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STUDIES ON THE CHROMATICITY CORRECTION AND DYNAMIC APERTURE OF THE AGS BOOSTER*

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Abstract Sextupole configurations with periodicity six and 24 are considered; the higher periodicity is selected on the basis of reduced emittance coupling between the horizontal and vertical motion. Results are given for proton and heavy ion acceleration cycles. The dynamic aperture from particle tracking is compared with the chaotic dynamic aperture.

INTRODUCTION

The Booster has six superperiods of 4 FODO cells with dipoles missing in the third and sixth half cells; the quadrupole distribution has a periodicity of 24. The cells have a phase advance of $\sim 72^o$; the nominal tune is: ν_x=4.82, ν_y=4.83.

Sources of chromaticity are: natural chromaticity, eddy currents in the dipole vacuum chambers, magnet saturation, and end fields of the dipoles; correction of the first three components is reported. Initially a sextupole configuration was chosen that would avoid use of half cells three and six; sextupoles were placed in half cells 1, 2, 4, and 7 – the (1,2,4,7) scheme. This distribution can produce complete emittance transfer between the horizontal and vertical motion and limits the total emittance $\epsilon_t = \epsilon_x + \epsilon_y$ to 60π mm mradians. The $2\nu_x$-$2\nu_y$=0 resonance, driven by the chromatic sextupoles, is responsible for the coupling. A configuration with sextupoles in all half cells greatly reduces the coupling; this scheme denoted by (ALL), has been selected for the Booster. Chromatic correction is achieved with two families of sextupoles (SF and SD) placed upstream of the focusing and defocusing quadrupoles, respectively.

MULTIPOLES

Eddy Currents[1]

Estimates were made on a stainless steel vacuum chamber, roughly oval in cross section, having 1.5 mm thick top and bottom, and 0.75 mm thick side walls. A dB/dt = 5 T/s was assumed. An expansion was made relative to the proton injection field of 1.560 kG (Bρ=2.149Tm); the multipole coefficients are:

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b_2=0.78 m^{-2}, b_4=-24 m^{-4}, and b_6=-1600 m^{-6}. The sextupole coefficient b_2 contributes $\Delta\zeta_x$=8.255 and $\Delta\zeta_y$=-7.717 to the chromaticity.

The contribution from the eddy currents will be reduced by using inconel dipole vacuum chambers. In addition, three turn coils are attached to the top and bottom of each chamber. The conductor spacing is selected to cancel fields from the eddy currents. The coils will be powered from dipole backleg windings; thus their excitation has the same time dependence as the eddy currents. The results in the present paper have been generated assuming no cancellation of eddy current fields by the chamber windings and with multipoles for a stainless steel chamber. The b_2 coefficient has been scaled linearly with dB/dt and inversely with $B(t)\rho$ during the proton and heavy ion acceleration cycles.

$$b_2(t) = \frac{dB/dt}{5} \times \frac{2.149}{B(t)\rho} \times 0.78 \qquad (1)$$

Saturation[2]

The dipole field reaches 12.75 kG during heavy ion acceleration, and sextupole fields from magnet saturation dominate those from eddy currents. The saturation multipoles are listed in Table I. Only b_2 is included when determining the chromaticity; all multipoles are included when evaluating the kick given to a test particle.

TABLE I Saturation Multipoles Expressed as $b_n(m^{-n})$

	B(kG)					
Mult	1.6	10.0	11.0	12.0	12.5	13.0
b_2	0.0026	-0.05	-0.087	-0.17	-0.24	-0.33
b_4	0.51	-9.73	-20	-41	-59	-79
b_6	410	-1200	-3300	-6100	-7400	-7800
b_8	6.6E+5	-6.6E+5	0.0	0.0	0.0	0.0
b_{10}	0.0	0.0	0.0	0.0	0.0	0.0

CHROMATICITY WINDOW FOR NO COUPLING

Sextupoles SF and SD were adjusted to increment the chromaticity equally in both planes, and the maximum emittance (ϵ_x or ϵ_y) was determined when particles having initial emittance $\epsilon_x = \epsilon_y$ were tracked. A scan with the (1,2,4,7) configuration shows a sharp valley in which little emittance transfer occurs.[3] Inclusion of eddy current multipoles only slightly alters the shape of the valley. Results are shown in Figure 1 for several initial emittances. The sharpness of the valley and the contribution from eddy current multipoles increases with emittance.

Similar runs were made with the (ALL) configuration. Results for initial emittance $\epsilon_x = \epsilon_y = 50\ \pi$ mm mradian are compared in Figure 2 for the (ALL) and (1,2,4,7) configurations. The scan with the (ALL) scheme shows a broad valley in which the emittance increases by less than 10% in an interval of $\pm$ 7.5 units around the natural chromaticity. In contrast, the (1,2,4,7) scheme limits the acceptance when $\varsigma_x = \varsigma_y = 0$. Hence, the (ALL) sextupole configuration has been selected. In following sections, the sextupole correction is studied for realistic proton[4] and heavy ion[5] acceleration cycles; results are reported for the (ALL) configuration only.

SEXTUPOLE STRENGTH FOR THE PROTON ACCELERATION CYCLE

The sextupole strengths for chromaticity correction have been determined throughout the realistic proton acceleration cycle of Figure 3. The time dependence of the eddy current sextupole is obtained with Eq. 1 and is plotted on Figure 4; the integrated field $\Delta B_2(t)\ell$ of sextupole correctors S = SF or SD varies with Bρ;

$$\Delta B_2(t)\ell = 0.5SB(t)\rho \quad (T/m). \tag{2}$$

The time dependence of chromaticity from eddy currents requires SF and SD to change during the acceleration cycle; a constant component of SF and SD depends upon the final chromaticity. The dependence of $\Delta B_2\ell$ for chromaticities 0 and -5 is plotted on Figure 5. The largest requirement for sextupole strength arises from shifting the chromaticity away from its natural value. The integrated sextupole field needed to correct the chromaticity to zero is approximately 2.5 times the strength required to correct it to -5.

SEXTUPOLE STRENGTH FOR A REALISTIC HEAVY ION CYCLE

The analysis is repeated with the heavy ion acceleration cycle of Figure 6. As before, b_2 is scaled linearly with dB/dt and inversely with Bρ. Saturation is included at high fields; the time dependence of the saturation b_2 is obtained by combining the data of Table I with a relation for the magnetic field, B(t)=1.38+0.025(t(ms)-40) kG, deduced from Figure 6. The time dependence of b_2 is shown on Figure 7; the peak results from dB/dt reaching a constant value relatively early in the acceleration cycle; b_2 for sulfur is enhanced by the lower magnetic field when dB/dt reaches its maximum. The $\Delta B_2\ell$ required for chromaticity correction are shown on Figure 8.

Dynamic Aperture

The dynamic aperture (maximum initial amplitude for which betatron motion is stable) has been determined by particle tracking over the momentum interval -0.5% $\leq \Delta P/P \leq$ 0.5%. For particles with equal initial emittances ($\epsilon_x = \epsilon_y$), the dynamic aperture with eddy current multipoles present is 103 mm. This value compares favorably with the chaotic dynamic aperture of 120 mm that corresponds to the chaotic orbit transition for a Henon–Heiles potential.[6] The chaotic dynamic aperture depends on ($\overline{b}_2/\overline{b}_1$) where $\overline{b}_2$ is the average sextupole strength per unit length and $\overline{b}_1$ is the average quadrupole strength per unit length.

DISCUSSION

Three components of chromaticity (natural, eddy current induced, and saturation induced) have been considered. All three components can be adequately corrected by two families of sextupoles. The distribution of sextupole correctors has an impact on the emittance transfer between the horizontal and vertical planes; this dictates that sextupoles be placed in all half cells. For fixed dB/dt, the relative importance of fields from eddy currents decreases as the guide field increases. At the high field end of the heavy ion cycle, eddy current effects are unimportant compared with magnet saturation.

The strengths of SF and SD consist of a time dependent portion resulting from the eddy currents and saturation and a fixed part that is necessary to shift the chromaticity from its natural value to the value desired. For both protons and heavy ion acceleration, the b_2 from eddy currents reaches its maximum relatively early in the accelerating cycle and then decreases inversely as B(t). The most demanding requirement is imposed during heavy ion acceleration where $B\rho$ may approach 18 Tm. A listing of the maximum requirements for $\Delta B_2 \ell$ is given in Table II for final chromaticity is either 0 or -5.

TABLE II Maximum $\Delta B_2 \ell$ (T/m) Required for Chromaticity Correction

		Protons		Heavy Ions*	
Scheme	Corrector	0.0	-5	0.0	-5
(ALL)	SF	-0.4	0.28	-2.2	-0.55
	SD	1.5	0.48	1.9	-0.50

(* Indicates inclusion of saturation multipoles.)

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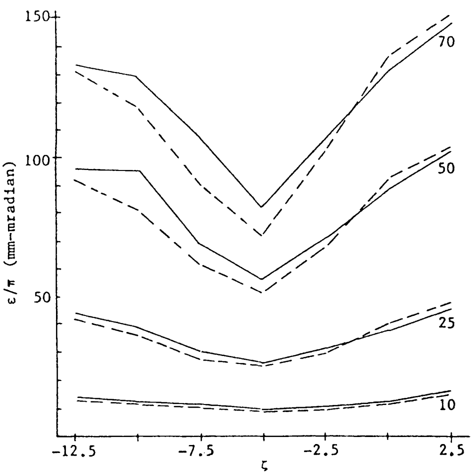

FIGURE 1 Dependence of chromaticity valley profile on particle emittance ($\epsilon_x/\pi = \epsilon_y/\pi = 10$, 25, 50 and 70 mm mrad) – (1,2,4,7) sextupole scheme. Dashed line – with eddy current multipoles; solid line – without.

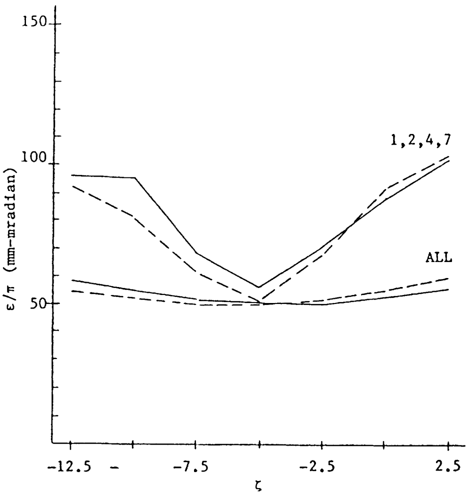

FIGURE 2 Maximum emittance for (1,2,4,7) and (ALL) schemes when initial emittances $\epsilon_x = \epsilon_y = 50\pi$ mm mrad. Dashed line – with eddy current multipoles, solid line – without.

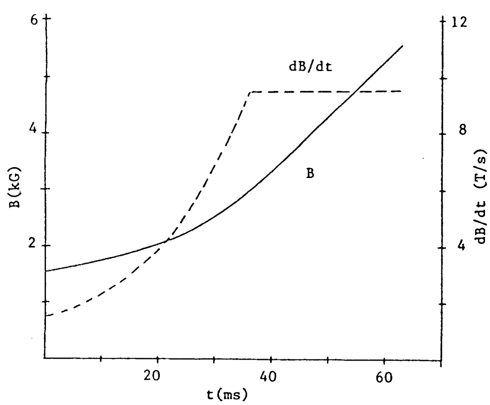

FIGURE 3 B(t) and dB/dt for the proton cycle; maximum dB/dt = 9.5 T/s. Cycle length is 62 ms.

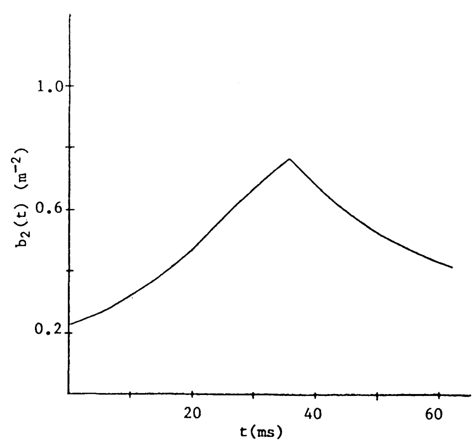

FIGURE 4 Eddy current sextupole coefficient $b_2(t)$ during the proton acceleration cycle.

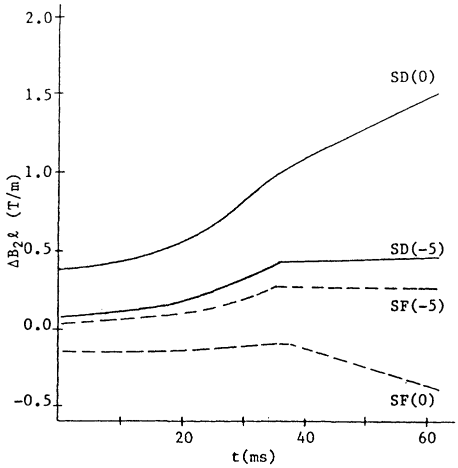

FIGURE 5 $\Delta B_2\ell$ to correct the chromaticity to (0) and (-5) with the (ALL) sextupole scheme. (Proton cycle.)

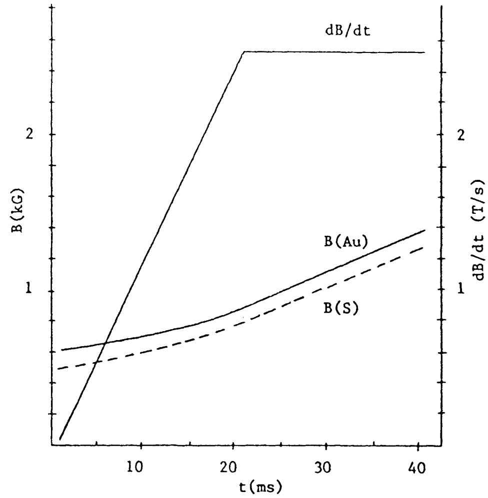

FIGURE 6 B(t) and dB/dt for the heavy ion cycle.

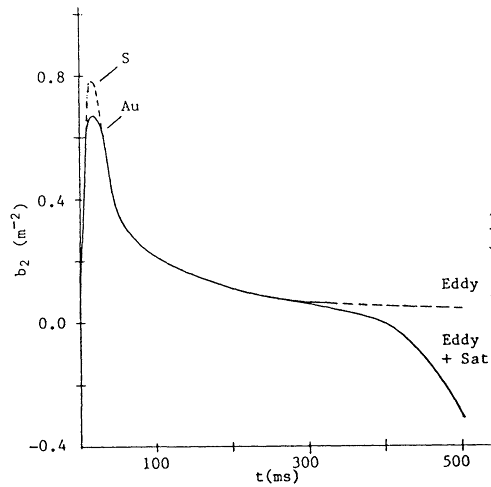

FIGURE 7 b_2 for Au and S. Dashed curve – eddy current multipoles only; solid curve – b_2 from eddy currents plus saturation.

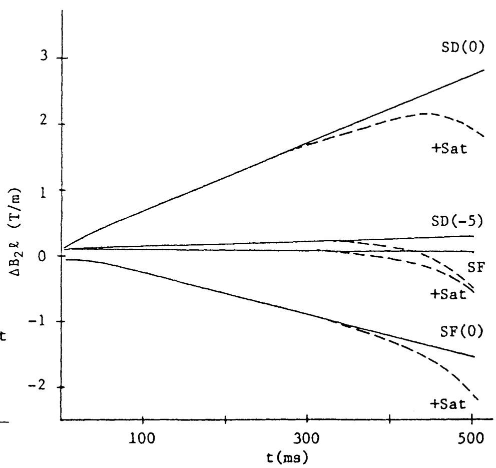

FIGURE 8 $\Delta B_2\ell$ to correct the chromaticity to (0) and (-5) with the (ALL) sextupole scheme. (Heavy ion cycle.)