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IFMIF RESONATORS DEVELOPMENT AND PERFORMANCE

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Abstract

The prototype IFMIF cryomodule encloses eight superconducting 175 MHz beta 0.09 Half-Wave Resonators (HWR). They are designed together with the power coupler to accelerate a high intensity deuteron beam (125 mA) from to 5 to 9 MeV. One prototype HWR and the 8 cavities to be hosted in the cryomodule have been manufactured, prepared and tested. The paper describes the phases of the cavities development, including fabrication, processing and RF frequency management. We focus on the results of the RF tests which have been performed for all bare and jacketed HWRs in a vertical cryostat.

INTRODUCTION

The 40 MeV 125 mA deuteron superconducting accelerator for IFMIF starts with 2 beta 0.945 cryomodule (CM) hosting 8 175 MHz half wave resonators (HWR) and superconducting solenoids, followed by high beta CMs. The Lipac prototype accelerator installed in Rokkasho, Japan includes the first low beta CM, for wich CEA has delivered all components except the solenoids with are contributed by CIEMAT [1]. What is unique to this cryomodule is the combination of SRF coaxial cavities which are usually part of low intensity ion accelerators and high beam power. In the IFMIF case, RF components have been designed to operate up to 200 kW CW. The fundamental power couplers (FPC) [2] dimensions are comparable to the HWRs'. Taking this into account has been one of the main drivers in the cryomodule design. HWRs are designed to operate in the horizontal position and support the cold mechanical tuner (top) and FPC (bottom). This sub-assembly constitutes an accelerating unit. The cryogenic circuit for the cavities, HWRs and solenoids are supported by a common titanium frame in the CM (Fig. 1).
The HWR parameters are summarized in Table 1.

Table 1: HWR RF Properties

Parameter	Value	Unit
Epk/Eacc	4.8	n.a
Bpk/Eacc	11	mT/(MV/m)
r/Q	140	Ohm
Operation Frequency	175.000	MHz
optimal beta	0.11	n.a.

The original design of the RF cavity shape has been unchanged since the early prototyping phase. The mechanical desing was competely modified for use with a compression tuner [3]. The cut view is shown on Fig. 1. Due to the tight radii in the end torii (the small torus radius and the fillet at the HPR port junction) high purity Nb blocks were machined to obtain the desired shape. Beam ports and central drift tube area were also cut from blocks.

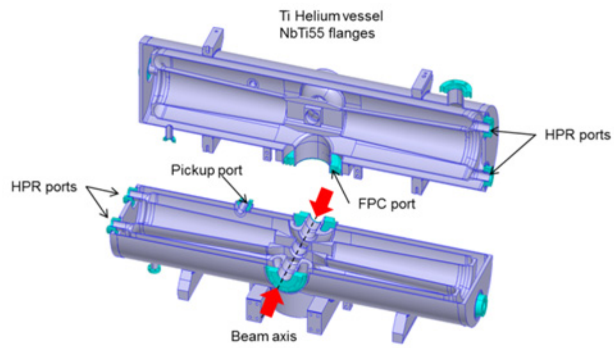

Figure 1: Jacketed HWR cut-view.

Some of the challenges to be overcome were to demonstrate:

- The thermal stability of the HWR operated in horizontal position,
- the process of tuning the cavity during its manufacturing and preparation steps, while staying above the floor limit of 3 mm Nb thickness
- the possibility of field emission free RF performance thanks to efficient cleaning despite the complex inner shape and tight access.

DESIGN EVOLUTIONS

The performance requirements for the HWR are E_{acc} > 4.5 MV/m with $Q_0 > 5.\ 10^8$. The minimum tuning range is 50 kHz. The mechanical design of the resonators is mainly driven by the use of a compression tuner, and the compliance with the Japanese High Pressure Gas Safety Law. In order to save beamline space, the tuner deforms both the cavity and the He vessel in the beam area.

The approval of the jacketed cavity as a pressure vessel requires detailed informations of the manufacturing and control sequence, and the detail on welding processes. As a consequence, the approval was obtained late into the manufacturing phase, implying several design adjustments to comply with licensing requirements.

Geometry modifications of the NbTi flange to Nb ports e-beam weld area (lap joint) was required in order to provide weld visual inspectability from both sides as the only way to demonstrate the full penetration of each joint. Test welds with macrographs were carried out for weld process qualification proving the 6 mm penetration initially but the possiblity of crack intiation was not ruled out, unless both sides of the weld could be inspected. To this effect, a bevel

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was machined in the NbTi flange on the He side, enabling full access for weld inspection.

Dye penetrant testing (DPT) was also required on the Ti vessel welds. This kind of test is generaly avoided in order to minimize cavity or clean room contamination. This concern led to the choice of a water-based DTP fluid with enhanced residues removal capability. This, combined with the protection of cavity flanges during DPT had no measureable effect on cavity performance.

CAVITY MANUFACTURING

A total of 9 HWR have been manufactured. The first one was used as a test bench for all RF tuning and preparation methods [4], and was not part of the Japanese HPGSL lincensing procedure. The RF frequency sensitivity measures at -177 kHz/mm with respect to it length. Completing the welds between the 4 cavity main parts (cavity outer body, stem and end torii, see Fig. 2) requires trimming based on initial geometry of the individual parts and corrections due to shrinkage variations during successive welds. A 50 kHz RF frequency spread was expected at the cavity delivery, but could not be reached, although at least 3 intermediate measurements were carried out during Nb resonator completion.

Details of weld areas and weld sequence were adjusted during fabrication, starting on the first series HWR for which the first torus-stem weld failed. After a second failure on another HWR, a new welding sequence of torii and HPR ports was devised. The initial angle between the electron beam and Nb parts was too low and caused instability. Stability was recovered by shooting the beam with an angle closer to normal.

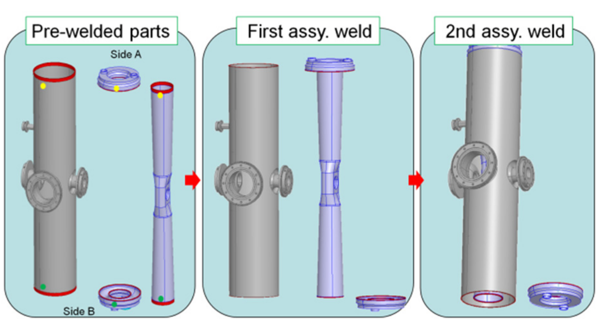

Figure 2: Main HWR parts welding sequence.

CAVITY PREPARATION

The preparation phases breakdown as follows:

- a first main BCP etching phase both for damage layer removal and frequency tuning, followed by High pressure water rinsing in the ISO5 HPWR booth and preparation for cold test.
- after the vertical test, the actual cold HWR RF frequency is confirmed. If too far from the target frequency, additional BCP tuning is carried out before any heat treatment, in order to minimize the etching time after heat treatment, subsequently the introduction of hydrogen in the Nb.
- a 650°C 24 hours high vacuum heat treatment is carried out at the manufacturer premises, followed by helium jacket integration.
- final BCP including final adjustment of the frequency, preparation With HPWR in ISO5 clean room
- qualification test of the jacketed cavity

The RF frequency and the minimum required Nb thickness of 3 mm Nb are extremely important parameters for cavity acceptance, besides the SRF performance. At each practical phase in the etching sequence, the RF frequency and Nb thickness is measured in order to take informed decisions on the next step.

For damage layer removal, at least two phases are necessary, flipping the cavity orientation midway. The acid blend (FNP 1-1-2.4) is injected through both bottom HPR ports and evacuated through the top ports. The temperature of the acid tank, which is actively cooled, is allowed to rise up to 13°C. Predefined levels of acid in the HWR have been defined beforehand (approximalety 1/3 and 2/3 of cavity height) to perform static 25 minutes etching HWR tuning (respectively for negative and positive shifts in frequency). The number of BCP tuning steps depends on the inital cavity frequency. These unit steps were most of the time performed in sequence of 3 at least in order to save on the setup time. The HWR was flipped between series of chemical tunings in order to balance the removal of material on each side, and monitor the thickness as frequently as possible. The occasional observation of Nb oxyde layers discoloration in horizontal ports have lead us to end always a series of static etching with a short (typically 10 min) circulation etching steps as the last operation before clean room preparation.

Figure 3: HWR preparation steps at Saclay. From left to right: chemical etching setup, HPWR in ISO5 clean room, view of HPWR nozzle through the FPC port.

The HPWR setup shown on Fig. 3 optimized for the IFMIF cavity geometry [4] was used, rinsing the cavity through each of the four HPR ports sequentially, totalling 7 hours of rinsing.

Lessons Learned from Chemical Tuning of HWRs

Chemical tuning is a time consuming process, more time being required for setup then drying prior to check the shifted frequency, than for actual etching. It had been an-

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ticipated to learn from the first cavities all etching/frequency related parameters in order to predict what the optimized etching sequence would be for a cavity with a given initial frequency offset. The behaviour of the first two HWRs was promising from this point of view [3]. However, the experience on the 8 series HWRs showed less predictability.

The initial overall frequency spread on the series cavities was 246 kHz as first delivered (bare HWRs). Following the initial plan with estimates of the effect of first heavy etching phases reduced the initial frequency spread of 246 kHz down to 123 kHz. This large value was mainly due to a single cavity HWR04.

Among the 9 IFMIF HWRs experiencing the chemical etching, a large spread of detuning per etching time unit was observed especially for the circulating acid setup, spanning over negative and positive values. The positive frequency shift was observed on two HWRs only. This observed fact was barely predictible, and our hypothesis is that the uneven distribution of grain orientation among the various niobium blocks was the underlying cause of it. Unlike the sheets, the blocks also display a large grain size distribution, with centrimetric grains always visible.

As a consequence, more frequency correction steps were required for the majority of HWRs, and the number of intermediate frequency controls was kept high. Eventually the frequency spread was reduced to the final value of 23 kHz on the 8 fully functional cavity batch.

The actual inital thickness of the Nb sheets for the cavity body was 3.4 and 3.6 mm, within our specification of 3.3 mm -0,+0.4 mm.The evolution of thickness was monitored during the period of chemical etching, with a focus on cavity parts made out of Nb sheets. The same measurement template covering 48 unique locations on the HWR was used for all cavities. On all HWR the minimum thickness requirement is satistified after all processing and tuning steps, but almost all the thickness margin was used up in some cases. If the margin on top of the nominal starting thickness of 3.3 mm had not been available, other methods for tuning would have been developped, with increased complexity.

BARE RESONATOR TESTS

A vertical test at 4.2 K of each HWR is performed after the main BCP etching steps, before the 650 °C heat treatement. All tests have been performed in the larger Saclay test Dewar, the cavity being held in vertical position.

Instrumentation available for all HWR tests is a set of 16 cernox sensors positionned on high H-field locations, power inlet, copper cap closing the 96 mm diameter fundamental coupler port. The pickup proble is biased (50 V potential) in order to collect electrons. A low dose-rate ionisation chamber is also used to measure radiation on the top plate of the cryostat, below the concrete radiation shielding blocks.

All Q versus Eacc curves are shown on Fig. 4. For these intermediate tests, no limitation was set in terms of accelerating field but the maximum forward power of was set as at 200 W to prevent damaging the RF cable network.

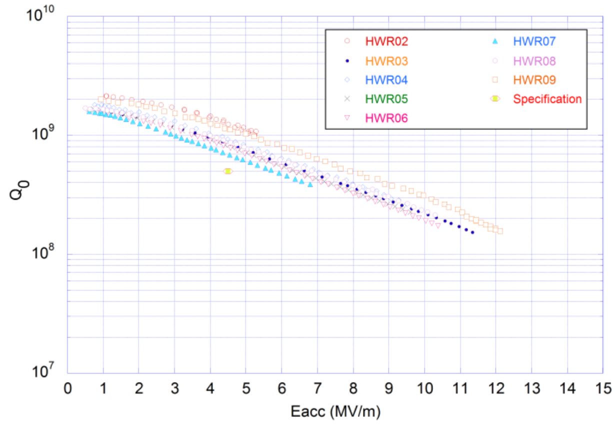

Figure 4: Q vs E_{acc} curves of bare HWRs.

All cavities but one display the same low field multipactor barrier, around 30 kV/m, not visible on the graphs. This MP barrier is not conditionned after the test, but was not an issue when operated with the power coupler in subsequent horizontal tests [5]. Two other barriers have to be conditionned in all cases, ranging from 1.2 to 3.5 MV/m. For most HWRs, the conditioning time was about 3 hrs. After processing, the full E_{acc} range is accessible. The finished HWRs must reach E_{acc}>4.5 MV/m for Q_0> 5 10^8 in order to proceed with the final steps of manufacturing. The best cavity reached a peak magnetic surface field of 135 mT and a peak surface accelerating field of 58 MV/m.

On several cavities, thermal stability test have been carried out by bringing the liquid He level below the beam tube height. In all cases tested (3 cavities), no influence on cavity behavior was observed until only about the lowest 20% of the cavity height was in contant with liquid He. The tests in the dedicated Sathori cryostat [5] have confirmed the thermal stability of the HWR which in this case was checked for the horizontal orientation of the HWR. The potential issue of gas formation in the inner conductor and subsequent inadequate cooling is ruled out.

A series of vertical tests were carried out for finalized jacketed HWRs. This time around, limitations were set on the extent of E_{acc} range testing, in order to prevent firing of field emission, and risk a re-processing of any HWR. All resonators have been tested up to the minimum accelerating field of 5.5 MV/m (i. e. 20% above specification) without quench. The corresponding results on Fig. 5 show a convergence of the performance of the finalized HWRs compared to previous series of tests of Fig. 4. In particular, it can be observed that the lower Q_0 HWR07 and earlier quenching HWR02 beneficitated from extra processing steps.

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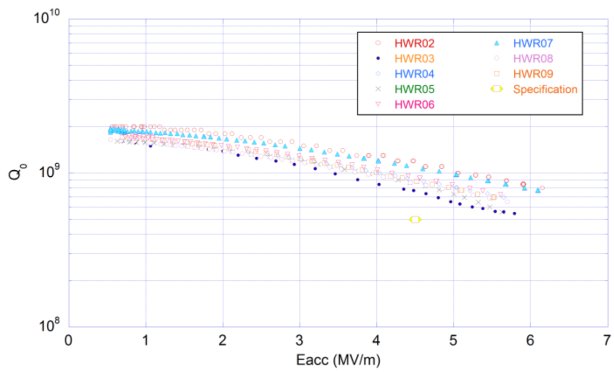

Figure 5: Final performance of HWR in vertical qualification tests.

No field emission was observed during the final qualification tests except for HWR05 for which the field emission onset was detected at E_{acc} = 5.6 MV/m.

CONCLUSION

The set of eight HWRs for the IFMIF superconducting linac have been succesfully manufactured and processed in order to obtain the required performance. They have been delivered to the Rokkasho site in a directly usable configuration for the cavity string assembly in the clean room.

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