BETA FUNCTION MEASUREMENT FOR THE AGS IPM*

H. Huang†, L. Ahrens, C. Harper, F. Meot, V. Schoefer
Brookhaven National Laboratory, Upton, New York, 11973, USA

Abstract

Emittance control is important for polarization preservation of proton beam in the Alternative Gradient Synchrotron (AGS). For polarization preservation, two helical dipole partial Siberian snake magnets are inserted into the AGS lattice. In addition, the vertical tune has to run very high, in the vicinity of integer. These helical dipole magnets greatly distort the optics, especially near injection. The beta functions along the energy ramp have been modeled and measured at the locations of the Ion Profile Monitor (IPM). For the measurements to be valid, the betatron tune, dipole current and orbit responses have to be carefully measured. This paper summarize the experiment results and comparison with the model. These results will lead to understanding of emittance evolution in the AGS.

INTRODUCTION

Emittance control is important for high luminosity in colliders. For polarized proton operation in Relativistic Heavy Ion Collider (RHIC), emittance preservation is advantageous due to its link to polarization preservation. In general, larger emittance results in larger depolarizing resonance strength and consequently, larger polarization loss. Several techniques have been employed in the AGS to preserve polarization, such as dual partial snakes [1], horizontal tune jump quadrupoles [2] and harmonic orbit corrections. To further reduce polarization loss in the accelerator chain, it is necessary to control the emittance growth. As the first step, we need to measure emittance reliably.

The main device in the AGS to measure emittance is the ion collecting IPM [3], which has been put in use for more than 20 years. They are installed at β_{max} locations to measure both horizontal and vertical emittances. The device shows that vertical emittance increases four times in the AGS during polarized proton acceleration. However, some reported emittance growth is not real. There are several problems with this measurement. First, polarized proton operation requires two partial snake magnets which are helical dipole magnets with constant fields during the whole AGS cycle. The high magnet field near injection causes significant optical distortion. Several compensation quadrupoles have been installed on both sides of each helical dipole to mitigate the optical effect but their effects are limited. The expected beta beating may distort the reported emittance values at low energies. Second, the space charge of bunched beam is stronger at higher energy due to smaller beam size which causes larger reported emittance [4]. The profiles obtained from the AGS IPM has known effects from space charge of bunched beam, which can only be mitigated at a flattop by turning off RF cavities.

The real currents of all active magnets and other beam radius can be logged for each AGS cycle. The AGS can be modeled by MAD-X with these input information. Using the lattice model with the helical magnets included, the beta functions at the IPM locations can be calculated along the AGS magnet ramp. One example of measured emittance for polarized protons with the modeled beta functions in both vertical and horizontal in AGS magnet cycle is shown in Fig. 1. Polarized protons are injected into the AGS at 150ms from the start of the magnet cycle (AGS T0) and is ramped immediately. The acceleration is finished at 582ms and about one second at flattop is used for extraction manuevers. For the measurement shown in Fig.1, the RF cavity was shut off at 1000ms and beam was debunched after 1000ms. The drop of reported emittance at 1000ms indicates the effects of space charge. The distortion of the beam profile is due to space charge force and is mitigated with RF off. The bunch intensity for these measurements was 2×10^{11}. The modeled vertical beta function near injection is less than half of the value at flattop. There are fluctuations in the measurements, but it is clear that the vertical emittance seems doubled from injection to the flattop, even taking into account the new beta functions and removing the space charge effect. On the other hand, the horizontal emittance growth is not so strong, if any. Since the helical dipole partial snake magnets

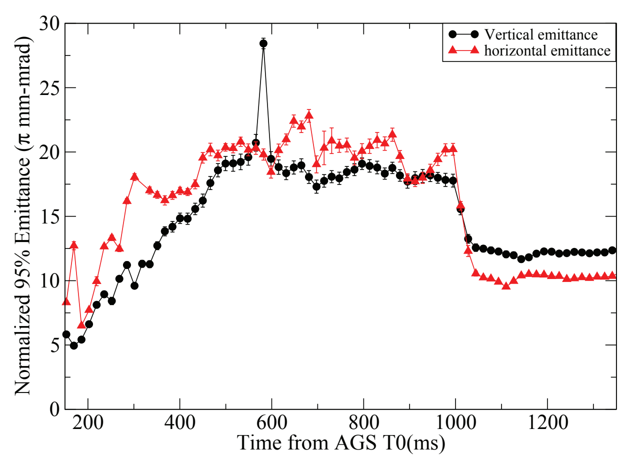

Figure 1: The normalized 95% emittance of both planes along the AGS magnet cycle. The energy ramp finishes at 582ms. The RF cavities are shut off at 1000ms and the "true" emittance at flattop is reported after that.

are hard to model, there is some doubt if the model gives the correct beta functions along the energy ramp. At higher energies, as the beam rigidity is higher, the effect from the helical dipoles are smaller. The model predicts that with

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

ISBN 978-3-95450-177-9

helical dipoles inserted, the vertical beta function near injection is only half of the nominal beta function value. To check the model and to get true emittance evolution along the energy ramp, the beta functions have to be measured along the ramp.

There are two other devices in the AGS which can measure emittance. First one is the polarimeter [5], which measures polarization by using silicon detectors to measure the recoil scattering particles between proton beam and a very thin carbon filament target(50μm×30nm×25mm). The drawback of the device is that the ultra thin target could be stretched due to beam heating and deform during motion. The obtained profile is then distorted and often overestimated. This method can only give an upper limit of emittance. In addition, it takes about 20-30ms to fly through beam, so it can only provide the beam profiles at flattop. The second one is the electron collecting IPM, which is expected to have no space charge effect. It has RF noise issues due to the noisy AGS environment and is still under commissioning [6].

β FUNCTION MEASUREMENT

The beta function can be learned by distorting the equilibrium orbit of a functioning machine - by adding a dipole kick - and measuring the orbit motion at the dipole. This measurement is model-independent. One needs position-measuring capability at the dipole, and one only learns the beta function at the dipole. With a dipole magnet right at the IPM, the centroid of the ion beam profile from the IPM provides the position measurement.

The beam position change due to a dipole kick is related to the local beta function, kick strength and the betatron tune. Beam position shift ΔY due to a known kick (with kick strength k) is given by

$$\Delta Y = \frac{1}{2} k\beta \cot(\pi Q) \tag{1}$$

where Q is betatron tune and β is the beta function in the corresponding plane. The kick strength is given as

$$k = \frac{Bdl}{B\rho} \tag{2}$$

where $Bdl = IT$ denotes the integrated magnetic fields of the dipole corrector, $B\rho$ is the magnetic rigidity of beam, I is the dipole corrector current and T is the transfer function of the dipole correctors. The shift in measured position of the beam centroid at IPM (ΔY_{IPM}) and the known dipole kick (k) can be used to calculate the beta function:

$$\beta = 2\frac{\Delta Y_{IPM}}{IT} B\rho \tan(\pi Q) \tag{3}$$

In the above equation, betatron tune and beam position shift are measured with tune meter and IPM, respectively. The dipole corrector current is set to have maximum position shift without beam loss. The transfer function is known as 2.8×10^{-4} T-m/Amp.

Dipole correctors have been installed at the locations of both the vertical and horizontal IPM in the AGS. They are used to generate a cusp in the closed orbit at the IPM. These are all standard beam and machine parameters. The measurements would seem straightforward. In reality, there are many subtleties for the measurement.

DATA QUALITY CONTROL

The emittance can be learned by measuring the width of the beam, and then translating that into an emittance by using the beta function at the measuring instrument. A straightforward measurement turned out to be a difficult and challenging one. To reach a benchmark error bar of 5%, we need to know following quantities well in the AGS magnet cycle: B field , betatron tune, beam centroid and readback current. It is necessary to estimate the errors for these calculated betas. From Eq. (3), taking partial derivatives, the dependence to each input can be calculated. For B field, taking the middle field 5kG on the ramp as example, 5% error means to know the B field down to 250G, which is easy to achieve. Polarized proton operation requires vertical tune near integer along the energy ramp (higher than 8.98) [1]. For betatron tune, the 5% error means that the betatron tune error needs to be less than 0.0005 for $\nu_y = 8.99$, or 0.001 for $\nu_y = 8.98$. These requirements can still be met for real measurement.

The dipole current readback at first was corrupted by beam noise. To alleviate this, filters were added to these signals on all dipole correctors associated with IPM. Once this was done, we were able to sufficiently determine that the functions were properly being followed and the current was known. The data was logged and they followed the set values within the 1%. The bottom line is that we need well controlled error for these quantities (B field, betatron tune, beam centroid, and read back dipole current (1kHz).

The IPM individual channel gains can also affect the results. The centroid and beam sigmas are affected by the channel gain correction at 4-7% level. If these are not properly calibrated/understood, it could exceed the 5% error for emittance measurement. The channel gain calibration was done and the emittance data shown are with the proper channel gains.

AGS BETA FUNCTION RESULTS

Proton beam is injected into AGS 150ms after the AGS magnet cycle starts(or from AGS T0). The beam is then accelerated and reaches a flattop energy of 25GeV at 582ms. There is a flattop of one second for extraction maneuver. The transition is crossed around 315ms from AGS T0. To preserve beam polarization, the vertical tune has to be pushed high (above 8.98) on the acceleration part. Ideally, the vertical tune should be pushed high right at the beginning of acceleration. However, the significant optics distortion introduced by the partial Siberian snakes results in large beta function beating at lower energies. The vertical tune has to stay low for beam survival. After that, the ver-

ISBN 978-3-95450-177-9

tical tune needs to be pushed high as soon as possible so that it is higher than 8.98 before the first major depolarizing resonance, which is located around 262ms from AGS T0.

The dipole kick current for the beta function measurement needs to move the beam as far as possible without scraping - to improve signal to noise both for beam displacement and for dipole current. Given the tune variation this is a challenge. Big changes between minimum and maximum currents make the slopes less sensitive to small underlying machine drifts. For each point, the bipolar dipole was fired in both positive and negative signs to get several position changes. The measurement was repeated several times and the average was used in beta function calculation.

The measured vertical tunes for AGS with partial Siberian snake on and the measured vertical beta functions are shown in Fig. 2. Several features are worth noting. First,

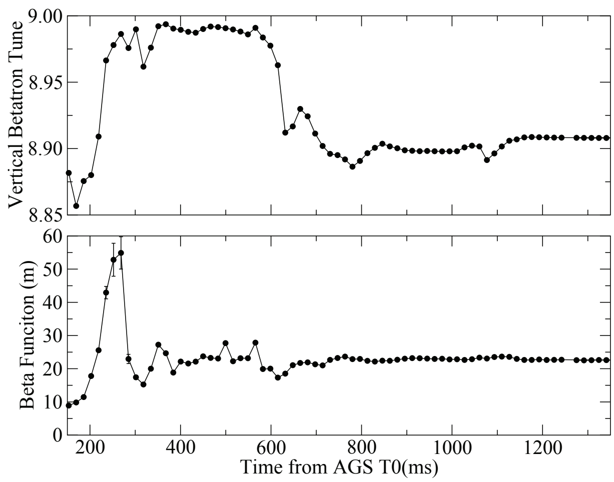

Figure 2: AGS vertical tunes (top) and vertical beta function(bottom) in an AGS cycle for AGS partial Siberian snakes on. The error bars are statistical errors only.

the measured beta function near injection is indeed less than half of the values at flattop. The optics near injection is distorted by the helical partial Siberian snake magnets, even in the presence of the compensating quadrupoles. The distortion effect diminishes quickly as beam energy goes up and the effect is negligible after 400ms. Second, the vertical betatron tune has to be pushed higher as soon as the ramp starts. The fast tune swing is associated with a large beta function swing. This large beta function variation is likely due to the helical dipole magnets and compensation quadrupoles, instead of high vertical tune. The high vertical tune after 300ms is still associated with beta function around 20 meters.

The vertical tunes in the AGS for partial Siberian snakes on and off are shown in Fig. 3. The beta function measurements for partial Siberian snake on case were done several times over a few sessions. The tunes plotted are the average of the measured tune over several months. So it is not surprising for a few points the tune values have changed quite a bit, which resulted in larger error bars. As these large er-

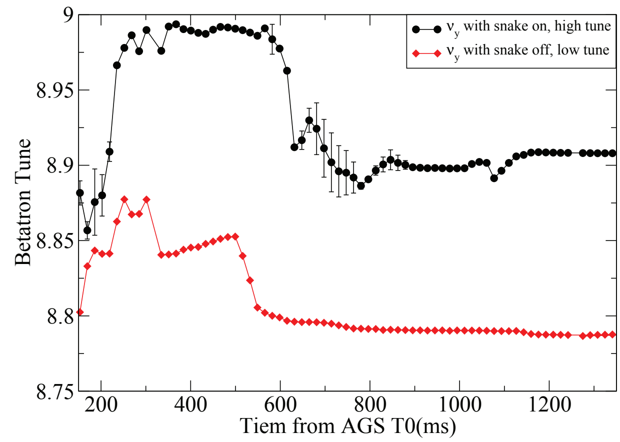

Figure 3: AGS vertical tunes in an AGS cycle for AGS partial Siberian snakes on and off. The error bars are statistical errors only.

ror bars are with tunes lower than 8.98, the impact on beta function measurement is not significant.

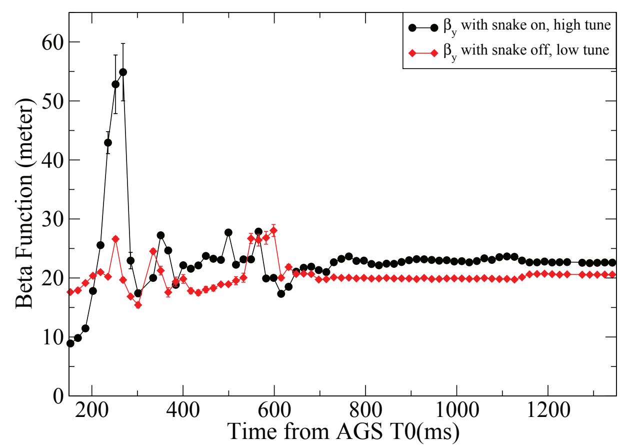

Figure 4: The measured vertical beta function for one AGS cycle. The flattop is reached at 582ms from the AGS T0. Transition is crossed around 300ms.

The measured beta functions with partial Siberian snakes on and off are shown in Fig. 4. For the optics without partial Siberian snakes, the beta functions at the IPM location is expected to be around 23m (β_{max}) from model. The measured beta functions vary around 20m through the AGS cycle. There are some fluctuations which could be from systematic errors. For the optics with partial Siberian snakes, the beta functions at the IPM location is expected to be around 25m at flattop, when the partial Siberian snake effect is small (but still visible for slightly larger beta function). At injection, the model predicts that the beta function should be less than half of the value at flattop. The measurements confirmed that overall trend.

In addition, there is a systematic difference between the beta functions from measurements and model. The measurement results are smaller by about 14%. The transfer function was one we don't have much information about

ISBN 978-3-95450-177-9

its accuracy. It is very possible that this number is off by 14%. The partial snake on and off data were taken on different years. However, the difference between model and measurements at flattop for both sets are the same. After multiplying the measurements with a factor 1.137, the beta functions from the measurements and model are plotted in Fig.5. For the partial Siberian snake on case, the small fluctuations in the modeled beta function on the ramp is due to the jump quadrupoles on, which adds to discrepancy as the jump quadrupoles were off during beta function measurement. Besides the large deviations during the vertical tune swing (between 200-300ms), the agreement in other portion is fine, for both near injection and at flattop. This may imply that the fudge factor 1.137 is reasonable. The model beta function also shows a beta function swing between 200-300ms, but in a much smaller scale. It should be noted that the γ_{tr} quadrupoles were not in this model. Although these γ_{tr} quadrupoles are in the lattice and their transfer functions are available, they are timed on Gauss clock (magnetic field) instead of real time. Currently, they could not be included in the real time MAD-X model. Some work is needed to include them in the model. For the partial Siberian snake off case, the model predicts a more or less flat beta function through AGS cycle. The measured beta functions has some fluctuations around that. Nevertheless, the modeled beta functions at flattop match the measurements after the fudge factor.

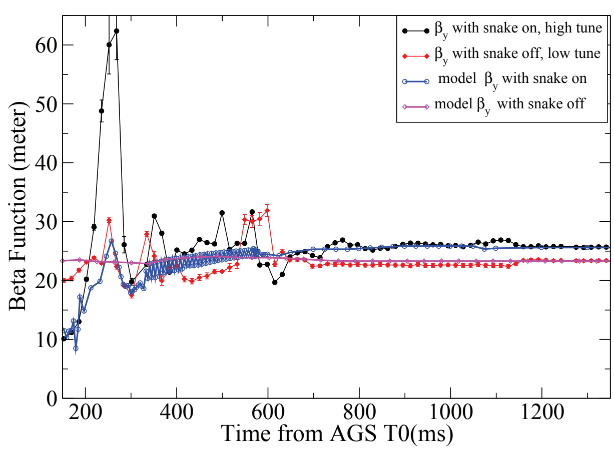

Figure 5: The measured vertical beta function for AGS with and without partial snakes. The flattop is reached at 582ms from the AGS T0. Transition is crossed around 300ms.

The horizontal beta function at the IPM can be measured with the same procedure. However, the location of horizontal IPM is between the two BPMs used by the RF system for the radial loop. To measure the beta function there, the RF system has to switch to phase loop so that the radius can be moved by dipole correctors. The RF system has to be on radial loop around transition crossing (300ms) but can be on phase loop during the rest period. The horizontal beta function measurement with RF system at phase loop has been tested but more beam time is needed to get this working.

SUMMARY

The Siberian partial snakes required for proton polarization preservation and near integer vertical tune(8.98-8.99) complicate the optics in the AGS. To understand if the observed emittance growth is real and where is the growth, the vertical beta functions at IPM locations are needed. Careful attentions have been put into betatron tune, dipole current and orbit response measurements. With these quantities measured, the vertical beta functions have been measured along the AGS ramp with partial Siberian snakes on and off. The modeled and measured beta functions agreed with each other at AGS flattop and near injection for partial Siberian snakes on and off case. The measured big swing of beta functions between 200-300ms for partial Siberian snakes on case requires more modeling work. So far the model does not give the same level of beta function variation. However, the measured and modeled vertical beta function near injection and in the later part of the AGS cycle already suggest that some vertical emittance growth is real, as much as 100%, but the source is not fully understood. Emittances have also been measured with beam debunched at flattop to eliminate the space charge effect. The horizontal beta function measurement has been worked on and but more beam time is needed to get this working. The modeled horizontal beta function implies not much horizontal emittance growth. The horizontal beta function measurement will be taken in the future.

REFERENCES

[1] H. Huang, *et al.*, Phys. Rev. Lett. **99**, 184501 (2007).

[2] H. Huang, *et al.*, Phys. Rev. ST AB. **17**, 0810001 (2014).

[3] H. Weisberg, *et al.*, Proceedings of PAC'83, Santa Fe, NM, USA, p. 2179.

[4] R.E. Thern, Proceedings of PAC'87, Washington, DC, USA, p. 646.

[5] H. Huang, *et al.*, Proceedings of IBIC2013, Oxford, UK, p. 492.

[6] R. Connolly, *et al.*, Proceedings of IBIC2014, Monterey, CA, USA, p. 39.