

# RAPIDLY TUNABLE RF CAVITY FOR ACCELERATORS\*

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## Abstract

The performance and efficient use of rapidly cycling accelerators would be improved with the fast frequency tuning and associated variable phase change provided by a tunable RF cavity. The progress in developing a cavity that can be tuned from 376 MHz to 400 MHz in on the order of 100 nsec is presented.

## INTRODUCTION

FAR-TECH, Inc. is developing a rapidly tunable RF cavity [1] based on BST(M) [2] ferroelectric material. The rapid response of the dielectric constant of the ferroelectric material, under proper conditions, may allow fast tunability of the resonant frequency of a cavity. While the response of the ferroelectric can be as fast as 10 nsec, the complications of driving the system will limit full range tuning to the order of 100 nsec. This fast tunability of the cavity frequency has a wide application in accelerators, including potential breakthroughs by eliminating bottlenecks in advancement of accelerator technology. As an example, fast cycling synchrotrons and fast-cycling non-scaling FFAGs (hereafter referred to as simply fast cycling accelerators) suffer a common problem of changes in synchrotron tune during subsequent revolutions around the accelerating ring. This phase slippage results in inefficient RF acceleration when fixed phase accelerating cavities are used. If the phase of the accelerating RF could be appropriately shifted during the revolution time, then the cavity could be used to accelerate a larger range of particle energies and the fast cycling accelerator could achieve greater final energy. The specific details of the fast cycling accelerator will determine the rate of phase change that is necessary to achieve the largest usable range.

One possible application for this tunable cavity is the recent design of the ion Rapid Cycling Medical Synchrotron (iRCMS) developed under a Cooperative Research and Development Agreement between Best Medical International and Brookhaven National Laboratory [3]. The iRCMS accelerates protons/carbon ions in a single ring up to 400 MeV/u and has a scheme for energy flexible extraction energy. For single harmonic number operation, the iRCMS requires a tunable cavity operating in the 0.65 - 3.57 MHz range. In general, the only way to achieve this tuning range is through the use of ferromagnetic (ferrite) materials.

Ferrite has been used to provide frequency tuning in cavities in the 10's of MHz region. Their use has proven problematic at high RF powers and higher RF frequencies because of the so-called quality-loss-effect (QLE) [4] and have insufficient speed of tuning needed for fast cycling

accelerators. Recent work in the development of new designs for ferrite cavities seek to reduce these problems [5, 6] with some success in terms of achievable accelerating gradient, but still operate at a frequency significantly lower than the proposed project and do not appear to address the issue of the tuning speed. With a rapidly tunable RF cavity operating at higher RF frequency, and with a higher Q value, the same rate of acceleration may be achieved with reduced RF power consumption.

## PRELIMINARY CAVITY DESIGN

The method of tuning the cavity, and a basic understanding of the cavity geometry is best understood using the design previously presented [1]. Fig 1 shows a SUPERFISH model of a preliminary design concept. The key feature of this design is the use of ferroelectric material. When the ferroelectric material is exposed to a biasing electric field (DC or slowly varying relative to the fundamental RF cavity frequency), the permittivity of the material is changed. In the design displayed in Fig 1, cylinders of ferroelectric material, separated by copper rings, span the space between the walls of a pillbox cavity. The copper rings can be structurally supported by rods (not shown), and are used to bias the rings and provide a biasing electric field along the longitudinal axis of the ferroelectric. In this design concept, the ferroelectric was cooled at the end walls and electrodes, which were themselves cooled with chilled water.

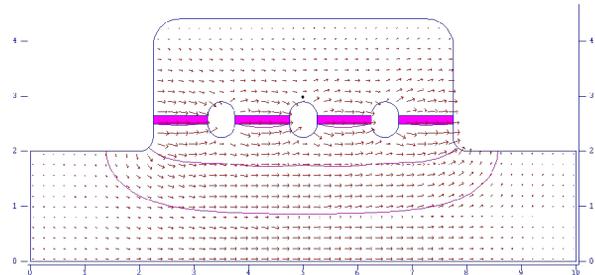


Figure 1: SUPERFISH model of the preliminary concept for the tunable RF cavity using ferroelectric materials. In this design, the center copper ring is held at ground potential while the two outside rings are held at a higher (positive or negative) voltage to provide a biasing electric field.

The clear problem with the preliminary design was the RF loading from the ferroelectric material. This loading resulted in a temperature rise on the order of thousands of °C. When the diameter of the ferroelectric cylinders is increased, the temperature rise decreases at the expense of some range in tunability. To achieve temperature rises less than 50°C, ferroelectric diameters ~50cm were required. Ferroelectric cylinders of such a large size are not practical to manufacture.

### TUBE BASED CAVITY DESIGN

The solution to the heating problem was three-fold. First, the radius of the ferroelectric rings was increased such that the material was far from the symmetry axis. Second, because of the impracticality of producing a ferroelectric ring with a radius  $\sim 25\text{cm}$ , the axis-symmetric ferroelectric ring was replaced with localized ferroelectric tubes located at that larger radius. Finally, the use of tubes allowed for the incorporation of active cooling of the ferroelectric using a dielectric fluid coolant. The localized nature of the ferroelectric tubes lead to the concept of using a biasing cartridge that is inserted in the cavity after the main cavity has been constructed and brought under vacuum. The layout of the tunable cavity is shown in Fig 2, where the localized ferroelectric tubes are shown in cyan near the top. This cavity design also included a 6 in x 1 in rectangular beam pipe which would be applicable to a NS-FFAG design where there is the requirement for a large aperture in one dimension, alternative uses would only require a round aperture.

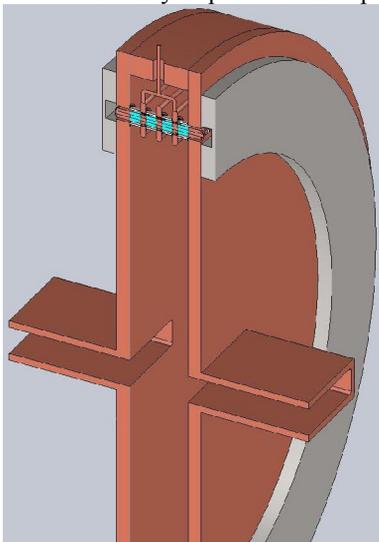


Figure 2: Section view of the tube based tunable RF cavity.

### SIMULATION RESULTS

The tube loaded tunable cavity was modeled in HFSS with the same beam pipe radius and cavity length (5.5 cm) as was used in the preliminary design. Thirty-two (32) ferroelectric tubes with a nominal dielectric constant of 450 were evenly spaced around the symmetry axis. For simplicity, the biasing electrode rings were not included and the ferroelectric tubes spanned the entire length of the cavity.

Basic accelerating cavity parameters for this model are shown in Table 1. The field values were normalized to a  $\beta = 0.4$  particle experiencing a 30 keV energy increase at the resonant frequency of the  $\text{TM}_{01}$  cavity mode. The effect of applying a 40 kV/cm bias was to shift the resonant frequency of the cavity by  $\sim 24$  MHz. In the worst case option, the total power dissipated by the structure was 7.84 kW with 4.2 kW dissipated by the

ferroelectric. For the 32 ferroelectric tubes, this corresponds to 132 W per tube. Frequency tuning and power dissipated in the ferroelectric with changing dielectric constant are both related to the relative quantities of stored energy between the vacuum field and the field in the ferroelectric. At lower dielectric constant, the frequency of the cavity is larger because there is less stored energy in the ferroelectric. With more stored energy available to the vacuum field, the power needed to drive the same acceleration is lower. In real operation, RF drive power would be nominally constant (with varying frequency) and the accelerating parameters would be adjusted. Assuming equal RF power drive of 7.84 kW, the heat dissipated in the lower dielectric constant case is 3.3 kW (103 W per tube) which is still lower than the unbiased case. The additional power would also result in greater than a factor of 2 increase in energy gain. This means that the best operating condition would be to have the cavity in a fully biased state (lowest dielectric constant) during the small fraction of the orbit time where the particle is being accelerated and use the rest of the revolution time to provide the re-phasing. If this were possible, and the design criteria was 30 keV energy gain, then the cavity could be operated with half the power – significantly reducing the heat load on the ferroelectric.

Table 1: Accelerating Cavity Parameters from the 32 Tube Model of the Ferroelectric Tube Loaded Cavity

Property	Unbiased	Biased
Permittivity	450	322
Frequency (MHz)	376	400
Q-Factor	3970	5890
Wall Loss (W)	3640	2070
Ferroelectric Loss (W)	4200	1510
Total Loss (W)	7840	3580
ZTT (M $\Omega$ /m)	0.57	1.26
R/Q ( $\Omega$ )	29.0	42.7

### FERROELECTRIC COLD TESTING

In order to gain experience with the ferroelectric, and in particular how the material behaves in an RF cavity, a copper structure was designed and fabricated for the purpose of testing BST(M) samples as a function of biasing.

Figure 3 shows a cross section of the cavity and included BST(M) disks. The bias voltage was introduced through a rod that enters through the side of the structure and is insulated from the copper using high-voltage insulation. Contact to the BST(M) was made using an indium gasket, and the entire stack was compressed by using an external clamp pressing down on the flexible

copper wall of the cavity. Care was taken not to apply too much clamping force (shown in Fig. 4) to the BST(M) for fear of breaking it, and the clamping force was kept below about 10 lbs. Due to break-down limitations of operating the BST(M) in air, and the difficulty of applying additional insulation to the assembly after stacking, the bias voltage was kept below 5 kV, or 25 kV/cm. The cavity resonant frequency was measured with a vector network analyzer connected to two loop coupler antennas placed at the top of the cavity.

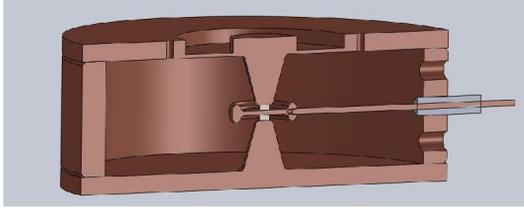


Figure 3: Section view of the cold test model. The center biasing electrode is placed between two ferroelectric samples (beige). The rod connecting the biasing electrode to the bias voltage supply can be removed.

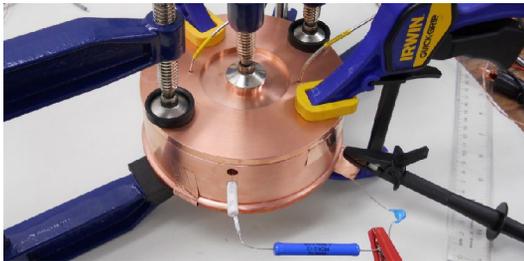


Figure 4: Experimental hardware setup.

The frequency vs. bias voltage data, together with HFSS simulations of frequency vs. permittivity was converted to the data shown in Fig 5, along with the manufacturer data [7] for the material. The differences between the two sets of data points could be due to a difference in the history of the biasing (hysteresis effect) among the two data sets.

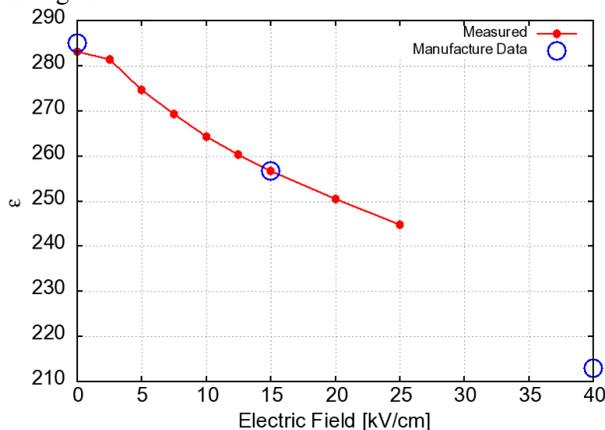


Figure 5: Permittivity of BST(M) vs. manufacturer data.

### PHASE SHIFT TIMING

The tunability of cavity frequency allows many different strategies to be used in order to maintain synchronicity between the cavity RF and beam crossing

times. Many FFAG ring designs have beam repetition times that vary by a factor of two from the start to the end of the acceleration cycle. If the harmonic number, the number of RF cycles per beam revolution, is kept fixed, it would require too high of a tuning range for the RF cavity, and therefore consume too much power. At the other end of the scale, too small of a tuning range can lead to too many harmonic jumps which could overtax the bias power supply.

Our study of the interplay between frequency tuning and specifics of an FFAG lattice was based on the 68 to 400 MeV/u carbon ring by Keil et. al. [8]. This machine has revolution times between 242 and 477 nsec. Using a 375 MHz base cavity frequency, and a +25 MHz tuning range results in the tuning diagram shown in Fig. 6. In that figure, the red dots represent the allowed harmonic frequencies as the particle accelerates and includes an estimate of the time-transit factor in the cavity. The very close spacing of the dots indicate that we are operating at a high harmonic number. The blue trace represents a cavity tuning path that uses *frequency modulation* plus *harmonic number jumping* over multiple harmonics and uses the full tuning range of the cavity. A harmonic jump is taken approximately eleven times during an acceleration cycle. The green trace assumes that the jump is over only a single harmonic, thus requiring a smaller tuning range.

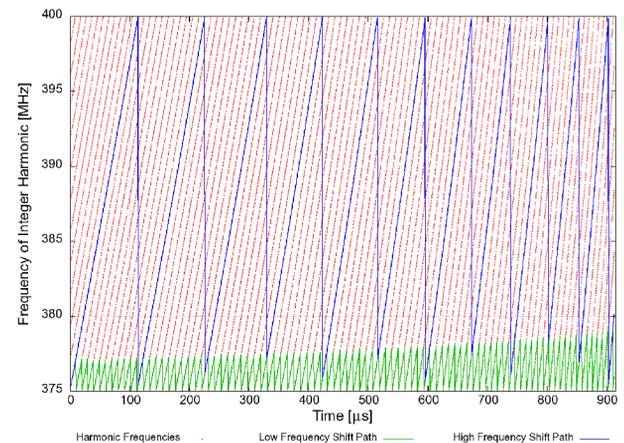


Figure 6: Tuning diagram for a 400 MeV/u carbon machine.

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