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RF CONDITIONING TOWARDS CONTINUOUS WAVE OF THE RFQ OF THE LINEAR IFMIF PROTOTYPE ACCELERATOR

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Abstract

The Linear IFMIF Prototype Accelerator (LIPAc) is designed to accelerate 125 mA of deuteron beam to 9 MeV in continuous wave (CW). The superconductive RF Linac has not yet been installed and the final accelerating stage now under commissioning is the RFQ. This system has been designed and developed by INFN (Italy) before installation in QST (Japan). The RFQ is the longest in the World with its 9.8 m and requires RF power injection from 8 independent and synchronized coupler ports. LIPAc demonstrated the acceleration of 125 mA deuteron beam at 5 MeV for 1ms with a 1 s repetition period in 2019. A fundamental milestone to extend beam operations to CW is the completion of the RFQ cavity RF conditioning up to CW. This work presents the strategy followed to successfully reach CW RF injection at 80% of the nominal 132 kV vane voltage. The field distribution correction scheme (acting on cooling system at various power levels) was successfully verified. We discuss as well the main challenges encountered on the way, which include updates of the RF system, failure of a circulator (by arcs) and the damages occurred on some of the RF couplers. Finally, the recent status and outlook will be provided.

INTRODUCTION

The International Fusion Materials Irradiation Facility (IFMIF) is designed as an accelerator based neutron source to test materials for use in the neutron harsh environment of fusion reactors [1]. The Linear IFMIF Prototype Accelerator (LIPAc) is designed to validate the most challenging technologies necessary to the successful construction and operation of IFMIF. Under the Broader Approach (BA) framework, most of LIPAc's components were designed and manufactured in Europe to be then installed and integrated in QST Rokkasho in Japan. LIPAc is a linear accelerator comprised of an ECR ion source (100 keV) an RFQ (5 MeV), a MEBT which includes 2 buncher cavities, a SRF LINAC (9 MeV) with 8 interleaved HWR superconductive cavities and solenoids with integrated steerers, a HEBT and a beam dump capable to withstand the 125 mA D+ beam at 9 MeV, which corresponds to 1.1 MW beam power in CW. In July 2019 LIPAc demonstrated the acceleration of 1ms pulse length of 125 mA of D+ [2, 3]. The installation and commissioning project is advancing in phases and the main goal of 2021-2023 is to achieve CW operations at nominal beam current at 5 MeV [3, 4]. One of the protagonists of this phase is the RFQ designed and procured by INFN, and the World`s longest with its 9.8 m [5]. The nominal vane voltage of 132 kV is sustained by the 175 MHz RF input of circa 1.2 MW, of which roughly 550 kW are dissipated to heat. During conditioning, without beam loading, 640 kW is sufficient to reach nominal vane voltage. The power is fed by 8 independent chains each of which is comprised by a solid state predriver (500 W max), a tetrode driver (16 kW max), a tetrode final amplifier (200 kW max) and a circulator with a matched and cooled load in its return port. The 8 chains are synchronized and driven by a LLRF with a White Rabbit interface [6]. We report here the status of the progress of the conditioning of the RFQ towards CW, the challenges encountered and the strategy forward.

SYSTEM IMPROVEMENTS

During the first commissioning and conditioning campaign necessary to achieve acceleration of 1ms beam pulse, a series of improvements and additional features were included in the RF system as described in [6]. Before restarting the conditioning campaign at duty cycle (d.c.) higher than 5%, two important improvements were introduced.

Coupler Surface Temperature

In 2018 one of the 8 RF window's ceramic broke during the phase calibration between two RF chains and it was replaced. Visual inspection showed melted o-rings and a black deposit in most of the ceramic`s surface on the vacuum side. Measurement of a fragment with Electron Probe Micro Analyser revealed that the deposit was mostly made of copper and oxygen. In 2019 the surface temperature of 3 out of 8 couplers rapidly increased to over 80 °C in a few seconds while interlocks to RF were inadvertently disabled. After the event, 5 couplers consistently exhibited higher surface temperature than others. We hypothesise that one contribution comes from multipacting activity and another to degradation of surface conditions after the event previously mentioned. Two Pt100 sensors were installed on each coupler to provide additional information and to interlock RF if over a threshold. A jacket with circulating cooling water was added around the coupler near the ceramic window to enhance the heat extraction.

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Pre-Driver Replacement

The LLRF is designed to regulate the relative balance of forward power between the 8 chains. It can also regulate the total forward power to keep a stable voltage readout of the pickup inside the RFQ resonator. During the conditioning process it is preferable to avoid regulation of forward power based on the field inside the cavity to avoid over-injection to compensate spurious electron activities. During RFQ conditioning, the pre drivers based on MOSFETs started to exhibit an unstable gain when operating in pulsed mode. The pre-drivers were replaced with a more recent model based on LDMOS with improved gain stability and dynamic range in CW and pulsed mode.

CW AT 80% VANE VOLTAGE

The strategy originally envisaged to reach conditioning of the cavity at nominal voltage in CW after beam operation at low d.c. in 2019 is as follows: while keeping the vane voltage to 132 kV and a pulse length of 1ms, gradually decrease the repetition period from 1 s to 10 ms. Then set the repetition period to 20 ms and slowly increase the pulse length to 20 ms. Duty cycle is increased after at least 5 minutes without neither arcs nor instabilities in vacuum and reflected power. If more than 20 minutes elapse without reaching stability, d.c. is reduced to the previous step.

By following this strategy, Fig. 1 shows how a d.c. of nearly 20% was reached after roughly 250 cumulative operational hours (c.o.hr). Until roughly 550 c.o.hr it was difficult to further progress due to very frequent peaks of reverse power or sudden vane voltage drops. Therefore, it was decided to first reduce the vane voltage to 105 kV (80% of nominal) and continue with the same procedure until CW operation was reached. Subsequently a slow increase of the forward power until nominal level would follow. At circa 850 total c.o.hr CW was reached. One of the main challenges at d.c. higher than 50% is the definition of an optimal RF rearming time after an interlock due to arc, vacuum or reflected power over threshold. If the rearming is faster than a few seconds, there is a high probability that another interlock follows. If too slow the powerful cooling of the RFQ and RF skid significantly reduce the systems temperature, drastically changing the operating point and thus requiring a slow re-warm up (>30 min). The Conditioning Automatic Support system described in [5] cuts the RF pulse whenever the cavity voltage drops below 90% of target and restarts RF in a few milliseconds. The occurrence of interlocks drastically decreases thanks to the use of this system. The vacuum base pressure in the cavity did not significantly vary with d.c. nor throughout the conditioning process.

COOLING BASED FIELD FLATTENING

The RFQ was fine tuned to achieve dipole and quadrupole field component perturbations lower than 2% throughout its entire length, well below the acceptance criteria of 4% [7]. While increasing d.c., the average dissipated power in the cavity increases leading to a proportional increase of the absolute quadrupole field perturbations. At 105 kV voltage, we measure an increase rate of roughly 0.04% max quadrupole perturbation every 1% d.c. By linear extrapolation we expect a max perturbation of circa 7% in CW at the nominal 132 kV vane voltage, well beyond acceptable level. The RFQ is divided into three equally long "super-module", each of which is cooled semi-independently so that a temperature gradient can be set across the cavity length. Figure 2 shows how this mechanism can successfully modify and compensate, when necessary, the field perturbation distribution, validating an important design feature of the RFQ.

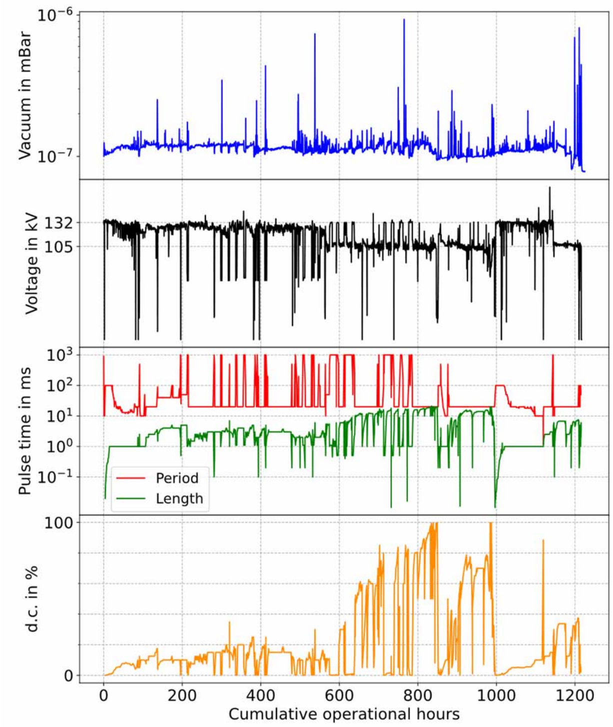

Figure 1: Evolution of RFQ conditioning in cumulative operational hours from October 2021 to April 2022. From top to bottom: (blue) vacuum pressure in the cavity; (black) vane voltage; (red) pulse repetition period and (green) pulse length; (orange) duty cycle.

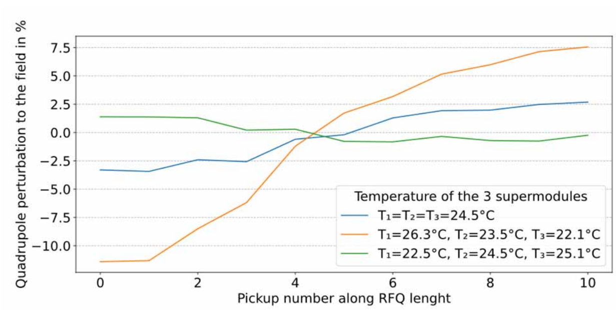

Figure 2: Effect of temperature gradient on quadrupole perturbation component along the RFQ. The three curves were measured while setting a gradient in the temperatures of the three super-modules T_1, T_2 and T_3.

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CHALLENGES

Circulator

After the winter maintenance break of 2021-22, the conditioning restarted with the first goal to reproduce stable CW operations at 105 kV. At circa 1000 total c.o.hr one of the 8 circulators reported arcs in one of its ports. After visual inspection inside the component one of the plate connections was found burnt with significant signs of sparks as shown in Fig. 3. All the circulators were carefully inspected, without finding a similar issue. The manufacturer shares our hypothesis that repeated thermal cycles lead to loosening of screws and degraded contacts, finally resulting in repeated severe arcing. The circulator port was professionally cleaned and refurbished during 2022. In the meantime, the RFQ conditioning continued with the use of 7 chains, which can procure enough forward power to reach nominal vane voltage in the absence of beam loading.

Figure 3: Damage by arcs to forward input port of a circulator.

RF Couplers

At around 1200 c.o.hr a significant vacuum leak (estimated around 10^{-2} mBar L/s) appeared consistently during RF injection. During tests to identify the leak source, it started to appear at lower and lower d.c. Fig.4 shows the time evolution of the pressure in the cavity as measured by 5 gauges across its length and the surface temperature of the 8 couplers (2 sensors per coupler). After RF is stopped, the vacuum returns to base pressure in circa 1 hour, which is compatible with the cool down time of the couplers. All couplers were removed from the RFQ for inspection. The 5 couplers which were consistently warmer than others showed the following common points as shown in Fig.5: a black ring deposit has formed in the high field region near the centre of the ceramic and on the inner copper conductor anchor, the Viton o-rings were deform with one of them severely damaged by heat. We hypothesise that the deposits are copper or its oxides generated during the two disruptive events that lead to a broken ceramic and high coupler temperatures in 2018 and 2019. These rings likely lead to additional joule losses and act as seeds for increased multipacting activity, both leading to extra localised heat. The RF window of the coupler design was improved to enhance cooling capabilities and the couplers are being reinstalled with air-vacuum side flipped ceramics [8]. A second set of alternative couplers has been developed and tested in recent years [9]. Testing at higher power in continuous wave has started to finalize the engineering validation.

CONCLUSION AND OUTLOOK

After the successful demonstration of the acceleration of 1ms 125 mA D+ beam at 5 MeV, the RF and RFQ systems were improved and conditioning towards CW resumed. Along the way various challenges were encountered, including the melt of one coupler's o-ring leading to severe vacuum leak and the damage of one circulator from arcing generated from a loose contact. Nonetheless CW conditioning was achieved at 80% of nominal vane voltage and the water-cooling-based mechanism to compensate the growing maximum absolute quadrupole field perturbation with d.c. was successfully demonstrated. The circulator was repaired; couplers design improved, and both are under installation with the expectation to resume cavity conditioning and beam operations before the second half of 2023.

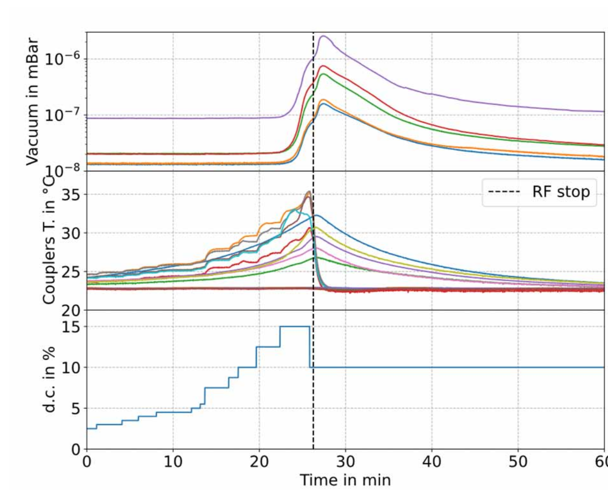

Figure 4: Time evolution of vacuum leak. (Top): vacuum pressure measured by 5 gauges; (Centre): Couplers surface temperature; (Bottom): duty cycle. Time constant of leak recovery after stop of RF injection is compatible with couplers cool down.

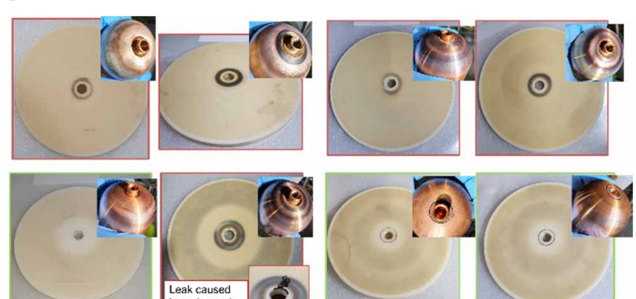

Figure 5: Ceramics and inner conductor anchors of coupler's RF window. Framed in red the five consistently warmer than others.

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