OPTICS ERROR MEASUREMENTS IN THE AGS FOR POLARIZED PROTON OPERATION*

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Abstract

A large distortion of the vertical beta function became evident in the Brookhaven AGS during the 2010 polarized proton run. This paper describes the beam measurements and model calculations made to verify the distortion of the optics, to infer possible sources and to explore correcting strategies. The optics distortion is only apparent when operating with a betatron tune very near the integer (as required for polarization preservation during acceleration in the AGS) and with the lattice chromaticity sextupoles powered. The measurements indicate a small (on the order of millimeters) unexpected systematic horizontal closed orbit displacement in the sextupoles that is not evident in beam position monitor measurements. Motivated especially by these observations a complete survey of the AGS was performed during the 2010 shutdown period. The results of that survey and their impact on the observed optical errors in the AGS are included.

INTRODUCTION

Acceleration of polarized protons with partial Siberian snakes, as in the Brookhaven AGS, requires that the vertical betatron tune be within a small window around an integer in order to preserve polarization [1]. In the AGS, the nearest integer is 9 and the vertical betatron tune is kept above 8.98 for most of the acceleration cycle and even above 8.99 for brief periods near the strongest vertical intrinsic resonances. Operation this close to the integer amplifies the effects of all orders of magnetic errors present in the lattice. In this paper we are concerned with the distortion of the vertical beta function and therefore with gradient errors.

Beta function distortion (or 'beta beating') is of particular concern during the AGS acceleration ramp because of the recent commissioning of the AGS jump quad system [2, 3]. This system creates (for reasons of polarization preservation, discussed in the reference) 82 jumps in the betatron tunes of both planes between injection and extraction energy by simultaneously pulsing a pair of identical quadrupoles (the so-called tune jump quads). The jumps are fast, 100 μs (or 30 revolutions), where the vertical betatron period at a tune of 8.98 is 50 turns and so the change in the lattice optics effected by the quadrupoles is non-adiabatic with respect to the vertical motion and therefore a possible source of emittance growth. The amplitude of the horizontal tune jump for each quadrupole is as much as 0.025. The quadrupoles are located in the AGS lattice one superperiod apart, which with 12 superperiods and a tune near 9 means that they are separated by a phase advance of approximately 270°. In addition, the AGS is nominally superperiod symmetric through most of the acceleration cycle, and so the quads are at locations where the beta functions are nominally equal. Under these optical conditions, the quadrupoles should cause minimal emittance growth.

Intensive study of the AGS vertical optics was in fact prompted by the observation, during the 2010 polarized proton developement run, that equal current changes in each of the jump quads were not producing equal changes in the vertical betatron tune. This implies unequal beta functions at the quadrupole locations.

* Work supported by Brookhaven Science Associates, LLC, under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

OBSERVATIONS OF BETA BEATING IN RUN 10

Tune Jump Mismatch

The change in tune expected from a single, thin quadrupole in a synchrotron is given by the well-known formula $\Delta\nu_z = -\Delta K\beta_z/(4\pi)$ where ν is the betatron tune, *z* represents the plane (horizontal or vertical), K is the integrated quadrupole strength and β is the beta function at the location of the quad.

The red trace in Fig. 2 shows the ratio of the vertical tune shifts measured with each of the two jump quadrupoles powered individually (with equal currents) as a function of time in the acceleration cycle at the start of run 10. This is a measurement of the relative vertical beta functions at the quadrupole locations.

Orbit Response Measurement

Prompted by the observed beta function mismatch at the two jump quads, we performed a measurement of the beta function at many more locations in the ring using the AGS orbit correctors. In the AGS there are four vertical orbit correctors in each superperiod, each of which actually contains within it a beam position monitor. A straight-forward measurement of the beta function at each of these locations is therefore possible by powering each orbit corrector in turn and measuring the change in the equilibrium orbit at the location of the powered corrector. The beta function is calcuated as:

$$\beta_z = \frac{2\Delta x}{\Delta\theta}\tan\pi\nu_z \qquad (1)$$

The red trace in Fig. 1 shows the initial measurement of the beta beating made in this way prior to any attempt to correct the optics. The measurement shown was made at an energy of about 16 GeV, which is about the middle of the AGS acceleration range.

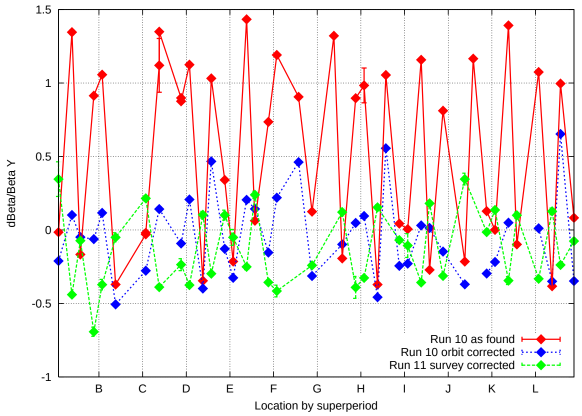

Figure 1: Measurements of vertical beta beating in the AGS. Red is as measured before any attempt at correction. Blue is an attempt to correct the underlying closed orbit distortion with the AGS low-field orbit correctors and green is a measurement made after a main magnet survey and realignment (without the orbit steerer correction). In all cases the vertical tune is 8.985.

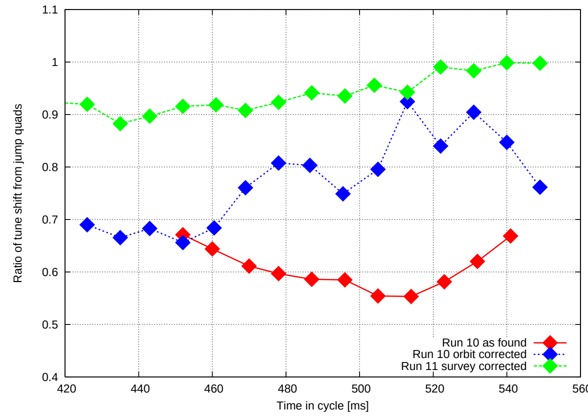

Figure 2: Ratio of the vertical tune shifts produced by powering each tune jump quad individually at equal current. By design in a superperiod symmetric AGS, the ratio should be one.

It is clear from this measurement that the accelerator optics deviated significantly (more than 100% beta beating) from the model expectations. Another difficult feature of a near-integer working point is that the cusps ordinarily created in the equilibrium orbit (by dipole errors) and the beta function (by quadrupole errors) are too small to measure, and so the location of individual errors is difficult or impossible. If the beta beating is the result of a single gradient error, then at a tune of 9 there are 18 possible source locations in the lattice. After scrutiny of the measured beta function and the AGS lattice components, it was determined that the phase of the measured wave was consistent with gradient errors at six of the twelve (superperiod symmetric) AGS vertical chromaticity control sextupoles. Subsequent measurements at top energy with the vertical sextupoles at large current and again at zero current confirmed that the source of the beta beating was indeed some combination of those magnets.

As an initial corrective measure, all of the twelve sextupoles were tested for shorted coils, but none were found.

CORRECTION VIA ORBIT CORRECTORS

Apart from shorted coils, another mechanism for the sextupoles to create vertical beta function distortion is feed-down from a systematic horizontal equilibrium orbit distortion. Model calculations suggested that the orbit distortion necessary in a single sextupole under normal operating strengths would be on the order of 1 cm. A survey error of such a magnitude is not physical given the constraints on the sextupole positions relative to adjacent magnets.

In order to distribute the source of the gradient error in such a way that the effects on the beta function would add together constructively, a sixth harmonic systematic horizontal equilibrium orbit distortion would have to be present. Further model calculations showed that a beta function of the phase and amplitude measured would require a sine-like sixth harmonic distortion of 1 mm where the zero phase of the sine is taken (by convention) to be the beginning of the AGS 'A' superperiod (where the twelve superperiods are labeled by letter from A-L). A 1 mm absolute orbit effect is below the level of the AGS beam position monitoring system to accurately detect, and so this effect cannot simply be measured and corrected for directly.

The AGS orbit correction system dipoles are capable of producing a sixth harmonic orbit distortion of the amplitude necessary for the low and mid-range energies of the AGS cycle, but are prevented by power supply limits from producing that amplitude at the highest energies and therefore cannot be used to correct completely for the orbit distortion. Recall that the dominant orbit response to a single dipole kick in the AGS is at the ninth harmonic ($\nu_y \approx 9$), and so the response at such a relatively low frequency is significantly reduced.

As an experimental verification that the beta beating was consistent with (and therefore correctable with), a sixth harmonic orbit distortion, one was applied through the acceleration cycle and the beta functions re-measured at E = 16 GeV. The results are shown on the blue traces in Figs. 1, 2 and show clear improvement over the uncorrected case.

RESULTS OF AGS SURVEY

The results above prompted a survey measurement of the AGS main magnets and chromaticity sextupoles (since a systematic horizontal survey error in the sextupoles was also consistent with the observed beta beating) during the shutdown between Runs 10 and 11 (summer of 2010). Since the AGS main magnets are combined function, horizontal displacements of these magnets are capable of driving significant closed orbit distortions.

The resulting measurements of transverse displacement

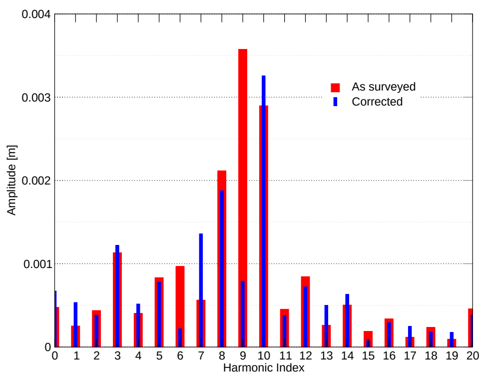

Figure 3: Harmonic content of modeled closed orbit in the AGS with full survey errors (red) and with the nine selected magnets put back to their design locations (blue). There is a marked improvement in both the harmonic that produces the measured beta wave (6) and the primary harmonic (9).

and magnet roll were included into a MAD-X model of the AGS lattice [4]. The initial model (no survey errors) had zero closed orbit everywhere. The closed orbits resulting from main magnet displacements were Fourier analyzed (Fig. 3). Of particular interest was the amplitude and phase of the sixth harmonic component, which was 1 mm in the sine phase, consistent with the observations of beta beating made during the previous run and with the hypothesis of sextupole feed-down.

The survey of the sextupoles showed several large displacements (on the order of a few millimeters), but not in a pattern with systematics capable of driving large beta function distortions.

Due to time limitations, it was not possible to realign all of the AGS magnets to their design positions. It was therefore decided to select a small subset of the magnets to reposition based on their efficacy in nulling out the net driving term of the sixth harmonic orbit distortion. Ultimately it was decided to reposition and unroll nine of the total 240 main magnets. Seven of the magnets were chosen such that moving them would most effectively diminish the net driving term for the closed orbit at the sixth harmonic. Two other magnets were included in the survey realignment because they were found to have significant roll errors (¿ 1 mrad). The driving terms were calculated using:

$$a_i = \sqrt{\beta_{y,i}} \sin(6\mu_i) \quad (2)$$

where $\beta_{y,i}$ and μ_i are the betatron amplitude and phase of the i^{th} corrector respectively (and similiarly for the orthogonal cosine phase). Shown in Fig. 3 are the Fourier components of the closed orbit predicted by the AGS MAD-X model with the main magnet survey errors before and after the realignment of the nine magnets. A four-fold improvement in the sixth harmonic was predicted.

OBSERVATIONS OF BETA BEATING IN RUN 11

Early in the present polarized proton run (Run 11), another orbit response measurement was made to verify the results of the AGS survey. The measured betatron tune and sextupole magnet currents from Run 10 were reproduced and the measurement repeated. The green traces in Figs. 1 and 2 show the improvement in the beta beat and quad beta function matching gained from the survey of the magnets. The beta beating is the same amplitude (but of different phase) as that observed when the sixth harmonic was corrected with the orbit steerers. There is a still a significant (of order 40%) beta function error around the ring. The source of this discrepancy is still being sought. Note that at the time of the measurement shown the orbit correctors were not being used to correct for the sixth harmonic component.

Similarly, the green trace in Fig. 2 shows the improvement in the relative beta function at the location of the tune jump quadrupoles, as measured by the tune shift produced at each quadrupole for equal current change.

CONCLUSIONS

The near-integer betatron tune required by polarized proton acceleration in the AGS amplifies even very small errors that are actually undetectable at lower tunes (e.g. $\approx$ 8.7 for gold ions). In particular, a large vertical beta function distortion was discovered and the source was traced to feed-down from sextupoles owing to a a small amplitude, long wavelength equilibrium orbit distortion that would not otherwise have been detected. The source of the closed orbit distortion was survey errors of the AGS combined function main magnets which were subsequently corrected by selecting and relocating a small number of the misaligned magnets back to their design positions so as to damp the harmonic primarily responsible for the beta beating.

REFERENCES

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