Test of Dielectric Materials in RF Cavity for Muon Accelerator

Yiqing Ding*
Purdue University & Fermilab

Abstract

Muon accelerator has been proposed as one of the new generation accelerators in the world due to its distinctive advantage in lowering synchrotron radiation. However, challenges are emerged as well. Muon's short lifetime requires the cooling and acceleration processes to be all accomplished within several milliseconds. An innovative system called Helical Cooling Channel (HCC) is therefore proposed. An HCC consists of a helical solenoid magnet, cooling material and Radio Frequency (RF) cavities. Muons will go through a process called ionization cooling, in which its emittance is reduced in a cooling material via a Coulomb interaction, and then be re-accelerated by RF cavities. The RF system should be small enough to fit into the helical solenoid. The size of RF cavity is restricted by the driving RF frequency. This constraint can be mitigated by inserting a dielectric material in the cavity. However, a surface breakdown on the dielectric material is taken place and it limits the available RF gradient. Putting a buffer gas in the cavity has been proposed to suppress the surface breakdown. A new gas-filled RF test cell has been designed to verify the breakdown suppression model. This design changes overall dielectric constant and thus changes the radius of the test cell. This paper discusses the effects of different dielectric materials and geometries. With a given resonant frequency, cavities with different materials and geometries are modeled in Superfish and those results are further tested in experiments. Several important properties and the realistic design for the cavity are further discussed as well.

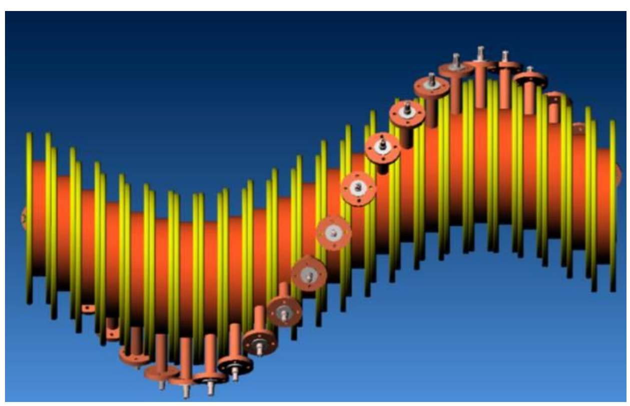
* ding42@purdue.edu

I. Introduction

Muon accelerator has been proposed as one of the new generation particle accelerators. Muon, different from hadrons, is an elementary particle, therefore a muon collider can generate a cleaner collision event between μ^+ and μ^- than hadron colliders. Meanwhile, compared with other leptons like electron, muon has its own distinctive advantage as well. The energy loss of accelerating charges due to synchrotron radiation is proportional to $\frac{E^2}{\rho^2 m^4}$, where E is the energy of the particle, m is mass and ρ is the bending radius. Muon's mass is approximately 221 times of mass of electron, thus muon can significantly reduce the energy loss due to synchrotron radiation. This advantage gives rise to a more compact machine with higher beam energy.

Muon, on the other side, is a tertiary particle and has a lifetime of 2.2 μs in the lab frame. The initial muon beam size is too large to fit into the acceleration system. For such a short lifetime, the muon beam emittance cooling and acceleration processes must all be accomplished within several milliseconds. A process called ionization cooling is proposed for the emittance cooling. All momentum components of muon are first reduced by hitting an energy absorbing material; then muon is re-accelerated through accelerating structures to replenish the lost energy. This process can only shrink the transverse beam emittance. However, the longitudinal beam emittance cannot be cooled down until the transverse emittance is exchanged into longitudinal one. To achieve this exchange, an innovative magnetic channel called Helical Cooling Channel (HCC) is designed (shown in Figure I).

***Figure I**: Integrated HCC cell: Helical solenoid magnets are in yellow, RF cavities are in orange and the vertical cylindrical structures from cavities are RF power couplers*



An HCC consists of a helical solenoid magnet, a continuous Radio Frequency (RF) system, and a homogeneous cooling material in the RF system. Higher (lower) momentum muons will travel longer (shorter) path length in the homogeneous cooling material embedded in the helical magnet. As a result, the amount of energy loss for each individual muon is dependent upon its momentum; this process is the emittance exchange. Because the cooling and emittance exchange take place continuously in the channel, a muon beam is quickly cooled down to the desired emittance [1]. Thus, the HCC structure is required to be very compact compared with the conventional particle accelerating system.

One of the key technical challenges is incorporating RF cavities into the helical solenoid magnet. By inserting a dielectric material in the cavity, the cavity size can be reduced significantly. However, no practical demonstrations for the particle acceleration dielectric loaded RF cavity have been made because the dielectric material induces a surface breakdown process. A gas-filled RF cavity has been proposed to suppress this process. A test cell has been designed and built to verify the concept of this novel RF cavity.

Design, modeling and the plan of testing different types of dielectric loaded cavities are discussed in this paper. Part II introduces several important theories in RF cavity design. Part III presents the design of dielectric loaded cavities. Part IV contains summary and the future plan.

II. RF Cavity Design Theory

i. Cavity Tuning

RF cavity is a metallic chamber that can convert alternating electrical currents to electro-magnetic fields. It is similar to an RF waveguide in which waves can propagate along the axial direction (z-direction). There are two field modes depends on whether electrical field or magnetic field is transverse to the direction of propagation; transverse electrical field (TE) mode and transverse magnetic field (TM) mode. Magnetic field inside TM mode is curl around center axis and electrical field is along z-direction as shown in Figure II. RF particle accelerating cavity generally uses a TM mode. The excited electric field in the cavity can boost particles by Lorentz force.

Electrical field and magnetic field inside the cavity can be analytically calculated in form of Bessel function through the boundary conditions. Frequency of TM modes is determined

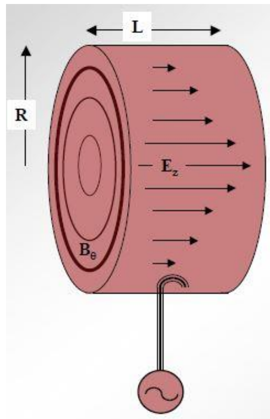
$$f_{nmp} = \frac{\omega_c}{2\pi} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{x_{nm}}{R}\right)^2 + \left(\frac{p\pi}{L}\right)^2} \quad (1)$$

where x_{nm} is the Bessel function variable, R is the radius of cavity and L is the length. Each cavity has numerous modes with different resonant frequencies. It is desired to have a mode with maximum acceleration field in cavity. TM_{010} mode, the lowest mode in TM modes, is typically used for particle accelerators. The frequency of TM_{010} is given as

$$f_{010} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\frac{2.405}{R} \qquad (2)$$

It can be seen the frequency is dependent on permeability (μ), permittivity (ε) and cavity radius. It suggests that the size of RF cavity can be small by inserting a large ε material in the cavity. As an example, the radius of an 800 MHz vacuum cavity is calculated as 14.4 cm with equation (2). The aim of this project is reducing the cavity radius to 0.75 or a half smaller than the radius of pillbox cavity by inserting the dielectric material. Therefore, the required ε will be at least 10.

Figure II: *Pillbox cavity with TM_{010} mode* [2]



There is another way to tune the resonant frequency in the cavity for the lowest excitation mode. An RF resonator system is model as an LCR electric circuit as given by

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad (3)$$

where L and C are inductive and capacitive components of the LCR resonator, respectively. This formula suggests that the resonant frequency can be shifted by changing either L or C or both. These changes are done by mounting a special shape electrode in the cavity as shown in later section.

ii. Quality Factor

Quality factor in an RF cavity is defined as the ratio of stored energy in one RF cycle to the dissipation power,

$$Q_0 = \frac{\omega U}{P_c} \qquad (4)$$

where ω is frequency, U is stored energy and P_c is the power loss. This equation defines the unloaded quality factor, which is a characteristic of the cavity and can be calculated with the resistivity and geometry of cavity. The quality factor for the dielectric loaded cavity will be affected due to the extra power loss on the dielectric material. It can be interpreted as

$$P_c = P_{wall} + P_{diel} \qquad (5)$$

where P_{wall} and P_{diel} are the power losses due to the wall and the dielectric material, respectively. Substituting equation (4) into (5), a relationship between different quality factors is established

$$\frac{1}{Q} = \frac{1}{Q_{wall}} + \frac{1}{Q_{diel}} \qquad (6)$$

where Q is quality factor of the entire cavity and Q_{wall}, Q_{diel} are the quality factors due to the wall and the dielectric material, respectively.

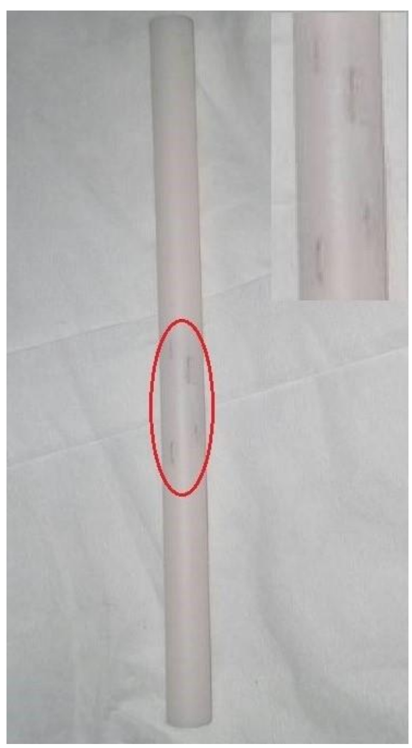
iii. Surface Breakdown

The insertion of a dielectric material into the cavity brings up another issue, that is Surface breakdown. With a strong electric field and the tunneling effect, field emission electrons are emitted from surface of materials. When the electron gains energy from the external electric field and hits a dielectric material, the secondary electrons are generated from the surface of material since the Secondary Emission electron Yield (SEY) of a dielectric material is generally high. The electron cascade is produced in the cavity. As a result, a huge current flow on the material surface and generate the electric breakdown. This process is called surface breakdown.

Surface breakdown is a crucial issue in a vacuum RF cavity. It strongly limits the available RF gradient. One possible solution is that the material is coated by an insulator which has a low SEY, e.g. TiN. Another possible solution is putting a high-pressurized gas in the cavity. Gas can act as a buffer to stop the cascade process. A dielectric loaded gas-filled RF cavity test has been demonstrated and achieved very high RF gradient which is the same as the dielectric strength of a loaded material. The maximum available RF gradient was 14 MV/m in the alumina rod loaded gas-filled RF test cell [3].

However, there was an electric shock that damages the dielectric sample as shown in Figure III. One possible explanation is that the material is damaged by the electric stress when the external field strength reaches the dielectric strength of material, i.e. the electric breakdown inside the material. The mechanism of electric shock should be investigated.

***Figure III**: Surface breakdown on the alumina ceramic rod:*
Cracks circled in red and enlarged at top right



III. Design of Dielectric Loaded Gas-filled RF Test Cell in Superfish

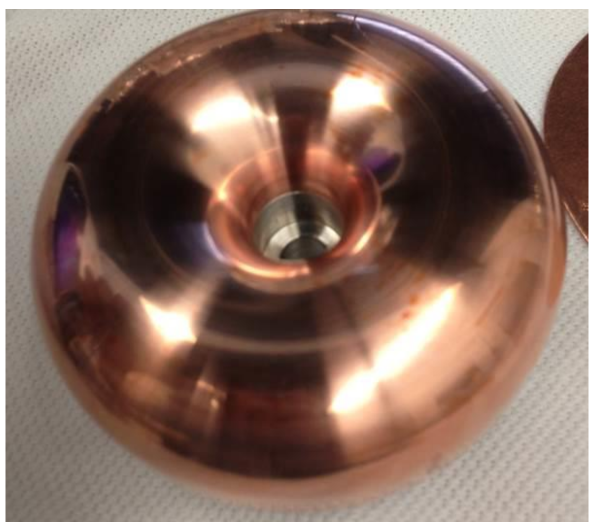
The software used to design the dielectric loaded gas-filled RF test cell is Poisson Superfish (Superfish). It is a collection of programs for calculating electromagnetic field in both static and RF environments. Those programs can work in either 2-D Cartesian or 3-D axially symmetric coordinate systems. In the case of the dielectric loaded cavity, 3-D axially symmetric coordinate is used.

The simulation effort aims at 1) tuning the RF resonant frequency (800 ~ 815 MHz), 2) studying the field distribution and the field quality (uniformity and strength on a sample surface) and, 3) investigating the quality factor in the test cell. Especially, we focused on 1) and 2) in this project.

i. Baseline Design

Software test starts from the baseline design; a simple dielectric rod with two donut electrodes.

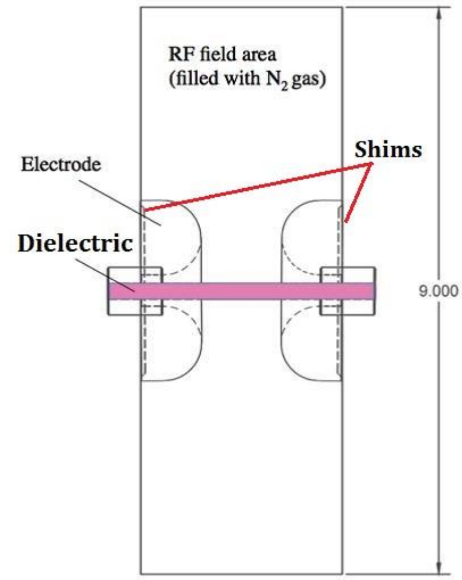
Figure IV*: Donut Electrode*



The donut electrode is in half ring-torus shape, as shown in Figure IV. It is made out of copper, while the cavity body is copper-coated stainless steel. Therefore, it is reasonable that the whole cavity can be treated as a copper bulk in the software. The two electrodes installed on both ends of the cavity serve to change L and C so the size of the dielectric material can be reduced.

The overall baseline configuration is shown in Figure V. In this configuration, a shim is installed below each electrode to reduce the resonant frequency. A dielectric rod is inserted at the center of cavity. Size and geometry of the rod are set. Through the adjustment of the shims, the cavity can be tuned to the driving frequency at 815 MHz.

Figure V: *Cut-off View of Baseline Configuration*



To explore the effects of different dielectric materials, two representative materials are chosen; Alumina ceramic and Teflon.

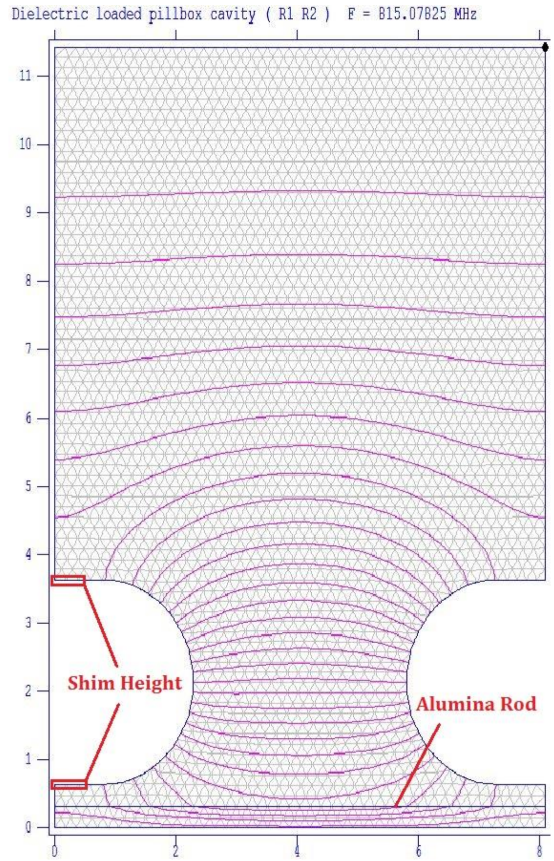
Table I: *Specifications of alumina rod*

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

Table I shows specific properties of the alumina rod used in baseline design. Alumina ceramic is a common industrial material. It has relatively high dielectric constant and permeability compared with other ceramics. The resonant frequency can therefore shift with a small amount of material.

The heights of the two shims are adjusted in Superfish to tune the cavity to the resonate frequency at 815 MHz. Superfish uses the axially symmetric coordinates, and thus the input geometry is only half of the cut-off view. Figure VI shows the software interface for alumina baseline design. The alumina rod, as suggested, is placed in the center. The red line segments marked as shim indicate the shim's height. Physically, those lines are the inner and outer walls of the shim. Figure VI demonstrates how field is parallel to the surface at the middle part of Alumina rod. It also suggests that the field strength at the triple junction (electric connection among the metal, an ambient gas and the ceramic rod) is low. That is very important when trying to avoid the local electric breakdown at the junction. Under such conditions, the shim height achieved is 0.04 cm and the inner and outer radiuses are 0.635 cm and 3.635 cm, respectively.

Figure VI: *Software interface for alumina baseline test*

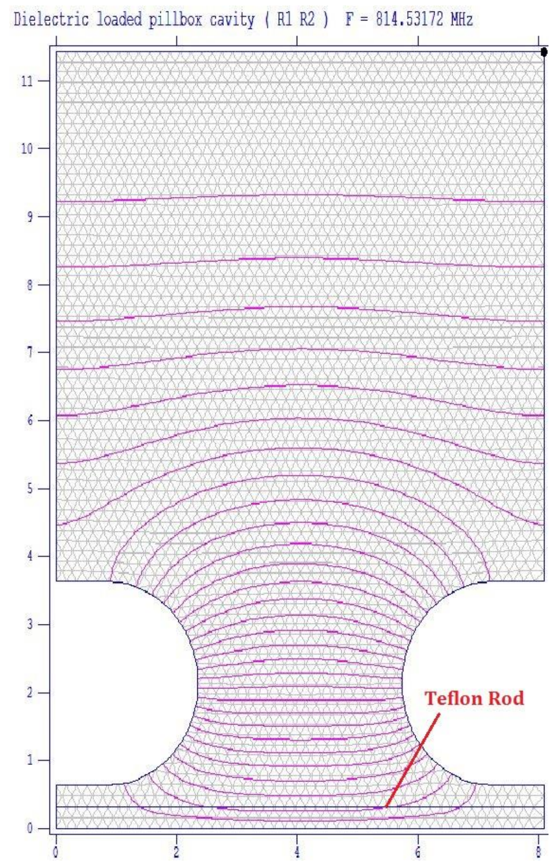


A dielectric constant of Teflon is not high as alumina's. But, due to its cheap price and high dielectric strength, it is still considered as an option. Through the same technical for alumina baseline design, the height of the shim generated is 0.1065 cm and the inner and outer radiuses are 0.635 cm and 3.635 cm, respectively.

Table II: *Specifications of Teflon rod*

Property	Value	Unit
Length	4	Inch
Width	0.25	Inch
Relative Dielectric Constant	2.1	
Loss Tangent	2.8e-4	
Dielectric strength	23.6	MV/m

Figure VII: *Software interface for Teflon baseline design*



These tests provide two sets of feasible designs for the cavity and both of them rely on the dimensions of the shim.

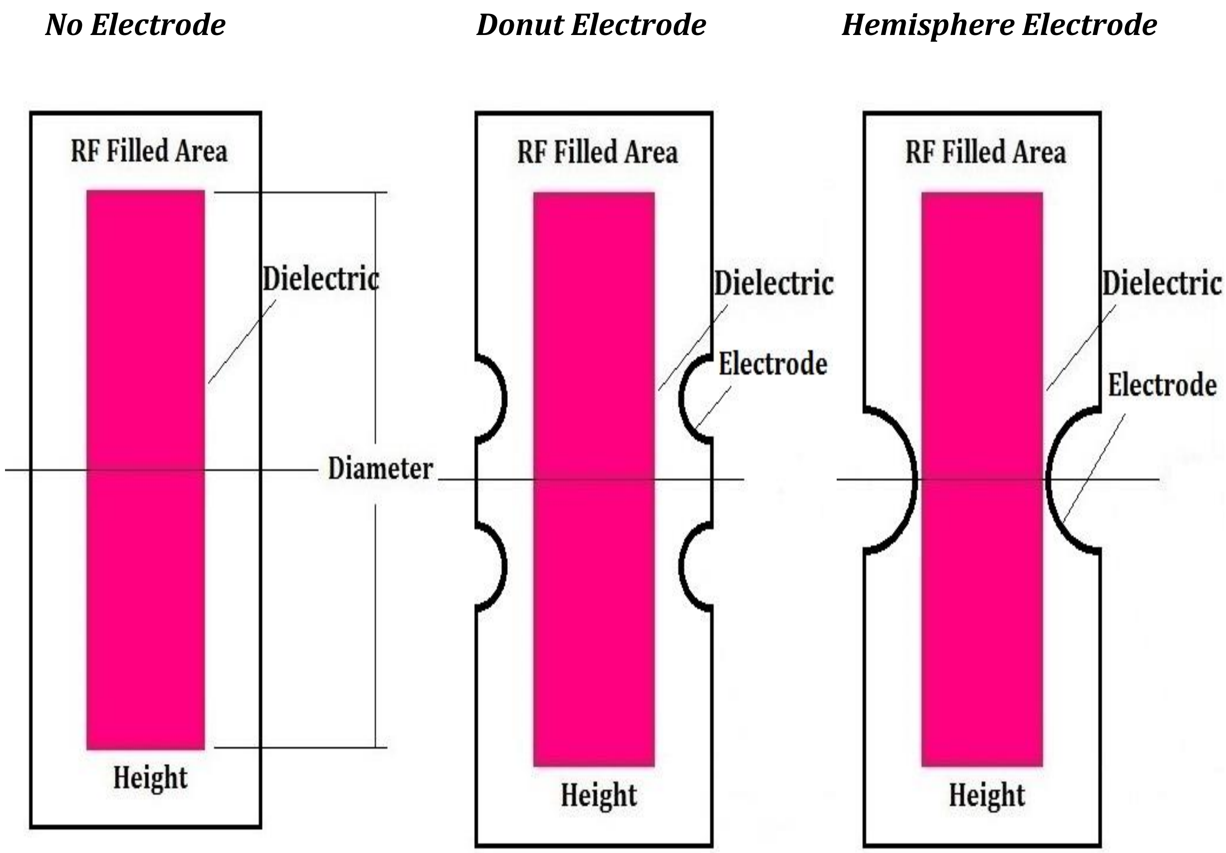
ii. Design of Disk Sample

The surface breakdown will be investigated in the configuration mentioned above, in which the RF gradient is applied parallel with respect to the material surface. We also designed the different test cell to apply high RF gradient perpendicular to the surface. The new test cell used a dielectric material shape of cylindrical disk. For simplicity, the supporting structures for the disk are ignored in software because it is a hypothetical test. The materials used in this design are the same as in baseline design except for the shape and dimensions.

Since the disk is not interfering with either ends of the cavity, a hemisphere electrode of 1-inch radius, besides the donut electrode, is also used as an option of electrode shape. Three different configurations therefore emerge; no electrode, the donut electrode and the hemisphere electrode. Cut-off views for all three configurations are shown in Figure VIII.

Dielectric disk is placed at both longitudinal and transverse centers. The size of disk is adjusted in both R and Z directions to realize the driving frequency 815 MHz in the RF test cell. Because there will be an infinite number of (R, Z) sets, only one set is chosen to show the feasibility of that configuration. Final results are shown in Table III and IV for alumina and Teflon, respectively.

Figure VIII: *Cut-off views of different electrode configurations*



**Buffer gas contained in all three cavities not marked. Pictures are not to scale.*

Table III: *Alumina disk test results*

	Test #1	*Test #2*	*Test #3*
Material	*Alumina*	*Alumina*	*Alumina*
Electrode	*None*	*Donut*	*Hemisphere*
Diameter(cm)	*17*	*9.4*	*11.4*
Height(cm)	*2.895*	*0.3*	*1.2*

**Electrode row shows which type of electrodes used. Definitions for diameter and height are shown in Figure VIII.*

Figure IX: *Software interfaces for alumina disk test*

No Electrode ***Donut Electrode*** ***Hemisphere Electrode***

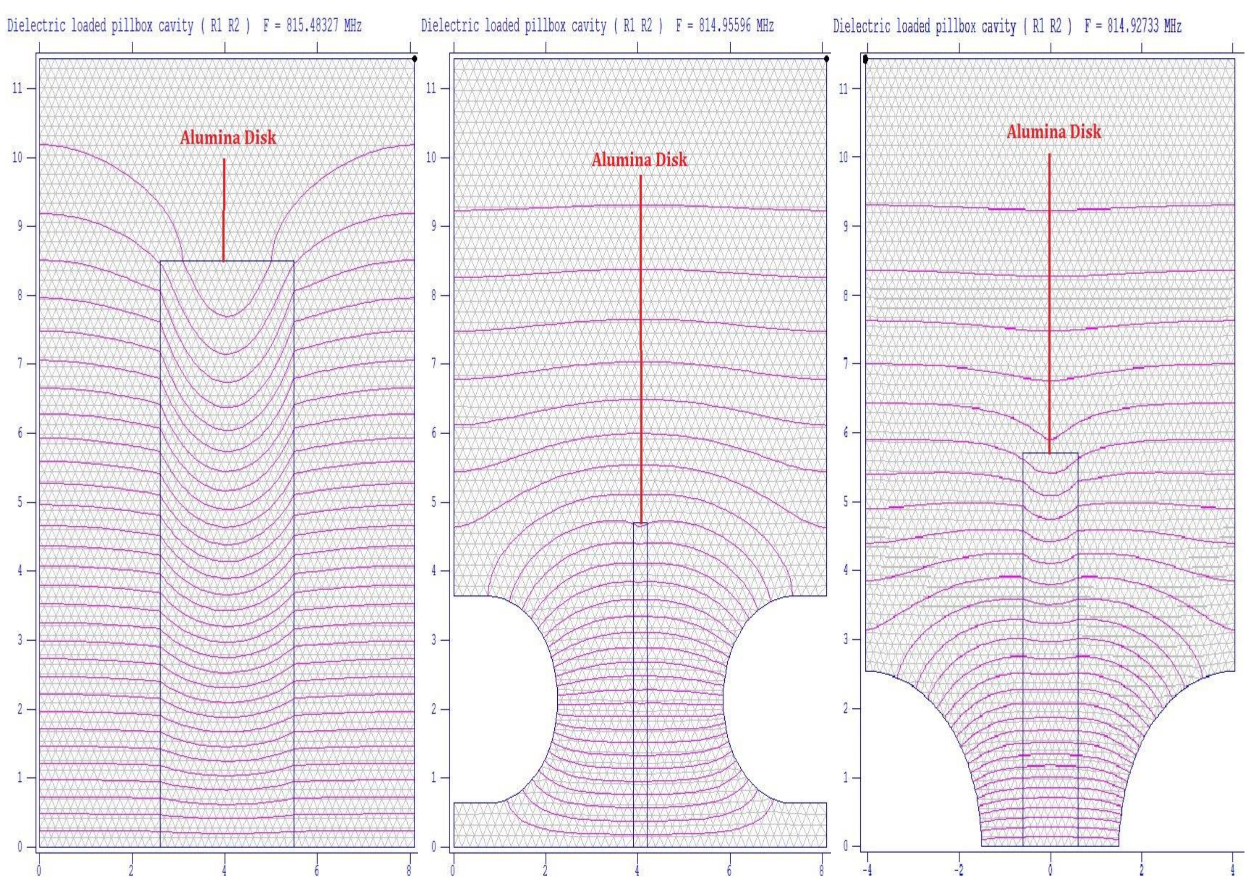
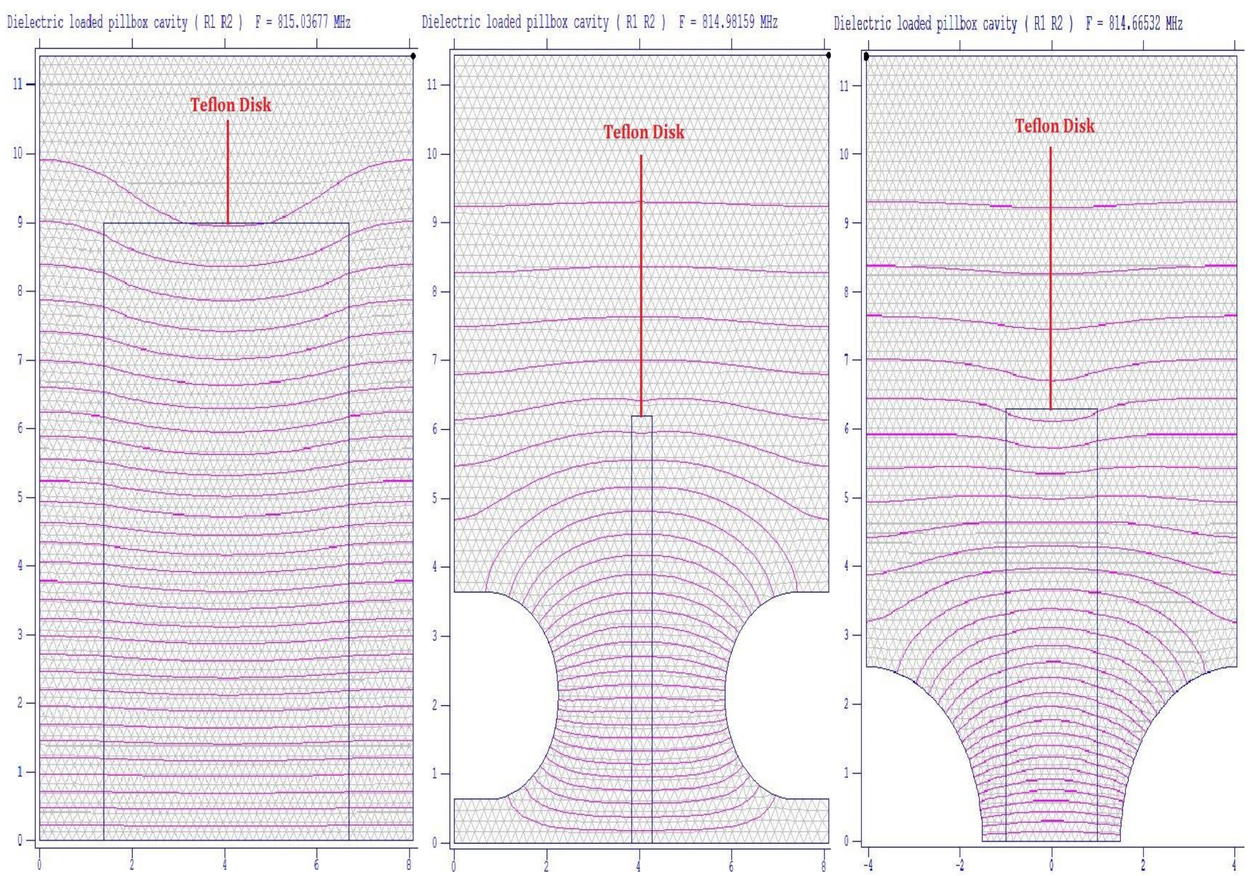


Table IV: *Teflon disk test results*

	Test #1	*Test #2*	*Test #3*
Material	*Teflon*	*Teflon*	*Teflon*
Electrode	*None*	*Donut*	*Hemisphere*
Diameter(cm)	*18*	*12.4*	*12.6*
Height(cm)	*5.295*	*0.44*	*2*

Figure X*: Software interfaces for Teflon disk test*

No Electrode ***Donut Electrode*** ***Hemisphere Electrode***



Not only several sets of feasible designs, but also some important rules for designing the dielectric loaded cavity are provided by those results. Electrodes can apparently shift resonant frequency significantly, and the hemisphere electrode has a smaller effect than the donut electrode does. Meanwhile, changes of size in different directions also have different effects: The frequency shift due to unit size change in Z-direction is much larger than shift due to unit change in R-direction.

iii. Quality Factor

The dielectric loaded cavity will ultimately be installed in the real accelerator and its RF quality (Q) factor is a matter of concern as well. Equation (6) shows that quality factor of the entire cavity is directly related to the loss tangent of the dielectric material. This is true only if the power loss in dielectric material is the dominator of all energy losses. Superfish simulation is conducted using the alumina baseline design. Since change in imaginary part of permittivity doesn't affect resonant frequency, we are able to maintain the current geometry and adjust Q factor.

It is shown that cavity has an unloaded Q factor at ~8000 when loss tangent is at ~1e-3 and there is a degradation in Q factor when loss tangent becomes higher than 1e-3. However, in the realistic experiment, this degradation cannot be observed when dielectric loss tangent is increased. This inconsistency implies that power loss in dielectric material is not the dominator. The realistic cavity body consumes more energy than shown in the software. It is proposed to improve Q factor of the cavity body by using a new shim. The new shim should have a better resistance so that the energy loss due to cavity can be reduced.

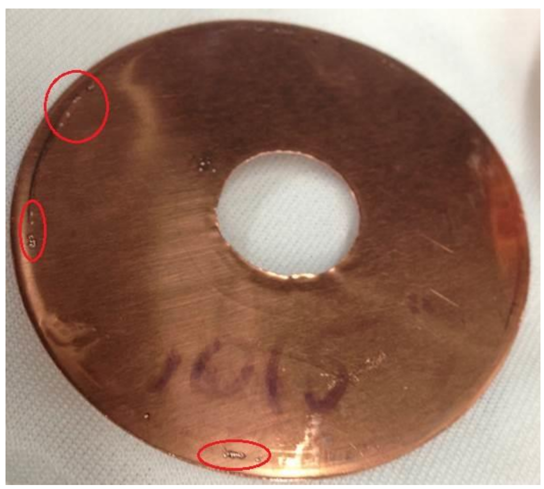
Another test concerning Q factor is conducted in Superfish as well. The current cavity and the future design both use copper as cavity wall material. It is proposed to change the wall material to adjust Q factor. In such case, the energy loss in the wall will be the dominating factor for total energy loss. Since this is only a hypothetical test, all other factors are ignored. The experiment shows that the new material has a much higher resistivity than copper, as expected.

IV. Summary and Future Plan

Software has provided a number of dielectric loaded cavity designs. These designs vary in geometries and materials. All of them have shown feasibility of achieving desired resonant frequency.

Next step to be taken is to test a new shim for the alumina baseline design. Previous experiment shows a dielectric breakdown happens at 14.5 MV/m, which is close to the expected breakdown strength for alumina. Another breakdown happens at 20 MV/m when there is no dielectric material. This breakdown is found to be at the surface of the bottom shim, as shown in Figure XI. To avoid such breakdown so a higher accelerating field voltage can be achieved, a new shim is designed and made. With this new shim, the breakdown strength is expected to be at 50 MV/m in no dielectric material, which is the dielectric strength for the buffer gas. With this new shim, Teflon will be tested to verify its effect on frequency experimentally.

Figure XI: *Surface breakdown at bottom shim (circled in red)*



As for the search of new dielectric materials, improving the dielectric strength of the material is becoming critical. A higher dielectric strength allows a higher accelerating voltage. TiO_2, a novel material, is proposed as an option. Since its loss tangent and dielectric constant are still unknown, some experiments are to be done using a network analyzer to find out these properties.

V. Acknowledgements

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