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A PERPENDICULAR BIASED 2ND HARMONIC CAVITY FOR THE FERMILAB BOOSTER*

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Abstract

A perpendicular biased 2nd harmonic cavity is currently being designed for the Fermilab Booster. Its purpose cavity is to flatten the bucket at injection and thus change the longitudinal beam distribution so that space charge effects are decreased. It can also with transition crossing. The reason for the choice of perpendicular biasing over parallel biasing is that the Q of the cavity is much higher and thus allows the accelerating voltage to be a factor of two higher than a similar parallel biased cavity. This cavity will also provide a higher accelerating voltage per meter than the present folded transmission line cavity. However, this type of cavity presents technical challenges that need to be addressed. The two major issues are cooling of the garnet material from the effects of the RF and the cavity itself from eddy current heating because of the 15 Hz bias field ramp. This paper will address the technical challenge of preventing the garnet from overheating.

INTRODUCTION

It is well known that the addition of a 2nd harmonic cavity (in this paper, 2nd harmonic means the frequency is twice that of the fundamental) can be used to improve capture of the beam at injection. It is also possible to use this type of cavity at transition as well, to aid in crossing transition. For example, see ref. [1]. Simulations have shown that, in order, to increase capture, the voltage of the 2nd harmonic must be greater than 10% of the total accelerating voltage of the fundamental. This value sets the minimum voltage for the 2nd harmonic design, which for Booster means that it is about 100 kV.

In order to achieve this voltage in the limited space in the Fermilab Booster tunnel, it was decided to pursue a cavity design that is perpendicularly biased rather than parallel biased. [2] The reason is that the high Q of the garnet material used for a perpendicular biased cavity allows this voltage to be achieved with a single gap rather than with a double gap that is required for a parallel biased cavity. A double gap cavity essentially means a doubling of the length w.r.t. a perpendicular biased cavity (PPBC).

However, this choice is not without risk. PPBC's have been proposed and built before, for example, for the SSC low energy booster [3] and the kaon factory at TRIUMF [4]. Although the TRIUMF prototype did achieve its required specifications [5], it eventually developed a vacuum problem. And the SSC cavity never achieved its design power because localized heating in the garnet caused it to fail. [6] The repair and postmortems of these failures are also challenging because safety requirements have to be met. For example, the handling of beryllium oxide (BeO) cooling disks that are sandwiched between the garnet disks.

Besides localized heating of the garnet from the RF, there are other challenges, like the eddy current heating from the magnetic bias field ramp that will not be discussed here.

NEW DESIGN

The new design is shown in Fig. 1. The goal is to exploit the SSC and TRIUMF experiences to create a cavity that can work reliably without overheating. Although this new cavity looks similar to the SSC and TRIUMF designs, it is actually quite different: (a) Removal of BeO cooling disks — cooling is achieved by water paths that are outside the cavity. This design allows cooling of the inside circumference and outside circumference of the garnets. (b) The garnet is no longer symmetric about the RF neck region.

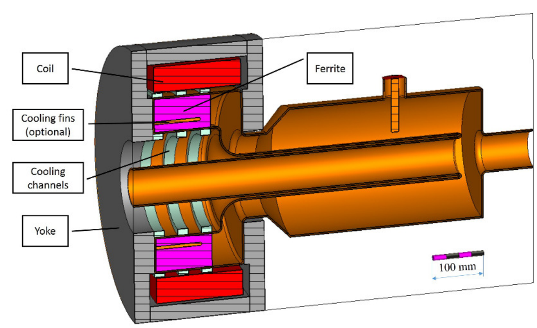

Figure 1: The cavity model.

Localized Heating

Localized hotspots are the major problem with all PPBC's designed and built so far. In order to mitigate this problem, it is essential that MWS be able to correctly calculate the heat density and the hot spots in the garnet material. Unfortunately, the magnetic and electric characteristics of the garnet material, AL800, that is used in the present design from published sources are insufficient for this application and thus, the AL800 properties have to be measured at Fermilab.

AL800 PROPERTIES

The biggest challenge in designing a workable cavity of this type is due to unavoidable nonuniformities in the garnet internal magnetic field. As the real and the imaginary parts of the biased garnet permeability are strong non-linear

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functions of the internal magnetic field, the appearance of localized hot spots in the material can be an unpleasant reality. It is the presence of these hot spots, and not the average power deposition, which is the major problem to be attacked. For the simulation to correctly predict the location and magnitude of these spots at a given resonant frequency, one must obviously know accurately both μ' and μ'' as a function of H. Such data is available but is both sparse and conflicting, and so new measurements were performed with samples of AL800.

DC magnetic field measurements were first performed in order to determine the static magnetization curve (μ' vs. H). [7] A stack of ten 0.5" thick garnets with 3" OD and 0.65" ID were placed in a solenoid. The magnetic field was measured by probes inserted between the garnets at 3 locations in z, for various values of solenoid current. With no garnet, the field inside the solenoid is quite uniform, however, once the garnet is placed inside this is no longer the case. The presence of air gaps surrounding the garnet and also the small (1.37 mm) air gaps caused by the magnetic field probes have a large effect on the field. This necessitated the use of a magnetic solver to simulate the expected probe readings. As the goal was finding the material properties, an optimization problem had to be set; COMSOL Multiphysics modeling environment was used to solve the problem. The magnetization curve was determined by comparing data and simulation, iteratively adjusting the parameters which define the curve (which is an input to the simulation), until the data and simulation matched. For the samples on hand, it was not possible to determine the curve with the simpler and more traditional toroidal measurement, since the ratio of OD/ID is large, and the magnetic field would have a large radial variation. More samples of appropriate dimensions are currently on order and will be used in a toroidal setup to verify the current magnetization curve, which is shown in Fig. 2.

Next, RF measurements were performed. The samples were placed in a coaxial line which was shorted at one end to form a quarter wave test resonator with a resonant frequency in the range of that of the real cavity. The test resonator was then placed in the same solenoid used for the DC measurements. The resonant frequency and Q were measured as a function of solenoid current. The test resonator was then simulated with CST Microwave Studio, in which losses are determined by ΔH, the width of the gyromagnetic resonance. The values of ΔH used in the simulation were adjusted until the predicted Q matched the data. The complex permeabilty is then determined as [8]

$$\Delta H = \frac{\tan\delta_M \omega_0^2 H_{\text{ext}}}{g\omega 4\pi M_s} \tag{1}$$

where $\tan\delta_M = \mu''/\mu'$. The results are shown in Fig. 3 and are approximated well by the formula $\mu'' = 8.572 \times 10^{-6} e^{1.5\mu'}$.

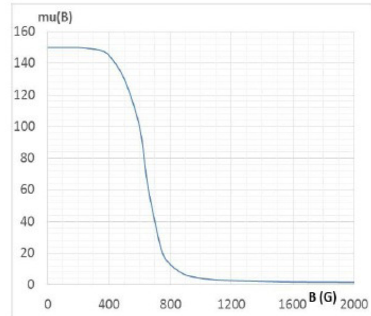

Figure 2: The real part of the permeability as a function of B for AL800. The region of interest is the lower knee of the curve where $\mu < 10$.

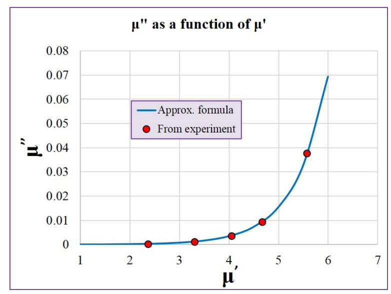

Figure 3: The real and imaginary parts of the permeability of AL800 that is of interest. These are the average values over the garnet volume.

Heat Distribution in RF Cavity

The essential limit for PPBC is determined by thermal losses in the garnet [8]. Therefore, the mechanical design must not only provide the required tuning range and accelerating voltage, it must also provide sufficient cooling for the garnet.

The specified tuning range for our cavity is from 76.75 to 105.35 MHz although it is envisioned that the cavity voltage is maximum at injection and transition. This large tuning range and high frequency affect the heating issue in two ways. First, the variation of μ' must be between 1.5 (limitation from bias field strength) and 3.5 – 4 (limitation from losses, see Fig. 3). We managed to provide this tuning range within acceptable limits as shown in Fig. 4.

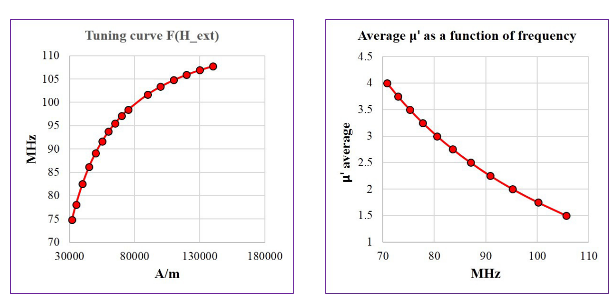

Figure 4: Tuning curve and μ' span.

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Second, due to the high frequency, the cavity is relatively small which makes cooling more difficult, especially without BeO disks. In order to make this thermal problem less severe a tuner design has been modified as described above from the initial design [9] and the cooling channels were placed as shown in the thermal model in Fig. 5. The parts of the solenoid yoke were included in the model since they act as additional heat sinks.

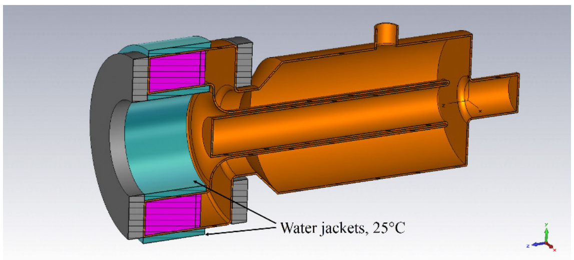

Figure 5: Thermal model of the cavity. The thermal conductivity of the garnet is 3.5 W/K/m.

Thermal analysis of the cavity is a multiphysics problem which we solve with the CST Studio Suite. The measured magnetic and electric values of the AL800 found in the previous section are used as input values for the CST simulations. In general the simulations consist of several coupled problems (steps). First, a non-linear magnetostatic problem with applied static bias field of a solenoid is solved to define the non-uniform internal magnetic field in the garnet. Second, a frequency domain (FD) problem is solved with this internal magnetic field applied to the dispersive garnet to define the RF field distributions and resonant frequency. Then, the μ'' corresponding to the calculated resonant frequency is applied to the garnet and this new FD problem is solved again to find the loss density distribution and peak thermal losses. These three steps are repeated at different levels of bias field until sufficient data is accumulated. In the final step, a thermal analysis is performed. Since all field and loss density distributions, and accelerating voltage amplitudes change during each Booster cycle, it is suitable for the CST transient thermal solver (TTS). However, we have to use the stationary thermal solver instead, because we do not have the TTS license. The peak RF losses in the garnet and the cavity walls are averaged over one Booster ramp to define the total thermal load. The specific ramps for frequency and field amplitude of the second harmonic cavity are taken into account, and the repetition rate is assumed to be 15 Hz. The stationary thermal losses in the ferrite derived this way are < 1 kW and the maximum loss density is 0.8 W/cm^3 for an accelerating voltage of 100 kV.

We had to make one more assumption for the stationary distribution of the loss density: although the loss density distribution changes with frequency, they are rather similar over the entire Booster cycle. So, we chose the distribution at 82.5 MHz shown in Fig. 6(a), to be representative of the local losses for any frequency in our range. The resulting temperature distribution is shown in Fig. 6(b). The maximum temperature in the garnet obtained in this thermal

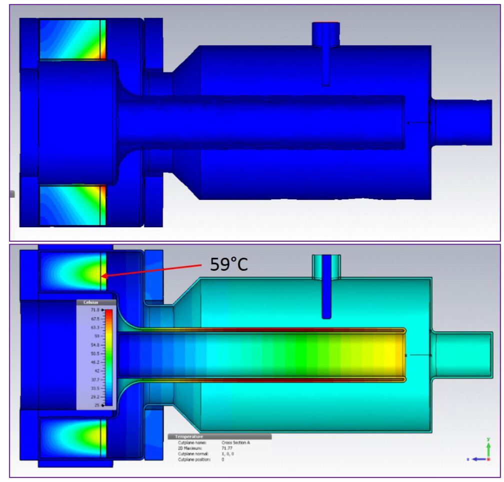

Figure 6: a) Loss density distribution used in thermal analyses. b) Temperature distribution in the cavity.

analyses is 59$_o$C, which is a very encouraging result because the Curie point is ~200°C for AL800.

CONCLUSION

A preliminary design of the RF cavity has been created and the thermal analysis shows very encouraging results. The next steps are: (a) create cuts in the shell of the RF cavity to mitigate eddy current effects that come from the magnetic bias field ramp; (b) design/build RF windows; (c) design/build higher order mode couplers; (d) connect the PA to a test cavity so that the voltage in the gap can be achieved; and (d) build a mock cavity for testing.

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