ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRO088

OPTIMIZATION OF THE PP AGS ZGOUBI MODEL IN THE LOW ENERGY RANGE*

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Abstract

At low energy the AGS lattice is strongly deformed by the two strong helical snakes, required to preserve the polarization. In addition to the complex, highly non-linear field featured by the two snakes, multiple non-linear coupling resonance lines are crossed by the beam in this region. Hence, the use of realistic models for the Siberian snakes is critical for the simulation of the early part of the AGS acceleration cycle. The AGS Zgoubi model uses direct tracking through OPERA field maps of the two snakes. While many processes may be harmful to both beam and spin dynamics in this region, it is critical to use a realistic model of the AGS at low energy. This paper presents the current model used and some of the challenges recently faced. We will also compare experimental beam dynamics results to those predicted by the Zgoubi model.

INTRODUCTION

The AGS accelerates polarized protons from $G\gamma = 4.5$ to $G\gamma = 45.5$. Multiple depolarizing spin resonances are crossed during the acceleration and preservation of the beam polarization is critical for the RHIC polarized proton spin program [1]. The AGS dual partial snakes configuration preserves most of the polarization. Spin dynamics in the AGS is detailed in companion papers [2–4] and operational aspects are treated in [5].

The partial snake is a special magnet featuring a helical dipole magnetic field designed to rotate the spin vector around the longitudinal axis. While there is a number of way to achieve this [6], the available solution for the AGS were strongly constrained by:

- the limited space available in the AGS straight section of at most 10 feet.
- spin dynamics requiring large enough spin rotation in the snakes to allow for the vertical tune to be brought into the spin gap [2].

The solution adopted involves two Siberian snake magnets driven at constant current separated by 1/3 of the ring:

- the warm snake located in SS20 of the AGS superperiod E. Normal conducting magnet with twisted coils to rotate the spin angle by $\phi = 10 - 12$ degrees with a maximum field modulus of 1.53 T at the center of the magnet [7].
- the cold snake located in SS20 of the AGS superperiod A. Superconducting magnet with a twisted cosine dipole coil design and corrector coils. It rotates the proton spin by and angle of $\phi = 20 - 28$ degrees with a maximum field of around 2 T [7].

The strong twisted dipole field creates important longitudinal and non-linear fields along the particle trajectory. Since the snakes are driven at constant current the effect on beam dynamics is stronger at low energy. Beam dynamics is notably complex below $G\gamma = 6 - 7$ due to:

- the low beam rigidity that maximizes the effect of the snakes field.
- the strong deformation of the AGS optics at injection forbids the beam to be injected with the vertical tune high enough to avoid the first vertical intrinsic spin resonances [2]. Therefore betatron tunes are quickly changed as the rigidity increases, resulting in the crossing of multiple non-linear coupling betatron resonances below $G\gamma = 6 - 7$.

MEASURED TUNE PATH IN THE AGS

Figure 1 shows the evolution of the betatron tunes in the early part of the AGS pp acceleration cycle. The injection tunes are optimized for intensity transmission from the AGS Booster. The vertical tune is increased as early as possible for spin dynamics purposes and the location of the horizontal tune is optimized for intensity transmission and emittance preservation.

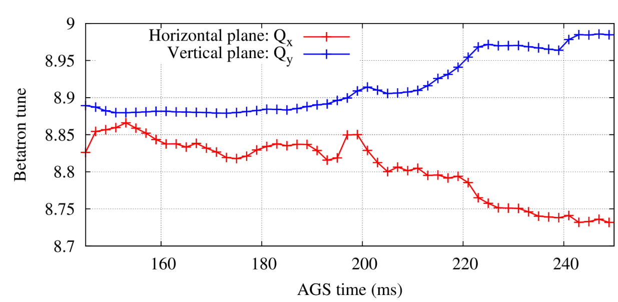

Figure 1: Measured tune path during the AGS pp Run14 below $G\gamma = 8$.

Figure 2 shows the tune path in a tune diagram. The region where the tunes are quickly moved to increase the vertical tune is usually called the tune swing and figure 2 shows that multiple resonant lines of relatively low order are crossed in this region.

The early part of the AGS acceleration cycle experiences intensity losses and emittance growth is not excluded. The

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

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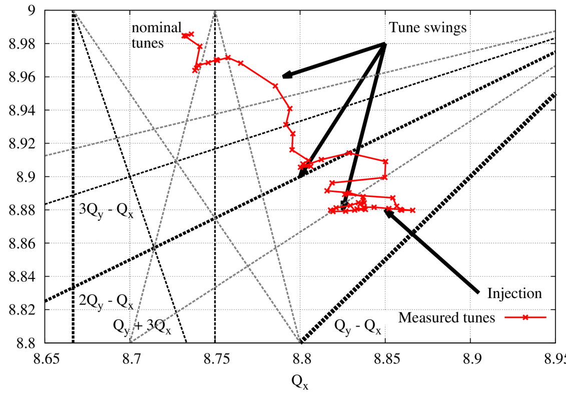

Figure 2: Tune diagram with measured tunes and important resonant lines.

crossing of low order betatron resonances could degrade the beam quality by increasing the transverse emittance or through beam losses.

The Zgoubi code [8] and the Zgoubi AGS online model [9] are used to simulate this region of the AGS acceleration cycle, to better understand observations and optimize the beam dynamics in this region.

SIMULATIONS AT LOW ENERGY

The Zgoubi model of the AGS [10] uses computed field maps, in which the particle trajectory is tracked using the Zgoubi step by step integrator [8]. More informations on the computed field maps and the snakes themselves can be found in a companion paper [7].

Realistic lattices were generated by the AGS Zgoubi online model using measured current in each of the AGS power supplies. Tunes in figure 1 as well as chromaticity measurements were used to tweak the modeled lattice in order to match the measurements [11].

The AGS Zgoubi model was investigated by tracking 528 particles picked in a 6D Gaussian distribution leading to transverse normalized 95% emittances of 8 π.mm.mrad. Longitudinal emittance of 1 eV.s and realistic acceleration rate were used. The tracking was done from $G\gamma = 4.55$ to $G\gamma = 21$ but will focus on the region below $G\gamma = 10$.

Different models of the AGS snakes magnets were tested with the Zgoubi code.

Original Snake Maps

The so called *original* maps are the ones used for the past few years and computed around the time of the snakes commissioning. Figure 3 shows the evolution of the number of particles during the Zgoubi tracking. In these simulations the particles were considered as lost when their excursion in one of the snake field map exceeds the physical aperture of the vacuum chamber. The losses observed in the simulations are larger than the ones observed in the AGS. Understanding the mechanisms behind the losses was critical but figure 3 does not give information on the sources of the losses.

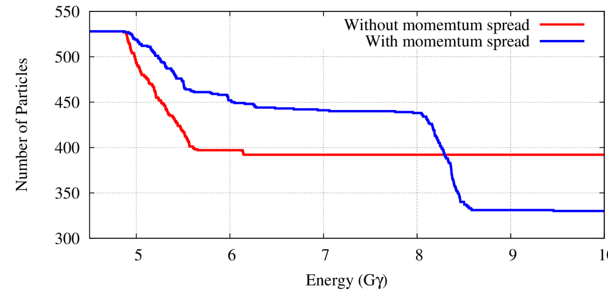

Figure 3: Evolution of the number of particles as a function of the energy for a tracking that uses the *original* snake maps.

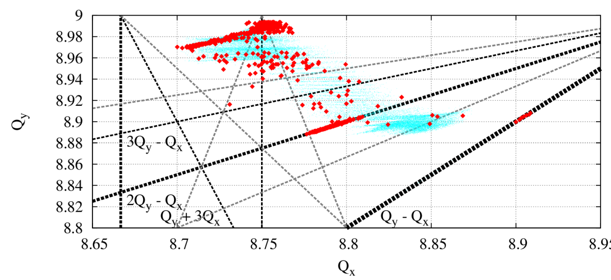

Figure 4: Tunes in the tracking using the *original* snake maps in a tune diagram of the 528 particles in cyan. If a particle is lost, its tune appears in red for its last 300 turns.

Figure 4 shows most of the losses along the resonance lines $Q_x - Q_y$ and $2Q_y - Q_x$. The losses around $Q_y = 8.98$ ($G\gamma > 8$) are not present in the absence of momentum spread (figure 3) and are likely due to the vertical tune and the vertical chromaticity too high in this region. However the losses before $G\gamma = 6$ are clearly due to non linear resonant lines.

To explain the differences between machine observations in the AGS and the simulations, the snake maps used were investigated. In particular the map of the warm snake was thoroughly tested and it appeared that:

- particles may reach the physical aperture of one or both of the snakes during the tracking. Large amplitude particle accoutered non-realistic fields. This was solved by using a smaller field map mesh and by using the element `'CHAMBR'` of the Zgoubi code to discard particles traveling outside the snake physical aperture.
- the computation mesh induced non-physical variations of the field in the central region of the magnet. This was solved by increasing the longitudinal density of the computation mesh.

A new map of the warm snake was computed and used to repeat the trackings done with the *original* snakes maps.

New Warm Snake Maps

Trackings using the new warm snake map and the same conditions as above were done. Results were very similar to the trackings using the *original* warm snake map. Figure 5 shows losses very similar to figure 4 in the early part of the

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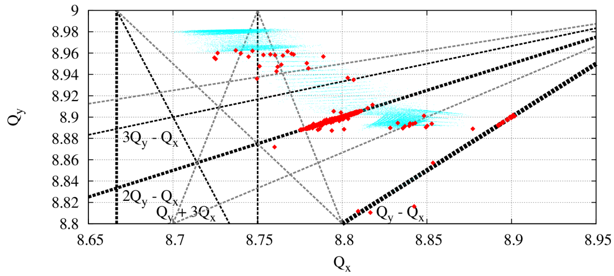

Figure 5: Tunes in the tracking using the new warm snake maps in a tune diagram of the 528 particles in cyan. If a particle is lost, its tune appears in red for its last 300 turns.

cycle. The proportion of particles lost is also very close to the case with the *original* warm snake map. Losses observed in figure 4 around $Q_y = 8.98$ disappeared with the new warm snake map but this could easily be due to small differences in vertical tune or chromaticty between the two trackings.

The losses before $G\gamma = 6$ were not accounted for by the new warm snake map. Behavior of the beam emittance in the Zgoubi tracking is also erratic in this region, making, for instance, studies of depolarization processes hard. Therefore it was proposed to compare the results above with a matrix model of the snakes.

Matrix Snakes Model

First order matrices were computed by tracking using the Zgoubi code through the computed field maps of the snakes at many rigidities between injection and extraction. Then resulting matrices were simpectified using the Cayley transform [12].

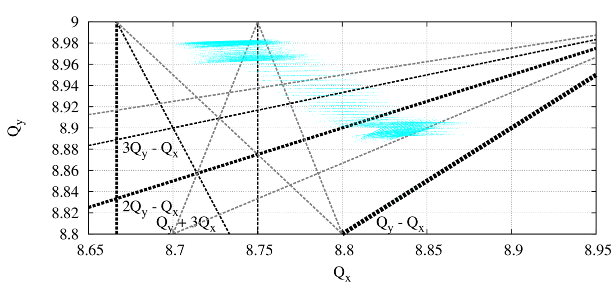

Figure 6: Tunes in the tracking using the matrix model of the snakes in a tune diagram of the 528 particles in cyan. If a particle is lost, its tune appears in red for its last 300 turns.

Figure 6 shows that no losses occurred during this tracking. However careful analysis shows that particles tend to remain close to the resonant line $2Q_y - Q_x$. Therefore the use of the matrix model removed the losses without removing all the strength in the $2Q_y - Q_x$ resonant line.

CONCLUSION

Comparison between different models of the snake maps did not allow yet complete understanding of the losses observed along the resonant line $2Q_y - Q_x$. The discrepancies between simulations and observation are not explained but it is known that the AGS beam dynamics in the low energy region is particularly complex.

As of now the matrix model of the snakes can be used at low energy for particular studies, mainly of spin dynamics, with good results [2]. However studies of beam dynamics in the low energy part of the AGS with snakes requires perfect understanding of the model behavior in this region. Ongoing efforts aim to clarify this in order to be able to reproduce observed beam dynamics with snakes using Zgoubi trackings with the snake field maps.

ACKNOWLEDGMENT

This research used resources of the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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