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BEAM COMMISSIONING OF THE IFMIF EVEDA VERY HIGH POWER RFQ

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Abstract

IFMIF, the International Fusion Materials Irradiation Facility [1], is an accelerator-based neutron source that will use Li(d,xn) reactions to generate a flux of neutrons with a broad peak at 14 MeV, equivalent to the conditions of the Deuterium-Tritium reactions in a fusion power plant. IFMIF is conceived for fusion materials testing. The IFMIF prototype linear accelerator (LIPAc) is jointly developed by Europe and Japan within the IFMIF EVEDA project: it is composed of an ion source, a LEBT, a RFQ, a MEBT and a SC linac, with a final energy of 9 MeV. The 4-vane Radio Frequency Quadrupole (RFQ), developed by INFN in Italy, will accelerate a 130 mA deuteron beam from 0.1 to 5 MeV in continuous wave, for a beam power of 650 kW. The 9.8 m long, 175 MHz cavity is composed of 18 x 0.54 m long modules, flanged together and aligned within 0.3 mm tolerance. The RFQ was completed, delivered and assembled at the Rokkasho site and is presently under extended RF tests. The second phase of beam commissioning (up to 2.5 MeV/u) was scheduled to start at the end of 2017. Several unexpected issues and incidents significantly delayed the original program, which is however proceeding step by step toward the full achievement of its goals.

INTRODUCTION

The main task of IFMIF-EVEDA project 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, which replies the front end of the IFMIF ones.

LIPAc is under installation and commissioning at the QST site in Rokkasho (Japan). The accelerator main components, designed, manufactured and tested by European institutions (CEA, CIEMAT, INFN, SCK-CEN) are (Fig. 1): Injector, Radio Frequency Quadrupole (RFQ), Medium and High Energy Beam Transport lines, Superconducting RF Linac, Beam Dump, 175 MHz RF System, Local Control Systems, Beam Instrumentation. The conventional facilities, building and main auxiliaries, the Central Control System, as well as the RFQ couplers, are provided by QST [2].

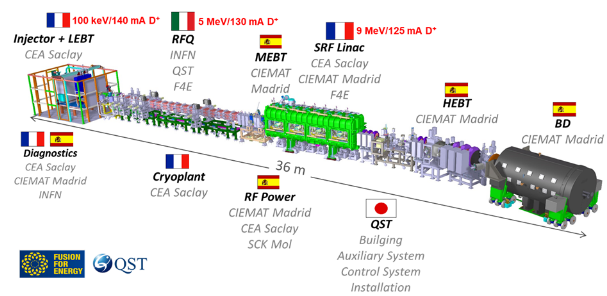

Figure 1: Linear IFMIF Prototype Accelerator.

The commissioning plan foresees four phases: Phase A (the production of 140 mA deuteron current at 100 keV in CW); Phase B (acceleration of 125 mA deuteron current at 5 MeV at 0.1 % duty cycle) (Fig. 2); Phase C (acceleration of 125 mA deuteron current at 9 MeV at 0.1 % duty cycle); Phase D (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.

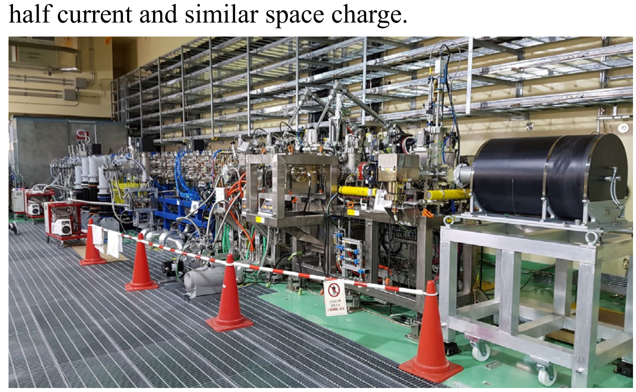

Figure 2: LIPAc phase B configuration (2.5 MeV/u pulsed). Low power beam dump, diagnostic plate, MEBT, RFQ, LEBT and source can be seen.

The program for the commissioning activities and their implementation is pursued as a joint effort of the host

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institution (QST), the European implementing agency (F4E) and the European institutes.

Phase A2 commissioning, consisting of the characterization of deuteron and proton beam up to RFQ input location was concluded in the first week of November 2016. Such a phase was extremely important in order to establish the correct RFQ input conditions and guarantee the required LIPAc performances [3-5]. When Injector reached specifications in pulsed mode, the program moved to Phase B, postponing the campaign for the fulfilment of DC operation goals after the first beam acceleration. In the meantime an additional phase started (B0), aimed at the characterization of injector parameters between LEBT solenoids with the injector connected to the RFQ. During this phase a relatively low current operation mode for the injector (13 mA protons) was also implemented and tested.

This first beam will result in a low risks operation, since the large acceptance of the RFQ guarantees good transmission even with important mismatching from the LEBT [6]. This will be extremely useful to decouple RFQ possible problems from injector ones. In Fig. 3, the RFQ transmission for the various beam components is shown.

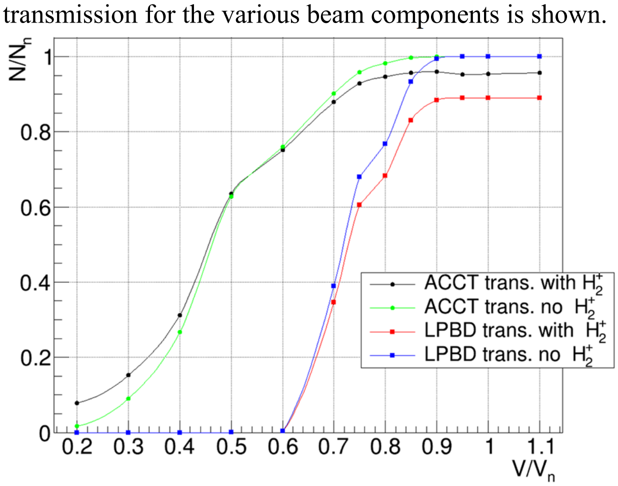

Figure 3: Simulated proton transmission from the RFQ with respect to different voltage ratios at the MEBT ACCT and the LPBD. The two curve ensembles are related to the calculations with and without contaminants.

Unfortunately some unexpected difficulties, described in the following paragraphs, caused a delay of the first transport of a pulsed beam through the RFQ.

RFQ CHARACTERISTICS AND POWER TESTS IN EUROPE

The RFQ is a 9.8 m structure composed of 18 modules, each realized by brazing of OFE copper parts (and 316LN for flanges). The voltage is ramped along the structure with a maximum of 132 kV, the maximum RF power dissipated is 86 kW/m. The system is powered by 8 independent RF chains (provided by CIEMAT) and couplers (200 kW each). The structure is pumped by 10 cryogenic pumps. All sealings are metallic [7] except for the RFQ power coupler windows where VITON® O'rings are used.

A partial high power test of RFQ structure (the last 3 modules, with largest power density, plus a prototype RF module used as a RF plug, for a total length of 2.021 m) was performed in 2015 [8] in Legnaro using the INFN_LNL commercial 200 kW 175 MHz power transmitter. This test validated the RFQ structure in high power cw mode.

LIPAc coupler low power tests revealed some criticalities in the original design that pushed towards a provisional solution. New temporary couplers [9] were developed and their satisfactory performance prompted us to promote their design as the baseline design of LIPAc RFQ.

With both the back-up solutions implemented, it was possible to carry on RFQ high power test and at the same time, to have couplers back-up solution validated.

After RF power conditioning of the new couplers with a bridge cavity, one of the couplers was connected to the RF structure composed of the three high energy side modules of IFMIF RFQ. This RF structure experienced bake-out at 110 °C for one week and RF power was injected for the first time at the end of November 2014. An AFT circulator provided by CIEMAT was used to decouple the RF amplifier from the cavity and a 200 kW water load borrowed by QST was placed on the dummy circulator arm. With this configuration the RFQ reached 110 % of nominal field in CW in 40 working days. The test was declared successfully concluded after 5 hours of CW operation without any failure (Fig. 4).

After the positive conclusion of RFQ high power test, the construction and high power tests of nine new high power couplers was ordered. High power test of all couplers was successfully concluded in October 2016, on time for their installation into the RFQ in Rokkasho [10].

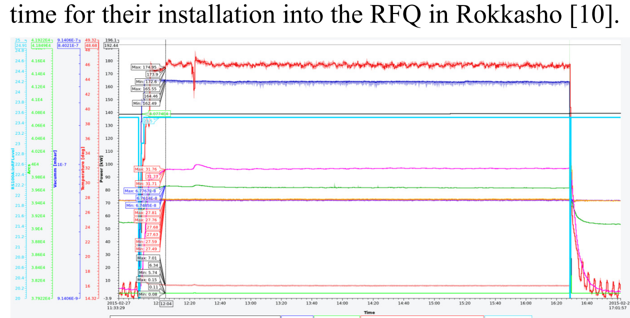

Figure 4: CW operation at the end of RFQ conditioning. Cavity test was successfully closed after a continuous running at nominal voltage for 5 hours.

INSTALLATION AND HARDWARE COMMISSIONING

After RFQ assembly in Rokkasho, dummy tuners and bead pull system were installed on the RFQ cavity to find the optimum configuration for cavity tuning. The 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 before tuners adjustment, the good quality of the cavity appeared, since dipole field components were below 2% and the frequency corre-

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sponded to 3D simulations. The geometry of the end plates without dipole correcting fingers was confirmed. After several iterations of dummy tuners positions, nominal field distribution was established, with spurious mode components below the 2% target limit [11].

Final tuners and final end plates were machined at required dimensions according to RFQ bead pull measurements results, installed and verified.

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 13100±200, 82% of SUPERFISH value with flush tuners, corresponding to a shunt impedance R_{sh} = 201 kΩ*m.

After bead-pull measurement RFQ was moved to its final position. Field flatness was then verified with pick-up measurements.

Finally, the 8 high power couplers were installed on the cavity and their rotational angles for minimum reflected power were identified. Considering that P_b=637 kW, Q=13100 and Q_{2D}=16000 (SuperFish), P_{2D}=452 kW (SuperFish) and $P_{Cu}=P_{2D}*Q_{2D}/Q$= 553 kW, the overall coupling coefficient giving zero reflection with beam is $\beta_0=(1+P_b/P_{Cu})$=2.16, so each coupler should present a β=0.27. After coupler installation the change in the quadrupole field components was acceptable (Fig. 5).

After completion of the eight CIEMAT 200 kW RF amplifiers [12] test, the first power injection in the RFQ occurred in July 2017, with just one chain. For the first time the RF system composed of 8 independent chains was coupled to RFQ cavity. The RF system is controlled by the LLRF system, with one master amplifier (so called 1A) and seven slaves (1B, 2A, 2B, 3A, 3B, 4A, 4B).

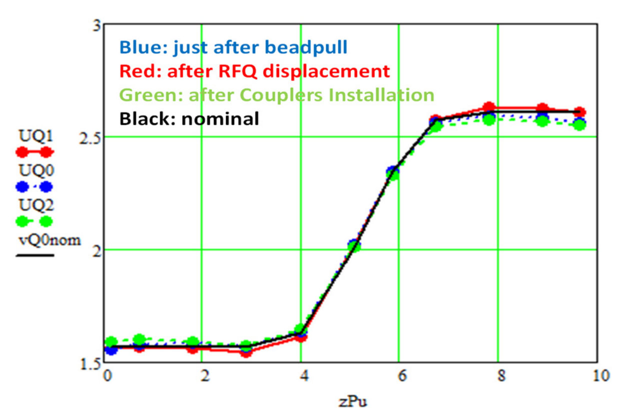

Figure 5: Evolution of the RFQ voltage along installation phases.

Phasing of RF Lines

The following step was phasing of the eight RF lines. In order to obtain a precise adjustment with low power values, it is possible to look for the maximum de-phase between RF lines: if two RF lines feeding the same power in the cavity are exactly 180° out of phase, the result is full reflection on both lines and zero power into the cavity. This method was applied to each of the seven master-slave RF lines couples. The result was checked by coupling eight RF lines, with 4 lines at the right phase, and the other 4 at 180°.

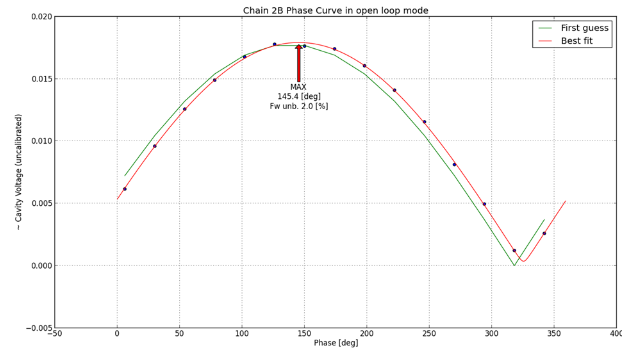

Figure 6: Chains phasing in general case of power unbalance. The curve minimum is obtained with couplers powered at 180° reciprocal phases. When power levels are perfectly balanced this will result in zero power into RFQ.

The routine implemented for phasing takes into account that RF lines can have some power unbalance and curve fitting is made with the phasors combination curve (Fig. 6).

Managing Interlocks

At the beginning power injection into RFQ required some adjustment. During RF start-up, an interlock immediately stopped RF. This was because the reflected power interlock on LLRF was based on instantaneous reflected power, which is equal to the input power both at the beginning and at the end of the pulse. To solve the problem a new interlock system based on the average value of reflected power was implemented. Moreover, in the first part of a cavity conditioning, a lot of multi-pacting phenomena caused mismatching and reflected power from RFQ. Whenever the LLRF system detected high reflected power towards the water load, the safety system stopped operation and amplifiers restarting time was in the order of 1 minute, slowing down the conditioning procedure.

In CW mode, RFQ conditioning reached 70 kW power level. This is the starting thresholds for circulators tuning units switch on. The first direction of the corrective action cannot be predetermined. When correction was not in the right direction, for few seconds there was a reflected power increase towards the corresponding amplifier and this could generate an interlock.

Another issue arose from water load power handling, since four water loads suffered from serious damages. Water loads were specified to withstand 50 kW CW and 200 kW for 100 ms. Nevertheless, it became clear that in some particular cases, RF power on these loads can overcome these limits. This happens, for instance, when only 7 RF chains are operating, and/or when there is a sudden 180° phase shift of one chain with respect to the others (e.g. caused by a discharge in its RF coupler). This results in an amount of power on the load corresponding to the unfed or dephased chain of about 140% and 400 % respectively, with respect to the input power of a single RF chain. In particular, the last occurrence was found sometimes to happen.

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RF Conditioning

The 132 kV nominal field for deuteron beam was reached and overcome with 5 % margin on January 14th of this year with very short RF pulse (20 micro-seconds) (Fig. 7).

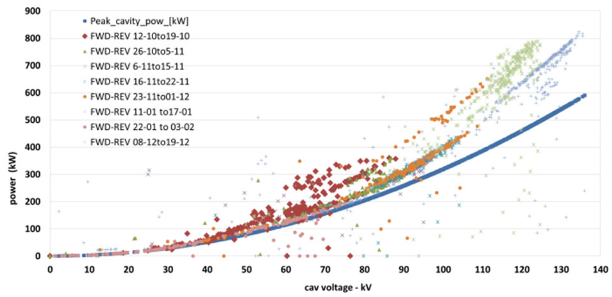

Figure 7: Plot of the forward power vs cavity voltage during RFQ conditioning. The blue curve represents nominal relation in case of RFQ quality factor. At high voltage, more power than nominal one is required to reach the nominal field because the pulse duration was lower than the one needed to establish flat-top cavity field.

CW operation started at low power level and reached 60 kW average power (Fig. 8). Over this CW base a 200 µs peak pulse was added up to reach 160 kW peak power.

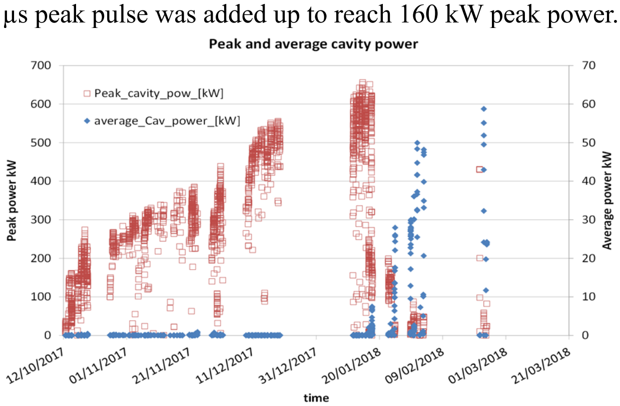

Figure 8: Peak and average cavity power.

RF Window Accidents

The RF conditioning process was slowed down by a couple of stopovers, both occurring to the RF windows.

At the end of February, after RF power injection without water cooling enabled, an over-temperature was registered in the coupler of chain 1B. After two days, a vacuum problem was detected in the RF window of chain 1A. It was decided to open the window to check for possible problems. The RF window was uninstalled and checked at the end of March. The vacuum O-ring closing the inner coaxial conductor was damaged due to high temperature. For this reason, O-ring, anchor connector and RF window were replaced with new components.

Before testing the effects of this change, a second accident happened during the PPS (Personal Protection System) check test. In such a test, RF power chains were expected to be disconnected from LLRF. Due to an incorrect cable connection, RF power was accidentally fed from chain 1A in the RFQ, while almost all interlocks coming from RFQ LCS (local Control System) to RF control system were disabled on the RF side. Therefore, RFQ experienced some sparks and vacuum level increased up to 2 x 10^{-5} mbar. The response time of the system, for reasons which are under investigation, was not fast enough to react and more than 50 sparks triggered an active interlock configured on the maximum number of sparks in 20 s, which finally stopped the RF power.

After these events, restarting of power conditioning was done with extremely caution. With 100 µs pulses, it seemed that the RFQ cavity had no multi-pacting problem at low power level. Since the RF system could not yet be operated in a very stable way with short pulses, the pulse length was increased step by step up to 2 ms, paying a lot of attention to vacuum status and arcs detection. Considering that no vacuum problem occurred and that RF system continued to lack stability in pulsed mode, we decided to switch to CW operation at low power. RFQ cavity remained stable even in these conditions. Then, RF power was gradually increased up to 70 kW, the maximum CW level reached in February 2018. In spite of the stable operation, temperature increases of about 1.5 °C were noticed in couplers 1A and 1B. At the same time a 9 % power additional loss (measured as the difference between the sum of input powers and the sum of load and cavity powers) was observed, and this circumstance persisted also after the multipacting phenomena faded. The following day, during phasing of 1A and 1B chains, coupler temperatures in these two chains started increasing by about five degrees. Suddenly, during phasing of chains 1A and 1B at 10 kW input power per chain, vacuum increased very fast and in 10 seconds the RFQ was at 1 bar. Last message coming from RFQ protecting system was an arc detected on 1A chain.

It was immediately decided to open coupler 1A and it was found out that alumina window was broken in three parts. Alumina break was very clean. Neither powders nor fragments penetrated into the cavity.

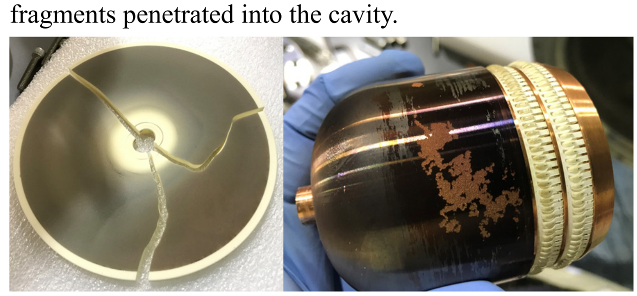

Figure 9: Damaged RF window (on the left) showing a strong deposition that subsequent analyses revealed to be copper deposition. Anchor connector (on the right) bolted on the alumina window experienced a lot of uncontrolled arcs that removed copper from surface and sputtered alumina surface itself.

The flawing coupler was immediately disassembled and a strong metallic deposition was found on the alumina vacuum side. It seemed that the alumina experienced a strong copper sputtering event that caused its metallization (Fig. 9 left). The suspect of copper deposition was based on the fact that vacuum side anchor connector made

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of copper and screwed on the alumina plate was covered with a lot of spark traces (Fig. 9 right).

During alumina disassembly it was noticed that Viton® O-rings tightening alumina with stainless steel flanges were both melted on the flanges side. It was decided to open the 1B RF window too, because, according to temperatures archived on EPICS archive, 1B window experienced temperature higher than 1A during the first accident.1B RF window presented no alumina metallization but Viton® O-rings tightening alumina with stainless steel flanges showed clear melting signs, much more evident than on the other window.

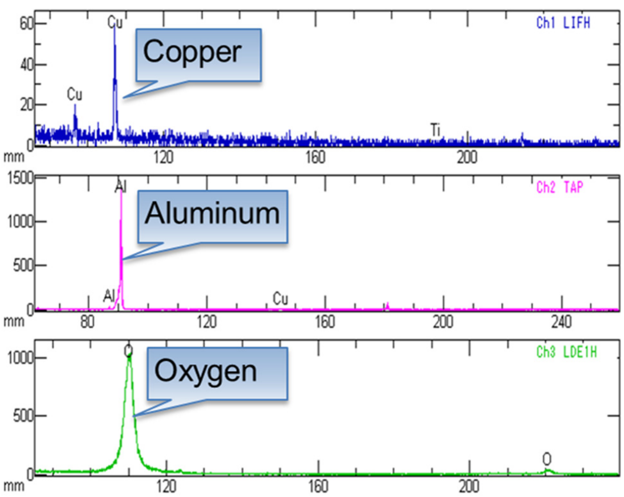

Figure 10: EPMA analysis results.

In parallel to 1B disassembly, 1A alumina surface was analysed with an Electron Probe Micro Analyser (EPMA) and copper deposition was confirmed (Fig. 10). Instrument resolution was not enough to estimate the real copper thickness, but after checking that 1B RF window experienced no copper deposition, it seemed reasonable attributing all the lack in the power balance that we experience the days before the event, to alumina copper metallization.

According to calculations, a 9 % lack of power can be justified by losses on a copper deposition of the order of 450 nm average thickness. In any case one piece of alumina was shipped back to Italy to measure copper deposition thickness.

RF window 1A experienced a fragile brake due to anomalous power dissipation in presence of copper sputtered surface. The coupler was removed and replaced with a blind flange. Vacuum was restored and no problem on the vacuum system was found. This same window, installed at the end of March and not yet RF conditioned, underwent uncontrolled arcs that very likely determined the anomalous surface metallization.

Coming back to the causes of arcs, they could be related to different causes:

- RF window was new, and it did not experience any baking
- RF coupler cooling system was inadvertently switched off
- Copper anchor connector was new and it was not conditioned
- Copper anchor connector traps air when connected to coupler and its degassing can take several days
- Configuration with just one coupler injection cause a 70 % reflected power.

It is important to underline that with all RFQ interlocks enabled the system is adequately protected.

The damaged alumina was substituted with the old one removed at the end of March after baking it at 240 °C in a vacuum oven available in Rokkasho. In order to ease degassing of trapped air inside 1A and 1B anchor connectors, degassing holes were opened on both anchors. New Viton® O-rings were used for all vacuum connection on both RF windows. Coupler 1A and 1B were reassembled few days after the event and RFQ conditions concerning vacuum and RF level (proton voltage, short pulses) were recovered in two weeks. Longer RF pulses (500 µs) and the first beam are expected in the next few weeks.

CONCLUSIONS

The IFMIF prototype accelerator is now installed in the configurations that allows the acceleration of pulsed beam of deuterons (or protons) up to 2.5 MeV/u (phase B of the LIPAc program). The involved hardware was commissioned, extensive beam test of the RFQ input conditions were performed.

The RFQ for the moment reached the nominal field only with short pulses. The RFQ structure was in 2015 tested in Italy (in a shorter configuration) up to full field cw. The problems encountered in final configuration seem mainly related with the complexity of the RF system (8 independent chains to be simultaneously and precisely operated on a single resonant load) and to specific problems encountered during its commissioning together with the RFQ (including few accidents with broken components). These problems are being tackled in these days.

The nominal conditions for the first beam have been achieved and we are working to improve reliability and availability of the system. Integration of the different subsystems revealed difficulties that are being presently addressed and will be overcome in the coming weeks.

DISCLAIMER

Views and opinions expressed herein do not necessarily reflect those of QST, Fusion for Energy, or of the authors' home institutions or research funders.

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