MEASUREMENT OF PROTON TRANSVERSE EMITTANCE IN THE BROOKHAVEN AGS [*]

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Abstract

High luminosity and high polarization in Relativistic Heavy Ion Collider (RHIC) require good control and measurement of emittance in its injector, the Brookhaven Alternating Gradient Synchrotron (AGS). In the past, the AGS emittance has been measured by using an ion collecting IPM during the whole cycle. The beam profiles from this IPM are distorted by space charge forces at higher energy, which makes the emittance determination very hard. In addition, helical snake magnets and near integer vertical tune for polarized proton operation distort the lattice in the AGS and introduce large beta beating. For more precise measurements of the emittance, we need turn-by-turn (TBT) measurements near injection and beta function measurements at the IPM. A new type of electron-collecting IPM(eIPM) has been installed and tested in the AGS with proton beam. The vertical beta functions at the IPM locations have been measured with a local corrector near the IPM. This paper summarizes our current understanding of AGS emittances and plans for the further improvements.

INTRODUCTION

Emittance control is important for high luminosity in colliders. For polarized proton operation in RHIC, emittance preservation is also beneficial to polarization preservation. 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, accurate emittances are needed.

Old devices in the AGS to measure emittance are the ion collecting IPMs [3], which have been in use for more than 20 years. Measurements show that the 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 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 planes 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 maneuvers. The transition is crossed around 315ms from AGS T0. 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.

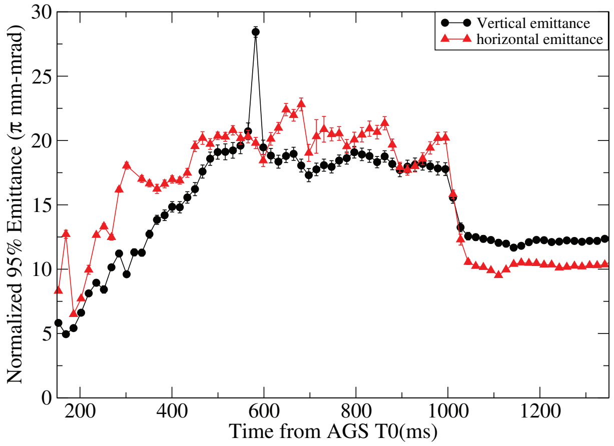

Figure 1: The normalized 95% emittance of both planes along the AGS magnet cycle. The energy ramp finishes at 582ms. The RF cavities are shut off at 1000ms and the "true" emittance at flattop is reported after that.

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

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Since the helical dipole partial snake magnets 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 effects from the helical dipoles are smaller. The model predicts that with 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, beta function measurements along the ramp are required.

β FUNCTION MEASUREMENT

The beta function can be measured 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. 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:

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

The 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.

AGS BETA FUNCTION RESULTS

The dipole kick current for the beta function measurement needs to move the beam as far as possible without beam loss - to improve signal to noise ratio both for beam displacement. Given the tune variation this is a challenge. For each point, the bipolar dipole was excited in both positive and negative signs to get several position changes. The measurement was repeated several times and the average was used for the beta function calculation.

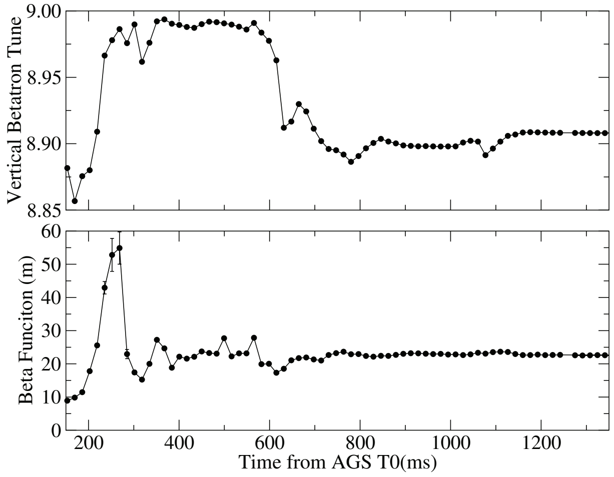

Figure 2: AGS vertical tunes (top) and vertical beta function(bottom) in an AGS cycle for AGS partial Siberian snakes on. The error bars are statistical errors only.

The measured 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, the measured beta function near injection is indeed less than half of the values at flattop. Since 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 are accelerated and the effect is negligible after about 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.

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 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 scaling the measurements with a factor 1.137, the beta functions from the measurements and model are plotted in Fig.3. 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 horizontal tune 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 transition tune jump quadrupoles were not in this model. 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 reasonable 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.

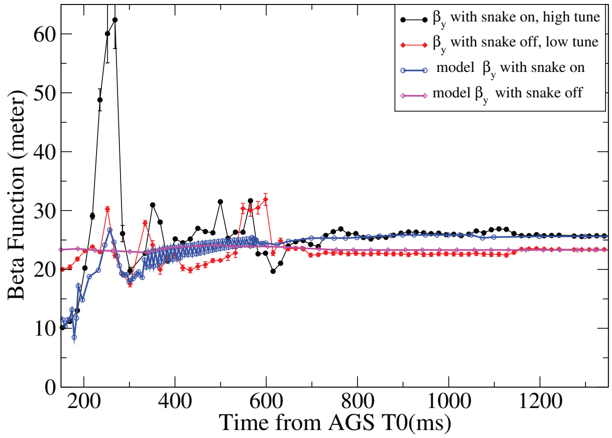

Figure 3: The measured vertical beta function for AGS with and without partial snakes. The flattop is reached at 582ms from the AGS T0. Transition is crossed around 300ms.

The horizontal beta function at the IPM can be measured with the same procedure. However, the location of the 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.

ELECTRON COLLECTING IPM

The electron-collecting IPMs [5] have been installed and commissioned in recent years. It has less space charge problem and can give better information on emittance. After commissioning and resolving various hardware issues, they provide emittance for the first time this year. From the TBT emittance measurement at injection, the optical mismatch at injection is not significant. The beta functions at the locations of eIPM have also been measured using the same procedure and compared with the model. The emittance from eIPM are shown in Fig. 4. These measurements were done while filling RHIC, so no emittance after beam was extracted for RHIC (around 920ms from AGS T0). The results show the similar emittance at flattop as the old IPM with RF off. It shows that the horizontal emittance is similar at injection and extraction. The vertical emittance has emittance growth about a factor 2. The large fluctuation in emittance on the ramp is due to fluctuations in the beta functions. The timing of the growth along the ramp would require more precise beta function measurement, which is planned to be done soon.

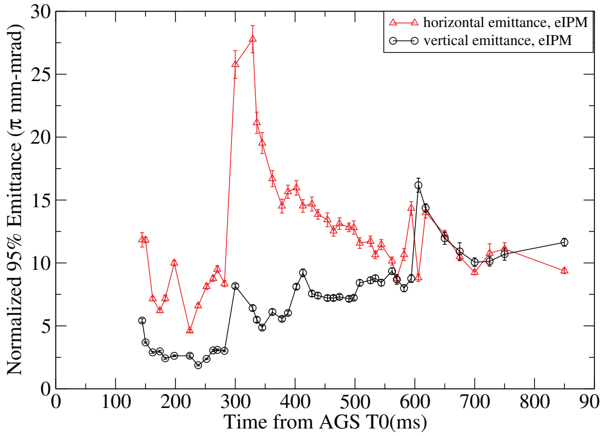

Figure 4: The normalized 95% emittance for AGS measured by eIPM. The measured beta functions are used.

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 to localize the growth, the vertical beta functions at IPM locations are needed. 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 horizontal beta function measurement has been worked on and but more beam time is needed to get this working. 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% The source is not fully understood. Emittances have also been measured using the newly installed eIPM. Qualitatively, the results near injection and flattop agree with the old IPM (with RF off). The details on the ramp require more accurate results for beta function measurements. The TBT emittance measurements done with eIPM show that there is not much optical mismatch at AGS injection. More beta function measurements and modeling work will take place in the near future.

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