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Fine decoupling test and simulation study to maintain a large transverse emittance ratio in hadron storage rings

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Abstract. In previous and existing hadron storage rings, the horizontal and vertical emittances are normally the same or very close. For the Hadron Storage Ring (HSR) of the Electron-Ion Collider (EIC), the design proton transverse emittance ratio is 10:1. To maintain this large emittance ratio, we need to have an online fine decoupling system to prevent transverse emittance exchange. For this purpose, we carried out fine decoupling experiments in the Relativistic Heavy Ion Collider (RHIC) and reviewed its previous operational data. Analytical prediction and numerical simulation are preformed to estimate how small the global coupling coefficient should be to maintain a 10:1 emittance ratio.

1. Introduction

The Electron-Ion Collider (EIC) presently under construction at Brookhaven National Laboratory will collide polarized high energy electron beams with hadron beams, reaching luminosities up to $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the center-of-mass energy range of 20-140 GeV. To achieve high luminosities, the EIC adopts crossing angle collision with more than 1000 bunches per ring, flat beams with small β^*s at the interaction point (IP), and strong hadron cooling [1].

For the collision between 275 GeV protons and 10 GeV electrons, the beam-beam parameters for both beams reach their highest values in EIC. The beam-beam parameters are 0.012 for protons and 0.1 for electrons. The beam sizes at interact point (IP) are (95 μm, 8.5 μm). The β^*s in the Hadron Storage Ring (HSR) are (80 cm, 7.2 cm). The un-normalized proton transverse emittances are (11.3 nm, 1.0 nm).

For previous or existing hadron colliders, the horizontal and vertical emittances are normally the same or close to each other. To achieve about a 10:1 emittance ratio in HSR, we will pre-cool the proton bunches at lower beam energies and employ strong hadron cooling at store energy to maintain this ratio. As we know, betatron coupling will mix transverse emittances. Therefore, fine decoupling is required in HSR to stop emittance transfer from the horizontal plane to the vertical plane. For HSR we may not have vertical cooling at store energy. If so, we also need to prevent any sizable emittance growth in the vertical plane.

The HSR of EIC will re-use the existing RHIC arcs. For RHIC, we developed a feedback system to continuously monitor and correct the global betatron coupling [2, 3]. This system was proved robust and routinely operated at injection, on the energy ramp, and at store. For HSR, considering the large transverse emittance ratio, we need to make sure that current RHIC decoupling feedback is sufficient for HSR's fine decoupling requirement.

In the following, we will first present experimental results from previous years and in 2021 to demonstrate fine decoupling and possible 10:1 transverse emittance ratio in RHIC. Then we will analytically estimate the emittance exchange due to global coupling and its requirement for HSR. In the end, we will carry out multi-particle simulation to determine and verify the global decoupling requirement.

2. Results from previous years

To demonstrate if we can achieve a large transverse emittance ratio in RHIC with current decoupling feedback, we performed several beam experiments in RHIC. The earliest one was done in 2017. In this experiment, we used Au (gold) ion beam. We filled the Yellow ring with nominal intensity bunches ($2x10^9$/bunch) for the first half of the bunch train and then half intensity bunches for the remainder. Intra-beam scattering (IBS) will generate longitudinal emittance growth and horizontal emittance growth through horizontal dispersion in the ring. IBS growth rate is related to bunch intensity and emittances. For RHIC, there is no vertical dispersion in the design lattice. We ramped Au ion bunches to 100 GeV/n and observed emittance growth for about 2 hours at store.

Figure 1 shows the emittance measurement data with Ion Profile Monitor (IPM). In the plot, there are two horizontal and two vertical emittance measurement data for Yellow ring at each time point, one for full bunch intensity and one for half bunch intensity. With global decoupling in Yellow ring, we observed a much slower vertical emittance growth than horizontal. After about 2 hours at store, the horizontal emittance reached double the vertical emittance. The vertical emittance increased slightly by 20-30% in 2 hours. At the end of experiment, we pushed the tune settings closer, from (0.2365, 0.2268) to (0.2340, 0.2291) in steps, we observed horizontal emittance transferred to vertical emittance.

A second experiment was done in 2018, where we focused on the minimum transverse tune split needed to stop the transverse emittance exchange. For this experiment, we also used Au ion beam at 100 GeV/n but with stochastic cooling. We deliberately switched off the horizontal stochastic cooling and kept the vertical plane cooling on. We adjusted the tune split by increasing the horizontal set tune to check at what tune split the horizontal emittance will not get cooled by the vertical cooling through betatron coupling. Figure 2 shows the measured tunes and emittances during this experiment.

The tune split before any tune change was about 0.001, as shown at 22:05:00. We lost tune tracking between 22:08:00 and 22:21:00. At about 22:20:00, as shown by a red arrow in the plot, the horizontal emittance began to grow. Then the tune meter was tuned back and the tune split was measured as 0.013. The minimum tune split ΔQ_{min} or the global coupling coefficient $|C^-|$ under the experimental condition was probably about 0.001-0.0015. This hints that we need to have the global coupling coefficient $|C^-|$ at least be 10 times less than the transverse set tune split to stop transverse emittance exchange.

3. Beam experiments in 2021

In 2021 we re-initiated a similar experiment with a main purpose to demonstrate a transverse emittance ratio 10:1 in RHIC and to test the capability of existing RHIC decoupling system. This experiment should have been be done at store energy with stochastic cooling as in 2018. Unfortunately stochastic cooling was not set up in 2021 since this run was dedicated for polarized proton operation. To increase the IBS growth rate in the horizontal plane to obtain a larger transverse emittance ratio, we carried out this experiment at injection with 7.3 GeV Au/n beam.

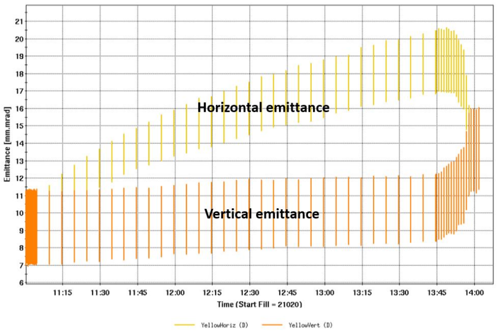

Figure 1. Emittance measurements at store in 2017 beam experiment. Transverse emittance ratio 2:1 was obtained.

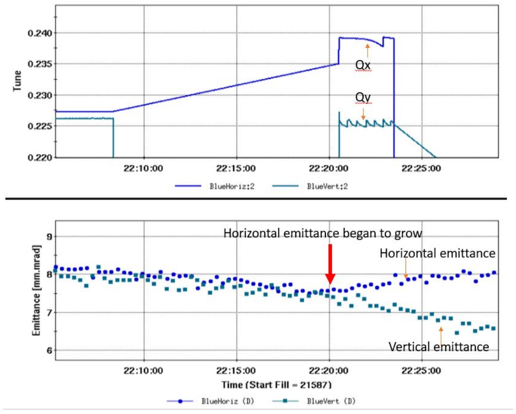

Figure 2. Tunes and emittances at store in 2018 beam experiment. When tune split larger than 0.013, the emittance exchange between the transverse planes stopped.

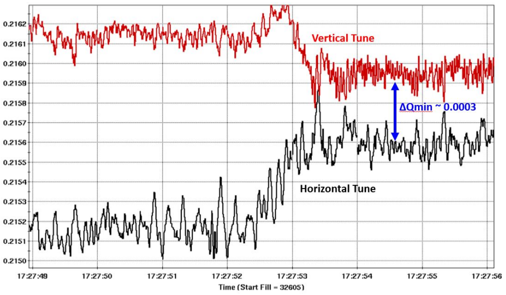

Figure 3. The minimum tune split ΔQ_{min} or $|C^{-}|$ about 0.0003 obtained in 2021 experiment.

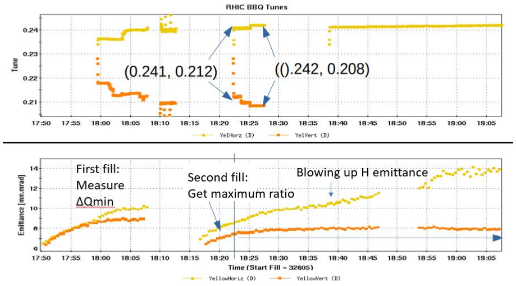

Figure 4. Measured emittances and tunes in 2021 beam experiment. Maximum 1.8:1 transverse emittance ratio was obtained at injection.

Before the experiment, we decoupled the Yellow ring with decoupling feedback and measured the minimum tune split ΔQ_{min} or global coupling coefficient $|C^{-}|$. Figure 3 shows that $\Delta Q_{min} = 0.0003$ can be obtained with current decoupling feedback and with some manual decoupling. This is the smallest ΔQ_{min} we have observed in RHIC. Then we injected 12 new bunches into the well decoupled ring to study how large emittance ratio we could obtain.

During this process, the vertical emittance basically stayed unchanged and horizontal emttance continued growing due to IBS. To increase the transverse emittance ratio in a short period of time, we decided to blow up the horizontal emittance with additional measures. We used horizontal offset injection, horizontal kick from base band tune meter (BBQ), and simply consecutive single kicks for tune measurement (Artus). Figure 4 shows the measured emittances and tunes in this experiment.

For this experiment, we were only able to demonstrate a maximum emittance ratio about 1.8:1 in 45 minutes at injection. With a very large horizontal emittance, we observed a very bad beam lifetime due to limited physical aperture. Again, this experiment should be done at store energy with stochastic cooling. We will come back to re-do it in 2023 RHIC Au run.

4. Analytical prediction

Here we present analytical prediction of transverse emittance exchange due to global betatron coupling. Based on Guignard's Hamiltonian perturbation theory [4], the horizontal and vertical emittances with betatron coupling are

$$\epsilon_x = \epsilon_{x,0} - \frac{|C^-|^2/2}{\Delta^2 + |C^-|^2}(\epsilon_{x,0} - \epsilon_{y,0}), \tag{1}$$

$$\epsilon_y = \epsilon_{y,0} + \frac{|C^-|^2/2}{\Delta^2 + |C^-|^2}(\epsilon_{x,0} - \epsilon_{y,0}), \tag{2}$$

where $\epsilon_{x,0}$ and $\epsilon_{y,0}$ are the emittances without any coupling, Δ is the fractional lattice tune split.

For the HSR of EIC, we need to control vertical emittance increase, say less than 5%. Based on above equations, with uncoupled transverse emittances (11 nm, 1 nm), we need to have $|C^-/\Delta| < 10$ to achieve that goal. For the original proton design tunes (0.310, 0.305) for HSR, we need to have $|C^-|$ less than 0.0005 which is reaching the best we can do with RHIC global decoupling feedback. To minimize the vertical emittance growth rate due to beam-beam interaction, we moved the proton design tunes to (0.228, 0.210) [5]. For the new design proton tunes, we only need to correct the global decoupling coefficient $|C^-| < 0.0018$ to have less than 5% of vertical emittance increase. In the RHIC routine operation, we are able to operate with $|C^-|$ less than 0.001. This means that RHIC global decoupling feedback meets the HSR's global decoupling requirement.

5. Numerical simulation

Next we carry out numerical simulation using SimTrack [6] to determine the decoupling requirement. First, we simulate with RHIC's Blue ring lattice for 100 GeV proton beam. We set the lattice tunes the same as HSR's tunes (0.228, 0.210). We use the existing skew quadruopole families to introduce global coupling in this simulation study. The initial horizontal and vertical emittances are set to be 9.5 nm and 1 nm. The emittance is about 9.5 nm in both transverse planes for the RHIC 255 GeV proton beam at store. We ramp up skew quadrupoles to their full strengths in 1000 turns and continue tracking for another 500 turns. In this study, we used 2000 macro-particles.

Figure 5 shows the evolution of both horizontal and vertical emittances for 10 sets of final skew quadrupole strengths, which corresponds $|C^-|$ from 0.001 to 0.018. From the simulation results, if we plan to have vertical emittance increase less than 5% from its original value 1 nm, the global coupling coefficient should be less than 0.002, which is in good agreement to our above analytical prediction.

Then we move to simulation with the HSR lattice. Here we use an older version of HSR lattice labeled as Version 2020Dec08. For this study, we randomly assign roll angles to all quadrupoles to generate global coupling. The RMS roll angles we used in the simulation study are 140 μrad, 100 μrad, 50 μrad, and 10 μrad, which correspond to $|C^-|$= 0.0065, 0.0045, 0.0022,and 0.00045. The evolution of vertical emittance is shown in Figure 6. Based on the simulation results, with design tunes (0.228, 0.210), the vertical emittance will not grow more than 5% if the global coupling coefficient is smaller than 0.0022, which is in agreement with our early analytical prediction too.

6. Conclusion

To be able to maintain a large 10:1 horizontal to vertical emittance ratio for the HSR of EIC, we carried out beam experiments in RHIC to test the capability of the existing global decoupling feedback system and to demonstrate 10:1 emittance ratio. In these experiments,

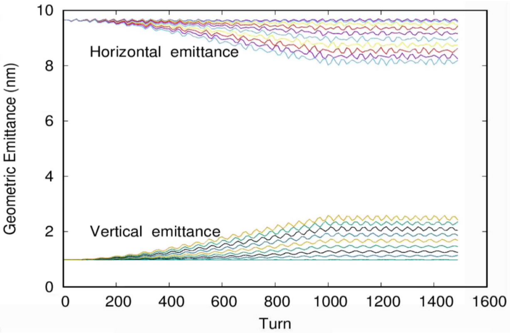

Figure 5. Evolution of horizontal and vertical emittances from numerical simulation done with RHIC lattice.

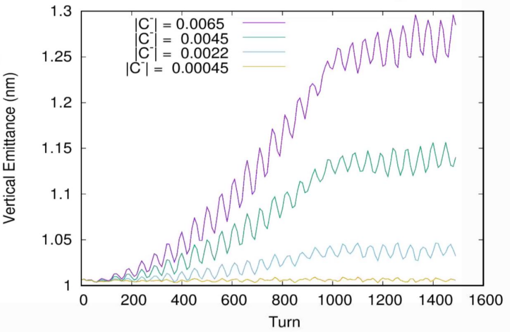

Figure 6. Evolution of vertical emittance from numerical simulation done with HSR lattice.

we demonstrated that we could reach a best global decoupling with ΔQ_{min} or global coupling coefficient $|C^-|$ less than 0.0003. However, we failed to demonstrate larger than 2:1 emittance ratio due to non-optimum experimental condition in 2021. From analytical calculation and numerical multi-particle tracking, we showed that with the new HSR design tunes (0.228, 0.210), we can have the proton's vertical emittance increase less than 5% if the global coupling coefficient is less than 0.002. For RHIC routine operation, we can easily correct global coupling less than 0.001 with the existing RHIC global decoupling feedback. We plan to re-do this beam experiment in 2023 RHIC Au run with stochastic cooling at store.

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