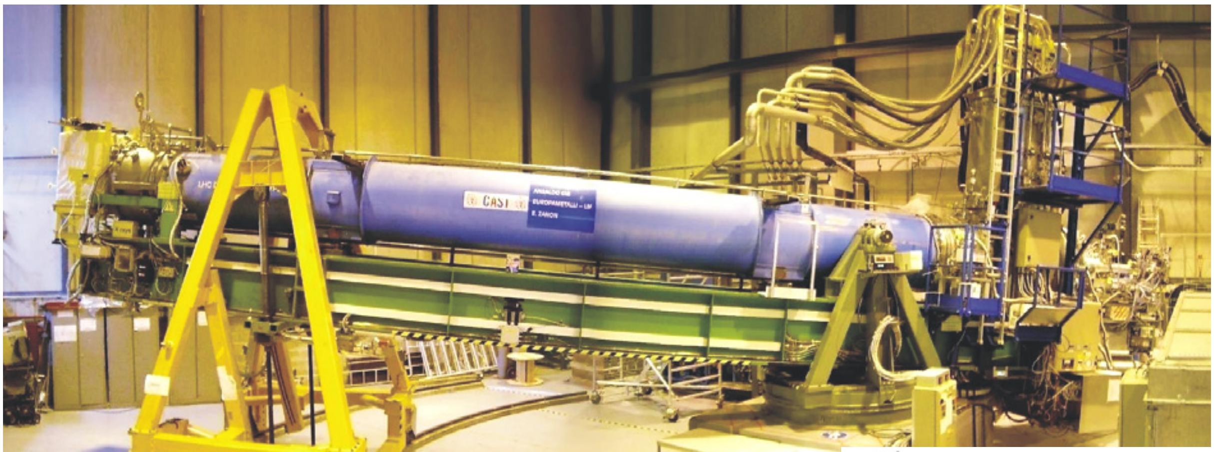
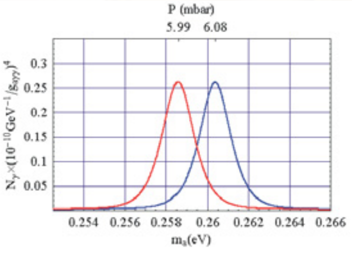
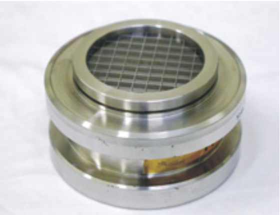
CERN-SPSC-2006-029
SPSC-TDR-001
CAST TDR 1
5 October 2006

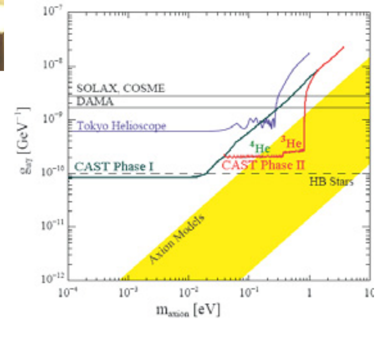
TECHNICAL DESIGN REPORT
of the
CAST ^{3}He GAS SYSTEM

CAST Collaboration, represented by
Nuno A. Elias, Tapio O. Niinikoski and Martyn Davenport
CERN, Geneva, Switzerland









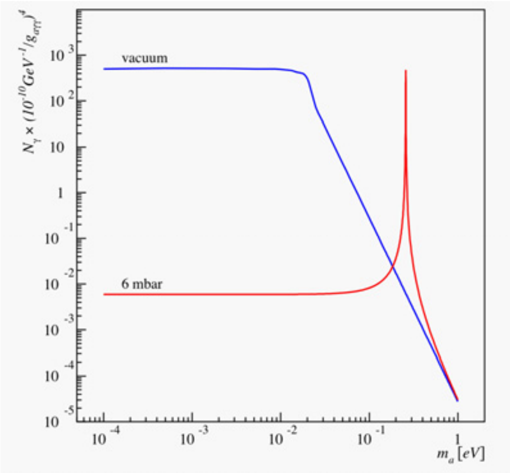
LIST OF CONTENTS

1. INTRODUCTION

1.1. CAST Phase II upgrade

CAST is an experiment designed to detect hypothetical axion-like particles, with a two-photon interaction, produced in the Sun by the Primakoff process. Solar axions, whilst traversing a laboratory magnetic field ("axion helioscope") can be transformed back again into X-rays with energies of a few keV and then detected by low-background X-ray detectors. Using a decommissioned prototype LHC dipole magnet, CAST Phase I data taking took place in 2003 and 2004 (a total of about 12 months running time). The results from the analysis of the data were published in [1] and [2]. No axion signal was detected, and therefore, basing on the data of 2004, a 95% CL limit to the axion-photon coupling is obtained $g_{a\gamma\gamma} \leq 0.9 \cdot 10^{-10}$ GeV^{-1} for an axion rest mass range for which coherence in vacuum is preserved, i.e. $m < 0.02$ eV. The result is about 7 times stronger than previous experimental limits and goes for the first time beyond the astrophysical limit from globular clusters.

During these first years CAST Phase I was operating with vacuum in the magnet bores, where the actual conversion of the solar axions to photons can take place coherently over the macroscopic length of 9.26 m. However, the coherence conditions for solar axion energies are fulfilled up to an axion rest mass limit of ~0.02 eV. For higher masses, the sensitivity decreases rapidly, since the incoming axion wave and the outgoing photon wave get more and more out of phase entailing deconstructive interference. Some 20 years ago, Karl van Bibber and co-workers proposed a scheme to recover coherence for massive axions as well: by adding gas of a specific density into the magnet bore, the photon velocity can be decreased to match with the velocity of the incoming axion. This restores coherence accurately for one axion rest mass value only, however, and the corresponding sensitivity curve features a bell-shaped resonance. The relative FWHM is of the order 10^{-3} — 10^{-4}, requiring high accuracy of the density control for the gas system.



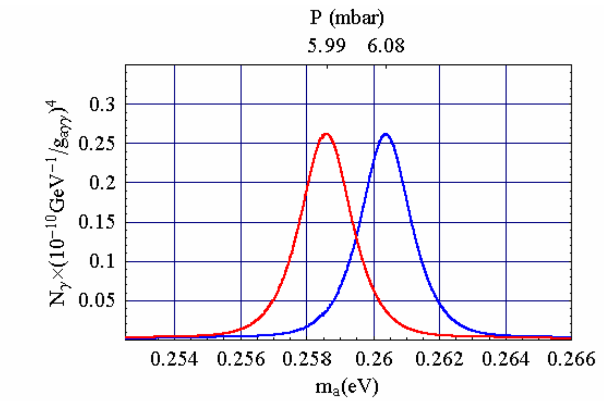


Figure 1a: The expected number of photons with vacuum (blue line) and ^{4}He gas at 6 mbar pressure and 1.8 K temperature (red line) in the magnet bores. The measurement time of 33 days is assumed in both cases.

Figure 1b: The expected number of photons vs. axion mass for two consecutive pressure steps (at 1.8 K), calculated for t=1 hour, an area S=14.5 cm^2 (one cold bore) and integrated over all energies. In order to cover all masses, it is required that two consecutive curves overlap at 50% of the peak height.

---

[1] K. Zioutas *et al.* [CAST Collaboration] Phys. Rev. Lett. **94** (2005) 121301 [arXiv:hep-ex/0411033].

[2] CAST Status Report 29.06. 2006, CERN-SPSC-2006-018, SPSC-SR-009.

In Figure 1a is shown the performance of CAST during the first period with vacuum in the magnet bores, as well one example with helium gas inside. This one case demonstrates the need to scan the accessible rest mass range in several hundred overlapping pressure settings, in order to widen CAST Phase II sensitivity towards higher masses thus increasing the discovery potential for more "massive" solar axions.

CAST Phase II is entering into new territory of the parameter phase space motivated by theory as well as by astrophysical and cosmological considerations. The first step was to open the cryostat and insert solid window separators between the cold bore gas circuit and the vacuum pipes leading to the X-ray detectors. In the summer of 2005 a program of quench tests was performed with low pressure ^{4}He fillings of the magnet bore to provide data in order to define the specifications for the gas system. The next step was to replace the separators with thin X-ray windows and install a simple ^{4}He gas system. Since December 2005, CAST has been operating using ^{4}He buffer gas inside the magnet bores, whilst making detailed plans to convert the gas handling system to ^{3}He .The ^{3}He gas system enables the search of axions with mass higher than that accessible with the current ^{4}He buffer gas system, because the saturation pressure of ^{3}He at 1.8 K is 135.58 mbar, almost 10 times higher than that of ^{4}He at 1.8 K, 16.405 mbar. The present gas system is therefore required to enable safe operation up to the saturation pressure of ^{3}He in the cold bores of the magnet.

The ^{3}He gas system thus presents major challenges because of two main reasons: the accuracy required in measuring the quantity of gas introduced into the cold bores, and the need to build the system so as to avoid any loss of the expensive gas. The latter is due to the higher operating pressure, entailing higher pressure produced in the case of a quench of the superconducting dipole magnet. This demands improved passive safety measures and a fast reaction of interlocks to avoid damage to the X-ray windows.

1.2. Gas system requirements

The following lists the requirements, based on experience gained during operation with ^{4}He, and on the quench tests performed before constructing the ^{4}He gas system:

- Safety against loss of ^{3}He
- Metering of the amount of ^{3}He in the magnet bores with the reproducibility compatible with the resolution and reproducibility of the temperature and pressure measurement of the gas metering volumes[3].
- Absence of thermo-acoustic oscillations
- Protection of the thin X-ray windows during a quench.
- Remote data logging of the state of the gas system, without feedback
- No safety release of ^{3}He elsewhere except to the safe storage vessel.

These requirements are endorsed by decisions of the CAST Steering Committee. The requirements of metering follow from the specifications of the best available commercial manometer, which has a resolution of 10 ppm of full-scale reading, and thermal drifts of $5.3\cdot10^{-3}$ mbar/°C in zero and 20 ppm/°C in reading. Although the absolute accuracy of the

---

[3] The temperature stability of the thermostated metering volumes is ±0.01 °C (±30 ppm). The pressure measuring instrument MKS Baratron 690A has the reproducibility limited by its resolution that is 10 ppm of full-scale reading, by the drift of zero 4 ppm/°C of full-scale reading, and by the drift of span 20 ppm/°C of the reading. The air-conditioned experimental hall has the thermal stability of ±2 °C.

instrument is only 500 ppm of reading, this is mainly due to the accuracy of calibration, and the long-term stability assures a sufficient resolution.

The number of unintentional quenches of the CAST magnet, classified by their causes, is given in Table 1 for the runs of 2003 — 2006. The table suggests that around 10 quenches can be expected during a full year of operation, and that the causes tend to be dominated by electrical power failures.

Year	Training	Natural	Cooling water of current supply	Current supply failure	Electromagnetic interference (2)	Human error	Quench Protection Fault	Power failure (natural)	Power failure (emergency stop)	Unknown	Sum of quenches	Magnet operation (hours)
2003	1	2	0	3	1	1	3	2	1	2	16	2100
2004	2	0	3	0	0	1	0	0	1	3	10	3000
2005	1	0	0	0	0	0	0	0	1	0	2	500
2006	1	0	0	0	0	0	0	5	3	0	9	1300

Table 1: Numbers of unexpected quenches of the CAST magnet classified according to their causes. The quenches provoked during the tests of 2005 are not included. The numbers for 2006 are up to the end of August.

1.3. Functions of the gas system

The following establishes the main functionalities of the ^{3}He gas system, listed in the order of occurrence at the time of commissioning and operation of the system:

- Purge of oil in the hermetic ^{3}He pumps
- Evacuation of all volumes at room temperature, and closure of the system
- Leak testing of all volumes at room temperature
- Transfer of ^{3}He from pressurized transport cylinder into the storage vessel of the gas system
- Metered transfer of ^{3}He into the magnet bores (by stepping of the density between runs, by stepping also during a run, and by continuous ramping during a run)
- Recovery of ^{3}He in the event of a magnet quench
- Normal recovery of ^{3}He
- Regeneration of charcoal traps
- Transfer of ^{3}He back into the pressurized transport cylinder.

During normal operation only the Metered transfer, Normal recovery of ^{3}He, and Regeneration of the charcoal traps are required. These functions should be made accessible by opening or closing valves and by operating pumps — no vacuum seals or connections must be opened or closed. For securing against failures of computers, control electronics and other active devices, the controls should be entirely manual, and the safety must be based on physical principles rather than automated actuators, with the exception of the electro-pneumatic valves that allow expanding and pumping the gas to a storage volume after a quench of the magnet. However, the precise metering and monitoring of the system, as well as any alarm systems, can and should be equipped with passive computer interfaces and, if feasible, with remotely commanded valves for normal filling and removal of the gas.

2. SPECIFICATIONS OF THE GAS SYSTEM

The diagram of the gas system is shown schematically in Figure 2. The gas transfer and the purge systems are standard ^{3}He handling systems used in the polarized target set-ups of CERN. The details of the two cold bore tubes in the magnet are not shown, because the bores are interconnected at both ends of the inner vessel of the magnet. The cold bores therefore form one volume of approximately 30 litres.

The hermeticity of the gas system is ensured by:

- all-metal construction wherever practical for all components, gaskets and instrumentation
- using high-quality torical elastomer seals with retaining rings or pressure-designed grooves in demountable connections
- excluding any usual gas connections with thread seals
- specifying hermetic ^{3}He handling pumps
- exhausting the safety release devices to the storage volume of ^{3}He
- making the X-ray windows as failsafe as possible, and leak and pressure testing them at low temperatures before mounting in the experiment
- careful leak testing of all components and assemblies prior to the initial filling with ^{3}He
- limiting access to the gas system to authorized personnel only.

All leak testing will be required to satisfy a leak rate smaller than 10^{-9} mbar litre/s, except for the pumps, whose specification is 10^{-7} mbar litre/s.

The gas system will be assembled by highly qualified technical staff of the CERN Central Cryogenic Laboratory. They are used to handling ^{3}He, and they perform rigorous leak tests as routine operations.

The gas system will be integrated in CAST to be compatible with existing equipment and lines, and to avoid any conflict with the magnet movement. To allow the necessary accuracy in the gas fillings, the sub-systems for filling and ramping will be mounted on the cryostat, thus reducing ‘dead volumes’, while the storage volume and the sub-system for circulation and recovery can be placed off the cryostat.

This is important because it will reduce considerably the weight put on pivot points of the magnet. Flexible lines will interconnect the systems placed on fixed regions, with components placed on moving parts.

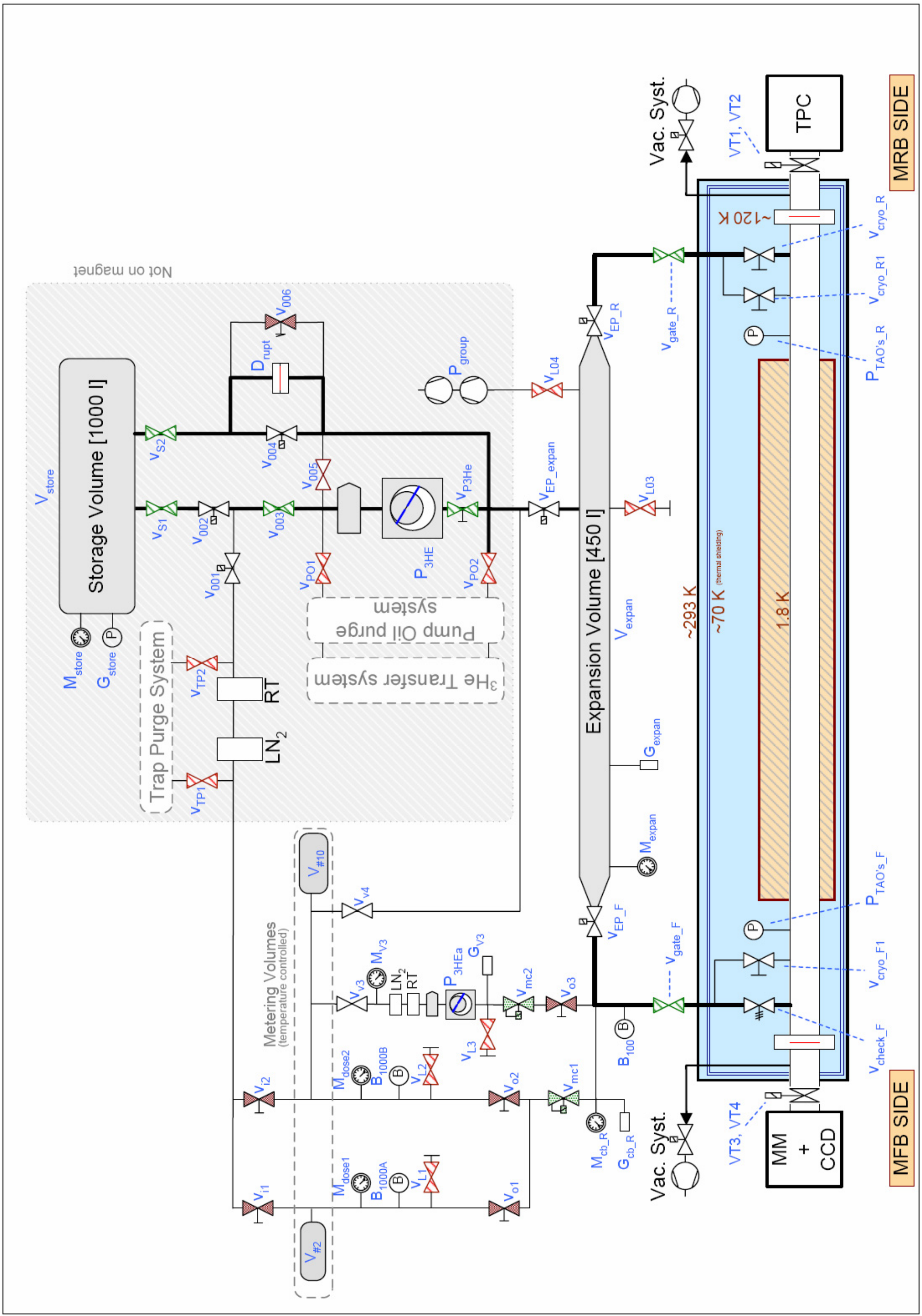


Fig.2 – Schematic diagram of the ^{3}He gas system, with the cold bore tubes shown as one volume inside the cold dipole magnet (blue). The thin X-ray windows are represented by red lines. The thick lines represent the large pipework used for normal and emergency recovery of ^{3}He. The green valves are blocked in open position, and the red ones in closed position, during all normal operation. The electropneumatic valves are open if the electrical power fails, and they open with a small forward pressure if the compressed air fails. The cryogenic check valve V_{check_F} opens at 30 mbar differential pressure, and the electropneumatic cryogenic valve V_{cryo_R} is also normally open.

3. WORKING PRINCIPLE AND FUNCTIONS OF THE MAIN SECTIONS

3.1. Main sections and operating principle

The system can be described as a hermetic closed gas circuit assuring full recovery of helium. It can be divided in functional sections with specific purposes:

1. Storage
2. Vacuum pumps for initial evacuation
3. Metering and Ramping of gas
4. Axion conversion region (cold bore)
5. Expansion volume
6. Recovery and circulation
7. Trap Purge System (detachable)
8. ^{3}He Transfer System (detachable)
9. Pump Oil Purge system (detachable)
10. Leak detector (detachable)

The system is maintained at sub-atmospheric pressure; the gas is stored in the storage volume, and purified from impurities before metering.

The precision of metering is obtained by the accurate temperature control of the metering volumes, and by the use of a metrology-grade pressure-measuring instrument to determine the amount of gas introduced into the cold bores.

The transfer of gas to the cold bore will be made using a cryogenic valve on MFB side. The temperature of the gas along the cold bore tubes should be maintained stable during run conditions.

The gas is confined in the cold bore region of the magnet with thin X-ray windows. Different scenarios have to be considered for the heating of the windows, and the heaters on the window flanges have to be foreseen also to make periodical bake-out of gases adsorbed on the window foils.

To avoid thermo-acoustic oscillations, the warm pipes linking to room temperature are isolated during normal operation by means of the cryogenic valves. These are a check valve V_{check_F} and a shut-off valve V_{cryo_R}, which are closed during normal operation, and open only during a quench when evacuating the cold bore.

In case of quench, the pressure of the gas increases rapidly, as shown by Fig. 3, and the cryogenic check valve on MFB side opens when the differential pressure reaches 30 mbar, whereas on the MRB side a cryogenic valve will open by quench triggering.

During the quench, the gas is safely evacuated from the cold bore to an expansion volume via two electro-pneumatic valves V_{EP_F} and V_{EP_R} . The X-ray windows should withstand at least 2 bar pressure in the cold bores.

These two electro-pneumatic valves will open by *quench-trigger* signal activation, and the gas is led to an expansion volume kept normally under vacuum. The pressure reached in case of quench should not exceed 1.2 bar even in the case that the main ^{3}He pump fails to start. Normally the pump will automatically start by the quench trigger, and it displaces the gas from the expansion volume to the storage volume.

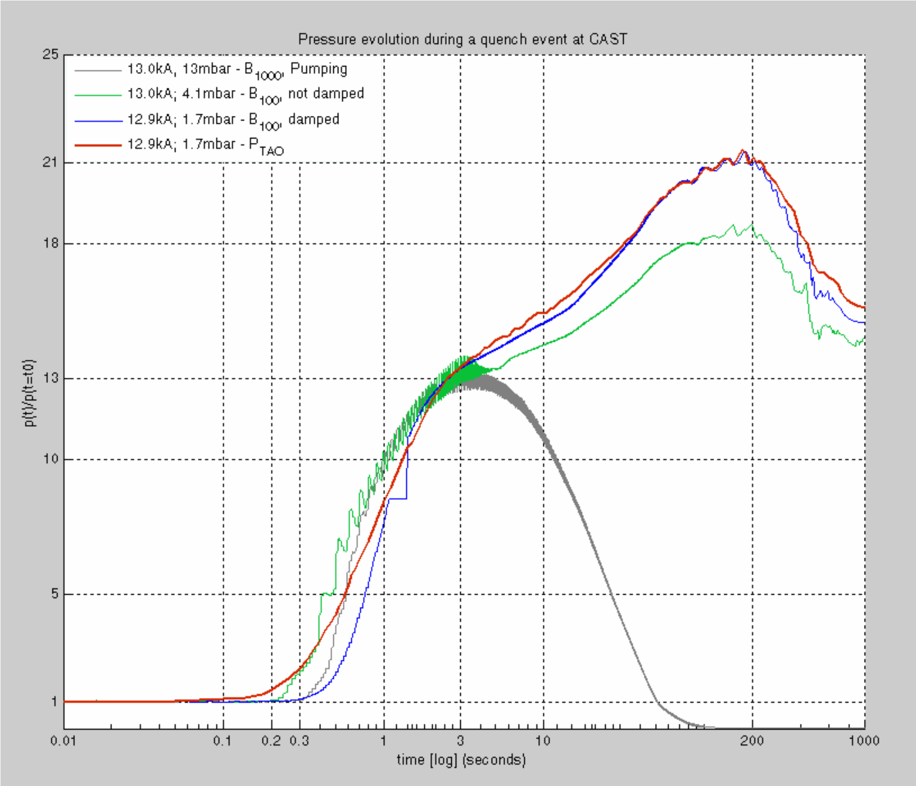


Fig.3 – Pressure evolution during a quench with ^{4}He in the magnet cold bores. The plot shows the pressure increase p(t)/p(t=t0) as a function of time, being t=t0 the quench time, and p the pressure recorded via different sensors. In the plot is displayed data from different sensors connected to the cold bore. Red, Green and Blue curves are measurements of an isochoric process (gas is kept in the cold bore), where the pressure of the gas increases due to the warming-up during the quench. The Grey curve was measured while pumping the gas with two 30m^3/h pumps. The thermo-acoustic oscillations are clearly visible in the green and grey curves.

The electro-pneumatic valves V_{EP_F} and V_{EP_R} will open in the case of failure of electrical power, and they are also partially opened in absence of compressed air. The permanent availability of compressed air is secured by a large buffer volume. The compressed air pipe work will be secured against accidental ruptures, and an alarm will be provided in the event of any anomaly in the compressed air system.

In case of accidental conditions where the ^{3}He pump will not automatically start (loss of power, unknown factors) and the pressure during a quench exceeds 1.5 bar, a rupture disk will open the cold bore to the storage volume and the pressure will be equalized below 1 bar. Moreover, the simmering seals of the ^{3}He pump will release the gas out if the pressure reaches 2 bar.

The system will be supported on the magnet structure on the airport side of the magnet. By doing this, no complications will arise because of the flexibility of lines.

3.2. Storage

All the necessary ^{3}He needed for the CAST physics runs should be first transferred to storage volume, dimensioned to keep the gas pressure below atmospheric. The gas in the storage volume will be contaminated by pump oil vapour, but oil mist will be filtered right behind the main ^{3}He pump.

3.3. Purging of the impurity traps

Before entering the metering volumes the gas passes through 2 charcoal traps, the first at room temperature and the second at liquid nitrogen temperature. The first one traps oil and water vapours, and it is regenerated by exchanging the charcoal cartridge. The second one can be warmed up in order to evacuate and purge the impurities using a neutral gas. The purge operations will be scheduled in shutdown periods, and ^{3}He will be evacuated from the traps before the purge.

3.4. Metering of gas

To scan over a wide range of axion masses CAST will need to control precisely the ^{3}He gas density in the cold bore. This is achieved by filling the cold bores with precisely metered amounts of gas in incremental steps, or by ramping between metered increments using a mass flow controller and a small auxiliary pump.

Each day two tracking periods take place, one in the morning and another in the evening, each of them with duration of ~100 minutes. Stepping of the gas density is done in equivalent pressure steps of between 0.0833 mbar and 0.1000 mbar (calculated with gas at a nominal temperature of 1.8 K). The step spacing between density settings corresponds to the density change required to shift the peak of the mass setting by one FWHM of the mass acceptance profile, as shown in Figure 1b. In order to cover the whole available mass range efficiently, data taking runs will have to cover at least two density settings per solar tracking.

Different options are foreseen for the metering and ramping of the gas into/from the cold bore:

- Increased stepping mode (two discrete density settings per tracking)
- Density ramping-up mode (ramp over a range between 0.25 to a max^{m} of 10 steps)
- Density ramping-down mode (ramp over a range between 0.25 to a max^{m} of 10 steps)
- Density ramping mode (up to a max^{m} of 100 steps per tracking); this option is under study
- Density scanning mode (ramping around a pressure setting)

Further details are given in section_4.3 and Annex 5.4.

The gas introduced in the magnet bores must be pumped out after each quench and other major interruption of the experiment. This raises the question of accuracy in reproducing a previous setting of the amount of the buffer gas. We shall therefore discuss below the accuracy and reproducibility of the mass of the buffer gas in the magnet bore tubes.

The measurement of the amount of gas transferred to the cold bore is calculated by accurately measuring the pressure decrease on the metering volumes that are maintained at constant temperature of 309.15 K by means of a thermostatic bath with ±0.01 K temperature stability. Given the stability of ±2 K in the temperature of the pipework (with about 25 cm^3 volume) exposed to the ambient temperature (due to air conditioning accuracy), the effective stability of the temperature in the 10 litre metering volume is 37 ppm.

A single full-scale (FS) pressure measurement in the 10 litre volume can be made with an accuracy of 42 ppm, taking into account the precision of the MKS Baratron gauge, and the drift of its zero and span under ambient temperature variation. At 10% of FS the relative accuracy is 134 ppm, yielding 49 ppm accuracy for the measurement of Δp between 100% and 10% FS readings. This and the effective temperature variation yield the reproducibility of

61 ppm for the amount of gas sent from the 10 litre metering volume into the magnet, for an amount of gas making a change of 1 mbar in the pressure of the buffer gas at 1.8 K temperature.

By repeating the metering process N times we can reproduce an earlier setting of the amount of gas in the magnet bore. This process increases the variance of the gas mass at 1 mbar by $\sqrt{N}$, and yields the relative uncertainty in the mass $\delta m/m$ and uncertainty in the absolute equivalent pressure δp_{eq} shown by the Table 2 below.

p_{eq} (mbar)	N	$\delta m/m$	δp_{eq} (mbar)
1	1	0.0061%	$6.11 \cdot 10^{-5}$
10	10	0.0193%	$1.93 \cdot 10^{-3}$
60	60	0.0473%	$2.84 \cdot 10^{-2}$
120	120	0.0669%	$8.03 \cdot 10^{-2}$

Table 2: Reproducibility with which a previous setting of the buffer gas mass can be reproduced, in the terms of relative mass and absolute equivalent pressure, using a 10 litre metering volume. It should be noted that below 10 mbar the step size is 0.0833 mbar, and 0.100 mbar at 60 mbar, as determined by the FWHM of the peak in axion conversion sensitivity in the terms of rest mass at different buffer gas densities.

We may conclude that up to 60 mbar the pressure can be reproduced reasonably well compared with the step size of 0.1 mbar, whereas at 120 mbar it would be desirable to improve the accuracy of the buffer gas mass measurement. This can be probably achieved most easily by increasing the size of the metering volume to 60 litres, in which case $p_{\mathrm{eq}} = 60$ mbar can be reached in 10 steps with 0.0112 mbar reproducibility, and $p_{\mathrm{eq}} = 120$ mbar can be reached in 20 steps with 0.0315 mbar reproducibility. This also speeds up the process of metering, because the thermal equilibrium time of the gas in the metering volume after a pressure change is of the order of 30 minutes. A further significant improvement in the reproducibility can be reached by stabilizing better the local temperature around the pressure gauge, and by further improving the stability of the thermostat of the metering volume.

An alternative more reproducible and faster way of reaching the high-end gas fillings would be to send all gas into the magnet, and then step or ramp down in pressure to the desired value. The pressure and temperature measured in the magnet bore should then be used for estimating a safe overlap between the fillings reached from below and from above.

The ramping is done using mass flow controllers that assure a constant mass flow rate. An additional small hermetic ^{3}He pump allows the removal of gas from the cold bore back to the metering volumes that are used for calibrating integrated readings of the mass flow controller. The reproducibility of the amount of gas after several successive ramps is similar to that of discrete stepping, because the amount of gas is always metered using the thermostated volumes and precise pressure gauges.

3.5. Axion conversion region (cold bore)

The axion conversion region (magnet cold bores) occurs inside two parallel straight pipes of ~10 meter (magnetic length 9.26m) and 43 mm diameter, the pipes are immersed in a transverse magnetic field of 9 Tesla (magnet current 13 kA) produced by the superconducting magnet kept at ~1.8 Kelvin by a superfluid helium cooling circuit. The magnet, mounted on a rotating platform, is kept aligned with the Sun during the experimental runs that take place for 1.5 hours during both the sunrise and the sunset.

Outside the magnetic length the pipe changes diameter (63 mm) until the window surface. The two cold bore pipes are allowed to communicate via two pipes of 35 mm diameter (one at each end of the magnet).

At each end of the cold bores two 15 µm polypropylene windows (thin X-ray windows) confine the gas in the cold region. The cold X-ray windows separate the ^{3}He gas region from the vacuum side connecting to the detectors. Figure 4 shows the extremity of the cold bore on the MRB window. In normal conditions these windows will be facing a unidirectional pressure difference. Depending on the amount of gas in the cold bores the pressure difference can go up to 120 mbar, except during a quench where the pressure can reach higher values. Further details of the windows will be given in section 4.1.

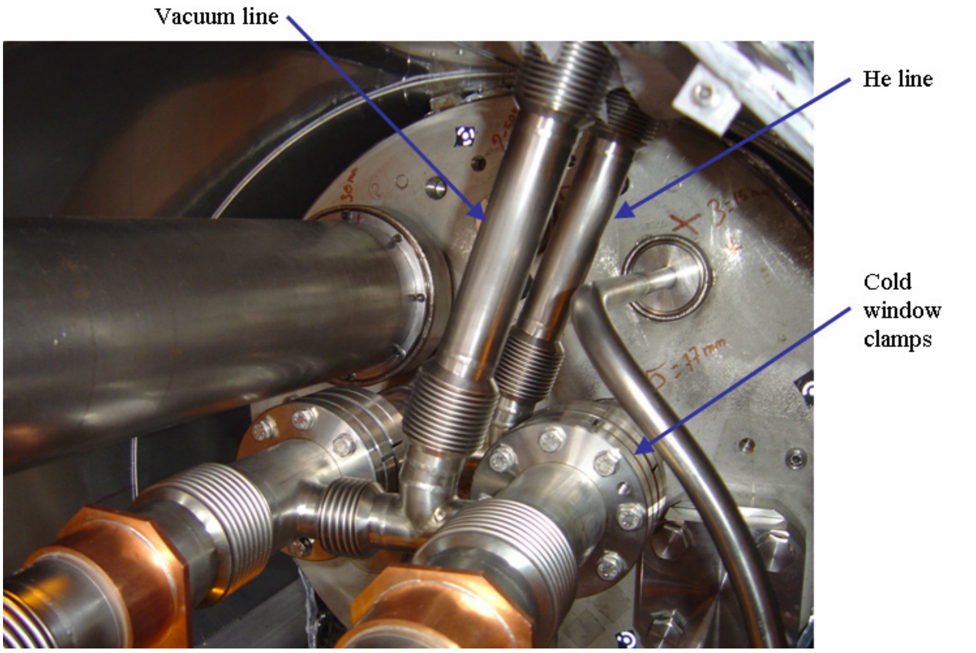


Fig. 4 – Picture of magnet extremity on the MRB side. The window flanges and clamps are indicated, the cold windows separate the magnet cold bore region that will be filled with gas from the vacuum side that leads to the detectors. Two near-vertical lines connect both systems to the outside of the cryostat at room temperature. Beyond the window flanges (hidden in the picture), the two parallel cold bore tubes enter the magnet, then traverse its entire length of 10m and connect to the MFB side.

The temperature of the windows can be modified, over a certain range, using heaters on the window flanges nearby. If no heating power is applied, the window foil becomes the coldest spot of the vacuum system, causing desorbed gases from surfaces to be cryo-pumped onto the window foil. The accumulation of frozen gases in a layer on the foil reduces the X-ray transmission. For layer thicknesses near to the wavelength of light, interference effects are produced and with appropriate backlighting, *dark spots* on the surface of the foil can be observed. The constant heating of windows is a preventive way to reduce the formation of *dark spots*, but also permits scheduled warming (bake-outs) to assure that any frozen gases are released from the window foil. Further details will be given in section 4.14.

3.6. Valves for preventing thermo-acoustic oscillations

The 35 mm pipes linking the cold bore tubes to the room-temperature pipework must be closed at the cold end, in order to avoid thermo-acoustic oscillations. These oscillations were precisely characterized during the first tests with ^{4}He, and they were eliminated by laminar-flow elements with large flow resistance, installed at the exits of the cold bore tubes. These reduce the gas flow severely in the viscous regime, while impeding relatively less the evacuation speed when the pressure and temperature reach molecular flow conditions. As the ^{4}He system will not be operated above the saturation pressure of 16 mbar at 1.8 K temperature, the pressure during a full quench of the magnet will reach no more than 360 mbar, and therefore no particular protection will be required for the cold X-ray windows.

For ^{3}He these laminar-flow elements must be replaced by cryogenic valves, which close well enough to avoid thermo-acoustic oscillations, and which open quickly enough to permit the rapid evacuation of the gas during a quench. These valves are V_{check_F} that opens at 30 mbar forward pressure, and the electro-pneumatic cryogenic valve V_{cryo_R} that is normally open. These valves are bypassed by small needle valves V_{cryo_F1} and V_{cryo_R1} that can be adjusted so that no oscillation will start, and that allow rapid equilibration of the pressure between the cold bore volume and the pipework leading to room temperature. The needle valve on the MFB side also enables accurate monitoring of the cold bore pressure using the B_{100} MKS Baratron pressure gauge.

3.7. Expansion volume and recovery of ^{3}He triggered by the magnet quench

During a quench the temperature of the magnet rises rapidly. If the cold volume remains closed, the gas pressure will rise proportionately as shown by Figure 3. When operating close to the saturation pressure of ^{3}He at 1.8 K the peak pressure would reach about 2.8 bar. This puts in danger the integrity of the X-ray windows, and forces to evacuate the gas sufficiently fast to keep the pressure below the safe operating pressure of the windows.

The cryogenic valves V_{check_F} and V_{cryo_R} , and the expansion volume provide a first safety to the system. The expansion volume is calculated in such way that the maximum pressure reached at the cold windows should be ≤ 1200 mbar in the worst case where the ^{3}He pump does not start and the full inventory of gas is in the cold bore when the quench happens. This corresponds to the situation of an electrical power failure, which happens typically 5 times per year of CAST operation. The expansion volume initially under vacuum thus acts as a buffer volume for the gas coming out of the cold bore during a quench.

The expansion volume is a pipe of 250 mm diameter and approximately 10 m length. All entry connections are equipped with metallic seals, because the gas coming out of the cold bore during a quench is cold. The gas will reach practically stagnation conditions after conical entry transitions, which increase the gas temperature and pressure. The gas will subsequently warm up in the large pipe before entering the main pump at a temperature close to ambient.

Further details will be presented in section _4.4.

3.8. Safety interlocks

The safety interlocks are to be powered by UPS equipment. The valves shutting off all outlets of the vacuum side of the cold X-ray windows are interlocked with a power failure, with a quench, and with a degradation of the vacuum (indicating possible rupture of any of the windows). Any of these conditions therefore isolates the volume towards the detectors by closing valves VT1, VT2, VT3 and VT4, and towards the vacuum pumps by closing the electro-pneumatic valves at their inlets. This action minimizes possible loss of ^{3}He in all scenarios that can endanger the integrity of the cold X-ray windows.

In case of power failure, and since most quenches result from power failures, valves V_{EP_F}, V_{EP_R}, V_{EP_expan} should automatically switch to their normally open position, allowing the gas in the cold bore to flow to the expansion volume. This provides a passive security in case of a quench due to a power failure, UPS power failure, and failure of the interlock system. The maximum pressure is thus reduced below 1.2 bar, which will be well below the rupture limit of the cold X-ray windows.

A quench triggers the interlock system to command the opening of the valves V_{EP_F}, V_{EP_R}, V_{EP_expan} connecting the cold bore to the expansion volume. The chain of actions will then depend on the amount of gas in the cold bore. If the pressure on the cold bore at 1.8 K is lower than 80 mbar, the maximum pressure after a quench will be below 500 mbar and well below the rupture limit of the cold X-ray windows.

If the pressure on the cold bore at 1.8 K is higher than 80 mbar, the interlock system will choose between two options of the recovery of ^{3}He, depending on whether the pump P_{3He} can run or not. If there is electrical power and the pump can run, the ^{3}He gas expanded into the expansion volume is pumped to the storage volume by opening the electropneumatic valves V_{EP_expan} and V_{002}, and by starting the pump P_{3He} immediately. The valves V_{001} and V_{004} are also interlocked so that they are forced to close, if they were open at this moment.

If the quench is caused by a power failure, or if the power fails after the quench trigger so that the pump cannot run, or if the pump fails to run because of its own interlocks (cooling water, overcurrent, jam of the rotor), the valve V_{004} is forced to open, thus permitting the gas to expand also from the first expansion volume to the storage volume, which is sufficiently large to contain the full inventory of the gas at a pressure below atmospheric.

The table of Annex 6.4 summarises the different failure scenarios and the actions that will be taken to ensure safety and limit the risk of loss of ^{3}He.

The table of Annex 6.6 summarises the position of the electrically powered valves in case of power failure.

3.9. Normal recovery of ^{3}He

There will be need to recover the ^{3}He from the cold bore volume at least on the following occasions:

- Maintenance or failure of the cryogenic circuits (liquifier/refrigerator, compressors, cooling water circuits, ^{4}He pumps etc.)
- Warm-up of the magnet for any other reason
- Bake-out of the X-ray windows (approximately once each month)
- End of the run
- End of the experiment

The recovery will be done by using the hermetic pump P_{3He} that reaches the ultimate partial pressure of helium below 10^{-3} mbar. The recovered helium contains oil vapour, but oil mist will be separated by a mist filter (coalescer) right after the pump. The oil accumulated in the filter will be automatically evacuated back to the entry of the pump.

Note that the storage volume can be entirely emptied into the cold volume by evacuating it by the pump P_{3He} *via the valves* V_{001} *and* V_{006}.

3.10. Pump Oil Purge system

Before using the hermetic rotary vane pump P_{3He} for helium, the oil must be purged of light vapours, water and other contaminants. The most suitable purge gas for this operation is dry N_2. The purge system is connected to valves V_{P01} and V_{P02}, and it consists of a small rotary vane pump for initial and final evacuation, a cylinder of dry N_2 with a pressure reducer, a helium leak detector, and a floating bead flowmeter. A cooled trap enables to monitor the cleanness of the nitrogen exhausted by P_{3He} during the purge. During the purge the pump will be operated as warm as possible, in order to speed up the evacuation of the oil contaminants.

The leak tightness of the pump will be tested during the purge by a helium leak detector.

Helium is not used for the purge operation because it would make leak testing impossible, and because it is desirable to keep the ^{3}He as free as possible of ^{4}He. The residues of nitrogen remaining in the oil will be removed by the liquid nitrogen cooled charcoal trap of the Purifier Trap System before precise metering and admission into the cold bore tubes.

3.11. ^{3}He Transfer System

The system allows the transfer the ^{3}He gas securely from its transport cylinders into the hermetic gas system of CAST. The transfer system is connected to the same ports as the pump oil purge system, and it consists of a small vacuum pump, precise manometers, progressively opening metallic valves, a leak detector, and a hermetic pressure reducer if the cylinder pressure is so high that manual valves alone cannot be used.

After evacuation and leak testing of the gas transfer pipework, the pressurized cylinder is opened to a manometer, which measures the initial pressure. The gas is then released through a small needle valve and V_{P01} into the Storage Volume until the pressures are equal in the cylinder and the Storage. The rest of the gas in the cylinder is then evacuated using the main pump P_{3He}.

This transfer system does not have a compressor to send the gas back to the transport cylinder after the experiment is terminated. A hermetic compressor can be added to it at the time when the gas will be shipped back to LLNL.

3.12. Purifier Trap and Trap Purge Systems

The ^{3}He will be purified before metering and introduction into the cold bore tubes, as was discussed above. This is done in two steps: in a charcoal trap at room temperature, before entering into a liquid nitrogen cooled charcoal trap. The first removes any residues of water, oil vapours and other condensable or heavy impurities, whereas the second removes all other gases except helium.

The traps must be regenerated from time to time. The charcoal of room temperature trap will be replaced by a new charge activated at a high temperature. The charcoal in the LN_2-cooled trap will be regenerated by warming it up to 150 °C and then purging it with dry N_2 before evacuating and cooling down.

The Trap Purge System has a vacuum pump, a leak detector, a cylinder of dry N_2 and pressure reducer, an oven that clamps onto the LN_2-cooled trap, and metallic valves that allow the practical execution of all operations.

3.13. ^{3}He Transport

The ^{3}He gas will be sent from and to LLNL in pressurized cylinders using special sea transport. The gas will be insured during the transport.

As was described above, the ^{3}He transfer system can be used for compressing the gas back to the transport cylinders. In order to do this, LLNL should send a suitable compressor to CERN. Otherwise, the transport back should be made in the CAST storage vessel, which has about 1 m^3 volume.

3.14. Window rupture risk analysis

The X-ray windows are clearly the weakest part of the hermetic gas system. The windows have a strongback on the vacuum side and they are tested to withstand 1.2 bar pressure difference between the cold bore and the vacuum. They may break at substantially higher pressure, and will certainly fail already at much lower pressure applied on the vacuum side. There will therefore be precautions against the loss of ^{3}He in the event of a rupture of one of the windows.

At least the following scenarios can lead to a rupture of one of the windows:

- A large leak of air into the part of the ^{3}He pipework that is open to the cold bore tubes. The cryopumped air would accumulate on the cold surfaces, and would degas during a wrong manipulation of the cryogenic circuit. This could potentially give pressure that could endanger the windows, if the ^{3}He system would not be evacuated and monitored during the magnet warm-up. It should be noted, however, that a quench raises the temperature of the magnet bores only to about 40 K temperature, which is too low for the cryopumped air to degas.
- A wrong manipulation or a large air leak in the vacuum side of the window causing it to break because of a pressure gradient in the wrong direction.
- A small leak of a detector window, followed by the cryopumping of one of the detector gas components onto the cold surfaces of the vacuum pipe between the two windows. This would require, however, that the cryogenic circuit is not operated under normal conditions, where there is no risk of cryopumping of any of the main components of the detector gases.
- A mechanical failure of a window caused by fatigue.
- A mechanical failure of the window caused by unknown factors.

In all of the above scenarios the gas confined inside the cold bore could flow through the broken window and be pumped out by the vacuum pumps that evacuate continuously the sector of beam tubes between the windows of the detectors and the cold windows.

To avoid such a release of ^{3}He into air, the following interlocks will be implemented:

- In case of quench, the electromagnetic valves VT1, VT2, VT3, VT4, must immediately close to protect the detectors of contamination or unwanted pressurization (this is already an established procedure).
- In case of a cold window rupture, the vacuum side of the window will need to be isolated from the vacuum pumps and from the detectors. This will be implemented by monitoring the pressure on the vacuum side using several highly reliable Pirani vacuum gauges, and in case of rapid rise of pressure, valves will close to isolate the lines. After that the ^{3}He gas (possibly slightly contaminated by the gases that leaked in) will be pumped back to the storage tank, and the cold windows will be repaired.

It should be noted that in these interlocks, ordinary UHV gauges cannot be used because of their inherent instabilities that would cause frequent unwanted ^{3}He pump-outs.

The purification of the ^{3}He gas after a contamination will take place by sending the whole inventory through the traps to the magnet bore tubes, and then pumping it back to the storage vessel. The traps and the 1.8 K cold bores will remove all possible impurities except ^{4}He.

4. DESIGN OF THE MAIN SECTIONS

4.1. X-ray windows

The cold thin X-ray windows that are now used in the ^{4}He runs, consist of a cylindrical stainless steel part (316LN) with CF63 flanges. On one side a strongback is machined by electro-erosion. This consisting of 5.2 mm square mesh, with 0.3 mm wide and 5 mm deep struts that serve as supports for the window foil. The strongback is then briefly electro-polished to remove any sharp edges on the edges of the struts. The 15 µm thick polypropylene foil is glued onto the frame and strongback struts using Araldite 2018 glue, and a stainless steel top ring is glued both to the polypropylene foil and to the flange to give extra resistance against peeling and to provide mechanical protection. The design of the window is shown in Figure 5.

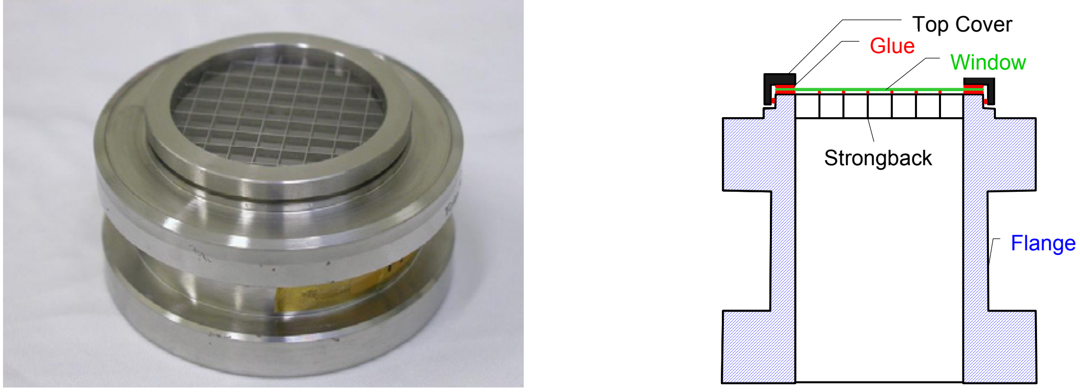


Figure 5 a and b – Picture and cross-section of the present cold thin X-ray window

The X-ray windows were leak and pressure tested in CERN Cryolab in the temperature range from 300 K to 1.8 K, and in the pressure range from 0 mbar to 1000 mbar. After their installation in the magnet, the total leak rate at room temperature was similar to the sum of the individual window leak rates, and at the normal window operating temperature of around 120 K the total leak is < 1.10^{-7} mbar l/s. This leak is characteristic of diffusion through the 15 µm thick polypropylene film of the windows.

In order to test the resistance against sudden pressure rise due to a quench at low temperature, the windows were subjected in CERN Cryolab to a repetitive sudden pressure rise from 0 mbar to 300 mbar at 4.2 K, with a total of 10 cycles. The windows showed no mechanical deterioration and remained leak tight during and after the tests.

A window with a 23 µm thick Mylar foil was also successfully tested at room temperature for a sudden pressure rise of 4 bar in Saclay; although the foil did not break, the strongback probably deformed slightly.

These results give us enough confidence to proceed with the same type of windows for ^{3}He, although additional tests of sudden rise of pressure from 0 bar to 1.2 bar at 120 K operating temperature are mandatory and are planned for the coming months.

4.2. Storage tank volume

We require that the storage volume be dimensioned to contain the entire inventory of the ^{3}He gas at a pressure below atmospheric. Its volume can then be estimated according to the formula:

$$\frac{P_{store} \cdot V_{store}}{T_{sore}} = SF\left[\frac{P_{cb}^{n} \cdot V_{cb}}{T_{cb}^{n}} + \sum_{regions} \frac{PV_i}{T_i}\right]$$

The left hand term is the amount of gas in the storage volume, the right hand multiplier is the safety factor $SF = 1.2$, and the terms in the brackets are the amount of gas in the cold bore for the highest pressure setting and the amount of gas in the dead volumes, notable those between the main pump and the storage tank, and the metering volumes.

At the highest steps of ^{3}He density (already well below the equivalent pressure of saturation, i.e. 135.58 mbar), the pressure in the storage volume will too low to fill the metering volumes up to a pressure required to make a step in the amount of gas in the cold bores. Because of this, the ^{3}He pump will be used for pressurizing the gas before sending it through V_{001} to the metering volumes.

The table resumes the properties of the gas in different regions:

	p [mbar]	*V* [litre]	*T* [K]	*SF* x *n* [mol]
Cold Bore	140	30	1.8	33.7
Other volumes (RT)	800	10	310	0.4
Other Volumes (OT)	800	10	77	1.5
Total				35.6

The total amount of moles needed is 36.9 mol. The storage volume will be maintained below atmospheric pressure (assume 900 mbar) and at ambient temperature (assume 293 K).

The following table resumes the properties of the volume.

	p [mbar]	*V* [litre]	*T* [K]	*n* [mol]
Storage volume	900	963	293	35.6

The volume of the storage tank would be 963 litres. To give an idea of the dimensions it would be a cylinder shape of about 800 mm diameter and 2000 mm length (standard dimensions to be checked). The estimated weight is about 300 kg. It should be made to withstand vacuum (avoiding elastic instability), and to withstand 500 mbar overpressure with respect to atmospheric pressure.

4.3. Metering Volumes

There should be 2 metering volumes to be placed inside the thermostatic bath(s). One small volume will be specifically for two density settings in the cold bore per solar tracking, the second volume will be used specifically for pressure ramping over a range of up to 10 density steps. The thermostatic bath should keep the temperature of the volumes constant at (36 ± 0.1) °C, for accuracy the size of the piping and other dead volumes outside the metering volumes should be minimized to avoid systematic errors due to ambient temperature variations.

	dp [mbar]	*V* [litre]	*T* [K]	*dn* [mol]
Cold Bore	2x0.1	30	1.8	0.04
Cold Bore	10x0.1	30	1.8	0.20

The metering volumes for should be:

	dp [mbar]	*V* [litre]	*T* [K]	*dn* [mol]
Metering Volume (MV#2)	600	1.63	309	0.04
Metering Volume (MV#10)	600	8.58	309	0.20

The volume of MV#2 would be of 1.63 litres. To give an idea of the dimensions it would be a cylinder shape of about 83 mm diameter and 300 mm length. The volume of MV#10 would be of 8.58 litres. To give an idea of the dimensions it would be a cylinder shape of about 190 mm diameter and 300 mm length. Both should be able to withstand vacuum and pressure up to 1500 mbar.

4.4. Expansion volume

The expansion volume is designed to collect the gas rushing out of the cold bore during a quench, so as to keep the maximum pressure inside the cold bore below 1200 mbar (without the ^{3}He hermetic pump running).

When a quench trigger signal is received, the interlock system will open the electro-pneumatic valves placed on both sides of the magnet, thus connecting the cold bore to the expansion volume. The hermetic ^{3}He pump will start running and another electro-pneumatic valve will allow the gas to be pumped from the expansion volume back to the storage tank. It is expected that the pressure in the cold bore will be lower due to the active pumping, but for the design we shall adopt the worst case scenario, where the pump or the electro-pneumatic valve connecting to the pump do not work properly. This may happen for example when the quench is caused by a power failure.

The expansion volume will be at room temperature, because there is no place available inside the cryostat, and the cooling power of the magnet is already near its limit. It will be placed alongside the cryostat and connected at both ends by electro pneumatic valves to the gas lines connecting to the cold bore. It will have around 10 m length; its size and shape are mainly restricted by the chariot that holds the screws for the vertical pivoting of the magnet.

Our quench tests with ^{4}He have shown that during a quench the pressure increases by a factor of 14 in the first 3 seconds and by a factor of 21 in the first 200 seconds, as shown by Fig. 3.

The worst case scenario would be in the last pressure setting 140 mbar (~33.7 mol of gas in the cold bore). The following formula summarises the mass balance:

$$SF\left.\frac{PV}{RT}\right|_{CB,beforequench}+\left.\frac{PV}{RT}\right|_{EV,beforequench}=P_{MAX}\left(\left.\frac{V}{RT}\right|_{CB,afterquench}+\left.\frac{V}{RT}\right|_{EV,afterquench}\right)$$

The expansion volume is kept in passive vacuum and thus the second term of the equation falls to zero, p_{MAX} = 1200 mbar, and the temperature of the cold bore after the quench will increase from 1.8 K to 37.8 K(x21). A Safety Factor of SF=1.2 was used here.

If the expansion volume of 450 litres is distributed along 10 meters, it must have a diameter of about 240 mm. The standard sizes of piping are 250 mm inner diameter and thus the expected maximum pressure is about 1100 mbar (including SF of 1.2). The estimated weight is about 300 kg.

4.5. Hermetic ^{3}He pump

The main hermetic ^{3}He pump has the tasks to empty the ^{3}He from the cold bore tubes into the storage reservoir, and, in the case of a quench, to recover the gas from the expansion volume back to the storage volume. The pump will also be needed for compressing the ^{3}He into the metering volumes, when the storage pressure is lower than the pressure required to fill these volumes. The specified pumping speed is 65 m^3/h and the pump weighs about 80 kg.

4.6. Trap purge system

During maintenance periods this mobile gas handling system is connected to the valves V_{TP1} and V_{TP2} that give external access to the otherwise-closed gas circuit. The charcoal of the room temperature trap will be replaced by a new charge activated at a high temperature. The charcoal in the LN_2-cooled trap will be regenerated by warming it up to 150 °C and then purging it with dry N_2 before evacuating and cooling down. The purge operation will take about 8 hours.

The Trap Purge System has a vacuum pump, a leak detector, a cylinder of dry N_2 and pressure reducer, an oven that clamps onto the LN_2-cooled trap, and metallic valves that allow the practical execution of all operations.

4.7. ^{3}He transfer system

This mobile gas handling system consists of a small vacuum pump, precise manometers, progressively opening metallic valves, a leak detector and a hermetic pressure reducer if the cylinder pressure is so high that manual valves alone cannot be used. The main pump will be used for the complete evacuation of the gas from its transport cylinder.

4.8. Oil purge system

This mobile gas handling system injects dry N_2 to the inlet of a pump for purging the pump oil. The nitrogen gas ballasts condensable vapours such as water and light hydrocarbons out of the pump oil. The purge system is connected to valves V_{P01} and V_{P02}, and it consists of a small rotary vane pump for initial and final evacuation, a cylinder of dry N_2 with a pressure reducer, a helium leak detector, and a floating bead flowmeter. A cooled trap enables to monitor the cleanness of the nitrogen exhausted by P_{3He} during the purge. During the purge the pump will be operated as warm as possible, in order to speed up the evacuation of the oil contaminants. The residues of nitrogen remaining in the oil will be removed by the liquid nitrogen cooled charcoal trap of the Purifier Trap System before precise metering and admission into the cold bore tubes.

4.9. Pressure sensors

These MKS Baratron 690 A instruments will allow the pressure to be measured with an absolute accuracy up to 0.05% and a resolution of 10^{-5} of the full-scale reading. One such sensor should be connected to each of the metering volumes (B_{1000a} and B_{1000b}). A third Baratron should be placed in a linking pipe to the cold bore in order to measure the pressure of the gas in the cold bore (B_{100}). This sensor will be placed upstream of the cryogenic needle valve that will have to be open for filling purposes and also in case the pressure of the cold bore needs to be read. These sensors tolerate an overpressure up to 3.1 bar.

4.10. Cryogenic pressure sensors

Cryogenic pressure transducers are foreseen to be installed at each end of the cold bore inside the cryostat, in order to confirm that thermo-acoustic oscillations (TAO) are insignificant. The absolute accuracy of such sensors is low (mainly because of their drift with temperature). Because the natural resonant frequency of the sensor and the bandwidth of their electronics are much higher than the TAO frequencies, these sensors will allow us to monitor and identify possible oscillations (with minimum amplitude ~0.01 mbar).

These sensors work on a pressure range up to 1.7 bar and tolerate an overpressure up to 3.4 bar.

4.11. Vacuum gauges

Vacuum gauges will be installed on several locations to monitor the evacuation of the system. These will be particularly important before ^{3}He is transferred to the system to assure that a good vacuum was achieved and to assure that degassing from surfaces is at a low rate. They are important as well to help in the calibration of the accurate pressure sensors (these need a vacuum better than $1\text{x}10^{-5}$ mbar).

4.12. Pressure manometers

Manometers that will allow the operators to check locally the pressures at critical points, without access to the slow control system. This may be particularly important in the case of power failures or other abnormal conditions.

4.13. Temperature sensors

Temperature sensors of different types will be installed in critical regions, especially in regions near the cold bore, window flanges, filling lines, thermostatic bath, etc. Some of the temperature sensors are needed for correcting the systematic deviations of the amount of gas in the cold bore tubes or in the metering volumes, due to the temperature variations of the parasitic volumes.

4.14. Heaters

Heaters will be installed on the cold window flanges. These will allow, if necessary, to heat and maintain the windows at a constant temperature, and to periodically bake-out possible trapped gases from the X-ray window foils. Figure 6 shows the location of the heaters and details of the two end of the cold bore.

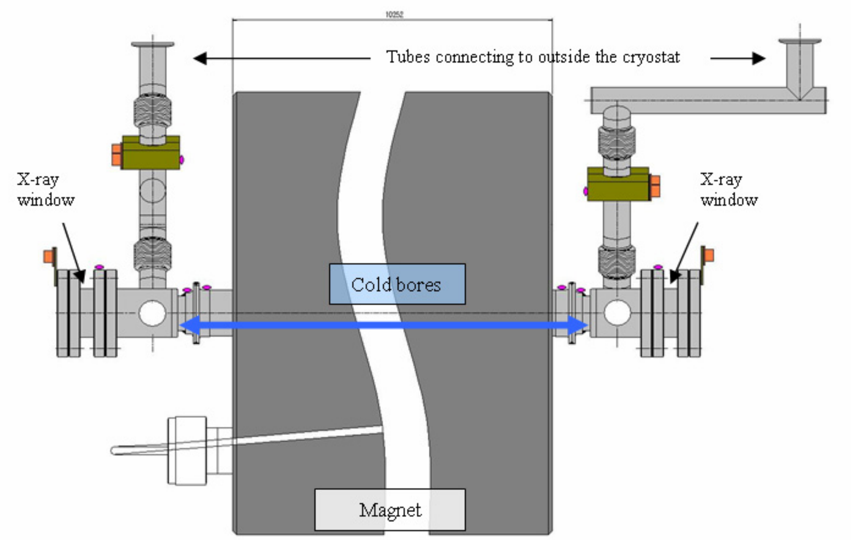


Fig.6 – Representation of the ends of the magnet MRB (left) and MFB (right). Heaters are placed on the cold X-ray windows flanges and represented in orange.

The heating of windows proved to be very useful to avoid gases desorbed from the vacuum side to be cryo-pumped onto the window foil, creating layers of trapped gases that reduce the X-ray transmission. The heating is done by setting the heater power, without feedback. Two different scenarios have to be considered regarding the temperature of the windows:

The first is to keep the window flanges at a temperature of ~120 K that gives a sufficient margin above the coldest point on the vacuum tubes (~70 K, thermalized by the magnet thermal screen). In this case, almost all applied power is transported from the window into the cold bore by convection.

As the convectional heat transfer increases with the pressure, the power to maintain the windows at 120 K might reach an uncomfortable level for the cryogenics. The second scenario avoids this problem by keeping the X-ray window flanges substantially colder. This may require more frequent bake-outs to assure a good transparency of the windows.

The solution adopted so far is to maintain the window flanges at 120 K, and to make monthly bake-outs to assure a good transparency.

4.15. Electro-pneumatic valves (EP valves)

These shut-off valves have different tasks depending of the region where they will be installed. Electro-pneumatic actuators were chosen for their speed and ability to be commanded by the safety interlock system acting on a quench trigger or a power failure. Most of these valves are also located in regions of difficult access requiring a remote operation.

Two electro-pneumatic valves (V_{EP_R} and V_{EP_F}) will be placed at each end of the expansion volume. These should open in case of quench (activated by the *quench trigger*), and remain open until an operator closes them on the panel. It should be possible to open them also from the panel (without quench trigger), but this operation should be restricted to experts with a key.

Another electro-pneumatic valve will be installed on the line connecting the hermetic ^{3}He pump to the expansion volume (V_{EP_expan}). This valve should open in case of quench, if the pump is running.

Valve V_{004} is an electro-pneumatic and is closed in case of quench, avoiding the gas to circulate from the storage volume through the pump.

Additionally, in case the ^{3}He pump fails to start, this valve could be commanded to open if the pressure Pexpan>Pstorage.

Valve V_{002} is an electro-pneumatic and is opened in case of quench, allowing the gas to go to the storage volume.

Valve V_{001} is an electro-pneumatic and is closed in case of quench, to avoid pressurization on the traps.

These electro-pneumatic valves should open at differential pressures higher that 1.5 bar. Compressed air outlets should be foreseen with large buffer volumes and a safety back-up supply to secure pressure during electric power failures. A monitoring and alarm system will be required to trigger valve actions in the event of a decrease in the compressed air pressure.

4.16. Cryogenic check valve

This valve (V_{check_F}) will allow the evacuation of the gas from the cold bore in case of quench, and will be open at 30 mbar differential pressure. The main characteristics are reliability at cryogenic temperatures, a reasonably low in-line leak rate when closed, low differential pressure for opening and high conductance when open.

This valve will be installed inside the cryostat on the gas line that connects the cold bore to the expansion volume on the MFB side. Its size should be minimized because of the very limited space, while the hydraulic diameter should be maximized for a good conductance.

Existing drawings will have to be reviewed, design and integration discussed and finally the modifications defined which will include cutting and welding of pipes in situ.

The diameter of these valves will be around 30 to 40 mm diameter but the final choice will be dependent of the market availability, and should open when a pressure difference higher than 30 mbar is applied.

4.17. Cryogenic valves

These valves will allow the separation and communication between the cold region and the regions at room temperature. Their main purpose is to almost close the buffer gas lines at the highest temperature gradient, in order to eliminate the thermo-acoustic oscillations. These lines cannot be entirely closed, however, because the buffer gas needs to be loaded in and it has to be pumped out, and the cryogenic pressure gauges need to be calibrated against the accurate Baratron sensor outside the cryostat at room temperature.

On the MRB side the valve V_{cryo_R} is used for pumping the cold bore to good vacuum, since on the other side the check valve will only open unidirectionally by pressure gradient. This valve, with a conductance of the same order of magnitude as the existing pipe work, will be closed, except when the cold bore has to be pumped or in case of quench (commanded by quench trigger). The main characteristics are reliability at cryogenic pressures, a reasonably low in-line leak rate when closed, low heat conductance to the magnet and possibility to be remotely commanded. This valve will be installed on the MRB side inside the cryostat on the gas line that connect the cold bore to the expansion volume, and its size should be minimized because of very limited space while maximizing its diameter for a good conductance.

This cryogenic valve and the cryogenic check valve will be bypassed by small cryogenic needle valves V_{cryo_R1} and V_{cryo_F1} to balance the pressure of the gas upstream and downstream, while reducing the flow so as to damp the TAO. These bypass valves are connected with 2 mm capillary tubes, and their orifices have a diameter of 0.7 mm. The needle valves have been used at CERN in the ^{3}He gas systems of dilution refrigerators in polarized targets for decades.

4.18. Dosing valves

The dosing valves will allow the possibility to set a maximum flow speed during transfer processes, this limits the risk of wrong manipulations, but most importantly gives control during fillings.

These valves Vi1, Vi2, Vo1, Vo2, can be manual valves like the existing ones for ^{4}He that include a shut-off valve, or can be electromagnetic valves to be operated remotely.

4.19. Mass flow controllers

The control valves Vmc1 and Vmc2 are part of the mass flow controllers and are operated by an electromagnetic coil, the control is done relative to the set point on the desired mass flow. These flow controllers will enable the ramping of the buffer gas density by providing a constant mass flow rate.

The valve Vmc1 will be used for ramping up the density in the cold bore, and the gas will be driven by the differential pressure between the metering volume and the cold bore. The valve Vmc2 will be used for ramping down the density in the cold bore, and the gas will be driven by the differential pressure between the cold bore and the vacuum at the inlet of the small ^{3}He pump, P^{3}He_a.

4.20. Gate valves

Two gate valves, V_{gate_F}, V_{gate_R}, placed at each end of the gas lines coming from the cold bore will allow to isolate the cold bore and make manipulations on the outside without risk of damaging the windows, or any leakage from the ambient. These valves will be kept open and only be closed in very exceptional conditions. These valves should never be closed when there is gas in the cold bore or with current on the magnet.

4.21. Shut-off valves

There are several shut-off valves placed on different regions of the circuit, basically these valves will allow very rare manipulations and/or be ports for pumping and leak testing. These valves should have a very low leak rate $<10^{-9}$ mbar l/s

4.22. Rupture Disk

In case of accidental conditions where the ^{3}He pump will not automatically start (loss of power, unknown factors) and the pressure during a quench exceeds 1.5 bar, a rupture disk will open the cold bore to the storage volume and the pressure will be equalized below 1 bar. This device provides ultimate safety against the worst failure conditions, including the failure of the safety interlock system.

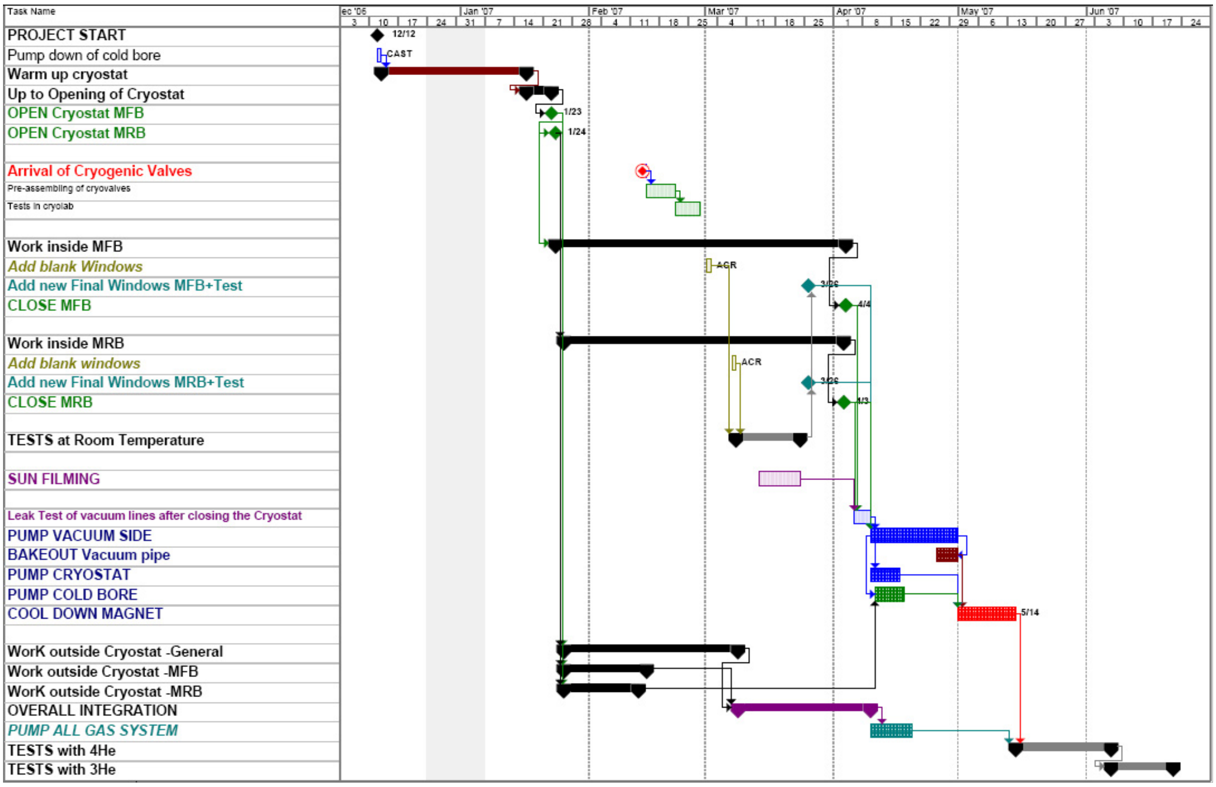
4.23. Valves and fittings

Valves and fittings have to be leak tight to ^{3}He, to avoid any loss of helium all fittings should be preferable UHV fittings or other all-metal sealed connections.

5. PROJECT PLANNING AND COST

The ^{3}He system is to be installed in the beginning of 2007 taking advantage of the planned CERN shutdown and magnet warm-up

The following diagram shows a resumed overview of the main tasks and durations.



Note: The previous map does not take in consideration limitations due to different tasks being done by the same resource at the same time. This will be updated once the final number of resources is given to the project.

Schedule: Milestones:

1) Magnet warm up………………………….. 13-Dec-2006
2) Open cryostat……………………………… 23-Jan-2007
3) Cryogenic valves arrive…………………… 14-Feb-2007
4) Install cold windows………………………. 26-Mar-2007
5) External part of 3he system ready………… 09-Apr-2007
6) Magnet cool down…………………………. 01-May-2007
7) Tests of gas system with ^{4}He……………… 15-May-2007
8) Complete tests with ^{3}He…………………… 21-Jun-2007

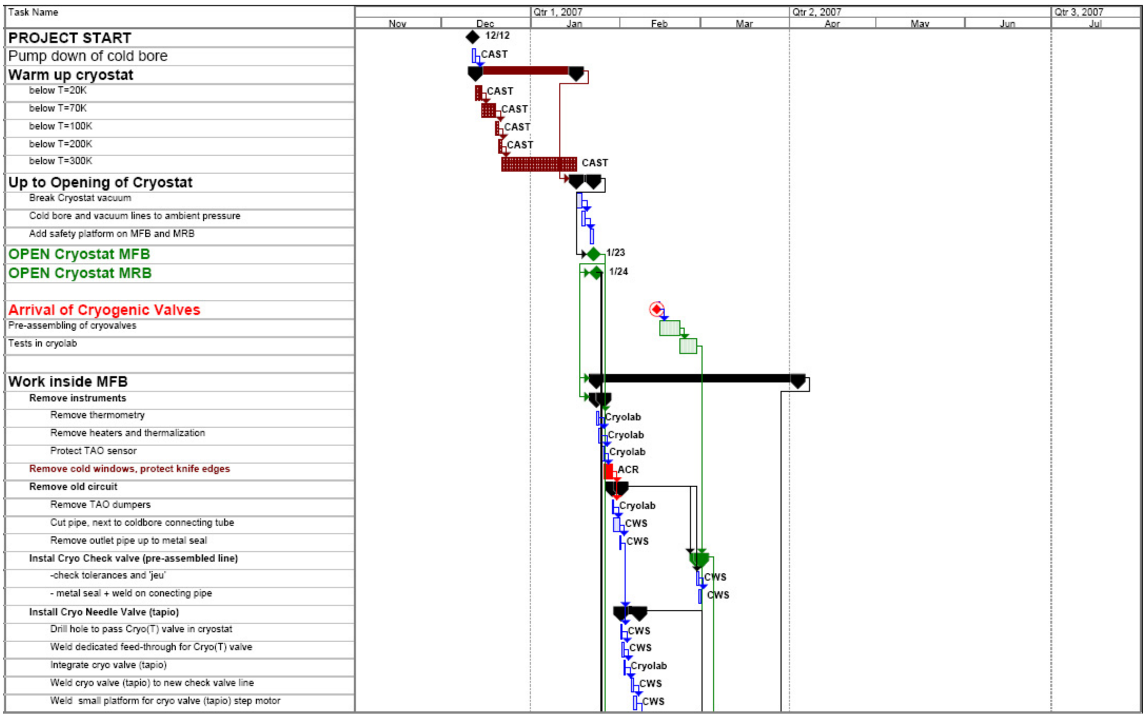
More detailed information can be found in Annex 6.1.

The project cost is estimated to be around 200kCHF, more details in Annex 6.2.

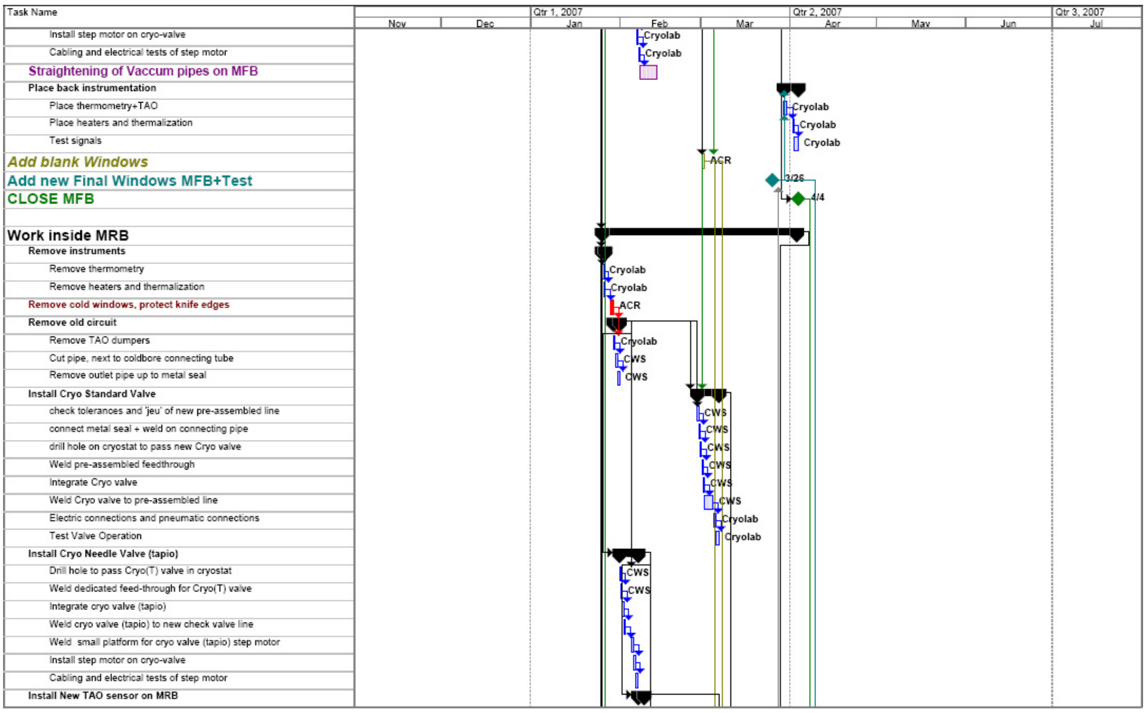
6. ANNEX

6.1. Project planning

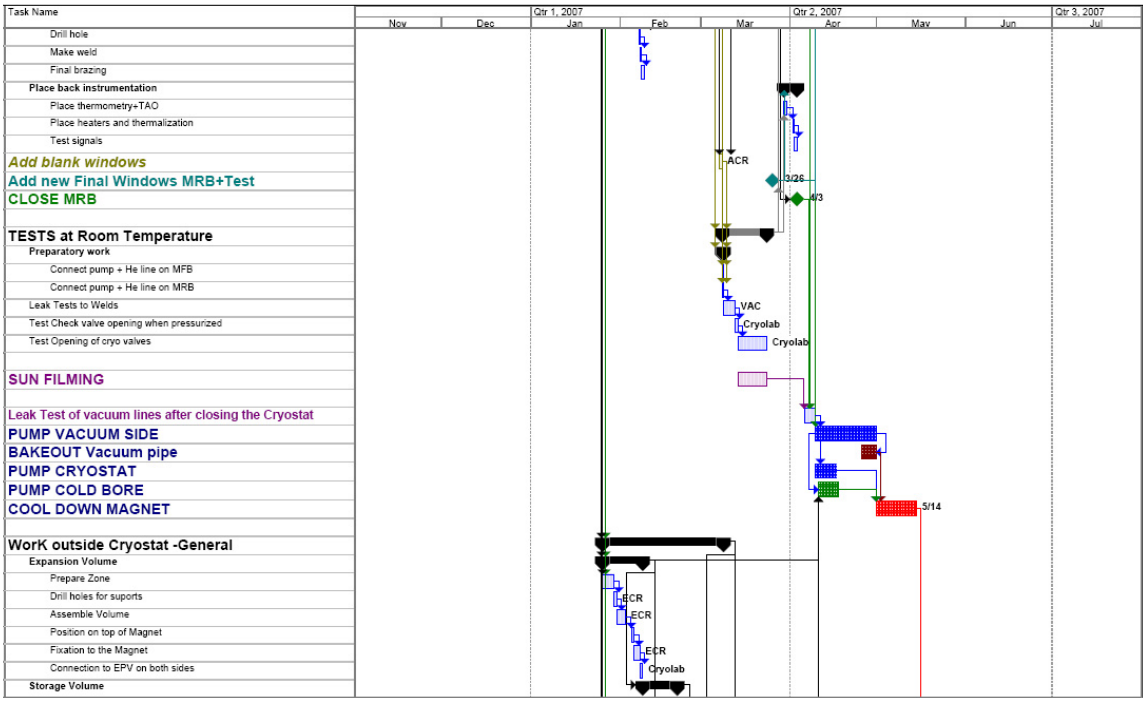
The following pages show the break down structure of the ^{3}He gas system with the estimated time for each task and task dependency. An update will be done once the final number of resources and its availability is known.



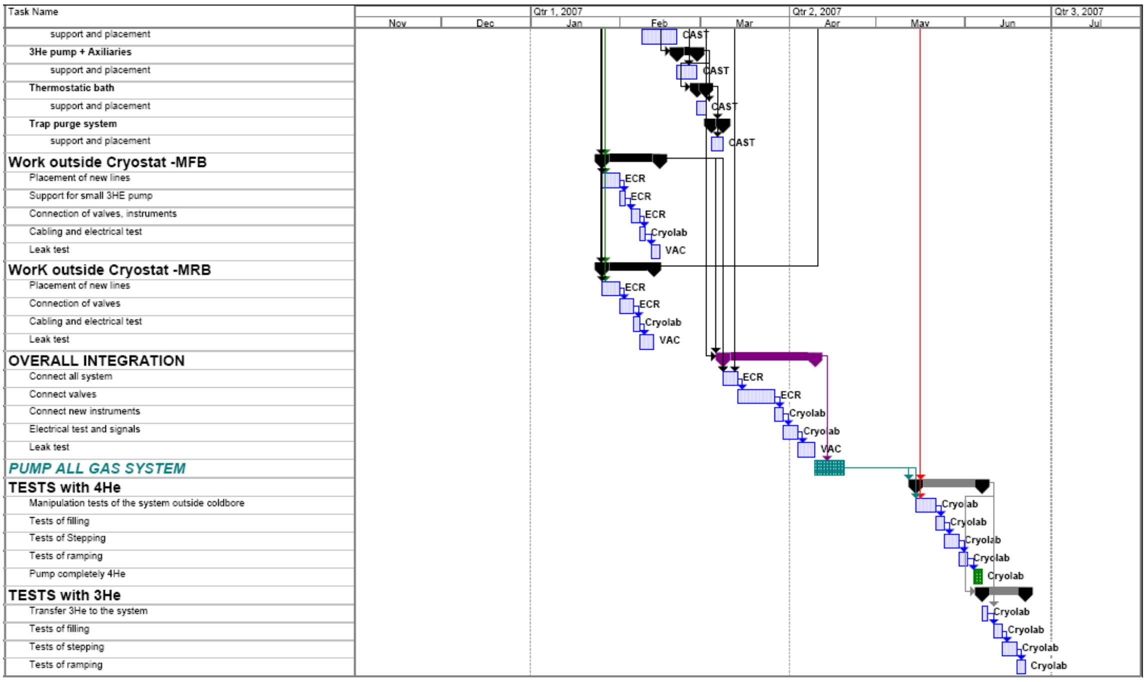
Task Name
PROJECT START
Pump down of cold bore
Warm up cryostat
below T=20K
below T=70K
below T=100K
below T=200K
below T=300K
Up to Opening of Cryostat
Break Cryostat vacuum
Cold bore and vacuum lines to ambient pressure
Add safety platform on MFB and MRB
OPEN Cryostat MFB
OPEN Cryostat MRB
Arrival of Cryogenic Valves
Pre-assembling of cryovalves
Tests in cryolab
Work inside MFB
Remove instruments
Remove thermometry
Remove heaters and thermalization
Protect TAO sensor
Remove cold windows, protect knife edges
Remove old circuit
Remove TAO dumpers
Cut pipe, next to coldbore connecting tube
Remove outlet pipe up to metal seal
Instal Cryo Check valve (pre-assembled line)
-check tolerances and 'jeu'
- metal seal + weld on conecting pipe
Install Cryo Needle Valve (tapio)
Drill hole to pass Cryo(T) valve in cryostat
Weld dedicated feed-through for Cryo(T) valve
Integrate cryo valve (tapio)
Weld cryo valve (tapio) to new check valve line
Weld small platform for cryo valve (tapio) step motor



Task Name
Install step motor on cryo-valve
Cabling and electrical tests of step motor
Straightening of Vaccum pipes on MFB
Place back instrumentation
Place thermometry+TAO
Place heaters and thermalization
Test signals
Add blank Windows
Add new Final Windows MFB+Test
CLOSE MFB
Work inside MRB
Remove instruments
Remove thermometry
Remove heaters and thermalization
Remove cold windows, protect knife edges
Remove old circuit
Remove TAO dumpers
Cut pipe, next to coldbore connecting tube
Remove outlet pipe up to metal seal
Install Cryo Standard Valve
check tolerances and 'jeu' of new pre-assembled line
connect metal seal + weld on connecting pipe
drill hole on cryostat to pass new Cryo valve
Weld pre-assembled feedthrough
Integrate Cryo valve
Weld Cryo valve to pre-assembled line
Electric connections and pneumatic connections
Test Valve Operation
Install Cryo Needle Valve (tapio)
Drill hole to pass Cryo(T) valve in cryostat
Weld dedicated feed-through for Cryo(T) valve
Integrate cryo valve (tapio)
Weld cryo valve (tapio) to new check valve line
Weld small platform for cryo valve (tapio) step motor
Install step motor on cryo-valve
Cabling and electrical tests of step motor
Install New TAO sensor on MRB

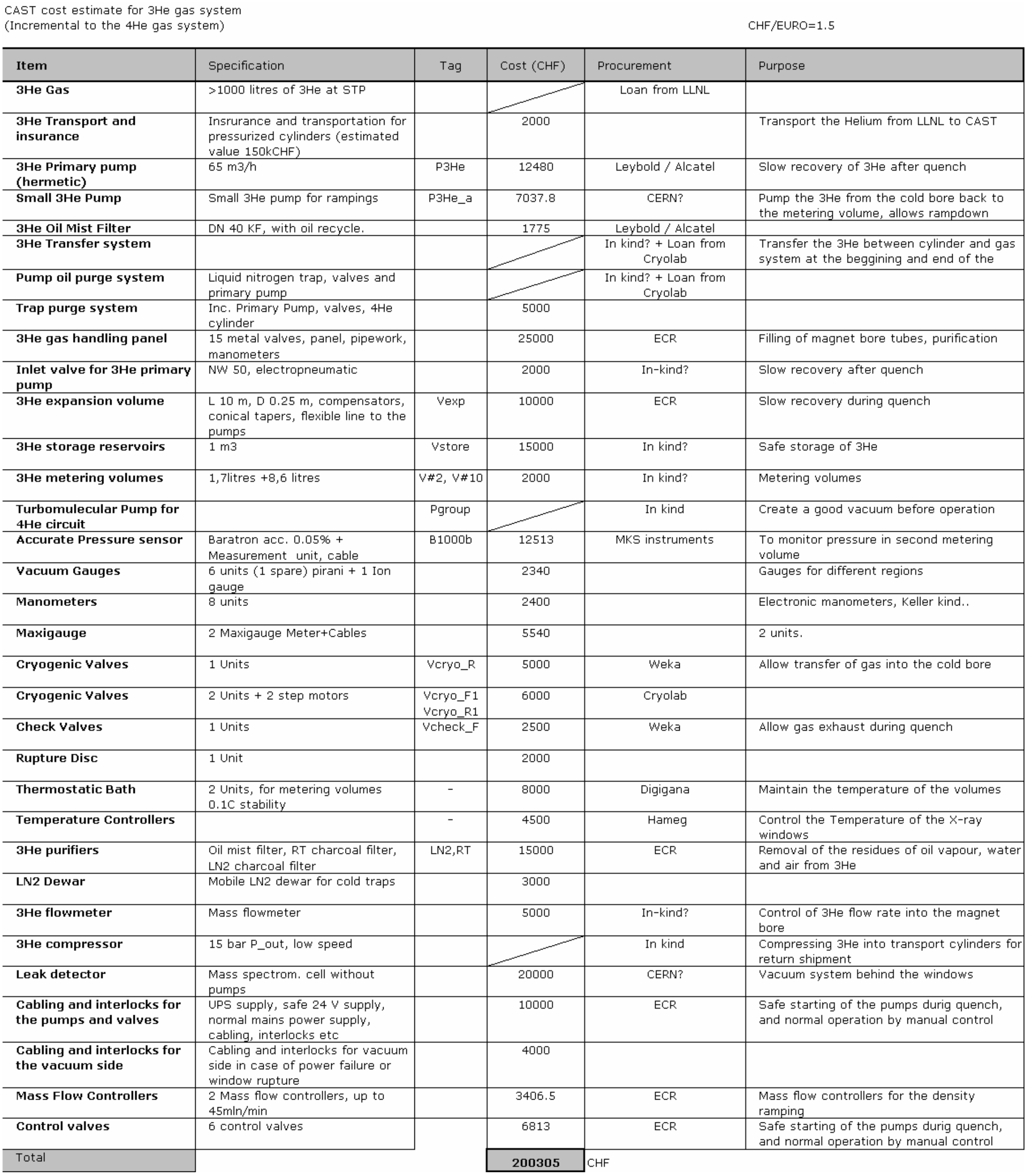


Task Name
Drill hole
Make weld
Final brazing
Place back instrumentation
Place thermometry+TAO
Place heaters and thermalization
Test signals
Add blank windows
Add new Final Windows MRB+Test
CLOSE MRB
TESTS at Room Temperature
Preparatory work
Connect pump + He line on MFB
Connect pump + He line on MRB
Leak Tests to Welds
Test Check valve opening when pressurized
Test Opening of cryo valves
SUN FILMING
Leak Test of vacuum lines after closing the Cryostat
PUMP VACUUM SIDE
BAKEOUT Vacuum pipe
PUMP CRYOSTAT
PUMP COLD BORE
COOL DOWN MAGNET
WorK outside Cryostat -General
Expansion Volume
Prepare Zone
Drill holes for suports
Assemble Volume
Position on top of Magnet
Fixation to the Magnet
Connection to EPV on both sides
Storage Volume



Task Name
support and placement
3He pump + Axiliaries
support and placement
Thermostatic bath
support and placement
Trap purge system
support and placement
Work outside Cryostat -MFB
Placement of new lines
Support for small 3HE pump
Connection of valves, instruments
Cabling and electrical test
Leak test
WorK outside Cryostat -MRB
Placement of new lines
Connection of valves
Cabling and electrical test
Leak test
OVERALL INTEGRATION
Connect all system
Connect valves
Connect new instruments
Electrical test and signals
Leak test
PUMP ALL GAS SYSTEM
TESTS with 4He
Manipulation tests of the system outside coldbore
Tests of filling
Tests of Stepping
Tests of ramping
Pump completely 4He
TESTS with 3He
Transfer 3He to the system
Tests of filling
Tests of stepping
Tests of ramping

6.2. Project Cost Estimate



CAST cost estimate for 3He gas system
(Incremental to the 4He gas system)

CHF/EURO=1.5

Item	Specification	Tag	Cost (CHF)	Procurement	Purpose
3He Gas	>1000 litres of 3He at STP			Loan from LLNL	
3He Transport and insurance	Insrurance and transportation for pressurized cylinders (estimated value 150kCHF)		2000		Transport the Helium from LLNL to CAST
3He Primary pump (hermetic)	65 m3/h	P3He	12480	Leybold / Alcatel	Slow recovery of 3He after quench
Small 3He Pump	Small 3He pump for rampings	P3He_a	7037.8	CERN?	Pump the 3He from the cold bore back to the metering volume, allows rampdown
3He Oil Mist Filter	DN 40 KF, with oil recycle.		1775	Leybold / Alcatel	
3He Transfer system				In kind? + Loan from Cryolab	Transfer the 3He between cylinder and gas system at the beggining and end of the
Pump oil purge system	Liquid nitrogen trap, valves and primary pump			In kind? + Loan from Cryolab	
Trap purge system	Inc. Primary Pump, valves, 4He cylinder		5000		
3He gas handling panel	15 metal valves, panel, pipework, manometers		25000	ECR	Filling of magnet bore tubes, purification
Inlet valve for 3He primary pump	NW 50, electropneumatic		2000	In-kind?	Slow recovery after quench
3He expansion volume	L 10 m, D 0.25 m, compensators, conical tapers, flexible line to the pumps	Vexp	10000	ECR	Slow recovery during quench
3He storage reservoirs	1 m3	Vstore	15000	In kind?	Safe storage of 3He
3He metering volumes	1,7litres +8,6 litres	V#2, V#10	2000	In kind?	Metering volumes
Turbomulecular Pump for 4He circuit		Pgroup		In kind	Create a good vacuum before operation
Accurate Pressure sensor	Baratron acc. 0.05% + Measurement unit, cable	B1000b	12513	MKS instruments	To monitor pressure in second metering volume
Vacuum Gauges	6 units (1 spare) pirani + 1 Ion gauge		2340		Gauges for different regions
Manometers	8 units		2400		Electronic manometers, Keller kind..
Maxigauge	2 Maxigauge Meter+Cables		5540		2 units.
Cryogenic Valves	1 Units	Vcryo_R	5000	Weka	Allow transfer of gas into the cold bore
Cryogenic Valves	2 Units + 2 step motors	Vcryo_F1 Vcryo_R1	6000	Cryolab	
Check Valves	1 Units	Vcheck_F	2500	Weka	Allow gas exhaust during quench
Rupture Disc	1 Unit		2000		
Thermostatic Bath	2 Units, for metering volumes 0.1C stability	-	8000	Digigana	Maintain the temperature of the volumes
Temperature Controllers		-	4500	Hameg	Control the Temperature of the X-ray windows
3He purifiers	Oil mist filter, RT charcoal filter, LN2 charcoal filter	LN2,RT	15000	ECR	Removal of the residues of oil vapour, water and air from 3He
LN2 Dewar	Mobile LN2 dewar for cold traps		3000		
3He flowmeter	Mass flowmeter		5000	In-kind?	Control of 3He flow rate into the magnet bore
3He compressor	15 bar P_out, low speed			In kind	Compressing 3He into transport cylinders for return shipment
Leak detector	Mass spectrom. cell without pumps		20000	CERN?	Vacuum system behind the windows
Cabling and interlocks for the pumps and valves	UPS supply, safe 24 V supply, normal mains power supply, cabling, interlocks etc		10000	ECR	Safe starting of the pumps durig quench, and normal operation by manual control
Cabling and interlocks for the vacuum side	Cabling and interlocks for vacuum side in case of power failure or window rupture		4000		
Mass Flow Controllers	2 Mass flow controllers, up to 45mln/min		3406.5	ECR	Mass flow controllers for the density ramping
Control valves	6 control valves		6813	ECR	Safe starting of the pumps durig quench, and normal operation by manual control
Total			**200305**	CHF	

‘In kind’ means that the item can be found/ produced in one of the collaborating institutes, and the cost can be reduced.

6.3. Main Work packages

- WP1 Platform for ^{3}He pump
- WP2 Design of the integration of new cryogenic and check valves inside the cryostat.
- WP3 Modifications of gas lines inside the cryostat
- WP4 Modification of cryostat to pass cryogenic valve head
- WP5 Installation of new cryogenic and check valves
- WP6 Construction of Storage volume
- WP7 Construction of Expansion volume
- WP8 Construction of metering volumes
- WP9 Construction of command panel to operate ^{3}He pump and electro-pneumatic valves.
- WP10 Construction of gas panel
- WP11 Installation of new cryogenic pressure transducer
- WP12 Construction of control panel to operate valves
- WP13 Design of control software for mass flow controllers and control valves
- WP14 Design of software to read instrumentation

6.4. Failure Scenarios

Failure Scenario	Trigger	Action on Vacuum side	Action on ^{3}He side
Power Failure		- Close VT1,VT2, VT3, VT4 - Close EP valves at the inlet of the vacuum pumps (2)	- Open V_{cryo_R}, V_{EP_F}, V_{EP_R} (3)
Power Failure + Quench	Quench trigger activation		
Power Failure + Quench + Window rupture	Quench trigger activation		
Power Failure (no Quench) + Window rupture	Pressure in the vacuum side of the window rises to $>10^{-3}$ mbar (1)		
Quench	Quench trigger activation	- Close VT1,VT2, VT3, VT4 - Close EP valves at the inlet of the vacuum pumps	If pressure in the cold bore < 80 mbar (4) - Open V_{cryo_R}, V_{EP_F}, V_{EP_R} (3) If pressure in the cold bore > 80 mbar (4) - Open V_{cryo_R}, V_{EP_F}, V_{EP_R} - Close V_{001}, V_{004}, V_{006} - Start Pump (*) - Open V_{EP_expan}, V_{002} (*)- if Pump fails - Open V_{EP_expan}, V_{004}
Quench + Window Breakage	Quench trigger activation + Pressure in the vacuum side of the window rises to $>10^{-3}$ mbar (1)		
Window rupture	Pressure in the vacuum side of the window rises to $>10^{-3}$ mbar (1)		

(1) – This condition alone is not sufficient to indicate rupture of the cold X-ray windows, but its increase from normal values ($<5\times10^{-6}$ mbar), up to 10^{-3} mbar indicate that the vacuum conditions are deteriorating. The reasons for deterioration of the pressure on the vacuum side of the window can be either caused by a leak on the vacuum side of the window that can originate a pressure gradient on the wrong direction through the window, or by a major leak of ^{3}He through the X-ray cold window coming from the cold bore.

(2) – These valves are normally closed in case of power failure

(3) – These valves are normally open in case of power failure

(4) – When a quench occurs and the pressure of the ^{3}He in the cold bore (p_{CB}) is 80 mbar, the maximum estimated pressure to be reached during the quench is ~500 mbar (gas expanding to the expansion volume). In this case, the pressure of the remaining gas in the storage volume is ~500mbar. For pressures lower than 80 mbar, and to avoid that the gas flows from the storage volume to the expansion volume (if pump fails), an interlock assures that V_{EP_expan} remains closed, and for $p_{CB}>$ 80 mbar activates the opening of V_{EP_expan} in case of failure scenario.

The table of Annex 6.6 summarises the position of the electrically powered valves in case of power failure.

6.5. Methods of Filling and Ramping.

This section describes the most interesting methods for filling and ramping that can be done with the ^{3}He system (although other cases can be also performed).

6.5.1. Option A: Two gas density settings per tracking

This operation allows a stepping of 2 density settings per day. It has the advantage that in sequential shifts, both morning and evening detectors measure the same conditions. This is done by having one metering volume 'V#2' dimensioned to contain the amount for 2 density settings. This volume is maintained at constant and controlled temperature by means of a thermostatic bath.

Initially this volume will be filled with gas at around 750 mbar, this operation has to be done sufficiently before the tracking time so that thermodynamic equilibrium is reached, and the attained values can be measured (preferable after the evening shift).

The filling of the metering volume is done by transferring the gas from the storage volume (by natural pressure gradient or with the help of the ^{3}He pump).

- This transfer of gas is driven by differential pressure from the storage volume to the metering volume via V_{S1}, V_{002}, V_{001} and V_{i2}.
- When the amount of gas in the storage volume is not enough to drive the transfer, the transfer is done with the help of the ^{3}He pump via, V_{s2}, V_{006}, P^3He, V_{003}, V_{001} and V_{i1} (in this case V_{002} remains closed).
- When the pressure in the metering volume reaches ~750 mbar the transfer is stopped (valves are closed). The accurate pressure sensor B_{1000a} should record the pressure during the whole process
- After the gas is transferred to the metering volume V#2 and thermodynamic equilibrium is reached, the pressure value is recorded with B_{1000a} (the thermodynamic equilibrium is expected to be obtained after 2 hours minimum).This operation can be done after the evening shift.

In the middle of the morning tracking, an amount of gas, equivalent to one density step, is transferred from V#2 to the cold bore. The amount of gas transferred is calculated by measuring very precisely the pressure difference before and after filling. The transfer of gas from the metering volume should make the pressure to decrease from ~750 mbar to ~450 mbar, this measurement is accurately done with a metrological capacitance pressure sensor (B_{1000A}).

- The transfer to the cold bore is done via V_{o1}, V_{mc1}, V_{gate_F}, and V_{cryo_F1}. (also the valve V_{cryo_R1} is kept open during the process to assure equilibrium between both sides of V_{cryo_R}).
- The final amount to which the pressure should be decreased is calculated from the final value reached (in stable conditions) after the metering volume is first filled.
- The transfer to the cold bore should not take more than 10 minutes.
- To allow a better precision on the value to be reached, the valve V_{o1} or V_{mc1} must be able to control the flow rate, and on the vicinity of the final

value to be obtained the flow should be reduced to allow a smooth approach

It is important that during this operation that the pressure should be constantly monitored by an operator.

The gas is left to stabilize until thermodynamic equilibrium is reached inside the metering volume, only at this time the transferred amount of gas can be recorded. The amount of gas transferred is calculated from the differential pressure on the metering volume before and after transfer (after stable conditions are reached).

In the middle of the evening tracking, the density of the gas in the cold bore is changed once again to another setting by transferring gas from V#2. The final pressure on V#2 should be ~150 mbar.

- The transfer to the cold bore is done via V_{o1}, V_{mc1}, V_{gate_F}, and V_{cryo_F1}. (also the valve V_{cryo_R1} is kept open during the process to assure equilibrium between both sides of V_{cryo_R}).
- The final amount to which the pressure should be decreased is calculated from the final value reached (in stable conditions) after the metering volume is first filled (to avoid systematic errors)
- The transfer to the cold bore should not take more than 10 minutes.
- To allow a better precision on the value to be reached, the valve V_{o1} or V_{mc1} must be able to control the flow rate, and on the vicinity of the final value to be obtained the flow should be reduced to allow a smooth approach.

After each transfer the thermodynamic conditions on the volume are left to stabilize, to allow an accurate measurement of the amount of gas transferred. After the end of the evening tracking when the thermodynamic conditions are again stable and the final conditions recorded, the metering volume can be filled again and a new cycle starts.

The following diagram shows the evolution of the pressure on both the metering volume and the cold bore, with the indication of when the different operations have to done and the necessary stabilization time.

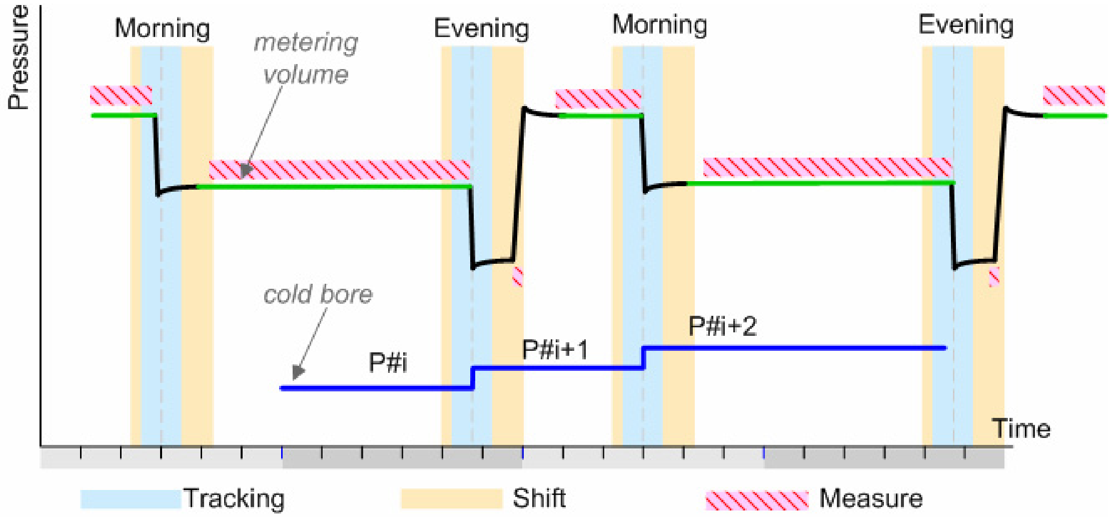


Fig.7- Two density steps per day, evolution of pressures in cold bore and metering volume.

A good coordination between the tracking time and the filling time is necessary, so that the same time is spent at each pressure setting.

It is important to have a good knowledge of how the detectors are behaving before any transfer to the cold bore is done otherwise it will require unnecessary re-visitation of a certain pressure setting necessitating a controlled metered removal of gas.

6.5.2. Option B: Continuous ramping up (or down) during tracking

The density ramping up allows the density of the gas in the cold bore to be changed continuously during the tracking period. This method relies on a mass flow controller that assures a constant flow of gas from the metering volume to the cold bore. This option is particularly interesting to make a fast scan over the whole mass spectrum, either to establish a limit or to search for huge signal.

This operation allows up to a 10 settings scan over a tracking period and the possibility that all detectors measure the same conditions.

This is done by having one metering volume 'V#10' dimensioned to contain the amount for 10 density steps. This volume is maintained at constant and controlled temperature by means of a thermostatic bath.

Initially this volume will be filled with gas at around 750 mbar, this operation has to be done sufficiently before the tracking time so that thermodynamic equilibrium is reached, and the attained values can be measured (preferable after the evening shift).

The filling of the metering volume is done by transferring the gas from the storage volume (by natural pressure gradient or with the help of the ^{3}He pump).

- This transfer of gas is driven by differential pressure from the storage volume to the metering volume via V_{S1}, V_{002}, V_{001} and V_{i2}.
- When the amount of gas in the storage volume is not enough to drive the transfer, the transfer is done with the help of the ^{3}He pump via, V_{s2}, V_{006}, P^3He, V_{003}, V_{001} and V_{i2} (in this case V_{002} remains closed).
- When the pressure in the metering volume reaches ~750 mbar the transfer is stopped (valves are closed). The accurate pressure sensor B_{1000b} should record the pressure during the whole process.
- After the gas is transferred to the metering volume V#10 and thermodynamic equilibrium is reached, the pressure value is recorded with B_{1000b} (the thermodynamic equilibrium is expected to be obtained after 2 hours minimum). This operation can be done after the evening shift.

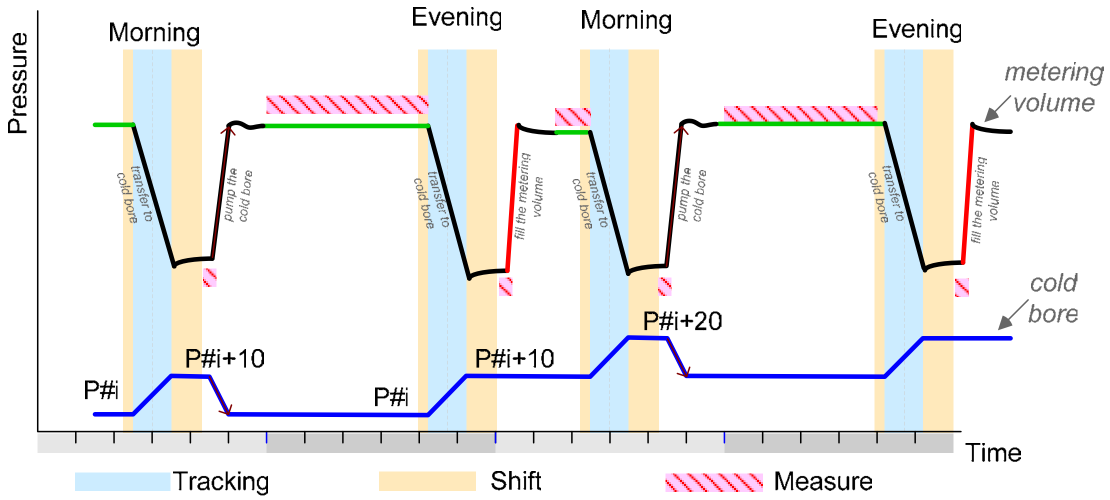


Fig.8- Continuous ramping up of the density during tracking, evolution of pressures in cold bore and metering volume.

At the start of the morning tracking, the gas is allowed to flow from the metering volume to the cold bore. A constant flow rate is assured by the mass flow controller Vmc1.

The knowledge of the behaviour of the mass flow controller is an important issue, since it is desired to produce a constant flow rate throughout the tracking time covering an accurate gas amount.

The maximum density ramping is equivalent to 10 steps (when the pressure in the metering volume is decreased from ~750 mbar to ~150 mbar), but lower ramps can be done by setting a lower mass flow on the mass flow controller.

The amount of gas transferred is calculated by measuring very precisely the pressure difference before and after filling. This measurement is accurately done with a metrological capacitance pressure sensor (B_{1000b}). A less accurate measurement can be extracted from the integration of the mass flow through the transfer time.

- The transfer to the cold bore is done via V_{o2}, V_{mc1}, V_{gate_F}, and V_{cryo_F1}. (also the valve V_{cryo_R1} is kept open during the process to assure equilibrium between both sides of V_{cryo_R}).
- The desired mass flow is set on the mass flow controller to be equivalent to e.g. n#10/90min [mol/min] (this would keep a constant flow equivalent 10 density settings over the time of a solar tracking).
- In order to have a better control over the amount of gas during the tracking time it is proposed that the transfer to be started ~5 minutes after the beginning of the solar tracking, and ended ~5 minutes before the end of tracking.
- In the end of the transfer valves are closed and conditions left to stabilize.
- The total amount of gas transferred to the cold bore is calculated after thermodynamic equilibrium is reached on the metering volume.

It is important that during this operation that the pressure is constantly monitored by an operator.

The gas is left to stabilize until thermodynamic equilibrium is reached inside the metering volume, only at this time the transferred amount of gas can be recorded.

After this operation the gas is pumped from the cold bore via the P^3He_a pump back to the metering volume v#10.

This is a delicate operation since the amount of gas to be pumped should be equal to the one previously transferred, only this way is it assured that both detectors measure the same conditions.

The gas flow is controlled via the mass flow controller and the final amount that was transferred can by calculated by measuring the final pressure after stabilization on the metering volume.

- The gas is pumped from the cold bore through valves V_{cryo_F1}, V_{gate_F}, V_{o3}, V_{mc2}, P^3He_a and V_{v3} back to the metering volume V#10 (also the valve V_{cryo_R1} is kept open during the process to assure equilibrium between both sides of V_{cryo_R}).
- The pressure on B_{1000b} is constantly monitored, and the value of the mass flow is recorded by the mass flow controller, this will give an indicative idea of when to stop the transfer, which should be finished by closing V_{o3}, V_{mc2}, V_{v3}, and turning off the pump. Finally the valves V_{cryo_F1} and V_{cryo_R1} should be closed.
- The total amount of gas transferred to the cold bore is calculated after thermodynamic equilibrium is reached on the metering volume.

At the start of the evening tracking gas is similarly transferred to the cold bore as during the morning tracking, similar operations and monitoring is made. A constant gas flow is transferred during the whole tracking.

After the tracking, the conditions in the metering volume are left to stabilize and finally conditions recorded, allowing the calculation of the amount of gas transferred.

At this point both morning and evening detectors have made measurements with the same conditions.

After the end of the evening tracking when the thermodynamic conditions are again stable and the final conditions recorded, the metering volume can be filled again and a new cycle starts.

This option requires a good coordination between time of start/end of tracking and start/end of transfer.

This option will introduce extra heat load to the magnet since warm gas is flowing to the cold bore, this also requires testing.

Another option would be to make continuous ramping down during tracking covering more than two pressure settings per tracking A (< 10 Settings per day, max #10 per tracking), similar proceeding is done and the following diagram explains the evolution of pressures.

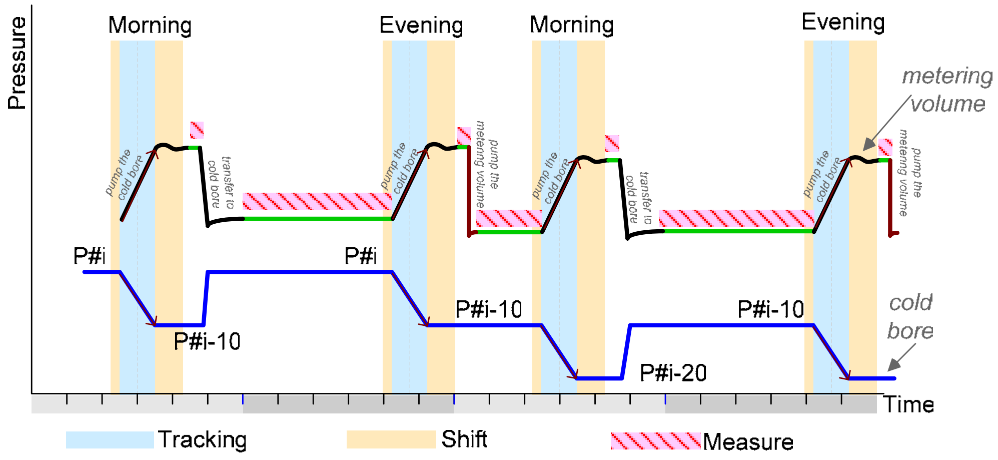


Fig.9- Continuous ramping down of the density during tracking, evolution of pressures in cold bore and metering volume.

In this case during the tracking period the gas is being pumped from the cold bore at a constant flow rate.

Each day, the metering volume has to be completely pumped out through V_{v4} and P^3He, to allow future filling with gas from the cold bore.

Again, this option has to be tested to know the behaviour of the mass flow controllers to know its limits on accuracy.

6.5.3. Option C - Density region scan (up to 10 Settings)

With this method a given density “region” can be scanned several times.

The procedure is to first pump a given amount via the P^3He_a from the cold bore to the metering volume V#10, and then send the same amount back to the cold bore.

The transfer and pumping can be done during tracking, as showed in the following diagram, where one needs a constant flow rate to complete the desired density step during the tracking time. This is done by means of the mass flow controllers.

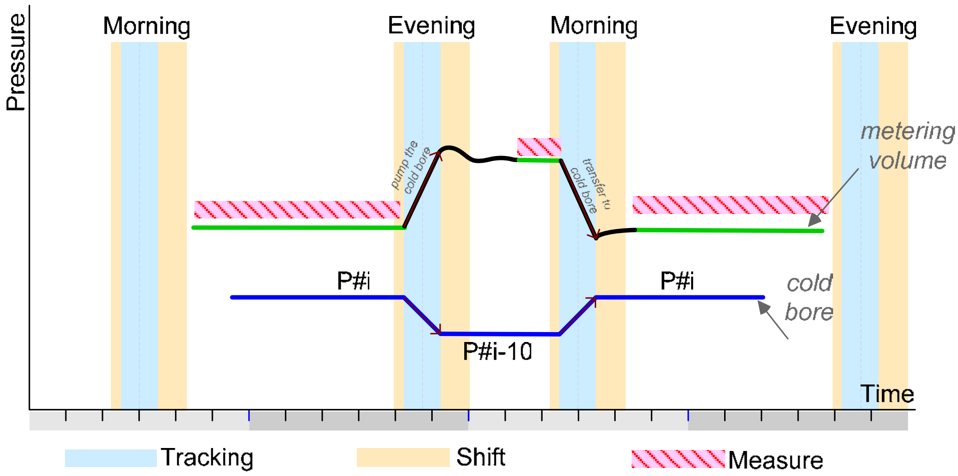


Fig.10- Density scan by ramping during tracking, evolution of pressures in cold bore and metering volume.

A simpler solution would be to make the scanning in steps, having the density constant through all the tracking period and making a change in density after(or before) the tracking period, this is particularly interesting for scanning of small density “regions”

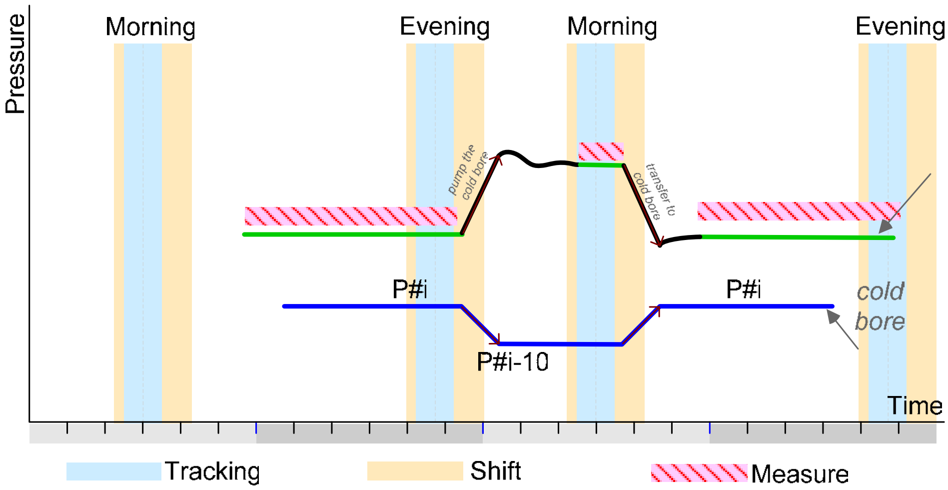


Fig.11- Density scan by changing step before tracking, evolution of pressures in cold bore and metering volume.

6.6. List of valves electrically powered and its position in case of power failure

Valve name	*Position when not powered*
VEP_F	Open
VEP_R	Open
VEP_expan	Closed
Vcryo_R	Open
V001	Closed
V002	Closed
V004	Closed
Vmc1	Closed
Vmc2	Closed
V006	Closed

Note: The valves placed on the vacuum system, such as VT1, VT2, VT3, VT4 and all other valves on at the inlet of vacuum pumps will fall in a closed position in case of power failure