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WIDE RANGE TUNE SCAN FOR THE HADRON STORAGE RING OF THE ELECTRON-ION COLLIDER*

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Abstract

The Electron Ion Collider (EIC), to be constructed at Brookhaven National Laboratory, will collide polarized high-energy electron beams with hadron beams, achieving luminosities up to 1×10^{34} cm^{-2} s^{-1} in the center-of-mass energy range of 20-140 GeV. The current fractional design tunes for the Hadron Storage Ring (HSR) are (0.228, 0.210) to mitigate the effects of synchro-betatron resonances. In this article, based on a strong-strong beam-beam simulation model, we carried out a wide range tune scan for the HSR to search for optimum working points. We confirmed that the current HSR design tunes (0.228, 0.210) are located in the best tune space we studied so far. We also suggest two possible working points (0.238, 0.206) and (0.735, 0.710) for further dynamic aperture and polarization studies.

INTRODUCTION

Beam-beam interaction simulation is used to optimize the beam-beam-related design parameters for the EIC design [1], such as beam-beam parameters, working points, transverse emittances, β^*s at the IP, and so on. The original design tunes are (0.310, 0.305) for the HSR and (0.08, 0.06) for the ESR. To mitigate the synchro-betatron resonance effects with a large crossing angle collision with flat beams at the IP, we moved the HSR design tunes to (0.228, 0.210). Also, for the ESR, to improve the electron polarization lifetime at store energies, we moved the ESR design tunes to (0.08, 0.14) [2].

In this article, we present our new wide-range tune scan results for the HSR. The goal of this study is to search for other good tune spots for the HSR. The optimum tunes or working points should deliver the peak design luminosity 1×10^{34} cm^{-2} s^{-1} and acceptable beam and luminosity lifetimes at store. For this study, we adopt the beam and machine design parameters for the highest luminosity collision mode with 275 GeV protons and 10 GeV electrons. Table 1 lists its main beam-beam interaction-related beam parameters [3].

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Table 1: Beam-Beam Related Beam Parameters for the Collision Mode between 275 GeV Protons and 10 GeV Electrons

quantity	unit	proton	electron
Beam energy	GeV	275	10
Bunch intensity	10^{11}	0.668	1.72
(β_x^*, β_y^*) at IP	cm	(80, 7.2)	(55, 5.6)
Beam sizes at IP	μm	(95, 8.5)	
Bunch length	cm	6	0.7
Energy spread	10^{-4}	6.8	5.8
Transverse tunes		(0.228, 0.210)	(0.08, 0.14)
Longitudinal tune		0.01	0.069

PREVIOUS HSR TUNE OPTIMIZATION

The nominal fractional tunes for the polarized protons in RHIC operation are (0.695, 0.685), which lie between the 2/3 and 7/10 resonance lines. Unlike RHIC, the EIC will collide protons with electrons, resulting in a positive beam-beam tune shift. If we mirror the RHIC tunes below the half integer, the HSR tunes will be located between the 3/10 and 1/3 resonance lines.

The initial choice for the HSR fractional tunes is (0.310, 0.305). Through our original beam-beam simulations, we observed significant proton emittance growth with beam-beam interaction. Using frequency map analysis (FMA), we were able to identify synchro-betatron resonances [4], as shown in Figure 1.

Two types of synchro-betatron resonances are visible with a large tune diffusion in y ellow: 1) $3\,Q_x + p\,Q_z$, which couples the horizontal and longitudinal proton motion. 2) $2Q_x - 2Q_y + pQ_z$, which couples the proton's three-dimensional motion. The fundamental reasons for these synchro-betatron resonances are: 1) a large crossing angle of 25 mrad, 2) a relatively long proton bunch length of 6 cm, and 3) a high synchrotron tune of 0.01. To mitigate the effects of synchro-betatron resonances, we decided to optimize the HSR design tunes and include second harmonic crab cavities in the HSR.

Initially, we moved the HSR design tunes from (0.310, 0.305) to (0.228, 0.224) along the diagonal in the tune space. With the new tunes, the resonance structure of the first type of synchro-betatron resonance changes to $4Q_x + pQ_z$, with

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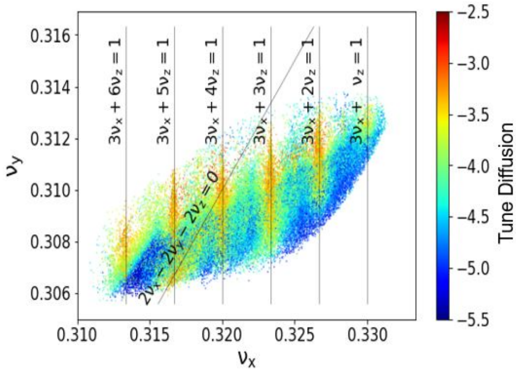

Figure 1: Frequency map analysis with the HSR tunes(0.310, 0305).

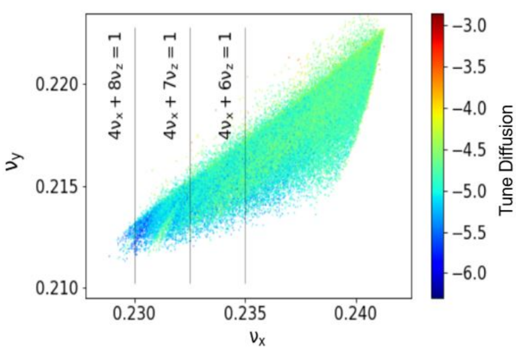

Figure 2: Frequency map analysis with the HSR tunes (0.228, 0.210).

a resonance order higher than $3Q_x + pQ_z$. Then, we further adjusted the HSR design tunes from (0.228, 0.224) to (0.228, 0.210) by only lowering the vertical tune to 0.210. Away from the difference coupling resonance line, the effect of the coupled synchro-betatron resonance $2Q_x - 2Q_y + pQ_z$ is mitigated with a higher value of p. Figure 2 shows the FMA with the new HSR design tunes (0.228, 0.210) and second harmonic crab cavities in the HSR, where the synchro-betatron resonances are barely visible.

NEW HSR TUNE SCAN

Simulation Model

In the following, we will adopt a strong-strong beam-beam simulation model for a wide range of tune scans for the HSR. In this model, both electron and proton bunches are represented by half a million macro-particles. There is only one interaction point at IP6. The ring is simply represented by a 6×6 uncoupled linear matrix. Crab cavities and synchrotron radiation effects are included. Both bunches are tracked up to 50,000 turns. The beam and optics parameters listed in Table 1 are used except for the HSR tunes. To save computing time, we will not adjust other optics or beam parameters, for example, to match the beam sizes at IP to maximize the luminosity.

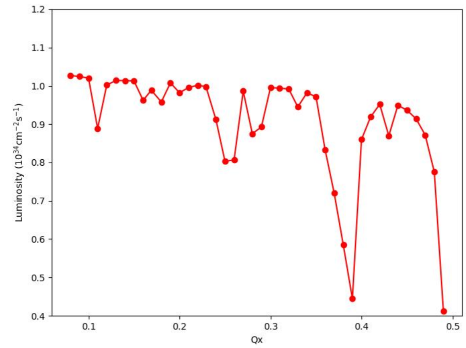

Figure 3: Calculated luminosity with HSR tune scan below half integer.

The strong-strong beam-beam simulation is subject to large numerical noises; the calculated beam size growth rates are only used for relative comparison. Our goal for this study is to look for possible HSR tune spots with smaller or comparable beam size growth rates compared to the current HSR design tunes (0.228, 0.210).

Below Half Integer

First, we scanned the fractional HSR working point along the diagonal in the $Q_x - Q_y$ tune space between 0 and 0.5. During this scan, we fixed the transverse tune split by ensuring that the fractional horizontal tune was always 0.018 higher than the fractional vertical tune. Figure 3 shows the averaged luminosity in the final 1000 turns. Drops in luminosity are observed when the working point is around 0.1, 0.25, 0.33, and close to 0.5. This can be explained by low-order betatron resonances. Together with the relative beam size growth rates linearly fitted from the last 30,000 turns, we located three possible good tune areas around 0.13, 0.22, and 0.31.

With a smaller tune scan step size, we performed a 2D tune scan around these three possible tune areas and found that the tune space around 0.22 has the largest stable area compared to the other two tune spots. Interestingly, the current design tunes for the HSR are actually within this good tune space. Figure 4 shows the relative proton's vertical emittance growth rates in the tune space around 0.225. The working points with vertical growth rates 50% higher than the case with the current design tunes (0.228, 0.210) are marked in red.

In another simulation study of position ripples at IP with a weak-strong simulation model, we found that the HSR tunes (0.226, 0.209) will deliver a smaller proton vertical emittance growth rate. This finding motivated us to explore this tune space with a smaller vertical tune close to 0.2. Figure 5 shows the relative vertical beam size growth rate for this study. There are two vertical bands in blue that deliver a smaller vertical beam size growth rate than the design tunes (0.228, 0.210). Based on the final luminosity and both horizontal and vertical beam size growth rates, we

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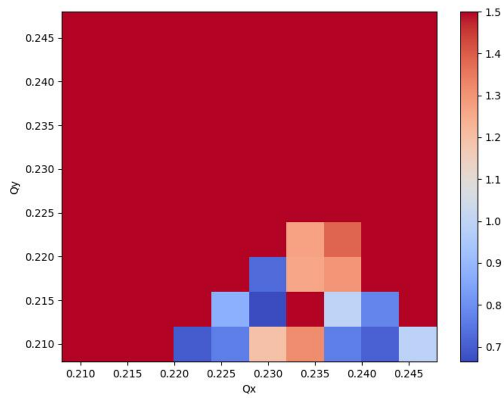

Figure 4: Relative proton vertical beam size growth rate for tune scan between 0.2 and 0.25.

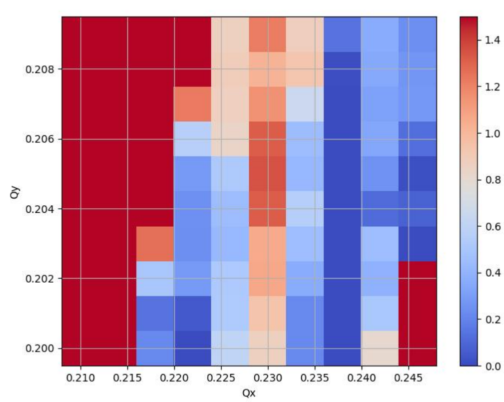

Figure 5: Relative proton vertical beam size growth rate with vertical tune between 0.2 and 0.21.

suggest a working point (0.238, 0.206) for further simulation studies. We plan to conduct beam experiments in RHIC and dynamic aperture calculations to determine the stop-band of the 5th-order resonance at 0.2.

Above Half Integer

Next, we performed the tune scan above the half integer from 0.5 to 1.0. Figure 6 shows the averaged luminosity in the last 1000 turns. The luminosity is higher when the tunes are around 0.55 and 0.725. Since the spin tune of the polarized protons in the HSR is 0.5, we only explored the tune space around 0.725.

We conducted a 2D tune scan below and above 0.7. The area of good tune space is larger with tunes above 0.7. Figure 7 shows the relative proton vertical emittance growth rates. From the final luminosity and relative proton horizontal beam size growth rate, we learned that the horizontal tune should not be higher than 0.74. Otherwise, the horizontal beam size will increase significantly, causing a drop in luminosity. We suggest a new good working point (0.735, 0.705) for further studies. The advantage of this working

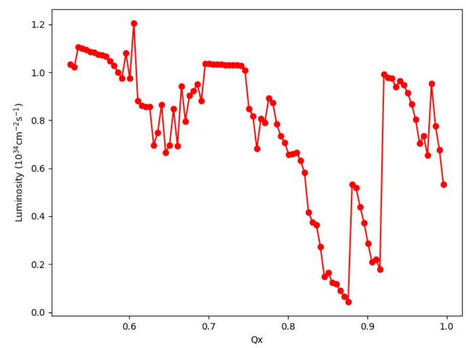

Figure 6: Calculated luminosity with HSR tune scan above half integer.

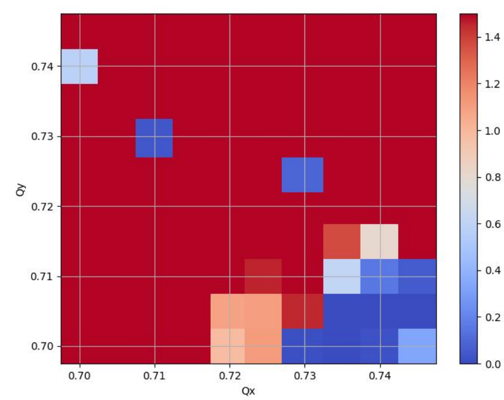

Figure 7: Relative proton vertical beam size growth rate in the 2-d tune scan between 0.70 and 0.75.

point is that it is located between 10th and 4th order resonances. Current HSR design tunes are located between 4th and 5th resonances.

SUMMARY

In this article, we presented the latest tune scan results for the HSR of the EIC. We confirmed that the current HSR design tunes (0.228, 0.210) are located in the best tune space we have studied so far. A lower vertical tune towards 0.2 will yield a smaller vertical emittance growth rate. We suggested a new working point (0.238, 0.206) for further studies. We will perform beam experiments in RHIC and dynamic aperture calculations to quantify the stop-band of the 5th-order resonance at 0.2. From the tune scan above the half integer, we found another good tune area around (0.735, 0.710). We plan to perform polarization and dynamic aperture studies to confirm it.

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