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CRYOGENIC TEST OF A 750 MHz SUPERCONDUCTING RF CRABBING CAVITY*

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Abstract

A superconducting rf dipole cavity has been designed to address the challenges of a high repetition rate (750 MHz), high current for both electron/ion species (0.5/3 A per bunch), and large crossing angle (50 mrad) at the interaction points (IPs) crabbing system for the Medium Energy Electron-Ion Collider (MEIC) proposed by Jefferson Lab. The cavity prototype built at Niowave, Inc. has been tested at the Jefferson Lab facilities. In this work we present a detailed analysis of the prototype cavity performance at 4 K and 2 K, corroborating the absence of hard multipacting barriers that could limit the desired transverse fields, along with the surface resistance (R_s) temperature dependency.

INTRODUCTION

Several prototypes of the rf dipole have already been proven to have attractive properties for deflecting and crabbing applications at low frequencies [1] due to their compact geometry and few parameter dependency of their rf properties. Far higher modes (HOM) spacing, absence of lower order modes (LOM), along with higher shunt impedances and easy multipacting processing are some of the features inherent to this geometry. In the present work we focus on the rf testing at 4 K and 2 K of a 750 MHz rf dipole designed as crab crossing corrector, both for electron and proton bunches in the MEIC.

Surface Treatment and Test Preparation

The 750 MHz crabbing cavity was designed at the Center for Accelerator Science (CAS-ODU) [2] and manufactured by Niowave, Inc. as part of a collaboration of both institutions. The cavity was fabricated using 3 mm thick, large grain Nb sheets (355-405 RRR) in 4 main parts deep drawn using dies and e-beam welded [3]. As part of the test preparation, the cavity surface received a treatment of 30 μm removal with horizontal electro polishing (HEP), followed by a 5 μm flash buffered chemical polishing (BCP) removal, and a 3 pass high pressure rinsing (HPR) using deionized water at 1250 psi. After the surface treatment and clean assembly, the effective surface resistances expected

were $R_s = 200 \text{ n}\Omega$ at 4 K, and $R_s = 23 \text{ n}\Omega$ at 2 K, thus the expected cavity correspondent unloaded quality factors were $Q_0(4\text{K}) = 6.57 \times 10^8$, and $Q_0(2\text{K}) = 5.71 \times 10^9$.

Probe Calibration

Copper rod electric antennas of 9.5 and 3.1 mm diameters were used as fundamental coupler probe (FCP) and field probe (FP) respectively. The distance from the probes tip to the cavity end cap entrance, along with their external coupling (Q_{ext}) were measured and recorded during the calibration. Fig. 1 shows the calibration data compared to Q_{ext} simulations on CST Microwave Studio[®] for perfect electric conductor rods of different diameters.

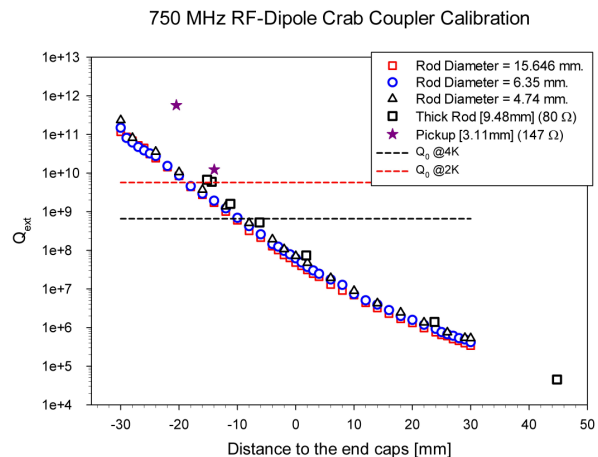


Figure 1: Fundamental coupler (star) and field (black square) probes calibration data, compared to Q_{ext} simulations on CST Microwave Studio[®] for perfect electric conductor rods of different diameters. The dotted lines show the cavity expected Q_0 at 4 K (black) and 2 K (red).

RADIO FREQUENCY MEASUREMENTS

The performance of the cavity is analyzed by measuring the unloaded quality factor (Q_0) as a function of the transverse voltage at 4 K and 2 K in the vertical test area (VTA) at Jefferson Lab. The Figs. 2 and 3 show curves for the measured unloaded quality factor as a function of the transverse electric field (E_T), and transverse voltage (V_T).

The Q_0 curve at 4 K shows two multipacting barriers at low gradients that even when stayed persistently at the same levels, were not difficult to break through. Once at 2 K, this multipacting barriers were seen around the same

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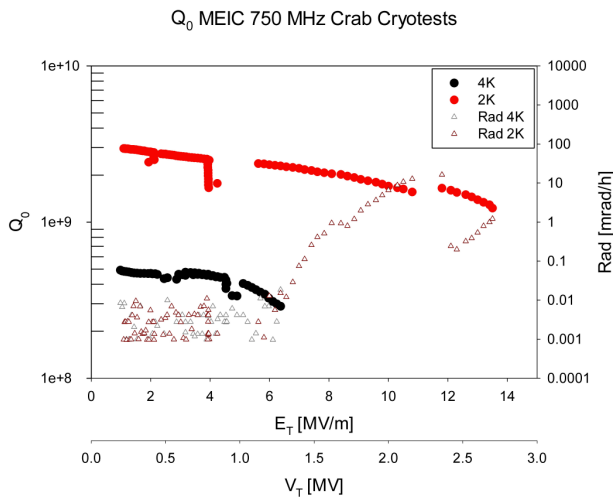


Figure 2: Measured quality factor showing the multipacting barriers and radiation generated during the 4 K and 2 K cryogenic tests. An event around 12 MV/m shows the burst of a field emitter that produces an abrupt reduction (2 orders of magnitude) in the X ray production.

gradient levels (since the cavity becomes more sensitive at 2 K, this barriers were seen at a gradient 10% lower than at 4 K), but once again they were fairly easy to break through and after the first 2 K full run, the barriers were not seen again. During the 4 K test the cavity achieved a transverse voltage of $V_T = 1.27$ MV that corresponds to a deflecting field of $E_T = 6.37$ MV/m and it was limited by the FCP Q_{ext} mismatch, as a measure of protection to the cables that were seeing a considerable amount of reflected power ($P_{ref} = 179$ W). The cavity was dissipating over 45 W at a transverse gradient of 6.37 MV/m, that corresponds to the peak surface fields $E_p = 28.35$ MV/m, and $B_p = 59.3$ mT.

At 2 K, the quality factor curve shows a slight slope with the gradient and an increasing X ray emission above 10 MV/m when the Q_0 starts decaying, possibly due to a hot spot on the cavity walls. The cavity achieved a transverse voltage of $V_T = 2.70$ MV ($E_T = 13.50$ MV/m) before quenching, and dissipated above 47 W at this field level, corresponding to electric and magnetic peak surface fields of $E_p = 60.08$ MV/m, and $B_p = 125.69$ mT. Fig. 2 shows the radiation levels for both the 4 K and 2 K cryogenic tests, measured under the lid on top of the Dewar. The operation crabbing voltage for the electron bunches at the MEIC is in between $1.35\text{ MV} \leq V_T \leq 1.80\text{ MV}$, depending on the β -functions for the beams at the crabbing cavity location, thus the maximum requirement is only 75% of the achievable transverse kick with a single cavity at cw (see Fig. 3).

Lorentz Force Detuning

The Lorentz force detuning is a measure of the deformation of the cavity volume due to the radiation pressure, where the radiation pressure due to the magnetic field exerts an outwards force on the cavity walls, while the electric

750 MHz Crab Cryotests with Multipacting Analysis

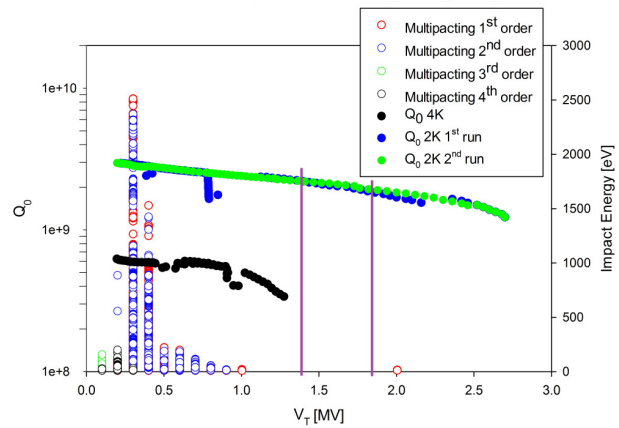


Figure 3: Q_0 measured at 4 K (solid black) and 2 K (solid blue and green) compared to the multipacting levels obtained from the TRACK3P-ACE3P simulations. The purple lines enclose the crabbing kick range needed per cavity in the MEIC.

field contribution to the radiation pressure pushes the cavity outer conductor inwards, all this is in accordance to the Slater's theorem. The measured change on the resonant frequency of the cavity due to the Lorentz force detuning is shown in Fig. 4. The Lorentz coefficient was calculated to be $k_L = -223.4$ Hz/(MV/m)². The high sensitivity to the radiation pressure is due to the relatively large flat surfaces on the loading elements subjected to the high electric fields. The Lorentz coefficient can be improved by adding stiffeners in the areas of higher deformation.

Pressure Sensitivity

In this section we discuss the change on the resonant frequency of the cavity due to mechanical stresses exerted on its walls resulting from the pressure differences between the vacuum inside the cavity ($\sim 10^{-9}$ torr) and the liquid Helium bath (755 torr) in which is submersed.

The cavity's pressure sensitivity was measured to be 0.7 kHz/torr by operating at low rf power in cw during cooling down from 4 K to 2 K, as shown in Fig. 5. Just as for the case of the Lorentz detuning, the pressure sensitivity can be easily reduced by adding properly placed stiffening elements to the cavity walls.

Surface Resistance

From the relation $R_S = G/Q_0$ we calculated the effective surface resistance R_S , using the measurements of the unloaded quality factor Q_0 performed on the cavity during the 4 K to 2 K cool down, taking into account the 750 MHz crabbing cavity design geometrical factor $G = 131.4 \Omega$. We used a gradient range of 0.49 to 1.99 MV/m to take the Q_0 measurements. Then, considering that the effective surface resistance expression can be written down as $R_S = R_{BCS} + R_{res}$, and using the BCS theory [4], we realized a fit to the data to

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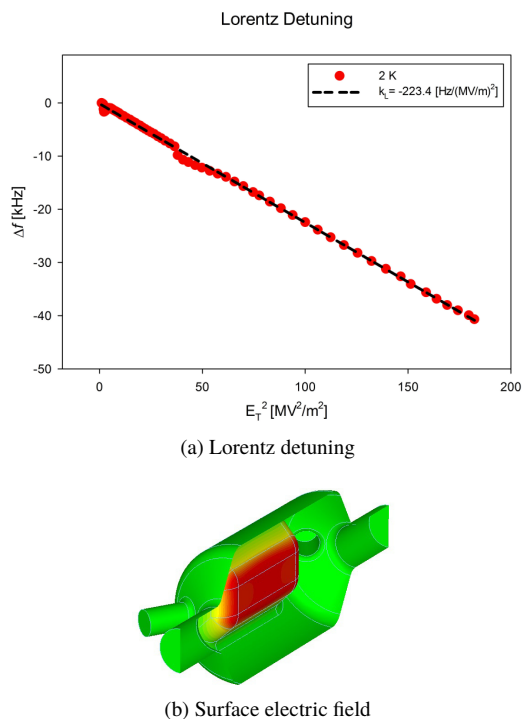


Figure 4: Lorentz coefficient from measurements of the resonant frequency shift during cool down (a). Cross section showing the electric surface fields from simulations, placed on the flat area of the loading elements (b).

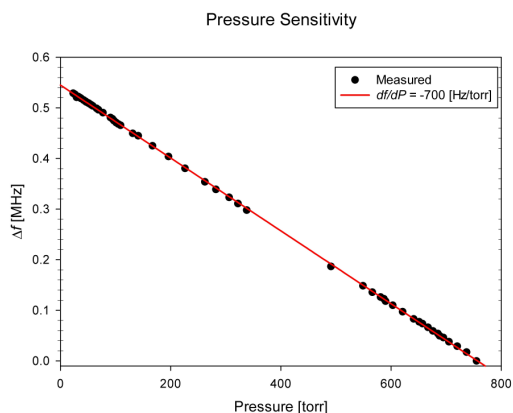


Figure 5: Pressure sensitivity from measurements of the resonant frequency shift during the liquid Helium pump down in the Dewar (from 760 to 23 torr).

find the residual surface resistance R_{res} . Then, the best fit is:

$$R_S [n\Omega] = \frac{6.9 \times 10^4}{T[K]} \exp\left[-\frac{19.6}{T[K]}\right] + 39.34. \quad (1)$$

An estimated of $39.3 n\Omega$ for the residual surface resistance was obtained (see Fig. 6), making the losses on the cavity higher than expected. Since this is not a fundamental feature of the cavity itself, we should be able to achieve a higher quality factor after reprocessing and cleaning the surfaces.

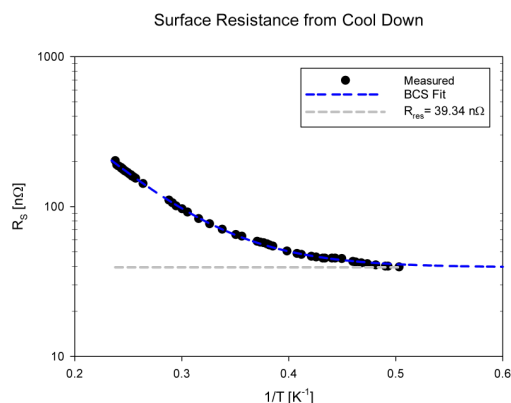


Figure 6: Residual surface resistance calculated using the effective surface resistance data measured during the cavity cool down and fitted to the BCS theory.

CONCLUSIONS

The achieved transverse voltages at 2 K are 50% above the requirements per cavity for the MEIC. The observed multipacting levels are in agreement with the simulation's results, and did not represent an obstacle for operations. During cryogenic testing, the cavity presented a good performance, with a high unloaded quality factor and fairly high field levels achieved: a transverse gradient of $E_T = 6.37$ MV/m, with electric and magnetic surface fields $E_p = 28.35$ MV/m and $B_p = 59.3$ mT respectively, and a transverse voltage of $V_T = 1.27$ MV at 4 K; and $E_T = 13.50$ MV/m, $E_p = 60.08$ MV/m, $B_p = 125.69$ mT, and $V_T = 2.70$ MV at 2 K. However, having measured a high residual surface resistance ($R_{res} = 39.4 n\Omega$), we claim to be able to improve the Q_0 values by a 6% at 4 K and by a factor of 4 at 2 K, all this assuming a feasible value of $R_{res} = 10 n\Omega$ after a new surface treatment.

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