HIGH-POWER RF CONDITIONING OF THE TRASCO RFQ

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Abstract

The TRASCO RFQ is designed to accelerate a 40 mA proton beam up to 5 MeV. It is a CW machine which has to show stable operation and provide the requested availability. It is composed of three electromagnetic segment coupled via two coupling cells. Each segment is divided into two 1.2 m long OFE copper modules. The RFQ is fed through eight loop-based power couplers to deliver RF to the cavity from a 352.2 MHZ, 1.3 MW klystron. After couplers conditioning, the first electromagnetic segment was successfully tested at full power. RFQ cavity reached the nominal 68 kV inter-vane voltage (1.8 Kilp.) in CW operation. Moreover, during conditioning in pulsed operation, it was possible to reach 83 kV inter-vane voltage (2.2 Kilp.) with a 0.1% duty cycle. The description of the experimental setup and procedure, as well as the main results of the conditioning procedure will be reported in this paper.

EXPERIMENTAL SETUP

The test was performed at CEA Saclay in January, February and March 2012.

The systems involved in the test are:

- RFQ cavity
- RFQ power system
- Vacuum system
- Cooling system
- Control system

The cavity under test is the first electromagnetic segment of the TRASCO RFQ [1], composed by two 1.2 m long OFE copper modules. The first module accommodates 12 gridded vacuum ports, the second one the 2 coupler ports. The RFQ end plates are equipped with dipole stabilizers [2, 3]. RFQ power level and field flatness are monitored by 16 pick-up loops, located inside the tuners along the 4 quadrants. The preservation of field flatness was verified looking at the pick-up signals, after transportation and positioning inside the CEA tunnel (Figure 1).

The core of the RF power system is the CEA 1.3 MW klystron, protected from the reverse power by a 1 MW circulator. The RF power is led into the RFQ tunnel through full-height WR2300 waveguide and then it is tapered to half-height WR2300 for the final distribution to the RFQ. Just upstream the RFQ, the RF power is split by a magic-TEE: two waveguide arms are coupled into the RFQ through 2 coupling loops, the 4^{th} arm goes to a 100 kW water load. Forward and reverse powers are measured by directional couplers in the two waveguide arms before power couplers.

The vacuum system is composed by a dry primary pump, a turbo pump and two cryogenic pumps. The system was designed to maintain a pressure level $P \leq 1.3 \times 10^{-6}$ mbar under proton gas load. In particular, cryogenic pumps are unnecessary in absence of proton beam and they have not been used for this test. Vacuum gauges are located above couplers and on the vacuum manifold. Gate valves and nitrogen filling channel allow keeping the cavity in inert atmosphere during transports.

Cooling system is designed to remove 300 kW of power and to finely tune the resonant frequency by temperature regulation. For this purpose, it is necessary to have two independent water loops with two regulating temperatures. In the cooling skid, the temperature of each water circuit can be regulated by mixing the cold inlet water with part of the warm water coming from the cavity. Furthermore, the global temperature of the system can be adjusted by regulating the amount of warm water circulating in the heat exchanger. Water flow inside RFQ cooling channel is finely set by flow regulating valves located on each cooling channel. These valves maintain the required flow within ±2% when input pressure varies in the range 1-10 bar. Water flows and input/output temperatures of both water loops are monitored.

Control system [4] is connected to the other subsystems in order to monitor their characteristic parameters (temperature, powers, water flows, pressures), to command their actuators (valves, pumps) and set-up variables (interlock thresholds, water temperatures). In particular, interlocks on temperature, pressure, water flow, forward power are processed by PLC (response time =10 ms), while arc detectors and reflected power are directly sent to klystron to interrupt power in a few µs.

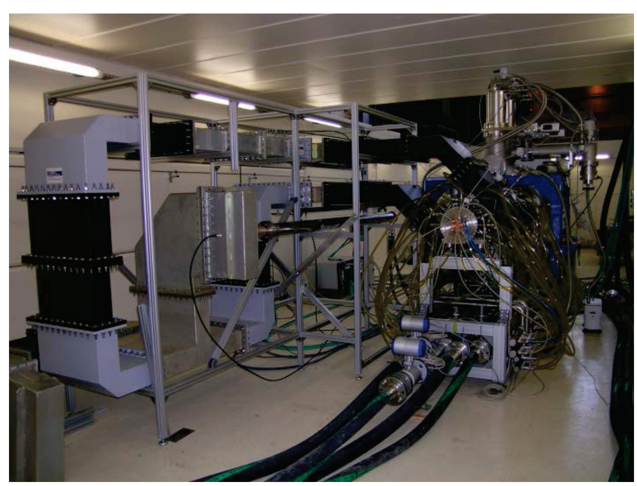

Figure 1: A view of TRASCO RFQ test in the IFMIF tunnel at CEA.

RFQ CONDITIONING

The unloaded quality factor Q_0=8460 was measured in the RFQ equipped with two aluminum couplers. Once the copper couplers were installed, the sum of the coupling coefficients $(\beta1+\beta2) = 1.036$ were obtained from the measurement of the cavity filling time τ=3.75 μs, at resonant frequency = 352.329 MHz. The two coupling coefficients are slightly mismatched, then we expect different values of reflected power in the 2 arms of the magic TEE, with less than 1% total reflected power in steady state operation. With that value of Q_0, the nominal voltage of 68 kV corresponds to cavity power P_{cav} = 192 kW (80 kW/m).

The RFQ resonant frequency control loop was not implemented for this conditioning test. The cavity was let free to be detuned, while the master frequency generator followed the RFQ resonant frequency. At low power level, a by-hand frequency control was sufficient. At high power operation (P_{cav} > 100 kW) an automatic frequency feedback control was required.

Three main phases of the RFQ conditioning are distinguishable, as highlighted in Figure 2 and 3.

From 24/01 to 30/01, RFQ was conditioned at very low duty cycle (<0.1%), to reproduce and never exceed Linac4 operating conditions (pulse length = 400 μs, rep.rate = 1.1 Hz, 82 kV), in order to allow the characterization of the X-ray emission at this regime. This phase was completed in 1 week, without any problem from the cavity point of view. In particular no discharges at 2.2 Kilp, no temperature changes or anomalous detuning were observed. Passing through all field levels, an important multipacting zone between 40 kV and 60 kV was noticed, to be treated with longer pulses. The presence of electron loading can be noticed in Figure 2, where the red squares are above the nominal curve, meaning that a large fraction of the power is not converted in accelerating voltage.

The period from 31/01 to 22/02 was dedicated to condition multipacting levels between 40 kV and 60 kV with pulses longer and longer. We adopted the following conditioning strategy:

- Fix a field level, with short pulse and long period;
- Lengthen the pulse length up to the complete conditioning of the level;
- Move on the next working point.

Because of 10 days of stop, the integrated time of this phase was 12 days.

Up to that time, the cavity frequency detuning caused by RF power was followed by changing the frequency of the signal generator by hand. Once the average power passed the 100 kW thresholds, the detuning at the power start was so fast that an electronic circuit was implemented, to give the frequency feedback to the signal generator. From 06/03 the CEA LLRF control was used.

From 23/02 to 14/03 the RFQ voltage was kept above 60 kV, except for the restart after large outgassing activity. In this phase of operations at high power level we noticed the first important discharge phenomena in the couplers, with consequent high vacuum levels (P > 10^{-4} mbar). To avoid long periods of vacuum recovery, interlock threshold of the reflected power was reduced and compensated with a longer blanking time, in order to skip the cavity filling time when the power is fully reflected.

The nominal voltage (68kV – 192 kW) in CW regime was reached in 07/03, and for 6 days the cavity was conditioned at this field with different duty cycles, always higher than 20 %.

Test was considered successfully closed in March 14th, after a continuous running at nominal voltage for 2 h. Temperature monitors did not show anomalous heating in high power steady state operation.

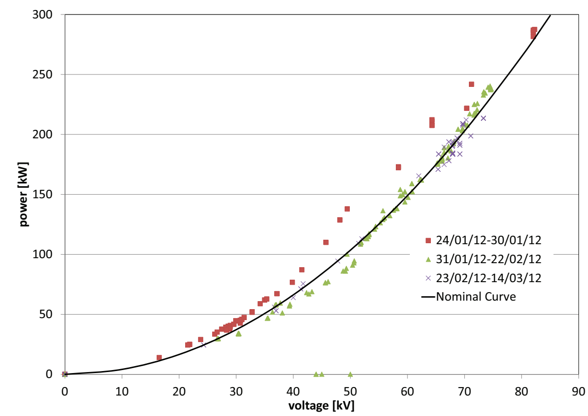

Figure 2: Peak cavity power, obtained as $P_{cav} = P_{forward} - P_{reverse}$, as function of the cavity voltage.

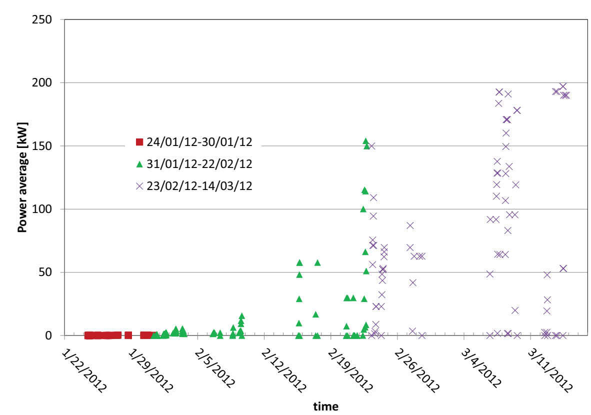

Figure 3: Cavity average power throughout the test.

RESULT ANALYSIS

Once the nominal steady state operation was reached, we observed an anomalous frequency detuning at 192 kW: Δf_{meas}= -238 kHz, to be compared with 2D simulation result Δf_{2D}= -132 kHz. Looking at the pick-up loops, we noticed that this frequency detuning was accompanied by an effect on the field flatness (Figure 4). A detailed simulation of the RFQ end-cells was performed with COMSOL [5], showing an important bending of the vane nose. The frequency perturbation profile obtained from simulation was imported in the

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transmission line model of the RFQ, to evaluate the induced field and frequency detuning. Figure 5 shows field shape reproduced. The simulated detuning is -245 kHz. The asymmetric field shape, as observed in measurements, is caused by the differences on the end cell geometries. It is important to notice that this is a steady effect, not degenerative.

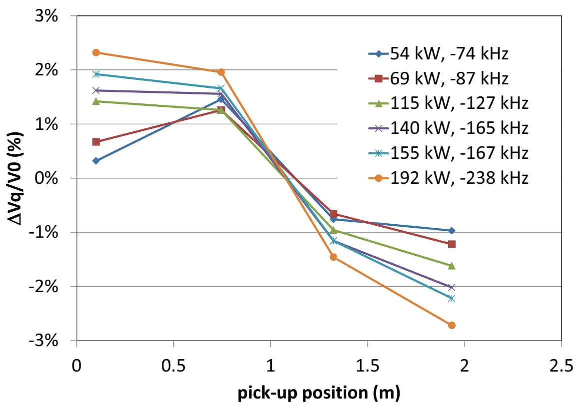

Figure 4: Field perturbation and frequency detuning measured at different power level.

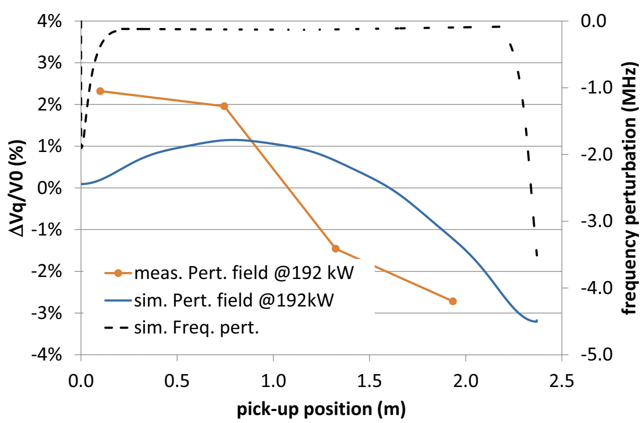

Figure 5: The measured voltage tilt at high power operation is reproduced by a transmission line analysis of the geometry deformation.

At the cavity open after the test, the power couplers showed evident copper sputtering. The RF coupler contacts were damaged and tainted by aluminium during the RF coupler test [6]. The contact degradation and aluminium oxide increase the resistance between hole and coupler wall. This could have generated a voltage difference with consequent discharges and copper sputtering, triggered off by cavity outgassing at high power operation. Sputtering phenomena was also found on the electrodes tip region, near the high energy termination plate. In this zone, R_0 changes and the electric field is a 6 % lower than the maximum value.

Finally, the chemical analysis of the cooling water revealed a copper concentration of 6.65 mg/l, due to the absence of a demineralization station in the cooling skid. In this condition, water conductivity was measured 35.8 μS/cm and PH of the water was measured 6.0.Before the test beginning, the cooling skid was filled with deionized water with 0.4 μS/cm resistivity and neutral PH.

Before removing termination plates (Figure 6), the unloaded quality factor Q_0 and coupling coefficients β_1 and β_2 were measured resulting in agreement with measurements before high power test. The quality of RF joint [7] was tested removing termination plates and then reinstalling them to look for a degradation of the unloaded quality factor. No Q_0 degradation was measured.

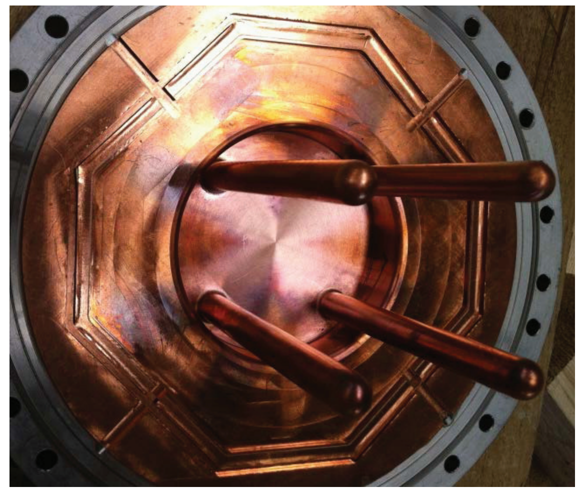

Figure 6: High energy termination plate inspection after high power test. V-shaped violet shadows caused by discharge phenomena are visible around dipole stabilizing rods.

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REFERENCES

[1] A. Pisent et al., “The TRASCO-SPES RFQ”, LINAC’04, Lübeck, August 2004, MOP16, p.69 (2004); http://www.jacow.org.
[2] F. Grespan et al., “Dipole stabilizing rods system for a four-vane RFQ: Modeling and measurement on the TRASCO RFQ aluminium model at LNL”, EPAC’06, Edinburgh, June 2006, TUPCH123, p.1301 (2010); http://www.jacow.org.
[3] F. Grespan et al., “RF measurements for TRASCO RFQ characterization”, LNL Annual Report, 2010, p. 262; http://www.lnl.infn.it.
[4] L. Antoniazzi et al., “Control System Implementation for TRASCO RFQ High Power Test”, LNL Annual Report, 2012, p. 264; http://www.jacow.org.
[5] http://www.comsol.com/.
[6] E. Fagotti et al., “High Power Tests Bench for the TRASCO RFQ Coupler”, TUPB094, these proceedings.
[7] E.Fagotti et al., “Completion of the fabrication of TRASCO RFQ”, LINAC’10, Tsukuba, September 2012, TUP057, p.536 (2010); http://www.jacow.org.