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EIC'S RAPID CYCLING SYNCHROTRON SPIN TRACKING UPDATE

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Abstract

The Electron Ion Collider (EIC) to be built will collide polarized electrons and ions up to 140 GeV center of mass with a time averaged polarization of 70% and luminosity up to 10^{34} cm^{-2} s^{-1}. The EIC's Rapid Cycling Synchrotron (RCS) will accelerate 2 polarized electrons bunches from 400 MeV to energies of 5, 10 and 18 GeV and inject them into the EIC's Electron Storage Ring. The design of the RCS has progressed to accommodate a larger magnet free section for the detectors and to meet the space requirements of the RHIC tunnel. We present progress on full 6D spin tracking studies of the RCS with the updated lattice using the Zgoubi code to include magnet misalignments, field errors and corrections as well as radiative effects.

INTRODUCTION

The Electron Ion Collider (EIC) to be built will collide polarized electrons and ions up to 140 GeV center of mass with a time averaged polarization of 70% and luminosity up to 10^{34} cm^{-2} s^{-1}. The EIC's Rapid Cycling Synchrotron (RCS) will accelerate 2 polarized electrons bunches from 400 MeV to energies of 5, 10 and 18 GeV and inject them into the EIC's Electron Storage Ring. To accommodate a longer magnet free section around the detectors we had to re-design the RCS's straight sections around 6 and 8 o'clock. The RCS is designed to accept four 7nC bunches from the pre-injector and merge them to achieve two 28nC bunches at injection energy and accelerate these two bunches to extraction energy.

The redesign made recovering the polarization and off-momentum dynamic aperture necessary to accelerate with the projected longitudinal emittance after the merge challenging. However as is detailed in another paper in these proceedings [1] a sufficient aperture and polarization transmission was achieved. In this paper we focus on the aspects of the polarization transmission for the new design. In particular we study the impact of misalignment and field errors.

IMPACT OF MISALIGNMENTS

Initial efforts with the new RCS lattice layout yielded optics which had very little beta-beat and a large off-momentum aperture. The estimated polarization loss at the level of 5 sigma also yielded polarization losses due to intrinsics less than 1%. In the past we would use an arbitrary metric of polarization transmission for a 1000 mm mrad rms emittance beam distribution. This of course was orders of magnitude higher than our physical aperture would permit. Previous lattices yielded intrinsic spin resonance induced polarization loss as estimated by DEPOL of under 5% at 1000 mm mrad. This initial lattice yielded transmissions of 15% at 1000 mm mrad, yet at the relevant operating emittances (40 mm mrad) we shouldn't have seen any polarization loss. However studying the effect of imperfection spin resonances driven by closed orbit distortions showed a lower threshold in terms of RMS orbit distortion for polarization loss. This of course is to be expected since it is well understood that the strength of both imperfection and intrinsic spin resonances are correlated due to their shared harmonic structure. Thus reducing the strength of the intrinsic spin resonances has the added benefit of reducing the strength of the average imperfection spin resonances. We revisited the RCS optics design and further pushed the intrinsic induced polarization losses to 8%, this did introduce some level of beta-beating however the overall off-momentum dynamic aperture was recovered and the sensitivity of the imperfections spin resonances to RMS orbit distortions was reduced as can be seen in Fig. 1.

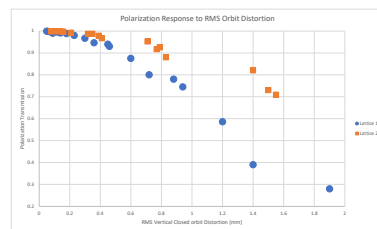

Figure 1: Comparison of polarization transmission due to imperfection spin resonances as function of RMS orbit distortion. Lattice 1, was our first RCS optics attempt with 15% intrinsic resonance induced losses at RMS emittance of 1000 mm mrad. Lattice 2 was our second and last RCS optics configuration with 8% losses at the same RMS emittance. This reduced imperfection spin resonance sensitivity as can be seen in the plot.

These results were confirmed using direct spin-orbit tracking in Zgoubi [2, 3] considering misalignments on the level of 0.6 mm RMS in the vertical plane and 0.3 mm RMS in the horizontal plane, as shown in Fig. 2.

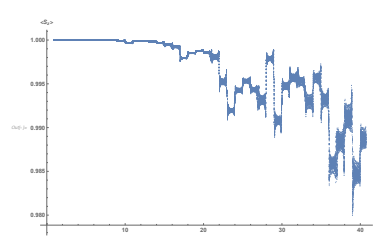

Figure 2: 13 particle tracking with 0.6 mm RMS vertical and 0.3 mm RMS horizontal closed orbit distortion.

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Table 1: RCS Longitudinal Bunch Parameters

Mode	σ_τ [ps]	σ_δ [%]	$\sigma_\tau \sigma_\delta E$ [eV s]
Injection 400 MeV	40	0.25	4×10^{-5}
Post Merge 400 MeV	180	0.25	18×10^{-5}
Extraction 18 GeV	30	.104	58.86×10^{-5}

DEVELOPING 6D RF RAMPS FOR SPIN-ORBIT TRACKING

Simulating the acceleration of polarized electron bunches in full 6D also requires generating a ramp with the necessary RF phase and voltage to match the bunch longitudinal parameters at injection and extraction and maintain the bunch stability against off-momentum dynamic aperture and collective instabilities while keeping the bunch within the RF bucket.

Since the proposed EIC's source and LINAC cannot achieve the necessary bunch charge of 28 nC per bunch with the necessary emittance and polarization, charge will be accumulated at injection energy (400 MeV) in the RCS. This will be accomplished by injecting a total of 8 LINAC bunches split into two trains of 4 bunches. Each bunch will have a total charge of 7 nC with bunch length of 40 ps RMS (τ)and a relative momentum spread of .25% RMS (δ). Each train of four bunches will be merged into a single bunch with total charge of 28 nC and final length of 180 ps while maintaining a relative energy spread of 0.25%. At 18 GeV the two 28 nC bunches should have bunch dimensions equal to 30 ps and 0.104% . Table 1 shows the longitudinal bunch requirements for the RCS.

RF EQUATIONS

For small amplitude oscillations we can approximate the ratio of the maximum amplitude off-momentum deviation $\hat{\delta}$ to the maximum $\hat{\tau}$ to the synchrotron frequency divided by η the phase slip factor,

$$\frac{\hat{\delta}}{\hat{\tau}} = \frac{\omega_s}{\eta}. \tag{1}$$

Here the synchrotron frequence ω_s is given by,

$$\omega_s = \omega_0 \sqrt{\frac{hV_0|\eta \cos\phi_s|}{2\pi E\beta^2}}, \tag{2}$$

with ω_0 the angular revolution frequency, V_0 the voltage on the RF cavity, E is the Energy and β the relativistic beta. We also know that the gain in energy per turn from the RF cavity is given by,

$$\Delta E = V_0 \sin\phi_s. \tag{3}$$

Substituting for $V_0 = \frac{\Delta E}{\sin\phi_s}$ we get,

$$\begin{aligned}
\frac{\hat{\delta}}{\hat{\tau}} &= \frac{\omega_0}{\eta}\sqrt{\frac{h}{2\pi}\frac{\Delta E}{E\beta^2}\frac{|\eta\cos\phi_s|}{\sin\phi_s}} \\
\left(\frac{\hat{\delta}}{\hat{\tau}}\right)^2 \frac{|\eta|2\pi E\beta^2}{\omega_0^2 h\Delta E} &= \frac{|\cos\phi_s|}{\sin\phi_s} \\
&= \cot\phi_s \\
\arctan\left[\left(\frac{\hat{\tau}}{\hat{\delta}}\right)^2 \frac{\omega_0^2 h\Delta E}{|\eta|2\pi E\beta^2}\right] &= \phi_s
\end{aligned} \tag{4}$$

This relationship holds true between $\pm\frac{\pi}{2}$, beyond that the absolute sign around cosine makes it no longer equivalent to ArcTan. If we are at energies with significant radiation loss this loss of energy U_0 per turn can be added to Δ E in our formula. Thus the RF voltage and phase can be presented as a function of bunch longitudinal parameters, energy and energy gain,

$$\begin{aligned}
\phi_s(\hat{\tau},\hat{\delta},E,\Delta E) &= \arctan\left[\left(\frac{\hat{\tau}}{\hat{\delta}}\right)^2 \frac{\omega_0^2 h(\Delta E + U_0)}{|\eta|2\pi E\beta^2}\right] \\
U_0 = C_\gamma \frac{E^4}{\rho}.
\end{aligned} \tag{5}$$

Here the expression of U_0 is the radiation loss per turn for a circular machine with local radius of curvature ρ and $C_\gamma = 8.8575 \times 10^{-5}$ m/GeV. Given the initial and final beam parameters as detailed in Table 1 we can use these to calculate the initial and final voltage and phase. If we choose to define simple linear function of energy which takes us between the initial phase ϕ_{si} and final phase ϕ_{sf} as well as the initial emittance ϵ_{Li} to the final ϵ_{Lf} we have:

$$\begin{aligned}
\phi_s(E) &= \phi_{si} + (E - E_i)\frac{\phi_{sf} - \phi_{si}}{E_f - E_i} \\
\epsilon_L(E) &= \epsilon_{Li} + (E - E_i)\frac{\epsilon_{Lf} - \epsilon_{Li}}{E_f - E_i}.
\end{aligned} \tag{6}$$

Using Eq. (1) with our interpolated emittance we can deduce the bunch length,

$$\begin{aligned}
\epsilon_L(E) &= \hat{\tau}\hat{\delta}E \\
\hat{\tau} &= \frac{\eta\hat{\delta}}{\omega_s} \\
\hat{\delta} &= \frac{\epsilon_L(E)}{E\hat{\tau}} \\
\hat{\delta} &= \frac{\epsilon_L(E)\omega_s}{E\hat{\delta}\eta} \\
\hat{\delta}(E,\Delta E) &= \sqrt{\frac{\epsilon_L(E)\omega_s(E,\Delta E)}{E\eta(E)}} \\
\hat{\tau}(E,\Delta E) &= \frac{\epsilon_L(E)}{E\hat{\delta}(E,\Delta E)}
\end{aligned} \tag{7}$$

Here we use Eq. (2) for the synchrotron frequency which is ultimately a function of energy gain per turn and energy through the RF voltage V_o and also we know that the slip

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factor η is also a function of energy. Next we can define how the energy gain per turn and thus total energy should evolve in time. We have chosen a smooth hyperbolic step-like function to describe how the change in energy $\Delta E(n)$ as a function of turn number n,

$$\Delta E(n) = \Delta E_i + (\Delta E_f - \Delta E_i)(1 - \frac{1}{1 + e^{a(n-b)}}) \quad (8)$$

Here the parameters b represents the location of the step and a the steepness of the step. Integrating Eq. (8) we can also obtain an expression for the total energy as function of turn number,

$$E(n) = E_i + \Delta E_i n + \frac{(\Delta E_i - \Delta E_f)(\ln[1+e^{ab}] - \ln[e^{ab}+e^{ax}])}{a} \quad (9)$$

APPLICATION TO RCS RAMP

We consider developing a turn-by-turn RF voltage and phase ramp from just after the merge is complete to extraction at 18 GeV. For the energy profile equation (Eq. (8)) we set $\Delta E_i = 0$ and $\Delta E_f = 2.64$ MeV (a bit higher than a nominal rate of 2.2 MeV since we wanted to complete the ramp in 8000 turns). We set $a = 0.0025$ and $b = 1300$. The net result is plotted in Fig. 3. Notice in this case our $\Delta E(0) \neq 0$

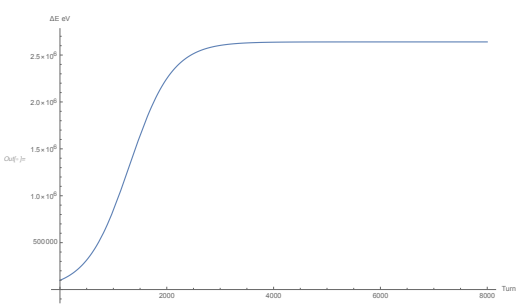

Figure 3: RCS ΔE Ramp

despite nominally being set to zero and the function actually starts with an energy gain per turn of 0.098 477 MeV per turn, while the final at $\Delta E(8000) = 2.64$ MeV or the set value. From this the initial and final phases can be calculated using Eq. (5) based on the initial and final $\hat{\tau}$ and $\hat{\delta}$ given in Table 1. This gives $\phi_{si} = 1.037\,68$ rad and $\phi_{sf} = 1.169\,35$ rad. The initial and final emittances can also be read off Table 1. With these values the whole turn-by-turn values for the phase can be seen plotted in Fig. 4.

As well the collective instabilities can be checked using the approximate formula for the microwave instability,

$$Imp = \frac{2\pi^3 E \alpha \hat{\tau} \hat{\delta}^2}{3Q} \quad (10)$$

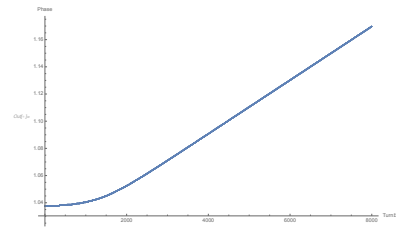

Figure 4: RCS ϕ_sRamp.

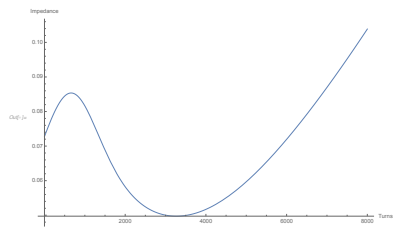

Figure 5: RCS Impedance Ramp.

Where Q is the bunch charge of 28 nC. For the RCS the rule of thumb is to keep Imp < 0.1 as can be seen from Fig. 5 we are below this threshold until the very end of the ramp where it reaches 0.1038 Ohms,

CONCLUSION AND FURTHER WORK

This analysis doesn't yet consider the impact of the approach to equilibrium emittances due to radiative effects. For this we will need to track with this RF ramping profile. This will no doubt require some modification of the ramp profile. Finally these ramp profiles will be used to develop a full 6D tracking including spin with misalignment and field errors applied to the lattice.

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