STATUS OF IFMIF-EVEDA RFQ

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Abstract

All IFMIF – EVEDA RFQ modules were completed in summer 2015. In the previous year the last three modules were RF tested at LNL at nominal power up to cw operation. At the beginning of this year all the modules were assembled in three 3.3 m long super-modules structures that were shipped to Japan. RFQ was then installed and tuned with provisional aluminum tuners and end plates to nominal frequency and field distribution. Replacement of movable aluminum components with copper fixed ones increased cavity quality value not affecting field flatness and frequency.

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 site in Rokkasho (Japan). Accelerating structures of the prototype linac, operating at 175 MHz, are the RFQ and the first Half Wave Resonator cryomodule (Fig. 1).

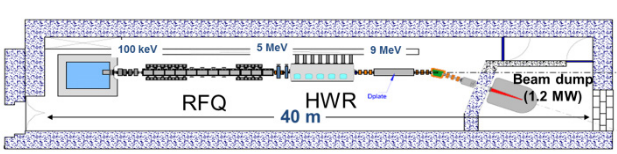

Figure 1: Schematic layout of the IFMIF-EVEDA prototype linac (125 mA, 9 MeV deuterons).

LIPAc realization is a strict collaboration between Japan and Europe. The detailed organization of such challenging project is discussed in [3].

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

Phase A commissioning was concluded first week of November. Such phase was extremely important to establish the correct RFQ input conditions and guarantee the required LIPAc performances [5-7]. Unfortunately injectors didn't reach specifications at 100% DC. However, considering that a low duty cycle operation for the injector was demonstrated, it was decided to conclude phase A2, that is the characterization of injector parameters at the RFQ input location and move towards phase B. Possibility to have additional time for a phase A3, that is the characterization of injector parameters in the middle of the LEBT, was maintained.

During phase A2 commissioning, RFQ was installed 3.3 m downstream its nominal position for assembling and tuning allowing, in parallel, injector commissioning. At the beginning of November, RFQ was finally installed in its final position (Fig. 2) in view of RF conditioning and beam commissioning (phase B).

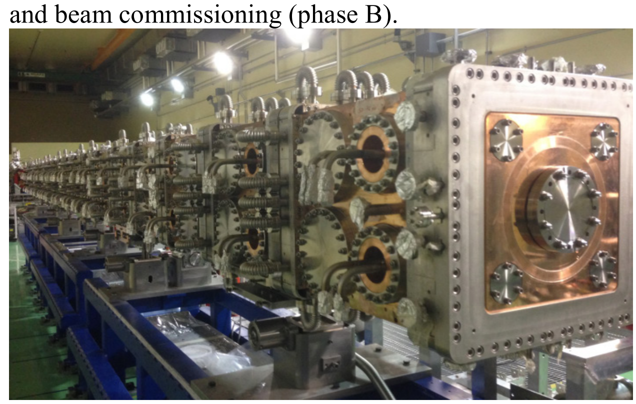

Figure 2: RFQ fully assembled and aligned in the final position.

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RFQ CONSTRUCTION

INFN was 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 INFN Legnaro National Laboratories, by an accelerator physics group with previous experience in RFQ realization and through Padova, Torino and Bologna INFN sections, with previous experience for mechanical development and realization in large international experiments (like for CERN LHC). The responsibilities were distributed accordingly, with Padova 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 realization steps, like mechanical design, high precision machining of critical components, QA and measurements, vacuum brazing and high power RF testing. This allowed the best efficiency when processes were given to industry, plus an important flexibility to solve the problems that sometimes 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 should allow hands-on maintenance of the structure itself. Beam losses less than10 mA in total and less than 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° to -32°, was optimized cell by cell, keeping the maximum surface field and increasing the acceptance up to 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 from B = 4 to B = 7 allowing an input beam with smaller divergence and an easier matching from the LEBT.

The inter-vane voltage in the accelerator section is ramped using a V(z) law 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 inter-vane voltage. The cross section was optimized for high shunt impedance and about 86 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 the use of 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 geometry despite intense RF dissipation.

Due to the extremely high beam current, the attainment of beam loss control is of paramount importance in such a structure. Beam losses are basically related to geometrical tolerances and in particular can be affected by: vane modulation machining, beam axis accuracy along the accelerator and voltage law accuracy along the structure.

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

The beam axis accuracy requires quadrupole center maximum misalignment of 0.1 mm. This was achieved with proper module characterization after brazing (CMM measuring), precise transverse alignment using laser tracker and precise longitudinal positioning determined by calibrated spacers machined according to laser tracker analysis of the modules connecting surfaces.

As for the third aspect, in few 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 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 µm, depending on modulation amplitude.

So the mechanical design was based on vacuum brazing with very strict tolerances on relatively large and heavy structures. 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 stresses and possible deformations in the 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. 3).

The four electrodes of each module were joined in vertical position together with SS components like head flanges, lateral flanges and cooling tube connectors. It

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was very important to develop the correct fixture, so to keep the pieces with the right tolerance during brazing, leaving the differential elongation possibility during the oven thermal cycle.

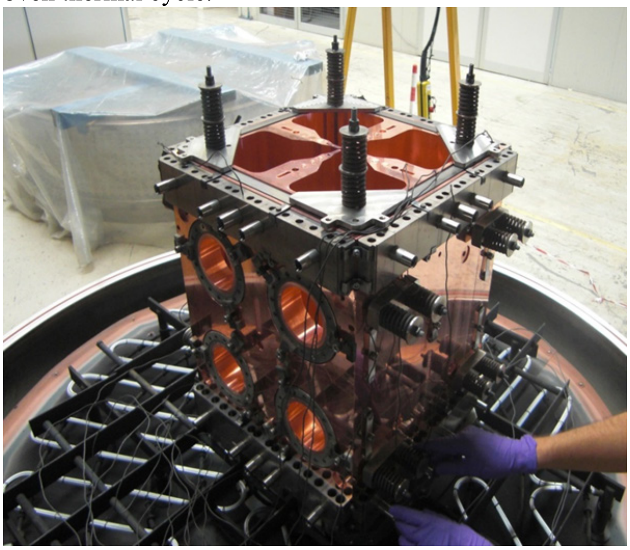

Figure 3: The RFQ module (550 mm long) in the vacuum oven

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

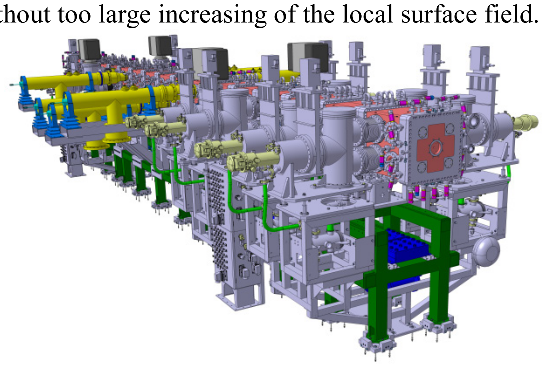

Figure 4: The three SMs integrated with the ancillaries

Modules are coupled in three groups of six modules each constituting “super-modules”(SM). Each SM has its own support (Fig. 4). The cooling system follows this architecture, with two cooling circuits one for the vanes and one for the tank skin, for each SM. 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 on the high energy side [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 eight independent RF chains and eight power couplers, 200 kW each: 650 kW for beam loading, 600 kW for power dissipation in copper plus margin for regulation.

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.

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 µm in average aperture R_0. These values can be well compensated by the tuner (range ±1MHz).

After brazing, each module needed to be mounted again on the milling machine. 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.

HIGH POWER TEST IN EU

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, the alignment, the tuning and the transportation with a truck to a different building were important procedures test. 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 600 kW power installed, mainly for RF system and refrigerator.

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Elements of the RFQ local control and cooling systems were used for this test as well as a circulator kindly borrowed by Ciemat. Unfortunately, just before test starting, a problem was discovered on the high power couplers produced by QST, which caused the impossibility to use those couplers for a power test. In order to keep the schedule and validate the design during module production, two new RF power couplers, both rated 200 kW, were developed at LNL and procured by Italian industry in few months.

As a result, it was possible to condition the RFQ in CW mode up to the operating field. In Fig. 5, the log of 5 operation hours at full power is reported. This corresponds to a field of 1.8 Ekp and to a power density of 86 kW/m [27].

Moreover, from the measurement of the pick-ups field it was possible to verify that the field distribution remained stable, with an error lower than 0.5%, from low field up 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 checking the resonance control system.

Figure 5: RFQ stayed at nominal power and CW operation for 5 hours. Then test was considered successfully concluded

RFQ ASSEMBY AND TUNING

The RFQ was assembled in Italy in three SMs. Each SM was mounted on an independent support. During assembly, each module was mounted on a temporary six degree of freedom support with sliding capability, aligned by means of the laser tracker and connected to the next one. Transverse position was determined by alignment while tightening the bolts, the longitudinal position by calibrated spacers inserted at the level of bolts. After each step a vacuum test was done to check the correct operation of the squared metallic seal.

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 various transport steps: from LNL to Milan airport by truck, from here to Frankfurt airport by aircraft, from here to Tokyo airport by aircraft and from here to Rokkasho site by truck. After SM unpacking, vacuum tests confirmed a vacuum leak lower than $2x10^{-10}$ mbar-l/s.

SMs and their associated support stands were pre-aligned using the rough alignment system able to regulate position with 0.5 mm precision over ±20 mm range in all directions. SMs were then precisely aligned within 0.05 mm respect to nominal references using the precise alignment system.

It is important to notice that during coupling of the SMs, alignment of the interface modules axes has higher priority respect to alignment of the SMs respect to reference beam axis. This means that low energy plate and high energy plate of the RFQ are forced to be on beam axis while single modules axes can be as far as 0.2 mm from the nominal beam axis in the vertical component.

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.

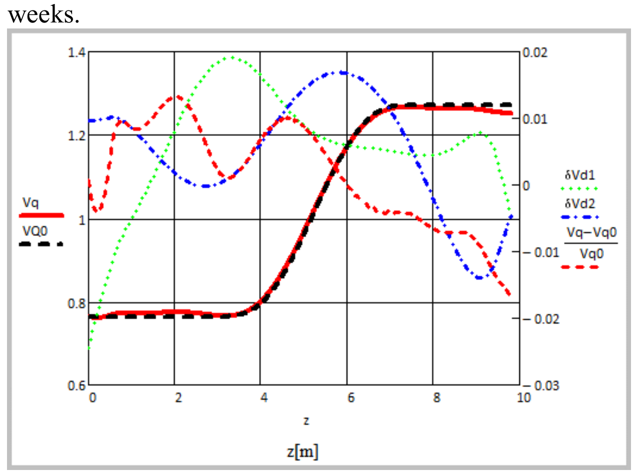

Figure 6: Bead pull measurement of the IFMIF RFQ field. VQ0 is the nominal field; Vq is the measured field (left scale); the dipole components and the relative error on the right.

From the first measurement with flush tuners the good quality of the cavity appeared, since dipole field components were 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 tuners positions, nominal field distribution was established, with spurious mode components below 2% target limit (Fig. 6).

Final tuners and final end plates were machined at required quotes according to RFQ bead pull measurements results. Machining was done in three steps in order to maintain enough tuning margin up to the conclusion of the process. In the first step copper termination plates and 16 copper tuners were replaced to dummy termination plates and dummy tuners. Bead pull measurements showed that final low energy termination plate caused a small change in the field flatness that was recovered by changing the penetration of the four tuners located near the plate. In the second step, 43 aluminum

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tuners were substituted with copper ones and no changes appeared on the field flatness. At the end, the remaining 49 aluminum tuners were replaced with the copper ones without affecting the field.

Finally the frequency, rescaled for vacuum and nominal temperature, was measured to be equal to 175.014 MHz and the quality factor Q_0 was equal to 13200±200, 82% of SUPERFISH value with flash tuners, corresponding to a shunt impedance R_{sh} = 201 kΩ*m.

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

CONCLUSIONS

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

The CW RF performances of the RFQ such as maximum field, power density, water temperature frequency control loop, were achieved in the high power test in Italy.

The air-transportation in three SMs and the assembly in Japan were successful. The RF field was 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 on May 2017.

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