COMPACT, TUNABLE RF CAVITIES

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Abstract

Compact RF cavities that tune rapidly over various frequency ranges are being developed using an innovative design with orthogonally biased ferrite or garnet cores for fast frequency tuning and liquid dielectric to adjust the frequency range and to control the core temperature. We describe mathematical and physical models of RF cavities suitable for FFAG and other applications as well as first measurements of candidate ferrite and dielectric materials. The first uses of the new cavity concept will be for improvements to the 8 GeV Fermilab Booster synchrotron.

INTRODUCTION

New developments in the design of fixed-field alternating gradient (FFAG) synchrotrons have sparked interest in their use as rapid-cycling, high intensity accelerators of ions, protons, muons, and electrons. Potential FFAG applications include medical accelerators of protons and light ions for cancer therapy [1], proton drivers for neutron or muon production, and rapid muon accelerators. The successful development of compact tunable accelerating RF cavities will establish or enhance the feasibility of FFAG machines for these puposes.

Another use of compact, rapidly tunable RF cavities is for older machines that require new capabilities but have limited space for new components. In the 8 GeV Fermilab Booster synchrotron, for example, second harmonic RF cavities could provide improved proton capture during injection as well as reduce beam losses as the beam passes through transition. Upgrading the RF system of the Fermilab Main Injector to be ready for a new H minus linac that would replace the Booster is another potential use.

CONCEPT

Figure 1 shows the conceptual design of the compact RF cavity that we are developing for FFAG and other applications. The fundamental design is based on a pillbox cavity. Ferrite occupies the region of high magnetic field, and a liquid dielectric occupies the region of high electric field, as shown in the figure. The liquid is also used to cool the ferrite. Fast tuning is accomplished with a solenoid biasing coil that surrounds the cavity. The frequency range is determined by the dielectric constant of the liquid, which can be chosen according to the requirements of a particular machine, and the separation of the irises. An iron return yoke surrounding the cavity shunts the biasing return field and reduces its effect on the beam.

An important feature of this design is that the solenoid biasing magnetic field is orthogonal to the RF magnetic field. There is reason to believe that the orthogonal biasing will have advantages in faster tuning and less RF heating loss [2].

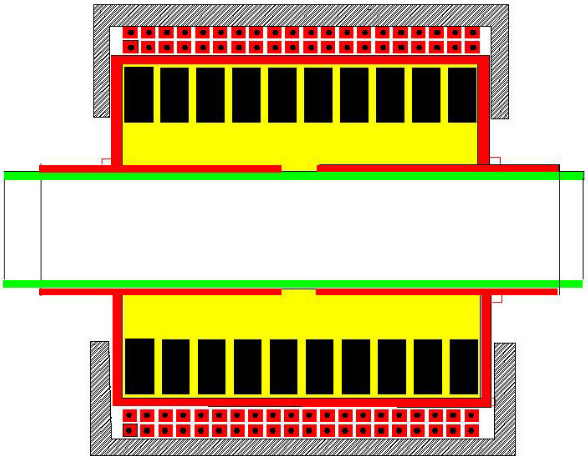

Fig. 1: Conceptual/schematic design of a compact, tunable RF cavity for FFAG and other applications. Ferrite cores (black) and liquid dielectric (yellow) surround a ceramic beam pipe (green) with an RF iris as shown. Coils (red) outside of the cavity generate a solenoid magnetic field that is transverse to the RF magnetic field. A laminated iron return yoke (black) localizes the field.

FIRST COMPUTER MODELING

We have started to analyze the proposed cavity design with SuperFish and ANSYS. For example, Figure 2 shows a first SuperFish analysis of an RF cavity model based on the ideas discussed above with parameters approximately appropriate for the Fermilab Booster. It is a simple pillbox with a reentrant beam pipe where the accelerating gap is sealed with a ceramic pipe. The liquid inside the cavity has dielectric constant of 4.5 and is used for adjusting the frequency range of the cavity and to cool the ferrite. The biasing coil is a simple water-cooled solenoid. An iron yoke that is not shown in the figure is used to return the biasing field flux. The biasing field is parallel to the beam axis and orthogonally biases the ferrite. The values of permittivity ε and permeability μ have not been adjusted to get the exact Booster requirements, but the calculation shows that the cavity will have a reasonable radial size. The radius is about 30cm, and the cavity is 50cm long. The SuperFish results are summarized in Table 1 for the unbiased ferrite and the biased ferrite cases. All calculated values refer to

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the mesh geometry only, using standard room-temperature copper. Here, the ceramic permittivity is not included, unlike the ANSYS case below. This is an ideal calculation without loss factors so its shunt impedance in practice must be corrected when losses are considered.

Table 1: SuperFish parameters for Booster Cavities

Parameter	Unit	Unbiased	Biased
EZEROT	MV/m	2.00000	2.00000
Frequency	MHz	38.1892	53.5265
rest mass	MeV	938.27	938.27
Beta		0.8500000	0.8500000
Kinetic E	MeV	842.865	842.865
Norm. factor	E0=2.0MV/m	14920.021	20226.85
Transit-time factor		0.9980552	0.996171
Stored energy	Joules	6.150	5.788
Surface R	mOhm	1.61225	1.90873
conductor R	μ Ohm-cm	1.72410	1.72410
Operating T	C	20.0000	20.0000
Shunt Z	MOhm/m	560.341	260.254
Z*T*T	MOhm/m	558.164	258.264
r/Q	Ohm	212.494	161.088
Average B on the outer wall	2.39587 W/cm^2	3707.82	5010.41
Maximum H	2.37226 W/cm^2	3700.29	4985.67
Maximum E	0.427349 Kilp.	3.90856	3.8904
Bmax/Emax	mT/(MV/m)	1.1897	1.6104
Emax/E0		1.9505	1.9378

PHYSICAL MODEL

The conceptual diagram shown in figure 1 is also a schematic of the simple model cavity that we have used to verify the mathematical predictions for frequency and quality factor of the design. The aluminum body, which was designed to be easily reconfigured to hold different ferrite rings or different liquid dielectrics, was built around a discarded ceramic beam pipe, with rubber O-rings such that the gap between the irises can be varied. The external solenoid bias winding is water cooled and can provide a magnetic field up to 0.15 T. Figure 3 is a picture of the model cavity. Figure 4 is an ANSYS display of it.

Figure 5 shows the frequency and quality factor measurements for the model cavity as a function of solenoid biasing current for the cases of air and transformer oil dielectrics.

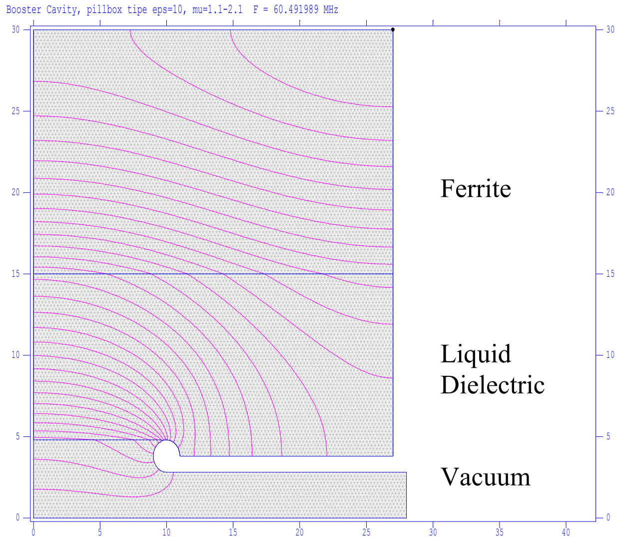

Fig. 2: First SuperFish analysis of an example of the proposed cavity, conceived as a replacement for the Fermilab Booster cavities. The outer radius is 30 cm.

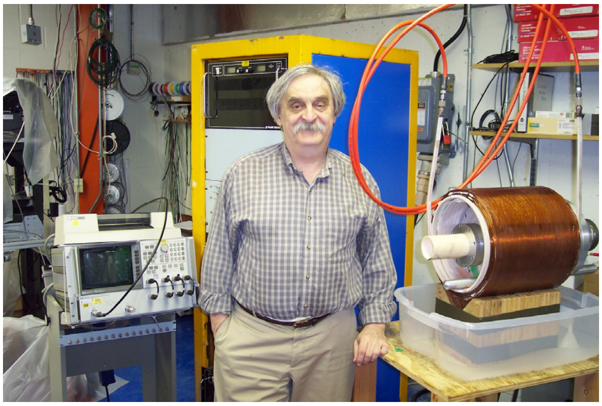

Fig. 3: Picture of new cavity and supporting equipment.

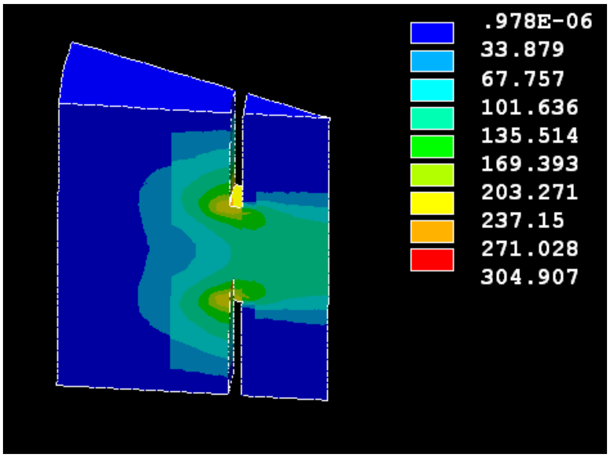

Fig. 4: ANSYS analysis of model cavity.

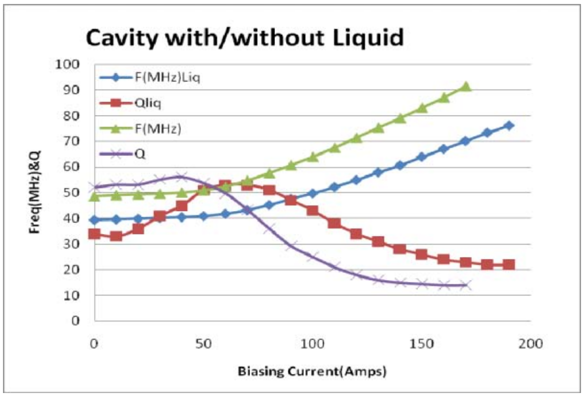

Fig. 5: Model test cell measurements.

FERRITE MEASUREMENTS

Figure 6 is a schematic of the test cell that was used to characterize the ferrite cores in a transverse magnetic field as shown in figure7. Figure 8 shows the results of the measurements of the ferrite cores that were available at Fermilab.

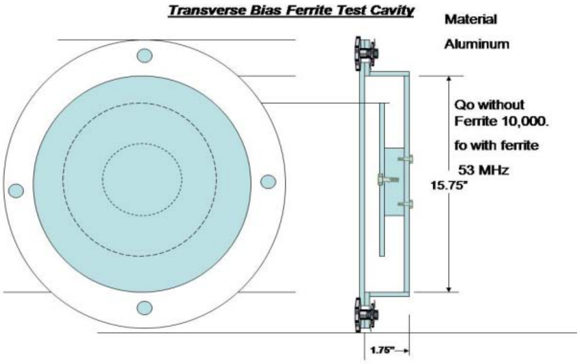

Fig. 6: Schematic of ferrite measurement cell.

SUMMARY AND NEXT STEPS

First measurements of the model cavity show excellent agreement with the numerical simulations using SuperFish and ANSYS based on the measured parameters of the ferrite cores. The measurements with a candidate dielectric fluid are also in good agreement with expectations.

The next steps will be to continue to investigate:

1) Available ferrite for cavity tuning, including resonant loss;

2) High dielectric constant liquids to make the cavity smaller, with manageable dimensions at low frequency;

3) Solenoid designs to orthogonally bias the ferrite, with laminated iron return yokes to localize the field;

4) The use of the fluid to cool the ferrite;

5) The dielectric window that separates the beam pipe vacuum from the dielectric fluid;

And to extend the study to include:

6) Eddy current effects, which can be calculated, but not studied in the model cavity which has thick walls;

7) RF power generator and amplifier requirements;

8) Biasing system power supply and controls;

9) Beam instabilities from bias solenoid fringe fields;

10) RF coupling options, capacitive or inductive, single or multiport.

11) Operational requirements to insure that dielectric fluid cannot enter the machine vacuum system.

The most important next step is to construct a useful RF cavity that can be tested in an operating machine. We believe that a second harmonic RF cavity that will improve the Fermilab Booster performance by increasing its capture efficiency provides an excellent opportunity.

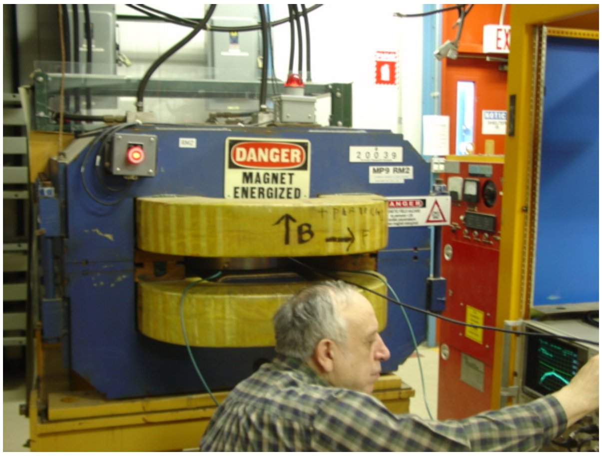

Fig. 7: Ferrite measurements in strong transverse field with another handsome fellow.

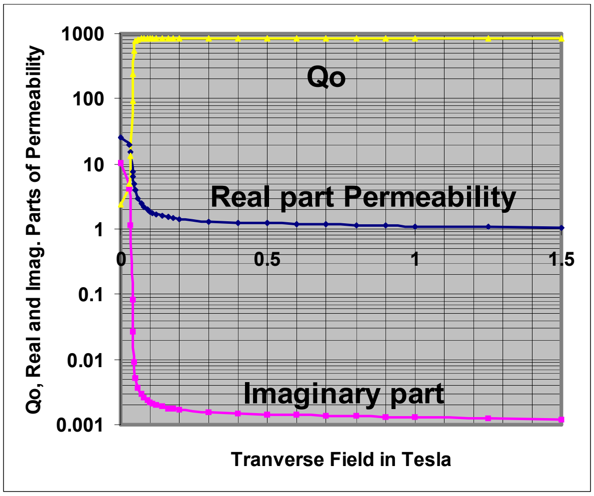

Fig. 8: Ferrite test results for first sample core Ferrite.

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[1]E. Keil, A. M. Sessler, D. Trbojevic, Phys. Rev. ST Accel. Beams 10, 054701 (2007)

[2] J. Griffin, MI-0018, Main Injector Note, FNAL