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STATUS OF THE IFMIF/EVEDA SUPERCONDUCTING 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 to test samples as possible candidate materials to a full lifetime of fusion energy reactors. A prototype of the low energy part of the accelerator (LIPAc) is under construction at Rokkasho Fusion Institute in Japan [1]. It includes one cryomodule containing eight half-wave resonators (HWR) operating at 175 MHz and eight focusing solenoids.

This article covers the progress of developments in the IFMIF/EVEDA cryomodule: the qualification of eight cavities, the RF conditioning results of eight high-power couplers, the manufacturing and test of the eight superconducting solenoids and the high power tests of fully dressed cavities performed at Saclay. The assembling status of the cryomodule at Rokkasho site is also reported.

THE IFMIF LIPAC SRF LINAC

The IFMIF/EVEDA SRF Linac mostly consists of one cryomodule designed to be as short as possible along the beam axis to meet the beam dynamic requirements. As depicted in Fig. 1, it is made of a rectangular section vacuum vessel, a warm magnetic shield, a thermal shield cooled with helium gas. A titanium frame supports the cold mass made of a cylindrical phase separator with cryogenic piping, the cavities and the solenoids.

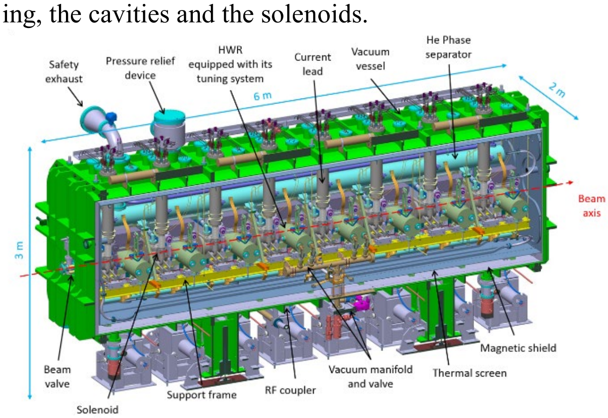

Figure 1: The IFMIF LIPAc cryomodule.

All the components have been manufactured and qualified. One of the main challenge during the manufacturing phase was to comply with the Japanese regulatory requirements with regard to HPGSL (High Pressure Gas Safety Law). It has been agreed in the collaboration that all components containing helium gas or liquid during operation of the LIPAc have to be designed, manufactured and tested according to ASME standards. For stainless steel components, the rules to follow depends on the internal diameter. Parts with diameter than 6 inches have to respect ASME Boiler and Pressure Vessel Code (BPVC). It concerns the phase separator and the solenoid packages. For smaller parts – i.e. the currents leads and the piping – ASME B31.3 applies.

The cavity was the most complicated part to be licensed due to the use of non-referenced materials (niobium, niobium-titanium alloy). Discussions started in 2013 between the Japanese Authorities (KHK) and the collaboration to define the licensing frame. Unexpected activities had to be performed, like numerical simulation and sample testing, to complete the application form of the half-wave resonator [2]. Finally, the document was approved by KHK in March 2016.

Most of the components were delivered to Rokkasho in 2018 and beginning of 2019 where they are currently stored awaiting to be assembled.

QUALIFICATION OF THE HALF-WAVE RESONATORS

The IFMIF HWR is a 175 MHz 0.09 beta half-wave resonator whose nominal accelerating field is 4.5 MV/m. A Saclay type tuning system is installed on the cavity and applies a compressive force on its beam ports to shift the frequency by -50 kHz maximum [3].

A pre-series HWR has been completed and tested during the production of the subcomponents of the series cavities. A series of intermediate and qualification tests have been carried out for this HWR, between each major steps of the production. It included the qualification of the differential etching technique to correct the frequency of the niobium cavity [4].

The series cavities have been manufactured and tested following the licensing requirements described in the approved application form. Each bare cavity has been tested in vertical cryostat before heat treatment and integration of the helium tank. A qualification test was performed on each jacketed cavity.

Table 1 and Fig. 2 present the vertical test results for all the cavities. All the qualification tests were carried out up to at least E_{acc}=5.5 MV/m that is to say with 20% safety margin with respect of the nominal accelerating field of 4.5

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MV/m (such margin might be useful during machine operation to recover with one HWR part of the beam energy if one other HWR is defective).. In addition, it has been decided to stop at the accelerating field of 6.5 MV/m in order to prevent firing field emission. There was no electron current nor X-ray measured at 5.5 MV/m on any of the HWRs, only X-ray onset detected for HWR05 at 5.6 MV/m.

All HWRs are within the cold tuning system range for 175 MHz operation. It is worth noticing that the frequency spread is 23 kHz after the chemical tuning process, whereas the spread was 246 kHz at the end of the manufacturing of the bare resonators.

Table 1: Test Results of the IFMIF Cavities

		Bare cavity	Jacketed cavity		
		Q0 @ low field	Q0 @ low field	Q0 @ Eacc_nom + 20 % (5.4 MV/m)	Frequency @ cold (MHz)
Pre-series	HWR01	1.60E+09	2.17E+09	1.08E+09	NA
Series	HWR02	2.14E+09	2.01E+09	9.45E+08	175.019
	HWR03	1.59E+09	1.59E+09	5.97E+08	175.041
	HWR04	1.85E+09	1.81E+09	7.9E+08	175.018
	HWR05	1.62E+09	1.62E+09	6.2E+08	175.030
	HWR06	1.54E+09	1.74E+09	7.65E+8	175.033
	HWR07	1.54E+09	1.86E+09	9.05E+08	175.040
	HWR08	1.67E+09	1.64E+09	6.9E+08	175.026
	HWR09	2.0E+09	1.66E+09	7.15E+08	175.033

Spécifications: Q0 = 5.0E+08 @ Eacc_nom = 4.5 MV/m

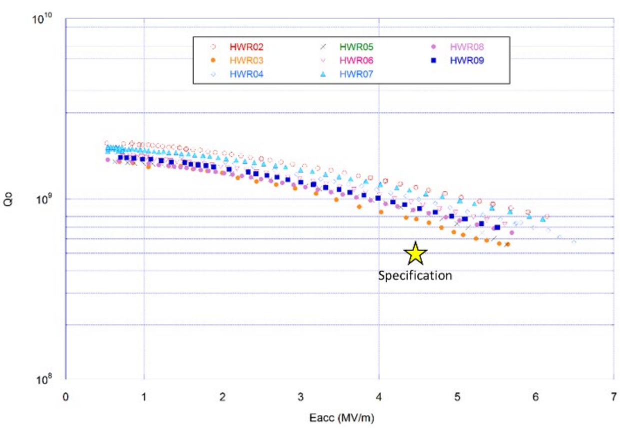

Figure 2: Q_0 Vs E_{acc} of the eight series cavities.

More details on the manufacturing and the qualification of the IFMIF cavities could be found in [5].

RF CONDITIONING OF THE POWER COUPLERS

The IFMIF power coupler is designed to transmit 175 MHz 200 kW CW to the half-wave resonator. The power coupler is a 50 Ω geometry and consists of three main parts: RF window, RF transition and cooled outer conductor. Except the RF transition made of aluminium, all the RF surfaces are bulk or coated OFHC copper. An active helium gas cooling system is used to interface the cavity with the room temperature. More details on the design of the power coupler could be found in [6] and [7].

The series manufacturing stage was preceded by a successful prototyping phase and the RF conditioning of the prototypes power couplers up to 100kW CW [8].

RF Performances of the Series Power Couplers

Site Acceptance Tests of the eight series power couplers were successfully performed [9]. Afterward, they were cleaned and assembled in CEA premises, then, transferred to CIEMAT RF test stand (Fig. 3). All the couplers reached the validation maximum power of 100 kW CW in TW and SW (full reflexion) configurations. This power level allows a reasonable margin for nominal operation, RF power on the LIPAc varying between 50kW and 70 kW.

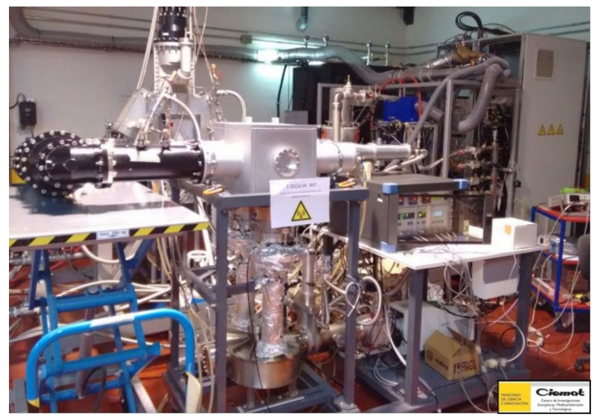

Figure 3: RF conditioning test stand.

Multipacting Behaviour

The power couplers named C5 (pair3) and C7 (pair4) showed multipacting activities between 10 kW and 20 kW in TW configuration generating an important temperature increase on the middle part of the cooled outer conductor, only for high RF duty cycles.

The heating multipacting occurring on C7 was particularly intense with temperatures going up to more than 100°C if the power is maintained at the MP RF power range. However, once RF power goes out of these power levels the temperature starts to decrease as if power was switched off (Fig. 4).

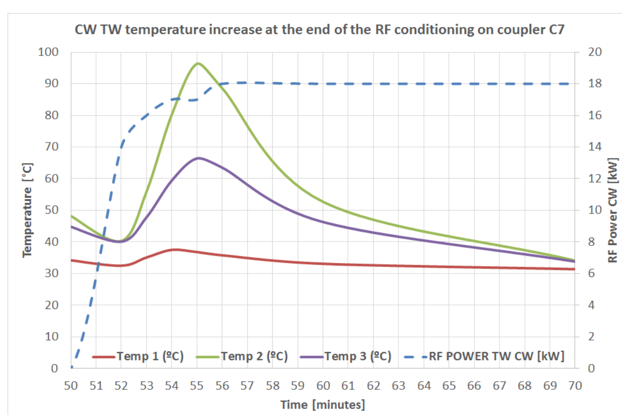

Figure 4: Heating of coupler C7 due to multipacting.

Some attempts to process the multipactor for coupler C7 was performed. Nevertheless, the temperature increase was too important, very time consuming and not controlled enough to continue this operation. A decision was taken to

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not completely process this MP. This was motivated by several arguments:

- First, the power ranges corresponding to the heating multipacting were far below the nominal operating RF power of the coupler on the cryomodule.
- Second, during operation, it is always possible to go rapidly through the multipacting region to limit the temperature increase. This was proved during the RF conditioning tests.
- Finally, multipacting level encountered during the test seems to be influenced by the RF configuration due to the assembly on the test box.

Vacuum Behaviour

At the end of the RF conditioning, the vacuum level measured for the operating RF power, between 50kW and 70kW, is less than 5x10^{-8} mbar for all the power couplers (Fig. 5). For some coupler pairs the vacuum starts to increase significantly at the end of the RF conditioning. This was correlated with a temperature increase on the test box and not on the couplers. We can also see that even for couplers were no heating mutipacting was measured their vacuum is degraded for the corresponding power range.

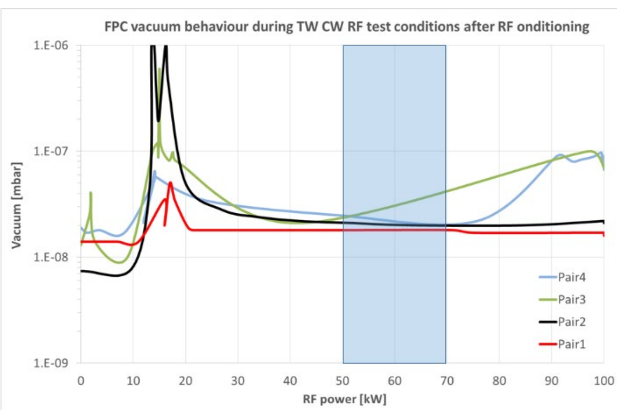

Figure 5: Final vacuum behaviour (TW).

QUALIFICATION OF THE SOLENOID PACKAGES

The eight solenoid packages of the IFMIF/EVEDA SRF Linac are provided by CIEMAT, as part of the Spanish contribution to LIPAc. Each solenoid package is made of a magnet package and a current lead package. Each magnet package consists of two nested superconducting solenoids, steerers and BPM (Beam Position Monitors) [10]:

- The inner solenoid focuses the deuterons beams. The outer solenoid is connected in series with the inner one but the current flows in opposite sense. This design limits the fringe field of the magnet package to 20 µT on the beam port flange of the cavity while achieving the 1.1 T.m field requirement.
- Two steerers correct the vertical and horizontal beam trajectory. They are designed to provide an integrated field of 3.51 mT.m.
- The BPM is welded on the package since it was not possible to integrate flanges in the space given by the beam dynamic requirements.

A magnet package prototype was produced at CIEMAT to validate the design and fabrication techniques [11]. The series fabrication of the eight units has been done in the industry, following the same procedures. Electrical measurements have been done at room temperature on individual coils, specifically, the resistance, self-inductance and insulation have been measured. Same parameters have been measured at different steps during the assembly, to avoid insulation failures.

Each set of coils have been cold tested at a vertical cryostat at CIEMAT to check the performance at nominal current. The helium vessel was not present because the cryostat diameter was not large enough (Fig. 6). All the solenoids reached critical current. They were first powered individually and then in couples, as in the final nested configuration. Four of them needed one quench before reaching critical current when individually powered, and only two were below nominal current. Only one couple had a quench before reaching critical current.


Figure 6: coils prepared for cold tests.

Then the coils were integrated in the stainless steel helium vessel. The vessel design and fabrication is compliant with ASME standard. Each vessel went through a pneumatic pressure test in the presence of an inspector of a notified body.

Mechanical measurements have been made on the coils and the helium vessel parts. The machining of the fiducial and vessel supports has been done once the vessel was completely welded, to cope with the expected deformations.

Finally, magnetic measurements at room temperature and low current were made to check the misalignment of the magnetic axis of the solenoids respect the fiducials. All the magnets were within tolerances, that is, less than +/- 0.5 mm deviation and 5 mrad tilt. Magnetic tests were done with a three axis Hall sensor at ALBA-CELLS laboratory

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(Fig. 7). It was not possible to make this test at cold conditions because no cryostat with the right size and warm bore was available.

The solenoids are currently undergoing final preparations, before they will be sent to Rokkasho in the second half of 2019.

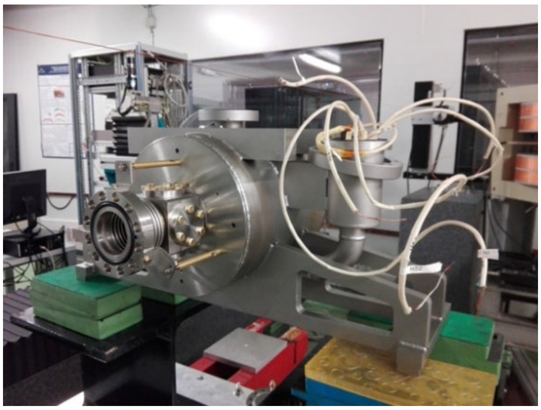

Figure 7: Magnetic measurements at ALBA-CELLS laboratory.

HIGH POWER TESTS OF ACCELERATING UNITS

In addition to the vertical test for individual HWR qualification, the validation test of two accelerating units (cavities equipped with its tuner and power coupler - Fig. 8), which is part of a mitigation plan, took place at CEA in a dedicated test stand called SaTHoRI (Satellite de Tests HOrizontal des Résonateurs IFMIF) before the delivery of the components in Japan for assembly.

These tests provided benchmark data for the cavity behaviour (RF, mechanical, field probe, tuner calibration…) and allowed to perform preliminary testing of some components of the SRF Linac: RF source, LCS components and instrumentation.

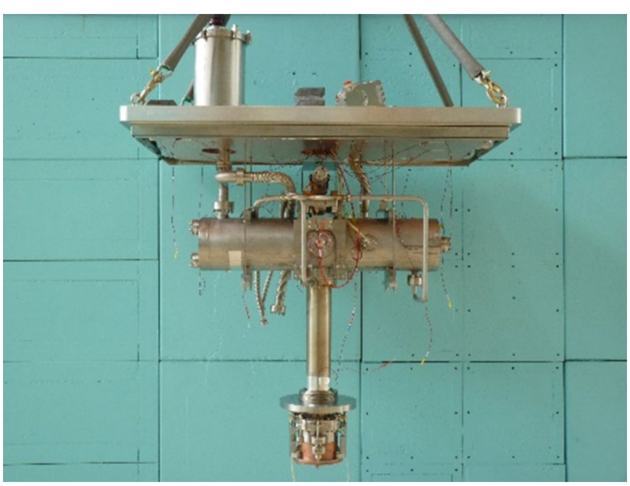

Figure 8: Cavity with its tuning system and power coupler installed on the top lid cryostat.

Test Stand at CEA Saclay

For the SaTHoRI test, a dedicated test stand has been installed at CEA-Saclay [12]. It is made of a 175 MHz CW RF source with a coaxial line, a cryostat connected to the already existing cryogenic system, a biological protection and cubicles for the local control system and instrumentation (Fig. 9).

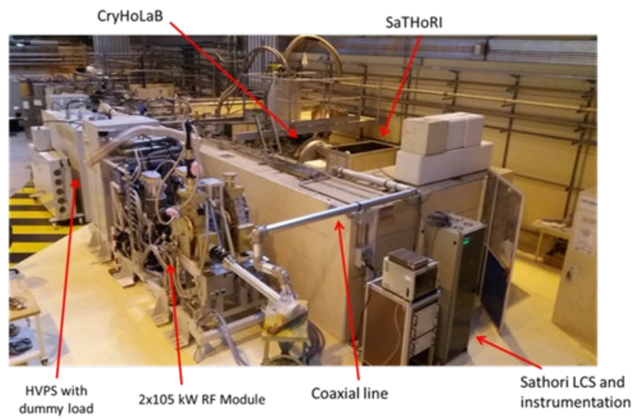

Figure 9: SaTHoRI test stand at CEA Saclay.

The RF source was developed by CIEMAT, and installed and commissioned at Saclay with the support of F4E.

Results

A first critical coupling test was performed to qualify the SaTHoRI cryostat with a known cavity to confirm cryogenic behaviour and magnetic shield efficiency. As the cavity was equipped with a critical coupling antenna, it was also possible to characterize precisely the behaviour of the tuner. The measured tuning range exceeds 50 kHz. Hysteresis measurements have been performed on small frequency adjustments representative of what could be the operational conditions on the accelerator. A 6 Hz peak-to-peak frequency pointing error results from repeated back and forth +/-15 Hz tuning motions. When extending the tuning cycles to a +/-150 Hz range, the pointing error is kept at the same amplitude. For comparison, the resonator bandwidth is 2.7 kHz when it is equipped with its power coupler.

Then two cavities have been successively qualified in high power tests in SaTHoRI: the pre-series cavity (HWR01) and the first series cavity (HWR03). The same tuning system and the same prototype power coupler have been used for both tests. The nominal accelerating field of 4.5 MV/m was achieved in the cavity with an injected power of 14 kW. Stable operation of the cavity for 30 minutes at 5.4 MV/m (nominal accelerating filed Eacc + 20% margin) has also been demonstrated (Fig. 10) with no field emission observed during the tests.

More details on the results of the tests of the two accelerating units are presented in [13].

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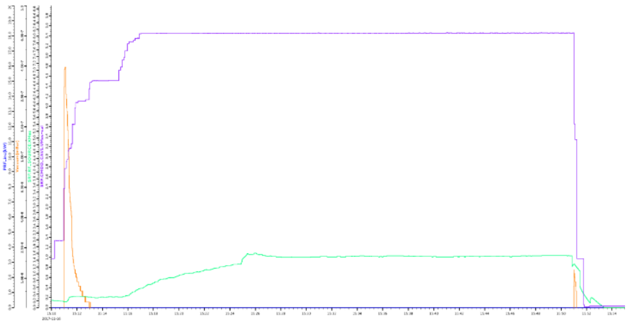

Figure 10: power ramp-up in HWR03: accelerating field (purple) and plateau at 5.4 MV/m for 30 minutes, vacuum (orange), integrated field emission (green).

CLEAN ROOM AT ROKKASHO FUSION INSTITUTE

An ISO 14644-1 class 5 fully equipped clean room has been built under the responsibility of QST at Rokkasho Fusion Institute [14]. One challenge was to fit the clean room in an existing building with the space requirements based on CEA assembly preliminary scenarios. It results in a clean room made of three areas with a mobile unit as shown in Fig. 11.

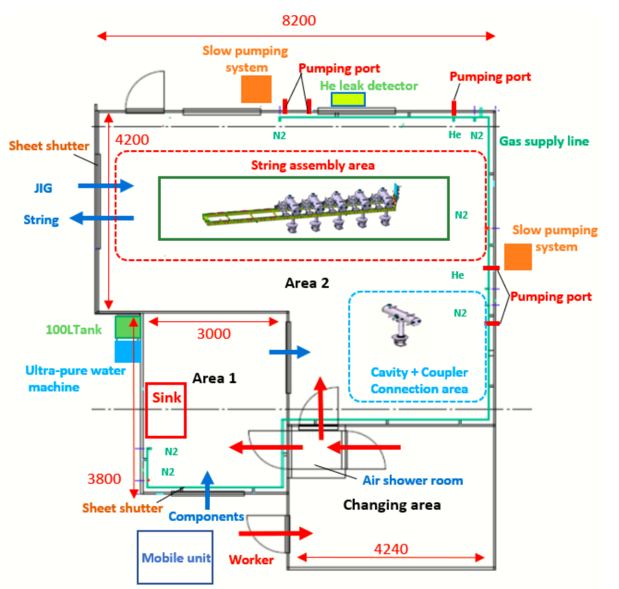

Figure 11: Layout of the clean room at Rokkasho Fusion Institute.

The first area is the changing room for the operators. From this area, it is possible to go either to the component entry hall (Area 1) or to the main clean room (Area 2) through an air shower.

Area 1 is dedicated to the entry and cleaning of tooling and components (except assembly jigs and support frame). This ISO 5 area is equipped with a sink and ultra-pure water, and an ionized nitrogen gun and particle counter to control the cleanliness of each component before entering the main clean room.

Area 2 is dedicated to the assembly of the cavity string. It is divided into two sub-areas, one for the assembly of a power coupler to a cavity, one for the string assembly. Several pumping ports and pure gas ports are located close to each assembly workstation: helium for leak testing; nitrogen for the ionized gun, for flushing the components during the assembly and for low venting after a leak test. A sheet shutter between this ISO 5 area and the rest of the building allows the entry of the big assembly jigs and the titanium frame, as well as the exit of the cavity string once this one will be completed.

The mobile station (ISO 6 soft wall clean room) is used for unpacking and preliminary cleaning to minimize the number of particles before introducing the components in Area 1. It is worth noticing that the cavities, couplers and solenoids will be packed in double sealed bags in clean room in Europe and that the cleaning operation at Rokkasho will consist of a rapid wiping with alcohol and cloth.

The clean room was completed in Summer 2018 and commissioned thereafter. No particle above 0.3 µm was detected at 1 meter above the ground in different locations in both ISO 5 areas, showing the efficiency of the FFU (Fan Filter Unit) and ULPA (Ultra Low Penetration Air) filters. Figure 12 depicts the inside of the clean room.

Figure 12: Inside the clean room.

One key element for a particle free cavity string assembly is the slow pumping system. The procurement of this was also under the responsibility of QST. The slow pumping system, which was designed by KEK, is based on a dry rough pump, a turbo molecular pump, several mass flow controllers and several vacuum valves. It is also equipped with a Q-mass spectrometer, a particle monitoring system and a filtered nitrogen slow venting line. An important feature of this system is that the pumping modes are automatically switched by the control system to minimize the risk of a wrong operation. Because of the lack of space inside the clean room, the slow pumping system is located outside. Flexible hoses are used to connect the component to pump to the slow pumping system through ports in the clean room walls. However, for convenience of operation during the assembly work, the control panel is installed inside the clean room (Fig. 13).

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Figure 13: Slow pumping system outside the clean room (left). Control panel inside the ISO5 area (right).

ASSEMBLY OF THE CRYOMODULE

Preparation Work

As presented in [15] and [16], many efforts have been put by CEA to prepare the clean room assembly. A tooling was developed to assemble a coupler on a cavity. This one and the associated procedure were qualified with the results of the high power tests of two IFMIF accelerating units. A test bench has been developed and used at Saclay to test, improve and validate key phases of the cavity string assembly. The test bench represent a bit more than one height of the real titanium frame and allows the positioning and assembly a cavity-coupler assembly and a solenoid. Mock-ups of a cavity, a coupler and a solenoid were manufactured to do trial assemblies outside and inside the cleanroom (Fig. 14).

Figure 14: Trial assembly in clean room at CEA Saclay using the dummy components.

Assembly Contract

The assembly of the cryomodule in Japan is under the responsibility of Fusion for Energy (F4E). After a worldwide call for tenders, the contract has been awarded to Research Instruments GmbH (RI).

Procedures

Based on input from CEA, the assembly procedures were prepared by RI over the course of 2018. A number of review meetings were held during which the procedures and associated control plans were matured to a level deemed acceptable to start the assembly.

In addition, the key procedure of the cavity-coupler assembly was tested, using the mock-ups and tooling which was purpose designed for the assembly (Fig. 15). During the trials, a number of minor modifications were made to the tooling to improve the ease of alignment of the components.

Figure 15: Cavity being lowered onto cavity-coupler assembly frame during trial assembly at RI premises.

Tooling Design and Manufacture

A number of different tools were designed and manufactured, including:

- Cavity-coupler assembly tooling: this was designed and manufactured by CEA.
- Cold mass assembly support frame.
- Thermal shield installation jig.
- Cold mass insertion jig.

With the exception of the cavity-coupler assembly tooling, all of the tooling was designed and manufactured by RI. All tooling is onsite in Rokkasho, the cold mass assembly support frame and the hoist being introduced in clean room beginning of 2019.

Assembly of the Cavity String

While not all of the components are available onsite, sufficient components are available to allow the first assembly steps to proceed.

Figure 16: Start of assembly work at Rokkasho Fusion Institute. The first two cavity-coupler assemblies on the cold mass support frame, with the third cavity-coupler assembly in the background.

In order to start, the preparation of the cleanroom was completed beginning of 2019. In March, the first three cavity-coupler assemblies were made (Fig. 16). In the first

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three assemblies, it has been difficult to reach the required leak rate for the interface. After a second try, the first assembly was leak tight. Improvements have been performed on the leak detection system and the procedure to precisely locate the tiny leak on the two other assemblies. Checking continues onsite to ensure the specified leak rates are met.

Challenges in Cryomodule Assembly

While the cryomodule assembly itself is a typically challenging cleanroom task, there have been a number of other challenges to overcome in the preparation of the assembly. The main two are:

- Managing the assembly in Japan: as Rokkasho is a remote location, and the assembly contractor, the cryomodule designers and manufacturers are all based in Europe this has been particularly challenging.
- Available space for the assembly: it was not originally expected to complete the assembly in Rokkasho, hence the space dedicated to performing this task was not purpose built. Rather the assembly steps have been made to fit in the available space. This implies that a number of compromises have had to be made in the preparation of the assembly procedures.

CONCLUSION

The manufacturing of the components of the IFMIF cryomodule and the qualification of the cavities, couplers and solenoids is now finished. The cavities performances are above the requirements and two accelerating units have been successfully qualified in horizontal cryostat.

Most of the components are now delivered in Japan, where the assembly of the cavity string has started. The cryomodule shall be complete during the first quarter of 2020 and then installed on the beam line of the LIPAc accelerator for the conditioning and the commissioning with beam.

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DISCLAIMER

This publication reflects the views only of several of the authors, and Fusion for Energy cannot be held responsible for any use which may be made of the information contained therein.

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