eRHIC/EIC at BNL

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NATIONAL LABORATORY

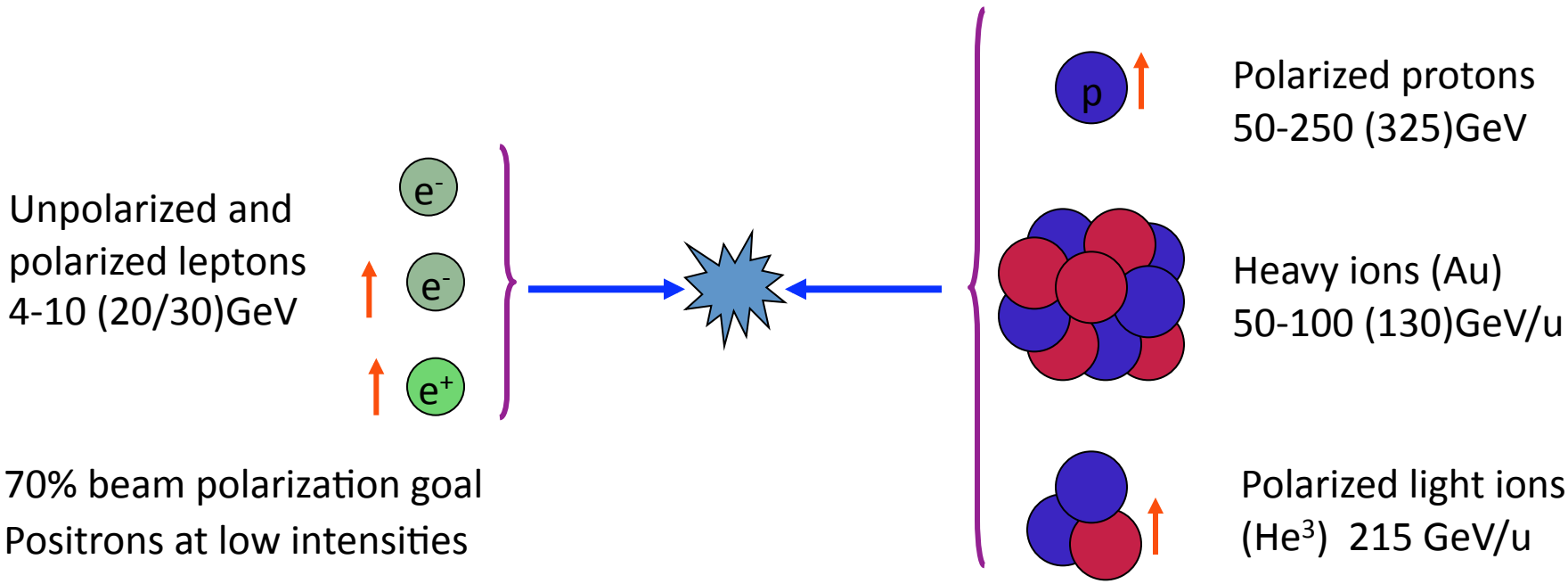
Outline

- eRHIC Overview
- Staging plan of eRHIC
  - MeRHIC project
  - Design status and Main R&D items for electron-ion collider
- Beam-beam effects in ERL based EIC
  - Electron beam issues
  - Proton/Ion beam issues
- Conclusion

eRHIC Scope -QCD Factory

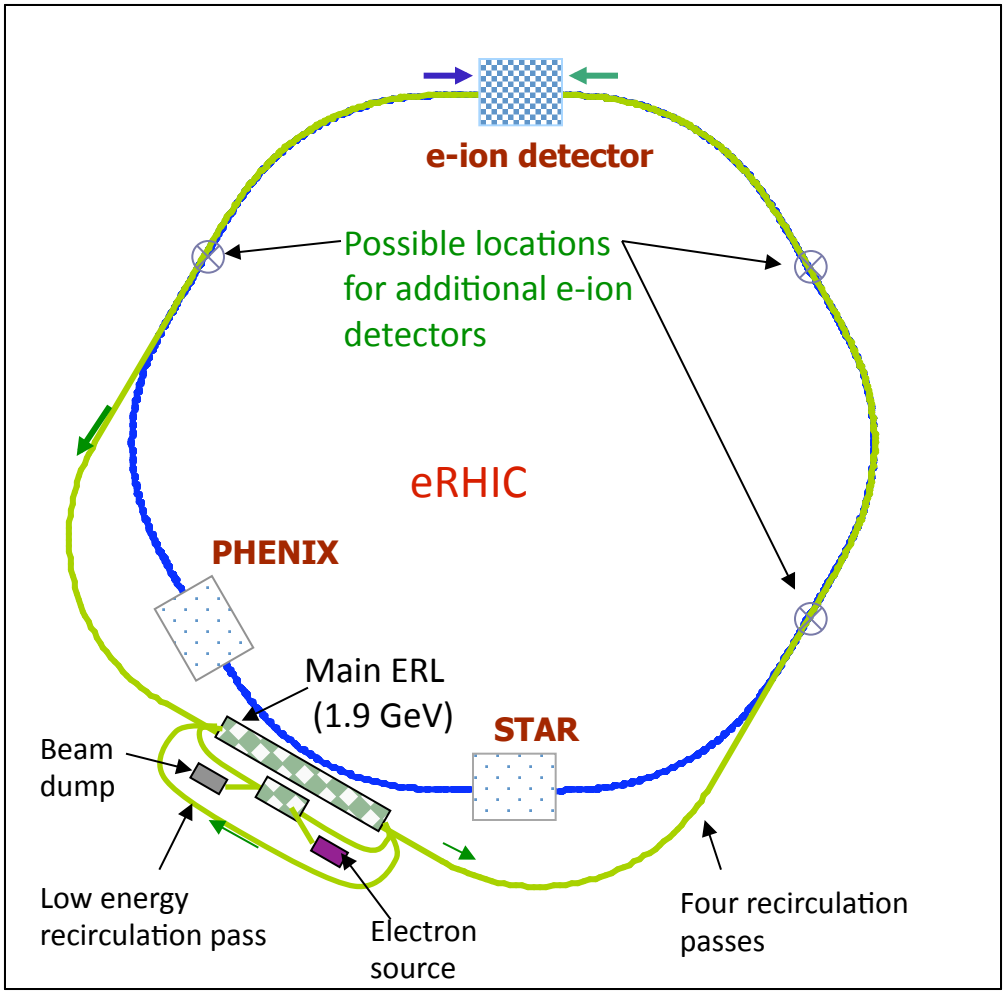
Electron accelerator

RHIC



Center mass energy range: 20-200GeV

ERL-based eRHIC Design



- 10 GeV electron design energy. Possible upgrade to 20 GeV by doubling main linac length.
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) and detectors;
- Larger luminosity achieved since electron beam is used only once.
- Full polarization transparency at all energies for the electron beam;
- Ability to take full advantage of transverse cooling of the hadron beams;
- Possible options to include polarized positrons.

Other design options

Under consideration also:

➢ *Medium Energy eRHIC (MeRHIC)*

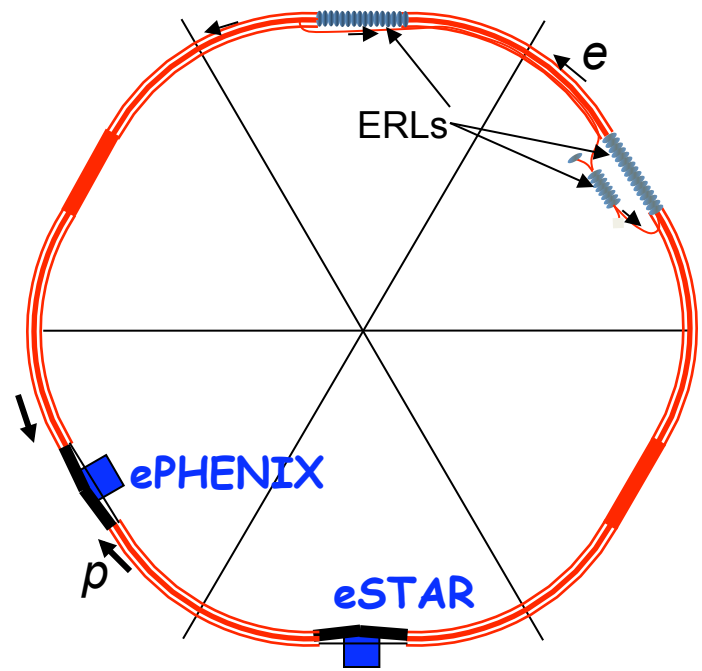
Electron energy up to 2-4 GeV. Acceleration done by an ERL linac placed in the RHIC tunnel. It can serve as first stage for following higher electron energy machine.
Luminosity ~ 10^{32} $cm^{-2}s^{-1}$(without cooling)

➢ *High energy (up to 20-30 GeV) ERL-based design with all accelerating linacs and recirculation passes placed in the RHIC tunnel.*

Considerable cost saving design solution.
Luminosity exceeds 10^{33} $cm^{-2}s^{-1}$

➢ *Ring-ring design option.*

Backup design solution which uses electron storage ring.
See eRHIC ZDR for more details.
The average luminosity is at 10^{32} $cm^{-2}s^{-1}$ level limitedby beam-beam effects.



ERL-based eRHIC Parameters: e-p mode

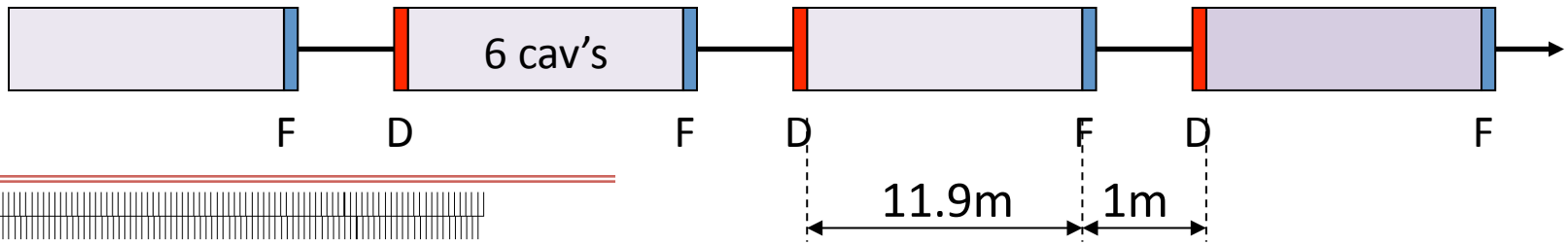
	High energy setup		Low energy setup	
	p	e	p	e
Energy, GeV	250	10	50	3
Number of bunches	166		166	
Bunch spacing, ns	71	71	71	71
Bunch intensity, 10^{11}	2	1.2	2	1.2
Beam current, mA	420	260	420	260
Normalized 95% emittance, π mm.mrad	6	460	6	570
Rms emittance, nm	3.8	4	19	16.5
β*, x/y, cm	26	25	26	30
Beam-beam parameters, x/y	0.015	0.59	0.015	0.47
Rms bunch length, cm	20	1	20	1
Polarization, %	70	80	70	80
Peak Luminosity, 1.e33 $cm^{-2}s^{-1}$	2.6		0.53	
Aver.Luminosity, 1.e33 $cm^{-2}s^{-1}$	0.87		0.18	
Luminosity integral /week, pb^{-1}	530		105	

Main R&D Items

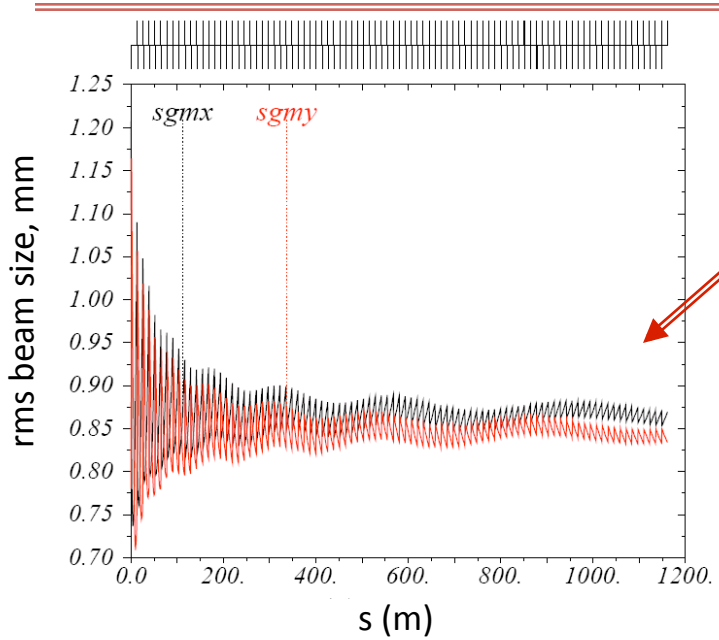
- Electron beam R&D for ERL-based design:
  - High intensity polarized electron source
    - Development of large cathode guns with existing current densities ~ 50 mA/cm^2 with good cathode lifetime.
  - Energy recovery technology for high power beams
    - Multi-cavity cryo-module development; high power beam ERL, BNL ERL test facility; loss protection; instabilities.
  - 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
- General EIC R&D item:
  - Proof of principle of the coherent electron cooling

Compact linac design

Increased number of 700MHz cavities inside one cryostat to 6 cavities.
3rd harmonic cavities (2 per cryostat) for the momentum spread minimization.
Cavity gradient: 19.5 MeV/m; Average acceleration rate: 8.2 MeV/m;
Total length of 1.9 GeV linac: 232m (instead of ~360m in the previous design).



E.Pozdeyev

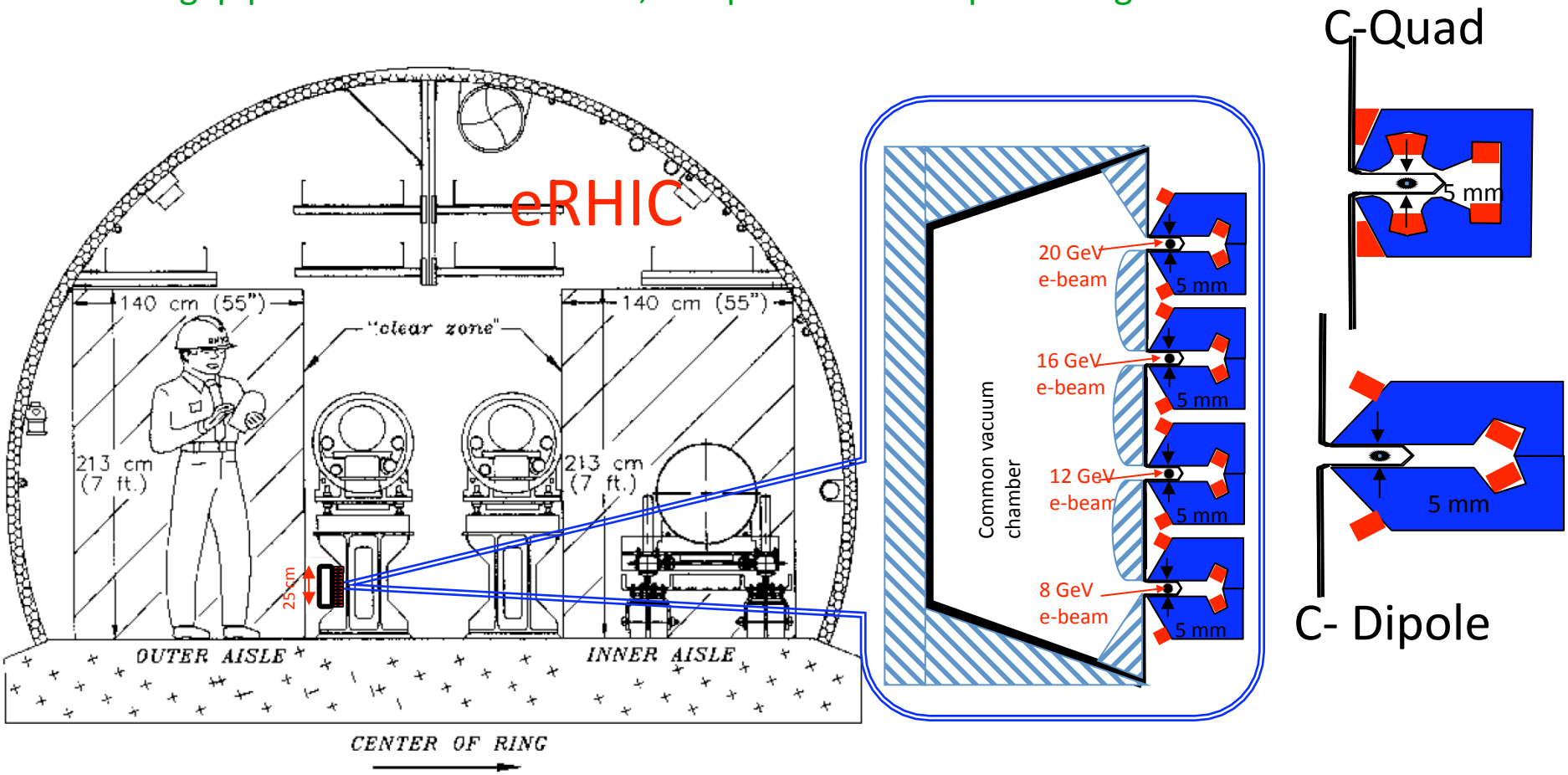


Evolution of rms beam sizes along the linac on all acceleration passes. Recirc.passes are presented by Unit matrix.
Doublet focusing (90º phase advance per cell)
Constant quadrupole gradient.

Compact linac design makes more realistic a design option with linac(s) placed inside the RHIC tunnel

eRHIC energy recovery loop magnets:LDRDproject

- Small gap provides for low current, low power consumption magnets



Staging of eRHIC: Energy Reach and Luminosity

- **MeRHIC**: Medium energy eRHIC
  - Both Accelerator and Detector are located at IP2 of RHIC
  - 4 GeV e^-x 250 GeV p(45 or 63 GeV c.m.), L ~ 10^{32}-10^{33}cm^{-2} sec $^{-1}$
  - *2 GeV option was moved into a back-up*
- **eRHIC, High energy and luminosity phase,** inside RHIC tunnel

Full energy, nominal luminosity

  - Polarized 10(20) GeV e^-x 250(325) GeV p(160 GeV c.m), L ~ 10^{33}-10^{34}cm^{-2} sec $^{-1}$
  - 30 GeV e x 120 GeV/n Au (120 GeV c.m.), ~1/5 of full luminosity
  - and 20 GeV e x 120 GeV/n Au (120 GeV c.m.), full luminosity
- **eRHIC up-grades – if needed**, inside RHIC tunnel

Higher luminosity at reduced energy

  - Polarized 10 GeV e^-x 325 GeV p, L ~ 10^{35} cm^{-2} sec $^{-1}$

Or Higher energy operation with one new 800 GeV RHIC ring

  - Polarized 20 GeV e^-x 800 GeV p (~300 GeV c.m), L ~ 10^{34} cm^{-2} sec $^{-1}$
  - 30 GeV e x 300 GeV/n Au (~200 GeV c.m.), L ~ 10^{32} cm^{-2} sec $^{-1}$

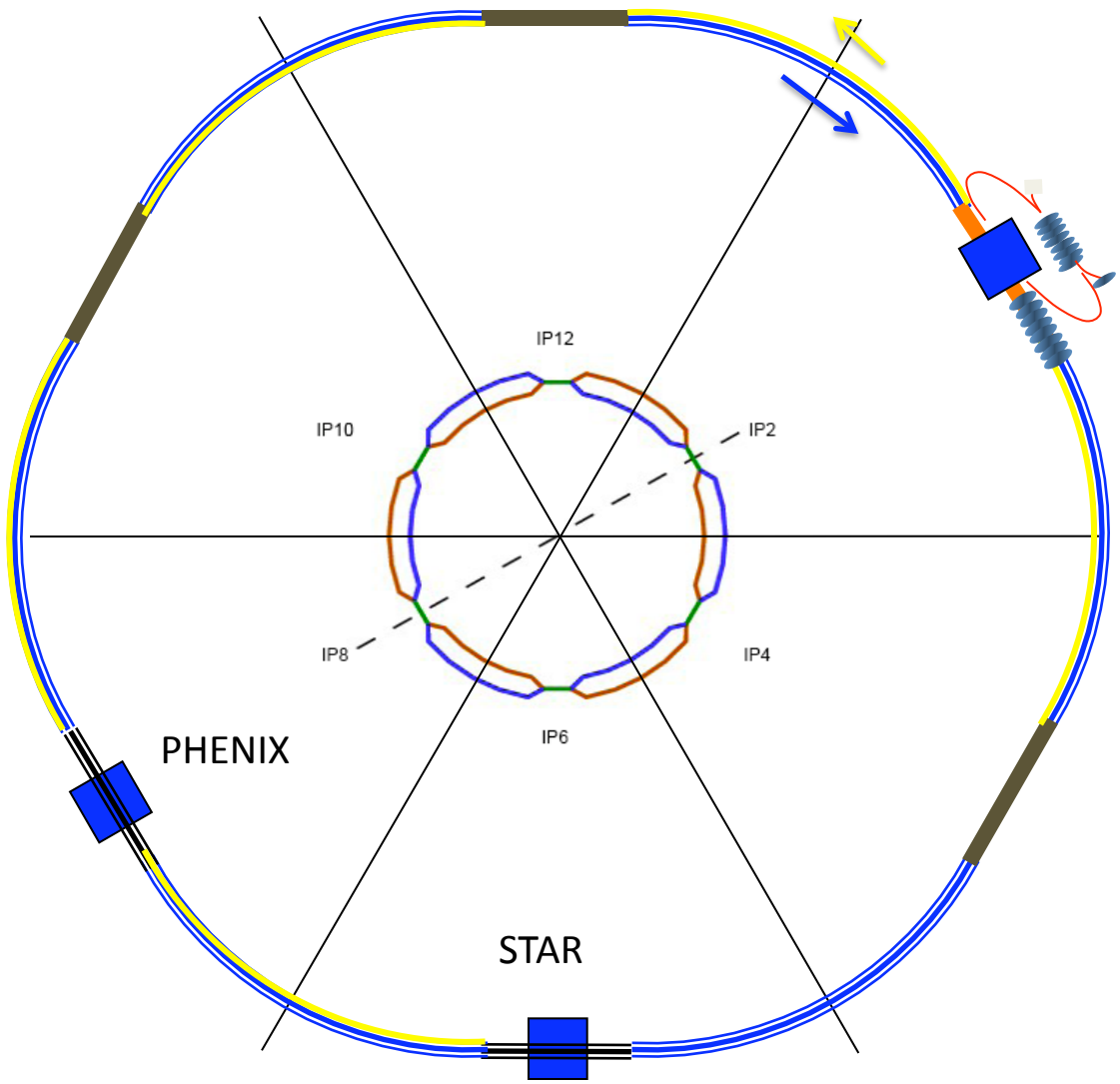
Staging of eRHIC

- **MeRHIC**: Medium Energy eRHIC
  - 90% of ERL hardware will be use for full energy eRHIC
  - Possible use of the detector in eRHIC operation
- **eRHIC – High energy and luminosity phase**
  - **Based on present RHIC beam intensities**
  - With coherent electron cooling requirements on the electron beam current is 50 mA
  - 20 GeV, 50 mA electron beam losses 4 MW total for synchrotron radiation.
  - 30 GeV, 10 mA electron beam loses 4 MW for synchrotron radiation
  - Power density is <2 kW/meter and is well within B-factory limits (8 kW/m)
- **eRHIC upgrade(s)**
  - **High luminosity, low energy requires crab cavities, new injections, Cu-coating of RHIC vacuum chambers, new level of intensities in RHIC**
    - Polarized electron source current of 400 mA at10 GeV, losses 2 MW total for synchrotron radiation, power density is 1 kW/meter
  - **High energy option requires replacing one of RHIC ring with 8 T magnets**

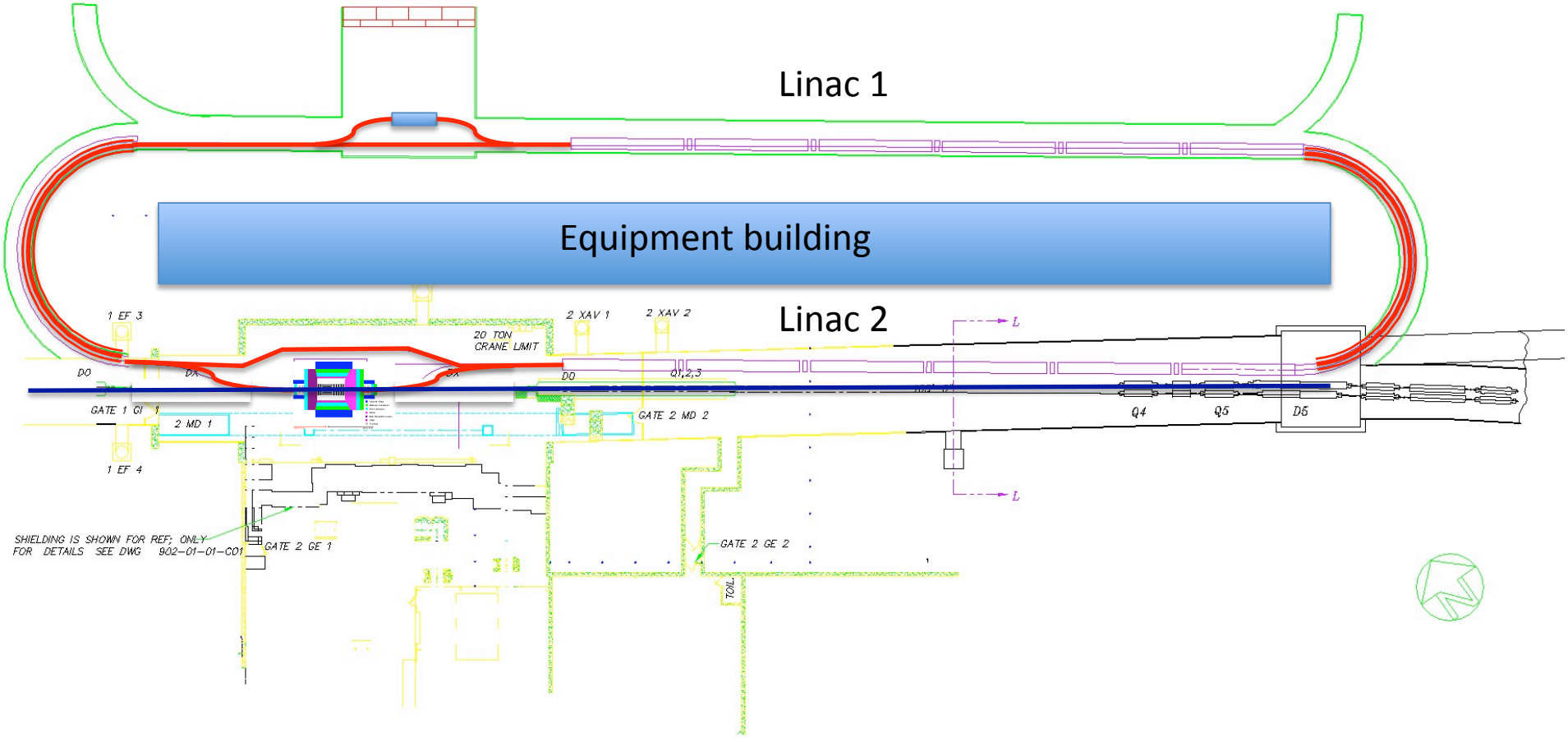
MeRHIC parameters for e-p collisions

	not cooled		pre-cooled		high energy cooling	
	p	e	p	e	p	e
Energy, GeV	**250**	**4**	**250**	**4**	**250**	**4**
Number of bunches	**111**		**111**		**111**	
Bunch intensity, 10^{11}	**2.0**	**0.31**	**2.0**	**0.31**	**2.0**	**0.31**
Bunch charge, nC	**32**	**5**	**32**	**5**	**32**	**5**
Normalized emittance, 1e-6 m, 95% for p / rms for e	**15**	**73**	**6**	**29**	**1.5**	**7.3**
rms emittance, nm	**9.4**	**9.4**	**3.8**	**3.8**	**0.94**	**0.94**
beta*, cm	**50**	**50**	**50**	**50**	**50**	**50**
rms bunch length, cm	**20**	**0.2**	**20**	**0.2**	**5**	**0.2**
beam-beam for p /disruption for e	**1.5e-3**	**3.1**	**3.8e-3**	**7.7**	**0.015**	**7.7**
Peak Luminosity, 1e32, $cm^{-2}s^{-1}$	**0.93**		**2.3**		**9.3**	

MeRHIC layout in RHIC tunnel

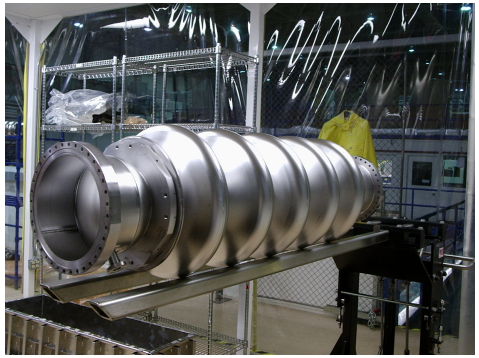


MeRHIC Layout



SRF Linac

I. Ben-Zvi, A.Burrill, R.Calaga, H.Hahn, L.Hammons …



The ERLs will use 703 MHz superconducting RF cavities
for the acceleration and the energy recovery.
State-of-the-art cavity design for high current beam operation.

Recently: successful cool down of a test cavity (ERL Test Facility),
first measurements of EM modes.

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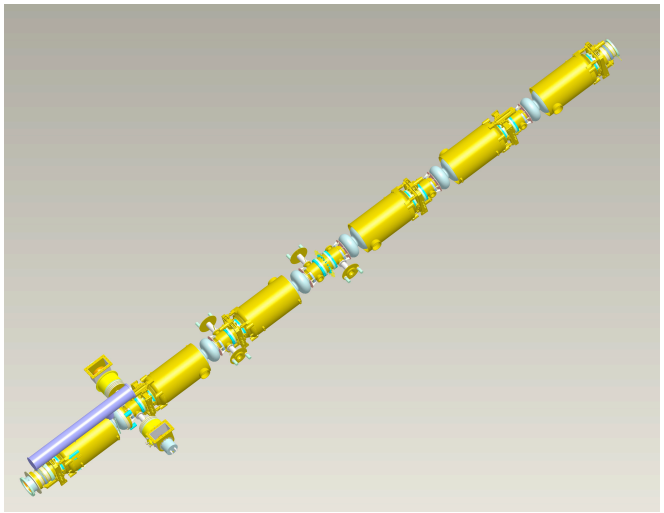
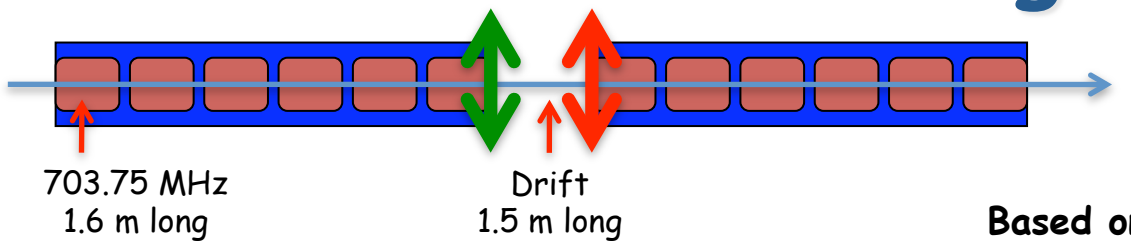
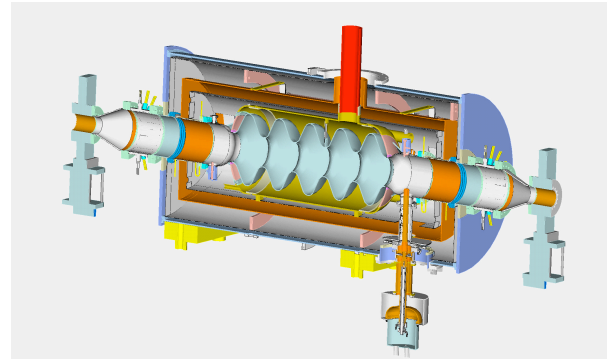
36 cavities per linac. Design of individual cryo-module,
incorporating 6 SRF cavities is under development.

The challenge: to make the design
(fundamental couplers, HOM dampers, tuners ..)
as compact as possible, to fit the existing
straight section of the tunnel.



MeRHIC Linac Design





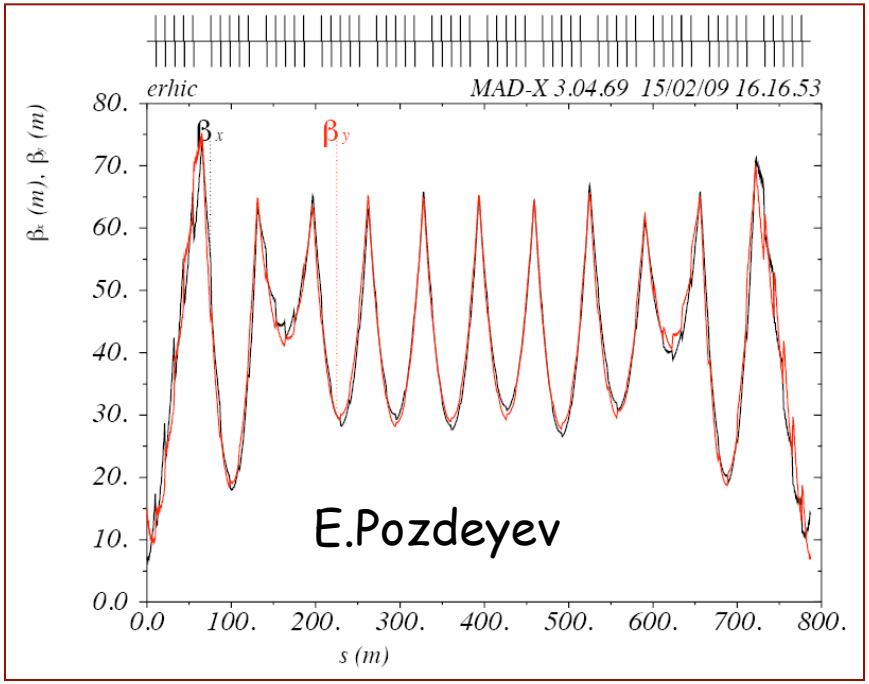
Based on revolutionary BNL SRF cavity with fully suppressed HOMs – reached design parameters last week
Critical for high current multi-pass ERL

100 MeV → 4 GeV → 100 MeV

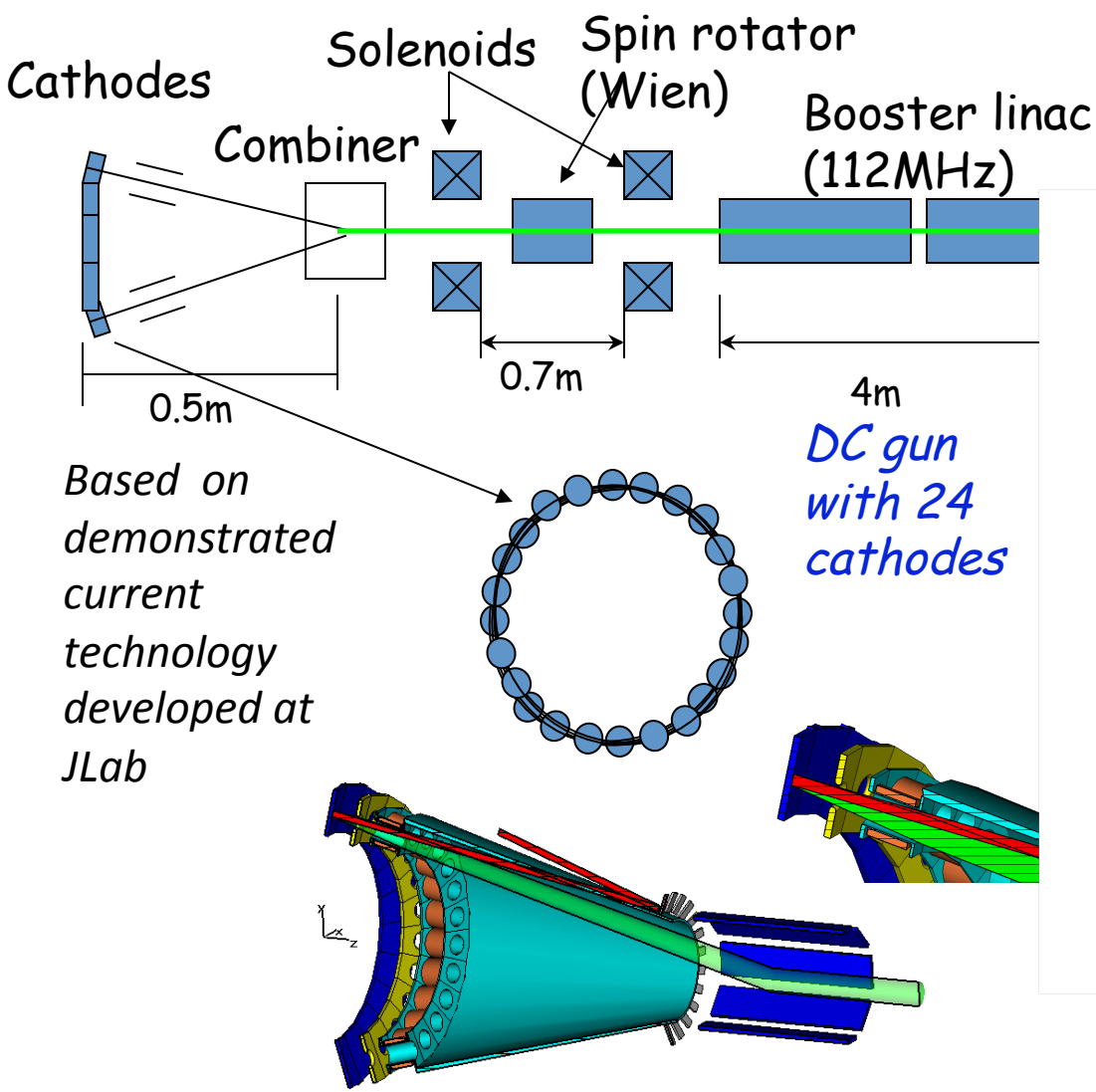
65m total linac length
All cold: no warm-to-cold transition

Current breakdown of the linac

- N cavities = 6 (per module)
- N modules per linac = 6
- N linacs = 2
- L module = 9.6m
- L period = 10.6 m
- E_f = 18.0 MeV/m
- dE/ds= 10.2 MeV/m

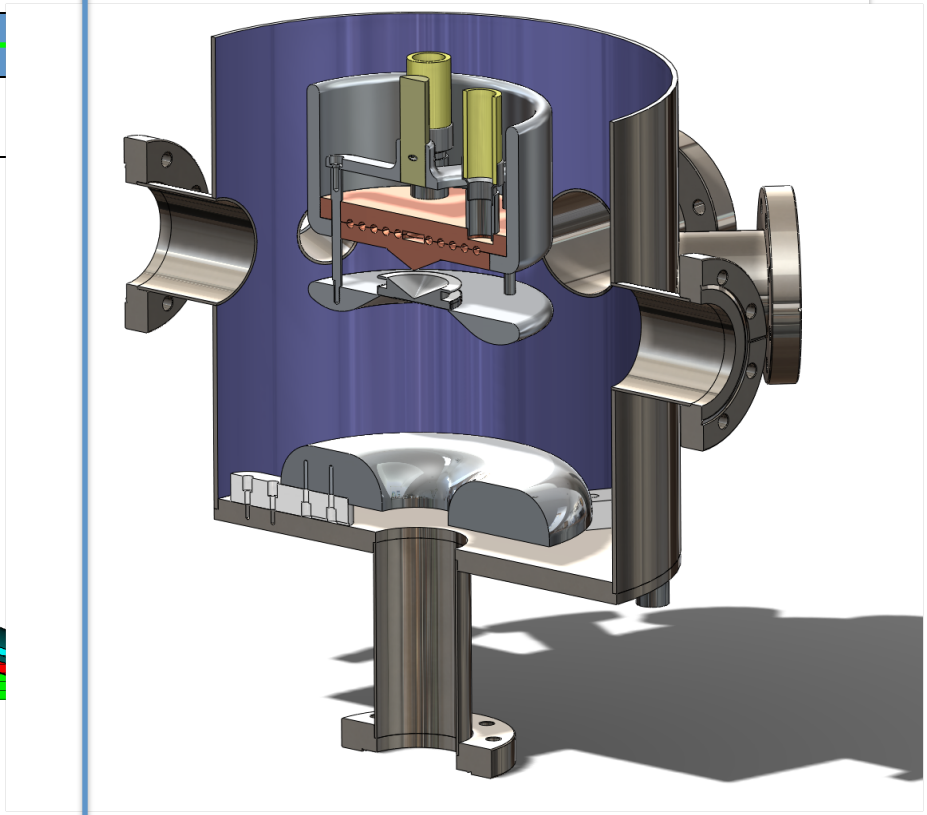


Main technical challenge: 50 mA CW polarized gun: we are building it



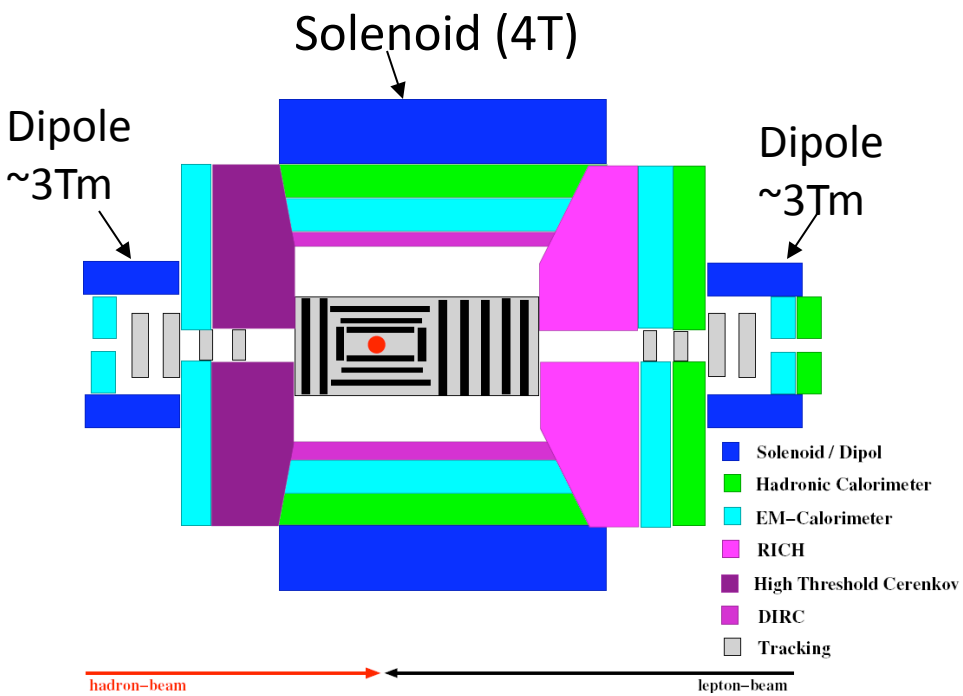
Single cathode DC gun

E.Tsentalovich, MIT

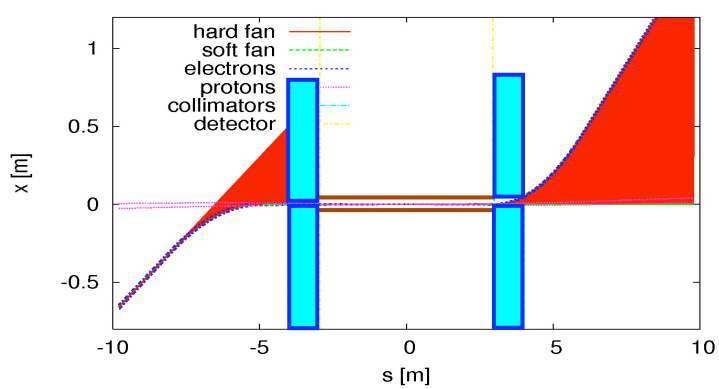


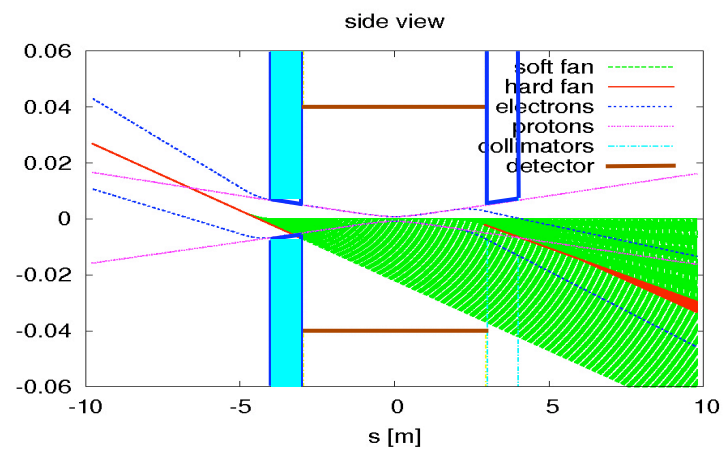
Accelerator and detector integration and SR protection

J.Beebe-Wang, C.Montag, B.Parker



To provide effective SR protection:
-soft bend (~0.05T) is used for final bending of electron beam
-combination of vertical and horizontal bends





Beam-Beam Effects

- Beam-Beam effect is caused by interaction between the two beams at the interaction region.
- At interaction region, a particle in one beam is experiencing the electromagnetic force generated by both opposing beam and the beam itself.
- The former force is called beam-beam force, while the latter is called space charge force.

$$\vec{F}_{12} = e(\vec{E} + \vec{v} \times \vec{B}) \approx e\vec{E}(1 + \beta_1 \beta_2)$$

$$\vec{F}_{11} = e(\vec{E} + (-\vec{v}) \times \vec{B}) \approx e\vec{E}(1 - \beta_1^2) = e\vec{E} / \gamma^2$$

Possible Countermeasures: (ring-ring, ERL-ring)

- Proper working point (Hold the tune spread due to nonlinear force)
- Electron lens (apply another force which has same form but opposite sign)

✓ Low-beta* electron optics

✓ Fight with collective effects in ion beam

✓ Electron beam is pinched by ion beam

Accelerator Keywords

Transverse Motion (x,x',y,y')

$$x_i / y_i(s) = \sqrt{\beta_{x/y}\varepsilon_{i,x/y}/\pi}\cos\left(\psi_{x/y}(s)+\psi_{0,x/y}\right)$$

$$\psi_{x/y}(s) = \int_0^s \frac{ds}{\beta_{x/y}(s)};\ x' = \frac{dx}{ds} = \frac{P_x}{P_0}$$

Transverse Tune

$$\nu_{x/y} = \frac{1}{2\pi}\oint \frac{ds}{\beta_{x/y}(s)}$$

One Turn Map Matrix

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{n+1} = \begin{pmatrix} \cos(\phi)+\alpha\sin(\phi) & \beta\sin(\phi) \\ -\gamma\sin(\phi) & \cos(\phi)-\alpha\sin(\phi) \end{pmatrix}\begin{pmatrix} x \\ x' \end{pmatrix}_n$$

where $\alpha = -\beta'/2, \gamma = (1+\alpha^2)/\beta$ and $\phi = 2\pi\nu$

Emittance

$$\varepsilon_{rms,x} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

$$\varepsilon_{i,x} = \gamma x^2 + 2\alpha xx' + \beta x'^2$$

$$Energy \cdot \varepsilon = const$$

Longitudinal Motion(Synchrotron Motion)

The synchrotron motion is much slower tan transverse motion. The tune for synchrotron motion in eRHIC design is 0.0043. The motion is nonlinear if oscillation amplitude is large.

Luminosity for two Gaussian beams:

$$L = \frac{N_1 N_2 fh}{2\pi\sqrt{\sigma_{x1}^2+\sigma_{x2}^2}\sqrt{\sigma_{y1}^2+\sigma_{y2}^2}}$$

Beam-Beam Field

For a transverse Gaussian distribution,

$$\rho(x,y) = \frac{n(z)e}{2\pi\sigma_x\sigma_y}\exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right)$$

(+/-4 sigma cut-off)

Bassetti-Erskine formular

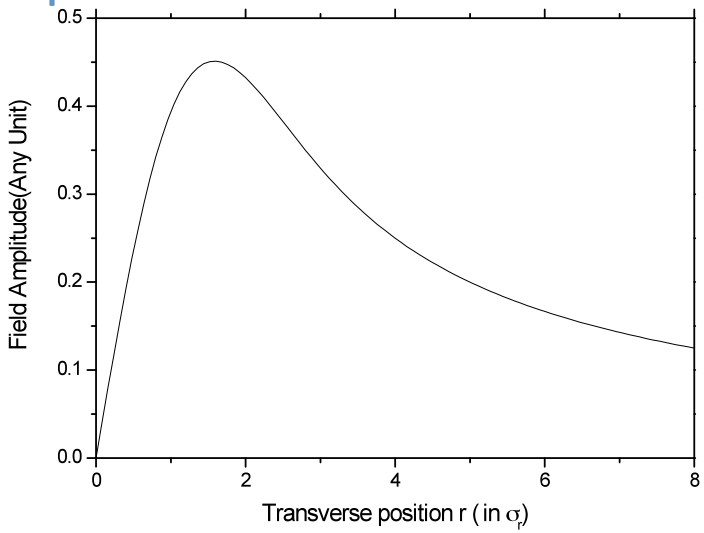
$$E_x - iE_y = -\frac{ine}{2\varepsilon_0\sqrt{2\pi\left(\sigma_x^2-\sigma_y^2\right)}}\left[w\left(\frac{x+iy}{\sqrt{2\left(\sigma_x^2-\sigma_y^2\right)}}\right) - \exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}\right)w\left(\frac{\frac{x\sigma_y}{\sigma_x}+i\frac{y\sigma_x}{\sigma_y}}{\sqrt{2\left(\sigma_x^2-\sigma_y^2\right)}}\right)\right]$$

For round beam case, the field have simple form

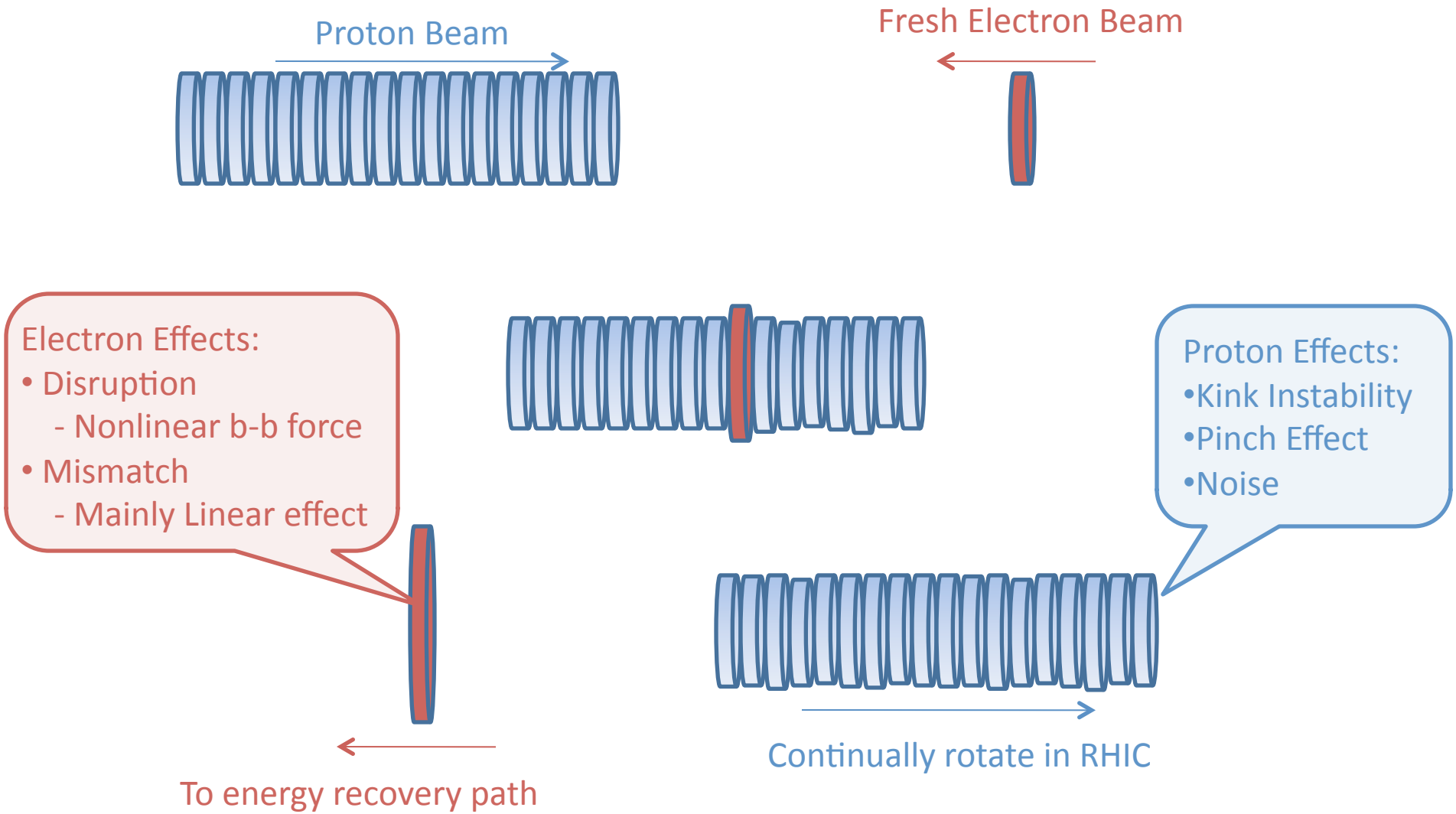
$$\vec{E}_r = \frac{n(z)e}{2\pi\varepsilon_0 r^2}\left[1-\exp\left(-\frac{r^2}{2\sigma^2}\right)\right]\vec{r}$$

Near axis, the field is linear.

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \frac{n(z)e}{2\pi\varepsilon_0\left(\sigma_x+\sigma_y\right)}\begin{pmatrix} x/\sigma_x \\ y/\sigma_y \end{pmatrix}$$



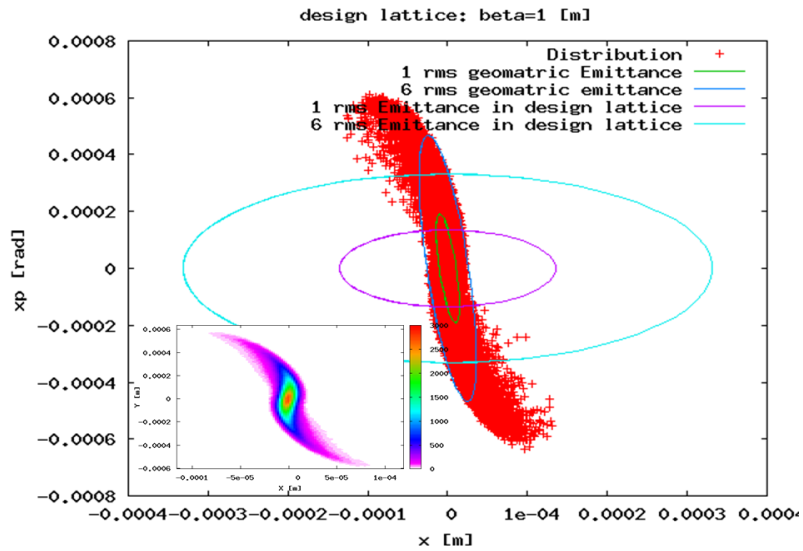
Beam-Beam In ERL Based eRHIC

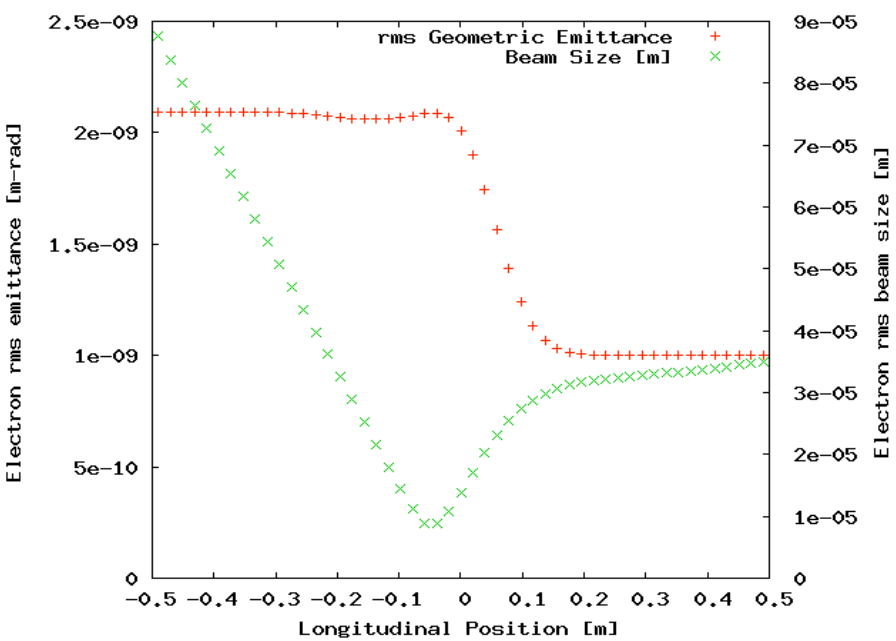


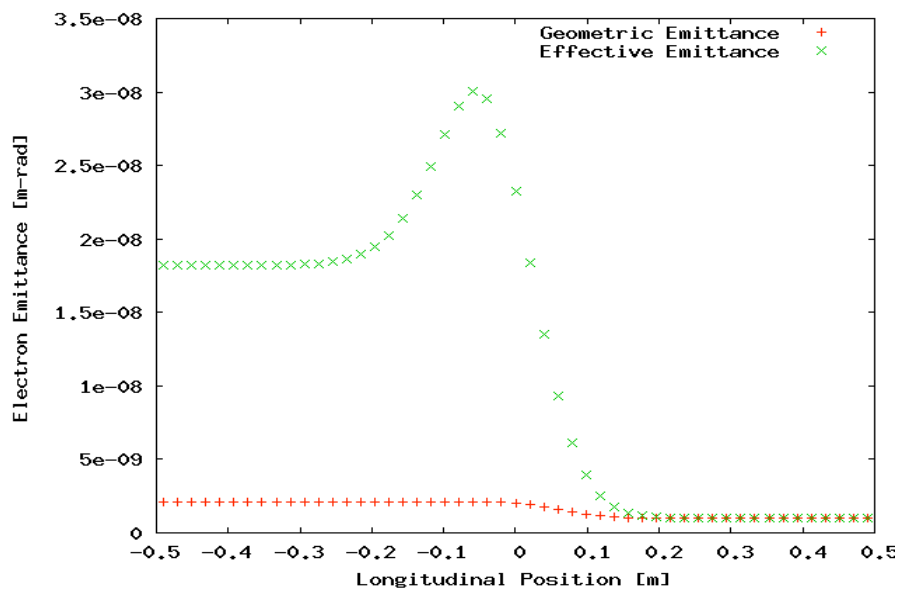
Electron Disruption Effect in eRHIC(β^* = 1m)

Electron beam travels from positive longitudinal position to negative.

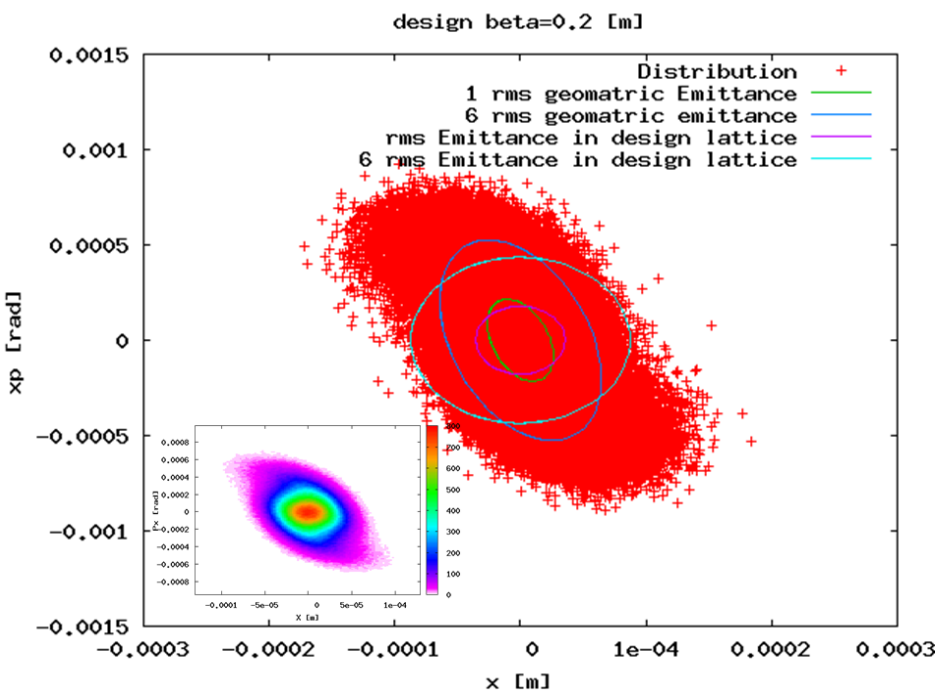
The nonlinear beam-beam force will cause the electron beam geometric emittance growth.

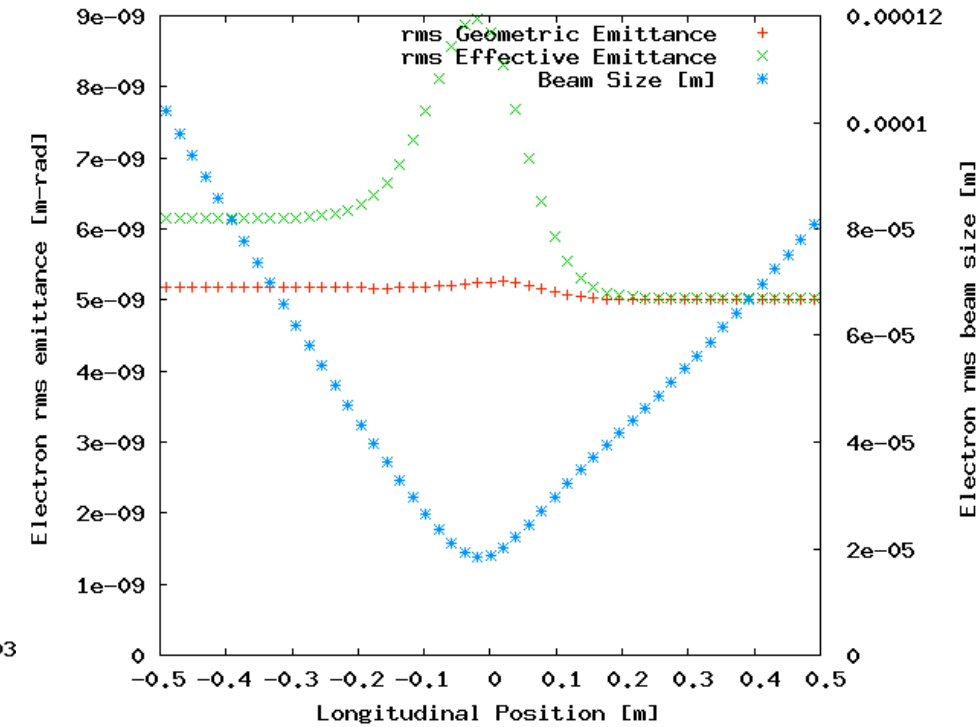






Electron Disruption Effect in eRHIC(β^* = 0.2m)





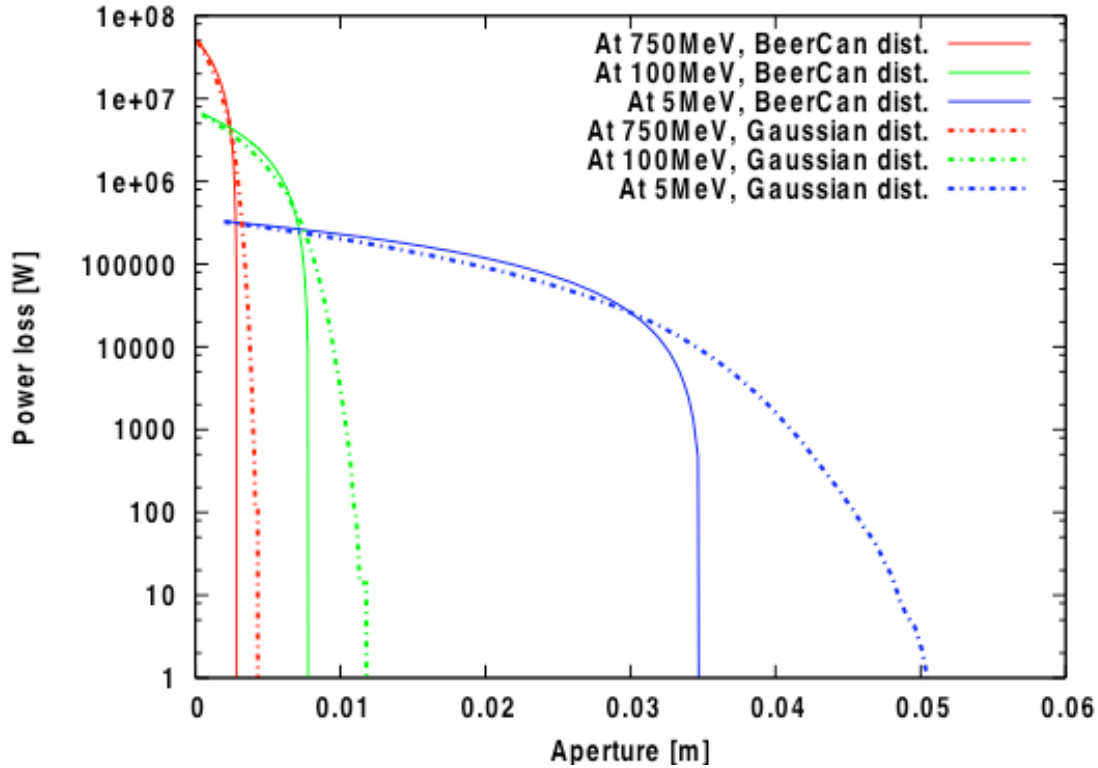
Mismatch effect is much smaller, from the discrepancy of geometric emittance and effective emittance.

Pinch effects also smaller! (Minimum electron size ~20 microns, compared with ~8 microns)

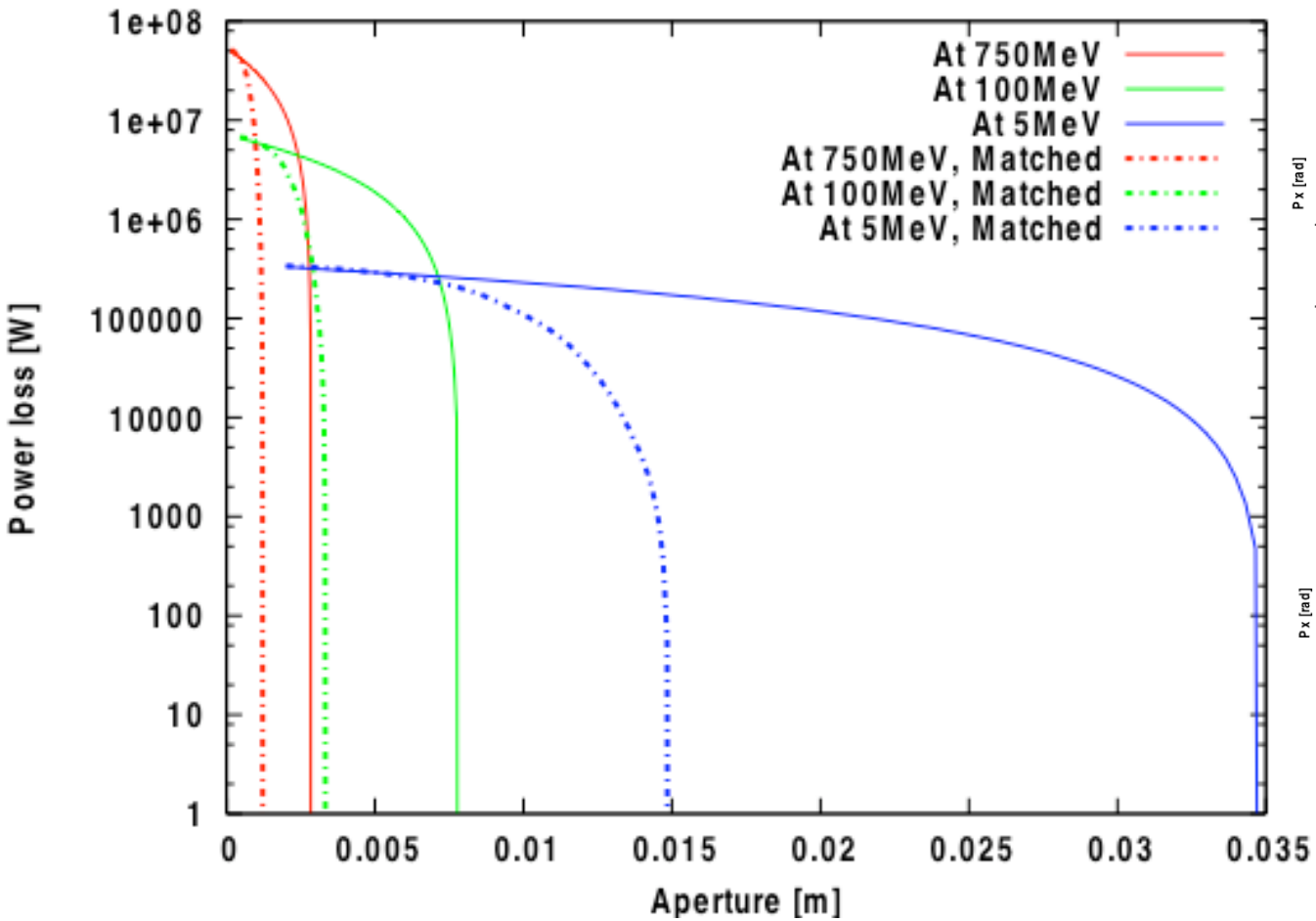
The beam loss at different position (Not-Cool case)

(Use beta=5m everywhere, easily scale later)

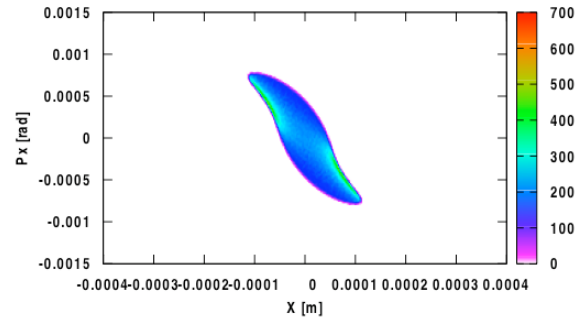
For both initial Beer-Can and Gaussian (4-σ cutoff) Distribution

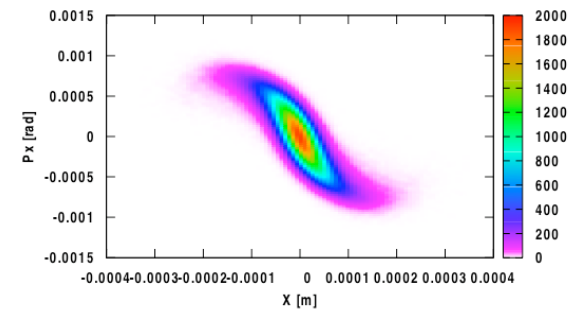


Position	Energy	Aperture Beer-Can	Aperture Gaussian
Lowest Energy at arc	750 MeV	2.9 mm	4mm
The exit of main linac	100 MeV	7.8 mm	10mm
Entrance of Beam dump	5 MeV (Dump All)	35 mm	53mm



Phase space of Beer-Can



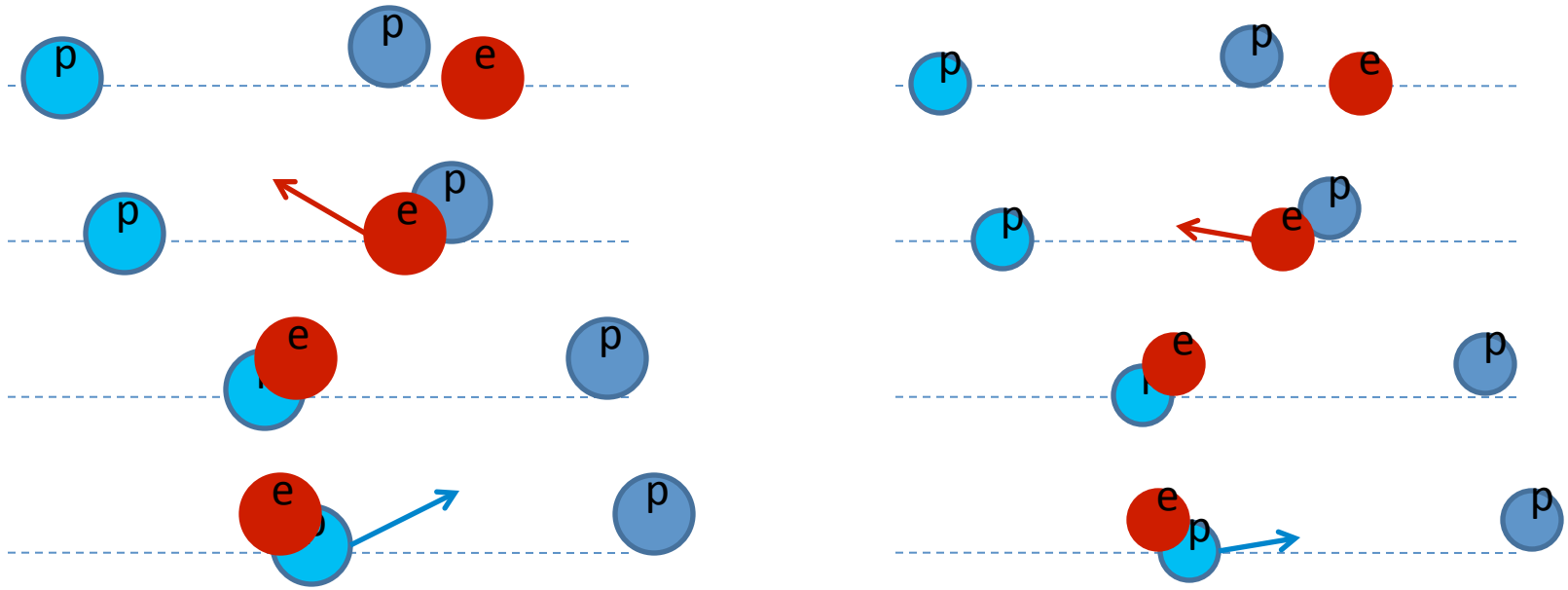


Phase space of Gaussian

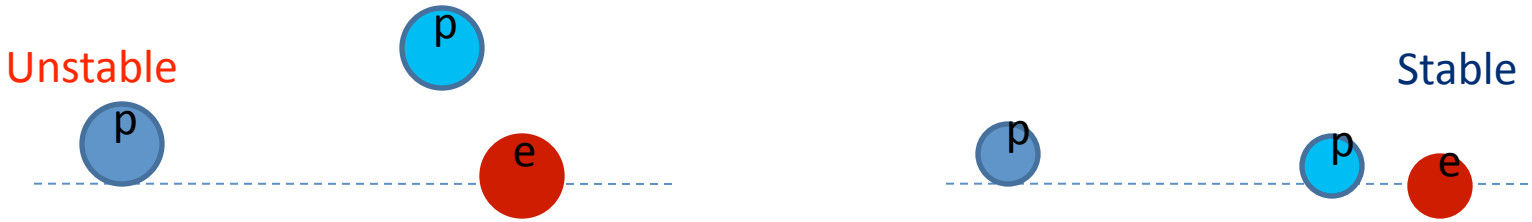
For Beer-Can distribution, if we match the optics after collision to the beam emittance shape, the required aperture will be largely reduced. (Gaussian distribution is more complicate than Beer-Can distribution)

Kink Instability of Proton Beam

Use 2-Particle model to illustrate kink instability, The two particles have same synchrotron amplitude but opposite phase. Let T be the synchrotron period.



After T/2, the head and tail exchange there positions



Threshold (Two-particle model)

One turn map for two particle:

$$M = \begin{pmatrix} \cos\phi + \alpha\sin\phi & \beta\sin\phi & 0 & 0 \\ -\gamma\sin\phi & \cos\phi - \alpha\sin\phi & 0 & 0 \\ 0 & 0 & \cos\phi + \alpha\sin(\phi) & \beta\sin\phi \\ 0 & 0 & -\gamma\sin\phi & \cos\phi - \alpha\sin\phi \end{pmatrix}$$

Kick from the leading particle to trailing one.

$$K_1 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ a & 0 & 0 & 1 \end{pmatrix} \qquad K_2 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & a & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad a = \frac{\sigma_{pz}}{2 f_p f_z} = \frac{N_p N_e r_p r_e \sigma_{pz}}{2\sigma_{px}^2 \sigma_{ex}^2 \gamma_p \gamma_e}$$

The total matrix for one synchrotron oscillation gives:

$$T = (K_2 M)^{N_s/2} \cdot (K_1 M)^{N_s/2}$$

$$T = \begin{pmatrix} 1 - \left(\frac{a N_s \beta}{4}\right)^2 M(N_s\phi) & \frac{a N_s \beta}{4} X(N_s\phi) \\ \frac{a N_s \beta}{4} X(N_s\phi) & M(N_s\phi) \end{pmatrix}$$

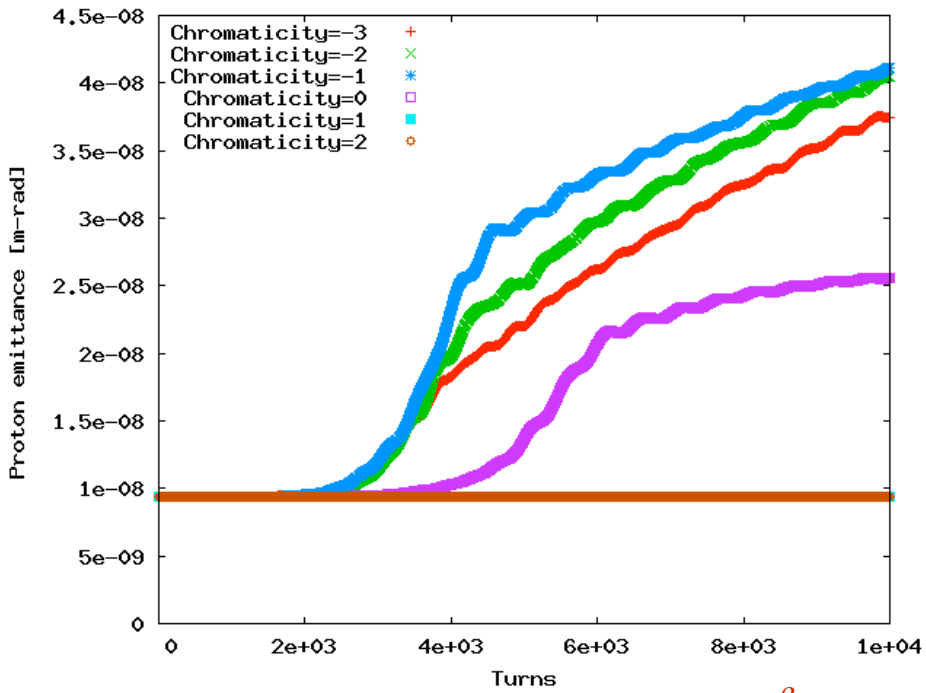
$$M(\phi) = \begin{pmatrix} \cos\phi + \alpha\sin\phi & \beta\sin\phi \\ -\gamma\sin\phi & \cos\phi - \alpha\sin\phi \end{pmatrix}$$

$$X(\phi) = \begin{pmatrix} -\alpha\cos\phi + \sin\phi & -\beta\cos\phi \\ \gamma\cos\phi & \alpha\cos\phi + \sin\phi \end{pmatrix} = M\left(\phi - \frac{\pi}{2}\right)$$

Threshold:

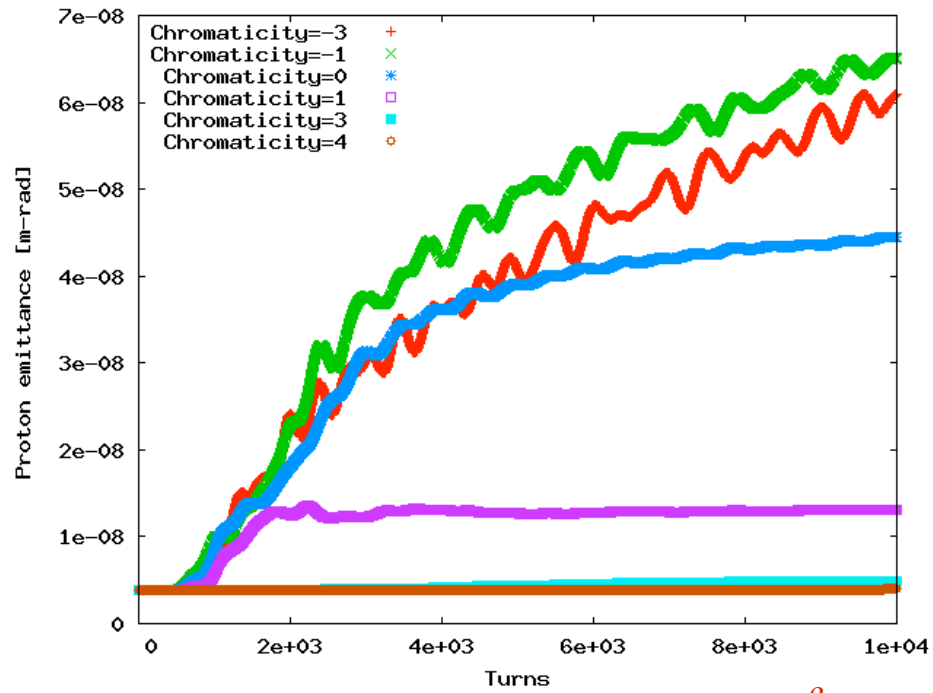
$$\frac{a N_s \beta}{4} < 2 \quad \Rightarrow \quad a < \frac{8\nu_s}{\beta}$$

Kink Instability is curable



Not Cooled case $\frac{a\beta}{8\nu_s} \sim 2.5$

Chromaticity=1 is needed



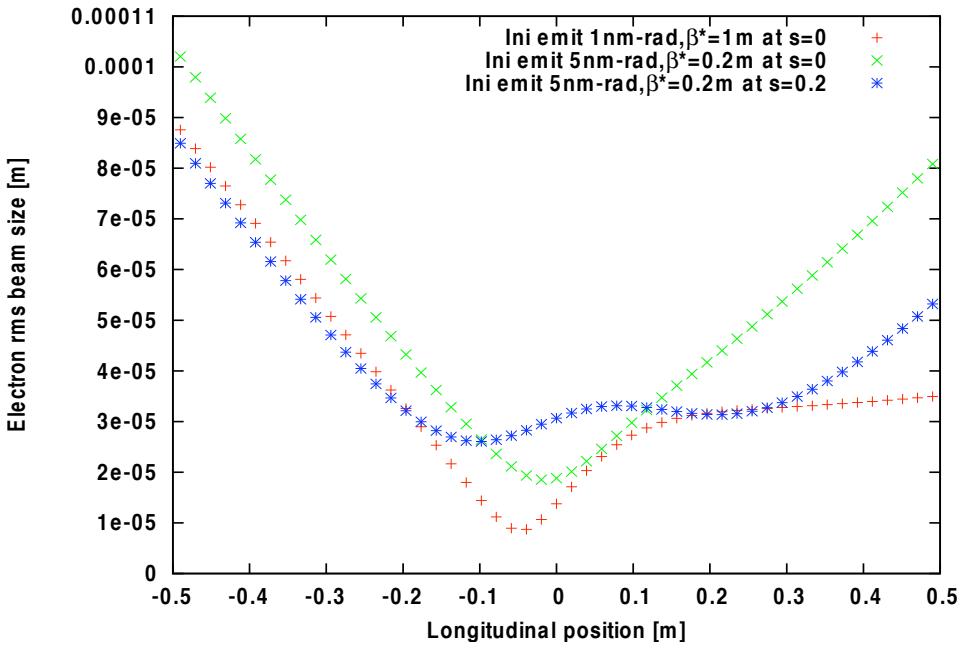
Pre Cooled case $\frac{a\beta}{8\nu_s} \sim 15$

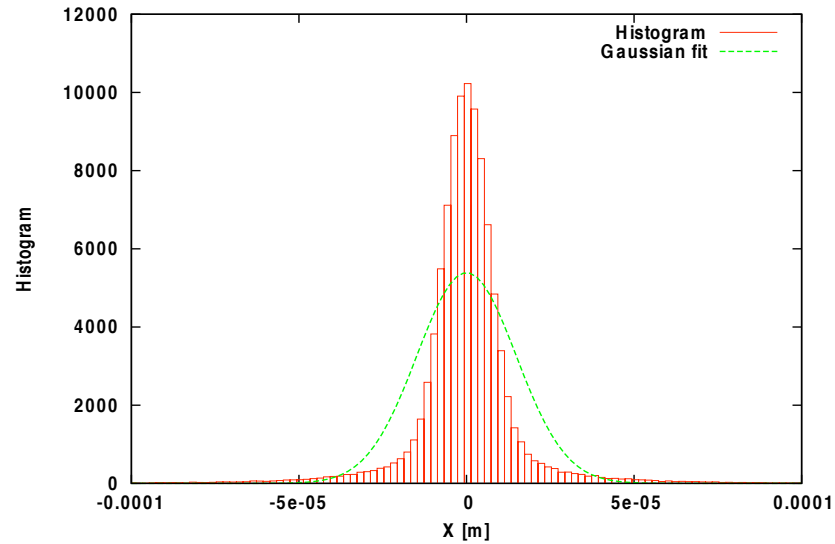
Chromaticity=4 is needed

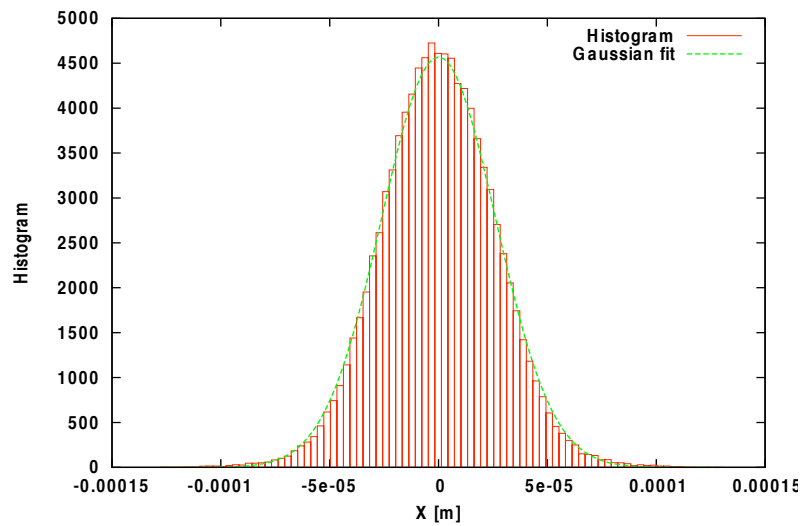
Assuming the rms energy spread is 5e-4

For the parameters beyond threshold, use Landau damping to suppress the beam emittance growth

Electron Pinch Effect







Electron pinch effect is very harmful for proton/ion beam. It enhance the proton/ion beam-beam parameter up to factor of 60!!

Can be cured by lower the electron beta*.

Conclusions

- MeRHIC will deliver 10^{32} $cm^{-2}s^{-1}$ level luminosity, eRHIC reaches at least 10 times higher.
- MeRHIC white paper and cost estimation are being prepared.
- Staging plan leads us to the exciting full energy eRHIC with smooth transitions, 90% of equipment in MeRHIC will be reused in eRHIC.
- New accelerator physics and technology are being discovered and learned during design the machine. The difficulties are being overcome!

Thank you for
the patience and time.

谢谢！