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PROGRESS ON THE CONSTRUCTION OF THE PERPENDICULARLY BIASED 2ND HARMONIC CAVITY FOR THE FERMILAB BOOSTER*

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Abstract

A perpendicularly biased tuneable 2nd harmonic cavity, designed for the Fermilab Booster, is being assembled for testing this summer (2018). The cavity will work at twice the frequency of the fundamental cavities, and will be on only during the injection and transition (or extraction) periods. The main reason for adding this cavity is to improve beam capture and reduce losses as required by Fermilab's Proton Improvement Plan (PIP). After three years optimization and study, the cavity design has now been finalized and all constituent parts have been received. We report on the cavity final design and on the status of the construction.

INTRODUCTION

Since our last report on the status of this cavity [1], its design has been finalized and all parts have been received. Some plating, welding, and brazing remains to be done, but the cavity is now in the early stages of assembly.

Cavity Overview

A model of the finalized cavity design is shown in Fig. 1. The cavity is perpendicularly biased, meaning that the bias magnetic field for tuning is perpendicular to the RF magnetic field. When the appropriate ferrite is used, in this case National Magnetics [2] AL-800 garnet, the Q and shunt impedance are higher than one typically sees in a parallel biased cavity. This is due to the inherently higher Q of the tuning material which is biased to near saturation. (See, for instance, [3]).

Although perpendicularly biased cavities have the advantage that RF losses are lower, the tuning range for this particular cavity is large and there were many technological challenges to overcome. Some of the concerns are 1) Achieving the required tuning range using a realistic bias magnetic field, 2) Keeping the magnetic field in the tuner as uniform as possible (including minimizing the effect of eddy currents), 3) Taking into account higher local permeability and heating of the garnet in areas of lower magnetic field, 4) Including the power amplifier/tetrode in the RF model to take into account the impact of the additional volume and tetrode output capacitance on the cavity tuning range, 5) Choosing a design concept for the tuner that would simplify removal of the heat generated by both the RF and eddy currents, and 6) Finding an

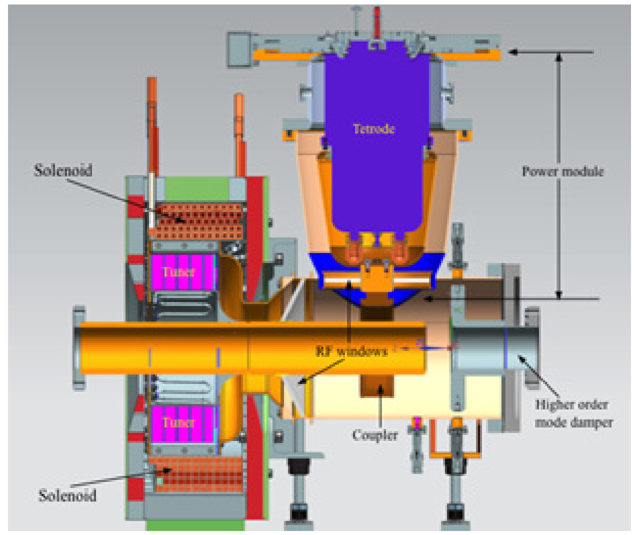

Figure 1: Model of the finalized cavity design. The length is 33.21 in. from flange to flange.

assembly technique that avoids the use of environmentally unfriendly materials (i.e. BeO) for the heat removal.

RECENT DEVELOPMENTS AND TESTS

A detailed report on the cavity design and related measurements may be found in [4]. Certain aspects of the cavity were only recently finalized and not discussed previously in this conference series, so we discuss them here.

Tuner Shim Ring

Regions of high RF power loss are those where the bias magnetic field is at its weakest. Simulations show a sharp increase in magnetic permeability where the tuner transitions from being loaded with garnet to being empty. To improve the field quality in this area, a shim ring was added to the front of the tuner stack. The shim ring, like the other garnet rings, is made from eight sectors of garnet epoxied together and to a full alumina ring. (Rings are made from sectors because the oven at the vendor cannot accommodate a full ring.) A photograph is shown in Fig. 2. Its position in the cavity is shown in Fig. 3. With the addition of the shim, the minimum value of the magnetic field in the garnet increases from 33 Oe to 67.3 Oe, and there is no longer any gyromagnetic resonance within the material.

Thermal analysis using the initial shim design, which had rounded edges, showed anomalous heating of the top alumina disk due to an elevated electric field between the shim and the cavity center conductor. The maximum value of the radial component of the electric field on the surface

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of the alumina at the triple point is ~40 kV/cm. This value was reduced to 27.5 kV/cm by reshaping the shim so the edges are angled, as shown in Fig. 4. An added advantage is that the minimum bias magnetic field is slightly increased from 67.3 Oe to 69.3 Oe and the localized permeability decreased from 12 to 11.75.

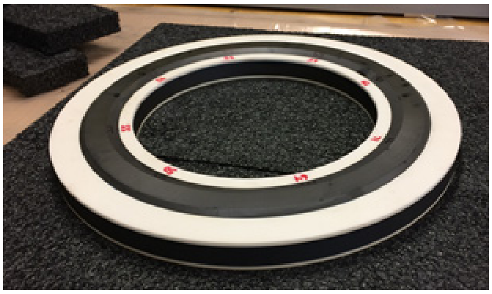

Figure 2: Tuner Shim Ring. The full ring consists of one ring of alumina on the bottom, one garnet ring, a second ring of alumina, and finally the angled shim ring.

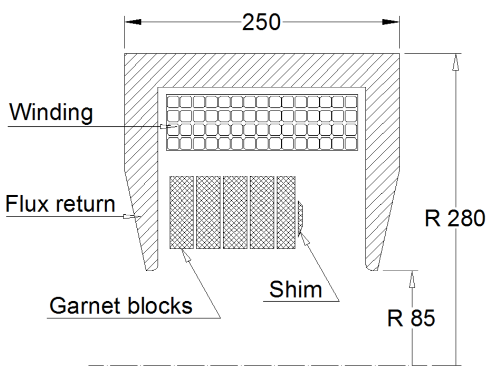

Figure 3: Position of the shim in the cavity. All dimensions in mm.

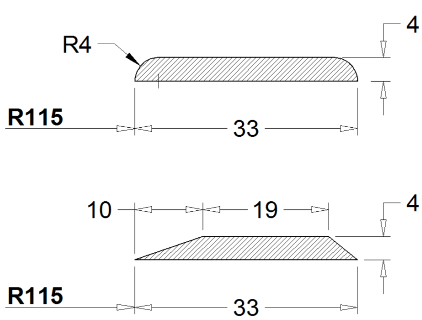

Figure 4: Initial and final shim designs. All dimensions in mm.

Solenoid and Bias Supply

The solenoid winding has three coils. Depending on the chosen scheme to power the magnet, the coils can be connected in series or independently. The initial plan was to use separate DC and AC coils, but in the final design the three coils are connected in series for a total of 59 turns, and will be powered by one bias supply. The DC current at injection is 139 A so that the tuner is biased for a cavity resonant frequency of 75.7 MHz. At ~106 MHz the current will be ~600 A.

Due to funding constraints in FY2018, the complete bias supply has not yet been purchased. The bias supply consists of four Performance Controls, Inc. GA301-VP amplifiers in parallel, and will be upgraded in the future. So initially, due to the limited amount of current from the existing supply, the cavity will be operated only for the first 3 ms at the most critical loss point, which is injection/capture.

Power Amplifier Tests

According to specifications, the Y567b tetrode used in the power amplifier (PA) can operate up to 108 MHz with 150 kW of power dissipated in the anode. Still, it is desirable to verify this by power testing the PA at our operating frequencies. In previous tests at 76 MHz we had obtained an output power of ~140 kW (the cavity requires 52 kW at injection). Before power testing at 106 MHz (the extraction frequency) it was necessary to modify the drive part of the PA.

A cathode resonator is used to match the 50 Ω output impedance of the TOMCO 8 kW solid state driver amplifier (SSD) to the tetrode input capacitance. It is a shorted transmission line with inductive impedance opposite that of the tetrode input capacitance, and is resistively loaded to make the resonance very broad to accommodate the ~30 MHz frequency swing. Its dimensions were chosen so that the reflected power was minimized at 76 MHz, where the cavity's shunt impedance is lower, but still acceptable at 106 MHz. After constructing the first cathode resonator, it was found that its response at 106 MHz was barely acceptable and not as predicted by the modelling. The trend was as if the tetrode input capacitance was frequency dependent. The cathode resonator was then redesigned so that the reflected power was minimized at 91 MHz instead of 76 MHz. Though the cavity will never operate at 91 MHz, this configuration produced acceptable amounts of reflected power at both 76 and 106 MHz.

With the redesigned cathode resonator, the power amplifier was tested at both 76 and 106 MHz. At 76 MHz a quarter wave output (anode) resonator was used. At 106 MHz, a quarter wave resonator would have been impractically small, so a three quarters wave resonator was used. A water cooled 50Ω load is loop-coupled to the anode resonator to absorb the output power, which is measured calorimetrically. For several values of DC anode voltage, the drive power was increased until the screen current was 300 mA. We obtained 110 kW and 145 kW maximum output power at 76 MHz and 106 MHz, respectively. Fig. 5 shows various quantities for the 106 MHz test. Details of the PA tests are documented in [5].

HOM Damping Cavity

To avoid any beam instabilities which could be caused by higher order modes, we have added a damper based on the design by Smythe [6]. Dimensions were initially calculated semi-analytically and then optimized using CST Microwave Studio, the goal being to suppress the HOMs while minimizing any effects on the fundamental. The HOM cavity is attached adjacent to the gap of the main cavity and can be seen in Fig. 1. Four damping loads are attached in parallel.

The fundamental operating mode and HOM 1, 2, and 4 (with the HOM cavity connected but without damping resistors) are shown in Fig. 6. The HOMs are well separated from the fundamental mode by >30 MHz, however, the Q of the fundamental is lowered with the addition of the HOM cavity. Its impact is greatest at the high frequency end where the Q is lowered by 10%.

The strongest HOM mode is HOM2. When the damping resistance is 20Ω (four 80Ω resistors in parallel), the shunt impedance of HOM2 at injection is reduced from 150 kΩ (without damping resistors) to 2 kΩ.

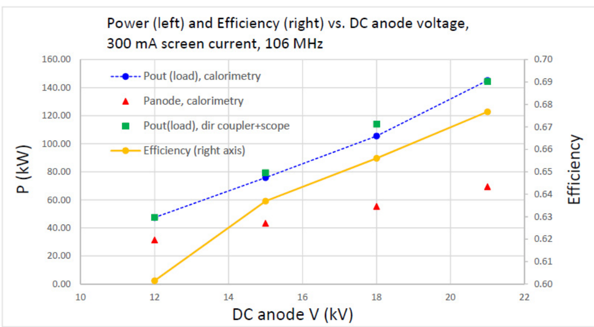

Figure 5: Output power, power dissipated in the anode, and efficiency for Y567b tests at 106 MHz.

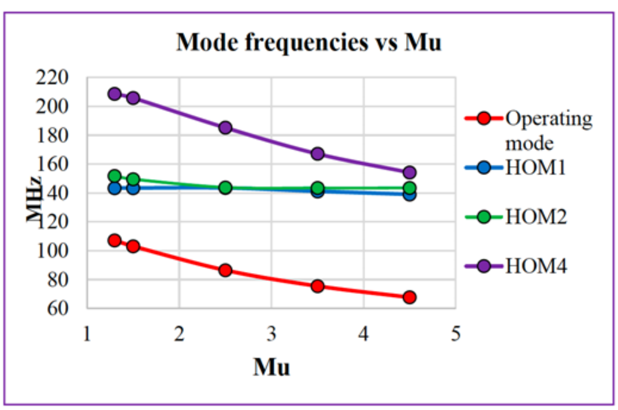

Figure 6: The behavior of the cavity modes with the HOM cavity but without damping resistors.

PARTS AND CONSTRUCTION

Apart from the solenoid, which is currently being fabricated in-house, all cavity parts have been received. In particular, the full set of garnet/alumina rings are on-hand. These consist of five standard rings (one of which is a spare) and two shim rings (also one spare). Each individual ring has been tested in a specially designed cavity as a function of bias field. Small "witness pieces" corresponding to each garnet sector and cut from near it in its mother brick, have also been tested to help with the quality control. The details of these two tests are discussed in [7].

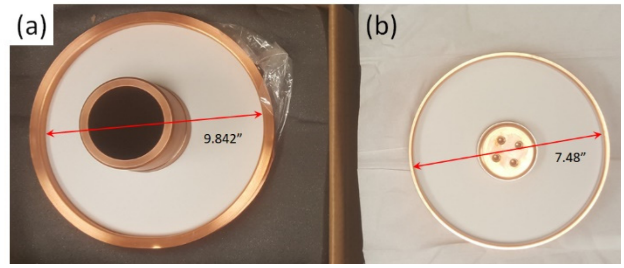

Figure 7(a): Conical tuner window, and (b) flat input window.

The alumina RF windows, shown in Fig. 7, have been fabricated and brazed to their copper center and outer conductor sleeves, and have been successfully leak-tested at Fermilab. There are two flat windows and two conical windows. One of each will be used in the cavity, and the remaining windows are spares. The former is used to isolate the PA volume and the latter, the tuner volume, from the rest of the cavity. This is so that a PA may be changed without breaking the cavity/beam vacuum, and so any outgassing materials used in the tuner construction do not contaminate the vacuum space.

Key copper/stainless steel parts of the cavity are shown in Fig. 8. The tuner outer conductor, which is made of stainless steel and divided into four sections to reduce eddy currents, will be copper plated on the inside, since this side contains the RF.

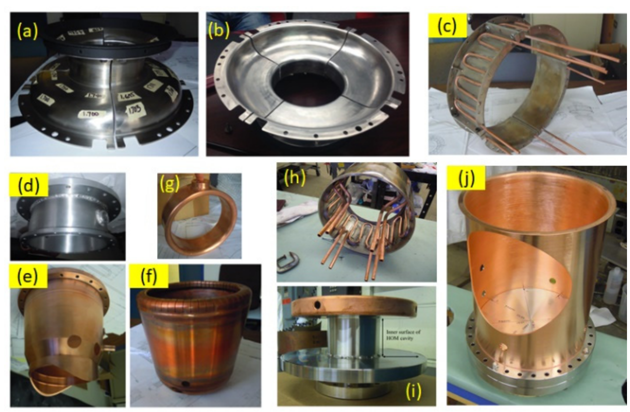

Figure 8: Copper and stainless steel parts of the cavity. (a) and (b): Garnet-free region of the tuner outer conductor. (c): Section of the tuner outer conductor which will contain the garnet. Both parts of the tuner outer conductor are split into four azimuthal sections to reduce eddy currents. (d) and (e): Two outer conductor sections of the PA part of the cavity. They contain ports for airflow, water cooling, monitoring, and the anode DC voltage input. (f): The PA center conductor which supports the tetrode and makes electrical contact with its anode. (g): The ring which capacitively couples the PA to the cavity. (h): The tuner center conductor with cooling lines. (i): The HOM damper cavity. (j): The main cavity outer conductor (vacuum section). The PA section shown in (e) will be attached at the large hole in the OD.

ACKNOWLEDGEMENTS

Many thanks to National Magnetics for the great effort put forth and the results achieved in the challenging task which was the manufacture of our garnet and the assembly of the tuner rings.

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