TOWARDS COMMISSIONING OF THE IFMIF RFQ

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on behalf of INFN team for IFMIF RFQ construction

Abstract

All 18 sections of the IFMIF RFQ were completed in summer 2015. A 2 m section (the last three modules and one prototype used as RF termination) were RF tested at LNL at the design value of 90 kW/m in cw conditions. The three 3.3 m long supermodules were sent to Japan in January 2016. The RFQ was installed and tuned with fixed tuners to the nominal field frequency and field distribution. The very high design shunt impedance was achieved.

INTRODUCTION

The required acceleration in continuous wave (cw) of 125 mA of deuterons up to 5 MeV poses IFMIF RFQ at the forefront frontier of high intensity injectors [1].

This RFQ is indeed meant to be the injector of a 5 MW deuteron linac (40 MeV final energy) for Fusion Material Irradiation tests. The International Fusion Materials Irradiation Facility (IFMIF) [2] project aims at producing an intense (about 10^{17} s^{-1}) neutron source facility, with spectrum up to about 14 MeV, in order to test the materials to be employed in the future fusion reactors. The facility will be based on two high power CW accelerator drivers, hitting a single liquid lithium target (10 MW power) to yield neutrons via nuclear stripping reactions.

The IFMIF-EVEDA project was funded at the time of the approval of ITER construction (2007); the task is to validate the IFMIF design by the realization of a number of prototypes, including a high-intensity CW deuteron accelerator (called LIPAc, linear IFMIF Prototype Accelerator) for a beam power exceeding 1 MW.

LIPAc is being installed at the QST (ex JAEA) site at Rokkasho (Japan). The accelerating structures of the porotype linac, operating at 175 MHz, are the RFQ and the first Half Wave Resonator cryomodule. The injector is composed by an ECR and a magnetic LEBT, the RF system is composed by similar RF units (8 for the RFQ and 8 for the HWR). The schematic lay out of LIPAc is shown in Fig. 1.

The realization of LIPAc is a strict collaboration between Japan and Europe, The detailed organization of such challenging project is discussed in [3], the main contribution are for QST the infrastructures of the site, for the European institutes (mainly CEA, Ciemat and INFN, coordinated by F4E) the accelerator components.

At present the injector is under commissioning, the RFQ is assembled and tuned, the MEBT and the diagnostic plate are under set up, the RF system is under completion [4]. The commissioning plane foresees four phases; Phase A: 140 mA deuteron current at 100 keV in CW, Phase B: 125 mA deuteron current at 5 MeV at 0.1% duty cycle, Phase C: 9 MeV deuteron current at 9 MeV at 0.1% duty cycle, Phase D: ramp up the duty cycle up to CW. In all phases we plan to characterize and use, together with the d beam, a proton beam with half energy, half current and similar space charge.

Now the commissioning phase A is ongoing, with a diagnostic plate and an Ellison scanner installed immediately after the nominal RFQ input. Such phase is extremely important to establish the correct RFQ input condition and guarantee the required LIPAc performances [5-7].

To allow the LEBT beam operation, the RFQ is installed 3.3 m downstream its nominal position for assembling and tuning. In November the RFQ will be installed in its final position in view of RF conditioning and beam commissioning phase B.

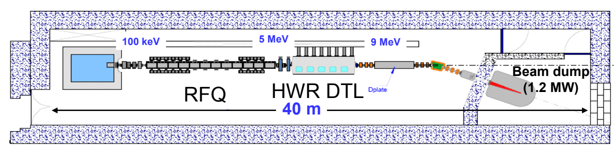

Figure 1: Schematic layout of the IFMIF-EVEDA prototype linac (125 mA, 9 MeV deuterons).

RFQ DESIGN AND MODULE CONSTRUCTION

INFN is in charge of the design and construction of the RFQ system, namely the accelerator structure, the vacuum system, the cooling system used for slow frequency tuning and the local control system. This activity was developed through the LNL labs, by an accelerator Physics group with previous experience in RFQ realization, and Padua, Torino and Bologna sections, with previous experience for mechanical development and realization in large international experiments (like for CERN LHC). The responsibilities were distributed accordingly, with Padua and Torino in charge of the RFQ module mechanical development and engineering integration respectively; about 30 people including physicists and engineers have been involved in RFQ realization.

A specific characteristic of this development has been the use of internal resources and installations, not only for the physical and local control design, but also for all the other steps of the realization, like mechanical design, high precision machining of critical components, QA and measurements, vacuum brazing, high power RF testing. This allowed the best efficiency when processes were given to industry, plus an important flexibility to solve the problems that occurred. Moreover, the various steps of the development have been openly discussed within the accelerator community and published in order to share opinions and have the best result for our difficult task [8-29].

The specifications of IFMIF-EVEDA RFQ are very challenging, since the 650 kW beam should be accelerated with low beam losses and activation of the structure to allow hands-on maintenance of the structure itself. Beam losses <10 mA in total and <0.1 mA between 4 MeV and 5 MeV are allowed.

The beam dynamics optimization led to a solution with high focussing parameter B, high voltage ramped in the middle part of the structure up to 132 kV. The design approach followed the standard subdivision in Shaper (approx. 1.5 m), Gentle Buncher (approx. 1.5 m) and Accelerator (approx. 7 m). The accelerator (with a linear synchronous phase variation from -60^0 to -32^0) was optimized cell by cell, keeping the maximum surface field and increasing the acceptance up to a large value (2 mm mrad norm.). A strong focussing factor (B=7) is necessary in the gentle buncher section in order to keep the tune depression above 0.4 in order to avoid the main space charge driven resonances. The focusing in the shaper rises now from B=4 to B=7 to allow an input beam with smaller divergence and an easier matching from the LEBT.

The intervane voltage in the accelerator section is ramped using a law *V(z)* in closed-form and continuous up to the 2nd derivative; it is possible in this way to have continuous cut-off frequency variations along the RFQ, as well as limited frequency excursions, keeping at the same time the maximum surface field below 1.8 Ekp. Along the structure.

The four vane resonator was the only practical solution for such high intervane voltage. The cross section was optimized (with geometrical variation of the inductive part to match the cut-off frequency) for high shunt impedance and about 90 kW/m maximum dissipated power.

The mechanical design is based on a brazed structure and metal sealing to guarantee the necessary high reliability. These two choices determined many aspects of the design (for example 316LN stainless steel for most of the interface points). The brazed approach for a structure with such a large cross section was developed by choosing 18 relatively short modules (about 550 mm long); the square shape has many mechanical advantages and good shunt impedance. Finally, efficient water cooling channels were needed to maintain the geometry in presence of the intense RF dissipation.

Due to the extremely high beam current, the attainment of beam loss control is of paramount importance in such structure. Now beam loss is determined, basically by geometrical tolerances, in three different ways: vane modulation machining, beam axis accuracy along the accelerator and voltage law accuracy along the structure.

The electrode machining can be very accurate and for this RFQ it was verified with continuous scanning CMM of each of the 72 electrodes (20 um max error in the modulation geometry of each module was achieved).

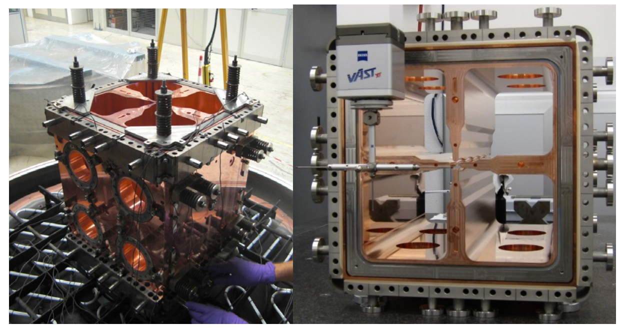

Figure 2: The RFQ module (550 mm long) in the vacuum oven and on the CMM machine.

The beam axis accuracy requires a precise alignment of the quadrupole center module after module (better than 0.1 mm). This was achieved with proper module characterization after brazing (CMM measuring), transverse alignment (monitored with laser trackers), and longitudinal positioning determined by calibrated spacers.

As for the third aspect, in this long structure the spurious modes have a frequency close to the operating mode, and the most critical aspect is the attainment of voltage accuracy within the specified values. This is determined by the local cross section shape and local cut off frequency mainly depending on pole tip positioning (capacitance between electrodes). In other words, it is related to the global deformation of the module mainly during brazing. The effect of part of this deformation can be recovered by the tuners, but the geometry of the module should be good enough to remain in the tuning range (±1 MHz in our case). This is the most demanding aspect for the mechanical design and quality management of the module production since the brazing process has to guarantee electrode displacements below 50-100 um (depending on modulation amplitude).

So the mechanical design was based on vacuum brazing with very strict tolerances on relatively large structures (and a weight of approximately 600 kg.). Even the procurement of the CUC2 raw material blocks was limited by the total mass amount and calls for a maximum longitudinal dimension of about 550 mm. The accelerator is therefore composed by 18 modules.

The blocks undergo deep drilling of the cooling channels, EDM rough machining (to minimize the stresses and the possible deformation in oven), annealing, final machining and brazing cycles: after the first prototypes and modules, produced with two brazing cycles, INFN developed the procedure used for the production of most of the modules: single brazing cycle (Fig. 2). The four electrodes of each module were joined in vertical position together with Stainless Steel details

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like head flanges, lateral flanges and cooling tube connectors; it was very important to develop the correct fixture, so to keep the pieces in tolerance at the brazing moment (liquidus point of the brazing material), but leaving the possibility of differential elongation during the thermal cycle in the oven.

The subdivision in many modules has various advantages: each module can be machined with very precise (and common) milling machines; vacuum ovens of these dimensions are also more spread. The cavity wall interruption has almost no consequence on power consumption (TE operating mode), while the vane interruption with a gap of about 100 μm can be made without too large increasing of the local surface field.

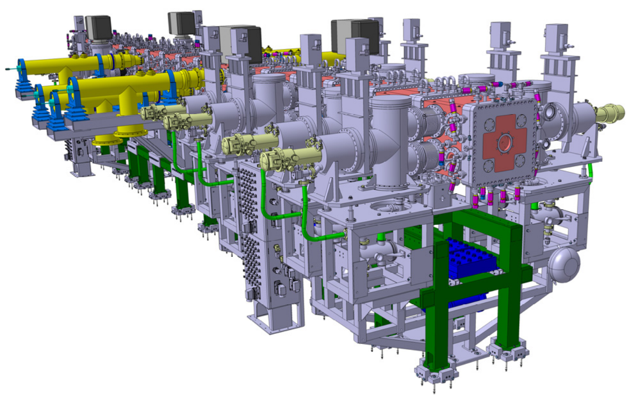

Figure 3: The three SMs integrated with the ancillaries.

The RFQ is subdivided in three “super-modules”(SM), with independent support (Fig. 3). The cooling system follows this architecture, with two cooling circuits (vanes and tank skin) for each third of the structure. The resonant frequency is controlled acting on the difference between vane and tank temperature. The thermal deformation of the cavity has been extensively simulated with 3D FEM to take into account the actual channel distribution, the stiffening determined by the head flange of each module, the lateral flanges for tuning, pumping and power coupling [26]. The most severe hot spots are foreseen in the vane undercut at high energy [27].

The vacuum system layout is based on cryogenic pumps mounted on pumping manifolds able to use two vacuum ports each. The nominal pressure with full power beam is lower than 5×10^{-7} mbar.

The RFQ is fed by 8 independent RF chains and 8 power couplers (200 kW each), 650 kW for beam loading and 600 kW power dissipation in copper plus margin for regulation. The slow tuning is provided by cooling water (electrode temperature fixed, external channels varying).

The RFQ is functionally divided in three supermodules (SM). Each SM is mounted on an autonomous support. The assembly of the modules is done using temporary 6DoF supports while at the end each SM is supported with an isostatic system and mechanical guides for sliding the SM and closing the head flanges.

The 18 modules were produced in three sets, corresponding to the three SMs; 6 machined and brazed in house, 12 in the industry by two different companies. The first produced SM was the high energy one. The intermediate energy SM, with most demanding machining due to the voltage ramping, was built internally by INFN. The in house capability to entirely produce a module was also important to recover the production problems for one of the two external contractors.

More in detail, the production started from 3d forged blocks, the channels were deep drilled and the vane shape was rough machined by EDM, then the electrodes were annealed. This first part of the production was done in house for all the 18 modules. Then the electrodes were milled to final geometry (including 3d modulation), checked with CMM, assembled and brazed.

In the production the constant quality control was clearly very important. Each module was tested with CMM and RF in various phases. In ref [25] the details of this comparison are shown, with a remarkable coherence of the results of the two methods. Overall the production showed an average spread of 350 kHz, or 46 um in average aperture R0. These values can be well compensated by the tuner (range $\pm$1MHz).

After brazing, each module needed to be mounted again on the milling machine for the reference planes. In this phase, the final machining of the reference plane was particularly important. It allows, via calibrated spacers, the proper closing of the head flange and relative positioning of the modules.

THE HIGH POWER TESTS IN EUROPE

A very important step of our risk reduction strategy was the implementation of high power tests in Europe. Indeed one of the problems encountered was the lack of experience in cw RFQ operation, and the necessity to validate the design and the construction technique, in view of the construction of 18 RFQ modules to be installed about 10000 km far away.

As a preliminary step in 2010, in collaboration with CEA, two modules of TRASCO RFQ (352 MHz designed by LNL and built in Italy for a different project) were installed at Saclay and operated cw. The RF system of IPHI project and an INFN cooling skid for frequency regulation were used [28]. Nominal field in cw mode was reached.

In 2012 it was decided to test in Italy at LNL a 2 m long structure, corresponding to the last three elements of IFMIF RFQ, assembled with a prototype module used for RF field matching. The assembly, alignment, tuning and transportation with a truck to a different building were an important test of procedures. This structure could be driven by a single 200 kW RF chain. In this way we could check the condition of maximum voltage, maximum field and maximum power density.

For this purpose, a specific test stand was built at LNL, with a light bunker and approximately 500 kW power installed (mainly RF system and refrigerator). In order to keep the schedule and validate the design during module production, the RF system and the RF power couplers (both rated 200 kW) were developed at LNL and procured in Italian industry. Elements of the RFQ local control and cooling systems were commissioned. In the RF network a circulator was kindly borrowed by Ciemat.

As a result, it was possible to condition the RFQ in cw mode up to the operating field. In Fig. 4, the log of 5 hour operation at full power is reported. This corresponds to a field of 1.8 Ekp, and to a power density of 90 kW/m [27].

Moreover, from the measurement of the pick-up field it was possible to verify that the field distribution was stable (in less than 0.5%) from 0 to nominal field. Finally, it was possible to close the RF frequency feed-back loop and stabilize the natural frequency of the cavity by means of the temperature difference between vanes and external structure.

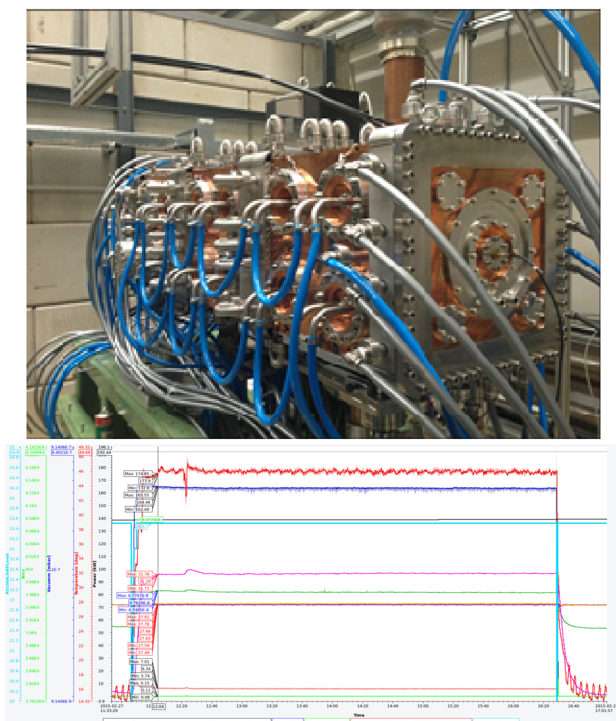

Figure 4: RFQ High Power Test: the experimental set up and the 5 hours at full power cw.

THE RFQ ASSEMBLY AND TUNING

The RFQ was assembled in Italy in three SM for air transportation to Japan. Each SM is mounted on an autonomous support. In the assembly, each module is mounted on a temporary 6DoF supports with sliding capability, aligned by means of the laser tracker and connected to the next one. Transverse position is determined by alignment while tightening the bolts, the longitudinal position by calibrated spacers inserted at the level of bolts. Each step allowed a vacuum test to check the correct operation of the square metallic seal.

During SM assembly some improvements were necessary [24], and in this way, it was possible to reach a reduction of module transverse misalignment down to 0.03 mm and longitudinal one down to 0.04 mm. In the meantime the helicoflex compression depths recovered the nominal range for all connections. Each SM was mounted on final isostatic support.

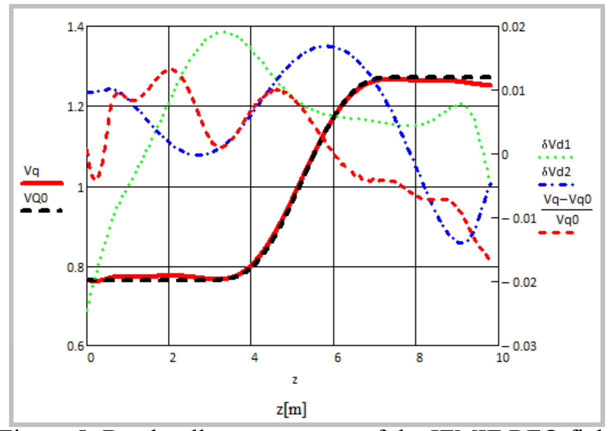

Figure 5: Bead pull measurement of the IFMIF RFQ field. VQ0 is the nominal field, Vq is the measured field (left scale); the dipole components and the relative error on the right.

The three SMs were completely assembled at LNL in January 2016. Before careful packaging, all the SMs were successfully tested in vacuum and filled with nitrogen gas. Shock recorders were screwed on the top of each SM to monitor the transferred to Milan airport by truck, to Frankfurt airport by aircraft, to Tokyo airport by aircraft and to Rokkasho site by truck. After SM unpacking, vacuum tests confirmed a vacuum leak lower than $2x10^{-10}$ mbar-l/s.

At this point it was possible to position the SMs on beam axis and align them with the same principle as for the modules, as to maintain 0.03 mm maximum misalignment between modules, and input/output beam ports on axis.

Just after RFQ assembly, dummy tuners and bead pull system were installed on the RFQ cavity to find the optimum configuration for cavity tuning. Bead-pull campaign to optimize end plates and 108 tuners penetrations started at the end of April 2016 and took two weeks.

From the first measurement with flush tuners the good quality of the cavity appeared, since dipole field components were very low (below 2%) and the frequency corresponded to 3d simulations. The geometry of the end plates without dipole correcting fingers was confirmed. After several iterations on dummy tuner position, the nominal field distribution was established, with spurious mode components below 2% (Fig. 5).

The dummy tuners and end plates were then replaced with final tuners in three iterations. The tuners were brazed at LNL, vacuum tested, and then machined in very short time in the laboratory workshop to the required dimension. This complex operation was completely successful and the field quality with permanent tuners

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was confirmed. In Fig. 6 the RFQ with final tuners, end cells and magnetic bead pull measurements can be seen.

Finally the frequency (rescaled for vacuum and nominal temperature) is 175.014 MHz and the quality factor Q0 is equal to 13200±200 (82% of SUPERFISH value with flash tuners), corresponding to a shunt impedance Rsh=201 kΩ*m.

The shunt impedance is clearly a very important parameter for a cw RFQ operating at high intervane voltage. The confirmation, in presence of all the 3d and "as built" details, of the very good value of the design was an extremely good result for us.

In Fig. 7, an internal view of the assembled RFQ from the low energy side is shown.

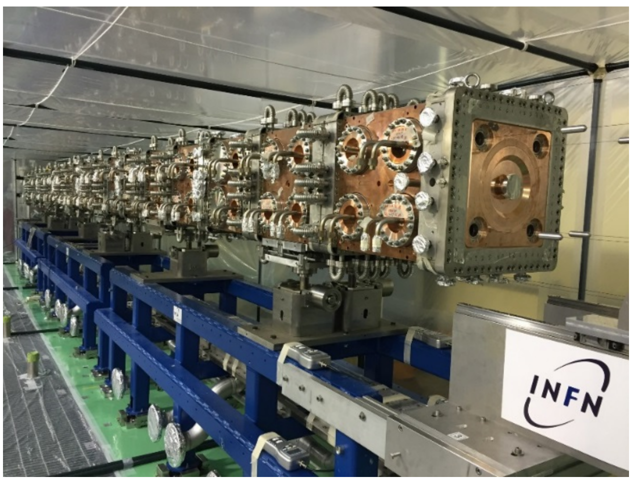

Figure 6: IFMIF RFQ installed – final copper tuners, brazed end plates and bead pulling system can be seen.

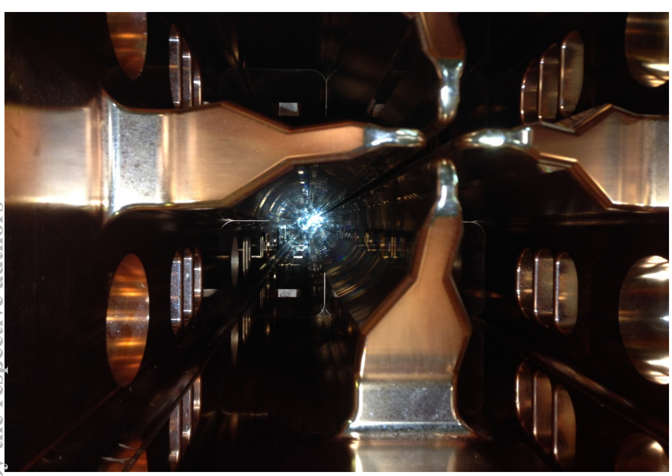
Figure 7: Inside view of the 10 m long RFQ.

CONCLUSIONS

The RFQ construction was concluded, 18/18 modules were accepted after RF and CMM tests completion.

The cw RF performances of the RFQ (maximum field, power density, water temperature frequency control loop) were achieved in the high power test in Italy.

The air-transportation in three supermodules and the assembly in Japan were successful. The RF field have been tuned to the nominal shape with specified accuracy (2%).

The excellent shunt impedance of the design has been achieved (Q_0=13200). Conditioning and beam commissioning will start in March 2017.

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