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SCANNING THE AC DIPOLE RESONANCE PROXIMITY PARAMETER IN THE AGS BOOSTER

K. Hock, F. Méot, H. Huang, N. Tsoupas, P. Oddo
BNL C-AD, Upton, NY 11973

Abstract

An ac dipole system will be installed in the AGS Booster in preparation for polarized helion experiments at RHIC and the future EIC. An ac dipole is a device that drives large amplitude betatron oscillations which cause all particles to sample the strong depolarizing horizontal fields in quadrupoles, resulting in a full spin flip of all particles. The amplitude of the vertical coherent oscillations induced by the ac dipole depends on the resonance proximity parameter, δ_m, which is the distance between the betatron tune and the modulated tune of the ac dipole. The rapid acceleration rate of the booster causes the modulated tune to decrease and δ_m to change. The absolute change in δ_m depends on the energy and the duration of the ac dipole cycle. Due to the non-zero momentum spread, particles with different momenta will have different value of δ_m and thus different coherent amplitudes. These effects are significant for helions crossing $|\mathrm{G}\gamma| = 12 - \nu_\mathrm{y}$ and are simulated using zgoubi. A suitable range of δ_m values that optimize spin flip efficiency and minimize emittance growth are determined.

INTRODUCTION

An ac dipole is being installed in the AGS Booster as part of the future polarized helion spin program for RHIC and the eRHIC EIC [1, 2] . An ac dipole is able to flip the spin of all particles in a bunch by forcing large amplitude vertical betatron oscillations with a sinusoidally oscillating field that is in phase with the betatron motion. These large amplitude oscillations cause all particles to sample the strong horizontal fields in quadrupoles and results in a preservation of polarization through spin flipping. Polarized helions will cross two intrinsic resonances in the Booster, $|\mathrm{G}\gamma| = 12 - \nu_\mathrm{y}$ and $|\mathrm{G}\gamma| = 6 + \nu_\mathrm{y}$ [3]. δ_m is known as resonance proximity parameter and is defined as

$$\delta_\mathrm{m} = \nu_\mathrm{m} - \nu_\mathrm{y}, \tag{1}$$

where ν_m is the modulated tune, and ν_y is the vertical betatron tune. ν_m is defined as,

$$\nu_\mathrm{m} = \frac{\mathrm{f_m}}{\mathrm{f_{rev}}} \tag{2}$$

where $\mathrm{f_m}$ is the oscillation frequency of the ac dipole, and $\mathrm{f_{rev}}$ is the revolution frequency. Experience of ac dipole operations in the AGS show that δ_m may need to move closer to zero for efficient spin flipping, allowing large amplitude vertical coherent oscillations with the same field [4].

As part of the Booster ac dipole project, simulations have been performed to display the spin flipping effectiveness of the ac dipole. These simulations have been performed assuming an ideal resonance proximity parameter, δ_m=0.01. It is important to understand the minimum δ_m value that provides efficient spin flipping and minimized emittance growth. The Booster ac dipole will have a fixed frequency of $\mathrm{f_m}$ = 250 kHz which will constrain the vertical betatron tune, ν_y, for a desired δ_m. To control the tune spread, sextupole supplies are used to bring the vertical chromaticity from its natural value for these optics of $\xi = -2.64$ to $\xi = -0.5$.

AC DIPOLE

The amplitude of the vertical coherent oscillations driven by an ac dipole is [4],

$$\mathrm{Y_{coh}} = \frac{\beta_\mathrm{yk}\theta_\mathrm{k}}{4\pi\delta_\mathrm{m}} \tag{3}$$

where β_yk is the vertical beta function at the location of the kicker, and $\theta_\mathrm{k} = \mathrm{B_m l/B}\rho$ is the deflection angle of the magnet, with $\mathrm{B_m}$ its peak field and l its length.

Since $\mathrm{f_m}$ is fixed, ν_y must be used to control δ_m. Although $\mathrm{f_m}$ is fixed, $\mathrm{f_{rev}}$ will be increasing through the ac dipole ramp which causes ν_m to decrease by $\Delta\nu_\mathrm{m}$. The change in ν_m for the duration of the cycle, $\Delta\nu_\mathrm{m}$, is

$$\Delta\nu_\mathrm{m} = \mathrm{f_m}\left(\frac{1}{\mathrm{f_{rev,o}}} - \frac{1}{\mathrm{f_{rev,n}}}\right) \tag{4}$$

where $\mathrm{f_{rev,o}}$ is the revolution frequency at the start of the ramp, and $\mathrm{f_{rev,n}}$ is the revolution frequency at the end of the ramp. If $\nu_\mathrm{m} > \nu_\mathrm{y}$, $\mathrm{Y_{coh}}$ will increase as ν_m decreases, whereas if $\nu_\mathrm{m} < \nu_\mathrm{y}$, $\mathrm{Y_{coh}}$ will decrease.

Due to Eq. (1) dependence on ν_y, the tune spread of the bunch is also incorporated. The RMS tune spread is defined as,

$$\sigma_{\nu_\mathrm{y}} = \xi\sigma_\mathrm{p} \tag{5}$$

where ξ is the chromaticity, and σ_p is the width of momentum spread. For helions in Run14 the momentum spread was $\sigma_\mathrm{p} = 1.19 \times 10^{-3}$. The resulting coherent amplitude at turn i is

$$\mathrm{Y_{coh}} = \frac{\beta_\mathrm{yk}\theta_\mathrm{k}}{4\pi[\mathrm{f_m}[\frac{1}{\mathrm{f_{rev,o}}} - \frac{1}{\mathrm{f_{rev,i}}}] + \delta_\mathrm{m} + \xi\delta_\mathrm{p}]} \tag{6}$$

The vertical envelope (in the absence of dispersion) of the beam through the ac dipole cycle, $\mathrm{R_{coh}}$, will follow $\mathrm{Y_{coh}}$ with the addition of the beam envelope,

$$\mathrm{R_{coh}} = \mathrm{Y_{coh}} + \sqrt{\beta_\mathrm{y}\varepsilon_\mathrm{y}} \tag{7}$$

Comparison of Eq.(3) and Eq. (6) are shown in Fig. 1.

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SIMULATION RESULTS

Simulations were performed with zgoubi for helions crossing the $|G\gamma| = 12 - \nu_y$ resonance [3, 5]. The optics and ac dipole parameters used are shown in Table 1 for the various values of δ_m, which also contains the required ac dipole strength for 99% spin-flip and the resulting emittance growth. Note that in the case of $\delta_m = 0.0025$ that the emittance dilution is so severe that a full spin-flip can no longer be achieved. These simulations were performed tracking 1,000 particles for 6,600 turns. The up, flat, and down ramp of the ac dipole are 1800, 2000, and 1800 turns respectively. For a ramp of this duration, $\Delta\nu_m \sim 0.0028$.

Table 1: Summary of the AC Dipole Strength Requirements and Emittance Growth at Various δ_m Values. Note the corresponding change to ν_y required to bring the two tunes in closer proximity to one another.

δ_m	ν_y	ξ_y	$B_m l$	ε_r	P_f
0.01	4.1892	-2.64	23.0	1.000	-99%
0.01	4.1892	-0.50	16.5	1.000	-99%
0.005	4.1942	-0.50	7.6	1.029	-99%
0.004	4.1952	-0.50	5.2	1.088	-99%
0.003	4.1962	-0.50	3.6	1.257	-99%
0.0025	4.1967	-0.50	2.8	3286.121	-92%

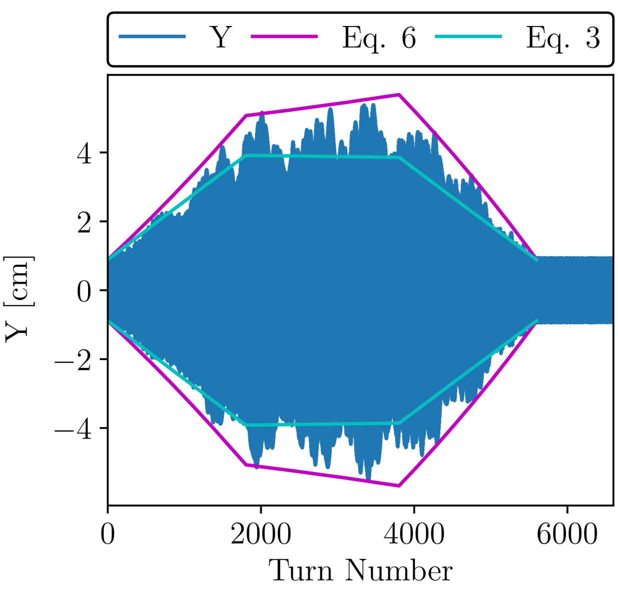

Figure 1: The vertical position of the bunched beam and its comparison with Eq. (3) and Eq. (6) for helions crossing the $|G\gamma| = 12 - \nu_y$ with $\xi = -2.64$.

By comparison of Fig. 3 and Table 1, the change in beam size becomes very non-adiabatic as δ_m approaches zero. The vertical motion of the bunch for the case of $\xi = -0.5$ is shown in Fig. 2. This non adiabatic change causes observable emittance growth with $\delta_m = 0.003$ and below. Fig. 1 shows the vertical beam position as a function of turn number for the extreme case of natural chromaticities. As observed in Fig. 1, the coherent amplitude from Eq. 6 tracks the envelope of the beam more accurately than Eq. 3 after including the initial envelope.

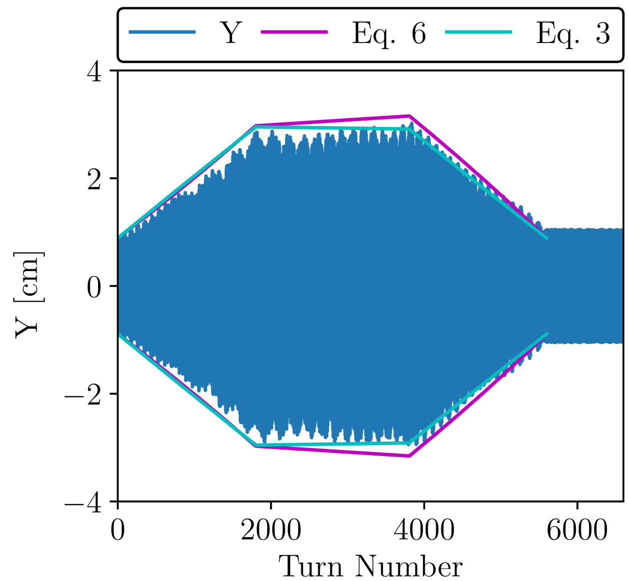

Figure 2: The vertical position of the bunched beam and its comparison with Eq. (3) and Eq. (6) for helions crossing the $|G\gamma| = 12 - \nu_y$ with $\xi = -0.5$.

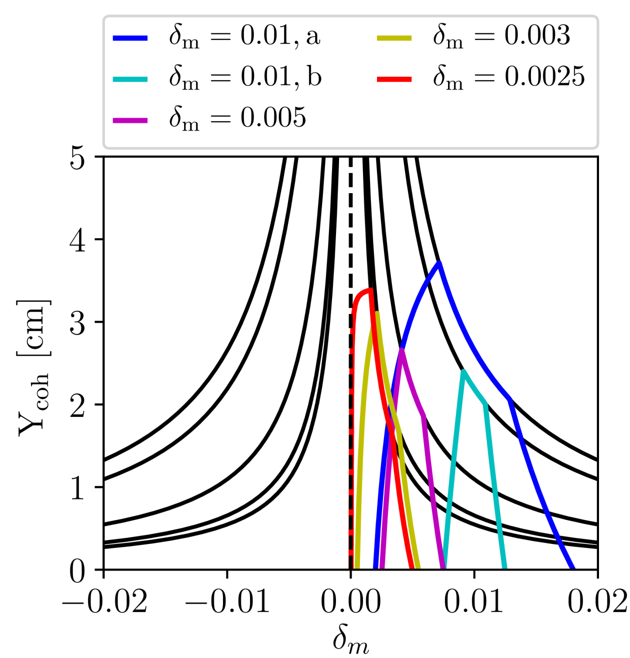

Figure 3: Comparison of coherent amplitudes with different δ_m values. $\delta_m = 0.01$, a corresponds to results with the natural chromaticity and $\delta_m = 0.01$, b is $\xi = -0.5$; all results besides $\delta_m = 0.01$ correspond to $\xi = -0.5$.

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With the ramp up and down durations of the ac dipole being determined by the synchrotron period, further efforts to reduce the length of the cycle can only come from the flat portion where the peak field of the ac dipole is held constant (while its strength varies sinusoidally). This would greatly impact spin flip efficiency.

CONCLUSION

Simulations have established a working operating range of vertical betatron tunes during ac dipole operation. Reducing δ_m below 0.005 should be avoided due to the reduced adiabaticity of the cycle as the excitation approaches the singularity at $\delta_\mathrm{m} = 0$. Controlling the chromaticity greatly reduces the envelope of the beam as it undergoes these large betatron oscillations.

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