ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST008

SIMULATIONS OF PROTONS TO EXTRACTION AT $G\gamma = 7.5$ IN THE AGS BOOSTER

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Abstract

To prepare for polarized helion collisions at the Electron Ion Collider (EIC), polarization transmission at the injectors for the Hadron Storage Ring must be studied and optimized. To this effect, an AC dipole has been installed in the AGS Booster to maximize polarization transmission of helions through several intrinsic resonances. This installation also allows polarized protons to be extracted at higher energy without polarization loss. By increasing the proton extraction energy from $G\gamma = 4.5$ to $G\gamma = 7.5$, protons will cross the $G\gamma = 0 + \nu_y$ and $G\gamma = 12 - \nu_y$ depolarizing vertical intrinsic resonances, the $G\gamma = 5$, 6, and 7 imperfection resonances in addition to the $G\gamma = 3$, 4 that are crossed in the present configuration, and be injected into the AGS at a higher rigidity. By simulation, it is determined that there is sufficient strength of the AC dipole to full spin-flip through each of the intrinsic resonances, and there is sufficient corrector current to preserve polarization through the three additional imperfection resonances. The higher injection rigidity facilitates the horizontal and vertical tunes being placed inside the AGS spin-tune gap at injection due to a substantial improvement on the AGS admittance at injection.

INTRODUCTION

The two types of resonances encountered by polarized beams in the injectors are imperfection resonances, which occur when

$$G\gamma = M \tag{1}$$

where M is an integer, G is the anomolous magnetic moment, and γ is the Lorentz factor, and intrinsic resonances, which occur when

$$G\gamma = mP \pm \nu_y \tag{2}$$

where m is an integer, P is the superperiodicity ($P = 6$ for the Booster, $P = 12$ for AGS), and ν_y is the vertical betatron tune. Imperfection resonances are the result of non-zero closed orbits that are primarily caused by misaligned quadrupoles. Intrinsic resonances occur when the spin precession is in phase with the particles betatron motion.

To preserve polarization in the AGS, there are two partial snakes whose settings allow for imperfection resonances to be avoided by prohibiting $\nu_s = M$, where ν_s is the spin tune. The betatron tunes can be placed near the integer ($\nu_y > 8.9$) to mostly avoid intrinsic resonances by prohibiting $\nu_s = \nu_y$ for vertical, which is referred to as being inside the spin-tune gap [1]. Due to the geometrical location of the two snakes, the stable spin direction in the AGS is nearest vertical every $G\gamma = 3n + 1.5$, where n is an integer. The cold snake in particular has strong optical distortions which decrease exponentially with energy [2]. These optical distortion adversely affect the admittance and how the tunes can be configured [3]. In efforts to further improve the polarization transmission of protons in the injectors, protons can be injected into the AGS at higher rigidity which can hypothetically allow for stronger snakes and allow both the horizontal and vertical betatron tunes to be set inside the spin-tune gap.

Protons are presently injected into the Booster at $G\gamma = 2.19$ and extracted into the AGS at $G\gamma = 4.5$. At injection both betatron tunes are kept above the half-integer ($\nu_y, \nu_x > 4.5$) and quickly moved near 4.9 to minimize effects from the space charge [4]. In this configuration, the $G\gamma = 0 + \nu_y$ resonance is avoided by keeping $\nu_y = 4.8$. In order to match the stable spin direction from the Booster to AGS, protons can be extracted at $G\gamma = 7.5$. This higher extraction energy will cause protons to cross the $G\gamma = 3$ through 7 imperfection resonances and the $G\gamma = 0 + \nu_y$ and $G\gamma = 12 - \nu_y$ intrinsic resonances. Simulations of intrinsic resonance crossing, imperfection resonance crossing, and AGS admittance at injection are performed using Zgoubi [5].

INTRINSIC RESONANCE CROSSING

An AC dipole has been installed in the Booster to overcome vertical intrinsic resonances that polarized beams will encounter as they are accelerated [6, 7]. It is able to induce a full spin-flip of all particles in the bunch by driving high amplitude vertical coherent oscillations, causing all particles of the bunch to sample the strong horizontal fields in the quadrupoles. The amplitude of these oscillations follows [8]

$$Y_{coh} = \frac{B_m l}{4\pi B\rho\delta_m}\beta_y \tag{3}$$

where $B_m l$ is the AC dipole strength, $B\rho$ is the rigidity, $\delta_m = \nu_m - \nu_y - n$ is the separation between the AC dipole tune (ν_m) and the vertical betatron tune, and β_y is the vertical beta function. The AC dipole tune is

$$\nu_m = f_m/f_{rev} \tag{4}$$

with f_m being the AC dipole oscillation frequency and f_{rev} is the revolution frequency. The AC dipole system is designed with a maximum $B_m l = 25$ Gm and an oscillation frequency of $f_m = 250$ kHz.

For protons crossing the $G\gamma = 0 + \nu_y$ resonance, the configuration is $\nu_y = 4.8088$ and $\nu_m = 0.1812$ which requires $B_m l = 12.3$ Gm at $\delta_m = 0.01$ to full spin-flip (as shown in Table 1). Protons crossing the $G\gamma = 12 - \nu_y$ resonance will require $\nu_y = 4.8161$ with $\nu_m = 0.1739$. In order to have a full spin-flip, the AC dipole strength $B_m l = 28.0$ Gm at

Table 1: Table summarizing AC dipole settings to spin-flip at the $G\gamma = 0 + \nu_y$ and $G\gamma = 12 - \nu_y$ intrinsic resonances.

Resonance	$\mathbf{0 + \nu_y}$	$\mathbf{12 - \nu_y}$
$G\gamma$	4.8088	7.1836
ν_m	0.1812	0.1736
δ_m	0.01	0.009
$B\rho$ [Tm]	7.789	12.143
ϵ_k	0.00246	0.00152
σ_y [mm]	1.83	1.47
$B_m l$ [Gm]	12.3	25.0

$\delta_m = 0.01$. As the maximum strength of the Booster AC dipole is $B_m l = 25.0$ Gm, δ_m will need to be reduced to a maximum of 0.009. Plots of 1,000 protons crossing the $G\gamma = 0 + \nu_y$ and the $G\gamma = 12 - \nu_y$ resonances are shown in Fig. 1 and Fig. 2, respectively. The $G\gamma = 12 - \nu_y$ resonance can be avoided entirely if ν_y is less than 4.5, but would complicate injection into the Booster.

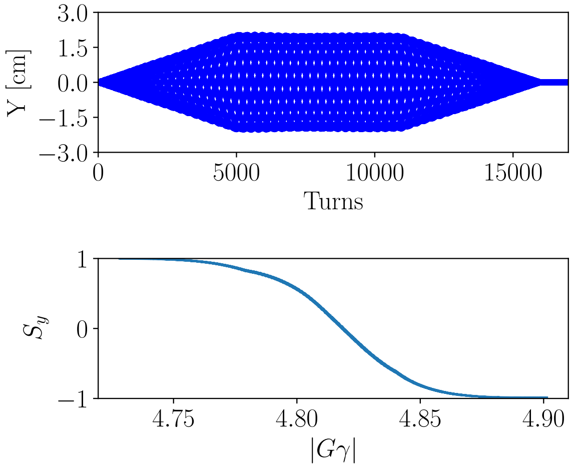

Figure 1: Simulations of protons crossing the $G\gamma = 0 + \nu_y$ resonance with $B_m l = 12.3$ Gm and $\delta_m = 0.01$ to induce a full spin-flip of the bunch.

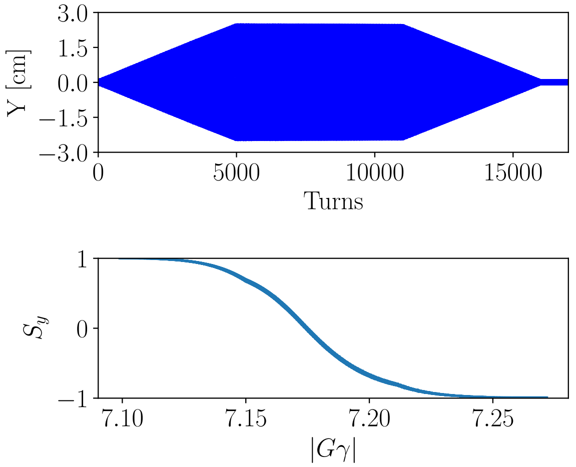

Figure 2: Simulations of protons crossing the $G\gamma = 12 - \nu_y$ resonance with $B_m l = 25.0$ Gm and $\delta_m = 0.009$ to induce a full spin-flip of the bunch.

IMPERFECTION RESONANCE CROSSING

To cross the $G\gamma = K$ resonance the $h = K$ orbit harmonic is corrected or enhanced, which either reduces the strength of the resonance to zero or enhances it to full spin-flip. The Booster has 24 vertical corrector dipoles [9] used for these orbit harmonic manipulations, and are powered according to

$$B_i = a_{i,h}(I_{\sin,h}) \sin(h\theta_i) + b_{i,h}(I_{\cos,h}) \cos(h\theta_i) \tag{5}$$

where i is the corrector number, θ_i is the location in the ring, h is the harmonic number, and $a_{i,k}(I_{\sin,k})$ and $b_{i,k}(I_{\cos,k})$ are the strengths of corrector i with current $I_{t,h}$ and t denotes the sine or cosine component. The maximum current of the corrector dipole power supplies is 25 A which is the main limitation, and have an excitation of 0.975 Gm/A. To simulate the resonance crossings, the quadrupole alignment data is added to the model which accurately reflects experimental data for the $G\gamma$ =3 and 4 imperfection resonances [10].

At each resonance, a scan of $I_{t,h}$, for $h = k$, is performed to find the optimal currents for harmonic correction, $\mu_{t,h}$. The results of each scan is fitted using a Gaussian of the form

$$\frac{P_f}{P_i} = 2\exp\left(\frac{I_{\sin,k} - \mu_{\sin,k}}{2\sigma^2_{\sin,k}}\right)\exp\left(\frac{I_{\cos,k} - \mu_{\cos,k}}{2\sigma^2_{\cos,k}}\right) \tag{6}$$

where P_f and P_i are the values of the polarization after and before the resonance, $\sigma_{\sin,k}$ and $\sigma_{\cos,k}$ are the widths. A simulated scan of $G\gamma = 5$ is seen in Fig. 3.

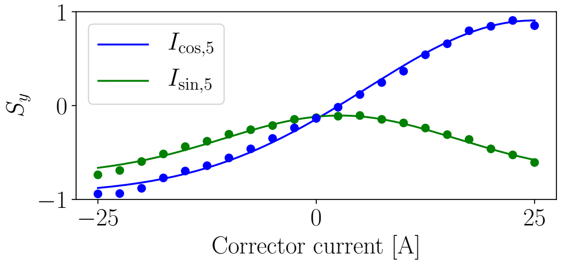

Figure 3: Harmonic scan of $I_{\sin,5}$, $I_{\cos,5}$ corrector currents for the $G\gamma = 5$ resonance crossing to find the optimal settings to preserve polarization.

With the scan and fit parameters, it is determined if the relevant orbit harmonic should be corrected or enhanced in order to preserve polarization. Table 2 shows the optimal corrector currents, the corresponding currents required to preserve polarization, and the maximum current on any one of the corrector dipoles.

Table 2: Table summarizing corrector currents required to preserve polarization at each additional imperfection resonance for nominal proton configuration.

K	μ_s	μ_c	$I_{\sin,K}$	$I_{\cos,K}$	$I_{\max}$
5	2.7±8.5	24.9±9.7	2.7	24.9	24.3
6	7.9±6.9	-2.5±0.8	-14.0	8.0	12.8
7	54.2±0.9	57.2±0.8	0.0	0.0	0.0

If ν_y is less than 4.5 to avoid crossing the $G\gamma = 12 - \nu_y$ resonance, different quadrupole strengths would be present and the $h = 4$ orbit harmonic would be dominant. The analysis is performed on this change in optics and summarized in Table 3.

Table 3: Table summarizing corrector currents required to preserve polarization at each additional imperfection resonance in the case that $\nu_y < 4.5$.

		Protons $\nu_y < 4.5$			
$G\gamma$	μ_s	μ_c	$\sin k\nu$	$\cos k\nu$	$I_{\max}$
3	4.2±1.2	4.5±0.9	4.2	4.5	6.2
4	2.5±6.4	0.7±5.0	2.5	0.7	2.4
5	1.0±0.9	11.5±0.9	0.0	-12.0	11.9
6	7.6±2.9	-2.1±0.9	-14.0	8.0	12.8
7	5.7±1.1	3.4±1.4	-10.0	10.0	14.2

AGS ADMITTANCE AT INJECTION

The optical distortions from the cold snake adversely affect the admittance [2, 3], which is the stable area of the beam within the limiting aperture of the machine. An example of an admittance calculation from simulation is shown in Fig. 4, where particles are tracked for $N = 200$ turns and the edge of the stability region is determined.

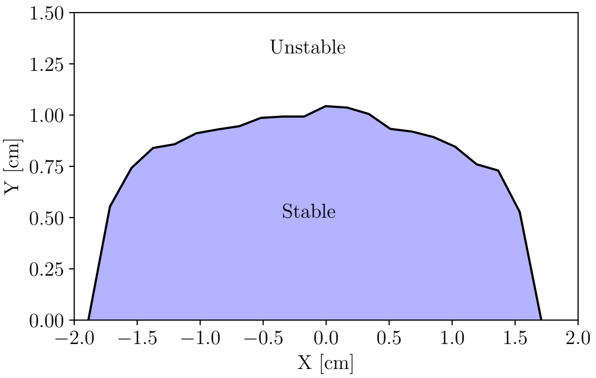

Figure 4: Example of the admittance where the algorithm finds the edge of the stability region for $N = 200$ turns.

Injection into the AGS at $G\gamma = 7.5$ has a factor of 12 reduction in these optical defects when compared to the $G\gamma = 4.5$ case. The effect this has on the admittance is observed in Fig. 5 with $G\gamma = 4.5$ (top) being substantially smaller than $G\gamma = 7.5$ (bottom). This improvement in admittance can not only allow both the tunes to be placed inside the spin-tune gap (that is $[\nu_x, \nu_y] > [8.9, 8.9]$), but can allow stronger snake settings to mitigate polarization loss during the AGS acceleration cycle.

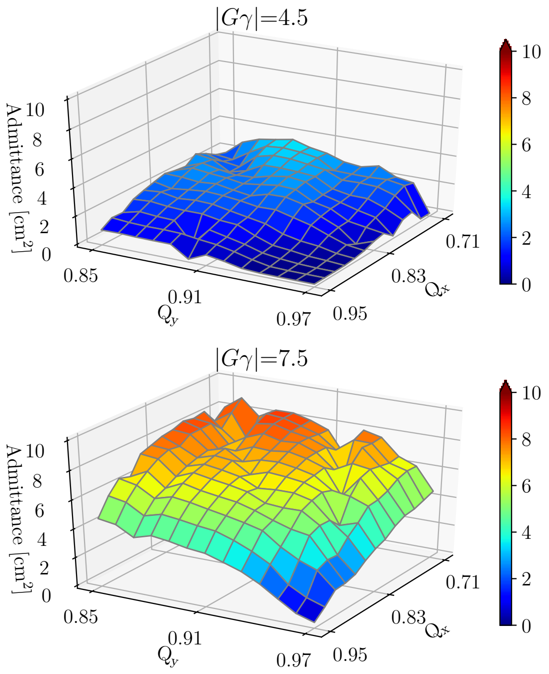

Figure 5: AGS admittance with injection at $G\gamma = 4.5$ (top) and at $G\gamma = 7.5$ (bottom).

CONCLUSION

Simulations of polarized protons crossing the $G\gamma = 0 + \nu_y$ and $G\gamma = 12 - \nu_y$ intrinsic resonance show the AC dipole has sufficient strength to induce a full spin-flip at each resonance. The strength required for the $G\gamma = 12 - \nu_y$ resonance necessitates that δ_m be less than 0.009. Simulations of imperfection resonances using misaligned quadrupoles from survey data showed there is sufficient corrector current to correct each of the additional imperfection resonances. The admittance simulations show that at $G\gamma = 7.5$ the admittance is substantially larger than at $G\gamma = 4.5$ and facilitates both horizontal and vertical tunes to be placed inside the spin-tune gap at injection. This improved admittance would also allow running with stronger snakes.

ACKNOWLEDGEMENTS

Funding Agency Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.

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