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CRYOGENIC PERFORMANCE OF AN SRF DEFLECTING CAVITY FABRICATED USING ALTERNATIVE TECHNIQUES FOR THE ARIEL eLINAC

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Abstract

A 650 MHz SRF deflecting mode cavity has been built and tested for use as a three-way beam separator in the ARIEL eLinac. The cavity operates in a TE-like mode and has been optimized for high shunt impedance with minimal longitudinal footprint. The device is the first SRF cavity to be fully fabricated in house at TRIUMF. The requirements of the cavity allowed for the development of low cost manufacturing techniques, including the use of Reactor grade niobium and atmospheric pressure TIG welding. The cavity has been fabricated and tested at 4 K and 2 K, obtaining a 4 K Q_0 of 4.6×10^8 at the operating voltage of 0.3 MV, surpassing the goal voltage and quality factor required for operation. Results of the cryogenic tests of the cavity will be presented here.

INTRODUCTION

An SRF deflecting mode cavity has been designed to perform three-way beam separation in the ARIEL eLinac. The 650 MHz cavity will be installed at the end of the main linac and will impart opposing transverse momentum to adjacent 1.3 GHz bunches bound for either the ARIEL facility for rare isotope production or to a recirculation loop to drive a THz or infrared Free Electron Laser (FEL). The third beam passing through the cavity will be the decelerated FEL drive beam after energy recovery which will pass through the cavity at the RF zero-crossing and receive no net momentum from the cavity.

The design of the deflecting cavity is described in detail in [1] and will provide a nominal 0.3 MV transverse deflection with less than 1 W of RF power dissipation at the operating temperature of 4.2 K. The cavity geometry is shown in Fig. 1. The cavity operates in a TE-like mode with the deflection imparted by an electric field between the ridges in the plane of the deflection. The two ports on the upstream (larger) end of the cavity provide access for a coaxial input coupler and coaxial Higher Order Mode coupler. A pickup antenna is inserted into a similar port on the downstream side of the cavity.

The cavity was fully fabricated in house at TRIUMF using non-standard fabrication techniques [2]. The cavity parts were machined from bulk Reactor grade niobium with a measured RRR of 53 and the joints were welded using TIG welding inside of a chamber purged with ultra-high purity argon gas at atmospheric pressure.

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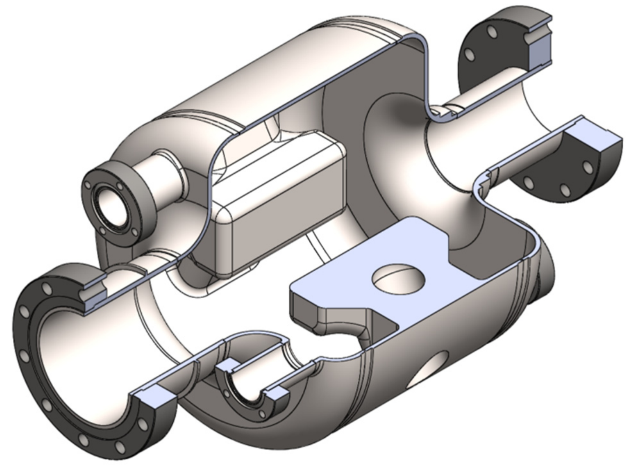

Figure 1: The SRF deflecting cavity geometry showing the fabrication of the ridges from solid niobium with a cooling channel to allow cooling from the inside of the ridge.

PREPARATION FOR COLD TESTS

After fabrication, the cavity underwent a BCP etch to remove 120 µm of material from the surface. The acid was chilled to 11.5°C and the cavity and acid actively cooled throughout etching. The cavity was etched in three steps to avoid non-uniform removal of material: 30 µm in the vertical orientation, 60 µm reversed, then a final 30 µm in the original orientation.

The surface quality achieved after BCP is quite poor, as shown in Fig. 2 and 3. The grain structure has been accentuated, and when viewed under magnification, the surface can be seen to have non-uniform grain sizes which reflect light differently depending on their size resulting in the pattern of light and dark areas seen in the image. Additionally, the lines on the surface seen in Fig. 3 appear to be made up of a series of pits which form channels across the surfaces of the cavity. These appear to follow along “macro-grain boundaries” within the material. It was suggested by the material vendor that insufficient forging of the ingot during production due to the large size of the material could be the cause of the non-uniform grain structure.

After etching, the cavity was rinsed in the high-pressure water rinse for a total of 6.5 hours resulting in an average coverage of 10 seconds/cm^2 with water pressure of 700 to 850 psi. The rinse wand was inserted through all the cavity ports, with the RF ports allowing for rinsing of the upper and lower faces of the ridges which are not accessible to direct rinsing through the beam pipe alone.

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After rinsing, the cavity was allowed to fully dry in the Class 10 clean room for a period of 16 hours before assembly.

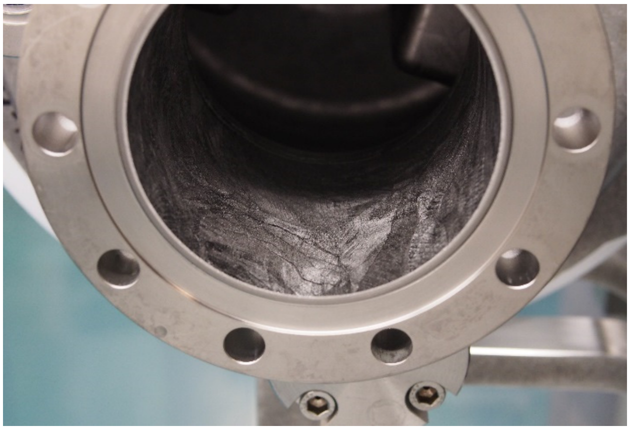

Figure 2: The surface appearance of the upstream beam pipe after the 120 µm etch.

Figure 3: The surface appearance of the ridge showing the pitting after the 120 µm etch.

The cavity was assembled with a niobium plate covering the upstream beam pipe flange cover to limit RF losses. Although the fields present on this flange cover are relatively low, if left uncovered the stainless steel would contribute a Q of 3×10^9 which would be a significant source of error in the measurement. A variable coupler was installed for these tests, providing critical coupling over the range of $Q_{ext} = 10^4$ to 10^{11}. A pickup antenna was installed with $Q_{ext} \sim 10^{11}$.

The cavity was tested in TRIUMF's SRF test facility at temperatures down to 2 K. A 500 W wide band RF amplifier provided the RF power to the cavity. The LLRF system used in the cold tests was based on the ISAC II LLRF systems, operating at an intermediate frequency of 140 MHz. The 650 MHz signal from the cavity was down-converted to 140 MHz to take advantage of this existing infrastructure. The cavity was tested in a new large diameter cryostat which allowed for the cavity to be mounted in the horizontal orientation during testing. This ensured that gaseous helium could not become trapped in the cooling channels and decrease their cooling efficiency. It was discovered after the initial tests that this cryostat contained an ambient magnetic field on the order of 300 mG, which was decreased to 35 mG for the final test by the addition of an additional layer of mu-metal shielding directly surrounding the cavity.

CRYOGENIC RF TESTS

The performance of the cavity was measured in cryogenic tests at temperatures between 4.2 K and 2 K to measure the intrinsic quality factor, Q_0, as a function of the transverse deflecting voltage, $V_\perp$. During the initial field ramp up at 4.2 K, several soft multipacting barriers were encountered, occurring over the voltage ranges of roughly 0.1 to 0.3 MV, 0.4 MV, and 0.7 to 0.8 MV. These were generally easily processed within a few minutes, or in some cases up to 10's of minutes, by increasing the coupling strength and driving several Watts of power into the cavity. After processing through these barriers once, multipacting was not observed again at the same voltage.

The measured cavity performance is shown in Fig. 4. At the operating temperature of 4.2 K the Q_0 at the nominal deflecting voltage of 0.3 MV was measured to be 4.6×10^8 and a maximum deflecting voltage exceeds 0.8 MV, surpassing the design requirements. At 2 K, the low field Q_0 increased to 1.5×10^9, but the cavity can be seen to suffer from a significant Q-slope.

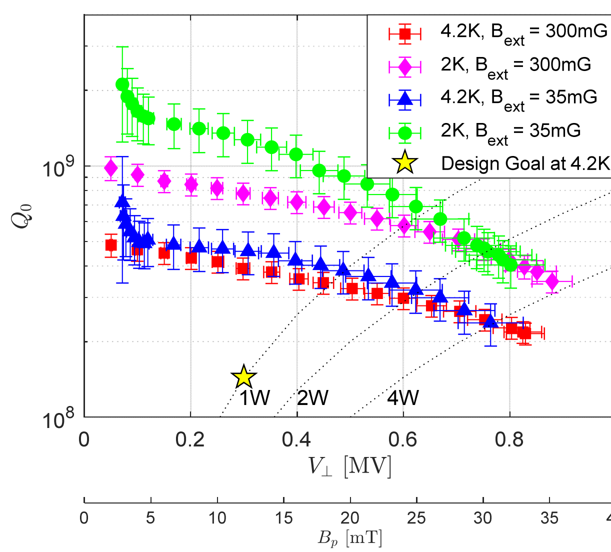

Figure 4: The cavity performance measured in ambient magnetic fields of 300 and 35 mG.

The solid ridges of this cavity are expected to contribute to a modest Q-slope due to the thermalization of the ridges at temperatures above the bath temperature at high fields, however not to the extent observed in the cryogenic tests. This thermalization effect was observed by taking a rapid series of Q_0 measurements immediately after the RF was turned on, resulting in the Q_0 decreasing by several % before stabilizing at a steady state value.

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A more probable explanation for the Q-slope could be the effect of the surface roughness and pitting. As proposed in [3], the field enhancement on the protruding edges of the surface features can lead to local heating and increased RF resistance as the field increases, leading to the decreased Q_0, and thermal quench of the cavity at the peak field reached.

The Q_0 was measured at several points during the cool-down from 4.2 K to 2 K allowing for determination of the field dependency of the residual and BCS components of the surface resistance. The total surface resistance of the cavity, R_s, was fitted to the equation:

$$R_s(T) = R_{res} + \frac{A}{T} e^{\Delta/(k_B T)} . \qquad (1)$$

The residual resistance, R_{res}, and BCS component at 4.2 K, $R_{BCS} = \frac{A}{4.2\text{K}} e^{\Delta/(k_B 4.2\text{K})}$, are plotted in Fig. 5 for the initial test in an ambient field of 300 mG before and after a 120°C bake, and when retested in a 35 mG field.

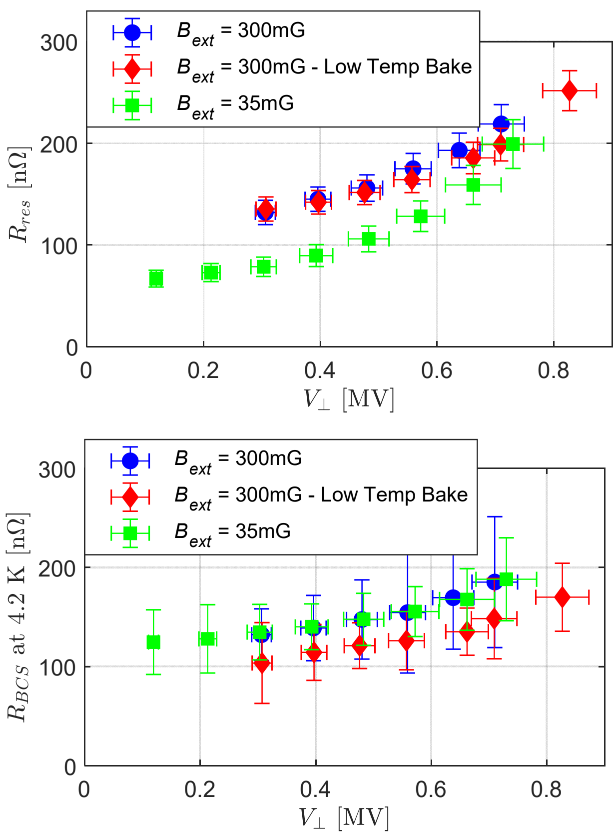

Figure 5: The field dependence of the residual resistance (top) and BCS resistance at 4.2 K (bottom), extracted from the surface resistance data.

The low field residual resistance measured at 35 mG ambient field is 70 nΩ, decreased from 135 nΩ with 300 mG, resulting in a magnetic susceptibility of 0.25 nΩ/mG. Even at low ambient field, the residual resistance is still relatively high and displays a strong field dependence suggestive that this results from the poor surface quality achieved by etching. The BCS resistance also shows a slight field dependence, although with a relatively large fitting error.

The pressure sensitivity of the cavity was determined by measuring the resonant frequency at a constant cavity voltage during the pump down of the cavity from atmospheric pressure during the 2 K cool down. The measured sensitivity was 9.7 Hz/mbar, compared to 13 Hz/mbar modelled with the reinforcing frame supporting the cavity.

The Lorentz detuning coefficient was determined by measuring the frequency shift of the cavity as the voltage was increased. This measurement was performed at 2 K since the pressure stability is much better than at 4 K resulting in a measured Lorentz detuning coefficient of $-5.4\ \text{Hz}/(\text{MV/m})^2$.

The cryogenic tests were repeated after performing a low temperature bake where the cavity was heated under vacuum to >100°C for a period of 51 hours. This was found to have only a marginal reduction on the BCS resistance (Fig. 5), as can be expected for a cavity fabricated from low-RRR material.

Likewise, the cavity was also tested after warming up to a temperature of 100 K for a period of 3 hours to test for Q disease. The cavity saw no significant change in its performance as the formation of lossy niobium hydrides is inhibited by the relatively high concentration of oxygen (140 ppm) in the Reactor grade niobium.

CONCLUSION

A 650 MHz superconducting RF deflecting cavity has been fabricated in house at TRIUMF using low RRR material and TIG welding for its fabrication. The cavity exceeds the performance requirements providing a 4.2 K Q_0 of 4.6×10^8 at the nominal operating voltage of 0.3 MV and reaching a deflecting voltage of 0.8 MV with peak fields of 25 MV/m and 32 mT. Although the surface quality of the cavity is relatively poor resulting in a residual resistance of 70 nΩ, the cavity is expected to easily provide the required deflecting voltage to allow for simulataneous operation of the ARIEL eLinac for both rare isotope production and driving a Free Electron Laser.

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