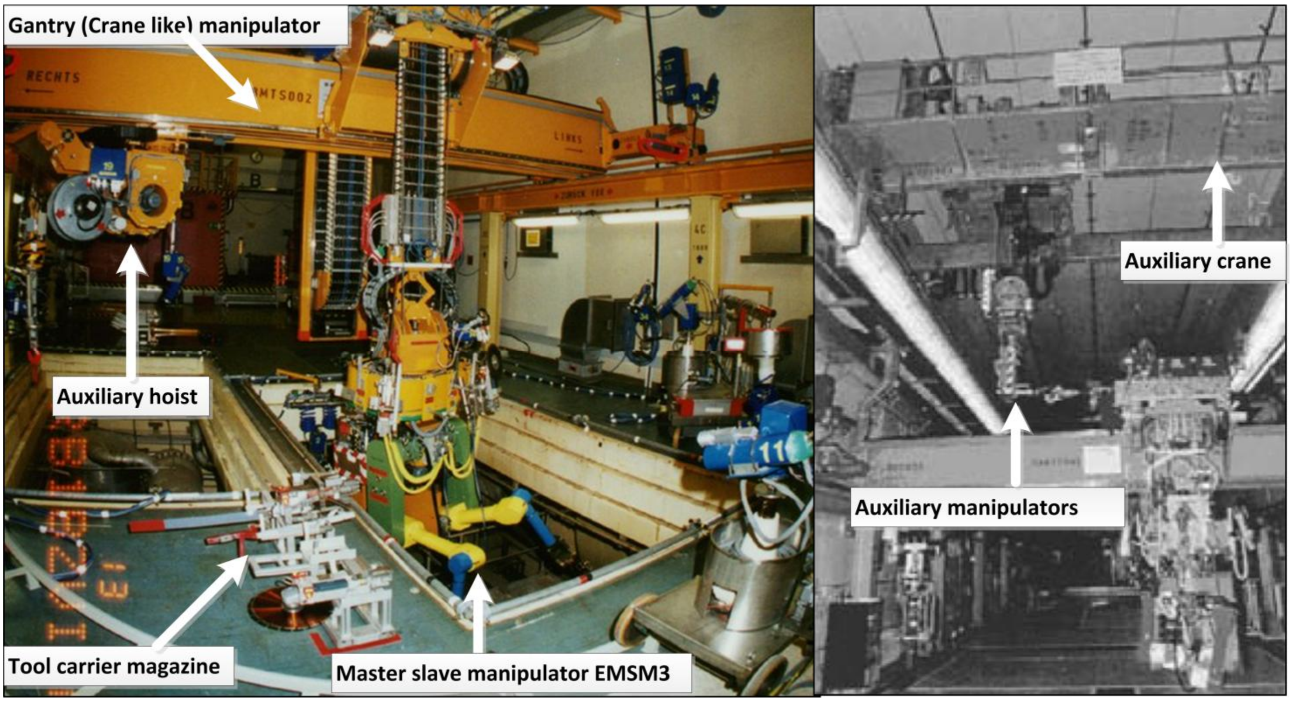


Figure 52. Dismantling system for the WAK facility (images courtesy of WAK-GmbH).

Remote maintenance of the facility was carried out primarily through the use of the EMSM3 Electrical Master Slave Manipulator (Figure 52). To achieve the vertical dismantling of the cells of the WAK facility, a manipulator carrier system with a mono-bridge gantry crane was constructed 3 m above the cell floor. It included 50 kN hoists, which carried an 8 DOF platform which carried the EMSM3. The EMSM3 used various tools to reduce the size of the radioactive waste, ultimately packing the waste into 150 L drums. These tools included a hydraulic shear, a grinder with a diamond disc and a hack saw, which were all stored in a tool carrier magazine. The EMSM3 was remotely controlled by an operator and it had bilateral force feedback. Its arms were used to cut and dismantle large blocks of radioactive waste.

Certain activated sections and pieces of equipment within the WAK facility could only be dismantled using equipment which was capable of accessing the area horizontally. The commercial crawler-digger BROKK 150 Carrier was modified as a power tool carrier. The SAMM arm is mounted on the end of the BROKK 150 Carrier to conduct remote manipulation. The SAMM arm was a six-axis hydraulic manipulator capable of performing tasks in a radioactive environment, and the SAMM arm had a 10^4 Gy radiation tolerance. This remotely controlled manipulator was equipped with a grinder, a stone saw or hydraulic cutter. The SAMM arm could be used in either robotic mode (i.e., automated sequences) or in manual remote control mode. The mobile horizontal RH equipment was used to disassemble the collection tank for medium-level liquid waste.[5].

(a) (b)

Figure 53. Horizontal RH and dismantling equipment for WAK facility (images courtesy WAK-GmbH).

The Dual Arm Work Platform (DAWP) at the dismantling of the Chicago Pile 5 (CP5) reactor

The Chicago Pile 5 (CP5) reactor was a heavy water-cooled reactor that operated from 1954 until 1979. The reactor underwent 18 years of cool-down before dismantling was conducted. The Dual Arm Work Platform (DAWP) was a remotely operated piece of equipment that was deployed to carry out the decommissioning of the nuclear reactor and its bio-shield structures. It was developed by a consortium of national laboratories and industry manufacturers. Schilling Robotics Systems and Red Zone Robotics provided the components for DWAP, and it was produced by ORNL and the Idaho National Engineering and Environmental Laboratory. The DAWP was composed of the following components, which were tested and deployed to assist in CP5 decontamination [102][103]:

Platform base: This was fabricated from a steel plate with bolted gaskets and a panel for hydraulic, electrical and electronic components. The 2245 kg base had 2 DOF, which translates to 46 cm. It rotated by 90 degrees so that the manipulator base could be moved horizontally to extend the working envelope. An overhead crane was used to transport the DAWP from the platform base across the activated area to conduct RH tasks.

Manipulators: The DAWP had two Schilling Titan III manipulators, which were fitted on top of the base to carry out remote manipulations. Each of the hydraulic manipulators had a 110 kg payload capacity, 6DOF, a maximum extension of 200 cm, and could be controlled remotely using a specially designed joystick. The Schilling Titan III used a force/torque sensor to measure the contact forces applied to objects in the task space. Electrical cabling and hydraulic piping routing were all done internally within the arms, which were radiation hardened.

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[5] The WAK carrier was designed by CYBERNETIX: http://www.cybernetix.fr/en/produit/102/motorized-carriers

<u>Minimal on-board electronics:</u> The number of onboard electronics and hydraulics on the DAWP were reduced to avoid electronic failures and hydraulic leakages and improve its reliability within a radioactive environment. These reductions necessitated a 100 ft long tether, which was used to maintain remote control of the DAWP. After accounting for floor pass-through, cable routing, strain relief and mounting at both ends, the DAWP's useable length was 60 ft. The tether was separated into two bundles, which were each wrapped so that the electrical cables would not be damaged in the event of a hydraulic leak. One of the bundles contained all of the electrical power and signal cables. The second bundle provided the hydraulic supply and return.

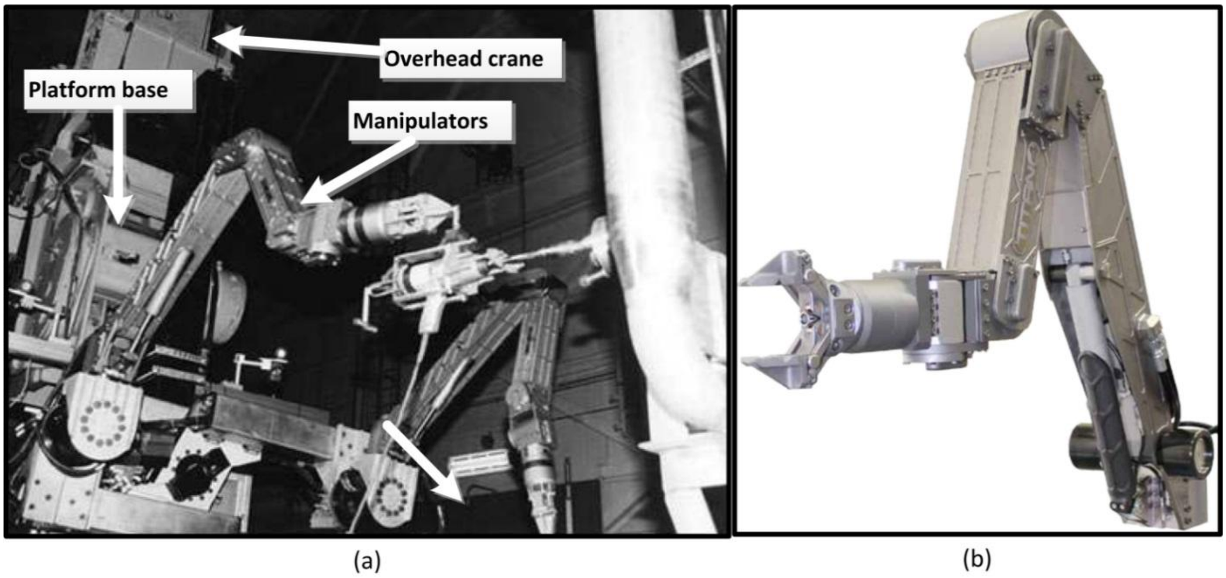
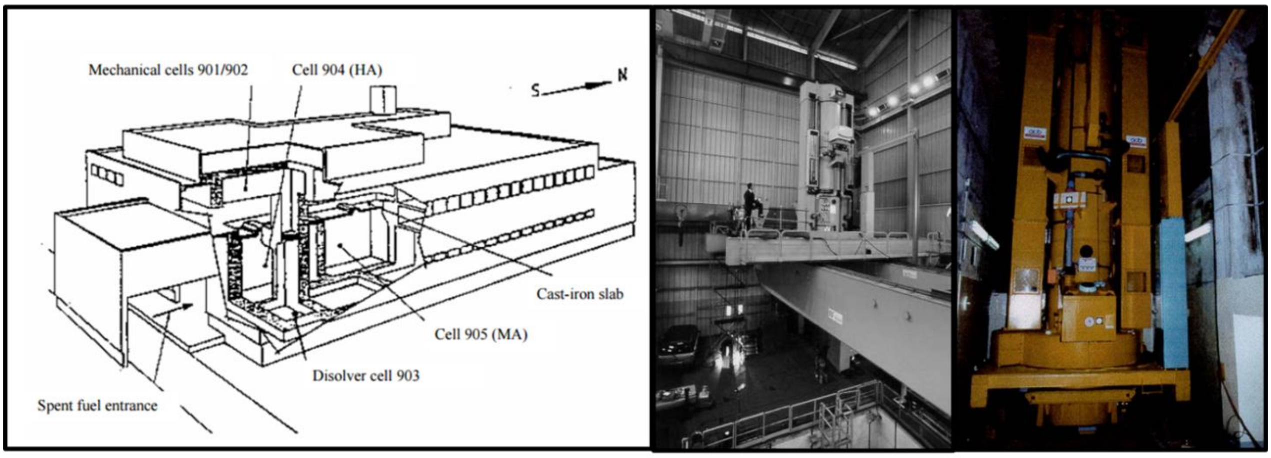


Figure 54. The DAWP at the dismantling of the CP5 reactor.

ATENA machine at Atelier de Traitement (AT1) facility

The Atelier de Traitement (AT1) (Figure 55) facility near Cherbourg, on the AREVA NC La Hague site, was built to reprocess fuels from fast-breeder reactors. The plant was operational from 1969 until 1979. After the completion of the cool-down period, following the processing of the fuel rods, dose rates ranged from 0.01 to 1 Gy/h [104], preventing human access to cells 902 to 904 and allowing access to cells 902, 905, 908 and 909, but only with shielding. Cells 903, 904 and 905 were designed to be dismantled with RH equipment. The ATENA machine (Figure 55) was developed to carry out this task. The AT1 facility's dismantling sequence was divided into the following steps [104]:

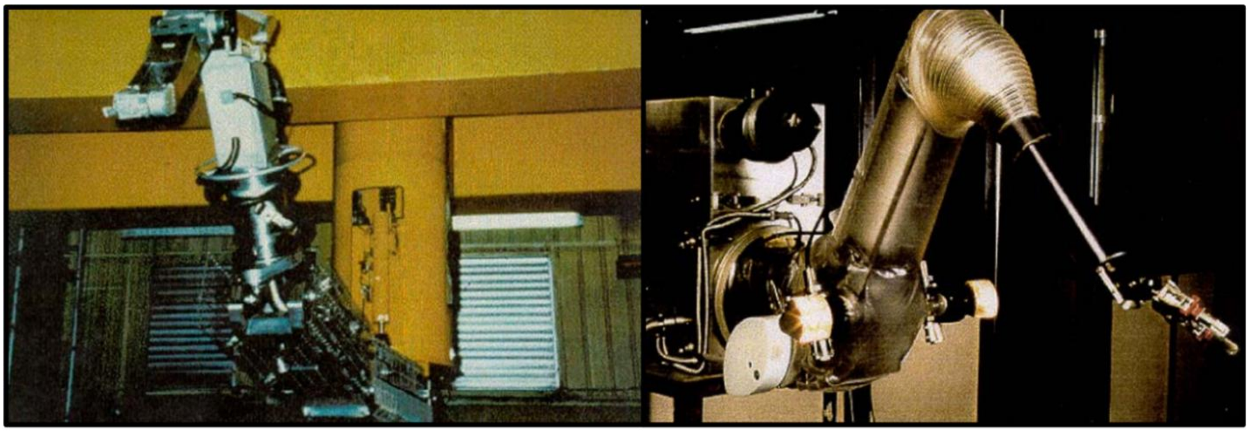
- Dismantling of unshielded alpha cells and glove boxes.
- Installation of the ATENA remote dismantling machine.
- Dismantling within the ATENA machine of the three main shielded blind cells (i.e. cells 905, 904 and 903).
- Dismantling of the various storage cells (e.g. the liquid waste stored in cell 907, the fission products in cells 908 and 909 and in the extension building) and general decontamination of the building.



(a) (b)

Figure 55. AT1 facility near Cherbourg on the AREVA NC La Hague site and the ATENA machine for remote maintenance.

The ATENA machine was used to dismantle the inaccessible parts of the AT1. It was built by Atelier Chantier de Bretagne (ACB) in Nantes, where tests in non-radioactive surroundings were conducted in late 1988 to early 1989.The MA 23M and RD 500 remote-controlled manipulators (Figure 56) were also tested in this environment. The ATENA machine was installed on top of the facility using an overhead crane that enabled it to access the different cells for remote decommissioning. The machine included an 11 m long telescopic link, which was connected to a robotic arm that could be retracted back under a very thick shielding flask. The shielding flask provided both containment and biological protection for the remote operators. The telescopic arm was equipped with either a cutting tool or an MA 23M or RD 500 remote manipulator.



RD 500 MA 23M

Figure 56. Remotely controlled ATENA manipulators: RD500 and MA23M.

The MA 23M and RD 500 remote-controlled manipulators were controlled from the control desk in the ATENA machine operations room. The MA 23M was capable of handling a payload capacity of 25 kg. The slave arm and master arm were connected via an electrical cable. The MA 23M encountered several problems during its operation and was only fully operational after 18 months of delay. The MA 23M was then replaced by the RD 500, which had a 50 kg payload capacity. The RD 500 was developed and designed by the French Alternative Energies and Atomic Energy Commission (CEA; Commissariat à l'énergie atomique et aux énergies alternatives), and was equipped with the following components [104]:

- Force feedback and ambient sensors to assist with remote operations.
- Programmable controllers with reliable, safe computer controls.
- Computer-assisted remote operators capable of performing autonomous or semi-autonomous work.

During the remote decommissioning operations, the ATENA machine itself broke down; and hence, a special work cell was set up to conduct maintenance on the ATENA machine. The ATENA machine was later disposed of as radioactive waste [104].

Areva La Hague nuclear fuel reprocessing plant hotcell equipment

France opened the La Hague reprocessing plant in 1966 to recycle spent nuclear fuel. The reprocessing effort was supported by the EU and Japan, and between 1976 and 2006, approximately 23,000 tons of fuel from Light Water Reactors were reprocessed in La Hague's two reprocessing lines. The goal of reprocessing is to dramatically reduce the volume of radioactive waste. Reprocessing plants represent a complex area for the performance of various chemical and mechanical operations, leading to a wide variety of radiological hazards that require RH. To reduce the doses for radiation workers, RH equipment was made an integral part of the La Hague hotcell facilities [105].

Initially, RH in the plant has been carried out using conventional, through-the-wall, MT200 telescopic manipulators, developed by La Calhene. However, since 2005, the MT200-TAO CEA telerobotic system (Figure 57) has been under evaluation in the COGEMA-La Hague reprocessing plant hotcell. The aim of this system is to eventually replace the conventional manipulators. The main targets of this project are to improve the security of difficult tasks and to improve the ergonomics of the workstation [105].

The CEA developed the TAO2000 [105] software platform as a dedicated solution to computer-aided force-feedback teleoperation (TAO is the French acronym for computer-aided teleoperation). The TAO2000 enables an operator to perform such functions as active weight balancing, accurate force surveillance, tool weight compensation, velocity adjustments and pursuit of a gripper using remote cameras The TAO2000 enables operators to perform tasks very effectively, which was also due to design changes to the basic mechanical manipulator. The TAO2000 also enables operators to use virtual guides and automatic robotic modes to provide assistance during remote maintenance. In 2012, the MT200-TAO was tested for 10 months inside the AREVA hotcell without any failures [106]. In 2014, it was listed for sale as an industrial product by Getinge-LaCalhène [107].

(a)Master manipulator (b)Slave manipulator

Figure 57. MT200 TAO AREVA hotcell operations [106].

The slave manipulator for the MT200-TAO (Figure 57) is a six-DOF, 4 m long manipulator with a payload capacity of 20 kg. Its transmission is based on gears and screws for the upper joints and on cables and chains for the lower joints. The automated playback modes assist the operators, and the repetitive tasks are performed automatically so that they do not put strain on the operator. HEP facilities currently do not use such capabilities for waste handling within their hotcells. Thus, the experience gained from the MT200-TAO development and testing of the computer-aided force-feedback teleoperator system can be useful for optimizing tasks within the hotcell.

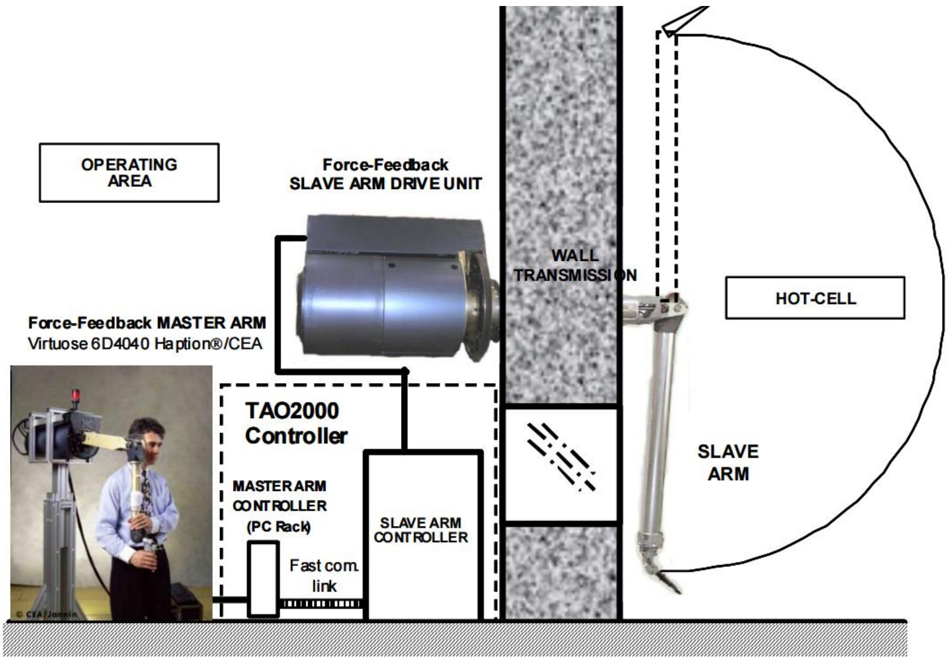


Figure 58. Hardware architecture of an MT200-based AREVA CAT system [106].

Mobile system: Rosie system for the dismantling of the CP5 reactor

The dismantling and decommissioning of the CP5 radioactive structure were carried out using the Rosie mobile robot work system. The Rosie system (Figure 59) was designed to move across the facility and dismantle various structures, while storing and retrieving radioactive waste so that it could later be disposed of safely. The system could be remotely controlled. Its power and telemetry subsystems allowed the control signals to be transmitted from the console to the locomotor and routed onboard to the various sensors and actuators[108].

(a) (b)

Figure 59. Rosie mobile robot system.

The system was divided into two major subassemblies: the locomotor (i.e. the mobile platform) and the heavy (hydraulic) manipulator [108]. The locomotor was a hydraulically powered platform, such that each wheel module had independent drive and steering motions, resulting in omni-directional capabilities. The hydraulic reservoir was located at the front, center part of the locomotor, directly behind the hydraulic pump and its electric motor drive, which powered the system. On the right hand side of the platform was the hydraulic processing system, including filters, the accumulator and the hydraulic cooling system. The onboard electronics were located in a sealed enclosure on the left side of the frame. This enclosure housed transformers, control computing, power supplies, video modulation equipment, and heat exchanger units. In the rear of the locomotor was a tether reel, which could carry up to 50 m (165 feet) of tether. If required up to 100 m (335 ft) of unreeled tether could be included to extend the vehicle's range [109]. The steering mode for the locomotor was divided into three different types, as follows [108][109][110]:

- 4-wheel Mode: The front and rear wheels steered in opposition, allowing turns in any radius, including pivots about the vehicle's center.
- Crab Mode: All wheels steered in the same direction, allowing the vehicle to translate linearly in any direction.
- Point Mode: The wheels automatically steered to turn the locomotor about a predetermined point. Assigning a tool’s location as this point allowed the vehicle to be repositioned without moving the tool.

The second major part of the Rosie was the heavy manipulator, which had a payload capacity of 900 kg. The heavy manipulator consisted of four joints: a vertical axis with waist rotation motion on the locomotor deck, a shoulder pitch motion, a linear forearm extension, and a wrist pitch at the tip of the forearm. Each of these four joints provided integral position feedback. Due to the possible tip-over scenario at full extension, the heavy manipulator was only able to lift 680 kg with a counterweight mounted on the turret and the rear pivoting axle in its locked position. This full load could be carried at full extension for approximately ±45 degrees of waist rotation [109]. The heavy manipulator could be controlled in either of two modes [109][110]:

- Joint Mode: Allowed the operator to individually control each joint on the heavy manipulator at a continuously variable speed.
- Coordinated Mode: Allowed the operator to steer the endpoint of the heavy manipulator, with all four joints automatically coordinating to achieve Cartesian motion.

The Rosie itself was designed to operate in radioactive regions. Its materials and components were selected to reduce the potential for radiation degradation. The robot arm of the Rosie structure could withstand a cumulative radiation dose of at least 10^3 Gy. The electronics were adequately shielded and replaced with components that were radiation-hardened. All onboard components of the system were also sealed for pressurized wash-down. The system's structures were designed to minimize both the exposed surfaces and the areas capable of collecting and trapping contamination [109][110].

The Rosie's tooling includes both hydraulic and electric-powered tooling. These tools were specifically modified to fit the heavy manipulator as end-effectors. Some of the key tools used to remotely handle radioactive waste were a dexterous manipulator, a dual-arm work system and a steel transfer can. The Predator arm was used to remotely remove graphite. Operations revealed that the Predator arm (Figure 60) was not well suited to the severe environments it experienced during graphite removal. In fact, only 227kg of graphite—out of a total of approximately 2268 kg originally planned—were removed and packaged by the arm without any human exposure to radiation. The traditional removal and dismantlement of such an area would have resulted in significant exposure to radiation by personnel. However, with its steel transfer can, Rosie safely off-loaded a total of 3832 kg of radioactive materials. Table 3 shows a detailed list of the tools used with the Rosie mobile robot system [109][110].

(a)Rosie heavy manipulator with Kraft Predator arm. (b)Predator arm used to remove the radioactive concrete.

Figure 60. Rosie mobile robot system with Kraft Predator arm.

Table 3. Rosie mobile robot system tool list

Rosie Tools	hydraulic pipe shear, abrasive water jet, reciprocating saw, excavation bucket, abrasive disk, drum grapple, impact wrench, concrete hole saw, plasma torch cable winch, jackhammer/breaker, mechanical scabbler, pulverizer, dexterous manipulator, dual-arm work system, steel transfer can.

The Rosie was typically controlled by a single operator working in an adjacent control room. In this way, personnel could maintain a safe distance from the radiation in the CP-5 reactor. The Rosie was a reliable system, and its down-time was limited up to one hour and 50 minutes. It was subjected to only two unplanned down-times. Neither event caused any safety or operational concerns. The Rosie mobile robot system was one of the first mobile robot systems used for the remote dismantling of reactor facilities, and it helped to establish the technologies used in mobile RH systems [109][110].

2.3 Classification of RH equipment for remote maintenance tasks

This section presents a classification of RH equipment, based on the study and survey in the previous sections. RH systems and techniques used in both HEP facilities and the nuclear sector can be categorized into the following systems (Figure 61):

- RH transporter systems
- Manipulators (Master Slave Manipulators, power manipulators, autonomous manipulators)
- Tooling systems (cutting tools, grinding tools, lifting tongs)
- Shielding (mobile shielding, such as shielding flasks, and permanent shielding, such as hotcells or shielding walls)
- Supportive systems (visual systems, material handling or packing systems, storage units, radiation warning and protection systems, communication systems, power supply networks)

Each of these categories are described in detail below.

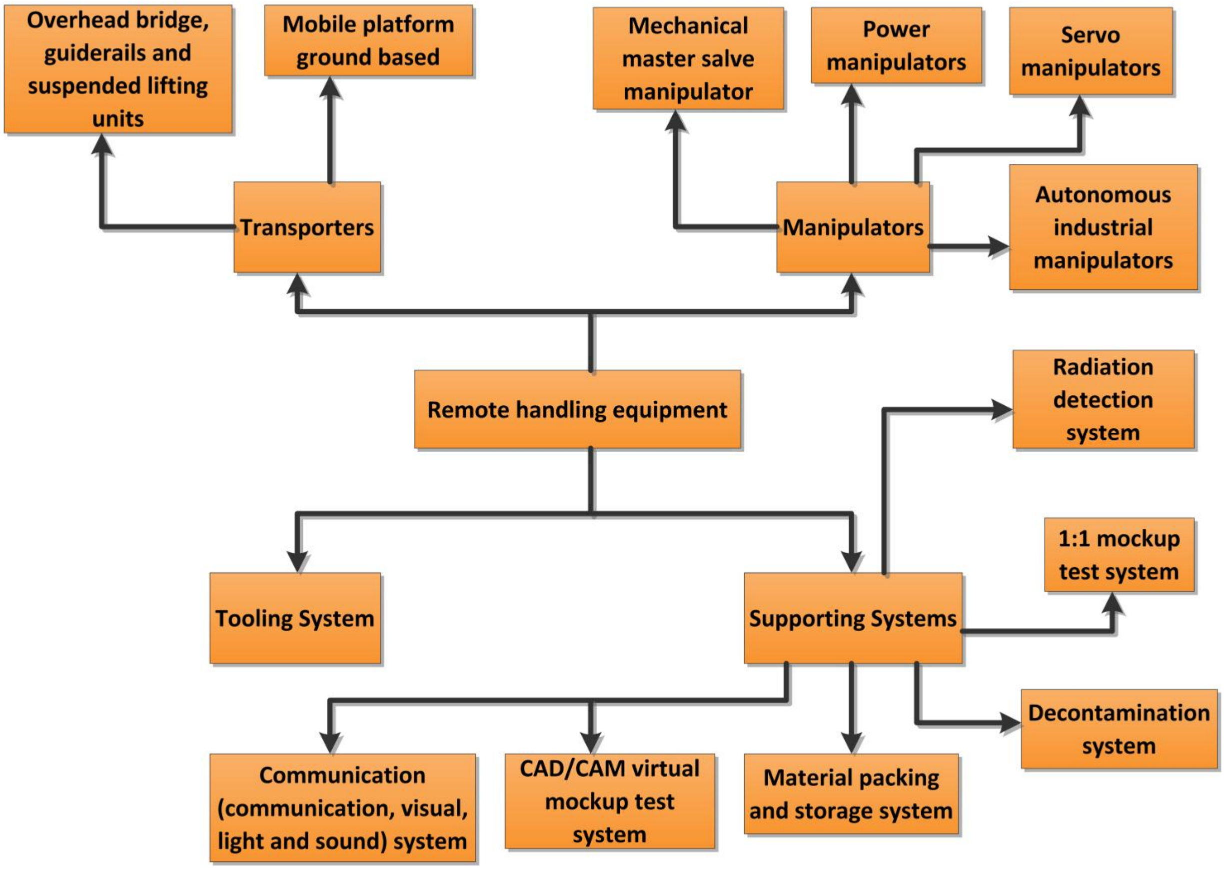


Figure 61. Design classification for the selection of RH equipment for remote maintenance tasks.

2.3.1 RH transporter systems

During RH operations, manipulators are typically used to perform tasks within hostile environments. Manipulators are normally stored in a secure location and are deployed to hot (activated) zones only for the duration of the remote maintenance tasks. RH transporter systems are used to move these manipulators into the hot zones. They have various components, including the tool exchange mechanisms, parking setups, carriers to transport the load, and mobility mechanisms (e.g. mobile platforms or guiderails).

The type of transporter systems used depends on:

- The nature and type of the RH task. For example, if only remote inspection needs to be performed, the carrier can be small; however, if a task includes the handling of heavy loads, the carrier must be larger.
- The required load capacity. The carrier is mainly used to transport the manipulator and the tools. Hence, the load (e.g. weight, forces, momentum, etc.) applied by these components influences the choice of carrier.
- The intervention environment and accessibility. Environmental factors include risk of fire, space restrictions, chemical state, and system integration.

- The radiation resistance capacity of the transporter system. This is a critical factor. In the handling of highly radioactive waste, the chosen carrier's ability to establish a truly realistic level of protection needs to be taken into account.
- The possibility for decontamination. Some RH tasks, such as dismantling, generally involve accessing regions within maintenance zones which have contamination. The transporters normally used in such facilities are expensive and designed for this dedicated purpose. This means that they are developed using complex, high-cost technologies that allows for decontamination. It is essential to design transporters that can be easily decontaminated in the event of any undesired or unforeseen event.

RH transporters can be divided into two major types:

- Overhead bridge, guiderails and suspended lifting units
- Mobile platform or guiderails ground-based

2.3.1.1 Overhead bridge, guiderails and lifting units

This category includes vertical lifting elements which contain the RH system The ATENA machine described in Section 2.2.2.2 is a perfect example of this category. The vertical lifting carrier has a telescopic link that can be extended downwards, and this is powered by hydraulic and electrical systems. The telescopic link is equipped with a robotic arm, which is remotely controlled to carry out RH tasks. The robotic arm is equipped with various end-effectors for dedicated tasks. Most robotic arms are controlled by operators, but, in rare cases, they perform the RH tasks automatically. Vertical lifting systems of this type are normally used to dismantle nuclear reactors in which the radioactivity is very high. The dismantling task sequences at nuclear power plants are normally carried out using a human-in-the-loop methodology. These robust systems allow deployments over a length of up to 25 m. The vertical lifting system, manipulator arm and tooling system are contained inside a flask to protect the equipment from unintended radiation and to ease the transport of the whole unit. The vertical lifting container is mounted on rails so that it can cover a larger area.

Some RH manipulators are directly attached to overhead rails, which transfer them to hot zones to perform RH tasks. The CERN ISOLDE robots, introduced in Section 2.1.2.2, are mounted on overhead guide rails that can remotely install ISOLDE radioactive targets. Such systems are very useful for RH of light loads and for repetitive tasks. In this specific example, the target that is handled is 30 kg, and its installation and removal are carried out 30 times per year, depending on the number of experiments carried out in the facility.

Overhead suspended units are another commonly used transporter mechanism. The WAK arm at the Karlsruhe reprocessing plant and the DAWP at CP5, both introduced in Section 2.2.2.2 , are suspended from the ceiling. Overhead suspended lifting units are connected to the rest of the system, via cables or equivalents, which are hung under a travelling crane bridge or gibbet. The overhead units are also equipped with robotic arms and tools that are remotely controlled to conduct RH task sequences.

2.3.1.2 Mobile platforms (ground-based)

Regions that are normally not accessible from the top are accessed using horizontal mobile platforms. Such platforms are very commonly used in inspection, maintenance and dismantling processes. The RH equipment in the LHC at CERN, described in Section 2.1.1.4, is a good example of this. The remotely operated crane for collimator exchange and the ROV are both mounted on top of mobile platforms. These mobile carriers are also commonly used with robotic arms to carry out dismantling and waste removal processes at plant decommissioning. The WAK facility in Karlsruhe (Section 2.2.2.2) uses the BROKK 150 carrier SAMM arm from a commercial crawler digger. Similarly, the CP5 facility used the Rosie system (Section 2.2.2.2), uses KRAFT Predator robotic arms to remove radioactive waste and carry out the decommissioning of the reactor power plant.

2.3.2 Manipulators

Manipulators are pieces of RH equipment that perform direct manipulations on activated components using specific end-effectors. Manipulators have one or more DOF, which allows them to handle radioactive components from various positions. In most cases, such manipulators have six DOF, plus an additional gripping function. RH tongs and all similar systems with limited motion capabilities are assigned to a sub-category of the manipulator family. Robotic arms are programmable robotic manipulators that function similarly to human arms. These can be articulated with either with rotational or linear movement. Manipulators can be autonomous or manually controlled.

The wide application of manipulators in the nuclear industry and HEP facilities is evident from the extensive literature review presented earlier in Sections 2.1 and 2.2. Manipulators are often a basic part of remote handing equipment, and they are used to reduce the need for human presence to carry out operations involving handling hazardous materials in radioactive environments. Manipulators are normally used for non-repetitive tasks, but in certain cases, industrial robots are deployed to carry out repetitive tasks such as changing of the targets at the ISOLDE facility. It is of utmost important that manipulators have the option for end-effector interchangeability, in order for them to cope with evolving environments. Manipulators can be either:

- Fixed: In this case, the manipulator is mounted to the wall, floor or celling. The manipulator can carry out tasks within the range of its work envelope. Such manipulators are dedicated to limited areas, such as the mechanical Master-Slave Manipulators in a hotcell.
- Mobile: In this case, the manipulator is mounted on top of a transporter (see Section 2.3.1), which can carry it to the necessary location, where the RH task will be performed. The operating space is equivalent to the combined work envelopes of the carrier and the manipulator. The tools for the manipulator are also mounted on top of the transporter, so that the manipulator can carry out a variety of task sequences during maintenance.

The transmission of manipulator movements is provided with the help of mechanical, electrical, pneumatic or hydraulic power systems. These have primarily been developed to comply with the rules listed in Section 1.3.2. Components containing sensitive equipment are kept away from radioactive sources, and shielding can be provided if needed.

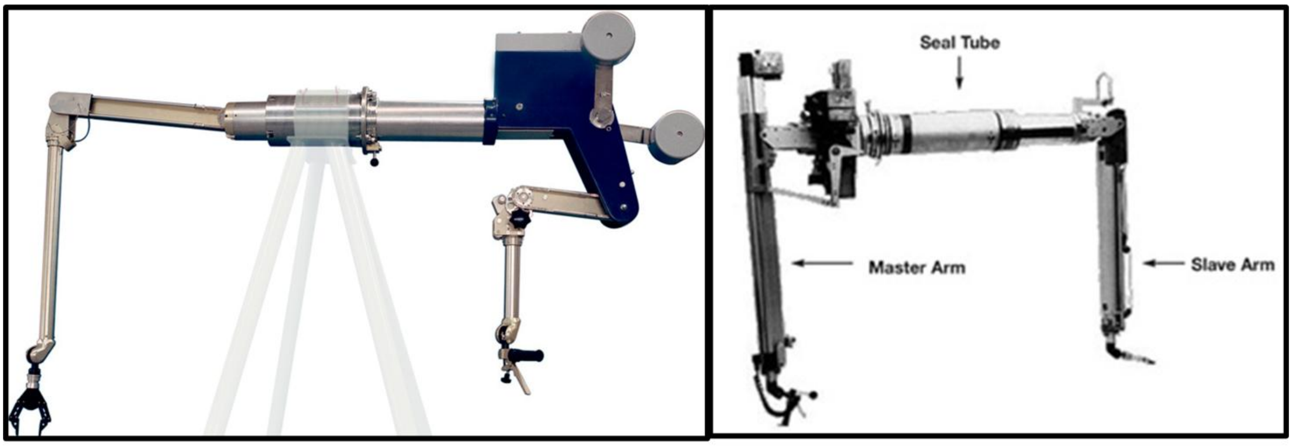
Manipulators, whether manually or autonomously controlled, can be divided into following main categories:

- Mechanical Master Slave Manipulators
- Power manipulators
- Servo manipulators
- Autonomous industrial manipulators

Manipulators have high levels of dexterity that are capable of performing a variety of tasks with appropriate tooling; however, the experiences at JET and PSI indicate that manipulators takes more time than if the task was completed through hands-on experience.

2.3.2.1 Mechanical Master Slave Manipulators

Mechanical Master Slave Manipulators (Figure 62) are the most commonly used type of equipment to remotely handle radioactive waste within hotcells in the nuclear industry, such as reprocessing plants and laboratories. A detailed definition of a mechanical Master Slave Manipulator is provided in ISO 17874-2 [111].



(a)Articulate arm (b)Telescopic arm

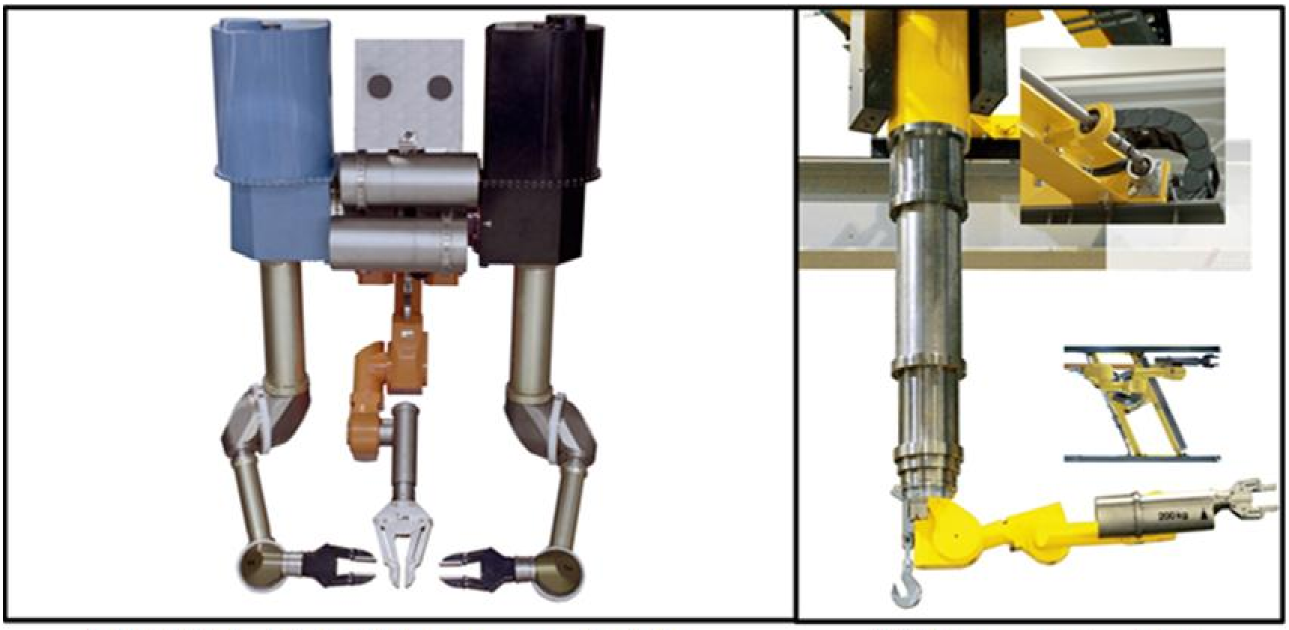
Figure 62. Mechanical Master Slave Manipulator.

These devices are composed of master and slave manipulators, which are connected to one another through a connection tube via mechanical links (e.g. cables, pinions, chains, shafts or metallic tapes). Mechanical manipulators have six DOF. Due to their mechanical backdrivability and mechanical design, they provide force feedback to the operator. The connection tube separates the master and slave manipulators through the wall to ensure communication between the hotcell and the operating zone. The operator visually monitors the hotcell manipulations through lead glass windows and camera-based visual monitoring systems. Mechanical Master Slave Manipulators can be further classified into two categories (Figure 62):

- Articulate-arm: The translation of the arm in this type of Mechanical Master Slave Manipulators is achieved through the use of two rotations of the shoulder and elbow joints. These are normally used for medium-load applications and in small work spaces.
- Telescopic-arm: The translation in these types of arms is achieved with the help of telescopic booms. Telescopic arms usually have higher load capacities and bigger working spaces.

2.3.2.2 Power manipulators

Power manipulators (Figure 63) are used in hotcell and in environments where heavy lifting is needed. They are usually used in large work spaces (e.g. hotcells)and are mounted on top of guide rails which cover large areas of manipulation. Power manipulators have 4 to 7 DOF, with payload capacities of 50-500 kg. They use telescopic links to extend from between 1 and 7 meters to access the working area. Control of this system is typically achieved with help of potentiometers and buttons which control the speed of each axis. Generally, it is possible to define a force limit and to send feedback signals to the operator concerning the gripping force. Power manipulators are very simple in design, with high mechanical gear ratios, very few (or no) sensors, and no sophisticated control technology. These qualities make them suitable for heavy-duty, low-dexterity tasks. In rare cases, power manipulators can include dexterous arms capable of performing remote manipulation; however, power manipulators are normally used for very simple tasks.



(a)TELBOT with A1000 power manipulators (b) Power manipulator

Figure 63. Power manipulators.

Power manipulators are used to handle and move objects, to create high forces throughout the entire volume of a cell and to bring elements to mechanical master slave workstations when high-skill tasks are required. ISO standard ISO 17874-4 defines power manipulator systems for RH radioactive devices [112]. One of the most dexterous robots currently in existence is TELBOT (Figure 63), which was produced by Walischmiller Engineering [113]. TELBOT is very versatile and suitable for the nuclear industry and chemical plants. Its arms have payload capacities ranging from 5 kg to 150 kg, are radiation-resistant, and it has a modular design that enables the TELBOT arm to experience unlimited rotation of all axes. Finally, TELBOT is a program-enabled robot, which means that it is capable of carrying out automated task sequences, if needed.

2.3.2.3 Telerobotic servo manipulators (remotely controlled)

Telerobotic servo manipulators are remotely operated systems that are either electrically or pneumatically powered. They include bilateral, electrical position control of both the master and slave devices (Figure 64), providing force-feedback capabilities to the operator. Current telerobotic systems can use dissimilar master and slave arms, due the absence of mechanical linkages between the two. Advances in telerobotics have allowed the reduction of the size of the umbilical, which passes through the shield of the hot zone, as well as rad-hardened multiplexing systems and embedded systems.

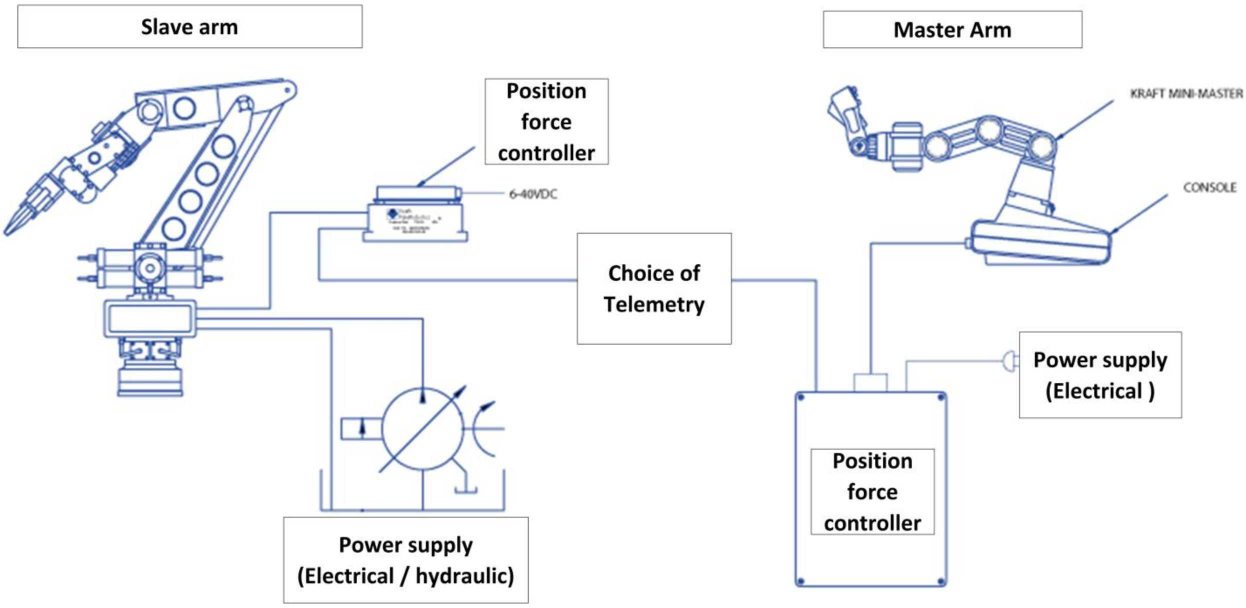


Figure 64. Outline of a telerobotic system for RH.

Telerobotics RH systems can be divided into two main types, based on their kinematic configurations:

- The kinematics configurations of the master and slave arms are identical. In such configurations, access to the torque applied by the payload on each axis is available at each articulation of the arms, and very fine force feedback is achievable. Mascot at JET and the Master Slave Manipulator at SNS ORNL use similar configurations.
- The kinematics configurations of the master and slave arms are dissimilar. Force information feedback quality is usually lower, due to loss in the slave arm structure. On the other hand, this scheme facilitates the use of different slave arm kinematics with the same master arm. It also makes it easier to use slave arms powered by different technologies (e.g. electricity, hydraulics...), and its indexing capabilities usually facilitate work in wider workspaces. Examples of such systems include MT200 TAO[107], the Maestro hydraulic arm cybernetix[6] and Stäubli RX170 at La Hague[106].

2.3.2.4 Autonomous industrial manipulators

Industrial robots are used to carry out certain repetitive remote maintenance tasks of RH. These industrial robots have higher reparability and reliability levels. However, they are frequently modified so that the equipment can be used in radioactive environments with relatively higher doses. The cost of developing new technologies for customized tasks during RH is very high; hence, industrial robots are modified to carry out task sequences. For example, HEP facilities like GSI and ISOLDE use the KUKA and Stäubli RX series robots to carry out remote maintenance tasks.

[6] http://www.cybernetix.fr/en/produit/99/slave-arms. This is a hydraulic manipulator arm designed specifically for work in extreme environments. It is the result of 10 years of research in close collaboration with the CEA (French Atomic Energy Commission). Maestro is designed to perform inspection, maintenance, dismantling, cleaning tasks, etc. It can be used in robot mode (automatic sequence) and in remote control mode, either with or without force feedback control. Its main qualities are its dexterity, its precision and its strength.

2.3.3 Tooling (end-effector) systems

The lifting, cutting, removing, installation and storage of radioactive waste material are essential parts of RH task sequences in HEP and nuclear facilities hotcells. These tasks, as mentioned previously, are performed by manipulator arms equipped with relevant tools. These tools play very critical roles in remote maintenance. Hence, various tools are designed as end-effectors for manipulators to carry out remote maintenance tasks effectively and in a flexible manner. Materials generated during decommissioning and remote maintenance can be lifted using grapples, clamshells or specially designed tools. For example, at CERN and GSI, specialized tooling has been developed to handle targets and beamline inserts. Since the RH tasks at CERN and GSI are close to the beamlines, such that any unintended operation could damage the beamlines, fail-safe mechanisms to detach the tools are also available for cases in which a handled part gets stuck. At the PSI hotcell facility, various conventional tools have been modified to cut and dismantle targets and beamline inserts. Similarly, cutting and cleaning tasks are also performed using specially designed tools. Cutting operations are normally performed using circular saws, nibblers, arc saws, plasma arc cutters, reciprocating saws, laser cutters, friction saws, grinders or rotary hammers.

2.3.4 Supportive systems

2.3.4.1 Communication (communication, visual, light and sound) systems

The control of RH equipment is conducted using dedicated communication systems within the facilities. At CERN LHC, there is a GPRS network that is used to communicate between the RH equipment and the control room. Some the facilities have leaky cables or dedicated Wi-Fi networks for this purpose. Some RH systems rely heavily on real-time operator feedback. Operator feedback is the main link between operators and RH equipment, and a good communication link is essential for performing tasks accurately and effectively. Currently, telemanipulators and robots are assisted by camera, lighting and sound systems. Signals from the assisting equipment are transmitted to a receiver and visually displayed on large monitors for the operator's use. With the use of stereo camera systems, data can also be fed to stereo monitors, providing the operator with limited depth perception.

2.3.4.2 Radiation detection system

Radiation detection systems are used to determine the most highly radioactive materials in a region, in order to remove these first from the site. In certain cases, radiation detection systems are assisted by infrared detection systems, which monitor heat-sensitive areas with radioactive elements. Radiation detection systems are used for various applications, including measuring alpha, beta, gamma and neutron radiation; checking floors for volatile organics and mercury; using infrared cameras to detect heat; using microphones and radios to detect sound; and taking temperature and humidity measurements.

2.3.4.3 Decontamination systems

The RH equipment used to handle radioactive components may require decontamination, depending on environmental conditions. Decontamination techniques are suitable for remote operation, and they include such processes as scrabbling, vacuuming, steam cleaning and spraying. Normally, RH equipment is covered with a protective coating to prevent it from becoming contaminated with dust particles. Typically, a specific area is designated for the decontamination process, and this area offers the equipment required to carry out the task.

2.3.4.4 Material packing and storage systems

Lifting, packing, removing and storing radioactive waste systems are integral functions of those RH systems which are designed to safely store waste. Material packing systems are normally attached to hotcell setups. Storage mechanisms are provided to store the waste in standard-sized barrels. The waste packing and handling positions are built from scratch in order to reduce operating costs during waste handling.

2.3.4.5 CAD/CAM virtual mockup test systems

CAD/CAM virtual mockup (e.g. VR4robots, DELMIA etc) is needed to carry out RH tasks in virtual environments before they are deployed on the real devices. CAD/CAM systems are used to establish virtual environments with the desired RH equipment and waste setups. Virtual mockup tests enable the system to carry out remote maintenance tasks virtually, while also enabling the designer to see possible short comings within the system design.

2.3.4.6 Full scale mockup test systems

The design, once finalized, requires testing through a full scale mockup to validate the design and carry out real-time testing. This process also enables the RH crew to gain necessary training, which later becomes useful in the real environment. Mockup testing also enables engineers to determine the reliability and acerbity of the RH equipment. If necessary, changes that have not been identified in virtual mockup testing are identified at this stage and corrected before the RH system is operational.

2.4 Systems Engineering (SE) and project management: State of the Art knowledge and practice

2.4.1 SE practices and theory

According to the International Council on Systems Engineering (INCOSE), SE can be defined as "an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionalities earl in the development cycle, documenting requirements and then proceeding with design synthesis and system validation while considering the complete problem: performance, cost and disposal" [114]. In other words, we can assume that SE is the knowledge that deals with the development of complex systems with multiple dimensions (mainly hardware and software) in large-scale projects.

The key literature which addresses the SE framework for developing complex systems are: The INCOSE SE handbook [114], the National Aeronautics and Space Administration (NASA) SE handbook [70], and the European Space Agency (ESA) European Cooperation for Space Standardization (ECSS) standards [115]. These handbooks and standards address various processes and activities related to the development of complex mechatronic systems. SE addresses various dimensions of system development, including requirements development (e.g. functional and nonfunctional requirement definitions, integration, verification and validation, solution-finding and qualification). However, according to research carried out on SE practices by INCOSE, the most significant project failures are caused by poor requirements gathering and a failure to develop compatible concept system designs [114].

SE also identifies the term “life cycle”, which it defines as an application of the SE approach for the purpose of understanding and implementing processes that addresses all phases of its existence to include system conception, design and development, production and/or construction, distribution, operation, maintenance and support, retirement, phase-out and disposal [114]. The SE approach considers life cycles to be very important in the accomplishment of particular complex objectives, ensuring that those objectives are achieved according to the original plan and in an organized manner.

Various generic and specific life cycles exist in SE and project management (Figure 65). One example of a project life cycle is the so-called “innovation funnel,” in which the life cycle development of a system begins with various inputs that are gradually refined, analyzed and selected over time, resulting in only one or a few formal project ideas that can be implemented for rapid completion [116]. Similarly, the “axiomatic design model” supplements the innovation funnel by dividing the design process into various domains. The “customer domain” phase seeks to gather user needs. The “functional domain” phase seeks to transform those needs into requirements. The “physical domain” phase seeks to transform these requirements into design parameters. Finally, the “process domain” phase is dedicated to the processes that will be used to transform the designed concepts into physical objects [117]. These two afore-mentioned life cycles originate primarily from project management approaches.

The V-Model and Spiral model (Figure 65) both originate primarily from SE itself. In the V-model, a project consists of six phases: conception of operations; requirements and architecture; detailed design; implementation; integration, testing and verification; and systems verification and validation. These phases are then optionally followed by an operation and maintenance phase [118]. The other most common life cycle for system development is the Spiral model. The Spiral model embodies the iterative nature of systems development, and it also includes six major phases: requirement analysis, functional definition, physical definition, design validation, production/development, and maintenance[119].

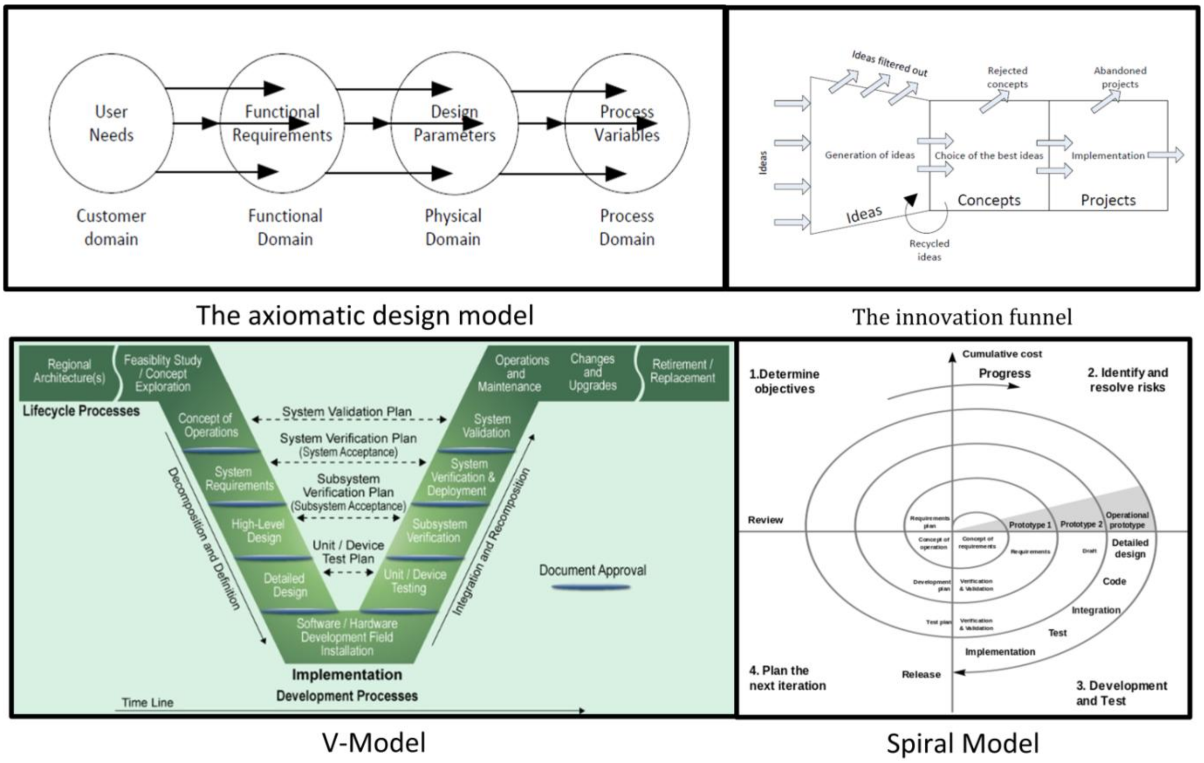


Figure 65. Lifecycles from project management and Systems Engineering.

There are various other model standards and life cycles for systems development (Figure 66). These life cycle models are normally divided into half a dozen or so steps that separate the major decision mile stones. Koissiakoff [120] presents a general SE life cycle that divides the various life cycles into three main SE stages, with each stage further subdivided into three phases:

- Concept development
  - Need analysis
  - Concept exploration
  - Concept definition
- Engineering development
  - Advance development
  - Engineering design
  - Integration and evaluation
- Post development
  - Production
  - Operation and support
  - Disposal and decommissioning

The study of various life cycles indicates that, in SE, generic life cycle descriptions share a relative heaviness (detailed procedure that require extensive resources to implement) in their definition and elaboration. As a result, research projects in HEP facilities (see the following section) are typically not explicitly developed using any particular SE approaches.

2.4.1 Development processes for RH systems in HEP facilities

To study the SE practices in the development of RH systems, close contact and collaboration was established with teams from PSI, CERN, JPARC and SPIRAL. To observe and understand the State of the Art practices in these facilities, multiple visits were conducted during the research period. Simultaneously, contacts with Japan National Laboratory for High Energy Physics (KEK), Fermi Lab, and TRIUMF were also established to facilitate a deeper understanding of their RH system and the development of each facility.

The studies conducted at these HEP facilities were focused on the design and development processes for RH systems. The analyses of the facilities revealed that the RH teams typically comprised engineers, most of whom do not implement SE practices to develop RH equipment. The discussions with the various teams revealed a pattern, as shown in Figure 68. It was found that RH teams are heavily dependent on support from organizations outside the HEP facilities, due to a lack of manpower and resources to develop RH equipment. CERN, JPARC, PSI, KEK and GSI rely heavily on engineering firms for their RH. Discussions with the teams also revealed a lack of documentation concerning RH systems. CERN has a relatively good documentation system; however, studies concerning design and development of RH are only partially documented. Information is normally present in the form of presentation slides, with very few detailed design documents existing which address RH.

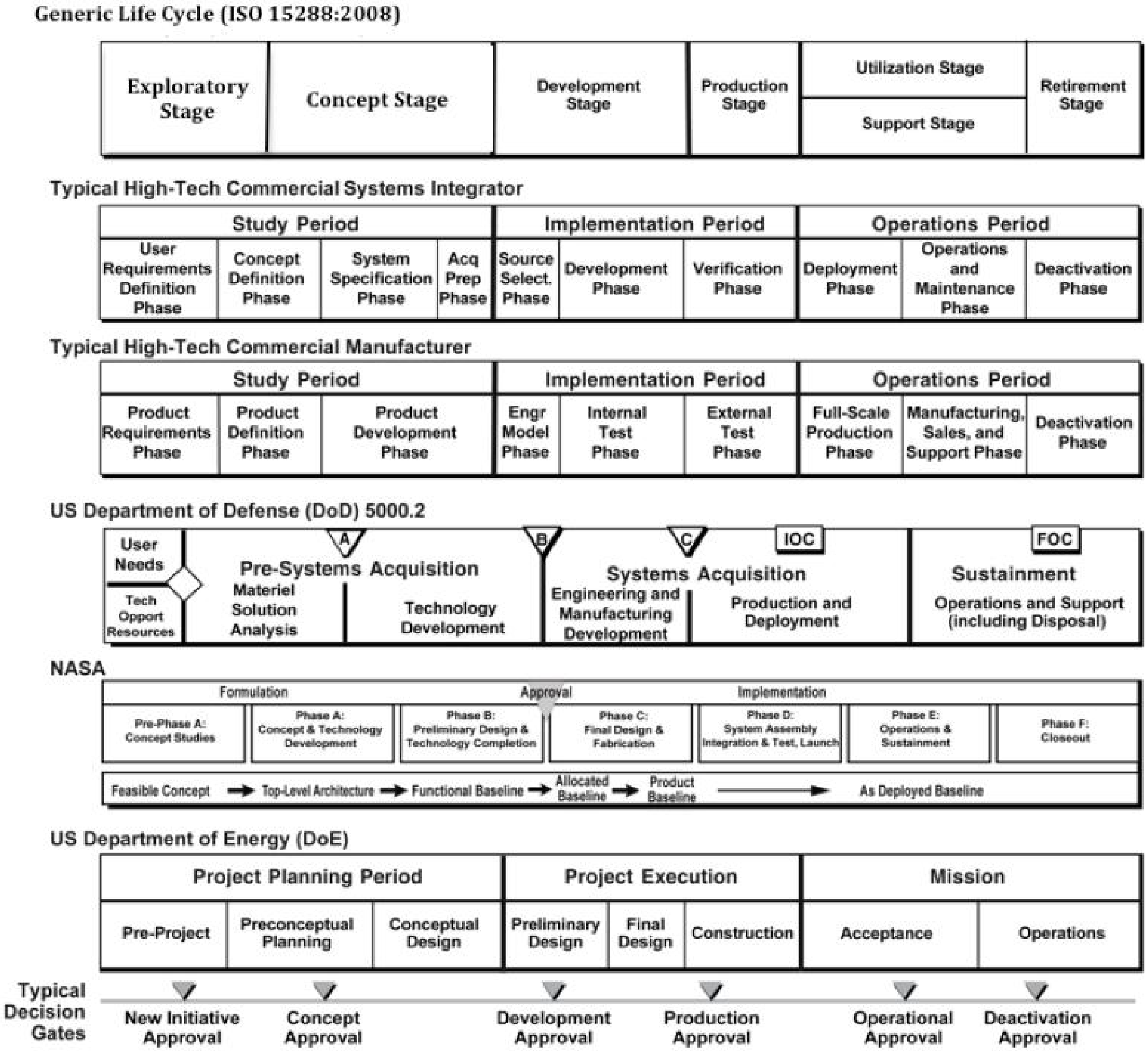


Figure 66. Comparison of different models of life cycles.

Needs Analysis	Concept exploration	Concept definition	Advanced development	Engineering design	Integaration & Evaluation	production	Operation and support	Disposal and decommissioning
Concept Development			Engineering Development			Post Development		

Figure 67. Generic SE life cycle model by Koissiakoff [120].

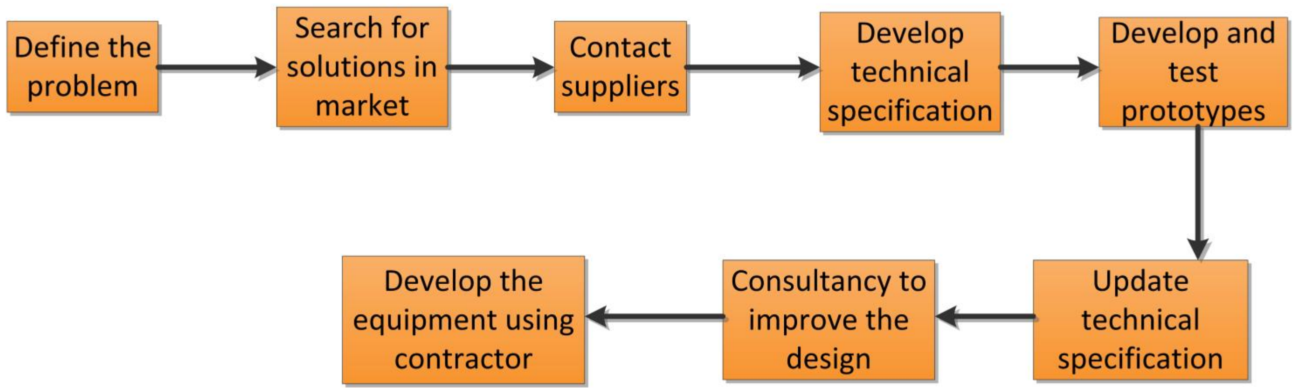


Figure 68. HEP steps for developing RH equipment.

It was concluded from the study that SE practices to develop RH concepts are nonexistent within HEP facilities. Deficiencies in recording and documentation are two of the most chronic issues caused by a lack of SE practices. The consequences of these issues make it hard to transfer knowledge among the RH teams in HEP facilities. In particular, this research project collaborated closely with the CERN ISOLDE robot exchange process, the PSI RH equipment development and the J-PARC RH equipment development processes. Documentation in all three of these cases is very limited, and there is a greater dependency on outside engineering firms.

2.4.2 Distinctiveness of HEP facilities and the State of the Art in SE

The development of HEP facilities is normally accomplished through one-of-a-kind projects, and the equipment developed during such projects is also unique. There are numerous differences between regular facility production and HEP facility production.

The RH equipment developed during the HEP projects tended to be one-off equipment, and could be termed “prototypes.” Due to this, its development was slow as a result of changes in functional needs and demands over time. The aim of equipment development is to develop a system with the best possible performance. This approach causes delays, since technical decisions are made very late in order to get the widest possible range of solutions. It is sometimes impossible to fix requirements for RH systems, due changes in the facilities. Moreover, on occasion, RH systems can also trigger major design changes within facility development.

The development of RH equipment in HEP facilities is also normally carried out with the collaboration of various teams. The equipment designs are carried out in different regions across the globe, which causes problems at both the organizational and technical levels. Projects of such magnitude are marred by project delays and slow design progress.

Such projects progress in very different manner to other large projects in differ sectors. This is due to the fact that they are public-sector-funded projects with non-profit operations. The research-focused operation of the facilities makes them prone to funding changes, cuts and delays that directly affect their equipment development resources and manpower.

HEP RH equipment is deployed in ionizing radiation environments. For this reason, equipment concept development needs to involve careful consideration of radiation dose analyses and planning.

Many State of the Art SE practices provide very detailed, elaborative tasks and processes, which make them impossible for HEP facilities to adopt whilst also reducing their resources and workforces. To expect HEP facilities to implement and adopt State of the Art SE practices is unrealistic on a full-scale level. However, the findings discussed above suggest that it is imperative to adopt a leaner SE approach for the development of RH equipment concepts, to avoid costs and unexpected failures. For example, the development of the shielding flasks at PSI was integrated later in the facility's life cycle and was not foreseen at earlier stages; thus, more than three shielding flasks exist at the facility for three different targets. Similarly, robots can replace the targets and beamline inserts at ISOLDE and GSI were added to the respective facilities at later stages and due that, the post processing, including logistics related to moving radioactive elements from the beamline to the storage zone, is a high-risk operation that can only be carried out after a long cool-down time. The aforementioned examples shows that lack of SE approach from start can solve the problem only partially. Implementing SE practices during the development stages of RH concepts can provide answers to such questions as: i) What are the requirements and needs? ii) Which equipment is suitable for the RH tasks? iii) What task sequences can carry out logistics for maintenance? iv) What are the future anticipated costs of the system? v) What effects will radiation have on the system? vi) What are the functional and RAMS analyses of the system?

A SE approach is needed for developing future accelerator facilities, such as FAIR, ESS, FRIB, and SPIRAL2. The Open SE approach, developed by the PURESAFE network, is an effort to provide such a lean SE approach. It will incorporate best practices and techniques from SE and project management, to be used when developing equipment specifically for particle accelerator facilities.

The following chapter of this thesis will focus specifically on the SE approach for the conceptual design of RH equipment and its logistics in an HEP facility. In particular, the study will address the RH equipment used in the Super-FRS main tunnel. Using this case study will show the feasibility and benefit of applying a simpler SE approach to a small-scale, complex, multi-disciplinary research project. The system engineering approach proposed in this thesis, along with the case study can be considered a reference for future integration into the Open SE project.

2.5 Summary

This chapter has presented a review and in-depth analysis of the State of the Art of RH systems in HEP facilities. It has studied the technologies, practices, logistics and design strategies of RH systems, along with a review of the RH equipment currently in use for remote maintenance in some of the facilities. The RH system State of the Art analysis conducted in this chapter has resulted in:

- A detailed analysis of logistics scenarios at HEP facilities across the globe. This survey also sought to identify various trends in logistics within HEP facilities. During the development of this survey, close cooperation was established with other facilities in order to learn about equipment design practices and tools used during design processes.

- A survey of the RH equipment used in both HEP facilities and nuclear power plants for remote maintenance, disposal, decommissioning and dismantling.

- The categorization and classification of RH equipment. This categorization enables design engineers to select the right equipment from conceptual developments for remote maintenance tasks.

This chapter also studied the State of the Art in SE practices for the development of complex machines. The SE practices used within HEP facilities were also examined in the context of RH equipment. With regard to SE practices, the study revealed:

- The practices used by NASA, ESA and ITER concerning the management of very complex projects and equipment. The direct application of such practices may be labor and time-intensive. For this reason, the direct application of such practices may result in project cost increase and delays. Hence, a leaner SE approach will be suitable for RH system integration into HEP facility infrastructure.

- There are no specific SE approaches for developing RH equipment within HEP facilities. The study revealed that SE and project management practices in the HEP facilities surveyed are nonexistent for the development of RH systems. RH for facilities is normally developed based on experience.

3 Development of a RH logistics concept for the Super-FRS main tunnel project at the FAIR Facility using an SE approach

As found from the State of the Art survey described in the previous chapter, SE and project management practices are either very limited or nonexistent in the development of RH systems at HEP facilities. RH for in these facilities is normally developed based on the experience of engineers and there are no existing SE approaches specifically designed for developing RH equipment. In this chapter, a generic SE approach is proposed for the development of RH logistics concepts for HEP facilities. This approach has been developed so that it can be generalizable and can be applied to the development of any other RH concept within HEP facilities. The integration of the proposed system into existing SE frameworks would require further studies, which lies outside the scope of this thesis.

This chapter also addresses the development of a specific RH system and logistics concept for the Super-FRS main tunnel. This demonstrates how applies the proposed SE approach can be applied to a real world problem, and can serve as a case study for future reference. The design and development process is elaborated in detail, with supporting information provided in an appendix.

The chapter is arranged as follows: Section 3.1 presents the proposed SE framework developed as part of this research. Section 3.2 provides a brief overview of the Super-FRS facility within the FAIR project, which serves as the case study. Section 3.3 goes into detail about the specific areas within the facility which require RH. It explains the Super-FRS beam losses along with key radiation hotspots, radiation environment and studies of the layout to develop a comprehensive understanding of the requirements and needs for RH in the Super-FRS. Section 3.4 explains the three main RH concepts developed for Super-FRS, based on these requirements and needs, using COTS equipment. It also lists the RH changes identified during the concept design stage. Section 3.4.5 discusses a survey of RH expert opinion and the key tradeoff analyses which was carried out to select between the concept designs Finally, Section 3.6 presents the results from the tradeoff analysis and a detailed discussion of these result.

3.1 Proposed SE approach for developing a RH systems logistics concept for HEP facilities

RH equipment is needed for the maintenance of those radioactive components which require regular replacement in HEP facilities. Even though various RH equipment systems are currently in use at various HEP facilities, very little documentation is available regarding the methods and practices used in their RH system design. In this regard, HEP facilities are very different when compared to the Eurpean Space Agency (ESA), the ITER nuclear fusion project and commercial nuclear power plants, where SE practices are highly developed and documented [70] [114][115]. The lack of SE practices can cause delays and increases in the cost of RH system design and development. It also results in a shortage of knowledge being transferred via high quality documentation, which could link the system requirements to the various design phases. This thesis proposes a SE approach for the development of RH logistics concepts within HEP facilities. A visual representation of the approach is shown in Figure 69. In this section, this SE approach will be explained in more detail and in later sections it will be implemented on a case study. As discussed in the previous chapter, SE practices have reputation of being labor and cost-intensive to carry out. However, as will be shown, the proposed SE approach can be implemented in a straight-forward manner and on a small scale.

The proposed SE approach can be divided into seven major processes:

- Step1 : Systems Requirement Development
- Step2 : State of the Art Survey
- Step3 : Concept Design
- Step4 : Design Trade Off and Analysis
- Step5 : Architecture Design
- Step6 : System Digital/Prototype Mockup Testing
- Step7 : System Commissioning and Operation

In this thesis, only the first four of these processes are applied to the case study. The remaining three processes are more oriented towards detailed design and designed implementation, in which is beyond the scope of this thesis.

The two most critical phases of any product development are requirements development and conceptual design, since during these phases most of the cost is built into the system. The concept design phase for RH equipment in HEP facilities can be divided primarily into four process and 12 sub-tasks, as follows:

<u>Systems Requirement Development:</u> The needs and requirements within IT, construction, engineering and industrial projects are of utmost importance. The RH equipment within an HEP facility interacts with other systems and infrastructures within the facility. Hence, it is very important to obtain a clear picture of the needs and requirements for a RH system. The first subtask in this process is to gather together all of the needs and requirements put forward by all stakeholders, in order to obtain clear picture of the comprehensive needs. The second subtask is to carry out an initial feasibility study

with the engineering team, in order to identify the viability of the project needs and requirements. The next step is to draft detailed operational requirements for the RH systems. The final step is to refine both the functional and nonfunctional requirements. From this process, two major documents will be obtained: the Systems Requirements Document (SRD) and the Technical Performance Measures (TPMs).

Technology Survey: The design and development of an engineering project is based on the study of existing RH equipment. This can be carried out in parallel with the development of requirements. The study of RH systems for HEP facilities can be subdivided into: the study of State of the Art RH equipment currently used within other HEP facilities and nuclear power plants; and the study of current RH concepts within the facility in question (e.g. solutions that have been considered or drafted during the design of the facility).. This practice generates a list of equipment and technologies that can be used to develop the RH system.

Conceptual Designs: Here, the data obtained during the first system requirements development and technology survey are compared. The TPMs are compared to the equipment list in order to short-list the viable equipment candidates, which can be used in conceptual designs of the RH concepts. The equipment list is then evaluated, alongside the requirements. At the end of this practice, a sub-set of the concept designs is identified as suitable to carry out RH task sequences within the HEP facility. These concept designs are then proposed to the engineering team for further analysis. The output of this process is documented in the form of a Conceptual Designs Document (CDD).

Design Tradeoff and Analysis: During this process, the conceptual designs are evaluated against each other. This process includes:

- Functional task sequence analysis: The RH task sequences for each concept are studied, analyzed and optimized by determining the critical path to carry out the task sequences. This analysis addresses issues of equipment utilization and task optimization. It also addresses key logistics issues and contact points with other HEP systems.

- Radiation analysis: During this analysis, the doses received by RH equipment are calculated in mSv/h and to determine the total dose in mSv. Measurements should be carried out in Sv to show the doses for humans working in the area, rather than for the robot which would be calculated in Gy. The doses in Gy can be derived from doses in Sv. This analysis is an integral part of concept evaluation, as it deals directly with the doses received. Radiation safety concerns must be fully integrated into the needs-gathering exercise from the start of the project, and are also important in later stages with regard to accurately evaluating equivalent dose estimates. The radiation analysis will directly address the requirements concerning project feasibility (i.e. whether the RH system can perform the tasks) and manufacturing and performance (i.e. whether the equipment is radiation-hardened and what modifications are needed). This radiation analysis can also serve as the basis for an ALARA evaluation if human intervention is needed in certain cases.

- Failure mode and effects analysis (FMEA): Here, the RH concepts are evaluated to identify all possible failures in a concept design and task sequence. Failures are prioritized according to how serious their consequences are, how frequently they occur and how easily they can be detected. The purpose of a FMEA is to eliminate or reduce possible failures, starting with the highest-priority ones. This addresses RAMS issues, while also identifying key failure points that require attention.

- Cost analysis: This analysis addresses the cost issues for the developed concepts and provides cost estimates.

- Requirements traceability analysis: During the requirements traceability it important to compare the concept design to the initial systems requirements in order to assess the design feasibility. The concept designs are proposed based on initial analyses, using TPM at an early stage. However, as the designs are suggested and developed, requirements traceability becomes a key analysis feature to insure the concept design is in accordance with the system requirements. The requirements developed during an early stage must be traceable within the design. This can be considered one subtask of system evaluation.

- Expert criteria evaluation:. The RH and HEP facilities development research fields are very narrow, and there are various people with experience in developing technologies for such RH task sequences. Hence, it is imperative to include the opinions of these experts in the selection of equipment. It is also important to run designs past these experts and, based on their feedback, to develop criteria to evaluate the concept designs. Here, the RH experts from HEP facilities and other fields are consulted in order to develop criteria to evaluate the concept designs. The RH experts are asked for their opinion (concerning RH problem) to develop weighted criteria that is later used to assess the concept designs during tradeoff analysis

The output of this analysis process is a Detailed Design Document (DDD) that describes the most suitable equipment, technologies and tools that can be developed into final designs for RH task sequences within the HEP facility. The detailed design obtained at this stage can be further developed into prototypes that can be tested using digital CAD mockups and full-scale prototype testing.

In the following sections, this proposed SE model will be applied to the development of RH equipment and logistics concepts for the Super-FRS main tunnel.

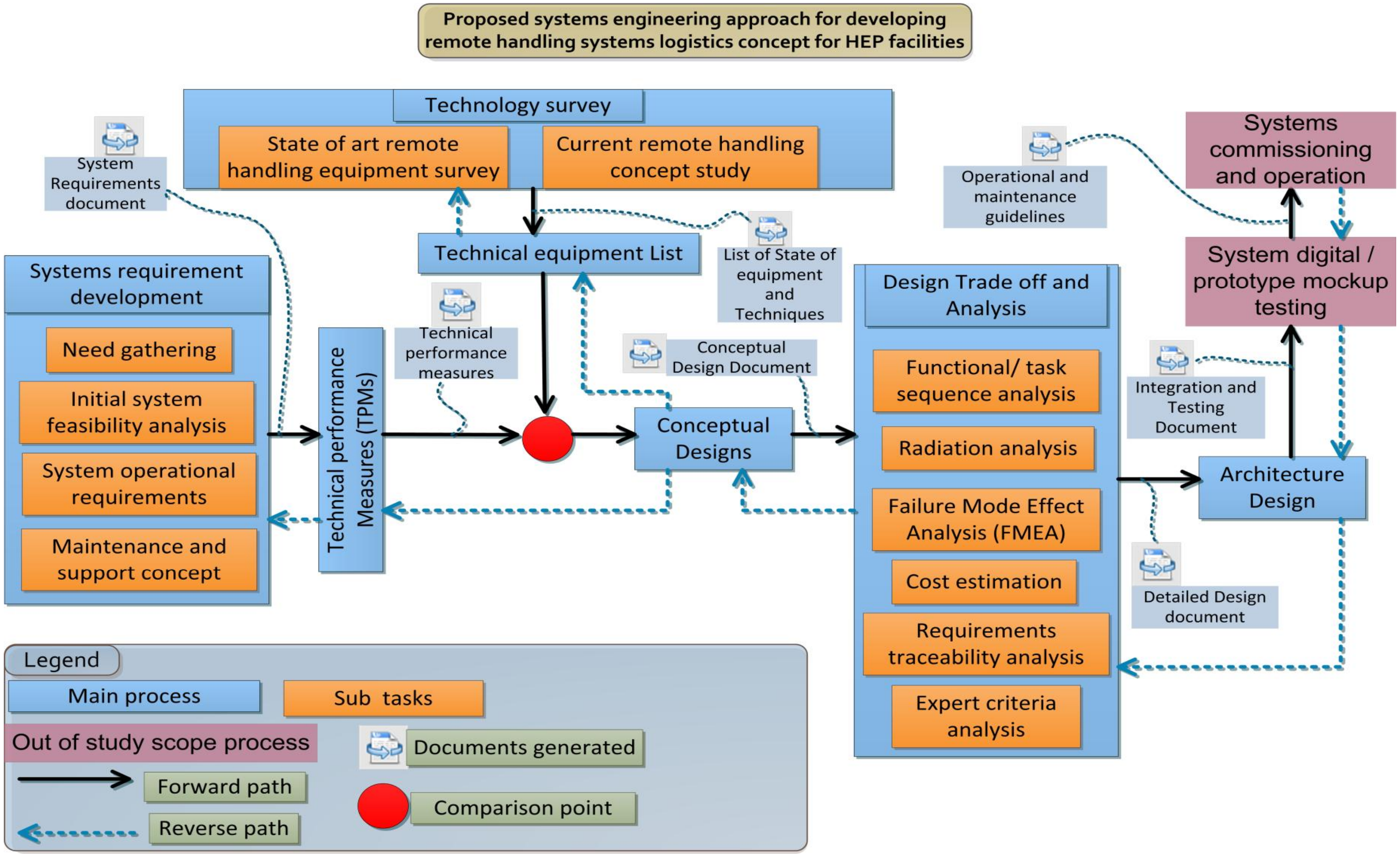


Figure 69. Proposed SE approach for developing RH systems logistics concepts for HEP facilities.

3.2 Application area: Super-FRS at the FAIR facility

The practical part of this research is primarily focused on developing a RH system and logistics concept for the Super-FRS facility in FAIR. Through the SE model proposed in the previous section, it is proposed that this work can be generalized to be used at other facilities. This section and the following section present the Super-FRS and its RH requirements.

When it is completed, the Super-FRS will be the powerful in-flight separator for exotic nuclei. Rare isotopes of all elements (up to uranium) will be able to be produced and spatially separated within a few hundred nanoseconds, thus allowing the study of very short-lived nuclei [2]. Presently, two complementary experimental methods are applied to achieve this goal: the inflight method and the isotope separation on-line (ISOL) method and the projectile fragmentation and fission. ISOL schemes produce radioactive ions at rest and employ post-accelerators to produce secondary beams. The produced fragments, including the rare isotopes of interest and the surviving primary beam leave the target in a forward direction. In the Super-FRS, the isotopes are separated via magnetic rigidity analysis and their different energy losses in matter [13]. To accomplish this, precision-shaped energy absorbers are employed. However, the primary beam intensity after the target, which has a maximum 50% interaction probability, is still so strong that it must never hit the degraders directly. The in-flight method employs projectile fragmentation and fission, involving 30 MeV/u to 1500 MeV/u heavy ions. The three branches of the Super-FRS large-acceptance superconducting fragment separator serve different experimental purposes (Figure 70). The Super-FRS is the application area for this research, and the details concerning its layout and beam loss are explained in detail in Section 3.3.2.

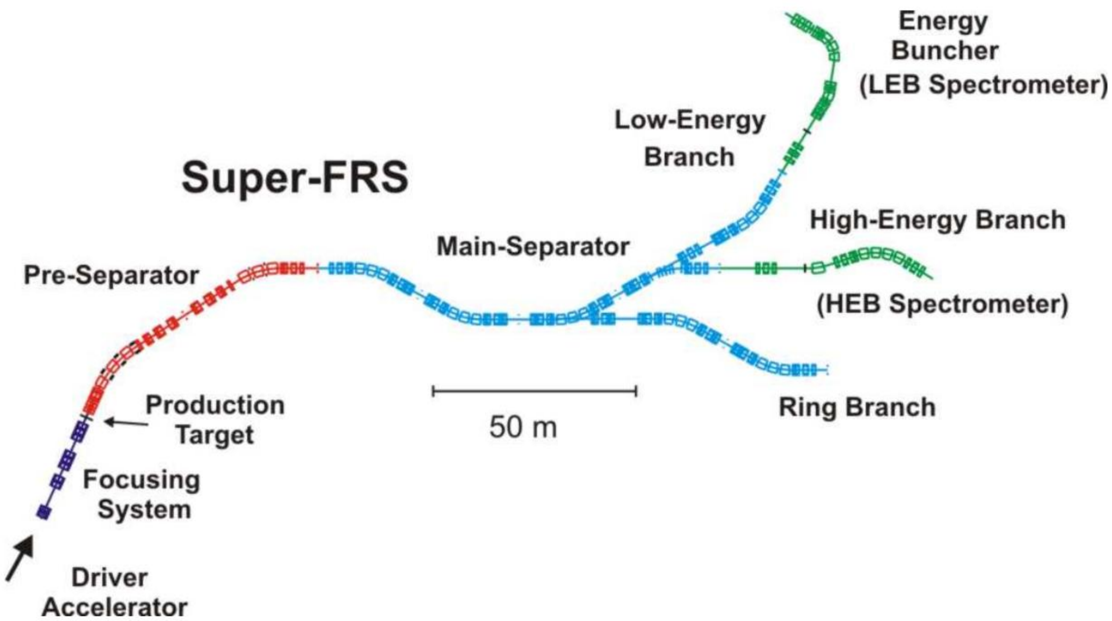


Figure 70. Layout of the proposed superconducting fragment separator (Super-FRS) for the production, separation and investigation of exotic nuclei. Spatially separated rare-isotope beams are delivered to the experimental areas via three different branches. The ion-optical layouts of the focusing systems, both in front of the production target and in the energy-buncher system (LEB-spectrometer), have been significantly modified to match the experi-

mental conditions. A high-resolution magnetic spectrometer (HEB-Spectrometer) has also been designed for the high-energy experimental area (R3B project) [14].

3.3 Requirements development

Identifying the correct requirements, according to user needs, is key to a project's success. However, identifying these needs is also *"the most difficult, most critical, most error prone and most communication-intensive aspect of development"* [121]. This task can be even more challenging for a research project, where needs tend to change more easily than they do during any other project.

The needs collection for the Super-FRS project was carried out by the current project team within GSI. The needs collection for the RH was conducted through meetings, informal conversations, discussions and studies of project documentation, in collaboration with the Super-FRS project engineering and user teams. The requirements development process involved:

- Initial studies of the Super-FRS facility's beam losses and radiation environment.
- Studies of the Super-FRS facility layout.
- Super-FRS group meeting to streamline the Super-FRS RH requirements.

3.3.1 Super-FRS facility beam losses and radiation environment

3.3.1.1 Beam losses in the Super-FRS

Based on the experience gained from the existing FRS facility, GSI is also responsible for the development of the Super-FRS facility shown in Figure 71. The new FAIR accelerators produce primary beam intensities of up to 10^{12} ions/s of ^{238}U at up to 1.5 GeV/u [14]. In general, the FAIR ion beams have 100 to 1000 times higher intensity than those currently available at GSI [13].

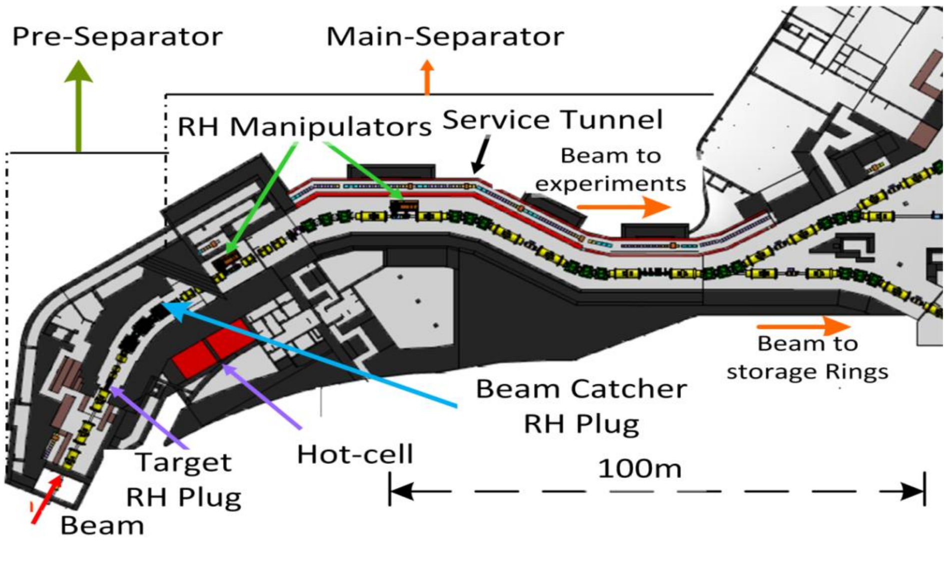


Figure 71. Super-FRS layout for production and separation.

The purpose of the Super-FRS is to select certain species of mostly exotic nuclei out of the large variety of different nuclides produced. This is done through the so-called Bρ-ΔE-Bρ method [21], in which, in addition to simple analysis through magnetic rigidity (Bρ), ions are further separated through a second Bρ analysis after passing through a layer of matter (a degrader), in which ions of different elements lose different amounts of energy (ΔE). While the first step primarily selects ions with similar mass-to-charge ratios, the second step adds selectivity through the ions' atomic numbers. In the Super-FRS, this method is applied twice: once each in the pre and main separators.

For effective radiation protection and maintenance planning, the beam losses in different sections of the Super-FRS must be carefully estimated to predict prompt dose. The goal is to select only a few ions out of up to 10^{12}/s; thus, the losses and their exact locations of occurrence can be predicted accurately. However, given the many different Super-FRS settings for either fewer or more rare isotopes, intensities within the main separator vary greatly.

To illustrate this situation, two examples were chosen: the selection of ^{132}Sn produced in a fission reaction from a ^{238}U beam and the selection of ^{100}Sn produced through a projectile fragmentation of ^{124}Xe (Figure 72). ^{132}Sn, and many other fission fragments with a similar mass and atomic number, can be produced in high quantities and are difficult to separate due to the larger momentum spread of the fragments behind the target [13] . In contrast, ^{100}Sn and its neighbors on the chart of nuclides are produced much less frequently and at higher energies.

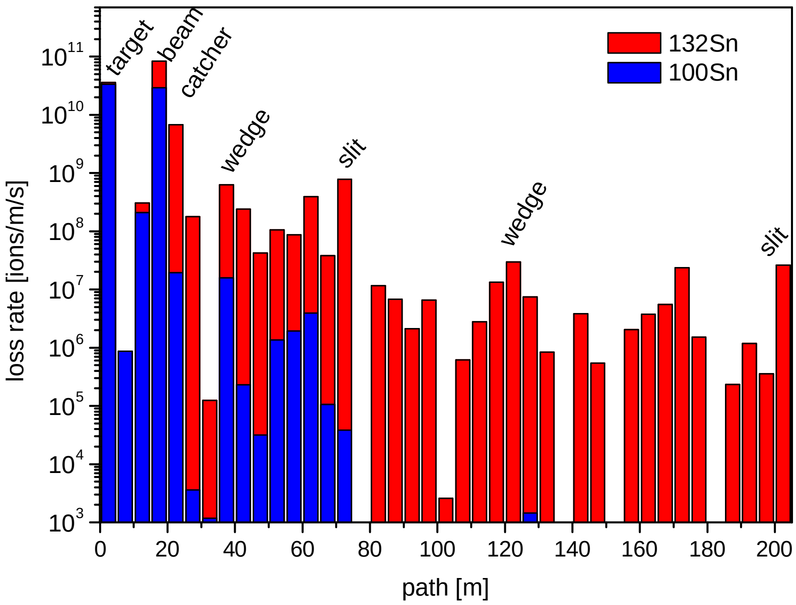


Figure 72: Number of ions lost along the path of the Super-FRS beamline per meter and second. For cases (i.e., ^{132}Sn and ^{100}Sn settings), an initial energy of 1.5 GeV/u and an intensity of 3.3×10^{11} ions (^{238}U or ^{124}Xe, respectively) was assumed. For clearer presentation, the numbers were averaged over 5 m wide bins. Key loss points are labelled [122].

The simulations were performed using the Monte Carlo code MOCADI [123] for ion transport in beamlines. We collected the losses for all relevant nuclides produced as a function of the position along the

Super-FRS beamline. This corresponded to around 1000 different nuclides for ^{132}Sn and 490 for ^{100}Sn. Since we are interested in estimating the level of activation of beamline components, the number of ions is not a good criterion on its own. The energy of the ions and their mass and atomic number are also important to include. Heavier ions contain more nuclides, but ions of higher charges can be stopped faster. These conditions were considered by comparing the number of emitted neutrons for each ion derived from a simplified scaling rule, as described in [124]. The number of ions lost (as shown in Figure 72) actually refers to the number of ^{114}Pd ions at 1300MeV/u per ion. This measurement lies roughly in the middle of the distributions of mass and energy for all ions in the Super-FRS. This MOCADI procedure also allows loss numbers to be defined for inserts like targets or degraders, through which the ions fly without being lost.

It is clear from the results that the main loss points are the target and the beam catchers; however, local maxima also occur later in the system. Such maxima appear at the degrader wedges and at the exit slits, where significant degrees of separation occur. Some ions drop out even before the slits (e.g. in the dipole regions). The Super-FRS has three branches [92], but only the path towards the storage rings was considered here, since this is the scenario in which the highest beam intensities can pass through the whole separator. In the other branches, beam tracking with detectors is used—something that is not possible at the high particle rates used in this scenario.

The difference between the two cases at the exit slit is also significant. Thus far, it is impossible to foresee how often each case will be used during operation. However, it is clear that the high-intensity case is only one of many—and, thus, will not run for the whole operation time, but will instead run for only a small fraction of this time, with correspondingly lower activation. Only in the pre-separator is it desirable to have a high intensity on the target for all of the operation time.

3.3.1.2 Radiation Environment in the Super-FRS

The Super-FRS seeks to stay far below the annual dose limit of 20mSv per year for radiation workers in controlled areas. For free access, the annual dose rate limit is 0.5 µSv/h [125][126]. The highest activation occurs in the target area (Figure 73) at the beginning of the pre-separator. This area begins with the beamline inserts (e.g. the Super-FRS production target) and ends with the three beam catcher chambers. These components have the highest level of activation as they are directly exposed to the intense primary beam [14]. After the beam has interacted with the target, a series of graphite and iron beam catchers are used to stop the beam at locations where the primary beam and selected fragments are separated. The pre-separator is exposed to a large amount of radiation and, thus, is activated even after the cooling period.

Figure 73 shows that, according to FLUKA [125] simulations, radiation levels inside the shielding are well above 0.5µSv/h during beam operation. FLUKA is a fully integrated Monte Carlo simulation package used to simulate interaction and transport of particle and nuclei in matter. The beam catchers experience high levels of activation, since they absorb up to 85% of the beam. The target and the beam catchers are develop radiation damage and will require multiple replacements during the course of the Super-FRS operation.

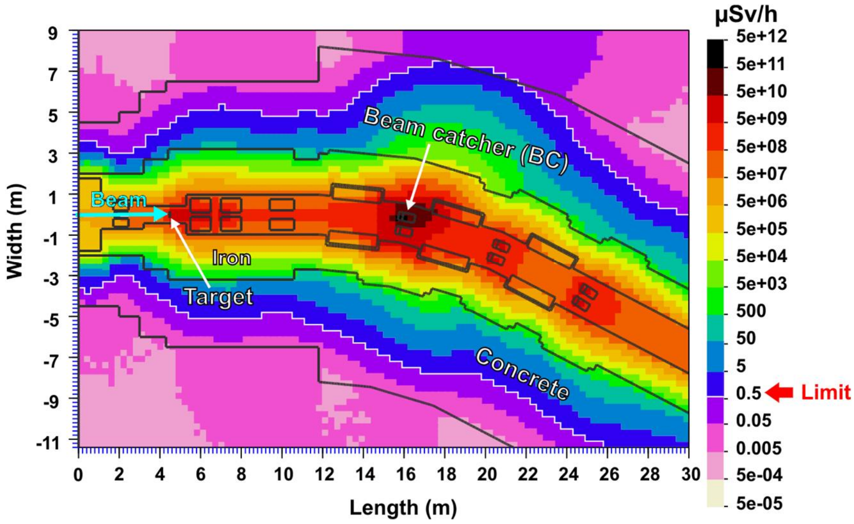


Figure 73. Dose rate calculation with FLUKA during beam operation.

Figure 74 illustrates the activation levels in the target region, calculated using FLUKA simulations. According to these simulations, the residual dose for the beam catchers falls in the Sv/h region even after 120 days of cooling. The working platform has a radiation level of 10 µSv/h and can be accessed by humans to make and break connections. However, human access to the top of the working platform is limited and controlled [125][126].

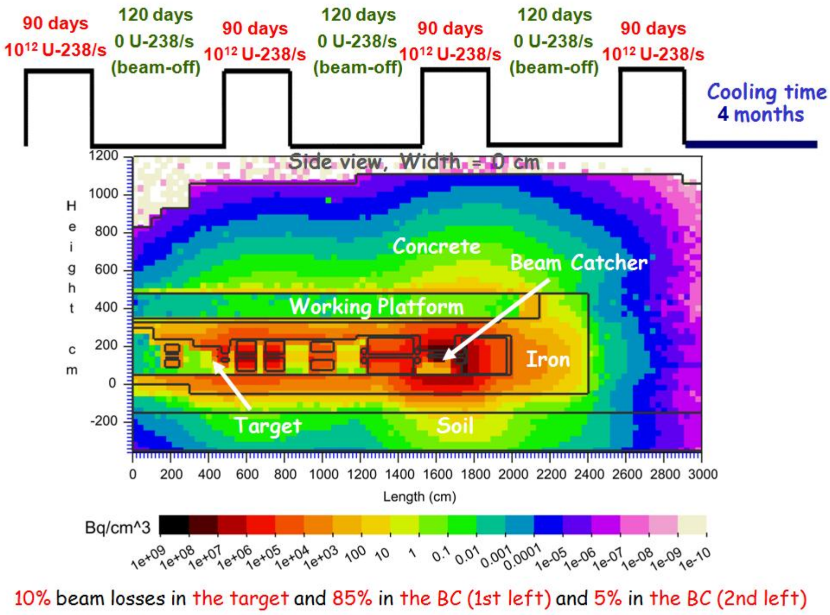


Figure 74. Activation levels (calculated from FLUKA simulations) near the beamline and on the working platform following various irradiation periods, as indicated at the top of the image.

The parts which experience the highest levels of activation can only be remotely handled within a hotcell. The beamline inserts, for example, are directly exposed to the primary beam as well as high temperatures and pressures. The work required to hold, move and exchange these inserts can only be accomplished by using RH inside the hotcell [14]. Within the hotcell, the part which has the highest level of activation is the beam catcher (Figure 72 & Figure 73). The residual dose rate calculation for gamma shielding for the beam catcher shows that a hotcell with a 1 m thick wall is suitable for RH (Figure 75).

The Super-FRS includes a 130 m long main separator, which is composed of four dipole stages with focusing elements in front and behind the dipole magnets. The main separator is also divided into three branches: a low-energy branch (LEB), a high-energy branch (HEB) and a ring branch (RB), as shown in Figure 71 [13]. The beam intensity and losses are reduced along the focal planes in the main separator, and radiation levels in the main separator are much lower than those in the pre-separator. The exposure of focal planes FMF1 and FMF2 to the high-intensity beam also causes higher levels of activation, as can be seen in Figure 15 [51]. The residual dose in the main separator is also lower, since it has lower levels of activation than the pre-separator.

The radiation analysis presented in this section indicates that the main separator experiences conditions similar to those of the existing FRS, with the second half of the pre-separator exhibiting similar characteristics to the current FRS target region. This means that, with regard to the RH system and logistics concept, the experiences and lessons learned from the FRS can be implemented in the Super-FRS.

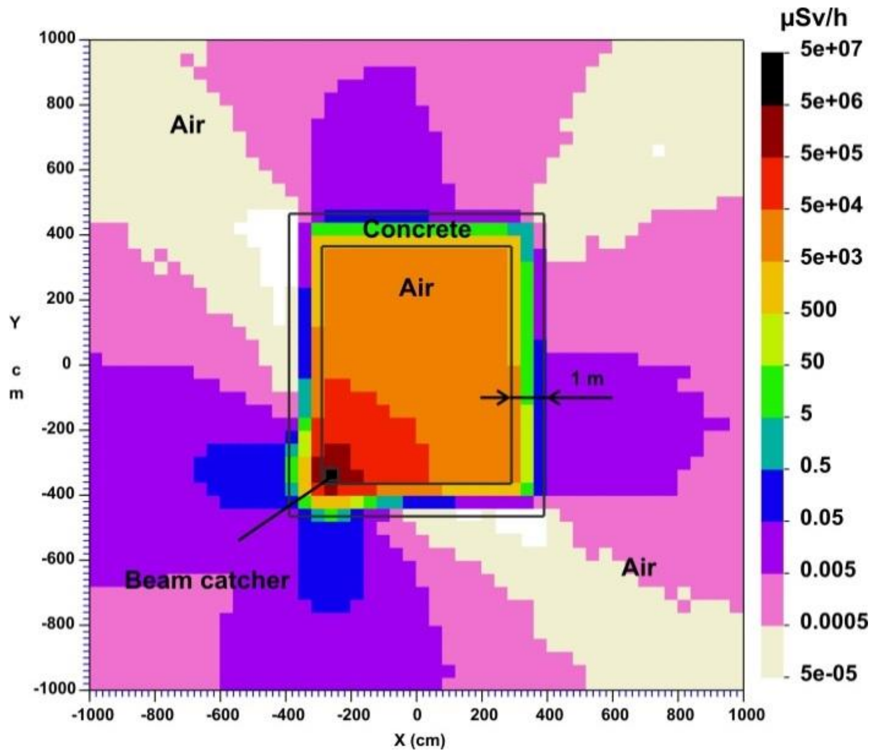


Figure 75. FLUKA simulation for beam catchers inside the hotcell with 1 m thick walls after 120 days of cooling.

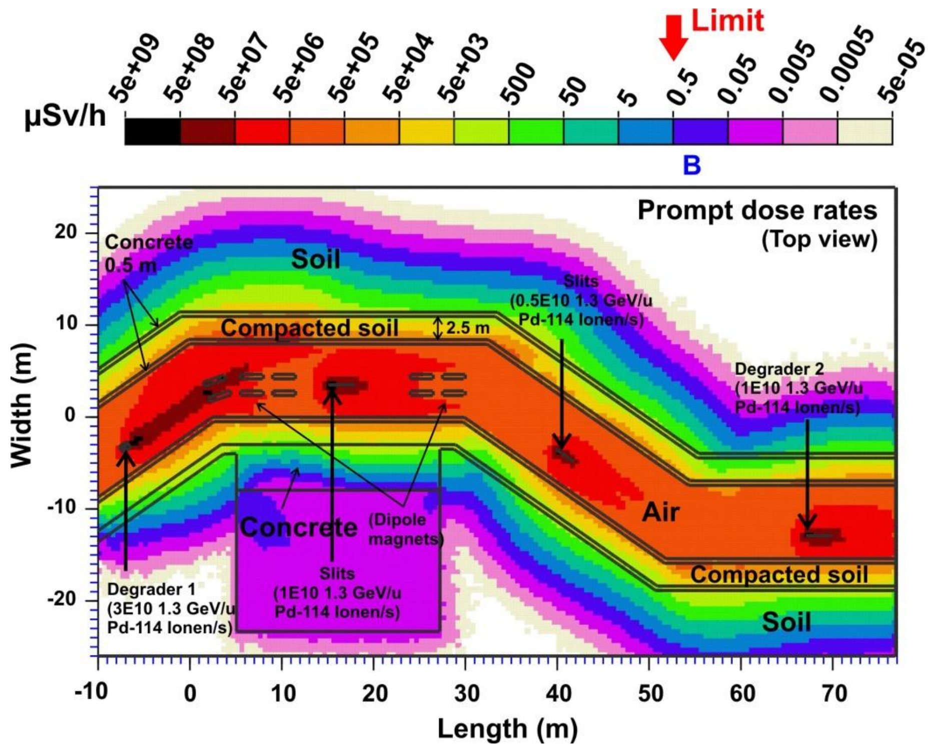


Figure 76. Main separator radiations prompt dose rates.

3.3.1.3 Studies of the Super-FRS facility layout

To develop the requirements for the RH system and logistics, it is critically important to conduct a detailed analysis of the beamline facility (Figure 77), as is being presented here. Specifically, in order to define the requirements for the RH task sequence, it is important to answer the following questions:

- What parts require RH? (Record their size, weight, location, fragility, etc.)
- Which path must be followed during the RH task sequence?
- What forms the interface between the components and the RH systems?
- What are the space requirements for the RH system?
- What level of dexterity is required during RH tasks?
- Are there environmental issues (e.g. heat, fire, chemical)?
- How many operations need to be carried out during RH?
- How fragile is the surrounding environment? (e.g. the beamline is designed to very delicate, and any damage to the beamline can disrupt facility operations)
- Are there any access issues? (e.g. reachability, obstruction, power supply, or commination signal losses)

In order to study the layout of the Super-FRS facility, comprehensive studies were conducted of the system designs (see Appendix I)[122][127]. Based on an analysis of the Super-FRS facility plans, it became clear that the facility could be divided into three major sections for RH purposes: the target area, the separator main tunnel and the hotcell region. The rest of this chapter addresses the RH logistics of the Super-FRS facility; however, in order to present the research at a sufficient level of detail, this is primarily limited to the RH logistics of the separator main tunnel.

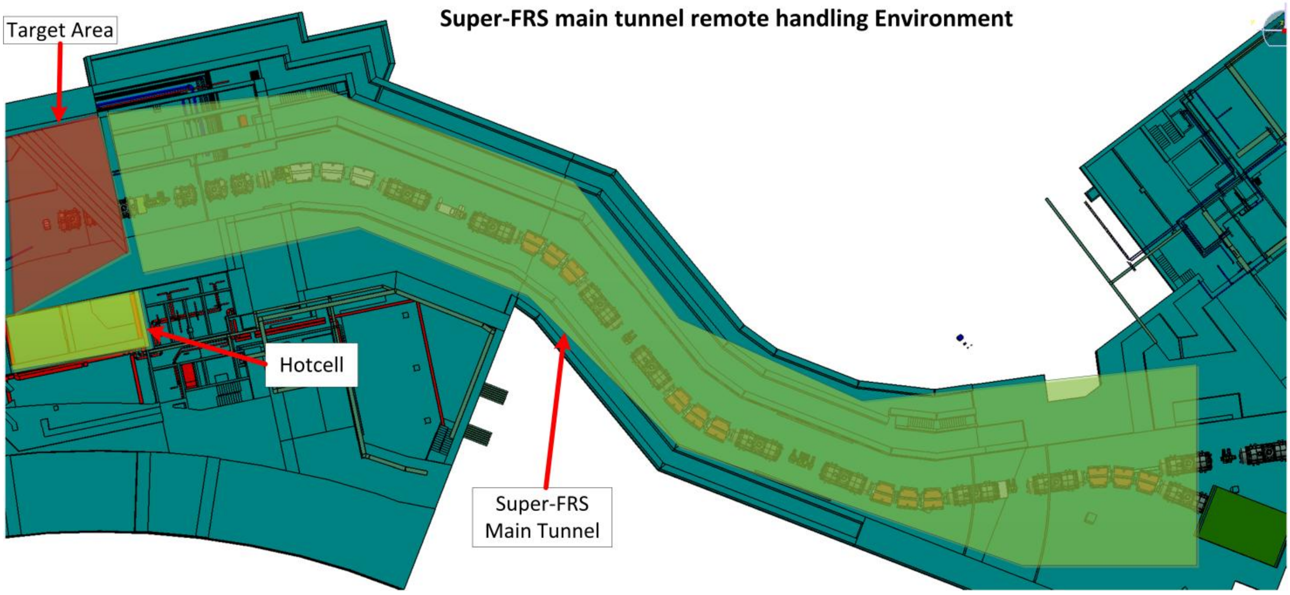


Figure 77. Super-FRS RH regions

3.3.1.4 Requirements development results and RH challenges

Detailed requirements for the Super-FRS Main Tunnel Remote Handling (MTRH) system were developed and documented as part of this research. The requirements development was carried out in collaboration with the engineers and physicists at the existing GSI Fragment Separator. As part of this process, one-on-one and group meetings were conducted in order to further understand the environment of the Super-FRS main tunnel and its RH needs. The detailed requirements were documented in the form of Systems Requirement Documents (SRDs), which is provided in Appendix II.

The process of requirements development enabled the identification of: the equipment requiring RH; the basic configuration of the Super-FRS RH environment, a functional tree of the RH task, an interface map between the components of the system and environment, a aintenance plan and classification of equipment requiring maintenance; and the Technical Performance Measures. These are expanded in detail in the following pages:

- <u>Equipment requiring RH</u>: RH in the Super-FRS tunnel primarily involves the exchange of beamline inserts. This involves the removal and replacement of vertical cartridges, as shown in Figure 78. The task also involves the transportation of activated beamline inserts to their correct locations within the tunnel, as well as the retrieval of the active beamline inserts to the storage area. The focal points FPF2, FPF3, FPF4 and FMF 2 (Figure 79) have critical X-slit, Y-slit and degrader wedge/disc elements that directly interact with the beam. Hence, these pieces of equipment are the most activated beamline inserts which require remote maintenance. Table 4 provides a detailed list of the Super-FRS main tunnel beamline chambers requiring remote maintenance. Many of the beamline inserts have different dimensions, shapes and sizes (see Appendix III). In total, 26 beamline inserts centered on four focal areas will require remote maintenance during the lifespan and operation of the FAIR facility.

- <u>The basic configuration of the Super-FRS RH environment:</u> The basic configuration is composed primarily of the FRS main tunnel, the vacuum chambers, the beamline inserts, the connector plates and the hotcell. Based on the analysis performed, two key drawbacks were detected in the design of the Super-FRS: i) a lack of a temporary storage facility within the tunnel and ii) the lack of a decontamination area for the RH equipment at the final parking area. The analysis also identified the key parking positions for the RH equipment, as well as the need for a power supply. Figure 79 shows the key RH points and travel paths within the Super-FRS tunnel.

Table 4. Super-FRS chambers (including dimensions and equipment) in the tunnel that require remote maintenance. The focal planes termed FPF are located in the pre-separator section of the Super-FRS, and the focal planes termed FMF are located in the main separator of the Super-FRS.

FPF	Chamber Dimension Length, width, height / mm	Beamline insert
2	3352*970*1280	Beam stop Single detector X-slits Scintillator detector Degrader discs Degrader wedges and plates Detector (space reserved) Single detector
3	990*720*1130	Y-slits XY-detectors
4	3552*970*1130	XY-detectors PDC detector Reserved space Y-slits Secondary target X-slits TOF-Detectors XY-detectors
FMF	Chamber Dimension Length, width, height / mm	Beamline Insert
2a	1190*970*1130	XY-detector X-slits
2b	1195*720*280	Y-slits Degrader discs Degrader wedges and plates Finger detector
2c	1154*660*1130	TOF Detector XY-Detector

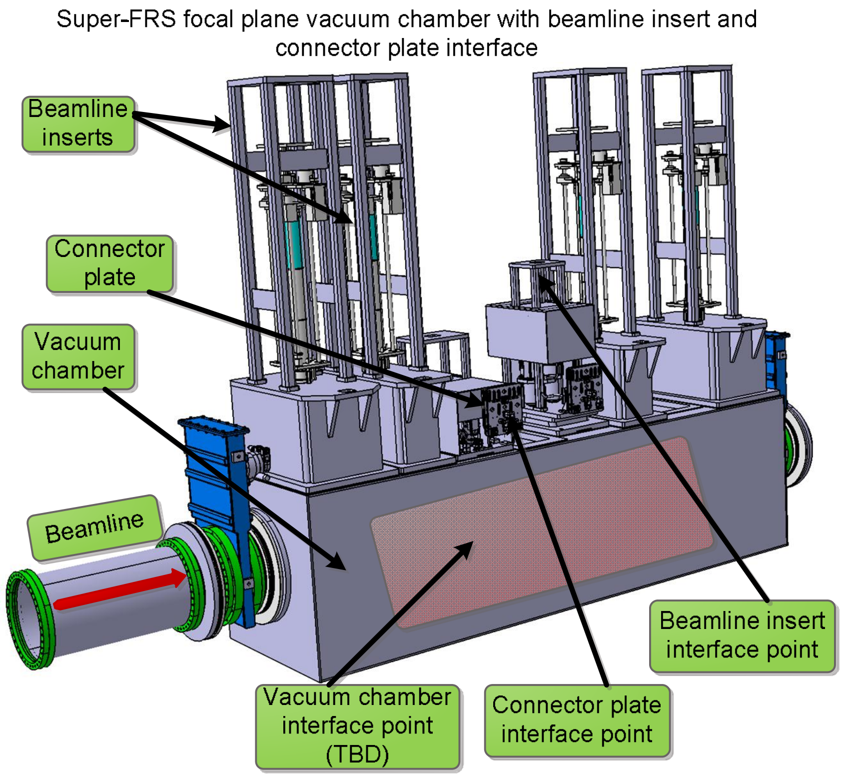


Figure 78. Interface points of the Super-FRS focal plane vacuum chamber, beamline insert and connector plate.

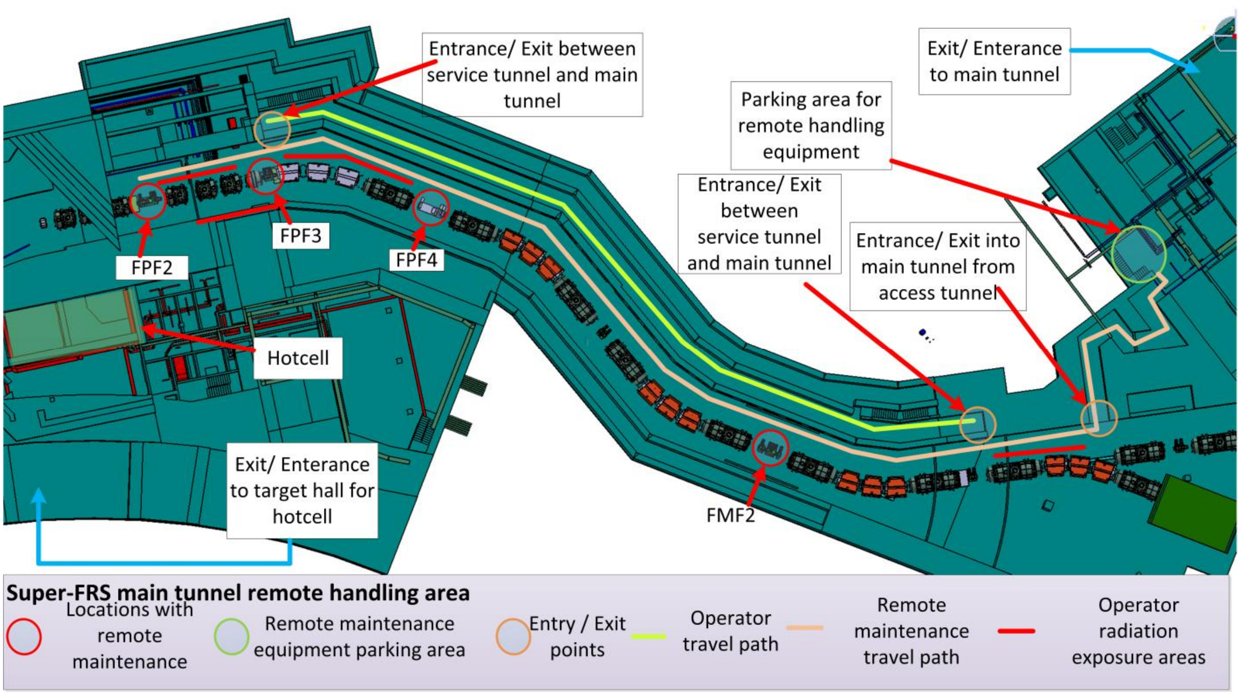


Figure 79. Basic configuration of the Super-FRS main tunnel RH area.

- Functional tree of the RH task: The functional tree of the Super-FRS RH system was identified based on the system's RH task sequence. The functional tree provides a three-layer hierarchy, which divides the functions into various layers. The functions are later used as comparison tools to track the different features of the RH system. These basic functions must be fulfilled by the developed RH equipment. The basic functions for Super-FRS main tunnel RH equipment are listed in the following Table 5.

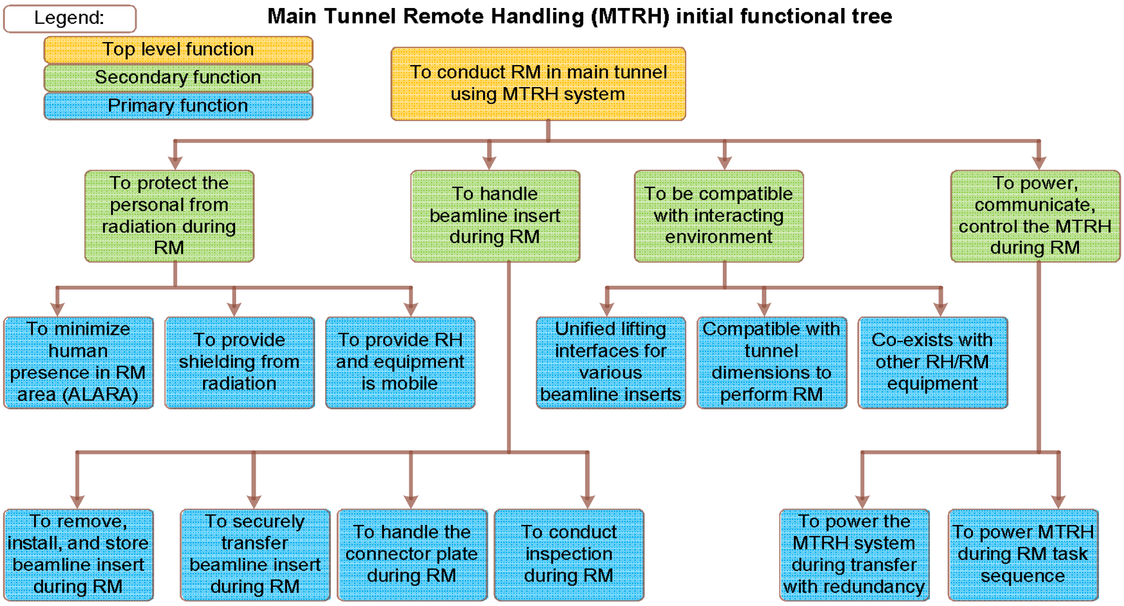


Figure 80. Initial functional tree of the MTRH system.

Table 5. Breakdown of basic functions into sub-functions of the Super-FRS main tunnel's RH equipment.

S.No.	Function
1	To conduct remote maintenance in the Super-FRS main tunnel using the MTRH system. (i.e. To install new beamline inserts and retrieve used or activated beamline inserts.)
1.1	To protect the working personnel from radiation during maintenance and to minimize doses.
1.1.1	To minimize human presence in the main tunnel during remote maintenance tasks (ALARA).
1.1.2	To provide mobile RH equipment that can conduct remote maintenance tasks (i.e., remove, store and transfer beamline inserts).
1.1.3	To provide shielding from radiation to negate harmful effects to both humans and on-board electronic equipment.
1.2	To handle (manipulate, repair, store, hold and transfer) beamline inserts during remote maintenance.
1.2.1	To remove activated beamline inserts, securely hold the activated beamline inserts and install new beamline inserts.
1.2.2	To securely transfer beamline inserts during remote maintenance and to eliminate the need for decontamination.
1.2.3	To handle connector plates during maintenance (i.e. to remove and install connector plates from beamline inserts during maintenance).
1.2.4	To conduct remote inspections of the beamline equipment and their surroundings in the main tunnel.
1.3	To maintain compatibility with the interacting environment.
1.3.1	To create a unified lifting interface for various beamline interfaces and the equipment requiring RH.
1.3.2	To maintain compatibility with tunnel dimensions (i.e., to achieve movement across the tunnel).
1.3.3	To maintain compatibility with equipment requiring RH (i.e., to ensure co-existence with tunnel equipment).
1.4	To power the system during the RH task sequence.
1.4.1	To power the mobile system during transportation.
1.4.2	To power the RH equipment when performing tasks like the removal and installation of beamline inserts.

· Interface map: Since complex systems have multiple interfaces, it is very important to identify and document them. An interface refers to the functional and physical characteristics required at a common boundary between two or more systems, end products, enabling products or subsystems. Functional and physical interfaces include physical, electrical, electronic, mechanical, hydraulic, pneumatic, optical, software and control interfaces. At this stage, it is most important to identify the key physical and control interfaces; due the fact the interfaces are the most critical shaping factors in RH system design. Therefore, in the case of the Super-FRS, we are currently only investigating these. The interface map is shown in Figure 81. It shows both the control and physical interface connections between the MTRH system, the Super-FRS equipment and disposal equipment. The different types of interfaces are defined in detail within the requirements document. The interface identification process enables the system design engineers to specifically identify the key RH requirements and critical design issues.

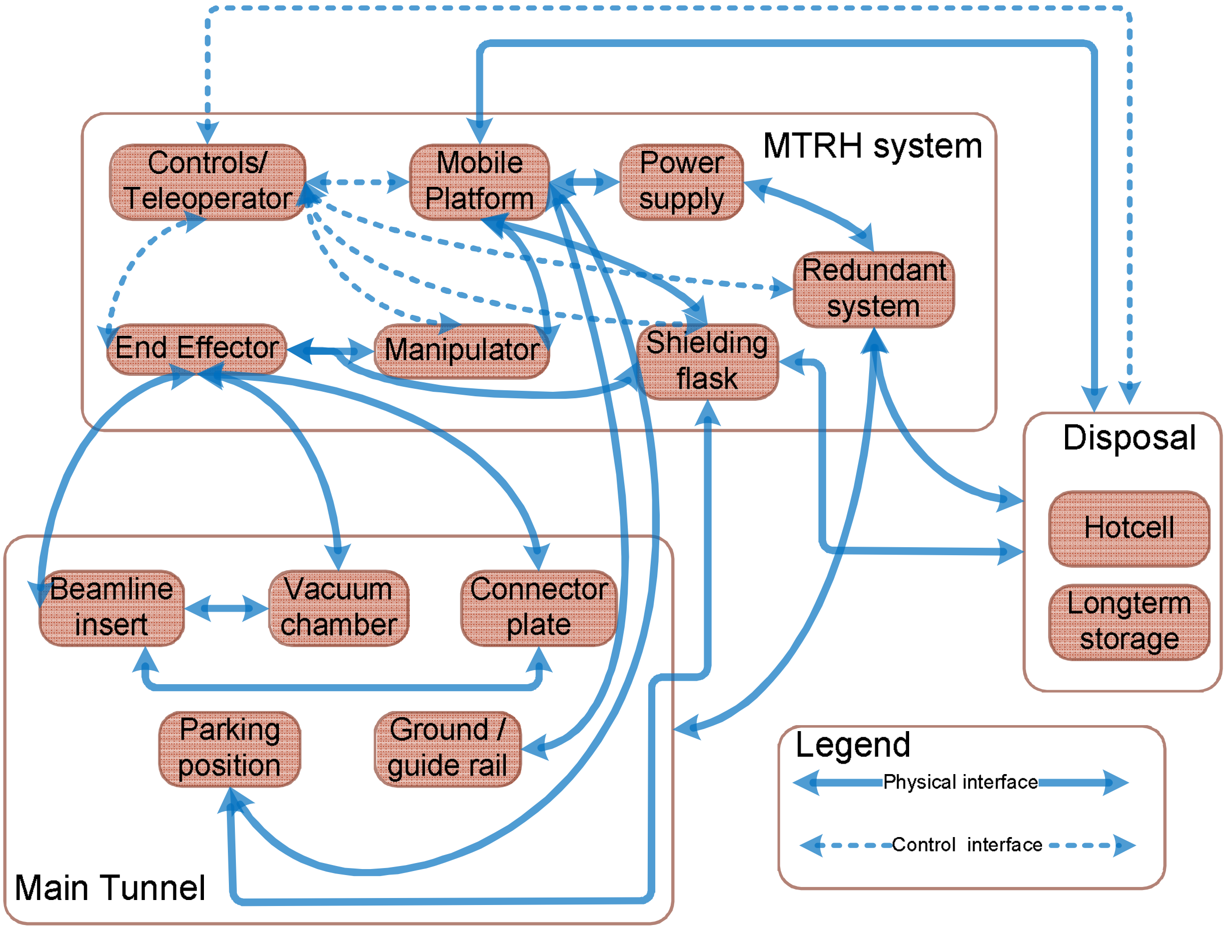


Figure 81. Super-FRS MTRH system interface map. The solid lines represents mechanical interface and the dotted lines shows the control interface.

· Maintenance plan (classification of equipment requiring maintenance): It is critically important to classify and categorize the equipment that requires remote maintenance, in order to allow the development of RH task sequences for maintenance and the development of adequate systems and tools to carry out that maintenance. RH classes and categorizations of the equipment requiring remote maintenance enable the designer to define the system functions and interfaces. Based on the frequency of planned maintenance and the likelihood of failure, four RH (RH) classes were defined:

- RH class 1 = components requiring regular, planned replacement
- RH class 2 = components likely to require repair or replacement
- RH class 3 = components that are not expected to require maintenance or replacement during the lifetime of the facility, but would need to be replaced remotely in the event of failure
- RH class 4 = components that do not require RH

Table 6 lists and classifies the equipment that may require RH during the FAIR operational lifecycle.

In addition to such RH classes, it is important to further divide the equipment in order to determine the facility's downtime. Based on the survey study, the remote maintenance for activated parts can be divided into two categories: scheduled and unscheduled. Each of the aforementioned categories can be further subdivided into two sections, depending on time and resource constraints: long-term maintenance (LTM) and short-term maintenance (STM). For the Super-FRS facility, remote maintenance (scheduled or unscheduled) was divided using these concepts of LTM and STM, as shown in the RH operational status table (Table 7). At this stage, it is still not clear how the beamline insert will behave during facility operations or how often maintenance will be needed.

Table 6. RH classification of Super-FRS main tunnel beamline equipment.

RH Class	Beamline component
1 ,2	Connection plate
1,2	Experiment specific instrumentation
2,4	X and Y slits
2,4	Degrader disk
2	Drivers for beamline inserts
2,4	Degrader wedges
3	Magnets and vacuum Chambers
4	Permeant detector

- Technical Performance Measures (TPMs): To develop the Super-FRS concept design, which is detailed in the following section, it is important to identify the key technical and operational parameters. Technical performance measures (TPMs) were used to identify key technical performance parameters for the Super-FRS RH concept design. Table 8 provides a list of the key TPMs for the Super-FRS MTRH system, which can used for the development of concept designs.

Table 7. RH operational maintenance status table (Inspired from ITER approach).

Super-FRS Operation State	Long Term Maintenance (LTM)	Short Term Maintenance (STM)	Test & Conditioning State (TCS)	Short Term Stand-by (STS)
RH shut down operations state:	X			
Scheduled vacuum chamber, magnets	X			
Unscheduled vacuum chamber, magnets	X			
Scheduled target area beam line inserts	X			
Unscheduled target area beam line inserts (pre-separator)	X			
Scheduled beam line inserts (main separator)	X	X		
Unscheduled beam line inserts (main separator)	X	X		
Schedule inspection of beamline inserts		X		
Unscheduled inspection of beamline insert		X		
RH shutdown maintenance state:	X			
Failure recovery/rescue of shutdown equipment	X			
Scheduled maintenance on shutdown equipment	X			
Unscheduled maintenance on shutdown equipment	X			
Test stand mock-up operations state		X	X	X
Test stand operations		X	X	X
Failure recovery/rescue of RH test stand equipment		X	X	X
Planned RH test stand equipment maintenance		X	X	X
Unplanned RH test stand equipment maintenance		X	X	X
RH equipment maintenance state:	X	X	X	X
Planned RH equipment maintenance	X	X	X	X

Table 8. MTRH system technical performance parameters

S.No.	Remote maintenance system design requirements
1.	To conduct remote maintenance
1.1.	Removal and installation of connector plates
1.2.	Removal and installation of heavy beamline insert up to 750kgs (plus safety factor)
1.3.	Safe environment for operator
1.4.	Longest beamline insert to be handled 2080mm
2.	Remote inspection of surroundings
3.	Transport of activated parts (within tunnel) (2x176m)
4.	Transport of activated parts (to main hot cell) (2x500m)
5.	Remote maintenance on beamline insert
5.1.	Minor repairs (short term maintenance i.e. inspection)
5.2.	Major replacements and repairs (Long term maintenance i.e. repair and replacement of parts) includes transfer of equipment to hot-cell.
5.3.	Disposal of activated components (HotCell)
6.	Suitable remote handling lifting point 2295mm (Critical for lifting interface design and connector plate design position for beamline inserts)
7.	Parking space maximum width for remote maintenance equipment 3047mm (Critical for remote handling system parking interface design) one side of the tunnel.
8.	Remote maintenance equipment must be prevented from becoming activated/contaminated itself

3.3.1.5 Output of the Super-FRS facility study

During this first part of the requirements development stage, we were able to identify:

- The key radiation hotspots within the Super-FRS facility.
- A list of equipment requiring remote maintenance.
- The RH environment.
- The system interfaces.
- System functional capabilities and operational needs.
- Classification of equipment requiring RH.
- Non-functional requirements.

- Technical performance parameters.
- Technical performance parameters

3.3.2 State of the Art survey and existing concept analysis

3.3.2.1 Existing concept analysis

To effectively develop a new RH concept, it is critically important to study any existing concept solutions which have already been developed. In the case of the Super-FRS, engineers had already proposed two RH concepts before this research work began. The experience at the existing GSI FRS target area had prompted engineers to adopt the same solutions for the remote maintenance of the Super-FRS. However, the studies performed in this research revealed that this approach would not be suitable, due to the differences between the two environments.

The concepts suggested for the Super-FRS at the FAIR facility included the installation of two industrial robots on FPF2 and FPF4 to carry out remote maintenance, as well as the installation of a single industrial robot mounted on guide rails to move across the tunnel.

Concept one: Stationary industrial robots: The first concept was to deploy two industrial robots with partial mobility to carry out RH tasks within the main tunnel using a guide rail. The concept was in its initial phases; however, problems were identified following the initial radiation assessment and main tunnel layout design analysis for the Super-FRS facility. The problems were as follows:

The first concept was to deploy two industrial robots with partial mobility (via a guide rail) to carry out RH tasks within the main tunnel. At the beginning of this research, the concept was in its initial phases; however, problems were identified following the initial radiation assessment and analysis of the main tunnel layout. The problems were as follows:

- The industrial robots would accumulate high radiation doses during beam operations and, hence, may be damaged. The on-board electronics would be the first to suffer damage due the high level of prompt doses.
- The industrial robots will cover a restricted beamline area and would not be flexible enough to carry out additional tasks.
- The logistics to retrieve the activated beamline inserts from FPF2 and FPF 3 would be severely compromised.
- During emergencies, access to the beamline for human intervention would be severely restricted.
- The design included a temporary storage area for beamline inserts within the tunnel that can cause radiation protection issues within the tunnel.
- In the event of accidents, the robots could become activated and would have to be termed radiation waste due to contamination.
- No decontaminant area within the tunnel was identified for the RH equipment.
- The transport and post-processing concepts of the activated beamline insert were not defined and neither were the disposal issues.

Concept two: Mobile industrial robot on ground-mounted guide rails: This concept design proposed the installation of a six-axis industrial robot on ground-mounted guide rails. The concept design was based on the experiences of existing solutions in ISOLDE, CERN, and the aforementioned GSI FRS. It was found to be much more acceptable than the first concept solution; however, the guide rail installation was a major hurdle. Specifically, the conceptual guide rails presented the following issues:

- Robot ground rails leads to restricted tunnel access, due to additional equipment presence in the tunnel. In the case of a magnet or vacuum chamber failure, removal of both the RH system and the rail would be needed. Hence, a system failure would cause a major restructuring of equipment within the Super-FRS main tunnel. Such restructuring (including removal and re-installation) would be very costly and time consuming, thus adding to the facility's down time.
- The rail itself would be located within the tunnel during beam operations; and hence, the guide rails themselves could be activated during the facility's operations. In the event of an accident or contamination, the guide rail would become radioactive waste which would require decontamination before it could be retrieved from the tunnel.
- The installation of guide rail was found to be very expensive, as calculated from the cost-per-meter for installation and maintenance within a radioactive environment.

Due to all these drawbacks, it was necessary to rethink and redesign the entire RH system and logistics concept for the Super-FRS main tunnel. However, although the concepts themselves were not used, the valuable lessons learned from studying them clearly demonstrate the importance of such a concept analysis within the SE approach.

3.3.2.2 State of the Art survey

The GSI and FAIR facility is a research institution with a limited available budget for the development of bespoke RH equipment. For this reason, GSI/FAIR does not tend to invest in developing new technologies for remote maintenance. Instead, it selects, modifies and adopts existing solutions within the market for its remote maintenance needs. Since the requirements for the RH of the Super-FRS facility are unique, it was important to conduct a State of the Art survey to identify the key technologies that could be used. The survey was conducted in extensive detail to study the various RH logistics within HEP facilities around the world, as well as to review the RH techniques used in the decommissioning of the nuclear power plants. This State of the Art survey has been described in detail in Chapter 2 (see Section 2.1 and section 2.2). The RH equipment described in the survey was then also classified and generalized to facilitate the use of the information by other researchers and RH engineers wishing to apply the results of this research to their own use cases (see Section 2.3).

3.3.2.3 Output of existing concept analysis and State of the Art survey

The analysis of existing concepts reveals issues with the RH system and logistics concepts for the Super-FRS main tunnel. Based on the existing concepts analysis following issues needs to be considered while developing Super-FRS RH concept:

- The RH system needs to be mobile in order to avoid radiation exposure and conduct RH tasks at different location within Super-FRS tunnel using one RH system.
- The onboard electronics from the RH system needs to be reduced, protected and replaced with radiation harden electronics to eliminate the risk of electronics damage due to radiation exposure.
- Decontamination area and system is needed to maintain the RH equipment in operable condition.
- The installation of guiderails on the ground is not fishable for Super-FRS mobile robot due radiation safety issues, due to tunnel accessibility for personal during system failure or emergencies, due to the high cost of installation and maintenance, and due the use of air-cushion system for transporting heavy beamline equipment such as magnets.
- A safe and secure storage location for activated beamline inserts needs to be identified and developed.

- Additional system for transporting active beamline inserts within beamline and hotcell needs to be developed

The State of the Art survey HEP facilities, technologies and logistics techniques enables the researcher:

- To identify the key technologies and practices currently used in the maintenance and decommissioning of HEP facilities and nuclear power plants.
- The analysis output is mapped in the form of equipment classification for RH design purposes (see section 2.3).
- The survey provides a detailed list of the technologies and companies capable of providing the services needed for the Super-FRS; however, the needs of the Super-FRS MTRH system and logistics are unique in that they require a new concept design using existing technologies prior to the initiation of the equipment development phase.
- The survey list of technologies developed during the survey will be used as a basis for the development of RH concepts.
- The survey divides HEP facilities into categories in order to systematically study the relevant RH systems and document the shortcoming in each RH systems and logistic designs.

The identification of major design issues at an early stage of concept development based on experience will enable the designer to avoid additional costs and any loss of RH functions that could occur once the facility is operational.

In studying current State of the Art systems, especially studies related to the procurement of CERN ISOLDE robot systems and GSI robot systems, it is evident that the requirements development process is currently either limited or non-existent. System implementation starts with technical specifications, which lead to the selection of robots that can be installed by a company to carry out maintenance. However, logistics are often ignored, which is why CERN still has no post-processing facility for spent targets at ISOLDE. This is also why the GSI FRS beamline inserts are located in a very tight space, from which retrieval is very time-consuming and challenging. The existing concept studies provide insight into the target plane and help to establish the needs of the MTRH system.

3.4 Concept design development

To develop the concept designs for the Super-FRS MTRH system, the TPM was compared against the list of equipment generated by the State of the Art survey. This resulted in a list of equipment which was suitable for the RH needs of the Super-FRS. The TPMs from the requirements development provided the technical basis for the concept design development. During this process, it was critical to incorporate the following considerations:

- Teleoperated vs. fully automated operation for RH.
- Shielding to protect the personnel and equipment.
- Maintenance of the RH equipment.
- Viewing capabilities.
- Risk of failure.
- Radiation tolerance issues of equipment.
- Access to maintenance and recovery.
- Who would operate and maintain the system.

Based on the above considerations and the TPM analysis described above, three concept solutions were developed. These three concept solutions are based on the use of COTS equipment which fulfills the RH needs with regards to reliability, availability, maintainability and safety. Some of the concept designs include COTS equipment that will require modification to ensure safe use within a radiation environment. The Concept Design Document (CDD) (see Appendix IV: Requirements and Functional Analysis) explains the concept designs in detail, along with the RH task sequences to maintain beam-line inserts in the Super-FRS main tunnel.

3.4.1 MTRH system concept one: Fully automated mobile robot

3.4.1.1 MTRH system concept one components

The MTRH system concept one (Figure 82) consists of:

- Six-axis (KUKA Titan) industrial robot: A six-axis robot is needed to perform remote manipulation (i.e. to remove and install the beamline insert onto the vacuum chamber and to carry out the connection and disconnection of the control panel).
- Mobile platform (KUKA Omnimove / Automated Guided Vehicle (AGV)): Two mobile platforms are need in this concept. The first one is equipped with the six-axis robot (KUKA Titan), a tool system for the KUKA Titan, a guidance system to guide the Omnimove across the tunnel, and a battery pack to power the mobile platform during the transfer between the maintenance area (FPF 2-4 and FMF2) and the parking area (Figure 79). The second mobile platform is equipped with shielding container to transport the activated beamline inserts to hotcell.
- Tools for RH: The robot must be equipped with specific, task-based tools to carry out RH tasks.
- Shielding container: There must be a container to securely hold and transport the activated beamline insert from the remote maintenance area (FPF 2-4 and FMF2) to parking area and, later, to the hotcell (Figure 79). The hotcell will be used in post-processing of the beamline inserts.
- Power supply system: The power system includes a battery pack to power the MTRH system during transportation and to power the robot supply system once it is parked at the maintenance location. In the event of a power failure, a redundant power supply is required to ensure the recovery of the mobile platform and the robot.
- Navigation: To safely guide the MTRH system across the tunnel, an autonomous navigation system (laser or magnetic) is required. The navigation system will be used to avoid collisions when guiding the robot to target locations.
- Parking system: In order to securely park the MTRH system, the mobile platform must be equipped with a parking system to ensure the absolute position of the MTRH system within the environment. The parking system can be equipped with hydraulic jacks.
- Communication system: To ensure communication between the robot system and the control room, dedicated wireless communication equipment is required (e.g. leaky cable, Wi-Fi network, 4G, etc.).
- Visual feedback: Networks of cameras are required across the tunnel and on-board the MTRH system to monitor the RH tasks. In the event of a failure in automatic mode, a camera system is important to enable the manual control and operation of the MTRH system.
- Remotely controlled crane: A crane must be used to rescue the robotic system in the event of failure.

3.4.1.2 MTRH system concept one: Task sequence (logistics)

This concept (Figure 82) is based on the idea that RH is carried out with full automation and minimal presence of a human-in-the-loop. However, in the event of any failure within the MTRH system's automated process, a human operator must be able to take charge in order to minimize system down time. The concept also requires high levels of sensory control to carry out RH tasks automatically within the Super-FRS tunnel. Also, beamline inserts need to be designed to be compatible with RH and appropriate interfaces developed for tooling and connectors. The RH task sequence for this concept is:

- The first mobile platform, fitted with the six-axis robot, is deployed from its parked state to the remote maintenance position (FPF 2-4 and FMF 2). The mobile platform uses a battery pack to power automated travel between the two locations and deploys a parking system to park the MTRH system at the target location (with an accuracy of ±2 mm) using optical and mechanical guiding mechanisms.
- Once the mobile platform is parked and connected to a power source, the six-axis robot calibrates its position within the space and prepares to perform the remote maintenance task.
- The second mobile platform, which is equipped with a shielding box, is moved and parked in the maintenance area (FPF 2-4 and FMF2) along with a new beamline insert on board and space for one activated beamline insert.
- The six-axis robot carries out the remote manipulation in the following sequence:
  - Equips itself with the appropriate tooling.
  - Carries out a preliminary inspection of the surroundings.
  - Removes the connector plate from the beamline insert and places it in a secure location.
  - Removes the activated/damaged beamline insert from the vacuum chamber.
  - Securely places the activated/damaged beamline insert into the shielding flask.
  - Lifts the new beamline insert from the shielding container.
  - Installs the new beamline insert onto the vacuum chamber
  - Attaches the connector plate to the new beamline insert.
  - Conducts a final inspection to ensure that the installations of the beamline insert and connector are secure
  - Finally, it returns to its home state.
- The second mobile platform is retrieved from the maintenance area, transporting the activated beamline insert into the hotcell for storage, remote maintenance or disposal.
- The first mobile platform is retracted from the maintenance area to the parking position.

One important requirement is to envelop the RH equipment in a protective cover, to reduce the chance of contamination. Before the final parking, the RH equipment must pass through a decontamination zone within the access tunnel, to ensure that it is free from radiation or active contamination.

3.4.2 MTRH system concept two: Teleoperated RH concept

3.4.2.1 MTRH system concept two: Components

The second concept (Figure 82) is based on having a human-in-the-loop. The aim is to carry out maintenance using a remotely controlled master slave manipulator. The components of this concept consist of:

- <u>Remotely controlled Master Slave Manipulator :</u> Various options exist for the telemanipulator, that includes: electrically powered MT200 TAOs, hydraulically powered Schilling Titan robots, pneumatically powered Festo Exohands, or customized industrial robots. The telemanipulator is equipped with tools and visual aids to carry out the remote operation. The Master Slave Manipulator is directly controlled by an operator, which implies trained personnel. It also means that there is a need is to ensure effective communication between the master and slave arms. This component can only be used to carry out fine manipulations, as it is not suitable for heavy lifting.

- Tools for RH: The robot will also be equipped with task-specific tools to carry out various parts of the task sequence.
- Mobile platform: This concept consists of a single mobile platform that is used for transporting the RH equipment between the maintenance area (FPF 2-4 and FMF2) and the parking area (Figure 79). The mobile platform is equipped with the MSM supports battery packs, shielding, and bays for holding the activated and new beamline inserts.
- Shielding wall and fixture for MSM: The mobile platform has shielding to encapsulate the activated beamline insert and protect the surroundings. If a mechanical MSM were to be adopted, shielding for the operator would also require; however, in this case, a remotely controlled telemanipulator is the right option to minimize human presence in the tunnel.
- Remotely controlled mobile crane: To lift and transfer the beamline insert between the vacuum chamber and the mobile platform, a remotely controlled mobile crane is required. This heavy lifting can only be performed using a remotely controlled crane, due to the low payload capacity of the Master Slave Manipulator.
- Navigation: To safely guide the MTRH system across the tunnel, an autonomous navigation system is required, using either laser or magnetic technology. This navigation system is used to avoid collisions when guiding the robot to target locations.
- Parking system: In order to securely park the MTRH system, the mobile platform needs to be equipped with a secure parking system to ensure the absolute position of the MTRH system within the environment. This parking system can be equipped with hydraulic jacks to lock the platform in position.
- Communication system: To ensure communication between the robot system and the control room, a dedicated wireless communication system (e.g., leaky cable, Wi-Fi network, 4G, etc.) is required.
- Visual feedback: Networks of cameras across the tunnel and on board the MTRH system are required to monitor the RH tasks. In the event of failure in automatic mode, a camera system is important to enable manual control and operation of the MTRH system.

This requires certain system modifications, including:

- Protection of the on-board electronic system by removal or replacement of electronics, or with shielding.
- Replacement of the supplied system cables with radiation-hardened cables.
- Protection from contamination, which is achieved through covering up the MTRH system with protective cover.
- Customized tooling to carry out RH tasks.
- Modifications to the connector plate interface and the beamline insert handling interface.
- A special tool to allow the crane to lift the beamline insert.

3.4.2.2 MTRH system concept two: Task sequence (logistics)

The human-in-the-loop idea of this concept means that the RH tasks are performed as a human would perform them by hand. As with the previous concept, the beamline insert must be designed for RH and appropriate interfaces developed (tooling and connectors). The RH task sequence for this concept is:

- The mobile platform with an MTRH system is deployed from the parking state to the remote maintenance position (FPF 2-4 and FMF2 in Figure 79). The mobile platform uses a battery pack to power its automated travel between the two locations, and it deploys a parking system to park the MTRH system at the target location (with an accuracy of ±2mm) using optical and mechanical guiding (due to radiation). The mobile platform also contains new beamline inserts.
- Once the mobile platform is parked and connected to a power source, the MSM can be used to perform remote maintenance tasks.
- The remotely controlled crane, equipped with tooling, is moved and parked at the maintenance area, and a parking system is deployed.
- The MSM is used to survey the surroundings using the appropriate tooling. If the beamline requires remote maintenance, the connector plate is disconnected.
- The remotely controlled mobile crane is use to remove the beamline insert from the vacuum chamber to the holding bay on board the mobile platform. If repairs to the beamline insert can be performed on-site, then they are carried out using the MSM. If the beamline insert requires remote maintenance in the hotcell, it is securely stored away in the shielding. The remote crane then installs the new beamline insert to the vacuum chamber from the mobile platform.
- The MSM is used to visually monitor the installation of the beamline insert. The connector plate is attached to beamline insert, and the MSM conducts a remote inspection to ensure that the installation process is complete.
- The remotely controlled crane is retrieved from the maintenance area and brought to the parking space.
- The mobile platform, along with the MSM and activated beamline insert, are also retrieved from the maintenance area to the parking space.
- The activated beamline insert, along with the shielding, is transferred into a secure transfer box to transport it into the hotcell for storage, remote maintenance or disposal.
- The remotely controlled crane and MSM are both decontaminated and parked until the next RH task sequence.

3.4.3 MTRH system concept three: Overhead robot RH concept

3.4.3.1 MTRH system concept three: Components

This third concept (Figure 82) consists of:

- <u>Overhead gantry coordinate robot:</u> An overhead gantry coordinate robot (the Hager Portal stacker PLF/Jumbo) is used to remove and install beamline inserts from the vacuum chamber and to inspect the surroundings. It can also be used as an overhead crane to handle other beamline components, such as vacuum chambers and vacuum motors. The robot can be equipped with an additional six-axis robotic arm to carry out remote manipulations, such as the inspection and repair of cryogenics or repair of connector plate onsite. The removal and installation of a connector plate is done automatically to reduce the complexity of the RH task. The gantry robot will require specific tooling to lift, remove and install the beamline inserts, while also performing inspection tasks. The gantry robot is programmed to carry out routine RH tasks automatically; however, in the event of an unstructured task sequence or a failure to carry out a task autonomously, human-in-the-loop (manual) control is essential.
- <u>Overhead guide rails:</u> Overhead guide rails serve as pathway for the gantry robot to move across the Super-FRS tunnel. The rails must be equipped with communication signals, power supplies (without umbilical cords) and parking stations which correspond to the RH tasks. The guide rails cover the whole tunnel, from the FPF 2-4 and FMF2 to the parking space.

- Tools for RH: The robot will also be equipped with task-specific tools for the different parts of the task sequence. Mobile platform (KUKA Omnimove / Automated Guided Vehicle (AGV)): A mobile platform is required for this concept. It will be equipped with a shielding box, a parking system, a guidance system to guide the Omnimove across the tunnel and a battery back to power the mobile platform during the transfer between the maintenance area (FPF 2-4 and FMF2) and the parking area (Figure 79).
- Shielding container. The shielding container securely holds the activated beamline insert during transportation from the remote maintenance area to the parking area. Later, the shielding container is moved into the hotcell for post-processing of the beamline insert (Figure 79).
- Power supply system: The power system includes a battery pack to power the mobile platform during transportation, as well as a power supply system to power the mobile platform once it is parked at the maintenance location. In the event of power failure, a redundant power supply will be required to ensure the recovery of the mobile platform and robot. The gantry robot is powered via overhead rails both during its movement across tunnel and its work on RH tasks.
- Navigation: To safely and autonomously guide the mobile platform across the tunnel, a navigation system is required, using laser or magnetic technology. This navigation system will be used to avoid collisions when guiding the platform to target location.
- Parking system: In order to securely park, the mobile platform needs to be equipped with a secure parking system to ensure the absolute position of the MTRH mobile platform within the environment. This can be equipped with hydraulic jacks to lock the platform in position. The gantry robot also requires a secure parking location. Finally, the overhead guide rails must be able to bear the load of all components during the RH tasks.
- Communication system: To ensure communication between the robot system and the control room, dedicated wireless communication systems (e.g., leaky cable, Wi-Fi network, 4G, etc.) are required.
- Visual feedback: Networks of cameras across the tunnel and on board the MTRH system are needed to monitor the RH tasks. In the event of failure in automatic mode, camera systems are important for ensuring the manual control and operation of the MTRH system.

3.4.3.2 MTRH system concept three: Task sequence (logistics)

This concept (Figure 82) is based on the idea that RH is carried out with full automation and minimal presence of a human-in-the-loop (only in special circumstances). However, in the event of any failure within the automated process, a human operator must be able to take charge to minimize system downtime. This concept also requires a high level of accuracy and the beamline insert, vacuum chamber, connector panel and tunnel layout must undergo engineering changes to incorporate the appropriate RH interfaces (for tooling and connectors). The RH task sequence is as follows:

- The overhead gantry robot is deployed on guide rails from the parking state to the remote maintenance position (FPF 2-4 and FMF2 in Figure 79). The overhead gantry robot receives power from the guide rail during the automated travel between the two locations. Once it is at the target location, the overhead gantry robot parks there using electrical and mechanical parking mechanisms.
- Once the overhead gantry robot is parked and connected to a power source, the robot calibrates its position within the space and prepares to perform the remote maintenance task.
- The mobile platform, equipped with the shielding box, is moved and parked in the maintenance area. It holds the new beamline insert and space for one activated beamline insert. The mobile platform is powered with a battery pack during its travel and, at the target location, is connected to a power source to charge the battery pack and operate the shielding box.

- Once the overhead robot and shielding box are in their locations, the connector plate is disconnected automatically.
- The overhead gantry robot conducts the remote manipulation using the following sequence:
    - Equips itself with the appropriate tooling.
    - Carries out the inspection of the surroundings.
    - Removes the activated/damaged beamline insert from the vacuum chamber.
    - Securely places the activated/damaged beamline insert into the shielding flask.
    - Lifts the new beamline insert from the shielding container.
    - Installs the new beamline insert onto the vacuum chamber.
    - The connector plate is connected automatically.
    - Conducts an inspection to ensure that the installations of the beamline insert and the connector are secure.
    - Retrieves itself to its home state.
- The mobile platform with the shielding box is retrieved from the maintenance area and used to transport the activated beamline insert into the hotcell for storage, remote maintenance or disposal.
- The overhead gantry robot is retracted from the maintenance area to its parking position.

It is important cover the RH equipment with a protective cover to minimize the chances of contamination. Before the final parking, the RH equipment must pass through a decontamination zone within the access tunnel in order ensure that it is free of radiation and active contamination.

3.4.4 Modifications to the MTRH new concept designs and beamline equipment

The COTS equipment used in all three of the concept designs of the MTRH system are normally designed for commercial industrial use. Therefore, most of the equipment is not designed specifically for handling nuclear waste. Major modifications are required in order to use such industrial systems for the maintenance task sequences within the Super-FRS. These modifications include:

- Removing and replacing on-board electronics from those robotics and communication systems which are not designed for survival within radioactive environments. These electronics are removed to a safe distance, replaced with radiation-hardened electronics or provided shielding. This step protects the MTRH system from failure.
- Replacing normal cables with radiation-hardened cables to ensure safe system operation.
- Selecting industrial equipment which has been designed for harsh environments, such as foundry robots. Such equipment requires fewer modifications.
- Taking protective measures to avoid contamination of the RH equipment. A decontamination area is required if there is any danger of contamination during the RH tasks. Contamination protection should also cover the MTRH system.
- Creating customized tools to conduct RH activities.
- Modifying the vacuum chamber, beamline inserts and connector panel designs for concepts 2 and 3.
- Installing guide rails, temporary storage areas for activated beamline inserts and decontamination areas, all of which will require major facility change requests.

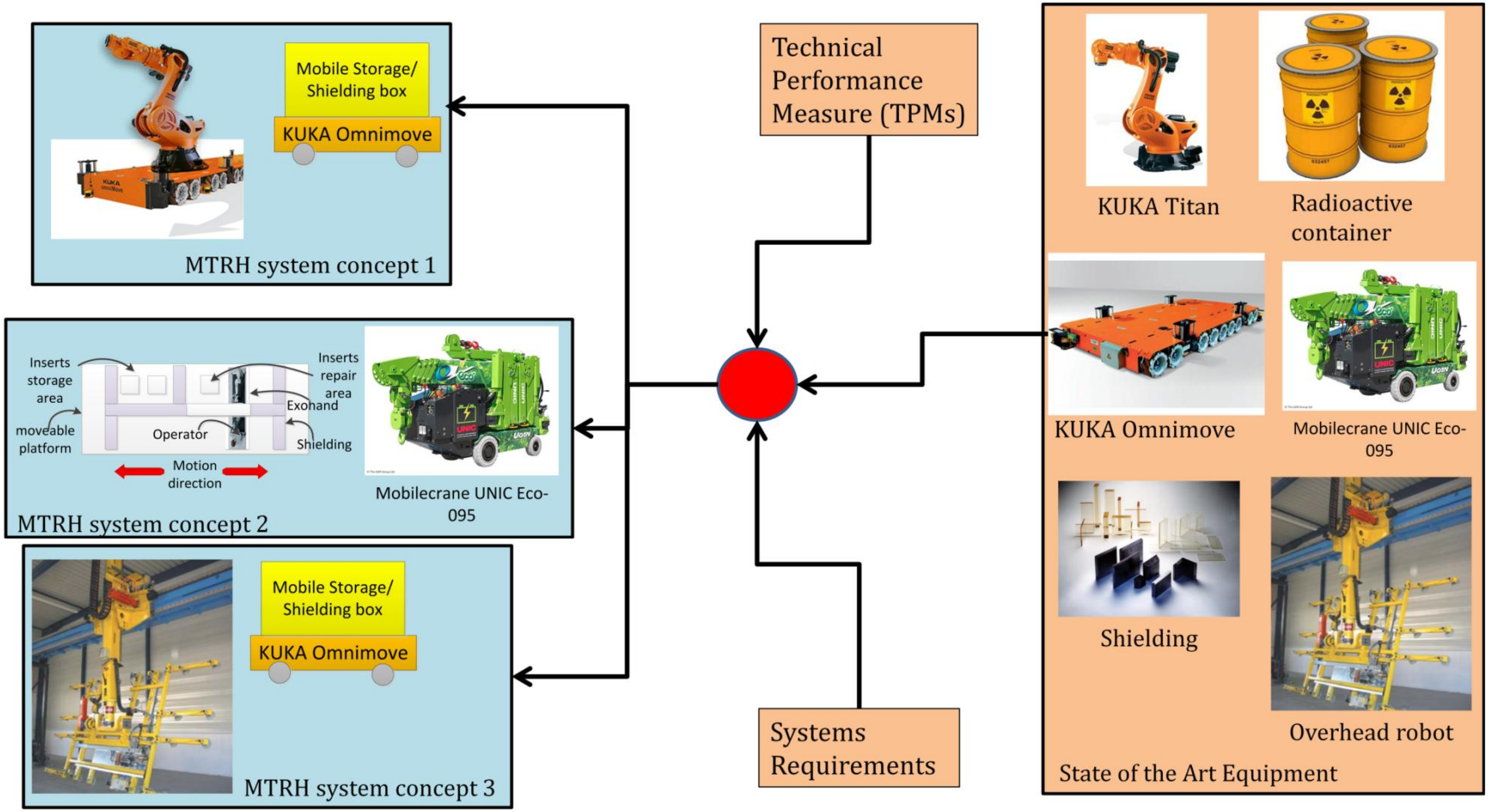


Figure 82. Concept designs for the Super-FRS MTRH system.

3.4.5 Key RH changes identified during the concept designs

The MTRH systems and logistics concept designs studies revealed 12 major issues with the facility's current planning, design and RH systems. It also revealed several changes which can be solve the issues. These issues and solutions include:

- The need for a temporary storage space to store reusable beamline inserts within the Super-FRS main tunnel.
- The need for additional space for parking, mockup testing and repairs of the MTRH system.
- The need for a decontamination area within the tunnel.
- The potential for unnecessary radiation exposure to any MTRH systems parked in the tunnel during beam operation. MTRH system components exposed to radiation doses can be damaged or activated.
- The impracticality of the MTRH system's initial concept designs (see section 3.3.2.1) due to the lack of mobility within the tunnel. These initial designs proposed that the MTRH system components were either installed on fixed stations or set on guide rails on the ground. This would have prevented access to the tunnel in the case that magnets, vacuum chambers or activated beamline parts needed to be recovered.
- The need for a mobile shielding container to transfer the activated beamline inserts from the Super-FRS main tunnel region to the hotcell.
- The need for a redundant system (e.g. an extra mobile crane) in the event of MTRH system equipment failure.
- The sensitivity of modern robotics systems to radiation damage, due to their electronics. These electronics need to be reduced, replaced with radiation-hardened equipment and/or shielded in order to ensure reliable operation of the MTRH system.
- The tunnel space analysis revealed that the KUKA Titan is currently the only six-axis robot which is capable of conducting heavy-duty RH to the specifications required of this application.
- The beamline insert designed at the FAIR partner institution must be designed for RH. The Super-FRS beamline inserts must have universal handling points and interfaces with the MTRH system.
- Before this research began, there was underdeveloped planning of the logistics (task sequences) required to carry out RH within the tunnel.
- The cost estimates for MTRH systems and its operations is currently overly limited in the in the FAIR budget. These will need to be re-adjusted if the MTRH system is to be built.

3.5 Tradeoff analysis for the selection of an MTRH system design for the Super-FRS tunnel

3.5.1 Survey of RH experts to identify key features of RH systems for a tradeoff analysis

In order to select suitable equipment for the MTRH system, a detailed tradeoff analysis was required for the three main concepts (see section 3.4). Interaction with several experts within the RH field was deemed necessary in order to ensure that the tradeoff analysis was based on correct assumptions of the information gained in the State of the Art survey. The personnel in contact with the development of RH equipment were considered suitable individuals to provide realistic and useful information for this purpose. However, surprisingly, RH research teams have had very limited contact with such RH experts. The lack of contact among the different RH sectors can be attributed to:

- Incentive: Companies are sometimes involved in fulfilling contracts and, thus, lack incentives to interact with researchers. Unlike research activities, industry activities are mainly profit-oriented.

- Accessibility: Researchers may find it difficult to contact industry professionals due to a lack of networking opportunities with businesses.

- Reluctance: Researchers may be reluctant to contact businesses due the nature of the (competitive) research or other reasons.

- Specificity: Research is conducted in an open-ended manner and the questions asked during research are correspondingly open-ended. However, industry businesses require more targeted and focused lines of questioning.

Despite these challenges, it was first necessary to contact RH experts and users within different industrial and research settings. In this way, the tradeoff analysis could be based on key features considered critical within the RH community. This, in turn, would assure a better assessment of the MTRH concept designs.

Due to the difficulties in receiving suitable written feedback from industry professionals, it was decided to conduct a survey based on group meetings and presentations. The feedback was not only limited to comments made during group meetings. The participants were also encouraged to provide feedback via email, allowing them to participate. The PURESAFE network provided the platform for bridging the gap between research and industry.

The survey was divided into two phases:

- First phase: A group meeting was held, during which the MTRH system requirements and concepts were presented in detail. The meeting sought to find answers to the following questions:

    - What practices are most often used to evaluate RH concept designs?

    - What tradeoff analysis would designers like to perform, but feel incapable of performing at the concept stage?

    - What are the expert opinions of the Super-FRS concept designs and their tradeoff analysis?

  The application specific questions above sought to answer to the following, more general, questions:

    - What are the most common practices for tradeoff analysis across the industry?

    - What are the essential features critical to a tradeoff analysis for RH equipment?

In the meetings, participants were asked to provide open feedback on a list of key features for tradeoff analyses of RH equipment. Based on detailed group meetings with experts from various institutions, lists of key factors were identified. These are summarized in Table 9.

- Second phase: The list of key factors (Table 9) was emailed to RH experts and presented in group meetings for a second review. In order to determine the importance of each factor, the experts were requested to review each one and assign a weighting. The right column of Table 9 provides average normalized weighting factors based on the RH experts' opinions, the higher the number the greater the importance in the tradeoff analysis.

Table 9. List of key factors for the RH concept tradeoff analysis

S.No	Key factors for the tradeoff analysis	Average normalized weighting factor
1	Reliability and availability of RH equipment within the Super-FRS environment (redundancy and recoverability of the system in the event of RH system failure during RH operations, which could lead to contamination).	16.95
2	Maintenance issues with RH equipment (maintenance requirements and procedures for RH equipment, including the ease of the RH system's maintenance, the cost of the RH system's maintenance and the waste generated during the RH system's maintenance).	6.4
3	Parking and working positioning of the equipment within the Super-FRS environment (exposure to radiation: What type of environment does the RH system need to survive during maintenance and while the system is not used? What dose is accumulated due to radiation exposure?).	7.25
4	Complexity of the RH equipment's design and operation (number of tasks that need to be performed by the RH equipment).	7.85
5	Response time for maintenance tasks (how fast the RH equipment can be mobilized).	3.55
6	Capability for load handling (according to the Super-FRS main tunnel needs).	6
7	Control choice for RH equipment (automated or telemanipulated).	5.9
8	Negation or reduction of the radiation doses suffered by personnel during maintenance.	14.35
9	Compatibility with the changing Super-FRS environment (adaptability of the RH system in the face of changing needs within the Super-FRS maintenance spectrum (e.g., maintenance of the FPF2 vacuum chambers) and the usage of the RH system for tasks other than FAIR tasks (e.g., anti-proton targets also require remote maintenance; is it possible to use Super FRS equipment in such cases?).	6.5
10	Ease of use (what are the operational requirements? is an expert needed, or can anyone perform the task?).	5.15
11	Cost of the RH equipment (cost of the RH system itself).	8.1

12	Cost of changes to the Super-FRS facility (beamline, tunnel, magnets, construction plans, etc.) that require RH maintenance due to the selection of a RH system: the impact of the RH system on the system requiring maintenance (e.g., an increase in the cost of the Super FRS beamline due to design changes resulting from the selection of a specific RH maintenance design).	8.15
13	The use of RH equipment in activated environments (if there are pre-existing data that the equipment is already used for RH).	3.85
	Total	100

A detailed and comprehensive tradeoff analysis was then carried out based on the key factors listed in Table 9.Following a detailed discussion of the available data and a consultation with a GSI engineering team, it was decided that four different tradeoff analyses would be conducted to select a suitable concept design for the Super-FRS MTRH system. These were:

- Requirement and functional analysis
- Radiation dose assessment and task sequence optimization
- Reliability analysis: FMEA analysis
- Cost estimation analysis

A comprehensive tradeoff analysis at the conceptual design stage provides a solid ground for selecting a RH concept solution which is suitable for the RH needs of the Super-FRS main tunnel. During this phase, various auxiliary tradeoff analyses were also conducted, including analyses of task-based telemanipulator, manipulator space and task sequence planning using specific tools, which are described in the next section. However, due to their specific nature, these analyses are not included in this thesis. These tradeoff analyses will be more mature once the architectural design of the Super-FRS facility is complete.

3.5.2 Tool and strategies to conduct a tradeoff analysis

To conduct a reliable tradeoff analysis, it is critical to select the right tools and strategies to obtain credible results, which can then be used to select the right concept design. In the case of the RH of the Super-FRS MTRH system, the different strategies and tools used are listed in Table 10, alongside their respective tradeoff analyses. The details concerning each tool are given in the respective tradeoff analysis section.

Table 10. Tools and their respective tradeoffs for the Super-FRS MTRH system.

S.No	Tradeoff Analysis	Tools
1.	Cost analysis	Cost estimation (detailed cost analysis based on market price is carried out to find the best price available for a concept solution)
2.	Requirements analysis	Requirements traceability matrix (requirements are compared against design features to ensure requirements traceability)
3.	Functional analysis	Function vs. components matrix (to identify key components that will perform system functions)
4.	Radiation dose analysis	FLUKA, FLAIR, Ivplanner (tools developed used to estimate beamline doses)
5.	Task sequence optimization	MatPlanner (DSM based software to optimize task sequence with constraints)
6.	Reliability analysis	FMEA analysis (Relia software)

3.5.3 System requirements and functional analysis

3.5.3.1 Requirements analysis tradeoff

The purpose of a traceability matrix is to maintain a linkage from the source of each requirement, through its decomposition and right up to implementation and verification. This traceability is required to ensure that all requirements are addressed, and that only what is required is developed. A traceability matrix is also useful when conducting impact assessments of requirements, designs or other changes of configured items.

This matrix should ensure traceability for each level of decomposition performed on the project. In particular, it should:

- Ensure that every lower-level requirement can be traced to a higher-level requirement or original source
- Ensure that every design, implementation and test element can be traced back to a requirement
- Ensure that every requirement is represented in both design and implementation
- Ensure that every requirement is represented in testing and verification

Traceability matrices have been created for all three of the MTRH system concepts. Each matrix compares a set of requirements derived from the System Requirements Documents (SRD) against a group of features of the MTRH concept design. The comparison shows whether and how well the concept meets the requirements. The traceability matrix cannot be included in this document due to the sheer size of the analysis; however, the features of the MTRH concept design and the results of the requirements tradeoff analysis are presented in Appendix IV.

Briefly summarized results for the requirements analysis are presented below in Table 11. These results indicate that no design fulfills 100% of requirements. This can be attributed to the following reasons:

- Some of the requirements (e.g. testing and inspection requirements, decommissioning requirements, computer hardware and software requirements and RH control room requirements) will be satisfied once an architectural design is selected for further development.
- Fulfillment of some of the requirements (e.g. RAMI requirements, applicable codes and standards requirements, structural requirements and safety design criteria requirements) requires collaboration with other development departments or approval from relevant authorities.

The requirements analysis indicates that MTRH concepts one and three fulfill more requirements than MTRH concept two. However, the differences among all three concepts, and MTRH concept two in particular, stem from the presence of a human-in-the-loop.

Table 11. Comparison of MTRH system concept design requirements and their tradeoff analyses.

S.No	MTRH concept description	Percentage of requirements fulfilled
1	Fully automated system with a six-axis manipulator mounted on a mobile platform	60.8
2	Teleoperated system with a remote-controlled crane for heavy lifting	59.1
3	Automated system with an overhead gantry robot and a mobile shielding container.	60.8

The percentages and numbers of the requirements met in the requirements analysis (see Appendix IV Table 24-Table 26) can be used to track the progress of the design process and to determine how well the design meets the customer's requirements at any stage. The results of the requirements tradeoff analysis can be used as benchmark to select the design with the greatest degree of requirements fulfillment. This research work uses a traceability matrix to ensure the traceability of requirements; however, for more effective requirements traceability, IBM DOORS requirements management software is recommended. IBM Doors is requirements management tool that is used to write and track the requirement as the project is developed.

3.5.3.2 Functional analysis

The development of any new system or product requires a functional analysis. The functional analysis applies to every phase of system development [128]; however, it is most useful during the conceptual design phase, during which various potential feasible solutions exist for the future system. The functional analysis has three major benefits:

- The identification of key system functions. This can then contribute to the refinement of the functional requirements. In the development process of the MTRH system, a functional tree was developed, and a systems requirements document was established to identify key functions.
- The identification of key interfaces. The functional analysis performed at the requirements stage identified the key interfaces within the MTRH system.

- The identification of key system components during the concept development phase. This functional analysis assists in the development of concept designs and detailed product trees for the system. In the MTRH system, the product tree for the concept design was developed during the concept development phase. It was based on the functional tree and interface diagram developed in the earlier functional analyses. The fictional analysis (involving product tree development) at this stage enables system design engineers to evaluate multiple options, without forgetting any potential solutions that could offer significant advantages.

At this conceptual stage, the functional tradeoff analysis for the MTRH system concept designs (see Appendix IV) is conducted in order to:

- Ensure that the developed concept designs are adequate and fulfill the functional requirements.
- Ensure that the concept design architectures of the MTRH systems (and subsystems) are clearly understood. This analysis clarifies the system subsystems and their functional relationships.
- Identify a detailed product tree for each concept design. This involves developing:
  - Internal interface connections for each concept.
  - The detailed product tree which can later be used to carry out a fault tree analysis (FTA) to identify key failure points. FTA analyses for the MTRH system concept designs are outside the scope of this stage; however, once detailed architectural designs are established, they can be used to identify key fault points.
  - Cost analyses (see Section 3.5.4).
  - Modified, refined and optimized task sequences for architectural design (see Section 3.5.5).
  - Updated and improved the task sequences, which designers can create during the concept design phase.

The functional tradeoff analysis results show that concept one requires fewer components to carry out the same task than either of concepts two and three.

Table 12. Function (Table 5, Figure 80) vs. subsystem matrix: Number of subsystems required to fulfill each high-level function at once.

Function vs. subsystem analysis				
Number of subsystems required to fulfil each high-level function				
Functional S.No.	Concept No.	One	Two	Three
1		12	13	14
1,1		9	10	12
1,1,1		8	6	10
1,1,2		6	5	6
1,1,3		2	3	3
1,2		4	6	6
1,2,1		3	4	7
1,2,2		3	2	6
1,2,3		2	2	3
1,2,4		3	3	3
1,3		8	9	9
1,3,1		2	4	3
1,3,2		4	5	6
1,3,3		3	6	8
1,4		2	2	2
1,4,1		1	1	1
1,4,2		1	1	1

The functional vs. subsystem analysis (Table 12 and Appendix IV) highlights the key subsystems and components required for each concept design to carry out the RH task sequence. This information, in turn, provides grounds for building a more detailed system interface map. The analysis also provides a basic list of subsystems and components that serve as building blocks for the concept designs (Table 13). These critical building blocks can be regrouped to modify concept designs or even generate new ones (if there is a change in system requirements or needs). Table 13 lists the various subsystems and components identified during the functional analysis which was conducted for the MTRH system concept designs. These are higher-level components within the product tree that will expand as the design of MTRH system progresses. The functional analysis approach can also be used to further expand the product tree detail (during the system architecture design stage) in order to monitor the connections within the MTRH system, subsystems and components (see Appendix IV Figure 97).

Table 13. Break down of the building blocks of the MTRH system concept designs, with system level one being the MTRH system (one unit) and system level five being the basic component level.

		MTRH system concept design		
		One	Two	Three
System level building blocks (subsystems/components)	One	1	1	1
	Two	4	4	4
	Three	7	8	7
	Four	21	26	21
	Five	61	68	63

The functional tradeoff analysis is, without a doubt, one of the most important and fundamental tools within the SE design process, since it contributes to the development of system requirements, provides detailed listings and comparisons of solutions and ultimately enables the designer to list the components required by each system to fulfill the necessary system functions. It also enables the designer to identify key interfaces within the system and with its surroundings. Its output can be used in developing and refining both the FTA (carried out at the architectural design level) and system task sequences.

The design of MTRH system concept one requires fewer components than concepts two and three to carry out the same tasks. However, concept one can only carry out the specified tasks of inspections, removal of the connector plate and replacement of the beamline insert. It has very little flexibility in the event of modifications to the Super-FRS beamline during the facility's lifespan (e.g. in the event that the vacuum chamber requires RH). The automated task sequence for concept one also requires a high level of positioning accuracy and a proper load distribution across all handling positions of the manipulator. Also, the onboard electronics require radiation protection in order to avoid failure during remote maintenance tasks.

The analysis also reveals that the subsystems of concept two require high levels of customization and higher dependency on the judgment of a human operator than those of concepts one and three, which are automated. However, the manipulator and remote maintenance approach used in concept two are the most widely used across the nuclear industry. The major advantage of using a Master Slave Manipulator within the tunnel involves the possibility for onsite remote maintenance and inspection of the beamline equipment. However, the Master Slave Manipulator, mobile platform, mobile crane, shielding would require considerable modification to facilitate use of this concept in the Super-FRS tunnel. It would also require more operator training.

The third concept design involves fewer subsystems and components than concept two and a couple more subsystems than concept one. It has the advantage that the gantry overhead robot can be used as a power manipulator (i.e. an overhead crane with specialized tools) to retrieve the beamline insert directly from the vacuum chamber. Due to its higher load capacity, this approach is flexible to the adoption of future beamline changes. It also has the flexibility to adapt to Super-FRS beamline equipment changes (e.g. the setup for the experiments at the FPF2 vacuum chamber). Special tooling and beamline equipment make the handling of such equipment possible. The overhead gantry robot can be equipped with a six-axis teleoperated robot that can carry out remote inspection and handling on either side of the Super-FRS beamline, and can cover a larger workspace than either of the other RH concepts. The six-axis manipulator can also be used to inspect and handle part of the Super-FRS cryogenic system. However, the implementation of this design is more challenging, due to unforeseen changes to the design of the Super-FRS beamline and main tunnel. In other words, major engineering changes to the Super-FRS main tunnel and beamline would be required to accommodate the overhead gantry robot. These include changes to the vacuum chamber, the beamline insert handling points, the connector plates, the facility cabling and the overhead rail structure.

Given the results of the functional tradeoff analysis, we can conclude that MTRH system concept one requires fewer components to carry out current RH tasks within the Super-FRS tunnel; however, it offers very limited flexibility for future changes. In contrast, concept two offers both onsite and offsite maintenance options due to its human-in-the-loop approach, while requiring fewer changes to the Super-FRS tunnel environment; however, this concept involves a higher degree of customization and the involvement of radiation workers during operations. Concept three offers greater flexibility, as well as a wider workspace envelope; however, it requires major modifications to the Super-FRS main tunnel.

3.5.4 System cost analysis

Cost analysis is one of the important deciding factors in the selection of concept designs. The development of new technical systems is normally focused on technical and performance aspects, with cost analyses often deferred until the end of the project. The cost analysis of systems at later stages can be critical to project success because improper cost estimations can create hurdles in system design and development. In other words, in order to justify the financial parameters of a project and consider the full system spectrum, cost analysis must be a key part of concept development itself.

Lifecycle costing is a comprehensive practice that includes costs associated with design, construction, production, distribution, operation, maintenance, support and disposal. For the MTRH concept selection, we will focus mostly on the RH system costs associated with technical components, human resources, and environmental design changes. The remaining life-cycle costs, such as operation, maintenance and disposal costs, must be calculated once a concept design has been selected for the architectural design stage.

The cost analyses for the Super-FRS MTRH system concepts were conducted using the estimated cost analysis from the IEEE Project Management Body of Knowledge (PMBOK)[129]. The concept designs are based mostly on the use of COTS equipment; hence, in order to determine the estimates, various factors were used as inputs. These included:

- The scope baseline, which is used as an input for cost estimation to determine a product description, acceptance criteria, key deliverables, project boundaries, assumptions, and system

constraints (requirements analysis). It also provides a system WBS (work break-down structure), which outlines the relationships among all the system components and functions (functional analysis).
- The project schedule, which is used to determine the time and resources needed to complete the design work.
- Human resources, which are used as an input to determine the workforce needed to develop and operate the RH equipment.

The cost analysis of the MTRH system concepts (Appendix V) was carried out within input from a detailed market survey and expert judgment. The expert judgment, which was guided by historical information, provided valuable insights into the environment. Information from similar previous projects (FRS, ISOLDE and J-PARC) was leveraged in order to correctly estimate the system costs. The cost analysis of the MTRH system (Table 14) indicates that concept three is the most costly option, costing up to 3 million euros, while concept one is the least costly. The cost analyses included market costs for feasibility studies, equipment, engineering changes and personnel training. Since the cost analysis for the MTRH system is an initial estimate, it does not include operation or maintenance costs, testing or support costs, or costs for disposal. These remaining costs must be calculated once the concept is finalized for architectural design.

Table 14. Total cost of the MTRH system concept designs (does not include the costs of operation, maintenance, testing, support, or disposal).

	Total value (in Kilo €)
MTRH system concept one	2020
MTRH system concept two	2130
MTRH system concept three	2795

3.5.5 System task sequence optimization and radiation dose assessment

It has already been discussed that the main tunnel area under focus presents high dose rates due to activated equipment. Radiation studies have been conducted, and the dimension necessary to shield the Super-FRS (calculated using the FLUKA Monte Carlo algorithm to estimate ambient prompt and residual dose rates) have been published [125][126]. FLUKA is used for analysis due the fact it is provides one of the most accurate beam losses analysis and is comprehensive software for radiation simulations.

To ensure radiation protection within the Super-FRS tunnel, it is important to carry out further radiation dose estimations for the Super-FRS using the FLUKA Monte Carlo algorithm for different scenarios. Table 15 lists all of the various scenarios for which the radiation analysis was conducted. For the purposes of this thesis, we will consider the long-term worst-case scenario as consisting of two years of operation and four weeks of cool down before the RH intervention. The operation phase includes three months of operation and one month of cool down rotated through three cycles per year and totaling six cycles overall. The radiation evaluation scenarios and FLUKA simulation analyses were carried out with the assistance of experts from the radiation team in order to ensure accurate results.

For the Super-FRS intervention scenario, (see Figure 79), FPF2 and its beamline insert maintenance are under focus because the beam intensity is very high at the point of interaction. Hence, for radiation analysis focal plane at FPF2 is considered to be the primary location. For the radiation dose calculation for the intervention scenario, the study will focus on the replacement of the beamline insert at FPF2. It is important to note that calculated doses are reported in µSv and that dose rates are reported in µSv/h. These units are used to achieve accurate estimates of the doses received by human workers, instead of the RH equipment. This analysis is important because it signifies the radiation doses saved due to the fact that operations are carried out using remote maintenance.

The estimated dose simulation for the FPF2 maintenance is conducted using the FLUKA simulation package. The Super-FRS tunnel is divided into two parts: Teil A and Teil B (part A and part B in German). This simulation is shown in Figure 83.

The radiation pattern used in this simulation involved two years of beam operations with intervals of three months of operation and one month of cool down. At the end of two years, it involved four weeks of cool down before the remote maintenance intervention at FPF2. The doses received along the access paths and the punctual dose rates were estimated using a 2D planner named IVPlanner, which was developed by Chris Theis (CERN, DGS-RP). The 3D planner RADIJS, designed by Thomas Fabry, was also used to confirm these values; however, its development was still on-going at the time of this research. Hence, the IVPlanner was preferred due to its operational capabilities and functionalities.

The use of the IVPlanner enabled the visualization of FLUKA data on top of the Super-FRS geometry. The received doses could then be estimated for personnel working in the area and conducting remote maintenance. The doses were estimated for two operators: the teleoperator and mobile crane.This approach enabled accurate dose estimation for each MTRH concept at the points and path of interest. For a detailed radiation analysis, see Appendix VI.

Previous to the radiation analysis, the RH task sequence for each concept was planned and optimized using Matricial Planner (MatPlan). MatPlan is an integrated software application for planning, scheduling and optimizing interventions in ionizing environments. This optimization is twofold: it involves a temporal optimization and also an ALARA optimization, related to the estimated radiation doses received by workers. MatPlan is developed using the Collaborative DSM framework based on the Design Structure Matrix (DSM) [130]. The Super-FRS RH scenario (Figure 79) task sequence was entered into the MatPlan software (Figure 84). After applying constraints, calculations were then performed to determine the optimized intervention scenario for remote maintenance. The software provides a report, as shown in Figure 85, and a Gantt chart for each solution. Figure 86 shows these results for the teleoperated concept option.

Table 15. Super-FRS main tunnel FLUKA simulation scenarios for intervention patterns (both planned and unplanned).

Scenario	Operation	Cool down time
Short-term	Two weeks	Two days
Mid-term	Four months	Four weeks
Long-term	Two years of operation, with three months of operation and one month of cool down rotated through three cycles/year (total: six cycles/two years)	Four weeks
Short-term (Unplanned)	Two weeks	One day
Mid-term (Unplanned)	Four months of operation	One day of cool down (for inspection) One week of cool down (for intervention)
Long-term (Unplanned)	One year of operation with three months of operation and one month cool down/year, with a sudden failure after the one week of cool down	One day of cool down (for inspection) One week of cool down (for intervention)

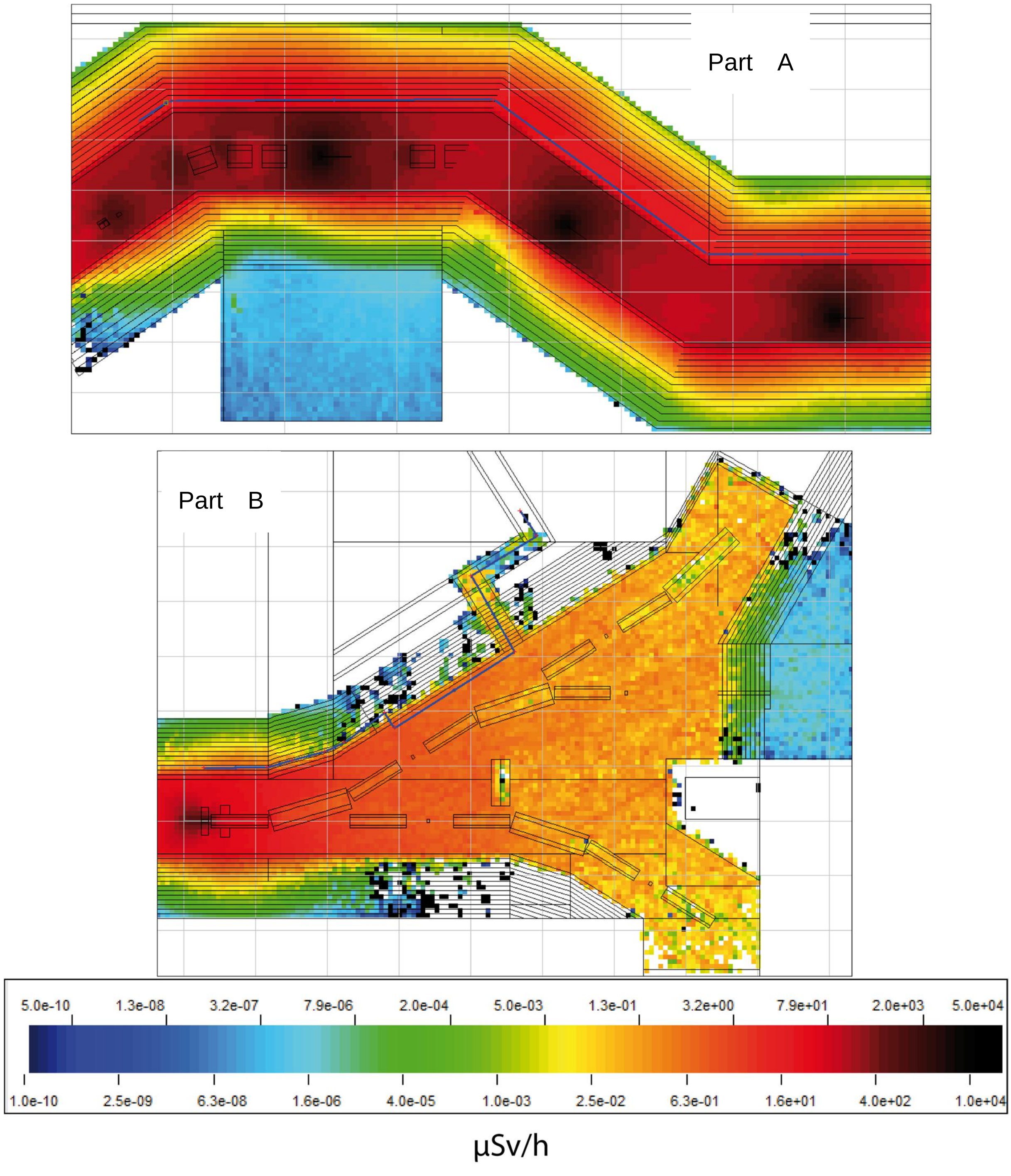


Figure 83. IV planner screen shot of the FLUKA simulations for the Super-FRS tunnel, showing Teil A and Teil B (Part A and Part B in German).

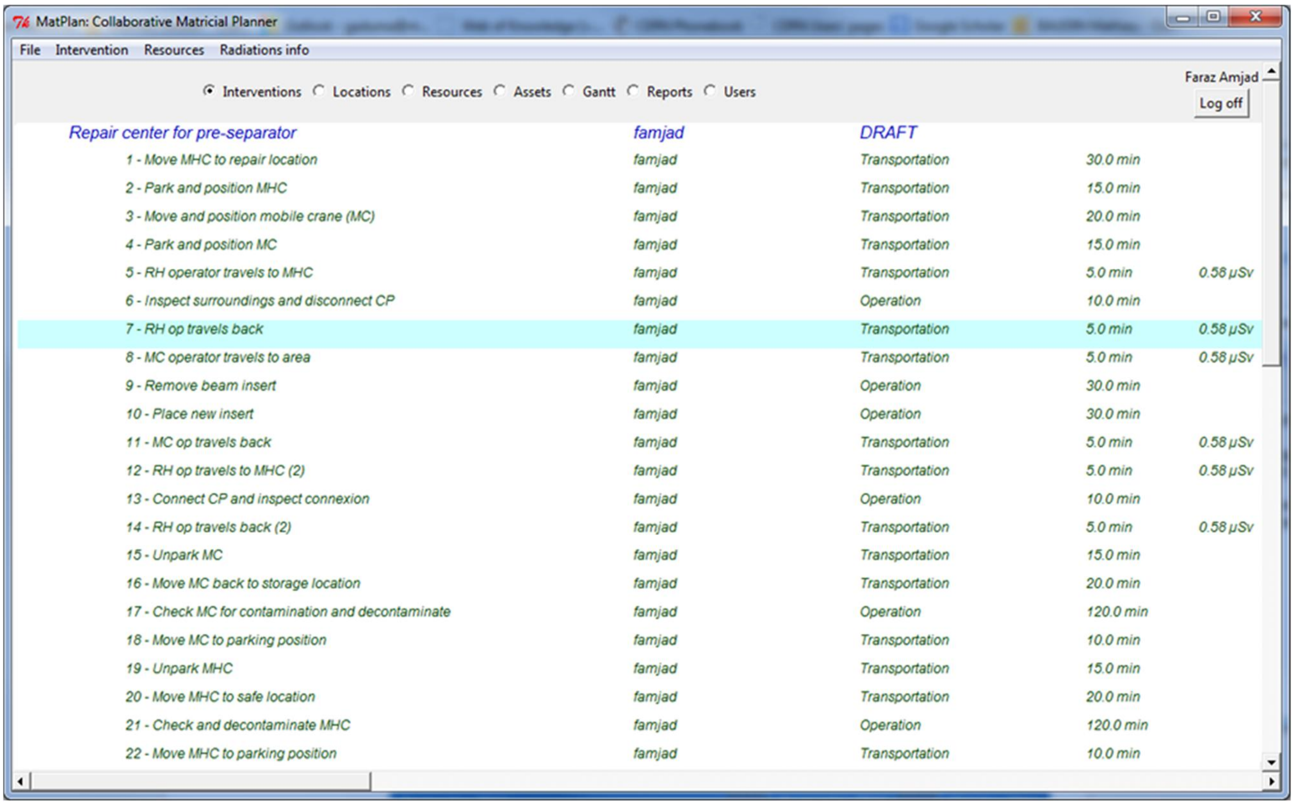


Figure 84. Screenshot of the main application screen of MatPlan, displaying interventions and tasks.

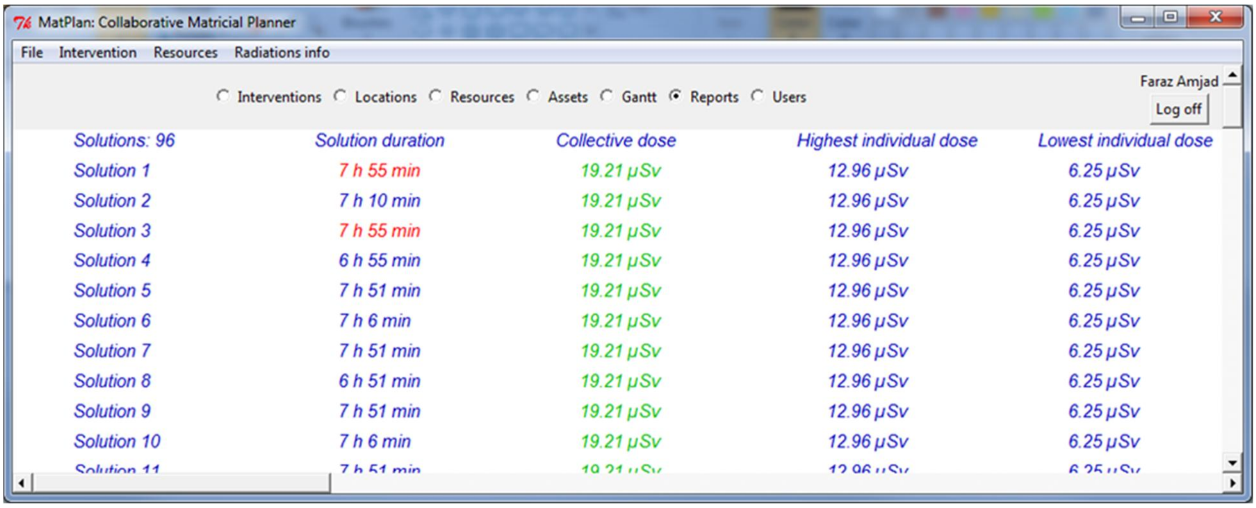


Figure 85. Screenshot of the report tab in MatPlan.

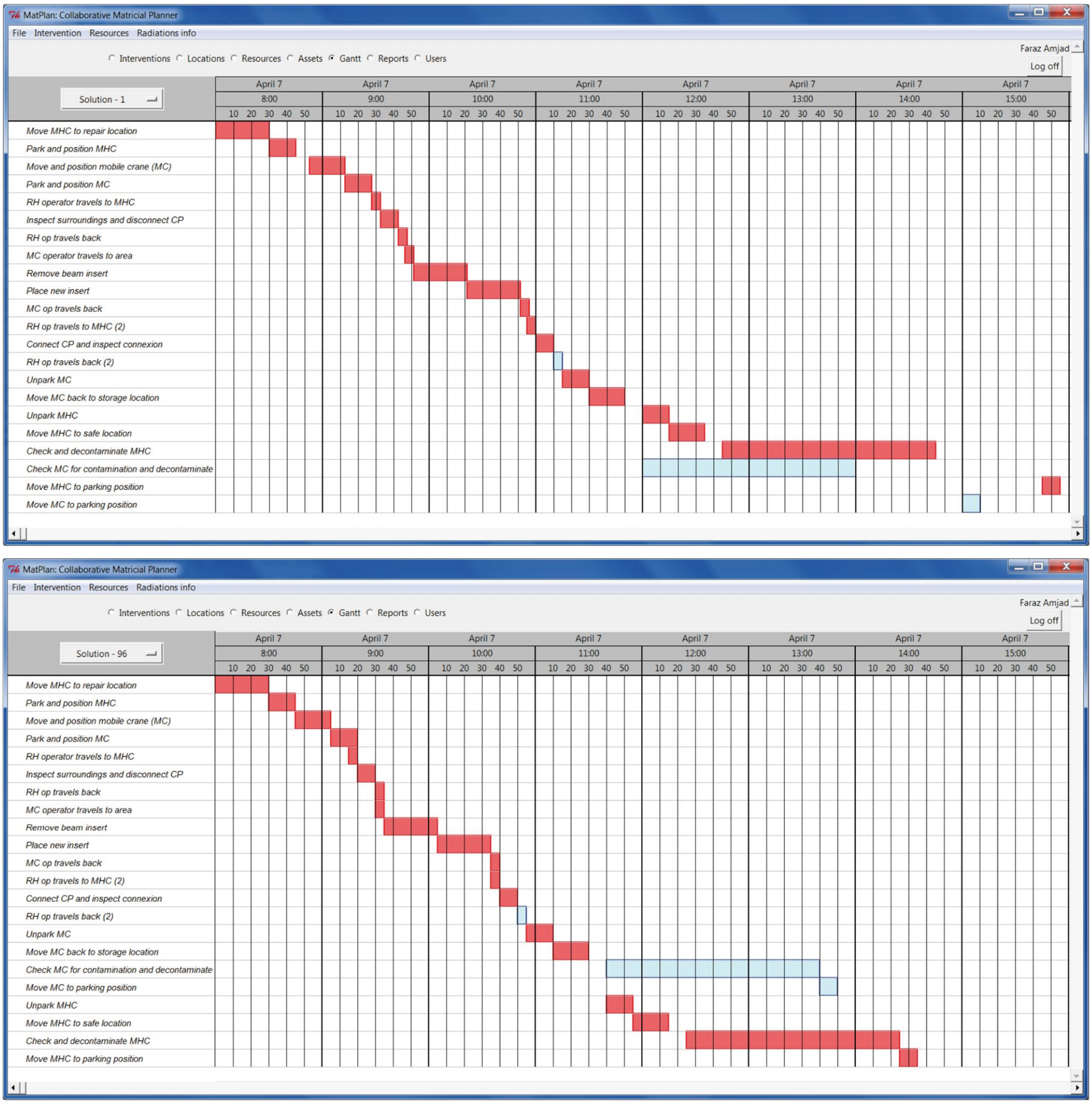


Figure 86. Screenshot of the Gantt tab in MatPlan, illustrating the two extreme solutions of the teleoperated case study.

3.5.5.1 Analysis results

The results obtained for the Super-FRS RH scenario are the very first dose estimates and duration predictions which have been calculated for any maintenance interventions within the Super-FRS. This technique will be used in the future to conduct further analyses of the RH scenario for later stages of the MTRH design. However, although not conducted for the final system design, the current extensive analysis still contains very useful information about the doses received and the planning and scheduling of the task sequence.

The analysis of the MTRH system concept design, using MatPlan, revealed that:

- Concept two, the teleoperated task sequence, had 96 individual solutions according to the set of constraints given in the matrix; however, the software optimization reduced this set to 16 possible solutions, by improving the constraints definition and by implementing new software updates. The solutions involve simulated duration ranges between 9h8min and 10h20min for the intervention, without additional maintenance steps (e.g. on-site repairs of the beamline insert itself). The Gantt charts of the two most extreme cases are displayed in Figure 86.
- By comparison, the simulations of the automated concepts (concepts one and three) result in longer interventions (8h50min to 10h45min for concept one and 8h30min to 10h25min for concept three). This is essentially due to the very slow speed of the automatic devices during the travel tasks and the lengths of the automated sequences (e.g. changing the end effector involves a wider range of subtasks than in the teleoperated case). Therefore, when no additional maintenance is performed, the teleoperated scenario was found to be quicker.
- The major downside of the teleoperated case is its high level of radiation dosages to workers. In the case of automated task sequences, no human involvement is needed to carry out the remote maintenance tasks. The beamline insert is eventually maintained once in the hotcell.

The estimated radiation doses for the Super-FRS RH task sequence (see Appendix VI) are summarized in Table 16, which shows the dose estimates for both equipment and personnel. The equipment speed was 0.1 to 0.3 Km/h and the personnel speed was 1 to 3 Km/h.

Table 16. Summary of the Super-FRS MTRH concept design results (see Appendix VI).

		Total cumulative doses (in µSv) for a single beamline insert					
		Concept one		Concept two		Concept three	
Equipment Speed	Personnel Speed	Equipment	Personnel	Equipment	Personnel	Equipment	Personnel
0,3 Km/h	3 Km/h	2926,80267	N/A	2783,086	106,8937	3212,16533	N/A
0,2 Km/h	2 Km/h	2975,79667	N/A	2843,38	107,6103	3371,07533	N/A
0,1 Km/h	1 Km/h	3123,07667	N/A	3024,66	109,7537	3655,50533	N/A

The radiation analysis revealed that:

- The human operators in concept two (i.e. the telemanipulator operator and the mobile crane operator) are subjected to doses of 107 µSv during the RH task sequence. The station for the operator is located at the end of Super-FRS service tunnel, which also provides protection from direct radiation. In this scenario, 3 km/h is considered to be the natural human velocity and traveling representing only about 5% of the intervention dosage with the remaining 95% received during static tasks. Considering that there are up to 27 beamline inserts, of which 15 may require replacement once a year, this amount could be up to 1.5 mSv per year received by personnel. The equipment would receive a total dose of 41.74629 mSv per year.
- Concepts one and three are fully automated and do not require on-site operators to operate the equipment. Concept one involves a dose to equipment of 2.93 mSv to handle one beamline insert and a total annual dose of 43.9 mSv to handle 15 beamline inserts. Similarly, Concept three

involves a dose of 3.2 mSv for one beamline insert and a total annual dose of 48.2 mSv to handle 15 beamline inserts.

The radiation analysis of the MTRH system provides an early-stage estimate of doses received by equipment and personnel. However, the estimated dose rate calculation at this stage does not take into account that:

- Beamline inserts could fail and require corrective maintenance.
- Beamline inserts can be switched to modify the installation configuration for physics experiments.

3.5.6 System reliability analysis: FMEA Analysis

Reliability is a key element of the SE development process. Various tools are used to measure the reliability of systems at different life cycle stages, such as reliability hazard analyses, failure mode and effects analyses (FMEAs), fault tree analyses (FTAs), and Reliability-Centered Maintenance.

In the case of the Super-FRS MTRH system, a detailed discussion of the concept design evaluation was conducted to select the right tool for reliability analysis. FMEA was selected to evaluate all three concept designs, due to the fact that it is a well-established, systematic method for evaluating a product or process. It identifies where and how the product might fail in order to assess the relative impacts of different failures. FMEA is often the first step of a system reliability study. The FMEA tool reviews many components, assemblies and subsystems in order to identify the critical elements prone to failure within a system. The reasons for selecting an FMEA for this study were as follows:

- Single-point failures are identified at design stage.
- FMEA provides a detailed ranking of failures based on Risk Priority Number (RPN) numbers.
- It provides a list of possible causes and effects of failure on the system.
- It is a uniform method for assessing potential failures, failure modes and effects on the system.
- The criteria for detection can also be determined at design stage.

In the case of the Super-FRS logistics, the equipment selected to perform the RH must be evaluated for reliability. In case of the Super-FRS, an FMEA is performed because:

- Identify potential failure modes for a Super-FRS concept designs.
- To assess the risk and causes associated with those failures.
- To rank the issues in terms of importance.
- Identify and carry out corrective actions to address the most serious concerns.

The FMEA for the Super-FRS was conducted in collaboration with RAMS specialists from within the PURESAFE network, to ensure that the results were accurate and credible. To conduct an effective FMEA, a cross-disciplinary team was selected to evaluate the concept designs. During this process, detailed information concerning the equipment and task sequences was explained to the FMEA analysis team. In the next step, a periodic identification was performed of the Super-FRS RH task functions, failures, effects, causes, controls and possible recommended actions. Values were assigned to each item to calculate the RPN number for the FMEA analysis. These values were: FMEA Severity (Se), Occurrence (Oi) and Detection (Di). Each value was ranked between 1-10, with 1 representing lesser and 10 representing greater risk. Table 17 presents a short summary of the FMEA analysis.

Table 17. Potential failure causes for the Super-FRS MTRH system obtained from the FMEA, including high-risk failure causes (Si=9-10 and Oi=10), medium-risk failure causes (Si=4-8 and Oi=7-9), and low-risk failure causes (Si=1-5 and Oi=1-7)

	Concept		
	1	2	3
Causes (severity level)			
High level (Critical/system down)	32	35	33
Medium level (Significant impact)	31	43	30
Low level (Normal/minor impact)	50	42	50
Total	113	120	113

The FMEA is based on six high-level tasks which were common to all three concepts (Table 18).

Table 18. MTRH system high-level task sequence breakdown for the FMEA tradeoff analysis.

Function ID	Function
1	Removal and installation of a beamline insert at the focal plane of the pre-separator in the main tunnel
2	Remote inspection of the Super FRS pre-separator area.
3	Transportation of the activated beamline inserts from the focal plane to the hotcell.
4	Remote maintenance (minor, major or disposal) of beamline inserts within the hotcell (minor includes cleaning and inspection, major includes replacement of damaged components, and disposal includes removal of damaged or radioactive components to long-term storage).
5	Ensuring a safe operating environment in the main tunnel.
6	Ensuring a safe operating environment in the hotcell.

3.5.6.1 Discussion of FMEA results for each MTRH concept

Each MTRH concept consists of six main functions of the RH equipment. The results of the FMEA analysis for each concept are summarized in Table 17 and discussed in this section.

Analysis of concept one revealed 24 failure types with 113 causes, totaling 33 different effects of failure. Table 17 shows the severity levels of the causes of failure. , with 32 high-risk, 31 medium-risk, and 50 low-risk causes that could jeopardize the RH task sequences and equipment. To reduce the risks associated with concept one, the FMEA analysis also lists 207 actions and 274 controls.

Analysis of concept two revealed 24 failure types with 120 causes, totaling 33 different effects of failure. Table 17 shows the severity levels of the causes of failure, with 35 high-risk, 43 medium-risk, and 42 low-risk causes that could jeopardize the RH task sequences and equipment for concept two. To reduce the risks associated with concept two, the FMEA analysis also lists 233 actions and 290 controls.

Analysis of concept three revealed 23 failure types with 113 causes, totaling 32 different effects of failure. Table 17 shows the severity levels of the causes of failure, with 33 high-risk, 30 medium-risk, and 50 low-risk causes that could jeopardize the RH task sequences and equipment for concept two. To reduce the risks associated with concept three, the FMEA analysis also lists 214 actions and 278 controls.

Based on the FMEA tradeoff analysis, concept two has the most failure causes at the highest severity level, while concept one has fewest failure causes at the highest severity level. Based on the FMEA analysis at this stage, we can conclude that concept one will have better reliability than the other two concepts; however, the critical causes serving as bases for failure must be eliminated through proper action and control to improve system availability.

3.6 MTRH system tradeoff analysis results

The MTRH tradeoff analysis was carried out in order to determine the effects of the key factors (listed in Table 9) on the concept designs and, thus, to select the design which best fulfills the RH needs of the Super-FRS. Based on expert opinions (Table 9), the tradeoff analysis (Table 10) is assigned relevant weighting factors (Table 19). The weighting factor for each tradeoff analysis was based on the values assigned to various factors from the results of a survey of RH experts. The value of each weighting factor has creditability because the experts were consulted before the tradeoff analysis was devised; hence, prejudice was reduced.

Table 19. Super-FRS tradeoff analysis, weighted and scored based on an expert criteria evaluation review (see Section 3.4.1).

S.No	Analysis	Weighting factor
1	Cost analysis	16.25
2	Requirements analysis and functional analysis	29.95
3	Radiation dose analysis and task sequence optimization	42.7
4	Reliability analysis	35.05

The tradeoff analyses carried out for the MTRH system concepts were ranked and listed according to the findings in Table 20.

Table 20. MTRH system concepts tradeoff analysis results: The results indicate that concept one scores maximum points based on our analysis and after including the weighing factors. Thus, concept analysis indicates that concept one is a favorable option.

			Un-weighted score from the tradeoff analysis			Weighted score from the tradeoff analysis		
S.No.	Analysis	Weighting factor	Concept one	Concept two	Concept three	Concept one	Concept two	Concept three
1	Cost analysis	16.25	3	2	1	48.75	32.5	16.25
2	Requirements analysis and functional analysis	29.95	5	2	4	149.75	59.9	119.8
3	Radiation dose analysis and task sequence optimization	42.7	5	2	5	213.5	85.4	213.5
4	Reliability analysis	35.05	3	1	3	105.15	35.05	105.15
	Total score		16	7	13	517.15	212.85	454.7

Table 20 shows both the weighted and un-weighted scores, which both indicate that concept one is the most suitable choice for the MTRH system. The results suggest that concept one is collectively a better design, capable of fulfilling the RH needs of the Super-FRS main tunnel. Concept one is also the most cost-effective compared to the other two designs and performs similar functions with fewer components. However, it still does not fulfill 100% of the needs and, hence, certain design modifications are required.

3.6.1 Discussion and analysis

This section presents detailed discussion concerning the results of this research that address the development and tradeoff analysis of the concept design requirements for the MTRH system using the SE approach for RH systems at HEP facilities,. In contrast to earlier HEP facility designs, these new facilities need to be designed and built with RH capabilities. The Super-FRS requirements clearly indicate various hotspots (activate components along beamline) that will require remote maintenance and analysis of the main tunnel indicates that RH activities will consist of two primary actions:

- Transportation manipulation.
- Dexterity manipulation.

The beamline inserts in the Super-FRS main tunnel will require separate transportation, storage and dexterity manipulations. Once removed from the vacuum chamber, each beamline insert will need to be transported to the hotcell for storage, repair or disposal. Replacing the beamline insert will require dexterous manipulation prior to transport manipulation. It will also require a separate hotcell for complex dexterity manipulation using Master Slave Manipulators and power manipulators.

Based on the system requirements analysis and State of the Art studies, the remote maintenance for activated parts can be divided into two categories: scheduled and unscheduled. Each of the aforementioned categories can be further subdivided into two sections: long-term maintenance (LTM) and short-term maintenance (STM), depending on time and resource constraints.

Based on the State of the Art survey and analysis of the effects of radiation on the Super-FRS equipment, the radiation sensitivities of electronic components were found to depend on multiple factors, including dose rates, time of exposure, biasing conditions (during and after radiation) and temperature[47]. RH tasks are carried out once the beam is shut down and after a cool-down period. The residual dose at this stage is only caused by the activated parts; hence, it is much lower than that when the beam is operational. In the case of the Super-FRS, the ratio between the prompt dose and the dose by activation after years of full usage lies between the factors of 10^5 and 10^6, depending on the cool-down time.

Dose rates can be predicted; however, it is hard to predict the exact lifetimes of electronic devices in different radiation environments due to the complexity of the devices and, to some extent, the differences among operating scenarios. In later stages of development, radiation hardness assurance accelerated testing would performed on electronics in a simulated environment, using the test procedures documented in MIL-STD-883 C, Method 1019.4 in the USA [131] and ESA/SCC basic specification no. 22900, Draft C in Europe [132]. Radiation hardness assurance testing is conducted to carry out failure detection and to improve reliability, while enable designers for redundancy with in the design in case of failure. The RH system profoundly depends on electronic circuitry and visual monitoring that will be exposed to radiation caused by activated parts. In order to prevent the RH equipment electronics from failing, it is important to: (1) use radiation-hardened electronics, (2) minimize the number of electronics directly exposed to radiation and (3) protect electronics from radiation if they are on-board the equipment during the maintenance process.

In the existing FRS target area, the permanently installed cameras are not radiation-hardened. As a result of being exposed to a strong neutron flux when the beam was operational, the camera system (both CCD and control unit) was completely damaged within a period of about six months. This system then required replacement. The controller box for the existing KUKA robot in the same target area is not installed on the robot, but behind concrete shielding. Even so, the actuators on the joints may be affected by particularly high doses of radiation. Most industrial robot manufacturers, such as KUKA and FANUC, do not provide warranties for robotic equipment or electronics used in ionizing radiation environments. As a safe limit, even for very sensitive semiconductor parts, the data indicate that doses of up to 1Gy can be received without failure [132].

Due to the complex nature of the Super-FRS equipment and the needs mentioned above, it is important to adopt a SE approach that can provide a concept design capable of resolving the RH issues inherent to the Super-FRS tunnel. In order to accomplish this, a SE approach was formulated following a study of State of the Art SE practices for the development of RH equipment in HEP facilities and research facilities. To make the SE approach reliable, it was important to include feedback from RH experts across the globe. These RH experts were contacted directly and surveyed as part of a tradeoff analysis to decide between the various concept solutions.

Based on this SE approach requirements and needs were first identified and documented in the form of system requirements documents. This provided a firm technical grounding to explore various solutions for the Super-FRS MTRH system. The critical role of requirements development is to identify the interfaces between the MTRH system and the Super-FRS environment. It also identifies the tasks required to be performed, the RAMS requirements and other non-functional requirements critical for development. Requirements development is considered to be one of the cornerstones of SE. In the case of the Super-FRS, a simple MS Office template was used to document the requirements; however more sophisticated software, such as IBM DOORS or polarion, can be used to effectively collect, edit and track requirements. Once the requirements—both functional and non-functional—were established, the next step was to develop concept designs to fulfill the Super-FRS's MTRH system needs. The three concept designs developed for the Super-FRS MTRH system were based on the TPMs established for the Super-FRS during the requirements phase, as well as on the knowledge drawn from the equipment classification in the RH survey (see chapter 0, section 2.3). The three concepts developed were based on COTS equipment already used in the industry and in various other facilities, with the goal of minimizing development costs. The developed concepts identified and addressed key issues that were missing from the existing RH planning in the Super-FRS. These issues were:

- RH equipment must be mobile, so that it is able to move through the tunnel during the maintenance period. This is due to the fact that there are multiple focal points and hotspots which each have beamline inserts that will require RH. In the RH solutions suggested before this research began, the RH stations had been either fixed or installed on rails that would have created obstructions within the main tunnel region during the retrieval of beamline inserts. In the event of magnet failure, the whole RH setup of the rails and the robots would have needed to be dismantled in order to conduct repair or replacement.
- The equipment parked within tunnel during beam operation is subjected to higher doses of radiation that may cause damage to the RH equipment.
- Interfaces: The beamline insert and vacuum chamber will be designed by multiple organizations from among the FAIR partner countries. Hence, there is a need for a common interface for RH. The beamline designs require remote maintenance; thus, it is important to design the equipment to include RH and interface points in order to optimize the RH and maintenance task sequences.
- The reduction, replacement, relocation and protection of onboard electronics are a priority. They reduce the risk of failure of the RH equipment due to failures of the electronics systems caused by radiation. The RH equipment must also be provided with contamination protection. Modification of the COTS equipment for the MTRH system is needed in order to use this equipment in the Super-FRS environment.
- The infrastructure lacks a facility to store activated beamline inserts.
- Failures regarding the installation of an overhead crane across the Super-FRS in the initial facility design represent a major drawback for the RH system infrastructure, since:
    - It is very costly to add a crane system at this stage.
    - This severely hinders the recoverability of major RH systems during failures.
    - This hinders the deployment of redundant systems to tackle RH system failures.
    - This reduces the load capacity for RH task sequences.
- The choice to use an industrial six-axis manipulator is limited to the KUKA Titan at this stage because the required payload is above 500 Kg and the dimensions of the tunnel are very limited and narrow.
- Transferring the activated beamline inserts across the tunnel and to the hotcell was not considered in earlier designs. A transfer shielding box on a mobile platform is, thus, required in order to successfully carry out RH task sequences.
- Master slave manipulation was not considered during the initial system designs.
- Task sequences for on-site remote maintenance were not defined. The post-processing and retrieval of beamline inserts were also not developed. In the case of on-site maintenance, the Super-FRS would require RH solutions involving temporary storage and repair locations (other than the main hotcell facility) that also provide master slave manipulation and storage.

The three suggested concept designs were all more detailed than earlier considered designs. However, the aim is to identify the most suitable design for the Super-FRS. This was achieved by conducting a tradeoff analysis of the three concepts in order to select one design for further development. The tradeoff analysis for the MTRH concept designs was divided into four major parts based on RH expert input and design needs and practices (see section 3.4.5 for detailed individual analyses). These four parts were:

- Cost analysis
- Requirements analysis and functional analysis
- Radiation dose analysis and task sequence optimization
- Reliability analysis

The overall results of the tradeoff analysis indicated that concept one was the best solution of the three. This is due the fact that this solution performs the current RH tasks with:

- Fewer required subsystems to carry out the RH task sequences within the Super-FRS tunnel.
- Lower equipment costs and infrastructure change costs than the other concept designs, which also require higher degrees of customization.
- Experienced and skilled GSI RH experts capable of using the KUKA robots for remote maintenance. These means that no further trainings are needed to develop the workforce, as existing workforce has these skills.
- A higher RAMS rating, due the fact that the KUKA titan is an industrial robot with a higher degree of reliability, known maintainability procedures and practices to ensure the availability of the system for remote maintenance task sequences.
- Fewer modifications to the COTS equipment and the Super-FRS infrastructure to ensure operational status in the FAIR Super-FRS environment.

Despite being the most suitable option, concept one still has some major drawbacks, which must be addressed during the architecture design phase, the procurement phase and the prototype testing phase:

- There is very little room for onsite maintenance in this concept and the scope of remote operations is limited. Concept one can only be used for pick-and-place maintenance in the tunnel (i.e. the removal and installation of the beamline insert).
- The system is not flexible to future changes. For example, the RH system will not be able to accommodate changes to the experimental setup of the Super-FRS, such as changes to the design of the vacuum chamber.
- The system does not fulfil 100% of the requirements and system redundancy requires major modifications.
- Maintenance of the industrial robotics after 30 years is not supported by equipment supplier (i.e. KUKA) according to law.
- The system has no master slave control during the remote manipulation of the beamline insert i.e. lack of man in the loop or manual manipulation.

The use of the proposed SE approach enabled engineers to identify key problems with initial concept designs, which had only been designed based on previous experience from engineers in GSI. Although this research only demonstrated part of the application of the SE approach, the implementation of the entire SE approach may enable the Super-FRS team to develop MTRH maintenance systems and logistics concepts which satisfy the complete set of requirements, TPMs, and technical backgrounds sampled in the equipment classifications during the State of the Art survey. The three concept designs and the selection of the optimum solution take into consideration the functional needs, RAMS issues and cost concerns by utilizing existing and conceptual State of the Art engineering designs for the MTRH system. With the help of a tradeoff analysis, the SE approach ultimately selected a concept design that can be further developed into a system that will be used at the Super-FRS facility.

3.7 Summary

This chapter has presented SE approach for developing RH solutions for HEP facilities. It has focused mainly on the development of the Super-FRS MTRH system for the FAIR facility, which served as a case-study for the proposed SE approach. It presented the Super-FRS RH environment within the tunnel, evaluated the beam losses across the Super-FRS and identified the critical locations requiring remote maintenance. Following the steps put forward by the SE approach, this chapter presented a brief overview of the requirements development process, which was carried out in a detailed manner and used to identify the key system functions, the TPMs (environmental and technical parameters) and the non-functional requirements. An analysis of the existing concept solutions at GSI was also presented and the technological classification of the RH equipment, presented in the previous chapter, was used to develop RH design concepts for the MTRH system based on COTS equipment. The possible advantages and disadvantages of each concept design for the MTRH system were presented, followed by a detailed tradeoff analysis. This analysis included a requirements analysis, a functional analysis, a radiation dose calculation analysis, an FMEA, a cost estimation analysis and a task sequence optimization analysis. The result of this process was the identification of an optimal design for an RH system which suits the needs of the Super-FRS.

4 Conclusion and Future Work

4.1 Conclusion

This thesis has presented a detailed SE approach for the development and evaluation of RH systems for maintenance of HEP facilities. Specifically, it has focused on particle accelerator facilities such as Super-FRS at FAIR in Germany. This approach has been generalized and can be applied to development of other RH systems in different facilities.

This work has made three key contributions to the knowledge. These three contributions are interdependent and related. Its first contribution was a detailed and comprehensive survey of State of the Art equipment, technologies and techniques used for RH at HEP and nuclear facilities across the globe. The first contribution, the survey of existing RH systems, was essential to fully comprehend the State of the Art RH equipment and diverse environments in both HEP facilities and nuclear reprocessing plants. The goal of this survey was to classify the equipment used for remote maintenance, categorize the various intervention scenarios, and determine the generalized needs for remote maintenance within HEP facilities. RH equipment and tools were listed and divided into categories, as were the existing approaches and techniques that are used to develop and evaluate concept designs for RH systems. Tasks such as this are not often covered or explained in a systematic way in the existing literature for HEP facilities. The first contribution provided additional information concerning HEP facilities RH system design practices and toll used during the design processes. The categorization and classification of HEP facilities in details enables design engineers to select right equipment for RH system designs to fulfill the RH requirements. The second contribution of the work was the proposal of a SE approach for the development of RH system concepts in HEP facilities. This contribution directly addresses the pressing issue of nonexistent SE approaches in these facilities and a lack of adoption of SE practices which exist for the development of complex equipment in other fields (e.g. those used by NASA, ESA and INCOSE).

The knowledge gained from the first contribution was then used as a basis for the proposed SE approach, which was the second contribution. The proposed SE approach is divided into seven major processes however the scope of thesis was limited to first four process implementation. The SE approach was to deliver a simplified SE approach that was compatible to HEP facilities designing resources. The SE approach attempted to integrate SE knowledge with RH expert's opinion to improve the RH system integration into the facility life cycle designing process. The final contribution, the development and evaluation of Super-FRS MTRH concept designs, was a practical demonstration of the proposed SE approach. Finally, several concept designs for the Super-FRS MTRH system were developed and evaluated as a case study for the proposed SE approach. As such, it validates the theory of the approach, while also acting as a worked example for any engineers wishing to apply it in future. The problems pointed out during the State of the Art studies such as the storage of activated parts and transportation and compatibility of HEP facilities equipment for remote handling were some of key major issues resolved during the Super-FRS case study by applying SE approach. Various facilities are currently facing unplanned upgrades with critical shortfalls in remote maintenance. However, with application of SE approach on the Super-FRS case study a detailed overview of RH environment was provided by calculating beam losses across the fragment separator to identify critical remote maintenance locations, and delivered a RH system designs that fulfills the RH needs (Section 3.6.1 provides a detailed results and analysis of SE approach implementation on Super-FRS remote maintenance).

Chapter two presented the results of an in-depth survey. This was necessary to gain a realistic insight into how RH systems are used, in what environments they are used, and with which technologies. The survey was divided into three main parts: i) State of the Art RH survey of HEP facilities; ii) State of the Art RH robotic equipment survey; and iii) Classification of the RH equipment for remote maintenance tasks. The first part of the survey specifically focused on HEP facilities. It was found that each and every existing facility had evolved over the course of past 60 years. Correspondingly, the RH systems in these facilities have also developed over the course of this time period and, therefore, development has been carried out without using any sort of standardized process. Despite this, the survey revealed some very interesting similarities in the conditions, systems and practices used for RH maintenance. The information gathered in the survey was formulated into a classification of HEP facilities based on the different RH environments. The four types of classification lay down a generalized basis for any RH environment and show what type of RH systems have been used for remote maintenance in those environments. A classification of RH equipment was also performed, with the aim of assisting RH design engineers to select which equipment can be used to fulfill the RH needs and requirements for their specific environment. As well as design engineers, this contribution can also be used by the planners of HEP facilities as a guideline to allow them to make provisions for RH systems even if it will not be designed along with the facility, but rather will be gradually introduced into the project as the facility develops.

Chapter three presented two contributions: the proposed SE approach and a worked example. Contribution two of this thesis focused on providing a simplified SE approach for developing the RH systems and logistics concepts for HEP facilities. This was necessary as the survey found that SE approaches in these facilities were nonexistent for the development of RH systems. The proposed approach is based on State of the Art SE knowledge but tailored to the specific needs of HEP facilities. It stipulates the milestones and target documentation required to record the knowledge which is developed during the process of RH concept design. The proposed SE approach is focused on three aspects:

i) Utilizing the knowledge available regarding the RH solutions at various facilities;

ii) Optimizing the resources and time allocation during concept development; and

iii) Documenting the knowledge at every stage of the process to ensure a concept design that is useable and fulfills the RH needs.

Chapter three also presented the third contribution of this thesis, which was the application of the SE approach to the development of concept designs of the Super-FRS MTRH system. Certain parts of the SE approach were elaborated on in further detail, using knowledge from the fields of requirements management, interface management, functional analysis, radiation protection, radiation analysis, and concept design engineering. Through this process, the MTRH system concept designs were developed and evaluated for the Super-FRS facility. This part of the research work also focused on developing a tradeoff analysis for three concept designs, in order to attain a single design that was reliable, acceptable (based on expert criteria), and fulfilled the basic needs and requirements. The SE approach was shown to be successful as the development and tradeoff analysis enabled the designers to explore new avenues and evaluate a variety of solutions to carry out maintenance. This included modular thinking into the MTRH designs and which beamline equipment required remote handling. The development addressed the issues of activated beamline storage transportation, onsite storage, onsite and hotcell maintenance issues, RAMS, initial cost estimation, automated and teleoperated equipment, and the flexibility of the MTRH system over the course of facility lifecycle. This contribution also demonstrated the use of various State of the Art tools that had previously either only been used individually or had never been used collectively in concept development, planning and evaluation of RH systems for HEP facilities.

The research work presented in this thesis paves the way for the future development of generalizable practices to develop concept designs of RH systems for HEP facilities. This research lays down the groundwork for developing RH systems in a systematic manner, utilizing SE knowledge and State of the Art advances in RH system technology from across the globe. It also provides a guideline example of how to document the knowledge created during the concept development process and uses tools that can provide better results to estimate possible doses. It shows the value of including expert opinion in designing the tradeoff analysis to ensure the selection of an optimal design.

4.1 Future work

This research project pushes for the adoption of systematic approaches to the development of RH systems for hazardous environments, such as those created due the increase in beam intensities at HEP facilities. The research has provided a comprehensive outlook regarding the technologies and equipment currently in use within HEP facilities and has fused this with system engineering knowledge to streamline the development of RH system concepts. The continuing growth in the construction of HEP facilities and the increase of beam intensities will result in a growing need to adopt generalizable approaches, such as the one presented in this thesis. It ensures that the developed solutions fulfill the RH needs of the facility, while maximizing the use of the available State of the Art technology. During the development of this thesis, close collaborations were carried out with RH engineers and researchers, and future prospects for the research have been identified. Some of the key fields for future research are listed below.

Extension of the SE approach for developing RH architectures for HEP facilities. For example, in particular, further improving the SE approach to allow optimization of the development resources, cost and time. Also, further integration of project management, SE, and design engineering practices is required to develop a comprehensive, unified framework for RH development within HEP facilities.

Further integration of radiological protection scenarios into the design process of RH systems and facility concepts. For example, currently, various software tools (FLUKA, IV planner, MatPlanner) are used individually to assess the situation for the radiation protection and intervention. The development of software with integrated features to analyze the pre and post interventions, besides the radiation protection, is one promising direction for research.

Some of the key technical issues of the RH equipment itself require further research. For example, these include aspects such as: master slave control across longer distances, accuracy and repeatability of RH tasks and optimization of energy consumption across long distance.

Also, further efforts and studies should be made to implement the proposed SE approach in the development of concept designs for RH systems in future facilities. Examples of such facilities include ESS, SPIRAL 2 and International Linear Collider projects (ILC). In this way, the proposed approach can be improved as well as becoming a standard approach for the development of RH concept designs within HEP facilities.

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Appendix I: Super-FRS Tunnel Layout

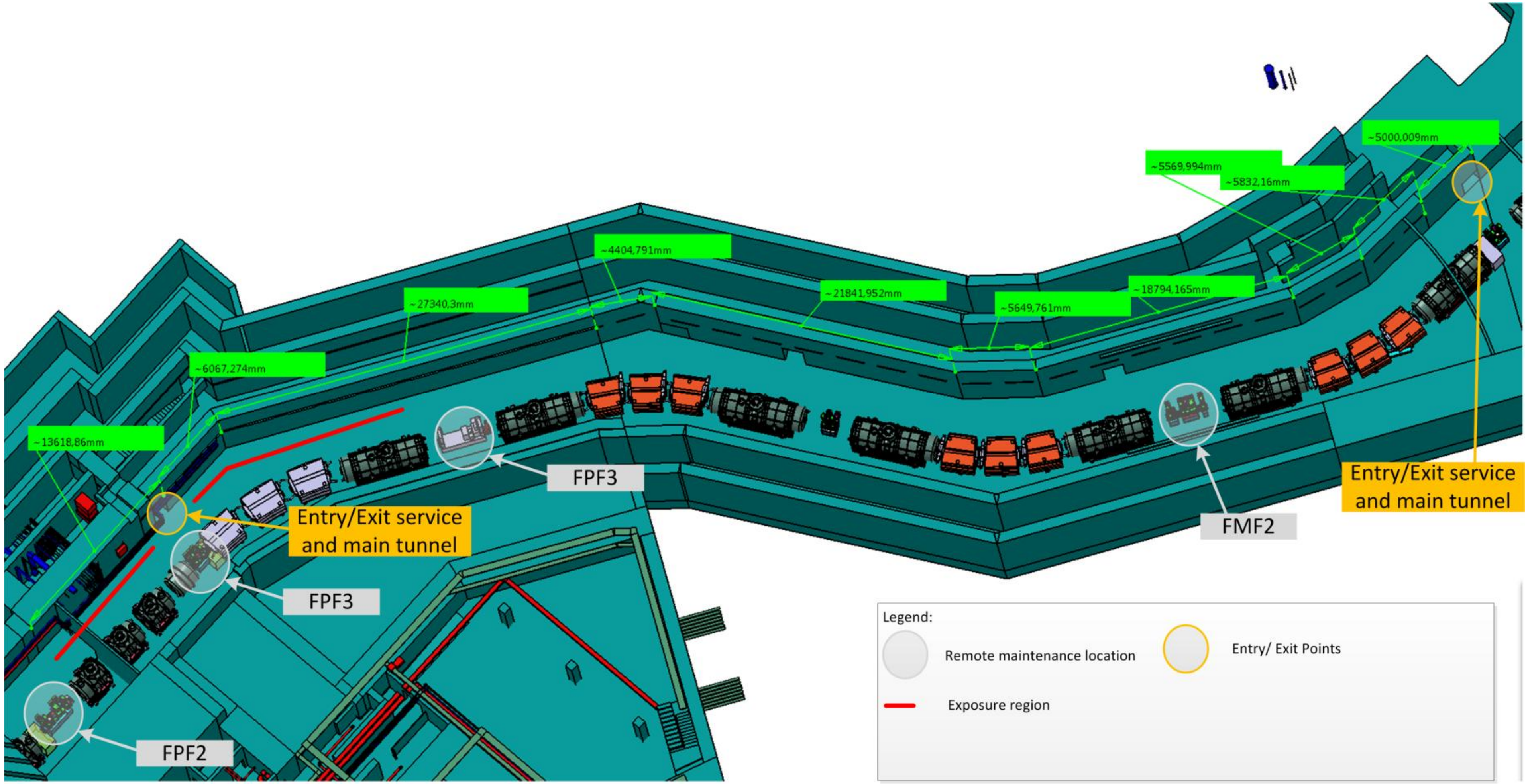


Figure 87. Distances along the Super-FRS main tunnel and regions of potential exposure during remote maintenance for equipment and radiation workers.

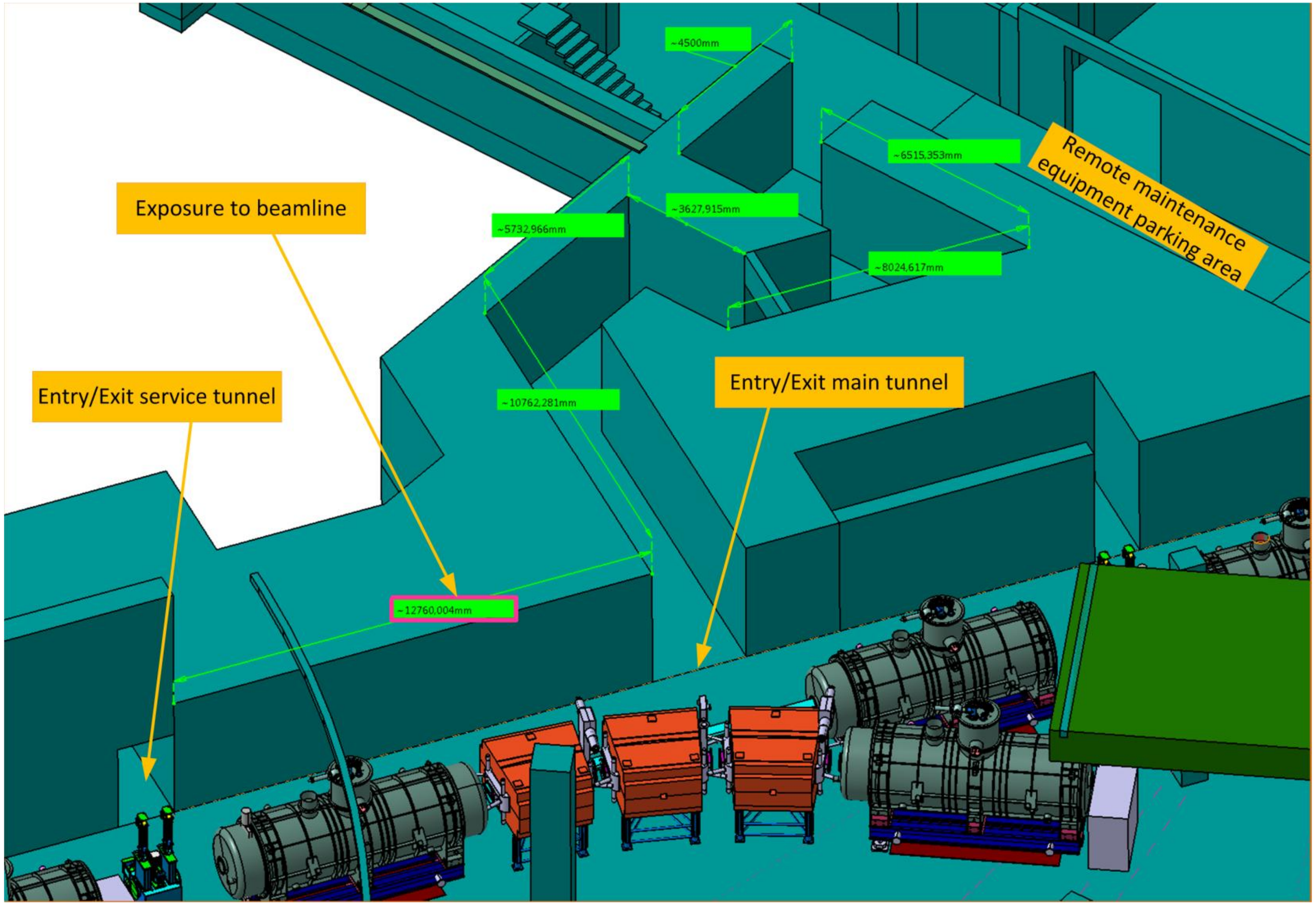


Figure 88. Super-FRS main tunnel entrance for RH equipment and humans.

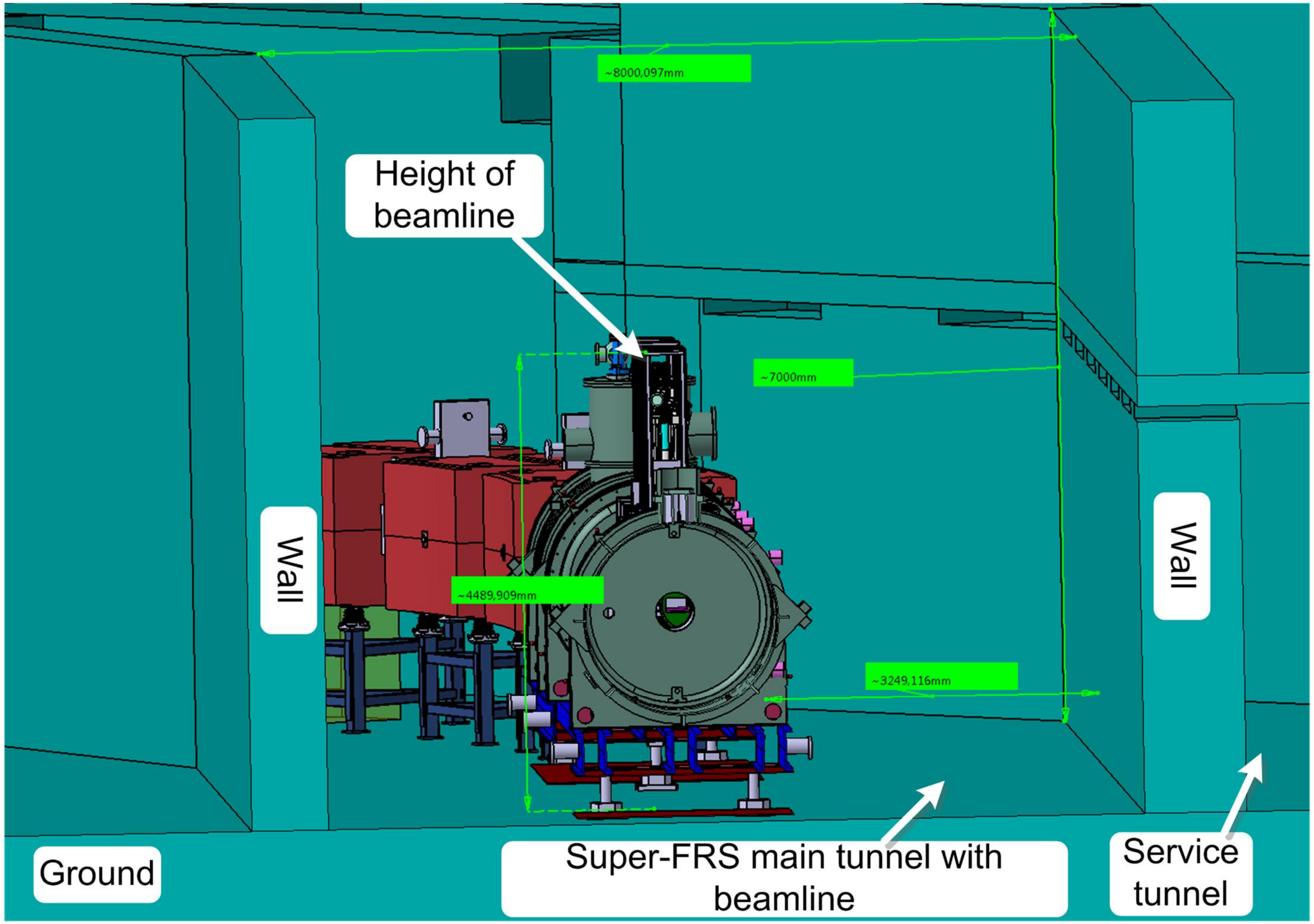
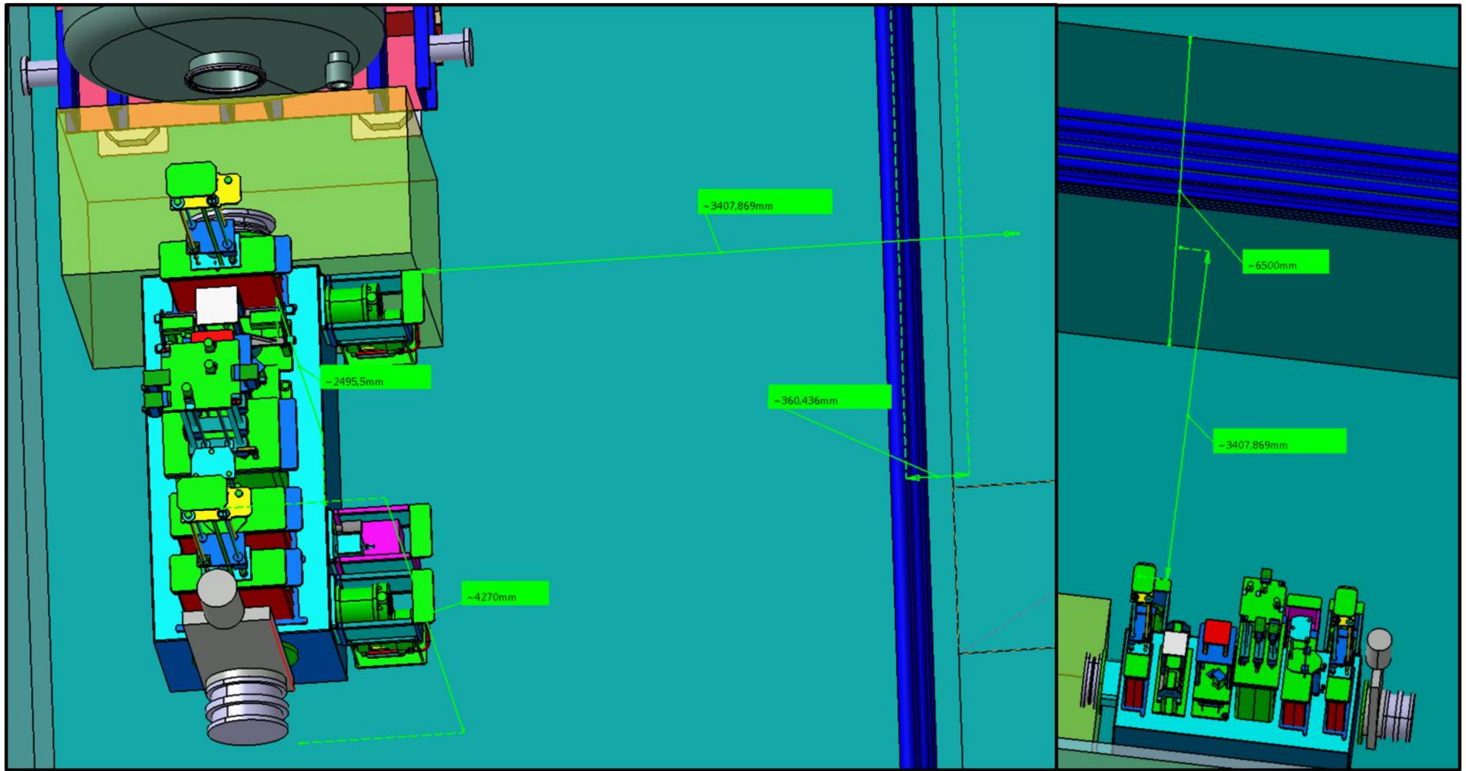


Figure 89. Cross section of the Super-FRS main tunnel, the working environment for the MTRH system.



FPF2 Mobile Equipment parking	
Description	Dimensions mm
Horizontal parking / Space (beamline to wall)	3047
Height of the box from the beamline	2138 (CAD)
Possible Handling point for beamline inserts (below)	2495 (CAD)

FPF 2 remote Handling equipment parking space analysis

Figure 90. RH equipment parking space analysis

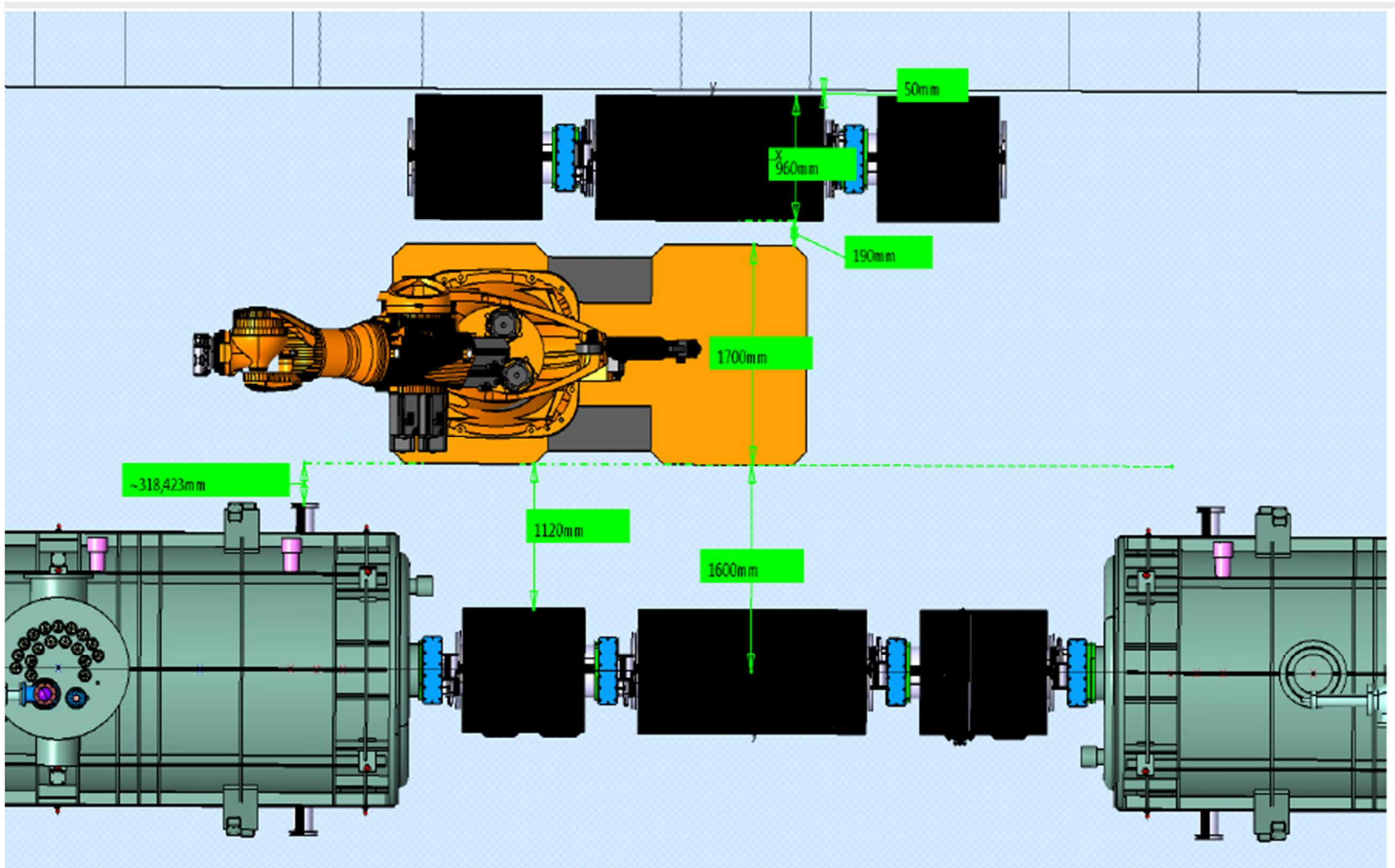


Figure 91. Parking space analysis at FMF2.

Appendix II: MTRH System for RH in the Super-FRS Main Tunnel: System Requirements Document (SRD)

PURESAFE	GSI/FAIR	2012 – 2013 PURESAFE project RH requirements	Systems Requirement Document Page: 1 / 65

Systems Requirement Document (SRD)

Super-FRS Main Tunnel Remote Handling (MTRH) System

	File name: Super_FRS_main_tunnel_RHsystem_Requirements_Document	**Date:** 14 Dec 2013
	Name	**Affiliation**
Authors	Faraz Amjad,	GSI
Reviewers	Helmut Weick, Christian Schlör	GSI
Approver		

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Appendix III: Super-FRS vacuum chambers

Suggested diagnostic chambers for the Super-FRS

		Name	Total space , mm	Dimensions Z*X(b)*Y(h), mm	Same design	Elements listed in the order following ion beam
U	1	TFF1	1547	1154***660***1130	IV	PS, T18, FF1(F2,X/Y,BIF,F2), T18, PS
U	2	PF2	4485	3352*970*1280		T23,VB,PF2(F3,BS,SXY,XS,SC,DD,DWP,Res,SXY,F3),VB,T1
U	3	PF3	1784	990*720*1130	XXX	B, PF3(F2,YS,SXY,F2), T20, VB
U	4	PF4	5170	3552*970*1130		T23,VB, PF4(F3,XY,PDC,Res,YS,TA,XS,TOF,XY,F3),VB, T23,T4
U	5	MF1	3332	2670*970*1130	X	B, MF1(F2,XY,XS,SC,XY,MUS,F2), T5, B, VA
U	6	MF3	3332	2670*970*1130	X	B, MF3(F2,XY,XS,SC,XY,BS,F2), T5, B, VA
U	7	MF2a	5170	1190*970*1130		VA,B, MF2a(F2,XY,XS,F2),
U	8	MF2b	--	1950*720*1280		B, MF2b(F3,YS,DD,DWP,FI,F2),
U	9	MF2c	--	1154*660*1130	IV	B, MF2c(F2,TOF,XY,F2), B,VA
U	10	HF1a	17660	1686*720*1130		VA,B, HF1a(F2,XY,BS,YS,F2),VB, T12,
U	11	HF1b	--	2110*970*1130		VB, HF1b(F2,MUS,TOF,XS,XY,F2), B, T13, B,VA
U	12	LF1	3332	990*720*1130	XXX	VA, B, T3, B, LF1(F2,SXY,BS,F2), B, VA
U	13	LF2	3344	2670*970*1130		VA,B,LF2(F2,XY,MUS,XY,XS,TOF,F2),B,VA,T6,T19,B,VA
U	14	LF3	6910	1750*970*1130	XX	VB, T10, LF3(F2,XY,Res1,XY,F2), T11, VB
U	15	LF4	??	1750*970*1130	XX	B, T14, LF4(F2,XY,Res1,XY,F2), T15, VB
U	16	LF5a	??	1750*970*1130	XX	B, T16, LF5(F2,XY,Res1,XY,F2), T17, VB
U	17	LF5b	??	1750*970*1130	XX	B, T16, LF5(F2,XY,Res1,XY,F2), T17, VB
U	18	RF1	5172	1190*970*1130		VA, B, T8, B, RF1(F2,XY,BS,F2),B,VA
U	19	RF2	3353	1750*970*1130	XX	B, RF2(F2,XY,XS,XY,F2), T9, B,VA
U	20	RF3	3330	2666*970*1130		B, RF3(F2,SXY,YS,MUS,XS,SXY,TOF,F2),T7,B,VA

B – Bellow DN400 & 2 CF-Flange, d_z=183 mm;
BS – Beam Stop plug, d_z=460. mm;
DD – degrader disc, d_z=410. mm;
DWP – degrader Wedge&Plate, d_z=510. mm;
MUS – energy loss detector, d_z=550. mm;
PDC – detector, d_z=410. mm;
FI – finger degrader, d_z=270. mm;
Res – reserved section, d_z=350. mm;
SC – Scintillator detector, d_z=410. mm;

BIF – Beam induced fluorescence detector, d_z=310 mm;
F1 – flange FLAT + tube DN400, d_z=205. mm;
F2 – Conflat Flange CF-F + tube DN400, d_z=107 mm;
F3 – flange FLAT + tube DN400, d_z=50. mm;
F4 – flange FLAT + tube DN400, d_z=300. mm;
F5 – flange FLAT + tube DN400, d_z=163. mm;
F3CF – CF-F + tube DN400, d_z=50. mm;
PS – pillow seal DN400, , d_z=360. mm;
Res1 – reserved section, d_z=460. mm;

SXY – position-detector ladder with short GEM TPC, d_z=310. mm;
T1 – DN400 tube, d_z=500 mm, with CF and CF flanges;
T2 – DN400 tube, d_z=114 mm, with FLAT and CF flanges;
T3 – DN400 tube, d_z=1826. mm, with CF and CF;
T4 – DN400 tube, d_z=705. mm, with CF-F and CF-F;
T5 – DN400 tube, d_z=146. mm, with CF-F and CF-F;
T6 – DN400 tube, d_z=348. mm, with CF-F and CF-F;
T7 – DN400 tube, d_z=150. mm, with CF-F and CF-F;
T8 – DN400 tube, d_z=3400. mm, with CF-F and CF-F;
T9 – DN400 tube, d_z=1320 mm, with CF-F and CF-F;
T10 – DN400 tube, d_z=2405 mm, with CF-F and FLAT;
T11 – DN400 tube, d_z=2355. mm, with CF-F and FLAT;
T12 – DN400 tube, d_z=3748 mm, with FLAT and FLAT;
T13 – DN400 tube, d_z=9496. mm, with FLAT and CF-F;
T14 – DN400 tube, d_z=??? mm, with FLAT and CF-F;
T15 – DN400 tube, d_z=???. mm, with FLAT and CF-F;
T16 – DN400 tube, d_z=???. mm, with FLAT and CF-F;
T17 – DN400 tube, d_z=???. mm, with FLAT and CF-F;
T18 – DN400 tube, d_z=???. mm, with FLAT and CF-F;

Figure 92. List of Super-FRS diagnostics vacuum chambers and beam line inserts

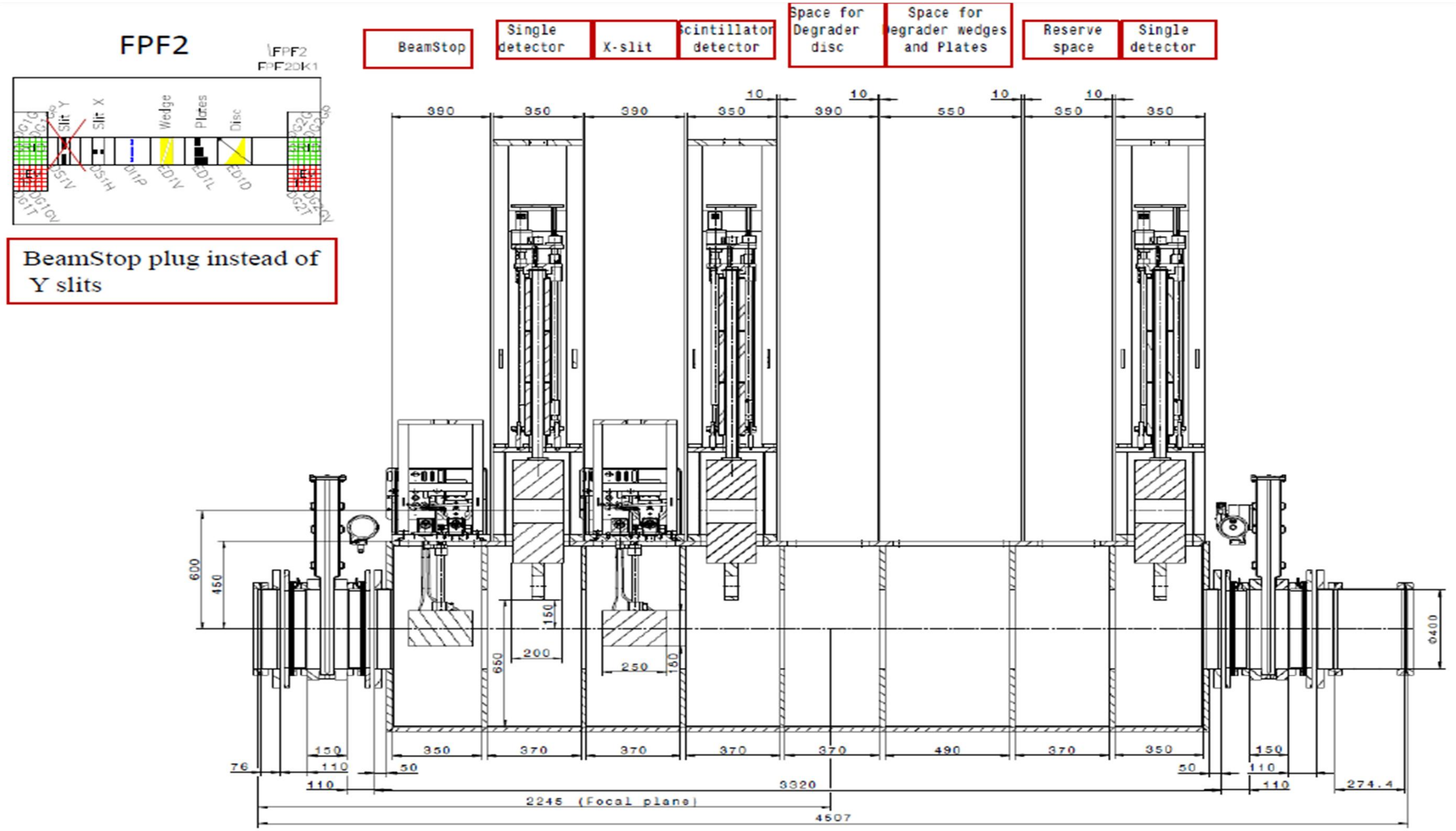

Figure 93. FPF2 vacuum chamber layout and beam inserts.

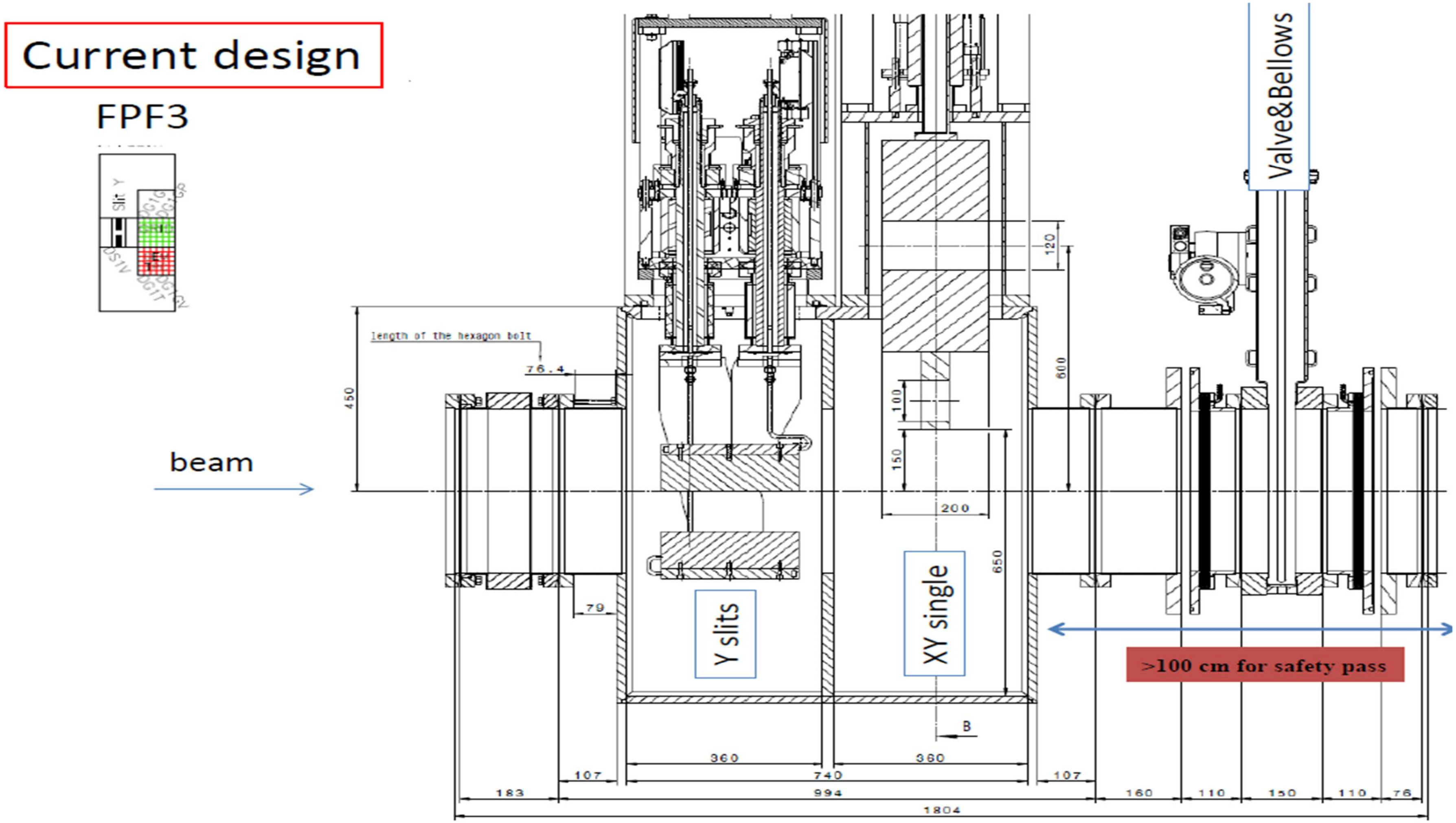

Figure 94. FPF3 vacuum chamber layout and beam inserts.

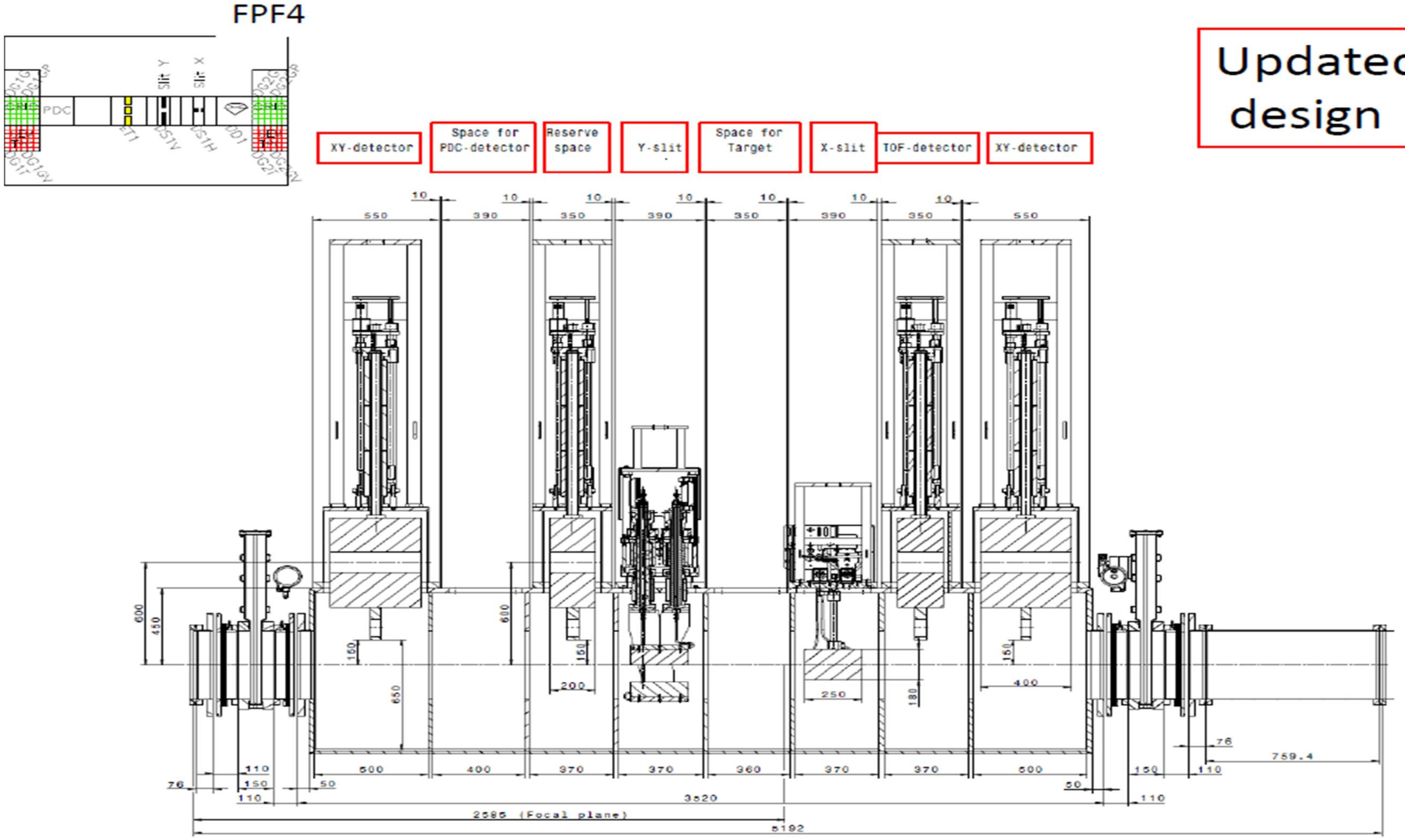

Figure 95. FPF4 vacuum chamber layout and beam inserts.

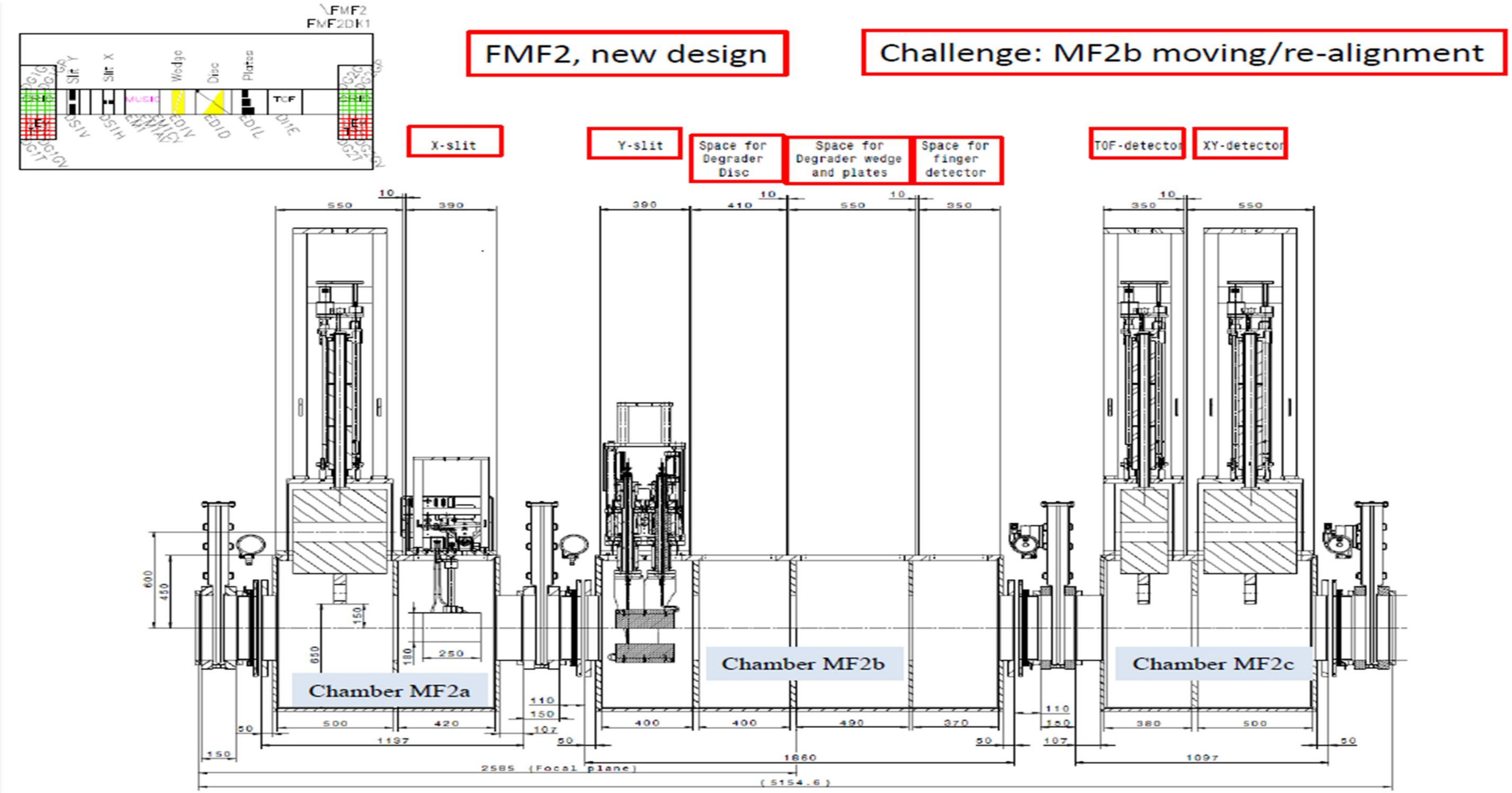

Figure 96. FMF2 vacuum chamber layout and beam inserts.

Appendix IV: Requirements and Functional Analysis

This appendix includes the detailed requirements traceability and functional tradeoff analysis for the Super-FRS MTRH system concept designs. The requirements analysis carried out for the MTRH designs were very extensive and compared the system requirements against the concept design features. In this section, features of all three concept design and results from requirements analysis are presented from Table 21 till Table 26.

Requirements analysis data

Feature list MTRH systems for Super-FRS main tunnel

I.D.	Features
F1	Modification to COTs system for radiation protection: · Replacement, shielding, or radiation hardening of MTRH system components. · Radiation hardened cable onboard the MTRH system components. · Contamination covers for the MTRH system components.
F2	Six axis (KUKA Titan) industrial manipulator (radiation tolerant).
F3	Mobile platform (KUKA Omnimove or AGV) (radiation tolerant). · For the six axis robot. · For the shielding container.
F4	Shielding container to transfer beamline inserts.
F5	Customized design for Super-FRS main tunnel: · Remote handling tools designed based on task specification. · Redesigned connector panel for Super-FRS beamline insert. · Beamline insert design modification for remote handling needs. · The codes and standard concerning the designed need to be fulfilled.
F6	Power supply system (to power the remote handling equipment during remote handling task sequence excluding during MTRH system transfer).
F7	Battery power pack (to power the MTRH system during transfer across the tunnel & as backup power in case of power failure).
F8	Automatic navigation system to drive the MTRH system into position.
F9	Automatic parking system to securely park the MTRH system.
F10	Communication and control system to operated and drive MTRH system (Automated task sequence and human in loop if required)
F11	Visual feedback (CCTV) system to provide overview of remote handling task sequence.
F12	Remotely controlled mobile crane used as a redundant system in case of MTRH system primary remote handling equipment failure.
F13	Modular and reliable design approach while using the COTs for the: · MTRH system components. · Connector plates. · Tooling system. · Control system.
F14	Failure Mode Effect Analysis (FMEA) of the remote handling task sequence.
F15	Establishing the detailed remote handling task sequence for remote maintenance within the tunnel.

Table 21. MTRH system concept **1** Features list (for the traceability matrix).

I.D.	Features
F1	Modification to COTs system for radiation protection: · Replacement, shielding, or radiation hardening of MTRH system components. · Radiation hardened cable onboard the MTRH system components. · Contamination covers for the MTRH system components. · Radiation shielding and fixture for MSM
F2	The remotely controlled MSM (e.g. electrical powered MT200 TAO, hydraulically powered Schilling titan robotics, pneumatic powered Festo Exohand, or industrial robot customized for MSM).
F3	Mobile platform (KUKA Omnimove or AGV) (radiation tolerant):
F4	Replacement repair and holding bay for activate beamline insert. The bay is also used for holding the bay in place. The bay also where the beamline insert held and transferred across to the storage location. The bay area is also equipped with shielding flask to transfer the beamline insert to hotcell.
F5	Customized design for Super-FRS main tunnel: · Remote handling tools designed based on task specification. · Redesigned connector panel for Super-FRS beamline insert. · Beamline insert design modification for remote handling needs. · The codes and standard concerning the designed need to be fulfilled.
F6	Power supply system (to power the remote handling equipment during remote handling task sequence excluding during MTRH system transfer).
F7	Battery power pack (to power the MTRH system during transfer across the tunnel & as backup power in case of power failure).
F8	Automatic navigation system to drive the MTRH system into position.
F9	Automatic parking system to securely park the MTRH system.
F10	Communication and control system to operated and drive MTRH system
F11	Visual feedback (CCTV) system to provide overview of remote handling task sequence.
F12	Remotely controlled mobile crane used as a basic system to handle heavy load such as lifting of the beamline inserts.
F13	Modular and reliable design approach while using the COTs for the: · MTRH system components. · Connector plates. · Tooling system. · Control system.
F14	Failure Mode Effect Analysis (FMEA) of the remote handling task sequence.
F15	Establishing the detailed remote handling task sequence for remote maintenance within the tunnel

Table 22. MTRH system concept **2** Features list (for the traceability matrix).

I.D.	Features
F1	Modification to COTs system for radiation protection: · Replacement, shielding, or radiation hardening of MTRH system components. · Radiation hardened cable onboard the MTRH system components. · Contamination covers for the MTRH system components. · Radiation shielding and fixture for MSM
F2	Overhead gantry coordinate robot (i.e. Hager Portal stacker PLF/Jumbo).
F3	Mobility of MTRH System: · Mobile platform (KUKA Omnimove or AGV) (radiation tolerant) for shielding container. · Overhead guide rails for gantry coordinate robot to move across tunnel.
F4	Shielding container to transfer beamline inserts.
F5	Customized design for Super-FRS main tunnel: · Remote handling tools designed based on task specification. · Redesigned connector panel for Super-FRS beamline insert. · Beamline insert design modification for remote handling needs. · The codes and standard concerning the designed need to be fulfilled.
F6	Power supply system (to power the remote handling equipment during remote handling task sequence excluding during MTRH system transfer).
F7	Battery power pack (to power the MTRH system during transfer across the tunnel & as backup power in case of power failure).
F8	Automatic navigation system to drive the MTRH system into position.
F9	Automatic parking system to securely park the MTRH system.
F10	Communication and control system to operated and drive MTRH system
F11	Visual feedback (CCTV) system to provide overview of remote handling task sequence.
F12	Remotely controlled mobile crane used as a primary component of MTRH system to transfer beamline insert.
F13	Modular and reliable design approach while using the COTs for the: · MTRH system components. · Connector plates. · Tooling system. · Control system.
F14	Failure Mode Effect Analysis (FMEA) of the remote handling task sequence.
F15	Establishing the detailed remote handling task sequence for remote maintenance within the tunnel

Table 23. MTRH system concept **3** Features list (for the traceability matrix).

MTRH systems for Super-FRS main tunnel requirements analysis results

MTRH concept 1				
Percentage of requirements met				
S.No.	Types of Requirements	Fullfiled	Total	Percentage
1	System functions requirements	7	7	100
2	Basic configuration requirements	14	14	100
3	Interface requirements	7	7	100
4	General requirements	5	5	100
5	Functional requirements	7	7	100
6	Assembly requirements	2	2	100
7	System operational requirements	3	5	60
8	System maintenance requirements	6	7	85.71428571
9	Structural requirements	0	8	0
10	Position accuracy requirements	2	2	100
11	Seismic requirements	4	5	80
12	Electrical requirements	0	2	0
13	Grounding and Insulation requirements	0	4	0
14	Instrumentation and control requirements	6	11	54.54545455
15	Computer hardware and software requirements	0	8	0
16	RH Control Room	0	6	0
17	RH Equipment	0	3	0
18	HVAC	0	1	0
19	Vacuum requirements	4	4	100
20	Thermal management requirements	3	3	100
21	Electromagnetic requirements	2	2	100
22	Material requirements	5	5	100
23	Installation requirements	2	2	100
24	Testing and inspection requirements	0	3	0
25	Decommissioning requirements	0	2	0
26	Safety design criteria requirements	13	16	81.25
27	Environmental Impact requirements	1	1	100
28	RAMI requirements	20	35	57.14285714
29	Applicable codes and Standards requirements	0	9	0
	Total	113	186	60.75268817

Table 24. MTRH system concept one: Percentage of requirements met.

MTRH concept 2 Percentage of requirements met				
S.No.	Types of Requirements	Fulfilled	Total	Percentage
1	System functions requirements	7	7	100
2	Basic configuration requirements	14	14	100
3	Interface requirements	7	7	100
4	General requirements	5	5	100
5	Functional requirements	7	7	100
6	Assembly requirements	2	2	100
7	System operational requirements	3	5	60
8	System maintenance requirements	5	7	71.4
9	Structural requirements	0	8	0
10	Position accuracy requirements	2	2	100
11	Seismic requirements	4	5	80
12	Electrical requirements	0	2	0
13	Grounding and Insulation requirements	0	4	0
14	Instrumentation and control requirements	7	11	63.6
15	Computer hardware and software requirements	0	8	0
16	RH Control Room	0	6	0
17	RH Equipment	0	3	0
18	HVAC	0	1	0
19	Vacuum requirements	4	4	100
20	Thermal management requirements	3	3	100
21	Electromagnetic requirements	2	2	100
22	Material requirements	5	5	100
23	Installation requirements	2	2	100
24	Testing and inspection requirements	0	3	0
25	Decommissioning requirements	0	2	0
26	Safety design criteria requirements	13	16	81.3
27	Environmental Impact requirements	0	1	0
28	RAMI requirements	20	35	57.1
29	Applicable codes and Standards requirements	0	9	0
	Total	112	186	60.2

Table 25. MTRH system concept two: Percentage of requirements met.

MTRH concept 3 Percentage of requirements met				
S.No.	Types of Requirements	Fulfilled	Total	Percentage
1	System functions requirements	7	7	100
2	Basic configuration requirements	14	14	100
3	Interface requirements	7	7	100
4	Genral requirements	5	5	100
5	Functional requirements	7	7	100
6	Assembly requirements	2	2	100
7	System operational requirements	3	5	60
8	System maintenance requirements	6	7	85.7
9	Structural requirements	0	8	0
10	Position accuracy requirements	2	2	100
11	Seismic requirements	4	5	80
12	Electrical requirements	0	2	0
13	Grounding and Insulation requirements	0	4	0
14	Instrumentation and control requirements	6	11	54.5
15	Computer hardware and software requirements	0	8	0
16	RH Control Room	0	6	0
17	RH Equipment	0	3	0
18	HVAC	0	1	0
19	Vacuum requirements	4	4	100
20	Thermal management requirements	3	3	100
21	Electromagnetic requirements	2	2	100
22	Material requirements	5	5	100
23	Installation requirements	2	2	100
24	Testing and inspection requirements	0	3	0
25	Decommissioning requirements	0	2	0
26	Safety design criteria requirements	13	16	81.3
27	Environmental Impact requirements	1	1	100
28	RAMI requirements	20	35	57.1
29	Applicable codes and Standards requirements	0	9	0
	Total	113	186	60.8

Table 26. MTRH system concept three: Percentage of requirements met.

Functional tradeoff analysis for MTRH system concept designs

In order to carry out the functional analysis the MTRH system concept designs, the following steps were used:

- Develop subsystem list for each MTRH system concept using bottom up approach while analyzing the system functions (see Table 27-Table 29)

- Evaluate the MTRH system concept design subsystems using a functions vs subsystems matrix. This identifies key subsystems that can be used for various functions.
- Based on the analysis, develop detailed product tree that can be used for the following purposes (this analysis is out of scope of this thesis):
    - Defining detailed list for the MTRH system architecture design (up to component level).
    - Fault tree analysis.
    - Develop a detailed task sequence by identifying physical and control interfaces.

Subsystems list for the MTRH system concept designs

Table 27. Subsystems list of MTRH system concept one.

I.D.	Component
S1	Six axis (KUKA Titan) industrial manipulator
S2	Task specific tooling system
S3	Shielding container to transfer beamline inserts
S4	Power supply system
S5	Battery power pack & backup power system
S6	Mobile platform (KUKA Omnimove or AGV)
S7	Automatic navigation system
S8	Automatic parking system
S9	Communication and control system
S10	Visual feedback (CCTV) system
S11	Remotely controlled mobile crane
S12	Contamination protection cover

Table 28. Subsystems list of MTRH system concept two.

I.D.	Component
S1	The remotely controlled MSM (e.g. electrical powered MT200 TAO, hydraulically powered Schilling titan robotics, pneumatic powered Festo Exohand, or industrial robot customized for MSM)
S2	Task specific tooling system
S3	Shielding wall, and fixture for MSM

S4	Replacement repair and holding bay for activate beamline insert. The bay is also used for holding the bay in place.
S5	Power supply system
S6	Battery power pack & backup power system
S7	Mobile platform (KUKA Omnimove or AGV)
S8	Automatic navigation system
S9	Automatic parking system
S10	Communication and control system
S11	Visual feedback (CCTV) system
S12	Remotely controlled mobile crane
S13	Contamination protection cover

Table 29. Subsystems list of MTRH system concept three.

I.D.	Component
S1	Overhead gantry coordinate robot (i.e. Hager Portal stacker PLF/Jumbo)
S2	Task specific tooling system. The overhead gantry crane can also be equipped with six axis manipulator that can be remotely controlled to carry out remote manipulation.
S3	Shielding container to transfer beamline inserts
S4	Power supply system
S5	Battery power pack & backup power system
S6	Mobile platform (KUKA Omnimove or AGV) to transfer the shielding container
S7	Overhead guide rails for gantry coordinate robot to move across tunnel
S8	Automatic navigation system
S9	Automatic parking system
S10	Communication and control system
S11	Visual feedback (CCTV) system

S12	Remotely controlled mobile crane
S13	Contamination protection cover
S14	Automatic disconnection of connector panel or use of tooling (F2)

Function vs Subsystem matrix analysis for MTRH system concept designs

Table 30. Function vs Subsystem matrix analysis for MTRH system concept one.

Functional vs Subsystem analysis *MTRH system concept one*													
Functional S.No.	Feature / Subsystem ID	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
1		X	X	X	X	X	X	X	X	X	X	X	X
1,1		X		X		X	X	X	X	X	X		X
1,1,1		X	X	X		X	X	X	X	X			
1,1,2					X		X	X	X	X	X		
1,1,3				X									X
1,2		X	X	X		X							
1,2,1		X	X	X									
1,2,2				X			X	X					
1,2,3		X	X										
1,2,4		X	X								X		
1,3		X	X	X	X		X	X	X			X	
1,3,1			X	X									
1,3,2		X					X	X	X				
1,3,3			X	X								X	
1,4					X	X							
1,4,1						X							
1,4,2					X								

Table 31. Functions vs Subsystem matrix analysis for MTRH system concept two.

Functional vs Subsystem analysis														
MTRH system concept two														
Functional S.No.	Feature / Subsystem ID	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
1		X	X	X	X	X	X	X	X	X	X	X	X	X
1,1		X		X	X		X	X	X	X	X		X	X
1,1,1		X	X					X	X	X	X	X	X	
1,1,2							X	X	X	X	X			
1,1,3				X	X									X
1,2		X	X	X	X			X					X	
1,2,1				X	X			X					X	
1,2,2				X	X									
1,2,3		X	X											
1,2,4		X	X									X		
1,3		X	X	X	X	X		X	X	X			X	
1,3,1		X	X		X								X	
1,3,2		X	X					X		X			X	
1,3,3				X	X	X					X	X		X
1,4						X	X							
1,4,1							X							
1,4,2						X								

Table 32. Functions vs Subsystem matrix analysis for MTRH system concept three.

Functional vs Subsystem analysis															
MTRH system concept three															
Functional S.No.	Feature / Subsystem ID	S1	S2	S3	S4	S5	S6	S7	S8	S9	S 10	S 11	S12	S 13	S 14
1		X	X	X	X	X	X	X	X	X	X	X	X	X	X
1,1		X	X	X		X	X	X	X	X	X		X	X	X
1,1,1		X	X	X		X	X	X	X	X	X	X			
1,1,2						X	X	X	X	X	X				
1,1,3				X										X	X
1,2		X	X	X			X	X					X		
1,2,1		X	X	X	X			X			X	X			
1,2,2				X		X	X		X	X	X				
1,2,3		X	X												X
1,2,4		X	X									X			
1,3		X	X	X		X	X	X	X	X			X		
1,3,1		X	X	X									X		
1,3,2		X	X	X			X	X					X		
1,3,3					X	X			X	X	X	X		X	X
1,4					X	X									
1,4,1						X									
1,4,2					X										

MTRH system concept designs product trees

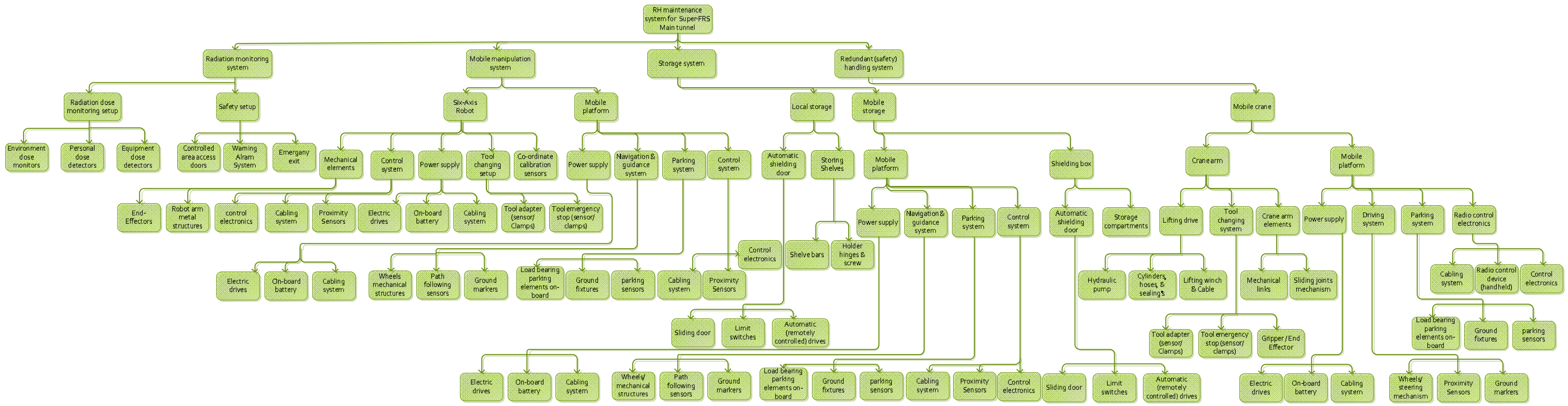

Figure 97. MTRH system concept designs product trees (1 of 3)

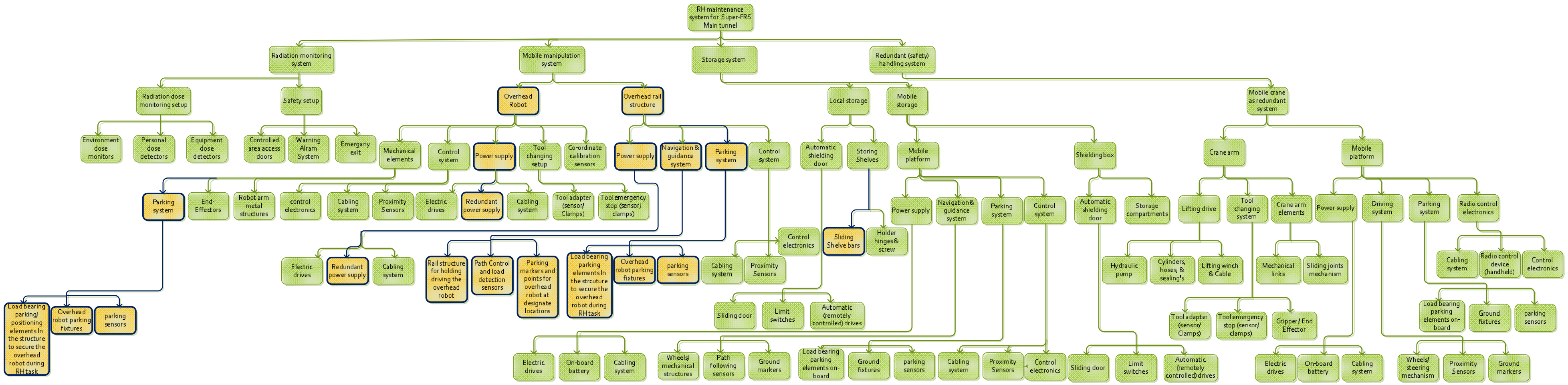

Figure 97. MTRH system concept designs product trees (2 of 3)

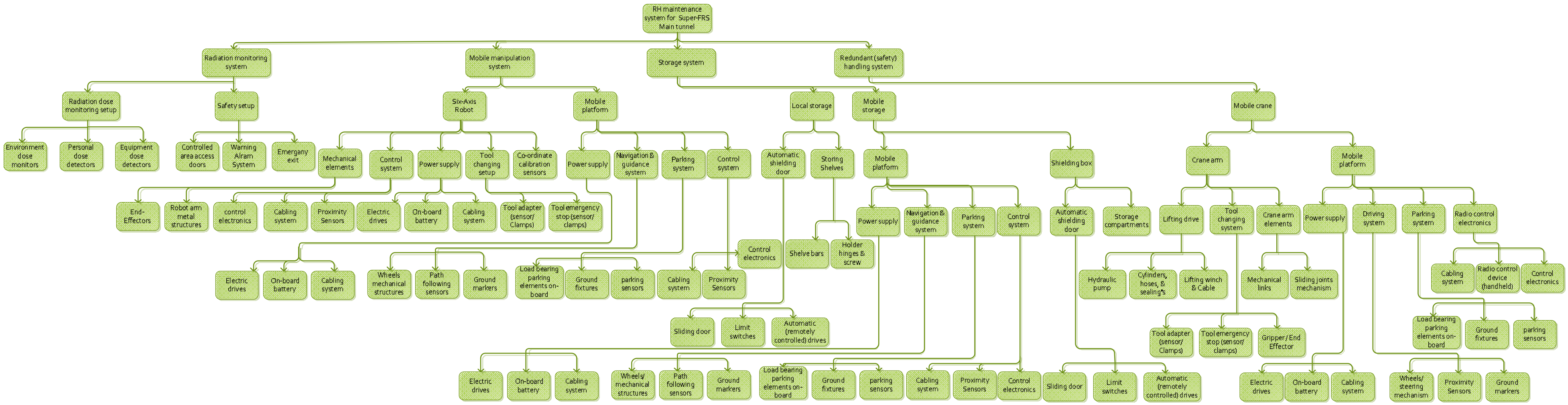

Figure 97. MTRH system concept designs product trees (3 of 3)

Appendix V: Cost analysis for Super-FRS MTRH system concept designs

This appendix addresses the cost estimation aspect of the MTRH system concept designs. Cost is a key decision factor in the selection and planning of the any engineering project. Since cost engineering is full separate field of its own, here we mainly concentrate on the cost estimates of the initial system development. The operating cost is not considered at this stage, only capital investment will be considered. These cost estimates are based on the market enquires and discussion with RH experts. However, although a more detailed cost analysis is outside the scope of this thesis, such cost analysis is of the utmost importance and more detailed cost estimation requires to be integrated into the final project analysis. The purpose of this cost analysis is to be used to compare the different concepts for sake of selecting the MTRH concept design. However, this analysis can also be used as baseline for estimating the final cost of the Super-FRS MTRH system.

Table 33. Initial cost estimates for Super-FRS MTRH system concept one.

Preliminary cost estimates MTRH system concept one		
S.No	Cost incurring entities	Value (in Kilo €)
1	Six axis (KUKA Titan) industrial robot cost	650
2	Tools for RH cost	65
3	Shielding container cost	25
4	Power supply system Parking system communication system Control system cost	80
5	Navigation cost	30
6	Visual feedback system cost	20
7	Mobile platform (KUKA Omnimove / AGV) cost	750
8	Remotely controlled crane	300
9	Personal training cost	100
10	Operational and maintenance cost	Not calculated at this stage
11	Testing and support cost	Not calculated at this stage
12	Disposal cost	Not calculated at this stage
	Total cost	2020

Table 34. Initial cost estimates for Super-FRS MTRH system concept two.

Preliminary cost estimates MTRH system concept two		
S.No	Cost incurring entities	Value (in Kilo €)
1	Remotely controlled Master slave manipulator (MSM)	700
2	Tools for RH	70
3	Shielding wall and MSM operational fixture	100
4	Power supply system, Parking system, communication system, Control system cost	80
5	Navigation	30
6	Visual feedback system	50
7	Mobile platform (KUKA Omnimove / AGV)	400
8	Remotely controlled crane	300
9	Modification to Super-FRS beamline system	200
10	Personal training	200
11	Operational and maintenance cost	Not calculated at this stage
12	Testing and support cost	Not calculated at this stage
13	Disposal cost	Not calculated at this stage
	Total cost	2130

Table 35. Initial cost estimates for Super-FRS MTRH system concept three.

Preliminary cost estimates MTRH system concept three		
S.No	Cost incurring entities	Value (in Kilo €)
1	Overhead gantry coordinate robot	700
2	Tools for RH	70
3	Shielding container	25
4	Dual arm schilling robotics titan 4 for remote manipulation	270
5	Power supply system, parking system, communication system, control system	80
6	Navigation	30
7	Visual feedback system	20
8	Mobile platform (KUKA Omnimove / AGV)	400
9	Remotely controlled crane	300
10	Modification to Super-FRS facility design	200
11	Modification to Super-FRS beamline system	200
12	Personal training	200
13	Overhead guide rail	300
14	Operational and maintenance cost	Not calculated at this stage
15	Testing and support cost	Not calculated at this stage
16	Disposal cost	Not calculated at this stage
	Total cost	2795

Appendix VI : Super-FRS Radiation Analysis

This appendix details the radiation analysis carried out for the Super-FRS MTRH system concept designs. The radiation analysis was carried out using State of the art tools and is based on the replacement of the beamline insert at FPF2 location. The results in this section provide the radiation analysis data, including dose rates across the critical points and dose received by equipment and personnel. Due to the fact that the radiation analysis is carried out using FLUKA simulation analysis, the Super-FRS main tunnel was divided into two sections Tiel A and Tiel B (in German Section A and B). The doses are shown in µSv in order to show the dose impact of radiation on humans, rather than on the RH equipment.

		Teil A		Teil B				
Speed	Situation	Dose rates (Average) (µSv/h)	Total dose (Average) (µSv)	Dose rates (Average) (µSv/h)	Total dose (Average)(µSv)	Dose Received (Average) (µSv)	Comulative dose (Average) (µSv)	Comments
0.3Km/hr	Travelling across tunnel (equipment)	162,2	48,25	2,4	0,693	97,886	2926,80267	Equipment travelling doses
	Performaing task (equipment)	409	1840,5			2828,917		Robot operation doses
			988,4167					Shielding box operation doses
0.2km/hr	Travelling across tunnel (equipment)	162,2	72,4	2,4	1,04	146,88	2975,79667	Equipment travelling doses
	Performaing task (equipment)	409	1840,5			2828,917		Robot operation doses
			988,4167					Shielding box operation doses
0.1 Km/hr	Travelling across tunnel (equipment)	162,2	145	2,4	2,08	294,16	3123,07667	Equipment travelling doses
	Performaing task (equipment)	409	1840,5			2828,917		Robot operation doses
			988,4167					Shielding box operation doses

Figure 98. Screen shot of the MTRH concept one radiation analysis table. “Cumulative dose received" column shows the doses received by the MTRH concept one moving at different speeds.

		Teil A		Teil B				
Speed	Situation	Dose rates (Average) (µSv/h)	total dose (µSv)	Dose rates (Average) (µSv/h)	total dose (µSv)	dose collected (µSv)	Total dose (µSv)	Comments
0.3Km/hr	Travelling across tunnel (equipment)	197	60	2,4	0,693	60,293	2783,086	Multiplied with two the doses are for two MRC and MC
	Performaing task (equipment)	225	1500	N/A	N/A	2662,5		Mobile repair center dose
			1162,5					Mobile crane dose
3km/hr	Travelling across tunnel (personal)	24,2	0,699	0,548	0,0145	0,7135	106,8936516	Multiplied with two the doses are for two MRC and MC operators
	Performaing task (personal)	45,2	45,2	N/A	N/A	105,4666516		Mobile repair center operator
			60,266652					Mobile crane dose operator dose
0.2km/hr	Travelling across tunnel (equipment)	197	89	2,4	1,04	90,44	2843,38	Multiplied with two the doses are for two MRC and MC
	Performaing task (equipment)	225	1500	N/A	N/A	2662,5		Mobile repair center dose
			1162,5					Mobile crane dose
2km/hr	Travelling across tunnel (personal)	24,2	1,05	0,548	0,0218	1,0718	107,6102516	Multiplied with two the doses are for two MRC and MC operators
	Performaing task (personal)	45,2	45,2	N/A	N/A	105,4666516		Mobile repair center operator
			60,266652					Mobile crane dose operator dose
0.1Km/hr	Travelling across tunnel (equipment)	197	179	2,4	2,08	181,08	3024,66	Multiplied with two the doses are for two MRC and MC
	Performaing task (equipment)	225	1500	N/A	N/A	2662,5		Mobile repair center dose
			1162,5					Mobile crane dose
1km/hr	Travelling across tunnel (personal)	24,2	2	0,548	0,0435	2,1435	109,7536516	Multiplied with two the doses are for two MRC and MC operators
	Performaing task (personal)	45,2	45,2	N/A	N/A	105,4666516		Mobile repair center operator
			60,266652					Mobile crane dose operator dose

Figure 99. Screen shot of the MTRH concept two radiation analysis table. “Cumulative dose received” column shows the doses received by MTRH concept two moving at different speeds. This is the only case where human operators are exposed to dose along with equipment.

		Teil A		Teil B				
Speed	Situation	Dose rates (Average) (µSv/h)	Total dose (Average) (µSv)	Dose rates (Average) (µSv/h)	Total dose (Average)(µSv)	Dose Received (Average) (µSv)	Comulative dose (Average) (µSv)	Comments
	Travelling across tunnel (Shielding box)	162,2	48,25	2,4	0,693	97,886		Shielding box transport doses
	Travelling across tunnel (overhead robot)	165	13,7	0,343	0,398	28,196		Overhead robot transport dose
0.3Km/hr	Performing task (overhead robot) Idle	447	968,5				3212,16533	overhead robot operation doses
	Performing task (overhead robot) handling beam	542	1129,167			3086,083		
	Performaing task (Shielding box)	409	988,4167					Shielding box operation doses
	Travelling across tunnel (Shielding box)	162,2	72,4	2,4	1,04	146,88		Shielding box transport doses
	Travelling across tunnel (overhead robot)	165	68,6	0,343	0,456	138,112		Overhead robot transport dose
0.2km/hr	Performing task (overhead robot) Idle	447	968,5				3371,07533	overhead robot operation doses
	Performing task (overhead robot) handling beam	542	1129,167			3086,083		
	Performing task (Shielding box)	409	988,4167					Shielding box operation doses
	Travelling across tunnel (Shielding box)	162,2	145	2,4	2,08	294,16		Shielding box transport doses
	Travelling across tunnel (overhead robot)	165	137	0,343	0,631	275,262		Overhead robot transport dose
0.1 Km/hr	Performing task (overhead robot) Idle	447	968,5				3655,50533	overhead robot operation doses
	Performing task (overhead robot) handling beam	542	1129,167			3086,083		
	Performing task (Shielding box)	409	988,4167					Shielding box operation doses

Figure 100. Screen shot of the MTRH concept three radiation analysis table. “Cumulative dose received” column shows the doses recieved by MTRH concept three moving at different speeds.

S.No.	Time for various situation	(in min)	(in hours)
1	Exposure time for mobile robot (concept one)	275	4,583333333
2	Exposure time for shielding box (concept one/three)	145	2,416666667
3	Exposure of over head robot to higher dose (concept three)	125	2,083333333
4	Exposure of robot to lower dose when idle (concept three)	130	2,166666667

Figure 101. Screen shot for the MTRH concept one and three. The table shows the radiation exposure time for both concepts. The time calculaitons are based on an initial definition of the RH task sequence. The task sequence can be optimized using MatPlanner.

S.No.	Time for various situation	(in min)	(in hours)
1	Total time needed for remote handling task in the tunnel	420	7
2	Total time needed for onsite remote mainteance and later transfer to the hotcell for the waste. Note exposure time for operator increases during onsite mainteance.	576	9,6
3	Total time needed for remote mainteance and transfer the beamline insert to hotcell (no onsite mainteance)	481	8,016666667
4	Exposure time for MRC operator to radiation travelling	40	0,666666667
5	Exposure time for MC operator to radiation	40	0,666666667
6	Exposure time for MRC during operation	60	1
7	Exposure time for MC during operation	80	1,333333333
8	Exposure time for the MRC unit during operation	400	6,666666667
9	Exposure time for MC unit during operation	310	5,166666667
10	Exposure time of MRC unit during onsite mainteance	95	1,583333333
11	Exposure time of MC unit during onsite mainteance	95	1,583333333

Figure 102. Screen shot for the MTRH concept two. The table shows the radiaiton exposure time for the MTRH concept two. This concept has more components and human involvement, hence the time calcuation is complicated when compared to concepts one and three. The time calculaitons are based on initial defined RH task sequence. The task sequence can be optimized using MatPlanner.

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