EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - PS DIVISION

CERN/PS 2000-075 (OP)
CERN-EP/2000-149

A SECOND GENERATION RADIOACTIVE NUCLEAR BEAM FACILITY AT CERN

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Geneva, Switzerland
8 December 2000

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The proposed Superconducting Proton Linac (SPL) at CERN would be an ideal driver for a proton-driven second-generation Radioactive Nuclear Beam facility. We propose to investigate the feasibility of constructing such a facility at CERN close to the present PS Booster ISOLDE facility. The existing ISOLDE facility would be fed with a 10 μA proton beam from SPL, providing the physics community with a low-intensity experimental area. A second, new facility would be built with target stations deep underground, permitting proton beam intensities of more than 100 μA. The secondary beams can be post-accelerated to 20-100 MeV/u and there will be a storage ring complex and large segmented detectors in the experimental area. Also, benefits from a muon-ion collider or from merging the ions and muons should be investigated. Since the antiproton decelerator would be nearby, the opportunities for antiprotonic radioactive atom studies should be pursued as well.

1. INTRODUCTION

The manifestation of the strong and weak interaction in the atomic nucleus, a finite many-body quantum mechanical system, can be rigorously investigated through nuclei with anomalous proton/neutron ratio. Co-ordinated efforts on technical developments in trapping, cooling and bunching of ions, heavy-ion acceleration, target-ion source chemistry, resonant ionisation, and charge state breeding leads to the possibility to produce these exotic nuclei in sufficient amounts and with properties allowing these specific studies.

Concentrated efforts in Europe, USA and Japan are underway to plan or construct new facilities for the production of high-intensity radioactive nuclear beams (RNB) and to further improve existing ones. According to a recent survey by the Nuclear Physics European Collaboration Committee (NuPECC), the size of the potential user community in Europe alone is over one thousand scientists. The basic approaches used to produce radioactive beams are the Isotope Separator On-Line (ISOL) method, and the fragmentation of fast projectiles followed by In-Flight separation (the IF method). The ISOL method followed by acceleration of the beam produces high-intensity and high-quality beams up to several 10 MeV/u, whereas the IF method is better for producing higher-energy beams of very short-lived nuclei from 50 MeV/u up to relativistic energies around 1 GeV/u. The two methods are to a large extent complementary, not only in their technical approaches but also in the delivered beam properties, as well as in the scientific goals set by the research community.

NuPECC, as a representative of the European Nuclear Physics Community, has declared as one of its future priorities [1, 2] the construction of second-generation facilities based on both methods. In terms of intensity of the radioactive beams, this means an increase by a factor of 1000 compared to the presently available beams. Additionally, a major effort is to be put on new technologies to manipulate and post-accelerate radioactive ions as efficiently as possible. Finally, a second-generation approach is requested for instrumentation, with the final goal of improving the overall sensitivity of experiments by a factor up to 10^6.

In its "Conceptual Plan for the Future Facilities", GSI has expressed its interest in building a leading fragmentation facility in Europe, corresponding to the second generation IF Facility [3]. Concerning the ISOL-type Radioactive Ion Beam (RIB) facility, NuPECC and the leading European research laboratories have set up a Research and Technical Development (RTD) project called EURISOL, which aims at a preliminary design of a truly second-generation facility based on the ISOL approach. In parallel with this RTD project, Europe is building new first-generation Radioactive Nuclear Beam (RNB) facilities at CERN, GANIL and Catania. A similar undertaking is underway at TRIUMF (ISAC) in Canada. Experience gained with these projects will be extremely useful for a future second-generation facility. The EURISOL RTD project was launched in the beginning of 2000. Concentrated Research and Development will then follow this two-year project on identified key technologies. The design of the facility, followed by its construction, could start around 2006. A close contact with the EURISOL study group would be a key element in the possible future realisation of this facility at CERN.

2. SECOND GENERATION ISOL-TYPE RNB FACILITY AT CERN

Since the technology on targets and ion sources for the production of radioactive ion beams is by far the most advanced at CERN, it is natural to consider that the future high-intensity facility could be placed at CERN. The SPL should eventually allow the increase of intensity of secondary radioactive ions beams by a factor of 100 to 1000. In the following, the conceptual plan is presented, which includes all the important aspects of the facility, from the high power targets, through various stages of acceleration and storage, to the experimental areas. The overall layout of the laboratory is shown in Figure 1. The experiments will cover a wide science programme, including solid state physics, biophysics, nuclear astrophysics, studies of fundamental symmetries and interactions and a full programme on structure and reaction studies of atomic nuclei very far from the valley of beta stability.

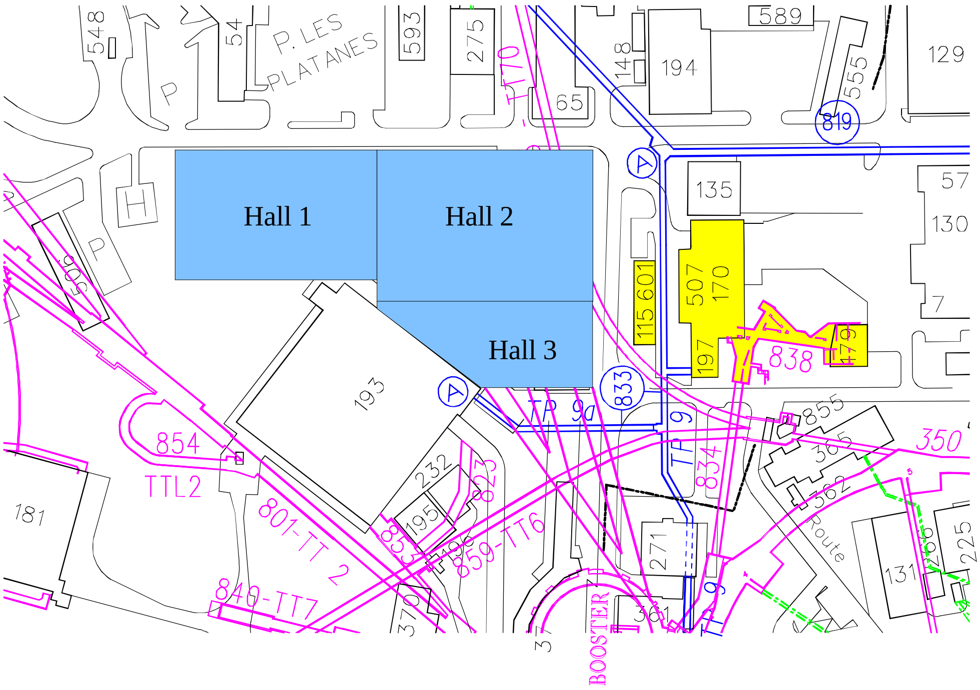

Figure 1: A conceptual plan of where the future CERN second-generation RNB facility could be located. Hall 1 would hold the storage ring complex and Hall 2, the post-accelerator and the multi-segmented detectors. In Hall 3 a class A laboratory for handling of radioactive targets would be housed. The three target stations would be accessed directly from Hall 3 avoiding any unnecessary transport of radioactive material on the site.

The conceptual design report for the SPL driver will be published as a CERN report in December 2000. The linac will use klystrons and RF cavities made available by the closure of LEP. The proposed nominal energy is 2.2 GeV with a duty factor of 16.5% and a bunch frequency of 352.2 MHz. The resulting pulse spacing would be 13.3 ms, with a pulse duration of 2.2 ms. The maximum number of particles in each pulse could reach $1.15\ 10^{14}$ H^-, of which a few percent would be sent to a second-generation RNB facility. This would result in an average current of a few hundred μA, but at a lower peak intensity than at the present PS Booster ISOLDE. An option to run the SPL at lower energies than the nominal 2.2 GeV is of interest for the proposed RNB facility. Several studies have been performed [4] on the energy dependence of the nuclear cross-sections using cascade calculations. The theoretical results have been verified partially at the PS Booster ISOLDE. They show an energy dependence of the production cross-section for typical ISOLDE targets, with the optimum energy ranging from as low as 100 MeV to at least the 2.2 GeV available with the SPL.

The driver beam will be transported to both the existing ISOLDE facility and to a new target area, which will be situated in the region of the present beam dump for the PS Booster. A first feasibility study, considering only radiation protection issues [5], shows that the present ISOLDE facility could accept up to a maximum of 10 μA of proton beam. The target area for a second-generation RNB facility will have to be located deep underground to permit proton beam currents of at least 100 μA, which is the present estimated maximum beam current tolerable on thick ISOL-type targets. A possibility of receiving a pulsed proton beam from the PS, the neutrino factory beam compressor, or a chopped SPL beam with pulses of roughly a millisecond length, would be of interest. Such a beam would permit the physics community to continue to profit from the techniques developed at the pulsed PS Booster ISOLDE facility.

The new target area will consist of two parallel target stations for the production beam. The stations will be made with independent access to permit push-pull operation between them. A third target station will be provided for pure development work, including the neutrino factory targets.

There are plenty of ideas for the target and ion sources for a second-generation RNB facility. Many of the ideas have already been probed by some very preliminary feasibility tests, but so far there has been no systematic major research effort in this domain. The time has now come to give this field a real boost, which is being undertaken within the EURISOL collaboration started by NuPECC. The study is financed by the European Union and an outline of the possible target and ion sources for a second-generation RNB type facility has been published in a recent report [2]. The report stresses the importance of pursuing many different avenues. An example is the neutron converter target concept, proposed by the Argonne group [6]. The choice of target material and the importance of the transport mechanisms inside the target itself, for high intensity targets, have been studied in connection with the development of the target [7] for the proposed SIRIUS facility at the Rutherford Appleton Laboratory. This study is of great importance for a second-generation RNB facility and will be further pursued. Among the ion sources to be studied are a compact ECR ion-source and further development of the ISOLDE LASER ion source. The latter offers efficiency and selectivity for a large number of elements, is routinely used at ISOLDE, and seems at present the best choice for operation in the hostile environment of high-intensity targets.

A second-generation RNB facility at CERN should have three experimental sections, according to the energy of the radioactive ion beam and the type of instrumentation used in the experiments. These are the low-energy area, where ions with energies up to 100 keV are used; the area where ion energies up to and above the Coulomb barrier (up to nearly 100 MeV/u) are used; and the storage and cooler ring (300 MeV/u) area, possibly connected to an electron ring (100 – 400 MeV) for electron-ion collider experiments. Additionally, possibilities provided by the proximity of an antiproton source and an intense source of muons should be investigated as novel approaches in characterising the structural features of exotic nuclei (such as their charge and mass density distributions via measurements on hyperfine splitting and isotope shifts). The future facility will be a multi-user facility with a potential to serve several experiments simultaneously.

3. POST ACCELERATOR SCENARIOS

The area for Coulomb-energy physics would be served by the Radioactive beam EXperiment at ISOLDE (REX-ISOLDE) accelerator, which could be dedicated to low-energy experiments with RNBs on light nuclei, as well as to nuclear astrophysics experiments and solid state physics experiments requiring deeper penetration of ions into samples. Adding another linac section to REX-ISOLDE to increase the energy up to the Coulomb barrier for light elements would be easily possible and should be done as soon as possible after the commissioning of the first phase.

As a new, second-generation approach, one could consider two alternative solutions for post-acceleration. One solution would be a superconducting linac extending the energy to 10 MeV/u as far as mass 230, and operating with 1+ charge state ions. The other, perhaps more attractive, solution would be to build a superconducting cyclotron (SCC) with a high enough K-value to reach 100 MeV/u energy. An SCC with an external ECR ion source could easily accelerate ions up to mass 230 with energy above the Coulomb barrier, and could simultaneously accelerate light ions to several tens of MeV/u. With a rather modest charge state needed, it could also produce efficiently light and medium heavy beams at Coulomb barrier energies. They would be used for transfer reactions probing the structure of the nuclei, fusion reactions synthesising nuclei along the Z=N line with proton-rich beams, and production of super-heavy elements with neutron-rich beams. A key element in the successful implementation of either the SC linac or the SC cyclotron is an efficient production and injection of highly charged ions. In principle, an attractive solution for this would be a low-energy beam cooler coupled to an efficient new-generation charge-state breeder. The beam cooler could be based on the well-proven principle of RFQ buffer-gas cooling, applied recently for radioactive ions at

CERN and University of Jyvaskyla. Very high transmission efficiencies have been measured for the two devices. Cooled and low-emittance beams could then be injected into the ECR source and captured in the source plasma for further ionisation.

4. EXPERIMENTS AND INSTRUMENTATION

The low-energy experimental area would essentially consist of the present ISOLDE experimental hall with the two present separators. The key instrumentation developed and operational at ISOLDE consists of various laser and other atomic spectroscopy set-ups, high-precision ion traps, the spectrometer for Mass measurements at ISolde with a Transmission RAdiofrequency (MISTRAL) facility, and the nuclear orientation facility. In addition, new detector technologies are constantly developed to meet the new requirements set by the experiments on rare isotopes and decays. These include advanced tracking detectors for gamma-rays, charged particles and neutrons. The increase in intensity and the overall increase in efficiency of RNB handling, and the improvements in detectors, could result in improvements in overall sensitivities of the order of 10^3 to 10^6. The experimental equipment needed for condensed matter physics and biophysics has to be included in the planning of the low energy area.

It will be interesting to investigate the possibilities offered by storing, cooling and re-acceleration of RNBs in the storage ring after post-acceleration. The very high intensities available at the new facility would lead to interesting physics opportunities, such as probing the nuclear charge distribution by the electron-ion scattering method. It would also be necessary to investigate the opportunities provided by the intense muon beams available through the new neutrino factory concept. Building up muonic radioactive atoms would be a unique tool in probing, for example, the charge distribution via precise measurements on hyperfine interactions of muonic atoms and ions. Also, benefits from a muon-ion collider, and especially from merging ions and muons, should be investigated. In such a merger concept, the capture of muons into different atomic (ionic) orbits could possibly be tuned by the relative energy of the interacting partners. Another potentially interesting approach would be to use a Penning ion trap, coupled with the low-energy muon storage device, in order to form thermal muonic ions of radioactive isotopes. Since the antiproton decelerator would be nearby, the opportunities for antiprotonic radioactive atom studies should be pursued as well.

In addition to the low-energy area, one needs a dedicated experimental area for experiments with the energetic radioactive ion-beams on fixed targets. Both the REX-ISOLDE and the higher energy accelerator (SC linac or SC cyclotron) provide beams to this area, which could house key instrumentation for nuclear physics and astrophysics experiments in this energy range. For fusion reaction experiments, a high-transmission vacuum or gas-filled separator is needed in addition to a recently-suggested [2] ion beam re-circulator ring that would be based on the use of thin targets with the possibility of multiple transversals of the target. This device would mainly be used in the synthesis experiments of super-heavy elements. In addition, transfer and inelastic reactions probing the nuclear shell structure should be exploited. All in all, high-granularity high efficiency tracking detectors, both for gamma-rays as well as for charged particles, would be needed in stand-alone mode and in combination with large-acceptance spectrometers for studies of reaction mechanisms as a function of the isospin degree of freedom. Finally, several of the above-mentioned studies would benefit tremendously from the availability of polarised beams and targets. Therefore, R&D should be initiated to search for possible methods of producing polarised beams; one possibility, recently suggested at CERN, would be to use circularly polarised laser light for resonant ionisation, as is already successfully done with linearly polarised laser light.

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