Accelerator Development for eRHIC

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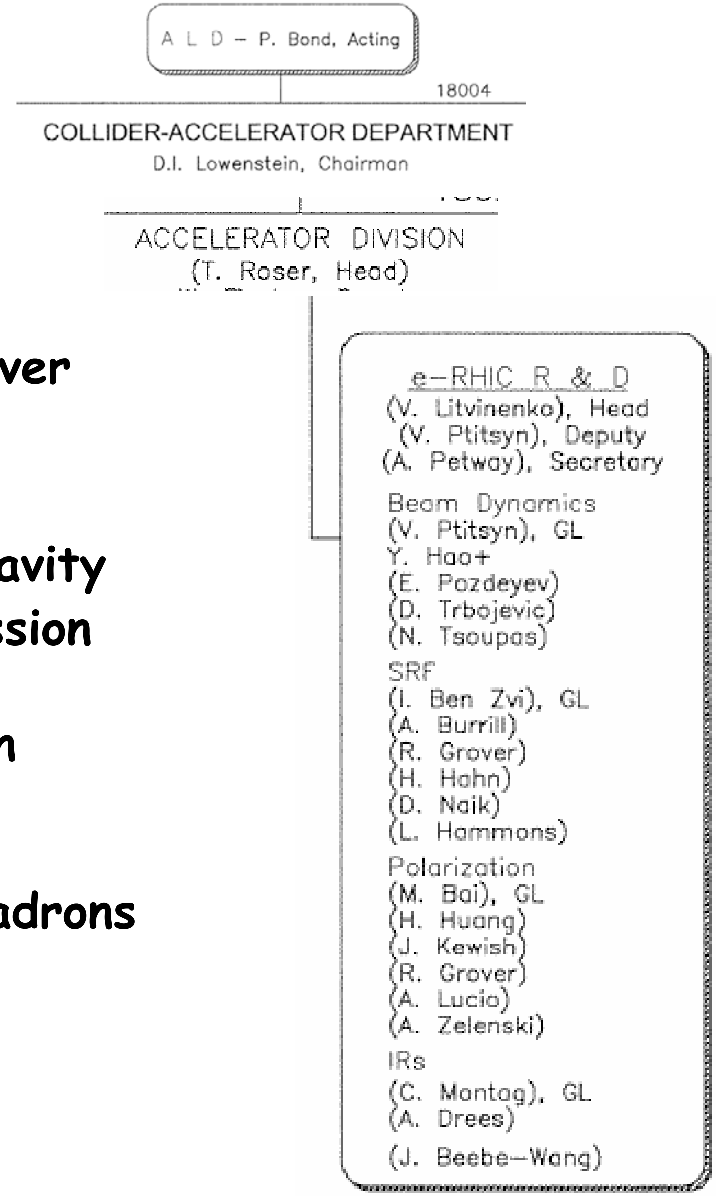
Content

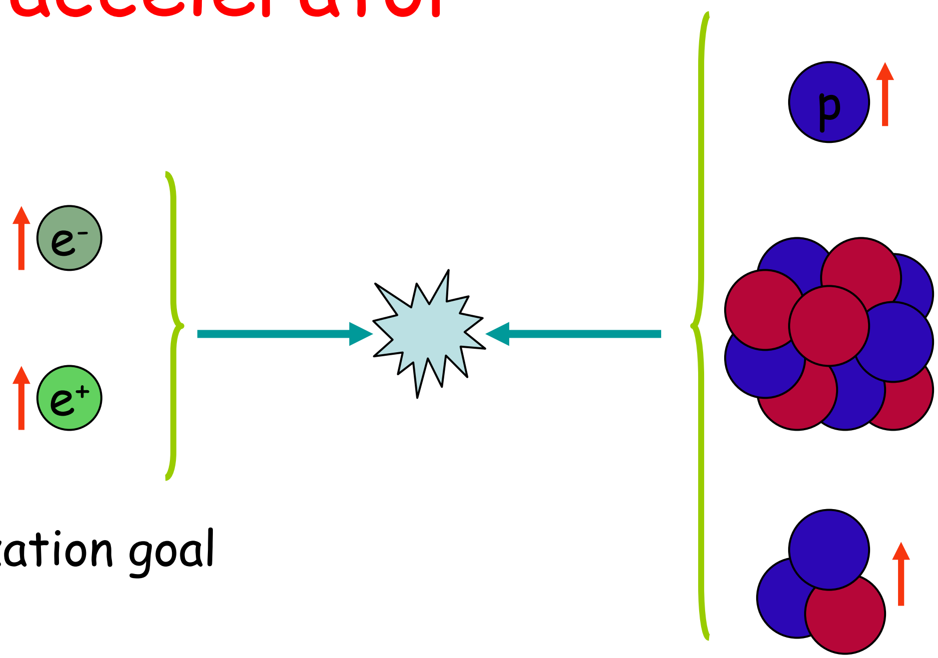


- What eRHIC is about
- Choosing the focus: ERL or ring for electrons?
  - Advantages and challenges of ERL driver
  - R&D items for ERL-based eRHIC
- New developments
  - First results from the VT of 5-cell cavity
  - Progress in understanding and suppression of kink instability
  - Simulation of electron beam disruption during the collision
  - Initial simulations of the beam-beam effects and choice of the tune for hadrons
- Conclusions

eRHIC Scope -QCD Factory

Electron accelerator

RHIC



Polarized leptons
$_2$↓5-10↑^{20} GeV

70% beam polarization goal

Polarized protons
$_{25}$↓ 50-250 GeV

Heavy ions (Au)
50-100 GeV/u

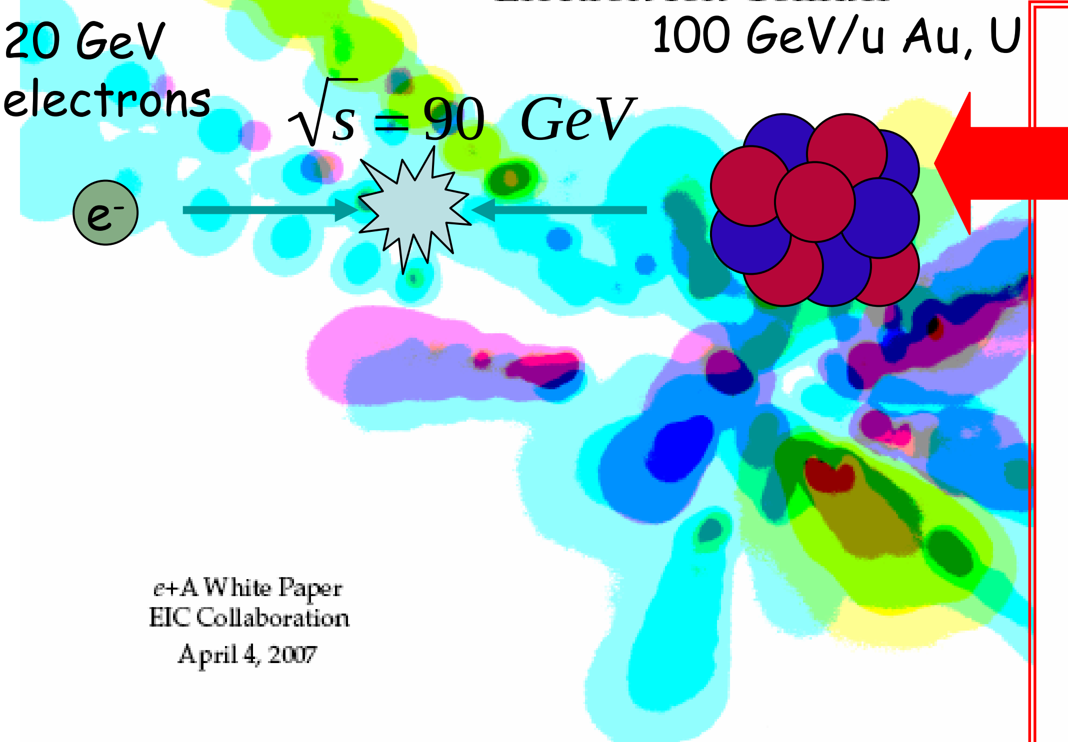
Polarized light ions
(He^3) 167 GeV/u

Center mass energy range: 15➢$_{10}$-100➣ ^{150}GeV

New development: eA program for eRHIC needs as high as possible energies of electron beams even with a trade-off for the luminosity. 20 GeV is needed and 25-30 GeV is strongly desirable.

Position paper on eA collider *by Thomas Ullrich at al.*

Physics Opportunities
with
e+A Collisions
at an
Electron Ion Collider



e+A White Paper
EIC Collaboration
April 4, 2007

Nuclear "Oomph" Factor

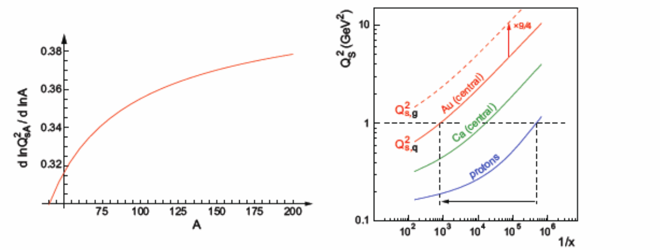


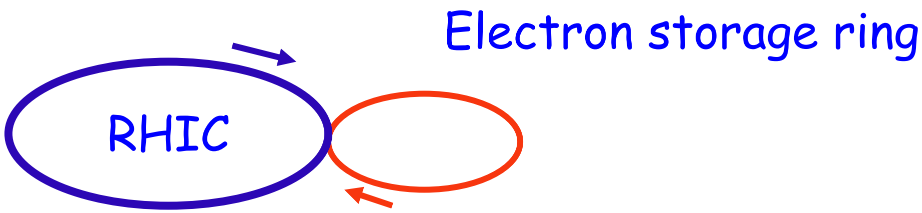
Figure 10: *Left: The A dependence of the saturation scale from the analysis of Ref. [16]. Right: The saturation scale at $b = 0$ in Au and Ca nuclei compared to the median saturation scale in a proton [15].*

- The machine needs to provide collisions of at least $\sqrt{s} > 60$ GeV to go well beyond the range explored in past fixed target experiments. The higher the energy, the longer the lever-arm in Q^2 and the greater the low-x reach.
- The machine must be able to provide ion beams at different energies. Measurements at various $\sqrt{s}$ are mandatory for the study of many relevant distributions such as F_L. Note that it is kinematically better for any experimental setup to lower the ion beam energy then the electron energy.
- The machine must provide a wide range of ions. For saturation physics studies beams of very high mass numbers (A $\geq$ Au) are vital.
- To collect sufficient statistics luminosities with $L > 10^{30}$ cm^{-2}s^{-1} are required.

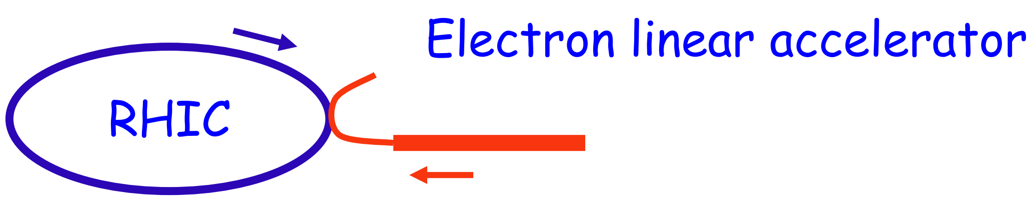
eRHIC is based on the main BNL's investment: hadron complex of RHIC

Choosing the focus: ERL or ring for electrons?

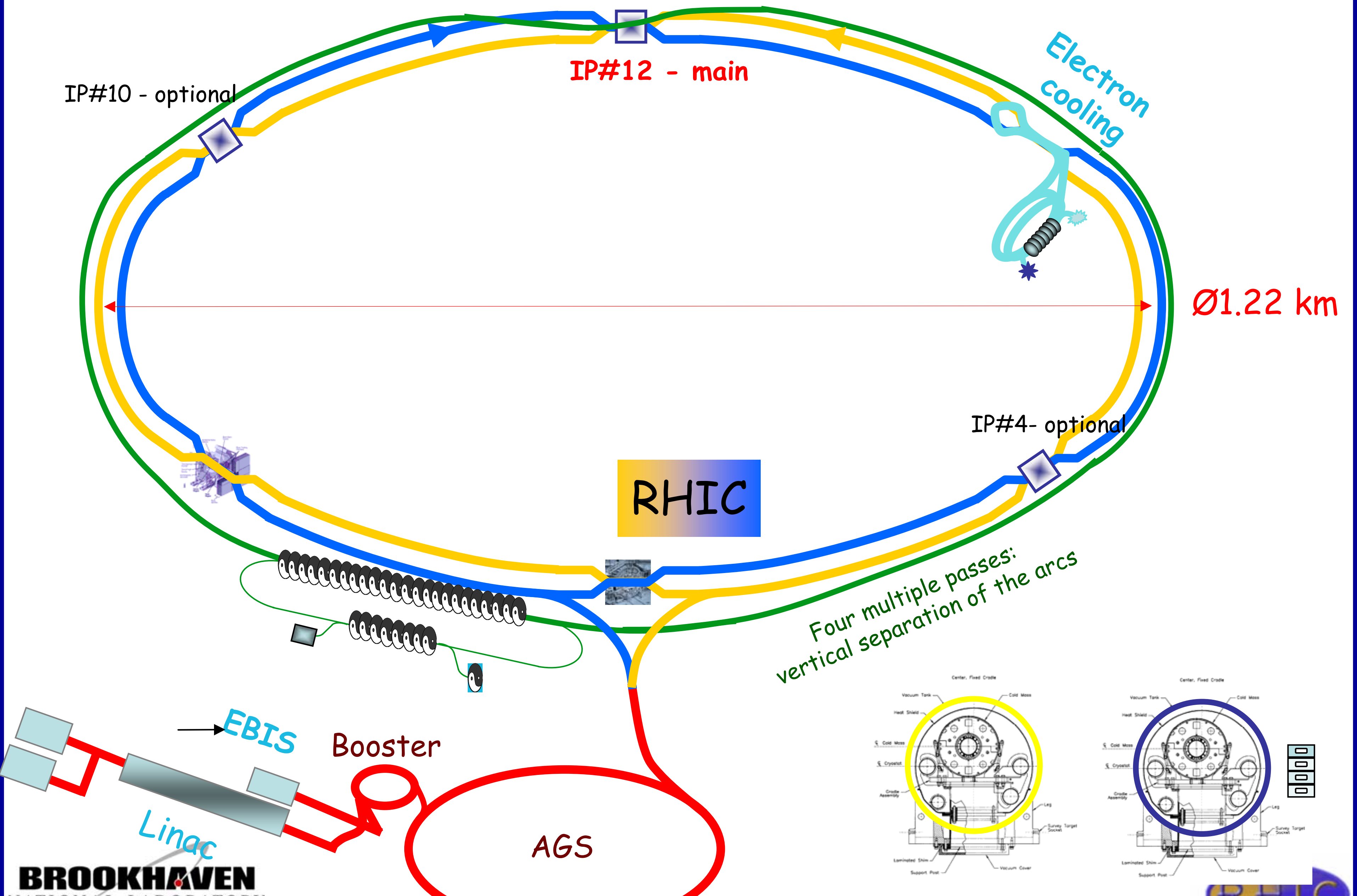
- Two main design options for eRHIC:
  - Ring-ring:



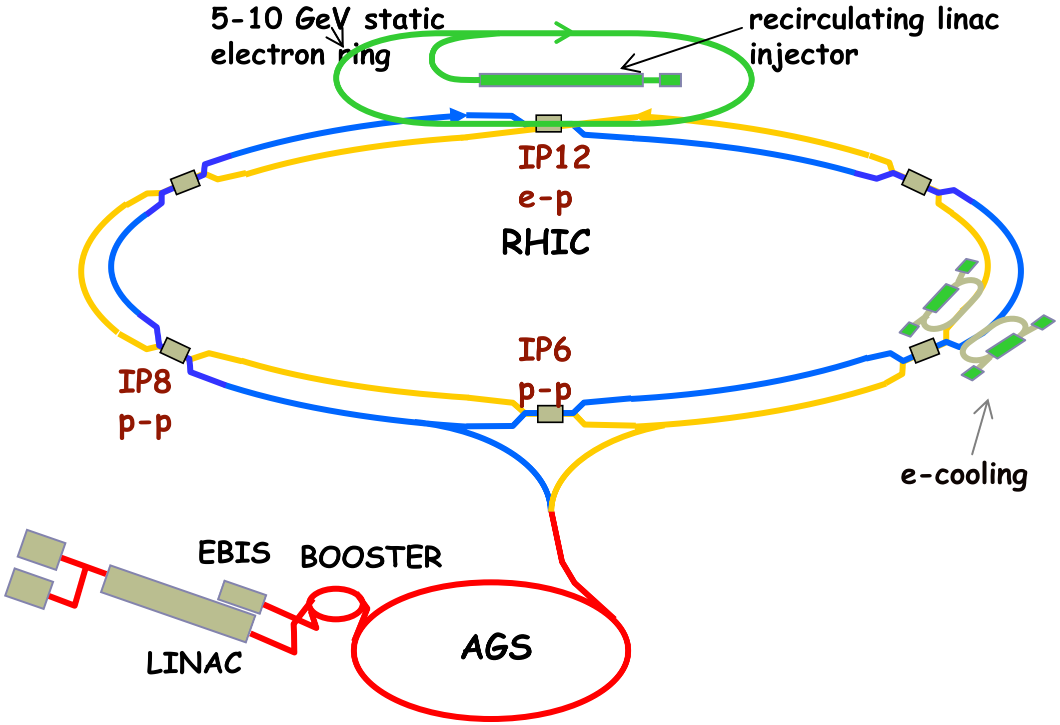
  - Linac-ring:



Linac-Ring Design based on 5-20+ GeV ERL: main choice



Ring-ring design - back-up option



- The electron ring of 1/3 of the RHIC ion ring circumference
- Full energy injection using polarized electron source and 10 GeV energy linac.
- e-ion collisions in one interaction point.
(Parallel mode : Ion-ion collisions in IP6 and IP8 at the same time are possible.)
- Longitudinal polarization produced by local spin rotators in interaction regions.
- ZDR design luminosities (for high energy setup):
  - e-p: 2.2 10^{32} $cm^{-2}s^{-1}$
  - e-Au: 2.2 10^{30} $cm^{-2}s^{-1}$
  - e-He^3: 1.5 10^{32} $cm^{-2}s^{-1}$

The e-ring design development led by MIT-Bates.
Technology similar to used at B-factories.

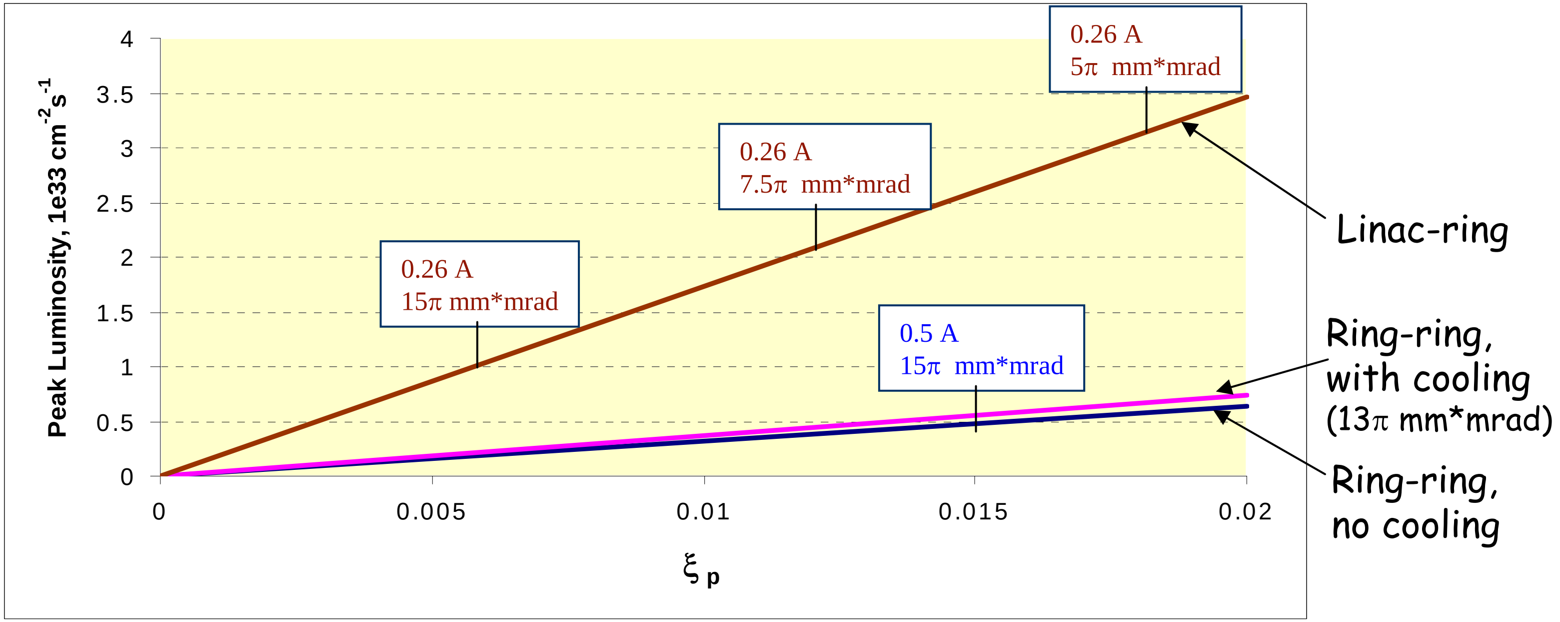
Advantages & Challenges of ERL based eRHIC

$$L = \left(\frac{4\pi \gamma_i \gamma_e}{r_i r_e} \right) (\xi_i \xi_e)(\sigma_i' \sigma_e') f \quad \Rightarrow \quad L = \gamma_i \, f \, N_i \frac{\xi_i Z_i}{\beta_i^* r_i}$$

- **Allows use of RHIC tunnel for the return passes and thus allow much higher (2-3 fold) energy of electrons compared with the storage ring.**
- **High luminosity up to 10^{34} cm^{-2} sec^{-1}**
- **Allows multiple IPs**
- **Allows higher range of CM-energies with high luminosities**
- **Full spin transparency at all energies**
- No machine elements inside detector(s)
- No significant limitation on the lengths of detectors
- **Energy of ERL is simply upgradeable**
- Novel technology
- Need R&D on polarized gun
- May need a dedicated ring positrons (if ever required?)

Luminosity with e-cooling

Calculations for 166 bunch mode and 250 Gev(p) x 10 Gev(e) setup;

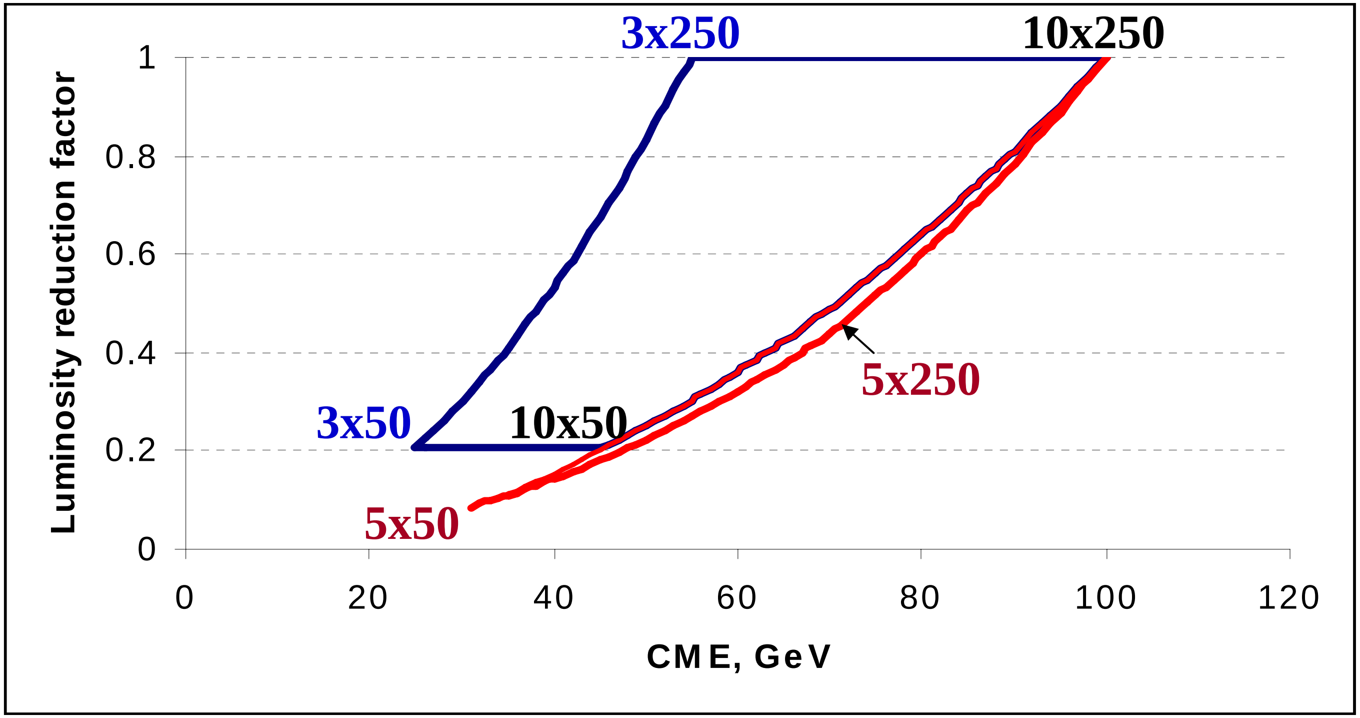


Markers show electron current and (for linac-ring) normalized proton emittance.
In dedicated mode (only e-p collision): maximum ξ_p~0.016-0.018;

Transverse cooling can be used to improve luminosity or to ease requirements on electron source current in linac-ring option.
For proton beam only e-cooling at the injection energy is possible at reasonable time (~1h)

Luminosity dependence on CME with cooling

In Ring-ring luminosity reduces 10-fold for 30 GeV CME.
Required norm.emittance (for 50 GeV protons) ~3 mm*mrad



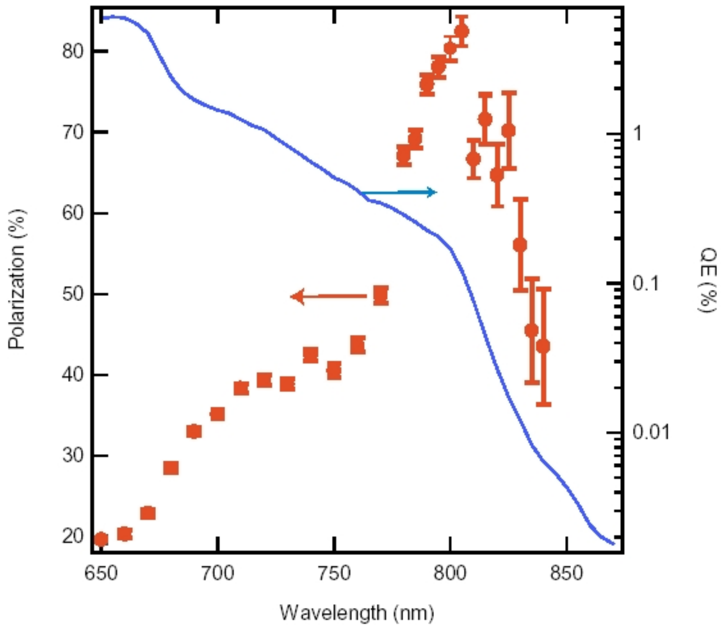
- For ring-ring the e-cooling improves luminosities for low energy proton modes.

  The optimal path for luminosity: E_e=10GeV/E_p=250GeV-> 10/50 -> 5/50
- For linac-ring operation in proton beam-beam limit the cooling can be used to reduce requirements on electron current.

  The optimal path for luminosity: E_e=10GeV/E_p=250GeV-> 3/250 (or 2/250) -> 3/50

Electron Polarized Source: main R&D item (MIT/Bates submitted proposal to DoE)

Photoemission from strained GaAs cathode.



High polarization ->Low QE

Present polarized CW sources:

- Mainz: <100 mA
- JLab(CEBAF):
  - 100 (200) μA in CEBAF operations
  - 1 mA (demonstrated in 2007)

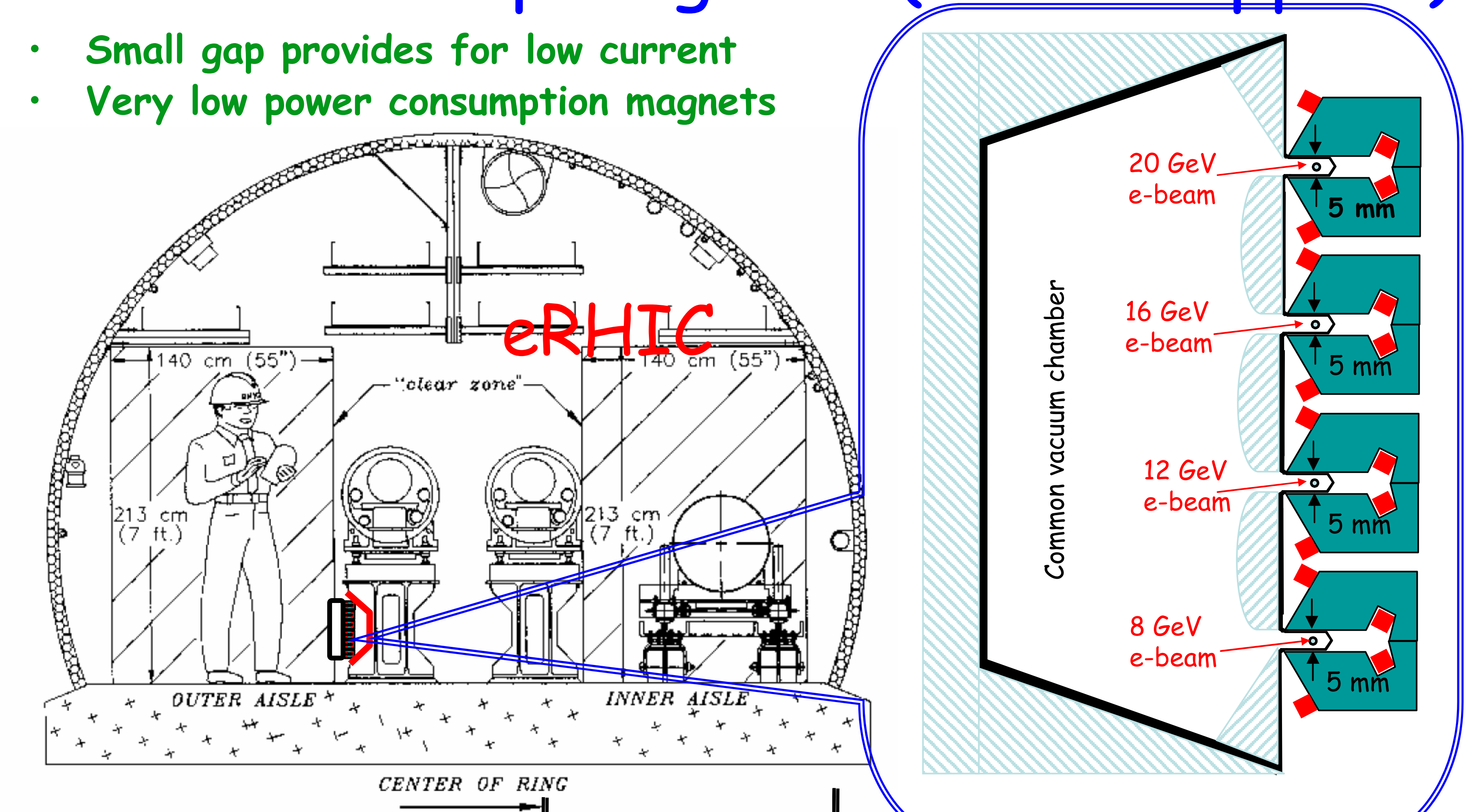
- eRHIC linac-ring requires several hundred mAs to go above 1.e33 luminosity

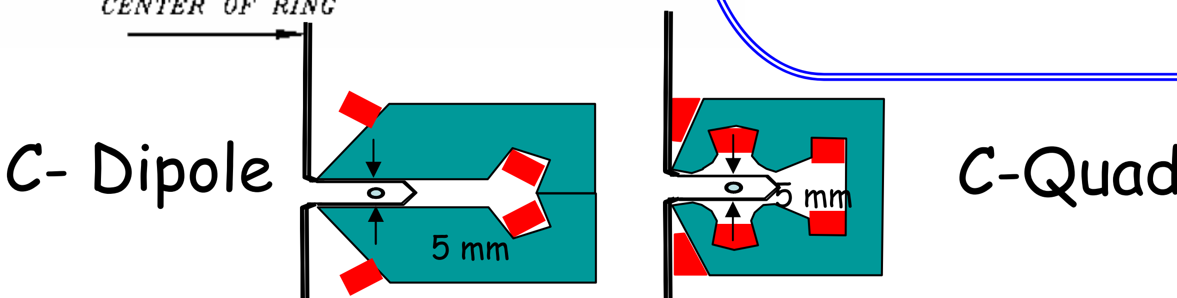
Proposed path:

- increase laser spot on the cathode,
- Free Electron Laser if high laser power is needed

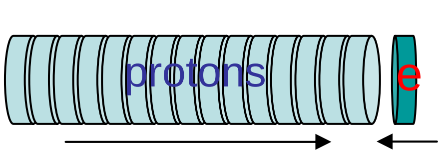
eRHIC loop magnets (LDRD support)

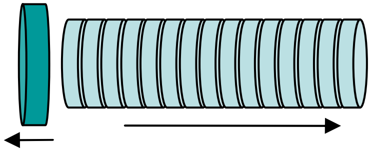
- Small gap provides for low current
- Very low power consumption magnets

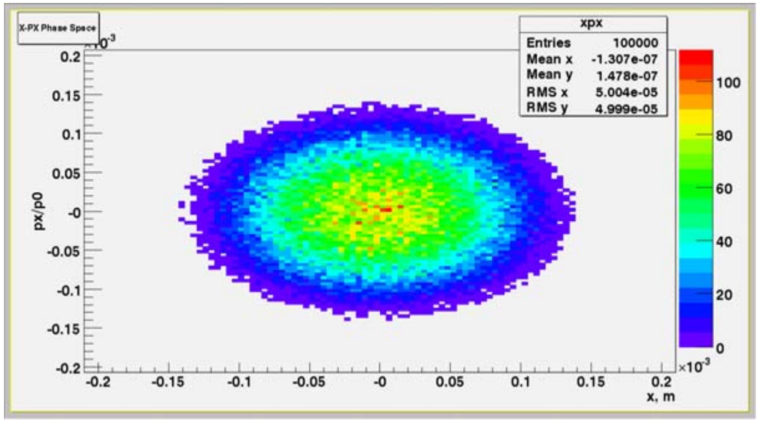




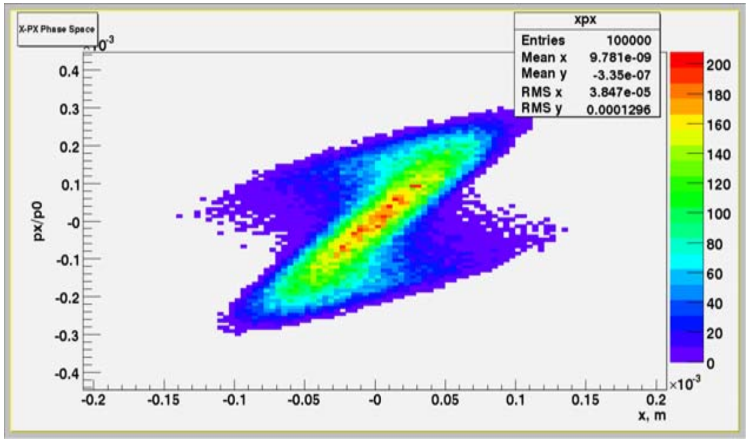
Beam Disruption -LINAC-RING



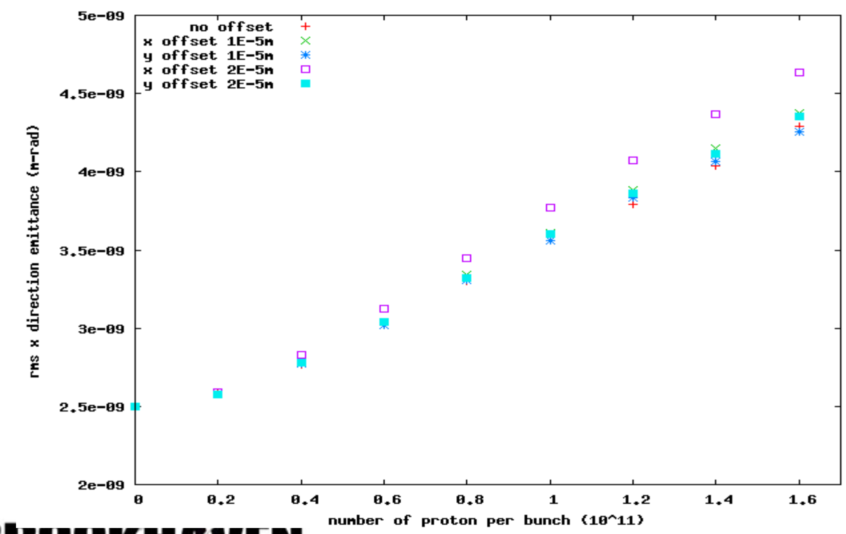


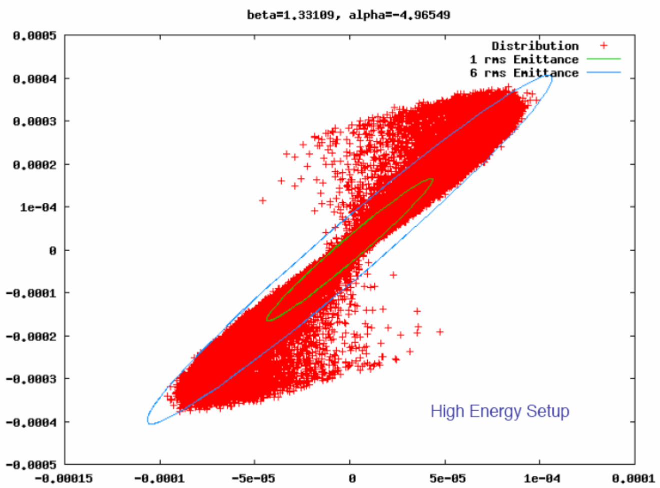


Interaction



Optimized

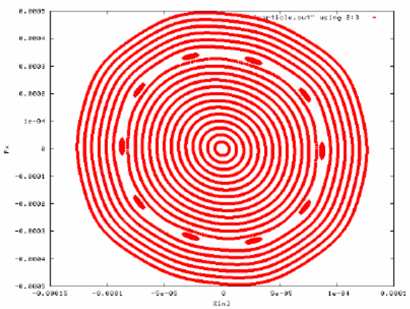


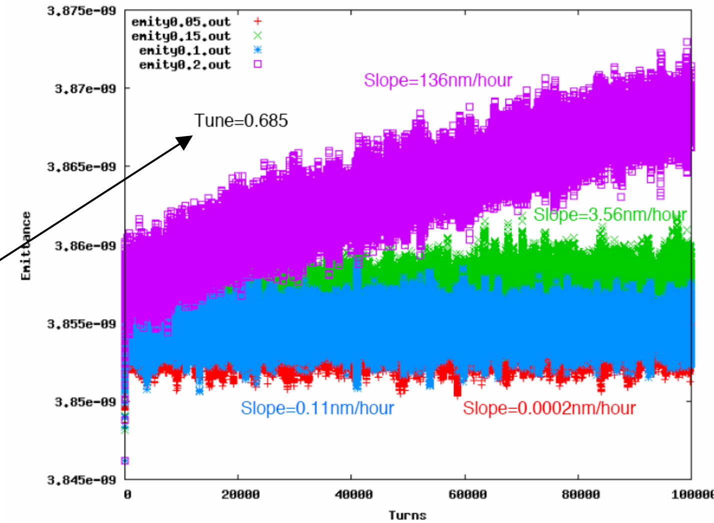


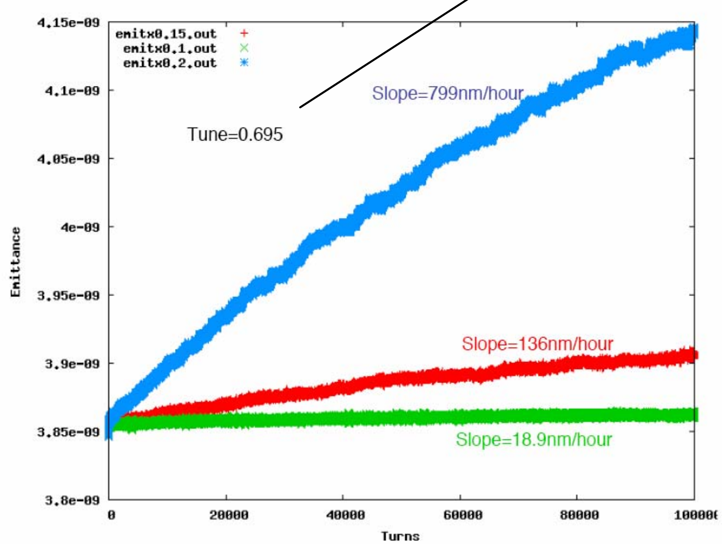
Other effects at the e-ion collision

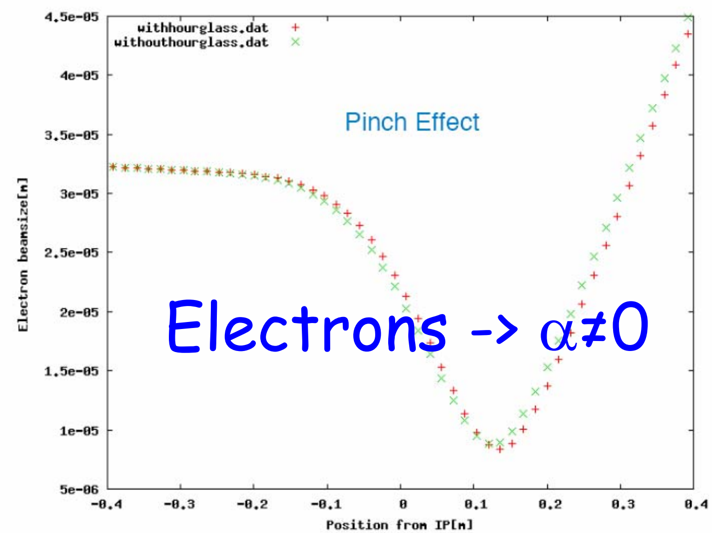
Emittance Growth

- A Multi-Particle strong-weak simulation is done to show the hourglass effect can cause emittance growth. (Force is nonlinear.)
- There is 10th order rensonance near the tune we choose(0.695 and 0.685).

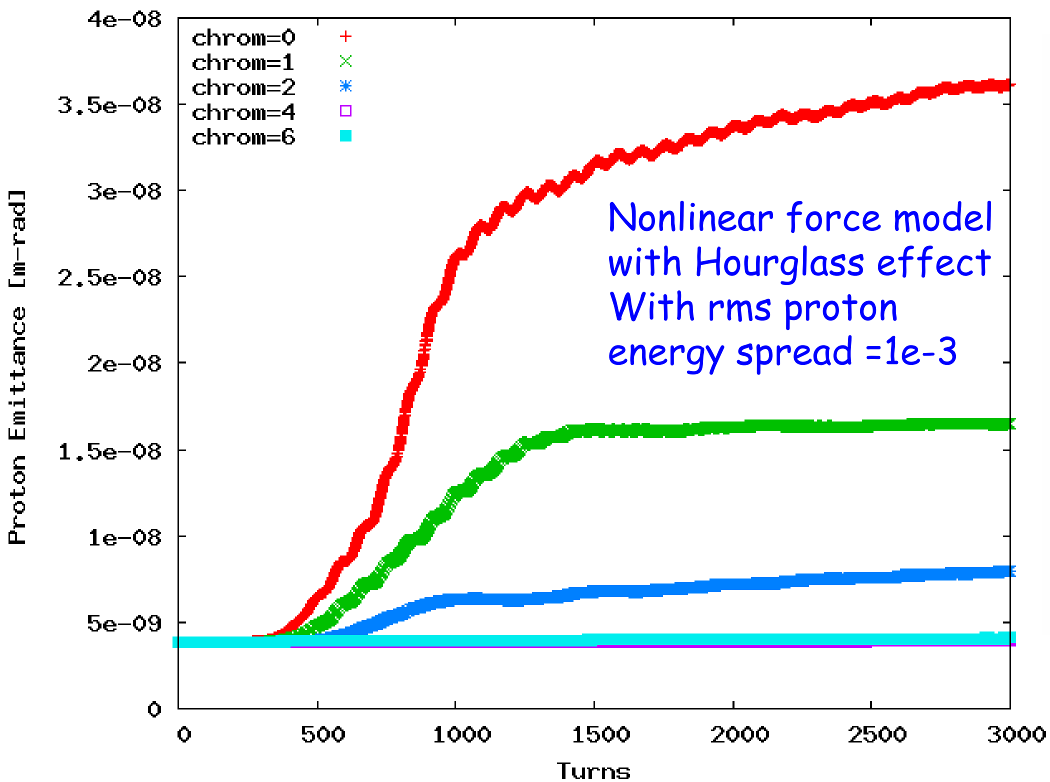


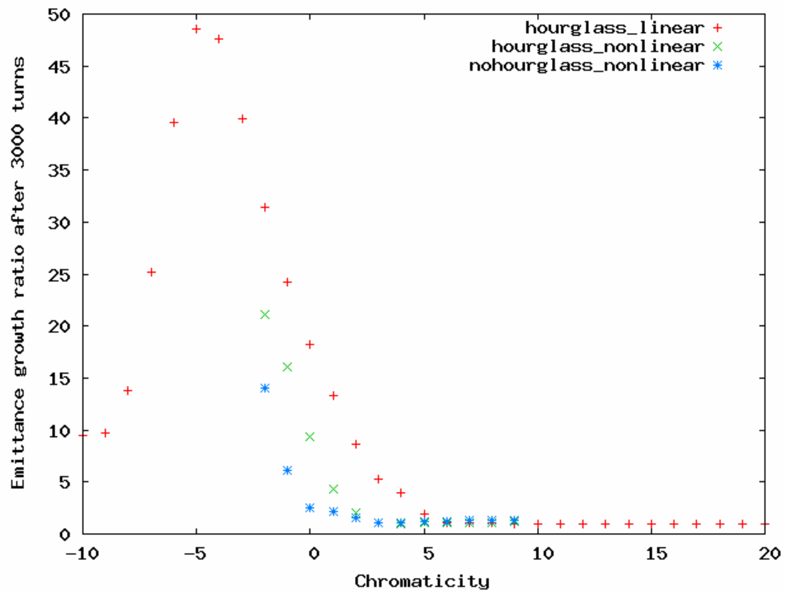






Chromaticity suppresses kink instability





The optimum chromaticity is around ξ = +4

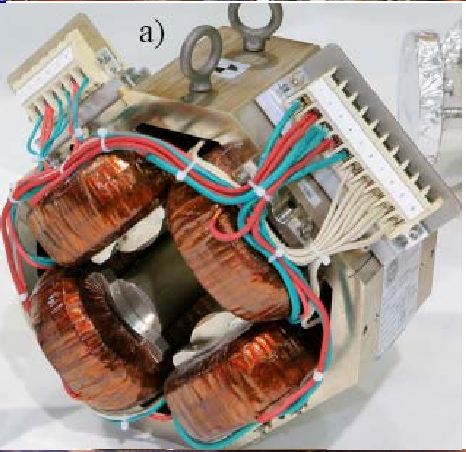
	High energy setup		Low energy setup	
	p	e	p	e
Energy (GeV)	250	10	50	3
Number of bunches	166		166	
Bunch spacing (ns)	71	71	71	71
Bunch intensity (10^{11})	2.0	1.2	2.0	1.2
Beam current (mA)	420	260	420	260
95% normalized emittance (π-mm-mrad)	6	115	6	115
RMS emittance (nm)	3.8	5.0	19	2.0
β*(cm), x/y	26	20	26	250
Beam-beam parameters, x/y	0.015	2.3	0.015	2.3
RMS bunch length (cm)	20	0.7	20	1.8
Polarization (%)	70	80	70	80
Peak Luminosity (1.e33 $cm^{-2}s^{-1}$)	2.6		0.53	

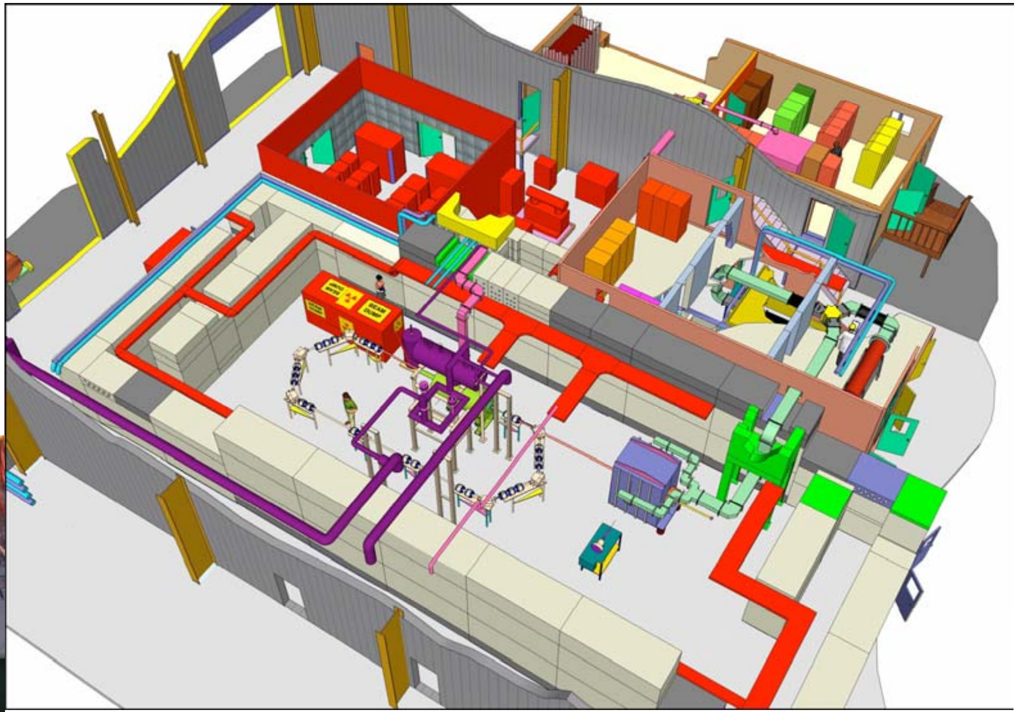
Conclusions

- High energy, high luminosity ERL-based electron-ion and polarized electron-proton collider is the most promising approach for eRHIC
- Presently there is no show-stoppers and a significant amount of R&D
- R&D ERL tests in 2009, MIT's progress with developing high current polarized gun, prototyping of small gap magnets will next step-stones towards QCD factory at BNL.

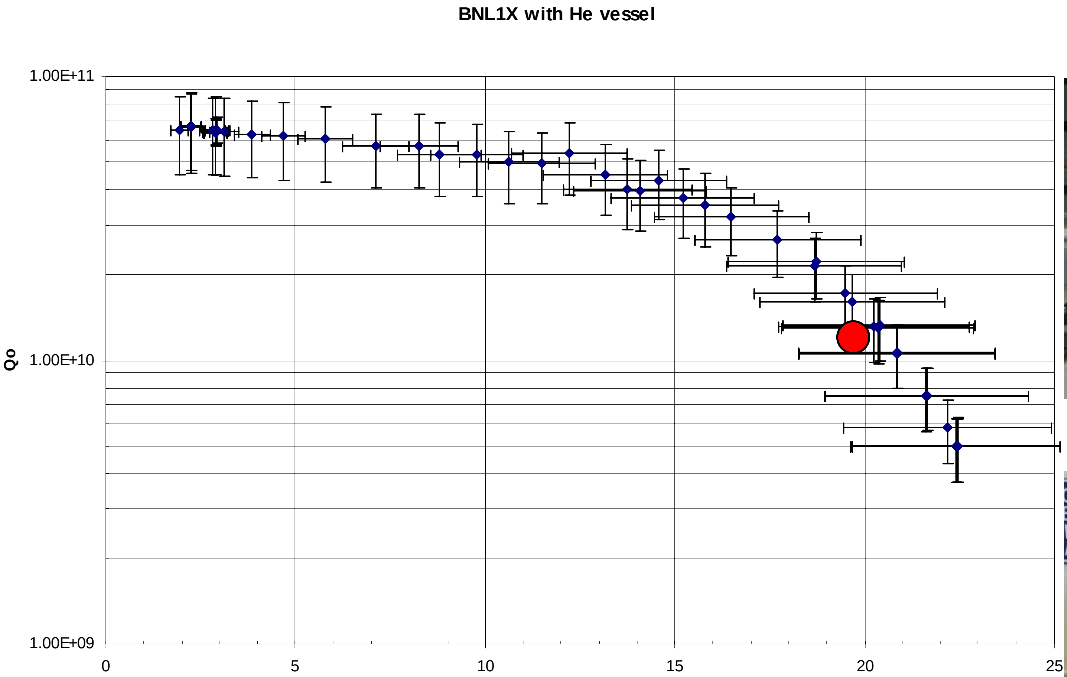
Back-up slides

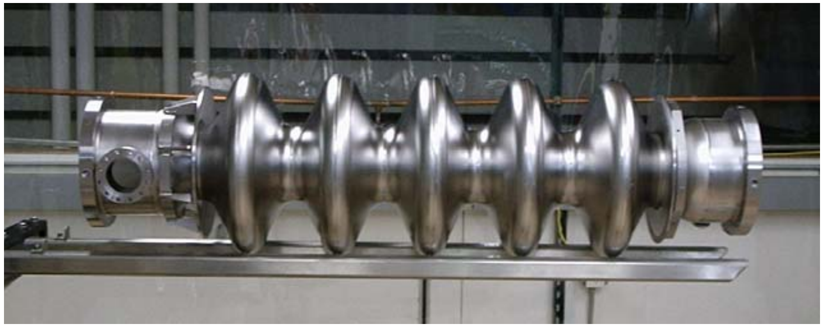
R&D ERL Commissioning start 2/09





5 cell cavity successfully processed





Topic of active research for eRHIC

- High charge / high average current, normal and polarized e guns
- High current ERLs
- High energy electron cooling of protons/ions
  - Electron cooling requires SRF-ERL technology
- Integration of interaction region design with detector geometry
- Detailed studies of disruption of the electron beam and kink instability
- Study possibility of shortening hadron bunches in RHIC or of suppressing kink instability by feedback

Major R&D issues

- Ring-ring:
  - The accommodation of synchrotron radiation power load on vacuum chamber. (To go beyond 5.e32 $cm^{-2}s^{-1}$ luminosity).
- Linac-ring:
  - High current polarized electron source
  - Energy recovery technology for high energy and high current beams
- Ion ring:
  - Beam cooling techniques development (electron, stochastic).
  - Increasing total current (ions per bunch and number of bunches).
  - Polarized He^3 production (EBIS) and acceleration

ERL spin transparency at all energies

Bargman, Mitchel,Telegdi equation

$$\frac{d\hat{s}}{dt} = \frac{e}{mc}\hat{s} \times \left[\left(\frac{g}{2}-1+\frac{1}{\gamma}\right)\vec{B} - \frac{\gamma}{\gamma+1}\left(\frac{g}{2}-1\right)\hat{\beta}(\hat{\beta}\cdot\vec{B}) - \left(\frac{g}{2}-\frac{\gamma}{\gamma+1}\right)[\vec{\beta}\times\vec{E}]\right]$$

$$a = g/2 - 1 = 1.1596521884 \cdot 10^{-3}$$

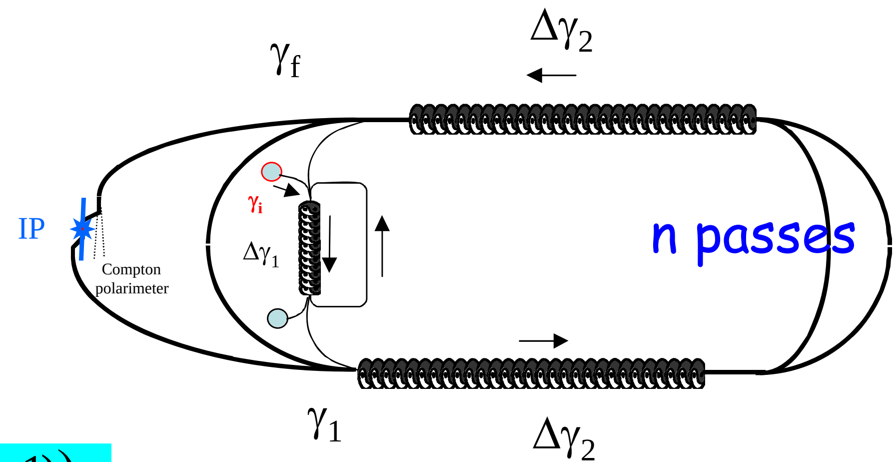
$$\hat{\mu} = \frac{g}{2}\frac{e}{m_o}\hat{s} = (1+a)\frac{e}{m_o}\hat{s}; \qquad \nu_{spin} = a\cdot\gamma = \frac{E_e}{0.44065[GeV]}$$

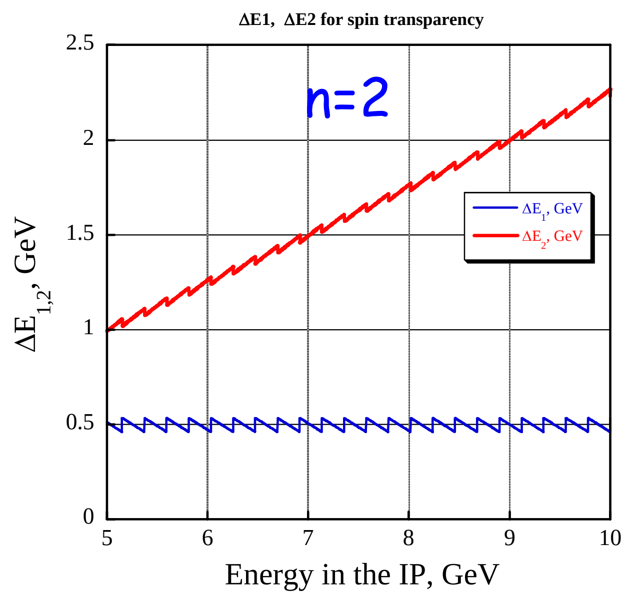
$$\Delta\varphi = a\cdot\gamma\theta$$

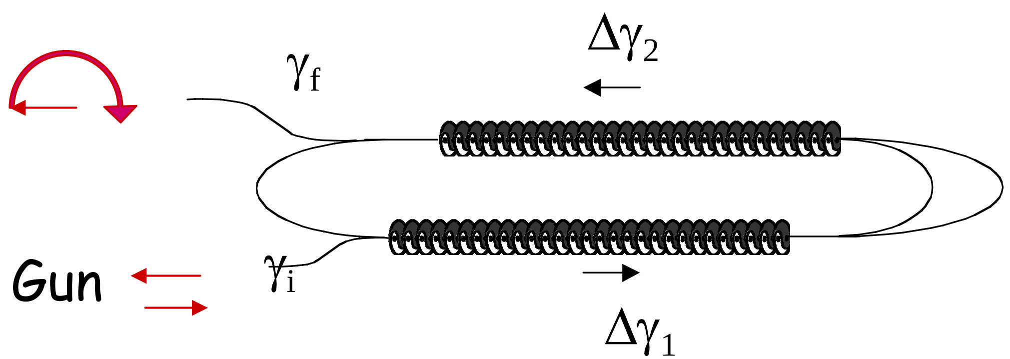
Total angle $\varphi = \pi a \cdot (\gamma_i(2n-1) + n(\Delta\gamma_1 \cdot n + \Delta\gamma_2(n-1)))$

Has solution for all energies!

$$\begin{cases} \gamma_i + 2\cdot(\Delta\gamma_1 + \Delta\gamma_2) = \gamma_f \\ a\cdot(\gamma_i(2n-1) + n(\Delta\gamma_1\cdot n + \Delta\gamma_2(n-1)) = N \end{cases}$$

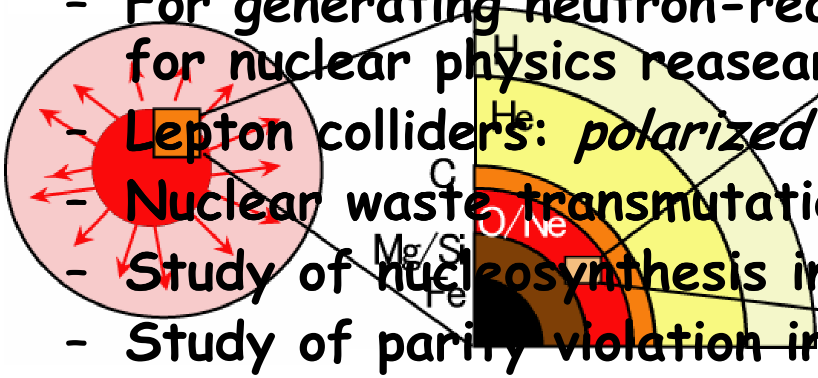


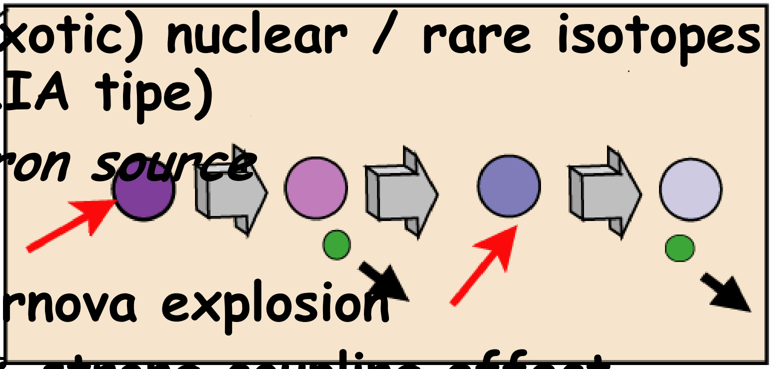




ERLs in High Energy and Nuclear Physics (3)

- ERL driven intense (~ 500kW CW!) γ-ray sources
  - For generating neutron-reach (exotic) nuclear / rare isotopes for nuclear physics reasearch (RIA tipe)
  - Lepton colliders: *polarized positron source*
  - Nuclear waste transmutation
  - Study of nucleosynthesis in supernova explosion
  - Study of parity violation in weak-strong coupling effect
  - "Bread-and-butter" γ-ray nuclear physics (HIγS type)





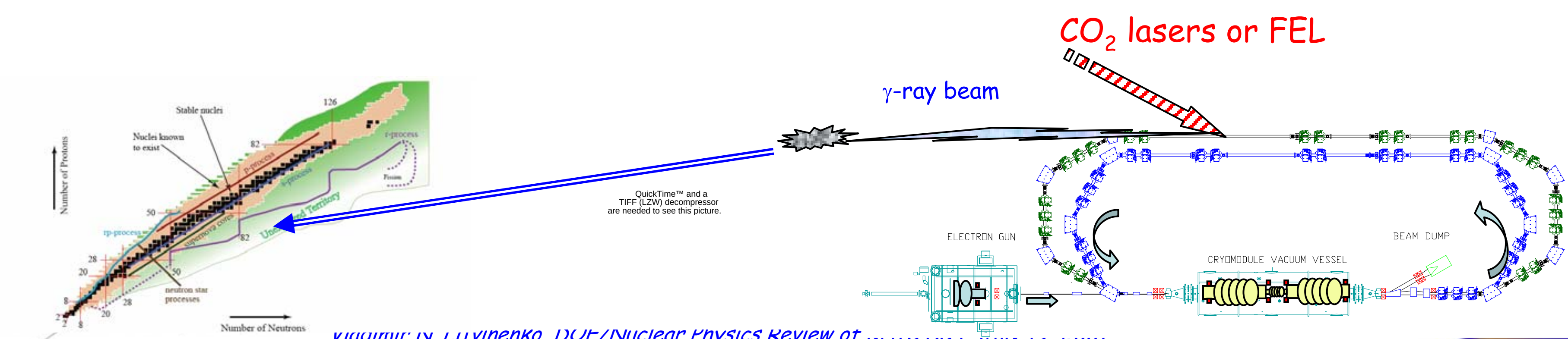
- Why ERL is needed
  - Low emittance, high intensity, recovery of used beam
  - FEL driver as well as the electron beam driver
- What is ERL's effect
  - Few orders (3-6) of magnitude increase in the flux and power

Potential of Energy Recovery Linacs for generating exotic beams of nuclei

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

- Idea came from SPIRAL II Project (electron option) to use 45 MeV electron beam to generated 10-20 MeV Bremmstrahlung γ-rays and use Giant Dipole Resonance (GDR) for photofission of ^{238}U into rare (neutron reach) nuclei http://ganinfo.in2p3.fr/research/developments/spiral2/index.html
- Because of the hard-edge in the energy spectrum, an ERL-based Compton γ-ray beam with high average power average is a better choice for such source
- BNL is developing both high-current high-energy ERLs and high power CO_2 lasers - the key ingredients of such source
- 3 GeV, 20 mA ERL (20 nC/bunch, 1 MHz rep-rate) in combination with <u>four</u> CO_2 lasers (2J/pulse, Rayleigh range of 0.2 cm, 500 Hz rep-rate x 500 reflections) will provide 90 kW (i.e. 4×10^{16}/sec) of γ-rays within the 10-20 MeV range of GDR
- This γ-rays beam has very small divergence ~ 150 μrad, and can be used to for photofission of ^{238}U to generate ~10^{16}/sec nuclei, including exotic once



Potential of Energy Recovery Linacs for generating exotic beams of nuclei

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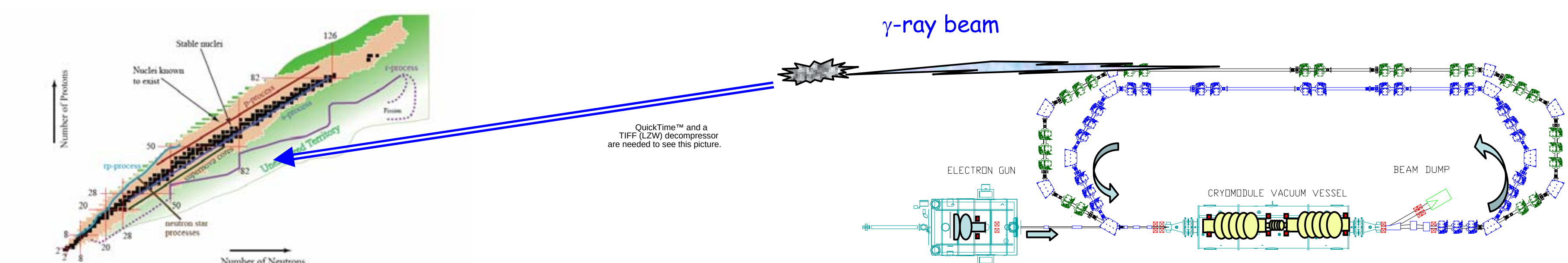
Potential of 10 mA 25 GeV eRHIC beam with 2 cm 25T magnet gives about 100 kW of synchrotron γ-radiation with critical energy of 10.4 MeV - crude but sure way of making the beam

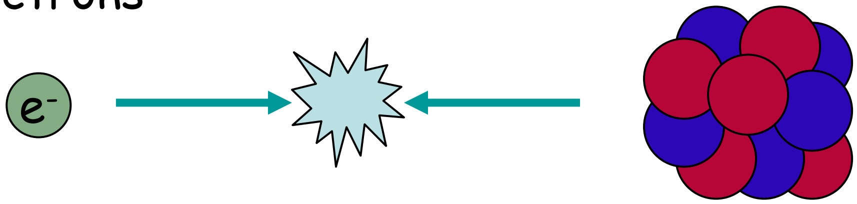
Other way is to use ERL fro both generation of the FEL light and back-scatter it into γ-rays, again with 100-500 kW level of power



$$\sqrt{s} \cong \sqrt{4E_1E_2} = 90 \ \ GeV$$

20 GeV electrons

100 GeV/u Au, U



Beam parameters

RHIC	main case
Ring circumference [m]	3834
Number of bunches	360
Beam rep-rate [MHz]	28.15
Protons: number of bunches	180
Beam energy [GeV]	26 - 250
Protons per bunch (max)	$2.0 \cdot 10^{11}$
Normalized 96% emittance [μm]	14.5
β^* [m]	0.26
RMS Bunch length [m]	0.2
Beam-beam tune shift in eRHIC	0.005
Synchrotron tune, Qs	0.0028
Gold ions: number of bunches	180
Beam energy [GeV/u]	50 - 100
Ions per bunch (max)	$2.0 \cdot 10^{9}$
Normalized 96% emittance [μm]	6
β^* [m]	0.25
RMS Bunch length [m]	0.2
Beam-beam tune shift	0.005
Synchrotron tune, Qs	0.0026
Electrons:	
Beam rep-rate [MHz]	14
Beam energy [GeV]	2 - 20
RMS normalized emittance [μm]	5- 50 *for* $N_e = 10^{10} / 10^{11}$ e^- *per bunch*
β^*	~ 1m, *to fit beam-size of hadron beam*
RMS Bunch length [m]	0.01
Electrons per bunch	$0.1 - 1.0 \cdot 10^{11}$
Charge per bunch [nC]	**1.6 – 16**
Average e-beam current [A]	**0.045 – 0.22**

BROOKHAVEN NATIONAL LABORATORY

RHIC

Parameter Table: Kink Instability

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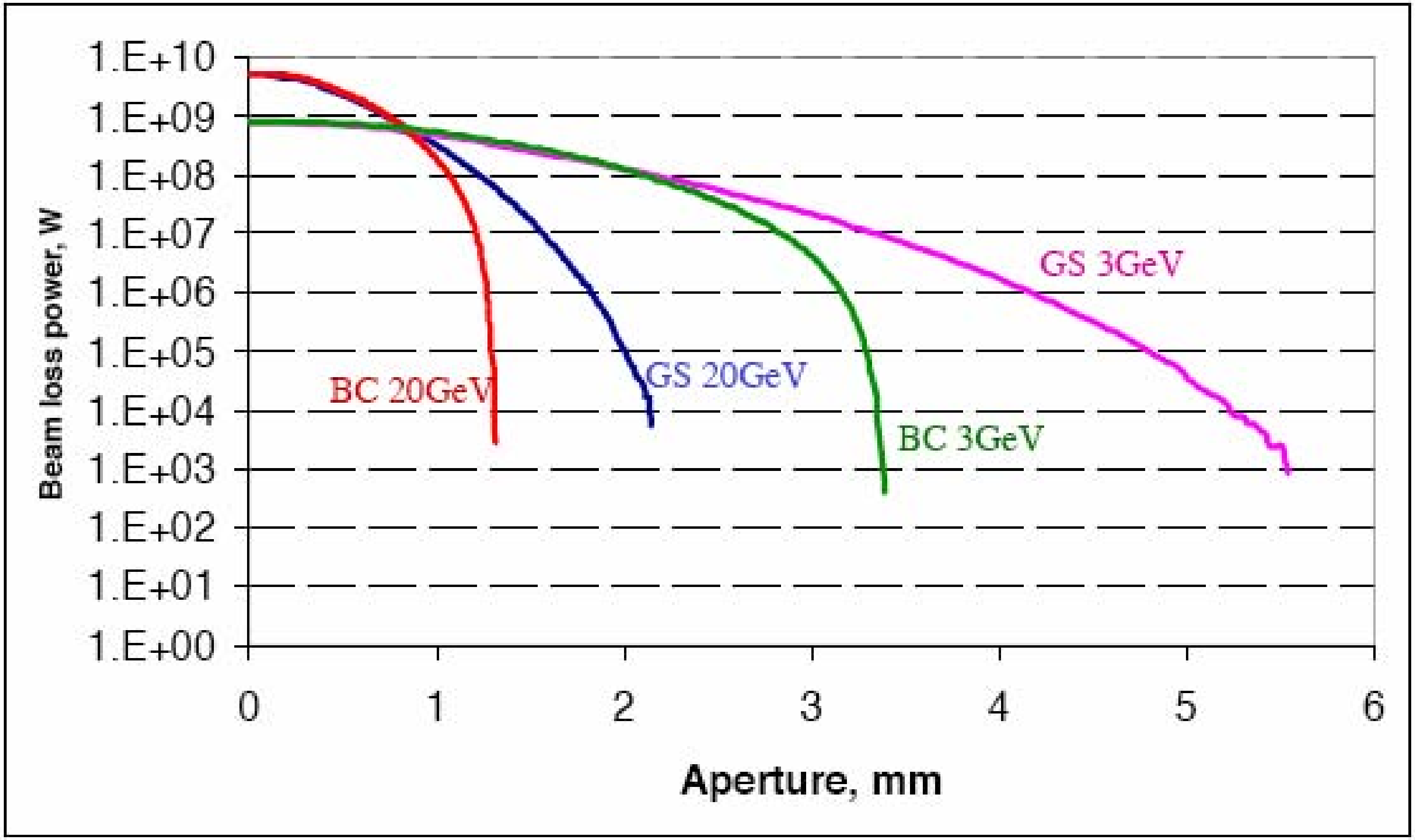
Peak Luminosity (1.e33 $cm^{-2}s^{-1}$)	2.6		0.53	

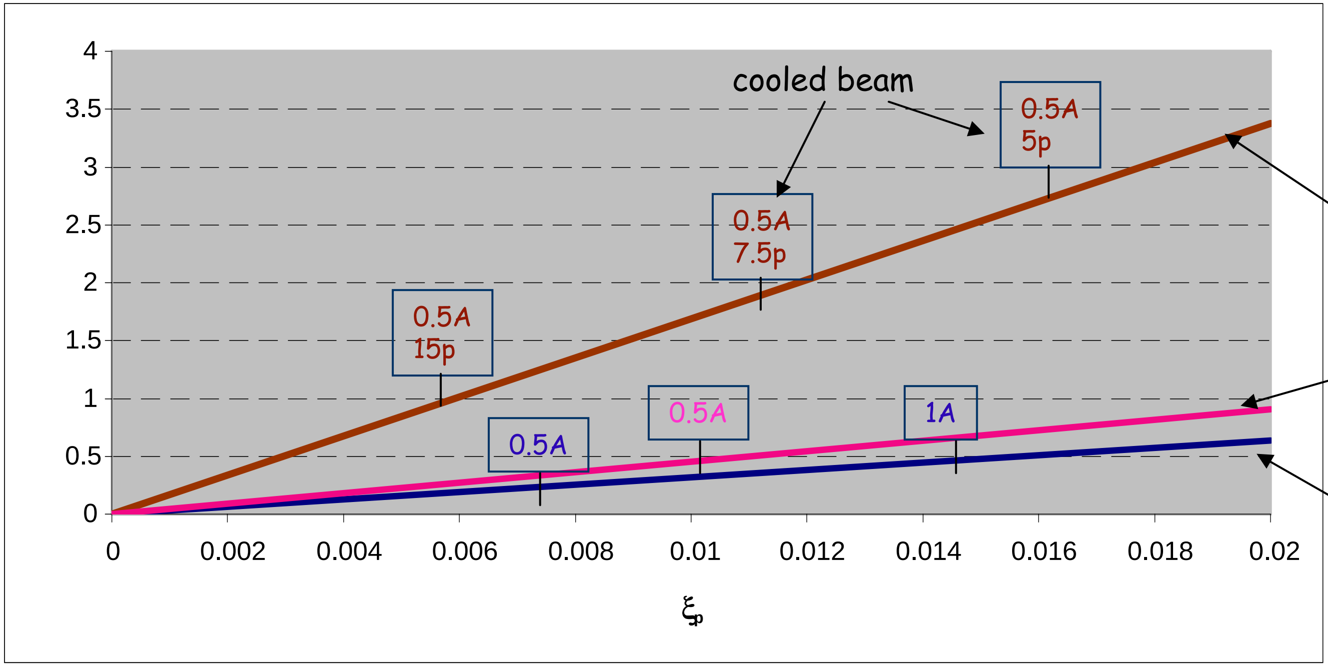
Power loss and magnet aperture (based on β=50m)



GS – Gaussian BC – Beer-Can

Luminosity with e-cooling

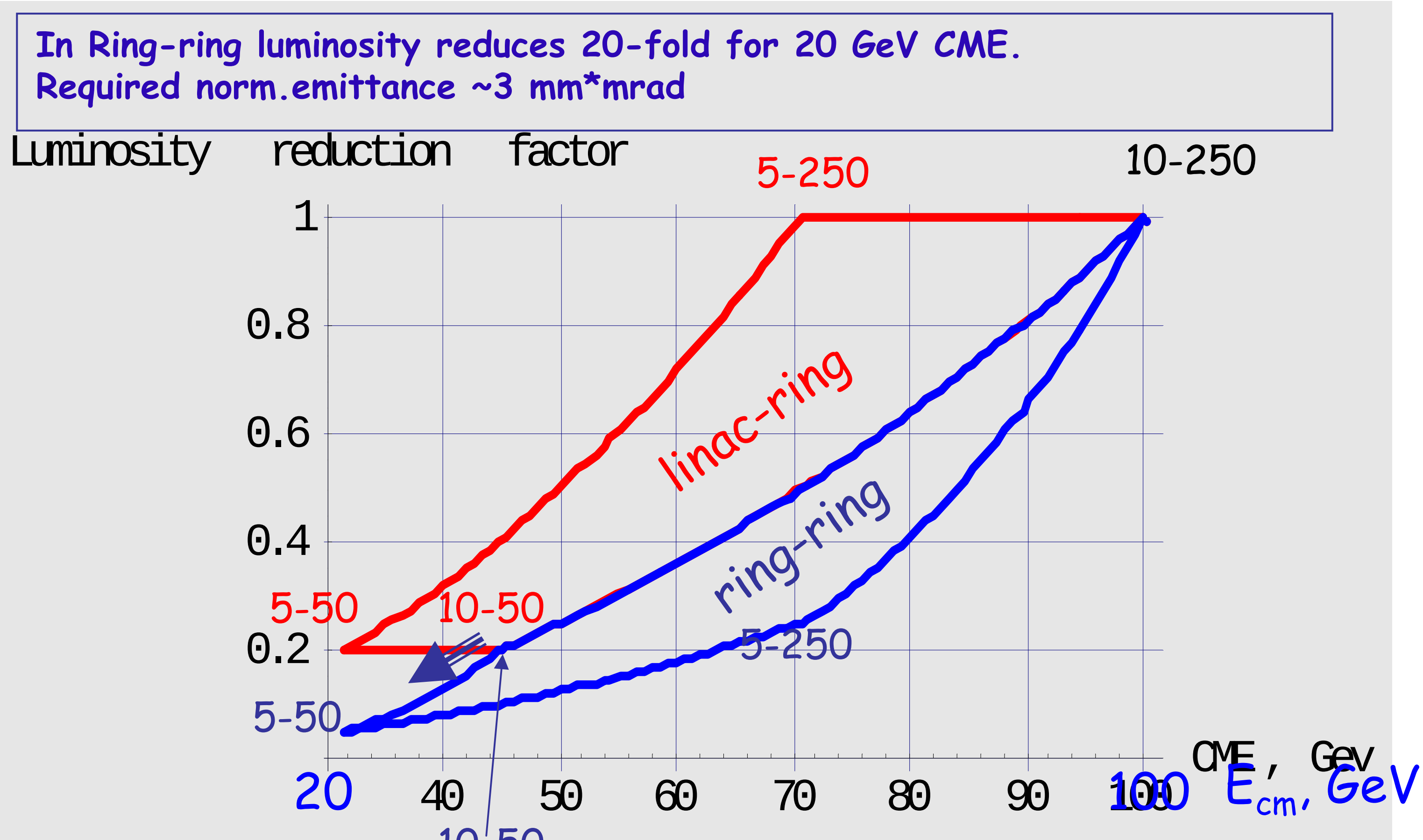
Calculations for 360 bunch mode and 250 Gev(p) x 10 Gev(e) setup; 1e11 p/bunch



Markers show electron current and (for linac-ring) normalized proton emittance.
In dedicated mode (only e-p collision): maximum ξ_p~0.016-0.018;

Transverse cooling can be used to improve luminosity or to ease requirements on electron source current in linac-ring option.
For proton beam only e-cooling at the injection energy is possible at reasonable time (~1h)

Luminosity dependence on CME with cooling



- For ring-ring the e-cooling improves luminosities for low energy proton modes.
  The optimal path for luminosity: E_e=10GeV/E_p=250GeV-> 10/50 -> 5/50
- For linac-ring operation in proton beam-beam limit the cooling can be used to reduce requirements on electron current.
  The optimal path for luminosity: E_e=10GeV/E_p=250GeV-> 5/250 (or 2/250) -> 5/50