TUNER OF A SECOND HARMONIC CAVITY OF THE FERMILAB BOOSTER*

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Abstract

Introducing a second harmonic cavity in the accelerating system of the Fermilab Booster promises significant reduction of the particle beam loss during the injection, transition, and extraction stages. To follow the changing energy of the beam during acceleration cycles, the cavity is equipped with a tuner that employs perpendicularly biased AL800 garnet material as the frequency tuning media. The required tuning range of the cavity is from 75.73 MHz at injection to 105.64 MHz at extraction. This large range necessitates the use of a relatively low bias magnetic field at injection, which could lead to high RF loss power density in the garnet, or a strong bias magnetic field at extraction, which could result in high power consumption in the tuner's bias magnet. The required 15 Hz repetition rate of the device and high sensitivity of the local RF power loss to the level of the magnetic field added to the challenges of the bias system design. In this report, the main features of a proposed prototype of the second harmonic cavity tuner are presented.

INTRODUCTION

Tunable second harmonic accelerating cavity of the Booster, which is in the development stage at FNAL, promises significant reduction of beam loss during injection, transition, and extraction periods [1]. The ramp of the resonant frequency of the cavity must closely follow the change of proton velocity during the accelerating cycles in the Booster, which has a 15 Hz repetition rate. The cavity consists of a power amplifier (PA) section and a tuner; the resonant frequency is controlled by a bias magnetic field in the gyrotropic material (AL800 garnet) in the tuner. The bias system of the tuner includes solenoid-type windings and a flux return that reduces the fringe magnetic field and improves the uniformity of the bias field in the garnet. To eliminate the impact of the eddy currents in the flux return during magnetic field ramps, it is assembled using thin silicon steel laminations. Eddy currents in the copper-coated stainless steel RF shell of the tuner generate heat comparable to the RF power loss in the garnet [2]. Cooling the shell becomes a design issue that must be properly resolved. Furthermore, the redistribution of the magnetic field in the tuner due to the eddy currents in the shell can locally move the working point of the garnet closer to the gyromagnetic resonance, which in turn increases the power loss [3].

In this paper, a design concept of the RF tuner for the prototype of the cavity will be presented. The temperature of the garnet material in the tuner will also be evaluated.

MAGNETIC SYSTEM OF THE TUNER

Figure 1 shows an artistic view of the second harmonic accelerating cavity with the end flange of the accelerating gap removed.

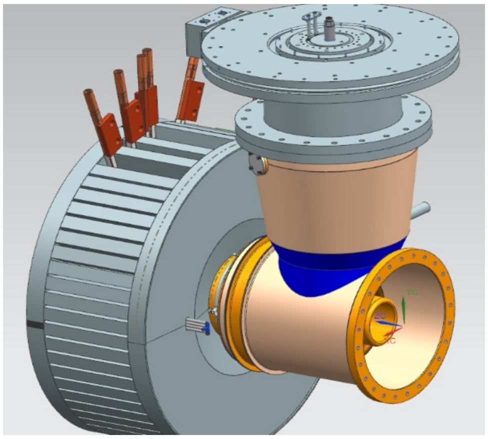

Figure 1: Tunable second harmonic cavity.

The tetrode-based PA is capacitively coupled to a quarter-wave-type coaxial resonator that has an accelerating gap at the open end and is equipped with a tuner at the shorted end. The frequency tuning is accomplished by controlling the inductance of the shorted coaxial line, which is filled with AL800 garnet, by changing the bias magnetic field. A schematic drawing of the tuner is shown in Fig. 2.

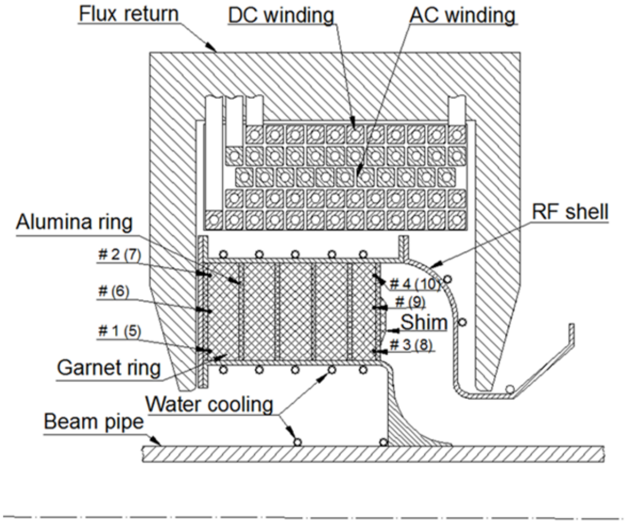

Figure 2: Schematic view of the tuner.

The initial concept of the bias magnetic system was reported in [4]. In the latest version of the design, the bias

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magnetic field is generated using two independent coils, both wound using 10.4 mm square copper wire with Ø5.8 mm hole for water cooling. The outer eleven-turn winding is used to bring the bias magnetic field to the level that sets the resonant frequency required at injection. This coil will be fed by DC current $I_{inj} \approx 745$ A. The expected power deposition in this coil is ~2.6 kW; this heat will be handled by water cooling. The inner 48-turn coil will work in the pulsed mode with the maximum current reaching ~600 A in 33.3 ms after the injection. The average power deposited in this coil is ~3.5 kW. To remove this heat, two cooling circuits must be used, so the pulsed coil will consist of two separate windings: 25 turns and 23 turns.

RF POWER LOSS IN THE TUNER

The rings of garnet are mounted inside the RF shell of the tuner, which is electrically connected to the PA section of the cavity. As the Curie temperature of AL800 garnet is just 200°C, it was important to make sure the temperature of the garnet could be kept below ~100°C. There are two major sources of heating in the tuner: RF loss in the garnet and alumina rings and heat deposition in the walls of the RF shell of the tuner due to eddy currents.

The RF loss in the tuner was evaluated in [2]. As the thermal conductivity of garnet is quite poor, alumina rings are placed between the ring-type blocks of garnet to improve the heat removal. Furthermore, the thickness of the garnet rings was optimized to limit the maximum temperature. As a part of the proposed heat management solution, thin layers of thermally conductive grease will be used to fill in the gaps between the alumina and garnet rings and the surface of the shell, which will be cooled with water.

It was also found in [2] that a significant local change of the bias magnetic field can take place due to strong non-linearity of the magnetic properties of the garnet. The presence of a 50-mm gap between the pole of the flux return and the nearest garnet ring (the shim; see Fig. 2) leads to a steep spatial change of the magnetic flux density in the garnet, which can be amplified by the correspondingly steep change of the material permeability [5]. If the magnetic field comes close to the gyromagnetic resonance condition, local power loss increases dramatically. To mitigate this effect, a shim, shaped to improve uniformity of the field, will be installed in the gap. Studies made in [6] have demonstrated that the anomalous RF power loss can be significantly reduced this way.

EFFECTS OF EDDY CURRENTS IN THE RF SHELL OF THE TUNER

The RF shell of the tuner must be sufficiently transparent to the ramping bias magnetic field that defines the required time profile of the frequency during accelerating cycles. Because the weight of the garnet and alumina rings is significant, the design of the shell must be structurally sound. Three-millimetre-thick stainless steel sheets are used to form the shell. Its inner surface must be copper-coated to reduce the RF power loss; the coating thickness should be several skin depths at the lowest frequency. As the skin depth in copper at 75 MHz is ~7.6 µm, the coating thickness of ~25 µm is used.

Eddy current in the shell can change the spatial profile of the bias magnetic field and also heat the shell. Although the main harmonic in the frequency spectrum of the bias field is 15 Hz, the impact of several higher order harmonics in the field frequency spectrum cannot be neglected.

Bias Magnetic Field Spatial Profile Change

If the RF shell is made azimuthally symmetric, the field distortion and power loss in the shell are so significant that this approach to the design is mostly prohibitive. To break the axial symmetry of the eddy currents in the shell, it is designed to be assembled from four insulated segments. With the TEM RF mode of oscillations in the tuner, it is most natural to use longitudinal slots that do not lead to significant changes of the impedance. Figure 3 shows a pattern of eddy currents in one of the segments of the shell. The addition of longitudinal slots in the cylindrical part of the shell can further restrict circulation of the eddy current in the shell. In [3], several cases that differed in the geometry and the number of the longitudinal slots in the shell were compared.

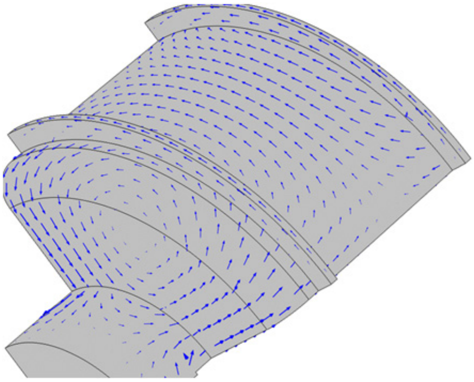

Figure 3: Eddy current pattern in the shell.

In [3] and [4], it was assumed that the bias system would have only one winding, so only one (pulsed) bias power supply was required. In this case, the rise of the bias magnetic field before it reaches the “injection” level leads to noticeable changes in the spatial distribution of this field. Figure 4 shows the transfer functions of the bias system for several “key” locations in the garnet rings for the “setting” current rise rate of 40 A/ms. The corresponding bias current time profile is shown in Fig. 5. The start of injection in this case is at t = 6 ms; at this moment, the time derivative of the bias current dI/dt = 0.

While the transfer functions for the ideal shell (with no eddy currents) would not change in time, clearly this is not the case for the electrically conducting shell. At the locations near the closed end of the shell (points 1, 2, 5, 6, and 7 in Fig. 2) the impact of the eddy current is the most pronounced. Before the moment of injection, eddy currents in the shell increase the magnetic field near each edge of the segments (points 1 and 2) and partially shield

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the field at the points in the in the middle section of the segments (points 5 to 7; shown in parenthesis in Fig. 2). Effectively, the field is pushed in the slots between the segments of the shell. The change of the magnetic field in time at the points located in the block closest to the accelerating gap (points 3, 4, 8, 9, and 10) are weaker because the wall with the eddy currents is relatively far away.

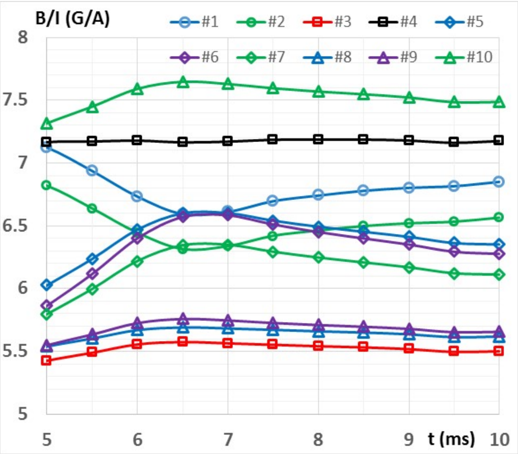

Figure 4: Transfer functions at the injection; four insulated segments in the shell.

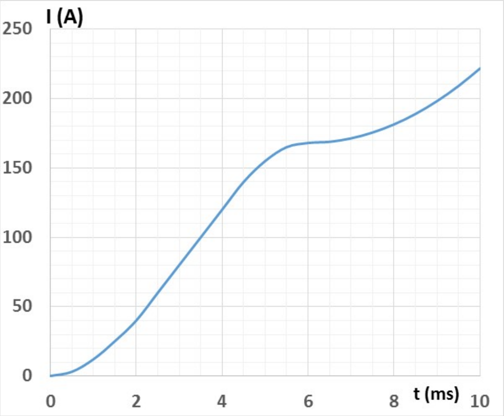

Figure 5: Bias current time profile.

Near the closed end of the shell, the bias magnetic field is azimuthally non-uniform at injection, but its minimum value is well above the gyromagnetic resonance. At the opposite end of the tuner, the field is essentially axially symmetric. Although the minimum field at this location is closer to the gyromagnetic resonance, it still lies comfortably within the acceptable region.

As was shown in [3], dividing the shell into more segments or adding longitudinal slots in the cylinders of the shell results in just modest improvement in the eddy current impact.

To eliminate the problem of the bias magnetic field distortion during injection, when this distortion is the most dangerous, a DC winding, shown in Fig. 2, is added to the magnetic system that generates the needed “injection” bias field. Eddy currents generated later in the cycle still heat the shell, but have relatively modest impact on the frequency ramp rate.

RF Shell Heating by Eddy Currents

The eddy current heating power is ~150 W per one segment of the shell. Although it is a seemingly small amount, it can lead to significant local temperature rise because of the poor thermal conductance of stainless steel. The shell cooling must be arranged to overcome the local overheating. Figure 6 shows the temperature map in the tuner for the case when the heat was generated both by the RF field in the garnet and alumina rings and the eddy currents in the shell. Cooling circuit locations in this case were optimized to limit the maximum temperature to a level below 100°C.

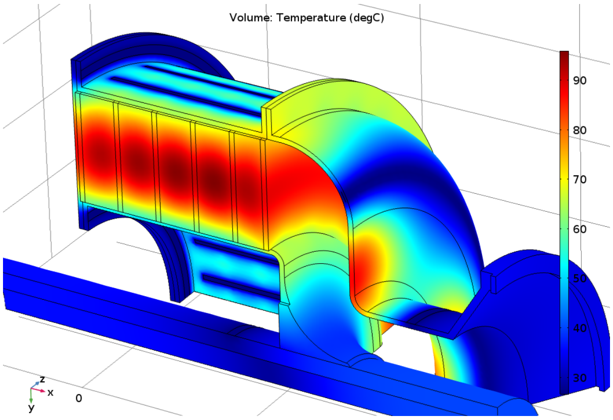

Figure 6: Temperature map in the tuner; RF power loss in the garnet and alumina rings and eddy current heating of the shell are taken into account.

The magnetic properties of the AL800 garnet can significantly change as the temperature approaches the Curie temperature of the material (200°C). As the saturation magnetization of the material drops with the temperature, a smaller bias field is needed to reach the same RF permeability (which defines the resonant frequency). This results in lower eddy current losses. Similarly, as the gyromagnetic frequency drops following the saturation magnetization [6], the RF power loss also becomes smaller. Based on these (quite favourable) tendencies, it is possible to conclude that the temperature dependence of the saturation magnetization of the AL800 material will not lead to the onset of the run-off effect.

CONCLUSION

A second harmonic tunable accelerating cavity is in development stage at Fermilab. The tuner of the cavity employs perpendicularly biased AL800 garnet material. A four-segment approach to the design of the tuner’s RF shell as well as the use of an additional DC winding to set the bias field at injection help to mitigate the negative impact of eddy currents in the shell. A cooling scheme was designed to limit the maximum temperature in the garnet rings of the tuner to below 100°C. The temperature behaviour of the magnetic properties of the material works in the favourable direction to prevent dangerous run-off situations from happening.

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