Analysis of Resonance-Driving Imperfections in the AGS Booster*

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Abstract

At the design intensity of 1.5×10^{13} ppp, the space charge tune shift in the AGS Booster at injection has been estimated to be about 0.35. The beam tunes are therefore spread over many lower order resonance lines and the associated stopbands must be corrected in order to minimize the amplitude growth due to resonance excitation. This requires proper compensation of the resonance-driving harmonics which result from random magnetic field errors. The observation and correction of second and third order resonance stopbands in the AGS Booster is reviewed, and an analysis of magnetic field imperfections based on the required corrections is given.

1 INTRODUCTION

The AGS Booster began operation [1] in 1992, delivering beam at one third the design intensity of 1.5×10^{13} ppp. The intensity was increased to 1.0×10^{13} ppp in 1993 [2], and 1.7×10^{13} ppp was attained in early 1994 [3]. An important part of the effort to reach the design intensity has been the correction of resonance lines encountered by the beam during injection and early acceleration. The Booster operates with the horizontal and vertical tunes (Q_x and Q_y) between four and five, and at the design intensity the space charge tune shift has been estimated to be about 0.35 at injection. With the nominal operating point at $Q_x = 4.82$, $Q_y = 4.83$ several of the second and third order lines shown in Figure 1 are encountered and the associated stopbands must be corrected in order to minimize beam loss. These resonances and the multipole fields which excite them are listed below:

Second Order (quadrupole):

$$2Q_x = 9, \;\; 2Q_y = 9 \tag{1}$$

Second Order (skew quadrupole):

$$Q_x + Q_y = 9, \;\; Q_x - Q_y = 0 \tag{2}$$

Third Order (sextupole):

$$3Q_x = 14, \;\; Q_x + 2Q_y = 14 \tag{3}$$

$$3Q_x = 13, \;\; Q_x + 2Q_y = 13 \tag{4}$$

$$2Q_y - Q_x = 5, \;\; 2Q_y - Q_x = 4 \tag{5}$$

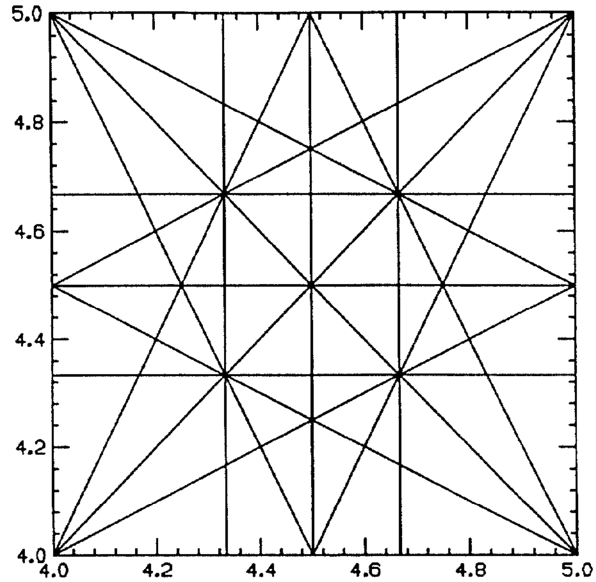

Figure 1: 2nd and 3rd Order Resonances

Third Order (skew sextupole):

$$3Q_y = 14, \;\; Q_y + 2Q_x = 14 \tag{6}$$

$$3Q_y = 13, \;\; Q_y + 2Q_x = 13 \tag{7}$$

$$2Q_x - Q_y = 5, \;\; 2Q_x - Q_y = 4 \tag{8}$$

The resonance correction system [4, 5] employs auxiliary windings placed on quadrupoles and sextupoles whose main windings serve to adjust the machine tunes and chromaticities. Special windings on the correction dipoles produce the required skew quadrupoles and skew sextupoles, and passive windings on the dipole vacuum chambers compensate the sextupole fields produced by eddy currents [6]. The various windings are excited so that appropriate azimuthal harmonics are produced which compensate the resonance driving harmonics resulting from random magnetic field errors. For the resonances $mQ_x + nQ_y = N$ these harmonics are essentially the Nth harmonic of the appropriate multipole and are of the form

$$C + iS = \beta_{AV}^{-(m+n)/2} \sum_j I_j K \beta_{xj}^{m/2} \beta_{yj}^{n/2} e^{i\psi_j}, \tag{9}$$

where

$$\psi_j = m(\mu_{xj} - Q_x\theta_j) + n(\mu_{yj} - Q_y\theta_j) + N\theta_j, \tag{10}$$

*Work performed under the auspices of the U.S. Dept. of Energy.
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$\beta_{AV} = 6.69$ m, I_j is the current in the jth corrector, K is the integrated strength (per unit current) of each corrector, θ is the azimuthal angle, and β_x, μ_x, β_y, μ_y are the usual Courant-Snyder parameters. The system is capable of correcting resonances (1–4) and (6) simultaneously, i.e. it can correct each of these resonances without affecting the correction of the others.

Resonances (1–3) and (6) were observed by programming the tunes to pass through each resonance at various times during the magnetic cycle. The beam intensity was reduced to a few 10^{11} ppp to ensure that the area occupied by the beam in tune space was as small as possible, and the loss upon traversal of each resonance was measured by observing the signal from a circulating beam current transformer. Figure 2 shows typical traces of signals observed as a resonance is crossed. The traces labeled A, B, C, D show respectively the signals proportional to the circulating beam current, the current in the tune quadrupoles, the main magnet current, and the current in the corrector magnets. The beam loss was measured for several different correction settings in order to accurately determine the setting required to minimize the loss. These measurements were made at four times during the magnetic cycle, indicated by dots in Fig. 2, with the the field, B = 1.8, 3.6, 5.4, 5.4 kG, and $\dot{B} \equiv dB/dt$ = 48, 87, 87, −87 kG/s. The corrections required to minimize the loss at each of the four times were found to depend linearly on B and $\dot{B}$, and expressions of the form

$$C = C_r + C_b B + C_t \dot{B}, \quad S = S_r + S_b B + S_t \dot{B} \tag{11}$$

were fit to the data. The constant terms (C_r and S_r) in these expressions are due to remanent fields, while those proportional to B and $\dot{B}$ are presumably due to magnet misalignments and/or imperfections, and uncompensated eddy currents. The results of the measurements and the effects of the corrections on the overall beam intensity are summarized below. Possible sources of the magnetic imperfections are discussed in Ref. [7].

2 QUADRUPOLE CORRECTION

For the $2Q_x = 9$ resonance we find

$$C = 65 + 15B + 2.4\dot{B}, \quad S = -14 + 22B - 0.9\dot{B} \tag{12}$$

and for the $2Q_y = 9$ resonance,

$$C = 77 + 29B + 1.5\dot{B}, \quad S = -23 + 16B - 2.6\dot{B} \tag{13}$$

where the units of B and $\dot{B}$ are kG and kG/s, and the units of C and S are gauss. The phase of the terms proportional to $\dot{B}$ in these expressions is consistent with the location of the vacuum chamber through which the H^- beam enters the booster which suggests that the eddy currents in this chamber may not be completely compensated.

During the course of determining these corrections we found that the required correction depended on the horizontal closed orbit distortions around the ring due to the displacement of the closed orbit in sextupole fields

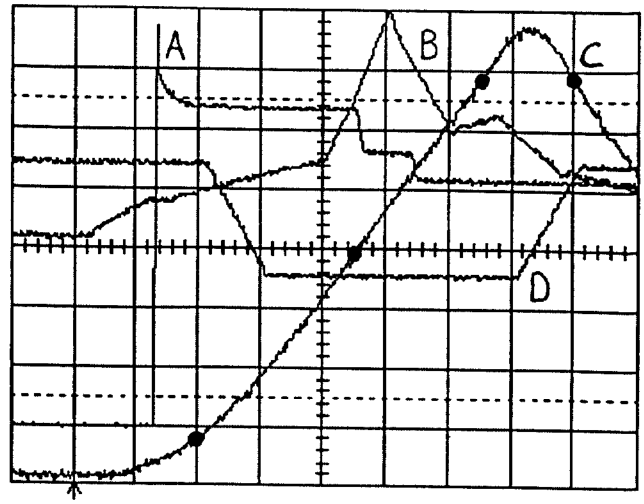

Figure 2: Beam Loss upon Crossing a Resonance.

which produces an effective quadrupole for the circulating beam. The contribution of this quadrupole to the resonance-driving harmonics is given by (9) with

$$K(s) = S(s)\left[\frac{\delta p}{p} D(s) + d(s)\right] \tag{14}$$

where $S(s)$ is the strength of the sextupole at azimuthal position s, δp is the departure of the momentum from the central momentum p, D is the dispersion, and d is the closed orbit distortion due to dipole errors. Sources of the sextupole field include the sextupoles used to adjust chromaticities, the fields near the ends of the dipole magnets, and uncompensated eddy currents. We found that we could eliminate the contribution due to d either by adjusting the quadrupole correctors or by introducing a ninth harmonic component in the closed orbit with the dipole correctors in the machine. The contribution due to dispersion is not the same for all particles in a beam of finite momentum spread and therefore cannot be compensated with a single setting of the quadrupole correctors. To eliminate the contribution (for all beam particles), a ninth harmonic sextupole field was introduced with available windings on the sextupole correctors.

3 SKEW QUAD CORRECTION

For the $Q_x - Q_y = 0$ resonance we find

$$C = 11 + 49B - .55\dot{B} \tag{15}$$

where the units of B and $\dot{B}$ are kG and kG/s, and the units of C are gauss. Data for the $Q_x + Q_y = 9$ resonance are incomplete as of this writing, but as with the corrections for resonances (1), we have found that the required correction depends on the closed orbit distortions around the ring with vertical displacements of the orbit in sextupole fields and horizontal displacements in skew sextupole fields both producing an effective skew quadrupole for the circulating beam.

4 SEXTUPOLE CORRECTION

For the $3Q_x = 14$ resonance we find

$$C = 7 - 1.1B + 0.37\dot{B}, \quad S = -33 + 15B + 0.50\dot{B} \quad (16)$$

and for the $Q_x + 2Q_y = 14$ resonance,

$$C = -10 + 3.5B + 0.44\dot{B}, \quad S = 18 + 5.4B + 0.20\dot{B} \quad (17)$$

where the units of B and $\dot{B}$ are kG and kG/s, and the units of C and S are G/cm.

5 SKEW SEXT CORRECTON

The original correction scheme for the booster did not include skew sextupoles because it was thought that these imperfections would be relatively weak. However in 1992–93 the $Q_y + 2Q_x = 14$ resonance was found to be quite strong, and as a result windings were placed on existing correctors to produce four skew sextupoles. The corrections required for this resonance are

$$C = 2 - 0.8B + 0.12\dot{B}, \quad S = -34 - 5.6B - 0.11\dot{B} \quad (18)$$

where the units of B and $\dot{B}$ are kG and kG/s, and the units of C and S are G/cm.

6 INTENSITY GAINS

To see the effect of the corrections at high intensity, the corrections were programmed on the high intensity machine cycle according to their measured dependencies on B and $\dot{B}$. On this cycle beam is injected at $B = 0.15$T with $\dot{B} = 3$T/s. Shortly after injection, $\dot{B}$ increases to 8.7 T/s where it remains through extraction at $B = 0.52T$. The effect of the sextupole and skew sextupole corrections is shown in Figure 3 where the upper and lower traces show the circulating beam current with these corrections turned ON and OFF. Here the peak intensity at injection was 24×10^{12} and with the operating point of $Q_x = 4.80$, $Q_y = 4.94$ the final intensity just before extraction with the corrections turned ON was 17×10^{12} ppp. With the skew sextupole corrections turned OFF (middle trace) the final intensity decreased to 15×10^{12} ppp. Turning off the sextupole corrections for resonances (3) reduced the intensity further by 1.0×10^{12} ppp. The quadrupole and skew quadrupole corrections had very little effect on the intensity at this operating point, which is consistent with the estimated space charge tune shift. We note that two octupoles and skew octupoles have been added the the correction system, but their effect on high intensity operation has not yet been determined.

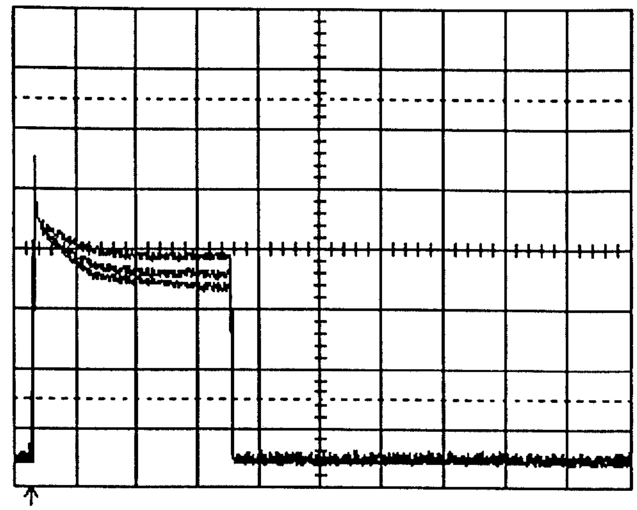

Figure 3: Beam Intensity with and without Sextupole Corrections (5×10^{12} ppp and 10 ms per division).

7 ACKNOWLEDGMENTS

The authors would like to thank the power supply group whose dedicated and enthusiastic support made possible the addition of the skew sextupole, ninth harmonic sextupole, and octupole correctors to the resonance correction system.

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