

# ANALYSIS OF THE RESULTS OF THE TESTS OF IFMIF ACCELERATING UNITS

N. Bazin, O. Piquet, G. Devanz, H. Jenhani, M. Desmons, S. Chel  
CEA, Université Paris-Saclay, Gif-sur-Yvette F-91191, France

## Abstract

The SaTHoRI test stand (Satellite de Tests HOrizontal des Résonateurs IFMIF) aims at characterizing an IFMIF-EVEDA jacketed and fully dressed cavity with its RF coupler and frequency tuner. Two accelerating units have been qualified at CEA Saclay. This paper presents the results and the lessons learnt for tuning and conditioning of the whole SRF-Linac.

## INTRODUCTION

The IFMIF/EVEDA project aims at validating the technical options for the construction of an accelerator prototype, called LIPAc (Linear IFMIF Prototype Accelerator). The superconducting cryomodule components have been qualified and have been shipped to Rokkasho Fusion Institute, Japan [1] where there are being assembled under the responsibility of F4E (Fusion for Energy) with CEA assistance. For this operation, QST has built a cleanroom [2].

In addition to the vertical test for individual half-wave resonator qualification, the validation test of two accelerating units (cavities equipped with a tuner and a power coupler) has been performed. These tests, which are part of a mitigation plan (see [3]), took place in a dedicated test stand called SaTHoRI [4].

## ACCELERATING UNITS

One of the accelerating units tested in SaTHoRI is depicted in Figure 1.



Figure 1: Cavity with its tuning system and power coupler installed on the top lid cryostat.

A unit is based on a 175 MHz beta 0.09 Half-Wave Resonator (HWR), equipped with a power coupler which has been designed to handle 200 kW continuous wave. They are designed to accelerate a high intensity deuteron beam

(125 mA) at the nominal accelerating field of 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 [5].

Two cavities have been 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 prototype power coupler used has been conditioned at room temperature up to 100kW in summer 2014 by CIEMAT [6] and stored under nitrogen atmosphere until it was installed on the pre-series cavity beginning of 2017.

## LOW POWER TESTS

Prior to the high power tests, a low power test has been performed. The first objective of the critical coupling test was to qualify the SaTHoRI cryostat with a known cavity (the preseries HWR01 equipped with its tuning system) to confirm cryogenic behaviour and magnetic shield efficiency. The results are presented in Figure 2. In a cryomodule-like (horizontal test), the maximum accelerating field is 7.5 MV/m. The measured  $Q_0$  at nominal field (4.5 MV/m) is  $8.5 \times 10^8$ , which is well above the specifications ( $5 \times 10^8$ ).

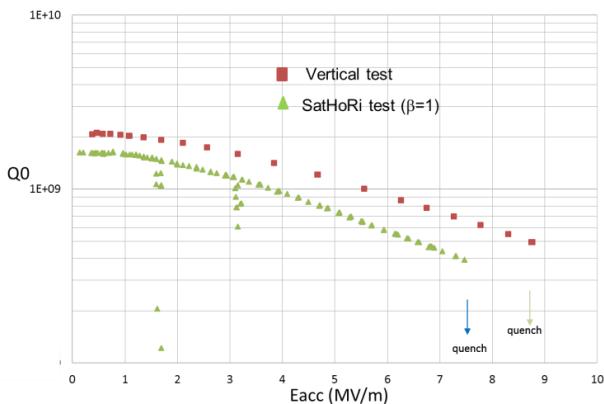


Figure 2: Horizontal test compared to vertical test.

## SEQUENCE FOR HIGH POWER TESTS

The test sequence for each accelerating unit is similar to what will be performed on the cryomodule during the conditioning phase:

- Conditioning of the power coupler at room temperature.
- Cool down of the cavity.
- RF measurements: calibration, frequency of the cavity, qualification of the tuning system,  $Q_{ext}$  of the coupler.
- Conditioning of the power coupler at cold.

- Power ramp-up in the cavity up to the 5.4 MV/m (20% above the nominal accelerating gradient).

The results for each stage are presented in the next sections.

## CONDITIONING OF THE POWER COUPLER

During conditioning of the power coupler, following signals are monitored and can trigger alarms or interlocks:

- Signal coming from the vacuum controller of the coupler.
- Two inputs for the arc detectors, one implement on the vacuum side of the power coupler, the other on the RF transition between the coaxial line and the coupler. The signal of the arc detector is compared to a threshold which can be adjusted using a potentiometer implemented on the front panel or using the control system software. If the signal is above the threshold, the output interlock signal is set to 1. This input signal is also sent to a fast acquisition system based on VME boards.
- One input for the electron pick-up implemented on the power coupler. The principle of this input is similar to the arc detector input.

An electronic module has been designed and manufactured to sum up the four interlock signals and communicate with the local control system (LCS).

The conditioning procedure is automatic and the RF power level is varied in a way to ensure the coupler protection: starting from short pulse (20  $\mu$ s) with low power (some hundreds of watt peak power level) and low repetition rate (2 Hz), then increasing the power up to 25 kW, the pulse length and the repetition rate until continuous wave operation at high power.

Because the prototype power coupler have been stored more than 2 years between its RF conditioning and its use in the high power tests, severe outgassing occurred during the room temperature conditioning of the coupler on HWR01, even at low power, short pulse and low repetition rate. Moreover, the recovery of vacuum level was very long after each outgassing due to the poor conductance of the pumping line connected to the cavity. For this reason, the efficiency of the pumping system has been improved before testing HWR03 which allowed a significant gain of time (refer to Figure 3 showing a conditioning sequence of the coupler of HWR03).

During the warm conditioning, as no coolant is flowing in the circuit of the outer conductor, an increase of temperature has been observed. In order to limit this one and to improve the evacuation of heat, the insulation vacuum of the cryostat was vented to atmospheric pressure with pure nitrogen.

Some multipacting levels were encountered in power ranges between 4-12 kW and 18-20 kW.

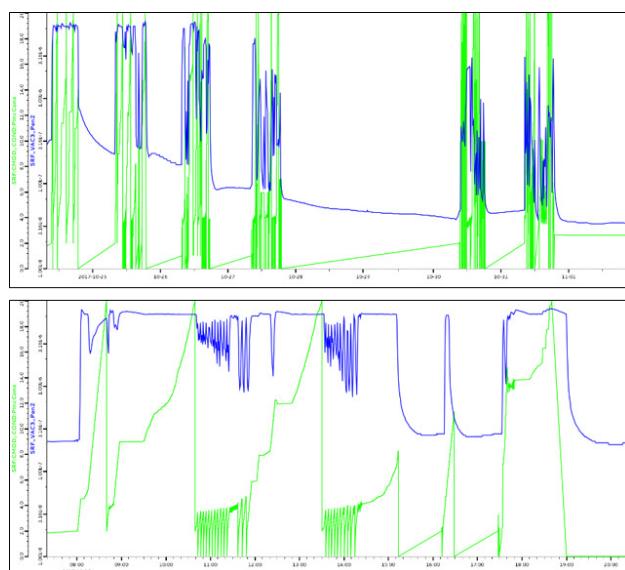


Figure 3: Conditioning at room temperature of coupler on HWR03 (RF power in blue, vacuum in green).

After the cavity is cooled down to liquid helium temperature (around 4.3K) and once the system temperature as well as the flow of cold helium gas in the outer conductor of the coupler are stabilized, the conditioning can start again following the sequence described above. Thanks to the efficient conditioning at room temperature, the conditioning sequence at cold takes less than three hours (Figure 4). Very limited electron activity is detected around 10-12 kW, so that outgassing remains in the 10-8 mbar range (under the interlock threshold).

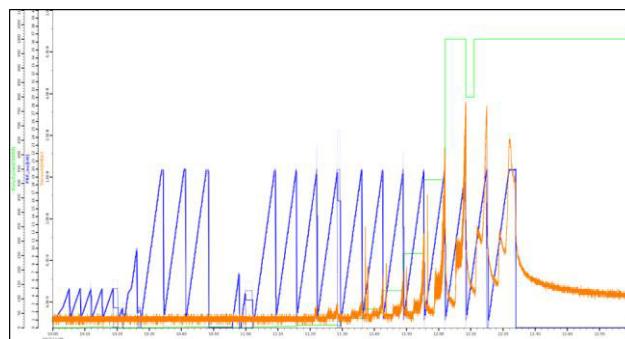


Figure 4: Conditioning at cold of coupler on HWR03 (RF power in blue, repetition rate in green, vacuum in orange).

## HIGH POWER TESTS

For the high power tests, the cavity is tuned to the frequency of 175 MHz and the cavity is fed by RF power. The nominal accelerating field of 4.5 MV/m is achieved in HWR01 with an injected power of 13.8 kW (Figure 5). It is worth noting that, at the administrative power limit of 20 kW defined as safe for this test without beam, the gradient reaches 5.4 MV/m.

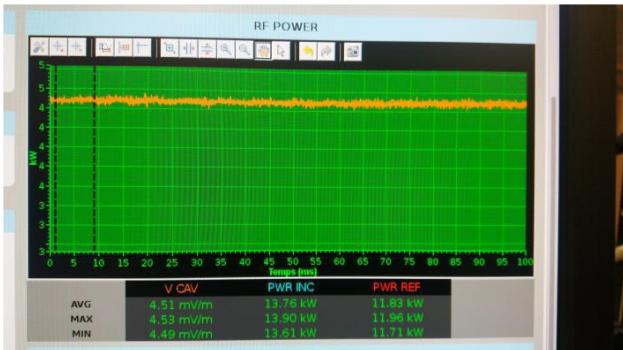


Figure 5: Signal from the pick-up probe corresponding to an average accelerating field of 4.51 MV/m measured on the HWR01 cavity with power coupler at  $P_i=13.8$  kW.

Nominal accelerating field of 4.5 MV/m was also achieved with HWR03, and stable operation of the cavity for 30 minutes at 5.4 MV/m (nominal accelerating field  $E_{acc} + 20\%$  margin) has been demonstrated (Figure 6). No field emission was observed during the test.

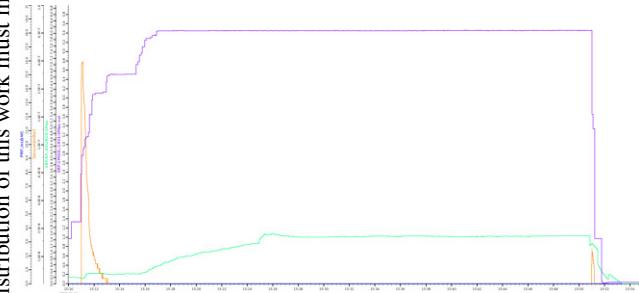


Figure 6: Power ramp-up in HWR03: accelerating field (purple) and plateau at 5.4 MV/m for 30 minutes, vacuum (orange), integrated field emission (green).

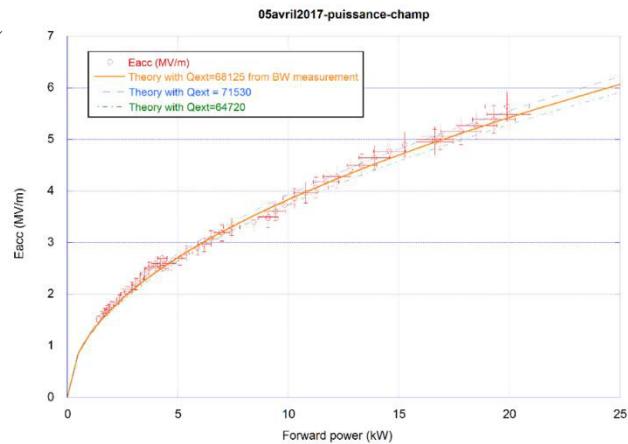


Figure 7: Measured accelerating field  $E_{acc}$  compared to the computed  $E_{acc}$  based on the measured  $Q_{ext}$ .

External quality factor  $Q_{ext}$  has been calculated from the resonator bandwidth measured using a vector network analyser. The value of  $6.81 \times 10^4$  is very close to the theoretical value of  $6.8 \times 10^4$ . Figure 7 shows the good agreement between the measured  $E_{acc}$  and the computed accelerating field  $E_{acc}$  based on the measured  $Q_{ext}$ .

During the overall continuous operation, there was no significant increase of the temperature (less than 0.5K) of

the coupler and the cavity. Tests of all cooling circuits of the power coupler (helium gas for the outer conductor and water for the inner conductor, the coupler ceramic window and the RF transition) have been also successfully performed.

## QUALIFICATION OF THE TUNING SYSTEM

### Measurement of the Hysteresis

As the cavity is equipped with a critical coupling antenna for the low power test, it is possible to characterize precisely the behaviour of the tuner.

The hysteresis, which is obviously difficult to predict, has been assessed on small frequency adjustments representative of what could be the operational conditions on the accelerator (Figure 8).

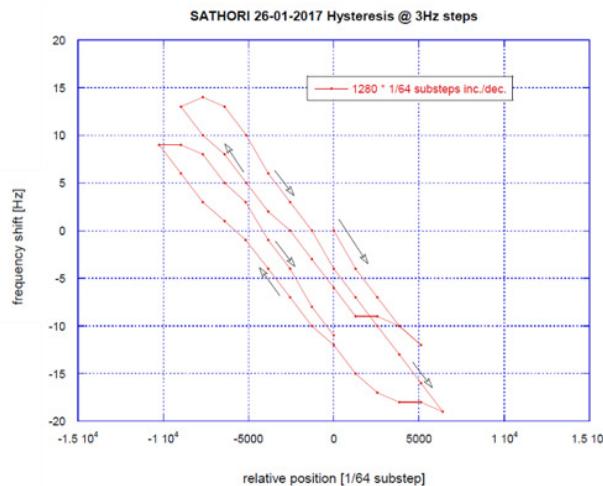
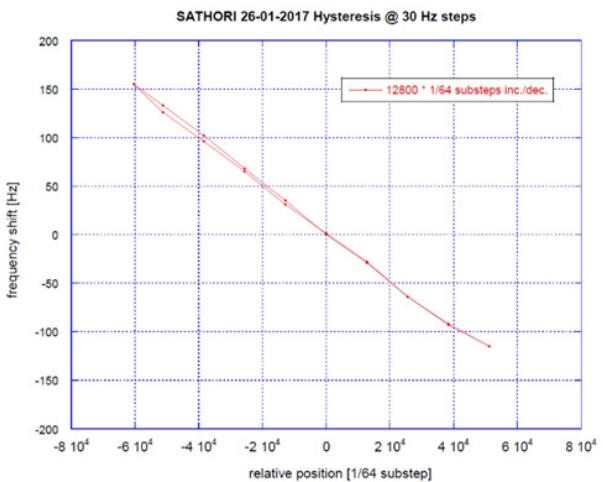


Figure 8: Hysteresis measurements of the tuning system.

A 6 Hz peak-to-peak frequency pointing error results from repeated back and forth  $\pm 15$  Hz tuning motions. When extending the tuning cycles to a  $\pm 150$  Hz range, the pointing error is kept at the same amplitude, so that it remains negligible with regards to the cavity bandwidth when equipped with its power coupler ( $\sim 2.7$  kHz).

## Tuning Range

Unlike the hysteresis, it is possible to measure the tuning range with or without the power coupler. For both equipped cavities, the tuning range was within the requirements of 50 kHz.

Figure 9 presents the typical tuning range which can be achieved with the frequency tuner measured on HWR03, which is the difference between the frequencies with respectively the tuner fully engaged (174.977 MHz, left peak) and the tuner disengaged (175.029 MHz, right peak).

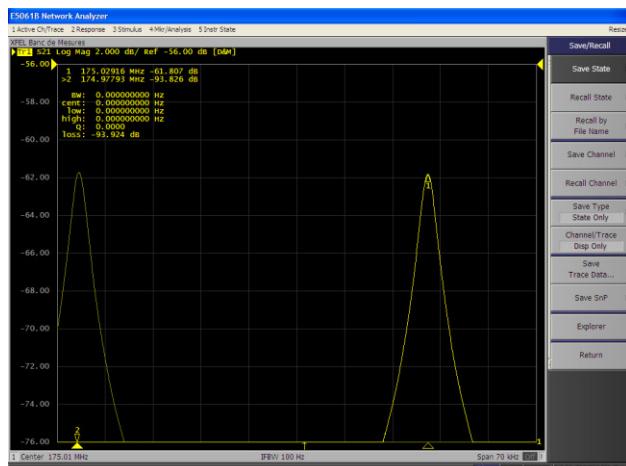


Figure 9: Tuning range of HWR03.

## Emergency Procedure

The tuning system applies a compressive force on the cavity. It has been designed to be disengaged during the cryomodule cooling down and warming up. As niobium has very low yield stress at room temperature, any applied load could damage the cavity when this one is not completely cold.

In case of a sudden warmup of the cryomodule or an electrical breakdown in the accelerator building at Rokkasho, an emergency sequence is implemented and can be called to bring the tuner in its parking position at twice the normal speed.

The slew time for the full tuning range have been measured for the two units: 26 minutes for HWR01, 28 minutes for HWR03. This time is adequate with the characteristics of the uninterrupted power supply for the SRF Linac at Rokkasho (45 minutes).

## LESSONS LEARNED

### Assembly Tooling

Due to the size and weight of the power coupler, a dedicated tooling has been developed at CEA [7] to assemble the power coupler on the half-wave resonator (see Figure 10).

The success of the tests of the two accelerating units validated both the tooling and the assembly procedure. The tooling is now at Rokkasho Fusion Institute where it has been adapted by the contractor for the assembly of the components of the LIPAC cavity string.



Figure 10: Assembly of accelerating unit in cleanroom at CEA-Saclay.

## Conditioning of the Power Couplers

The conditioning procedure developed for the SaTHoRI tests has proven to be efficient, and same procedure will be used for the conditioning of the eight power couplers of the SRF-Linac.

In particular, processing at room temperature has to be performed with a vacuum vessel at atmospheric pressure (vented with Nitrogen or without closing tapes) in order to avoid uncontrolled temperature drifts due RF losses in the outer conductor of the power coupler.

Moreover, it is expected a substantial outgassing at the beginning of the conditioning at room temperature. This one depends on the storage time between the RF conditioning on the coupling cavity and the RF conditioning on the cryomodule and on the time exposure to air of the RF surface of the power coupler during assembly. If outgassing is too high, conditioning can be limited. Then, it would be worth adding to the internal pumping line of the cavity string [8] a pumping system on the beam valve on one end of the cavity string (Medium Energy Beam Transport line upstream the cryomodule or High Energy Beam Transport line downstream the cryomodule) in order to improve the pumping capacity on the beam vacuum.

Because of these two points, it should be possible to do only the warm RF conditioning of one coupler at a time on the cryomodule.

## Control System

Part of the hardware of the local control system which has been tested on the SaTHoRI test bench was satisfactory and will be implemented on the SRF-Linac. Thanks to the tests and measurements performed at Saclay, the software, mainly the HMI (human – machine interface), has been improved. Most of the procedures developed for the SaTHoRI tests, as the drive of the motor of the tuning system, have been fully qualified and will be implemented on the SRF-Linac.

Specific electronic modules were developed to monitor the RF signals (forward power, reflected power, cavity

voltage). It was of course necessary for several sequences (conditioning, ramping) and would be more than useful to diagnose potential problems during the SRF-Linac operation.

### Quench Detection System

No quench detection system was implemented in the LLRF used for the SaTHoRI tests what will be corrected for the operation of the SRF-Linac at Rokkasho.

For this reason, no system able to detect a quench was available for the first test at high RF power. However, a prototype electronic card has been developed and implemented during the second high power tests to detect a potential quench of the HWR03 cavity. As the tests were performed without beam, the principle of the quench detection system has been based on instantaneous values of forward and reflected powers. Basically, as soon as the ratio reflected power / forward power is outer a range, as it happens when a quench occurs, an interlock is triggered which switchs off the RF power. The range depends on the RF cavity and coupler parameters and need some experiments to be adjusted. However, as no quench occurred during the second SaTHoRI test, the quench detection system has never been triggered.

## CONCLUSION

High power tests of the two accelerating units performed in the so-called SATHORI test stand were successful, validating the IFMIF-EVEDA superconducting accelerating unit: half-wave resonator with its tuning system and power coupler in the final cryomodule configuration. The nominal accelerating field of 4.5 MV/m was achieved with an injected power of 14 kW. Cavity has been operated at 5.4 MV/m (20% margin) and remained stable with no significant increase of the temperature in the system. Thanks to these tests, the tooling, assembly procedure in clean room of a cavity with its power coupler, specific sequences of the local control system were also validated.

## ACKNOWLEDGEMENT

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