STATUS OF THE PERPENDICULAR BIASED 2ND HARMONIC CAVITY FOR THE FERMILAB BOOSTER*

C.Y. Tan†, J.E. Dey, K.L. Duel, J.C. Kuharik, R.L. Madrak, A. Makarov, W.A. Pellico, J.S. Reid,
G. Romanov, M. Slabaugh, D. Sun, I. Terechkine, Fermilab, Batavia, IL 60510, USA

Abstract

This is a status report on the 2nd harmonic cavity for the Fermilab Booster as part of the Proton Improvement Plan (PIP) for increasing beam transmission efficiency, and thus reducing losses. A set of tuner rings has been procured and is undergoing quality control tests. The Y567 tube for driving the cavity has been successfully tested at both injection and extraction frequencies. A cooling scheme for the tuner and cavity has been developed after a thorough thermal analysis of the system. RF windows have been procured and substantial progress has been made on the mechanical designs of the cavity and the bias solenoid. The goal is to have a prototype cavity ready for testing by the end of 2017.

INTRODUCTION

The design of the 2nd harmonic cavity for the Fermilab Booster is near completion, and the goal is to have it built by the end of 2017. Many computer simulations to refine the mechanical design, together with sub-component tests have been done to ensure the success of this project. The first batch of tuner rings has been received and is going through quality control tests. The Y567 tetrode has been tested at both the injection frequency (76 MHz) and extraction frequency (106 MHz). The RF windows have been procured and will be received soon. The bias solenoid has been designed and procurement of parts for building it has started. The mechanical design is undergoing final approval. This paper summarizes all the progress that has been made up to this point. More details can be found in the supplementary papers from this and recent conferences [1–5] and their citations therein. The mechanical model of the cavity without the higher order mode (HOM) cavity is shown in Fig. 1.

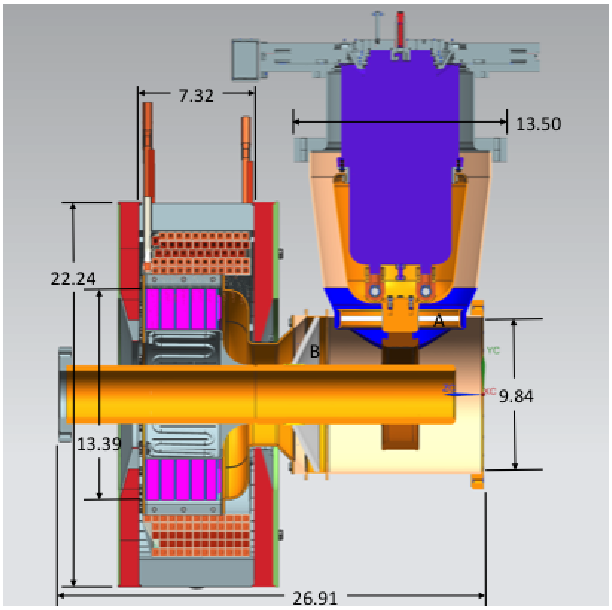

Figure 1: The 3D mechanical model of the cavity. Not shown is the HOM cavity that will be bolted to right side of the cavity in this figure. All dimensions are in inches. A and B are the ceramic windows.

MECHANICAL DESIGN

The geometry of the cavity has been driven by RF and heating simulations. Several mechanical design decisions were based on the need to disassemble the cavity completely should any part need maintenance or replacement. The mass of the solenoid is large compared to the cavity, so it rests on a linear guide that allows it to be slid away from the cavity. With the solenoid out of the way the tuner can be disassembled or moved to a better work location. The weight of the tuner is supported with rods and by stiffening the outer conductor shell. Conversely the stiffness of the outer shell is reduced due to it being divided into quarters to minimize the effect of eddy currents [6].

Minimizing loading on the two brazed ceramic windows drives the need to carefully consider how the cavity is supported, and presents challenges to disassembly since they permanently fix the inner and outer conductors together.

The tuner is a stack of garnet-alumina assemblies (called tuner rings). A tuner ring assembly consists of 8 sectors of garnet glued together to form a flat cylinder, which is then glued to an alumina ring. The gluing is done with a thermally conductive epoxy that with squeezing and clamping can be reduced to a final thickness of approximately 0.005". The epoxy that is used is Stycast 2850FT with catalyst 9 [7]. Final machining is performed on the joined assembly to achieve a tightly controlled profile. An example of one of the completed tuner rings is shown in Fig. 2.

RF Windows

There are two ceramic (99.5% pure alumina) RF windows for this cavity: window A separates the PA side (air) from the cavity, and window B separates the tuner side (air) from the cavity (see Figures 1 and 3). Both windows will be welded to the cavity. Because the center conductor portions of these two windows are either a solid copper cylinder (window A) or copper beam pipe with 0.393" thick walls (window B) the

---

* Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

† cytan@fnal.gov

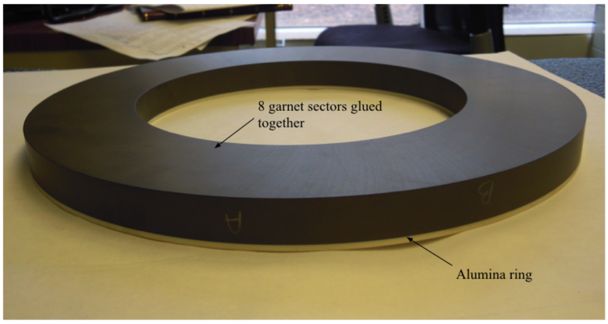

Figure 2: A completed garnet ring consists of 8 garnet sectors glued together onto an alumina substrate.

RF generated heat in the ceramic parts will be adequately carried out by these center conductors to adjacent water cooled copper parts as well as by the outer conductor. Simulations showed that the temperature increase in the ceramic window is under 10°C (1°C for window A and 6°C for window B). Therefore, there is no dedicated water cooling designed for the ceramic windows at the present time.

To solve the problem of thermal expansion differences between the ceramic disks and the heavy copper parts during brazing, a thin copper sleeve was designed. Each ceramic disk will be brazed to a sleeve and the sleeve will be brazed to the heavy copper part. At the time of this report, all the copper parts have been fabricated and ceramic disks have been made and rough ground.

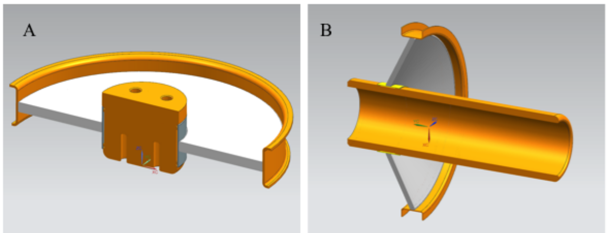

Figure 3: The mechanical model of the windows A and B. The ceramic parts are rendered in either white or grey. The copper parts are rendered in gold.

TUNER DESIGN

Frequency control of the cavity is accomplished by using magnetically biased AL800 garnet in the cavity tuner. The bias field is generated by a specially designed magnetic system. Fig. 4 shows a sketch of the tuner.

The RF shell of the tuner, where the tuner rings are mounted, is made of three millimeter thick stainless steel. To minimize RF power loss in the walls, the inner surface of the shell is coated with 25 µm thick copper. To minimize the effect of eddy currents in the shell, it is constructed from four segments electrically insulated from one another [6]. The magnetic system consists of a DC winding, which sets the lowest frequency of the cavity, corresponding to injection, and an AC coil, which is fed by a pulsed power supply with the time profile of the current that ensures the desired frequency ramp. Finally, there is a flux return, which forms the magnetic field in the volume of the tuner filled with garnet rings. Because garnet has strong non-linear magnetic properties, it must be properly accounted for when the magnetic circuit of the tuner is configured. Failure to do so can result in unacceptably high RF losses in the garnet ring that is the closest to the accelerating gap. Knowing the magnetization properties of the garnet is the key factor that can help in avoiding this problem. Magnetic shims, made of garnet material, can also help with field uniformity.

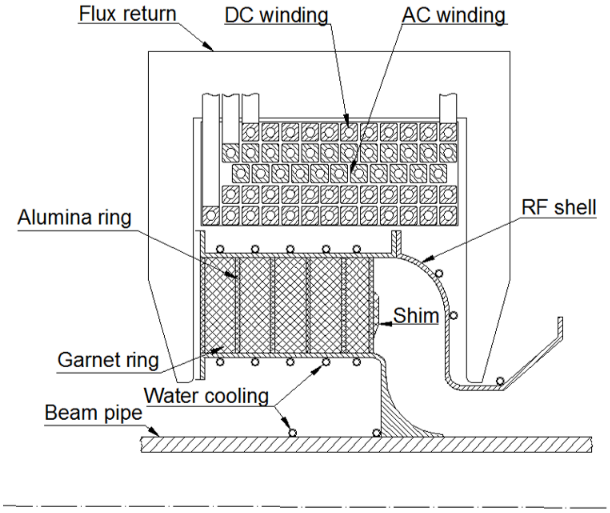

Figure 4: This is the cross section of the tuner with the bias solenoid surrounding it.

Heating and Cooling

As RF loss in the garnet is quite significant, heat removal becomes one of the major problems to address in the tuner design. To maintain the temperatures of the garnet that fills the tuner to acceptable levels, it is made of five garnet rings separated by alumina discs, which have much better thermal conductivity. Low loss, high thermal conductivity grease [8] will be used to avoid air gaps between the garnet rings and the shell.

The shell is made of four insulated segments, which greatly helps in making the shell transparent to the AC magnetic field. Nevertheless, because the thermal conductivity of stainless steel is quite poor, heating of the shell by eddy currents cannot be neglected. Strategically placed cooling lines help to avoid overheating of the shell. Fig. 5 shows the temperature map of the tuner.

The maximum temperature in the garnet reaches almost 100°C. Since the Curie temperature of the AL800 garnet is just 200°C, one can expect significant change of the magnetic properties as the temperature rises. Fortunately, the saturation magnetization drops with temperature for this material. As a result, the magnetic field corresponding to the gyromagnetic resonance becomes lower thus reducing the risk of anomalous RF loss in the material. Furthermore, the magnetic bias field that is needed to reach the required

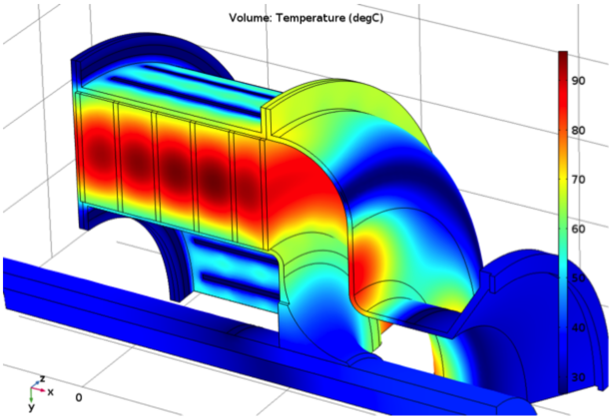

Figure 5: The temperature map in the tuner that takes into account both the RF losses in the garnet and alumina rings and the eddy current loss in the shell.

RF permeability levels in the garnet gets lower, so a lower current is needed to get a goal frequency. These two effects help to avoid the run-off effect.

SIMULATION RESULTS

At this stage of the cavity design, the focus was on the mechanical details that inevitably affect RF performance. The requirements of the parts fabrication, cavity assembly, cooling issues, etc. forced us to move away from the optimal set of parameters that maximized the RF performance. The changes to the mechanical design were implemented successively into the RF model. At each step, the RF performance was checked and compensations were made as needed. The mechanical design was also changed with input from the RF verifications. During this process, some mechanical flaws were detected and eliminated.

Some critical issues related to the input/tetrode part of the cavity were fixed. We had to move the tetrode up by 15 mm to create sufficient room for cooling tube connections at the bottom of the tetrode. We developed a special socket for the tetrode to reduce the electrical length of the tetrode transmission line, optimized its shape and the shape of the internal “shroud” to reduce stored energy and restore the cavity’s tuning range. It was proposed to use the cooling tubes inside the tetrode transmission line made of PEEK material. The simulations with PEEK tubes ($\epsilon = 3.3$, $\mu = 1$, $\tan\delta = 0.003$) and distilled water ($\epsilon = 78.4$, $\mu = 1$, $\tan\delta = 0.005$ at 100 MHz and 25°C) inside them confirmed the acceptability of this proposal because the electric field is very weak at the tube location and is almost parallel to the tubes. Thus, the field enhancement on the ceramic and water boundaries is minimal. The frequency shift and the thermal losses in the materials are negligible too.

The simulations with the slotted tuner shell and the garnet disks that were the actual engineering dimensions revealed a concern: the E-field has been enhanced at the boundaries of the copper-garnet-air and copper-alumina-air junctions (“triple points”, see the example in Fig. 6).

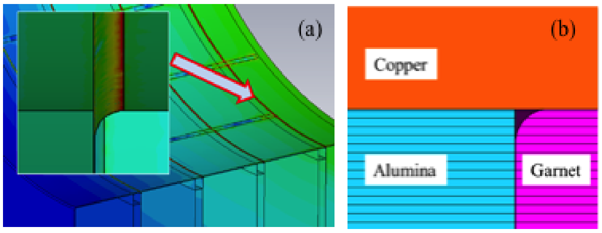

Figure 6: (a) Surface field enhancement on the garnet edge and (b) schematic view of the junction.

In order to mitigate this problem, we will use the same thermal grease that will be used to fill in any air gaps in the tuner. In order for the grease to reduce the field enhancement, we have found a grease that has a high dielectric constant $\epsilon \approx 6$ [8]. Using this grease, the field enhancement on the material boundaries is reduced by 6 to 7 times (see Fig. 7) from our simulations.

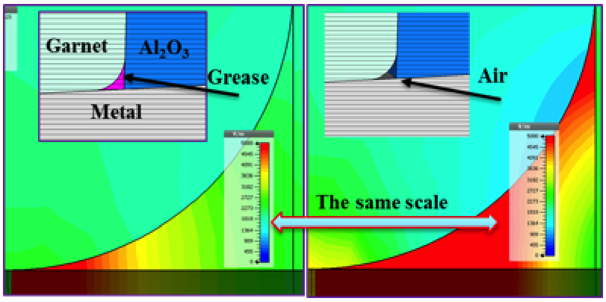

Figure 7: Electric field in the gap with and without grease filling.

CONCLUSION

The design and construction of the cavity is progressing well. Critical parts such as the RF windows will be delivered soon. Tests on the witness pieces of the garnet rings indicate that their permeabilities have met technical specifications. Quality control tests of the garnet rings will proceed soon. It is projected that all components will be delivered by the end of 2017, and thus a prototype cavity will be ready for testing by then.

REFERENCES

[1] C.Y. Tan *et. al.*, “Design of a perpendicular biased 2nd harmonic cavity for the Fermilab Booster”, in *Proc. IPAC’16*, Busan, Korea, May 2016, paper MOPMW027.

[2] R.L. Madrak *et. al.*, “Progress on the design of a perpendicularly biased 2nd harmonic cavity for the Fermilab Booster”, in *Proc. NAPAC’16*, Chicago, USA, 2016, paper MOPOB28.

[3] R.L. Madrak *et. al.*, “Measurements of the properties of garnet material for tuning a 2nd harmonic cavity for the Fermilab Booster”, in *Proc. NAPAC’16*, Chicago, USA, 2016, paper MOPOB29.

[4] I. Terechkine *et. al.*, “Tuner of a Second Harmonic Cavity of the Fermilab Booster”, presented at IPAC’17, Copenhagen, Denmark, May 2017, paper THPIK113, this conference.

[5] I. Terechkine et. al., "Static Magnetization Properties of AL800 Garnet Material", presented at IPAC'17, Copenhagen, Denmark, May 2017, paper THPIK116, this conference.

[6] I. Terechkine, "Eddy currents in the tuner of the 2-nd harmonic booster cavity", FNAL TD note TD-17-003, April, 2017.

[7] Henkel Adhesives, Loctite Stycast 2850FT, `http://www.henkel-adhesives.com/product-search-1554.htm?nodeid=8802585018369`

[8] MG Chemicals, 8616-Super Thermal Grease II, `http://www.mgchemicals.com/products/greases-and-lubricants/thermal-greases/super-thermal-grease-ii-8616`