HIGH POWERED TESTS OF DIELECTRIC LOADED HIGH PRESSURE RF CAVITIES FOR USE IN MUON COOLING CHANNELS *

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Abstract

Bright muon sources require six dimensional cooling to achieve acceptable luminosities. Ionization cooling is the only known method able to do so within the muon lifetime. One proposed cooling channel, the Helical Cooling Channel, utilizes gas filled radio frequency cavities to both mitigate RF breakdown in the presence of strong, external magnetic fields, and provide the cooling medium. Engineering constraints on the diameter of the magnets within which these cavities operate dictate the radius of the cavities be decreased at their nominal operating frequency. To accomplish this, one may load the cavities with a larger dielectric material. Alumina of purities ranging from 96 to 99.8% was tested in a high pressure RF test cell at the MuCool Test Area at Fermilab. The results of breakdown studies with pure nitrogen gas, and oxygen-doped nitrogen gas indicate the peak surface electric field on the alumina ranges between 10 and 15 MV/m.

INTRODUCTION

The design of a muon cooling channel utilizing high pressure gas filled radio frequency cavities has progressed significantly since its inception [1–3]. The use of ionization cooling to focus a muon beam relies on normal conducting RF cavities operating in multi-Tesla external magnetic fields. Filling such cavities with a high pressure gas has been proven successful [4], and the amount of plasma loading due to the beam traversing a cavity has been quantized [5].

The Helical Cooling Channel provides continuous six dimensional cooling through the use of a helical arrangement of superconducting solenoid magnets and hydrogen gas filled RF cavities. The cavities must fit within the magnets, and their transverse size is therefore limited by the achievable magnet bore diameter [6]. For pillbox cavities filled with 160 atm of hydrogen gas at the frequencies under consideration (325 and 650 MHz), an additional mechanism is needed to bring their diameters down to the constrained size. Loading the cavities with a high dielectric constant material provides a solution.

Alumina (Al_2O_3) is being pursued for these dielectric loaded high pressure gas filled RF cavities because of its dielectric constant ($\epsilon_r \approx 9$) and small loss tangent ($\tan\delta < 10^{-3}$). Samples were obtained from various vendors, and tested for their dielectric constant and loss tangent [7]. Coorstek was selected as the vendor, and an alumina torus was designed to bring the resonant frequency of a 1 GHz pillbox cavity into the 800-810 MHz range.

Tori of 96, 98.5, 99.5 and 99.8% alumina were fabricated, and tested in a test cell filled with high pressure nitrogen gas under high power to determine the achievable accelerating gradient.

EXPERIMENT

The high pressure test cell used in the past for gas RF breakdown studies [4] and plasma loading measurements [5] was refitted for these measurements. The on axis electrodes that were used in the past to localize the electric field and bring the resonant frequency down to 805 MHz were removed. Filled with 1 atm air, the frequency of the test cell was 1004.06 MHz. Teflon spacers were used to hold an alumina torus in the center (longitudinally) of the test cell. The torus was designed to allow a beam to traverse the test cell on axis, while bringing the frequency into the 800-810 MHz range. The corners were rounded as to minimize local electric field enhancement. Figure 1 shows a cartoon and photo of the interior of the test cell.

Each of the four alumina tori were tested at nitrogen gas pressures ranging from 2 atm to 90 atm. There were issues with holding pressure in some cases, and so higher pressures could not be achieved with each torus. The electric field in the test cell was slowly increased until a spark was observed, at which point the drive amplitude was lowered. At least 10 sparks for each combination of gas pressure and alumina purity were recorded this way. Data were collected on a combination of high sampling rate oscilloscopes.

RESULTS

Figure 2 shows the cross sectional electric fieldmap for (one half of) the high pressure test cell loaded with the alumina torus (and teflon spacers). Note that the location of highest electric field is on the curved interior surface of the alumina. Table 1 shows the ratio of the maximum electric field on the surface of the alumina and copper wall to the average accelerating gradient. The average accelerating gradient is defined as $E_{\mathrm{acc}} = \frac{1}{L}\int_{r=0} E_z dz$, where L is the length of the test cell.

In this configuration, the electric field on the surface of the alumina is 60% larger than the field on the surface of the copper wall, and 76% larger than the average accelerating gradient. Figure 3 shows the results of the electric field on the surface of the alumina at which sparking occurred as a function of gas pressure.

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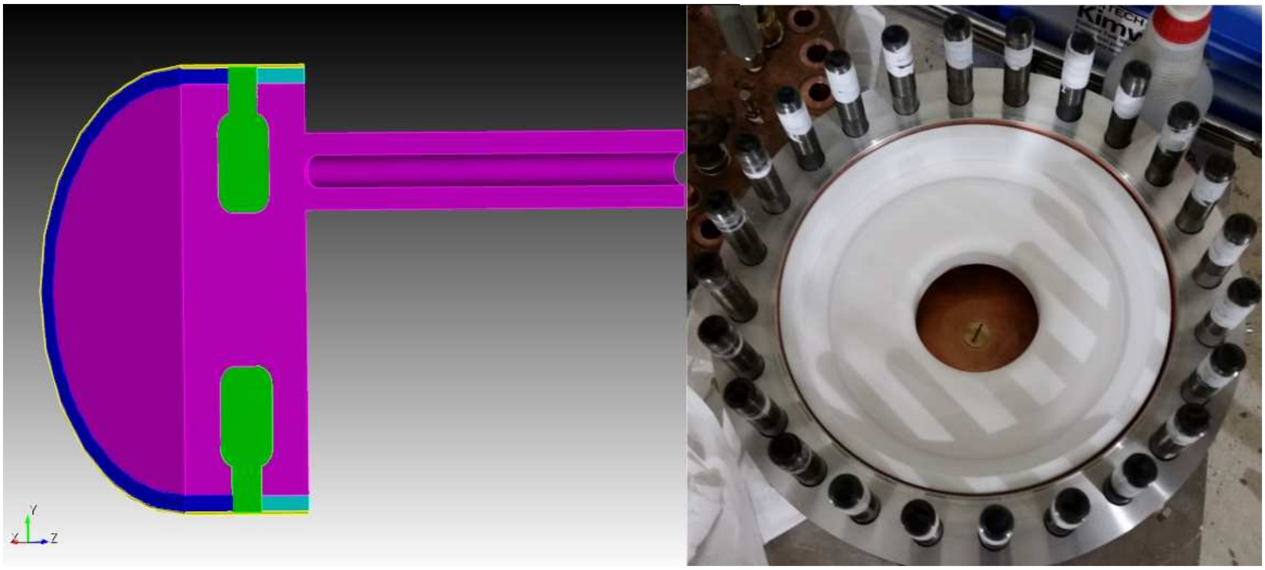

Figure 1: The high pressure test cell with an alumina torus and teflon spacers. On the left is a cartoon of the interior of the cavity (including coupler) in which the nitrogen gas (magenta and yellow), alumina torus (green), and teflon spacers (blue and teal) are shown. On the right is a photo of the interior of the cavity with one end plate removed. The alumina torus and one teflon spacer are visible, as well as the copper plug (on axis), clamping bolts, and one of two RF and pressure seals.

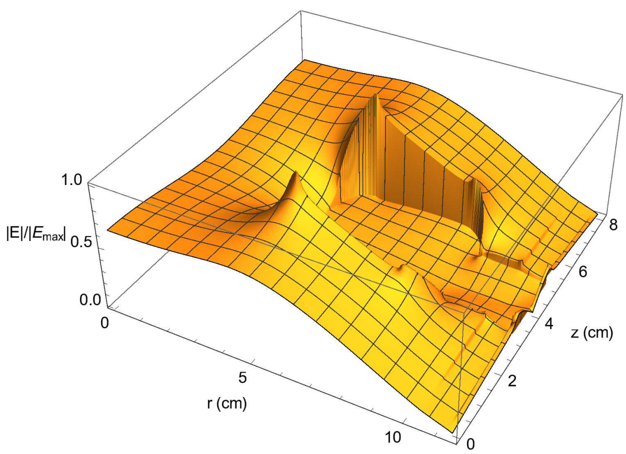

Figure 2: Electric field map for the dielectric loaded high pressure test cell. The plot has been normalized to the maximum electric field, which occurs at the interior rounded surface of the alumina.

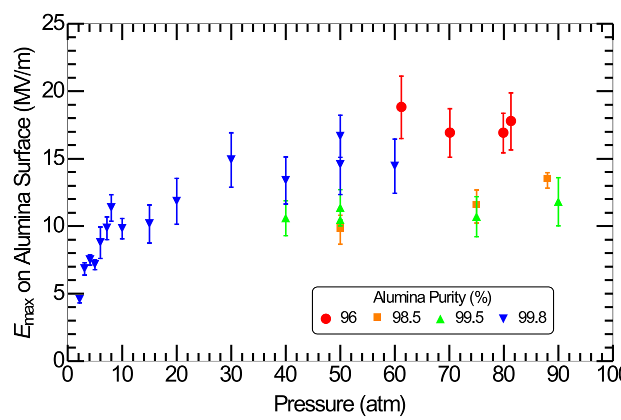

Figure 3: Electric field on the surface of the alumina torus at which sparking occurred as a function of pure nitrogen gas pressure. The error bars represent the standard deviation of the measurements.

Table 1: Ratios of Peak Electric Fields on the Surface of Alumina and Copper to Average Accelerating Gradient

Ratio	Value
$\|E\|_{alum}/\|E\|_{acc}$	1.76
$\|E\|_{Cu}/\|E\|_{acc}$	1.10
$\|E\|_{alum}/\|E\|_{Cu}$	1.60

For pressures below 10 atm, the breakdown gradient follows the Paschen curve for nitrogen gas breakdown. Above 10 atm, the alumina is the limiting factor for achievable gradient. The maximum gradient is slightly dependent on purity, and ranges from 11 MV/m for 99.5% to 17.5 MV/m for 96%.

ELECTRODE MODIFICATION

The results presented above indicate the achievable accelerating gradient falls within the range of 6.3-10 MV/m, which is insufficient for the Helical Cooling Channel. In an effort to improve the accelerating gradient, small hemispherical electrodes were fabricated and inserted on the cavity axis. These electrodes provided a perturbation to the electric field such that the region of highest field was shifted away from the alumina, while not pushing the frequency of the test cell too low. Figure 4 shows the fieldmap of the cavity with the electrodes.

The field enhancement at the tip of the electrodes provides a peak electric field on the surface of the alumina that is now only 32% higher than the average accelerating gradient, as seen in Table 2.

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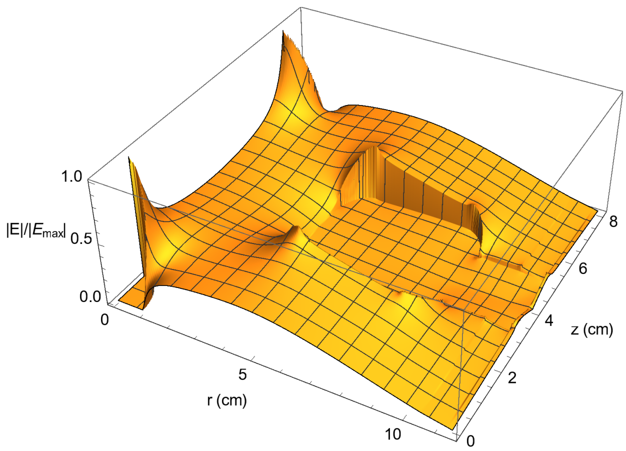

Figure 4: Electric field map for the dielectric loaded high pressure test cell. The plot has been normalized to the maximum electric field, which occurs at the tip of the copper electrodes.

Table 2: Ratios of Peak Electric Fields on the Surface of Alumina and Copper to Average Accelerating Gradient, for the Case in Which Copper Electrodes Were Inserted on the Axis of the Test Cell

Ratio	Value
$\lvert E\rvert_{alum}/\lvert E\rvert_{acc}$	1.32
$\lvert E\rvert_{Cu}/\lvert E\rvert_{acc}$	2.50
$\lvert E\rvert_{alum}/\lvert E\rvert_{Cu}$	0.53

Figure 5 shows the breakdown gradient for the 99.8% alumina torus that was tested with and without the electrodes. The maximum field on the surface of the alumina agrees quite well within the statistical uncertainty.

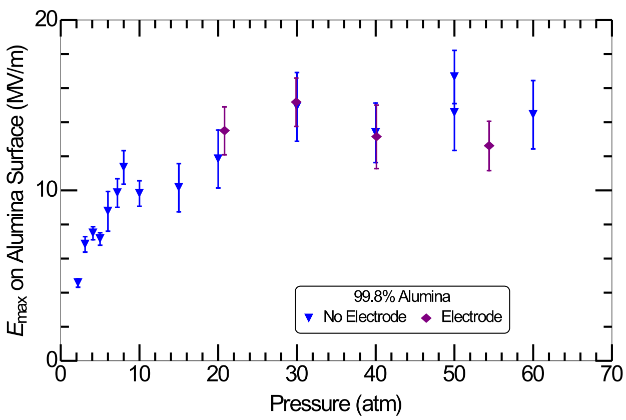

Figure 5: Electric field on the surface of the alumina torus at which sparking occurred as a function of pure nitrogen gas pressure. The cases of with and without the copper electrodes are shown. The error bars represent the standard deviation of the measurements.

Figure 6 shows the improvement the electrodes made on the accelerating gradient. The mean average accelerating gradient 20 atm and above is 10.3 MV/m for the case with the electrodes, compared to 8.4 MV/m without.

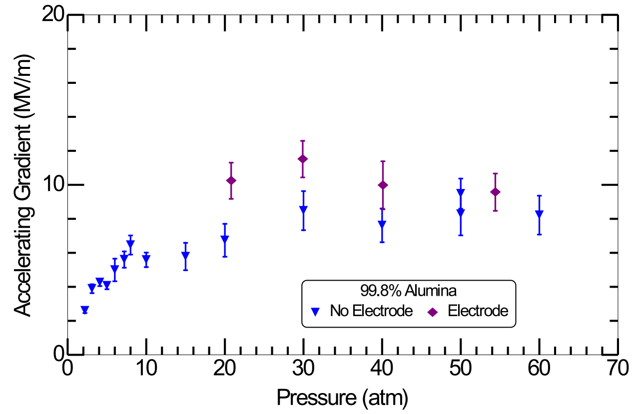

Figure 6: Average accelerating gradient at which sparking occurred as a function of pure nitrogen gas pressure. The cases of with and without the copper electrodes are shown. The error bars represent the standard deviation of the measurements.

CONCLUSION

Preliminary high power RF tests of a dielectric loaded high pressure cavity indicate the maximum surface field on alumina ranges from 11-17.5 MV/m. Improvements on cavity geometry tested with the 99.8% alumina torus raised the mean average accelerating gradient from 8.4 MV/m to 10.3 MV/m. This result indicates it is possible to design a dielectric loaded high pressure cavity with an average accelerating gradient of 20 MV/m while maintaining a surface field on alumina below 17.5 MV/m.

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