BEAM TEST OF A DIELECTRIC LOADED HIGH PRESSURE RF CAVITY 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. Three 99.8% alumina tubes will be inserted in a high pressure RF test cell and subjected to an intense proton beam at the MuCool Test Area at Fermilab. The goal of the test is to demonstrate an average accelerating gradient of 20 MV/m, required for the Helical Cooling Channel, and to study how the presence of alumina affects the plasma evolution and loading.

INTRODUCTION

High power tests of a dielectric loaded high pressure gas filled normal conducting radio frequency (DLHPRF) cavity have shown that a torus of 99.8% alumina induces breakdown when the surface field reaches 14.8 MV/m at 20 atm of nitrogen [1]. A torus is not an ideal design for a DLHPRF cavity, as for a simple pillbox geometry, the region of peak electric field is on the inner curved surface of the dielectric. A simpler design, that of a tube, is shown in Figure 1.

Figure 2 shows the electric field distribution for the geometry shown in Figure 1. The maximum field on the surface of the alumina is 47% that of the maximum field in the cavity, which is a significant improvement over the torus design. Table 1 lists the ratios of the peak electric field on the surface of the alumina to the average accelerating gradient for the torus and tube designs.

EXPERIMENT

A tube geometry for the alumina insert will allow an average accelerating gradient of 20 MV/m, the design gradient of the Helical Cooling Channel, while maintaining a maximum field on the surface of the alumina below that at which breakdown occurs [2]. An experiment is planned to demonstrate this, as well as investigate the influence alumina has on the plasma interaction and loading of the test cell when it is subject to an intense proton beam.

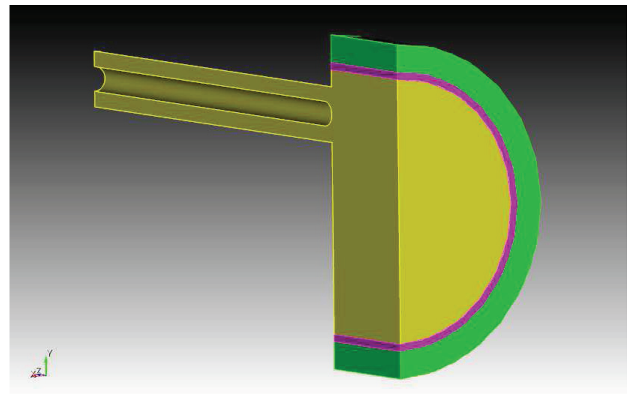

Figure 1: A cartoon of the interior of the high pressure test cell (including coupler). The volume filled with nitrogen gas (green and yellow) and alumina tube (magenta) are shown.

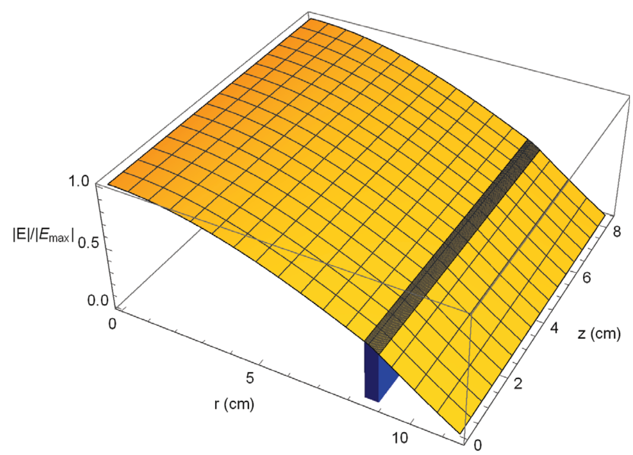

Figure 2: Normalized electric field distribution for the high pressure test cell loaded with an alumina tube. The shaded blue region indicates the area the alumina occupies.

A beam test at the MuCool Test Area at Fermilab of a high pressure gas filled RF test cell has been performed, and the effect of the resultant plasma on the performance of the cavity quantified [3]. A similar beam test is planned for the DLHPRF test cell, with beam and cavity parameters listed in Table 2.

NITROGEN GAS PHYSICS

A high energy beam passing through a gas filled RF cavity will ionize the gas, creating a plasma along the beam

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

Ratio	Torus	Tube
$\lvert E\rvert_{alum}/\lvert E\rvert_{acc}$	1.76	0.47
$\lvert E\rvert_{Cu}/\lvert E\rvert_{acc}$	1.10	1.00
$\lvert E\rvert_{alum}/\lvert E\rvert_{Cu}$	1.60	0.47

Table 2: DLHPRF Beam Test Parameters

Parameter	Unit	Value
Beam pulse length	μs	7.5-9.5
Microbunches per pulse		1500-1900
Protons per microbunch		2.1E8
RF pulse length	μs	40
RF electric field	MV/m	5-25
Nitrogen gas pressure	atm	2-70
Oxygen concentration	%	0-5

path within the cavity. Measurements in nitrogen gas have previously been made for the amount of energy dissipated per charged particle pair and the recombination rate of electrons with ions, as well as the electron attachment time to oxygen and the ion-ion recombination rate in oxygen doped nitrogen using the high pressure test cell [3, 4]. The plasma dissipates energy from the cavity, and it is therefore crucial to neutralize it as quickly as possible. Three processes contribute to this: recombination of electrons with nitrogen ions (slow), attachment of electrons to oxygen molecules (fast), and recombination of oxygen ions with nitrogen ions (very slow).

Figure 3 shows measurements of the plasma processes relevant for pure nitrogen gas: the recombination rate (β) of electrons with nitrogen ions, and the energy dissipation (dw) per RF cycle per charged particle pair, in this case electrons and nitrogen ions, as a function of electric field amplitude. Note the electric field at which the recombination rate data were collected is ~100 times smaller than that of the energy dissipation data, and that the recombination rate falls with field, meaning the majority of recombination occurs near the zero crossings of the electric field.

Figure 4 shows measurements of the plasma processes relevant when nitrogen gas has been doped with oxygen: the attachment time (τ) of electrons to oxygen molecules, and the energy dissipation per RF cycle per charged particle pair, in this case a combination of electrons and nitrogen and oxygen ions, as a function of the concentration of oxygen. At oxygen concentrations approaching 1%, the lifetime of an electron falls below 1 ns, and the energy dissipation is almost entirely due to ions.

These results indicate doping nitrogen with oxygen is very beneficial to the plasma loading in the cavity.

Breakdown measurements of an alumina torus in the high pressure test cell filled with pure nitrogen and nitrogen doped

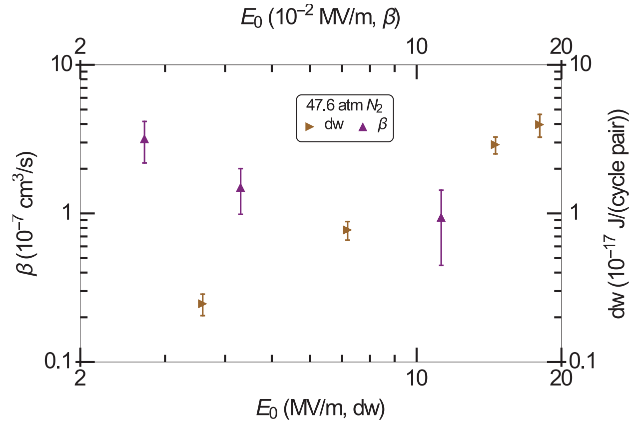

Figure 3: Recombination rate of electrons with nitrogen ions and energy dissipation per charged particle pair per RF cycle as a function of electric field amplitude. The error bars represent the statistical uncertainty for β, and the statistical and systematic uncertainty for dw.

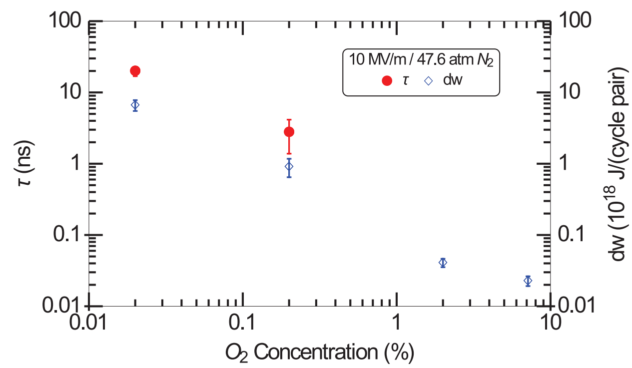

Figure 4: Attachment time of electrons to oxygen molecules and energy dissipation per charged particle pair per RF cycle as a function of oxygen concentration. The error bars represent the systematic uncertainty for τ, and the statistical and systematic uncertainty for dw.

with oxygen or sulfur hexafluoride have also been taken [1]. Figure 5 shows the results.

For the cases of pure nitrogen, or nitrogen doped with oxygen, the gradient at which the cavity breaks down follows the Paschen curve for nitrogen well at pressures up to 10 atm. Above 10 atm, the maximum electric field on the surface of the alumina becomes the limiting factor to the achievable gradient in the cavity. At 20 atm and above, the surface field plateaus, with the average values given in Table 3.

Within the statistical uncertainty of the measurement, there is no discernable dependence on the dopant concentration or species of the maximum surface electric field on the alumina. So while doping nitrogen with oxygen mitigates plasma loading, it does not appear to improve the breakdown limit imposed by the alumina.

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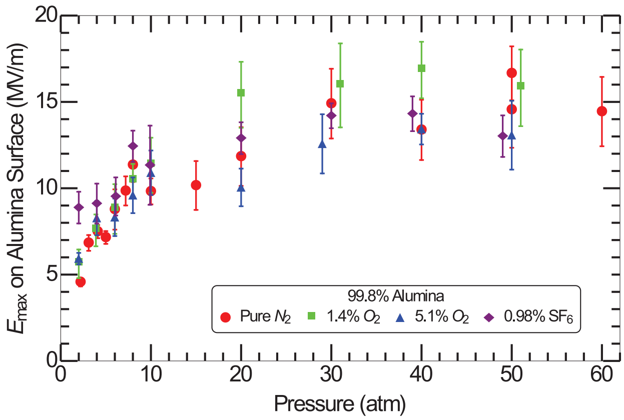

Figure 5: Maximum electric field on the surface of the 99.8% alumina torus as a function of gas pressure for pure nitrogen, and nitrogen doped with oxygen or sulfur hexafluoride. The error bars represent the statistical uncertainty.

Table 3: Average Electric Field on the Surface of the Alumina Torus Above 20 atm for Which the Test Cell Experienced Breakdown

Gas Combination	E (MV/m)
N_2	14.8
N_2 + 1.4% O_2	16.2
N_2 + 5.1% O_2	13.0
N_2 + 0.98% SF_6	13.8

CONCLUSION

A simple alumina tube geometry should allow a high pressure gas filled normal conducting pillbox RF cavity loaded with a dielectric to operate at the design average accelerating gradient of the Helical Cooling Channel, 20 MV/m, without inducing breakdown due to the electric field on the surface of the alumina. A beam test at the MuCool Test Area at Fermilab is planned in order to demonstrate this performace, as well as compare the plasma processes in the presence of the alumina tube to those without it. The results garnered should validate the use of dielectric loaded high pressure RF cavities for use in gas filled muon cooling channels.

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