RF CAVITIES LOADED WITH DIELECTRIC FOR MUON FACILITIES *

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Abstract
This paper discusses RF cavities loaded with dielectric material that could be used in various muon collider facilities. Most of the existing pill-box cavity designs are too large in diameter to fit efficiently in the current cooling lattice designs. The paper describes novel compact dielectric loaded RF cavities designs that fit efficiently in muon cooling lattices and allow multi-frequency cavity designs in the same size cavity by changing the dielectric constant or size. The paper describes the designs of 400 and 800 MHz cavities for the (HCC) helical cooling channel. In addition to the use of the dielectric to reduce the radial size of gas-filled cavities in helical cooling channels, dielectric-loading has the potential use in vacuum cavities for suppression of dark current emission. Cavities that can be used for the phase rotation channel in the front end of a muon collider or neutrino factory are also presented.

INTRODUCTION

For the construction of compact and hence efficient helical cooling channels (HCC), the space available for RF cavities is limited. Simulations by Balbekov [1] have shown 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 which reduces the average accelerating gradient.

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 in the HCC will bring most of the magnetic material into saturation and it would lose its desired magnetic property. Also, magnetic materials are very 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

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

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

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

The calculation of Q_{diel}, start from the definition of the stored energy: the stored energy is

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

$$D = (\varepsilon' - i\varepsilon'')E,$$

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

$$\nabla \bullet D = \rho, \ \nabla B = 0, \ \nabla \times E = -i\omega B,$$

$$\nabla \times H = i\omega D + J, \ J = \sigma E$$

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

$$P = \Re e \frac{1}{2} \oint_S E \times H^* dS =$$

$$\frac{\omega}{2} \int_V (\mu'' HH^* + \varepsilon'' EE^*) dV + \frac{1}{2} \int \sigma EE^* dV$$

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

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

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

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

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 inserts 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, tanδ=0.0002.

400 MHZ CAVITY FOR HCC

The geometry for a 400-MHz cavity that will fit in a HCC is shown in Figure1. The present design for the 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. AL-995 Alumina ceramic is used in the simulation. The outside cavity wall has to be about 1cm thick to sustain high gas pressure. The cavity designed for resonance at about 400 MHz has an outside radius of 15.1cm and an inner bore radius of 8.8 cm. 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

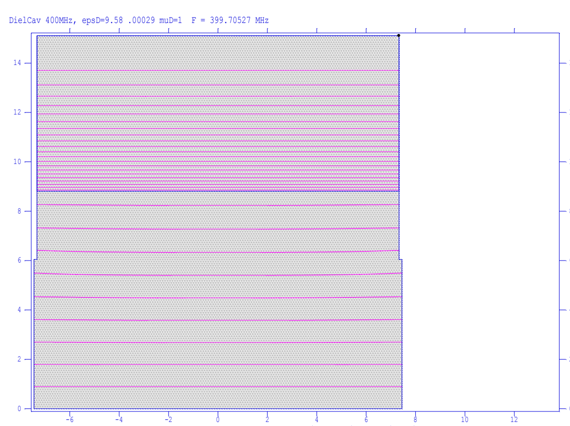

Figure 1: 400MHz cavity with dielectric insert.

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

Table 1. SuperFish output for 400MHz run.

800 MHZ CAVITY FOR HCC

The geometry for an 800-MHz cavity that will fit in its corresponding HCC is 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. In the simulation AL-995 Alumina ceramic is used and that the outside cavity wall has to be about 0.5 cm thick to sustain high gas pressure. This 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.

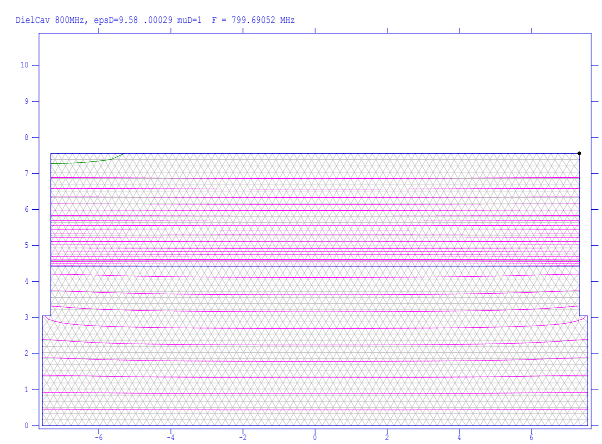

Figure 2. 800MHz cavity with ceramics insert and short drift tube, SuperFish output

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

Table 2. 800MHz example, SuperFish calculated parameters.

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.

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

Table 3. Pure pill box, 800MHz parameters.

RF CAVITY FOR PHASE ROTATION AND MUON CAPTURE

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

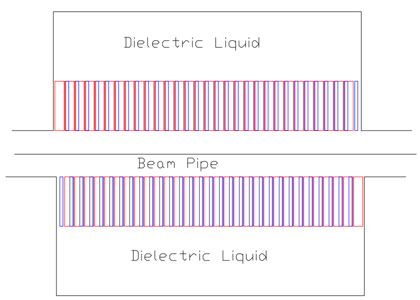

Figure 3: Dielectric Loaded Cavity for Phase Rotation

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, 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 be also used to cool the dielectric. Compare the ferrite-loaded tuneable 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. T

CONCLUSIONS AND FUTURE PLANS

We believe that dielectric-loaded cavities are the correct solution for any channel with very strong and continuous magnetic focusing. It has been shown in Muon Inc studies that that gas-filled cavity prevent breakdown in very high solenoidal magnetic fields. Experimental and engineering studies are needed to verify this concept.

REFERENCES

[1] K. Yonehara and V. Balbekov, Proceedings of EPAC08, Genoa, Italy

[2] K. Yonehara, et al, this conference

[3] D. Neuffer, "'High Frequency' Buncher and Phase Rotation", Proc. NuFACT03, AIP Conf. Proc. 721, p. 407, (2004).

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