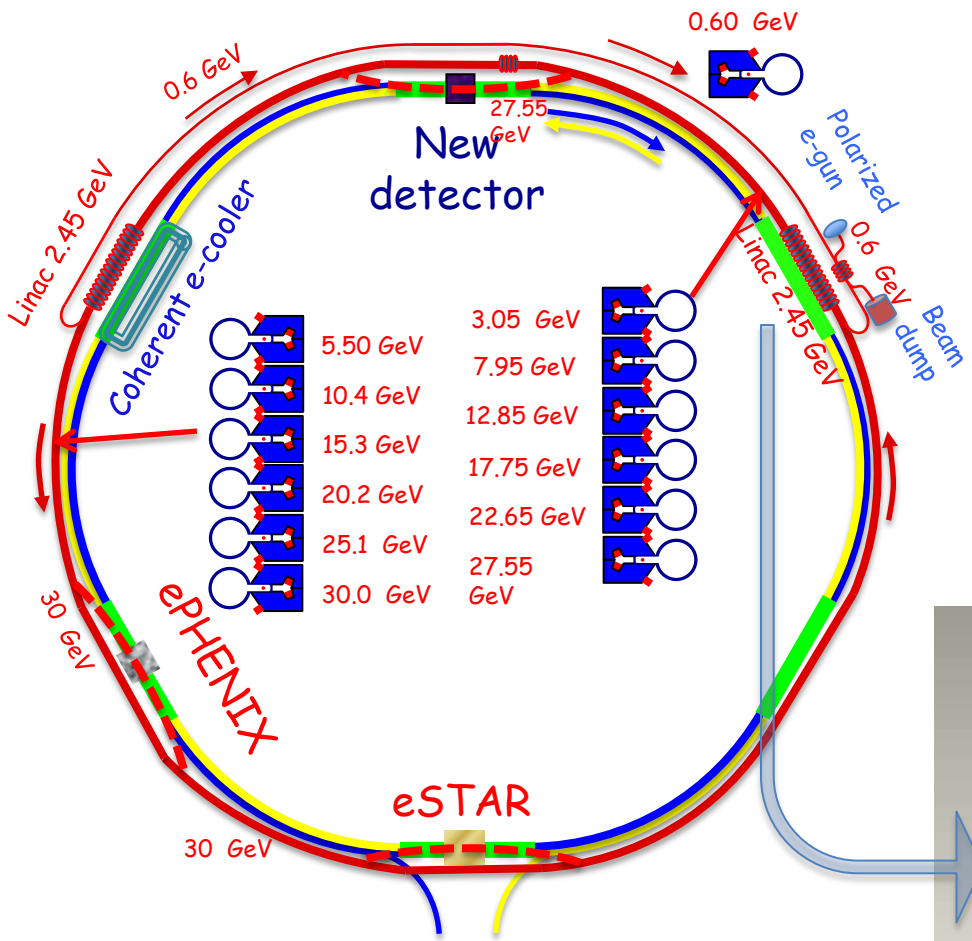
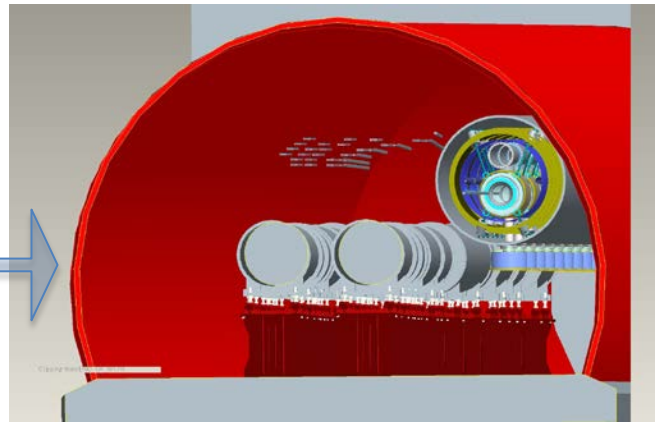
eRHIC Accelerator R&D (Part I)

Y.Hao on behalf of eRHIC design team
Collider-Accelerator Department
Brookhaven National Laboratory

eRHIC, the future EIC



- ✓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 10 to 30 GeV, by increasing the linac lengths.
- ✓Up to 3 experimental locations



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Overview & Outline

L_{peak}, $(cm^{-2}s^{-1})$ ~5 10^{31} ~4 10^{32} 10^{34}

HERA

eRHIC ring-ring

RHIC

$\xi_e \sim 0.1$

eRHIC linac-ring

ERL/SRF/HOM damping

	e	p
Energy, GeV	10	250
Number of bunches/time between bunches	107 nsec	111
Bunch intensity (nucleons) ,10^{11}		4
Normalized emittance of hadrons (95%) and electron (rms) , mm mrad	16	1.2
rms bunch length, cm	0.2	5
β*, cm		
Beam-beam parameter for hadrons/ Disruption parameter for electrons		
Space charge tune shift		
Luminosity per nucleon, × 10^{34} $cm^{-2}s^{-1}$		2.7

Polarized e Source

Coolin g

IR Design/Crab Crossing

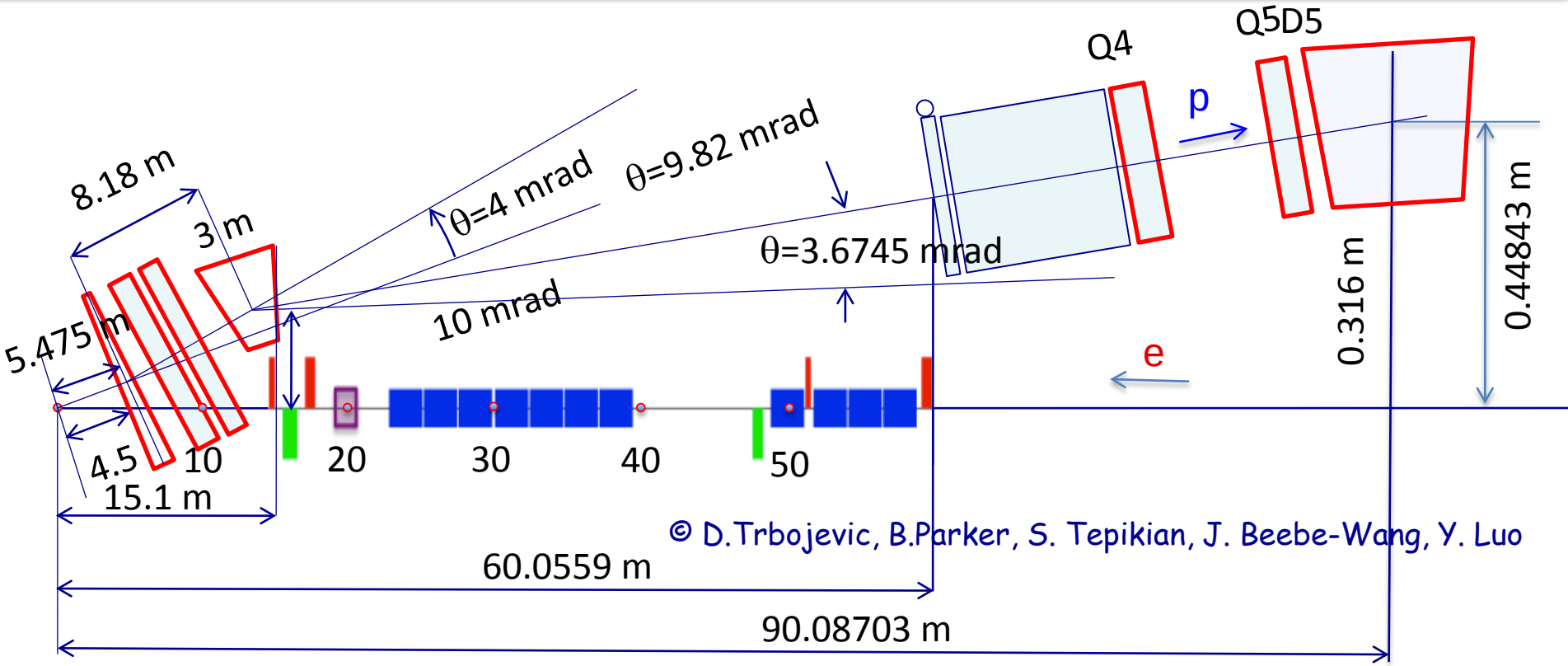
Beam-Beam study

Compensate space charge

New R&D items:

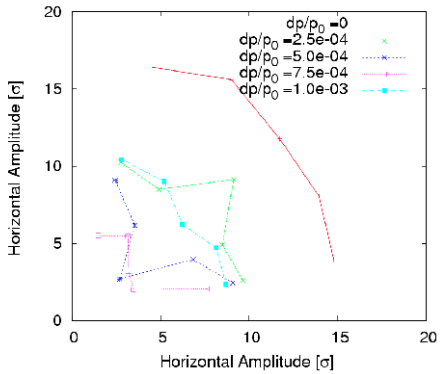
Small magnet for energy recovery path

IR design



© D.Trbojevic, B.Parker, S. Tepikian, J. Beebe-Wang, Y. Luo

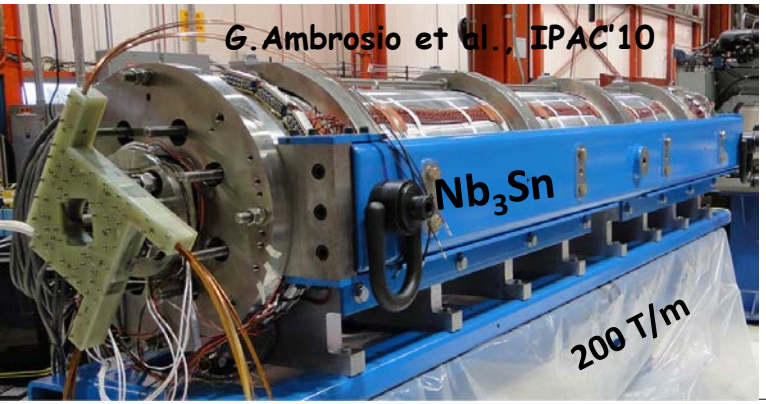
- 10 mrad crossing angle and crab-crossing
- High gradient (200 T/m) large aperture Nb_3Sn focusing magnets
- Arranged free-field electron pass through the hadron triplet magnets
- Integration with the detector: efficient separation and registration of low angle collision products
- Gentle bending of the electrons to avoid SR impact in the detector



The special IR magnet

- Large aperture for passage of neutrons and gammas, circulating beam and off-momentum charged particle.
- Based on Nb_3Sn magnet technology developed for LHC IR upgrade

LHC IR magnet prototype



eRHIC Q1

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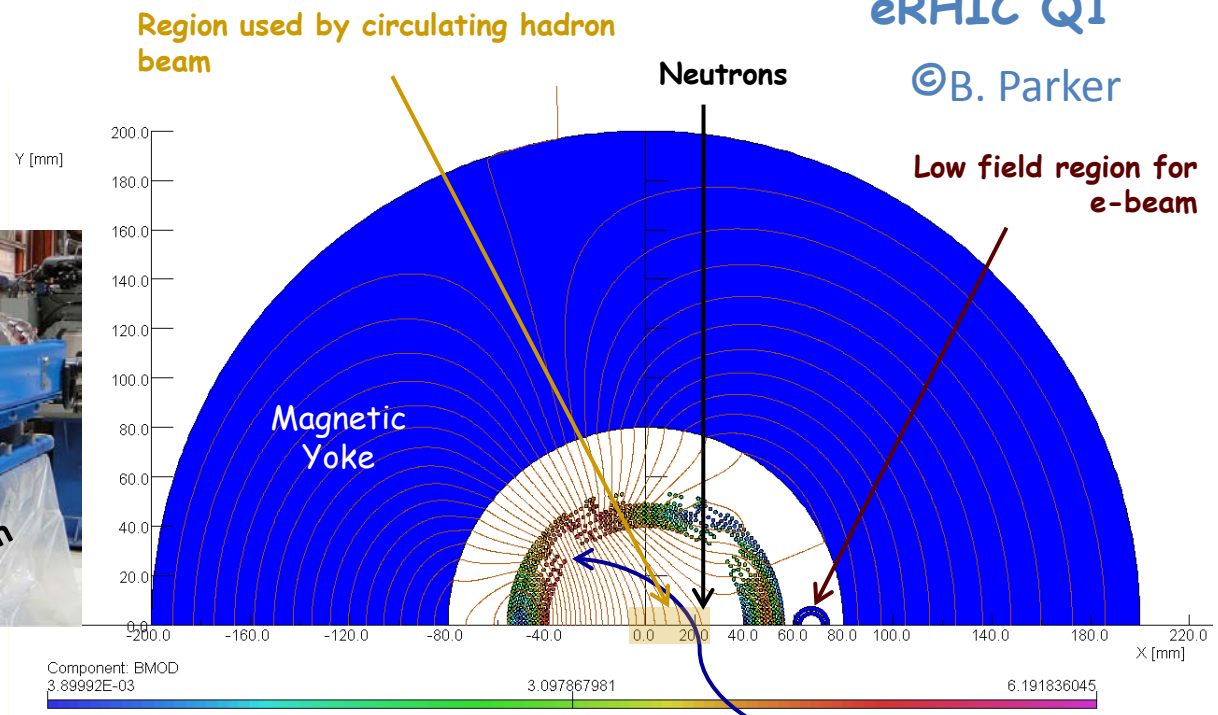
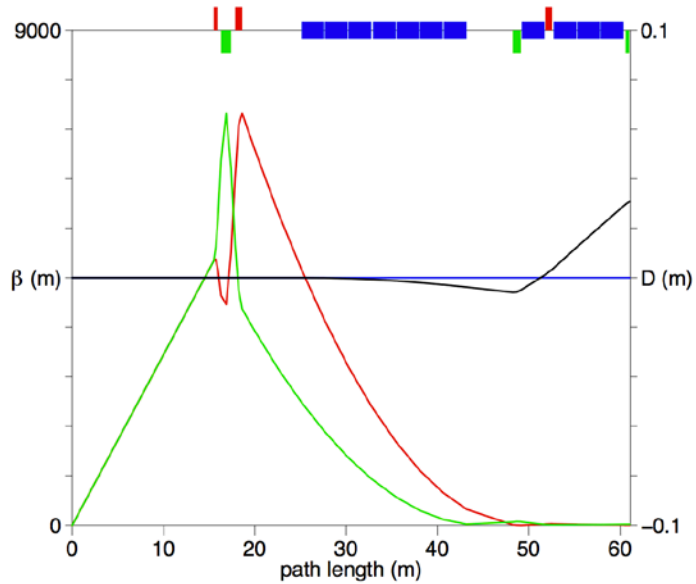
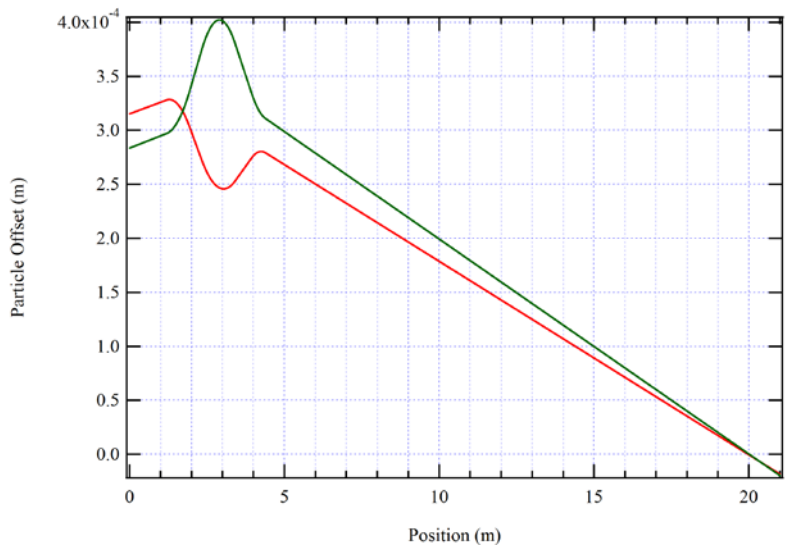


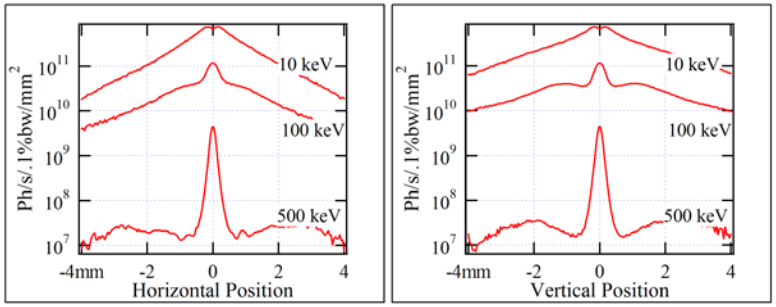
Plot of |B| (Tesla) for the Coil Structure

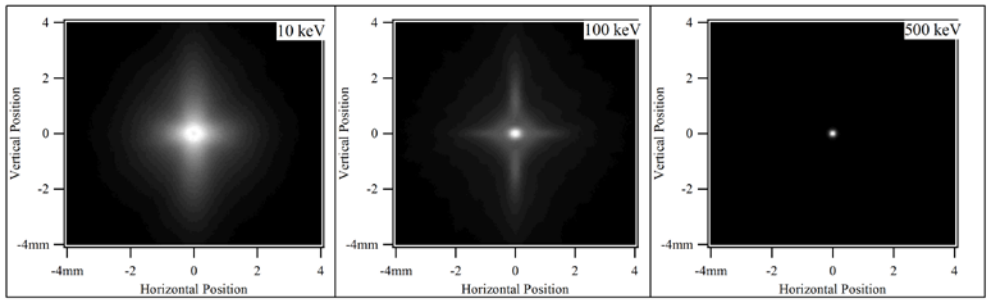
Peak field is 6.2 T

Synchrotron Radiation @ IR







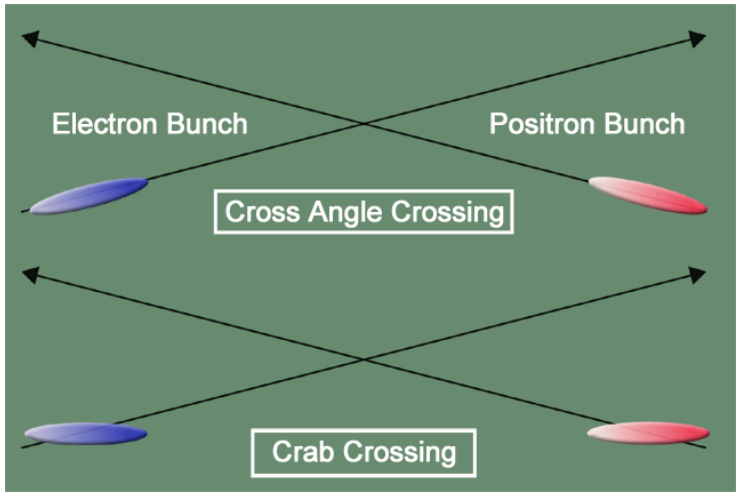


Preliminary study of synchotron radiation at triplet. Detail studies are undergoing to determine the necessity of radiation collimation or lattice optimization.

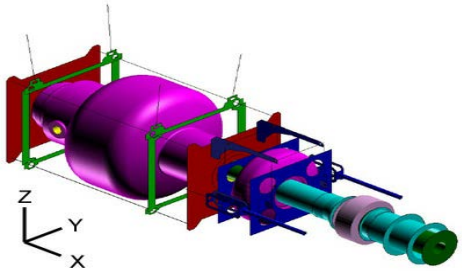
@ Y.C. Jing, O. Tchoubar

Crab Crossing

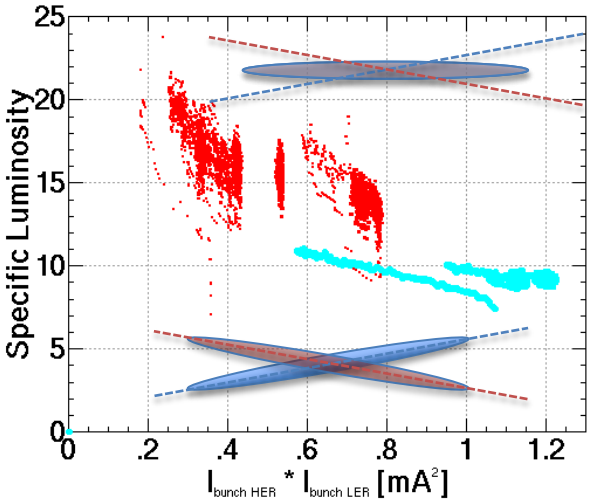
Idea Introduced by R. B. Palmer SLAC PUB 4832



To realize crab crossing, Crab Cavity is needed to give kick to the particle depend on its position in the beam .



Used at KEK B-factory

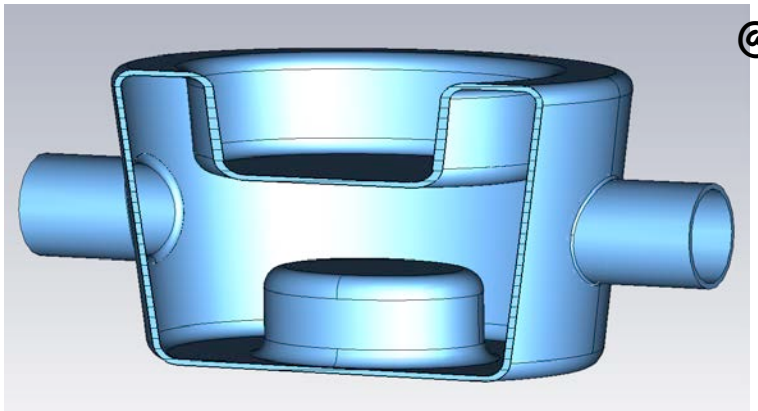


- ✓ For eRHIC: The presence of crab cavity has much larger effect in recovering luminosity than electron colliders.
- ✓ Linear part of RF sinusoidal field should be used. The hadron bunch is long even after cooling. Use harmonic cavities to improve linearity.
- ✓ Fundamental +3rd + 5th ,
  f_{fund}= 183 MHz, V_{fund} = 24 MV, V_{3rd}=1.3 MV, V_{5th} =0.09 MV
  OR
  Fundamental +2nd + 3rd
  f_{fund}= 244 MHz, V_{fund} = 22 MV, V_{2nd}=4.4 MV, V_{3th} =0.5 MV
- ✓ Crab-cavity designs on the basis of the quarter wave and half wave SRF cavities has been developed

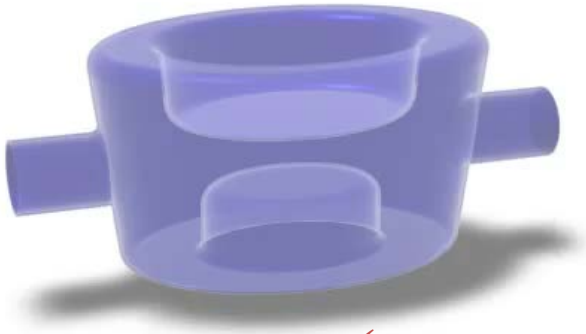
@ V. Litvinenko, I. Ben-Zvi, S. Belomestnykh, Q. Wu

Crab cavities in design

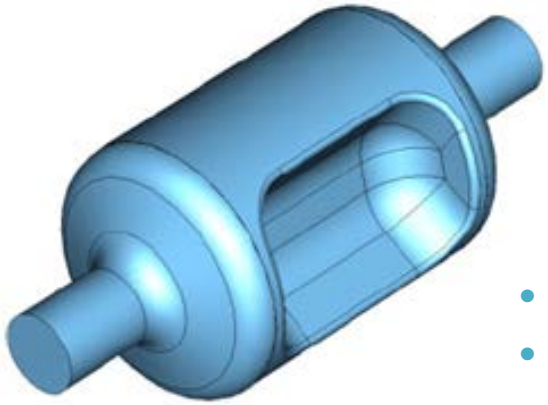
eRHIC need low frequency crab cavity. Compact design are desired. Two design are undergoing



@ Q.Wu, I. Ben-Zvi, S. Belomestnykh, R. Calaga



- ✓ More Compact
- ✓ Easier HOM damping
- ✓ Higher R/Q

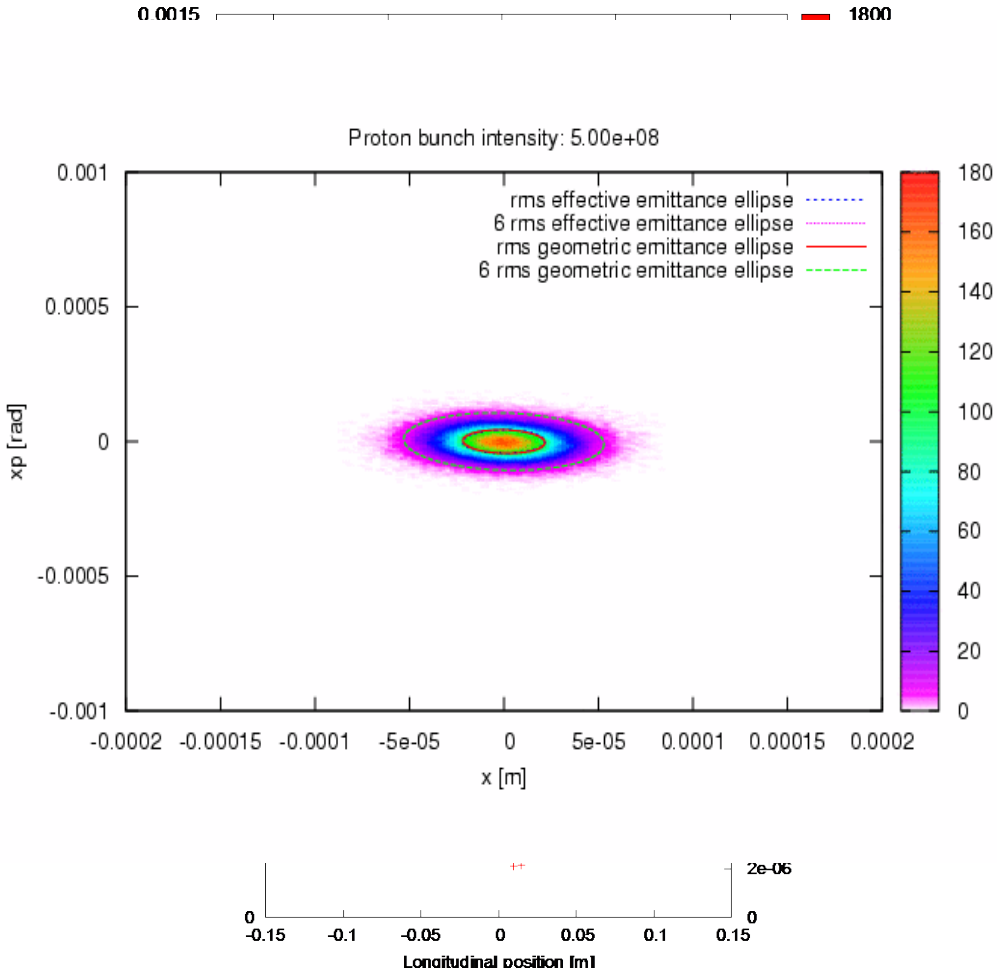


- Symmetric design
- Low peak field

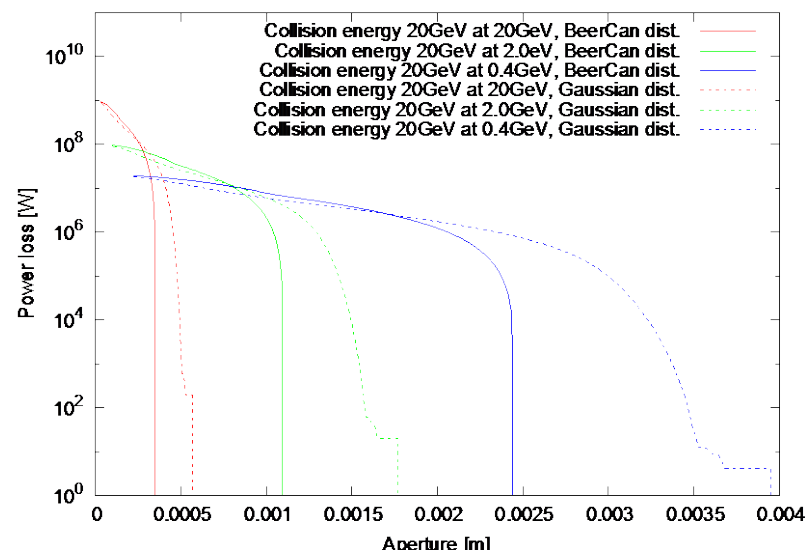
@ J. Delayen, S. De Silva

Beam-Beam effects Disruption & Mismatch

The advantage of higher luminosity of a ERL base EIC than a ring-ring counterpart comes from the stronger beam-beam effect of the electron beam. It also bring challenges to solve.



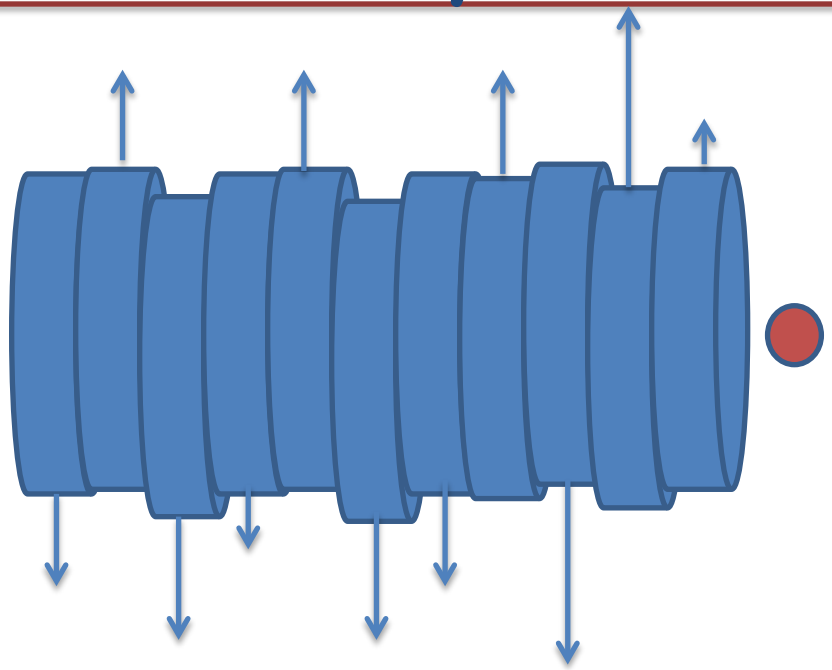
Disruption parameter varies from 0 to 27. The effect defines the aperture requirement of the aperture after collision. The is the most important factor to determine the aperture.

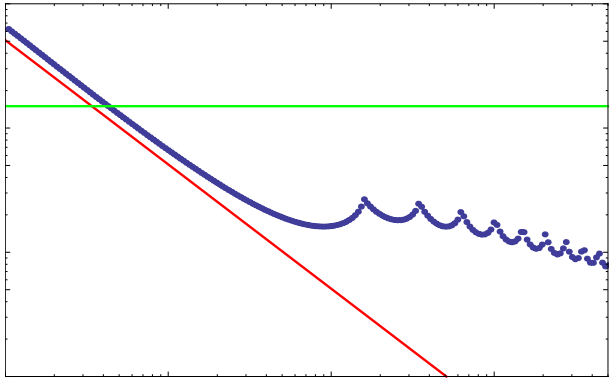


Beam-Beam effects
Kink Instability

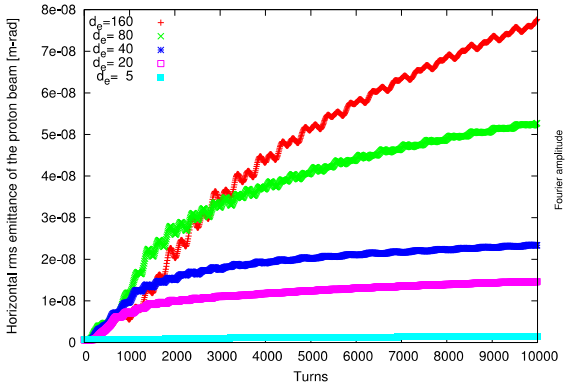
Hadron beam becomes instable, since the interaction serve as a wake field.

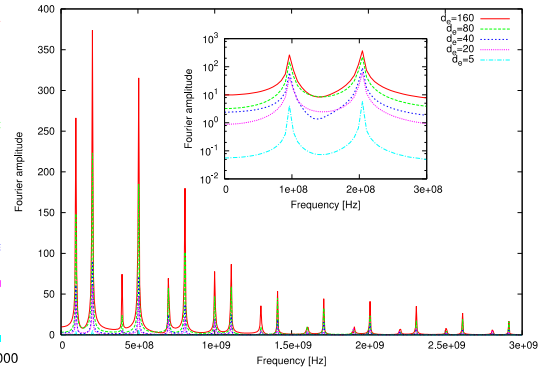
eRHIC parameter exceed the threshold of the instability, which is related to ξ_i and d_e.





Simulation results:



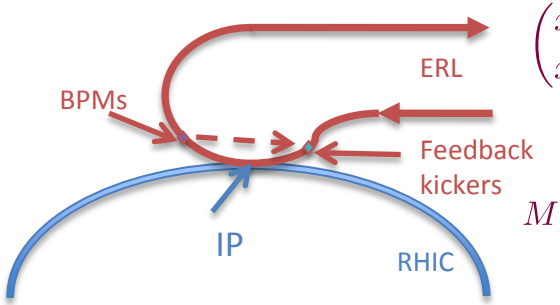


A simple model anticipates:

$$\xi_p d_e < 4\nu_s/\pi$$

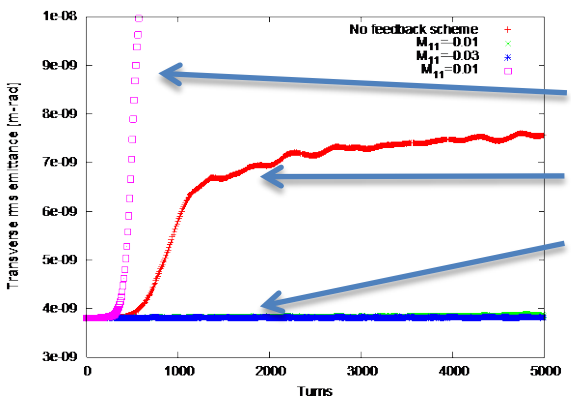
Suppress of Kink Instability

- Feedback on electron beam accelerator



$$\begin{pmatrix} x_c \\ x'_c \end{pmatrix}_{n+1,i} = M \begin{pmatrix} x_c \\ x'_c \end{pmatrix}_{n,f}$$

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}$$



With Feedback
Wrong sign of gain

No feedback

With Feedback

Merits

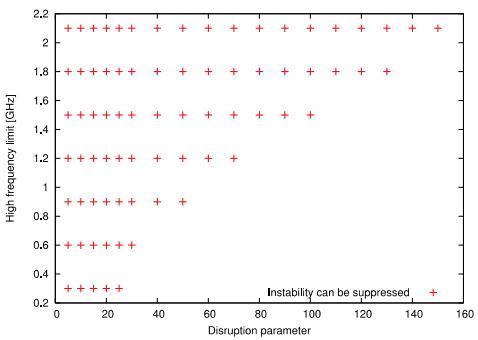
- Simple
- Low frequency ~14 MHz
- Works for under de ~ 25

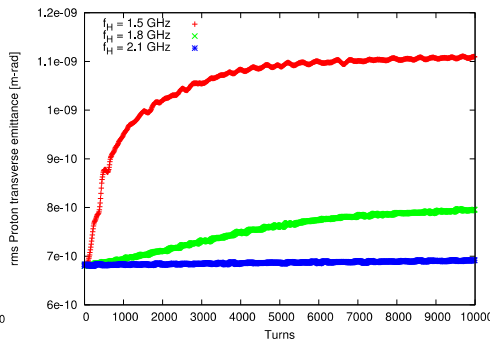
Drawbacks

- Gain need to be adjusted for different ion bunch
- Not for de > 25

- To suppress the instability of a wider range of de, a pickup-kicker can be used.
- The system is modeled as:

$$W(\tau) = R \int_{f_L}^{f_H} \cos(2\pi f \tau)\, df$$

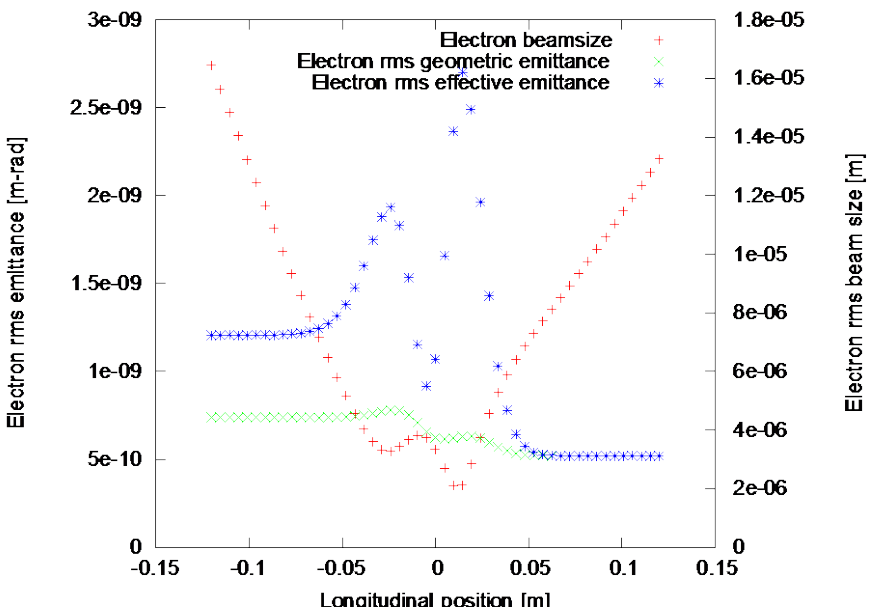




- Full Range of disruption parameter up to 150 is demonstrated, with the highest frequency response of 2.1GHz
- The frequency requirement is the function of the ion bunch length and longitudinal distribution, and irrelavent with others. However the gain is determined by the strength of the beam-beam force.

Other beam-beam effects

Electron beam gets strong focusing force.
Pinch effect



The pinch effect enhances the local beam-beam parameter of the hadron beam.

In the mean time, there is free luminosity boost, ~20%.

Electron beam is fresh before each collision.
Noise of the hadron beam

Electron beam offset ➔ dipole error for the hadron each turn ➔ beam center shift

For white noise

$$\sqrt{< x_i^2 > (t)} = \sqrt{t/\tau + < x_i^2 > (0)} \qquad 1/\tau = \frac{8\pi^2\xi_i^2}{T} < d_n^2 >$$

If a Lorentz noise spectrum $g(\omega) = 1/(\omega^2 + \alpha^2\omega_0^2)$ is assumed, reduction factor is:

$$R(\alpha) = \frac{1 - \exp(-2\alpha)}{1 + \exp(-2\alpha) - 2\cos(2\pi\nu)\exp(-\alpha)} = \frac{\alpha}{1 - \cos(2\pi\nu)} + O(\alpha^3)$$

Electron beam intensity and beam size error ➔ quad error for the hadron each turn ➔ hadron beam size increase

For white noise, exponentially growth with growth time: $\tau = \frac{T}{4\pi^2\xi_i^2}\frac{1}{(\delta f/f)^2}$

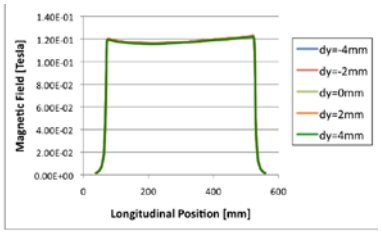
Lorentz noise spectrum, the reduction:

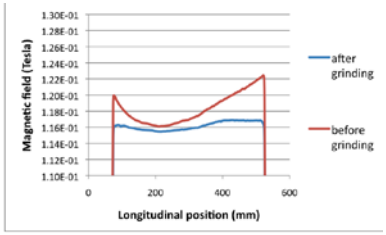
$$R(\alpha) = \frac{1 - \exp(-2\alpha)}{1 + \exp(-2\alpha) - 2\cos(4\pi\nu)\exp(-\alpha)} = \frac{\alpha}{1 - \cos(4\pi\nu)} + O(\alpha^3)$$

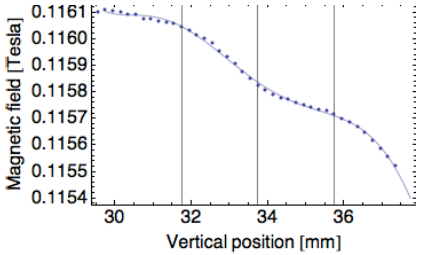
Cooling and feedback system can mitigate the effect of both errors

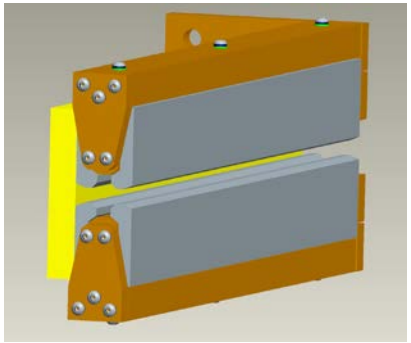
Development of compact magnets

- Few thousand magnets in electron beam lines
- Small gap -> efficient and inexpensive-> low cost eRHIC
- Designed and manufactured two prototypes of dipole and quadrupole
  - We used EDM for initial prototypes
  - Later we started using grinding
- We built magnetic measurement system and measured prototypes
  - Dipole field performance is close to specs
  - Quadrupole field requires major improving
- Ordered mini-series of prototypes at BINP (Novosibirsk)

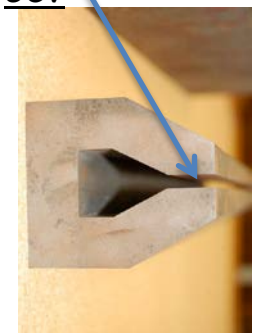








Gap 5 mm total
0.3 T for 30 GeV



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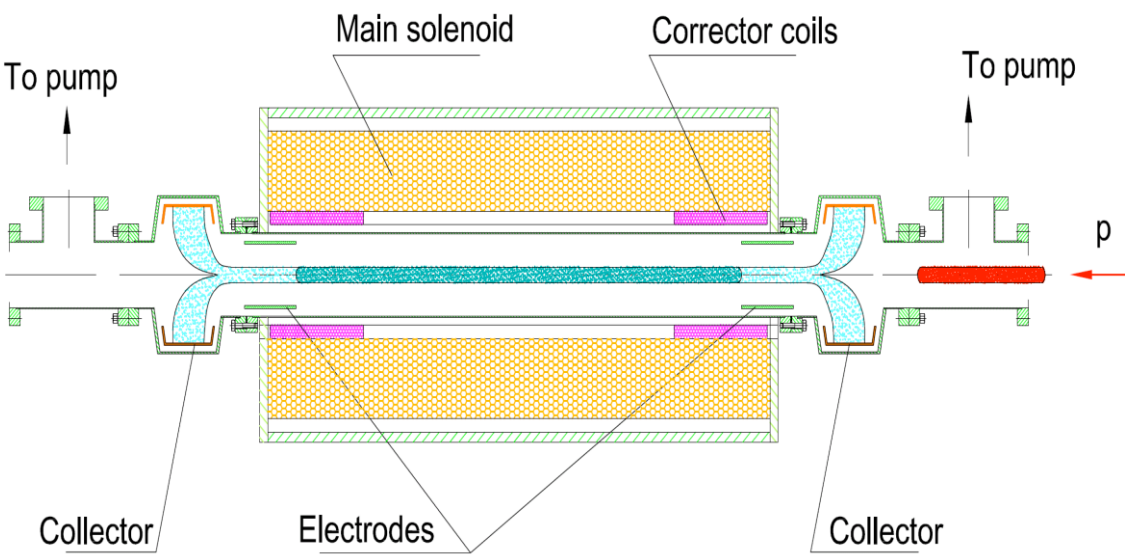
Space charge compensation

- The space charge tune shift is one of the limiting factor of luminosity ($L \propto \Delta Q_{sc}\gamma^3$) when the hadron energy is low.
- Now the space charge tune shift is set to <0.035 to ensure desire beam lifetime. The compensation scheme will enable us to enhance the luminosity largely at low energy.
- Schematic drawing of electron column (one of the candidate):



If work as expected, it removes the limitation for the luminosity in low energy case.

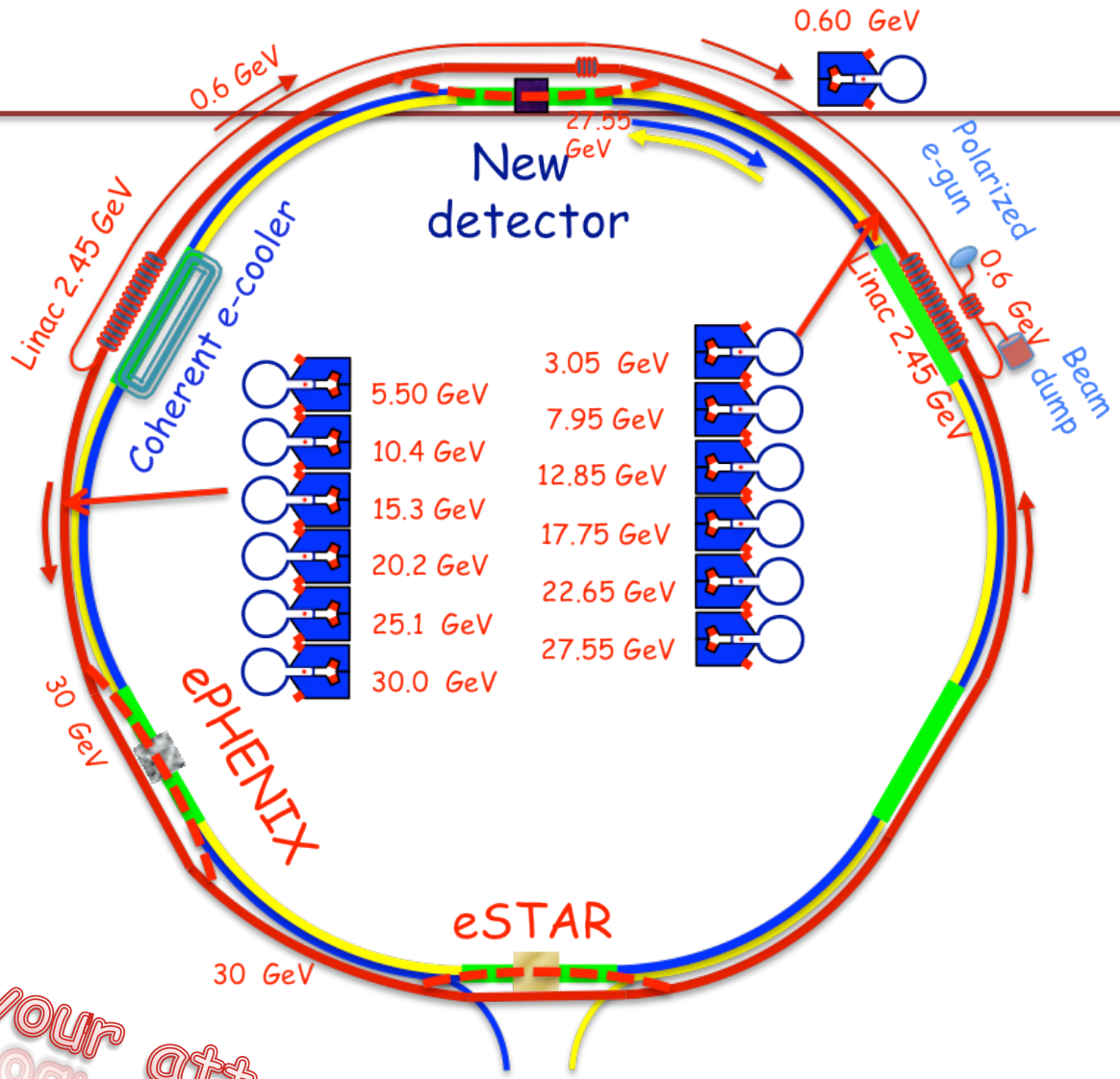
$$L \propto \Delta Q_{sc}\gamma_i^3$$

$$L \propto \gamma_i$$

Summary for this part

- No show-stoppers were found
- Several novel approaches are brought up and require R&D effort.
  - Novel design of IR region
  - Extensive beam-beam simulation is performed to prove the feasibility of the entire parameter range. Long-term tracking, interplay with other effects are still undergoing.
  - Prototypes are made for compact magnet, which gave us experiences and lessons.

BROOKHAVEN NATIONAL LABORATORY



Thank you for your attention!