ELIC Beam-Beam Simulation Studies

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Outline

• Introduction
• Model, Code and ELIC Parameters
• Simulation Results with Nominal Parameters
• Parameter Dependence of ELIC Luminosity
• New Working Point
• Multiple IPs and Multiple Bunches
• Summary and Outlook
Electron-Ion Collider at CEBAF

ELIC luminosity Concepts
- High bunch collision frequency (1.5 GHz)
- Short ion bunches (5 mm)
- Super strong final focusing ($\beta^* \sim 5$ mm)
- Large beam-beam parameters
- Need High energy electron cooling
- Need crab crossing colliding beams

<table>
<thead>
<tr>
<th>Beam energy</th>
<th>GeV</th>
<th>250/10</th>
<th>150/7</th>
<th>50/5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure-8 ring</td>
<td>km</td>
<td>250/10</td>
<td>150/7</td>
<td>50/5</td>
</tr>
<tr>
<td>Bunch collision freq</td>
<td>MHz</td>
<td>499/1499</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>0.66/1.65</td>
<td>0.46/0.99</td>
<td>0.57/1.15</td>
</tr>
<tr>
<td>Particles/bunch</td>
<td>$10^9$</td>
<td>2.7/6.9</td>
<td>1.9/4.1</td>
<td>2.3/4.8</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$10^{-4}$</td>
<td>3/3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch length, rms</td>
<td>mm</td>
<td>5/5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hori. emit., norm.</td>
<td>$\mu$m</td>
<td>0.70/51</td>
<td>0.42/35.6</td>
<td>0.28/25.5</td>
</tr>
<tr>
<td>Vertical emit., norm.</td>
<td>$\mu$m</td>
<td>0.03/2.0</td>
<td>0.017/1.4</td>
<td>0.028/2.6</td>
</tr>
<tr>
<td>Beta*</td>
<td>mm</td>
<td>5/5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vert. b-b turn-shift/IP</td>
<td></td>
<td>0.01/0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak lumii. per IP</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>2.9/8.6</td>
<td>1.2/3.6</td>
<td>1.1/3.3</td>
</tr>
<tr>
<td>Number of IPs</td>
<td></td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity lifetime</td>
<td>hours</td>
<td>24</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Energy Luminosity Ion Species Polarization
- Longitudinal at the IP for both beams
- Transverse polarization of ions
- Spin-flip of both beams
- All polarizations $>70\%$ desirable
Introduction: Beam-Beam Physics

Transverse Beam-beam force between colliding bunches
- Highly nonlinear forces
- Produce transverse kick between colliding bunches

Beam-beam effect
- Can cause beam emittance growth, size expansion and blowup
- Can induce coherent beam-beam instabilities
- Can decrease luminosity

linear part $\rightarrow$ tune shift
nonlinear part $\rightarrow$ tune spread & instability
Luminosity and Beam-beam Effect

Luminosity of a storage-ring collider

\[ L = \frac{N_e N_p f_c}{2\pi \sqrt{\sigma_{xe}^2 + \sigma_{xp}^2 \sqrt{\sigma_{ye}^2 + \sigma_{yp}^2}}} \]

we assume both are Gaussian bunches, \( N_e \) and \( N_p \) are number of electrons and protons in bunches, \( f_c \) is collision frequency, \( \sigma_{xe}, \sigma_{ye}, \sigma_{xp} \) and \( \sigma_{yp} \) are bunch spot size

Beam-beam parameter (tune-shift)

(characterizes how strong the beam-beam force is)

\[ \xi_{ye} = \frac{r_e^e N_p \beta_{ye}^*}{2\pi \gamma_e \sigma_{yp} (\sigma_{xp} + \sigma_{yp})} \]

Where \( r_e \) is electron classical radius of, \( \gamma_e \) is relativistic factor, and \( \beta_{ye}^* \) is vertical beta function at interaction point

(when \( \sigma_{xe} = \sigma_{xp}, \sigma_{ye} = \sigma_{yp}, \) and \( \beta_{xe}^* = \beta_{xp}^*, \beta_{ye}^* = \beta_{yp}^* \))

\[ L = \frac{I_e \gamma_e \xi_{ye}}{r_e^e \beta_{ye}^*} \frac{1}{2} \left( 1 + \frac{\sigma_y}{\sigma_x} \right) \propto \xi_{ye} \]

proportional to b-b parameter

Increasing beam-beam parameter
\rightarrow increasing luminosity
\rightarrow increasing beam-beam instability

Beam-beam is one of most important limiting factors of collider luminosity
ELIC Beam-beam Problem

ELIC IP Design

- Highly asymmetric beams (3-9GeV/1.85-2.5A and 30-225GeV/1A)
- Four interaction points and Figure-8 rings
- Strong final focusing (beta-star 5 mm)
- Very short bunch length (5 mm)
- Employs crab cavity
- Electron and proton beam vertical b-b parameters are 0.087 and 0.01
- Very large electron synchrotron tune (0.25) due to strong RF focusing
- Equal betatron phase advance (fractional part) between IPs

Short bunch length and small beta-star

- Longitudinal dynamics is important, can’t be treated as a pancake
- Hour glass effect, 25% luminosity loss

Large electron synchrotron tune

- Could help averaging effect in longitudinal motion
- Synchro-betatron resonance
Simulation Model, Method & Codes

Basic Idea of Simulations

**Collision @ IP + transport @ ring**
- Simulating particle-particle collisions by particle-in-cell method
- Tracking particle transport in rings

Particle-in-Cell Method
- Bunches modeled by macro-particles
- Transverse plane covered with a 2D mesh
- Solve Poisson equation over 2D mesh
- Calculate beam-beam force using EM fields on mesh points
- Advance macro-particles under b-b force

BeamBeam3D Code
- Developed at LBL by Ji Qiang, etc. (*PRST 02*)
- Based on particle-in-cell method
- A *strong-strong self-consistent* code
- Includes longitudinal dim. (multi-slices)

Code Benchmarking
- several codes including SLAC codes by Y. Cai etc. & JLab codes by R. Li etc.
- Used for simulations of several lepton and hardon colliders including KEKB, RHIC, Tevatron and LHC

SciDAC Joint R&D program
- SciDAC grant COMPASS, a dozen national labs, universities and companies
- JLab does beam-beam simulation for ELIC. LBL provides code development, enhancement and support
ELIC e-p Nominal Parameters

Simulation Model

- Single or multiple IP, head-on collisions
- Ideal rings for electrons & protons
  → Using a linear one-turn map
  → Does not include nonlinear optics
- Include radiation damping & quantum excitations in the electron ring

Numerical Convergence Tests

to reach reliable simulation results, we need

- Longitudinal slices >= 20
- Transverse mesh >= 64 x 128
- Macro-particles >= 200,000

Simulation Scope and Limitations

- 10k ~ 30k turns for a typical simulation run (multi-days of NERSC supercomputer)
- 0.15 s of storing time (12 damping times)
  → reveals short-time dynamics with accuracy
  → can’t predict long term (>min) dynamics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Proton</th>
<th>Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>150</td>
<td>7</td>
</tr>
<tr>
<td>Current (A)</td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>Particles (10^10)</td>
<td>1.04</td>
<td>0.42</td>
</tr>
<tr>
<td>Horiz. Emit., norm. (μm)</td>
<td>1.06</td>
<td>90</td>
</tr>
<tr>
<td>Vert. Emit., norm. (μm)</td>
<td>0.042</td>
<td>3.6</td>
</tr>
<tr>
<td>βx / βy (mm)</td>
<td>5 / 5</td>
<td>5 / 5</td>
</tr>
<tr>
<td>σx / σy (μm)</td>
<td>5.7/1.1</td>
<td>5.7/1.1</td>
</tr>
<tr>
<td>Bunch length (mm)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Damping time (turn)</td>
<td>---</td>
<td>800</td>
</tr>
<tr>
<td>Beam-beam parameter</td>
<td>0.002</td>
<td>0.017</td>
</tr>
<tr>
<td></td>
<td>0.01</td>
<td>0.086</td>
</tr>
<tr>
<td>Betatron tune νx and νy</td>
<td>0.71</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td>0.88</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>0.06</td>
<td>0.25</td>
</tr>
<tr>
<td>Peak luminosity (cm^2 s^-1)</td>
<td>7.87 x 10^{34}</td>
<td></td>
</tr>
<tr>
<td>Luminosity with hour-glass effect (cm^2 s^-1)</td>
<td>5.95 x 10^{34}</td>
<td></td>
</tr>
</tbody>
</table>
Simulation Results: Nominal Parameters

- Simulations started with two Gaussian bunches with design parameters, reached equilibrium after one damping time.
- No coherent beam-beam instability observed.
- Luminosity stabled at $4.3 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ after damping time.
- Sizes & lengths for both bunches remain design values except vertical size & emittance of electron bunch increased by a factor of 1.8 and 2.7 respectively.

<table>
<thead>
<tr>
<th></th>
<th>Electron</th>
<th>Proton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>$4.3 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$x_{\text{rms}}$ (norm)</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>$x_{\text{emit}}$ (norm)</td>
<td>0.97</td>
<td>1.00</td>
</tr>
<tr>
<td>$y_{\text{rms}}$ (norm)</td>
<td>1.76</td>
<td>1.00</td>
</tr>
<tr>
<td>$y_{\text{emit}}$ (norm)</td>
<td>2.73</td>
<td>1.01</td>
</tr>
<tr>
<td>$z_{\text{rms}}$ (norm)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$z_{\text{emit}}$ (norm)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>h. tune shift</td>
<td>0.017</td>
<td>0.002</td>
</tr>
<tr>
<td>v. tune shift</td>
<td>0.087</td>
<td>0.010</td>
</tr>
</tbody>
</table>

Normalized to design parameters.

Electron Proton

- Lumi
Electron current dependence of Luminosity

- Increasing electron beam current by increasing bunch charge while bunch repetition rate remains the same, hence also increasing beam-beam interaction.
- Luminosity increase as electron current almost linearly (up to 6.5 A).
- Proton bunch vertical size/emittance blowup when electron current is at above 7 A.
- When electron beam reaches 5 A, proton dynamical vertical tune shift is 0.01 and above, while electron vertical tune shift goes down due to blowup of proton beam.
- Coherent b-b instability observed at 7 ~ 7.5 A.
Coherent Beam-Beam Instability

- Electron current is 7.5 A
- Coherent motion only in vertical size
- Not a dipole mode since $<x>=<y>=0$
- Proton vertical beam size blowup at and above this beam current value
- Period of coherent motion is a fraction of damping time
Proton current dependence of Luminosity

- Increasing proton beam current by increasing proton bunch charge while bunch repetition rate remain same, hence also increasing beam-beam interaction
- Luminosity increase as proton beam current first approximately linearly (up to 1.5 A), then slow down as nonlinear beam-beam effect becomes important
- Electron beam vertical size/emittance increase rapidly
- Electron vertical and horizontal beam-beam tune shift increase as proton beam current linearly
Betatron Tune Working Point

- Equilibrium luminosity strongly depends on synchrotron and betatron tune working point
- Working point should be away from synchrotron-betatron resonance lines
- Tune footprint, enlarged by beam-beam effect should avoid cross low order resonance lines
- Simulations have shown a better working point

<table>
<thead>
<tr>
<th>Electron $v_x, v_y$</th>
<th>Proton $v_x, v_y$</th>
<th>Luminosity $10^{34}$ cm$^{-2}$ s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.91, 0.88</td>
<td>0.71, 0.7</td>
<td>4.15</td>
</tr>
<tr>
<td>0.71, 0.7</td>
<td>0.91, 0.88</td>
<td>3.22</td>
</tr>
<tr>
<td>0.73, 0.725</td>
<td>0.91, 0.9</td>
<td>Unstable</td>
</tr>
<tr>
<td>0.748, 0.75</td>
<td>0.91, 0.88</td>
<td>Unstable</td>
</tr>
<tr>
<td>0.63, 0.645</td>
<td>0.71, 0.7</td>
<td>5.77</td>
</tr>
<tr>
<td>0.91, 0.88</td>
<td>0.63, 0.645</td>
<td>Unstable</td>
</tr>
<tr>
<td>0.96, 0.46</td>
<td>0.71, 0.7</td>
<td>2.38</td>
</tr>
</tbody>
</table>
Simulation studies show

- systematic better luminosity over beam current regions with new working point,
- coherent instability is excited at same electron beam current, ~ 7 A
Multiple IPs and Multiple Bunches

**ELIC full capacity operation**
- 4 interaction points, 1.5 GHz collision frequency
- 20 cm bunch spacing, over 10500 bunches stored for each beams
- Theoretically, these bunches are coupled together by collisions at 4 IPs
- Bunches may be coupled through other beam physics phenomena
- A significant challenges for simulation studies

**What concerns us**
- Multiple bunch coupling
- Multiple IP effect
- Introducing new instability and effect on working point
- Earlier inciting of coherent beam-beam instability
- New periodicity and new coherent instability (e.g. Pacman effect)
Reduction of Coupled Bunch Set

ELIC ring cir.: ~ 2100 m, IP-IP distance: ~ 90 m  2100/90 ~23.3

Simplified model: ring cir. = 24 $D_{\text{ip-ip}}$

- A 24-bunch set of one beam will collide with only a 24 bunch set of the other beam
- 10k bunches decoupled into multiple 24-bunch independent sets
### Multiple IPs and Multiple Bunches

#### Collision Table

| step | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| IP1  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| IP2  | 2 | 1 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| IP3  | 13| 12| 14| 15| 16| 17| 18| 19| 20| 21| 22| 23| 24| 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
| IP4  | 14| 13| 12| 11| 10| 9 | 19| 18| 17| 16| 15| 14| 13| 12| 11| 10| 9 | 18| 17| 16| 15| 14| 13| 12 |

- Even and odd number bunches also decoupled
- When only one IP, one e bunch always collides one p bunch
- When two IPs opens on separate crossing straights and in symmetric positions, still one e bunch collides with one p bunch

**Full scale ELIC simulation model**

- 12 bunches for each beam
- Collisions in all 4 IPs
- Bunch takes 24 steps for one complete turn in Figure-8 rings
- Total 48 collisions per turn for two 12-bunch sets
• Simulated system stabilized (luminoisty, transverse size/emittance) after one damping time (more than 100k collisions)
• Luminosity per IP reaches 5.48x10^{34} m^{-1}s^{-2}, a 5% additional loss over hour-glass effect
• Very small additional loss due to multiple-bunch coupling
• No coherent beam-beam instability observed at ELIC nominal design parameters
• More studies (parameter dependence, coherent instability, etc.) in progress
Summary

• Beam-beam simulations were performed for ELIC ring-ring design with nominal parameters, single and multiple IP, head-on collision and ideal transport in Figure-8 ring

• Simulation results indicated stable operation of ELIC over simulated time scale (10k ~ 25k turns), with equilibrium luminosity of $4.3 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, roughly 25% reduction for each of hour-glass and beam-beam effects

• Studies of dependence of luminosity on electron & proton beam currents showed that the ELIC design parameters are safely away from beam-beam coherent instability

• Search over betatron tune map revealed a better working point at which the beam-beam loss of luminosity is less than 4%, hence an equilibrium luminosity of $5.8 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

• Multiple IP and multiple bunch simulations have not shown any new coherent instability. The luminosity per IP suffers only small decay over single IP operation
Outlook

• Toward more realistic model of beam transport
  - Needs of including real lattice and magnet imperfections
  - Trade-off (due to computing power limit): full particle-tracking in ring and weak-strong beam model
  - Short term accurate vs. long term (inaccurate) behavior

• Move to space charge dominated low ion energy domain
  - Pancake approximation of beam-beam force vs. full 3D mash calculation
  - New limit = Laslett tune-shift + beam-beam tune-shift ?

• Advanced interaction region design
  - Crab crossing
  - Traveling focusing
  - Crab waist
Future Plan

- Continuation of code validation and benchmarking
- Single IP and head-on collision
  - Coherent beam-beam instability
  - Synchrot-betatron resonance and working point
  - Including non-linear optics and corrections
- Multiple IPs and multiple bunches
  - Coherent beam-beam instability
- Collisions with crossing angle and crab cavity
- Beam-beam with other collective effects

- Part of SciDAC COMPASS project
- Working with LBL and TechX and other partners for developing and studying beam dynamics and electron cooling for ELIC conceptual design
Acknowledgement

- Helpful discussions with R. Li, G. Krafft, Ya. Derbenev of JLab
- JLab ELIC design team
- Support from DOE SciDAC Grant
- NERSC Supercomputer times