Strong-Strong Beam-Beam Interaction Studies for a Ring-Ring Based Electron Ion Collider

LDRD Project #16-046
Motivation

• Increase synergy between accelerator facilities at BNL (initiated by NSLS-II)
• Build up New capabilities at BNL to meet challenge of a possible future Electron Ion Collider eRHIC

- BNL future project eRHIC Electron Ion Collider (Linac-Ring Collider) encountered technical difficulties which cannot be resolved within the new years

- Exploration of alternative concept (Storage Ring Collider) required to build up expertise and the provide the command of tools which did not exist at BNL

- New concept has similarities to the first lepton hadron collider HERA (1992-2007, Germany) with similarly challenging operating parameters where effects have been observed occasionally that, if occurring on a regular base, would disqualify the Ring-Ring concept

⇒ The clarification and understanding of this effect was a strong motivation for this LDRD
LDRD goals and expected results

• perform state-of-the-art and beyond numerical beam-beam interaction studies of stability of colliding beams in e-RHIC.

• demonstrate that the ambitious e-RHIC beam-beam parameters are possible and to thus mitigate the risk that such instabilities would present to a successful e-RHIC proposal.

• provide solid information on the stability of electron-hadron collisions in e-RHIC and whether the anticipated high luminosities are achievable.

• contribute to the decision on the optimum design for the electron-ion collider at BNL.
LDRD work plan and milestones

- Procurement of a powerful computer and its integration in NSLS-II Accelerator Physics computing cluster as a dedicated node for beam-beam simulations.
- Installation of the BBSS computer code developed by K. Ohmi (KEK) with the developers’ help. This code was previously used to study the performance of the KEKB e+e- collider, and for studies of the luminosity limitations in the Large Hadron Collider (LHC).
- Comprehensive convergence studies of the simulation code.
- Benchmarking the simulations against experimental data from HERA and RHIC.
- Running strong-strong beam-beam simulations for eRHIC, scanning betatron tunes to find the optimal working point, estimation of the threshold beam intensity of coherent instabilities.
- Separate artificial effects from non-perfect modeling from real dynamical effects
- Analysis of the results, presenting them at the reviews and conferences.
Beam-Beam Effects

- The interaction of particles in one beam with the opposite beam when the two beams collide is called the “Beam-Beam effect”. Its strength limits the performance of colliders (number of collisions per unit of time).

- Beam-Beam effect can make the beams unstable (oscillation), leads to poor beam life time or even causes the beam to get lost, poor performance.

- The new facility required operating under beam-beam effects on the highest level ever achieved or beyond.

- Because the beam-beam interaction is highly nonlinear, the beam-beam effect requires extensive simulations using complex dynamical models (we need to model the simulation of $\sim 10^{13}$ electrons with $\sim 10^{13}$ protons of the opposing beam an vice versa).

- In order to get results, we need to use advanced computing using parallel computer processors.
Need to be in command of powerful computer codes

• Start from existing codes
  - BBSS (K.Ohmi, KEK)
  - BeamBeam3D (J.Qiang, LBNL)
    https://web.fnal.gov/collaboration/COMPASS/Documents/scidac08beambeam.pdf

• analyze the performance and add features and improvements if needed and possible
Convergence studies and benchmarking with experimental data

Optimal simulation parameters have been determined for the strong beam-beam simulations by comprehensive convergence studies of the BBSS code.

The optimal parameters have been found to be:

- $10^6$ macroparticles for both proton and electron beams.
- Slicing the hadron beam (5 cm long) into 15 longitudinal slices and the electron beam (0.8 cm long) into 2 slices.
- Transverse mesh size for field calculation: 128x128 grid points.

Benchmarking with HERA experimental data:

- No beam-beam instability observed at the design beam parameters, consistent with 2006 HERA-II runs.
- Beam-beam effects seen at 4 times the design bunch populations in simulations up to 100k turns:
  - increase in the proton emittance: 18% (H), 27% (V).
  - increase in the electron emittance: 16% (H), 32% (V).
  - steady state observed after 100k turns, with bunch sizes reaching stationary values.
Main Result: eRHIC Coherent Instability

Nominal intensity is factor of 2 lower than the coherent instability threshold
Result on Artificial Noise Effects

• The use of a manageable number (10^6) of “super particles” to model the (10^{11} particles) real beam leads to artificial noise and artificial growth in beam size (bad) which is hard to distinguish from real dynamic effects.

→ By systematic studies and making modifications to the codes, these effects can be characterized with as artificial (and therefore not worry some).
Summary and Conclusion

• Coherent and incoherent beam-beam effects have been studied using weak-strong (SimTrack) and strong-strong codes (BBSS and BeamBeam3D).

• Optimal simulation parameters have been determined for the strong beam-beam simulations by comprehensive convergence studies of the BBSS code.

• Optimal tune working points (set of beam oscillation frequencies) have been found using weak-strong and strong-strong simulations:
  \[ Q_x = 0.31, \quad Q_y = 0.305 \quad \text{for protons} \]
  \[ Q_x = 0.08, \quad Q_y = 0.06 \quad \text{for electrons} \]

• Threshold intensity of the coherent instability has been found using strong-strong simulations: \( N_p = 2.2 \times 10^{11} \) (2 times larger than nominal).

• Strong-strong simulations show that with crab crossing the optimal tune working points perform similarly to the head-on collision case.

• For the nominal eRHIC parameters, neither fast emittance growth nor coherent instability was observed in the simulation results at the optimal working points (single interaction point).

• Dedicated simulations are in progress to precisely determine any slow emittance growth of the proton beam at nominal intensity.
Back Up Slides
Weak-Strong and Strong-Strong Simulations

Weak-strong:
• Strong bunch is represented by a 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;
• Used to study single particle's long-term stability.

Codes:
• SimTrack: a compact C++ code for particle orbit and spin tracking
  Y. Luo, NIM A (2015) 95-103; Y. Luo e.a., PRSTAB 15, 051004 (2012); Y. Luo e.a., PRSTAB 19, 021001 (2016)
• 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:
• Both bunches are represented by a large number of macro-particles;
• Particle-in-cell method used to solve 2-D Poisson equation;
• Self-consistent treatment, time consuming, with numerical noise;
• Used to study coherent beam-beam motion and its stability.

Codes:
• BBSS (K.Ohmi, KEK)
• BeamBeam3D (J.Qiang, LBNL)
  https://web.fnal.gov/collaboration/COMPASS/Documents/scidac08beambeam.pdf
Beam-Beam Performance of Other Colliders

<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>PEP-II</th>
<th>TEVATRON</th>
<th>RHIC</th>
<th>HERA</th>
<th>eRHIC</th>
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<tr>
<td></td>
<td>e−</td>
<td>e+</td>
<td>e−</td>
<td>e+</td>
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<td>p−</td>
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<td>26</td>
<td>9</td>
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<td>Number of bunches</td>
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<td>1732</td>
<td>36</td>
<td>36</td>
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<td>180</td>
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<td>1637</td>
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<td>3026</td>
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<tr>
<td>hor</td>
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<td>1.8</td>
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<td>RMS energy spread (10^{-3})</td>
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<td>0.7</td>
<td>0.61</td>
<td>0.77</td>
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<td>Beam-beam parameter (per IP)</td>
<td>0.102</td>
<td>0.127</td>
<td>0.07</td>
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<td>Luminosity (10^{33} cm^{-2} s^{-1})</td>
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<td>0.431</td>
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<td>0</td>
<td>0</td>
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2 IPs are assumed for eRHIC. If operating with 1 IP, the beam-beam parameters can be larger.
### eRHIC Machine and Beam Parameters Used for Beam-Beam Simulations

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<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>protons</th>
<th>electrons</th>
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<tr>
<td>Radiation damping time</td>
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<tr>
<td>Emittance</td>
<td>nm</td>
<td>16/6.1</td>
<td>24.4/3.5</td>
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<td>Beta at IP</td>
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<td>0.62/0.073</td>
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<td>Bunch length</td>
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<td>1</td>
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<tr>
<td>Beam-beam parameter</td>
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<td>0.092/0.083</td>
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<td>Betatron tune</td>
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<td>Synchrotron tune</td>
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<td>Crab cavity RF frequency</td>
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<tr>
<td>Luminosity</td>
<td>(10^{33}) cm(^{-2})s(^{-1})</td>
<td>2.9</td>
<td></td>
</tr>
</tbody>
</table>
eRHIC Weak-Strong Beam-Beam Simulations
Luminosity vs betatron tunes

Electron tune scan, 50k turns
Relative luminosity:

\[ \frac{L}{L_0}, \quad L_0 = 2.9 \cdot 10^{33} \text{ cm}^{-2} \text{s}^{-1} \]

Proton tune scan, 1M turns
Relative luminosity decay:

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

\( L_{\text{ini}} \) – first 10k turns, \( L_{\text{fin}} \) – last 10k turns
eRHIC Weak-Strong Beam-Beam Simulations

Frequency maps

Electron tune footprint

\[ \xi_x = 0.092, \quad \xi_y = 0.083 \]

2048 turns

Proton tune footprint

\[ \xi_x = 0.014, \quad \xi_y = 0.005 \]
Horizontal beam size vs electron tunes

G. Bassi, A. He
Horizontal beam centroid vs electron tunes

unstable

G.Bassi, A.He
eRHIC Strong-Strong Beam-Beam Simulations

Luminosity

G.Bassi, A.He

BBSS

Relative luminosity, 10k turns

$L_0 = 2.9 \cdot 10^{33} \text{ cm}^{-2} \text{s}^{-1}$

Relative luminosity, 50k turns

BeamBeam3D

Y.Hao
• Synchrotron radiation
• Coupling of oscillations
• Equilibrium between excitation and damping determines $\xi_{\text{lim}}$

Luminosity vs. proton bunch population

- Electrons: $Q_{x0} = 0.08$, $Q_{y0} = 0.06$
- Protons: $Q_{x0} = 0.310$, $Q_{y0} = 0.305$