RAPIDLY TUNABLE RF CAVITY FOR FFAG ACCELERATORS

D. Newsham[#], N Barov, J.S. Kim, FAR-TECH, Inc. San Diego, CA 92121, U.S.A.

Abstract

The fixed-field alternate gradient (FFAG) synchrotron offers an attractive solution for systems that require rapid acceleration over a wide range of energies. The ability to rapidly tune the frequency of the accelerating cavity in the "non-scaling" variety of an FFAG synchrotron represents a fundamental barrier to their implementation in a wide variety of applications for proton, ion and muon acceleration. Initial results of the rapidly tunable cavity design for specific application to proton and light ion medical FFAG accelerators are presented.

INTRODUCTION

A mature lattice design for a cancer therapy complex utilizing 250 MeV protons and 400 MeV carbon ions utilizing a non-scaling fixed-field alternate gradient (NS-FFAG) [1] lattice was recently described [2, 3]. In this design, the orbit time around the machine is approximately 47 nsec and the energy gain per revolution in the ring is around 250 keV. Updated versions of this complex operate at an accelerator frequency near 375 MHz [4, 5]. In that design, the method for implementing a tunable RF cavity was to provide a cavity with a Q of approximately 50. This corresponds to a bandwidth of approximately 2%, and results in losses on the order of 100 kW. This brute force approach basically dumps the power and replaces it with properly phased RF every with orbit around the ring. While it solves the tuning problem, it does so in an inefficient manner. Additionally, the radius of a standard pillbox cavity is greater than 30 cm; making it a large device even with a reentrant design.

Ferromagnetic (ferrite) materials have long been used to provide frequency tuning in cavities in the 10s of MHz region. They have proven problematic at high RF powers and higher RF frequencies because of the so-called quality-loss-effect [6] and have insufficient speed of tuning needed for NS-FFAGs. Recent work in the development of new designs for ferrite cavities seek to reduce these problems [7, 8] 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.

In addition to the rapid tuning and power characteristics, an RF cavity for the envisioned NS-FFAG medical accelerator must be as short as possible with 10 cm being the goal. FAR-TECH, Inc. has conceived of and has proposed to develop an innovative RF cavity design* using ferroelectric material that satisfies these characteristics.

[#]newsham@far-tech.com

*Patent applied for.

PRELIMINARY RF CAVITY DESIGN

Figure 1 shows a cut-away solid model of a preliminary design of the FAR-TECH tuned RF cavity. The key feature of this design is the use of a ferroelectric material [9]. When the ferroelectric material is exposed to a biasing DC electric field, the permittivity of the material is changed. In the design displayed in Figure 1, cylinders of ferroelectric material, separated by copper cylinders, span the space between the walls of the pillbox cavity. The copper cylinders are structurally supported by thin rods in a manner similar to a drift tube linac (DTL) Although similar to a DTL in appearance, the spacing between the cylinders is much less than $\beta\lambda$, where β is the particle velocity divided by the speed of light and λ is the vacuum wavelength at the RF frequency. These copper cylinders (and their support rods) are used to provide a DC electric field along the longitudinal axis of the ferroelectric and have the potential to provide cooling.

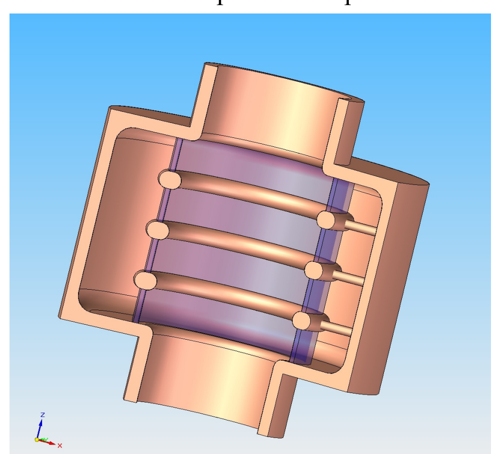

Figure 1: Solid model drawing showing the layout of the preliminary tunable RF cavity under investigation.

Ferroelectric Material

The ferroelectric being considered for study is a barium-strontium titanate (BST) compound [9]. This material has been used in the design of fast phase shifters operating at 1.3 GHz [10] and 700 MHz [11, 12]. The nominal dielectric constant of the ferroelectric is 550-600 and can be increased by as much as 20% with a bias electric field of 45 kV/cm. The basic properties of the BST ferroelectric can be found in Table 1. The low loss tangent ($\sim 5 \times 10^{-4}$) and fast rise time (< 10 ns) of the material are of particular interest for this application. Because of a desire to keep the voltage needed to provide the biasing electric field below 50 kV while providing a maximal range of tuning, the length over which the voltage will be applied (longitudinal length of the ferroelectric cylinder) was limited to a fraction of the cavity length.

Table 1: Properties of BST ferroelectric ceramic measured near 700 MHz [11]

Parameter	Value
Nominal dielectric constant, ε	~550
Tuning range, Δε	~20%
Response time	< 10 ns
Loss Tangent at 700 MHz	$\sim 5 \times 10^{-4}$
Breakdown limit	200 kV/cm
Thermal conductivity	7.02 W/m-K
Specific heat	0.605 J/g-K
Density	4.86 g/cm3
Thermal expansion	10.1 µm/m-K

RF Simulations

SUPERFISH (CFISH) was used to simulate the RF cavity design with a geometry and resulting electric fields shown in Figure 2. This simulation included a calculation of the losses from the ferroelectric material and the stems needed to bias the copper rings. The inner diameter of the cavity was initially adjusted to achieve a frequency of 375 MHz with the ceramic having a dielectric constant of 600. These values of the frequency and dielectric constant were chosen to be near the middle of the desired tunable range. To investigate the range of achievable frequencies, dielectric constants of 550 and 650 were also simulated. With the range of dielectric constants studied, the frequency variation range was 361-391 MHz (30 MHz or 8% full range). The results of this analysis are shown in Table 2. The power losses were calculated for an average on-crest energy gain of 30 keV per cavity for protons with a normalized velocity of $\beta = 0.4$, consistent with the current LBNL/BNL/CERN design [4]. For the same energy gain per cavity, the cavity under study consumes less than 1/3 the power and has a significantly increased tunable range when compared to the previously mentioned design without any optimizations performed on the design.

Table 2: Results from the SUPERFISH simulations of the tunable RF cavity with varying values rf the ferroelectric permittivity for protons with $\beta = 0.4$

Dielectric constant	550	600	650
Resonant frequency, MHz	391.7	375.3	360.8
Cavity Q	1433	1423	1413
Cavity r/Q, Ohm	22.6	22.0	21.4
Energy gain, keV	30	30	30
Cavity wall losses, kW	8.0	8.4	8.8
Ferroelectric losses, kW	19.6	20.2	20.8
Stem losses, kW	0.2	0.2	0.2
Total losses, kW	27.8	28.8	29.8

DEVELOPMENT PLANS

Current development plans include an optimization of the preliminary design and a cold test to determine the properties of the ferroelectric near 375 MHz.

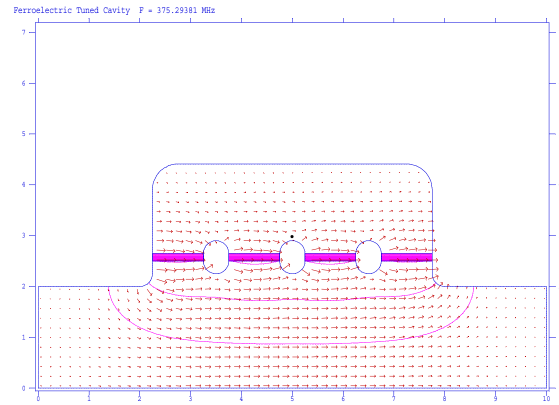

Figure 2: SUPERFISH model of a proposed tunable RF cavity using ferroelectric materials. In this design, the center copper ring is held at ground potential while the two outside rings are held at a higher (positive or negative) voltage to provide a biasing electric field.

Design Optimization

The preliminary design of the RF cavity has significantly larger frequency tuning range than is needed for use in the proton/carbon ion medical therapy FFAG accelerator. As designed, the exceptionally compact size of the cavity leaves a substantial radial space to increase the diameter of the ferroelectric cylinder and still remain compact. One possible design variation would be to change the geometry to a reentrant design. Also, increasing the radius of the ferroelectric may result in a lessening of the extremely high capacitance that it introduces and may result in a decreased sensitivity of the cavity frequency to changes in the dielectric constant of the ferroelectric. If this increase in radius also results in a lowered RF electric field at the dielectric, there may be reduced RF losses in the material; however increasing the radius of the ferroelectric also increases the volume and may serve to increase the losses.

We plan to use SUPERFISH and HFSS to determine an optimal design with the hope of using a reduction of the tunable range to decrease the power load on the ferroelectric. Additionally, the RF studies will include an analysis of the maximum achievable gap voltage with existing and proposed high power RF sources, and the identification of the factors that limit the operating regime of the design.

In this preliminary design of the RF cavity, the power loss in the ferroelectric is on the order of 20 kW peak. This power is basically spread evenly between the four ferroelectric cylinders. If we assume that the protons/carbon ions in the FFAG accelerator have a 47 ns orbit time and make 1500 orbits, then the minimal RF pulse width is on the order of 70 µs. Using a modest safety margin and assuming a 200 µs RF pulse width with a repetition rate of 100 Hz, the total average power deposited in a 1 cm piece of ferroelectric is 100 W (1.0 J per RF pulse). Based on the material properties shown in Table 1, this would result in an instantaneous temperature increase of approximately 0.2 K per RF pulse. As an initial overestimate of the power handling capabilities of the design, if the total power were deposited at the longitudinal center of the ferroelectric, the temperature difference across the ceramic needed to transport the average 100 W of power to the ends, where it can be removed by water cooling the copper biasing rings, is approximately 150 K. Although a significant overestimate, these rough numbers indicate that cooling will be required in the design and may pose a problem. Methods to provide active cooling to the ceramic are being investigated. It should be noted that the design trade off to reduce the power loss in the ferroelectric at the expense of tuning range and an increased ceramic diameter at the same power loss would directly ease the cooling requirement, and any increase in repetition rate would serve to make the problem worse.

Cold Test

The properties of a BST ferroelectric cylinder of comparable geometry to the preliminary design have been measured in the near 700 MHz [11]. There have been no published studies of the ferroelectric material closer to 375 MHz. We plan to perform a simple cold test to determine the dielectric constant and range of variation of the dielectric constant of a sample of the BST ferroelectric material near 375 MHz. Figure 3 shows a sketch of a possible cold test cavity. This sketch shows a pillbox cavity that is loaded by a single ferroelectric cylinder. There is a radial cut in the pillbox to separate it into two halves that will allow for an applied DC electric field. While a simple radial cut will provide ample opportunity for RF power to exit the cavity and would affect both the mode and the Q-factor of the cavity, such losses and precision in design do not affect the needed measurements provided these losses are taken into account in the modeling of the cold test cavity. Holes are bored down what would be the "axis" of the pillbox cavity to provide for a bead pull test. Additional holes would be added for the insertion of probes.

To determine the potential size and sensitivity of the test cavity, a SUPERFISH run was performed for a simple ferroelectric loaded pillbox cavity. The cavity was 7.5 cm in diameter with a ferroelectric cylinder with a radius of approximately 2 cm. The SUPERFISH simulation results for the large range of dielectric constants are shown in Figure 4 and show a notable shift in frequency as the dielectric constant varies.

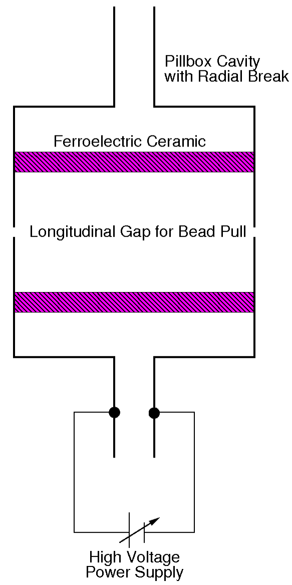

Figure 3: Sketch of a ferroelectric loaded cold test cavity.

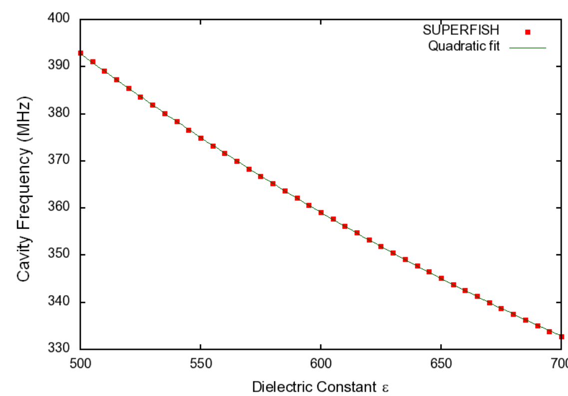

Figure 4: Effect of a varying dielectric constant on the fundamental pillbox cavity frequency.

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