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CORRECTION OF HORIZONTAL PARTIAL SNAKE RESONANCES WITH PULSED SKEW QUADRUPOLES AT THE BROOKHAVEN AGS*

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Abstract

Proton polarization is preserved in the AGS by using helical dipoles partial snakes to avoid depolarizing vertical resonances. These same helical dipoles also drive numerous (82) weak horizontal resonances that result in polarization loss. These horizontal resonances occur at the same energy (and therefore frequency) as depolarizing resonances driven by linear betatron coupling. A new scheme has therefore been implemented to correct the snake-driven resonances with the placement of skew quadrupoles in the AGS ring powered to cancel the resonance driving term at each horizontal resonance crossing. The skew quadrupoles are required to pulse independently for each resonance to account for the variation of drive term phasing with energy. Fifteen thin skew quadrupoles have been installed in the AGS ring to implement this correction. We describe the correction principle, the magnet design and commissioning results from RHIC Run 24.

INTRODUCTION

Polarized proton beam is accelerated in the AGS from a total energy of 2.35 GeV to 23.8 GeV. This corresponds to a range of $G\gamma$ from 4.5 to 45.5, where G is the anomalous gyromagnetic ratio and γ the relativistic factor. Polarization preservation over this energy range is accomplished mainly through use of two helical dipole partial snakes [1]. In an ideal, planar synchrotron without snakes, the spin tune (number of spin precessions per revolution) is equal to $G\gamma$ and will therefore would sweep through all fractional values between 0 and 1 many times over the AGS energy range. Depolarizing resonances occur whenever the spin tune $\nu_s = N \pm Q_y$ (for Q_y the vertical tune). The depolarizing effect is particularly strong if N is a multiple of the superperiodicity (12 in the case of the AGS). The partial snakes manipulate the spin tune of the protons, such that while it will still vary with the particle energy, it will never take values in a band around each integer (the so-called "spin tune gap"). Setting Q_y to a value within the spin tune gap avoids all the strong vertical intrinsic resonances [2]. In the AGS, this generally means that Q_y must be above 8.96.

The partial snakes, however, drive additional resonances related to the horizontal tune, Q_x, which occur whenever $\nu_s = G\gamma \pm Q_x$. The horizontal resonance are weak, but numerous- the AGS beam passes through 82 of them over the normal acceleration range. Left unmitigated, they result in 15-20% relative polarization loss for typical AGS operation. These resonances could in principle be avoided by setting Q_x to also be in the spin tune gap, but that has proven operationally difficult due to difficulty preserving intensity and emittance with both tunes near the integer. At present, about half the polarization loss is eliminated using a fast horizontal tune jump to speed the crossing through each resonance [3–5].

The resonance condition for these snake-driven resonance ($\nu_s = G\gamma \pm Q_x$) is identical to that of resonances driven by betatron coupling [2, 6]. It can therefore be shown that by carefully driving betatron coupling during a partial snake resonance crossing, one can provoke a spin resonance equal in amplitude and opposite in phase to the snake driving term and cancel the resonance completely. In the presence of both a partial snake and a betatron coupling resonance of amplitude ϵ_x, the net resonance driving term is given by

$$\epsilon = \frac{1}{2\pi} \int \delta_n(\theta - \theta_s) e^{-iG\gamma\theta + iK\theta} \left[1 - \left(\tilde{x}' \frac{(1 + G\gamma)}{2} + \epsilon_x\right) e^{\pm iQ_x\theta}\right] d\theta \tag{1}$$

where θ is the azimuthal location around the ring, δ indicates a delta function at the snake location θ_s, K is the resonance tune, $\tilde{x}'$ is the maximum horizontal angular deviation of the particle from the reference trajectory. Additional partial snakes only modify the amplitude and phase of the net snake drive term. Since the resonance terms add linearly as complex numbers, a collection of skew quadrupoles added to the lattice can be powered to excite betatron coupling to exactly cancel the snake terms. An important technical difficulty arises because the relative phasing of a coupling resonance driven by a skew quad and that driven by a partial snake have different dependencies on the energy and the lattice. This means that different correction currents have to be calculated (and applied) in the skew quads for each resonance. For a typical AGS ramp rate of 110 units of $G\gamma/sec$, and $Q_x = 8.72$ this means that adjacent resonance occur every 4-5 milliseconds. Correction therefore requires fast ramping skew quadrupoles, which we describe in the next section.

MAGNETS AND POWER SUPPLIES

In principle, for any given resonance, only two coupling sources are required (to provide two orthogonal resonance vectors). Constraining the resulting tune shift, however, brings the number of requirements to four. Since the spin resonance phasing is different for each resonance, one then must look for a minimal (or at least reasonably small) set of

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coupling sources that cover the space for all 82 resonances (and have reasonable field and length). Numerical studies indicated that 15 short skew quadrupoles suffice in the AGS. The phase of the spin resonance driven by each skew quadrupole is determined by its location in the lattice. They were therefore chosen to be short (mechanical length 0.17 m), in order to maximize the possible installation locations. Table 1 summarizes the magnet properties.

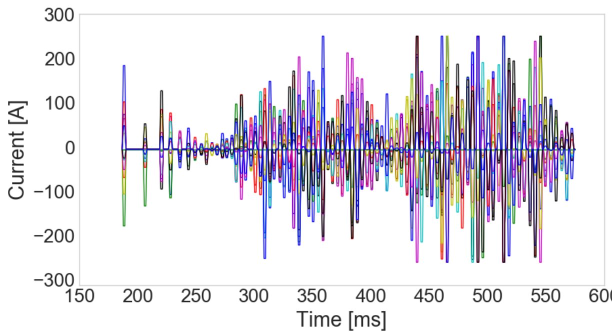

Figure 1: Current functions for the 15 skew quadrupoles used for spin resonance correction. Each color is one magnet. The AGS acceleration ramp lasts about 400 ms.

The magnets are designed to ramp to setpoint (as high as ± 275 A) in 1 ms, hold a flattop of 1.3 ms and ramp down in 1 ms. The flattop of each pulse is to be centered on the resonance crossing time. A typical set of current functions is shown in Fig.1. A number of features are designed to minimize heating from eddy currents during the pulsing: the magnets are constructed of 0.635 mm laminated steel, the pole coils are stranded (4 strands) for minimal cross sectional area, and the turns end about 1/2" from the pole tip where the fields are highest. Figure 2 shows a magnet as installed in the AGS. Reference [7] gives a full description of the magnet design.

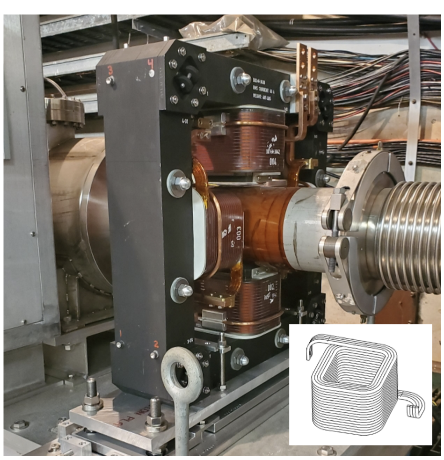

Figure 2: Skew quadrupole magnet as installed in the AGS ring. Inset in lower right shows the stranded pole tip cable.

In order to prevent high power, high frequency draw from the electrical grid, each power supply includes a 600 V capacitor bank. Voltage is supplied for the 82 pulses during the

Table 1: Summary of Skew Quadrupole Magnet Parameters

Magnet Parameter	Value
Length (mechanical) [m]	0.17
Bore diameter [m]	0.16
Pole tip field (max) [T]	0.15
Integrated gradient (max) [T]	0.32
Current (max) [I]	± 275
Lamination thickness [mm]	0.635

400 ms AGS acceleration ramp and then restored slowly during the remaining 3.2 seconds of the 4 second AGS repetition period.

COMMISSIONING

Commissioning the correction system began in March of 2024. Since the polarization loss from any given resonance at the normal acceleration rate is small (0.1-0.5%), their impact is not measurable in a practical time period. A dedicated machine configuration with a slow crossing of a single resonance is therefore used to study the effects of the skew quadrupoles on an individual resonance.

For this proof-of-principle study, the proton beam in the AGS is ramped to a flattop energy such that $\nu_s \approx G\gamma$=45.74. The horizontal tune at the start of the flattop is 8.70. The polarization with Q_x held at 8.7 for the duration of the flattop establishes the polarization without a resonance crossing. Ramping the Q_x from 8.70 to 8.78 over 200 ms (through the resonance at 8.74) is sufficiently slow to cause a measurable (≈20%) relative reduction in the polarization. Three individual skew quadrupoles are then powered, in turn, at their full current amplitudes (positive and negative). The three skew quads are chosen such that the resonances they drive (calculated via SPRINT[8]) will be substantially in phase with the snake drive term, out of phase with it, or

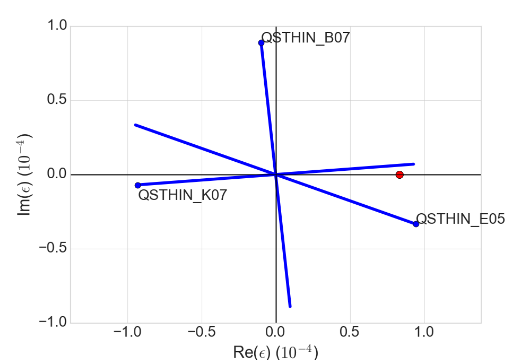

Figure 3: Depolarizing spin resonance drive terms (from SPRINT) for each skew quadrupole over their full range of current ±275 A (blue). The end corresponding to positive current is labeled with a dot. The red dot on the real axis represents the partial snake drive term. The K07 skew quadrupole in positive current almost exact cancels the snake term.

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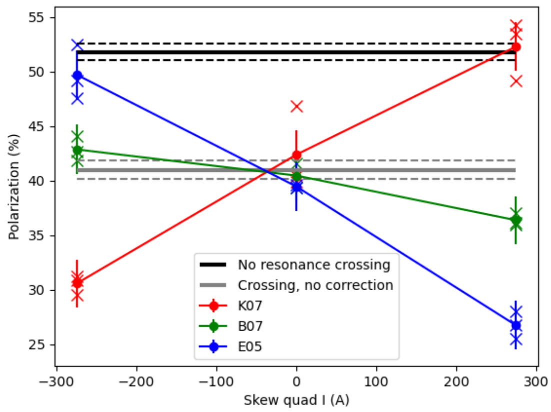

Figure 4: Polarization versus skew quadrupole during during a slow resonance crossing. Polarization (with statistical error) without a crossing is shown in black. Crossing the resonance reduces the polarization by 20% (relative), shown in gray. Colored traces indicate polarization as a function of skew quad strength (name by location in the ring). For a single corrector of the right phase (like K07), the resonance can be totally corrected.

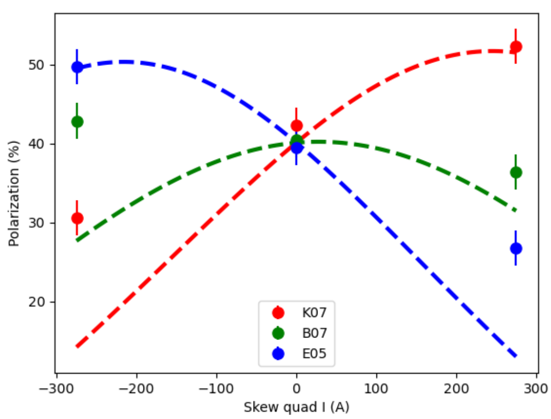

Figure 5: Measured polarization (circles) versus skew quadrupole current scan during a slow resonance crossing compared to a SPRINT model prediction (dashed lines). The model predicts well the uncorrected loss and the low loss regime. The disagreement for large resonance strength and for the 'orthogonal' corrector B07 is the subject of ongoing studies.

orthogonal to it (see Fig. 3) . Figure 3 indicates that the skew quadrupole at the K07 location should produce full correction of the resonance (zero polarization loss) when powered at full current in one polarity. The experimental results for the three skew quad current scans are shown in Fig. 4 and show the correction effect. The polarization resulting from positive current in K07, the best aligned corrector, is the same as the polarization without a crossing.

Figure 5 shows the same polarization versus current data, now compared with model expectation. The model expectation comes from a SPRINT calculation of the resonance drive terms due to both the snakes and the skew quadrupoles and application of the Froissart-Stora formula for the measured resonance crossing rate and a horizontal emittance of 2 µm. The results agree well for the no crossing and correction cases, but diverge for the 'orthogonal' skew quadrupole drive term and in the regime where the resonance drive term is increasing. The reason for this discrepancy is not yet understood. Because the polarization loss depends nonlinearly on the resonance strength, it is possible that errors in the resonance strength calculation have a much smaller effect near zero net strength than they do when the strength increases. Simulation and beam studies are planned to better characterize the source of the error.

CONCLUSIONS

A set of 15 fast-ramping skew quadrupoles have been designed installed in the AGS as part of an effort to fully correct the 82 weak depolarizing resonance associated with the partial snakes. A proof of principle measurement has been made, showing that the betatron coupling from the skew quadrupoles is capable of eliminating polarization loss from one of these resonance in a specialized test setup at a fixed energy. Work continues to better understand the resonance drive terms and extend the correction to the acceleration ramp.

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