HIGH POWER TESTS OF ALUMINA IN HIGH PRESSURE RF CAVITIES FOR MUON IONIZATION COOLING CHANNEL*

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Abstract

As an integral part of our proposed muon ionization cooling channel we aim to use high-pressure gas-filled RF cavities partially loaded with dielectric material to reduce the radial size at a given frequency. A first experiment has been conducted to investigate surface breakdown of an alumina ceramic embedded into an existed 800 MHz high-pressure test cavity. The configuration for this experiment attempts to maximuze the field parallel to the surface of the dielectric. It was found that the dielectric could withstand a surface electrical field of 14 MV/m while in the cavity filled with 1000 psi N2 gas. This document will discuss the concept, design, and latest experimental results.

INTRODUCTION

Many in the high-energy physics community consider it necessary to build a lepton collider in order to tune measurements of the Higgs boson, and to study possible physics beyond the standard model. Although there are several contenders for the position of the new lepton collider, a muon collider is the most compact and offers the highest COM energy [1]. However, there are several obstacles preventing the realization of a muon collider. One of the greatest challenges is the process of muon beam cooling.

High-pressure gas cavities will be utilized in muon ionization cooling schemes. The current cooling design also requires these RF cavities to be inserted into a helical lattice contained inside strong solenoids producing magnetic fields of 5–15 T [2]. It will therefore be beneficial to reduce the radial size of the cavities. A proposed method of reducing the radial size of the RF cavities at a given frequency is to insert a dielectric material into the cavity. Eq. 1 gives the resonance frequency for the (TM_{010}) mode of a pillbox cavity. A material with dielectric constant 9.6 will allow for a reduction in radius of about 3 for a fully filled cavity. Under the current proposal the cavity will not be filled with dielectric. The aim is to reduce the radial size of the cavity by about 1.4.

However, dielectric materials tends to cause a surface breakdown in vacuum cavities. Since high-pressure hydrogen gas has been shown to inhibit breakdown events for RF cavities in strong magnetic fields, it is believed that surface breakdown will also be inhibited in a ceramic-loaded cavity. In fact, this technique has been applied for a high power RF window [3].

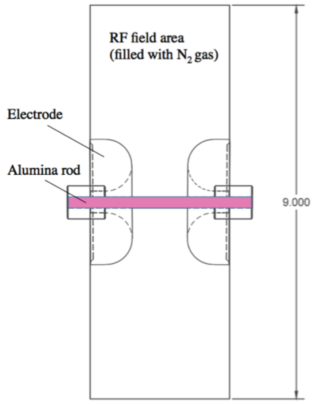

Figure 1: Cross-sectional view of designed RF test cell.

The concept has been experimentally validated at Fermilab. This document will discuss the recent experimental results for a high-pressure RF cavity partially filled with alumina.

DESIGN TEST CELL

A pillbox RF cavity that is filled with dielectric admits a simple solution for the accelerating mode (TM_{010}) as given by

$$\omega_{010} = \frac{2.405}{R\sqrt{\mu\epsilon}}, \tag{1}$$

where μ, ϵ, and R are the permittivity, permeability and a radius of the pillbox, respectively. However, a cavity that is partially filled with a dielectric material no longer admits such a simple pillbox solution. In particular, the positioning of the material inside the cavity, as well as the materials dimensions will contribute to the shift in resonance frequency of the cavity. Therefore, 2D RF simulator `SUPERFISH` [4] has been utilized to predict the resonant frequency in our partially filled dielectric test cell (TC).

Figure 1 shows the cross-sectional view of the designed TC. The ceramic used is a high-purity alumina rod, which has been inserted through the electrodes along the cavity axis. The parameters used for alumina in the simulation are shown in Tab. 1 as given by the vendor.

The RF electrical field in the TC is plotted in Figure 2. Electric field magnitudes are given normalized to a value

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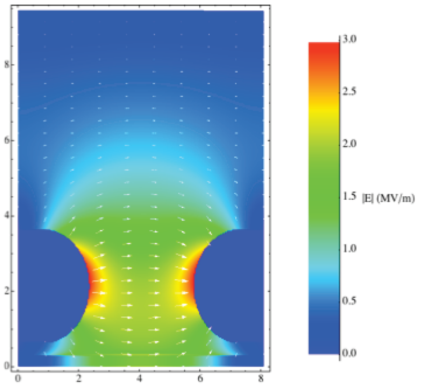

Figure 2: RF electric field for the TC with a dielectric material. Because of symmetry only the top half of the test cell was simulated in `SUPERFISH`. The simulated field for the TC with a dielectric material. Because of symmetry only the top half of the test cell was simulated in `SUPERFISH`. `MATHEMATICA` used for above plot.

of 1 MV/m along the z-axis of the TC. Red (blue) shows region of high (low) electric field magnitudes. Although wall and electrode segments have higher maximum electric field magnitudes than the dielectric fact, previous tests (without dielectric alumina) have shown that high-pressure hydrogen and nitrogen are capable of preventing electric breakdown for fields up to 60 MV/m even when the TC is in a magnetic field of 3 T [5, 6, 7]. Indeed, maximum achievable surface field was limited by the property of the electrode material. In case of copper electrode, the breakdown limit is 50 MV/m. The goal of this test was to sustain a surface field of no higher than the previously mentioned dielectric strength of alumina (16.7 MV/m) [8]. It was therefore expected that the higher field magnitude along the electrodes would not be an issue.

Figure 3 shows the calculated magnitude of the electric field in longitudinal and radial directions along wall segments of alumina rod. Around the center of the TC the electric field is parallel to the surface. The peak parallel field is 2.05 MV/m in this calculation. Although the field drops off moving away from the center of the TC, it is above 2.0 MV/m for a centimeter in length from 3.5 to 4.5 cm. The parallel field maintains 95% of its maximum value for nearly 2 cm along the length of the alumina rod.

Table 1: Specification of Tested Alumina (Al_2O_3) Rod

Property	Value	Unit
Length	4	inch
Width	0.25	inch
Purity	99.8	%
Relative dielectric constant	9.6	
Loss tangent	10^{-4}	
Dielectric strength	16.7	MV/m

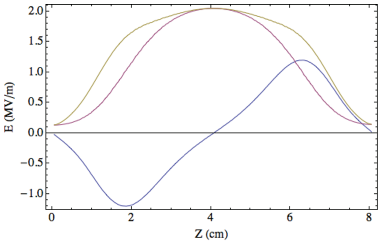

Figure 3: RF electric field strength along surface of alumina rod with a peak field gradient 2.05 MV/m. Magenta and blue lines are the longitudinal and radial components, respectively. The yellow line shows the total field strength.

Figure 4: Top plate of the TC with 'donut' electrode. Am RF power coupler is shown at 5 o'clock. There are two RF pickup antennas (1 and 10 o'clock). A gas inlet is shown at 7 o'clock. Three small holes are an optical feed through.

The radial field reaches its largest value of 1.2 MV/m under the curved part of the electrode. We made an attempt to keep this field small, but it is not expected that the radial electric field will be the main breakdown mechanism in this experiment.

The connection between the metallic bodies and alumina rod was also considered carefully in the design. An electrode with a 'donut' shape was used to shield the triple junction created from the meeting of the copper, alumina, and gas from high electric fields. By using this shape, the field strength at the junction was kept to around 5% of the peak field gradient. Metallic bonds between materials were avoided to prevent interference with the resonance condition. Additionally, there was no surface treatment on the tested alumina rod.

EXPERIMENT AND RESULT

Figure 4 shows the assembled electrode on the top plate of the TC, which incorporates a coaxial RF input power coupler, two pickup antennas, three small ports for optical diagnostics and one port for the gas inlet.

During experiments - once the klystron frequency was tuned to the resonance frequency - about 100 RF pulses were sent to the TC to make sure that there was no breakdown. RF pickup and optical signals were recorded with a fast digital oscilloscope at each fixed RF gradient. The RF gradient was ramped up in steps of 0.5 MV/m. The reason for such a rather fine increase was to avoid any per-

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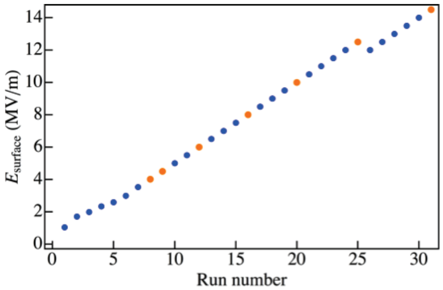

Figure 5: History of peak RF surface gradient search of the alumina rod. A blue point indicates the peak E_{surface} with no optical signal while an orange one indicates the peak E_{surface} with strong lights observed in the TC.

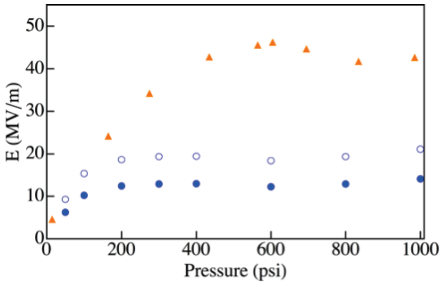

Figure 6: Measured maximum electric field as a function of N2 gas pressure. An orange point is taken in 2009 [7]. An open blue circle is the estimated peak electric field in the TC (protrude of copper electrode). A closed blue circle is the peak electric field on surface of the alumina rod.

manent damages to the alumina rod. For the same reason, the klystron gradually turned on to slowly induce RF fields in the TC. The klystron was operated with 0.5 Hz repetition rate. Forward and reflected RF power were observed routinely during the test.

Fig. 5 shows the evolution of the peak RF field on the alumina during the experiment runs. No sparks were encountered below 4 MV/m. We observed a couple of unusual breakdown events at E_{surface} = 4, 4.5, and 6 MV/m, respectively. Hereby, the RF surface field could not reach its maximum value as some amount of RF power was consumed for the light emission process. These breakdown events resembled multipacting phenomena although we never experienced multipacting in gas-filled RF cavities. Further investigation is needed to understand the mechanism of these events. Interestingly, this breakdown process disappeared at higher RF fields. Instead, we observed an ordinary breakdown event at E_{surface} = 8 MV/m. The RF pickup signal dropped suddenly, while the optical signal went up rapidly. Conditioning for about 30 minutes was required at this field level to recover the TC and further increase the field level. There were similar breakdown events at 10 and 12 MV/m. At 12 MV/m we conditioned the cavity for a time of 2.5 hours at a RF repetition rate of 10 Hz. The resonant frequency was in stable during this time implying that the permittivity of the alumina stays constant. Afterwards, we challenged to obtain the breakdown limit of alumina, but met severe breakdown events at 14.5 MV/m. We conclude that the maximum peak surface field encountered is 14 MV/m.

Finally, we measured the maximum achievable RF field as a function of the N2 gas pressure as shown in Figure 6. The peak field in the TC (open blue circles) is compared with the maximum RF field measured in the past, i.e. without the ceramic rod in the TC (orange triangles). Both curves agree well in the lower pressure regime (200 psi). It suggests that the breakdown process is managed by the gas. However, the breakdown mechanism seems to change at gas pressures beyond 200 psi, when the maximum peak field becomes independent from the gas pressure. In this regime, the maximum sustainable field should be associated with the material property of the alumina rod. Being short by about 2.7 MV/m grants further investigations.

SUMMARY

The surface breakdown process of alumina in an existing high-pressure gas-filled RF cavity was studied experimentally. We encountered a limit in the sustainable surface peak field, which corresponds to 84 % of the breakdown strength of the material used. However, the dielectric strength values vary based on alumina purity and vendor. The cavity could be recovered several times even after observing severe breakdown phenomena at lower field levels, the nature of which are not fully understood. We also investigated the gas pressure dependence and found that the maximum sustainable field agrees well with past measurements. The results suggest that the surface breakdown on a dielectric material exposed to high fields in an RF cavity can be managed by filling the cavity with a high-pressure gas.

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