ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMF003

DYNAMIC TUNING OF THE APS-U BOOSTER 5-CELL CAVITIES*

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Abstract

The booster synchrotron for the APS-U is being upgraded to accommodate high-charge bunches, up to 20 nC, for extraction into the MBA lattice. The booster is required to operate at 85% efficiency in order to achieve bunch swap-out into the storage ring. In order to compensate for significant beam-loading effects as well as support a frequency ramp to achieve higher efficiency, a ferrite tuner is being considered to dynamically adjust the cavity frequency. A tuner design will be presented that spans 60 kHz and utilizes a low-loss YIG garnet similar to that used in the Recycler Ring at Fermilab.

INTRODUCTION

The booster for the APS-U will increase the injected beam energy of a 20 nC charge, or 16mA beam current, from ~450 MeV to 6 GeV at extraction. However, a significant beam-induced voltage is produced on resonance in the five-cell booster cavities which dramatically reduces the booster extraction efficiency to well below 85%. To compensate for this, various options have been investigated [1]. One promising scenario proposes detuning the cavity by -30 kHz at injection from the nominal 352 MHz, while returning close to -2 kHz detuning for optimal tuning at extraction to avoid excessive rf power requirements. This has been shown in elegant [2] simulations to dramatically improve the booster efficiency [1].

To increase booster efficiency, it is also desired to inject into the booster on-momentum and extract approximately -1% off-momentum. This requires an rf drive frequency ramp with a frequency at injection that is -30 kHz relative to the frequency at extraction [3]. This brings the total cavity detuning range to approximately 60 kHz.

To accommodate the total frequency range across the booster cycle, two ferrite tuners for each five-cell booster cavity are being explored to nominally span 60 kHz. The design uses perpendicularly biased ferrites as described in [4-6]. The concept is based upon tuners that are currently in operation in the Recycler Ring at Fermilab [7].

TUNING CURVE

The internal geometry of the ferrite tuner, shown in Fig. 1, utilizes magnetic coupling to extract energy from the cavity followed by a shorted coaxial transmission line loaded with a perpendicularly biased ferrite. The tuner response curve, shown in Fig. 2, is dependent, in part, upon the magnitude of the coupling of the tuner with the cavity, as well as the electrical length of the tuner assembly [8]. The greater the coupling, the greater the frequency shift of the cavity. In addition, the interaction increases significantly as the electrical length of the tuner approaches $\lambda/2$ as shown at the locations of rapid changes in frequency in Fig. 2.

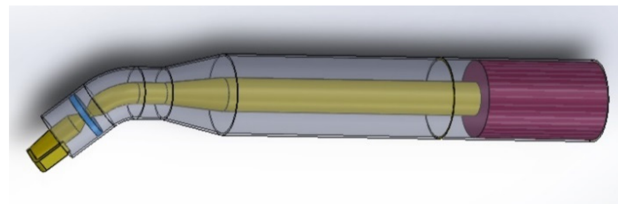

Figure 1: Internal tuner geometry with ceramic window and ferrite.

As the interaction increases, the field strength and the losses in the tuners also increase. This represents the limiting behaviour for the maximum frequency shift attainable by the tuners. In Fig. 3, resonance behaviour is evident as the power loss density rises dramatically at values of permeability where the slope of the frequency change increases significantly at intervals of a half wavelength.

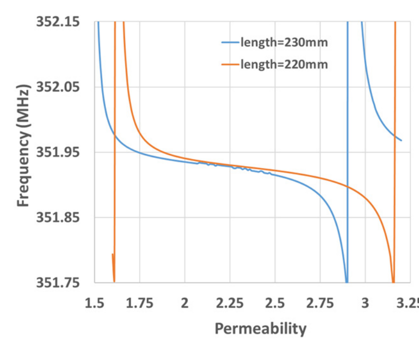

Figure 2: Frequency interaction with tuner as ferrite permeability changes for various ferrite lengths.

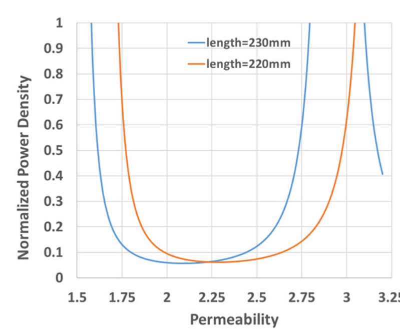

Figure 3: Normalized power loss density in the ferrite for various ferrite lengths.

Losses increase in the tuner due to the increasing electromagnetic field levels near the tuner resonance. Losses

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also increase near the resonance of the ferrite material, or gyromagnetic resonance, where the applied magnetic field interacts strongly with the natural resonant motion of the magnetic dipoles of the ferrite. This effect can be seen in [7] where the quality factor of the tuner declines rapidly for a given bias level. For this reason, perpendicularly biased ferrites are operated in, or close to, saturation, well beyond gyromagnetic resonance.

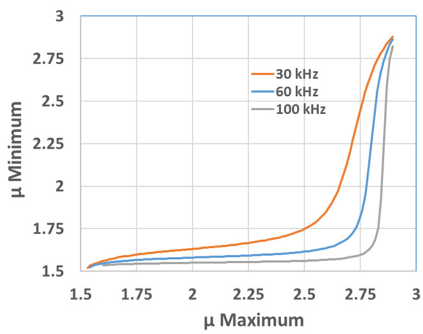

Figure 4: Range of permeability from μ_{min} to μ_{max} to achieve the selected tuning range of 30, 60, or 100 kHz.

TUNER DESIGN

The tuner design is intended to minimize ferrite losses, and resultant thermal effects, as well as reduce breakdown levels, and at the same time require only moderate demands on the necessary hardware. The tuner fundamentally consists of a DC biasing magnet, ferrite, coupling loop, and coaxial transmission line. Although the design is based on many factors, primary issues include the following:

- Determination of the DC biasing field
- Material properties of the ferrite, e.g., gyromagnetic resonance, saturation, and Curie temperature
- Ferrite rf magnetic and electric losses
- Peak electric fields throughout tuner
- Peak ferrite temperature and non-uniformity of the biasing field

National Magnetics material AL-800 [9], a YIG garnet with Aluminum dopants, is being considered for the ferrite material due to its low saturation current and low losses, as well as its extensive characterization in Fermilab's Recycler Ring. The magnetic losses have been measured and are estimated to have a loss tangent of 0.0035 [10]. It is well-known that ferrite magnetization degrades with temperature and ultimately goes to zero at its Curie temperature. As a result, low losses and an adequate cooling network are critically considered.

Due to the geometrical constraints imposed by the coaxial structure and end effects, the biasing magnetic field is non-uniform across the ferrite. This non-uniformity creates a range of local values of permeability requiring special consideration to ensure that the biasing of the ferrite everywhere remains outside of the gyromagnetic resonance in order to limit the potential temperature rise.

Saturation is reached at a relatively modest magnetic field level of 800 G for AL-800. An 8000 Amp-turns magnet creates a magnetic field in the ferrite which produces a permeability in the material approaching 2. This may be considered as a lower limit to the usable range of permeability for the tuner. As an upper limit, the permeability cannot exceed ~3 in order to avoid the high-loss region characterized by the gyromagnetic resonance. The span of permeability required for tuning ranges from 30 kHz - 100 kHz is shown in Fig. 4 where μ_{max} is selected to avoid the gyromagnetic resonance, and μ_{min} is subsequently determined by the desired frequency range. Due to the non-uniformity of the biasing field, the maximum permeability was capped at 2.9.

The time-dependent frequency and voltage ramping profiles that are expected to be used from injection to extraction are shown in Fig. 5 and will operate at a 1 Hz rate with a rapid ramp-down in order to reduce the duty factor. Fig. 6 shows the aggregate power loss density in the ferrite, and the peak electric field along the non-vacuum length of the transmission line as a function of μ_{max} for the ramping profiles shown in Fig. 5. The optimal value of μ_{max} for minimizing losses and peak fields in the ferrite are found in Fig. 6 for a given tuning range. The range of permeability spanning from μ_{min} to μ_{max} can be determined using Fig. 4. for a given μ_{max}.

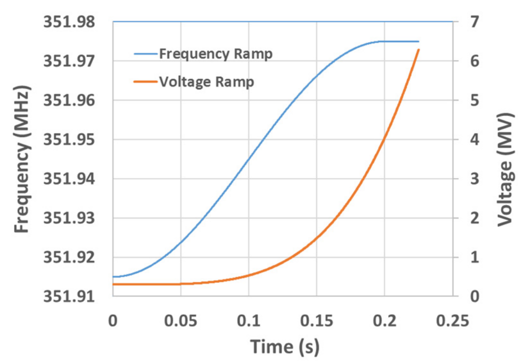

Figure 5: Time-dependent frequency and voltage ramp across a booster cycle.

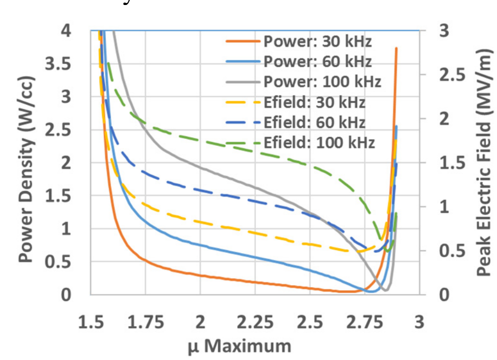

Figure 6: Power loss density in the ferrite and peak electric field in the non-vacuum length of the tuner for tuning ranges 30 kHz – 100 kHz.

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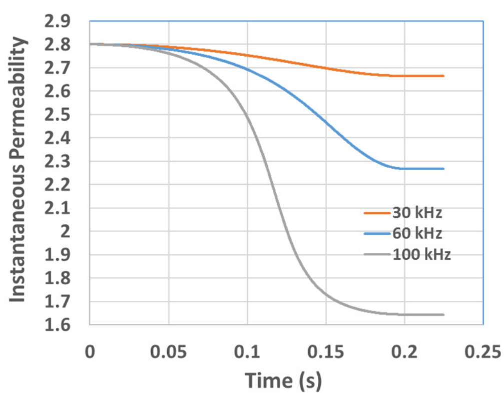
TIME EVOLUTION OF PARAMETERS

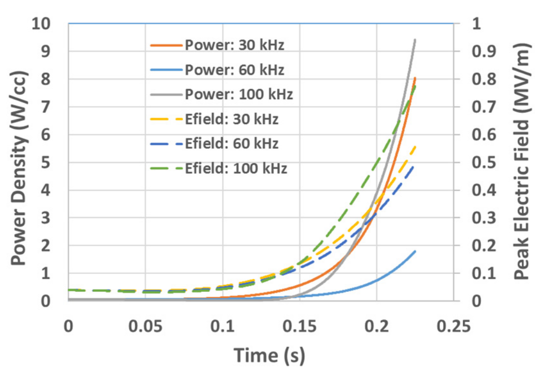
Based on the frequency ramp in Fig. 5, the variation of permeability with time is shown in Fig. 7(a) for the case where μ_{max} is 2.8. The minimum permeability extends until the frequency span is achieved based on the tuning curve in Fig. 2 and summarized in Fig. 4.

Losses in the tuner are calculated at the appropriate ferrite permeability based on the frequency ramp as well as on the instantaneous magnitude of the voltage ramp. These interactions are incorporated in Fig. 7(b) where the power loss density and peak electric field magnitude are plotted as a function of a single booster cycle.

In order to achieve the minimum of 60 kHz tuning range, a range up to 100 kHz is being targeted for sufficient headroom to compensate for the degradation of the performance of the tuners from temperature rise, unbalanced field levels in each of the tuners, and non-uniform permeability in the ferrite volume.



(a) Ferrite permeability over the ramp cycle.



(b) Power loss density in the ferrite and peak electric field in non-vacuum portions of the tuner during the ramp cycle.

Figure 7: Time evolution of the instantaneous permeability and fields within the ferrite for frequency spans of 30, 60, and 100 kHz. The maximum permeability is set to 2.8.

CONCLUSION

A ferrite tuner has been analysed for the APS-U booster with a nominal tuning range of 60 kHz. The tuner is based on a design tested and installed in the Recycler Ring at Fermilab which utilizes a perpendicularly biased YIG garnet. The ferrite is low loss and requires a relatively low saturation field which reduces the complexity of the biasing system.

The tuning characteristics of the tuner have been evaluated and material properties of the ferrite have been considered. The time dependence of the rf interaction with the tuners is based on frequency and voltage ramps that are necessary to maintain booster efficiency requirements while increasing the beam energy to 6 GeV at extraction. Optimal ferrite values were found for reducing breakdown voltages and minimizing losses in the tuner. The operating range of the ferrite maintained a reasonable demand on the magnet biasing circuit and avoided high-loss regions.

ACKNOWLEDGEMENTS

We are grateful to R. Madrak of FNAL for conversations regarding the ferrite design, operational experience, and material testing details.

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