# Interaction Region Design for ELIC and Beam-Beam Simulations

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for the ELIC Study Group at

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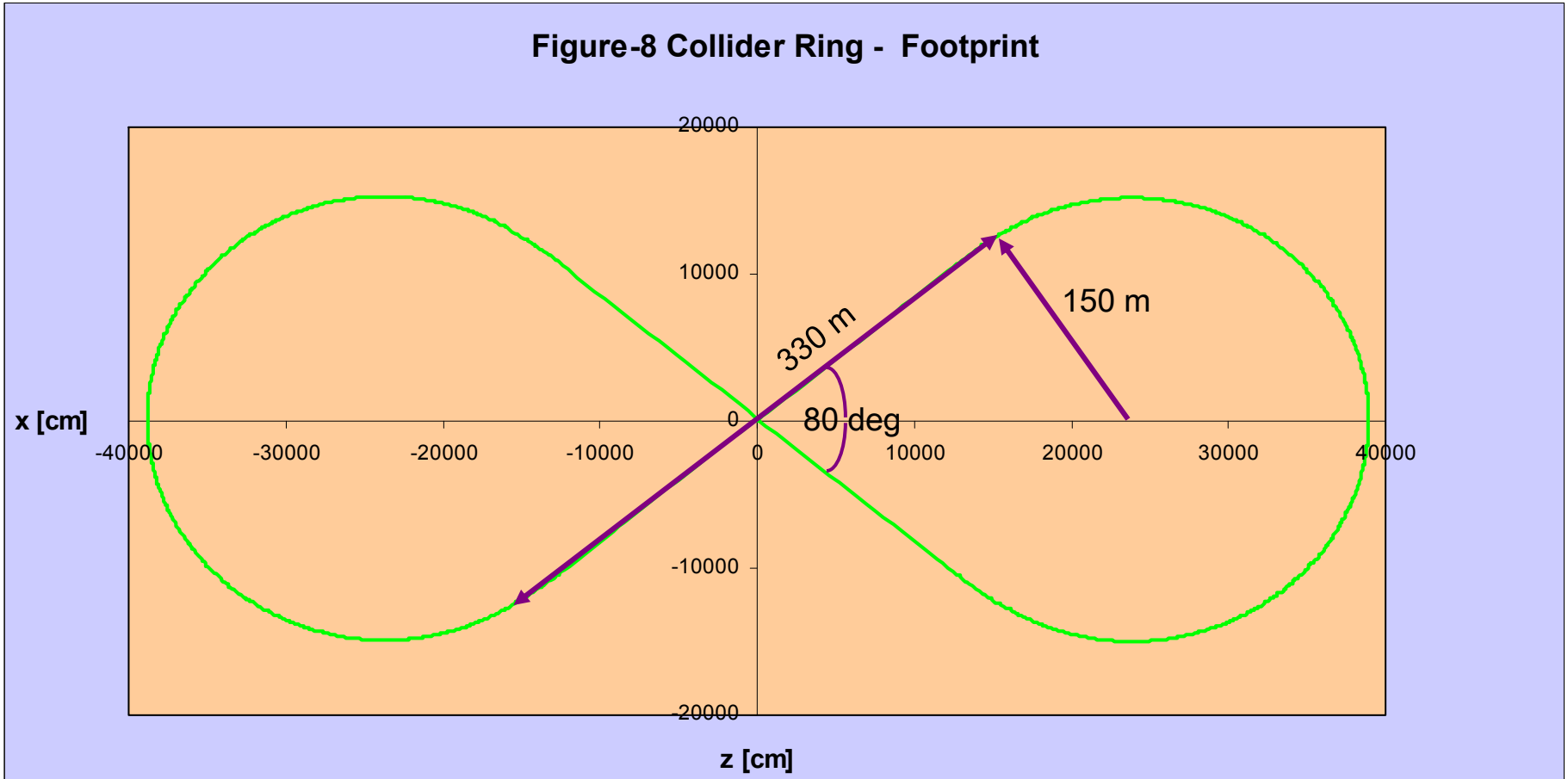
# Ring-Ring Electron–Ion Collider (9 on 225 GeV)

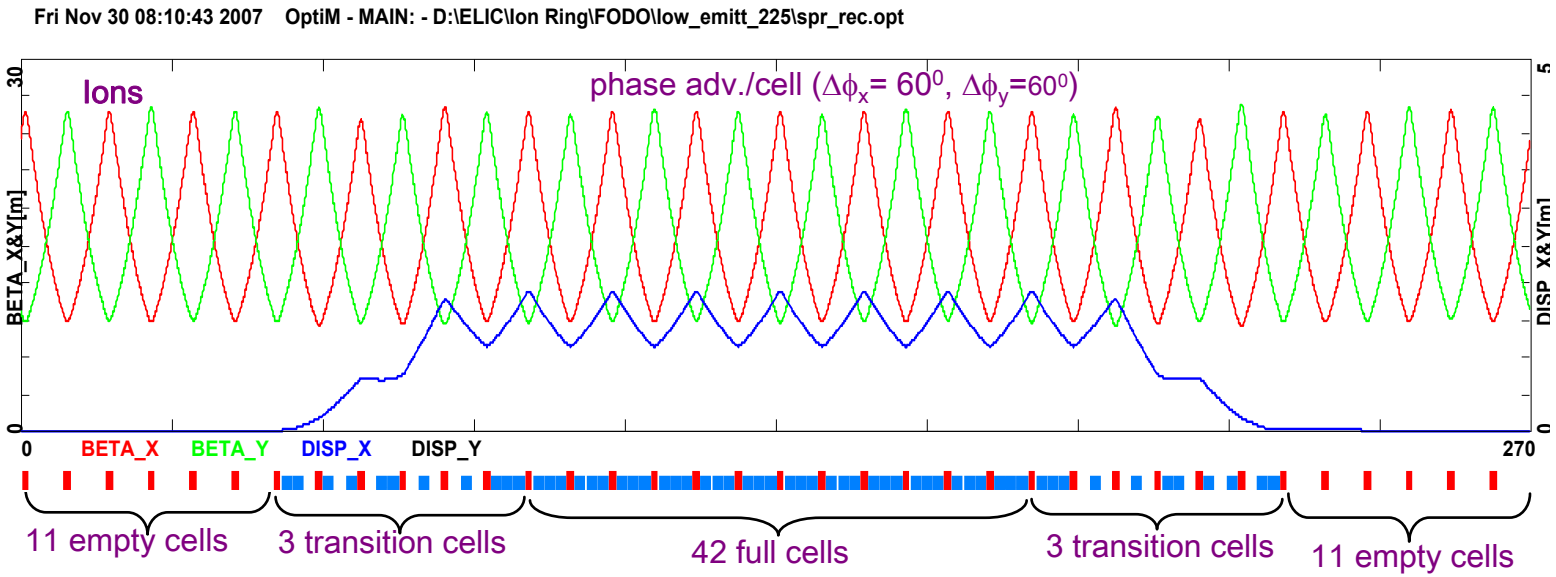
- Interaction Region requirements – Unprecedented High Luminosity: **$7.8\times10^{34}$** [$cm^{-2}$ $s^{-1}$] (peak luminosity per IP)
  - Enabled by short ion bunches ($\sigma_z$ = **5** mm), low $\beta^*$ (**5** mm), high rep. rate (**1.5** GHz)
  - 'Crab Crossing' required to alleviate luminosity reduction and to avoid parasitic beam-beam interaction
  - Four Interaction Regions, IRs (detectors)
  - Chromatic compensation with sextupoles required
- Collider Lattices – Architecture

# Figure-8 Ring with 80 deg. Crossing - Layout




Ring circumference: 2100 m

# Figure-8 Rings Lattices (half) – at 225 and 9 GeV

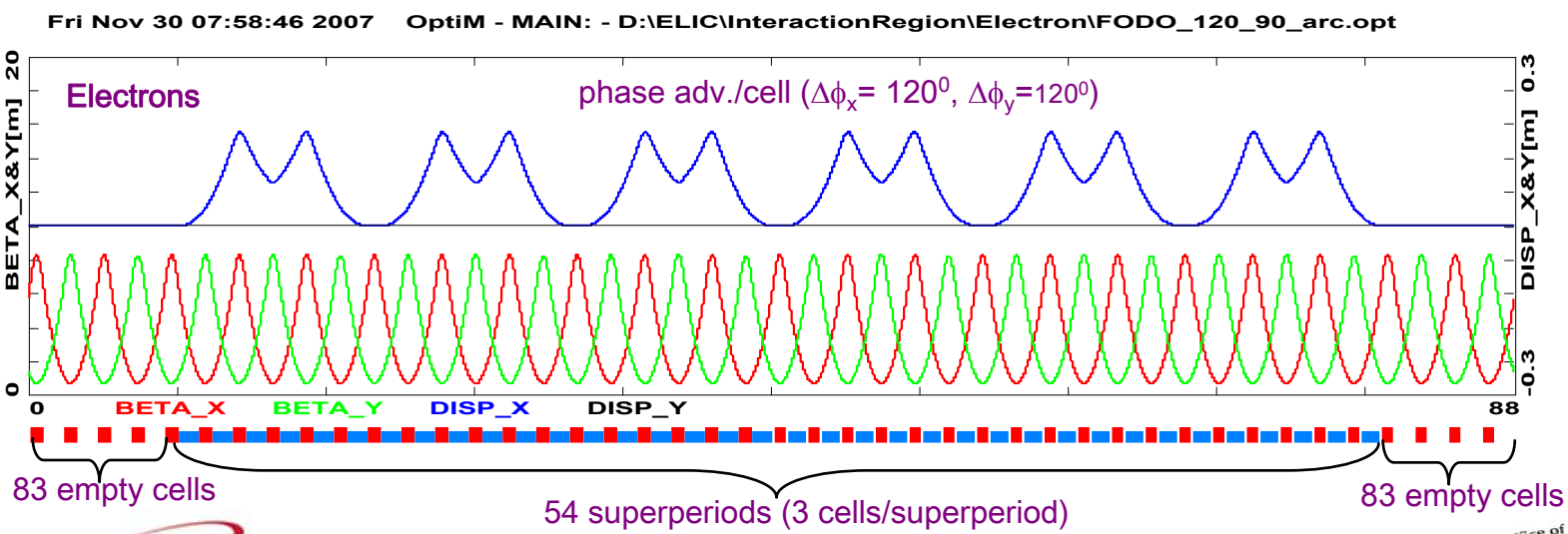



**Dipoles:**:

$Lb=170 cm
$B=73.4 kG
$rho =102 m

**Quadrupoles:**

$Lb=100 cm
$G= 10.4 kG/cm



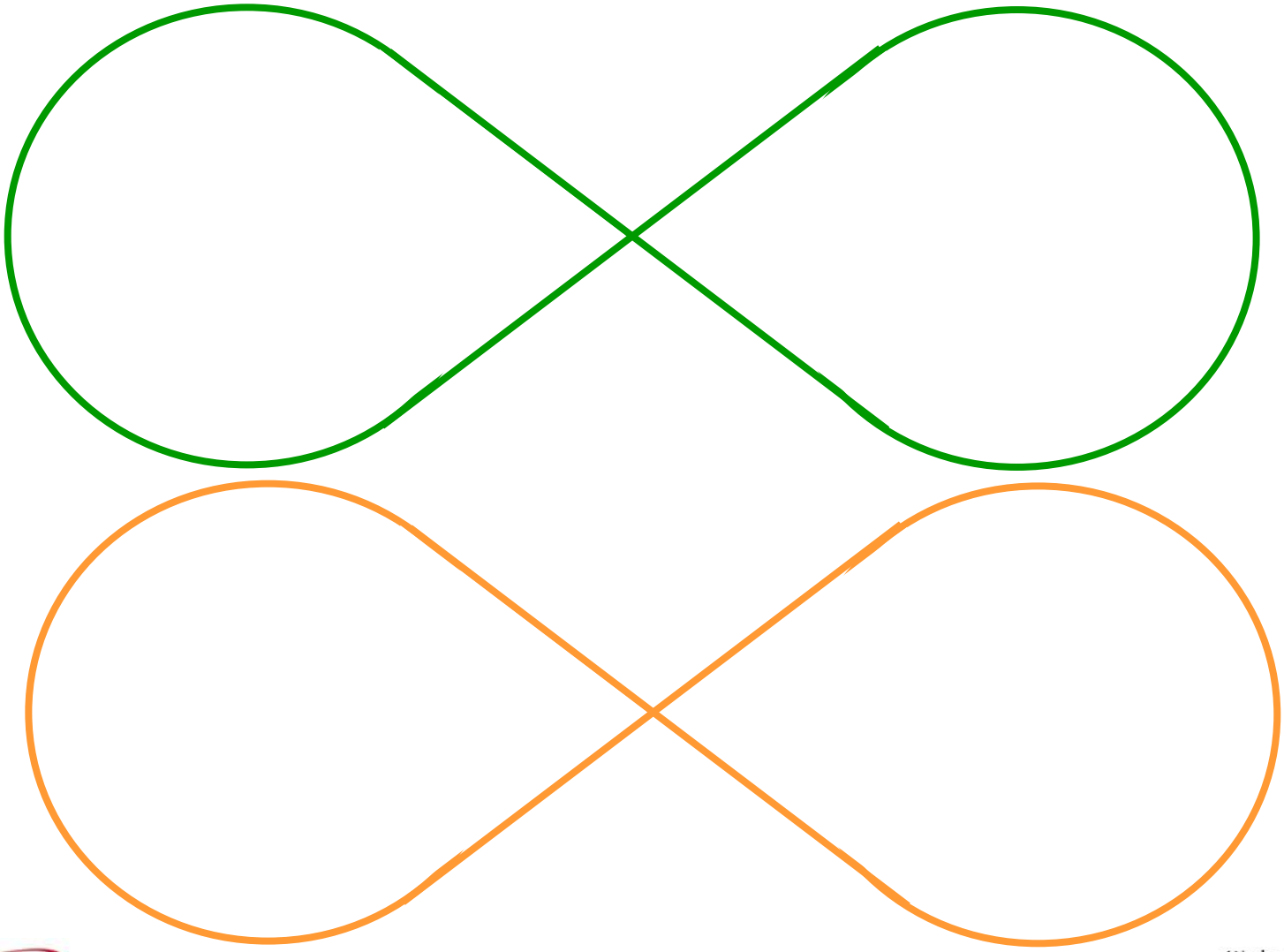

**Dipoles:**:

$Lb=100 cm
$B=3.2 kG
$rho =76 m

**Quadrupoles:**

$Lb=60 cm
$G= 4.1 kG/cm

# Figure-8 Rings – Vertical ‘Stacking’



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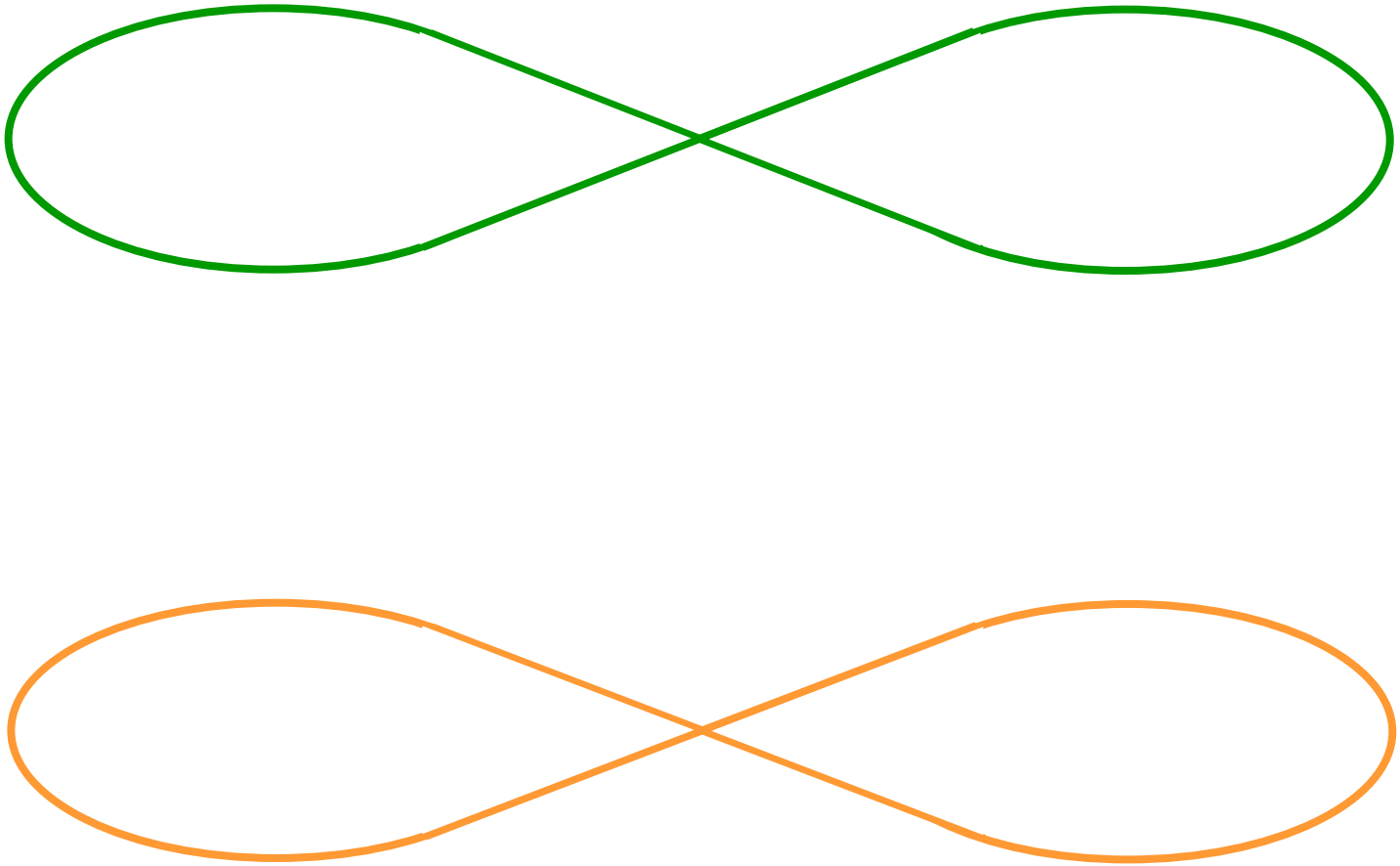

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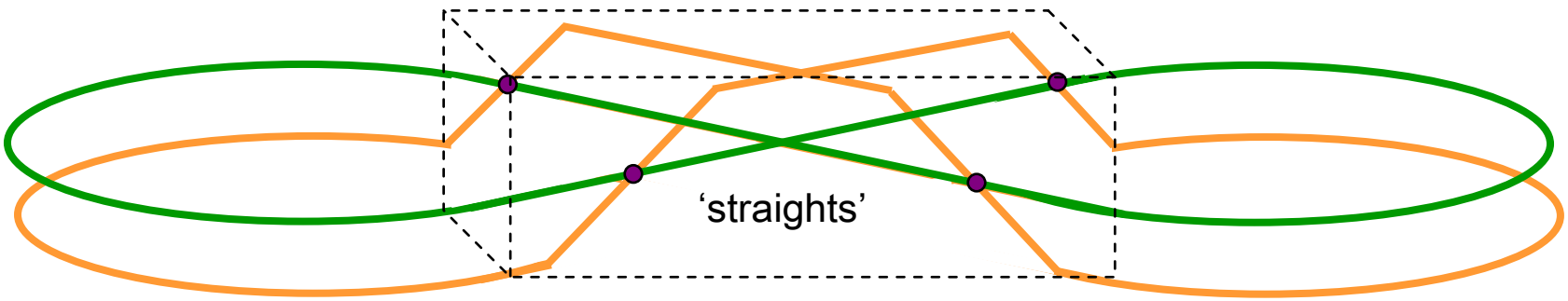
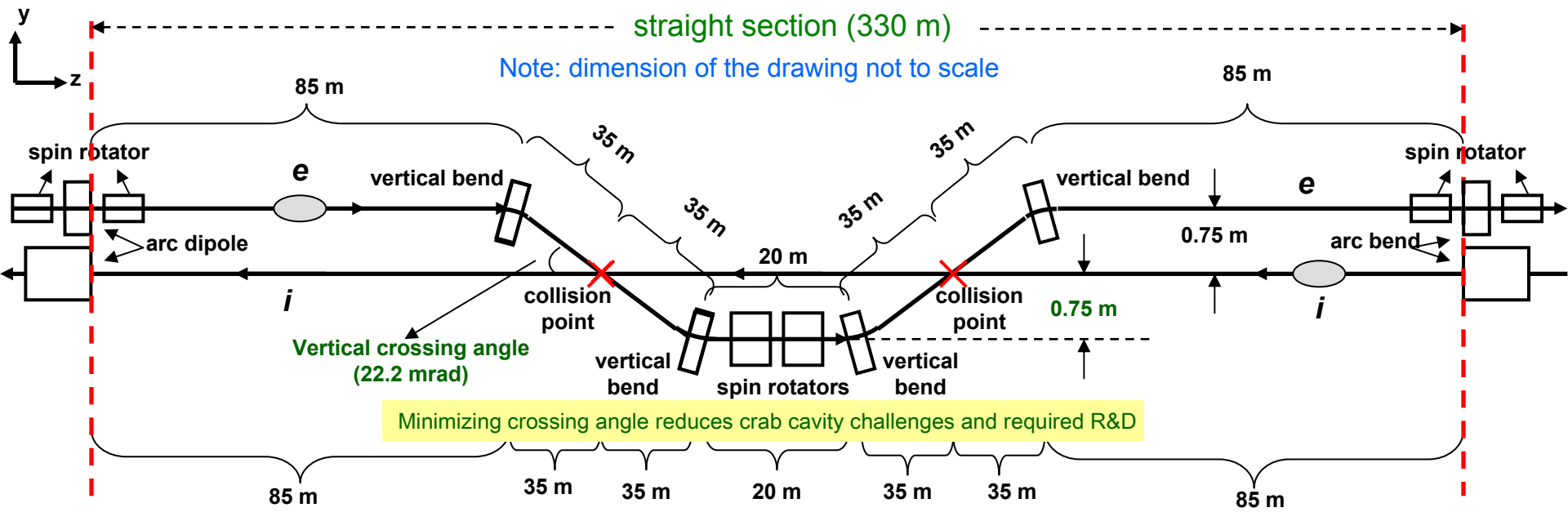
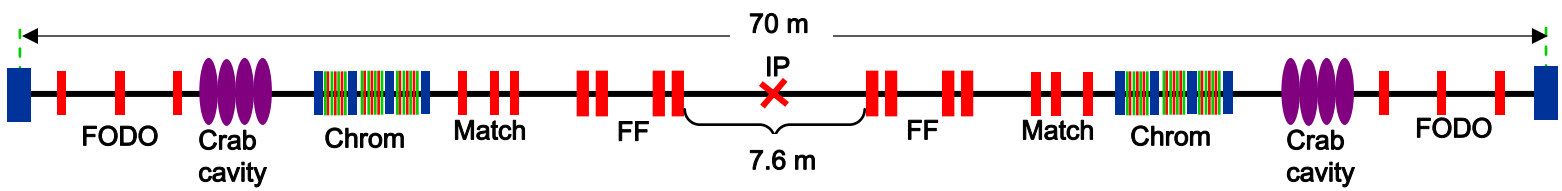


# Figure-8 Straights with two IPs

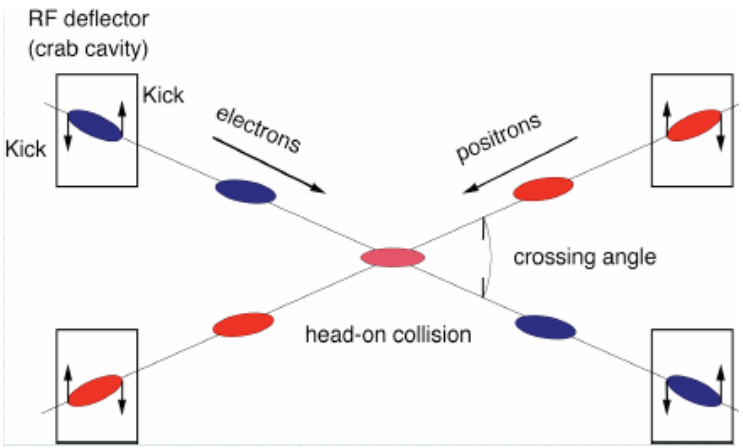



- 85 m free space to accommodate e/p injection/ejection, SRF cavity, electron cooling, and electron polarimeter

# ‘Crab Crossing’ – Longitudinal bunch deflection

K. Oide

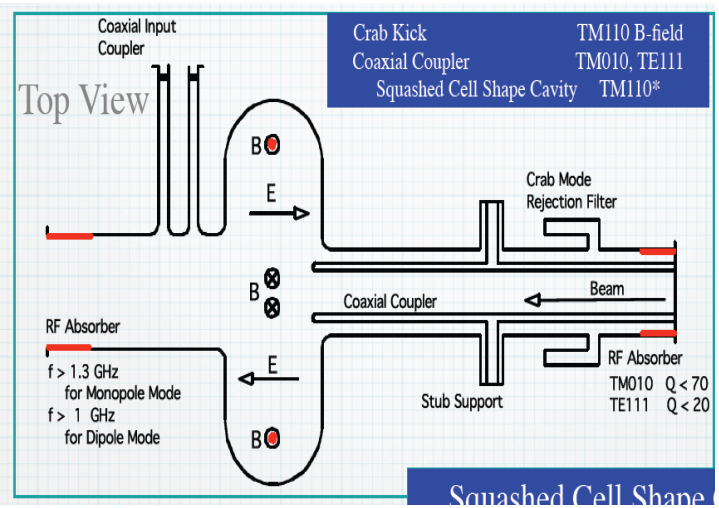



**Crab Cavity requirement for 22 mrad crossing:**

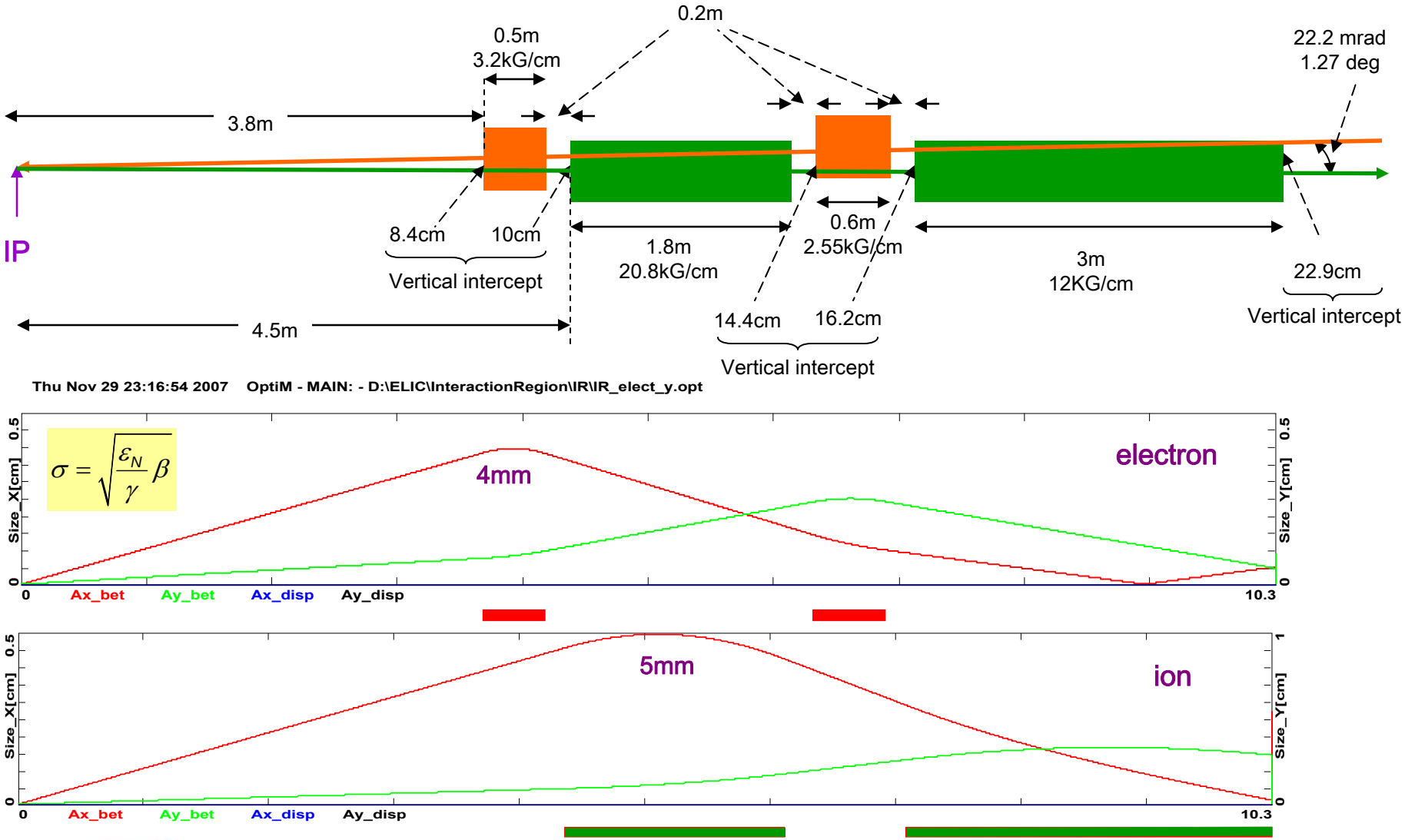
**Electron**: 0.8 MV – (KEK, single cell, 1.8 MV)

**Proton**: 17.6 MV (multi-cell cavity)

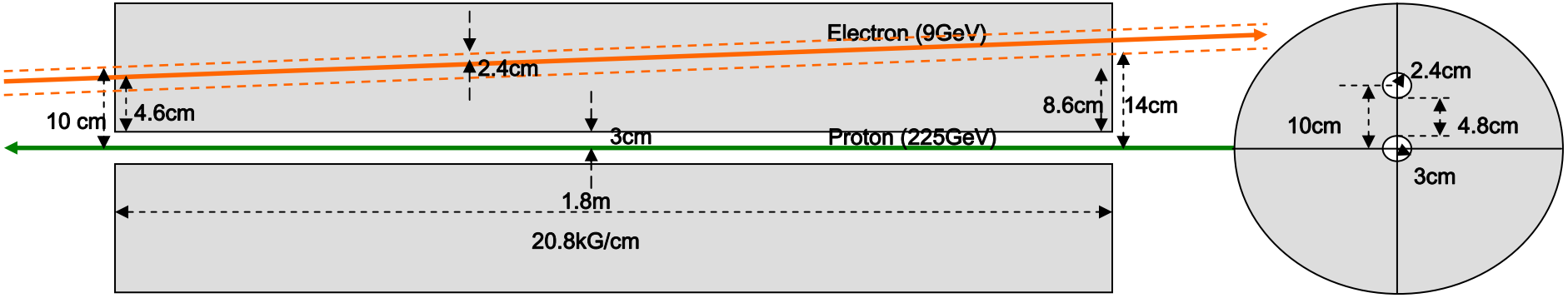
KEK B-Factory ‘Crab Cavity’ - Squashed cell cavity @ TM110 B field



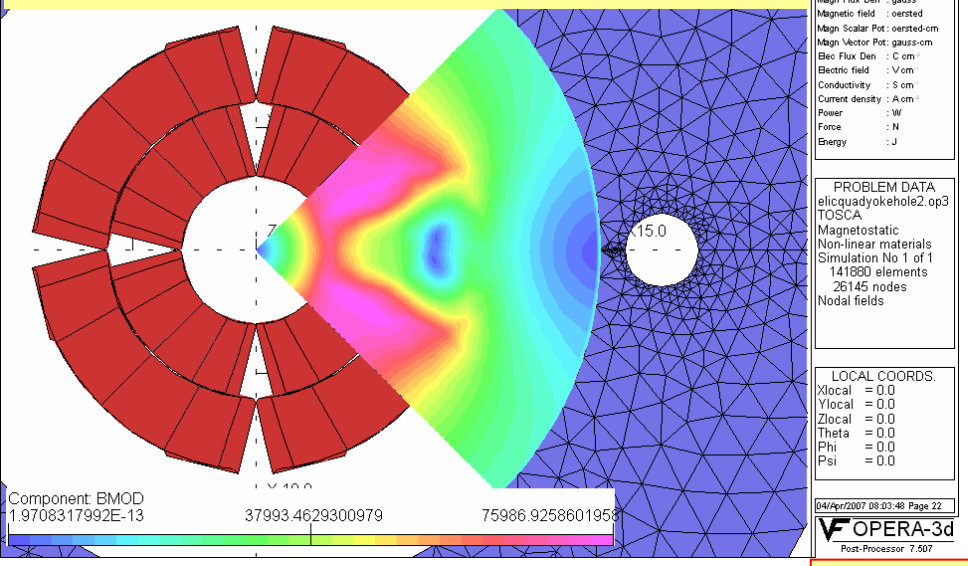
# IP Magnet Layout and Beam Envelopes



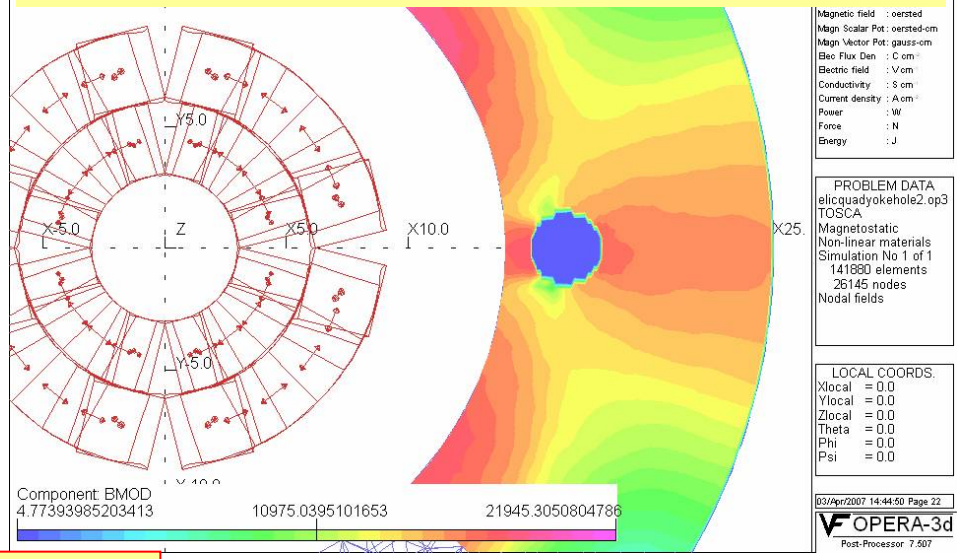
# Superconducting 'Lambertson' Quad with electron pass thru




## B-Field in coil and force collar



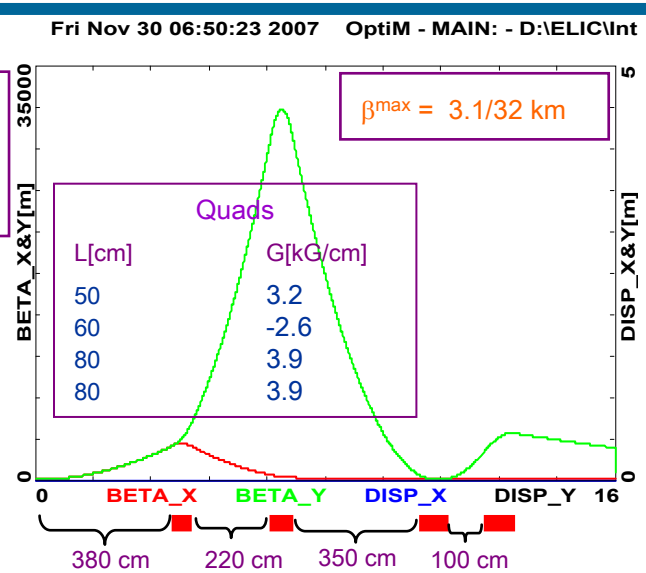

## B-Field in cold yoke around electron pass

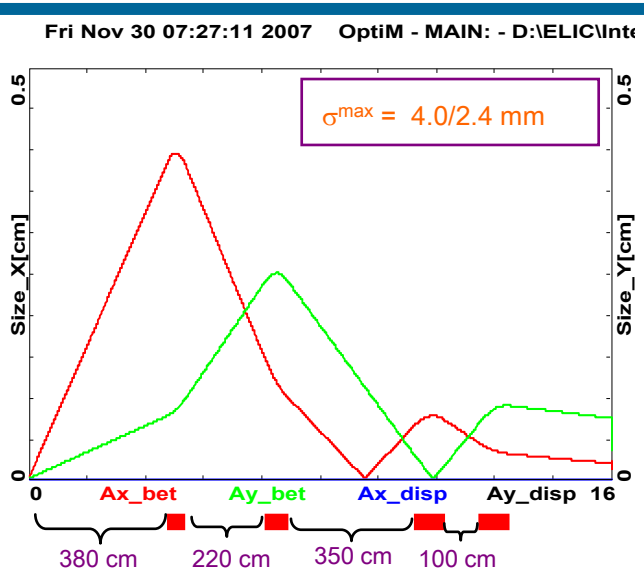



Paul Brindza

# IRs with 22 mrad crossing angle – Betas and Beam envelopes

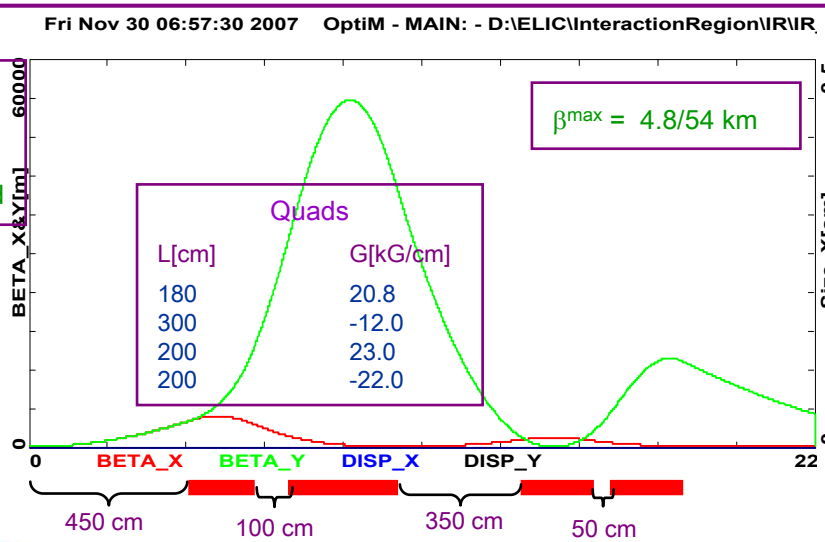
$E_{electron}$ = 9 GeV
$\beta^*$ = 5/5 mm
$\varepsilon_N$ = 90/3.6 μm rad

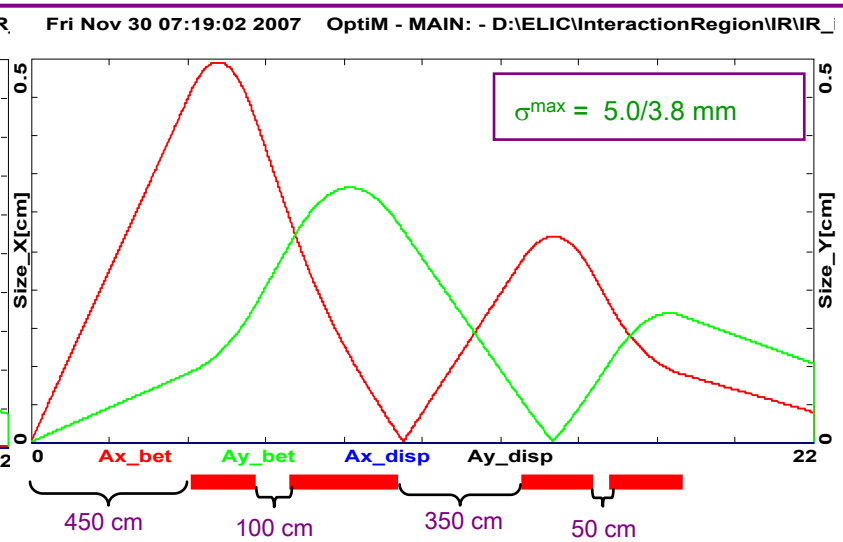



$$\sigma = \sqrt{\frac{\varepsilon_N}{\gamma}\beta}$$

$E_{ion}$ = 225 GeV
$\beta^*$ = 5/5 mm
$\varepsilon_N$ = 1.3/0.06 μm rad

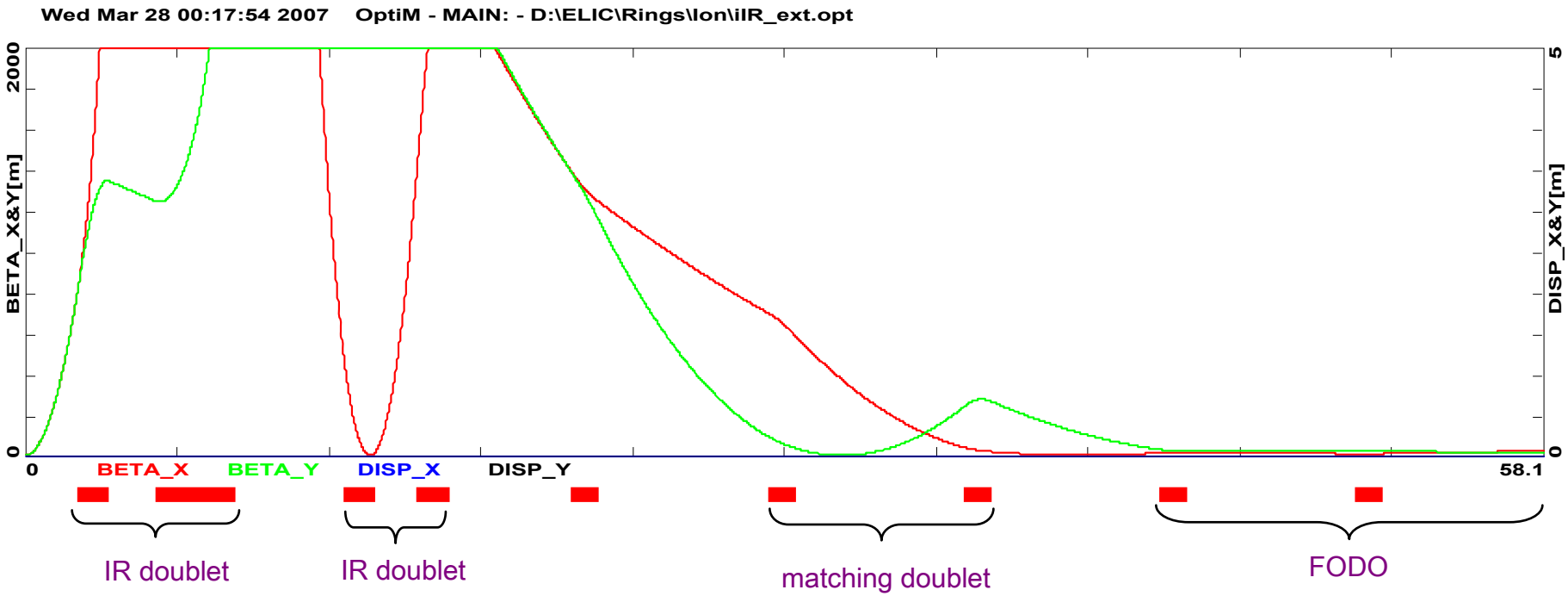


# IR - matching to the Ring

$\beta_x^* = 5$ mm
$\beta_y^* = 5$ mm

$E_{ion} = 225$ GeV



# Chromatic Aberrations and Mitigation schemes

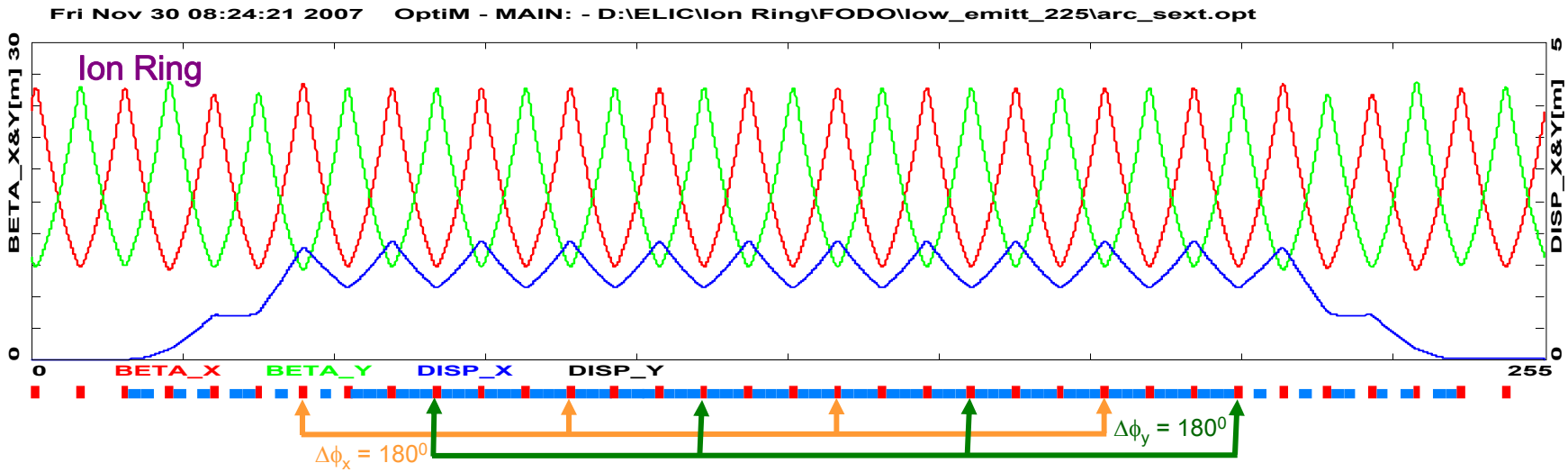
- Chromatic aberrations
  - natural chromaticity of the collider ring
  - beta chromaticity in the IR

$$\xi = \frac{L^* + L_q/2}{\beta^*} \approx \frac{400}{0.5} = 800$$

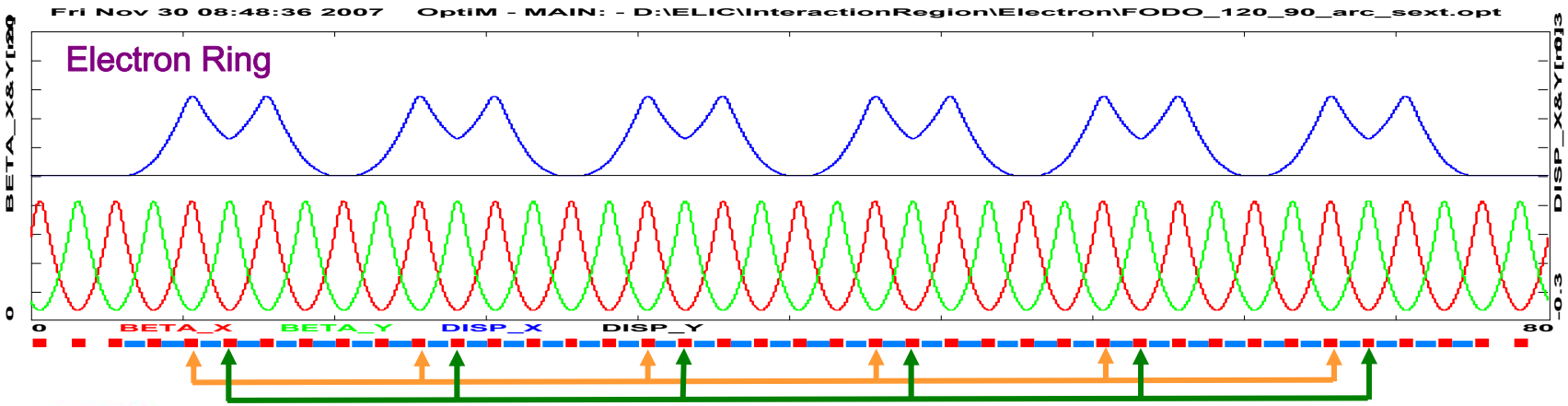
$$\Delta\nu = \xi \frac{\Delta p}{p} \approx 800 \times 3 \times 10^{-4} = 0.24$$

- Mitigation schemes
  - Chromaticity correction in the Arcs (two families of sextupoles)
  - Sextupoles in the IR quads
  - Dynamic Aperture – octupoles in the IR quads
  - Localized Chromatic corrections outside the IR

# Natural Chromaticity Compensation with two families of Sextupoles

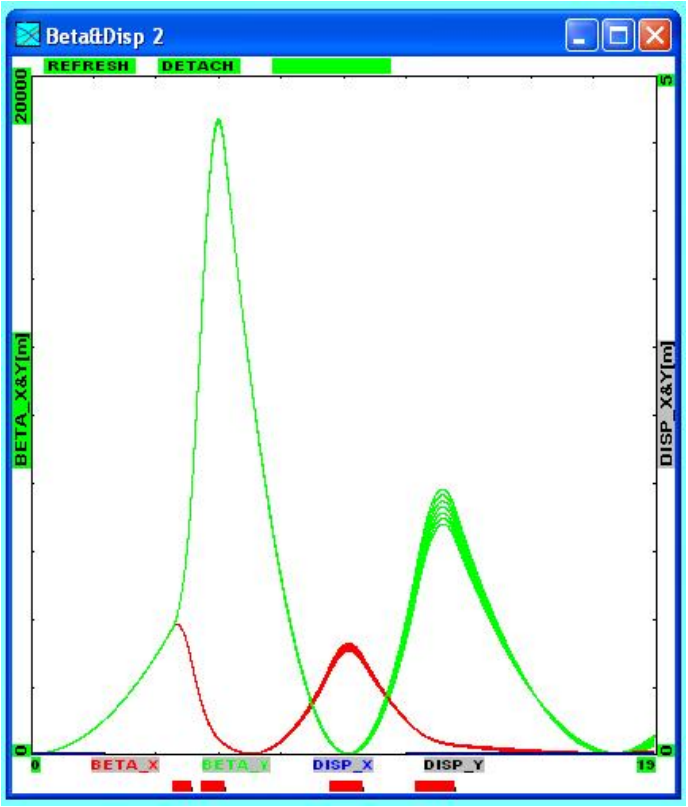



Cancellation of geometric aberrations generated by sextupoles through 'pairing' them with a minus identity transformation between them



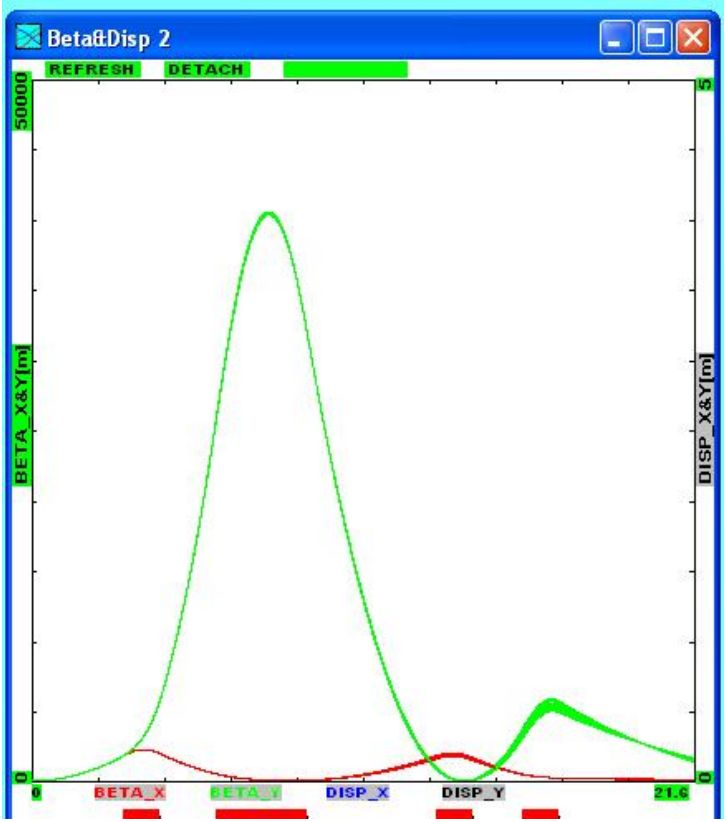
# IR Beta Chromaticity

IR electrons




$$\sigma = \sqrt{\frac{\varepsilon_N}{\gamma}\beta}$$

IR Ions




$\Delta p/p = 0.001$

# Beta Chromaticity mitigation

- IR beta functions strongly vary for off momentum particles
- It is measured by the beta chromaticity functions:

$$a_x = \frac{\partial}{\partial \delta_p} \alpha_x - \frac{\alpha_x}{\beta_x} \frac{\partial}{\partial \delta_p} \beta_x ,$$

$$b_x = \frac{1}{\beta_x} \frac{\partial}{\partial \delta_p} \beta_x ,$$

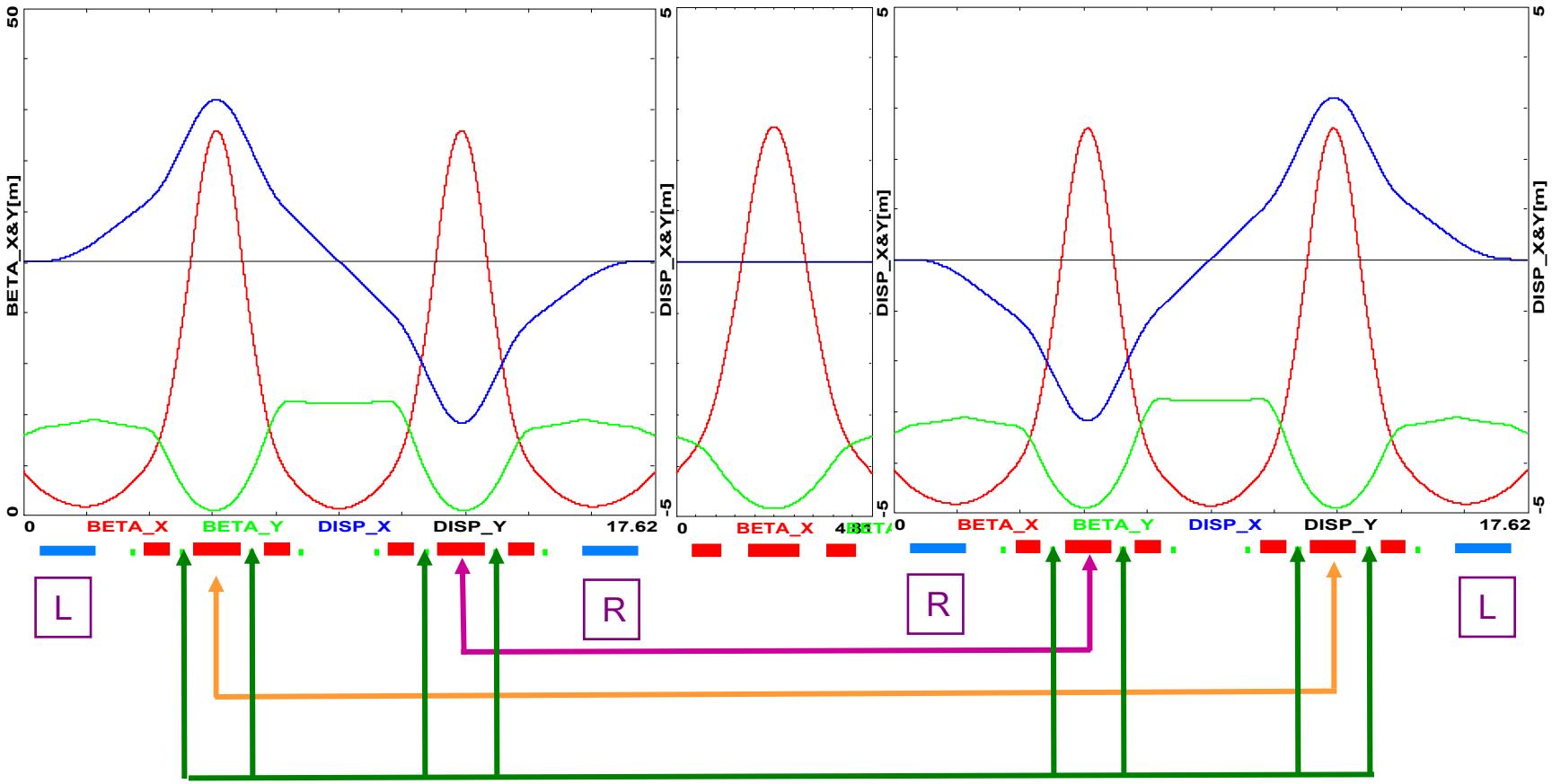
or by is the so called ‘envelope’ dispersion

$$w_x = \sqrt{a_x^2 + b_x^2} ,$$

- Typical values of the w-functions ~ 100, need to be ~10
- **Beta Chromaticity** could be corrected with sextupoles:
  - placed in the FF quads - dispersion must be generated/controlled in the IR
  - in the dedicated dispersion insert outside the IR in the matching section (mid values of betas)

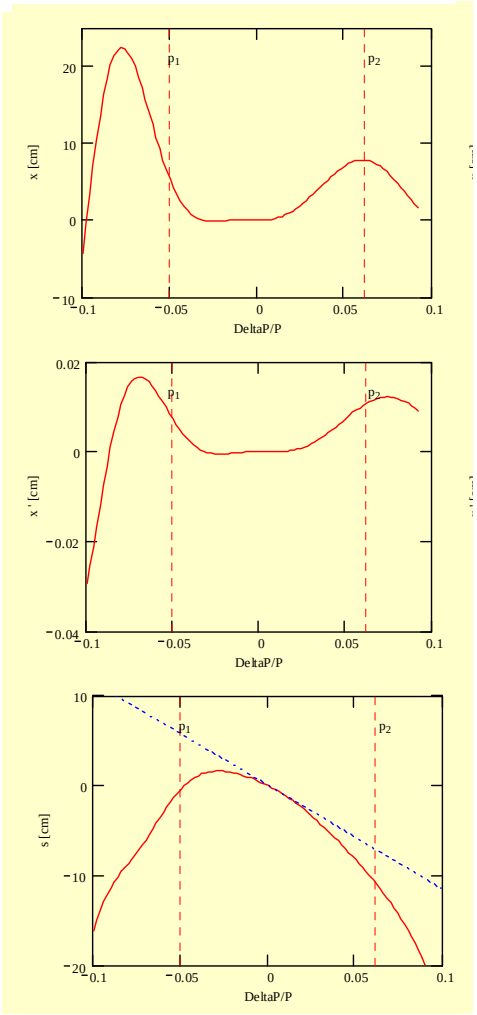
# Chromatic Compensation Block – Prototype

**Compensation Block** - Multipoles (sextupoles and possibly octupoles) introduced into a dedicated dispersive insert (chicane or snake to generate dispersion) with a special highly symmetric Optics



# Chromatic Compensation with Sextupoles

no sextupole corrections




- Dispersion
- Dispersion-prime
- $M_{56}$

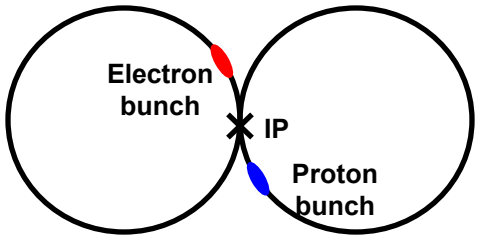
# Conclusions

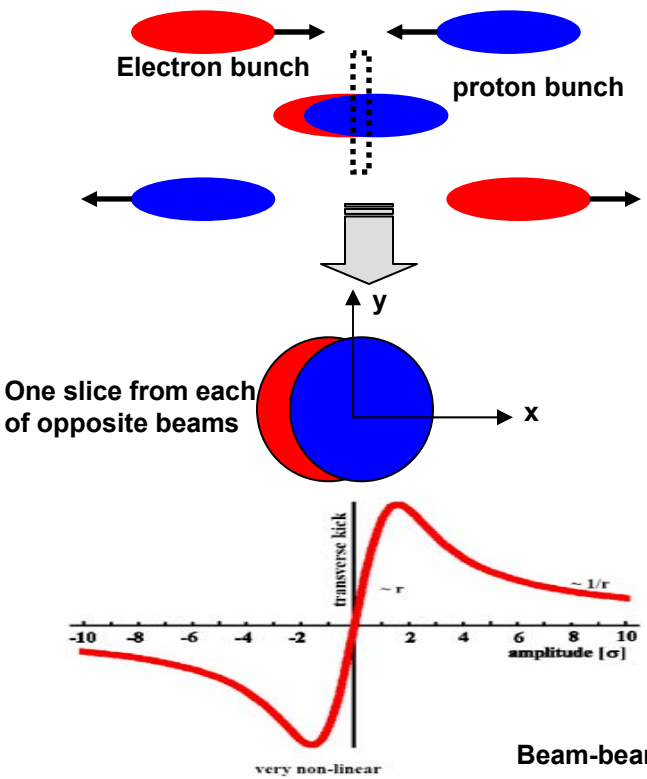
- Compelling case for High Luminosity ELIC
  - Based on present assumptions ~$10^{35}$ [$cm^{-2}$ $s^{-1}$] luminosity is feasible … more studes needed…
- IR Conceptual Design of the major sub-systems
  - FF Lambertson quads
  - 'Crab Crossing'
  - Chromatic Compensation with two families of sextupoles
- Still to come
  - Compensation for higher order effects (spherical aberrations)
  - Dynamic Aperture tracking studies

# Outline

- Introduction
- Model, Methods, Simulation Code and ELIC Parameters
- Simulation Results with ELIC Nominal Design Parameters
- Parameter Dependence of ELIC Luminosity
- Tune Map and Working Point
- Summary

# Introduction: Beam-Beam Physics




Beam-beam force

## E & M force between colliding bunches

- Confined to transverse plane due to ultra-relativistic motion
- Highly nonlinear forces
- Produce transverse kickers between colliding bunches

## Beam-beam effect

- Can cause bunch emittance growth, size expansion and blowup
- Can induce coherent beam-beam instabilities
- Can decrease luminosity and its lifetime

## Impact on ELIC IP design

- Strong final focusing (beta-star 5 mm)
- Short ion bunch length (5 mm)
- Employs crab cavity
- Four interaction points and Figure-8 rings
- electron beam vertical beam-beam tune shift is 0.087

# Luminosity and Beam-beam Effect

## Luminosity of a storage-ring collider

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

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

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

proportional to b-b parameter

**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**

Increasing beam-beam parameter

→ increasing luminosity

→ increasing beam-beam instability

## 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, $\gamma_e$ is relativistic factor, and $\beta^*_{ye}$ is vertical beta function at interaction point**

Beam-beam effect

- linear part → tune shift
- nonlinear part → tune spread

# Simulation Model, Method & Codes

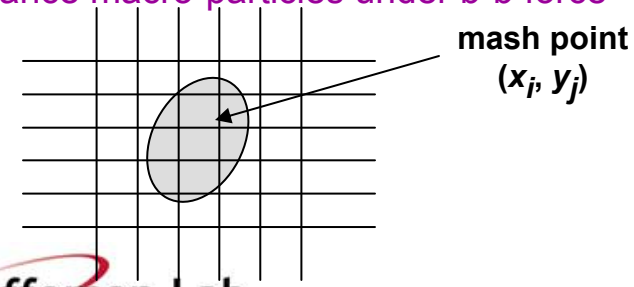
## Basic Idea of Simulations:

***Collision@IP + transport@ring***

- Simulating particle-particle collisions by particle-in-cell method
- Tracking particle transport in rings

## Particle-in-Cell Method:

- Colliding bunches are modeled by groups of charged macro-particles
- Transverse plane is covered with a 2D mash
- Solve Poisson equation over 2D mash
- Calculate beam-beam force using electromagnetic fields on mash 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-consistence*** 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

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

# ELIC e-p Nominal Parameters

## Simulation Model

- Single collision point (IP)
- One proton bunch and one electron bunch
- 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 mash >= 64 x 128
- Macro-particles >= 200,000

## Simulation Scope and Limitations

- 5k ~ 10k turns for a typical simulation run (multi-days of a128-node NERSC supercomputer)
- About 0.05 s of storing time (12 damping times)
  - → reveals short-time dynamics with accuracy
  - → can't predict long term (>min) dynamics

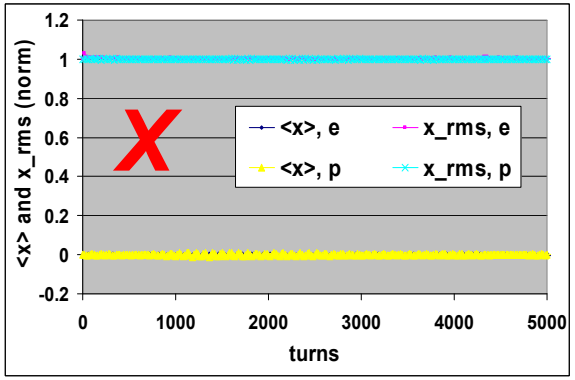
***It is first phase of a long-term research plan***

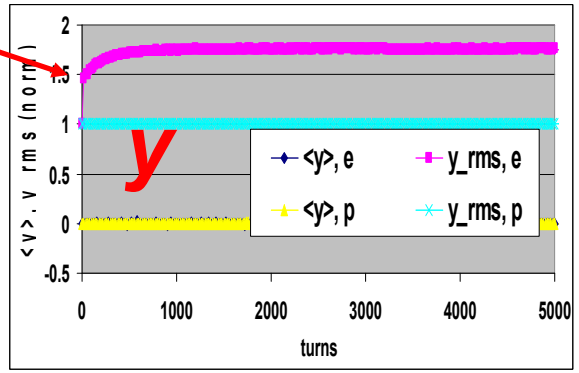
| | | Proton | Electron |
|---|---|---|---|
| Energy | GeV | 150 | 7 |
| Current | A | 1 | 2.5 |
| Particles | $10^{10}$ | 1.04 | 0.42 |
| Hori. Emit., norm. | μm | 1.06 | 90 |
| Vert. Emit., norm. | μm | 0.042 | 3.6 |
| $\beta^*_x / \beta^*_y$ | mm | 5 / 5 | 5 / 5 |
| $\sigma_x / \sigma_y$ | μm | 5.7/1.1 | 5.7/1.1 |
| Bunch length | mm | 5 | 5 |
| Damping time | turn | --- | 800 |
| Beam-beam parameter | | 0.002<br>0.01 | 0.017<br>0.086 |
| Betatron tune $\nu_x$ and $\nu_y$ | | 0.71<br>0.70 | 0.91<br>0.88 |
| Synchrotron tune | | 0.06 | 0.25 |
| Peak luminosity | $cm^{-2}s^{-1}$ | $7.87 \times 10^{34}$ | |
| Luminosity with hour-glass effect | $cm^{-2}s^{-1}$ | $5.95 \times 10^{34}$ | |

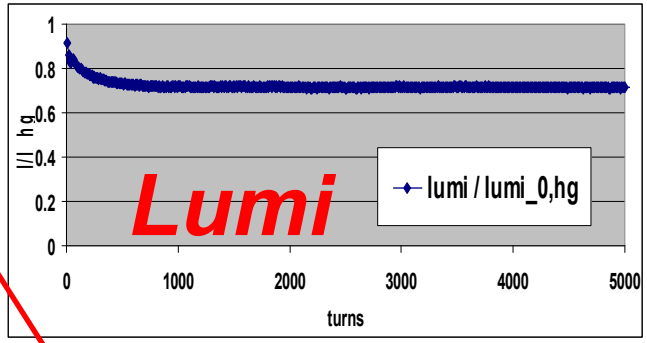
# Simulation Results: Nominal Parameters

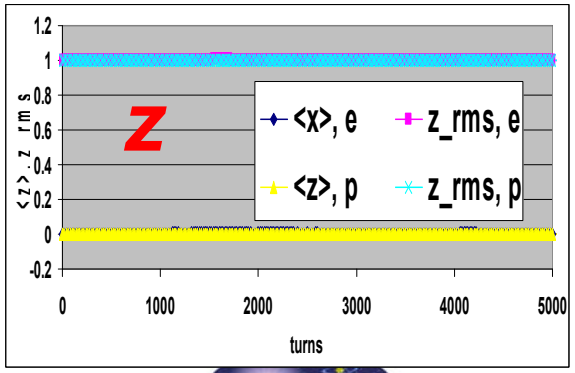
- Simulations started with two Gaussian bunches with design parameters, reached equilibrium after one damping time
- No coherent beam-beam instability observed.
- Luminosity stabled at ***$4.3 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$*** after damping time
- Sizes & lengths for both bunches remain design values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

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



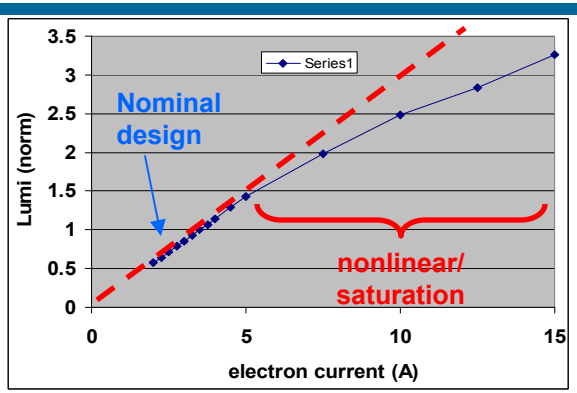



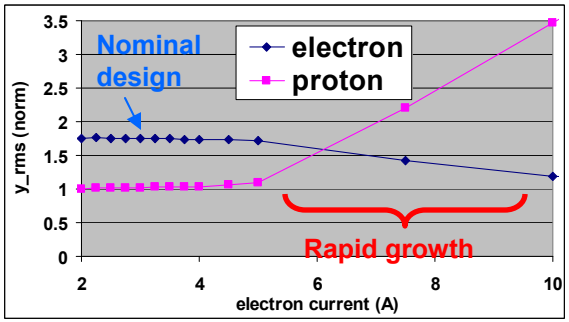



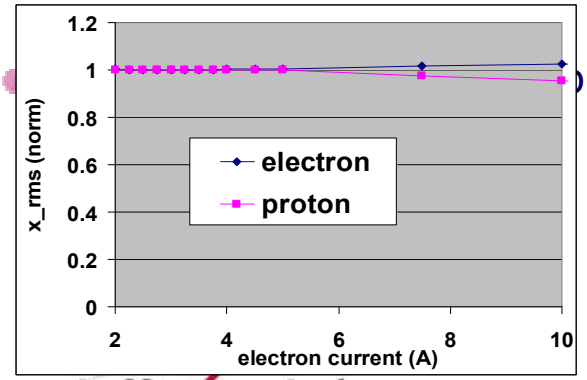

Normalized to design parameters

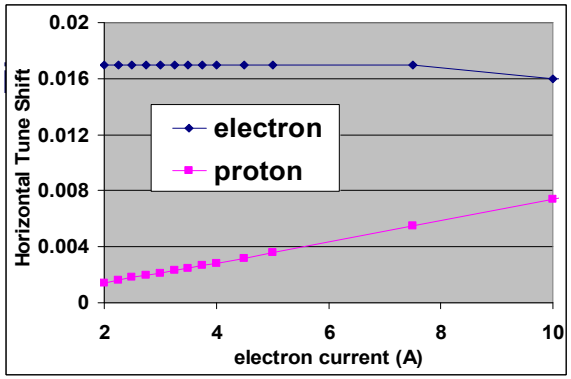
# Electron current dependence of Luminosity

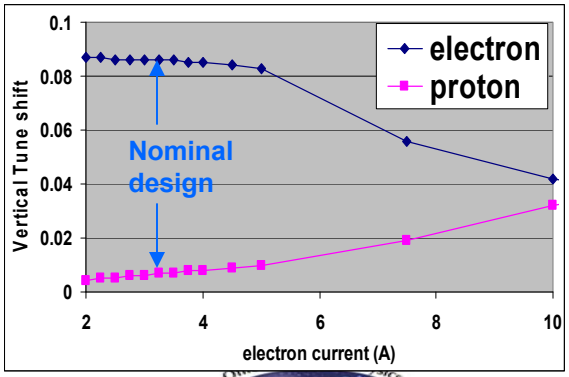
- Increasing electron beam current by increasing bunch charge while bunch repetition rate remains the same, hence also increasing beam-beam interaction
- Luminosity increase as electron current first linearly (up to 5 A), then slow down as nonlinear beam-beam effort becomes important
- Proton bunch vertical size/emittance blowup when electron current is above 5 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



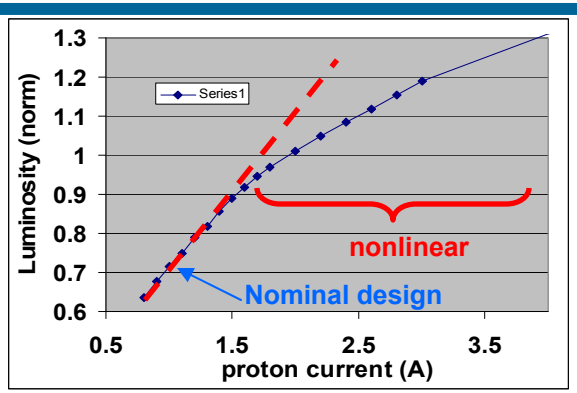



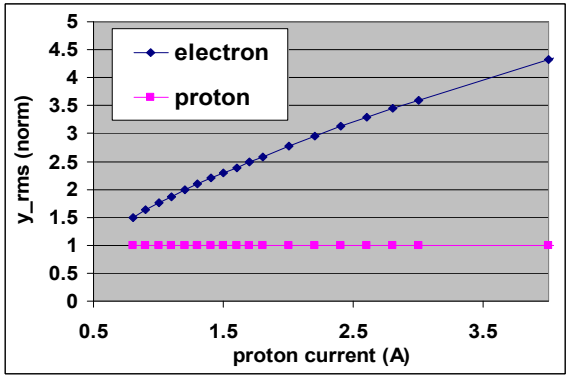



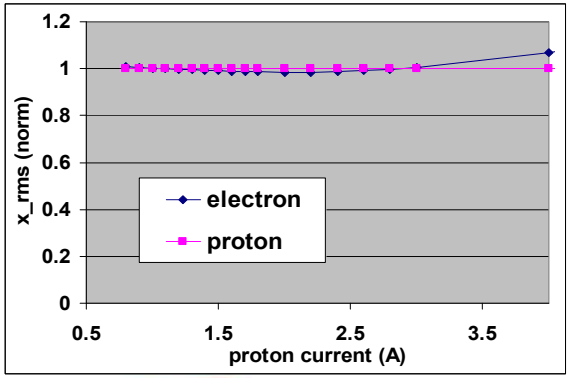



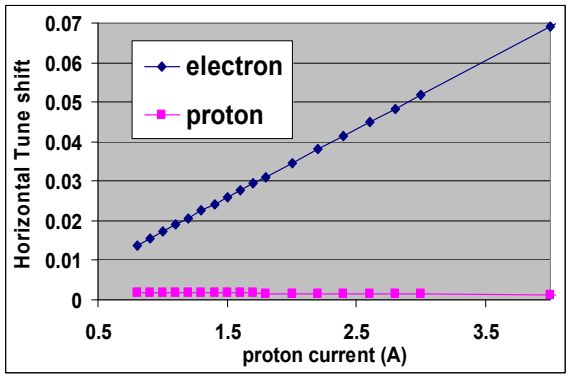
# Proton current dependence of Luminosity

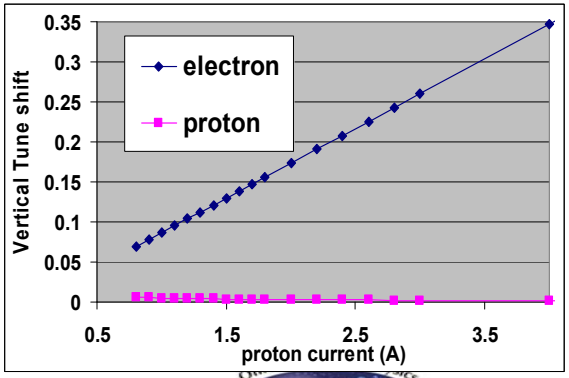
- Increasing proton beam current by increasing proton bunch charge while bunch repetition rate remain same, hence also increasing beam-beam interaction
- Luminosity increase as proton beam current first approximately linearly (up to 1.5 A), then slow down as nonlinear beam-beam effort becomes important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



# Bunch length and Luminosity

## ELIC equilibrium luminosity

- Depends on bunch length
- Highest luminosity is around 2.5 mm bunch length
- About 10% optimization over the nominal design

## Source of luminosity reduction

- Hour glass effect → geometric/optical effect

  When bunch length is close to beta star

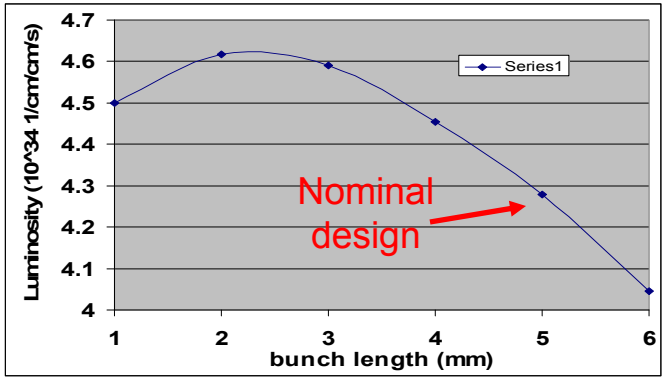
- Beam-beam effect → dynamical effect

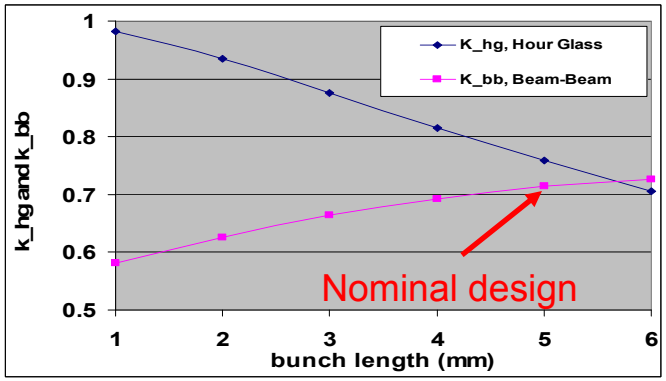
  When disruption of beam-beam force on beam size and emittance is not negligible

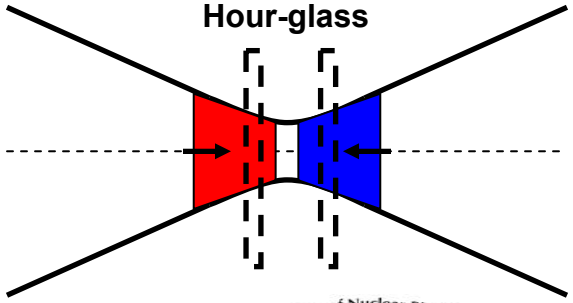
$$L_{sim} = L_{peak} k_{hg} k_{bb}$$

## Conclusion

- About 75% reduction for each effect at nominal design
- Not worth to push for shorter bunch length for 10% gain of luminosity



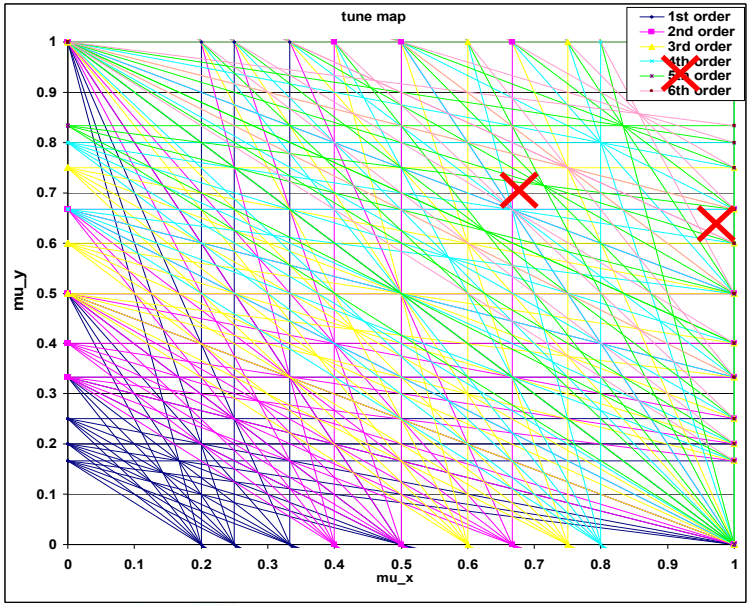
# Betatron Tune Working Point

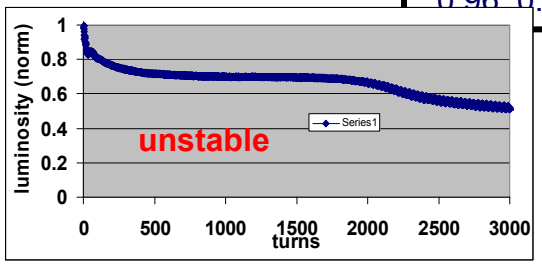
- Equilibrium luminosity strongly depends on synchrotron and betatron tune working point
- Working point should be away from synchrotron-betatron resonance lines
- Tune footprint, enlarged by beam-beam effect should avoid cross low order resonance lines
- Simulations have shown a *better working point*

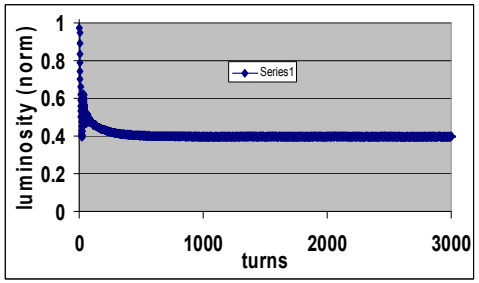
| Electron ($\nu_x$, $\nu_y$) | Proton ($\nu_x$, $\nu_y$, $\nu_s$) | Luminosity ($10^{34}$ cm$^{-2}$ s$^{-1}$) |
|---|---|---|
| 0.91, 0.88 | 0.71, 0.7 | 4.15 |
| 0.71, 0.7 | 0.91, 0.88 | 3.22 |
| 0.73, 0.725 | 0.91, 0.9 | Unstable |
| 0.748, 0.75 | 0.91, 0.88 | Unstable |
| 0.63, 0.645 | 0.71, 0.7 | 5.77 |
| 0.91, 0.88 | 0.63, 0.645 | Unstable |
| 0.96, 0.46 | 0.71, 0.7 | 0.88 |

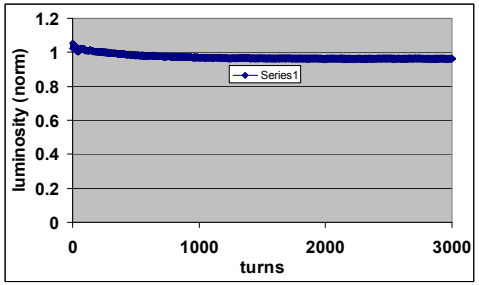
nominal

A better WP ?




**beam-beam reduction factor**

$$k_{bb} = 0.97$$

# Summary

- Beam-beam simulations were performed for ELIC ring-ring design with nominal parameters, single IP, head-on collision and ideal transport in Figure-8 ring
- Simulation results indicated stable operation of ELIC over simulated time scale (10k turns, 0.05 s), with an equilibrium luminosity of $4.3 \cdot 10^{34}$ $cm^{-2}s^{-1}$, roughly 75% 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 coherent beam-beam instability
- Studies of luminosity vs. bunch length suggested a 10% luminosity optimization if bunch length is reduced to 2.5 mm. Such optimization is not worth pursuing however due to potentially amplification of other beam instabilities such as IBS.
- 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 $5.8 \cdot 10^{34}$ $cm^{-2}s^{-1}$

# Future Plan

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

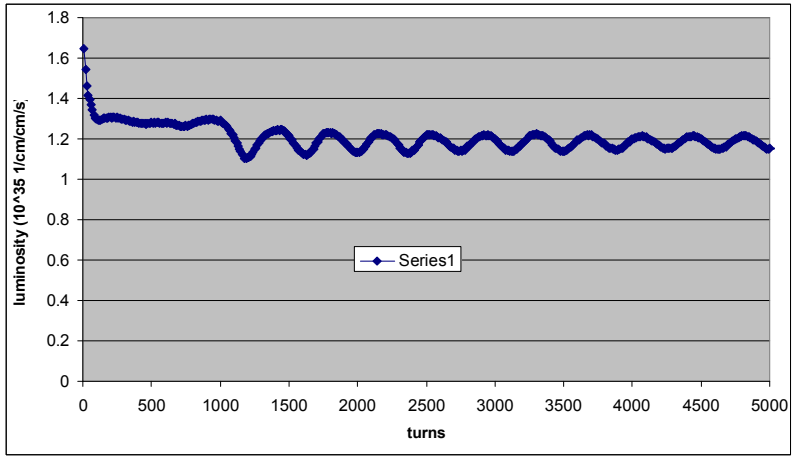
- Part of SciDAC COMPASS project
- Working with LBL and TechX and other partners for developing and studying beam dynamics and electron cooling for ELIC conceptual design

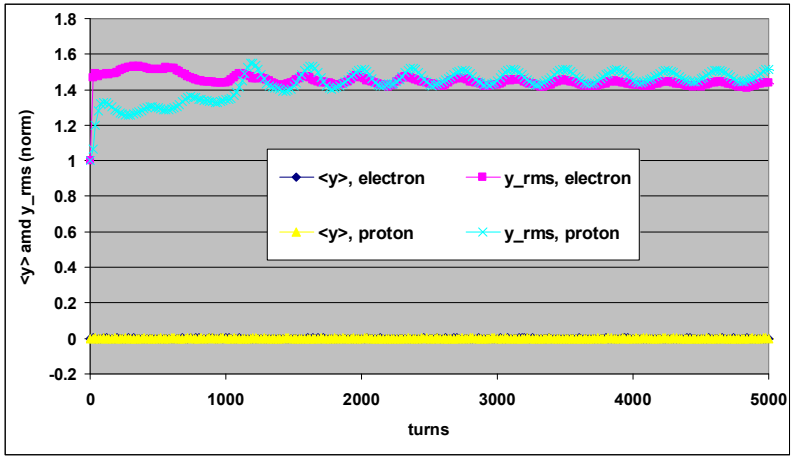
# Acknowledgement

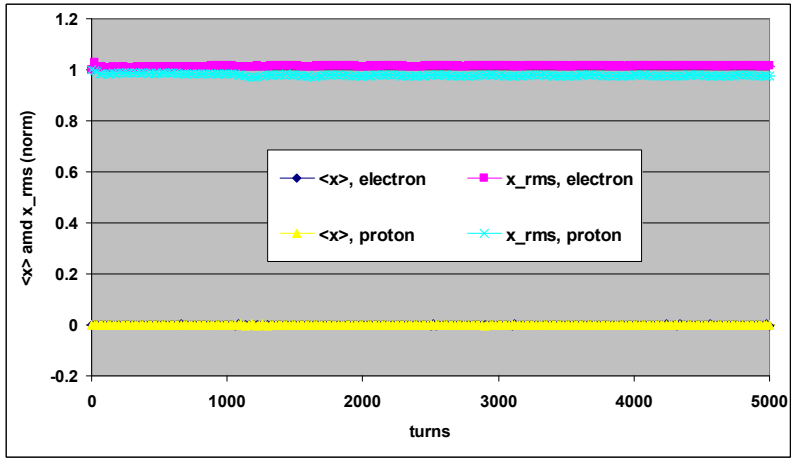

- Collaborators: Rui Li of JLab and Ji Qiang of LBL
- Helpful discussions with Geoff Kraftt of JLab
- JLab ELIC design team
- Support from DOE SciDAC Grant
- NERSC Supercomputer times

# Coherent Beam-Beam Instability

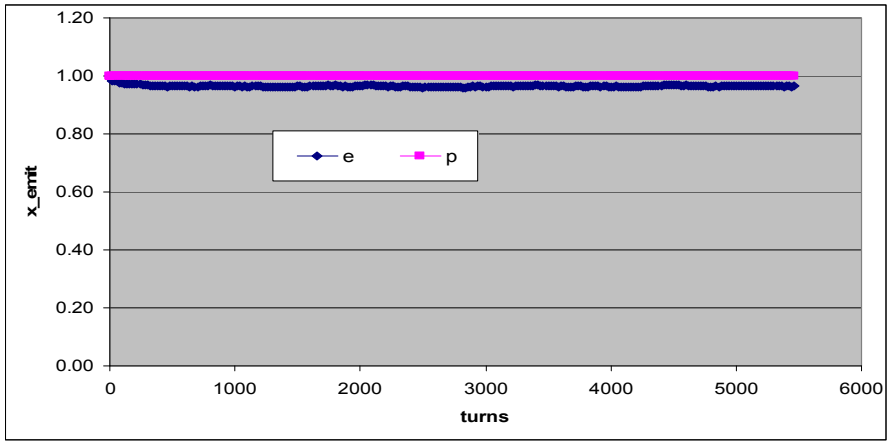
- Electron current is 7.5 A
- Oscillation only in vertical direction
- Not a dipole mode since <x>=<y>=0
- Period is about damping time

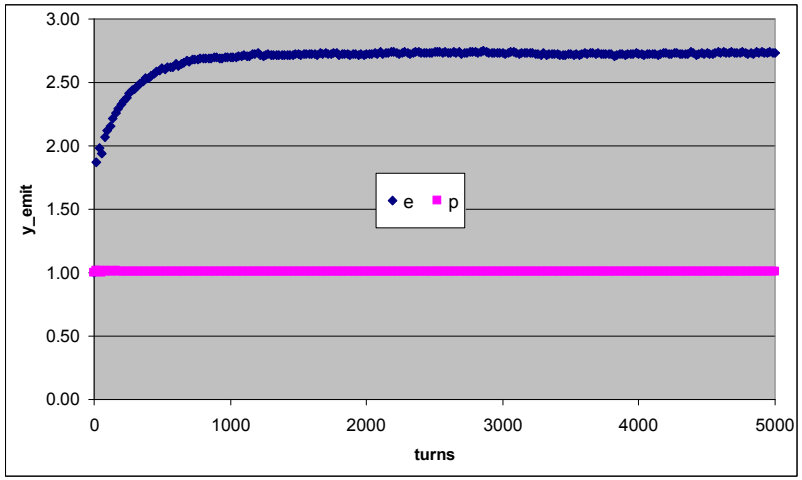
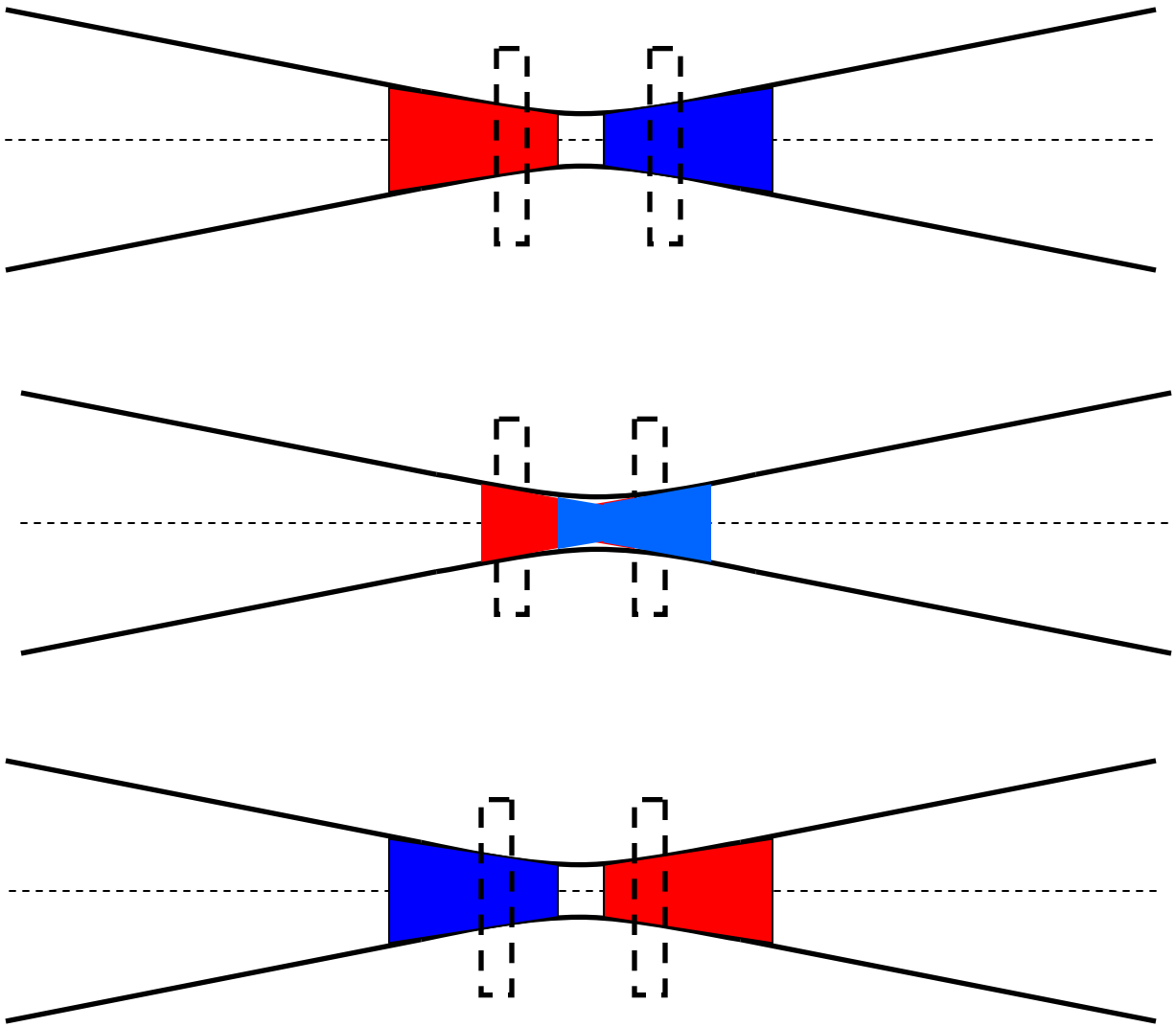


# Backup Slides: More on Nominal Setting






# Backup slide: Illustration of Hour Glass Effect