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PROGRESS ON RCS eRHIC INJECTOR DESIGN*

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Abstract

We have refined the design for the Rapid Cycling Synchrotron (RCS) polarized electron injector for eRHIC. The newer design includes bypasses for the eRHIC detectors and definition of the lattice layout in the existing RHIC tunnel. Additionally, we provide more details on the RF, alignment and orbit control, and magnet specifications.

INTRODUCTION

We present recent progress on the design for the proposed eRHIC electron injector, the Rapid Cycling Synchrotron (RCS). This accelerator will provide spin polarized electrons for energies up to 18 GeV. The proposed accelerator will fit in the existing RHIC tunnel, employ standard technology, and accelerate an electron bunch to top energy in 100–200 msecs. Such a ring has been previously developed in [1]. Here we consider a machine with a slower acceleration rate and with detector bypass regions between each arc. In the past it was believed that such a device would cause profound polarization loss due the combined effects of many depolarizing resonances. We have recently devised a lattice which by virtue of the symmetry of construction and high operating tunes, avoids all significant depolarization sources in the energy range of its operation.The main parameters of the RCS are summarized in Table 1.

RESONANCE FREE DESIGN

There are several types of depolarizing spin resonances encountered when polarized electrons are accelerated. The most important of these are the intrinsic spin resonances and the imperfection spin resonances. Both are due to coherent transverse spin kicks which occur primarily in the quadrupole fields of the lattice. Intrinsic spin resonances arise from vertical betatron oscillations, while imperfection spin resonances are due to vertical closed orbit distortions [2].

In a typical circular lattice where the field is dominated by the guide dipole field the rate of spin precession per turn, or spin tune (ν_s), is determined by the energy and conveniently expressed as $G\gamma$, were $G = (g-2)/2$ is the anomalous magnetic moment, and γ is the relativistic factor. Therefore, a depolarizing intrinsic spin resonance occurs whenever the spin tune $G\gamma = nP \pm Q_y$. Here n is an arbitrary integer, P is the periodicity of the lattice, and Q_y is the vertical betatron tune.

Table 1: RCS Parameters

Basic Parameters of the RCS injector	
Injection Energy [MeV]	400
Top Energy [GeV]	18
α_c momentum compaction	0.000373
Max Relative Pol. loss [%]	5
Circumference [m]	3842.14
Ramping repetition rate [Hz]	1
Acceleration time [msec]	100–200
Acceleration turns	8000–16000
# of 'spin effective' periods	96
Integer Horizontal Tune	57
Integer Vertical Tune	61
Max vertical orbit rms [mm]	0.5
Number of Arc Cells	192
Number of straights	6
Number of dipoles	386
Number of quadrupoles	576
Number of sextupoles	420
Round Beam pipe diameter [mm]	40
Number of bunches	1
Charge per bunch [nC]	1–10
Radio frequency	563 [MHz]
Cavity peak Voltage [MV]	60
bunch length [mm], [ps]	1.8, 6
H and V emit. norm. [mm-mrad] inj	55,55
H and V emit. norm. [mm-mrad] ext	775, 115
Max energy deviation dp/p	7.8e-04
U_0 Rad. per e^- 18 GeV [MeV/turn]	36
Hor. damping time (18 GeV) [s]	0.0129

Thus the first two important intrinsic spin resonances which an accelerating electron will encounter occur at $G\gamma = Q_y$ and at $G\gamma = P - Q_y$ (for $P > Q_y$) . If we now ensure that both Q_y and $P - Q_y$ are greater than the maximum $G\gamma$ value, or Q_y is greater and $P - Q_y$ is less than the lowest $G\gamma$ value, then all the important intrinsic spin depolarizing resonances will be avoided.

For our lattice design we chose $P = 96$; this constrains the integer part of the vertical betatron tune to be $41 < [Q_y] < 55$, since we accelerate to energies less than $G\gamma = 41$. Here $[Q_y]$ indicates the nearest integer of the vertical betatron tune. For our current design we chose $[Q_y] = 50$. As a result, the

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two first intrinsic resonances will occur near $G\gamma = 50$, and $G\gamma = 96 - 50 = 46$.

A side benefit is that in addition to the intrinsic resonances, the imperfection resonance strengths are also minimized with this lattice design. This is because the strongest imperfection resonances, like the intrinsic resonances for a pure ring, will be at $nP \pm [Q_y]$.

GEOMETRY OF RHIC

The existing RHIC tunnel resembles a hexagon with rounded corners rather than a circle, and therefore has a natural periodicity of six. However, if we consider that the spin precession, which advances as $G\gamma$, occurs in the dipoles, one can recover the periodicity of 96 from the point of view of $G\gamma$ precession. This can be accomplished by designing the straight sections such that their betatron phase advance is equal to 2π. In this way the straight sections will not contribute to the integral which defines the strength of the spin resonance (see Figure 1). Thus we can maintain the 96 periodicity from the point of view of the spin precession.

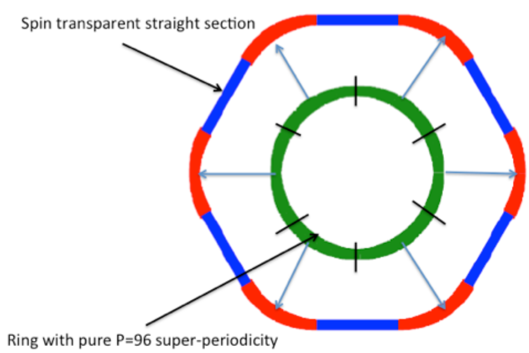

Figure 1: Projecting the pure ring lattice with 96 periodicity onto the RHIC six fold periodic ring.

The proposed layout for the RCS places it at a radius outside of the existing RHIC beam line but within the tunnel.

DETECTOR BYPASS DESIGN

Experiments are located at interaction points (IP), IP6 and IP8. At these locations the RCS beam line bypasses the detector achieving greater than 3 m displacement from the center for IP8 based on the current sPHENIX detector design. At IP6 this is increased to greater than 4.4 m based on eSTAR designs. This displacement is achieved by removing the last and first dipole for each of the 6 arcs, and moving them longitudinally to the center of the straight section near the IP. In this configuration the RCS beam trajectory misses the detector center by 3.86 m. Moving one dipole plus reducing the strength of second arc dipole by 36% and adding another dipole with the remaining bend angle or 64% strength to the center of the straight in IR6, achieves a 4.46 m displacement accommodating the larger eSTAR detector.

In order to access the various instrumentation and supplies we maintain the IP8 bypass design for IP2, 4, 10 and 12. The path of the bypass is shown in Figure 2. Here X is the distance measured from the location of the detector center. This modifies the straight section optics, with the negative consequence of raising the maximum β function from 50 to 78 m. It reduces the threshold for emittance versus polarization loss. However, the polarization loss effect is mitigated by minimizing the sum of the intrinsic resonances up to $G\gamma < 40.8$.

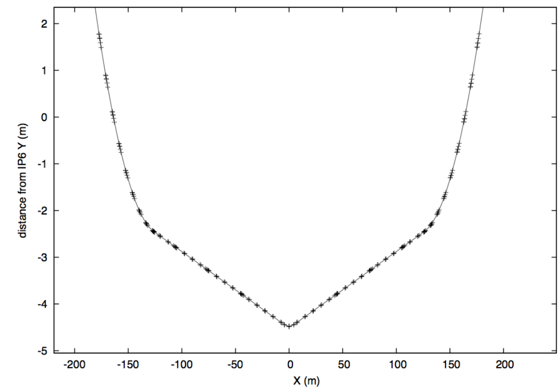

Figure 2: Beam line trajectory around the detectors at IP6. Here X is the longitudinal position and Y is the horizontal displacement from the IP.

POLARIZATION PERFORMANCE

In Figure 3 the intrinsic spin resonances are calculated for the RCS lattice. Assuming a 200-msec acceleration ramp rate (16000 turns) we can estimate the net polarization loss for a beam with a given rms normalized emittance. Note these include the effects of the bypass in all the straight sections.

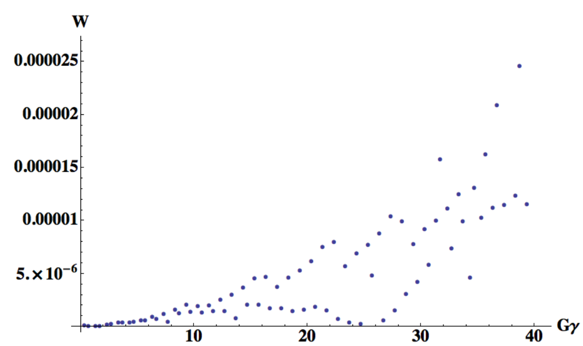

Figure 3: Depol calculated absolute intrinsic spin resonances ($w = |\varepsilon_K|$) for RCS at 10 mm mrad normalized emittance.

For well isolated resonances the amount of depolarization caused by acceleration through any given spin resonance can be evaluated using the Froissart-Stora formula [3]

$$\frac{P_f}{P_i} = 2e^{-(\pi|\varepsilon_K|^2/2\alpha)} - 1, \tag{1}$$

where ε_K is the spin resonances at $G\gamma = K$, and

$$\alpha = \frac{1}{\omega_{\rm rev}}\frac{d\nu_s}{dt} \tag{2}$$

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is the spin tune crossing rate divided by the angular revolution frequency ω_{rev}, and P_f/P_i is the ratio of final to initial vertical polarization. For a flat orbit in a constant vertical field $\alpha \approx \mathrm{d}(G\gamma)/\mathrm{d}\theta$. The Froissart-Stora formula represents a solution to the T-BMT equation [4] for the special case of crossing an isolated spin resonance.

Since the intrinsic spin resonance strength is proportional to the square root of the normalized emittance we can rescale an intrinsic spin resonance at one emittance to an arbitrary emittance using:

$$|\varepsilon(\epsilon)|^2 = \frac{\epsilon}{\epsilon_c}.|\varepsilon(\epsilon_c)|^2. \quad (3)$$

Here ϵ_c is the emittance of the calculated intrinsic spin resonance. With this the Froissart-Stora formula can be calculated for an arbitrary emittance particle $P_f/P_i(\epsilon)$. Assuming the beam distribution follows a Gaussian $\rho(\epsilon,\epsilon_0) = e^{-\epsilon/2\epsilon_0}/2\epsilon_0$, with ϵ_0 the rms normalized emittance, we can integrate to obtain an estimate for the average polarization crossing a single resonance:

$$\int_0^\infty \rho(\epsilon,\epsilon_0)\frac{P_f}{P_i}(\epsilon)\mathrm{d}\epsilon$$

$$\left\langle\frac{P_f}{P_i}\right\rangle = \frac{1-\frac{\pi|\varepsilon_0|^2}{\alpha}}{1+\frac{\pi|\varepsilon_0|^2}{\alpha}}. \quad (4)$$

Using this the product of all the spin resonances crossed from 400 MeV to 18 GeV ($G\gamma = 0.907$ to 40.82),

$$F(\epsilon_0) = \Pi_K \langle \frac{P_f}{P_i}(\epsilon_0)_K \rangle, \quad (5)$$

where K is index for the spin resonances through $G\gamma = 40.82$. This yields the total relative polarization transmission through the acceleration cycle for a given rms emittance. For normalized rms emittance as high as $\epsilon_0 = 1000$ mm-mrad, we calculate more than 98 % transmission through the ramp for this lattice including the effects of the bypass in all straight sections. Our actual injected rms emittance is 18 times less than 1000, or 55 mm-mrad normalized.

More of an issue are the imperfection spin resonances which are driven by the vertical closed orbit errors. Unlike intrinsic spin resonances, imperfection resonances are independent of the emittance, so the depolarization effect applies to all particles equally in the bunch.

We performed particle tracking using the 6D spin-orbit tracking code Zgoubi [5], including radiative effects, for 8 large amplitude particles at 1000 mm-mrad normalized emittance. We used a 50–200-msec ramp rate with orbit errors generated by vertical kicks equaling 1 mm rms of orbit distortion. We also included up 0.1 % random gaussian quadrupole gradient errors. The results showed for the slowest ramp rate of 200 msecs 94 % polarization transmission was achieved. However, when encountering repeated imperfection resonances, simulations show a phenomena of polarization restoration, since the imperfections act coherently over the whole beam. We are doubtful that this represents the 'true' physics since the simulation may be underestimating the level of phase mixing or spin diffusion. As a result we feel a more conservative measure would be to estimate polarization loss by calculating the imperfection resonance strengths up to $G\gamma = 40$ using DEPOL [6], then calculate the Froissart-Stora results for each of these imperfections encountered on the ramp and finally take the product of all the Froissart-Stora results. We performed this type of calculation for various levels of quadrupole misalignments and various random seeds using MADX program and the DEPOL to calculate the imperfection resonance strength. Using this approach we find that 95% polarization transmission can be achieved if the orbit is held to 0.5-mm rms orbit distortion. Standard singular-value decomposition (SVD) can easily achieve this level of correction for quadrupole misalignment errors of 0.2 mm rms, which represents standard survey alignment tolerances.

Even with uncorrected misalignment errors we should be able to accelerate to as high as 23 $G\gamma$ (over 10 GeV) and still lose less than 5 %. Above 10 GeV, we find that we can get above 40 $G\gamma$ (18 GeV) by maintaining closed orbit rms orbit distortion of ≈ 0.5 mm rms. In addition, static orthogonal imperfection bumps can be used to tune out any residual polarization loss.

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