Application of BeamBeam3D to ELIC Studies

Yuhong Zhang, JLab

Ji Qiang, LBNL

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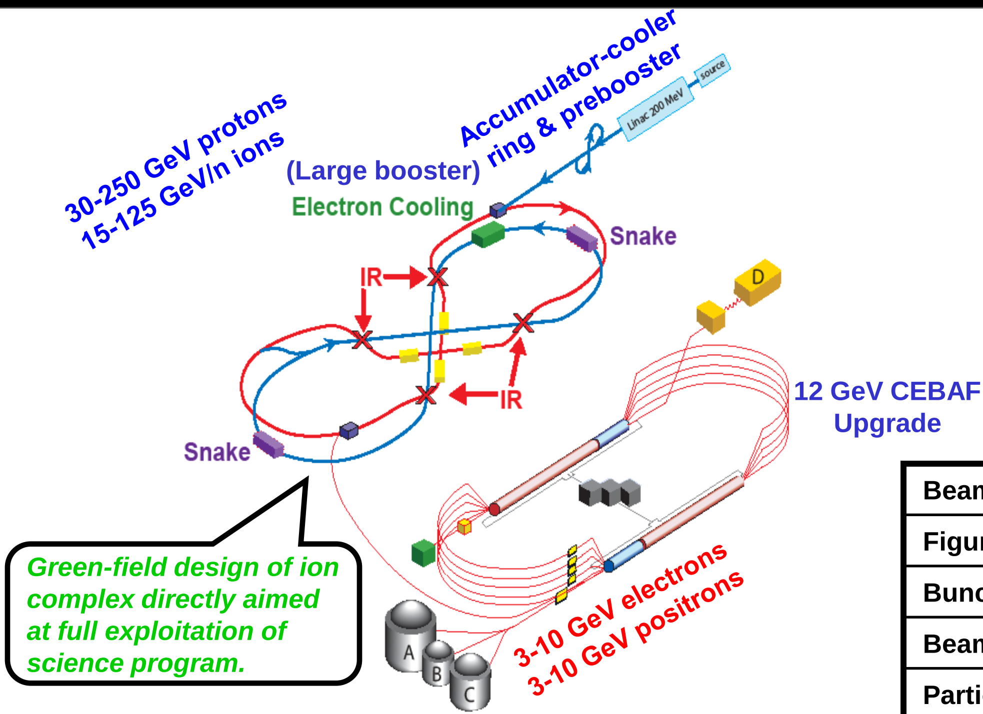
Outline

- 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



Energy CM 20~100 GeV, asymmetry ~ 10

Luminosity 10^{33} up to 10^{35} cm^{-2} s^{-1} *per* IP

Ion Species Polarized H, D, ^{3}He, up to A = 208

Polarization

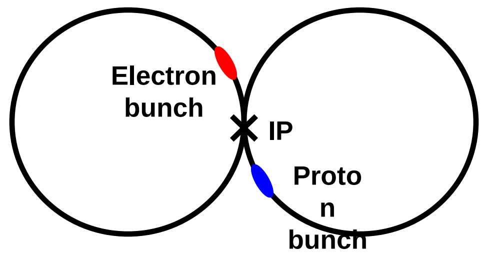
- Longitudinal at the IP for both beams
- Transverse polarization of ions
- Spin-flip of both beams
- All polarizations >70% desirable

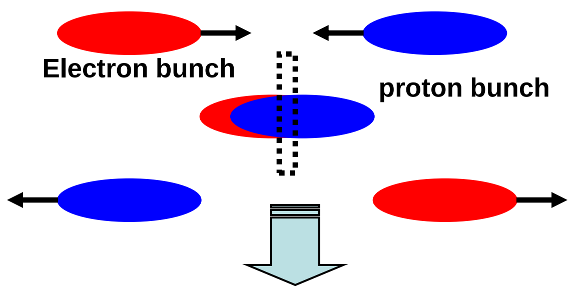
Beam energy	GeV	250/10	150/7	50/5
Figure-8 ring	km	2.5		
Bunch collision freq	MHz	499/1499		
Beam current	A	0.66/1.65	0.46/0.99	0.57/1.15
Particles/bunch	10^9	2.7/6.9	1.9/4.1	2.3/4.8
Energy spread	10^{-4}	3/3		
Bunch length, rms	mm	5/5		
Hori. emit., norm.	µm	0.70/51	0.42/35.6	0.28/25.5
Vertical emit., norm.	µm	0.03/2.0	0.017/1.4	0.028/2.6
Beta*	mm	5/5		
Vert. b-b turn-shift/IP		0.01/0.1		
Peak lumi. per IP	10^{34} $cm^{-2}s^{-1}$	2.9/8.6	1.2/3.6	1.1/3.3
Number of IPs		4		
Luminosity lifetime	hours	24		

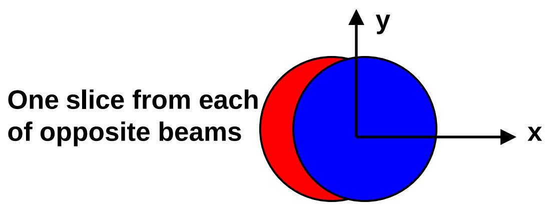
ELIC luminosity Concepts

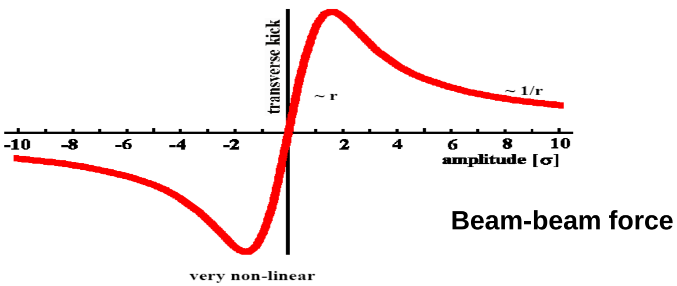
- High bunch collision frequency (1.5 GHz)
- Short ion bunches (5 mm)
- Super strong final focusing (β^* ~ 5 mm)
- Large beam-beam parameters
- Need High energy electron cooling
- Need crab crossing colliding beams

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 → tune shift

nonlinear part → 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, σ_{xe}, σ_{ye}, σ_{xp} and σ_{yp} are bunch spot size

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

$$L = \frac{I_e \gamma_e \xi_{ye}}{r_c^e \beta^*_{ye}} \frac{1}{2}\left(1 + \frac{\sigma_y}{\sigma_x}\right) \propto \xi_{ye}$$

proportional to b-b parameter

Beam-beam parameter (tune-shift)

(characterizes how strong the beam-beam force is)

$$\xi_{ye} = \frac{r_c^e N_p \beta^*_{ye}}{2\pi\gamma_e \sigma_{yp}(\sigma_{xp} + \sigma_{yp})}$$

Where r^c_e is electron classical radius of, γ_e is relativistic factor, and β^*_{ye} is vertical beta function at interaction point

Increasing beam-beam parameter

→ increasing luminosity

→ 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

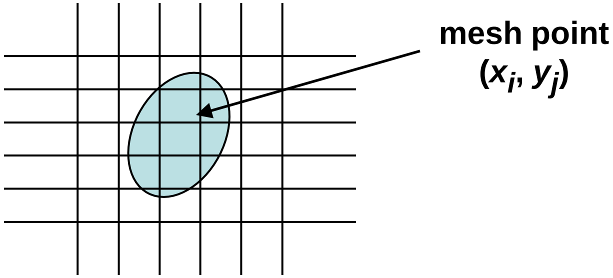
Basic Idea of Simulations

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 maeh 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

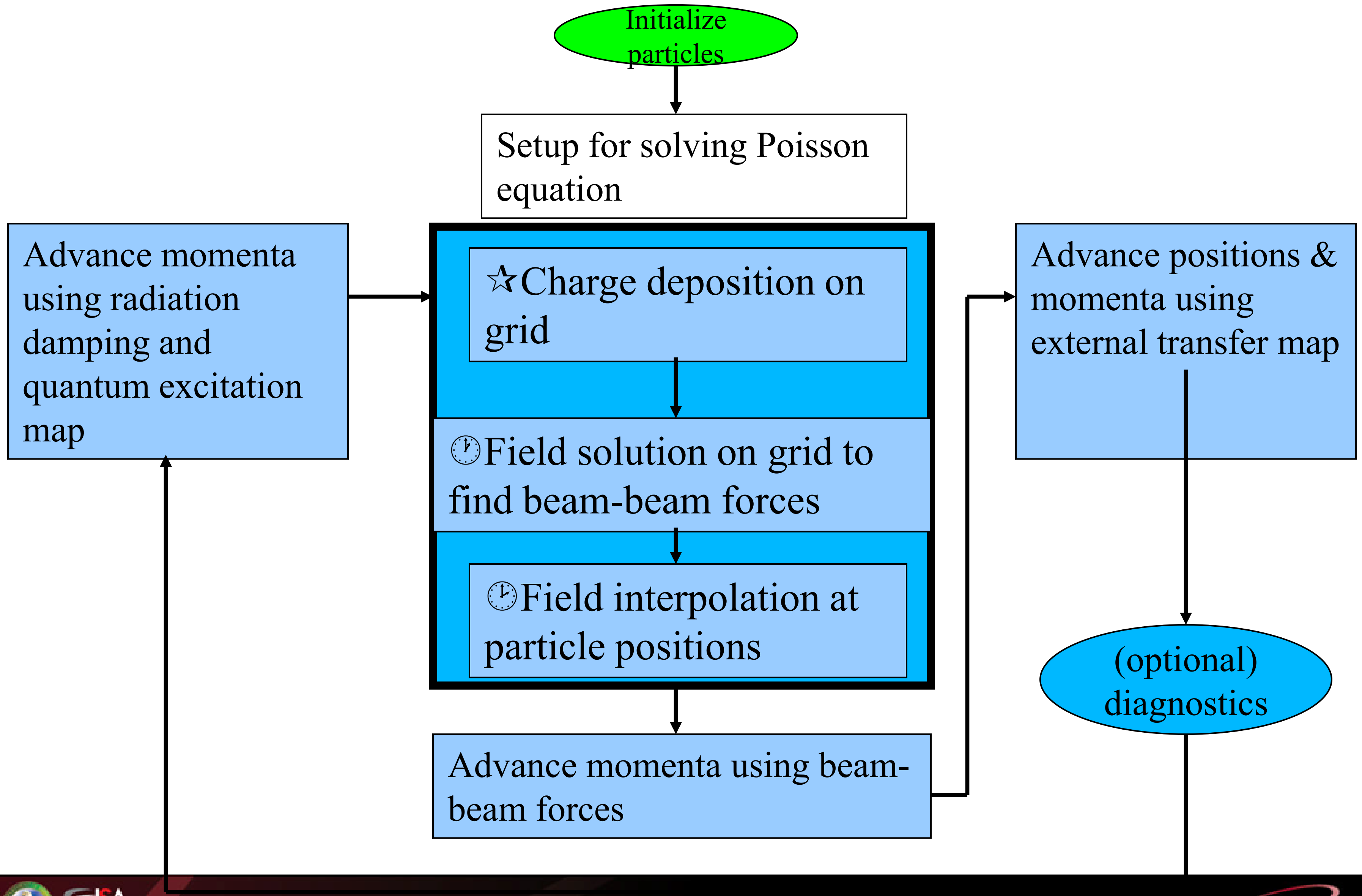
SciDAC Joint R&D program

- SciDAC grant COMPASS , a dozen national labs, universities and companies
- JLab does beam-beam simulation for ELIC. LBL provides code development, enhancement and support

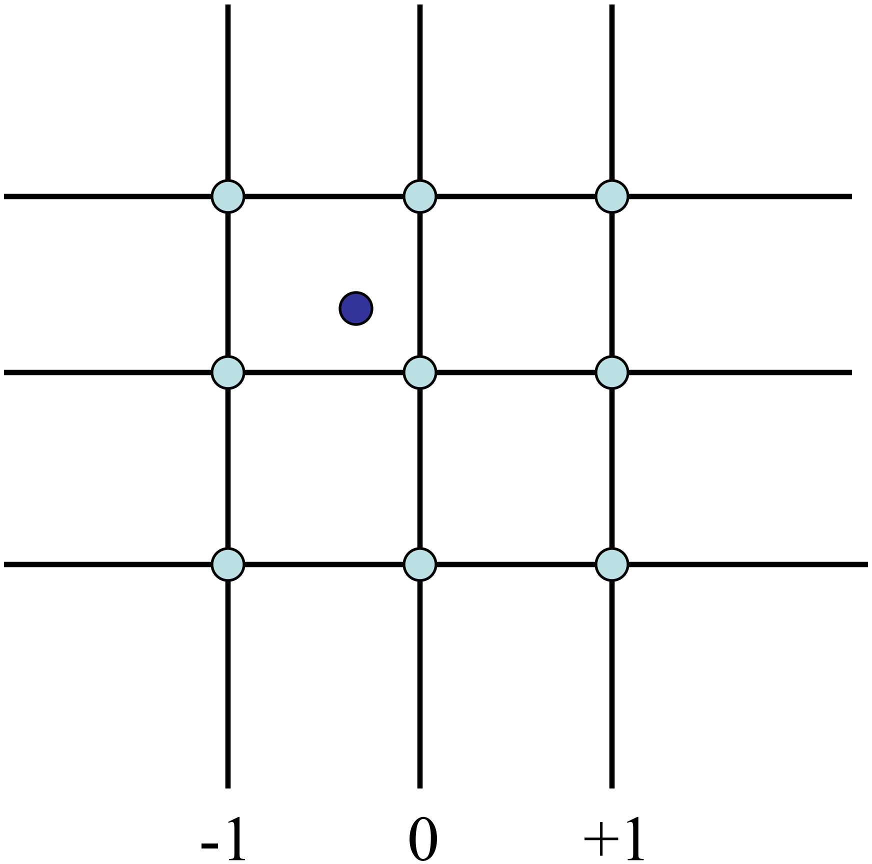
BeamBeam3D:
Parallel Strong-Strong / Strong-Weak Simulation Code

- Multiple physics models:
  - strong-strong (S-S); weak-strong (W-S)
- Multiple-slice model for finite bunch length effects
- New algorithm -- shifted Green function -- efficiently models long-range parasitic collisions
- Parallel particle-based decomposition to achieve perfect load balance
- Lorentz boost to handle crossing angle collisions
- Multi-IP collisions, varying phase adv,…
- Arbitrary closed-orbit separation (static or time-dep)
- Independent beam parameters for the 2 beams
- Conducting wire, crab cavity, electron lens compensations

Particle-In-Cell Method



Quadratic Deposition/Interpolation

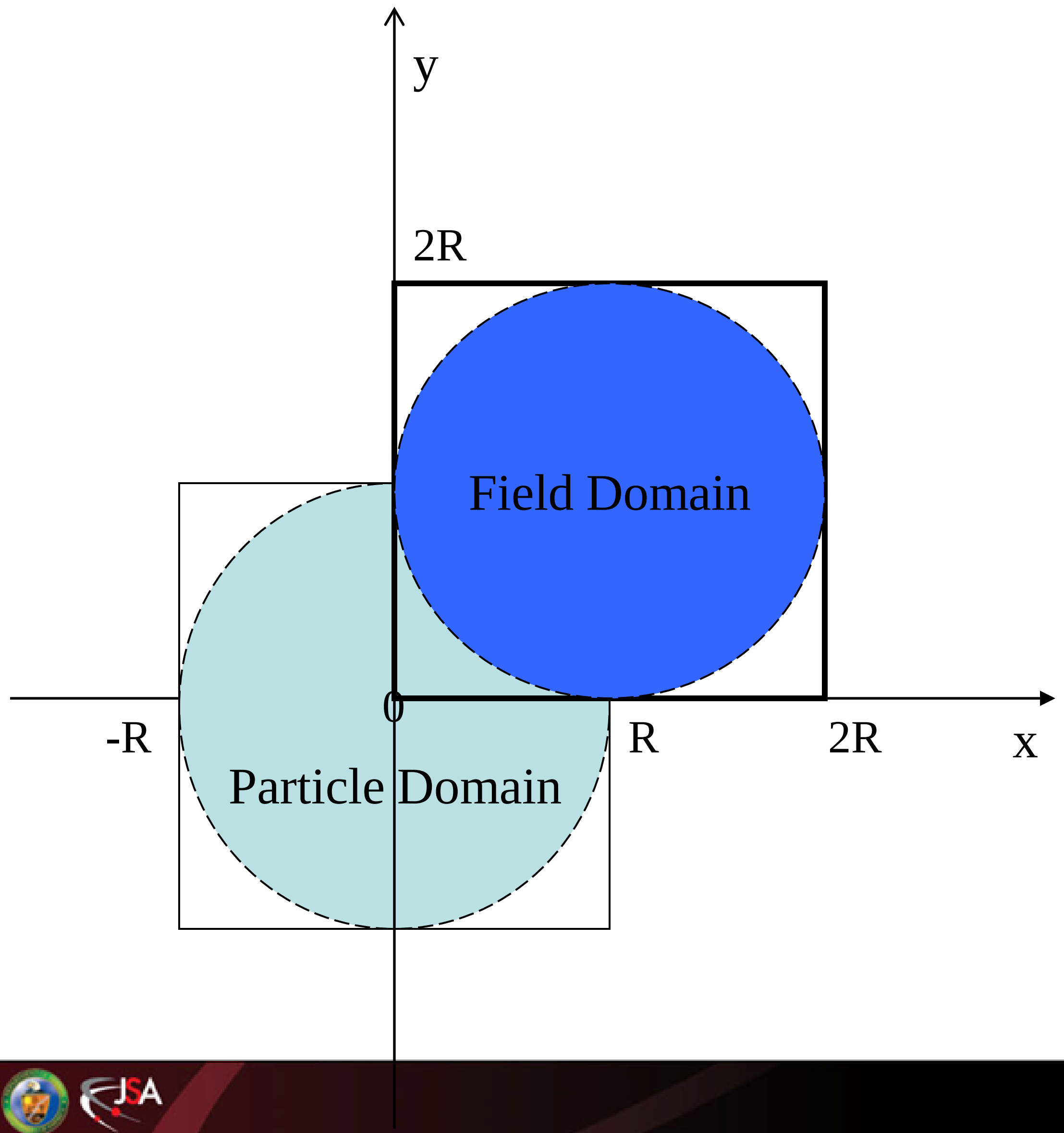


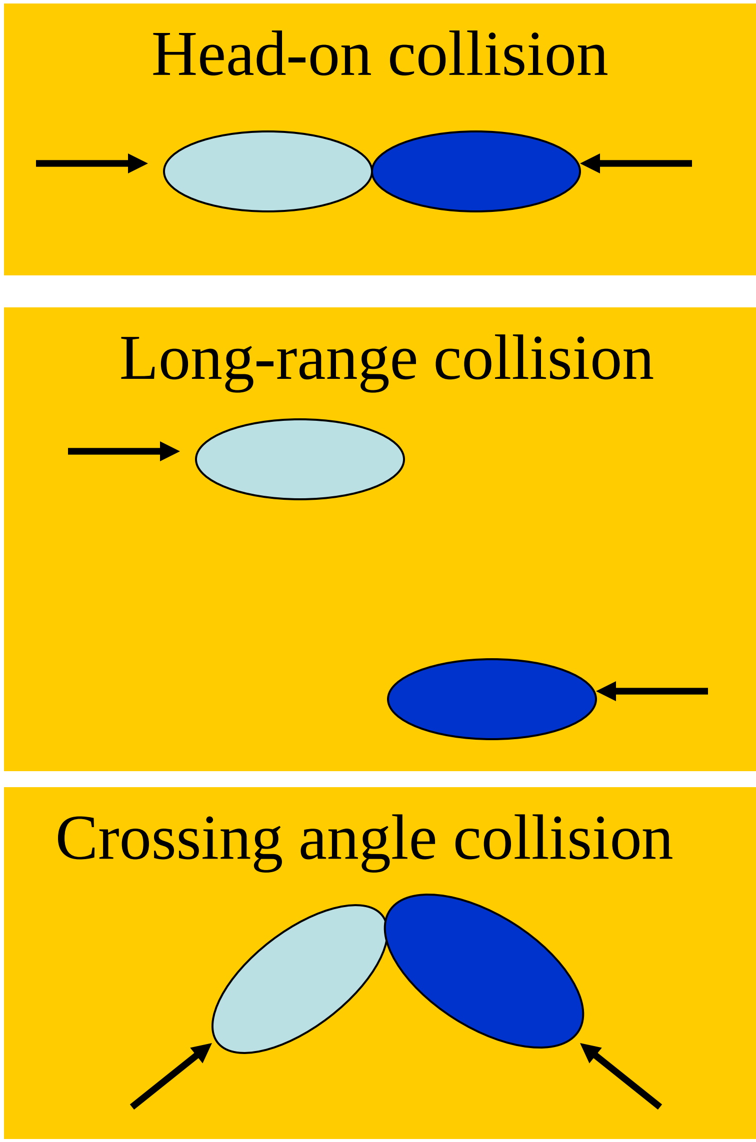
$$w_x^{+1} = \frac{1}{2}\left(\frac{1}{4} - r_x + r_x^{\,2}\right)$$

$$w_x^{0} = \frac{3}{4} - r_x^{\,2}$$

$$w_x^{+1} = \frac{1}{2}\left(\frac{1}{4} + r_x + r_x^{\,2}\right)$$

A Schematic Plot of the Geometry of Two Colliding Beams





Green Function Solution of Poisson's Equation

$$\phi(r) = \int G(r, r')\rho(r')dr' \quad ; \; r = (x, y)$$

$$\phi(r_i) = h\sum_{i'=1}^{N} G(r_i - r_{i'})\rho(r_{i'})$$

$$G(x, y) = -\frac{1}{2}\log(x^2 + y^2)$$

Direct summation of the convolution scales as N^4 !!!!
N – grid number in each dimension

Green Function Solution of Poisson's Equation (cont'd)

Hockney's Algorithm:- *scales as* $(2N)^2\log(2N)$

- Ref: Hockney and Easwood, ***Computer Simulation using Particles***, McGraw-Hill Book Company, New York, 1985.

$$\phi_c(r_i) = h\sum_{i'=1}^{2N} G_c(r_i - r_{i'})\rho_c(r_{i'})$$

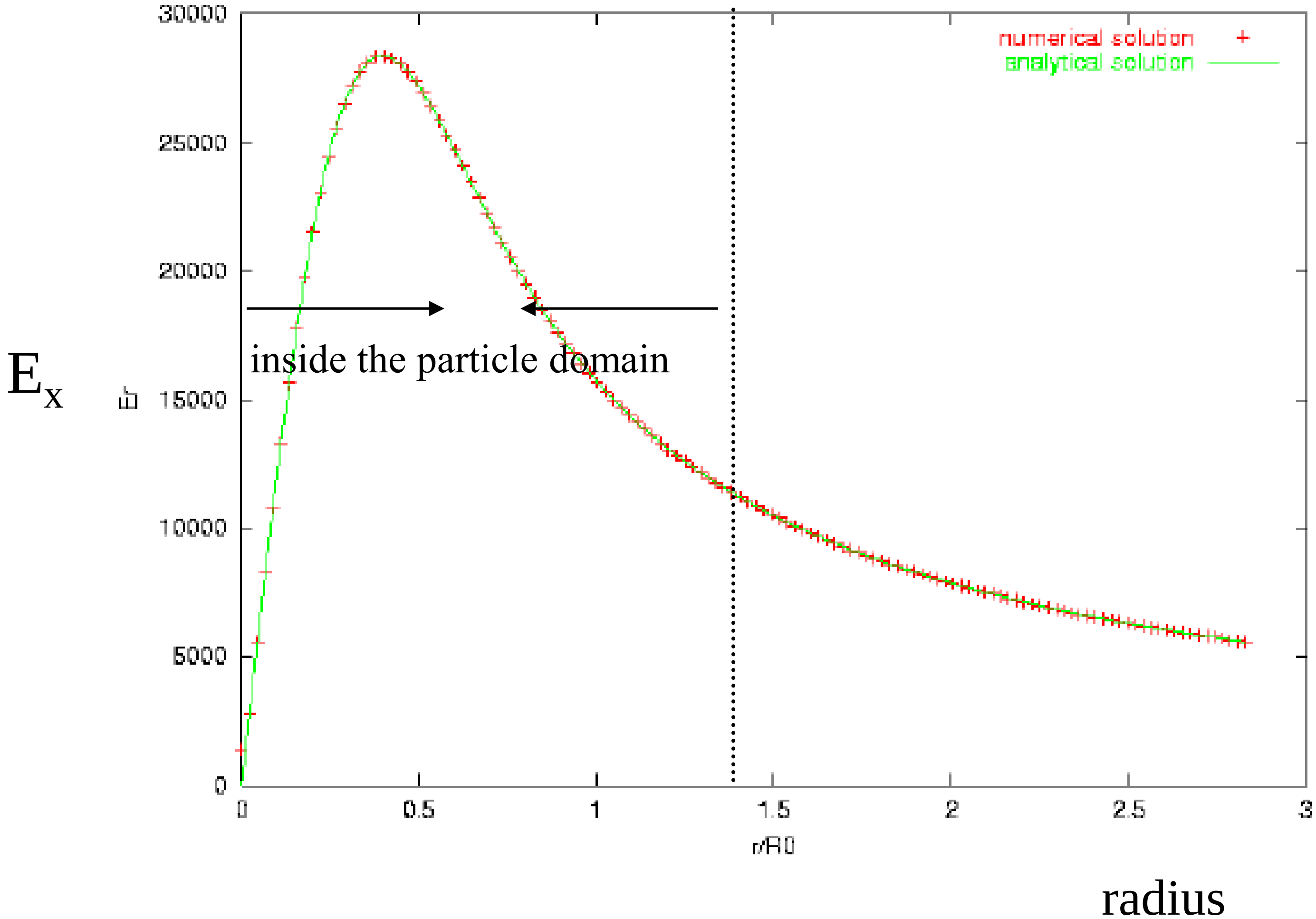
$$\phi(r_i) = \phi_c(r_i) \quad \text{for i} = 1, \text{N}$$

Shifted Green function Algorithm:

$$\phi_F(r) = \int G_s(r,r')\rho(r')dr'$$

$$G_s(r,r') = G(r + r_s, r')$$

Comparison between Numerical Solution and Analytical Solution (Shifted Green Function)



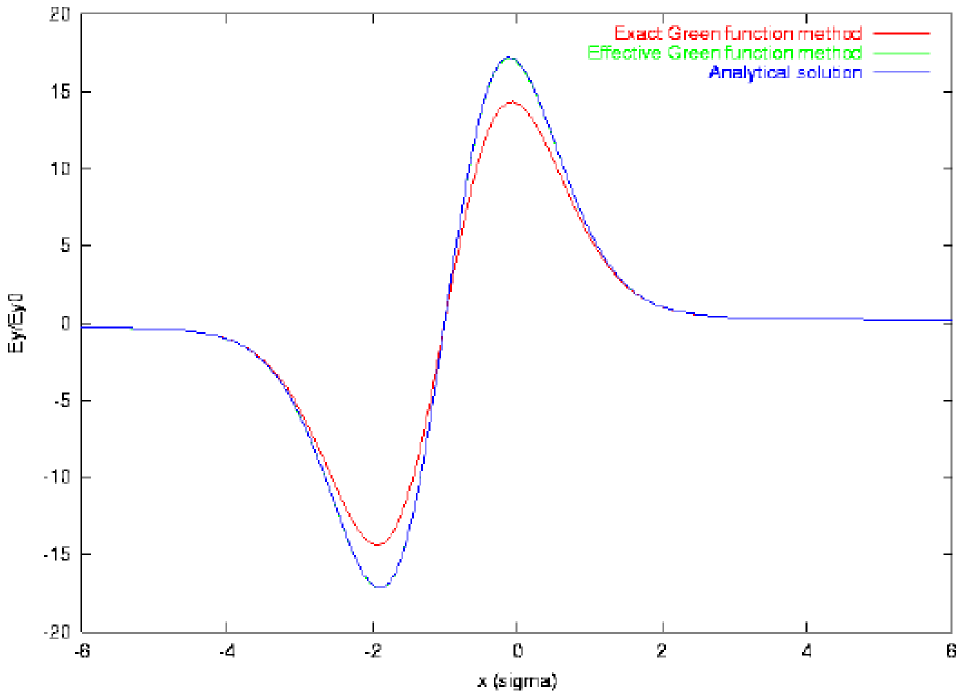
Green Function Solution of Poisson's Equation (Integrated Green Function)

Integrated Green function Algorithm for large aspect ratio:

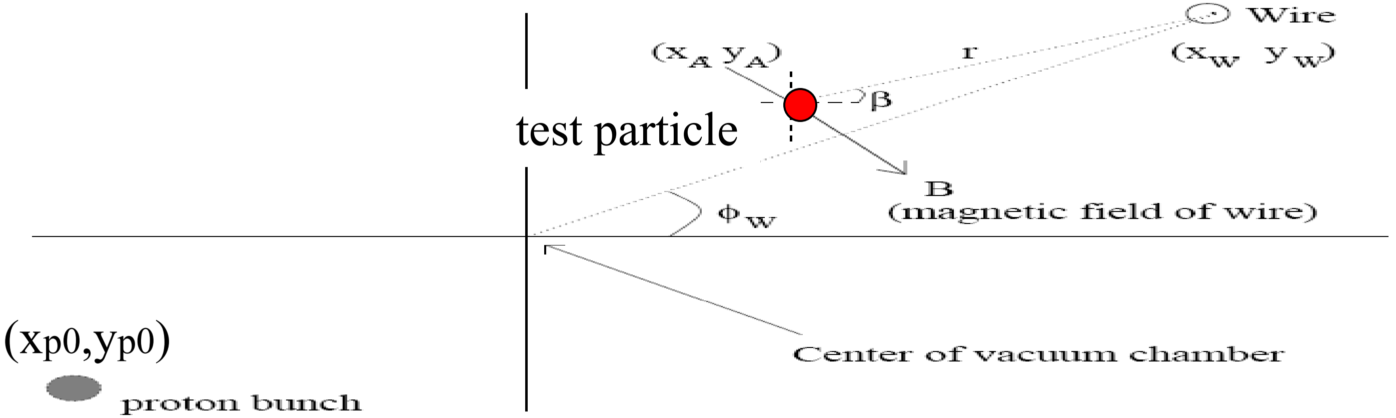
$$\phi_c(r_i) = \sum_{i'=1}^{2N} G_i(r_i - r_{i'})\rho_c(r_{i'})$$

$$G_i(r,r') = \oint G_s(r,r')\,dr'$$

E_y



Model of Conducting Wire Compensation



$$\Delta x'_{BB} = \frac{2N_p r_p}{\gamma_p} \frac{x_A - x_{P0}}{[(x_A - x_{P0})^2 + (y_A - y_{P0})^2]} \left\{1 - \exp[-\frac{1}{2\sigma^2}[x_A - (x_{P0})^2 + (y_A - y_{P0})^2]]\right\}$$

$$\Delta y'_{BB} = \frac{2N_p r_p}{\gamma_p} \frac{y_A - y_{P0}}{[(x_A - x_{P0})^2 + (y_A - y_{P0})^2]} \left\{1 - \exp[-\frac{1}{2\sigma^2}[(x_A - x_{P0})^2 + (y_A - y_{P0})^2]]\right\}$$

$$\Delta x'_W = -\frac{B_y L}{(B\rho)} = \frac{\mu_0}{2\pi} \frac{I_W L}{(B\rho)} \frac{x_W - x_A}{(x_W - x_A)^2 + (y_W - y_A)^2}$$

$$\Delta y'_W = \frac{B_x L}{(B\rho)} = \frac{\mu_0}{2\pi} \frac{I_W L}{(B\rho)} \frac{y_W - y_A}{(x_W - x_A)^2 + (y_W - y_A)^2}$$

$$x_W = x_{P0}, \quad y_W = y_{P0},$$

$$\frac{\mu_0}{2\pi} \frac{I_W L}{(B\rho)} = \frac{2N_p r_p}{\gamma_p} \Rightarrow I_W L = ecN_p$$

B.Erdelyi and T.Sen, “Compensation of beam-beam effects in the Tevatron with wires,” (FNAL-TM-2268, 2004).

Thin Lens Approximation for Crab Cavity Deflection

$$x^{n+1} = x^n$$

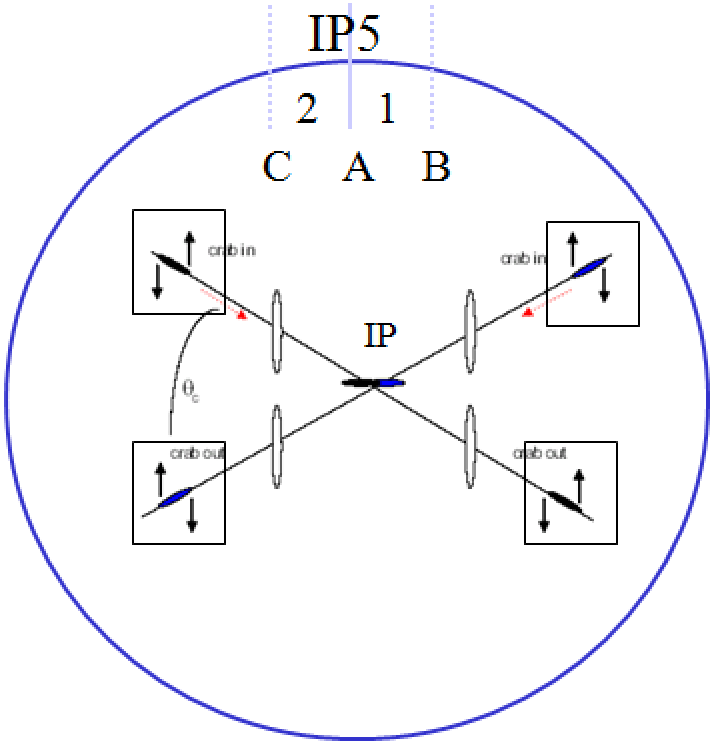
$$Px^{n+1} = Px^n + \frac{qV}{E_s}\sin(\omega z^n / c)$$

$$z^{n+1} = z^n$$

$$\delta E^{n+1} = \delta E^n + \frac{qV}{E_s}\cos(\omega z^n / c)$$

$$here:$$

$$V = \frac{cE_s \tan\phi}{\omega\sqrt{\beta_{x,crab}\beta_x^*}}$$



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

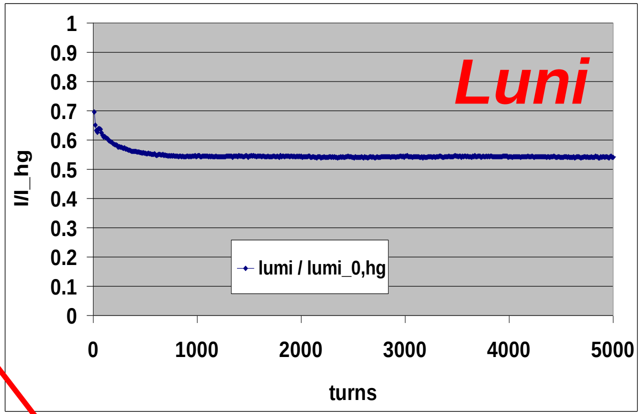
- 10k ~ 30k turns for a typical simulation run (multi-days of NERSC supercomputer)
- 0.15 s of storing time (12 damping times)
  → reveals short-time dynamics with accuracy
  → can't predict long term (>min) dynamics

		Proton	Electron
Energy	GeV	150	7
Current	A	1	2.5
Particles	10^{10}	1.04	0.42
Hori. Emit., norm.	μm	1.06	90
Vert. Emit., norm.	μm	0.042	3.6
β_x / β_y	mm	5 / 5	5 / 5
σ_x / σ_y	μm	5.7/1.1	5.7/1.1
Bunch length	mm	5	5
Damping time	turn	---	800
Beam-beam parameter		0.002 0.01	0.017 0.086
Betatron tune ν_x and ν_y		0.71 0.70	0.91 0.88
Synchrotron tune		0.06	0.25
Peak luminosity	$cm^{-2}s^{-1}$	7.87×10^{34}	
Luminosity with hour-glass effect	$cm^{-2}s^{-1}$	5.95×10^{34}	

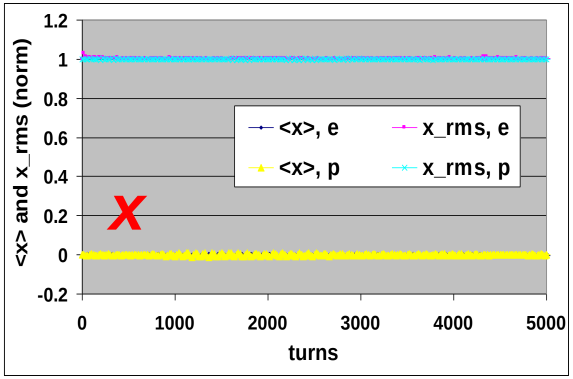
Simulation Results: Nominal Parameters

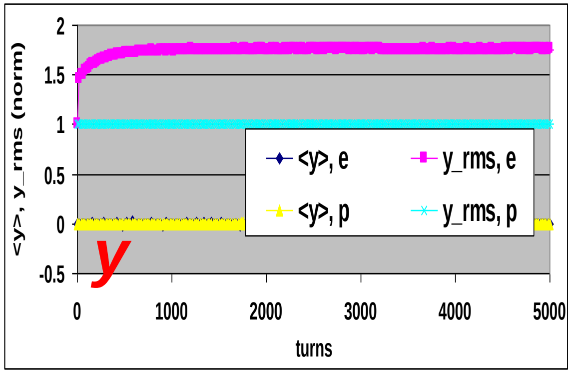
- Simulations started with two Gaussian bunches with design parameters, reached equilibrium after one damping time
- No coherent beam-beam instability observed.
- Luminosity stabled at ***$4.3 \cdot 10^{34}$ cm^{-2}s^{-1}*** after damping time
- Sizes & lengths for both bunches remain design values except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

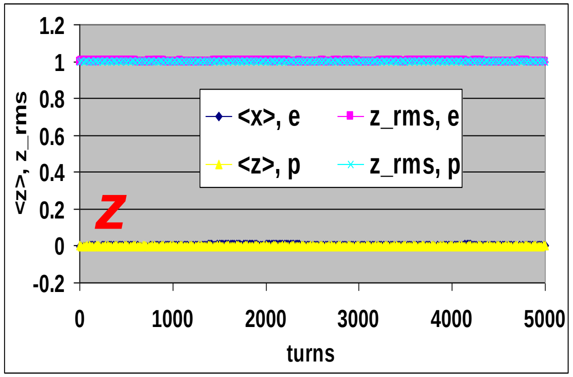
	Electron	proton
Luminosity	$4.3 \cdot 10^{34}$ cm^{-2}s^{-1}	
x_rms (norm)	1.00	1.00
x_emit (norm)	0.97	1.00
y_rms (norm)	1.76	1.00
y_emit (norm)	2.73	1.01
z_rms (norm)	1	1
z_emit (norm)	1	1
h. tune shift	0.017	0.002
v. tune shift	0.087	0.010



Normalized to design parameters

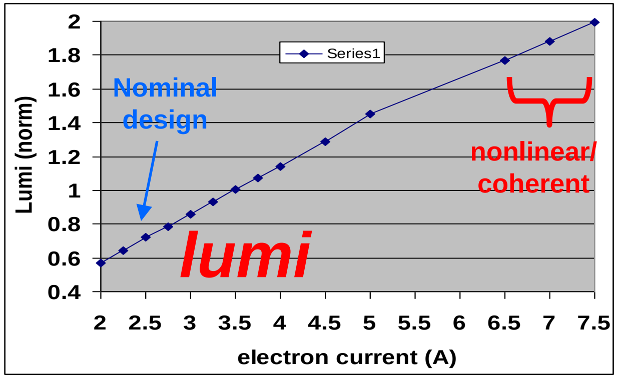


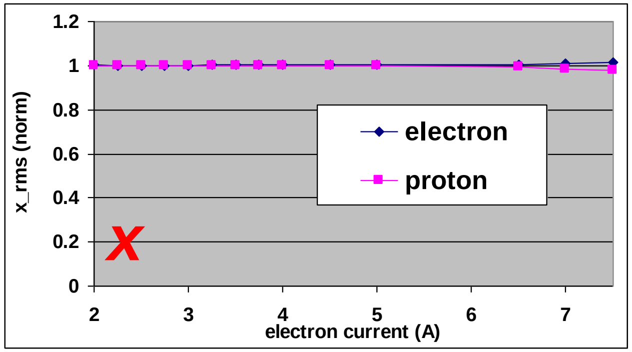


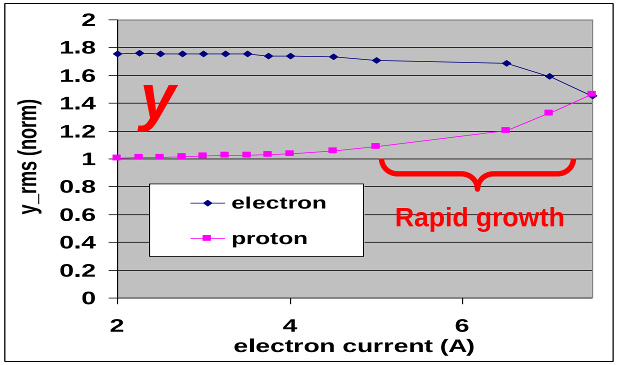


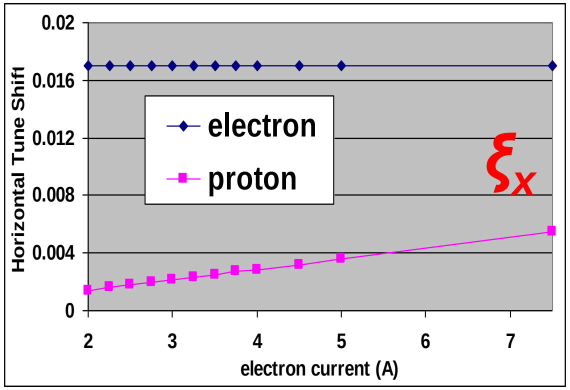
Electron current dependence of Luminosity

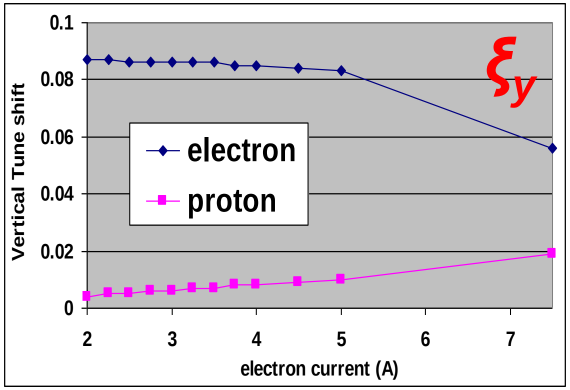
- Increasing electron beam current by increasing bunch charge while bunch repetition rate remains the same, hence also increasing beam-beam interaction
- Luminosity increase as electron current almost linearly (up to 6.5 A)
- Proton bunch vertical size/emittance blowup when electron current is at above 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





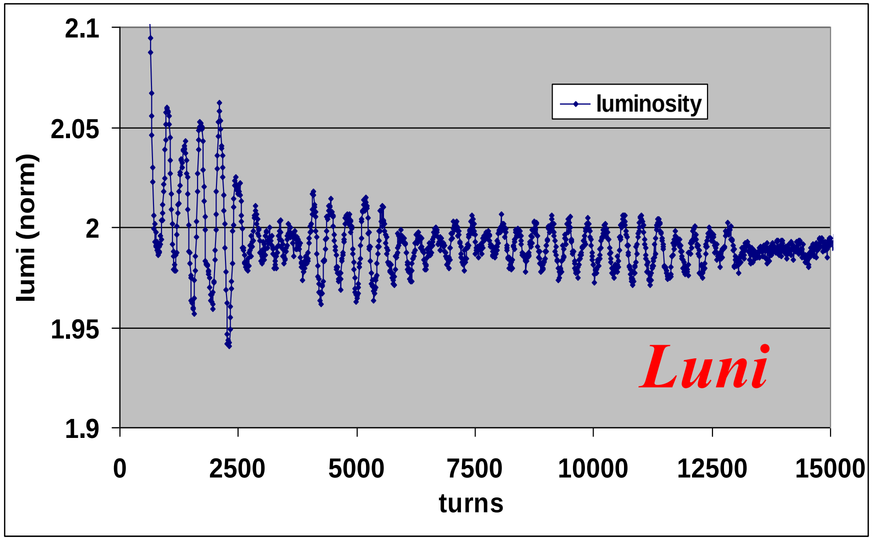


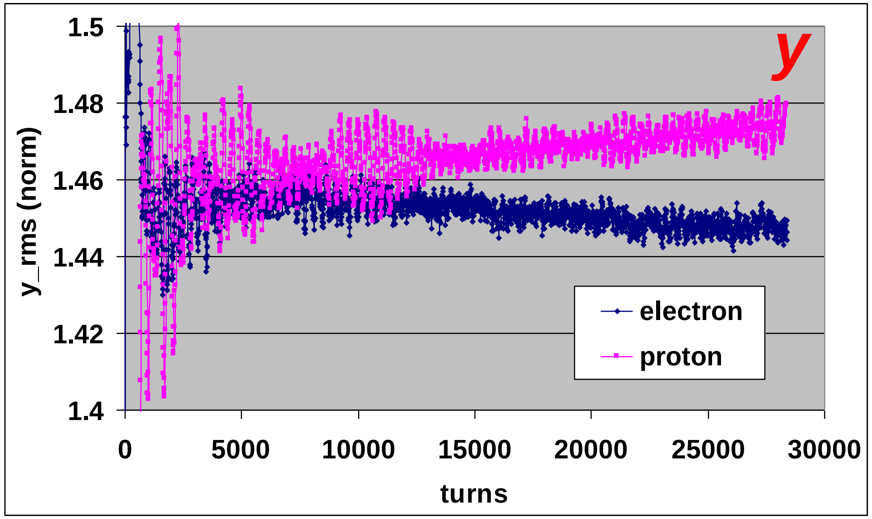




Coherent Beam-Beam Instability

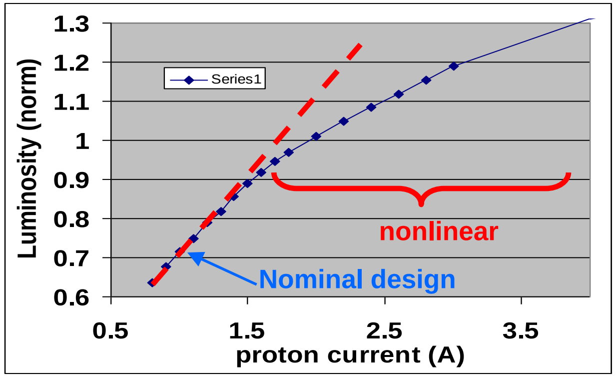
- Electron current is 7.5 A
- Coherent motion only in vertical size
- Not a dipole mode since <x>=<y>=0
- Proton vertical beam size blowup at and above this beam current value
- Period of coherent motion is a fraction of damping time

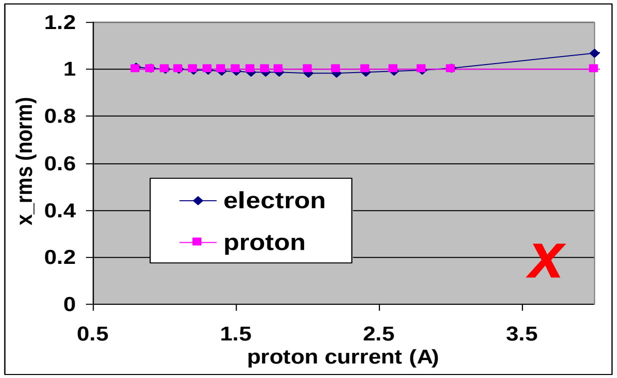


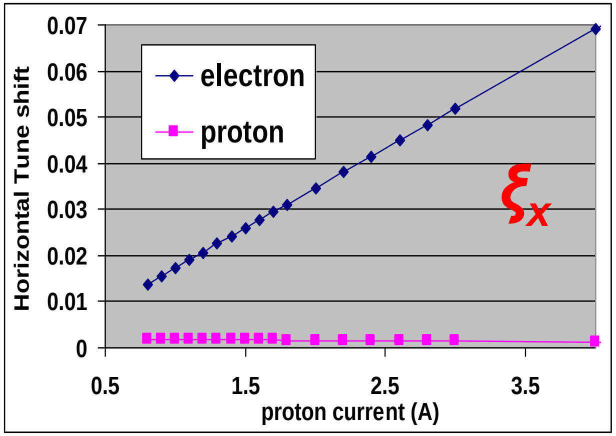


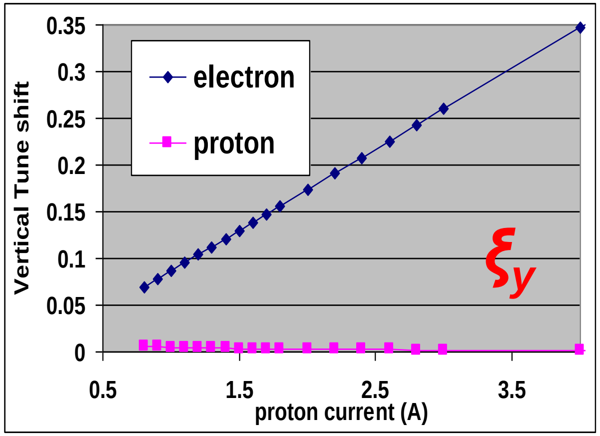
Proton current dependence of Luminosity

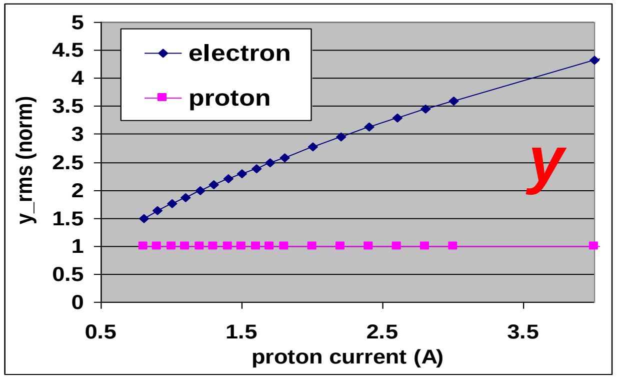
- Increasing proton beam current by increasing proton bunch charge while bunch repetition rate remain same, hence also increasing beam-beam interaction
- Luminosity increase as proton beam current first approximately linearly (up to 1.5 A), then slow down as nonlinear beam-beam effect becomes important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









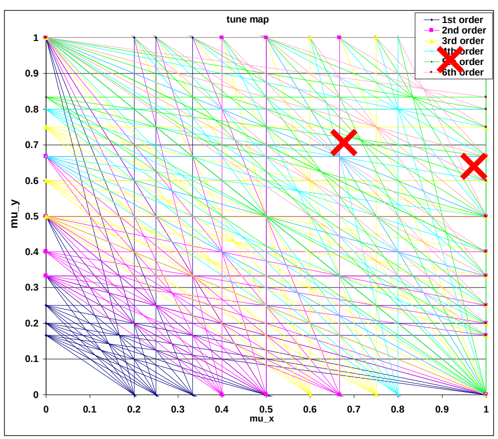


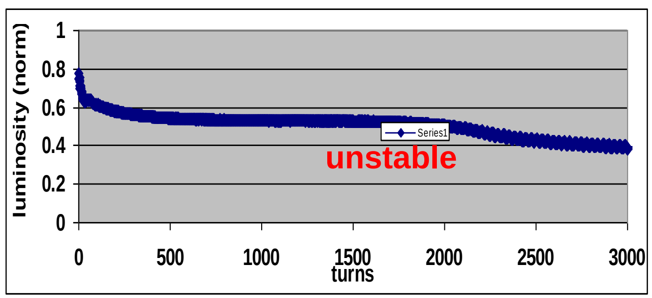
Betatron Tune Working Point

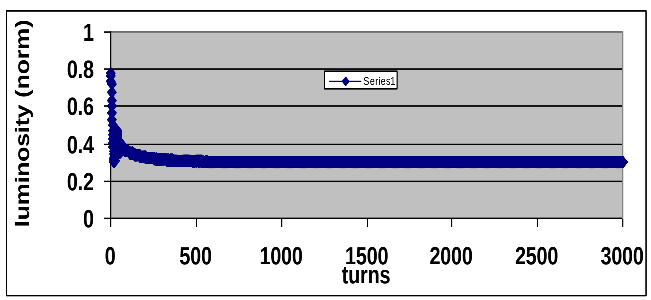
- Equilibrium luminosity strongly depends on synchrotron and betatron tune working point
- Working point should be away from synchrotron-betatron resonance lines
- Tune footprint, enlarged by beam-beam effect should avoid cross low order resonance lines
- Simulations have shown a *better working point*

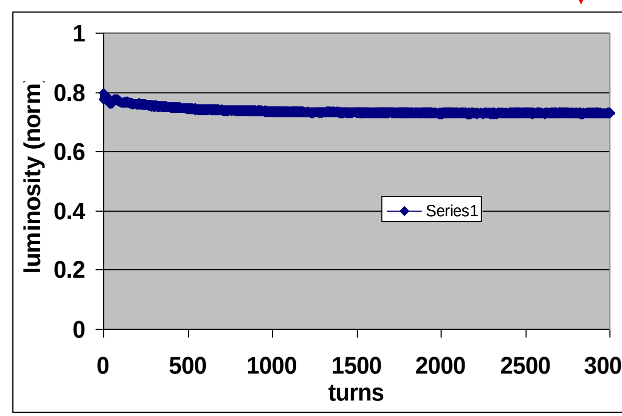
nominal

Electron ν_x, ν_y	Proton ν_x, ν_y	Luminosity 10^{34} cm^{-2} s^{-1}
0.91, 0.88	0.71, 0.7	4.15
0.71, 0.7	0.91, 0.88	3.22
0.73, 0.725	0.91, 0.9	Unstable
0.748, 0.75	0.91, 0.88	Unstable
0.63, 0.645	0.71, 0.7	5.77
0.91, 0.88	0.63, 0.645	Unstable
0.96, 0.46	0.71, 0.7	2.38

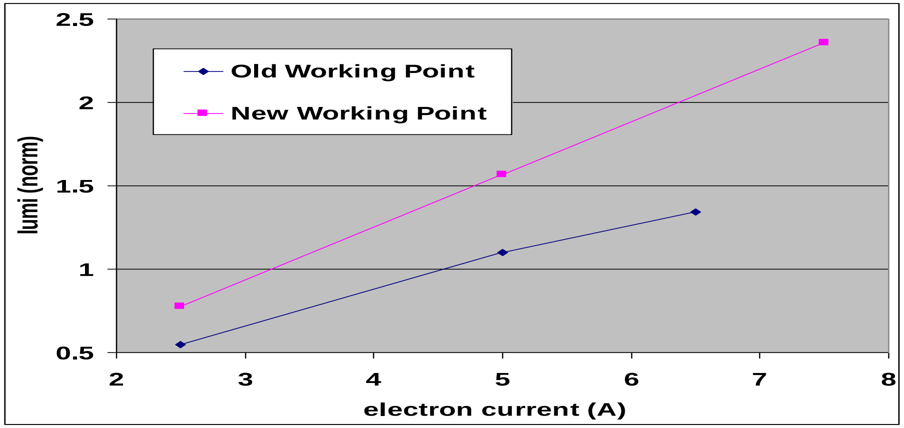


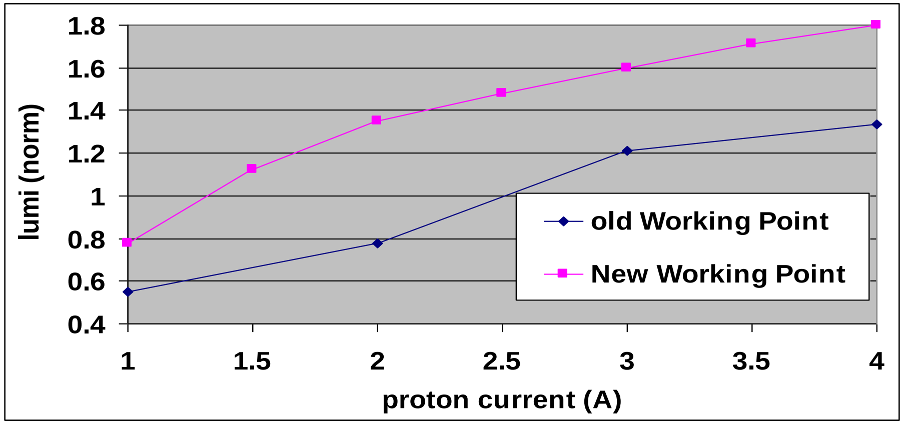


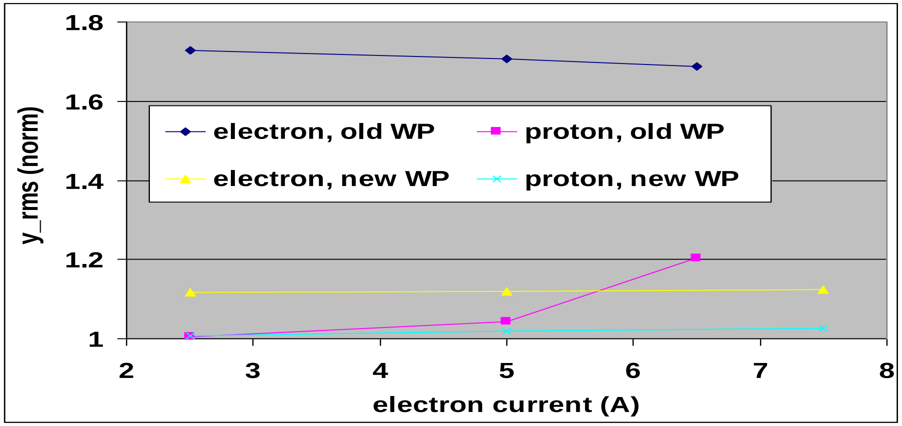


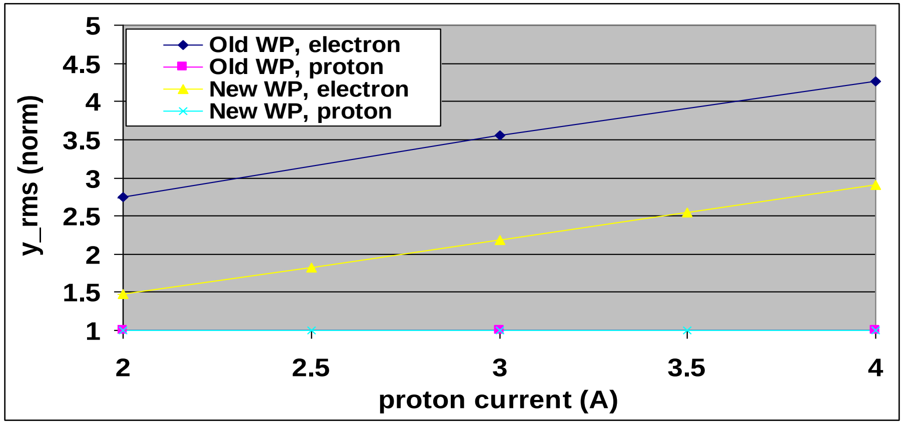


New Working Point (cont.)









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

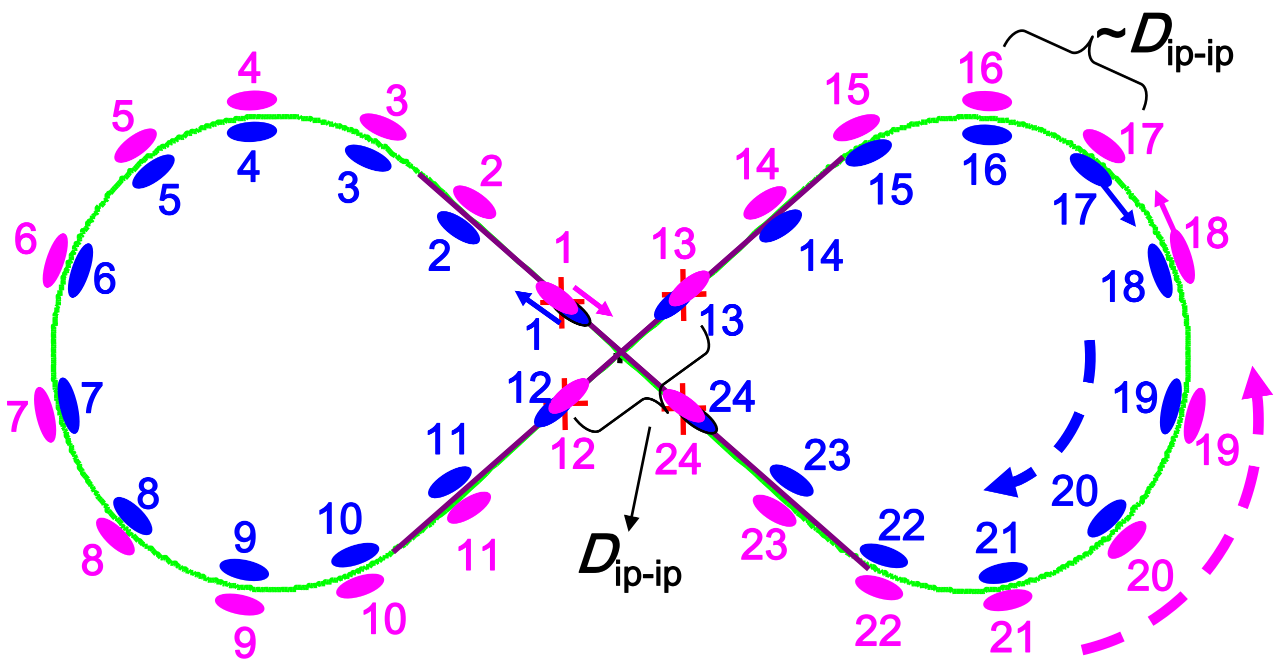
- Multiple bunch coupling
- Multiple IP effect
- Introducing new instability and effect on working point
- Earlier inciting of coherent beam-beam instability
- New periodicity and new coherent instability (eg. Pacman effect)

Reduction of Coupled Bunch Set

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

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

- 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

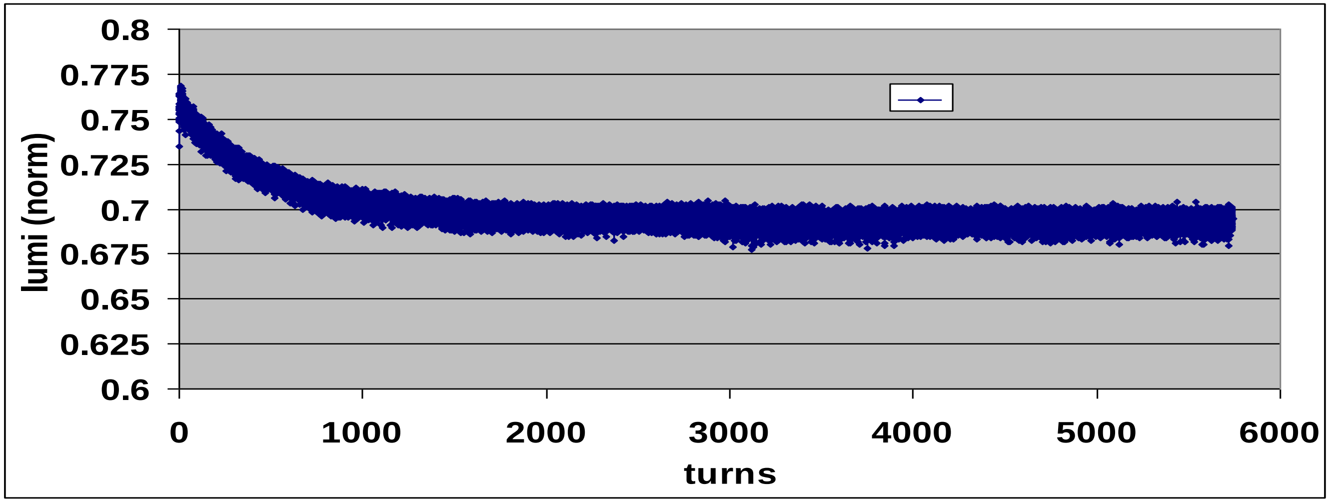
step	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
IP1	1 1	24 2	23 3	22 4	21 5	20 6	19 7	18 8	17 9	16 10	15 11	14 12	13 13	12 14	11 15	10 16	9 17	8 18	7 19	6 20	5 21	4 22	3 23	2 24
IP2	2 2	1 3	24 4	23 5	22 6	21 7	20 8	19 9	18 10	17 11	16 12	15 13	14 14	13 15	12 16	11 17	10 18	9 19	8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

- 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

Multiple IPs and Multiple Bunches (cont.)



- Simulated system stabilized (luminoisty, transverse size/emittance) after one damping time (more than 100k collisions)
- Luminosity per IP reaches 5.48×10^{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 $4.3 \cdot 10^{34}$ cm^{-2}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 $5.8 \cdot 10^{34}$ cm^{-2}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

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