RF CAVITIES LOADED WITH DIELECTRIC FOR MUON FACILITIES *

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Abstract

This report discusses RF cavities loaded with dielectric that could be used in various ways for muon facilities. The examples given are for 400 and 800 MHz cavities. Our initial motivation was to use dielectric to reduce the radial size of gas-filled cavities in helical cooling channels, but dielectric might also be useful in vacuum cavities for suppression of dark current emission. We also studied cavities that can be used for the phase rotation channel in the front end of a muon collider or neutrino factory.

INTRODUCTION

For construction of compact and hence efficient helical cooling channels (HCC), the space available for RF cavities is limited. Based on his simulations, Balbekov [1] has suggested a relationship between the radial size of the coils in a HCC and the maximum RF frequency that can be used to contain the beam longitudinally. For a channel that uses 400MHz, the largest gas-filled cavity that will fit inside a coil has a radius of 16 cm, and the beam radius is 6 cm [2]. The required electric gradient is 16 MV/m. The channel would benefit from near-continuous acceleration. The conventional way of making the cavity radius smaller is to make the cavity re-entrant, but in that case there is a large drift space without accelerating field, reducing the average accelerating gradient.

Here we take a different approach. The standard formula for the resonant frequency of a pill box cavity filled with dielectric of relative permittivity ε_r and relative permeability μ_r is given by

$$\omega = \frac{2.405c}{R\sqrt{\varepsilon_r \mu_r}}$$

This suggests that the cavity radius can be made smaller for a given resonant frequency if part of the cavity volume is filled with dielectric or magnetic material. For the HCC, magnetic material is not an option: the strong magnetic fields will be distorted, and most of the magnetic material would be brought into saturation and lose its desired magnetic property. Also, magnetic materials are lossy at RF frequencies. So the only viable option is dielectric material. Once the cavity is loaded with dielectric, the quality factor Q and RF power loss in the cavity will be changed. The Q for a cavity loaded with dielectric is given by

$$\frac{1}{Q} = \frac{1}{Q_{wall}} + \frac{1}{Q_{diel}}, \quad \text{where} \quad Q_{diel} = \frac{\varepsilon'}{\varepsilon''} = \frac{1}{\tan\delta}$$

These relations are derived below:

The quality factor Q is defined as the energy stored W divided by the power loss per cycle P_{loss}/ω

$$Q = \frac{\omega W}{P_{loss}}$$

For the vacuum cavity, power is lost on the conducting walls. For a cavity filled with lossy dielectric, power is also lost inside the dielectric. So $P_{loss}=P_{wall}+P_{diel}$. Then

$$\frac{1}{Q} = \frac{P_{wall}+P_{diel}}{\omega W} = \frac{1}{Q_{wall}} + \frac{1}{Q_{diel}}$$

To calculate Q_{diel}, starting from the definition of the stored energy: $D = (\varepsilon' - i\varepsilon'')E$, the stored energy is

$$W \equiv W_E = \Re e \frac{1}{2}\int E \cdot D^* dV = \frac{\varepsilon'}{2}\int E \cdot E^* dV .$$

The power transferred across a closed surface is

$$P = \Re e \frac{1}{2}\oint_S E \times H^* dS, \quad B = (\mu' - i\mu'')H \text{ then from}$$

Stokes theorem

$$\oint_S E \times H^* dS = \int_V \nabla(E \times H^*) dV =$$
$$\int_V (\nabla \times E) H^* dV - \int_V (\nabla \times H^*) E dV$$

For a steady-state field varying sinusoidally with time, Maxwell's equations are

$$\nabla \bullet D = \rho \quad \nabla B = 0, \ \nabla \times E = -i\omega B,$$
$$\nabla \times H = i\omega D + J, \ J = \sigma E$$

So the real part of the above equation (for the power flow inside so that vector dS is –dS) is

$$P = \Re e \frac{1}{2}\oint_S E \times H^* dS =$$
$$\frac{\omega}{2}\int_V (\mu'' H H^* + \varepsilon'' E E^*) dV + \frac{1}{2}\int \sigma E E^* dV$$

Assuming that there are no free charges and that the material is a pure dielectric, the power that flows through the surface S in volume V that is dissipated in the dielectric is

$$P_{diel} = \frac{\omega \varepsilon''}{2}\int_V E E^* dV .$$

So the quality factor for the dielectric piece is inversely proportional to the loss tangent:

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$$Q_{diel} = \frac{\omega W}{P_{diel}} = \frac{\omega \frac{\varepsilon'}{2} \int E \cdot E^* dV}{\frac{\omega \varepsilon''}{2} \int_V EE^* dV} = \frac{\varepsilon'}{\varepsilon''} = \frac{1}{\tan \delta}.$$

The wall Q factor is calculated in the usual way using the power loss on the walls. From the above equation, it is clear if the loss tangent is of order 10^{-4}, a cavity loaded with ceramic will have acceptable Q and RF power losses.

To reduce the cavity radius significantly and control the RF power loss in the cavity, a dielectric material that has large dielectric constant and low loss tangent is required. As an example of a dielectric that has the desired properties, we have considered AL-995, a ceramic material from Morgan Crucible Company.

400 MHZ CAVITY FOR HCC

First we calculate the geometry for a 400-MHz cavity that will fit in a HCC as shown in Figure 1. The present design. of this HCC calls for the gas-filled cavity to have an outside radius of 16cm, a beam radius of 6cm and an optimal gradient of 16 MV/m. We assume that AL-995 Alumina ceramic will be used and that the outside cavity wall has to be 1cm thick to sustain high gas pressure. So the cavity has an inner radius of 15.1cm. The result is that the ceramic cylinder has an inner radius of 8.8cm for a frequency of ~400MHz. In the calculations, the field is normalized to 16MV/m. The small drift tube is included to be able to separate cavities and introduce cooling of the external walls.

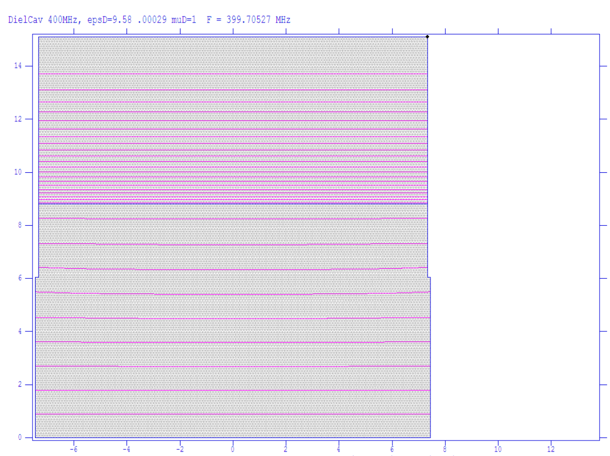

Figure 1: 400MHz cavity with dielectric insert.

Table 1. SuperFish output for 400MHz run.

Freq(MHz)	399.7	StoredEnergy(Joul)	26.58
Q	6284	ZTT(MOhm/m)	3.1
PowerTotal(MW)	10.62	Emax(MV/m)	18.5
PowerWall	8.89	HMax(kA/m)	93

800 MHZ CAVITY FOR HCC

Next we calculate the geometry for an 800-MHz cavity that will fit in its corresponding HCC as shown in Figure 2. According to the present design, this channel calls for the gas-filled cavity to have an outside radius of 8cm, a beam radius of 3cm and optimal gradient of 16MV/m. We assume that AL-995 Alumina ceramic will be used and that the outside cavity wall has to be 0.5 cm thick to sustain high gas pressure. So the cavity has a radius of 7.4cm. The Superfish output shows that for a frequency of ~800 MHz, the ceramic cylinder has an inner radius of 4.4cm. In the calculations, the field is normalized to 16 MV/m. As before, the small drift tube is included to be able to separate cavities and introduce cooling of the external walls. Table 2 summarizes the basic parameters.

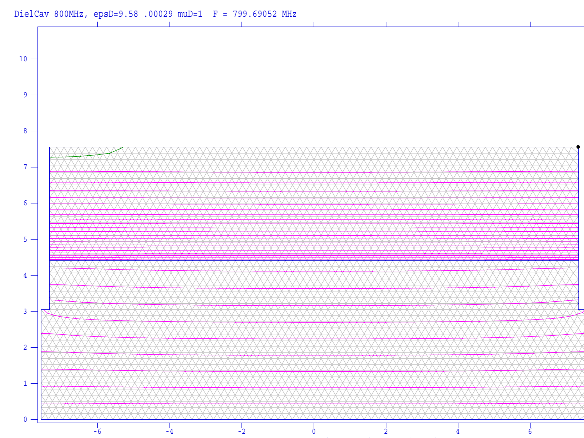

Figure 2. SuperFish output for 800MHz cavity with ceramic insert and short drift tube

Table 2. 800MHz example, SuperFish calculated parameters.

Freq(MHz)	799.7	StoredEnergy(Joul)	6.8
Q	5474	ZTT(MOhm/m)	3.5
PowerTotal(MW)	6.28	Emax(MV/m)	17.9
PowerWall(MW)	5.4	HMax(kA/m)	95

For comparison SuperFish output is presented here for a pill box cavity without ceramic. Table 3 summarizes the basic parameters. In this case the cavity radius is 29 cm. Note the considerable difference in radius compared to a dielectric-loaded cavity.

Table 3. Pure pill box, 800MHz parameters.

Freq(MHz)	801	StoredEnergy(Joul)	6.8
Q	15000	ZTT(MOhm/m)	10
PowerTotal(MW)	3.6	Emax(MV/m)	48
PowerWall(MW)	3.6	HMax(kA/m)	44

RF CAVITY FOR PHASE ROTATION AND MUON CAPTURE

In Neuffer's Phase Rotation Channel[3], ideally the RF frequency is changing continually from 300 to 200MHz, and an average 10MV/m of accelerating gradient is needed to bunch and rotate the muon beam. In most of the channel vacuum cavities are needed, and the whole channel is immersed in a solenoidal field for transverse focusing of the beam. In this channel dielectric cavities can be used to suppress the dark current in the gap as well as having a single size that can achieve a changing frequency by changing the size of the dielectric insert. Figure 3 shows the concept where in the gap the dielectric is interleaved with stainless steel rings to suppress sparking, and the main body of the cavity is filled with dielectric liquid for cooling and fine tuning.

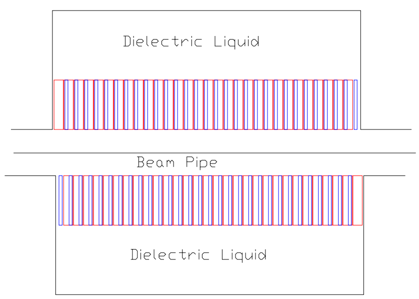

Figure 3: Dielectric Loaded Cavity for Phase Rotation

From these sample calculations it is clear that it will take a large amount of RF power to make a gradient of 16 MV/m in the cavities, so a way to handle power loss in the cavities is needed. In the case of a HCC, it will be natural to run the cavities below room temperature. One option is to run the cavities at liquid nitrogen temperature, noting that the resistance as a function of temperature for copper is given by

$$\rho[n\Omega - m] = 15.4(1 + 0.00451(T[K\} - 273) .$$

This will lower the power loss on the wall by more than a factor of three. The liquid nitrogen can also be used to cool the dielectric. Compare the ferrite-loaded tunable cavities [4], in which dielectric oil is used to cool the ferrite.

The next technical question is whether the dielectric can sustain such a large electric field. For the materials we are considering, a typical dielectric strength is 31 kV/mm for DC voltage. The usual breakdown of ceramic happens on the surface, and it is related with electrons that cascade along the surface. In gas-filled cavities the hope is that pressurized gas will suppress the breakdown in the same way that it suppresses the development of dark currents. That supposition will have to be tested.

CONCLUSIONS AND FUTURE PLANS

We believe that dielectric-loaded cavities are a promising solution for any channel with very strong and continuous magnetic focusing. Experimental and engineering studies are needed to verify this concept.

REFERENCES

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[4] M. Popovic et al, "Compact, Tunable RF Cavities ", Proc. Of EPAC08, p. 802, (2008).