Systematic study of beam-beam effects in electron ion colliders by a combination of strong-strong and weak-strong simulations

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On behalf of eRHIC beam-beam study team

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Outline

- Introduction to eRHIC Design
- BB Study Strategies for eRHIC
- Head-on Collision Study
- Crabbed Collision Study
- Summary
- Appendix: Additional Considerations
Relativistic Heavy Ion Collider (RHIC)

- RHIC at Brookhaven National Laboratory collides heavy ions and polarized protons since 2000.
- RHIC injectors includes AGS, Booster, Linac and ion sources from EBIS and Tandem Accelerator. Beam top energy: proton 255GeV, ion 100GeV/nucleon.
- Two physics experiments: STAR (IP6), PHENIX (IP8).
RHIC Upgrade: eRHIC

Main Accelerator Design Goal for eRHIC:

- \( L \sim 10^{33} - 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) (exceeding HERA luminosity by 2 orders of magnitude)
- High electron and proton polarization (>70%); Realizing complex spin pattern for electrons and protons
- Large acceptance detector with detector elements integrated in the accelerator IR for forward particle detection
- Minimizing the construction and operational cost of accelerator
Pre-CDR Design Concept

- Added electron storage ring (5-18 GeV)
  - Up to 2.1 A electron current.
  - 10 MW maximum RF power (administrative limit)
- Flat proton beam formed by cooling
- On-energy polarized electron injector (RCS is a cost-effective injector option)
- Polarized electron source and 400 MeV injector linac: 10nC, 1 Hz

*(slide: courtesy of V. Ptitsyn)*
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Strong-strong and Weak-strong

1) Strong-strong beam-beam simulation

Both bunches represented by million macro-particles
Particle-in-cell method used to solve 2-D Poisson equation
Self-consistent treatment, time consuming & numerical noise
**Used to study coherent beam-beam motion and its stability**
A must when beam-beam parameter is large

2) Weak-strong beam-beam simulation

Strong bunch represented by rigid Gaussian and weak bunch by macro-particles
Exact analytical solution for beam-beam force, time efficient & no numerical noise
However not a self-consistent treatment
Element-by-element tracking with lattice nonlinearities possible
**Used to study single particle's long-term stability**
Very productive for small beam-beam parameter situation (in most our cases)
Staged Simulation Studies

1) Without full lattice design (early design stage):
   - focus on multi-particle and long-term tracking
   - focus on slow emittance blow-up, luminosity decay from BB parameter scans: tunes, bunch intensity, crab cavity, etc.

2) With detailed lattice design:
   - focus on single-particle tracking and long-term dynamic aperture element-by-element tracking include lattice nonlinearities
   - interaction between BB and lattice nonlinearities
   - re-do parameter scan: tune, bunch intensity, crab cavity, etc.
Simulation Codes

- **Weak-strong Codes**
  - SimTrack: a compact C++ code for particle orbit and spin tracking.
  - EPIC: a two-pass weak-strong code to mimic strong-strong simulation with asymmetric bunch length.
    - Y. Hao, Beam-beam effect study in ERL based eRHIC, Ph.D Thesis, Indiana University, 2008
  - C. Montag, Beam-beam Simulations with Realistic Crab Crossing for the eRhic Ring-Ring Electron Beam. IPAC-2016.

- **Strong-strong Codes**
  - BBSS (K.Ohmi, KEK)
  - BeamBeam3D (J.Qiang, LBNL)
  - SimTrack (Y. Luo, BNL) also can be used for strong-strong BB simulation
## Machine and Beam Parameters

<table>
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<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Proton</th>
<th>Electron</th>
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<td>Circumference</td>
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<td>Energy</td>
<td>GeV</td>
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<td>Number of bunches</td>
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<td>Emittance</td>
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<td>Beta at IP</td>
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<td>Bunch length</td>
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<td>Beam-beam parameter</td>
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<td>Energy spread</td>
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<td>Crab cavity RF frequency</td>
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<td>Crossing angle</td>
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<tr>
<td>Luminosity</td>
<td></td>
<td>$10^{33}$ cm$^{-2}$s$^{-1}$</td>
<td>$2.9$</td>
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</table>
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Dynamic Beta Effects

Proton tune scan

Electron tune scan

Y. Luo
Electron ring
\[ x = 0.092, \quad y = 0.083 \]

Proton ring
\[ x = 0.014, \quad y = 0.005 \]
Weak-strong: tune scan

Electron tune scan, 50k turns

Relative luminosity: \[ \frac{L}{L_0}, \quad L_0 = 2.9 \times 10^{33} \text{ cm}^2 \text{s}^{-1} \]
Proton tune scan, 1M turns

Luminosity decay: \[ \frac{L}{L_{\text{ini}}} = \frac{L_{\text{fin}}}{L_{\text{ini}}} \]

initial 10k turns, \( L_{\text{fin}} \) last 10k turns

\[ \Delta L = L_{\text{fin}} - L_{\text{ini}} \]

Y. Luo
Strong-strong: tune scan

Electron tune scan: Horizontal beam centroid motion \( <x> \)

G.Bassi, A.He, W.Guo

with code BBSS
Electron tune scan: luminosity

G. Bassi, A. He, W. Guo
Beam-beam Limit: weak – strong simulation

Proton intensity scan
Final luminosity after 50k turns.

Electron intensity scan
Luminosity loss percentage in 1 hour (averaged from 1M turn tracking).

- Final L (10^{33} \text{ cm}^{-2}\text{s}^{-1})
- \(N_p \times 10^{11}\)
- Design \(N_p :\)

- \(\delta L/L\) in 1 hour (%)
- \(N_e \times 10^{11}\)
- Design \(N_e : 5\%/\text{hour}\)
Beam-Beam Limit: strong-strong simulation

electrons: $Q_{x0} = 0.08, \quad Q_{y0} = 0.06$
protons: $Q_{x0} = 0.310, \quad Q_{y0} = 0.305$

Luminosity vs. proton bunch population

nominal
Beam-Beam Limit: 2-D bunch intensity scan

Define

$$\kappa = \frac{L(N_p, N_e)}{L(N_{p0}, N_{e0})} \frac{N_{p0}}{N_p} \frac{N_{e0}}{N_e}$$

If there is no emittance blow-up, $\kappa$ will remain constant.
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Scheme of Local Crabbing

- To compensate the geometric luminosity loss due to a horizontal crossing angle of 22 mrad, and to avoid the long-range beam-beam interaction, crab cavities are to be used to make sure the electron and proton bunches collide head-on at IP.
- **Local crabbing scheme** is to be adopted. Two sets of crab cavities are located on both sides of IP, with a $\pi/2$ horizontal betatron phase advances to IP.

![Diagram of crab cavities](image)

The voltage of crab cavity:

$$\hat{V}_{rf} = -\frac{cE_s}{4\pi f_{rf} \sqrt{\beta_x^* \beta_{cc}}} \theta_c$$
Crabbing with different frequencies

Y. Hao, Y. Luo

Weak-strong simulation (SimTrack)

Strong-strong simulation (BeamBeam3D)
By comparing with the ‘frozen’ electron case, we believe there is physics reason that cause the lumi-degradation observed in the strong-strong simulations.
**3\textsuperscript{rd} Harmonic Crab Cavities**

Y. Hao, Y. Luo

- To compensate the sine shape of crab cavity voltage, it is possible to add a third order harmonics. The foundational crab cavity frequency can be 112MHz, the 3\textsuperscript{rd} harmonics will be 336MHz.
- Simulation results show that we can **gain 5% more luminosity by adding 3\textsuperscript{rd} harmonic crab cavities to proton ring**. The optimum ratio of crabbing angles for the fundamental and 3\textsuperscript{rd} harmonics crab cavities are **1.16 : (-0.16)**

![Without 3\textsuperscript{rd} C.C.](chart1.png) ![With 3\textsuperscript{rd} C.C.](chart2.png)
Dispersion at C.C.

- The effects of dispersion $D_x$ and $D'x$ at crab cavities are studied with both weak-strong and strong-strong simulations.
- $D'x$ plays an important role to emittance growth and luminosity evolution.
- Simulation results show that the tolerance for $D'x$ should be less than 0.5.

Strong-strong simulation
Noises in Crab Cavity

From studies of LHC Hi-lumi, the PSD of the noise of LLRF control is very important to achieve reasonable results. Need to understand the most driving frequencies for EIC.
Summary

- Both weak-strong and strong-strong beam-beam simulation are used to study the beam-beam effects in the future electron-ion collider design of eRHIC.
- We studied the beam-beam interaction related beam and optics parameters. The simulation results show that the present design parameters are reasonable and the design luminosity is achievable.
- The present design tunes of both rings are in the good working point area. The design bunch intensities and the beam-beam parameters are well below the beam-beam limits.
- More studies are going on to understand and determine any possible beam-beam related beam emittance growth or beam lifetime reduction.
Backup slides
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Two Collisions Per Turn

- Previous BB studies focused on 1 collision per turn for each bunch.
- If we want to **delivery collisions to two experiments** and both beams have the same filling pattern, each bunch will have 2 collisions per turn.
- If we keep bunch intensities and beta* as the design, the beam-beam parameters and beam-beam tune spread will be doubled.
Simulation Results (I)

- 2 collisions per turn: at IP6 & IP8, or at IP6 & IP12.
- Both weak-strong and strong-strong BB Simulations were performed.
- In the strong-strong beam-beam simulation, we did a 2-d bunch intensity scan.

**center motion \( <x> \):** blue-proton, red->electron

2 collisions/turn : IP6 & IP8
Simulation Results (II)

- Define \( \kappa = \frac{L(N_p, N_e)}{L(N_{p0}, N_{e0})} \frac{N_{p0}}{N_p} \frac{N_{e0}}{N_e} \)

- Simulation results show that each bunch can not collide twice per turn with present design beam and optics parameters.
Bunch Filling Scheme

- To deliver collisions to two experiments simultaneously without reducing the bunch intensities, one solution is to adopt **bunch shift scheme** (M. Blaskiewicz etc.) to avoid 2 collisions per turn for any bunch.

- **RF System**:
  - proton ring: 112MHz, 1440 buckets, bucket width 2.66m
  - electron ring: 560MHz, 7200 buckets, bucket width 0.53m

- **Filling Patterns**:
  - proton: 1 bunch / bucket, 1440 bunches
  - electron: \[3 \times (240 \times 5 + 3 + 239 \times 5 + 2) = 7200 \text{ buckets, 1437 bunches}\]

- **PHENIX experiment moved south** by 0.53m (1 electron bucket width)
With the bunch shift scheme

1) Each bunch only collides once per turn at IP6 or IP8.
2) There are 720 collisions at IP6 (STAR) each turn, 717 collisions at IP8 (PHENIX).
3) Integrated luminosity per experiment is half of that with only 1 experiment.

Assumption:
1) Proton bunches go counter-clockwise, electron bunches clockwise.
2) Proton bunch 1 and electron bunch 1 collide at IP6.
LR BB Effect

- The common beam pipe at the experiment IRs is +/-4.5m.
- LR BB effect with 2 experiments has to be evaluated.
- From the following table, the minimum separation with 2 experiments are $82\sigma_p$ and $71\sigma_e$.
- Therefore, the LR BB effect is negligible for eRHIC design.

<table>
<thead>
<tr>
<th></th>
<th>1 experiment</th>
<th>2 experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of LR BB</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Nearest distance to IP [m]</td>
<td>1.33</td>
<td>0.53</td>
</tr>
<tr>
<td>Horizontal separation $d$ [mm]</td>
<td>29.26</td>
<td>11.66</td>
</tr>
<tr>
<td>Local beam sizes $(\sigma_p, \sigma_e)$ [mm]</td>
<td>(0.212, 0.291)</td>
<td>(0.142, 0.165)</td>
</tr>
<tr>
<td>Separation in beam size $(\frac{d}{\sigma_p}, \frac{d}{\sigma_e})$</td>
<td>(138, 101)</td>
<td>(82, 71)</td>
</tr>
</tbody>
</table>
Radiation Damping Decrement

Y. Luo

- To reach the beam-beam parameter 0.1 for the electron ring, based on KEKB experience, it requires radiation damping decrement 1/4000, or the radiation damping time 4000 turns in transverse plane.
- To achieve the same radiation damping decrement at all beam energies, superbends are being considered for lattice design.

![Schematic Superbend](image-url)
Simulation Results (I)

• Here we study the effects of damping decrement to beam-beam interaction.
• **Strong-strong BB simulation** was performed with different damping time from 4000 turns to 8000 turns. Electron energy is 10 GeV for this study.

**Centroid motion \( <x> \) [um]**

**Luminosity**

![Graph showing centroid motion and luminosity](image)

**Graph Legend:**
- \( T_d=4000 \text{turn} \)
- \( T_d=5000 \text{turn} \)
- \( T_d=6000 \text{turn} \)
- \( T_d=7000 \text{turn} \)
- \( T_d=8000 \text{turn} \)
Simulation Results (II)

- We continue increasing the radiation damping time beyond 8000 turns.
- With a longer SR damping time, it takes a longer time to reach equilibrium.
- The difference in equilibrium beam sizes is small if radiation time is less than 16,000 turns.
- BB simulation shows that we may have damping time longer than 4000 turns.
Transient BB Effect During Bunch Replacement

• Required electron bunch in the eRHIC storage ring up to 50nC, which exceeds the electron gun capability and also leads to instabilities in the rapid cycling synchrotron (RCS) injector.

• At physics store, to maintain acceptable electron polarization, bunch-by-bunch replacement with a frequency of 1Hz.

• Design injection scheme:
  ➢ longitudinal phase space injection
  ➢ 5 bunches of 10nC from RCS into one electron bunch of storage ring.

• The emittance growth during to BB parameter variation

\[
\epsilon_1 = \frac{\epsilon_0}{2} \cdot \left( \frac{\beta_1}{\beta_0} + \frac{\beta_0}{\beta_1} \right)
\]

\[
\beta_1^* = \beta_0^* \cdot \frac{\sin(2\pi Q_0)}{\sin(2\pi Q_1)}
\]

(by M. Blaskiewicz)
Weak-strong Simulation Results

- **Weak-strong Beam-beam simulation** was performed to evaluate the proton bunch emittance growth during the electron bunch replacement.
- In simulation, proton bunch represented by macro-particles, electron bunches by rigid distribution. Electron bunches are injected with $8\sigma_p$. SR damping is included.

![Graph showing emittance evolution](image)

*Figure 2: Proton beam emittance evolution during 100 electron bunch replacements, with electron bunches being accumulated in 5 steps each time, and injected off-energy.*