DIELECTRIC LOADED HIGH PRESSURE GAS FILLED RF CAVITIES FOR USE IN MUON COOLING CHANNELS*

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Abstract

High brightness muon beams require significant six dimensional cooling. One cooling scheme, the Helical Cooling Channel, employs high pressure gas filled radio frequency cavities, which provide both the absorber needed for ionization cooling, and a means to mitigate RF breakdown. The cavities are placed along the beam's trajectory, and contained within the bores of superconducting solenoid magnets. Gas filled RF cavities have been shown to successfully operate within multi-Tesla external magnetic fields, and not be overcome with the loading resulting from beam-induced plasma. The remaining engineering hurdle is to fit 325 and 650 MHz single cell pillbox cavities within the bores of the magnets using modern technology while minimizing the peak RF power per unit length. Partially filling the cavities with a dielectric material and making them slightly reentrant accomplishes the goal of fitting shrinking the diameter of the cavities. Alumina (Al_2O_3) is an ideal dielectric, and the experimental test program to determine its performance under high power in a gas filled cavity has concluded.

INTRODUCTION

Muon cooling channels based on ionization cooling have been studied extensively over the past decade and a half. Maximizing cooling efficiency dictates strong magnetic fields (>1 T) at the location of absorbers within the cooling lattice. Radio frequency cavities are used to replace the longitudinal energy lost in the absorbers, and are therefore subject to strong magnetic fields as well. Early studies immediately observed degredation in the accelerating field of traditional vacuum cavities in magnetic fields up to 5 T [1,2].

To mitigate breakdown induced by external magnetic fields, the idea of filling cavities with a high pressure gas was introduced [3]. Given a suitable choice of gas (i.e. hydrogen), this has the additional benefit of providing the cooling medium. Such a technique has been shown to mitigate breakdown [4].

A beam traversing a gas filled RF cavity will ionize the gas, and the resulting plasma serves as a mechanism to transfer energy from the cavity to the gas; known as plasma loading. Experiments were performed to characterize the relevant processes in such an environment [5,6]. The results have been used to simulate and predict the amount of plasma loading in a cooling channel based on gas filled cavities, which steers the design parameters [6,7]. Plasma loading is believed to be manageable for the beam intensities envisioned to meet the luminosity requirements for a muon collider.

HELICAL COOLING CHANNEL

The cooling scheme based on gas filled RF cavities is the Helical Cooling Channel (HCC) [3]. The HCC provides six dimensional cooling through ionization cooling (for which hydrogen gas is the cooling medium) and emittance exchange. This is accomplished by placing gas filled cavities within the bores of superconducting solenoid magnets, and arranging them in a helix. The helix is in turn placed within a larger, external solenoid, and the magnet system provides the necessary B_ϕ, B_z and dB_ϕ/dr field components.

Three dimensional and cross sectional views of the HCC are shown in Figs. 1 and 2. Optimization of the magnet and RF cavity parameters remains to be done, which will be described in more detail in the following sections.

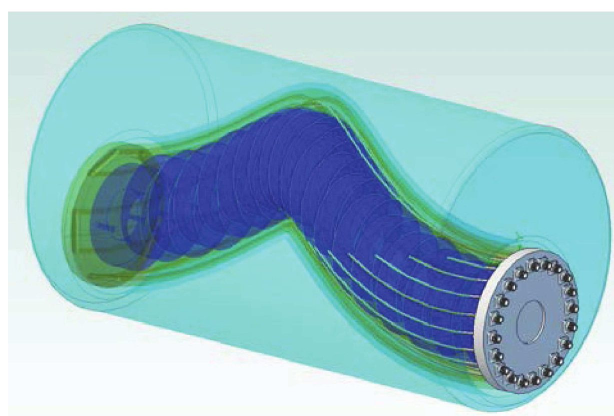

Figure 1: Three dimensional view of one cooling cell of the HCC utilizing dielectric loaded high pressure gas filled cavities [8].

Magnets for the HCC

The Helical Cooling Channel is divided into sections, each with a higher magnetic field than the previous. The early and middle sections utilize either NbTi or YBCO tape, and prototypes have been modeled and fabricated [9–11]. Higher field sections require Nb_3Sn, which presents the additional complication of requiring a reaction cycle to a temperature of 650 °C, limiting the material choice for coil support. A collaring concept was introduced to address this, mechanical

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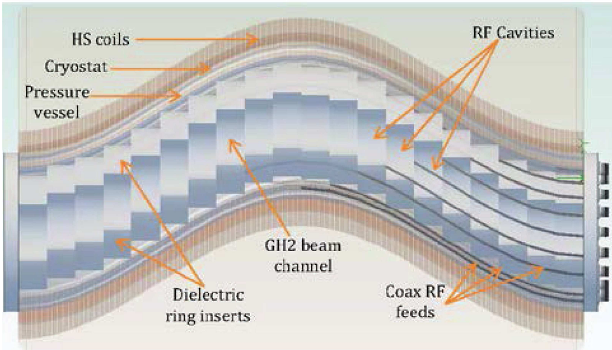

Figure 2: Cutaway view of one cooling cell of the HCC utilizing dielectric loaded high pressure gas filled cavities. The helical solenoid coils, cryostat, pressure vessel, RF cavities, and coaxial RF power feeds are all shown [8].

stress analyses were performed, and a model coil made of copper was wound on an acrylic support [12].

A three dimimensional view of the coil configuration is shown in Fig. 3 and Table 1 lists the parameters for each of the six cooling channel sections.

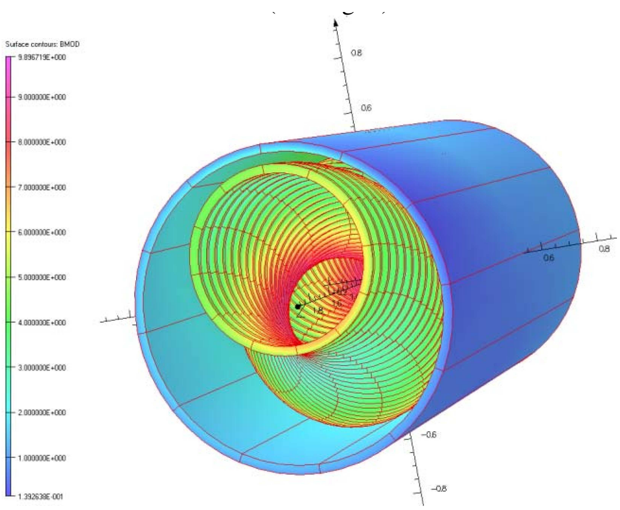

Figure 3: Coil configuration in the HCC. The helical solenoid and outer straight solenoid are shown, with flux density [13].

Table 1: Design Parameters for the HCC Sections [14]

Section	f	λ	B_ϕ	dB_ϕ/dr	B_z
Units	**MHz**	**m**	**T**	**T/m**	**T**
1	325	1.0	1.29	-0.50	-4.25
2	325	0.9	1.43	-0.62	-4.73
3	325	0.8	1.61	-0.79	-5.32
4	650	0.5	2.58	-2.01	-8.51
5	650	0.4	3.22	-3.14	-10.63
6	650	0.3	4.30	-5.58	-14.18

RF Cavities for the HCC

There are two considerations driving the design of the RF cavities for the Helical Cooling Channel: size restrictions, and power consumption. The cavities, along with the associated instrumentation and plumbing, must fit within the cryostat of the helical solenoids. (Note that room temperature operation is assumed.) Additionally, the peak power per unit length must be kept as small as possible to minimize cost.

There are two methods to address the first issue. Loading the cavities with a dielectric will shrink the cavity diameter for a given frequency. This has the advantage of providing the entire length of the cavity for acceleration, and the disadvantage of increased power consumption due to dielectric losses. Introducing nose cones on each side of the cavity, which enhance the electric field and increase the capacitance, can alternatively be used to shrink the diameter for a given frequency. This method has the advantage of reducing the peak power per cavity, and the disadvantage of reducing the active length of the cavity and increasing the peak electric field within the cavity.

Table 2 lists the physical parameters for the RF cavities in the first five sections of cooling channel based on magnet bore constraints.

Table 2: HCC RF Cavity Parameters [14]

Section	f	Radius	Length
Units	**MHz**	**cm**	**cm**
1	325	28.02	7.73
2	325	28.02	6.90
3	325	28.02	6.07
4	650	14.01	3.57
5	650	14.01	2.73

TESTS OF DIELECTIC LOADED HIGH PRESSURE CAVITIES

The 805 MHz test cell that was used for past breakdown and beam tests [4–6] was refit in order to study the performance of configurations with an alumina insert [15]. Several torus-shaped alumina inserts of varying purity were fabricated and tested to determine their dielectric strength. Figure 4 shows a fieldmap of the normalized electric field within the cavity and Fig. 5 shows the results of the surface field on the alumina at which sparking occurred in the cavity.

The concept of this design was to minimize the amount of dielectric needed by placing it in a region of larger electric field as compared to a simple tube at a larger radius. Unfortunately the design accelerating gradient of 20 MV/m was not achievable in this configuration. Small electrodes were added on axis, making the cavity slightly reentrant and redistributing the electric field so that its peak was located on the tip of the electrodes, in an effort to increase the accelerating gradient. The results are shown in Fig. 6.

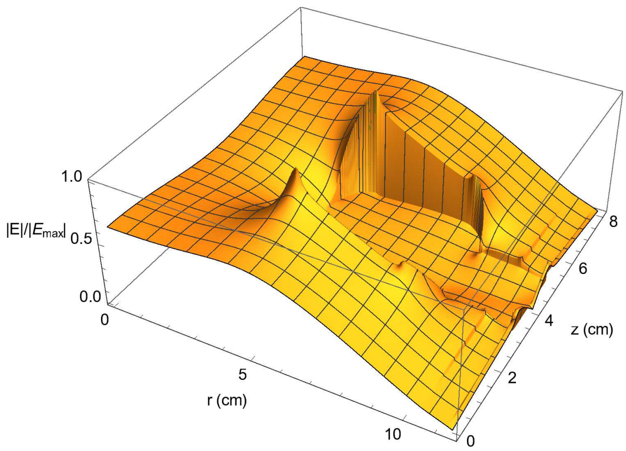

Figure 4: Electric field map for the dielectric loaded high pressure test cell [15]. The plot has been normalized to the maximum electric field, which occurs at the interior rounded surface of the alumina. The r = 0 line corresponds to the longitudinal axis of the cavity.

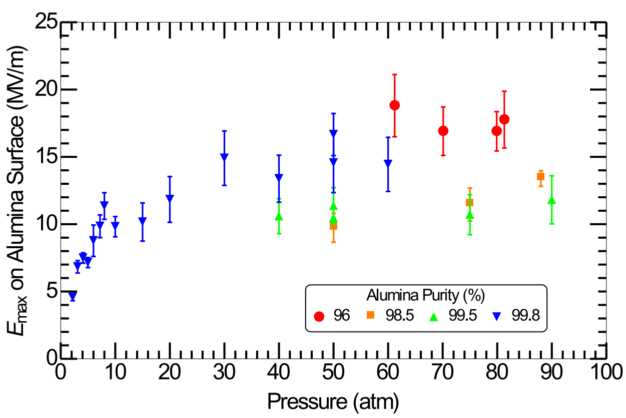

Figure 5: Electric field on the surface of the alumina torus at which sparking occurred as a function of nitrogen gas pressure [15]. The error bars represent the standard deviation of the measurements.

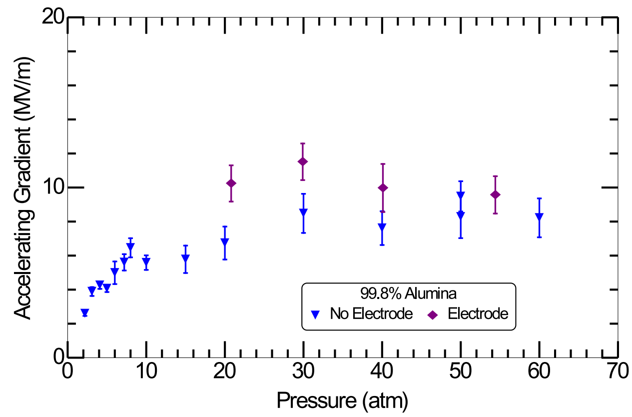

Figure 6: Average accelerating gradient at which sparking occurred as a function of pure nitrogen gas pressure, for the case of with and without copper electrodes [15]. The error bars represent the standard deviation of the measurements.

The addition of electrodes improved the average accelerating gradient from 8.4 MV/m to 10.3 MV/m. This indicates that optimizing the cavity and insert geometry would allow the use of alumina to shrink the diameter of cavities without inducing breakdown.

Two inserts of a simple tube geometry made of 99.8% alumina were procured and tested under high power in the high pressure test cell. The results of these tests were inconclusive, as there was sparking observed in the region of the RF (coaxial) coupler due to the close proximity (< 5 mm) of alumina to the inner conductor. This must be taken into consideration for future designs.

CONCLUSION

Breakdown studies of a high pressure gas filled RF cavity loaded with a dielectric have demonstrated the peak surface electric field an alumina insert can withstand before inducing breakdown. The addition of small electrodes improved the accelerating gradient, while maintaining the peak surface field on the alumina. This indicates that a combination of dielectric loading and reentrant cavity design should be sufficient to satisfy the physical constraints based on superconducting magnet bore size and minimize power consumption, without degrading the performance of the cooling channel.

Measurements of the loss tangent of commercially produced 99.5 and 99.8% alumina are in the 10^{-5} range [16], while that of ultralow loss TiO_2 doped polycrystalline alumina has been measured in the 10^{-6} range [17]. A paper study on the optimization of the unloaded quality factor and shunt impedance of a dielectric loaded accelerating structure operated at 5.7 GHz in the TM_{02} mode demonstrated an improvement by about a factor of 10 in Q_0 and several in shunt impedance over a similar conventional acclerating structure [18]. It was shown that decreasing the loss tangent from 10^{-5} to 10^{-6} improved both by almost a factor of two, as well. This is encouraging for the prospects of dielectric loaded high pressure gas filled cavities for use in muon cooling channels. Future work will focus on optimizing the design of the RF cavity and alumina insert to minimize power consumption.

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