DESIGN AND MANUFACTURING STATUS OF THE IFMIF-LIPAC SRF LINAC

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Abstract

The IFMIF accelerator aims to provide an accelerator-based D-Li neutron source to produce high intensity high energy neutron flux for testing of candidate materials for use in fusion energy reactors. The first phase of the project, called EVEDA (Engineering Validation and Engineering Design Activities) aims at validating the technical options by constructing an accelerator prototype, called LIPAc (Linear IFMIF Prototype Accelerator) whose construction has begun [1], [2]. It is a full scale of one of the IFMIF accelerator from the injector to the first cryomodule. The cryomodule contains all the necessary equipment to transport and accelerate a 125 mA deuteron beam from an input energy of 5 MeV up to output energy of 9 MeV. It consists of a horizontal vacuum tank approximately 6 m long, 3 m high and 2.0 m wide, and includes 8 superconducting HWRs working at 175 MHz and at 4.45 K for beam acceleration. 8 Power Couplers provide RF power to the cavities up to 70 kW CW in the LIPAc case and 200 kW CW in the IFMIF case, with 8 Solenoid Packages acting as focusing elements. This paper gives an overview of the progress, achievements and status of the IFMIF SRF LINAC.

CRYOMODULE DESIGN

The SRF LINAC for the LIPAc phase mainly consists of a cryomodule designed to be as short as possible along the beam axis in order to meet the beam dynamics requirements [3]. Figure 1 shows the 12.5-ton cryomodule which consists of a rectangular section vacuum vessel, room temperature magnetic shield, MLI, thermal shield cooled down by GHe from the phase separator return line, and cold-mass wrapped in MLI.

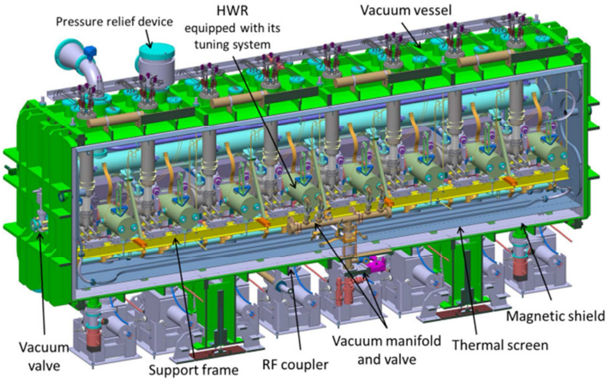

Figure 1: IFMIF LIPAc cryomodule cut view.

The cold mass is made up of the cylindrical phase separator; cryogenic circuit; titanium cavity support frame, attached to the vacuum vessel by TA6V rods ensuring lateral and horizontal positioning; 8 HWRs equipped with their frequency tuning system and power couplers; and 8 superconducting solenoids (see Figure 2). Due to their size and weight, the couplers are mounted vertically and connected to each HWR at their mid-plane.

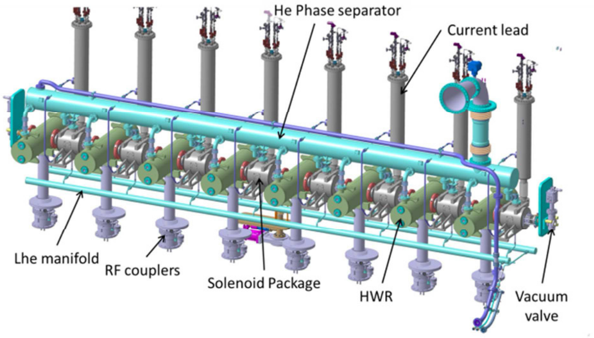

Figure 2: 3D view of the cold mass.

Several prototypes have been built during the design phase: One solenoid prototype was successfully tested [4]; the conditioning of the couplers was performed at room temperature by CIEMAT in April 2014, which qualified the design and fabrication respectively made by CEA and CPI for their use in CW mode up to 100 kW [5]; the superconducting HWR prototype, which was first equipped with a plunger for frequency tuning, was finally qualified in Dec. 2012 after removing the plunger and associated flanges [6], [7], [8], and replacing these with a more standard mechanical tuner including a disengagement system. Such a solution based on wall deformation of the half-wave resonator led to a lengthening of the cryomodule in order to accommodate it. The flange to flange length of the HWR was increased by 100 mm, and the total length of the cryomodule up to 5866 mm.

RISK MITIGATION STRATEGY

The new design of the cryomodule was submitted to a panel of international experts at a Detailed Design Review (DDR) held in June 2013 at Saclay. A detailed risk analysis taking into account the DDR remarks was also carried out. It highlighted the main risks which are related to safety, regulation, assembly, performance tests, connection, and transportation of the cryomodule. Mitigation measures to prevent the occurrence of the most

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critical events were proposed and have been implemented: assessment of the various assembly and transportation scenarios, studies in order to mitigate the risks due to magnetization, and numerical simulation in order to check the cryogenic behavior of the cryomodule. The main risks identified have been mitigated either by design or by additional tests.

Design Optimization

A new support frame with a simplified geometry was devised (cf. Figure 3). In order to reduce the risk of magnetization of 316L parts due to the operation of the solenoids and steerers, material of the support frame as well as supporting elements of the phase separator is Ti40. Studies and measurements on other parts (motors, rollers, circlips, Invar tie rods, rolling components and c-shape elements supporting the cavities) inside the magnetic shield of the cryomodule liable to induce magnetization were also carried out. Several improvements have been performed in order to mitigate the magnetic risk and Figure 4 shows an example of such an improvement. Subsequently, having a support frame in Ti40 and optimizing the distribution of the braids permits to reduce the cooling down (and warming-up) time of the cryomodule by a factor of greater than 3.

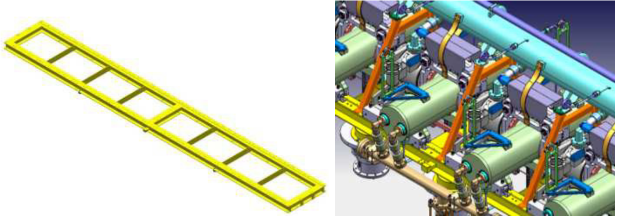

Figure 3: New support frame in Ti 40 (on the left-hand side) and supporting elements of the support frame (in orange in the figure on the right-hand side).

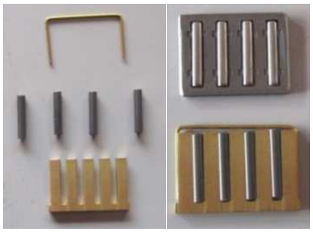

Figure 4: Needle bearing specially developed in order to avoid any magnetization issue. Picture on the left and bottom right show "homemade" bearings with ceramic needle and brass cage. The top right image shows the off-the-shelf rollers originally intended to be used.

The seismic risk has also been mitigated. Three analyses were performed by F4E in order to check the cryomodule behavior in case of earthquake and the effect of the reinforcements. A seismic spectrum was built according to criteria defined in ASME III, Appendix N, Analysis Methods and the peak ground acceleration map from the Global Seismic Hazard Assessment Program (GSHAP) was used to determine the ground accelerations at Rokkasho site (values with 10% probability of exceedance in 50 years). A 5% damping effect for bolted structure was also taken into account.

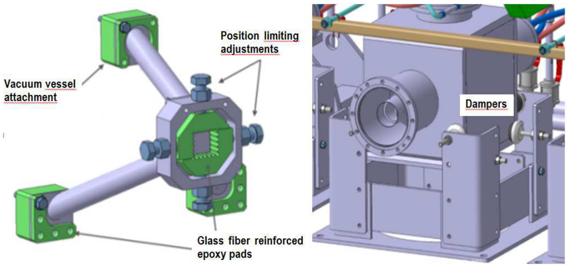

Figure 5: anchoring tripod of the support (left) and dampers for power coupler T-transition (right).

The first seismic analysis highlighted the risk of cold mass swinging along the beam axis that could damage internal vacuum piping, bellows and lateral tie-rods for horizontal positioning of the support frame. To this end, an additional mechanical structure, consisting of two tripods equipped with thermally insulated adjustable jaws, was designed to anchor the frame along the beam axis (cf. Figure 5). The tripods are designed to sustain a 1.2 g acceleration of the 2.5 ton cold-mass without damage. The second seismic analysis confirmed the efficiency of the two tripods, but revealed new induced weaknesses that led to 4 major reinforcements: dampers for the coupler T-transitions were added to avoid power couplers swinging (cf. Figure 5), the phase separator supports were reinforced with a longitudinal TA6V bar, the plate in the middle of the cold mass support to which is attached the invar rods was stiffened, and the invar rods diameter increased from 8 to 12 mm. The third seismic analysis validated these reinforcement measures and showed a maximum stress of 113 MPa in the Invar rod, a maximum longitudinal displacement of both end cavities of about 1.7 mm (cf. fig. 6) and a transversal one less than 1.2 mm.

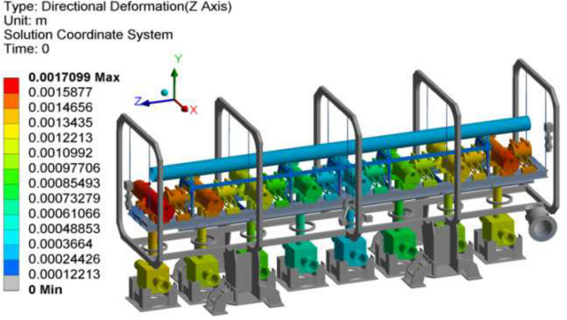

Figure 6: Transversal displacements of cryomodule components (color scale unit: meter).

The internal cryogenic circuit has also been revised after detailed studies of the potential overpressure accidents induced by sudden vaporization of liquid helium inside the cryomodule. The most severe accident (beam vacuum loss with massive air leak) or group of accidents defined the reference heat load for the pressure safety analysis and was used as input to design the pressure relief systems. The Cryomodule helium bath is protected by a 150-mm safety chimney, followed by a 250-mm exhaust duct and a burst disc. A small pressure safety valve protects the burst disc in case of minor pressure variations. In any case, the pressure will remain below 1.5 bara. The cryomodule insulation vacuum is protected in case of helium leak by a 150-mm safety tape. The beam vacuum is also protected from accidental helium leak by a high vacuum burst disc of diameter 40 mm.

Tests Before Cryomodule Assembly

In order to test, optimize and validate the clean room assembly procedures and the associated tools, a test bench, consisting of a frame, slightly larger than one eighth of the final support size and equipped with the linear guides and positioning system, has been manufactured. In order to start the tests before the delivery of the actual key components of the cryomodule, a dummy cavity, solenoid and coupler were manufactured (cf. Figure 7) and will be used to perform tests outside and inside the clean room to validate the assembly procedure and the tools. The dummy will then be used to train the operators for the assembly of the whole string.

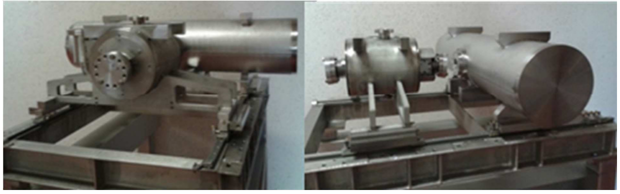

Figure 7: Dummy HWR cavity, solenoid and coupler.

It has also been decided to perform an intermediate characterization of a jacketed and fully dressed cavity with its coupler and tuner in a dedicated test cryostat. It is a powerful mitigation plan for detecting potential issues during operation of such a complete set of components. Amongst others, these tests will include the measurement of the following values: RF dissipation in the coupler flange and gasket (different field configuration); heat transferred and power radiated from the coupler to the cavity; and Q_{ext} of the power coupler connected to the cavity. By comparison with the tests of individual components, quality of the clean room assembly, power coupler conditioning with cold surface, and stabilization with LLRF will be assessed. To this end, a dedicated test cryostat called “SaTHoRI” has been designed and is under construction. It is a box-shaped top-loading satellite cryostat (cf. Figure 8) of the existing CryHoLab horizontal test cryostat at Saclay [9]. It supports and shields the HWR from radiation and magnetic fields, while cryogenic fluids are provided by the Cryholab module.

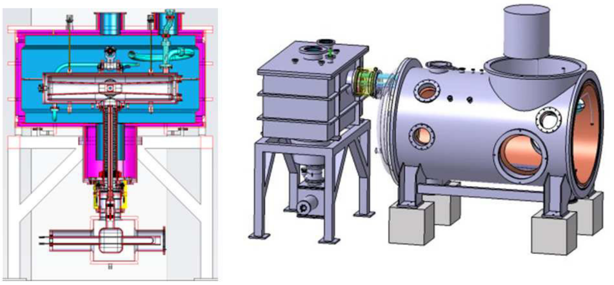

Figure 8: SaTHoRI test cryostat (left) and connection to CryHoLab (right).

MANUFACTURING STATUS

All components containing LHe and/or GHe during operation of the LIPAc have been designed, and will be fabricated and tested according to ASME standards for pressure vessels and piping, and, whenever possible, ASME certification will be obtained. In order to optimize the project schedule and avoid delays in the manufacturing of the series cavities, the contract was launched in parallel with the ongoing licensing activities to approve the component for use in Japan. The manufacturing of the cryomodule vacuum tank and thermal shield started in early 2015. The series coupler contract was launched in June 2014 and the couplers will be delivered in 2015. The procurement of all the other cryomodule components is expected to be completed within this year.

CONCLUSION

The IFMIF cryomodule design has been optimized over the last year and a half; the main risks have been identified and mitigated. A test stand dedicated to qualification of a cavity equipped with its coupler and frequency tuner is under preparation, with the first measurements being expected for the end of 2015. The manufacturing phase is on-going. The production of series couplers, series cavities, cryomodule vacuum tank and thermal shield has started, and will be followed by fabrication of less critical components within 2015.

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