Flat Beam Related Experiments

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Background

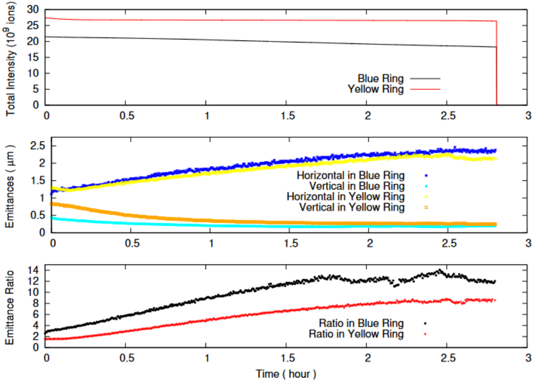
EIC baseline design

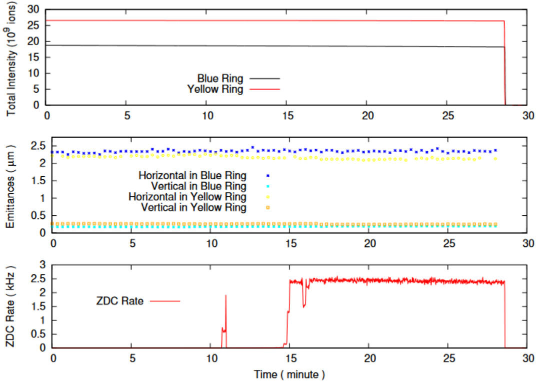
- The flat hadron beam — emittance ratio $\mathrm{H}:\mathrm{V} = 11:1$ — is used to maximize the peak luminosity. The random fluctuations in the real world and higher-order resonances may lead to the vertical emittance growth.
- The crab cavities are essential to recover geometry luminosity loss. The crab cavities are used in both the ESR and the HSR. The imperfect crab cavity setup leads to linear synchro-beatron coupling.
- The combination of large beam-beam parameters have never been demonstrated before. The vertical emittance growth is observed in many simulations. The working point optimization is the most effective way to suppress the vertical emittance growth.
- The Strong Hadron Cooling (SHC) is considered an efficient strategy to counteract the IBS diffusion. Nonetheless, it appears that the SHC will not be ready on the first day of the future EIC operations, and the vertical cooling capacity is not large enough.

These experiments aim to identify the most significant challenges and potential solutions related to flat hadron beams.

Background

We demonstrated 11:1 emittance ratio at store in RHIC run-23





Effective cooling is essential to generate flat beam, and the betatron coupling should be weak enough to avoid emittance transfer

Proposals Covered in This Talk

- Proposal 24-03: Accelerate a flat gold ion beam from 31 GeV to 100 GeV in the RHIC Yellow Ring

- Proposal 24-11: Study on IBS growth in presence of crab dispersion for flat beam

- Proposal 24-12: Investigate beam-beam impact on hadron beam flatness

Motivation of proposal 24-03 (ramping)

- Previous flat beam demonstration was performed for gold ion beam at 100 GeV. For the EIC design, the flat beam profile will be produced at the injection energy of 24 GeV.
- The beam optics varies between the injection energy and the top energy. The ramping process should adiabatically transition the beam from its initial state to its final state. Maintaining the beam's flat profile requires careful management of these transitions to ensure that any changes are gradual and controlled, minimizing disruptions to the beam's properties.
- Cooling is turned off as the beam accelerates from its injection energy to its maximum energy. During ramping, the vertical emittance is particularly susceptible to the effects of random diffusion processes, such as the IBS, power supply ripple etc. Each of these can introduce variations in the beam, potentially impacting the performance.

This experiment aims to explore the feasibility of ramping a flat beam and may provide best practices to preserve the beam's flat profile throughout the process.

Procedure of proposal 24-03 (ramping)

Experiment Description: Au ion beam, Yellow ring

- establish the ramps: 9.8GeV to 31GeV gold ramp, and 31GeV to 100GeV ramp.
- set up vertical and longitudinal stochastic cooling at 31 GeV for gold beam in the Yellow ring.
- accelerate 11:1 emittance ratio gold beam from 31 GeV to 100 GeV.

Beam Time Request: totally $3 \times 16 = 48$ hours

- First session: 16 hours, set up 31 GeV ramp , vertical and longitudinal cooling set up at 31GeV in Yellow ring.
- Second session : 16 hours, (continue cooling setup if needed), ramp development 31->100GeV
- Third sessions: physics experiments, get flat beam at 31GeV in the Yellow ring and ramp up to 100GeV, totally 16 hours, may be split into 8hours * 2 sessions.

Readiness of proposal 24-03 (ramping)

- Ramp development: 9.8 $\mathrm{GeV} \rightarrow$ 31 GeV (from run-19 Au 31GeV ramp),
  31 $\mathrm{GeV} \rightarrow$ 100 GeV (new ramp) , Guillaume
- Operation preparation: tape sequence, etc, Ian, Travis, ...
- Stochastic cooling : 31 GeV , vertical and longitudinal in Yellow ring, Kevin
- review previous run-19 operation data: Yun, Vincent, Guillaume
- Fine tuning on ramp (orbit, working point, coupling etc.): Yun, Chuyu, Derong

Summary of proposal 24-03 (ramping)

Experiment Number:	24-03
Beam Experiment Title:	Accelerate a flat gold ion beam from 31 GeV to 100 GeV in the RHIC Yellow Ring
Spokesperson(s):	Y. Luo
Status:	Proposed
Team:	K. Mernick, G. Robert-Demolaize, T. Shrey, V. Schoefer, I.Blackler, Y. Luo, D. Xu, C, Liu, C. Montag, M. Blaskiewicz
Experiment Goal:	To demonstrate accelerating \`flat\` gold beam with a large transverse emittance ratio 11:1 from 31 GeV to 100 GeV
Benefits:	A large emittance ratio is required for the EIC HSR design. With phased cooling at injection and store, we need to demonstrate we are able to accelerate such \`flat\` beam from injection to store while keeping this large emittance ratio on energy acceleration.
Experiment Description:	Three main steps: 1) establish the ramps: 9.8GeV to 31GeV gold ramp, and 31GeV to 100GeV ramp. 2) set up vertical and longitudinal stochastic cooling at 31 GeV for gold beam in the Yellow ring. 3) accelerate 11:1 emittance ratio gold beam from 31 GeV to 100 GeV.
Hazard Analysis:	None
Approved By:	
Date Approved:	
Resources:	
Instrumentation:	BBQ, IPM, orbit/tune/coupling feedback, etc.
Application:	MCR applications
Time:	1) First session: 16 hours, set up 31 GeV ramp , vertical and longitudinal cooling set up at 31GeV in Yellow ring. 2) Second session : 16 hours, (continue cooling setup if needed), ramp development 31->100GeV 3) Third sessions: physics experiments, get flat beam at 31GeV in the Yellow ring and ramp up to 100GeV, totally 16 hours, may be split into 8hours * 2 sessions. totally 48 hours for this entire experiment.
Personnel:	All team members and MCR on duty crew.
Intentional Beam Loss?	No

Motivation of proposal 24-11 (IBS)

- Crab cavities introduce synchro-betatron coupling, which is characterized in terms of crab dispersion.
- In the EIC-HSR design, there are 5 degrees off to the ideal value. The kick from the upstream crab cavity can't be cancelled by the downstream one. The crab dispersion leaks out of the IR.
- The leaked crab dispersion has little impact on the dynamic aperture. The beam-beam performance can be restored by adjusting crab cavity voltages. However, its impact on the vertical IBS time remains unknown.
- The existing IBS models are all 2.5D, taking the momentum dispersion into consideration.

This experiment tries to examine the influence of crab dispersion on vertical IBS time, and supply experimental data to assist in the development of a 3D IBS model.

Procedure of proposal 24-11 (IBS)

Experiment Description: Au ion beam, Yellow or blue ring

1. Set the golden beam to flattop energy and activate the cooling system to generate a flat beam
2. Adjust the dispersion bump around the RF cavity to observe crab dispersion effects
3. Turn off cooling and measure emittance growth time for varying dispersion conditions
4. Change beam flatness and repeat steps (2-3)
5. Establish a 3D IBS model and benchmark with experiment results

The estimated time to assess the IBS time across four varying emittance ratios (1:1, 1:2, 1:3, 1:5) and three different dispersion or disersion prime values at RF, is 12 hours.

Readiness of proposal 24-11 (IBS)

- Previous study demonstrated that IBS time is measurable at RHIC and there are available knobs to adjust dispersion around RF cavity at IR4
  - Experimental studies of IBS in RHIC: A. V. Fedotov et al., HB2006, WEBY03
  - IBS Simulation with different RF configurations in RHIC: C. Liu et al., tech note, BNL-113205-2016-IR
- Linear transverse-longitudinal coupling theory
  - Combined effects of crab dispersion and momentum dispersion: D. Xu et al. Phys. Rev. Accel. Beams 25, 071002
  - Closing crab dispersion by dispersive RF cavity: D. Xu, et al. IPAC2023, MOPA040
- The non-zero momentum dispersion at RF cavity will excite synchro-betatron coupling. The longitudinal osciallation will transform momentum dispersion into crab dispersion.
  - For the EIC-HSR, the residual crab dispersion at the IP is: $\mathcal{H}_\zeta = 1.5 \times 10^{-6}\ \mathrm{m}^{-1}$
  - To get similar coupling, the required dispersion at RF cavity: $(k_{\mathrm{rf}} \cdot eV/E)^2\, \mathcal{H}_\eta \geq \mathcal{H}_\zeta$
  - We plan to use 197 MHz cavities at IR4, which provide $2-3\ \mathrm{MV}$ in total. Guillaume is checking the lattice to maximize the above metric function
- Alternatively, we can adjust the beam's trajectory to pass through the cavity off-center, idea provided by Chuyu. Binping will check the electro-magnetic field at large offset.

Summary of proposal 24-11 (IBS)

Experiment Number:	24-11
Beam Experiment Title:	Study on IBS growth in presence of crab dispersion for flat beam
Spokesperson(s):	Derong Xu
Status:	Proposed
Team:	Derong Xu;Yun Luo;Guillaume Robert-Demolaize;Kevin Mernick;Travis C Shrey
Experiment Goal:	Measuring IBS growth rate for golden flat beam in presence of crab dispersion
Benefits:	We will gain a deeper comprehension understanding of the interplay between synchro-betatron coupling and IBS. It will offer crucial input for the HSR lattice design and provides guidance on determining the necessary vertical cooling rate.
Experiment Description:	The leakage of crab dispersion from the IR is adopted in the HSR lattice design. This leakage will lead to synchro-betatron coupling along the whole ring. However, existing IBS models exclusively consider 2.5D dynamics, incorporating betatron coupling and momentum dispersion. To accurately forecast the vertical IBS growth rate in the HSR, a comprehensive 3D IBS model becomes essential. This experiment holds significance for the EIC design as it contributes to a deeper comprehension of the interplay between synchro-betatron coupling and IBS. Furthermore, it offers crucial input for the HSR lattice design and provides guidance on determining the necessary vertical cooling rate. The general procedures includes: (1) Set the beam to flattop energy and activate the cooling system to generate a flat beam (2) Adjust the dispersion bump around the RF cavity to observe crab dispersion effects (3) Turn off cooling and measure emittance growth time for varying dispersion conditions (4) Change beam flatness and repeat steps (2-3)
Hazard Analysis:	None
Approved By:	
Date Approved:	
Resources:	
Instrumentation:	(1) cooling to generate flat beam at store energy (2) a dispersion bump around RF cavity to generate and control crab dispersion in RHIC ring (3) emittance measurement tools for capturing IBS growth time
Application:	Common operation application
Time:	12 hours (estimate)
Personnel:	Necessary operational support
Intentional Beam Loss?	No

Motivation of proposal 24-12 (Beam-beam)

- The resonance line $\nu_x - \nu_y + p\nu_z = 0$ goes across the hadron beam footprint. In ideal case, it doesn't drive observable vertical emittance growth in the beam-beam simulation.
- There are many random fluctuations in the real machine. When the random diffusion is included, a significant emittance transfer between horizontal and vertical plane is observed in beam-beam simulation.
- The working point optimization turns out the most effective and economic way to suppress the vertical emittance growth.

We must investigate whether the flat beam can survive random diffusion in presence of beam-beam interactions. If not, we must explore mitigation strategies.

Procedure of proposal 24-12 (Beam-beam)

Experiment Description: Au ion beam, both rings

1. Set the cross angle $(0, 1.5\ \mathrm{mrad})$ and choose flatness $(1.0, 0.5, 0.33)$
2. Set the beam to flattop energy and activate the cooling system to generate desired flatness in both RHIC rings
3. Bring two beams into collision with a small crossing angle, turn off cooling, and observe beam loss rate and/or emittance growth rate
4. Perform the following scan: (a) scan ν_x while keeping ν_y unchanged (b) scan ν_y while keeping ν_x unchanged (c) scan ν_x and ν_y while keeping $\nu_x - \nu_y$ unchanged
5. Choose a different crossing angle and beam flatness, and repeat steps (2-4)

The estimated time to is 24 hours.

Readiness of proposal 24-12 (Beam-beam)

- Based on prior runs, we select the working point as $(0.235, 0.225)$ and adjust the longitudinal tune to approximately 0.004.
- In the case of a round beam, the beam-beam parameters is chosen as $\xi_{x0} = \xi_{y0} = 0.005$. To avoid potential aperture issues, the $\beta^*_{x,y}$ are not squeezed for the flat beam. The crossing angle is also adjusted to enhance the resonance strength.
- The random fluctuations are not artificially controlled.
- Plenty of beam-beam simulations have been performed for the EIC. We (Derong etc.) will carry out simulation studies for RHIC flat beam collision.

Summary of proposal 24-12 (Beam-beam)

Experiment Number:	24-12
Beam Experiment Title:	Investigate beam-beam impact on hadron beam flatness
Spokesperson(s):	Derong Xu
Status:	Proposed
Team:	Derong Xu;Yun Luo;Guillaume Robert-Demolaize;Kevin Mernick;Travis C Shrey
Experiment Goal:	Demonstrate if flat beam can survive with synchro-betatron resonance in the beam-beam footprint
Benefits:	(1) Gain deep understanding about synchro-betatron resonance, (2) important input to achieve EIC flat hadron beam
Experiment Description:	The flat beam collision is adopted for future EIC to achieve high luminosity. The working point is chosen to avoid coupling resonance and its low-order synchro-betatron sidebands. However, the high-order synchro-betatron resonances are unavoidable due to the large beam-beam tune spread. There is a concern that the resonances 2*nux − 2*nuy + p*nuz = 0 will drive large vertical emittance growth, especially when the beam are subject to random fluctuations in real world, such as power supply ripple, IBS diffusion etc. This experiment aims to investigate beam-beam collisions with or without a small crossing angle (0 − 2 mrad), generating a flat beam through cooling. Parameters like emittance growth rate, beam lifetime, and beam loss will be measured at various working points and crossing angles, including scenarios simulating unexpected crab crossing behavior in the future EIC. We study around nux − nuy − 2*nuz = 0 for gold-gold collisions. Based on prior runs, we select the working point as (0.235, 0.225) and adjust the longitudinal tune to approximately 0.004. In the case of a round beam, we request beam-beam parameters ξx0 = ξy0 = 0.005. Assuming only the vertical emittance undergoes cooling, the horizontal emittance remains constant. To avoid potential aperture issues, the βx,y are not squzzed for the flat beam. The beam-beam parameters are scaled up according to the beam flatness. Procedures: (1) Set the cross angle to 0, 1, or 2 mrad and choose flatness 1.0 or 0.5 (2) Set the beam to flattop energy and activate the cooling system to generate desired flatness in both RHIC rings (3) Bring two beams into collision, and observe beam loss rate, emittance growth rate etc. (4) Perform the following scan: (a) scan nux while keeping nuy unchanged, (b) scan nuy while keeping nux unchanged, (c) scan nux and nuy while keeping nux − nuy unchanged (5) Choose a different crossing angle and beam flatness, and repeat steps (2-4)
Hazard Analysis:	None
Approved By:	
Date Approved:	
Resources:	
Instrumentation:	(1) Tune adjustment and measurement (2) Cooling to achieve flat hadron beams in both ring (3) Crossing angle within 2 mrad (4) Emittance growth and beam loss
Application:	(1) flat hadron beam in both rings
Time:	24 hours (estimate)
Personnel:	Necessary operational support
Intentional Beam Loss?	No

Summary

- The flat beam collision scheme is essential to achieve the highest luminosity goal for the future EIC. The flat beam has never been achieved in the routine operation of hadron storage ring.
- The vertical emittance of the flat hadron beam is susceptible to several factors, including betatron or synchro-betatron coupling, beam-beam interactions, random diffusion, among others.
- Three experiments are proposed to advance flat beam dynamics for future EIC
  - Proposal 24-03: Accelerate a flat gold ion beam from 31 GeV to 100 GeV in the RHIC Yellow Ring
  - Proposal 24-11: Study on IBS growth in presence of crab dispersion for flat beam
  - Proposal 24-12: Investigate beam-beam impact on hadron beam flatness
- These experiments will provide important input for the EIC design and potentially for future commissioning.

Thank you!