INCORPORATING PARTIAL SIBERIAN SNAKES INTO THE AGS ONLINE MODEL*

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Abstract

In order to preserve polarization during polarized proton operation for RHIC, two partial Siberian Snakes are employed in the AGS, where a large number of strong spin depolarizing resonances must be crossed. These snakes cause a significant distortion to the injection lattice of the AGS and must be included in the online model. In this report, we discuss the problem of modeling snakes as optical elements, particularly as MAD-X elements, and present results comparing measurement to the AGS online model.

OVERVIEW

Polarized proton beam in the RHIC complex is created in the OPPIS source and accelerated though a 200 MeV Linac. The beam is then accelerated in the Booster and subsequently injected into the Alternating Gradient Synchrotron (AGS) at a a Gγ = 4.5, and accelerated to a Gγ of 45.5 Here G is the anomalous g-factor magnetic moment of the proton (G = 1.7928) and γ is the relativistic Lorentz factor.

In order to preserve polarization of the beam during acceleration through intrinsic and imperfection depolarizing resonances, the AGS lattice has been outfitted with two partial Siberian snakes. The snakes magnets are helical dipoles which, to provide sufficient spin rotation in the limited physical space available in the AGS lattice, have a "double pitch" structure [1]. That is, the far upstream and downstream regions of each snake are helices of one pitch and the central regions are of different, slower, pitches. One snake is superconducting and the other is normal conducting and they are called the 'cold' and 'warm' snakes respectively.

The central helical field of the cold snake can be run as high as 2.5 T, but it typically operated at 2.1 T. These field strengths correspond to rotations of the proton spin vector of 10 % (or 18 degree) and 15% (or 27 degree), respectively, around the longitudinal axis. The warm snake is operated with a central helical field of 1.53T, which corresponds to a spin rotation of 5% (9 degrees) about the longitudinal axis. Both snakes are run with constant current throughout the AGS acceleration cycle.

Each of the two snakes is strongly focusing in both planes and they represent a significant perturbation to the AGS optics. Both snakes require external magnetic elements to provide matching to the typical AGS lattice and each therefore has four quadrupoles near it used to compensate for perturbations to the linear optics [2].

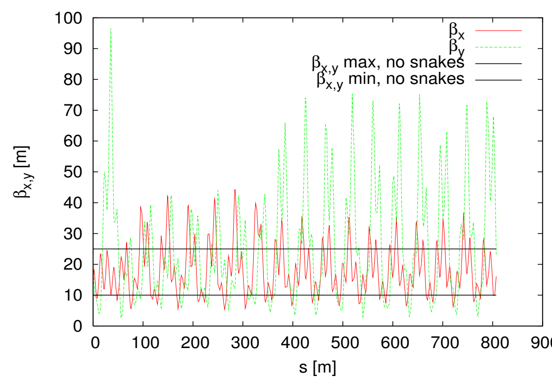

Figure 1: Modeled AGS β functions at injection energy with both snakes included and using operational currents in the compensation quadrupoles. Black lines show the maximum and minimum beta functions in a lattice without snakes. The compensation quadrupole currents that are ultimately determined to be optimal are often far from the modeled fit.

The beam orbit inside the helical dipoles is itself a helix. At injection energy, this helix has a radius of approximately 2 cm and ideally beam is delivered into the snake displaced horizontally by that amount, with no vertical displacement. As the beam rigidity increases, the radius of the helix decreases like γ^{-1}.

The cold snake also has a significant off-axis longitudinal magnetic field component. A 1 meter long superconducting solenoid has been included in the design of the snake to compensate for that effect. However, since the beam's offset from the central axis is a function of energy and the solenoid can only be operated DC, the coupling contribution from the cold snake's longitudinal field can only be completely cancelled at a single beam rigidity.

Accurate modeling of the snakes is critical to polarized proton operation because avoidance of intrinsic and imperfection depolarizing resonances simultaneous requires tight control of the vertical closed orbit and a vertical betatron tune near an integer value (9 in the case of the AGS). This is a region of configuration space that tends to be both physically and numerically sensitive.

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HELICAL DIPOLE FIELDS

Following Ptitsyn [3], in right-handed polar coordinates (r, ϕ, z) with the z coordinate pointing along the direction of beam motion we may write the solution to Laplace's equation for the scalar potential in the current free region in the aperture of the helical dipole as

$$\psi = \sum_{m=1}^{\infty} I_m(mkr)(a_m cos(m\theta) + b_m sin(m\theta)) \quad (1)$$

Here one takes advantage of the helical symmetry to use $\theta = \phi$ - kz as the polar coordinate and k is the pitch of the helix which is here taken to be constant over the length of the magnet. I_m is the modified Bessel function.

The magnetic field derived from this potential is:

$$\begin{aligned} B_r &= -k * \sum_{m=1}^{\infty} I'_m(mkr)(a_m cos(m\theta) + b_m sin(m\theta)) \\ B_z &= k * \sum_{m=1}^{\infty} mI_m(mkr)(b_m cos(m\theta) - a_m sin(m\theta)) \\ B_\phi &= -\frac{1}{kr} B_z \quad (2) \end{aligned}$$

The simplified relationship between B_ϕ and B_z is a result of the helical symmetry of the field.

It is apparent from this form that there are intrinsic nonlinearities to the field since I_m is proportional to r^m as r approaches zero.

The non-zero off axis longitudinal field contribution is also visible.

CURRENT STATUS

The current AGS online model is implemented using a CDEV server that takes real-time snapshots of magnet current settings and uses MAD-X to calculate model parameters.

The snakes are currently implemented in the AGS online model in MAD-X using only the linear matrices produced by integration of the field maps [4]. The transfer maps so calculated are numerical Taylor expansions about an assumed off-axis ideal orbit (x, y) = (20 mm, 0 mm). Figure 2 shows the level of disagreement in the measured and modeled betatron tunes in a typical operational polarized proton lattice. Since the fields of both snakes are constant in time, their effect on the lattice decreases as the beam becomes more rigid and the snakes become more transparent to betatron motion. The disagreement between measurement and model is thus most significant early in the acceleration cycle, where it is near 0.05 units. Gaps in the model data, where there are measurements but no model prediction, are points in the cycle for which MAD-X could not find a closed orbit given the supplied magnet currents. The large horizontal disagreements near γ = 8 are the result of the transition γ_{tr} jump, which is not yet included in the online model.

It was shown by Luccio et al in 2006 that the second-order expansion of the snake field about the ideal trajectory results in a significant dependence of the vertical focal length on the horizontal orbit position [5]. Correct implementation of the calculated second-order matrices in MAD-X is made difficult by the fact that one cannot offset arbitrary matrices, and so the model interprets the expansion as being around the origin rather than around a point 2 cm to the outside of the ring. Additionally, the measured closed orbit in the AGS is not included in the model, so strong sensitivity to closed orbit offsets caused by the snake are not properly accounted for. This is particularly relevant for calculating closed orbit bumps that traverse the snakes.

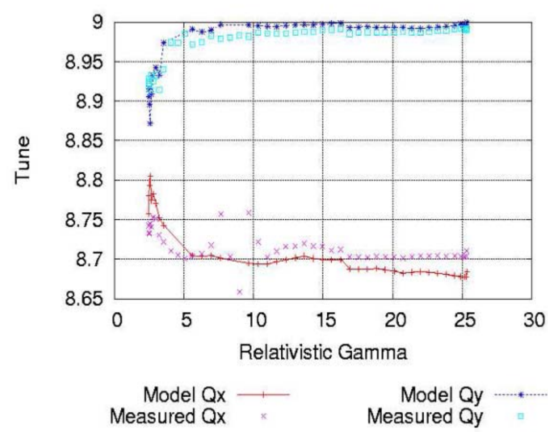

Figure 2: AGS online model tune predictions and measurements for operational currents, calculated using linear snake transfer matrices.

EQUIVALENT ELEMENT APPROACH

One approach used primarily to gain the ability to offset the snake from the central axis was to develop a sequence of normal and skew quadrupoles of a combined length equal to that of the snake and to fit their focusing strengths to reproduce the linear snake transfer matrix.

This approach is adequate for offline studies where the closed orbit at the snake is predictable and static and when the nonlinear effects of the snake are not important. For online modeling, this approach fails to take into account the possibility that the actual closed orbit through the snake may not be ideal and is not constant throughout the cycle. Even in the case where the orbit can be assumed to be near the ideal trajectory, the offset changes as the beam is accelerated and becomes more rigid and the ideal trajectory moves closer to the central axis. There is also no natural scaling for the parameters of these elements as a function of the beam rigidity, and so the individual element strengths must be re-fit for each beam energy one wishes to model.

SUMMARY AND PLANS

The above outlined challenges indicate that accurate modeling of the AGS snake elements requires a full non-linear description of the fields to be implemented in the model. The closed orbit can then be calculated using the entire field, at which point a Taylor expansion can be performed around online calculated orbit, rather than around a predetermined ideal orbit. The Polymorphic Tracking Code [6] seems ideally suited to such a task, given its separation of tracking coordinate system from the magnetic field and its ability to perform high order expansions.

This is a primary motivation for the upgrade of the AGS online model to include multiple modeling platforms [7].

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