Flat-Beam Experiments: Beam Dynamics Studies

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Proposals Covered in This Talk

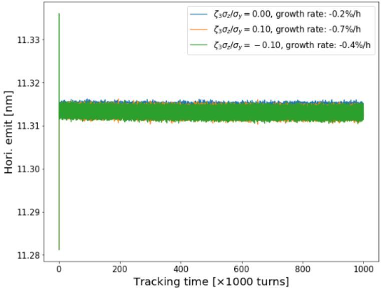
- Proposal 24-11: Study on IBS growth in presence of crab dispersion for flat beam

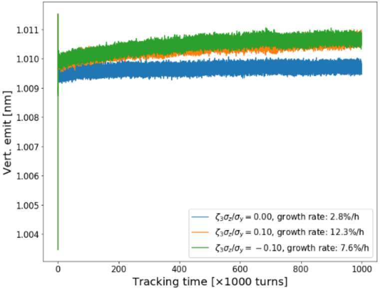
- Proposal 24-12: Investigate beam-beam impact on hadron beam flatness

- Proposal 25-08: Exploring Sextupole Settings to Reduce Vertical Emittance Growth in Flat Beam Collision

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

- **Motivation**: This experiment investigates whether the weak linear synchro-betatron coupling produces any observable effects.
  - The crabbing is not closed in the HSR, resulting in residual crabbing that introduces linear synchro-betatron coupling, which may drive vertical emittance growth for a flat beam.
  - The tolerance for vertical crabbing is stringent, with a limit around $10 \sim 20\ \mu\text{rad}$, which is difficult to directly measure this number.





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

- **How to generate a weak crabbing in RHIC**: The linear synchro-beatron coupling can be generated by a dispersive RF cavity

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} & 0 & 0 \\ m_{21} & m_{22} & m_{23} & m_{24} & 0 & 0 \\ m_{31} & m_{32} & m_{33} & m_{34} & 0 & 0 \\ m_{41} & m_{42} & m_{43} & m_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & m_{56} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & r_{65} & 1 \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} & 0 & 0 \\ m_{21} & m_{22} & m_{23} & m_{24} & 0 & 0 \\ m_{31} & m_{32} & m_{33} & m_{34} & 0 & 0 \\ m_{41} & m_{42} & m_{43} & m_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 + r_{65} m_{56} & m_{56} \\ 0 & 0 & 0 & 0 & r_{65} & 1 \end{bmatrix}$$

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} & 0 & m_{16} \\ m_{21} & m_{22} & m_{23} & m_{24} & 0 & m_{26} \\ m_{31} & m_{32} & m_{33} & m_{34} & 0 & m_{36} \\ m_{41} & m_{42} & m_{43} & m_{44} & 0 & m_{46} \\ 0 & 0 & 0 & 0 & 1 & m_{56} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & r_{65} & 1 \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} & r_{65} m_{16} & m_{16} \\ m_{21} & m_{22} & m_{23} & m_{24} & r_{65} m_{26} & m_{26} \\ m_{31} & m_{32} & m_{33} & m_{34} & r_{65} m_{36} & m_{36} \\ m_{41} & m_{42} & m_{43} & m_{44} & r_{65} m_{46} & m_{46} \\ 0 & 0 & 0 & 0 & 1 + r_{65} m_{56} & m_{56} \\ 0 & 0 & 0 & 0 & r_{65} & 1 \end{bmatrix}$$

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

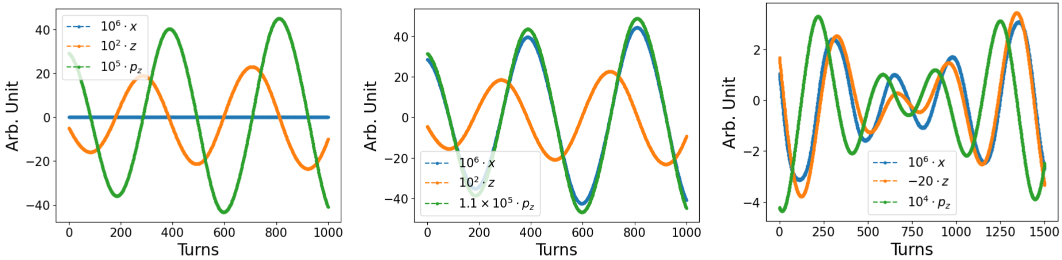
- **Modification**:
  - The synchro-betatron coupling can be modulated by adjusting the dispersion around RF cavities.
  - The initial plan was to measure the vertical IBS growth rate under varying coupling conditions. However, the dispersion around the RF cavities **cannot be widely adjusted**, creating a risk of observing nothing.
  - The new plan is to fit the crab and momentum dispersion from the BPM turn-by-turn data.
    (1). Assume BPM readings from linear model:

$$x = x_\beta + \eta_x p_z + \zeta_x z$$

    (2). The dispersion η and crabbing ζ can be generated by adjusting momentum dispersion around RF cavity.
    (3). The longitudinal coherent oscillation z and p_z can be modulated by RF: RF phase oscillates at a small amplitude at a frequency just above the synchrotron frequency @Mike Blaskiewicz
    (4). x_β is a fast oscillation, and can be averaged out. η_x and ζ_x should be able to fitted from turn-by-turn data.
    (5). The emittance growth rate will still be measured.

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

- **Toy model**: (BPM, RF, Linear matrix)
  RF settings: 197 MHz, 2 MV, phase $= 0.2\sin(0.0026 \times 2\pi \times n)$
  (1) $\eta_x = 0$, $\eta'_x = 0$, (2) $\eta_x = 0.1$ m, $\eta'_x = 0$, (3) $\eta_x = 0$, $\eta'_x = 0.1$



No horizontal reading for case (1); dispersion dominated for case (2); crab dispersion dominated for case (3). Necessary to check the lattice around RF cavities to maximize BPM readings before the experiment.

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

- **OC**:@Ian Blackler
- **Experiment goal**: (1) Determine whether a weak crabbing can be inferred from BPM turn-by-turn data, and (2) Measure vertical emittance growth for a flat beam to assess whether dispersion at RF cavities impacts the vertical emittance growth.
- **Benefits**: (1) Validation of Beam Dynamics Models: 3D IBS model, linear dynamics about momentum and crab dispersion. (2) Diagnostic Development: If crabbing can be reliably inferred from BPM data, it opens the new possibility of crabbing measurement.

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

- **Experiment Description**:
  1. Accelerate the golden beam in either blue or yellow ring to flattop energy and activate the cooling system to generate a flat beam. Same ramping file as run25 Au.
  2. Adjust the RF system to drive dipole oscillation in longitudinal plane @Kevin Mernick, and the BPM to correctly capture the signal @Rob Hulsart
  3. Turn off cooling, measure emittance, and record BPM data
  4. Vary the local dispersion bump around the RF cavity @Guillaume Robert-Demolaize, possibly activate the cooling again to get same flat beam, and then repeat measurement in step 3
  5. Change beam flatness (tentatively measuring four emittance ratios 1:1, 1:2, 1:5, 1:11) and repeat steps (2-4)
  6. Data analysis: fitting the turn-by-turn data to a linear 6-D model, applying statistics model to improve measurement accuracy. Share data with people of proposal 25-05 @Xiaofeng Gu

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

- **Resources**
  - Instrumentation: IPM, BPM, BBQ, etc.
  - Application and necessary hardware modification (1) flat beam at top energy: stochastic cooling, Ramp Editor, orbit/tune/coupling feedback, (2) crabbing: adjustable local dispersion bump around RF cavity (197 MHz cavities with total voltages 2-3 MV) (3) persistent longitudinal oscillation: modification to RF system and BPMs, (4) others like loggers etc. etc
  - Time: totally 12 hours in 3 sessions, (1) Session I, 2 hours, verify the modifications to the RF and BPM systems, and test the dispersion bump around the RF cavity, (2) Session II and III, 5 hours each, generate flat beam of different flatness and take data
  - Personnel: all team members plus MCR on-duty crews
- **Readiness and operation check**: (1) flat golden beam at top energy, demonstrated before, ramping same as run25, collision not needed, no requirement on filling pattern, 1-2e9 ions/bunch (2) no special lattice required, except a local dispersion bump around RF cavity, available knobs confirmed by @Guillaume Robert-Demolaize, (3) modification to RF cavities and BPMs, confirmed by RF (@Kevin Mernick) and instrumentation people (@Robert Hulsart)

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

- **Comments**:
  - The synchrotron dipole oscillation may affect emittance growth
  - Check the beam optics around RF cavities before the experiment
  - BPM readings are noisy: in addition to optimizing the lattice to maximize the synchro-beatron coupling, (1) the crab dispersion at large β function tend to larger, (2) a statistics model may recognize the noise

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

The performance of e-h collision is sensitive to the working point, which is demonstrated in EIC simulation and HERA operation. 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.

- **OC**: @Alex Burkhart
- **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 maintain flat beam profile for EIC design and future operation

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

- **Experiment Description**: Au ion beam, both rings, for each combination of crossing angle $(0, 1\ \mathrm{mrad}, 2\ \mathrm{mrad})$ and transverse emittance ratio $(1:1, 1:4, 1:9)$
  1. Set the beam to flattop energy and activate the cooling system to generate desired flatness in both RHIC rings
  2. Bring two beams into collision with a small crossing angle, turn off cooling, and observe beam loss rate and/or emittance growth rate
  3. 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
  4. Choose a different crossing angle and beam flatness, and repeat steps (1-3)

Physical aperture of $2\ \mathrm{mrad}$

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

- **Resources**
  - Instrumentation: IPM, BPM, BBQ, etc.
  - Application (1) flat beam at top energy: stochastic cooling, Ramp Editor, orbit/tune/coupling feedback, (2) crossing angle, (3) others like loggers etc. etc
  - Time: totally 24 hours in 3 sessions, 8 hours each for different crossing angle, generate flat beam of different flatness, collide both beams at IP6, and take data
  - Personnel: all team members plus MCR on-duty crews
- **Readiness and operation check**: (1) flat golden beam at top energy, demonstrated before, ramping same as run25, 28*28 bunches, 1-2e9 ions/bunch (2) no other requirements, working point study quite common for RHIC

Proposal 25-08: Exploring Sextupole Settings to Reduce Vertical Emittance Growth in Flat Beam Collision

While optimizing the working point is an effective strategy to suppress vertical emittance growth for flat beam collision, it is constrained by dynamic aperture considerations and coherent beam-beam instability. Therefore, an active approach to mitigating vertical emittance growth is necessary. One potential solution is adjusting the sextupole settings, as the dispersion at the sextupoles can contribute to synchro-betatron coupling.

- **OC**: @Rachel Terheide
- **Experiment goal**: The primary goal of this experiment is to explore the feasibility of optimizing sextupole settings to reduce or suppress vertical emittance growth in flat beams.
- **Benefits**: (1) Develop an active strategy to suppress vertical emittance growth for future EIC design, (2) Provides insights into the role of sextupoles in managing synchro-betatron resonance effects

Proposal 25-08: Exploring Sextupole Settings to Reduce Vertical Emittance Growth in Flat Beam Collision

- **Experiment Description**: Au ion beam, both rings, collide with a non-zero crossing angle

1. Set the beam to flattop energy and activate the cooling system to generate desired flatness in both RHIC rings
2. Bring two beams into collision with a small crossing angle, turn off cooling, and observe beam loss rate and/or emittance growth rate
3. Adjust sextupole strengths while maintaining overall chromaticity, and test if vertical emittance growth rate depends on sextupole settings. Repeat this step at different flatness or emittance ratio.
4. Choose a flatness from the above step. Optimize sextupole settings to minimize the vertical emittance growth.

@Chuyu Liu suggested running simulations before the experiment. It is better to compare an optimized sextupole setting instead of random trial in step 3.

Guillaume Robert-Demolaize pointed out the linear lattice might be different because of the sextupole feeddown effect. Are tune and coupling feedback sufficient?

Proposal 25-08: Exploring Sextupole Settings to Reduce Vertical Emittance Growth in Flat Beam Collision

- **Resources**
  - Instrumentation: IPM, BPM, BBQ, etc.
  - Application (1) flat beam at top energy: stochastic cooling, Ramp Editor, orbit/tune/coupling feedback, (2) crossing angle, (3) others like loggers etc. etc
  - Time: totally 12 hours in 2 sessions, 6 hours each, generate flat beam, collide both beams at IP6, and take data. Session I will explore sextupole settings for different beam flatness. Session II will optimize sextupole settings.
  - Personnel: all team members plus MCR on-duty crews
- **Readiness and operation check**: (1) flat golden beam at top energy, demonstrated before, ramping same as run25, 28*28 bunches, 1-2e9 ions/bunch (2) no other requirements, multiple families of sextupole can be used for this experiment, confirmed by @Yun Luo

Summary

- The flat beam collision scheme is essential to achieve the highest luminosity goal for the future EIC.
- The vertical emittance of the flat hadron beam is susceptible to several factors, including betatron or synchro-betatron coupling, beam-beam interactions, random diffusion, etc.
- Three experiments are proposed to advance flat beam dynamics for future EIC
  - Proposal 24-11: Mimic crabbing in RHIC via adjusting momentum dispersion around 197MHz crab cavities, measure crabbing from BPM turn-by-turn data, and observe crabbing impact on flat beam. Can share data with proposal 25-05
  - Proposal 24-12: Investigate beam-beam impact on hadron beam flatness, explore the tune space for flat beam collision
  - Proposal 25-08: Explore sextupole setting to reduce vertical emittance growth in flat beam collision, explore an active strategy to suppress the vertical emittance growth.

Proposals 24-12, 25-01 (by Yun) and 25-08 are all about flat beam collision. They can share experiment time and provide input for the other two experiments.

Thank you!