MEASUREMENTS AND MODELING OF EDDY CURRENT EFFECTS IN BNL'S AGS BOOSTER *

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Abstract

Recent beam experiments at BNL's AGS Booster have enabled us to study in more detail the effects of eddy currents on the lattice structure and our control over the betatron tune. The Booster is capable of operating at ramp rates as high as 9 T/sec. At these ramp rates eddy currents in the vacuum chambers significantly alter the fields and gradients seen by the beam as it is accelerated. The Booster was designed with these effects in mind and to help control the field uniformity and linearity in the Booster Dipoles special vacuum chambers were designed with current windings to negate the affect of the induced eddy currents. In this report results from betatron tune measurements and eddy current simulations will be presented. We will then present results from modeling the accelerator using the results of the magnetic field simulations and compare these to the measurements.

Table 1: Booster Parameters.

Parameter	Value
Circumference	201.78 (1/4 AGS) m
Ave. Radius	32.114 m
Magnetic Bend R	13.86557 m
Lattice Type	Sep. Function, FODO
No. Superperiods	6
No. of Cells	24
Betatron Tunes,X,Y	4.82, 4.83
Vacuum Chamber	70 x 152 mm Dipoles
	152 mm (circular) Quads
Max. Rigidity	16 Tm
Injection Rigidity	2.2 Tm (200 MeV protons)
	0.9 Tm (1 MeV/n Au(32+))
Acceleration Rate	8.9 T/s up to 8 Tm (7.5 Hz)
	1 T/s up to 16 Tm (0.7 Hz)

INTRODUCTION

The AGS Booster is a rapid cycling alternating gradient synchrotron. It was designed to accelerate heavy ions, high intensity protons, and polarized protons, as a pre-injector to the AGS. To allow good control over the lattice and nonlinear characteristics of the lattice, a full set of trim controls were designed into the system. In addition, significant work went into designing systems to minimize effects of $\dot{B}$-induced eddy currents. Careful study of the eddy current effects on the Booster tune control were presented in [1]. That report concentrated on the main quadrupoles, the tune trim windings system, and eddy currents in the tune quadrupole vacuum chambers. In this report we will concentrate on the dipole magnets, the dipole vacuum chambers, and the eddy current correction coils in the dipole vacuum chambers. Extensive studies were made of the vacuum chamber eddy currents and the eddy current correction coil system in [2, 3, 4, 5]. Parameters of the AGS Booster are given in table 1.

BOOSTER TUNE CONTROL

The Booster arc dipoles and the main quadrupoles are powered in series. Since the arc dipoles have an intrinsic focusing component, the defocussing quadrupoles are slightly longer than the horizontal focusing quadrupoles. This brings the vertical tune up closer to the horizontal tune. 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 bare Booster tunes are 4.63 horizontal and 4.61 vertical, at low rigidities.

For tune control, a set of single turn coils are wound on the main quadrupoles and connected to 1100 amp power supplies. These power supplies operate with a current loop that responds to the back-emf induced from the high $\dot{B}$ on the main coils. This, in addition to the eddy current in the quadrupole vacuum chambers alters the field gradient seen by the beam, shifting the betatron tune a measurable amount [1].

BOOSTER MAIN DIPOLES

The Booster main dipoles are H type sector dipoles with a magnetic length of 2.42 m and a bend angle of 10 degrees per magnet. The vacuum chambers are built to follow the arc of the dipole bends. $\dot{B}$ induced eddy currents in the vacuum chambers produce nonlinear fields that are larger than errors in the rest of the magnets. The most significant nonlinear field is a large sextupole component. To reduce this component, correction coils on the vacuum chamber are connected to windings around the iron of the main dipoles. Current produced in the winding from the $\dot{B}$ is shunted to

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the vacuum chamber coils in such a way as to cancel the eddy currents in the chamber. The coils cannot completely cancel the eddy currents, which are distributed over the entire surface of the chambers, but they are designed to cancel a significant sextupole component of the field produced by the eddy currents in the chamber. The extra windings reduce the overall field but less so in the center of the chamber than the edges. The net result, shown in [2, 3, 4] and as seen in our own simulations, is the eddy currents reduce the dipole field seen by the beam, but with significant nonlinear components, and the correction windings flatten the nonlinear fields and increase again slightly the dipole field seen by the beam. Figure 2 shows the results of an Opera [6] simulation of a Booster dipole with the vacuum chamber eddy currents and the correction coils. The data for this simulation all corresponds to the horizontal median plane (HMP).

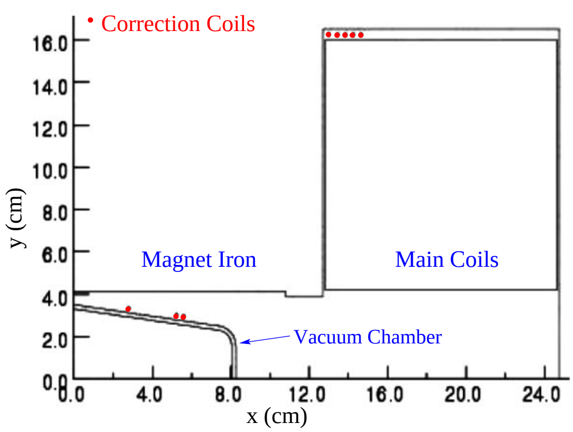

Figure 1: Booster Dipole cross section model used to study eddy currents.

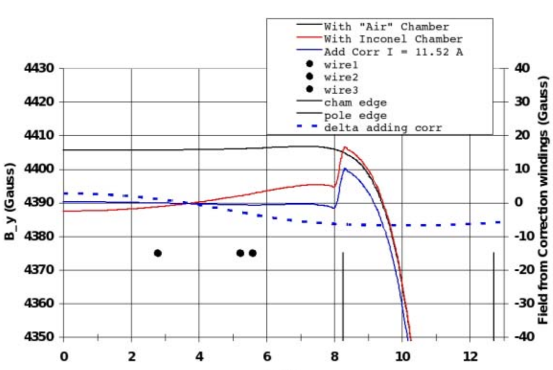

Figure 2: Field on HMP without vacuum chamber, with vacuum chamber, and with correction coils.

Booster Dipole Magnetic Simulations

In [2, 3, 4] to simulate the eddy currents in the vacuum chambers the computer code "Poisson" was used. The vacuum chambers had to be segmented into cells to simulate the different current densities in the chambers. Using the modern computer code Opera with transient analysis we were able to more realistically simulate the induced eddy currents, since it was not necessary to segment the vacuum chamber, and improve on the Poisson results. In figure 3 we show both the Poisson data and the Opera results. The Y=0 data is for the field on the HMP, relative to the field at X=0. The Y=1.6 and Y=2 cm data is relative to the Y=0 data. For particles above or below the HMP the distortion in the field due to the correction coils becomes greater. At 2 cm above the median plane the field varies by as much as 0.5 G over 2 cm in the radial plane. The results of the Poisson simulation predicted a smaller distortion, although the basic character is the same.

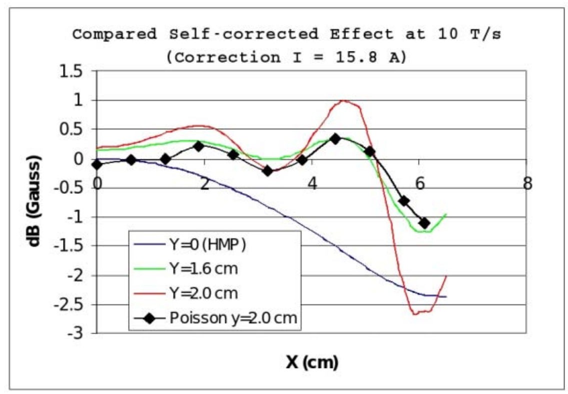

Figure 3: Field distortion for 10 T/s at 0, 1.6, and 2 cm above the HMP with the effect of the correction coils included.

TUNE MEASUREMENTS

Figure 4 shows measured vertical betatron tune as a function of magnetic rigidity for three different magnet cycles with different ramp rates. Also shown is the static model of the Booster as reference. Measurements of horizontal tune show the same character. This figure is just an example useful to illustrate the problem. For each case the accelerator was configured in what we define a bare state. The tune trim windings were programmed for zero current (as measured) throughout the magnet cycle. Arrows are drawn on the figure to show the points that were measured on the rising edge of the magnet cycle ($\dot{B} > 0$) and on the falling edge of the magnet cycle ($\dot{B} < 0$). Since the effect of the power supply response to the back-emf of the main coils was canceled out by programming the measured current in the quadrupoles to be 0 amp, these curves show the effect on the betatron tune from just the eddy currents. The measurements show the betatron tune increases with increasing $\dot{B}$. If this was due to just eddy currents in the quadrupole vacuum chambers, the effect would be the reverse, since the eddy currents reduce the field gradient seen by the beam, when the $\dot{B}$ is positive. The eddy currents in the dipole vacuum chamber, with the reduction due to the currents in the correction windings, reduce the field in the dipoles more than the reduction in gradient in the quadropoles due to eddy currents in their vacuum chambers. This results in stronger relative gradients in the quads and thus higher tunes with positive $\dot{B}$.

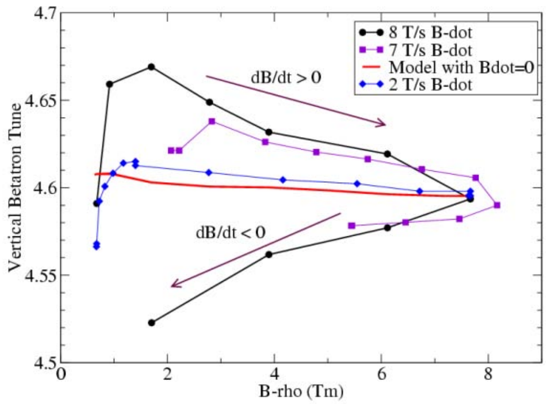

Figure 4: Measured Vertical Betatron Tune vs Magnetic rigidity for 3 different $\dot{B}$.

Optics Modeling Results

In order to test the hypotheses presented in the previous discussion we developed our MAD simulation of the AGS Booster to include the $\dot{B}$ corrections for both the quadrupoles and the dipoles. We used the results of Opera simulations of the magnets to quantify the amount of eddy current produced in the vacuum chamber and the reduction to the field and field gradients. In figure 5 the vertical betatron tunes for the 8 T/s $\dot{B}$ case (shown in figure 4) are shown for 2 different simulations. In the first case only the eddy currents in the quadrupole vacuum chambers are taken into account. The model shows that for positive $\dot{B}$ the vertical tune should decrease. Clearly eddy currents in just the quadrupoles cannot explain the measured tunes. In the second case the effect of the drop in the dipole field due to the eddy currents, including the correction coils, is included. The agreement with the measured data is extremely good for the case that includes both the quadrupoles and the dipoles.

SUMMARY

Eddy currents in a rapid cycling accelerator, if allowed to become significant, can affect the optics of the accelerator in many different ways. In the case of the AGS Booster the results of the potential produced by the high $\dot{B}$ are threefold. First is the transformer coupling of the trim quadrupole power supply, which responds to the back-emf

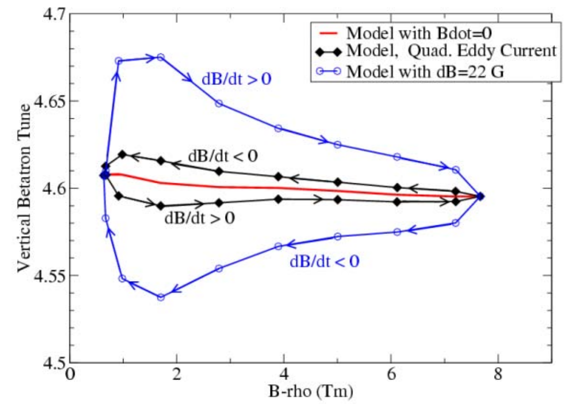

Figure 5: Results for $\dot{B} = 8T/s$ of 2 different simulations.

of the main coils. Secondly, the eddy currents produced in the quadrupole vacuum chambers themselves reduce the field gradient seen by the beam. Finally, the eddy currents in the dipole vacuum chambers, along with the vacuum chamber correction coils, reduce and alter the field seen by the beam and change the ratio of the quadrupole field to the reduced dipole field, that in our case causes a net increase in focusing strength seen by the beam.

REFERENCES

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[6] Opera is a product of Vector Fields, Inc. (http://www.vectorfields.com/)