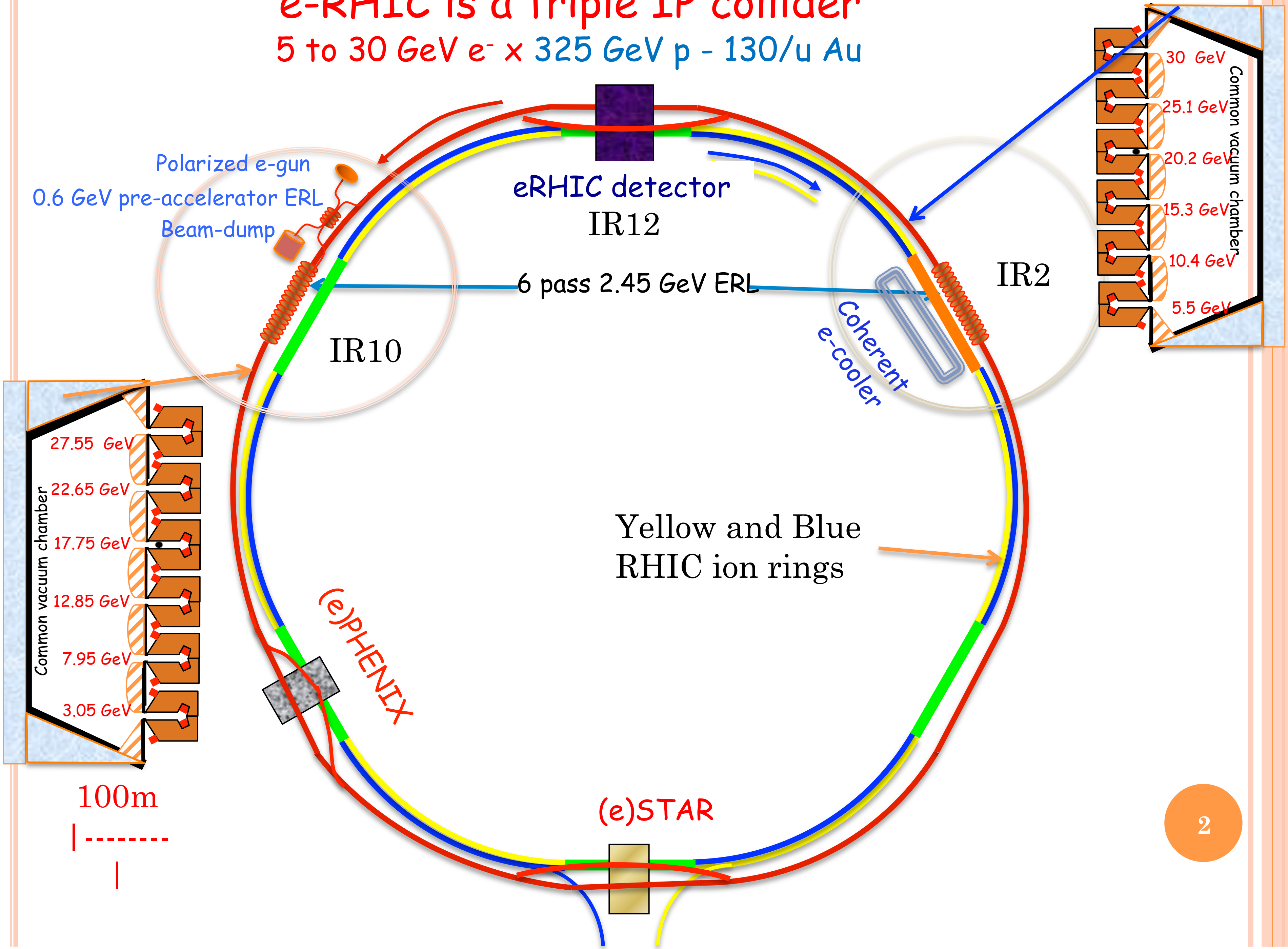
Beam-beam Simulation at eRHIC

Y. Hao, V.N. Litvinenko, V. Ptitsyn,
Collider-Accelerator Department
Brookhaven National Laboratory

September 29, 2010 HB 2010 Workshop, Morschach

e-RHIC is a triple IP collider

5 to 30 GeV e⁻ x 325 GeV p - 130/u Au



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.

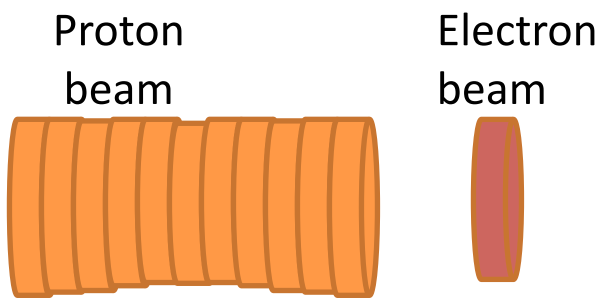
Those effect are being studied in details using a dedicated simulation code EPIC, written by Y. Hao (Ph.D. Theses, 2008)

The goal was to have the time efficient code.
The result should be obtained on the scale of hours, not days.

Special Features in Beam-Beam Simulation 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:

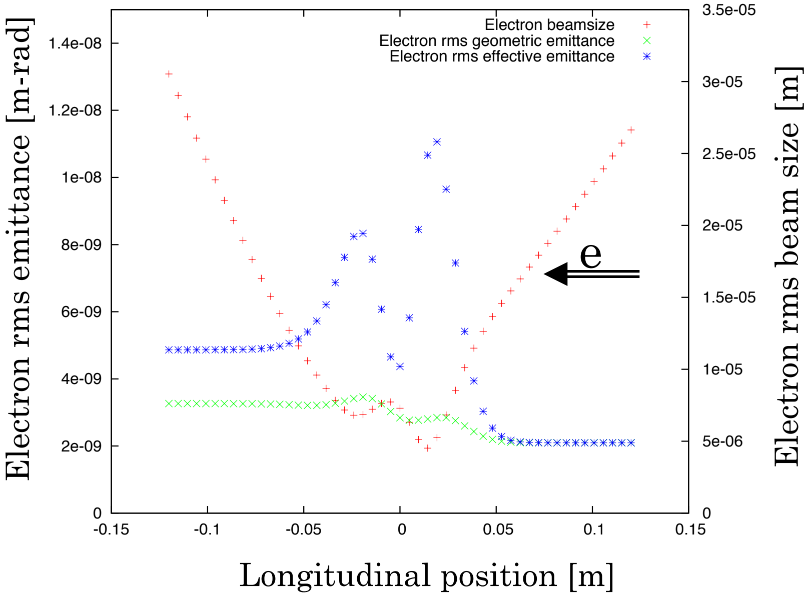
  The proton beam macro-particles (> 50K) collides with electron beam (one slice) which parameters (position offset, rms size, radial distribution …) were calculated along the collision region from first pass data.

- Field is calculated either using formula for Gaussian distribution or using Gauss law (from radial distribution).

- Proton beam transport between collsions using the transport matrix.

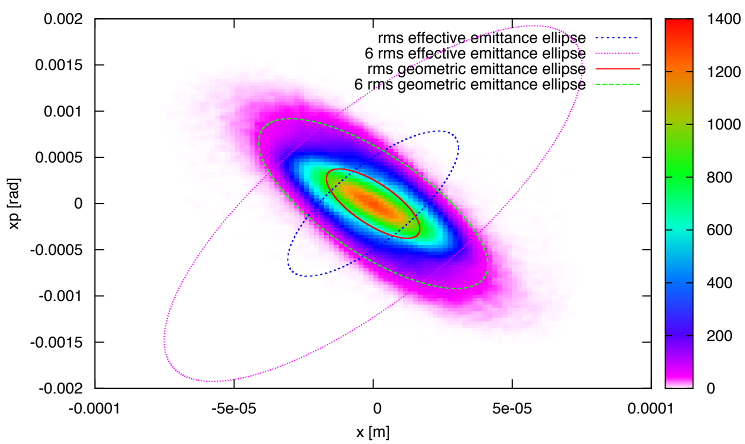
  Includes chromaticity, amplitude dependent betatron tune spread, synchrotron oscillations.
- Uses parallel computing

ELECTRON BEAM DISRUPTION

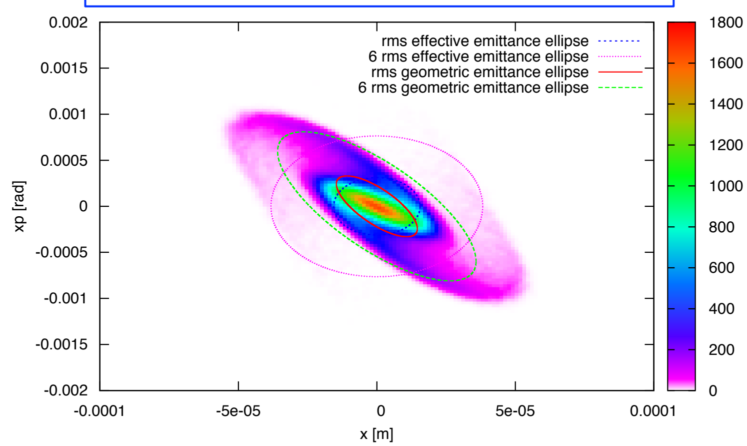


- The electron beam transverse distribution is strongly affected by the collisions.
- Increase of "effective" emittance due to the mismatch.
- Increase of "geometrical" emittance due to the disruption.
- A correct choice of the interaction region electron optics (β^* and s^*) and the electron beam emittance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

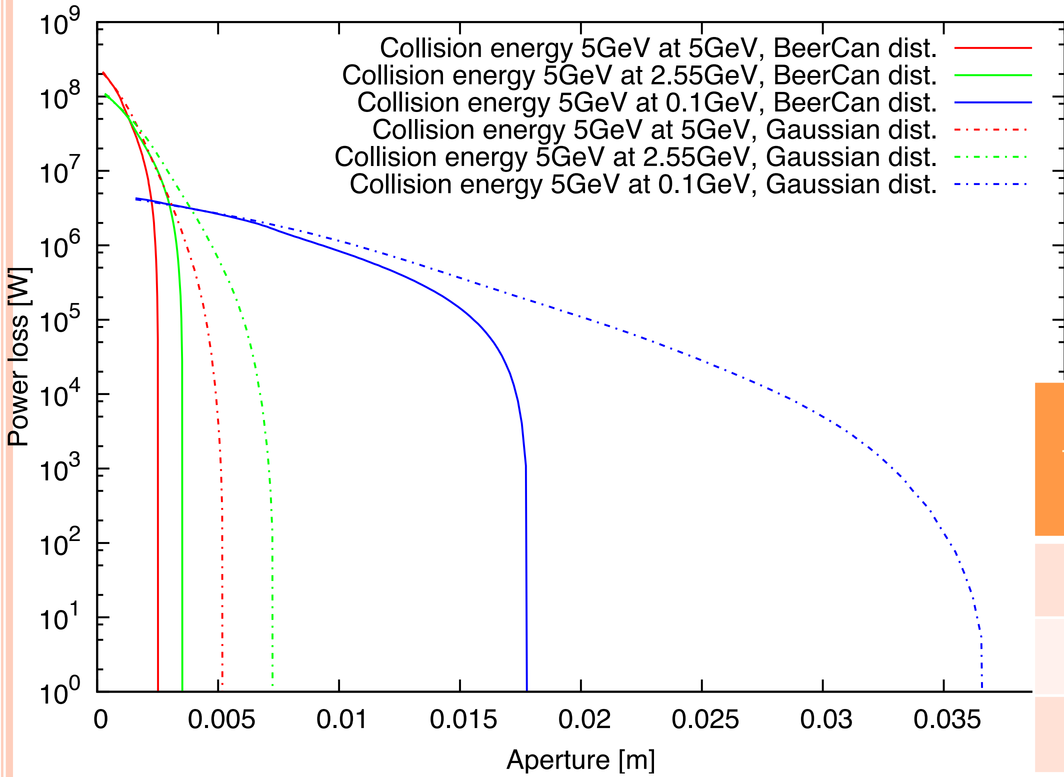
β^*=2.5 cm, s^*=3 cm, ε_{rms} = 4.2 nm

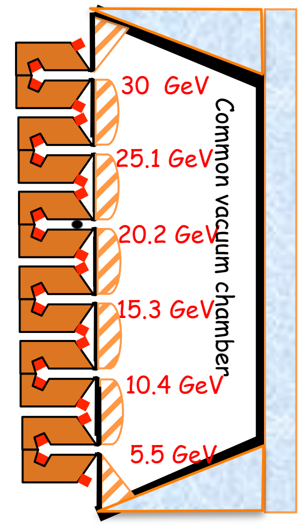


β^*=5 cm, s^*=0 cm, ε_{rms} = 2.1 nm



POWER (BEAM) LOSS REQUIREMENTS ON APERTURE

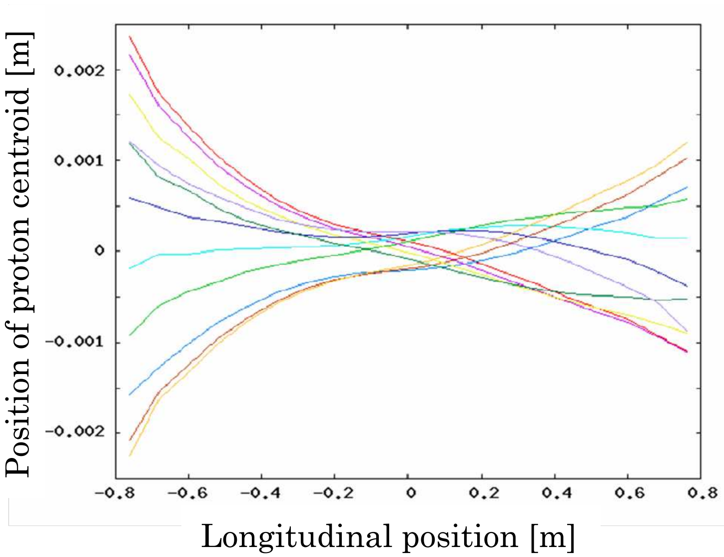




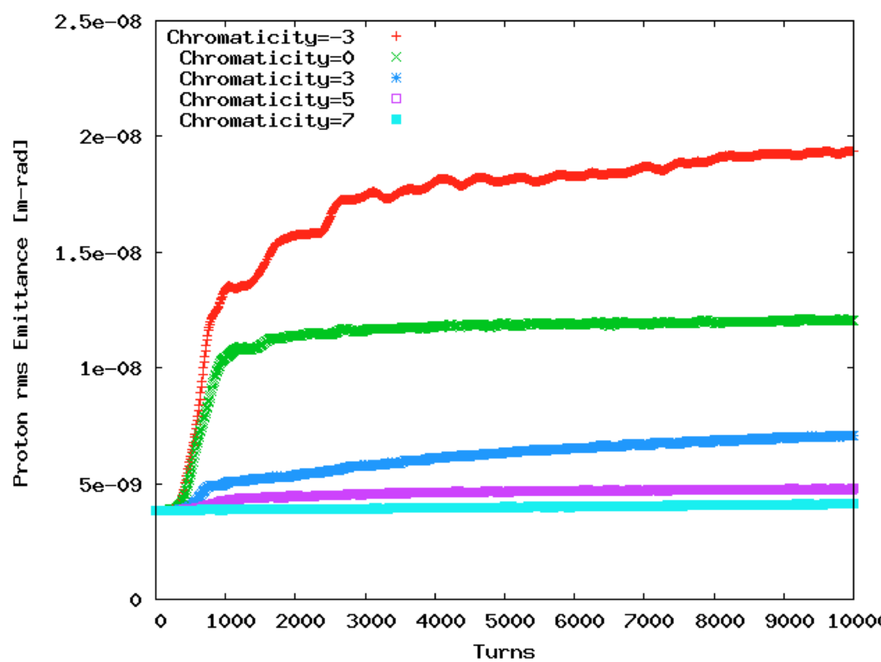
Aperture of 1KW loss @	Ini. BeerCan	Ini. Gaussian
5GeV	2.5mm	5mm
2.55GeV	3.5mm	7mm
0.1GeV	17mm	33mm

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

Kink Instability



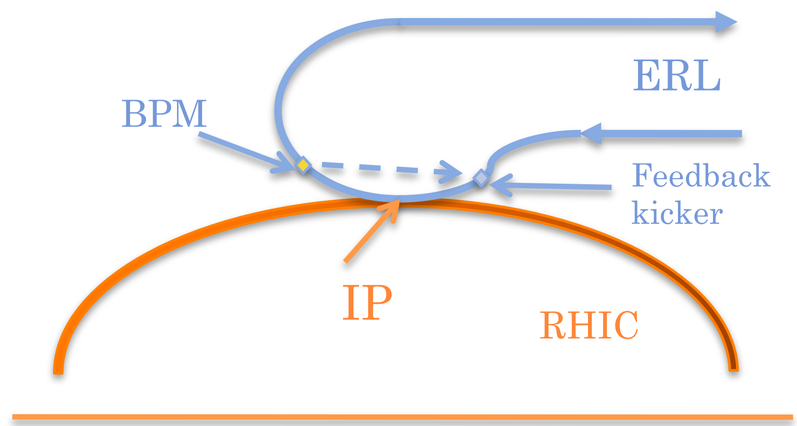
The head-tail type interaction in proton beam by means of electron beam.
The dipole mode of the instability is well seen in the simulations.

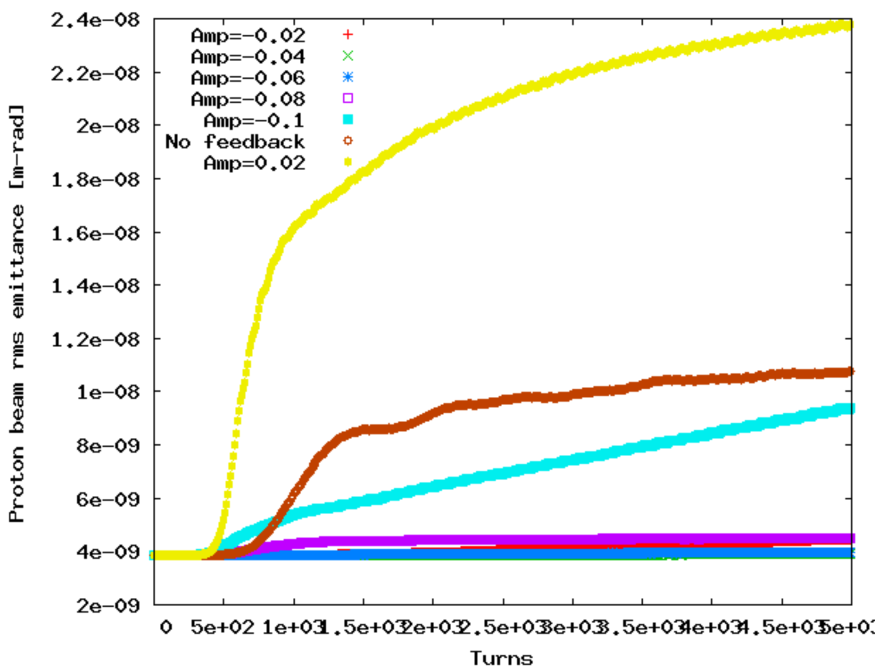


In eRHIC the instability can be cured with chromaticity larger than 6.

FEEDBACK STABILIZATION OF KICK INSTABILITY IS POSSIBLE

Large chromaticity is unpleasant in real machine operation.

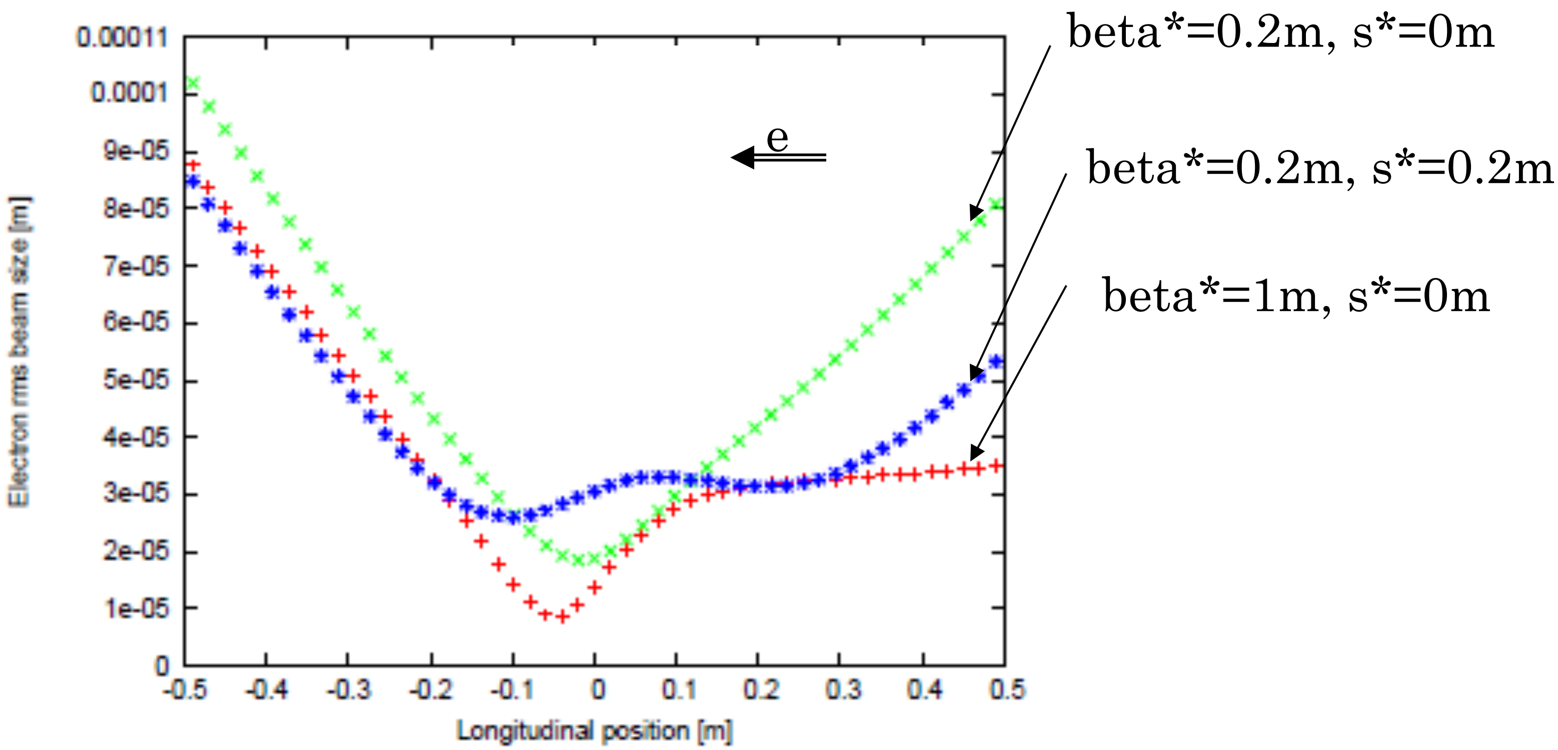




Proof-of-principle simulation run for the feedback system.

Different curves corresponds to different amplitude coefficient connecting BPM measurements and applied kick.

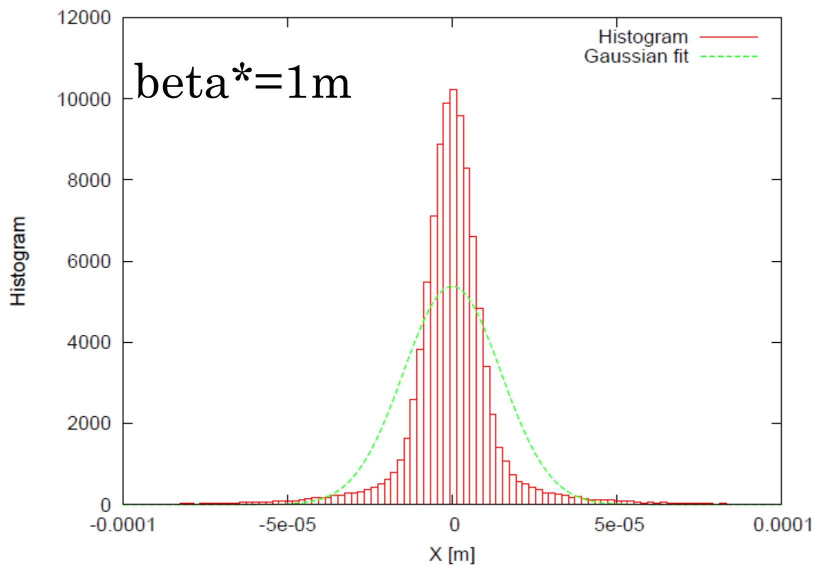
DEPENDENCE OF THE ELECTRON BEAM SIZE PINCHING ON IR LATTICE

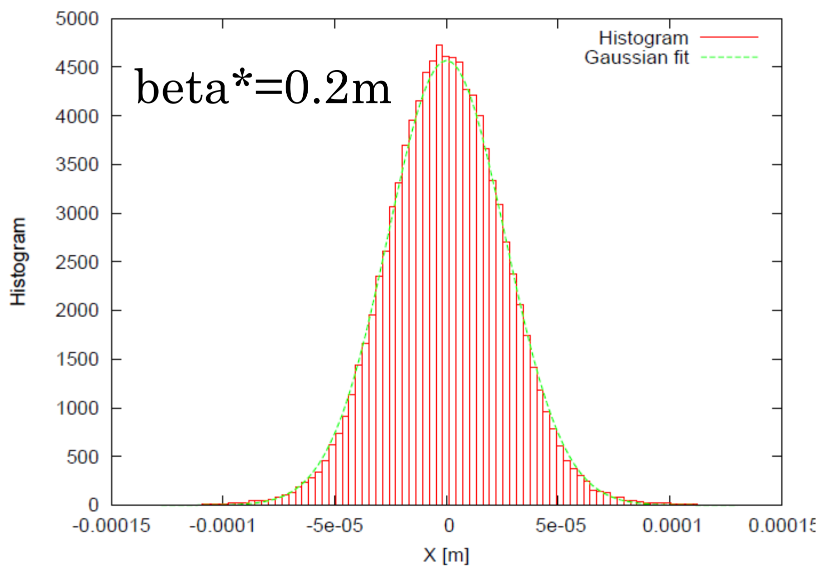


Issues coming with the pinch effect:

- 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





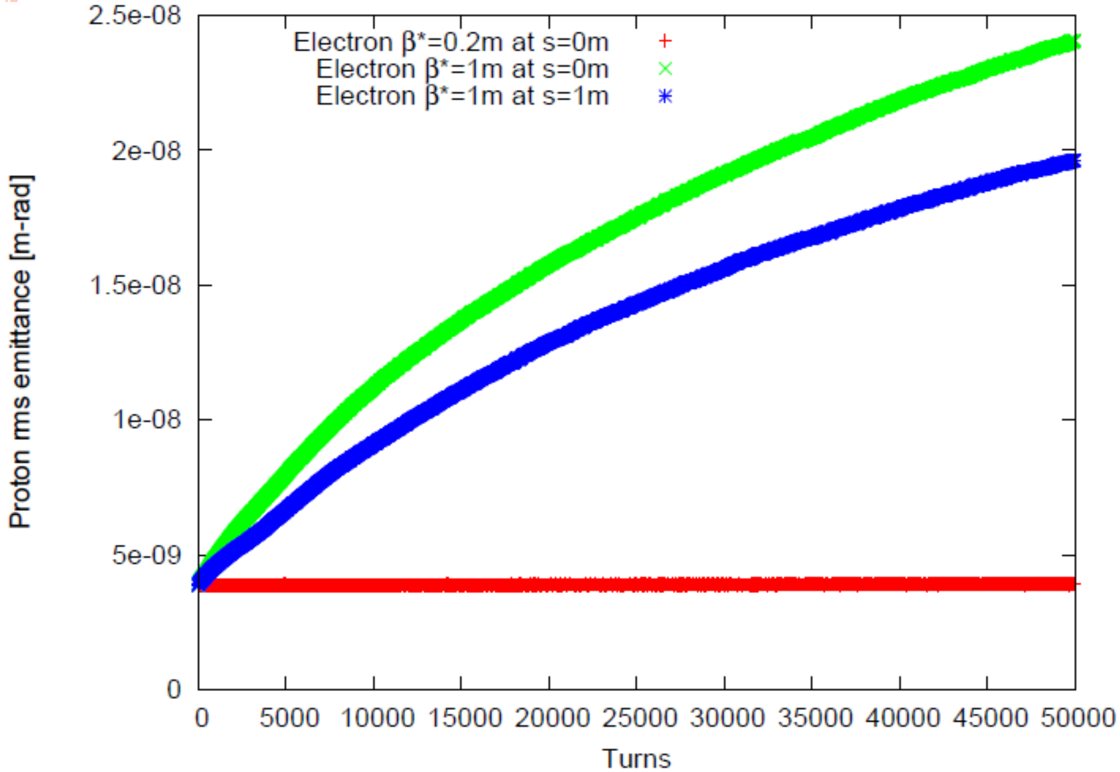
- The electron beam distribution is deformed by the nonlinear beam-beam force and deviates from Gaussian form: longer tails, dense core.

- It enhances the emittance growth of the proton beam.

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

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

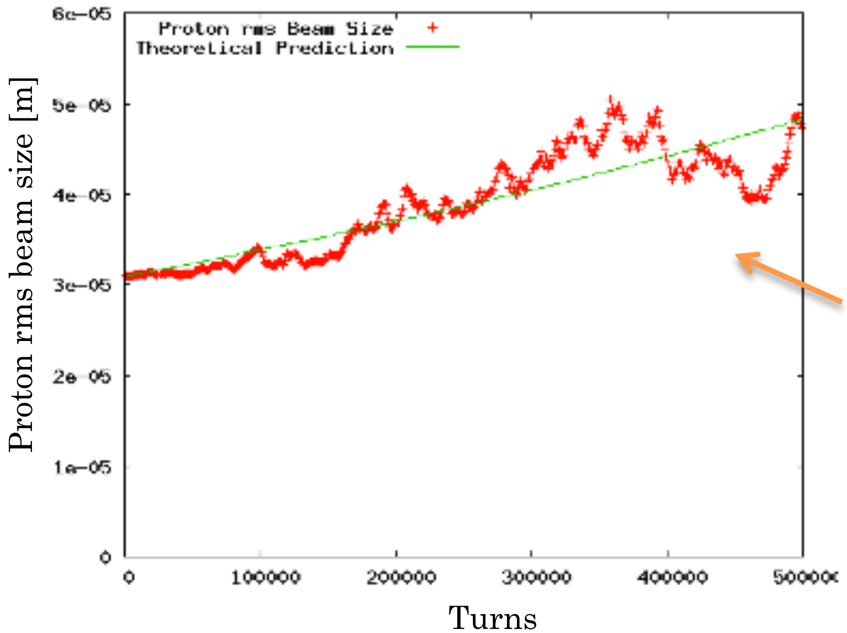
INCOHERENT PROTON EMITTANCE GROWTH



The proton beam emittance growth depends on electron IR optics choices.

Initial luminosity for Blue and Red lines is the same, but the emittance growth is very different.

EFFECT OF ELECTRON PARAMETER FLUCTUATIONS ON THE PROTON/ION BEAM



Assuming a white noise spectrum,

Dipole Errors:
(trans. offset)

$$\sqrt{\langle x_p^2\rangle(t)} = \sqrt{\frac{\langle d_n^2\rangle \beta_p^{*2} t}{2T f_p^2} + \langle x_p^2\rangle(t=0)}$$

Quad Errors:
(intensity, trans.size)

$$\sqrt{\langle x_p^2\rangle(t)} = \sqrt{\langle x_p^2\rangle(0)}\exp(t/\tau)$$

$$\tau = \frac{4Tf_p^2}{\beta_p^{*2}}\frac{f_p^2}{\langle\delta f_{pn}^2\rangle} = \frac{T}{4\pi^2\xi_p^2}\frac{f_p^2}{\langle\delta f_{pn}^2\rangle}$$

To give the reasonable limitation on the electron accelerator stability, We need to evaluate the realistic frequency spectrum of the

- Laser
- Magnet error
- Earth movement.

SUMMARY

- The EPIC code was written to study the features of the beam-beam interactions, specific to the linac-ring collision scheme, in a time efficient way.

- The beam-beam simulations have been essential for the understanding achievable luminosity, defining the IR and lattice parameters.

- In further plans:
  - the interplay of beam-beam and space charge;
  - crab-crossing;
  - multiple collisions.

The distribution of different disruption (0-108.4)