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IN-SITU PLASMA PROCESSING ON A 172 MHz HWR CAVITY AT THE ARGONNE TANDEM LINAC ACCELERATOR SYSTEM

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Abstract

Maintenance and cleaning of superconducting rf cavities is labor intensive task that involves disassembling the cryostat holding the resonators and removing them to be cleaned. At the Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory, a project is underway to research cleaning the cavities in-situ by plasma processing. Previous plasma processing research by SNS, MSU, FNAL, IJCLab, and JLab has been successful in improving field emissions post processing. It is advantageous to pursue research in this method, allowing for possible use on modern ATLAS cryomodules, A-tank and G-tank quarter-wave resonators (QWR). The results presented show initial plasma ignition testing and plasma simulations for the coupled E and B fields, both done on a 172 MHz HWR cavity previously designed as early R&D for FRIB. Future plans are also included, laying out next steps to test plasma processing on the same HWR cavity and eventually a QWR.

INTRODUCTION

The first rf superconducting accelerator for heavy ion acceleration, ATLAS, has been in operation since the 1970's with the first successful acceleration of an ion beam in 1978 [1]. Significant upgrades have occurred over the years, including installing and upgrading quarter-wave resonator cavities (QWR) to replace the original split-ring resonator design. In 2009 a major upgrade took place, installing G-Tank, a cryostat containing seven 109 MHz $\beta = 0.15$ QWR cavities, increasing the deliverable energy of ATLAS by providing 15 MV additional voltage [2]. These were removed, upgraded, and re-installed in 2022 (Fig. 1). In 2014, A-Tank, a cryostat containing seven 72 MHz QWR $\beta = 0.077$ cavities, was installed, further increasing the accelerating potential of ATLAS [3]. A-tank has since yet to be removed for cleaning.

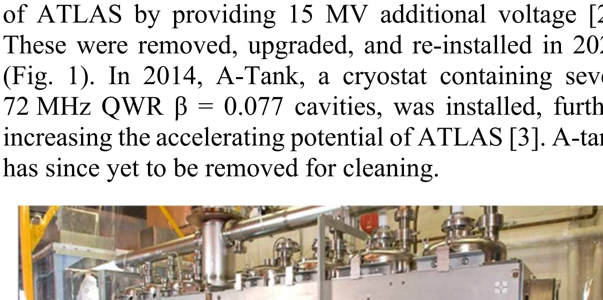

Figure 1: G-Tank upgrade work performed in clean room.

The design of G-tank and A-tank QWR resonators included specific attention to reducing the particulates on the rf surfaces, therefore reducing field emissions from the resonators and improving their efficiency [2]. For these resonators to be of peak performance, the rf surface must remain clean, only allowing a low number of particulates. At this point (i.e., 2023), the A-tank resonators are showing a degradation in performance characterized by higher field emissions and an increased heat load on the cryogenics system. Investigations are underway to identify where the particulates have developed inside the cryostat indicating which resonators have been contaminated and possibly the cause. Unfortunately, pulse conditioning and thermal cycling are no longer adequate to reduce field emissions and recover performance. Cleaning these resonators and returning them to their prior performance, would require removal for six months to a year to be Electropolished (EP), rinsed, baked, and re-installed. This would severely impact the facility's current yearly goal of delivering ~6000 beam hours.

Figure 2: A-Tank cryostat in ATLAS beamline.

Cavity removal is not only time consuming and cumbersome but also exposes equipment to the risk of damage, owing to the cramped quarters in which the cryostats sit (Fig. 2) [4]. In recent years, a solution has been investigated in a collaborative effort by FNAL, SLAC, MSU/FRIB, JLab, and IJCLab for plasma processing of the resonators in-situ of the cryomodules. Proven to reduce field emissions (FE), this process could be applied to A-tank and possibly future work on G-tank [5, 6]. This technique utilizes the vacuum and rf coupling system already installed to the cryomodule in addition to the cavity's fundamental and higher order modes (HOM), so no additional upgrades or significant installation of new equipment is required. The plasma is created by injecting a Ne-O_2 or Ar-O_2 gas mixture into the cavity, maintaining around 100-200 mTorr pressure and 10% O_2, and then delivering rf power via the fundamental coupler [5 ,7] Results have found this method effective for removing hydrocarbons from the internal srf surface of the cavity, thereby reducing FE. Hydrocarbon removal is observed via a Residual Gas Analyzer (RGA) showing the peak material removed. This process is cycled in specific time intervals

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found to be effective for improving the FE of QWR and HWR cavities [5, 6, 8].

Initial plasma processing tests are done on a spare 172 MHz β = 0.26 HWR cavity, which was previously a model designed during early R&D for The Facility for Rare Isotope Beams (FRIB). The cavity's first ten modes were simulated using CST to verify where the electric field would be most present and uniform. This helps us identify which modes, in addition to the fundamental mode, to test with our electric field coupler.

EXPERIMENTAL SETUP

Plasma processing initial test setup for the 172 MHz HWR cavity is shown in both Fig. 3 (vacuum system) and Fig. 4 (rf electronics system).

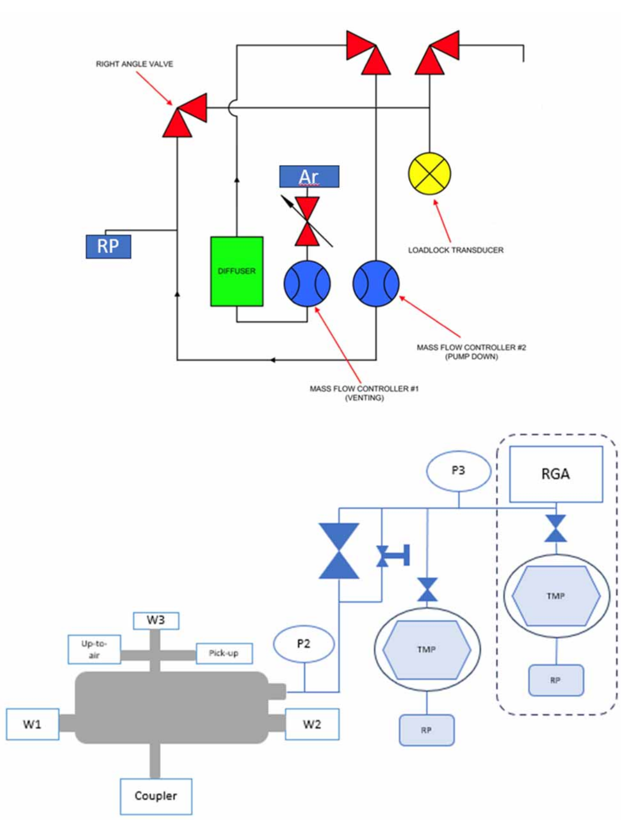

Figure 3: Lower image is the vacuum system for plasma processing. A dashed box surrounds an RGA, Turbo pump, and rough pump that is a separate system yet to be installed. W's marked with a number indicate a window viewport and P's indicate pressure gauges. The up-to-air system is the upper image, where the Argon gas is injected and regulated with a mass flow controller.

Figure 3 includes an additional section that has yet to be added, marked in a dashed line rectangle. This RGA system will be added later before plasma processing tests begin. All other components have been installed and leak tested for plasma ignition initial tests. The coupler on all QWR cavities in ATLAS is inserted in the bottom port of the resonator. In this test setup, the same coupler model is used but inserted into the beam port to allow coupling of the electric field at room temperature. In addition, the pickup antenna is inserted opposite to the other beam port. Previous tests at FNAL and FRIB saw evidence of sputtering of the coupler from plasma processing [8]. Multiple windows were installed to mitigate this issue and have a clear visual on the plasma when ignited, including a window with direct sight on the coupler (Fig. 3).

Vacuum System

Using the up-to-air system regularly applied in ATLAS testing, the vacuum design gives better applicability to future in-situ testing. This system has two Mass Flow Controllers (MFC) that allow us to control the amount of Ar-O_2 ratio inside the cavity. For initial plasma ignition tests, only one MFC is in-use, controlling the Ar gas flow. No O_2 is being used for these initial tests.

Leak tests show that the cavity setup can maintain a vacuum pressure of 1.6E-6, which is suitable for our needs. By maintaining this vacuum pressure, then closing off the larger bypass valve (Fig. 3), gas can be introduced to the cavity without harming the RGA via the needle valve and 1/8th inch pipe connection line. Once the needed Ar gas pressure is established inside the cavity, the needle valve and the bypass valve are adjusted to let a small amount of gas into the RGA line, maintaining safe vacuum pressure for RGA functionality. By monitoring the RGA mass scan, the processed particles can be identified. After processing the cavity for a set amount of time, the system can be easily pumped out and brought back to vacuum.

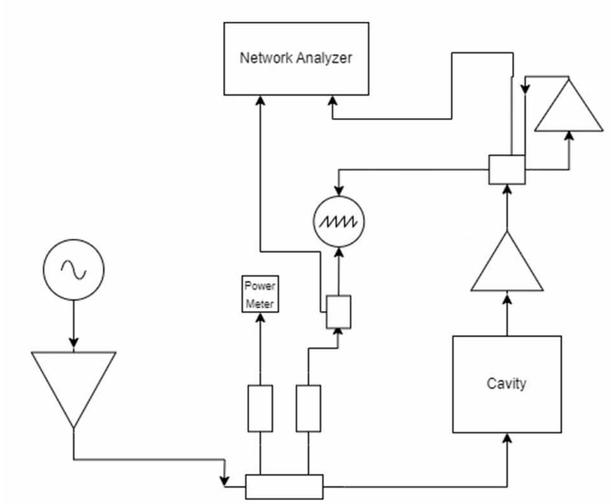

Figure 4: The electronics setup for plasma processing. A rf generator sends a signal to an amplifier with an internal circulator, then through a dual-directional coupler. The signal is sent to a power meter, through to a bidirectional coupler and into a network analyzer, and through to the cavity. The pickup signal is sent to an amplifier and a splitter to be monitored on an oscilloscope, and the network analyzer, all with appropriate attenuation.

RF Electronics System

Multiple devices are used to monitor the frequency and power at different stages of the system (Fig. 4). This setup

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is unique in that it uses a dual directional coupler and the network analyzer in an unusual way. The original setup for this design was created at FRIB for plasma processing. A network analyzer is used to measure the S21 value showing the cavity's resonant frequency before and after plasma ignition. An oscilloscope is connected to the signal output with a splitter and appropriate attenuation to view the frequency shift associated with plasma ignition. Power meters are connected at both the input and output rf power ports, monitoring the forward, and reflected power to prevent harm to the network analyzer and oscilloscope.

As mentioned earlier, the sputtering of the coupler is a concern. Indication of this sputtering can be monitored by installing a Bias-T on both the coupler input power and the pickup detected power, connected to picoammeters [5]. When plasma is ignited in the regions of the coupler or pickup antenna, a higher current output will be read on these devices. This is also a technique introduced by FRIB.

An older rf generator was explicitly chosen to adjust the frequency output without inhibiting rf output, which would kill the plasma. This feature is found in older rf generators and is less common in newer models. Newer rf generators often have this safety net installed for various reasons, making it difficult to sustain a plasma when shifting the frequency as needed. The rf amplifier used for the first tests has a frequency range inclusive only of the fundamental mode, 172 MHz, with a 100-watt maximum power output. This is adequate for the initial tests, though other amplifiers must be used for HOM's. Conveniently, this amplifier has an internal circulator that will protect the devices from too much reflected power.

SIMULATIONS, MEASUREMENTS, AND CALCULATIONS

To better understand the HWR cavity, simulations in CST for the first ten eigenmodes were run. These first ten modes give a good range of options for HOM's and project the electric and magnetic fields onto the cavity rf volume, with CST's default setting of 1 Joule stored energy.

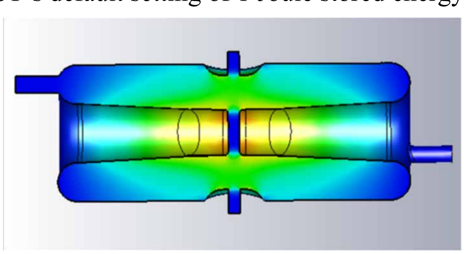

Figure 5: Mode 1 Electric Field of HWR at 173.61 MHz.

Figure 5 shows the electric field of the fundamental mode projected onto the rf volume, indicating the beam port as the best position for the coupler. It is necessary to plasma process the cavities at room temperature, preventing cryo-pumping. Because of this, the cavity is assumed to have weaker coupling compared to superconducting temperatures. Simulating the typical Q_o of ATLAS resonators in the 6E6 range, different insertion distances for the coupler were tested to give a range of ideal coupling strengths (Table 1). This simulation concluded that the coupler needed to be inserted at least two inches into the cavity beam port. With the spare electric coupler, this distance was achievable. The advantage of this coupler is its moveability, which can be inserted or removed up to 7 inches under normal circumstances. Unfortunately, an adapter was required to be used because the flange size differs on the coupler versus the beam port, significantly reducing mobility.

Table 1: Simulated Q_{ext} Values for Coupler Insertion

Insertion Distance (in)	Q_{ext}
1.00	1.86E11
2.00	4.80E7
2.25	6.37E6
2.50	9.40E5
3.00	5.48E4

When measuring the S11 and S21 values, the coupler was fully inserted into the cavity. The pickup on the opposite beam port is flush with the interior surface distance. With this setup, the S11 measurement and calculation yielded S11 = 0.99907, giving a β1 value of 4.6521E-4. Directly measuring the S21 value with the network analyzer gave a loss of -68.44 dB and a loaded Q of Q_L = 5484.4. Calculating the Q_{ext1} with the β1 value yields Q_{ext1}= 1794E7 (coupler Q). Therefore, Q_{ext2} is found to be 7.123E7 (pickup Q). This barely gives enough coupling strength to cavity Q that we can input power into the rf volume to ignite the plasma.

Based on these measurements and calculations, most of the power is dissipated into the walls of the cavity. Because of this, we can assume the power dissipated (P_{diss}) is roughly equal to the power in (P_{in}). Using this relationship and Eq. (1), we obtain an equation for the voltage across the gap of the resonator (v) related to the forward power output by the rf amplifier (P_{fwd}) [9].

$$P_{in} = \frac{4P_f/(Q_{ext1}Q_o)}{({}^{1}/_{Q_o} + {}^{1}/_{Q_{ext1}})^2} = 3.12e^{-04}P_{fwd.} \qquad (1)$$

Using our simulations from earlier we can obtain the voltage across the accelerating gap of the cavity, based on the electric field distribution and the shunt impedance (Eq. (2)) relative to the Q of the cavity [9].

$$R_a = \frac{V^2}{P_{diss}} \qquad (2)$$

This relationship resolves to Eq. (3), where we can solve for the appropriate power needed, assuming the voltage across the accelerating gap is great enough to overcome the ionization energy of Ar gas at 15. 6 eV,

$$V = 54.4\sqrt{P_{fwd}}. \qquad (3)$$

Using this information and developed base knowledge of plasma processing from previous efforts, we find that the necessary power forward required by the amplifier is of the range between 15 and 25 watts for Ar gas.

INITIAL PLASMA IGNITION RESULTS AND FUTURE PLANS

With the combined results of our calculations and the previous work done for plasma processing on HWR

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cavities, a starting pressure of 15 mTorr was selected, to avoid igniting plasma in the coupler based on the gap distance. A plasma discharge was verified visually, starting with ~45 Watts forward power and increasing to 50 Watts at 15 mTorr (Fig. 6). This was the first-time striking plasma with this setup. Unfortunately, as seen in the photos, the plasma was ignited in the coupler. The plasma ignition was repeatable, but we were not able to move the plasma into the rf volume in the accelerating gap.

We believe this occurred because we used the Paschen curve for the DC power case, which will rely heavily on the gap between the electrodes the electron will move between. Though, in RF the electric field strength is more important for the understanding of where the plasma will strike. After removal and inspection, the coupler had no signs of damage.

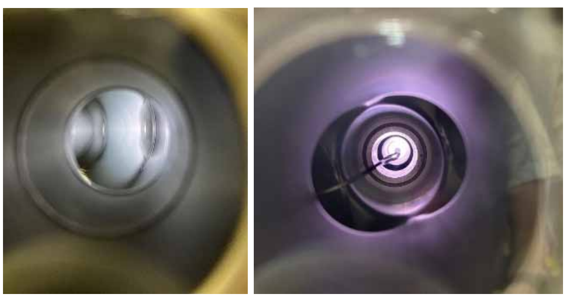

Figure 6: Plasma ignition in 172 MHz HWR cavity. (Plasma ignition is focused in the coupler in the right image from W3 (ref. Fig. 3 for W3 position). A “halo” or “glow” from the plasma in the coupler is seen in the left image, from W1 (ref. Fig. 3 for W1 position)).

A frequency shift is associated with plasma ignition, indicating the power is being dissipated into the plasma instead of the cavity walls. Using this frequency shift, we can calculate the plasma density and optimize by adjusting variables of forward power, gas flow, and input frequency. Eq. (4) shows the relationship between the electron number density (n_o), the resonant frequency (f_o), and the frequency when plasma discharge is detected (f),

$$n_o = 4\pi^2 \frac{\varepsilon_o 3 m_e}{q_o^2}(f^2 - f_o^2) \quad (4)$$

This is also used by other collaborators to verify when plasma is ignited without having a visual, then calculating for the electron density [5, 10].

Next steps for the plasma processing initiative in ATLAS will optimize plasma ignition in the cavity by experimentation and comparison to simulation for power distribution. Coupler position will have to be modified in addition to an investigation into using HOM’s. After the Ar ignition is optimized to ignite only in the cavity, a similar process can be applied to optimize after introducing 10% oxygen. The separate pumping system for the RGA will be installed prior to plasma processing with the gas combination. Once installed and plasma ignition is optimized again, the final step will be to analyze the output of the RGA at different plasma densities, hopefully observing hydrocarbons in the output of the RGA data. A time cycle can be developed for continued plasma processing tests. After this is tested, a cold test bringing the HWR cavity to superconducting temperatures and measuring the FE could be performed to evaluate the efficiency of plasma processing. Future goals are to apply these techniques to a QWR, and eventually in-situ to the QWR installed in A-tank and G-tank in ATLAS.

CONCLUSION

Minimal testing has been performed on the cavity up until this point. Most of the work presented is the setup and confirmation of variables needed to perform the tests. Simulations are a powerful tool to help analyze the possible outcomes of experiments but do not have 100% accuracy with experimental results. By comparing the results tested to the simulations presented, we can better understand our predictability for future work.

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Previous work done by FNAL, SNS, FRIB, JLab, and IJCLAB on plasma processing efforts gave a significant base to start this work. The continued collaborative effort, now joined by ANL, will continue to be of great benefit to the scientific community. W. Hartung of FRIB, B. Giaccone and P. Berrutti were of great help in establishing our understanding and progress in this project. Support by ATLAS staff has been greatly appreciated. J. McLain continues to advise on plasma dynamics, helping us to understand what is expected to occur during the plasma processing. Encouragement, guidance, and support from M. Kelly and G. Zinkann has accelerated the progress of this project. ATLAS Operations staff including B. Blomberg, M. Hendricks, and the operators have continuously supported development efforts. The project thus far has been collaborative on all fronts, supporting future work in ATLAS, a DOE Office of Science User Facility.

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