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Beam-Beam Simulations at MEIC

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Outline

- Overview of the MEIC
  - Motivation for beam-beam simulations
- Beam-beam simulation model
  - Code used in the simulations
  - Scope of simulations
- Simulation results
- Future plans
- Summary

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Overview of the MEIC

- Jefferson Lab has been pursuing design studies of an electron-ion collider for future nuclear physics research (2007 Long Range Plan, DOE/NSF Nuclear Science Advisory Committee)
- Based on CEBAF, the collider would provide collisions between polarized electrons and polarized light ions or unpolarized heavy ions at multiple interaction points (IP)
- Staged approach:
    - Immediate goal: low-to-medium energy collider (MEIC) CM energy up to 51 GeV
    - Future upgrade option: a high-energy collider CM energy 100 GeV or higher

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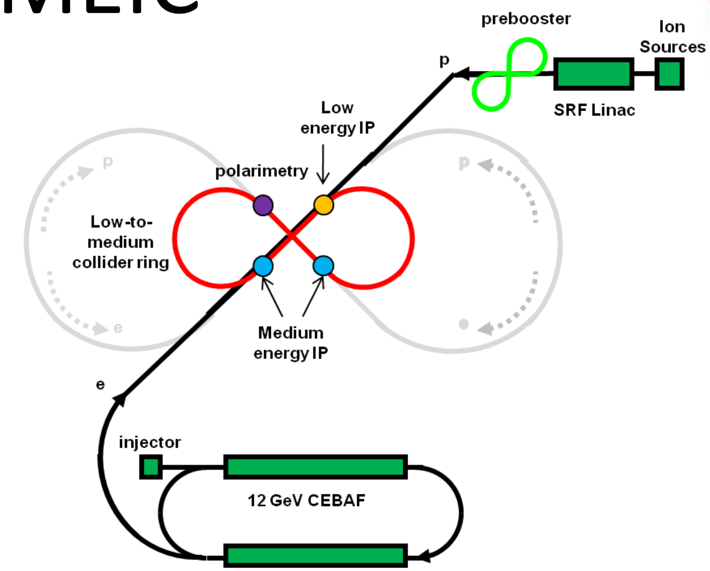
Overview of the MEIC

		p-beam	e-beam
Beam Energy	GeV	60	5
Collision frequency	MHz	1497	
Particles/bunch	10^{10}	0.416	1.25
Beam current	A	1	3
Energy spread	10^{-3}	0.3	0.71
RMS bunch length	mm	10	7.5
Horizontal emittance, norm.	µm	0.35	54
Vertical emittance, norm.	µm	0.07	10.8
Synchrotron tune		0.045	0.045
Horizontal β*	cm	10	
Vertical β*	cm	2	
Distance from IP to front of 1st FF quad	m	7	3.5
Vert. beam-bam tune shift/IP		0.007	0.03
Proton beam Laslett tune shift		0.07	
Peak Lumi/IP, 10^{34}	$cm^{-2}s^{-1}$	0.56	



High luminosity achieved by:
- high bunch repetition rate
- high average current
- short bunches
- strong focusing at IP (small β*)

$$L = \frac{f_c N_e N_p}{2\pi\sqrt{\sigma_{x,e}^2 + \sigma_{x,p}^2}\sqrt{\sigma_{y,e}^2 + \sigma_{y,p}^2}}$$

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Motivation for Beam-Beam Simulations

- Key design MEIC parameters reside in an unexplored region for ion beams
  - very small (cm or less) β^* to squeeze transverse beam sizes to several μm at collision points
  - moderate (50 to 100 mrad) crab crossing angle due to very high (0.5 to 1.5 GHz) bunch repetition (new for proton beams)
- Investigating the beam-beam effect becomes critically important as part of feasibility study of this conceptual design
- The sheer complexity of the problem requires us to rely on computer simulations for evaluating this non-linear collective effect
- Goals of numerical beam-beam simulations:
  - Examine incoherent and coherent beam-beam effects under the nominal design parameters
  - Characterize luminosity and operational sensitivity of design parameters
  - Take into account coupling to single particle nonlinear dynamics in rings

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Simulation Model

- Numerical beam-beam simulations can be divided into two parts:
  1. Tracking of collision particles at IPs
  2. Transporting beams through a collider ring
- Modeled differently to address different physics mechanisms and characteristic timescales
- In this talk, we focus on disruption of colliding beams by non-linear beam-beam kicks (study 1., and idealize 2.)
- Beam transport idealized by a linear map, synchrotron radiation damping and quantum fluctuations
- Strong-strong regime: both beams can be perturbed by the beam-beam kicks

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Simulation Code

- We use BeamBeam3D code (LBNL) (SciDAC collaboration):
  - Self-consistent, particle-in-cell
  - Solves Poisson equation using shifted Green function method on a 3D mesh
  - Massively parallelized
  - Strong-strong or weak-strong mode
- In our present configuration, results converge for:
  - 200,000 particles per bunch
  - 64x128 transverse resolution, 20 longitudinal slices
- Simulation runs executed on both NERSC supercomputers and on JLab’s own cluster

Scope of Simulations

- Model new medium-energy parameter set for the MEIC
- Approximations/simplifications used:
  - Linear map
  - Chromatic optics effects not included
  - Damping of e-beam through synchrotron radiation
  - No damping in ion/p-beam
  - Head-on collisions
  - 1 IP
- Strong-strong (self-consistent, but slow) mode:
  - Only study short-term dynamics – several damping times (1 damping time ~ 1500 turns ~ 5 ms)

Simulation Results

- We address the following issues:
  - Search for a (near-)optimal working point

    Automated and systematic approach
  - Dependence of beam luminosity on electron and ion beam currents
  - Onset of coherent beam-beam instability

Searching For Optimal Working Point Using Evolutionary Algorithm

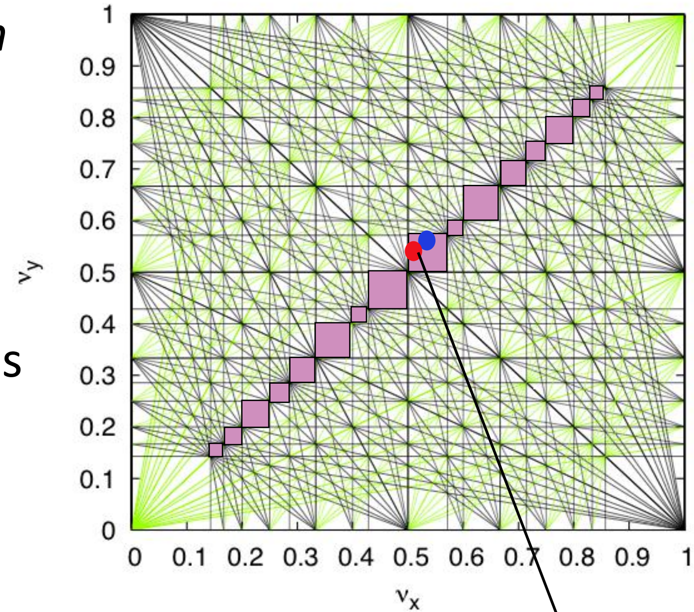
- Beam-beam effect and collider luminosity are sensitive to synchro-betatron resonances of the two colliding beams
- Careful selection of a tune working point is essential for stable operation of a collider as well as for achieving high luminosity
- Optimize a non-linear function using principles of natural selection, mutation and recombination (*evolutionary algorithm*)
    - Objective function: collider's luminosity
    - Independent variables: betatron tunes for each beam (synchrotron tunes fixed for now; 4D problem)
    - Subject to constraints (e.g., confine tunes to particular regions)
- Probably the only non-linear search method that can work in a domain so violently fraught with resonances (*very* sharp peaks and valleys)

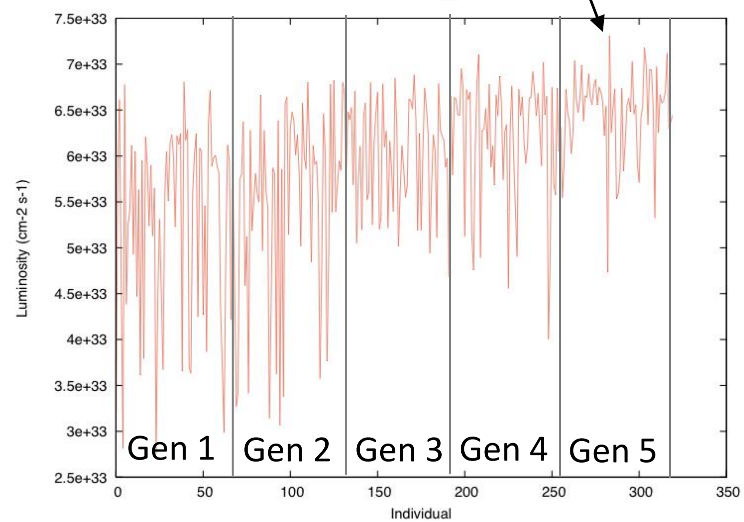
Searching For Optimal Working Point Using Evolutionary Algorithm

- Resonances occur when $m_x\nu_x + m_y\nu_y + m_s\nu_s = n$
  m_x, m_y, m_s and n are integers (m_s=0 for now)
- Green lines: difference resonances (stable)
- Black lines: sum resonances (unstable)
- Restrict search to a group of small regions along diagonal devoid of black resonance lines

- Found an excellent working point near half-integer resonance
  (well-known empirically: PEP II, KEK-B…)
  e-beam: $\nu_x = 0.53$, $\nu_y = 0.548456$, $\nu_s = 0.045$
  p-beam: $\nu_x = 0.501184$, $\nu_y = 0.526639$, $\nu_s = 0.045$
- *Luminosity about 33% above design value in only ~300 simulations*

- Main point: have a reliable and streamlined way to find optimal work point





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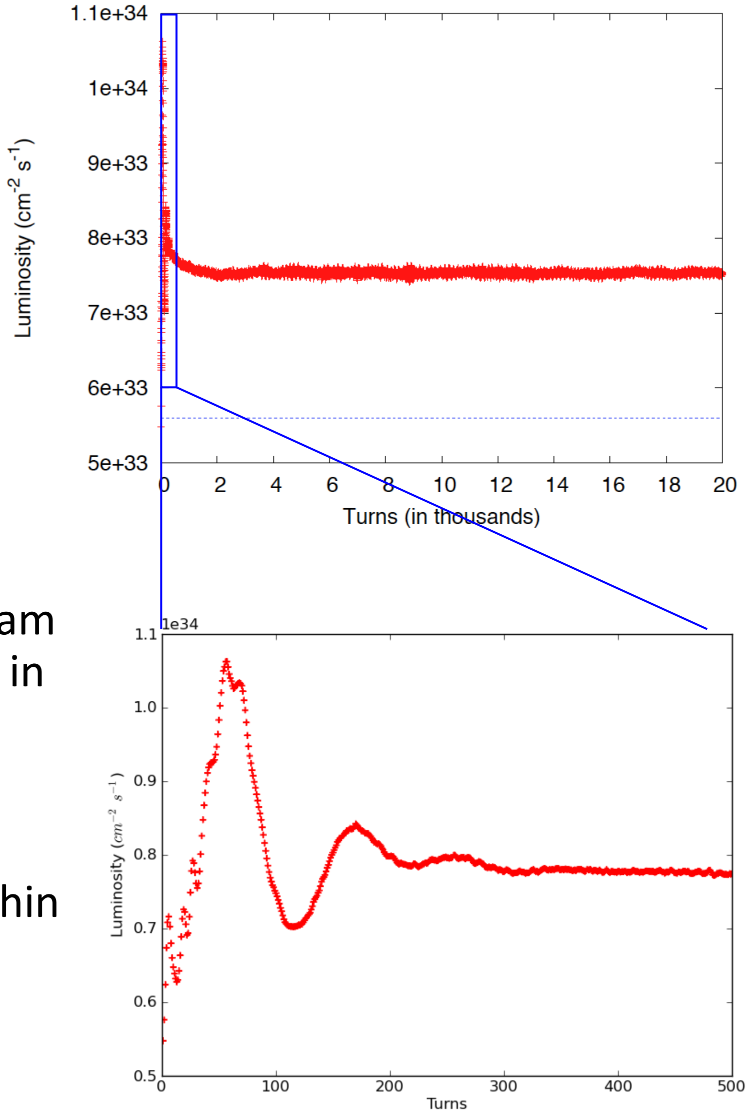
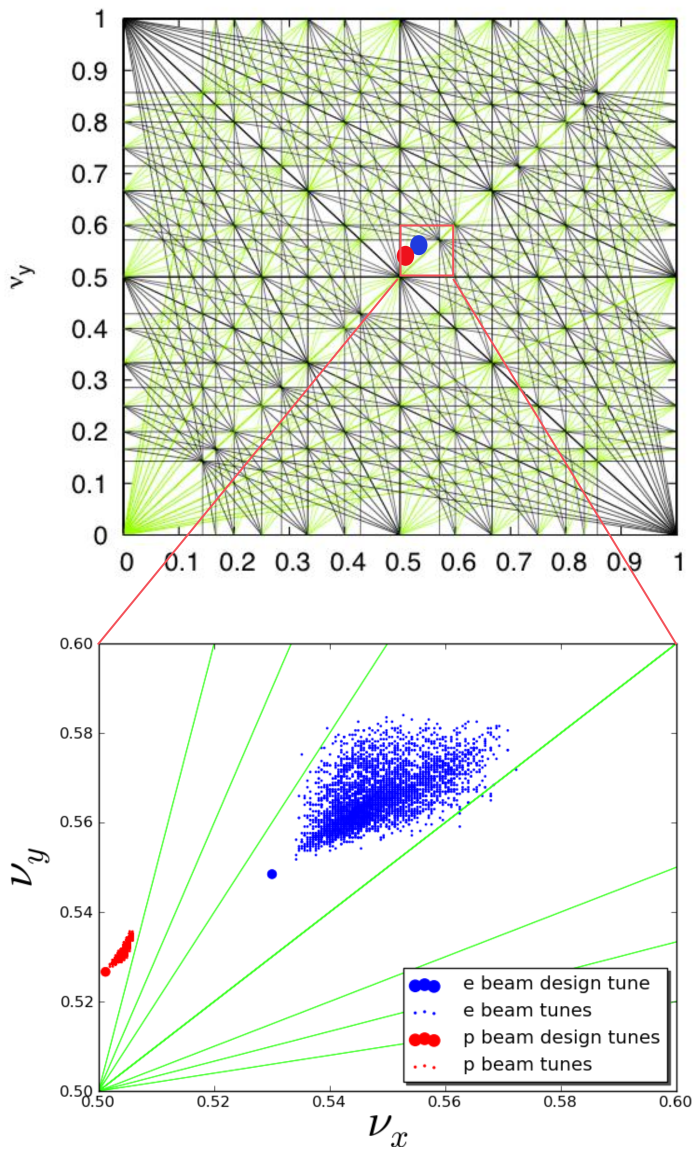
Luminosity at the Optimal Work Point

- For the optimal working point found earlier, compute luminosity for a large number of turns (20,000 ~ 66 ms) (a few days on NERSC/JLab cluster)
- After an initial oscillation, the luminosity appears to settle (within a fraction of a damping time) at a value exceeding design luminosity
- It appears that the beams suffer reduction in beam transverse size at the IP, which yields luminosity in excess of the design value
- Detailed study of phase space is underway
- Main point: short-term stability is verified to within the limits of strong-strong code



Betatron Tune Footprint

- For the optimal working point found earlier, compute tunes for a subset of particles from each beam and see where they lie in relation to the resonant lines (up to 7th order resonances plotted)



- Resonance lines up to 6th order plotted
- Tune footprint for both beams stays comfortably away from resonance lines

- Main point: for stability, the tune footprint of both beams must be away from low-order resonances

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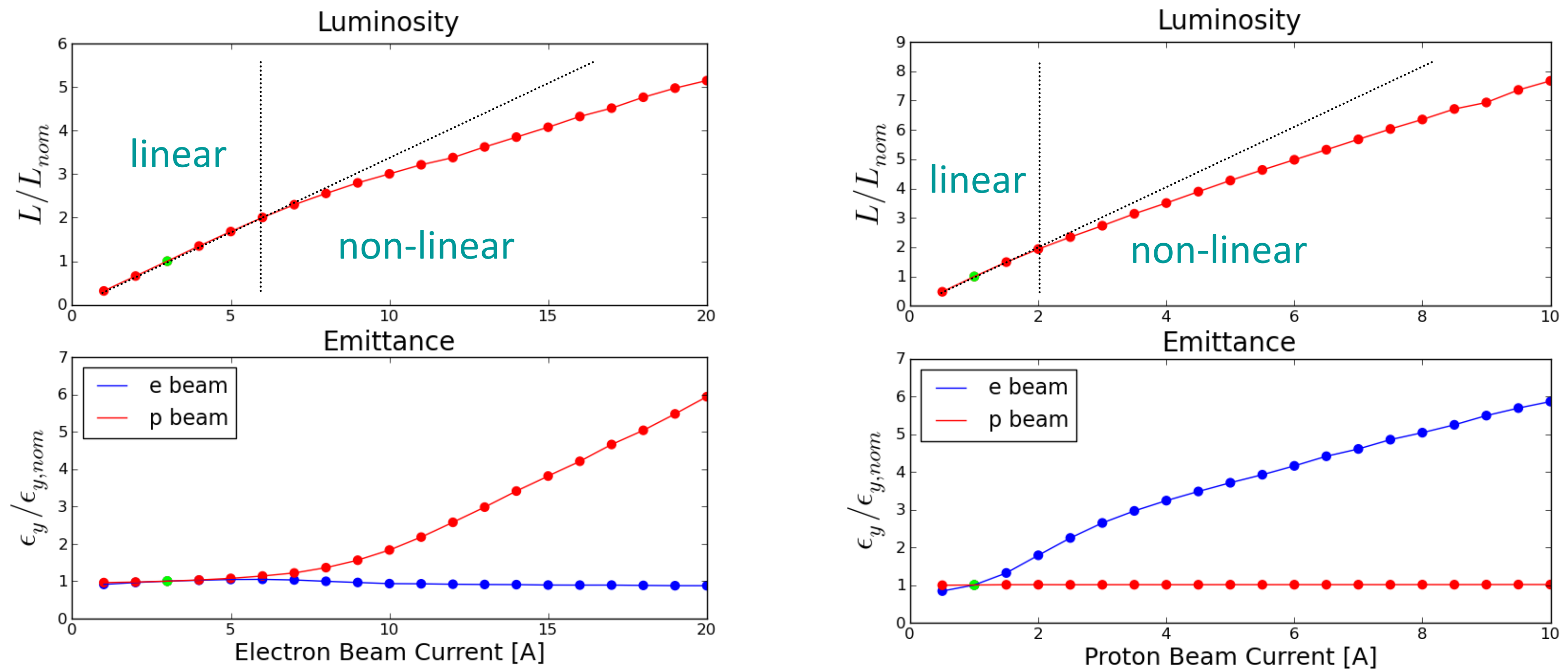
Dependence of Luminosity on Beam Current



- Near design beam current (up to ~2 times larger): linear dependence
- Far away from design current for proton beam: non-linear effects dominate
- Coherent beam-beam instability is not observed
- Main point: as beam current is increased, beam-beam effects do not limit beam stability

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Future Plans

- Outstanding issues we will address in future simulations:
  - Including non-linear dynamics in the collider rings:
    - Non-linear optics
    - Effect of synchrotron tune on beam-beam
    - Chromatic effects
    - Imperfect magnets
  - Crab crossing (high integrated-voltage SRF cavities)
  - Other collective phenomena:
    - Damping due to electron cooling in ion/proton beams
    - Space charge at very low energy (?)
  - Long-term dynamics: use weak-strong simulations

Summary

- Beam-beam effects are critical for the MEIC
- We developed methodology to study beam-beam effects
  - Used existing and developed new codes/methods
- Presented first results from numerical simulations
- Main point: beam-beam effects do not limit the capabilities of the MEIC
- Ultimate goal of beam-beam simulations: verify validity of MEIC design and optimize its performance

Backup Slides

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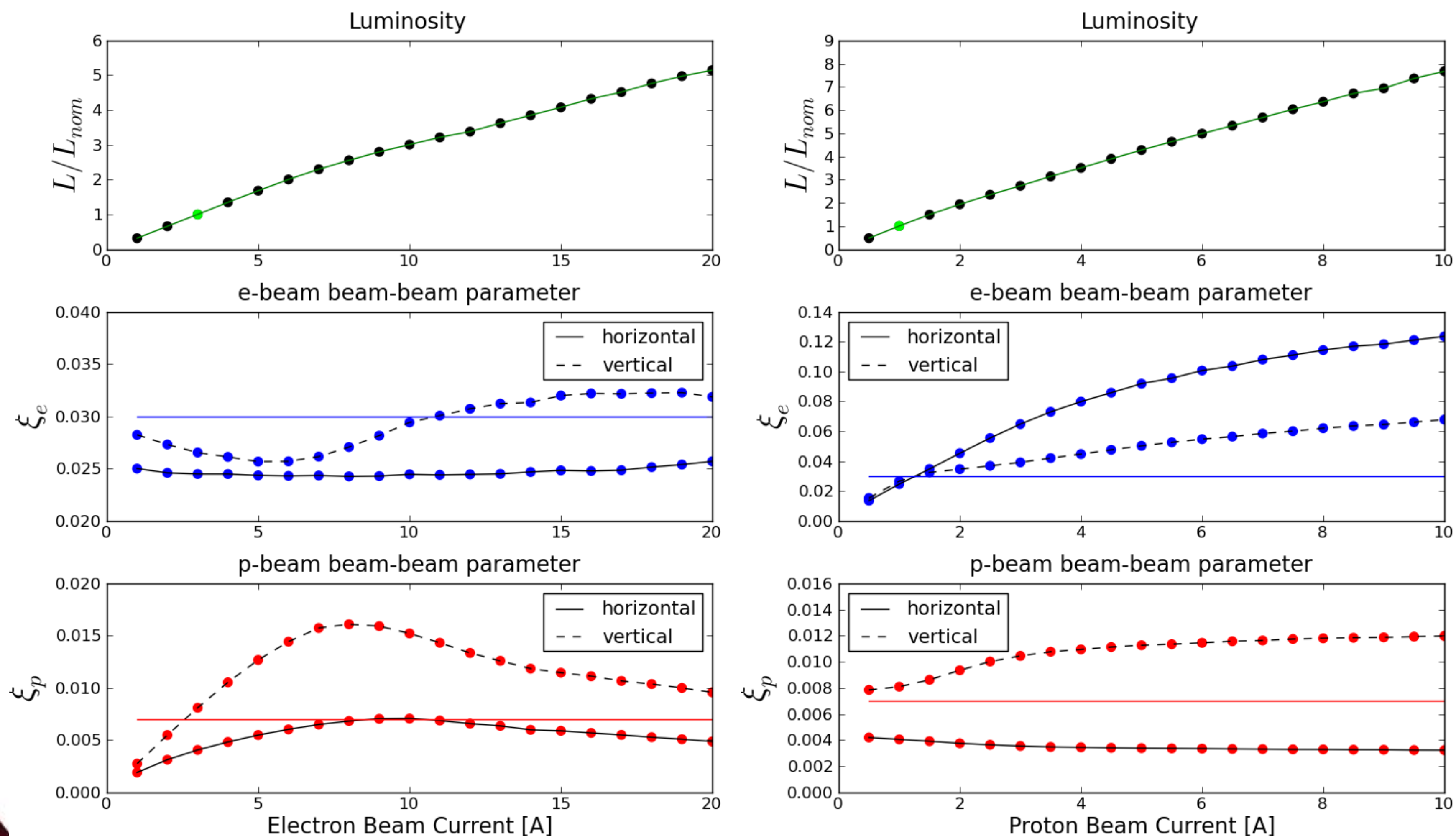
Dependence of Effective Beam-Beam Tuneshift on Beam Current



$$\xi_{e,x} = \frac{N_p r_e}{2\pi\gamma_e \varepsilon_{e,x}\left(1+\frac{\sigma_y}{\sigma_x}\right)}$$

$$\xi_{p,x} = \frac{N_e r_p}{2\pi\gamma_p \varepsilon_{p,x}\left(1+\frac{\sigma_y}{\sigma_x}\right)}$$

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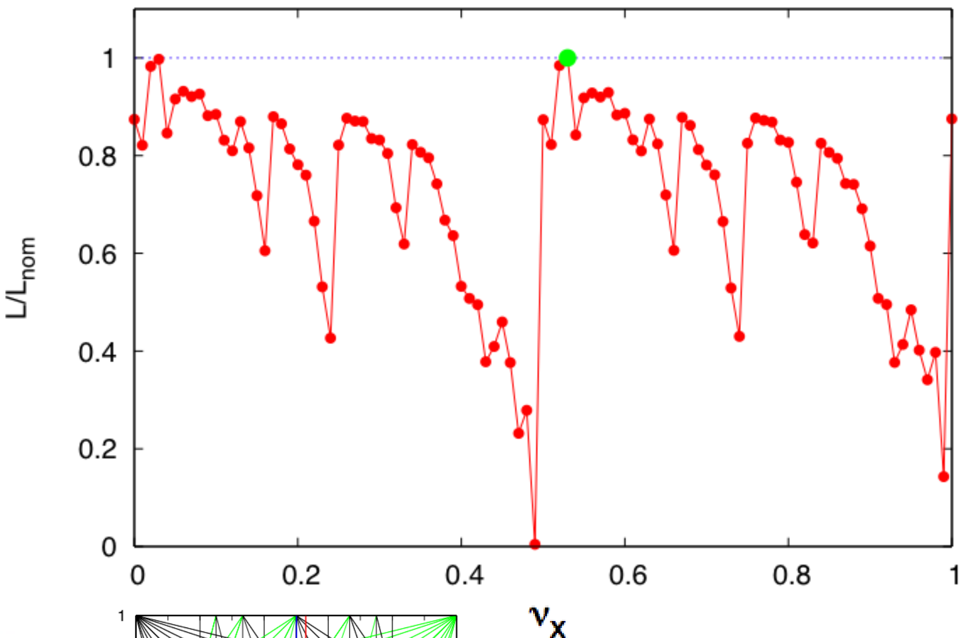
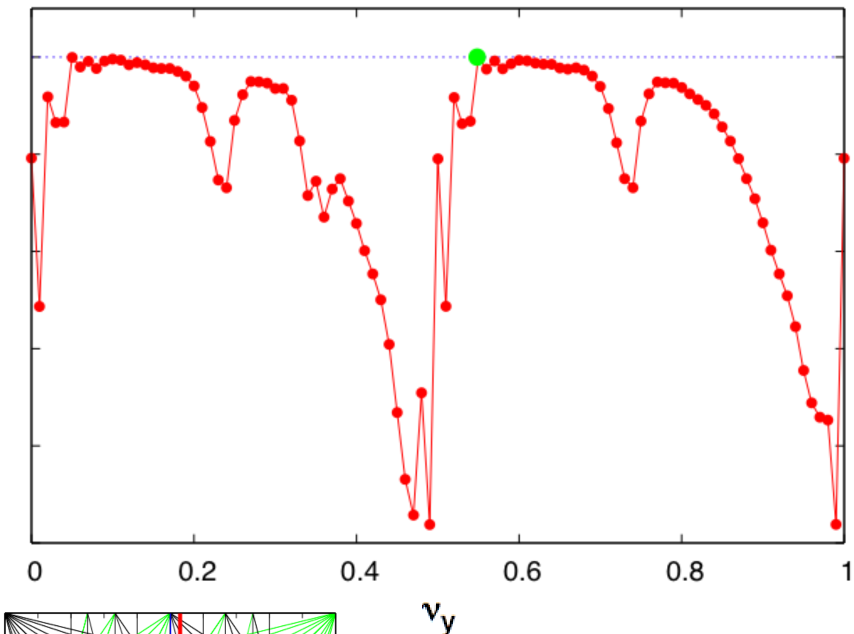
Tune Scan

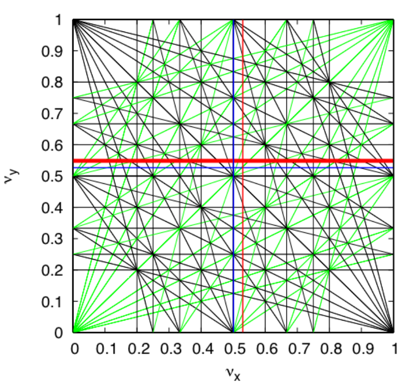
Electron Beam

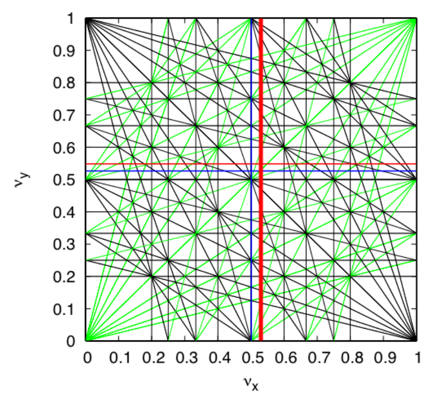
Vary Electron X Tune



Vary Electron Y Tune







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Tune Scan

Proton Beam