HIGH POWER CONTINUOUS WAVE TEST OF RF COUPLERS FOR THE RFQ OF THE LINEAR IFMIF PROTOTYPE ACCELERATOR

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Abstract

The International Fusion Materials Irradiation Facility (IFMIF) is an accelerator-based D+ on Li target neutron source designed to test materials for application in future fusion reactors. The Linear IFMIF Prototype Accelerator (LIPAc) is designed to validate key components for IFMIF accelerator. LIPAc is designed to accelerate 125 mA D+ beams to 9 MeV in CW with an ECR source (100 keV), a RFQ (5 MeV), a yet to be installed SRF LINAC, matching sections, and a beam dump. The RFQ requires 175 MHz RF input of up to 160 kW in CW from each of its 8 ports. During the RF conditioning of the cavity at high duty cycle the RF coupler's elastomers and alumina vacuum windows experienced damages. A second set of RF couplers has been designed and tested at low power with a high Q load circuit in 2016. In this work we report the recent high-power tests (200kW CW) of two couplers with a bridge cavity. We describe the setup, report results, and the challenges encountered including severe multipacting in the bridge cavity. To conclude we present an outlook of future tests.

INTRODUCTION

The fusion energy community recognized the necessity of neutron irradiation facilities to test materials for use in next generation reactors. The International Fusion Materials Irradiation Facility (IFMIF) will provide the required neutron energy and fluence by acceleration of D+ at 40 MeV onto a liquid lithium target. Under the Broader Approach (BA) agreement, Japan and Europe designed and built the Linear IFMIF Prototype Accelerator (LIPAc) in Rokkasho, Aomori, Japan to validate the main key technologies necessary to fulfil the challenging requirements of beam acceleration for IFMIF. LIPAc consist of an Electron Cyclotron Resonance (ECR) ion source capable to extract ~160mA of D+ at 100 keV in CW, a LEBT, the longest RFQ in the world to bunch and accelerate particles in CW to 5 MeV, a MEBT that includes 2 buncher cavities, 8 Half Wave Resonator (HWR) cavities Superconductive RF (SRF) LINAC to boost beam to 9 MeV, a HEBT, and a dump capable to receive the ~ 1.1 MW beam power in CW. The installation and commissioning of LIPAc is progressing in stages [1]. In 2024-25 the SRF will be installed, until then a transport line replaces it to conduct systems validation and beam characterization at 5 MeV up to CW. During the RF conditioning process of the RFQ, in December 2021, RF power was successfully injected in CW to sustain 80% of the cavity vane voltage [2]. In early 2022, the Viton O-ring sealing the vacuum RF window of two of the eight RF couplers of the RFQ got damaged and partially melted [3]. The original design of the RFQ RF couplers foresaw a ceramic window brazed to the metal body [4]. Tests of a prototype revealed ~30% insertion losses, which were explained by a too thick TiN coating of 100 nm on the alumina window to suppress secondary electron emissions. This set of couplers was redesigned and manufactured in 2016 with an appropriate ~5 nm TiN coating. Due to a lack of availability of high-power RF equipment, they were tested with a high load I-Q circuit to be validated under similar EM fields expected while connected to the RFQ [5]. In the meantime, a backup set of couplers with vacuum sealed by Viton O-rings were designed, manufactured, and tested at high power in CW to minimize risk of impact to project schedule [6]. Due to their excellent performance on the test bench, they were installed in the RFQ and used for all operation of LIPAc so far. Since 2019 it became evident that five of the eight couplers exhibit external body temperature significantly higher than others, which we hypothesis are due in part to multipacting (MP) [7] and in part to insufficient heat extraction from the inner conductor near the ceramic window. In 2022-23 the design of these couplers was significantly improved, and an upgraded version was installed to continue beam operations towards high d.c. [8]. In parallel, the original couplers were tested to validate thermomechanical and RF properties at high-power in CW.

TEST BENCH

The nominal RFQ operation requires RF injection at 175 MHz of ~600 kW during conditioning and ~1.2MW considering beam loading during acceleration. The RF is provided by 8 chains each capable to provide up to 220 kW in CW and synchronized by a LLRF powered by White Rabbit [9]. To complete the validation of the original RF cou-

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plers, it is necessary to demonstrate that their thermomechanical properties are adequate to operate with >200 kW forward power (FWD) and 160 kW FWD + at least 20 kW reflected power (REV) in CW. To perform this test the set up shown in Fig. 1 was developed. One of the RF chains designed for RFQ operation injects up to 220 kW through a coupler (CPL1) to a re-entrant resonant cavity that bridges the RF to a second coupler (CPL2) towards a cooled and matched load. To provide efficient cooling to the inner conductor of the couplers, they are by design paired with a λ/4 T shaped waveguide (T-WG).

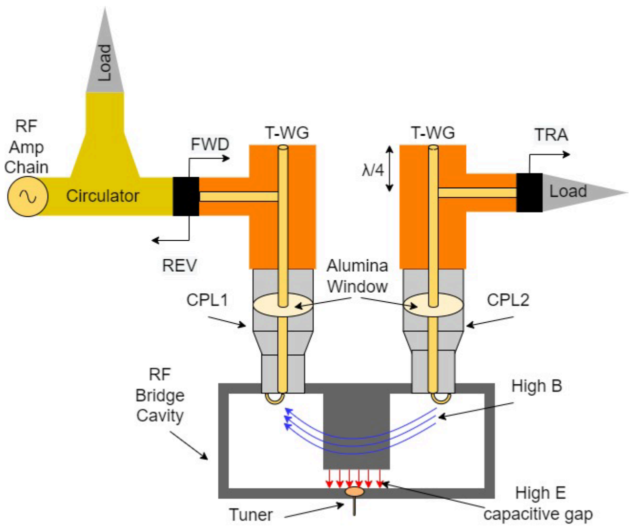

Figure 1: Schematic view of high power test bench for LIPAc RFQ`s RF couplers.

Cooling

The cavity is manufactured in aluminium, because it is lightweight, is significantly cheaper than copper, has good thermal conductivity and decent electrical conductivity. The cavity insertion losses are measured with virtual network analyser to be ~12%, which translate to ~26 kW of heat to be extracted from the inner surfaces of the cavity. A spiral channel is machined in the central stub to provide ~16 L/min of cooling water. Aluminium tends to easily corrode in the presence of many other metals and in particular copper, so a fine mesh filter (50 µm) was installed at the outlet to trap debris, which presence was confirmed by chemical analysis of filter after completion of test. Additionally, the walls of the cavity are excavated to host three copper serpentine pipes to circulate additional ~40 L/min in total of cooling water. Figure 2 shows the expected temperature distribution of the different parts of the cavity, which are expected to increase the outgassing of surfaces, but still be acceptable. Each coupler has three water cooling lines, each with a flow of roughly ~5 L/min: a spiral within the antenna and nearby portion of outer and inner conductor, a circle in the external body around the alumina window, and the inside of the inner conductor from near the antenna up to the λ/4 protrusion of the T-WG. The load, circulator, and amplifiers of the RF chain are separately cooled by their skid.

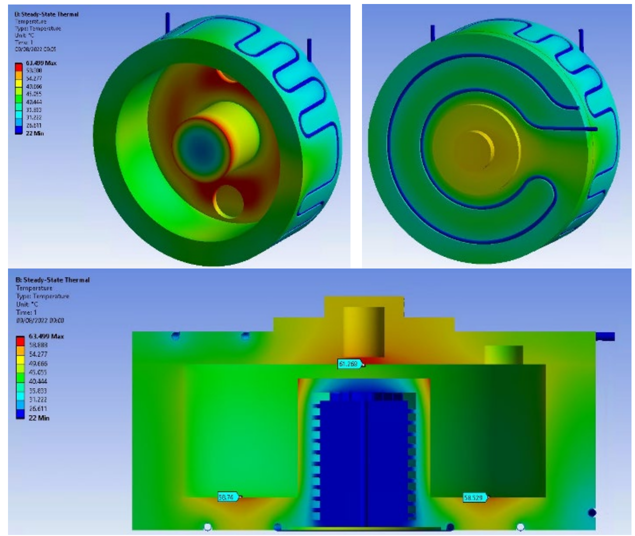

Figure 2: Thermal simulation of bridge cavity, tuner and couplers not shown. Top left: internal surface; Top right: external lid surface; Bottom: cutout view.

Vacuum

A ~80 L/s turbomolecular pump is connected to a DN 63 CF flange which is covered with a copper grid with circle holes covering ~60% area to minimize current disruption inside the cavity. A scroll pump follows with a line for purging with nitrogen. A large Viton O-ring seals the lid of the cavity to its main body, with E-serts used to facilitate bolting. SUS flanges with thick Cu layer for couplers and the insertion of a tuner are also sealed with Viton O-rings. The cavity and couplers were baked at ~100 ºC for ~72 hours before operation. RF fingers are placed in all the gaps were current flows. The typical vacuum pressure during operation is around $5{\cdot}10^{-7}$ mBar.

Instrumentation

The test bench is equipped with a series of sensors to monitor the experiment and interlock RF injection whenever necessary. A cold cathode gauge measures the vacuum pressure inside one of the two couplers, a Residual Gas Analyser (RGA) measures the vacuum partial pressure of components with total atomic mass lower than 100. To perform calorimetry measurements, the cooling water flow is measured in every channel and the inlet/outlet water temperature is sensed with PT100 installed on the surface of the SUS fitting of central cavity stub cooling circuit and the ones of CPL1 near the antenna and alumina window. A light sensor is installed on each of the coupler, looking toward the inner conductor near the alumina window to detect possible arcs or MP in vacuum. Arc sensors are also installed in the elbows of coaxial lines outside vacuum and inside each port of the circulator. Two InfraRed (IR) cameras monitor the surface temperature of the entire test bench from different angles. Several directional coupler antennas are connected to an oscilloscope to monitor the flow of RF power, tough in this work we will mostly focus on the forward power from circulator to CPL1 (FWD), the reflected power from CPL1 back to circulator (REV) and the power transmitted to CPL2 and forwarded to the load (TRA) as shown in Fig. 1. The maximum expected electric field in the cavity`s capacitive gap of 20 mm is ~9 kV/mm, so the entire test bench is surrounded with a double layer of 1 mm thick lead sheet to shield personnel and equipment by X-ray emissions. A proportional counter measures the dose outside the shielding for safety reasons. No emission above background level was detect throughout the entire test. Three PT100 are installed on the cavity and each of the coupler external surface to monitor where simulations predict the highest temperatures.

Control

The control and most of the data archiving (excluding RGA, IR, oscilloscope, flowmeters) is implemented in EPICS. By design, the cavity resonant frequency is very sensitive to the width of the capacitive gap between central stub and the lid (~3 MHz/mm). A ~6 cm diameter copper circle in the middle of the lid can be inserted/extracted by a manual linear motion drive to tune the cavity resonant frequency. To facilitate its operation, we developed and installed an actuator based on a step electric motor that can be controlled remotely by a Raspberry Pi microcontroller.

TEST

As the cavity and couplers surfaces required RF conditioning, the ramp up of FWD to CW at 220 kW was envisaged in three phases.

Phase 1

Pulse repetition period (RP) is kept at 1s and pulse width (PW) at 10 µs. The loaded Q of the cavity is ~300, the injected power is increased/decreased linearly to the plateau value in 7 µs to minimize spikes of REV at the beginning/end of the pulse. FWD plateau power is slowly ramped to 220 kW. This stage is completed within roughly 1 day of operation without detection or arcs, but roughly one pulse in 100 would be nearly fully reflected.

Phase 2

While keeping FWD at 220 kW, the PW is increased slowly to 15 µs and then the RP is decreased from 1 s to 10 ms within roughly 72 hours. Although no arc was detected, every ~5 minutes, the injected power would suddenly be totally reflected starting the middle of the pulse leading us to suspect either a poor sensitivity of the arc detectors, or the location of the arc to be inside the cavity, far from the light sensors near the windows of the couplers. During this phase the vacuum pressure during the test improves from $\sim 1 \cdot 10^{-6}$ mBar to $\sim 6 \cdot 10^{-7}$ mBar. In this phase we notice that the REV shape flickers pulse to pulse during the linear ramp up of the FWD. We hypothesise that a MP region is encountered at intermediate power levels, so we significantly speed up the first half of the ramp up/down. As expected, this leads to higher instantaneous REV during loading/unloading of the cavity, but at the same time the pulse shape is significantly more stable and frequent micro outgassing sensed by vacuum gauge disappear.

Phase 3

While keeping FWD at 220 kW and RP of 10 ms, we slowly elongate PW. After stretching the pulses to a few dozens of µs, it became evident that the REV shape was not constant within the pulse. The cavity tuner position was scanned to minimize REV, but the result was only a shift in time of its waist within the pulse as shown in Fig. 3. It is also at this stage that we notice that the vacuum main component is water after roughly one hour without power injection. As soon as pulses of more than few kW are injected, the water content decrease rapidly, while oxygen and hydrogen increase at same rate until becoming the dominant residual gases. MP and/or plasma formation in the cavity could explain both behaviours. We first test whether MP can be suppressed with progressive RF conditioning of surfaces. After >12 hours long operation at constant setting we measure no statistically significant difference of vacuum pressure, its component, RF power balance, pulse shape or component surface temperature. MP is a resonant phenomenon that often occurs within a band of power/frequency, so we measure the pulse shape over a large range of combinations of FWD power and frequency provide by RF chain. Figure 4 shows that for FWD above few kW, there is no suitable operation point where REV is flat within pulse and is an acceptable percentage of FWD. Figure 5 shows the Pareto front of REV flatness and average for FWD > 50 kW with 3 examples. We conclude that MP/plasma formation exists for FWD higher than few kW in the entire frequency band that the RF amplification chain is designed for.

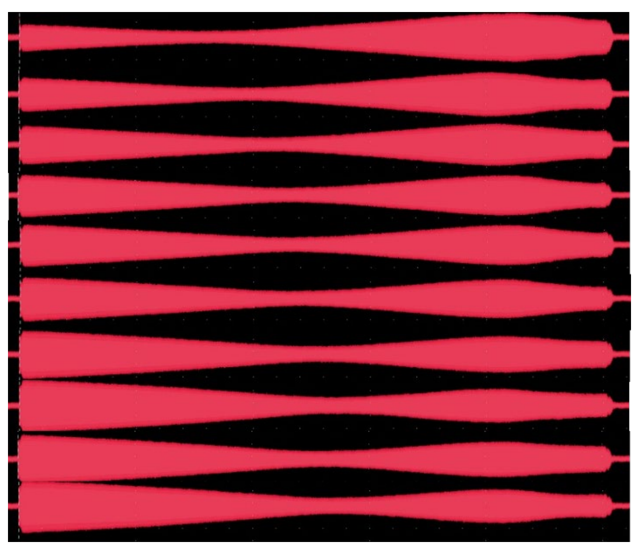

Figure 3: REV pulse shape for FWD = 220 kW, PW = 1 ms, RP = 20 ms; From top to bottom the cavity tuner is linearly swept to change cavity resonant frequency by a total of ~30 kHz.

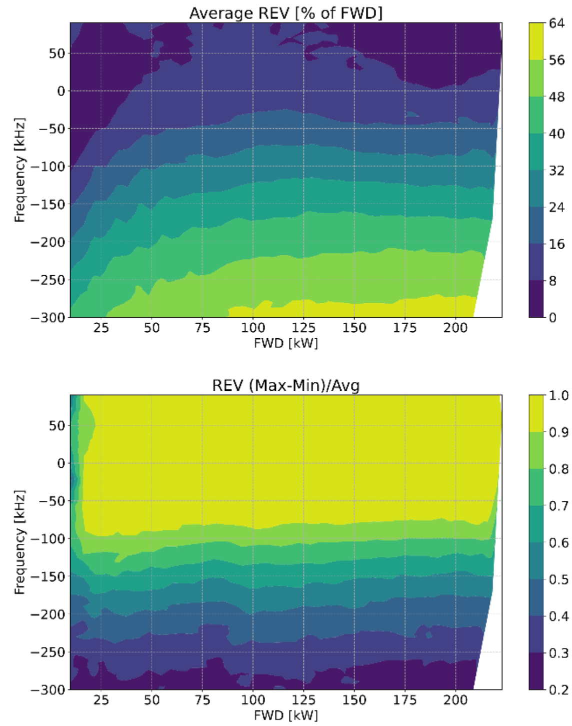

Figure 4: Scan of FWD power and its frequency (expressed in reference to 175MHz). Top: ratio of average REV and FWD within the pulse; Bottom: Flatness of REV within the pulse expressed as the difference between its maximum and minimum normalized to the average (0 means completely flat).

High Duty Cycle

Although it is not possible to avoid MP, we try to validate the thermomechanical design of the couplers by subjecting CPL1 to high duty cycle and power injection with a very substantial REV component, which constitute even harsher condition that necessary to complete the test. Figure 6 shows the pulse shape for a duty cycle of ~96% (PW = 3.85 ms, RP = 4 ms) with FWD at ~175 kW with REV oscillating within the pulse at an average of ~115 kW. The TRA oscillate around ~30 kW, clearly not enough to make any conclusion on the performance of CPL2. The duty cycle is not further increased as the circulator struggles to avoid peaks of reflected power towards the final tetrode amplifier due to fast phase shifts by MP. Figure 7 shows the photo of the test stand in visible light and IR at this operation point. The maximum temperature on CPL1 is 28.5 °C which is only ~3 °C higher than cooling water. We estimate from cooling water calorimetry measurements that ~75 W are dissipated near the coupler window, ~600 W near the antenna loop. Figure 8 shows the spatial distribution of X-ray dose integrated over roughly 48 hours of operation at a duty cycle of 2%. It is likely that the major X-ray contribution is located at the bottom gap of the cavity and the two sensors located at the centre are partially shielded by the thick central stub.

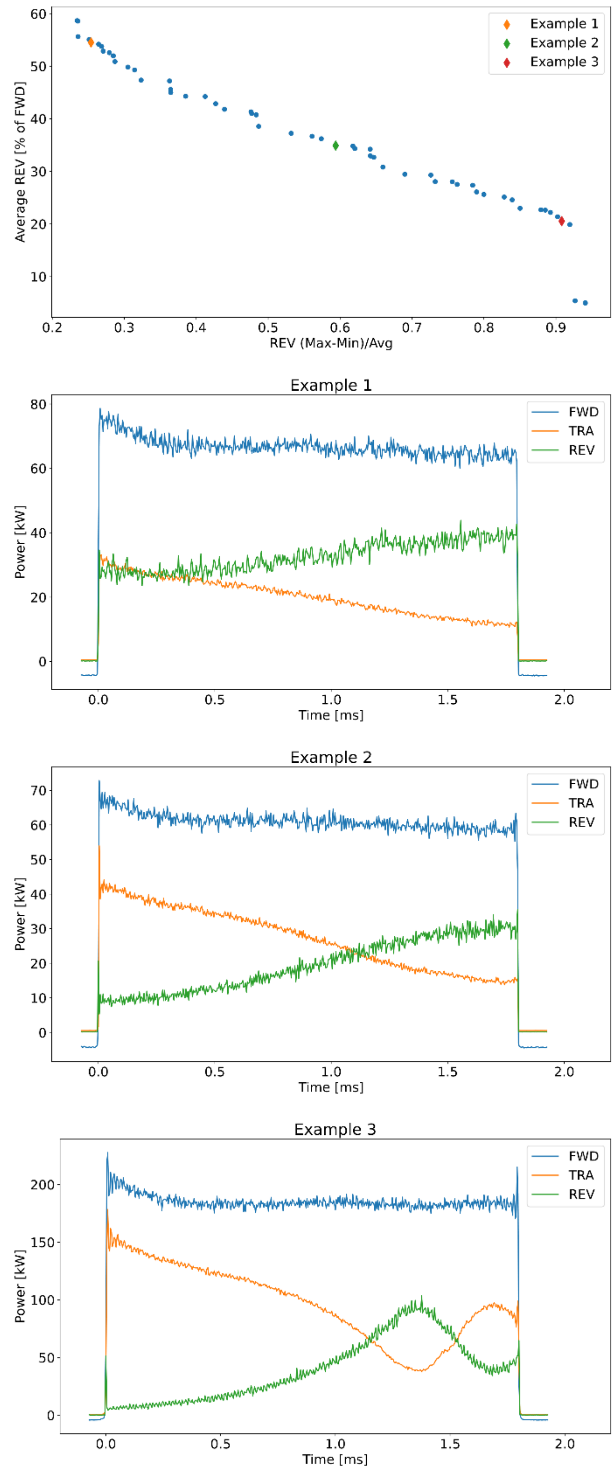

Figure 5: Pareto front for FWD > 50 kW of the compromise for flatness of REV and its average within the pulse. Three examples of pulse shape and their position on the Pareto front.

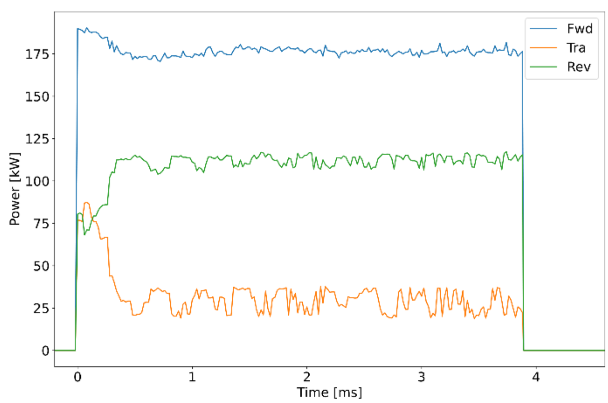

Figure 6: Pulse shape at 96% d.c., PW = 3.8 ms, RP = 4 ms.

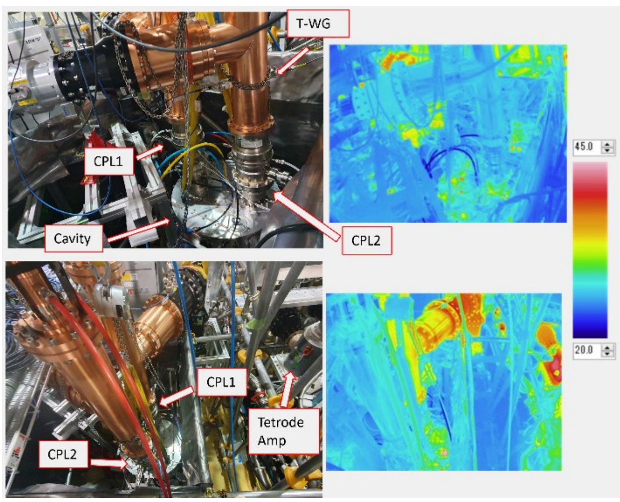

Figure 7: Photo from two different angles of the test bench whit FWD ~ 175 kW, duty cycle of 96%. Left: visible light; Right: infrared.

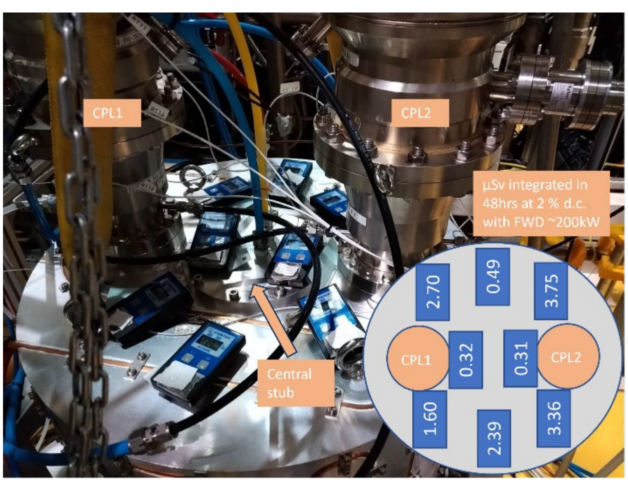

Figure 8: Dose integrated over 48 hrs at 2 % d.c. with FWD ~200 kW.

Cavity Visual Inspection

After the completion of the test the cavity was disassembled for a visual inspection. Figure 9 shows the main discoveries during visual inspection inside of the cavity after test. Top left shows traces of MP/arcs near the tuner, with RF fingers that protruded and melted due to heat. Top right shows heat marks from RF losses on the cut for air pocket evacuation from near the cavity lid O-ring. Bottom right shows the deformation by heat of the copper layer of CPL1 input flange likely due to poor initial bonding. Black heat marks on CPL1 near this part are visible. For future tests we plan to plate the entire cavity surface and couplers input flanges with copper to reduce losses, secondary electron emissions and avoid introducing gaps between metals. A Cu mesh will be added on evacuations cuts and the tuner will be removed to avoid edges and gaps in the high electric field region between the central stub and the lid. RF and thermomechanical simulations are ongoing to verify if cavity detuning due to deformations at CW can be accommodated by the limited bandwidth of the RF amplifier chain.

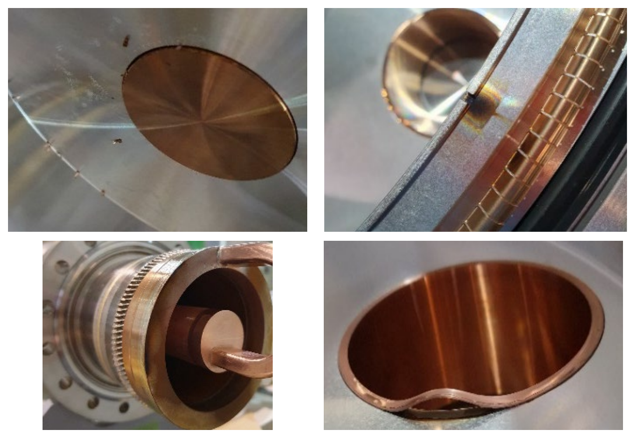

Figure 9: Visual inspection of cavity after test - see text.

CONCLUSION

Two RF couplers designed for LIPAc`s RFQ have been testes with high power at nearly CW. The test could not be performed as designed due to persistent MP/plasma formation in the bridge cavity used. Nonetheless one of the couplers was subjected to much harsher condition than test goal and exhibited excellent thermomechanical behaviour with negligible surface temperature increase and more than adequate cooling. The bridge cavity will be repaired and improved to supress MP and all the other 8 couplers produced will be tested to complete their validation and RF conditioning for potential use in LIPAc RFQ in the following years.

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