A High Precision Model of AGS Booster Tune Control

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A HIGH PRECISION MODEL OF AGS BOOSTER TUNE CONTROL *

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Abstract

In this note we will describe the Booster tune quadrupoles, magnetic measurements, bare tune measurements, and a 3 dimensional model we developed in order to understand various aspects of the tune quadrupole magnets that were not or could not be measured directly. We will present data on tune shifts caused by $\dot{B}$ effects (e.g., vacuum chamber eddy currents) and results of a 3 dimensional model of eddy currents. Finally we will present results from a MAD model of the Booster tunes and the predicted tune control ranges at the highest Booster rigidities.

1 INTRODUCTION

Accelerator models invariably depend on magnetic measurements of the various components in the accelerator lattice. For quadrupoles, accelerator simulators such as MAD expect to be given a length and a gradient. In the case of the AGS Booster only integrated gradients were measured [1, 2]. This is sufficient when the magnets are not operated at the highests currents. Otherwise saturation effects need to be included. Since MAD expects a length and a normalized gradient ($K_1 = \frac{1}{B\rho}\frac{\partial B_r}{\partial r}$) as parameters for a quadrupole, using a fixed length and a gradient based on integrated field measurements will not predict the tunes accurately. This is because the integrated field has to be re-expressed to be interpreted as a gradient in the center of the quadrupole.

$$\frac{\partial B_r}{\partial r}|_{z=0} = \frac{1}{L_{eff}} \int_{-\infty}^{\infty} \frac{\partial B_r}{\partial r} dl \qquad (1)$$

Since L_{eff} is not a constant, but varies as a function of field at the pole tips, the value used by MAD must vary as the field increases (or the gradient needs to be renormalized to include the change in effective length).

2 DESCRIPTION OF THE BOOSTER TUNE QUADRUPOLES

The Booster lattice is built as a separated function, FODO type lattice in which the defocusing quadrupoles are slightly longer than the focusing quadrupoles. The Booster arc dipoles and the two types of quadrupoles are powered in series. Using the tune trim coils the tuning range at low rigidities allows shifting the vertical tune up high enough to compensate for space charge tune shifts and avoid the strong integer stop band at ν_y = 4. Stop band corrections are used to correct for all the significant resonances between ν_y=4 and ν_y=5.

The design bare Booster tunes were around 4.82. After most of the quadrupole cores had already been built, though, it was found, from magnetic measurements, that the strengths of the quadrupoles relative to the arc dipoles was 4.0% too low [4]. As a result, the bare Booster tunes are now around $\nu_x = 4.63$ and $\nu_y = 4.61$, at low rigidities. A complete listing of the booster quadrupoles characteristics can be found in references [1, 2].

Although the cores of the two types of magnets are different lengths, the coils are all the same length. This means the overall length of the magnets is the same, although the magnetic lengths are different. This does not significantly affect the magnetic characteristics.

Not all quadrupole vacuum chambers are round. Currently in DQ5 and FQ5 there are special "eared" chambers, as shown in figure 1. After completion of the modifications for BAF, there will be 3 such chambers in the Booster (DQ3, DQ5, FQ5). Note that all vertical quadrupoles are located at odd locations (DQ3,DQ5, etc.) and all horizontal quadrupoles are located at even locations (DQ2,DQ4, etc.).

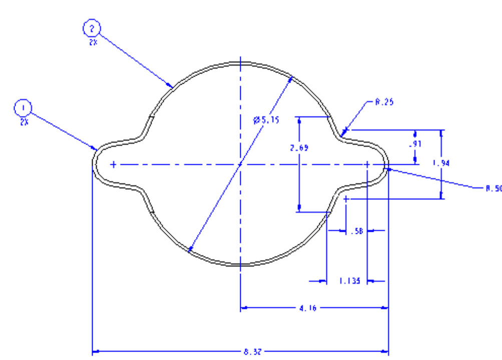

Figure 1: DQ3, DQ5, and FQ5 Vacuum chambers cross section

3 BOOSTER TUNE MEASUREMENTS

In the 1992 and 1993 Booster commissioning notebooks we found two independent sets of Booster bare machine

* Work performed under the auspices of the U.S. Dept. of Energy.

tune measurements. For these tune measurements the same procedure was followed. In each case the tune quadrupole power supplies were left on, but with zero current (this was to prevent the back-emf due to the main windings from causing field to be pulled out of the magnets), the chromaticity functions were set for zero chromaticity (non-zero currents in sextupoles), the beam intensity was made low (to avoid space charge tune shifts at injection), and the RF was left on (radius set to zero) during the main magnet invert (to allow measurements during negative $\dot{B}$). What is uncertain in these measurements is what the chromaticity really was, how close the radius was to, and stayed at the center of the quadrupoles, and whether or not the orbit was corrected. In addition the data did not include the current error in the tune quadrupoles (how much the real current deviated from zero as a function of time or $\dot{B}$). In any case the measured bare tunes for the two sets are very consistent with each other. These measurements show a large affect from the $\dot{B}$. Figure 3 shows the data.

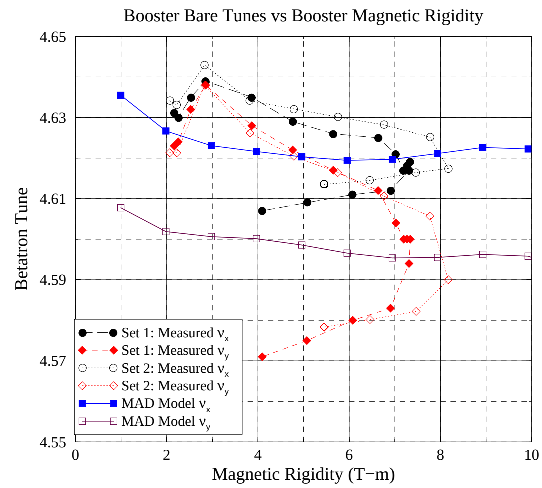

Figure 3: Bare tunes prediction with measured data

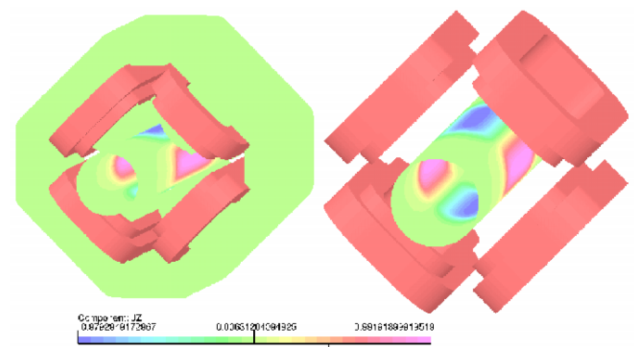

Figure 4: Opera3D model of a booster long quadrupole, showing vacuum chamber eddy currents. In the right hand figure the iron core of the magnet was taken out to show the vacuum chamber more clearly.

4 3 DIMENSIONAL MODEL OF THE TUNE QUADRUPOLES

Since we did not have measurements of the effective length of the quadrupoles as a function of current (or field) we developed a 3 dimensional model of both the short and long quadrupoles using Opera3D. An image of the long quadrupole for this model is shown in figure 4. The results of the modeled effective lengths are shown in figure 2. This data was fitted to a third order polynomial, which is used in the MAD lattice file to define the length of the Booster quadrupoles.

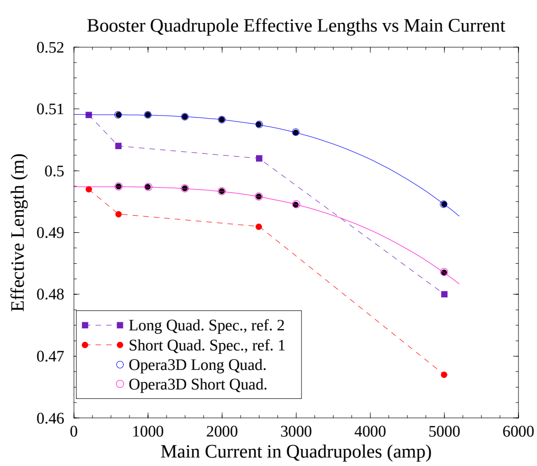

Figure 2: Tune quadrupole effective lengths as a function of current

5 VACUUM CHAMBER EDDY CURRENT AND $\dot{B}$ EFFECTS

To model the vacuum chamber eddy current effects we first created a 2 dimensional model of the quadrupoles with a round Inconel vacuum chamber. The purpose of this was to see whether eddy currents in the quadrupoles were significant enough to explain the measured tune shifts. Since it was a 2D model we could not see the relative difference between long and short quadrupoles, and the predicted tunes shifts were equal, but significant. We next created a 3D model and found there is little difference in the effect from the 2D model. Using the predicted change in gradients it became immediately apparent that the eddy currents do not, by themselves explain the observed $\dot{B}$ effects. In fact they cause the gradient to be reduced, decreasing the tunes, not increasing.

Figure 4 shows the Opera3D model of a long quadrupole with a vacuum chamber. The z-component of the current density in the pipe is shown with different colors for different current densities. Those shown in the figure correspond to the maximum $\dot{B}$ that was modeled. The eddy currents flow inside the vacuum chamber around the pole tips, with red/pink (left and right hand sides) indicating current flowing out of the paper (clockwise for the upper right coil). Current in the coils flows in the opposite direction (counterclockwise for the upper right coil). The result is a reduction in the gradient seen by the beam.

In order for the bare tunes to increase with increasing $\dot{B}$, the gradient in the magnets must increase with increasing $\dot{B}$. To match the measured data, we included a set of calibration coefficients. The purpose of this is to allow a correction to be included for the power supply response to the back EMF due to the $\dot{B}$. We found these coefficients need to be $C_H = 3.4$ and $C_V = 4.8$ A/T/sec, which would put about 30 A current through the trim windings at maximum $\dot{B}$, which is consistent with what we measure today.

$$I_X = I_{DIPOLE} + 0.2 \cdot (I_{Xtrim} + \dot{B} \cdot C_X) \quad (2)$$

where X is replaced with either H or V. The equations used in the model are: for the short quadrupoles,

$$K_1 = (1 - 0.00004179 \cdot \frac{1}{B}\frac{\partial B}{\partial t}) \cdot \frac{1}{B\rho L_{eff}} < \frac{\partial B_r}{\partial r} > \quad (3)$$

and for the long quadrupoles,

$$K_1 = -(1 - 0.000041942 \cdot \frac{1}{B}\frac{\partial B}{\partial t}) \cdot \frac{1.003}{B\rho L_{eff}} < \frac{\partial B_r}{\partial r} > \quad (4)$$

and for the long quadrupoles with eared vacuum chambers,

$$K_1 = -(1 - 0.000062913 \cdot \frac{1}{B}\frac{\partial B}{\partial t}) \cdot \frac{1.003}{B\rho L_{eff}} < \frac{\partial B_r}{\partial r} > \quad (5)$$

where L_{eff} and $< \frac{\partial B_r}{\partial r} >$ are derived from the respective polynomials and B is derived from the polynomial expansion for the main arc dipoles.

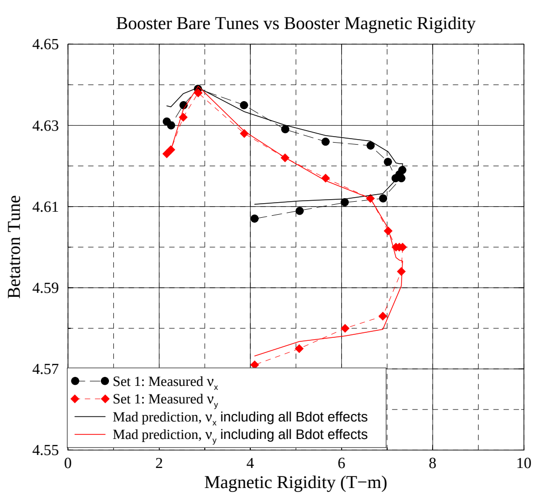

Figure 5: bare tunes prediction using 3D transient model and power supply response to $\dot{B}$

6 EDDY CURRENT EFFECTS OF EARED VACUUM CHAMBERS

The eared vacuum chambers also change the quadrupole moment as a function of $\dot{B}$. Since the eared vacuum chambers are thicker than the normal vacuum chambers, the eddy currents are larger by about 25%. Due to the symmetry of the structure the higher order field components for sextupole, octupole, and above tend to cancel out, and have magnitudes that are insignificant.

7 BOOSTER TUNE CONTROL AT HIGH FIELDS

Using this new model of the Booster we can now predict how much tune space is accessible when we operate at very high fields, assuming we can change the tune trim quadrupoles by $\pm$ 1000 A. Figure 6 shows the amount of tune space available for rigidities from 14 Tm to 17 Tm.

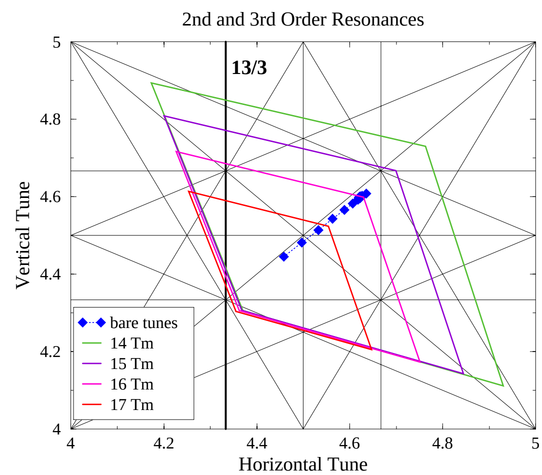

Figure 6: Tune control at high field, using $\pm$ 1000 A in tune trim supplies.

8 CONCLUSIONS

We now have a precise model of the Booster tunes and tune control through the tune trim power supplies. In addition we have studied the affect of eddy currents in the quadrupole vacuum chambers and demonstrated that measured tune shifts as a function of $\dot{B}$ are affected, in part, by these eddy currents, but are due more significantly to power supply response to $\dot{B}$.

9 REFERENCES

[1] E.Bleser, "Booster Short Quadrupole Production Measurements", Booster Technical Note No. 174, September 12, 1990.

[2] E.Bleser, "Booster Long Quadrupole Production Measurements", Booster Technical Note No. 176, September 13, 1990.

[3] R.Bianco and E.Bleser, "Summary of the Magnetic Measurements for the Short Booster Quadrupoles", Booster Technical Note No. 226, August 15, 1995.

[4] W.T.Weng, Department memo to D.Lowentstein. June 12, 1990.