

# HIGH-POWER RF TEST OF IFMIF-EVEDA RFQ AT INFN-LNL

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## Abstract

A partial test at full power and CW duty cycle was performed at INFN-LNL on the last elements of the IFMIF RFQ, approximately two meters of structure, using a specific electromagnetic boundary element on the low energy end. The aim is to reach, in the RFQ coupled with its power coupler system, after an adequate period of conditioning, CW operation at nominal field level (132 kV between electrodes) for at least two hours without breakdown. The description of the experimental setup and procedure, as well as the main results of the conditioning procedure are reported in this paper.

## INTRODUCTION

The main goals of the IFMIF RFQ high power test are summarized in the machine state diagram in Figure 1:

1. The RF CONDITIONING of the cavity, performed in Frequency Follower Mode (FF), to prove the RFQ operation at full power regime;
2. The setting up of nominal parameters of the system (temperatures, valve opening, frequency) which identifies the START-UP condition for the cavity;
3. The demonstration of stable operation of the system in RESONANT FREQUENCY CONTROLLED (RFC) mode.

## EXPERIMENTAL SETUP

The RFQ was transported from LNL-LAE building to the LNL 3<sup>rd</sup> experimental hall in November 2014 and it was placed in the test tunnel by crane (Figure 2). This transfer gave the opportunity to verify the maintenance of the field flatness after transport. Figure 3 shows a difference of 0.5% between the two, which is within the measurement accuracy.

In the tunnel the RFQ was baked out, by using a dedicated equipment composed of insulation panels and blower. After 8 days at 100°C, the cavity showed a final vacuum level of  $8 \times 10^{-9}$  mbar.

The test was performed between December 2014 and February 2015. The systems involved in the test are:

- The RFQ cavity, composed of the last 3 modules of the IFMIF RFQ (module 16-17-18) and Prototype 2 as boundary element on the low energy end. The Cavity Length was 2.021m (Figure 2).
- The RF power system [1], composed of 175 MHz – 220 kW CW amplifier based on the TH781 tetrode, coaxial wave-guide line, AFT circulator from CIE-MAT;
- The Vacuum system, which includes a rough dry pump and turbo pump as pre-vacuum stadium, a cryogenic pump as main pump and an ionic pump as back-up in case of cryo-pump failure or purge.;

- The Cooling system, consisting of a water skid with 2 independent cooling circuits (warm circuit and cold circuit), to finely tune the resonant frequency by temperature regulation.

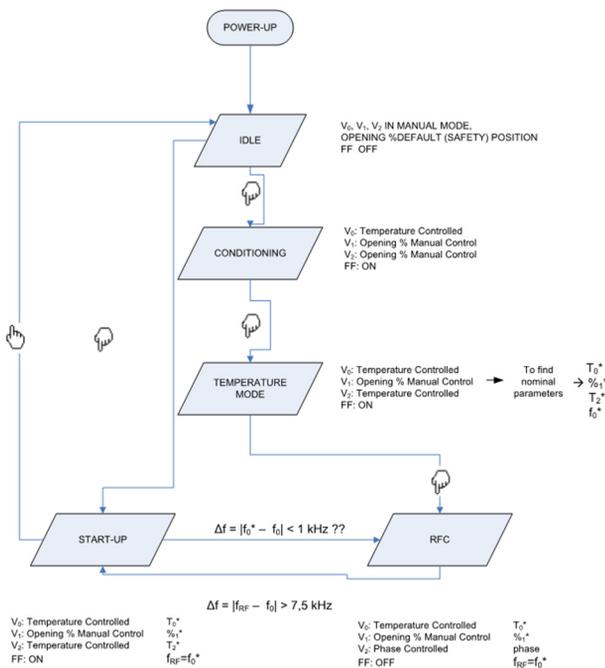


Figure 1: machine state diagram for the IFMIF RFQ high power test.  $V_0$ =input valve,  $V_1$ =cold circuit valve,  $V_2$ =warm circuit valve, FF=RF frequency follower, FLC=field level control, RFC=Resonant frequency control,  $f_{RF}$ =RF generator frequency,  $f_0$ =cavity resonant frequency.



Figure 2: A view of IFMIF RFQ test-bench in the IFMIF tunnel at INFN-LNL.

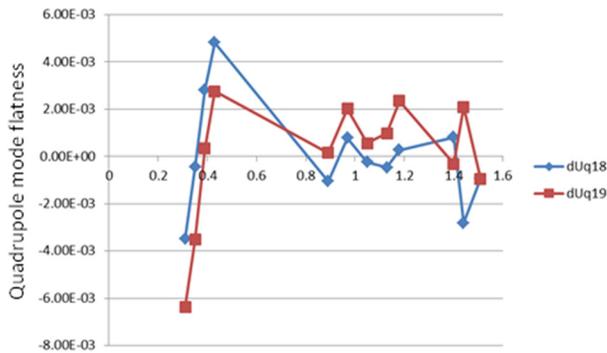


Figure 3: Bead-pull measurements done before (#18) and after (#19) RFQ transfer from LAE building to 3rd experimental hall.

The Control system, based on EPICS and PLC technology, is connected to the other subsystems in order to monitor their characteristic parameters, to command their actuators and to set-up variables (interlock thresholds, water temperatures).

In detail, the available diagnostics are:

- A directional coupler to measure FWD and REV power between Amplifier and Circulator;
- A directional coupler to measure FWD and REV power between Circulator and RFQ;
- A pick-up to establish the field level in the RFQ cavity;
- 16 pick-ups to determine field flatness in operation;
- The cavity power level is benchmarked by a power calorimetric measurement-;
- A vacuum gauge is located in the vacuum manifold;
- Input and output temperatures of the 2 RFQ cooling circuits;
- Mass flow of the 2 cooling circuits;
- of coupler temperatures;
- Water temperature of the RF load circuit;
- 2 arc detectors are located on the RFQ end plates looking between electrodes;
- 2 arc detectors are located on the circulator.

### RFQ CONDITIONING

An unloaded quality factor  $Q_0=12500$  was measured with a Vector Network Analyzer in the RFQ equipped with the final coupler, the coupling coefficient  $\beta$  being adjusted by coupler rotation to get the critical coupling with a return loss  $> 50$  dB ( $Q_L = 6250$ ). This value is confirmed by the loaded cavity filling time  $\tau_L=11.6\mu s$ . With that  $Q_0$  value, the nominal voltage of 132 kV corresponds to a cavity power  $P_{cav} = 173$  kW (86 kW/m).

In the conditioning phase the RFQ was let free to be detuned, and the master frequency generator followed the RFQ resonant frequency (FF: ON).

Three main phases of the RFQ conditioning are distinguishable, as highlighted in Figure 4.

From 28/11 to 12/12, RFQ was conditioned at low duty cycle ( $<1\%$ ), in order to calibrate RF measurements and distinguish multipacting levels. The period from 18/12 to

09/01 (Christmas holidays excluded) was dedicated to cavity conditioning at medium-high duty cycle (Range 10-80%), sometimes exceeding nominal peak power (max 192 kW-139 kV at 50% duty cycle). From 21/01 to 27/02 (with 2 weeks of stop from 26/01 to 11/02) the RFQ was kept at 100% duty cycle. In this period, the calorimetric measurement of RFQ cavity power were also set up, in order to benchmark the RF measurements. Figure 5 shows that, at power  $< 100$  kW, the measured power and voltage correspond to the theoretical curve, while at higher power level the measurements are above the nominal curve, meaning that a fraction of the power is not converted in accelerating voltage due to electron loading.

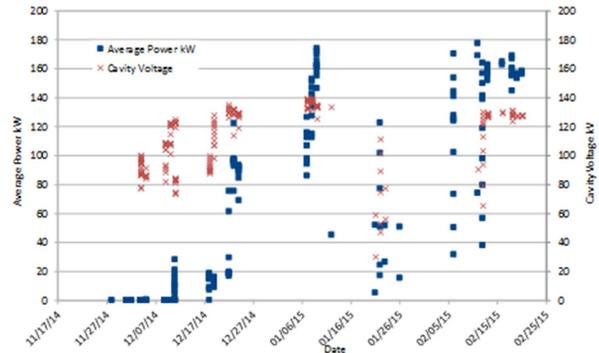


Figure 4: average FWD power and cavity voltage along the test time.

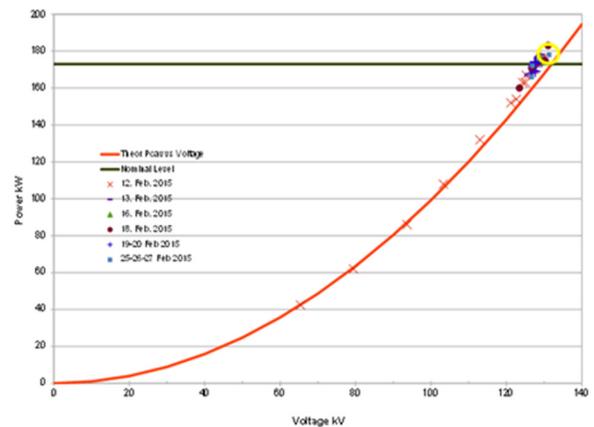


Figure 5: Cavity power (calorimetric measurements) vs. cavity voltage. The yellow circled dot corresponds to the nominal voltage level.

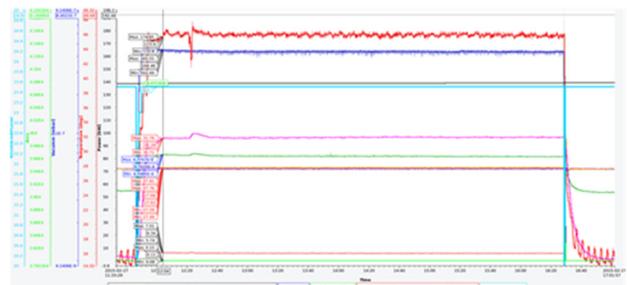


Figure 6: on February 27th the RFQ remains 5 hours at nominal field level. This state corresponds to the yellow circle in Figure 5.

The nominal voltage (132kV – 180 kW) in CW regime was reached on February 18th, but for less than 2 hours. The test was considered successfully closed in February 27th, after continuous operation at nominal voltage for 5 h (Figure 6).

### RESULT ANALYSIS

Once the nominal steady state operation was reached, the pick-up voltage measurements at different power level were compared with the bead pull measurement, in order to observe anomalous field detuning due to RF power. Because of important mechanical deformations during construction of Prototype 2, the quadrupole voltage presents a drop of 4% in the first half meter. Measurements show that in the power range from 0 kW to 140 kW there is no evidence of degenerative effects of the field flatness (Figure 7), as encountered during the TRASCO RFQ test [2].

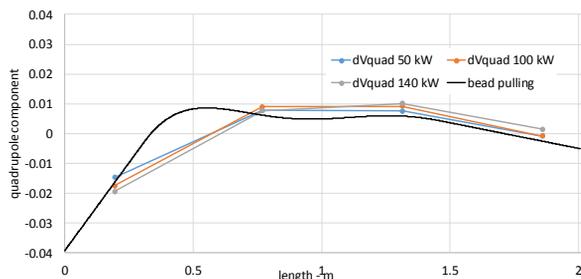


Figure 7: Field perturbation and frequency detuning measured at different power level.

### RESONANT FREQUENCY CONTROL

Closed loop controls are crucial parts in accelerator operation [3]. For the power test several close loop controls were set-up:

- Frequency Follower control (FFC), to set the output frequency of the RF amplifier at the natural frequency of the RFQ.
- RF power Level Control (FLC), to maintain constant power inside the cavity.
- Temperature control of cooling water circuits.
- Resonant Frequency Control (RFC) to control the cavity natural frequency by means of the cooling water temperature.

In the final installation FFC and RLC will be provided by the LLRF system developed by CIEMAT. The set-up and tuning of cooling and frequency control requires several step:

- Fine calibration of temperature and RF frequency measures.
- Characterization of the system, in particular to understand the response times related to valves movements or power changes.
- Tuning of the close loop controllers (PID), performed online at well-conditioned power level.

Once the RF conditioning was completed, the cavity could remain in stable operation for long time period. In

this situation the cavity was set in TEMPERATURE CONTROLLED state (Figure 1): FF is still ON, two valves in temperature (V0, V1) are played with and the 3<sup>rd</sup> is in manual opening in order to find the parameters that lead the RFQ resonant frequency  $f_0$  to get close to operation frequency of 175 MHz. These four parameters ( $T0^*$ ,  $\%1^*$ ,  $T2^*$ ,  $f0^*$  in Figure 1) are then imported into START-UP state as nominal parameters.

The switch to the RFC state occurs provided that a frequency error lower than 1 kHz for a time longer than 30 second occurs. If this condition is verified, FF is switched OFF, FLC is switched ON and the valve of the warm circuit V2 is controlled in order to set to zero the phase/frequency error. If the frequency error exceeds 7.5 kHz (1 dB cavity bandwidth) for a time longer than 1 seconds, the system jumps back from RFC to START-UP state.

Figure 8 shows that the RFC condition is kept for more than 1.5 hours at 100 kW CW, with frequency oscillation lower than 2 kHz.

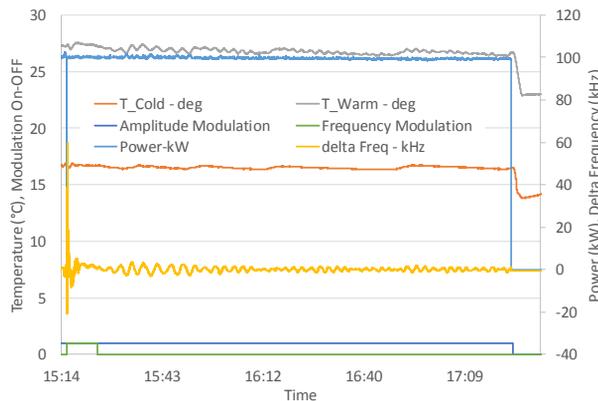


Figure 8: proof of RFC at 100 kW power level.

### CONCLUSIONS

The High Power Test of IFMIF RFQ demonstrated the RF and thermos-mechanical design of the cavity for full power operation and a method in order to control the resonant frequency by water cooling system. We are very grateful to P. Bottin, A. Colombo, A. Baldo for their technical support on the test assembly and disassembly.

### REFERENCES

- [1] E. Fagotti *et al.*, “The Couplers for the IFMIF-EVEDA RFQ High Power Test Stand At LNL: Design, Construction And Operation”, in *Proceedings of LINAC2014*, Geneva, Switzerland, p. 643.
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