

TECHNICAL AND LOGISTICAL CHALLENGES FOR IFMIF-LIPAC CRYOMODULE CONSTRUCTION

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Abstract

This paper provides an overview of the final design and fabrication status of the IFMIF cryomodule, including the design issues, and deals with the strategies implemented in order to mitigate the main technical and logistical risks identified. The seismic constraints as well as licensing requirements, transportation issue and assembly process are also addressed. The IFMIF cryomodule presented here will be part of the Linear IFMIF Prototype Accelerator (LIPAc) whose construction is ongoing [1, 2]. It is a full scale prototype of one of the IFMIF accelerators, from the injector to the first cryomodule, aiming at validating the technical options for the future 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 cryomodule contains all the equipment to transport and accelerate a 125 mA deuteron beam from an input energy of 5 MeV up to 9 MeV. It consists of a horizontal cryostat of about 6 m long, 3 m high and 2 m wide, which includes 8 superconducting HWRs for beam acceleration working at 175 MHz and at 4.5 K, 8 power couplers to provide RF power to cavities, and 8 Solenoid Packages as focusing elements.

OVERVIEW OF THE IFMIF LIPAC PROJECT

The International Fusion Materials Irradiation Facility (IFMIF) aims at producing intense neutron fluxes so as to characterize materials envisioned for future fusion reactors. To this end, two identical Linacs, each accelerating a continuous-wave 125-mA deuteron beam at the final energy of 40 MeV, would be necessary to produce by break-up interactions of the D^+ beam with the Li target the required 10^{17} neutrons per seconds with the appropriate energy [3]. Because the accelerators have to reach unprecedented performances, the feasibility is being tested through the design, manufacturing, installation, commissioning and testing activities of a 1:1-scale prototype accelerator from the injector to the first cryomodule referred to as the Linear IFMIF Prototype Accelerator (LIPAc) shown in Figure 1. The IFMIF project is carried out under the framework of the Broader Approach Agreement between Europe and Japan. It is presently in its Engineering Validation and Engineering Design Activities (EVEDA), and the accomplishment in summer 2013, on schedule, of its Engineering Design

Activities (EDA) allowed the successful development of the IFMIF Intermediate Engineering Design Report (IIEDR) [4]. The EU contributions to the LIPAc accelerator (CEA-Saclay, CIEMAT, INFN Legnaro and SCK-CEN Mol) are coordinated by the Fusion for Energy organization. The D^+ injector and LEBT have been installed and are nowadays being tested on the Rokkasho site (JAEA) in Japan.

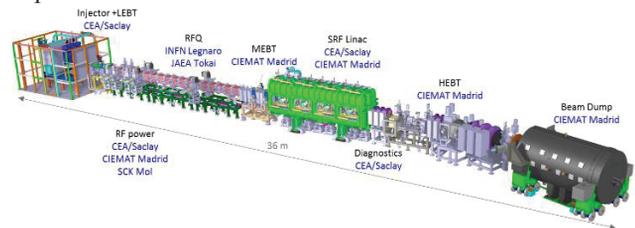


Figure 1: IFMIF LIPAc accelerator.

CRYOMODULE DESIGN

The IFMIF SRF LINAC for the LIPAc phase mostly consists of a cryomodule designed to be as short as possible along the beam axis so as to meet the beam dynamics requirements [5]. Figure 2 shows the 12.5-ton cryomodule made up with 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.

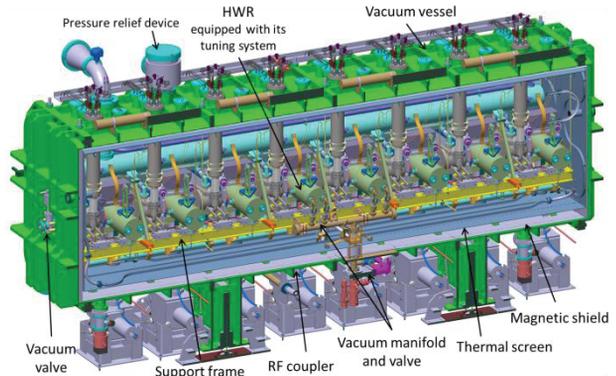


Figure 2: IFMIF LIPAc cryomodule cut view.

The cold mass is made up of the cylindrical phase separator, cryogenic circuit, titanium cavity support frame, hanging from the top of the vacuum vessel thanks to ten TA6V rods plus 4 TA6V rods ensuring lateral and horizontal positioning; 8 HWRs equipped with their

frequency tuning system and power couplers; and 8 superconducting solenoids (see Figure 3). Due to their size and weight, the couplers are mounted vertically and connected to each HWR at their mid-plane.

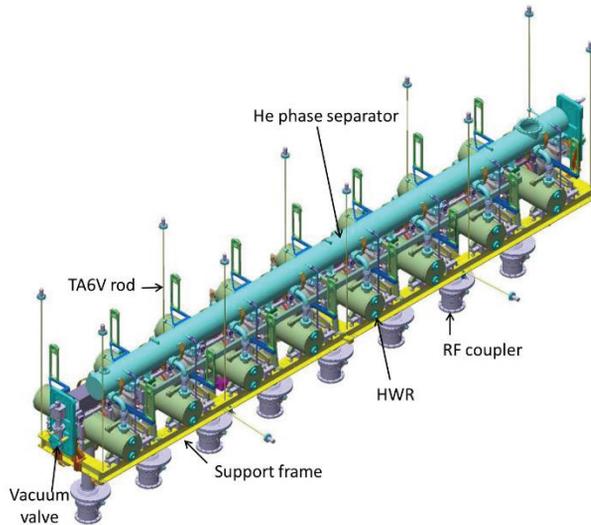


Figure 3: 3D view of the cold mass.

The support frame enables to hold together all the cold mass components from the first assembly steps in clean room to the final assembly inside the vacuum tank. It aims to minimize the handling of a heavy cold mass (around 2.5 tons) and to avoid as much as possible to damage the components. It also allows assembling the cold mass and adjusting the component alignment outside the vacuum tank. The cryomodule is for that reason designed in two main sub-assemblies as illustrated in Figure 4: the cold mass (described above) and a vacuum vessel fitted with magnetic and thermal shields. The vacuum tank is also outfitted with traps and doors to allow the access to the cold mass and to carry out the necessary controls and possible maintenance after installation in the vault at Rokkasho.

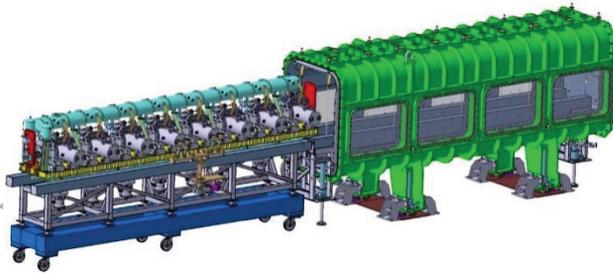


Figure 4: 3D view of the cold mass and cryostat before insertion.

DEVELOPMENT PLAN OVERVIEW

The development plan for the design, fabrication, and validation of the cryomodule may be roughly summed up as follow:

First, several prototypes have been built during the design phase in order to test and validate the critical components: One solenoid prototype was successfully tested [6]; 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 Company for their use in CW mode up to 100 kW [7, 8]; the superconducting HWR prototype, which was first equipped with a plunger for frequency tuning, was finally qualified in December 2012 after removing the plunger and associated flanges [9-11], and replacing these with a more standard mechanical tuner including a disengagement system (such a solution based on the cavity wall 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).

Next, the new cryomodule design 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 afterwards carried out. It highlighted 63 noticeable risks. The main risks which are related to safety, regulation (pressure equipment licensing, seismic risk), assembly, performance tests, connection, and transportation of the cryomodule.

Subsequently a mitigation plan to prevent the occurrence or the most critical events was proposed and has been implemented which led to the design optimization. It was also decided to perform early testing on dedicated test bench and mockups so as to check critical components and operations (clean room assembly) before the beginning of the cryomodule assembly.

RISK MITIGATION MEASURES

The most significant mitigation actions to preclude the occurrence of the identified catastrophic events may be categorized in 4 types: Seismic analysis to check the cryomodule robustness to earthquakes, studies and design improvements in order to mitigate the risks due to magnetization, numerical simulations in order to check the cryogenic and thermal-hydraulic behavior of the cryomodule, and last but not least, tests before cryomodule assembly (with dummy components and additional integrated test of a HWR, FPC and tuner assembly).

Seismic Analysis

Static analyses plus 3 response spectrum analyses were performed in order to check the cryomodule behavior in case of earthquakes. 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 shows the seismic spectrums used for the response spectrum analysis.

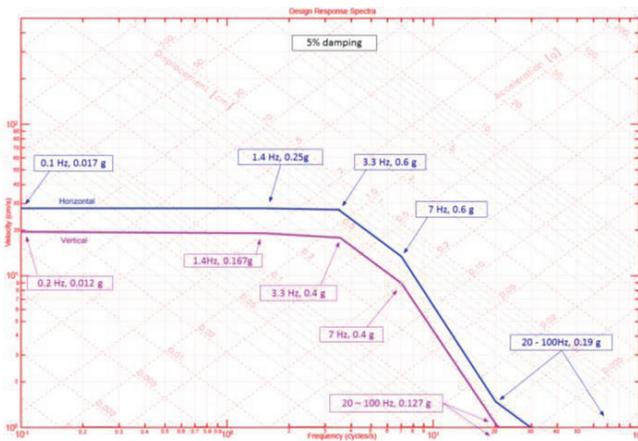


Figure 5: Seismic spectra used for the Response Spectrum analysis.

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 6). The tripods are designed to sustain a 1.2 g acceleration of the 2.5 ton cold-mass without damage.

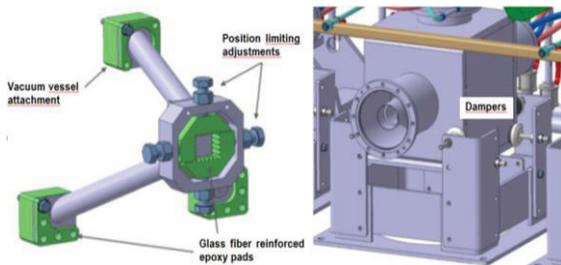


Figure 6: anchoring tripod of the support (left) and dampers for power coupler T-transition (right).

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 6), the phase separator supports were reinforced with a longitudinal TA6V bar, the plate in the middle of the cold mass support to which are attached the invar rods was stiffened, and the invar rods diameter increased from 8 to 12 mm (cf. Figure 7).

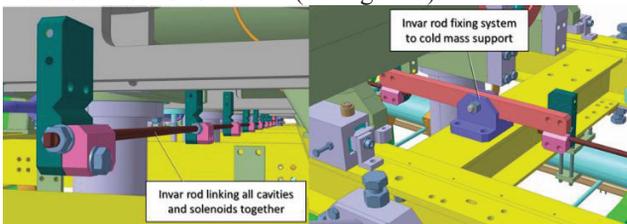


Figure 7: On the left, Invar rod whose diameter was increased to cope with the seismic constraints. On the right, reinforced plate in the middle of the support frame.

The third seismic analysis validated these reinforcement measures and showed a maximum longitudinal displacement of both end cavities of about 1.7 mm as shown in Figure 8 and a transversal one less than 1.2 mm.

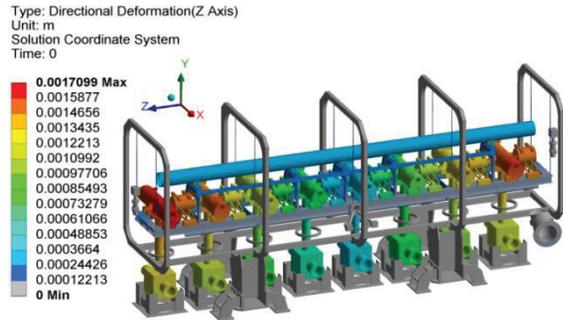


Figure 8: Transversal displacements of cryomodule components (color scale unit: meter).

Owing to the reinforcements, the stress in the various parts of the cryomodule structure has been significantly reduced. The maximum stress in the whole cryomodule is located in the Invar rod and reaches the relatively low value of 113 MPa. The maximum stress (40 MPa) on the vacuum vessel itself is located at the level of the feet as shown in Figure 9.

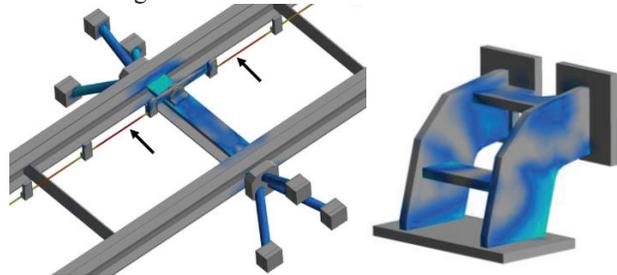


Figure 9: Location of the maximum stress in the whole cryomodule structure indicated by the 2 black arrows (left figure). Maximum stress on the vacuum vessel (40 MPa) appears at the level of the feet (right figure).

Magnetic Risk

The residual magnetic field around the superconducting cavities is a crucial factor for their performance. A warm μ -metal magnetic shield is installed on the inner walls of the vacuum vessel in order to preclude having a residual Earth magnetic field above $2\mu\text{T}$ (20 mG). Although a 1-mm thick μ -metal shield would have been enough to shield the Earth magnetic field, the screen has been designed with a 2-mm thickness because this provides a better mechanical strength and gives extra margins with regard to the magnetic shield effectiveness. However, some components inside the cryomodule could be magnetized by the fringe field of the solenoids. In order to mitigate such a risk, it has been chosen to replace as is possible parts which can be magnetized near the cavity areas where the magnetic field is the highest.

In this way, a new support frame with a simplified geometry was devised (cf. Figure 10), the support frame as well as supporting elements of the phase separator

originally designed to be in 316L stainless steel is henceforth in Ti40. 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.

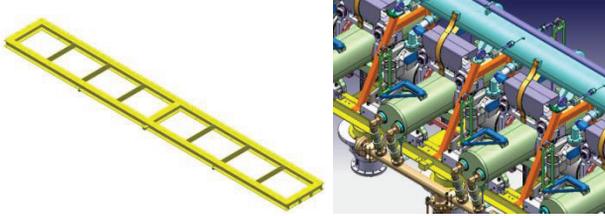


Figure 10: New support frame in Ti 40 (on the left-hand side) and supporting elements of the support frame (in orange on the right-hand side).

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 [12]. Several improvements have been performed in order to mitigate the magnetization risk. Figure 11 shows an example of the changes carried out on the off-the-shelf needle bearings supporting the cavities in order to cope with the risk.

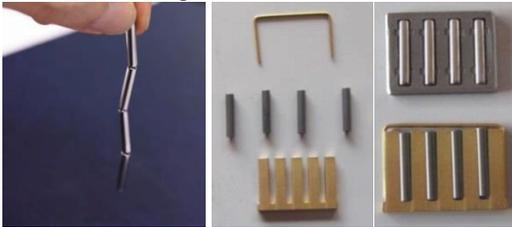


Figure 11: On the left, magnetized needles from the foreseen off-the-shelf roller. In the middle picture, bearing specially developed in order to avoid any magnetization issue. On the right picture: “homemade” bearings with ceramic needles and brass cage (bottom) and off-the-shelf rollers originally intended to be used (top).

The residual magnetic field generated by the cryogenic stepper motors could also be a magnetic issue. As an illustrative example, Figure 12 shows measurements performed to evaluate the residual magnetic field they generate when they are turned off. Since they are far enough from the cavities and especially from the areas where the magnetic field is at its highest value, near the HPR ports, this should not be an issue for the performance of the cavities (Figure 12 shows that beyond 100 mm the residual field tends to be negligible). Magnetic measurements on the parts liable to be magnetized near the critical zones of the cavities such as circlips for example showed that they were already naturally magnetized and emitted significant magnetic fields, upwards to 1 mT. They were originally foreseen to be procured in steel but they will be eventually provided in titanium. More measurements shall be performed on others components (ex: bearings of the tuning system) when they are available in order to check they meet the magnetic requirements.

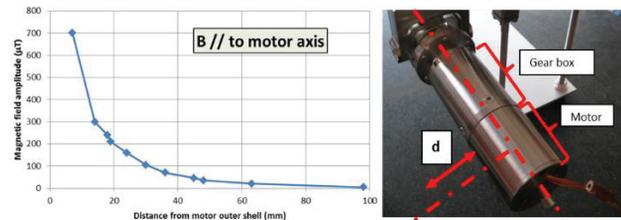


Figure 12: Measurement to characterize the magnetic field generated by the cryogenic motors.

Cool-down and Thermal-Hydraulic Behavior

In order to mitigate as much as possible the risks associated with the cool down of the cryomodule before the beginning of its construction, numerical simulations were performed to crosscheck the semi-analytical global cooldown already calculated. The numerical model of the cooling down for a full scale cryomodule was carried out using a dedicated code for the simulation of thermo-hydraulic processes in cryogenic systems. The idea was to highlight any potential imbalance especially in the inlet feeding lines, potentially preventing the cryomodule from cooling down correctly with a reasonable time span taking into account the expected performance of the cryoplant to be built at Rokkasho. The global model of cooling down shows an expected duration of about 80 h. The numerical simulation devoted to the analysis of the mass flow rate distribution during the cooling down at about 50 K shows that the distribution between the different channels remains balanced in acceptable values within plus or minus 10 % around the theoretical average mass flow rate.

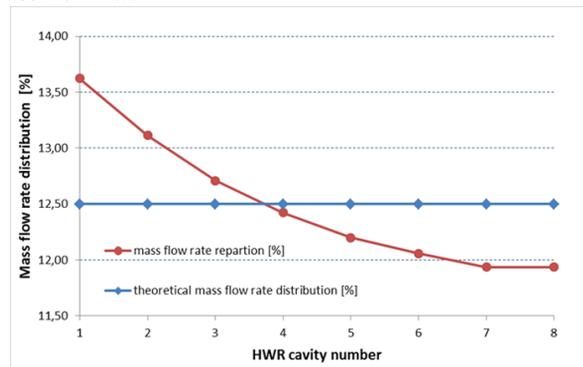


Figure 13: Distribution of the mass flow rate in the cavities flow compared to theoretical distribution.

As expected, the first cavity channel is hydraulically favored compared to the last one but, in any case, the calculation shows that no thermo-hydraulic imbalance in the cryogenic channels should preclude a satisfactory cooling of all the cavities. As an illustration, Figure 13 shows an example of distribution flow rates in the cavities when applying an arbitrary 10-K step in temperature at the inlet of the cavities distribution main pipe. Various temperature steps were tested to assess the thermo-hydraulic response of the system and no distribution imbalance has been highlighted.

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 out of the confined vault volume. 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.

Early Testing before Cryomodule Assembly

In order to mitigate critical events during the cavity string assembly as well as to optimize and validate the clean room assembly procedures and the associated tools, a test bench, consisting of a frame, slightly longer than one eighth of the final support size and equipped with the linear guides and positioning system, has been manufactured (cf. Figure 14). In this way, it is possible to start the tests before the delivery of the actual key components of the cryomodule. A dummy cavity, solenoid and coupler were therefore manufactured and will be used to perform tests outside and inside the clean room to validate the assembly procedures and the tools. The component welds are leak tight in order that it be possible to check the leak tightness of the gaskets between the dummy cavity, solenoid and coupler. The dummy components will be thereafter used to train the operators to perform the assembly of the whole string.



Figure 14: On the left, cavity string assembly test bench. On the right, Dummy HWR cavity solenoid and support frame (slightly longer than one eighth of the actual one).

An intermediate characterization of a jacketed and fully dressed cavity with its coupler and tuner in a dedicated test cryostat will also be carried out. It is an efficient 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 parameters: RF dissipation in the coupler flange and gasket (different field configuration), heat transferred and power radiated from the coupler to the cavity as well

as Q_{ext} of the power coupler connected to the cavity. By comparison with the tests of the individual components, the quality of the clean room assembly, the power coupler conditioning with cold surface, and the stabilization with LLRF will be assessed. To this end, a dedicated test cryostat called “SATHORI” (“SATellite de Tests HORIZONTAL des Résonateurs IFMIF”) has been designed. It is a box-shaped top-loading satellite cryostat (cf. Figure 15 and Figure 16) of the existing CryHoLab horizontal test cryostat at Saclay [13]. It supports and shields the HWR from radiation and magnetic fields, while cryogenic fluids are provided by the Cryholab module.

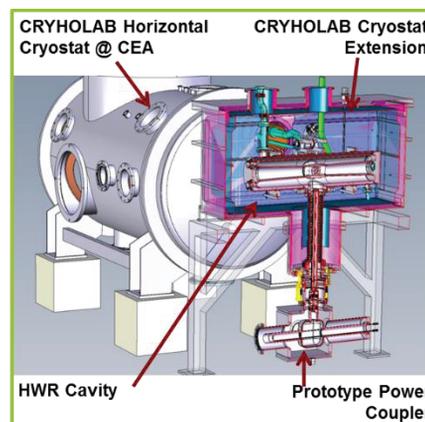


Figure 15: SATHORI test cryostat (right) and connection to CryHoLab (left).

The construction of the SATHORI test bench has already begun. The manufacturer for the cryostat was notified in January 2015 and the Production Readiness Review was passed in June 2015. All the other activities (electrical power, water cooling, air cooling, control command, etc.) to prepare the SaTHoRI test stand have shown good progress and the test bench should be ready before the end of 2015.

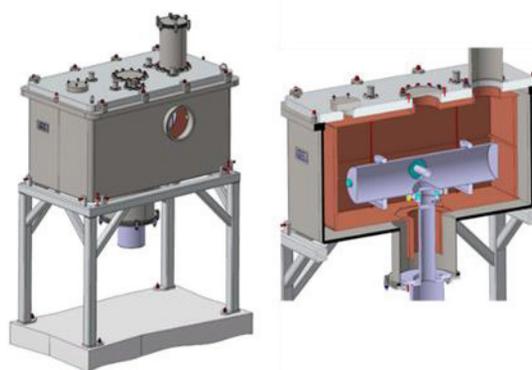


Figure 16: Actual design of the SaTHoRI cryostat made by the manufacturer and approved by CEA.

Transportation Risk

The original plan was to transport by sea the cryomodule fully assembled and tested in a dedicated test RF test stand at Saclay. Marine transportation is the cheapest solution. However this implies at least 5 loadings/unloadings of the cryomodule with the

associated risks of severe shocks which could damage fragile components such as the coupler window. This is due to the intrinsic brittleness of the ceramic window and particularly due to the fact that the coupler antennas cannot be clamped once the coupler are assembled in the cryomodule. In addition, the window coupler might be damaged or weakened by fatigue resulting from ocean swell. A window failure would mean that the whole cryomodule is totally unusable since the beam vacuum would have been contaminated. This catastrophic event would imply a complete dismounting of the cryomodule to clean up the beam vacuum components and especially the cavities. The risk of contamination of the beam vacuum during the 2 months' journey of the shipment is also to be taken into account. Due to the duration of the journey an active pumping system fed by some parallel redundant UPS (Uninterruptible Power Supply) would be necessary to keep in any case a vacuum level below 1 mbar to prevent dust from moving [14]. Contamination during transportation by ship could result in field emission, limited performance, gradient limitation, or even the cryomodule not usable. Some internal piece of equipment (bellows, tie rods, etc.) could also be damaged during the transportation because of shocks and/or handling operations out of specifications making at worst the cryomodule also not usable. Moreover, some internal parts such as thermal transitions, bellows, piping, hoses, etc. are not accessible for installation of damping or clamping equipment. The first and obvious mitigation measure to overcome the above-mentioned issues is to avoid the maritime transportation. In this way, it has been decided that the cryomodule will be either assembled at Saclay then transported by plane or assembled in Japan. These two scenarios are being evaluated for the times being. In any case, studies to evaluate the rupture mechanism of the coupler and testing of a mock up on vibration and shock tables will be carried out in order to assess more precisely the shock and vibration levels the couplers can withstand and possibly to have a better understanding of the fatigue failure occurrence.

LICENSING PROCEDURE

The risk of not meeting the Japanese regulatory requirements with regard to HPGSL (High Pressure Gas Safety Law) had been identified as a potential definite show-stopper for the cryomodule project. Indeed, since there are cryogenic fluids inside the IFMIF cryomodule, it must comply with HPGSL. Imported pressure vessels must pass the inspection by the High Pressure Gas Safety Institute (KHK) and receive stamping or marking plate indicating their passage before being transferred or delivered. The cavity is the most complicated part to be licensed due to the use of non-referenced materials (Nb, NbTi) and the complicated geometry. This component is referred to as a Designated Equipment according to the Ordinance of the Ministry of Economy and must go through the designated equipment inspection conducted by KHK. The agreed strategy between CEA, F4E and

JAEA, and negotiated with the Japanese authorities was to design, fabricate, and test all the cryomodule components according to ASME BPVC or B31.3 (ASME BPVC for the cavity). The first discussion between CEA, F4E, JAEA and the Japanese Authorities about the cavity licensing took place in December 2011 at KHK Institute in Tokyo. The cavity licensing procedure with the Japanese Authorities really started in December 2013 with the presentation to Aomori prefecture and KHK experts of the preliminary version of the application form. Seven meetings with KHK were necessary prior to the official submission of this document in June 2015. The licensing activity has been an unexpectedly time and resource consuming activity to perform the numerical simulations, deal with the many questions raised by KHK, prepare, and test the samples (raw materials and associated welds, ie. NbTi, Nb, NbTi-Ti, NbTi-Nb, Nb-Nb), and complete the application form. The positive decision given by the KHK review committee realizes a key milestone of the IFMIF/EVEDA cryomodule development. There is still a lot of work to be done on the licensing activities but licensing of the cavities is no longer a show stopper for the cryomodule development.

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 contract between CEA and the manufacturer, E. Zanon Company, was signed by the end of 2014. The cavity manufacturing study phase lasted longer than expected due to the licensing process on the cavity design still on going until June 2015. The definition of the manufacturing and control file, including the final manufacturing drawings (welding locations and symbols with welding details) could be added to the application form, which was a mandatory requirement from KHK. The weld control plan was also defined which enabled to determine and justify the weld type joint efficiency used in the application form. The manufacturing studies for the fabrication of the cavities ended up by the end of May and the acceptance by CEA of Zanon's studies was made on June 4, 2015. The qualification of the welds according to ASME BPVC is ongoing (with a Lloyd's register third part inspector) and the pre-series cavity should be delivered at Saclay in October 2015 for chemical etching [15]. Figure 17 and Figure 18 show examples of some cavity components already machined. After the annealing treatment and the tests in vertical cryostat, the tests in the SATHORI test bench are expected to start in early 2016.



Figure 17: Preassembly of a beam port.



Figure 18: From left to right, cavity torus with one HPR port, central drift tube, conical stem.

The manufacturing of the cryomodule vacuum tank and thermal shield started in early 2015. The series coupler contract was launched in June 2014 and they should be delivered before the end of 2015. The procurement of all the other cryomodule components is expected to be launched within the end of the year so as to all the components will have been fabricated, tested and qualified by March 2017.

CONCLUSION

The IFMIF cryomodule design has been optimized over the last two years. The main risks related to the fabrication and performance of the LIPAc cryomodule have been identified and mitigation actions have been implemented. The design of the IFMIF cavity has successfully passed the designated inspection by KHK and is approved. The licensing of this component had been identified as a major risk for the development of the IFMIF LIPAc cryomodule. Yet, licensing is not anymore a show stopper although a lot of work is still to be done for the licensing of the manufacturing of the cavities as well as for the other cryomodule components and cryomodule assembly. The pre-series cavity is being manufactured and is expected to be delivered at Saclay in October 2015 for chemical tuning and the first test (vertical cryostat). The first test of a fully equipped cavity in realistic conditions in a new dedicated test cryostat will start by early 2016. The fabrication of the series cavities is ongoing and the fabrication phase of the critical

components has started. All the cryomodule components are expected to be delivered by the end of 2016 and qualified by March 2017.

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