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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 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 is under construction at Rokkasho Fusion Institute in Japan. It includes one cryomodule containing 8 half-wave resonators (HWR) operating at 175 MHz and eight focusing solenoids. This paper presents the status of the IFMIF SRF Linac.

THE IFMIF LIPAC SRF LINAC

The IFMIF LIPAc 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 Figure 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.

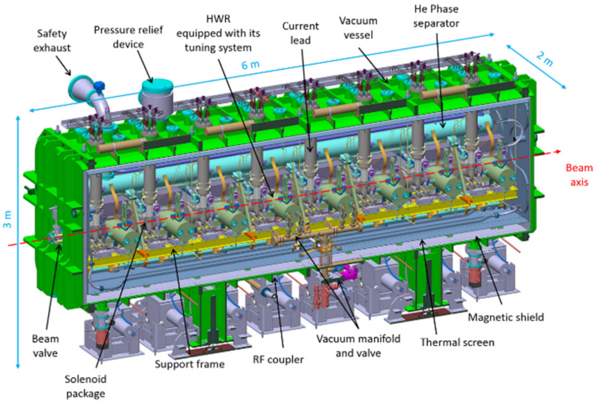

Figure 1: The IFMIF LIPAc cryomodule.

More details on the design of the cryomodule as well as the development plan and the actions taken to mitigate some risks are detailed in [1]. The next sections will present the manufacturing status of the main components of the cryomodule.

CAVITY STRING COMPONENTS

Cavities

The manufacturing of a series of 8 HWRs is in progress. An additional pre-serial cavity has been completed and tested during the production of the subcomponents of the series. A series of intermediate and qualification tests have been carried out for this HWR, between each major steps of manufacturing, and for all configurations:

- A vertical test (VT) of the niobium resonator be-fore heat treatment, after an average removal of 180 micrometers with BCP,
- A qualification VT after 650°C heat treatment and tank integration. The measured Q_0 was at $1.2\text{x}10^9$ at the nominal E_{acc} of 4.5 MV/m, and the quench field at 8.7 MV/m,
- An horizontal test in SaTHoRI using the same close-to-critical coupling RF feeding antenna,
- The horizontal test of the complete accelerating unit configuration, with the power coupler (Q_{ext}=$6.8\text{x}10^4$) and cold tuning system. The maximum accelerating field obtained was 5.5 MV/m in this configuration (administrative limit for high power test) (Figure 2).

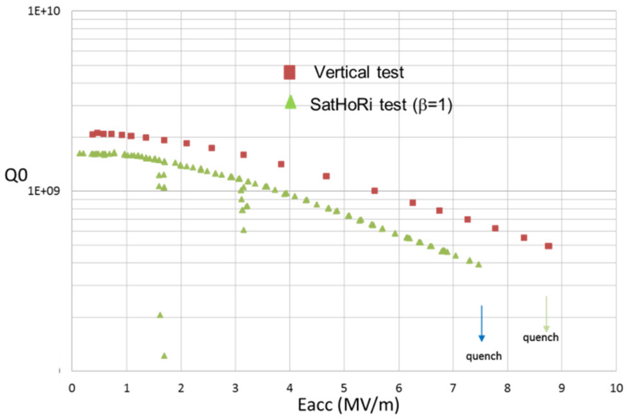

Figure 2: Horizontal test compared to vertical test for the pre-series cavity.

The first series HWR has been completed. The manufacturing has been completed following the licensing requirements, in terms of materials and weld qualifications, non-destructive testing on the cavity itself (radiography of welds) and titanium vessel (dye penetrant test) and final pressure testing of the helium space at 1.9 bar above atmospheric pressure.

The first vertical test of the bare resonator has been performed earlier this year. Although the cavity was not yet heat treated and had undergone several runs of static BCP etching to adjust its frequency, the Q_0 at nominal field was slightly above the specification of $5\text{x}10^8$. The next step is the preparation of the completed cavity and the qualification test.

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After experiencing reproducibility issues in the operations related to the closing weld which is actually a dual weld of the torus to the cavity body and inner conductor, some tests had to be perform in order to consolidate the process. The initial sequence of HPR ports welding and torus welding had to be swapped in order to solve the problem, and resume the last steps of the production. Since then, two serial bare niobium resonators have been completed. Three other resonators sub-assemblies are ready for the closing weld operations.

Statistics on this production are still too low to skip the VT of bare resonators before heat treatment and after main BCP steps for damage layer removal and frequency adjustment by differential etching. The actual etching sequence is a balance of the two types which are respectively with acid circulation and with static acid. The details of the preparation of the cavities is given in [2]. The experience with the pre-series and the first series HWR shows that at this stage, the chemical etching has to be tailored for each cavity, based on its as-delivered resonant frequency. This has led us to test various etching configurations with only two cavities, which did not generate particular issues.

Power couplers

The manufacturing of the first series Fundamental Power Couplers (FPC) pair was accomplished in April 2016 [3]. The Site Acceptance Tests (SAT) at CEA demonstrated important vacuum leak on the bellows of the external conductor of each coupler. For the first one, the leak rate was estimated to about 10^{-4} mbar.l/s. For the second one, it was not possible to pump down the bellows to less than a pressure of 5 mbar. The same bellows have experienced successful leak tests following the brazing operations in the manufacturer premises.

These bellows has a function of a mechanical interface between the coupler body and the cryomodule flange interface. It was designed to allow stokes of +/- 4mm and +/-2mm for respectively axial and lateral directions with low induced mechanical constrains. The aim is to preserve the integrity and the alignment of the cryomodule RF subsystems during the displacement of the cold mass and the shrinkage of the couplers due to the cryomodule cooldown.

Further tests performed by the manufacturer on other external conductors showed that additional bellows already tested after brazing becomes leaky. Investigation and analysis showed that many factors were at the origin of the leaks. In fact, the principal factors contributing to generate the leak are the followings:

- The use of several high temperature cycles during the manufacturing process seems to alter the mechanical properties of the bellows bulk material.
- The presence of some glass beads, coming from copper plating bead blasting finishing, inside the bellows waves was not prevented using protective masks. The finishing operation, which is one of the final manufacturing processes, is not supposed do impact the bellows. However, some beads goes inside of some waves on the back side of the bellows and are very difficult to clean.
- The choice of a thickness of only 0.15 mm for the bellows, to reduce the stiffness, makes them relatively fragile after the thermal cycles. It was noticed that during the pump down of the bellows some opposite surfaces of the waves are pressed ones against the others.

The conclusion of the analysis is that the thin bellows, weakened with the manufacturing processes thermal cycles can have their waves strongly collapsed during the pump down with some sharp beads between the two surface coming in contact. After several pumping and venting operation during the leak tests, a puncture could occur.

The tests showed that bellows can start to have a leak after several pumping and venting operations. Cracking noise due the pressure applied by the waves surfaces on the glass beads are heard during the pumping. Optical microscopy performed on one of the investigated sample which was cut from a leaky bellows showed a puncture. The size of this later corresponds to the glass beads size (Figure 3). In addition, the opposite side of the bellows showed an impact trace demonstrating that the two surfaces applied an important pressure on the bead during the pump down.

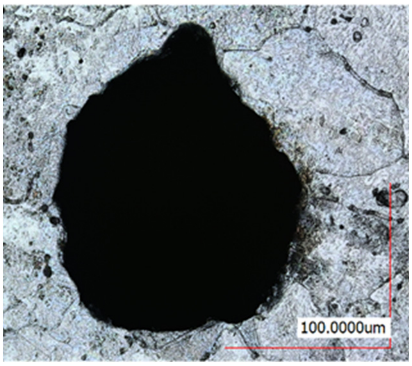

Figure 3: hole in the bellows.

To solve this problem several corrective actions have been implemented by the coupler manufacturer:

- Use of less fragile 0.2mm thick bellows instead of 0.15 mm thick ones. The subsequent stiffness increase is still acceptable.
- Upgrade of the protection tools and cleaning conditions by using more adapted hardware.
- Addition of more intermediate leak tests were requested during the production process.
- Applying of pumping and venting cycling sequences on the bellows to survey their behaviour reproducibility and their tightness.

The eight series power couplers were manufactured under these new conditions. The factory acceptance tests (FAT) of the reworked first two FPC was hold in October 2016. After shipping to CEA Saclay, they have been prepared in ISO 5 clean room in January 2017, and sent to CIEMAT for the assembly on the cavity coupling (Figure 4) and the RF conditioning.

The FAT of the other six power couplers was hold in March 2017. The SATs of all the power couplers were successful achieved in June. The last six FPC have been prepared in clean room a Saclay and are ready to be sent to Spain for the RF conditioning.

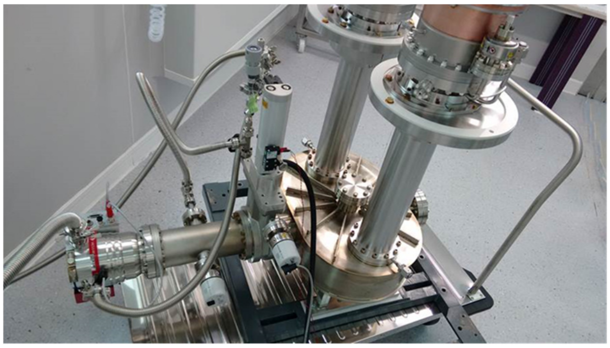

Figure 4: The first pair of power couplers assembled on the RF coupling cavity.

COMPONENTS OF THE CRYOMODULE

As presented in [4], most of the major components of the cryomodule are manufactured and delivered at CEA Saclay.

As explained in [1], all components containing helium gas or liquid during operation of the LIPAc have been designed, and are fabricated and tested according to ASME standards, as agreed in the collaboration to meet the Japanese regulatory requirements with regard to HPGSL (High Pressure Gas Safety Law). The phase separator is one of the components which have to respect the ASME Boiler and Pressure Vessel Code (BPVC). It ensures the storage, separation of liquid helium (LHe) and gaseous helium (GHe) and its distribution to the components of the cryomodule. It is a 5200 mm long and 206 mm diameter cylindrical vessel made of stainless steel with more than 30 openings connected to the cavities, the solenoid packages and the power couplers. Several tests were performed during the production to control the quality of the welds and a pressure test of the phase separator was performed at the end of the manufacturing in presence of a third party inspector.

The thermal shield is another component to contain helium gas. It is made of several aluminium panels with pipes welded on them. Only the piping shall be ASME B.31.3 “Process Piping” compliant. Pressure tests of the piping were hold in presence of a third party inspector in the manufacturer’s premises, as well as leak tests.

As presented in [5], the cryomodule will be assembled at Rokkasho Fusion Institute in Japan under the responsibility of F4E (Fusion for Energy) with CEA assistance. To fulfil the assembly of the cavity string, a cleanroom will be built on the site under the responsibility of QST (Quantum & Radiological Science and Technology). Therefore it is mandatory for CEA to control every parts. Every component is controlled: visual inspection, dimensional control, leak test and pressure tests when necessary. Moreover, several blank assembly have been performed to control the interfaces between sub-systems. A blank assembly of the thermal shield in the vacuum vessel was performed at the manufacturer’s premises before the welding of the pipes on the panels.

The magnetic shield, which protects the cavities against the background magnetic field in order to avoid trapping magnetic flux while cooling down through transition, is made of 2 mm thick mu-metal panels installed on the inner surface of the vacuum vessel. After the manufacturing of the panels of the magnetic shield and before heat treatment, a blank assembly of the shield in the vacuum vessel has been performed at CEA. Due to minor manufacturing defects of the vacuum vessel, some holes in the panels had to be enlarged and special washers manufactured.

Preparation work has also been performed by CEA to prepare the assembly of the cavity string in clean room. This one is made of height cavities (half wave, 175 MHz) with their power couplers, height superconducting focusing solenoids with their BPMs (Beam Position Monitor), two cold-warm transitions with their beam gate valves and one pumping line supported by a titanium frame. A test bench has been developed and used at CEA to test, improve and validate key phases of the cavity string assembly. The test bench represents a bit more than one height of the real frame and allows the positioning and assembly a cavity/coupler assembly and a solenoid [6]. Mock-ups of a cavity, a coupler and a solenoid were manufactured and used in trials assemblies first outside the cleanroom and then inside in cleanroom conditions [7]. Based on the experience acquired with the test bench, a sequence for the assembly of the cavity string has been written by CEA.

A tooling has also been developed for the assembly of the power couplers on the cavities, which is one of the first operations to be performed in clean room for the assembly of the cavity string. The tooling and assembly sequence were first tested with the dummy cavity and power coupler outside of the cleanroom. Real components were then assembled in cleanroom conditions to perform the SaTHoRI test (see next section) the success of this test validates the tooling and the assembly operations. However, minor improvements shall be implemented for the tooling which will be used for the assembly at Rokkasho.

SaTHoRI

The SaTHoRI test stand (Satellite de Tests HOrizontal des Résonateurs IFMIF) aims at characterizing a jacketed and fully dressed cavity with its RF coupler and frequency tuner. A dedicated test cryostat has been manufactured and connected to an existing horizontal test cryostat which provides the cryogenic coolant.

The pre-serial cavity was first tested with critical coupling with two objectives: the first one was to qualify the SaTHoRI cryostat with a known cavity to confirm cryogenic behaviour and magnetic shield efficiency. The cavity performances was slightly similar to the ones in vertical cryostat. The maximum accelerating field is 7.5 MV/m. The measured Q_0 at nominal field (4.5 MV/m) is 8.5×10^8, which is above the specifications (5×10^8). The second objective was to test the cold tuning system. This one allows a tuning range which exceeds slightly the specified value of 50 kHz. Hysteresis measurements have been performed. A 6 Hz peak-to-peak frequency pointing error results from repeated back and forth +/-15 Hz tuning motions. For comparison, the bandwidth of the resonator equipped with its power coupler is 2.7 kHz.

After the first test with critical coupling, the cavity has been prepared for a high power test with a IFMIF/EVEDA power coupler prototype (Figure 5). After warm and cold conditioning of the power coupler, the cold tuning system with its control has been retested and the same performances have been obtained than with the critical coupling test. Then RF tests have been performed and an average accelerating field of 4.51 MV/m was measured on the HWR cavity with power coupler at for an input RF power of 13.8 kW. More details on the SaTHoRI test stand and results can be found in [8].

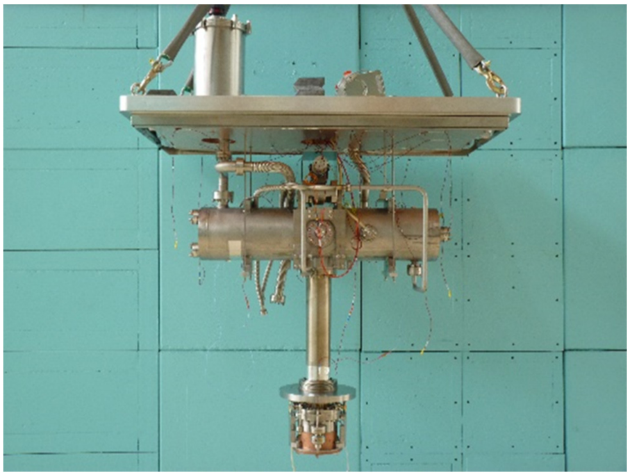

Figure 5: Cavity with its tuning system and power coupler prepared for the SaTHoRI test.

CONCLUSION

The manufacturing of the components of the IFMIF/EVEDA SRF Linac is progressing well. The series cavities are in progress, all the power couplers have been manufactured and prepared in clean room at CEA Saclay. Most of the major components of the cryomodule are delivered at Saclay are being prepared for the shipping to Rokkasho Fusion Institute in Japan.

The successful SaTHoRI test validates the IFMIF/EVEDA superconducting accelerating unit: half wavelength cavity equipped with helium tank, with tuning system and power coupler in the final cryomodule configuration. Thanks to these tests, the tooling, assembly procedure in clean room of a cavity with its power coupler, sequences of the control system were also validated.

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