ADVANCES IN PLASMA PROCESSING FOR MEDIUM- AND HIGH-BETA CAVITIES OF THE ESS LINAC*

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Abstract

Plasma processing is increasingly recognized as an effective technique for mitigating field emission and restoring the performance of superconducting radiofrequency (SRF) cavities. A collaboration among CEA, ESS, and INFN is currently working to adapt and optimize this method for the medium- and high-beta elliptical cavities installed in the ESS linac. This contribution summarizes the ongoing efforts toward implementing plasma processing both in fully assembled cryomodules and in cavities prepared for vertical testing. Here, we present the first experimental results obtained on a medium-beta 704 MHz cavity equipped with different couplers, along with preliminary investigations carried out on the high-beta 704 MHz cavity.

INTRODUCTION

One of the main factors limiting the performance of superconducting radio-frequency (SRF) cavities is field emission. To address this issue, plasma processing has attracted increasing attention as an effective technique for removing hydrocarbon contaminants from cavity surfaces, which are known to trigger electron emission. By improving the niobium work function [1], this method contributes to the reduction of field emission.

Recent studies [2, 3] have demonstrated that low-pressure reactive plasma discharges generated using a mixture of a noble gas and oxygen are effective in cleaning surface impurities. Consequently, the mitigation of field emission can lead to a significant improvement in SRF cavity performance. Within this framework CEA, ESS and INFN are jointly developing a plasma processing procedure specifically designed for medium-beta MB (β = 0.67) 704.42 MHz 6-cell and high-beta HB (β = 0.86) 704.42 MHz 5-cell ESS cavities.
Two different application scenarios are currently under investigation. The first consists of plasma treatment of the cavity in a vertical test stand (VTS) before cold RF measurements. The second, more advanced approach, involves performing in-situ plasma processing directly inside the cryomodule. This latter solution is particularly promising, as it enables field emission mitigation without removing the cavities from the cryomodule, significantly reducing downtime, manpower, and operational costs. In addition, a reduction in field emission directly translates into lower RF power dissipation within the cryomodule.

The plasma processing technique is based on the generation of a room-temperature plasma sustained by an RF-induced glow discharge. During the procedure, a noble gas—typically argon or neon—with a small oxygen admixture is injected into the cavity. Free electrons in the plasma, with kinetic energies of the order of 10 eV, dissociate molecular oxygen into highly reactive atomic species. These reactive species interact with hydrocarbon contaminants deposited on the niobium surface, converting them into volatile compounds such as CO_2, CO, and H_2O. The gas flow then removes these reaction products, while their evolution is continuously monitored by a residual gas analyzer (RGA). Besides increasing the niobium work function, this cleaning process also lowers the secondary electron emission coefficient, both effects contributing to the mitigation of field emission.
In this work, we present simulations and preliminary results obtained on the *MBLG002* ESS cavity (Q_0 of about 10^4 at room temperature), using either a unity coupler ($Q_{ext} \approx 6 \cdot 10^9$) or a custom, more coupled antenna (Q_{ext} of approximately 10^5), emulating the coupling of the power coupler. In addition, S_{21} and S_{11} measurements have been performed on a HB cryomodule, and preliminary simulations have been started.

RF AND VACUUM SETUP

Unlikely 1.3 GHz cavities, where Higher Order Mode (HOM) couplers are commonly used for plasma ignition, these ESS cavities lack such couplers; therefore, RF power is injected through the main coupler (MC) port. Initial measurements were carried out using the unity coupler in order to investigate the possibility of igniting plasma and performing plasma processing in the VT configuration. However, at room temperature this antenna is only weakly coupled to the cavity, resulting in non-optimal operating condition for plasma ignition and stable operation.
Figure 1 presents the latest schematic layout of the RF and vacuum setup adopted for the experimental tests. The RF system includes a Vector Network Analyzer (VNA), power meters, bidirectional couplers, two frequency synthesizers, amplifiers, a spectrum analyzer, and power splitter/combiners. In addition, the cavity is equipped with viewports on the beam tube flanges that allow direct plasma observation through a dedicated camera system. From the vacuum perspective, the current configuration operates under static vacuum conditions, with the pumping system connected on the MC side and gas injection line located on the pickup (PU) side.

* This work was partially supported by the European Union's Horizon Europe Marie Sklodowska-Curie Staff Exchanges programme under EA-JADE grant agreement no. 101086276
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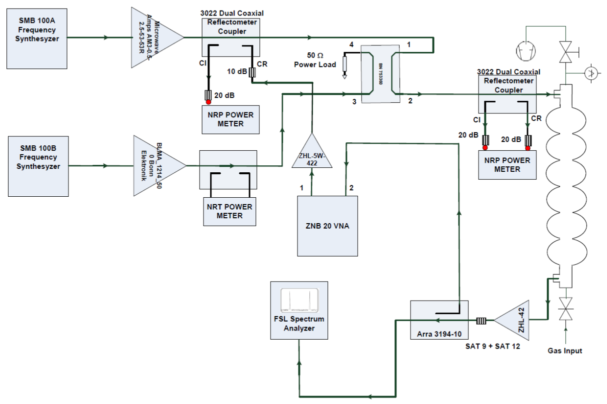
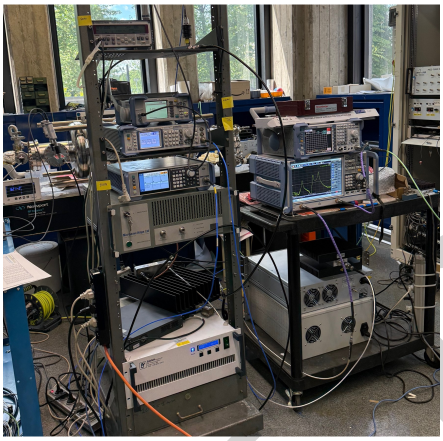
At this stage of the experimental campaign, only pure N_2 (first ionization energy ≈ 14.6 eV) has been used, instead of the noble gas-oxygen mixture discussed in the Introduction. The present approach aims first at demonstrating reliable plasma ignition under simplified conditions and subsequently at achieving controlled plasma propagation from one cell to the next, ensuring complete coverage of the cavity volume. Once this procedure has been successfully validated, the oxygen will be introduced into the gas mixture. No RGA has been integrated yet.



(a) RF and vacuum schematic



(b) RF system

Figure 1: RF experimental setup used for plasma processing tests.

EXPERIMENTAL ACTIVITY ON *MBLG002* CAVITY

Unity Coupler

The first tests were performed using the unity coupler (short titanium antenna, $Q_{ext} \approx 6 \cdot 10^9$). In this configuration, due to the weak coupling, only one relevant mode was observed in the 1-2 GHz range, at 1.448 GHz. Under these conditions, and for pressures between 0.3-0.45 mbar, plasma ignition was achieved; however, the discharge remained confined within the MC beam tube. Attempts to transfer the ignited plasma to adjacent cells were unsuccessful. These preliminary results suggest that a different antenna configuration is required. During these tests, plasma was also unintentionally ignited at the MC antenna. Once the Fundamental Power Coupler (FPC) has been installed, an inspection of the inner tube surface will be carried out to verify possible surface modifications. As shown in Fig. 2, the effects of the unintended ignition are visible both on the antenna and the ceramic window. Furthermore, surface analyses (i.e. XPS, SIMS) of the antenna are planned to investigate the origin of the observed yellow discoloration and to verify whether it is related to titanium nitride formation.

(a)

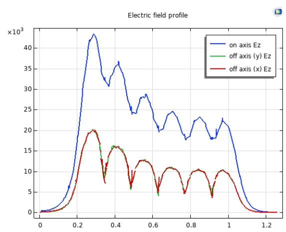
(b)

Figure 2: Unity coupler after plasma ignition of MC: (a) yellow stain on titanium antenna, (b) dark stain on the ceramic.

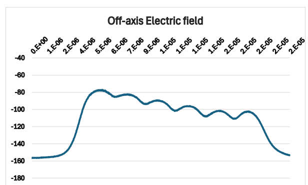
Simulations and Bead-pull

All these activities have been supported by electromagnetic simulations. Eigenmode and modal analyses were performed using ANSYS HFSS and COMSOL to investigate the electromagnetic field distributions of the cavity modes, compare the simulated S_{21} transmission spectra with the experimental results, and evaluate the Q_{ext} of the different modes. These studies are essential to identify which modes are suitable to ignite the glow discharge or to sustain the plasma once ignited and to propagate it throughout the entire cavity. The adopted plasma-bridging technique consists in overlapping modes to sustain and extend the discharge between adjacent cells without extinguishing the plasma.

In parallel, a bead-pull system was implemented to correlate simulations with experimental measurements. Using a setup composed of pulleys and micrometer translation stages, the field profiles of all the relevant modes were measured. The acquisition was automated through a Python-based control system, which drove the stepper motor while simultaneously recording the VNA data. In this way, both on-axis and transverse (x and y) field profiles were obtained (Fig. 3).



(a)



(b)

Figure 3: Example of a) simulated on- and off-axis electric field distributions, and b) measured electric field distribution.

Custom Antenna

To proceed with experimental activities while waiting for the installation of the FPC on the MB cavity, a custom titanium antenna was used in place of the one employed for the vertical test. Having the same geometry of the unity coupler but a longer length (138 mm), it is characterized by a lower external quality factor ($Q_{ext} = 1.15 \cdot 10^5$), making it significantly more strongly coupled, with a Q_{ext} comparable to the FPC ($Q_{ext} \approx 7.5 \cdot 10^5$). In Fig. 4 the S_{21} and S_{11} spectra for this antenna are reported.

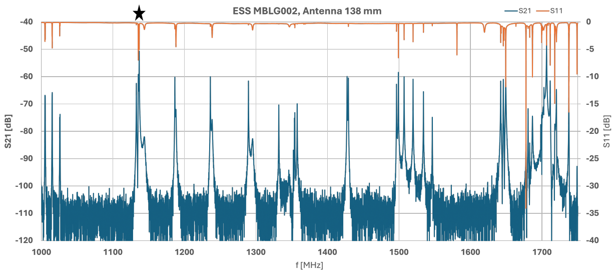


Figure 4: Trasmission and reflection spectra (S_{21} and S_{11}) for 138 mm titanium antenna, in the 1-1.75 GHz range. The star shows the 1.135 GHz mode chosen for the ignition.

Several modes are clearly coupled and could therefore be exploited for our purposes. Once the mode suitable for initiating the discharge had been identified and the plasma bridging strategy had been defined, the first step was to determine the Paschen's curve for the selected mode, namely the one at 1.135 GHz. Figure 5 shows the RF amplifier power required for the plasma ignition, at different pressures.

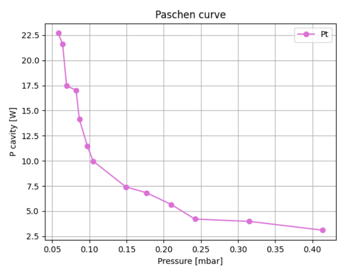


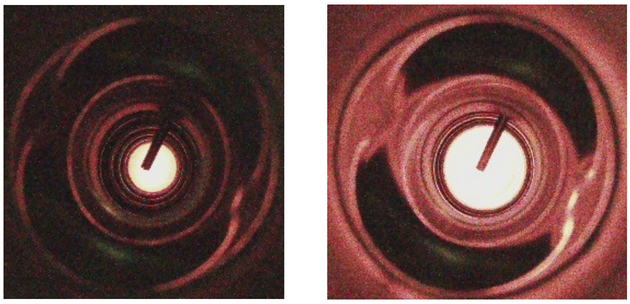
Figure 5: N_2 Paschen's curve for the custom antenna, at 1.135 GHz. P is the transmitted power into the cavity.

The selected mode ignites the plasma in the first cell on the PU side (Fig. 6a). Subsequently, the other selected modes enabled the plasma to be transferred progressively from this cell to the sixth one, namely the last cell on the MC side. Fig. 6b shows the plasma moved in the 4^{th} cell.

At each transition from one cell to the next, the plasma was tuned in order to increase its density while reducing the power required to sustain it.

HIGH-BETA ESS CAVITIES

Concerning the high-beta cavities, S_{21} and S_{11} measurements were performed on the four cavities assembled in the CM50 cryomodule prior to its installation in the accelerator string. This activity provides access to the cavities in



(a) (b)

Figure 6: Plasma a) ignited in the first cell, PU side, at 1.135 GHz, b) moved to the fourth cell, with 1.188 GHz mode.

their final string/cryomodule configuration and allows to start understanding the possible frequency shifts introduced during the different stages of the cryomodule preparation. The cavities were kept under vacuum during the measurements, although the cryomodule insulation vacuum had not yet been pumped down. The next step will be to repeat the measurements after pumping down the insulation vacuum and following the door-knob installation. In addition, simulations are being carried out to be compared with experimental data and to identify suitable modes for plasma ignition and controlled plasma transfer from one cell to another.

CONCLUSION AND FUTURE ACTIVITIES

In the coming months, the plan is to install the FPC (provided by ESS and CEA) on the *MBLG002* cavity and to carry out experimental activities using this antenna, including variations of the gas mixture, like the use of He instead of N_2. All medium-beta cavities are installed in the ESS linac; therefore, this configuration represents already the one that will be used for plasma processing in cryomodules. In addition, the development of a possible vacuum and gas injection layout has been initiated in order to move from the current static vacuum configuration to a dynamic pumping scheme. The design, inspired by the FRIB model [4], has been conceived to comply with the ESS safety requirements and with the tunnel configuration, which represents the realistic final operating layout. In parallel, experimental activities on HB cavities will continue at the ESS site. In addition, S_{21} and S_{11} measurements will be repeated on different cryomodules to increase the statistics on the frequency shifts introduced by the different steps during the cryomodule preparation for tunnel installation.

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