Beam-Beam Effects in an ERL-based Electron-Ion Collider

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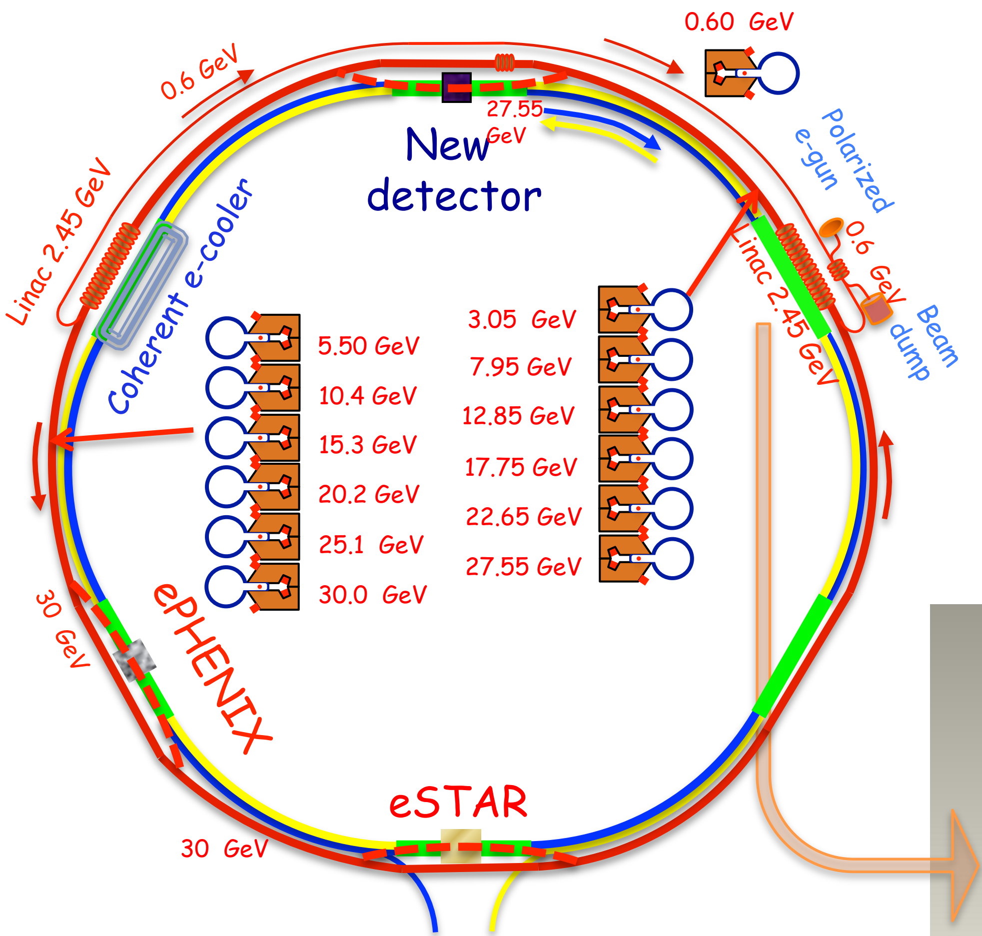
ERL-based eRHIC is future e-ion collider

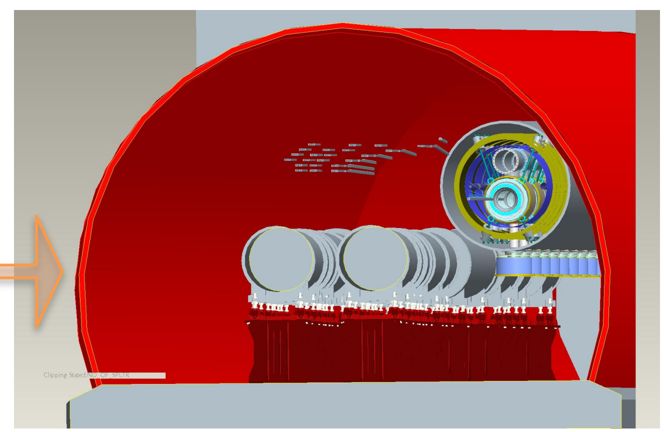


Linac-ring collision scheme

✓All-in tunnel staging approach uses two energy recovery linacs and 6 recirculation passes to accelerate the electron beam.

✓Staging: the electron energy will be increased in stages, from 5 to 30 GeV, by increasing the linac lengths .

✓Up to 3 experimental locations



Main R&D Items of eRHIC Design

- Electron beam R&D for ERL-based design:
  - High intensity polarized electron source
    - Development of large cathode guns with existing current densities ~ 50 mA/ cm^2 with good cathode lifetime.
  - Energy recovery technology for high power beams
    - multicavity cryomodule development; high power beam ERL, BNL ERL test facility; loss protection; instabilites.
  - Development of compact recirculation loop magnets
    - Design, build and test a prototype of a small gap magnet and its vacuum chamber.
  - **Beam-beam effects: e-beam disruption**

- Main R&D items for ion beam:
  - **Beam-beam effects: electron pinch effect; the kink instability …**
  - Polarized ^{3}He acceleration
  - 166 bunches
  - Proof of principle of the coherent electron cooling.
  - Crab-crossing

FEATURES OF BEAM-BEAM INTERACTION OF LINAC-RING SCHEME

Compared with "standard" beam-beam interactions in collider rings, the linac-ring collision scheme brings on very specific effects:

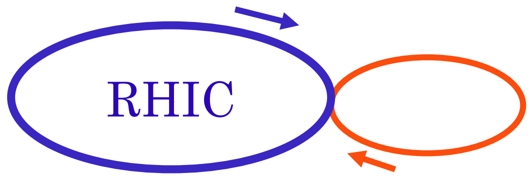
- Electron beam disruption.
- Fluctuation of electron beam parameters.
- Kink instability of the proton beam.
- Effect of electron beam pinch on the incoherent proton beam emittance growth.

Those effect are being studied in details using a dedicated simulation code EPIC (Y. Hao, Ph.D. Theses, 2008)

I won't discuss the effects on the proton beam in this talk.
The focus will be on the electron beam disruption, which increase the beam emittance and modifies the transverse beam distribution.

Beam-Beam Interaction Strength

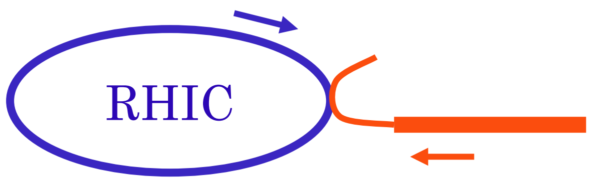
Ring-ring:



($\xi_e < 0.1$)

The beam-beam parameter is the linear betatron tune shift from the beam-beam force: $\xi_e = \frac{1}{4\pi}\frac{\beta^*}{f_e} = \frac{\beta^* N_p r_e}{4\pi\gamma_e r^2}$

Linac-ring:



Disruption parameter: $d_e = \frac{l_p}{f_e} = \frac{l_p N_p r_e}{\gamma_e \sigma_p^2}$

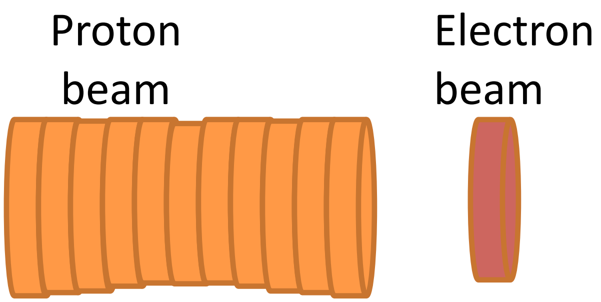
Electron finishes ~ $\sqrt{d_e}/4$ oscillations inside the proton beam

Range of eRHIC disruption parameter:
$d_e \sim 1.5$ (30 GeV (e) x 100 GeV(p))
$d_e \sim 140$ (5 GeV (e) x 250 GeV(p)) → (ξ_e *up to 6.8 !*)

Special Features of Beam-Beam Interactions of ERL based eRHIC

- Asymmetric Collision Strength
  - Electron distribution is distorted in one collision. Single pass simulation is required.
  - Proton/ion beam is only slightly affected in one collision. Accumulated effect over thousands turns needs investigation.

- Asymmetric Bunch Length
  - Protons: > 5cm
  - Electrons: ~2 mm



Features of the EPIC code

- A collision is simulated in two-pass scheme.
- First pass:
  The electron beam (~50K macro-particles) passes through the rigid proton beam, which is sliced longitudinally (> 20 slices).
- Second pass:

  The proton beam macro-particles (> 50K) collides with electron beam (one slice) which parameters (position offset, rms size, radial distribution …) were calculated along the collision region from first pass data.

- Field is calculated either using formula for Gaussian distribution or using Gauss law (from radial distribution).
- Proton beam transport between collisions using the transport matrix.

  Includes chromaticity, amplitude dependent betatron tune spread, synchrotron oscillations.
- Uses parallel computing

What we want to get from the simulations?

Find/verify the IR optics which allows:

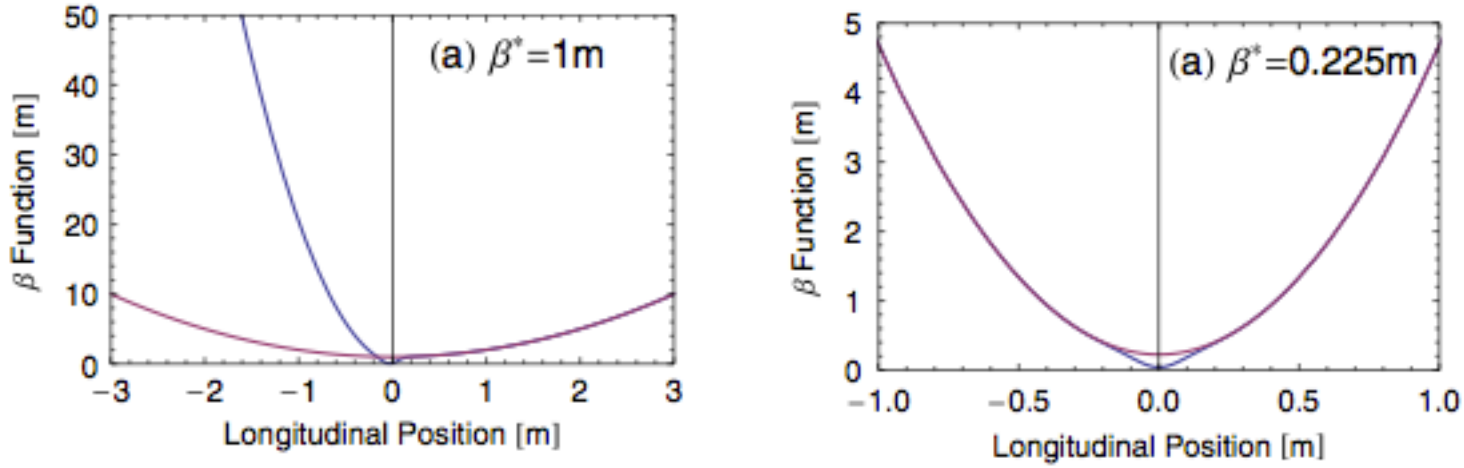
- Minimized linear mismatch and nonlinear disruption of the electron beam by the collisions
- Avoiding the excessive pinching of the electron beam throughout the interaction area
- Sufficiently high luminosity

Scans of β^*, s^* and the electron emittance to find the optimal optics conditions.

Beam-Beam Matched Optics Solutions

At not very large disruption parameters the "matched" optics solution can be found for linear beam-beam effect.

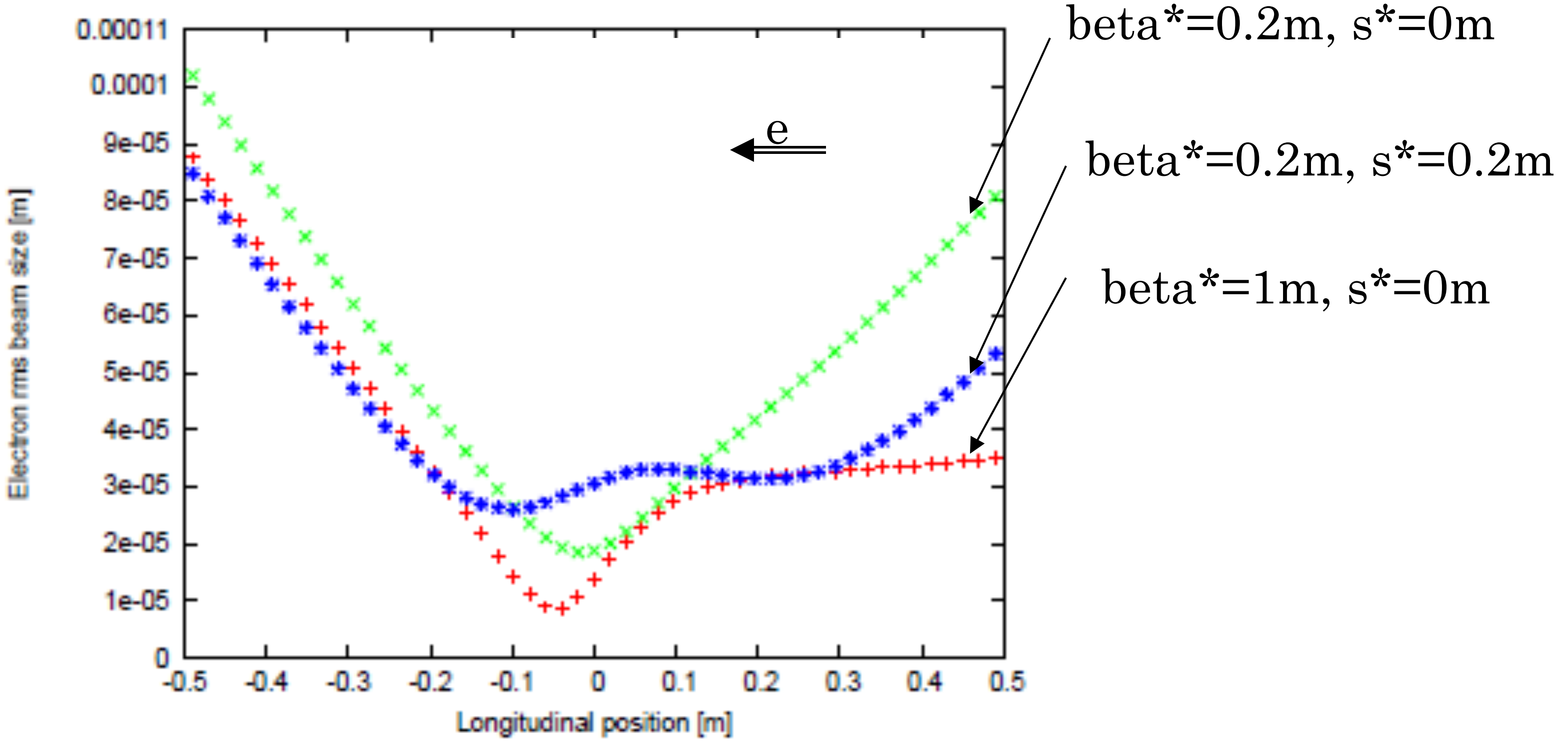
red curve: without beam-beam; blue curve: with beam-beam



For large disruption parameters we would like to have the solution with minimized mismatch.

Those "linear matched" optics solutions are not optimal, but the optimal solutions, with full non-linear beam force, are usually not far away in the optics parameter space.

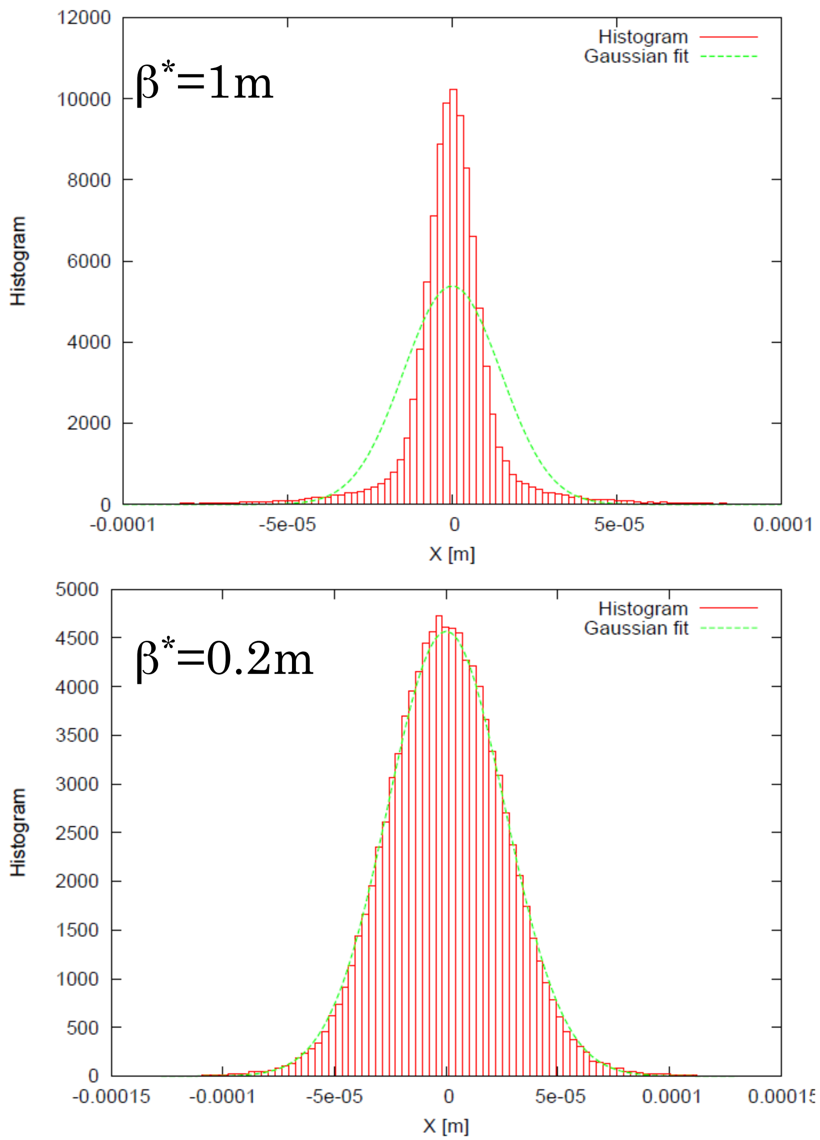
DEPENDENCE OF THE ELECTRON BEAM SIZE PINCHING ON IR LATTICE



Issues coming with the pinch effect:

- Luminosity enhancement (~average beam size)
- Enhanced beam-beam parameter -> Incoherent proton beam emittance growth (minimum beam size)
- Longitudinal beam-beam parameter modulation -> synchro-betatron effects

Deformation of the electron distribution

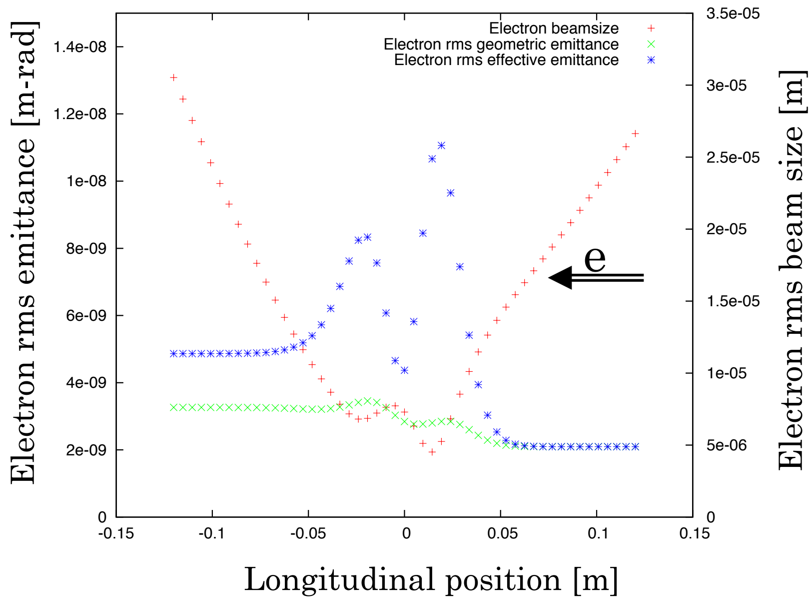


- The electron beam distribution is deformed by the nonlinear beam-beam force and deviates from Gaussian form: longer tails, dense core.

- The field calculation uses Gauss law (for round beam shape).

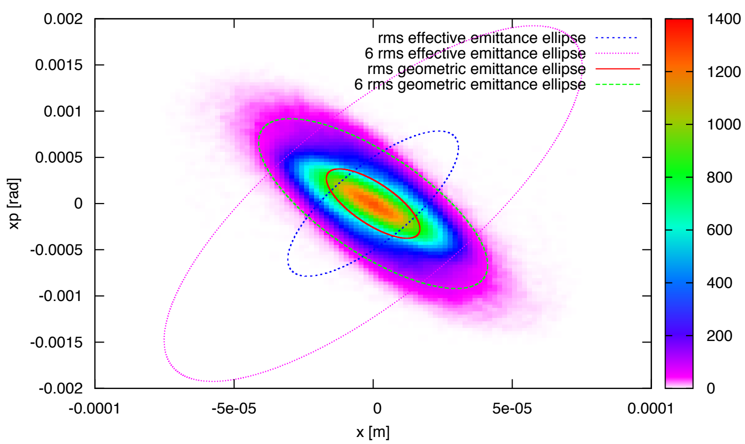
- The distribution deformation depends on the IR optics choice and initial beam emittance.

ELECTRON BEAM DISRUPTION

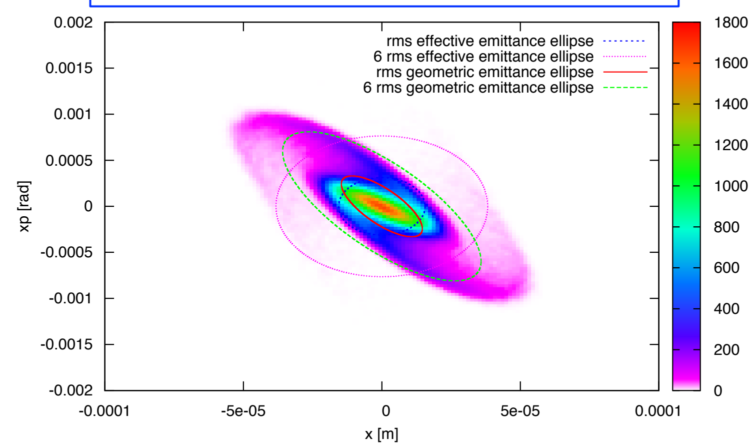


- The electron beam transverse distribution is strongly affected by the collisions.
- Increase of "effective" emittance due to the mismatch.
- Increase of "geometrical" emittance due to the disruption.
- A correct choice of the interaction region electron optics (β^* and s^*) and the electron beam emittance allows to minimize both the mismatch and the disruption.

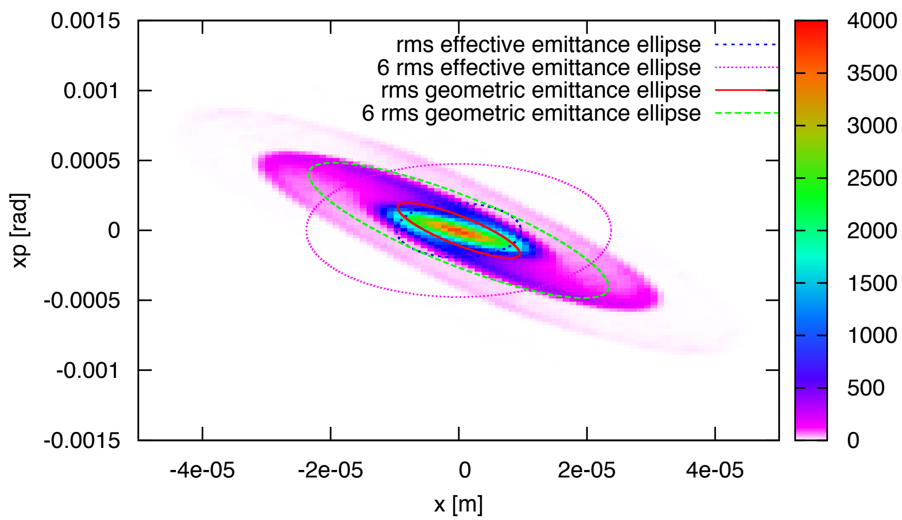
β^*=2.5 cm, s^*=3 cm, ε_{rms} = 4.2 nm

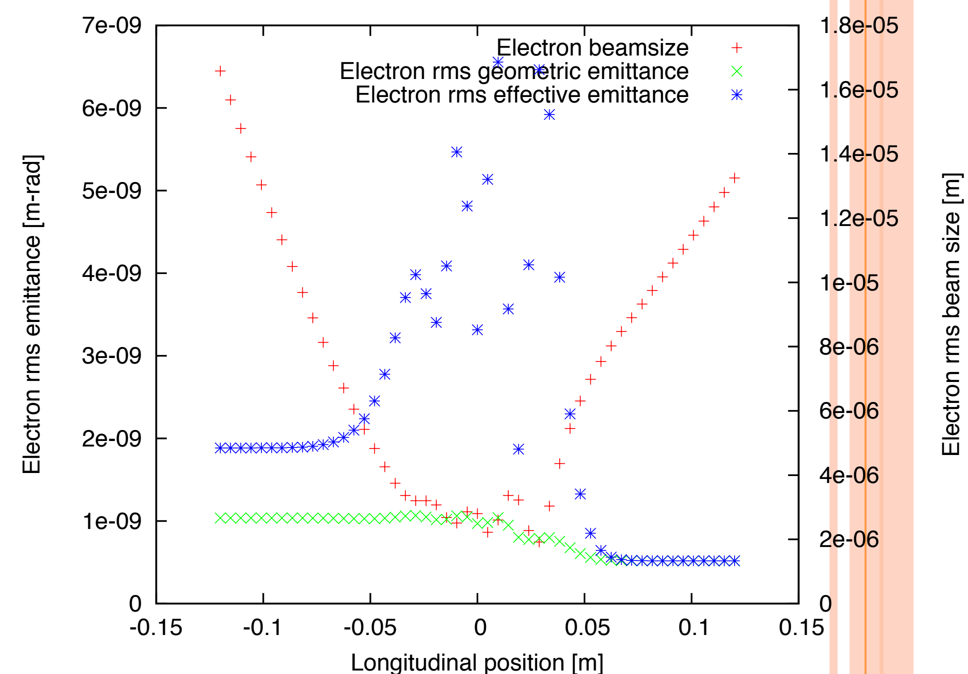


β^*=5 cm, s^*=0 cm, ε_{rms} = 2.1 nm



Simulation Results for large disruption case
325 GeV Proton beam & 5 GeV Electron beam



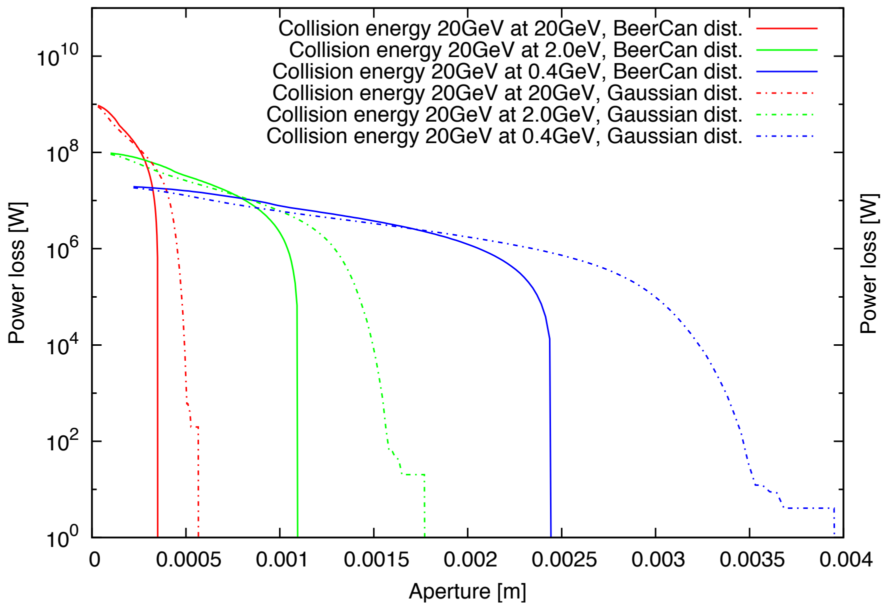


High disruption parameter case (d>100). The electron beam finishes 2 full oscillation in the opposing beam. Long tail is formed due to the nonlinearity. The resulting luminosity is 2.3e34 $cm^{-2}s^{-1}$.

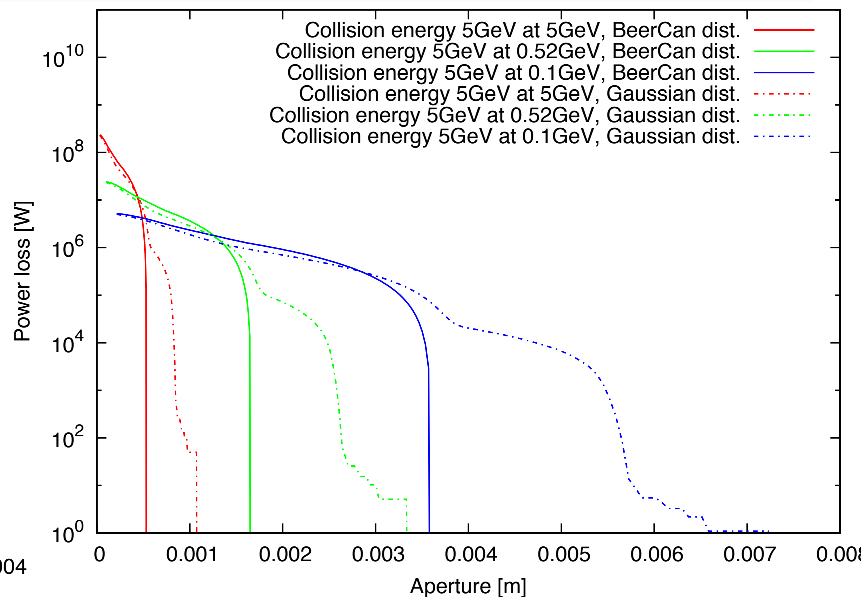
Recirculation Pass aperture Requirements

The electron beam after passing the collision has to be decelerated in ERLs and transported in recirculation passes.

Plots show the beam loss power on the beam pipe in dependence of the pipe aperture for different recirculation passes



Electron energies:
After collision: 20 GeV
Lowest energy path: 2.0 GeV
Path to pre-linac: 0.4 GeV



Electron energies:
After collision: 5 GeV
Lowest energy path: 0.52 GeV
Path to pre-linac: 0.1 GeV

Gaussian initial distribution is taken with 4-sigma cut-off.

SUMMARY

- Beam-beam effects are important R&D item for the ERL-based electron-hadron colliders.
- The beam-beam simulations have been essential for the understanding achievable luminosity, defining/confirming the IR lattice parameters.
- The electron transverse distribution is considerably modified by the beam-beam interactions. The emittance is increased due to both the linear mismatch and non-linear disruption.
- Tails of the electron transverse distribution define the aperture requirements for the magnets of lower energy recirculation passes in eRHIC

[1]. Y. Hao, Ph.D. thesis, Indiana University (2008).
[2]. Y.Hao and V. Ptitsyn, PRSTAB, 13, 071003 (2010).
[3] Y. Hao, V.N. Litvinenko, V.Ptitsyn, TUOAN4, PAC'11, New York.

The distribution of different disruption (0-108.4)