PROGRESS IN IFMIF HALF WAVE RESONATORS MANUFACTURING AND TEST PREPARATION

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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. The first phase of the project aims at validating the technical options for the construction of an accelerator prototype, called LIPAc (Linear IFMIF Prototype Accelerator). A cryomodule hosting 8 Half Wave Resonators (HWR) at 175 MHz will provide the acceleration from 5 to 9 MeV. We report on the progress of the HWR manufacturing. A pre-series cavity will be used to assess and optimize the tuning procedure of the HWR, as well as the processing steps and related tooling. A new horizontal test cryostat (Sathori) is also being set up at Saclay in the existing SRF test area. The Sathori is dedicated to the IFMIF HWR performance check, fully equipped with its power coupler (FPC) and cold tuning system. A 30 kW-RF power will be available for these tests.

LICENCING ASPECTS

Since the LIPAc cryomodule [1] will be installed in Rokkasho, Japan, its design and fabrication have to comply with HPGSL law. The nominal temperature is 4.45 K, this corresponds to a nominal pressure of 1.2 bar. Cryogenic circuits and safety equipment of the cryomodules have been designed in order to have a maximum working pressure of 0.15 MPa in the 18 L HWR helium vessel. In practice, the mechanical cavity design already presented [2] was analyzed by the manufacturer for him to propose a detailed manufacturing sequence and weld procedures following the ASME methodology. The geometries of electron beam welds (EBW) between Nb ports and NbTi flanges were modified in order to increase the joint efficiency, using ASME as a reference. For most Nb-NbTi welds, the consequence was to make them equivalent to full penetration welds. The direct effect is to reduce the amount of required inspection testing involving radiography through the complete Nb resonator and thick flanges, which in our case would have been un-conclusive. Eventually, only visual inspection and third party inspection of the welding process will be required for the Nb to NbTi welds. The requirement of 100% radiographic inspection of Nb-Nb EBW joints will be limited to those classified as longitudinal welds and to beam tube welds. The longitudinal GTAW welds of the Ti vessel will be subjected to 100% radiographic testing as well. A final pressure test will be performed with a proof pressure in the He vessel at 0.875 MPa above atmospheric pressure.

The first milestone of HWR licensing has recently been passed with the submission of the application form to the Japanese authority which processes pressure vessel applications, KHK. This document includes all manufacturing drawings, procedure, weld classification, qualification and test plan, FEM analysis of the corresponding mechanical model of the HWR with detailed description of weld areas.

MANUFACTURING

A total of 9 HWR will be manufactured. The first one, a pre-series HWR is prepared up-front to check the whole manufacturing, RF frequency tuning and final treatments procedures. The pre-series cavity will be used in Saclay test area only and can be manufactured before the weld qualification process required for the cavity licensing is complete. Several weld test samples have already been produced by the manufacturer. In particular, they cover Nb-Nb full penetration electron beam welds (EBW), and thicker EBW welds joining the NbTi flange to the FPC Nb port, with a required final thickness of 6 mm.

HWR Parts Manufacturing

The beam ports (Figure 1) have been machined from high purity bulk Nb (RRR>250).

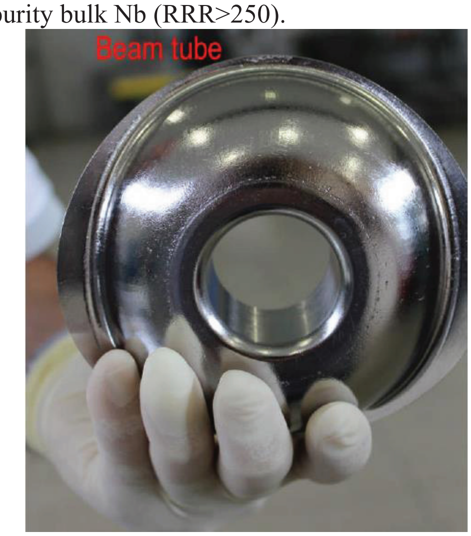

Figure 1: beam port of the HWR.

It is also the case for the central part of the inner conductor (IC) and the toroidal end caps, shown on Figure 2 along with one conical half of the IC.

After completion of the bare resonator manufacturing, it will be delivered for chemical etching and vertical testing at Saclay. The HWR will then be heat treated in a vacuum furnace for de-hydrogenation. The final fabrication step will be the welding of the Helium vessel.

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Figure 2: Nb parts of the pre-series HWR.

Tuning Procedure

Part of the RF frequency tuning is performed during manufacturing by intermediate mechanical and RF measurements on blank assemblies. A specific sequence has been setup for the pre-series cavity which will be simplified for 8 production cavities. The three intermediate configurations are shown on Figure 3. At each step, trimming, frequency and geometry controls will be performed. We expect to obtain the 'as manufactured' target frequency within 50 kHz.

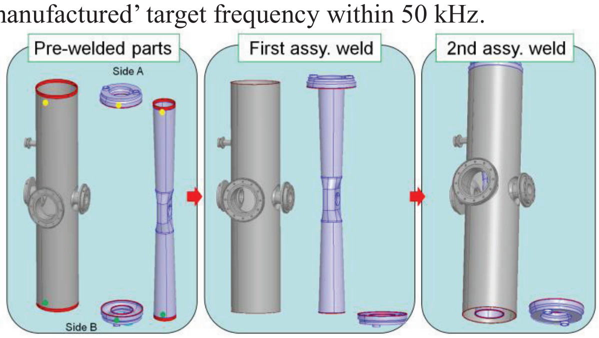

Figure 3: Intermediate HWR configurations for RF frequency tuning by trimming operations.

The residual frequency error after any subsequent operations (cavity dressing, chemical etching) will be corrected using differential etching if deemed necessary. This way, the final tuning by plastic deformation which is not compatible with the licensing process of the HWR is avoided.

PREPARATION SEQUENCE AND TOOLING OPTIMIZATION

The preparation sequence of the resonators is listed below:

- BCP etching (120 µm removal),
- Cleaning in ISO7 clean room to prepare introduction in ISO5 clean room,
- High Pressure Water Rinsing (HPWR) in ISO5 specialized cabinet,
- Vertical test (fast cooldown),
- Heat treatment at 650°C in a vacuum for 24 hours.
- Cavity dressing with the helium vessel,
- BCP etching is performed (minimum 20 µm), with the goal of minimal material removal and final frequency adjustment if required.

The HWR is then tested once more in the vertical cryostat for its final acceptance.

BCP Etching Setup

The resonator is chemically polished (standard Buffer Chemical Polishing) with circulating acid mixture (membrane pump), while set in vertical position. The acid used is a mixture of HF(40%), HNO3(65%) and H3PO4(85%) in volume proportions 1-1-2.4.

The acid is stored in a PEHD tank (200 L capacity), chilled through a Teflon heat exchanger to control the acid temperature accurately. The acid temperature is maintained below 20°C.

The cavity is filled from the bottom through the 2 HPWR ports and the acid exits through the 2 upper HPWR ports. The acid runs back to the tank by gravity. This setup will be used for uniform and differential etching.

HPWR Setup

The cavities will be rinsed in the ISO5 clean room on the vertical HPWR system, on which the nozzle stays at a fixed position while the resonator is spinning and lifted by two independent motorized systems (Figure 4).

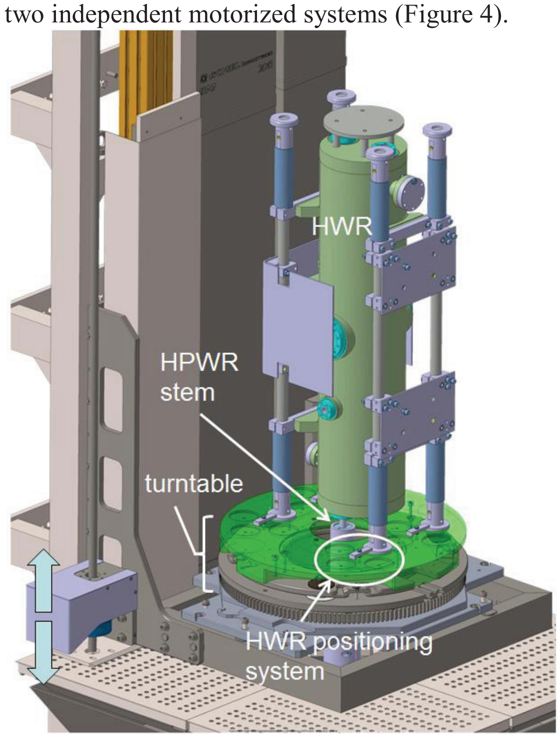

Figure 4: HPWR setup in ISO-5 clean room.

The nozzle head is welded to the 100 bar ultrapure water feeder stem. Two pairs of HPWR ports are located on the cavity caps. One pair (side A) is aligned in the same direction as the beam tubes, and the other pair (side B) is aligned in the orthogonal direction. Taking into account the HWR geometry, this arrangement assigns side A and B ports to the rinsing of specific areas of the RF surface, in particular on the central part of the inner conductor. In principle, it could be possible to have both sides of the cavity rinsed when using B-side ports. This would not be possible on the A-side because the beam ports are in the way of the nozzle while travelling through the cavity. However, the length of feeder stem of the HPWR system must be bound within certain limits in order to keep its lateral stiffness acceptable. Having too long a feeder tube has already proven to generate oscillations on its first bending mode while circulating high pressure water in the system. This issue must be avoided especially when dealing with a narrow cavity. The feeder stem diameter is fixed at 18 mm. We have set the maximum feeder stem free length at 700 mm. The frequency of the first mechanical mode is above 28 Hz in this configuration, which can be considered as safe.

Starting from this constraint of total feeder stem length, the optimization of the nozzle head requires knowing how each of its jets will cover the cavity surface while the cavity is cleaned using the 4 ports in sequence. To this aim, a 3D ray tracing program was used to determine the rinsed areas. The principle is to mimick the water jets using light beamlets and using a shell model of the cavity as a screen, a color patch represents the impact area. The main advantage of a ray tracing program over a CAD software is that it is optimized to find the first impact point of the beamlet with the modelled geometry. When considering the HPWR process in a complex shape like the one of our HWR, masking effects are the main cause of incomplete rinsing of the cavity surface.

The light beams motion can be programed to follow the rotation and translation of the nozzle with respect to the cavity. This way, the area cleaned by a given jet can be determined and analysed separately, giving the opportunity to tune the angle of each opening of the nozzle. By giving a different color to each beamlet, and overlaying the results for all jets and HPWR ports, it becomes possible to check if un-rinsed area exist for a given nozzle configuration, or if the effect of two nozzle opening are redundant. By combining single beamlet simulation and global simulation, it becomes possible to optimize the nozzle head design for our HWR. The incomplete rinsing of a surface can be observed as flat gray or black areas in the simulated images. The striped aspect of the coloured areas is due to the angle step of 5° used for the simulation of the rotation of the cavity around the HPWR stem, in order to save computing time. In reality the rotation movement is continuous.

First, the 4-angle setup [85°, 60°, 0°,-30°] which was formerly used for the prototypes was analysed (Figure 5). Large portions of the conical parts and more importantly high E-field areas in the central part appear as not rinsed.

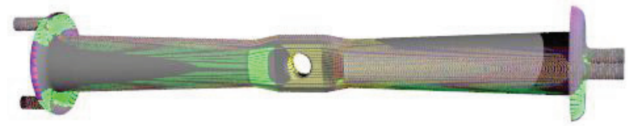

Figure 5: IC rinsing with 4-angle setup [85°,60°,0°,-30°].

The rinsing of the conical part can only be improved using a forward jet with an angle closer to 90°. Figure 6 shows the contribution of the jets at 60°, 0°, and -30°, and the contribution of a jet at 87° which improves the overage of the conical part of the inner conductor. The beam ports have been introduced in the simulation in order to take into account their potential masking effect on the most forward jet.

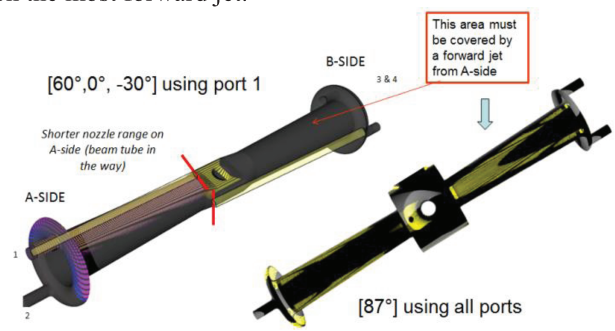

Figure 6: Improvement of cone coverage with a 87° jet.

The jet angle set [87°, 60°, 0°,-30°] is still not sufficient to cover the central part of the inner conductor, and the un-rinsed area appear in flat grey on Figure 7.

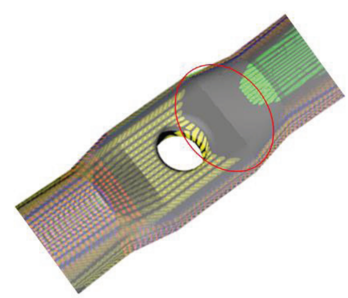

Figure 7: Un-rinsed high E-field area on the IC.

A systematic study of nozzle angles between 55° and 85° was carried out, showing that the area could not be covered by a single jet, but only by a combination of two jets. Replacing the jet at 60° by two jets at 58° and 76° solves the problem as illustrated by Figure 8.

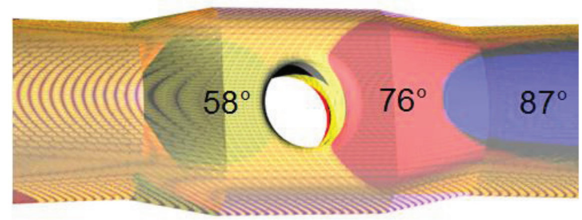

Figure 8: Complete coverage of the high E-field area.

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Most of the surface of the outer conductor is covered using the [85°,76°,58°,0°,-30°] angle set, however the toroidal HWR end caps are not sufficiently rinsed in the direct vicinity of the HPR port. This can be fixed by changing the angle of backward jet from -30° to -60° in order to specialize this jet for targeting the torus area. The improvement of the concentration of the jet impacts is shown on Figure 9.

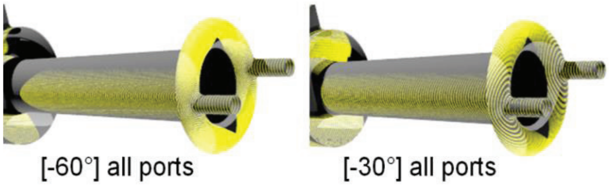

Figure 9: The -60° jet improves of the torus coverage.

In order to avoid excessive redundancy between jet angles, they can be simulated by pairs, for example (Figure 10), for 0° and 87° then -60° and 87°. Although -60° and 0° have a large overlap on the conical parts, the contribution of the -60° jet on the torus clearly appears as beneficial.

Figure 10: Coverage comparison between -60° and 0°.

The simulation of the full use of all jets on all HPWR ports has been run with a higher angular resolution of the cavity rotation movement of 1°, keeping the same rate of vertical displacement at 4.5 mm per turn. The results of the simulation for the chosen configuration of nozzle angles [87°,76°,58°,0°,-60°] is presented on Figure 11.

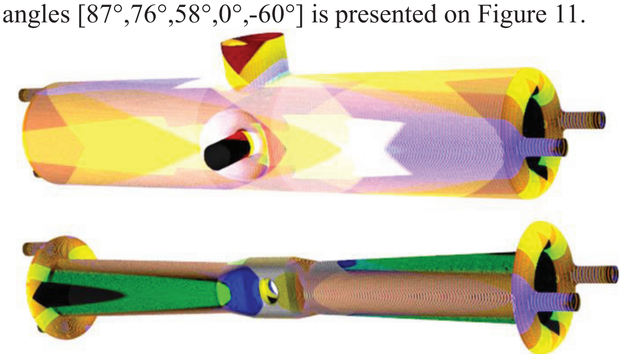

Figure 11: Full simulation of the chosen nozzle head.

Areas on the conical parts remain un-rinsed even after this optimization. The masking effect of the cone itself is the origin of this issue, and cannot be avoided with the present HWR geometry. The jets at 0°, 58° and 76° angles which cover the high E-field area of the HWR will be doubled on the actual nozzle head.

SATHORI HORIZONTAL TEST STAND

In order to assess the design a full acceleration unit of the LIPAc cryomodules (HWR equipped with cold frequency tuner and FPC in vertical position), a new test stand composed of an horizontal cryostat is being set up specifically for this task. The already existing Cryholab horizontal test cryostat was not compatible with the geometry of the HWR and FPC assembly. The new cryostat (Sathori) was designed as a satellite of Cryholab. They share a common insulation vacuum space, and the new cryostat connects to the existing cryogenic circuits of Cryholab (liquid He for the cavity He-gas for the FPC and liquid N_2 for the thermal shield). This way we take advantage of the existing cryogenic distribution, instrumentation, and process control. One of the LIPAc 176MHz 2x105 kW CW RF power source will be delivered and installed in the test area at Saclay. For the Sathori tests, 30 kW RF power is sufficient to carry out complete validation tests on a cavity at the nominal accelerating gradient with sufficient margin. The connection to mains, cooling system and additional high power RF components have been procured accordingly. The layout of the new setup is shown on Figure 12.

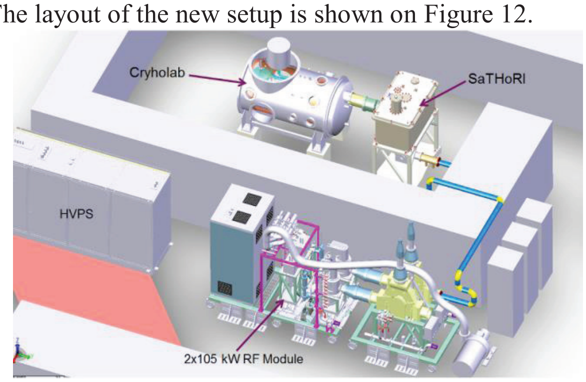

Figure 12: Cryholab-Sathori layout in Saclay test area.

Sathori Cryostat

Sathori has been designed as a top loading cryostat. It includes a stainless steel vacuum vessel, a copper thermal shield at 77K, a room temperature magnetic shield, and a top plate made from aluminium alloy.

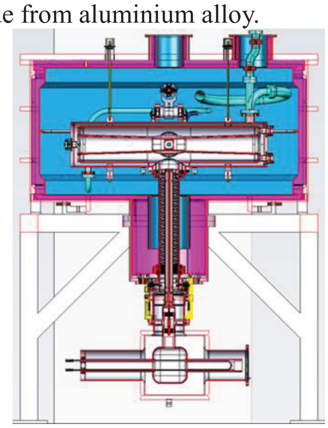

Figure 13: Cut view of Sathori equipped with HWR, tuner and FPC.

All the equipment inside the cryomodule is supported by this top plate except the lower part of the magnetic shield which is fixed on the vacuum vessel. Figure 13 shows the arrangement of the HWR and FPC inside the cryostat.

The detailed design and manufacturing of the vacuum vessel and thermal shield has been subcontracted in industry. The final design of these components and the parts under manufacturing are shown on Figure 14.

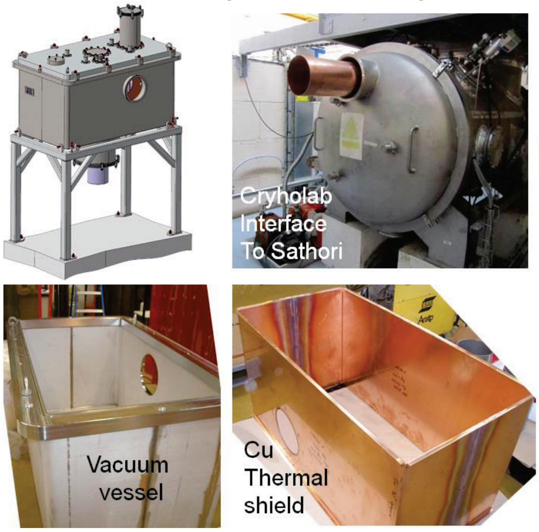

Figure 14: Manufacturing of Sathori components.

Magnetic Shield

One of the primary interests of the new cryostat is to test the accelerating unit in configurations which are representative of the LIPAc cryostat operation. The simulation of potential problems related to the vicinity of the SC solenoids at this stage of the project is highly valuable [3]. The Sathori magnetic shield must ensure good shielding from the earth magnetic field for reliable cavity performance testing with a goal of 2 µT at the HWR surface. The design shown on Figure 15 reaches this objective using 2 mm thick mu-metal sheets.

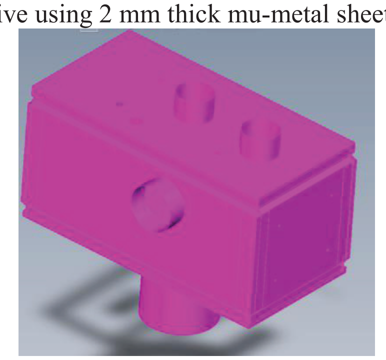

Figure 15: Sathori magnetic shield design.

In order to make possible the use of an external coil to produce magnetic field at the cavity surface, apertures are required on the side panels of the shield. Removable circular magnetic shield caps (Figure 16) will be used for all non-magnetic-field related tests.

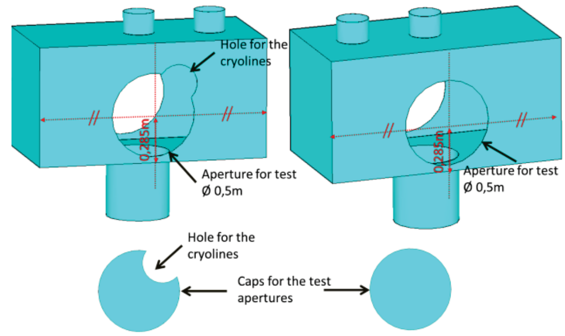

Figure 16: Magnetic shields apertures and caps.

SATHORI TEST PROGRAMME

The pre-series HWR and samples of serial HWR will be tested in Sathori. For the pre-series, additional tests will be performed, starting with reference tests of the HWR with critical coupling:

- Performance assessment of the Sathori module and its magnetic shield using the HWR in the same configuration as the vertical test,
- Test of the tuner and tuner controls,
- Test of sensitivity of HWR to external magnetic field and quench recovery, flux trapping, possible magnetization of surrounding components,
- Tests of the effect of thermal gradients during cooldown on HWR performance.

Tests of the HWR equipped with the prototype FPC will follow:

- Test of all coupler cooling circuits (He, water) in cryomodule-like environment,
- Behavior of the complete system in CW mode,
- Test of LIPAc instrumentation

If successful, this set of tests will also provide a validation of all the preparation, assembly sequence, clean room procedures and tooling related to the HWR, FPC and their assembly.

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