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APPROACHES TO OPTIMIZING SPIN TRANSMISSION IN LATTICE DESIGN

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Abstract

We present our experiences in optimizing the proposed Rapid Cycling Synchrotron (RCS) injector for the eRHIC Storage ring and the RHIC 2017 lattice. We have developed a Python code to drive lattice calculations in MADX [1] which are then used to calculate spin resonances using the DEPOL algorithm [2]. This approach has been used to minimize intrinsic spin resonances during the RCS acceleration cycle while controlling lattice parameters such as dispersion and beta functions. This approach has also been used to construct localized imperfection bumps using a spin response matrix and the singular valued decomposition (SVD) algorithm. It has also been used to reduce interfering intrinsic spin resonances during the RHIC acceleration ramp.

INTRODUCTION

The design of lattices to transport beam with minimal polarization loss requires special attention to the potential sources of depolarizing spin resonances. In the past accelerators where usually optimized initially without consideration of their spin effects. Later careful spin matching and harmonic bumps were applied to reduce the effects of the various spin resonances. These were usually performed by using simple analytical estimates which were then verified using more exact numerical calculations using codes like DEPOL [2]. However the process was slow and decoupled from the optics calculations since for small perturbations the optic changes were assumed to be small. Later the use of full and partial snakes reduced the need to worry as much about the strength of the spin resonances.

However experience with the full snakes in RHIC and partial snakes in the AGS have shown that optimizing the underlying spin resonances can still have an important impact on the performance of the lattice even with snakes. For example the overlap of minor spin resonances during strong spin resonances crossings has been shown to reduce polarization transmission on the RHIC ramp [3].

Also in the design of a future high energy polarized electron injector for the proposed eRHIC facility, snakes are not a viable option due to the large orbit excursion and radiative effects they induce in lighter particles. So a new design has been developed which exploits high periodicity to avoid spin depolarizing resonances [4]. This new design required optimizing for both the beam dynamics and polarization transmission.

We have developed a Python code which we call SOptim [5], to perform these types of optimizations. It uses MADX [1] as an optics calculator and performs its own DEPOL calculations across a specified range of spin resonances. It then varies the magnet strengths, usually quadrupoles, or vertical corrector magnets to achieve a desired spin resonance structure and optics.

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SOptim CODE STRUCTURE

The core of the code is a function which takes the name of a MADX sequence file, a string containing the names of the magnets to be varied, and a vector of associated magnet strengths. These are read together with the anomalous G factor, emittance and a switch to indicate if an intrinsic or imperfection spin resonance calculations are to be performed.

This function then feeds the sequence and new magnet strengths to MADX and takes back the optics and orbit information which is then used to perform a native spin resonance calculation following the DEPOL algorithm. These are done for a currently hard coded range of spin resonance energies.

The function returns an array of spin resonance strengths, twiss parameters, dispersion values and a flag indicating if the twiss calculation failed or not, as well as a MADX readable string containing the magnet settings used. This string is saved once the optimization is completed so that it can be easily included in future MADX calculations.

The values for the spin resonances and optics values are then combined with various weights to produce an overall penalty function. This penalty function is then iterated upon using Scipy's [6] minimize function which is part of its optimize library. The minimize function can use a variety of optimizers and takes bounds for the magnet settings.

Alternatively it is possible to construct spin response matrix which relates the spin resonance strengths to the magnet settings. One can invert this using a pseudo inverse to either suppress of generate spin resonance 'bumps'.

RHIC LATTICE OPTIMIZATION

Studies of polarization transport with two orthogonal snakes during the RHIC acceleration ramp revealed the importance of interfering spin resonances [3]. For example during the crossing of the strongest intrinsic spin resonance at $G\gamma = 422.685$ it was found that the weak spin resonance located at $G\gamma = 423.325$ plays an important role in determining the total polarization transmission. As is shown in Figs. 1 and 2 it was shown that minimizing this can improve the total spin transmission. We used the SOptim code to reduce these neighboring resonances. The results from spin-orbit 6D tracking are shown in Fig. 3, where the polarization transmission versus emittance is greatly expanded. Similar optimization was applied around the three major spin resonances at $G\gamma = 422.685, 382.325$, and 260.685 for both the Blue and Yellow RHIC rings.

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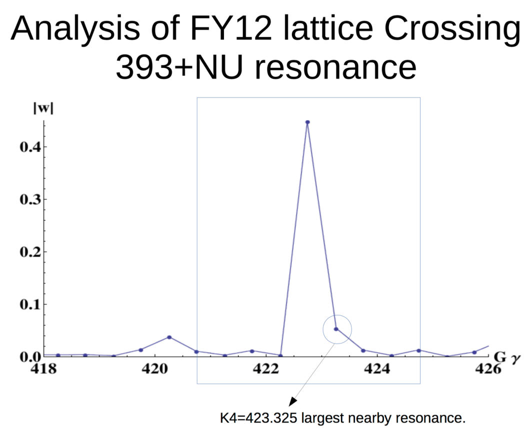

Figure 1: Spin Resonance magnitude |w| versus beam energy in terms of the anomalous G factor times relativistic gamma.

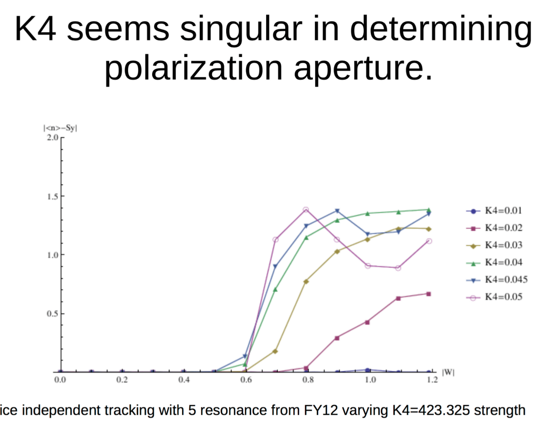

Figure 2: Showing the magnitude of net spin loss after accelerating through the primary resonance. This is plotted against the spin resonance magnitude of the primary resonance |w| (proportional to the action or emittance of the particles). We see the effect of changing the neighboring resonance.

RCS LATTICE OPTIMIZATION

The proposed eRHIC injector is designed to accelerate polarized electrons from 400 MeV to 18 GeV. A periodicity of 96 and tune of 50 was necessary to avoid all the intrinsic spin resonances in this energy range. However the natural 6-fold symmetry of the existing RHIC tunnel made achieving the 96 periodicity challenging. Our solution was to make the contributions to the spin resonance integral from the straight sections negligible. This was made more difficult since detector bypasses are necessary for such a machine.

We used the SOptim code to drive down spin resonance strengths in the accelerating energy range from $G\gamma = 0.9$ to 41. The results yielded a lattice with intrinsic spin resonances with strengths so low that the cumulative effects only start to manifest themselves at the 5% loss level above 1000 mm·mrad emittance for the 100 msec proposed ramping rate. The resultant intrinsic spin resonances are shown in Fig. 4.

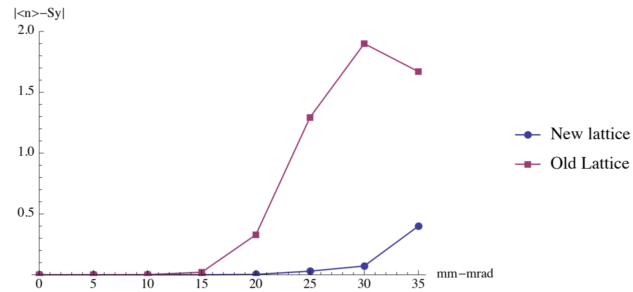

Figure 3: Polarization deviation from invariant spin field direction versus emittance curve after crossing $G\gamma = 422.685$ spin resonance. Comparing old RHIC 255 GeV lattice (old lattice) to optimized lattice (new lattice).

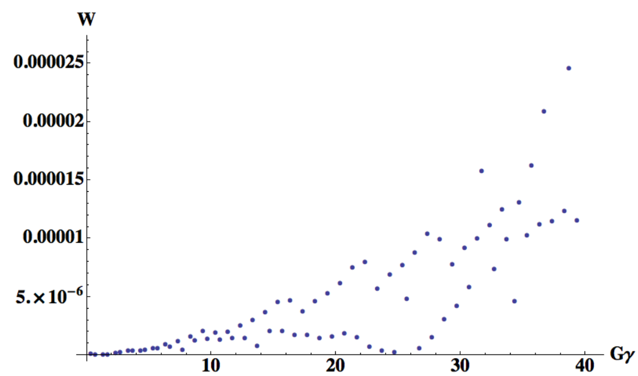

Figure 4: Plot of intrinsic spin resonances versus $G\gamma$ for a particle of 10 mm-mrad normalized emittance. This is the result of spin optimization code SOptim applied the RCS lattice after applying symmetry breaking detector bypasses.

RCS IMPERFECTION BUMPS

Control of the effects of imperfect spin resonances remains an important issue for the design of the RCS. Studies showed that if we can control the RMS vertical orbit distortion to the 0.5 mm level we should be able to achieve above a 95% polarization transmission. In the event this isn't achieved, we proposed using orthogonal imperfection bumps. These bumps target the real and imaginary part of the spin resonance. Before the commissioning of the partial snake in the AGS, imperfection bumps were used extensively to tune out imperfection driven polarization losses. More recently tests with orthogonal bumps using a spin response matrix method have been performed in RHIC [7].

By building a corrector to imperfection spin response matrix ($\vec{M}_S$) using SOptim, one can calculate the necessary corrector strengths to achieve isolated and orthogonal bumps at any point in the ramp. Here we use,

$$\vec{C} \cdot \vec{M}_S = \vec{\varepsilon}, \tag{1}$$

where $\vec{C}$ is a vector containing all the correctors, $\vec{\varepsilon}$ is a vector containing all the real and imaginary parts of the

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imperfection spin resonances which are targeted. In our case it is 80 elements long containing the real and imaginary imperfection resonances at $G\gamma = 1$ to 40. Inverting this non-square matrix using a pseudo inverse one can use it to construct an arbitrary set of imperfection bumps across the whole energy range.

Using this approach we have constructed such bumps representing arbitrary imperfection bumps in the imaginary and real plane for $G\gamma = 34$ to 40. This is the energy range we expect that imperfections could be strong enough to depolarized the beam greater than 5%. These bumps are plotted in Fig. 5. Here we produced resonance strengths as high as ±0.005, everywhere else has imperfection strengths less that 10^{-5}. A spin resonance strength of 0.005 at 100 to 200 msec ramp rates, represent 10 to 15% spin kick respectively.

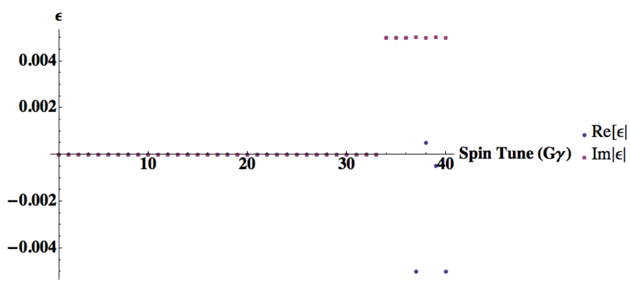

Figure 5: Real and imaginary imperfection resonance strengths versus $G\gamma$ for a fixed corrector magnet settings constructed using spin response matrix.

The associated corrector magnet strengths are all less than $\pm 3 \times 10^{-5}$ rad as shown in Fig. 6. With imperfection bumps constructed in this fashion, there is no need to alter the corrector strengths over the acceleration cycle. They only need to ramp with the main dipole current.

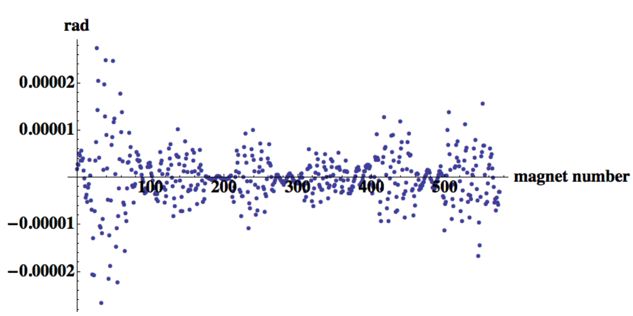

Figure 6: Corrector magnet settings versus magnet number, which resulted in Imperfection resonances shown in Fig. 5.

Thus using these bumps, we should be able to control any foreseeable imperfection spin resonances in the RCS.

CONCLUSION

The Python code SOptim is tool which can assist in the optimization of hadron and lepton lattices for spin transmission. It accomplishes this by calculating both the spin resonances and optics for a given lattice and employing various optimizing approaches to achieve either global suppression of a range of spin resonances or by constructing arbitrary spin bumps to cancel spin resonances.

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