DESIGN OF THE HIGH BETA CRYOMODULE FOR THE HIE-ISOLDE UPGRADE AT CERN

L. Williams[1], A. Bouzoud[1], N. Delruelle[1], J-C. Gayde[1], Y. Leclercq[1], M. Pasini [1,2], J-P. Tock[1], G. Vandoni[1], CERN, Geneva, Switzerland[1], KUL, Leuven, Belgium[2].

Abstract

The major upgrade of the energy and intensity of the existing ISOLDE and REX-ISOLDE facilities at CERN will require the replacement of most of the existing ISOLDE post-acceleration by a superconducting linac based on quarter-wave resonators. The first stage of this upgrade involves the design, construction, installation and commissioning of two high-β cryomodules downstream of REX, the existing post-accelerator. Each cryomodule houses five high-β superconducting cavities and one superconducting solenoid. As well as providing optimum conditions for physics, where the internal active components must remain aligned within tight tolerances, the cryomodules need to function under stringent vacuum and cryogenic conditions. To preserve the RF cavity performance their assembly and sub-system testing will need to be carried out using specifically designed tooling in an ISO class 5 (US Fed. class 100) clean-room. We present the determining factors constraining the design of the high-β cryomodules together with the design choices that these factors have imposed.

INTRODUCTION

The High Intensity and Energy (HIE)-LINAC aims to increase the energy and quality of post-accelerated Radioactive Ion Beams (RIBs), delivered by the ISOLDE nuclear facility at CERN [1]. The linac will be composed of two sections, one for low and one for high energy, containing cavities designed with geometric reduced velocities, β_0, of 6.3% and 10.3% respectively. The high energy section will be built first and will boost the energy of the existing facility from 3 MeV/u to 10 MeV/u. The low energy section will replace the resistive 7-gap and 9-gap resonators and provide the full energy variability of the RIB. The building blocks of the accelerator are superconducting Quarter Wave Resonators (QWRs) which will be copper cavities sputtered with a thin film of niobium. The cryo modules will share the insulation vacuum with the beam vacuum. Common vacuum is already used in superconducting linacs for the acceleration of heavy ion beams in the range of 5-10 MeV/u, as it allows the inter-cavity distances to be minimised. Beam dynamics studies [2] demonstrate that this parameter has to be minimised in order to allow the acceleration of a wide variety of nuclei and beam energies. Figure 1 shows a general view of the high energy cryomodule.

INTERNAL STRUCTURES

All services arrive through the top plate. The top plate supports the complete internal assembly that, once aligned and pressure and leak-tested will be lowered into the vacuum vessel with dimensions (along the beam axis) 2.3 m, width 1.1 m, and height 2 m. A rigid, stress relieved, dimensionally precise lower structure will support and allow during their assembly, the initial alignment of the five cavities and the solenoid, the so-called active components. For reasons of cost, ease of manufacture, thermal conductivity, straightforward stress relieving and low density, and being amagnetic, the preferred material for this structure is cast aluminium alloy, which was preferred to copper in spite of its higher specific heat. The supporting structure will be machined, stress relieved, finish machined and hard annodised. The design of this structure shall minimize its mass and ensure that during a complete thermal cycle its material remains elastic and when cooled, retains its basic prismatic shape. To this end, the inclusion of strategically placed copper thermalisation elements to be cast into the aluminium structure and weldable to suitably-sized copper straps to permit the controlled extraction of heat from the structure back to the helium vessel is under study. The cavities are held in this lower structure through hollow support rings situated around the beam line. This is done to optimize the alignment precision by minimizing the number of reference handoffs and by reducing to zero the lever arm between the cavity support and the beam line. Since in this case the cavities are supported on their outer body and pressurized by their center part, the frequency sensitivity to operating pressure (detuning) is increased by a factor of three. However the sensitivity obtained remains within that required for the ISOLDE cavities at the steady state cryogenic operating pressure of 1.3 bar ± 10 mbar. The support structure with the 5 cavities and the solenoid, together weighing about 1100 kg will be suspended directly from the module top plate via 3 slender, poor thermally conducting tie-rods in stainless steel or titanium. The attachment of these rods to the top plate will be made via three alignment mechanisms that will allow positional adjustments under vacuum in the vertical and lateral directions, the rods will be thermalised to the thermal shield supply line at 55 K. An independent alignment system, also installed on the top plate, will permit the position of the solenoid axis to be adjusted under vacuum in the vertical and lateral directions with respect to the common axis of the five cavities.

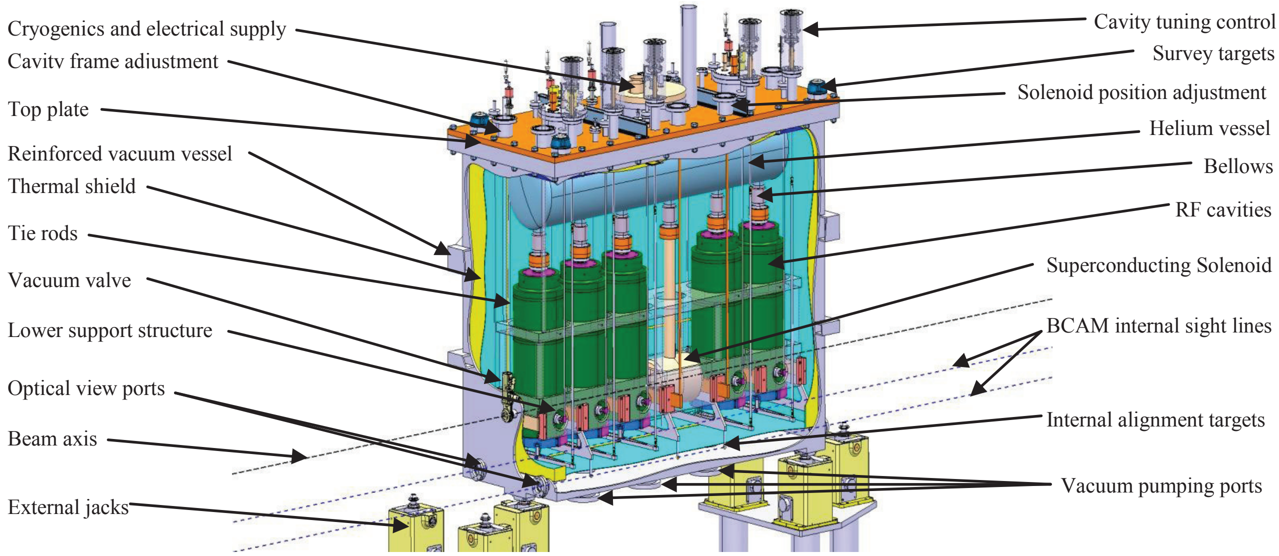

Figure 1: The HIE-ISOLDE high beta cryomodule.

All positional adjustments must be made from the top plate nearly 2 m distant from the particle beam axis. A mechanism sufficiently stiff and devoid of backlash will be required to obtain precise and repeatable movements. A mechanism using levers and cams is under study. To avoid seizures, care is required when selecting materials for alignment mechanisms that operate to generate relative movements under vacuum.

ALIGNMENT

Beam-physics simulations show that the optimum linac working conditions are obtained when the main axes of the active components, cavities and solenoid, are aligned on the REX Nominal Beam Line (NBL) within a precision of 0.3 and 0.15 mm respectively at one sigma level along directions perpendicular to the beam axis. The NBL is defined by the best fit line of the REX machine elements after smoothing. This precision will be obtained via classical survey operations and by the integration of a built-in alignment and monitoring system. The alignment system provides the position of each of the active components with respect to a common axis representing the NBL. During the installation phase the system will be used for the final adjustment of the active components once the complete cryomodule has been pre-aligned by survey. During operation it will allow permanent geometrical monitoring, and it is planned to install a similar system in the cryomodule assembly clean room to ensure correct alignment during construction. The alignment system is based on the creation of a closed geometrical network that is continuously measured using a set of opto-electronic sensors, optics and precise mechanic elements, all linked to external references defined in the NBL coordinate system (Figure 2). The positions of the cryomodule active components are measured in this geometrical frame. Precise metrologic tables are inserted in the inter-module space. Double sided Brandeis Camera Angle Monitor (BCAM) [3] CCD cameras installed on these tables look at each other and at four end pillars fixed in the floor. The pillars locations are determined via survey in the NBL coordinate system and are used as datum points. This creates two external sight lines, one on each side of the linac, and allows the position of the inter-module tables to be known. A second set of double sided BCAMs is installed on the same inter-module tables. They are used to observe the reference targets on the active components through precise glass viewports along two internal sight lines placed symmetrically on the right and left side of the linac. Each

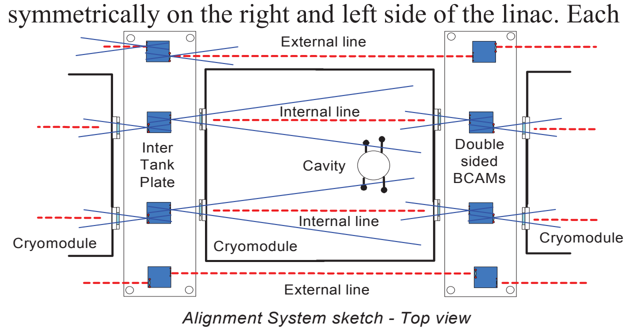

Figure 2: The BCAM alignment system.

Active component is equipped with four reference targets all attached at precisely known positions with respect to the beam axis of the component. Their measured position will be used to determine the principal axis position and orientation of each active component with respect to the beam axis. Different active targets are being studied: illuminated silica-silica optical fibre ends, silica-silica optical fibre illuminating at its end a light-diffusing ceramic sphere, as well as passive reflective targets. The solution adopted must be compatible with high vacuum and cryogenic conditions. The geometrical frame and the position of each active component will be calculated from the redundant observations using a specific 3D compensation software and taking into account the targets image coordinates on the BCAMs, the mechanical dimensions of supports and links, the BCAMs internal and external calibration parameters, thermal effects and distortions due to the optical ports between atmosphere and high-vacuum. First simplified simulations have been carried out on a single side of the alignment system. They show that the reconstruction of the "absolute" position, in the NBL coordinate system, along the axis perpendicular to the beam line of the active component target centres can be obtained with a precision of about 0.1 mm at 1 sigma level depending on the level of redundancy on the external line and with the active component targets observed simultaneously by the upstream and downstream BCAMs.

CRYOGENICS

An overhead six-port cryogenic line will be installed to link a single helium refrigerator ultimately to all six cryomodules. The installed refrigeration capacity will allow cooling of the complete six-module chain from ambient to operational temperature in about one week, and a single module in 24 hours. The first stage involves thermal shield cooling from ambient temperature to about 75 K to ensure cryo-pumping onto the shield of a maximum of residual gas away from the inner surfaces, especially those of the RF cavities. With the cryogenic supply pressure limited to 14 bar this takes about 12 hours. In a second stage, exhaust gas from the thermal shield will be admitted into the active components at a pressure of 13 bar to cool them towards 75 K. Cryogenic pressures are to be limited to maximize flexibility of the bellows connecting the active components and to influence their alignment as little as possible. In the third stage, liquid helium at 4.5 K will be supplied directly to the active components. As long as the gaseous helium produced during this stage will have a temperature above 10 K, it will be recovered by a dedicated line. Once below 10 K, the evaporated helium will be returned directly to the low pressure 4.5 K line of the refrigerator, which then defines the steady-state conditions of each cryomodule. Warm-up will follow a reverse sequence, the active components being warmed first to 75 K before the entire equipment is returned to ambient temperature.

VACUUM

A common beam and insulation vacuum has been selected [4] and, for best performance, is required in the 10^{-8} mbar range after cryo-pumping. Metal seals will be used on all openings to the vacuum vessel, with the exception of the top plate seal. Here a 7 m long elastomer (vacuum baked Viton, or EPDM for more severe radiation conditions) seal will be installed initially, but the mechanical design of the flanged joint will be rigid enough to allow a metal seal to be substituted in the case of excessive permeation or radiation damage. Vacuum valves, of which one will be fast acting, will be mounted in the beam-line on each end of each cryomodule to close the beam apertures during transport, and, in service, to rapidly isolate a suspect module and preserve vacuum in the rest of the beam-line. The vacuum vessel will be fabricated from 15 mm thick plates in hot-rolled, solution annealed AISI 304L stainless steel, specifically preselected for low permeability. This material may be welded with minimum porosity, thoroughly cleaned and is sufficiently amagnetic. The vessel is reinforced with external ribs, optimally positioned to minimize deformations under vacuum, in particular near the top plate and where the alignment viewports are mounted. It will weigh about 3.5 tonnes.

Multi-Layer Insulation (MLI)

Insulation of the thermal shield with a 10 layer MLI blanket would afford at least a 6-fold reduction in heat influx to the 70 K cryogenic circuit. In addition, in the case of a vacuum degradation leading to rapid helium boil-off, the inner diameters of the safety valve and helium exhaust line may be reduced, with a 5-layer MLI blanket on the helium vessel, from 72 mm to 29 mm (assuming a relieving pressure of 15 bar) leading to further reduced heat inputs through a reduced sized chimney. Out-gassing tests carried out at CERN on a 1 m^2 ten-layer non-interleaved blanket composed of aluminized mylar, cleaned and assembled to be ISO class 5 clean-room compatible, have returned out-gassing rates of 4.5 $\cdot 10^{-9}$mbar l s^{-1} cm^{-2}, or about 22 times that obtained from unbaked stainless steel. Out-gassing behavior was dominated by that of water. This same blanket will be installed in the RF cavity test cryostat at CERN to assess qualitatively the effects over time of its presence in shared vacuum on the performance of the cavity. Two vacuum pumps each of capacity 700 l/s are able, with a margin of 40%, to cope with the total permeation and out-gassing, including that of MLI. In the case of a catastrophic loss of vacuum to air, water vapour condensation may deteriorate the MLI aluminized reflective surfaces to a point where, when dried during vacuum pumping the aluminized layer may fracture, pulverize and dissociate itself from the mylar. It may be argued that such a brutal loss of vacuum should be extremely rare and if occurring would in any case require an entire revision of the complete cryomodule under clean-room conditions. The decision to install MLI or not, will be taken with reference made to experience with existing installations, and once tests to determine its compatibility with RF cavity operation have been completed.

REFERENCES

[1] M. Pasini, et al, HIE ISOLDE Linac: Status of the R&D Activities"
HIAT'09 Venice, July 2004, TH-05, p.182 http://www.JACoW.org.
[2] M.A.Fraser et al, Phys. Rev. ST Accel. Beams 14, 020102 (2011).
[3] BCAM "Brandeis Camera Angle Monitor", http://alignment.hep.brandeis.edu.
[4] V. Parma, et al, "Concept Design Studies of the REX-ISOLDE Cryo-modules at CERN"
LINAC'08, Victoria BC, September 2008, THP120, p.1081 http://www.JACoW.org.