Potential of ERL (Energy Recovery Linac)-based electron-hadron collider: from eRHIC to LHeC

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Design consideration of two scenarios for electron-hadron collider eRHIC at Brookhaven (ring-ring and ring-ERL) clearly demonstrated use of energy-recovery linac as the electron drive allows attainment of significantly higher luminosities. This talk will be focus of ERL based design of eRHIC, its advantages and challenges.

Relevance of this approach for LHeC will be also discussed.

Credits

- At BNL: V.Ptitsyn, Y.Hao, I.Ben Zvi, E.Pozdeyev, D.Trbojevic, L.Hammons, C.Montag, A. Drees, T.Roser
- Collaborators at MIT-Bates, especially E.Tsentalovich and B.Surrow
- Ya.Derbenev, JLab

Content

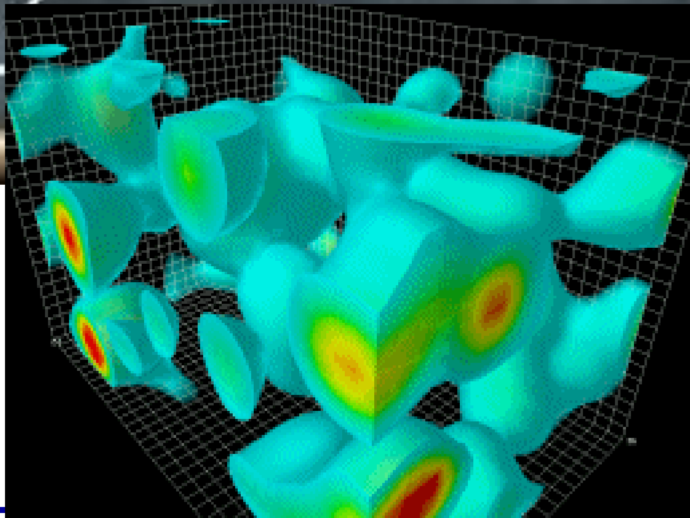
- What eRHIC is about
- Choosing the focus: ERL or ring for electrons?
  - Advantages and challenges of ERL driver
  - R&D items for ERL-based eRHIC
  - New developments
    - First results from the VT of 5-cell cavity
    - Small magnets for eRHIC loops
    - Progress in understanding and suppression 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
    - Coherent electron cooling *(talk this Thursday)*
- Relevance to LHeC - some results & numbers
- Conclusions

Conclusions first

- **ERL-based eRHIC would have 7 to 40 times higher luminosity** compared with traditional ring-ring case
- In LHeC use of an ERL will provide for luminosity ~3.7×10^{34} cm^{-2} sec^{-1} (20 time higher than ring-ring **at the same level of RF power)**
- Use **ERL** and cooling for LHeC is both power and energy effective: it allows to operate with **much lower electron beam currents** while delivering the same luminosity

ERLs in High Energy and Nuclear Physics

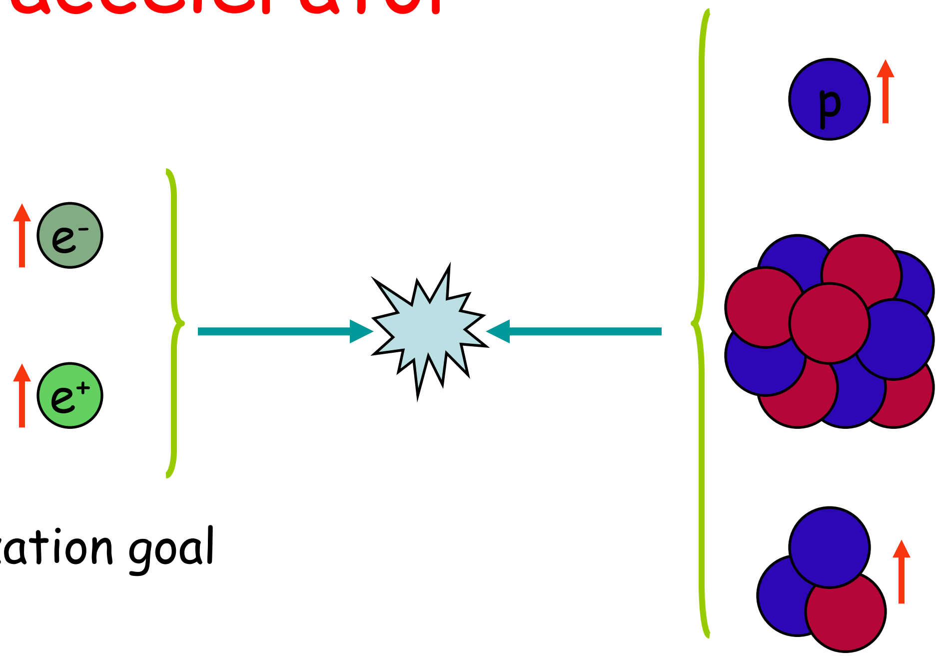
- **High energy electron-hadron and lepton colliders**
  - electron-hadron collider: *1 project, eRHIC,* 20GeV x 250 GeV
  - Lepton colliders: *none*
- Why ERL is needed
  - It allows to increase luminosity compared with ring-ring option
- What is ERL's effect
  - QCD-laboratory to study strongest fields in the universe



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

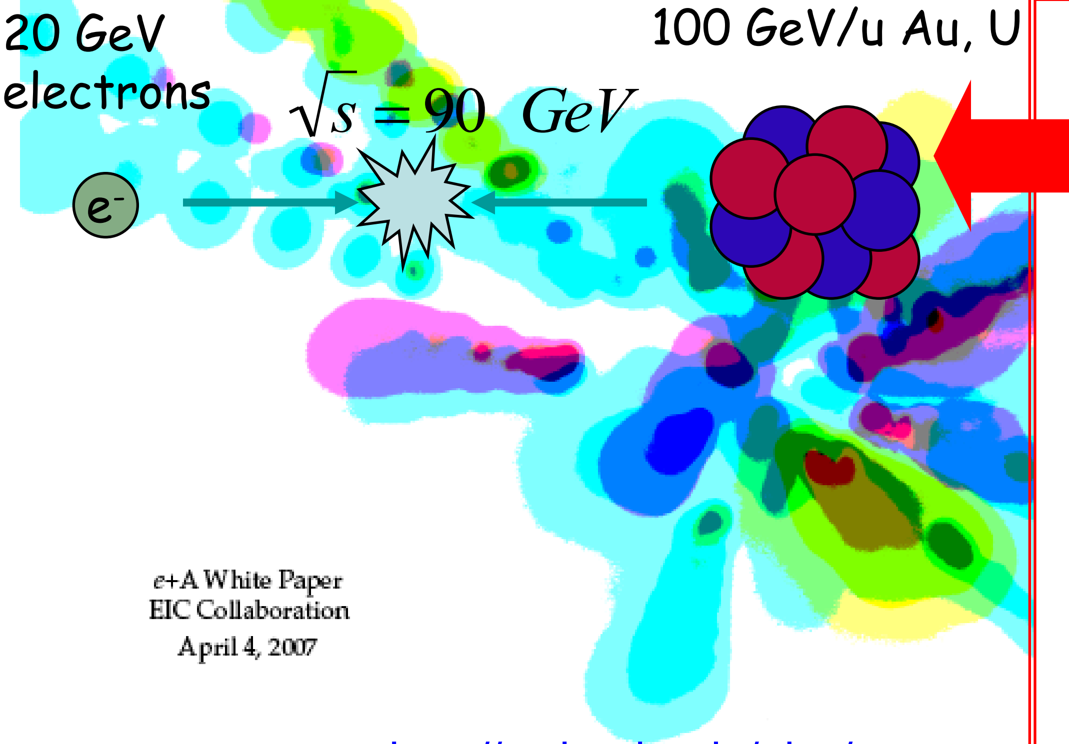
Polarized light ions
(He^3) 167 GeV/u

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

http://web.mit.edu/eicc/

Nuclear "Oomph" Factor

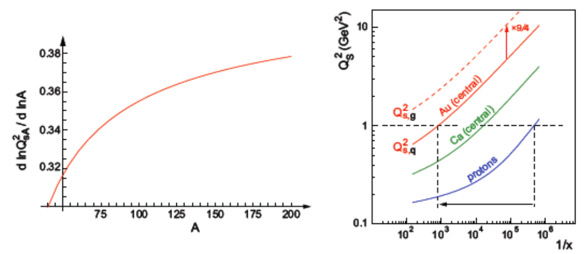


Figure 10: *Left: The A dependence of the saturation scale from the analysis of Ref. [16]. Right: The saturation scale at b = 0 in Au and Ca nuclei compared to the median saturation scale in a proton [15].*

- 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.

The Electron-Ion Collider Collaboration

http://web.mit.edu/eicc/

The Electron-Ion Collider Collaboration consists of more than 100 physicists from over 20 laboratories and universities from around the world who are working to realize a powerful, new facility in the United States with the aim of studying the particles (gluons) which bind all the observable matter in the world around us. This new facility, known as the Electron-Ion Collider (EIC), would collide intense beams of spin polarized electrons with intense beams of both polarized nucleons and unpolarized nuclei from deuterium to uranium. Large, new detectors are being designed to detect the high energy scattered particles as well as the low energy debris as a means to definitively understand how the matter we are all made of is bound together.

Physics case

* Argonne National Laboratory, Argonne, IL
* Bhabha Atomic Research Centre, Mumbai, India
* **Brookhaven National Laboratory, Upton, NY**
* University of Buenos Aires, Buenos Aires, Argentina
* University of California, Los Angeles, CA
* University of Colorado, Boulder, CO
* Columbia University, New York, NY
* University of Glasgow, Glasgow, United Kingdom
* Hampton University, Hampton, VA
* University of Illinois, Urbana-Champaign, IL
* Iowa State University, Ames, IA
* University of Kyoto, Kyoto, Japan
* Lawrence Berkeley National Laboratory, Berkeley, CA
* Los Alamos National Laboratory, Los Alamos, NM
* University of Massachusetts, Amherst, MA
* MIT Laboratory for Nuclear Science, Cambridge, MA
* MIT-Bates Linear Accelerator Center, Middleton, MA
* Max Planck Institut fur Physik, Munich, Germany
* University of Michigan Ann Arbor, MI
* New Mexico State University, Las Cruces, NM
* Old Dominion University, Norfolk, VA
* Penn State University, PA
* RIKEN, Wako, Japan
* RIKEN-BNL Research Center
* Soltan Institute for Nuclear Studies, Warsaw, Poland
* SUNY, Stony Brook, NY
* Tel Aviv University, Tel Aviv, Israel
* **Thomas Jefferson National Accelerator Facility, Newport News, VA**

Topic of active AP research for eRHIC

- High charge / high average current, normal and polarized e guns
- High current, multi-pass ERLs, TBBU
- High energy electron cooling (including coherent e-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
- Possibility of using crossing angle and crab cavities

Goals for eRHIC

Physics Requirements

- To provide electron-proton and electron-ion collisions
- Energy ranges:
  - 2-10 GeV polarized e^- or 10 GeV polarized e^+
  - 26-250 GeV polarized protons or 100 GeV/u Au
- Luminosities:
  - > 10^{33} $cm^{-2}s^{-1}$ region for e-p
  - > 10^{31} $cm^{-2}s^{-1}$ region for e-Au
- >70% polarization degree for both lepton and proton beams
- Longitudinal polarization in the collision point

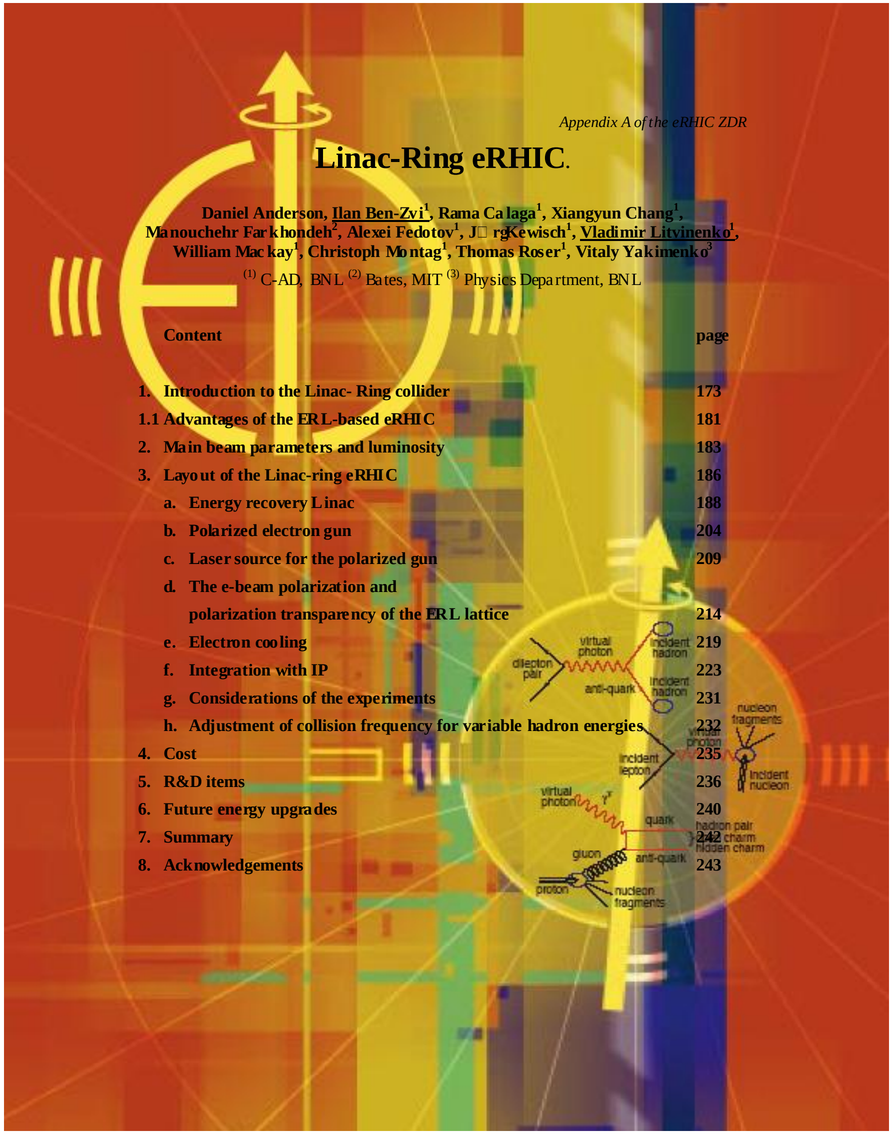
eRHIC

Zeroth-Order Design Report

BNL: L. Ahrens, D. Anderson, M. Bai, J. Beebe-Wang, I. Ben-Zvi, M. Blaskiewicz, J.M. Brennan, R. Calaga, X. Chang, E.D. Courant, A. Deshpande, A. Fedotov, W. Fischer, H. Hahn, J. Kewisch, V. Litvinenko, W.W. MacKay, C. Montag, S. Ozaki, B. Parker, S. Peggs, T. Roser, A. Ruggiero, B. Surrow, S. Tepikian, D. Trbojevic, V. Yakimenko, S.Y. Zhang
MIT-Bates: W. Franklin, W. Graves, R. Milner, C. Tschalaer, J. van der Laan, D. Wang, F. Wang, A. Zolfaghari and T. Zwart
BINP: A.V. Otboev, Yu.M. Shatunov
DESY: D.P. Barber

Editors: M. Farkhondeh (MIT-Bates) and V. Ptitsyn (BNL)

http://www.agsrhichome.bnl.gov/eRHIC/



Appendix A of the eRHIC ZDR

Linac-Ring eRHIC.

Daniel Anderson, Ilan Ben-Zvi[1], Rama Calaga[1], Xiangyun Chang[1], Manouchehr Farkhondeh[2], Alexei Fedotov[1], J rgKewisch[1], Vladimir Litvinenko[1], William Mackay[1], Christoph Montag[1], Thomas Roser[1], Vitaly Yakimenko[3]
(1) C-AD, BNL (2) Bates, MIT (3) Physics Department, BNL

Content **page**

New eRHIC R&D group at Collider-Accelerator Department mostly from members of the AP and e-Cooling groups

http://www.bnl.gov/cad/eRhic/

e–RHIC R & D
(V. Litvinenko), Head
(V. Ptitsyn), Deputy
(A. Petway), Secretary

Beam Dynamics
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Y. Hao+
(E. Pozdeyev)
(D. Trbojevic)
(N. Tsoupas)

SRF
(I. Ben Zvi), GL
(A. Burrill)
(H. Hahn)
(D. Naik)
(L. Hammons)

Polarization
(M. Bai), GL
(H. Huang)
(J. Kewish)
(A. Luccio)
(A. Zelenski)

IRs
(C. Montag), GL
(A. Drees)

(J. Beebe–Wang)

18054/18056

Superconducting Accelerator and Electron Cooling
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X. Chang
E. Choi
A. Fedotov
H. Hahn*
D. Kayran
J. Kewisch
(G. McIntyre)
D. Naik
D. Pate
(E. Pozdeyev)
G. Wang+
Q. Wu+

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M. Bai
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Y. Luo
(M. Minty)
J. Wei, LOA
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K.A. Brown
C. Gardner
J.W. Glenn
H. Huang
N. Tsoupas

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C. Montag
V. Ptitsyn
(G. Robert–Demolaize)
S. Tepikian

LARP
(A. Drees), GL
N. Abreu
R. Calaga (MD)
G. Robert–Demolaize

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

eRHIC will take full advantage of e-cooling

RHIC: ions (D, Cu, Au…) 10-100 GeV/u
polarized protons 25-250 GeV

2 superconducting rings
3.8 km circumference

Intra-Beam Scattering: The ions collide with each other, leading to accumulation of random energy (heat) derived from the guide fields and the beam's energy.

Electron cooling: The high-current high-brightness electron beam from an ERL will cool the RHIC ions while propagating in a 100-m long straight section

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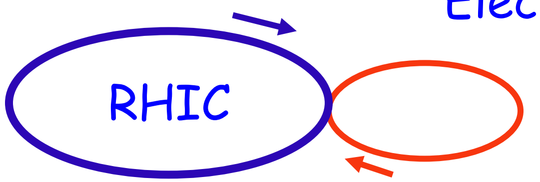
Choosing the focus: ERL or ring for electrons?

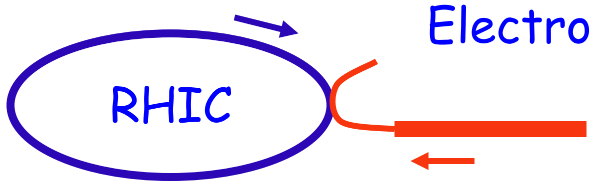
- Two main design options for eRHIC:
  - Ring-ring:

Electron storage ring

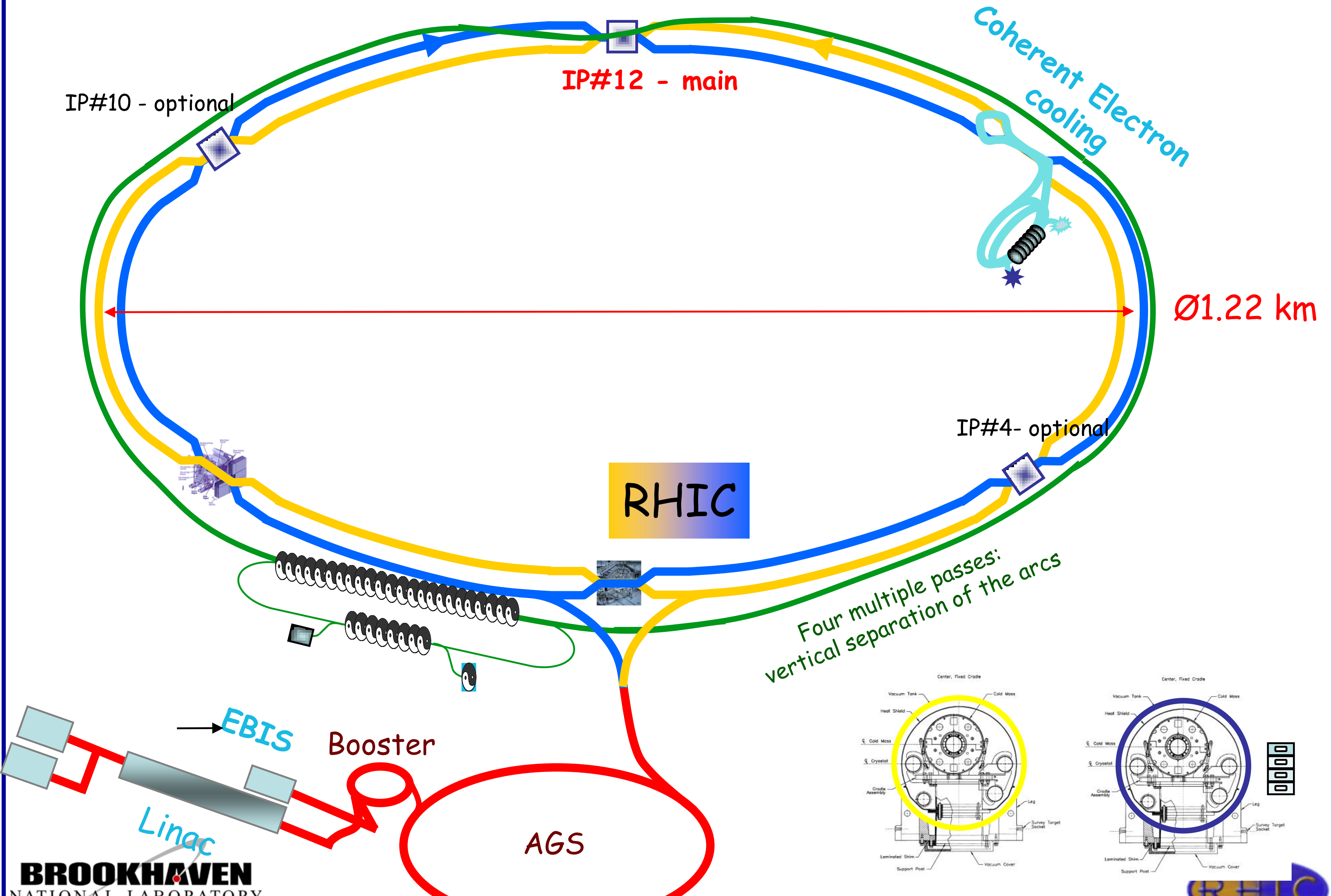


  - Linac-ring:

Electron linear accelerator



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



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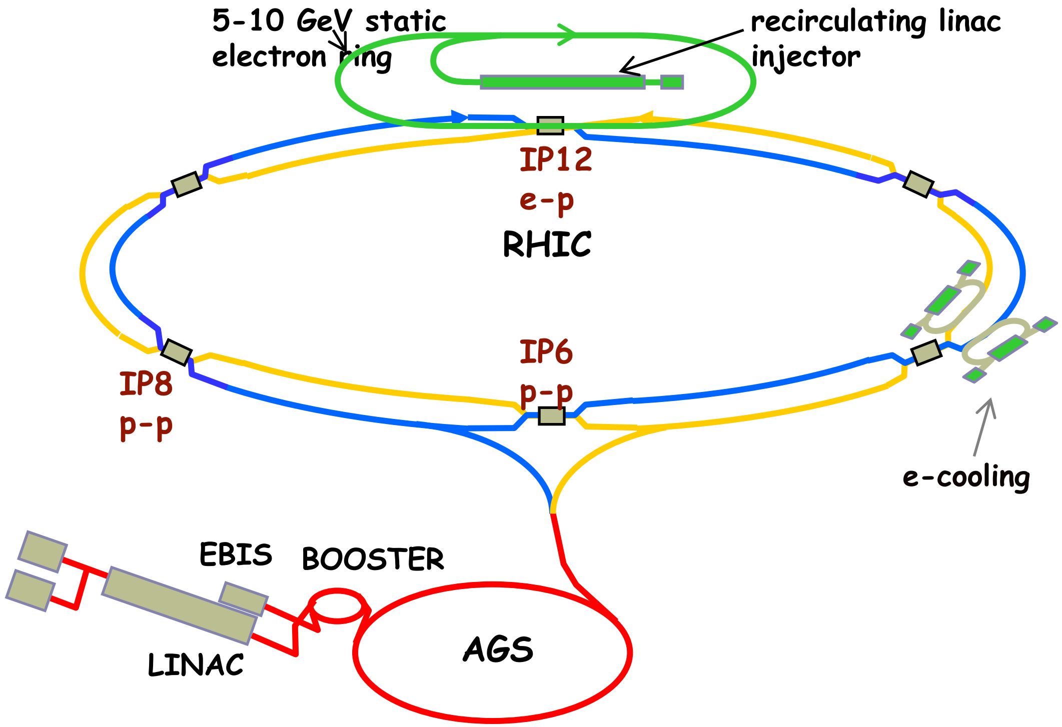
Ring-ring design - back-up option



- 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.

In linac-ring eRHIC luminosity is determined by the hadron beam!

$$L = f_c \frac{N_e N_h}{4\pi\beta_h^* \varepsilon_h}$$

Round beams $\beta_e^* \varepsilon_e = \beta_h^* \varepsilon_h$

$$L = \gamma_h \cdot (f_c \cdot N_h) \cdot \frac{\xi_h \cdot Z_h}{\beta_h^* \cdot r_h}$$

In parallel with STAR and PHENIX

$$\xi_h = \frac{N_e}{\gamma_h} \frac{r_h}{4\pi Z \varepsilon_h} = 0.007$$

Luminosity **10^{33} cm^{-2}sec^{-1}**	*Protons 26 GeV*	*Protons 50 GeV*	*Protons 100 GeV*	*Protons 250 GeV*
Electrons 5(2)-10(20) GeV	**0.28**	**0.52**	**0.96**	**2.8**

Luminosity (per nucleus) **10^{31} cm^{-2}sec^{-1}**	*Au 50 GeV/u*	*Au 100 GeV/u*
Electrons 5(2)-10(20) GeV	**1.4**	**2.8**

Dedicated eRHIC mode with 250 GeV p or 100 GeV/u Au

$$\xi_h \rightarrow 0.02 \quad \Leftrightarrow \quad L_{p\ e} \rightarrow 1 \cdot 10^{34}$$

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Advantages & Challenges of ERL based eRHIC

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

- **High luminosity ~ 10^{34} cm^{-2} sec^{-1}**
- **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.**
- **Takes full advantage of the cooling of hadron beams to reduce electron beam current and RF power consumption**
- **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

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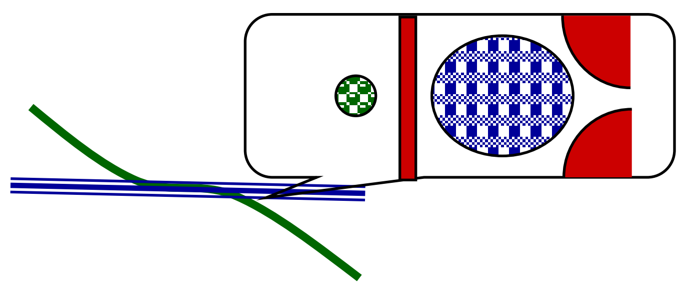
Integration with IP

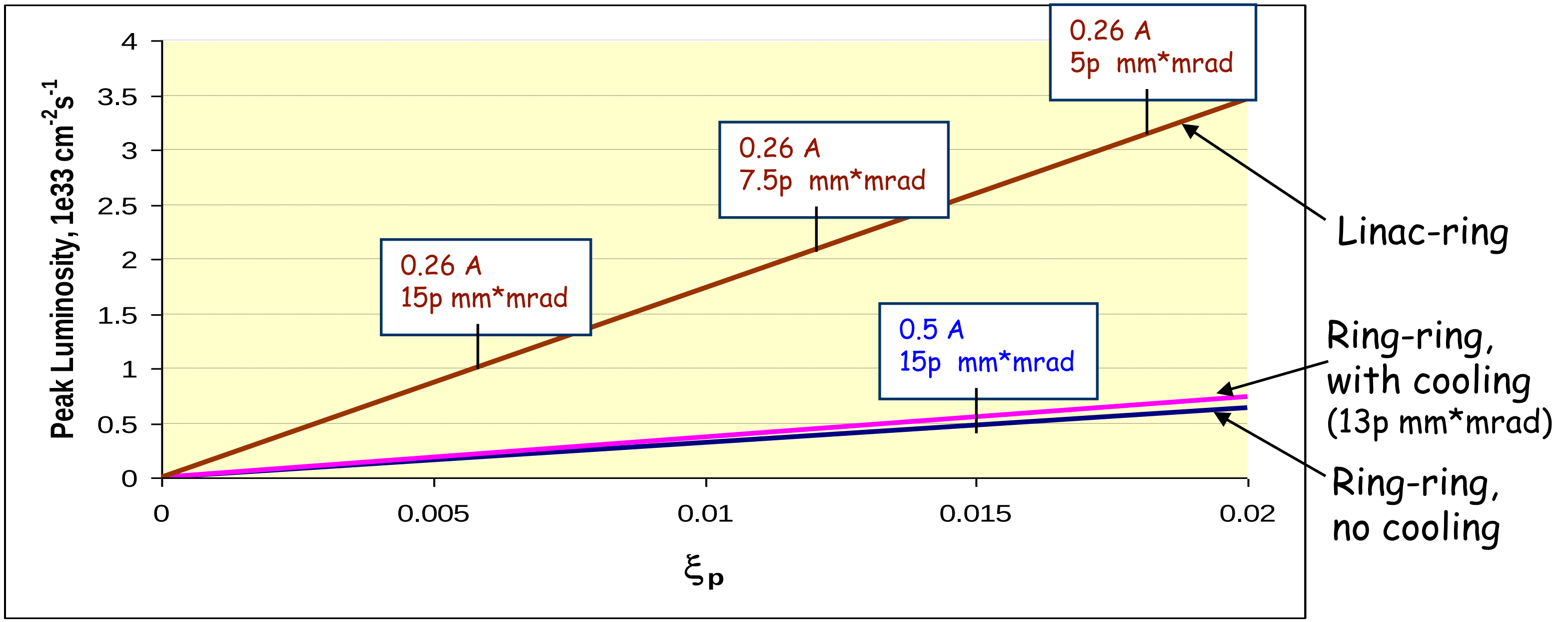
$E_x = 12\sigma_{p,x} + 5\sigma_{e,x} + d_{septum}$ = 12¿ 0.93mm + **5 ¿ 0.25mm** + 10mm = 22.4mm.

- Round-beam collision geometry to maximize luminosity
- Smaller e-beam emittance resulting in 10-fold smaller aperture requirements for the electron beam*
- Possibility of moving the focusing quadrupoles for the e-beam outside the detector and the IP region, while leaving the dipoles used for separating the beam
- Possibility of further reducing the background of synchrotron radiation



Luminosity with conventional 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)

Courtesy of V. Ptitsyn

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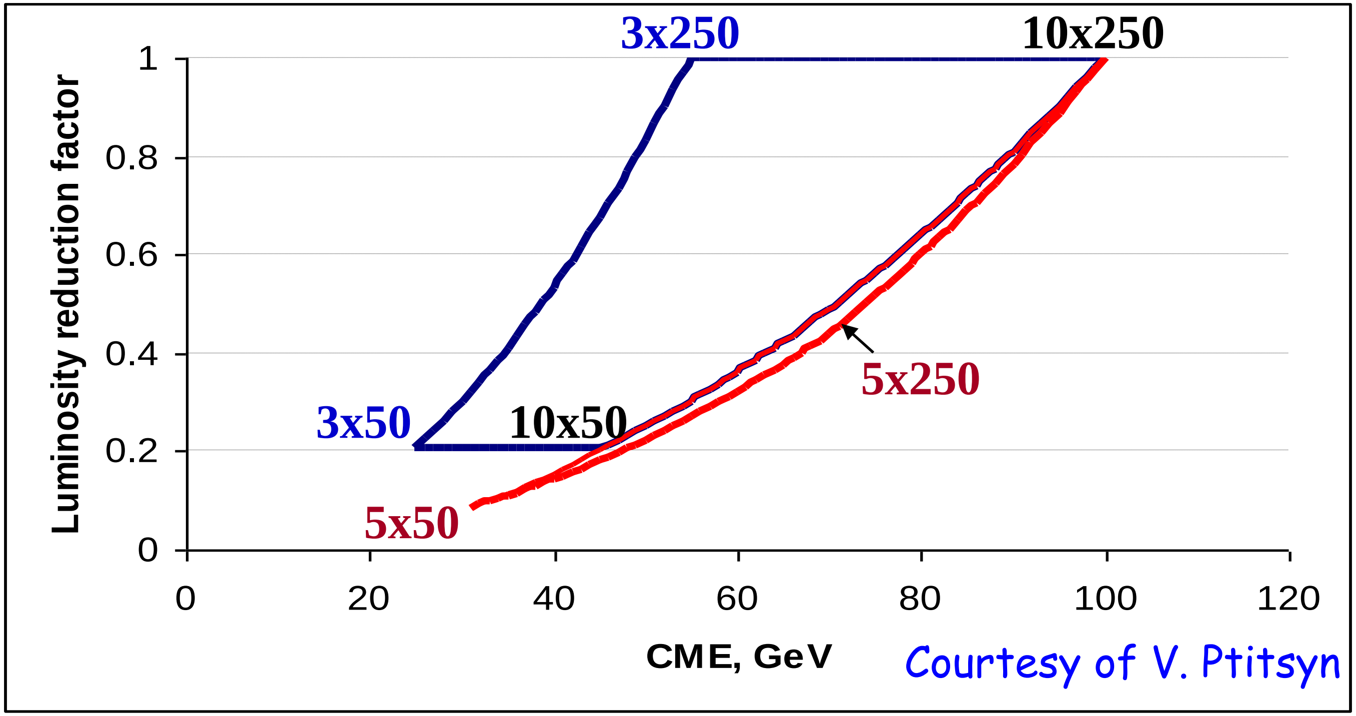
Luminosity dependence on CME with cooling

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

Beam parameters for a standard e- cooling case

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**

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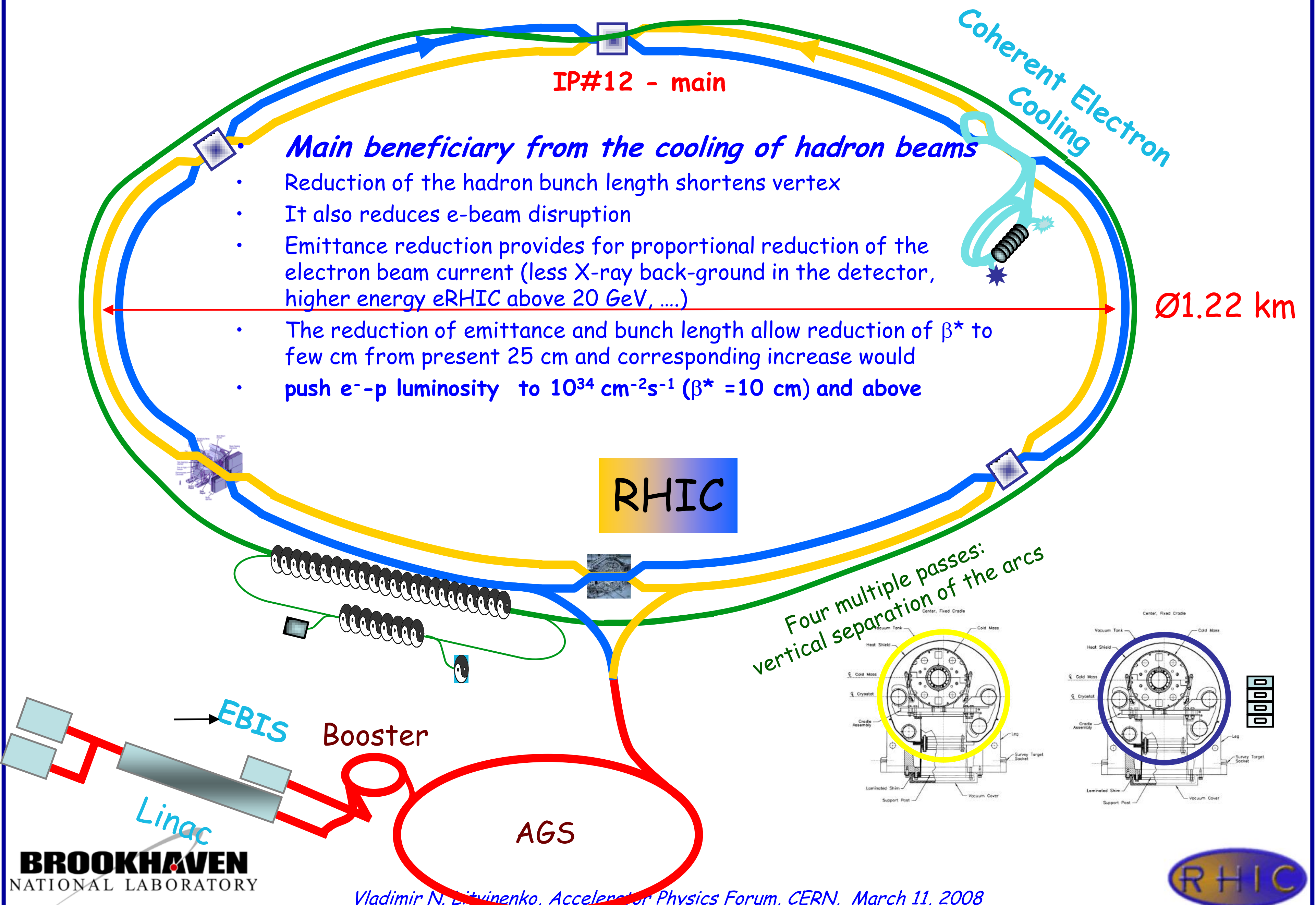
eRHIC based on 10-20 GeV ERL

Main beneficiary from the cooling of hadron beams

- Reduction of the hadron bunch length shortens vertex
- It also reduces e-beam disruption
- Emittance reduction provides for proportional reduction of the electron beam current (less X-ray back-ground in the detector, higher energy eRHIC above 20 GeV, ….)
- The reduction of emittance and bunch length allow reduction of β^* to few cm from present 25 cm and corresponding increase would
- **push e^--p luminosity to 10^{34} $cm^{-2}s^{-1}$ (β^* =10 cm) and above**



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Cooling of hadron beams with coherent electron cooling

Machine	Species	Energy GeV/n	SC, hrs	Synchrotron radiation, hrs	Electron cooling, hrs	CEC, hrs
RHIC	Au	100	~1	20,961 ∞	~ 1	0.03
RHIC	p	250	~100	40,246 ∞	> 30	0.8
LHC	p	450	?	48,489 ∞	> 1,600	0.95
LHC	p	7,000	?	13/26	∞ ∞	< 2

Details in my talk this Thursday, March 13

Main advantages of ERL + cooling

$$L = \gamma_p \frac{f_{col} N_p}{\beta_p^* r_p} \xi_p \qquad \xi_p = \frac{r_p}{4\pi} \cdot \frac{N_e}{\varepsilon_{p\ norm}};$$

$$\frac{N_e}{\varepsilon_{p\ norm}} = const \Rightarrow \xi_p = const, \quad L = const$$

$$N_e \propto \varepsilon_{p\ norm} \Rightarrow I_e \propto \varepsilon_{p\ norm} \Rightarrow P_{SR} \propto \varepsilon_{p\ norm}!$$

- Main point is very simple: if one cools the emittance of a hadron beam in electron-hadron collider, the intensity of the electron beam can be reduced proportionally without any loss in luminosity o increase in the beam-beam parameter for hadrons
- Hadron beam size is reduced in the IR triplets - hence it opens possibility of further β* squeeze and increase in luminosity
- Electron beam current goes down, losses for synchrotron radiation going down, X-ray background in the detectors goes down….

Main advantages of ERL + cooling (cont..)

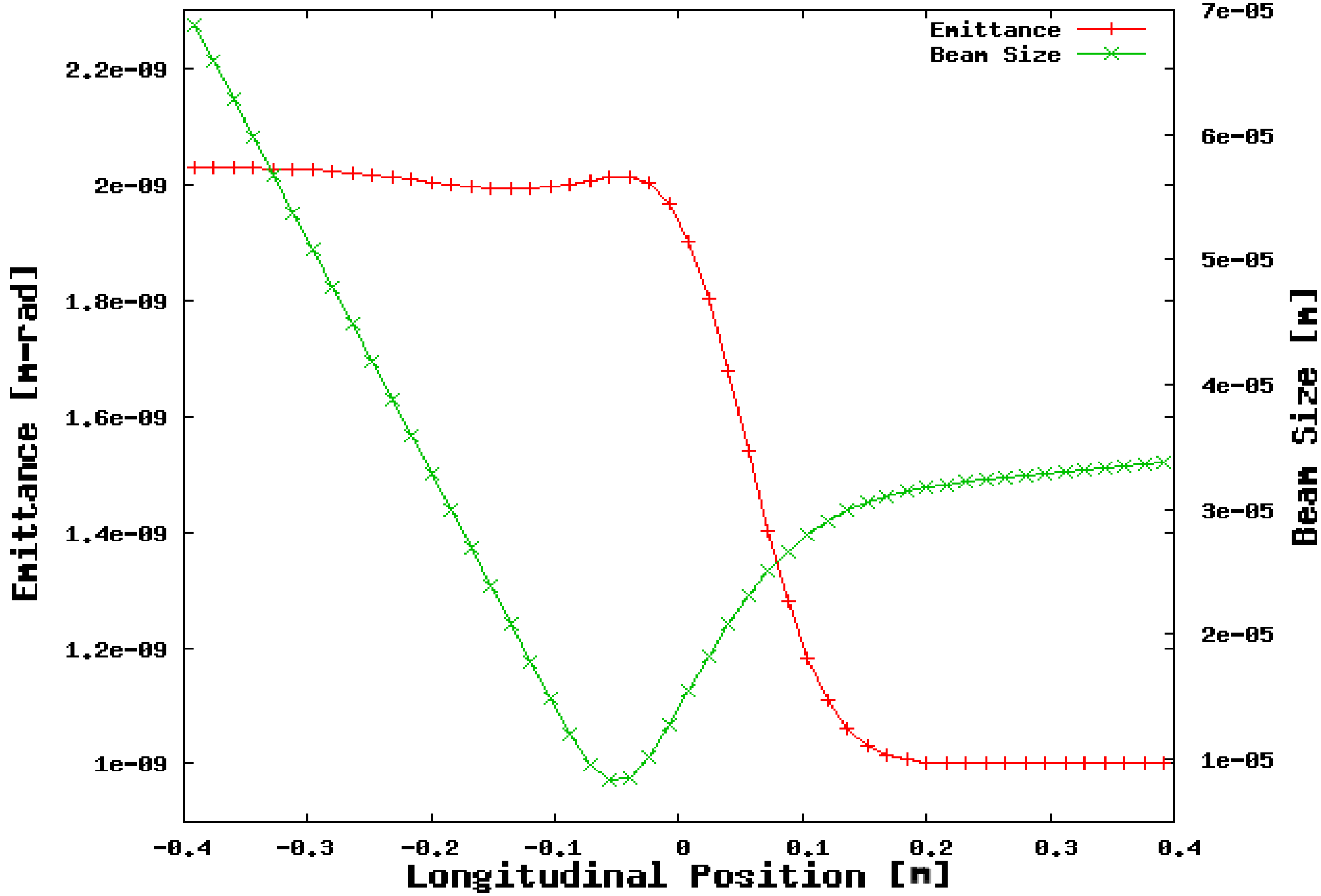
- Where is the limit?

$$D = \frac{Z_h N_h r_e}{\gamma_e \beta_h^* \varepsilon_h} \sigma_{s\ h}$$

- Electron beam disruption (which better describes affect on electron beam in linac case) can cause emittance growth and kink instability of the hadron beam

$$\Lambda = D \cdot \xi_h / Q_{s\ h}$$

Electron Disruption



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

The focusing force will attract the electron to center and form the effect so called 'pinch effect'

Courtesy of Y.Hao

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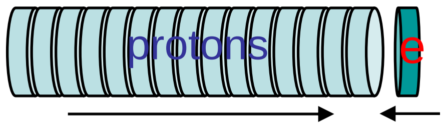
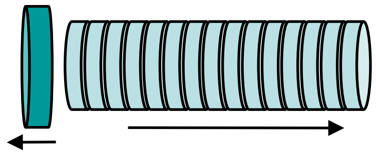
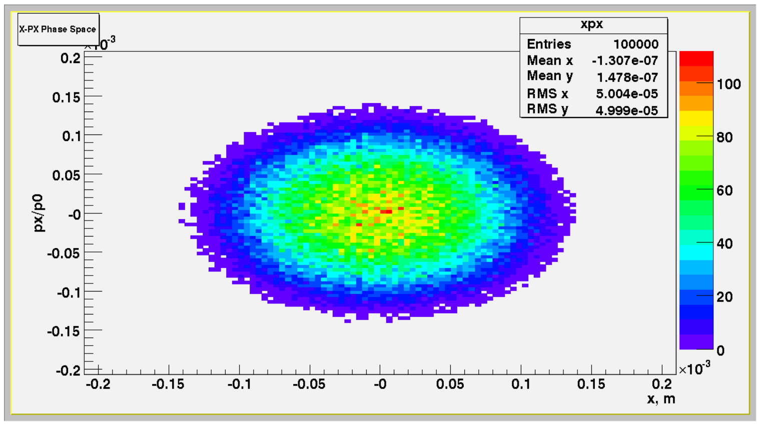
RHIC

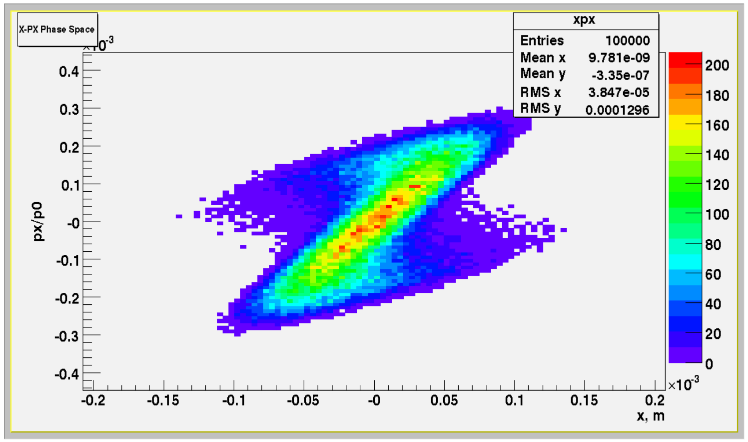
Beam Disruption -LINAC-RING



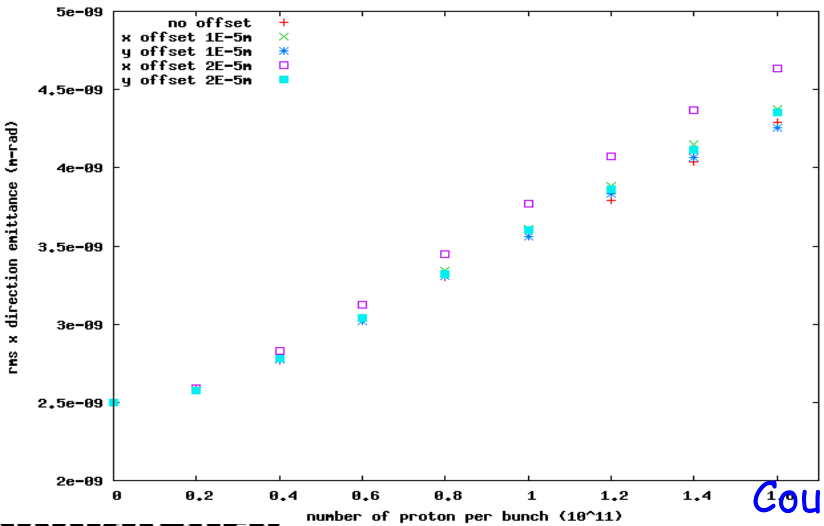


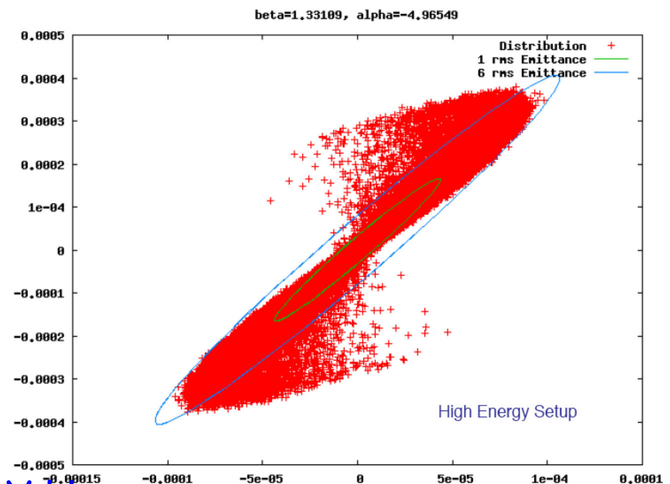


Interaction



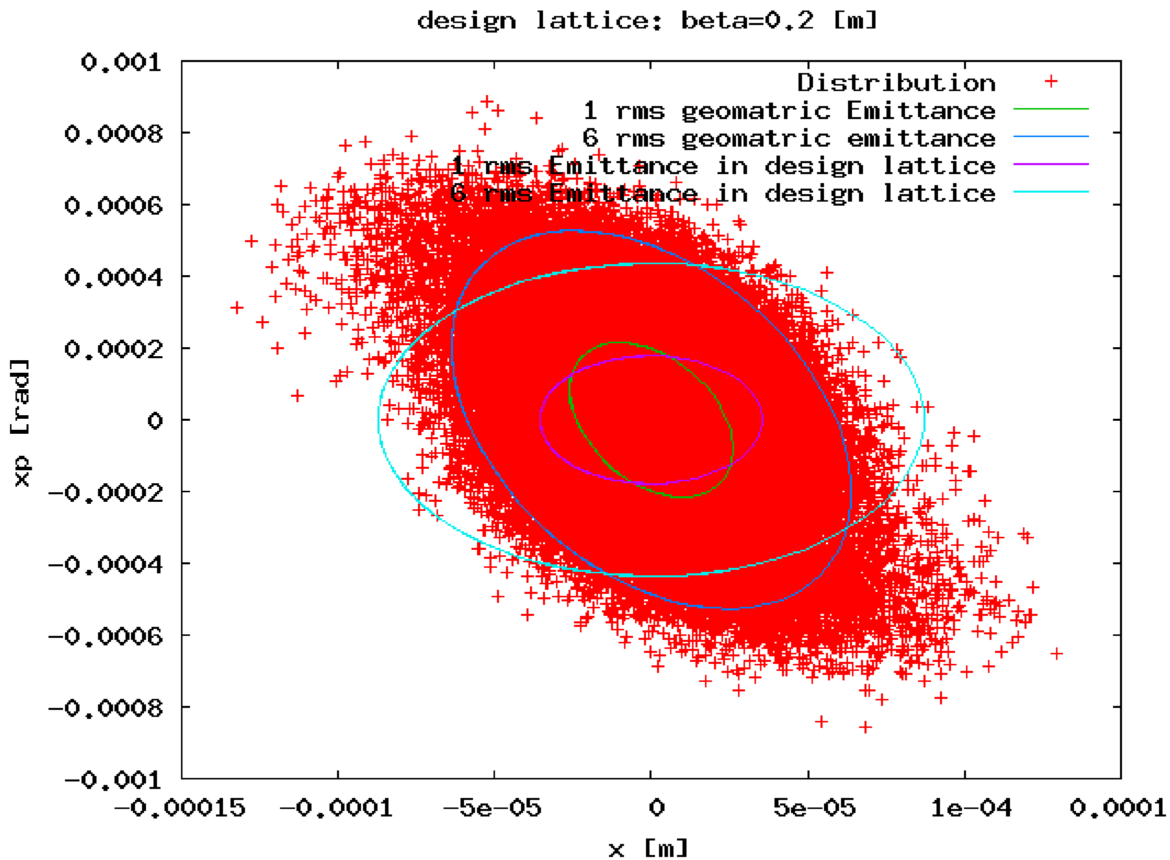
Optimized





Courtesy of Y.Hao

After Optimization: not bad at all



Need 1.8e-7 m-rad admittance in design optics.

And the average electron beam size at interaction region is 26 micron.

Courtesy of Y.Hao

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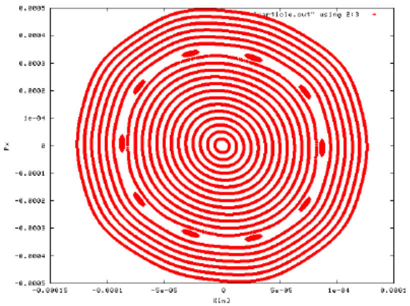
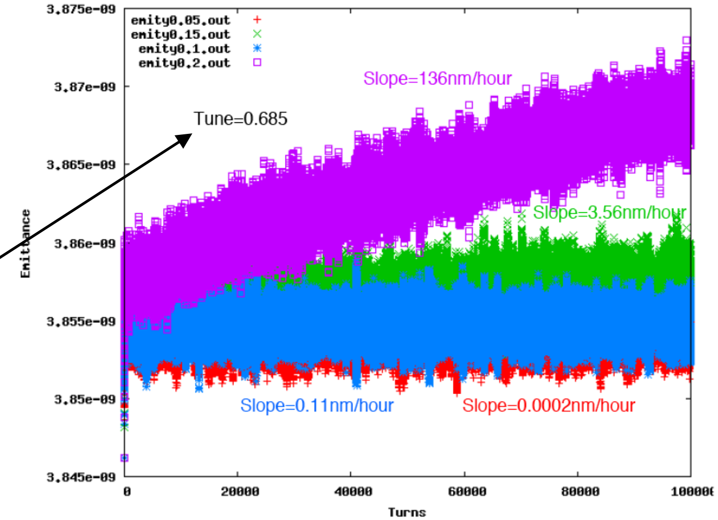
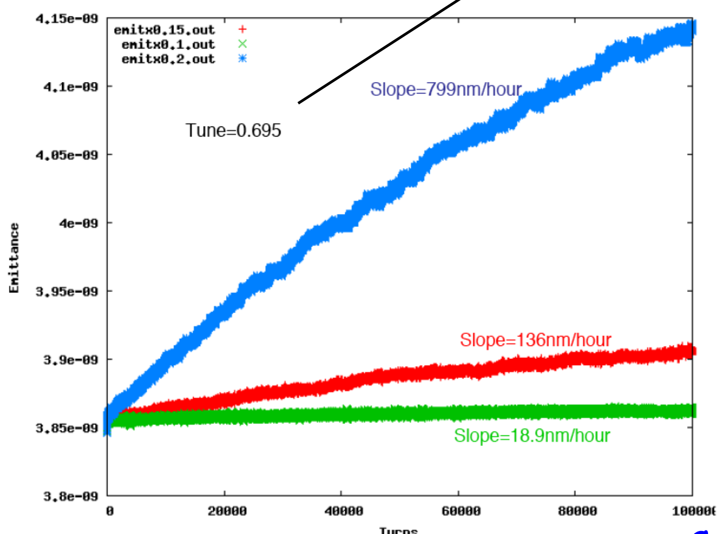
Other effects at the e-ion collision

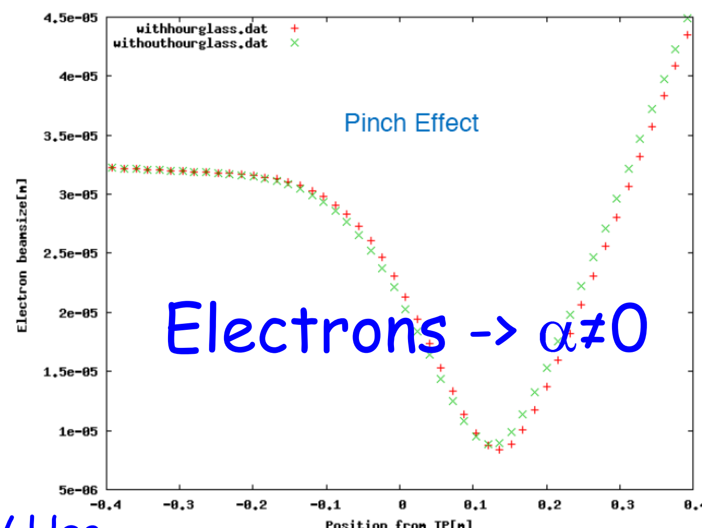
Emittance Growth

- 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).



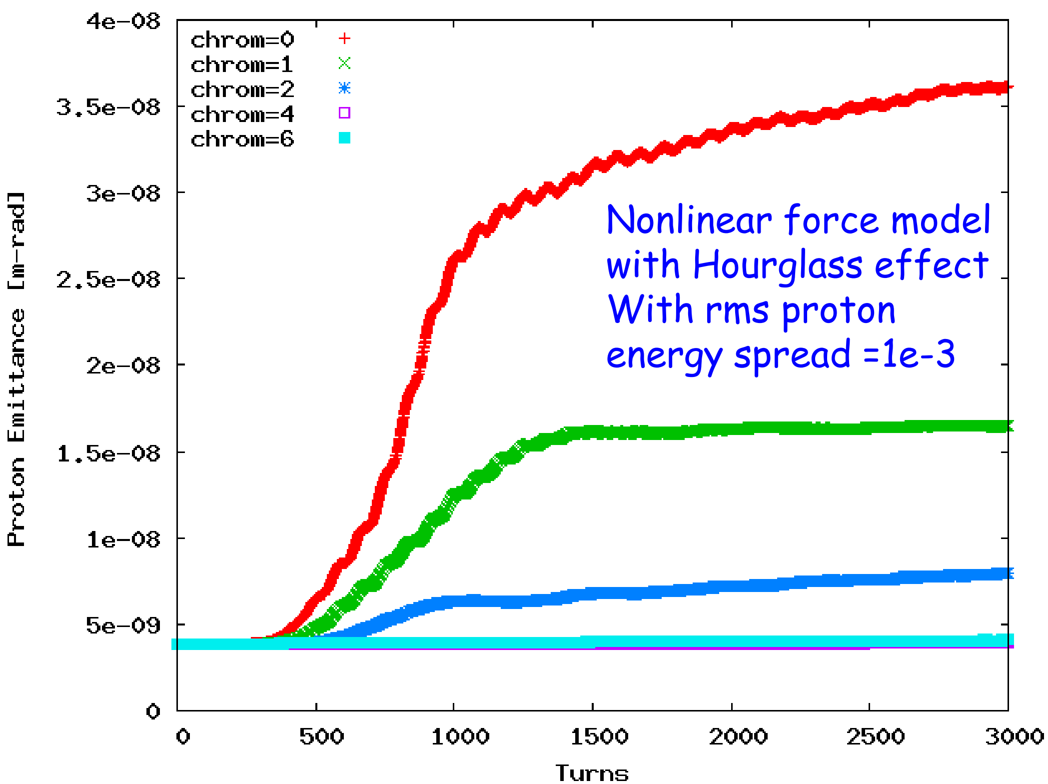


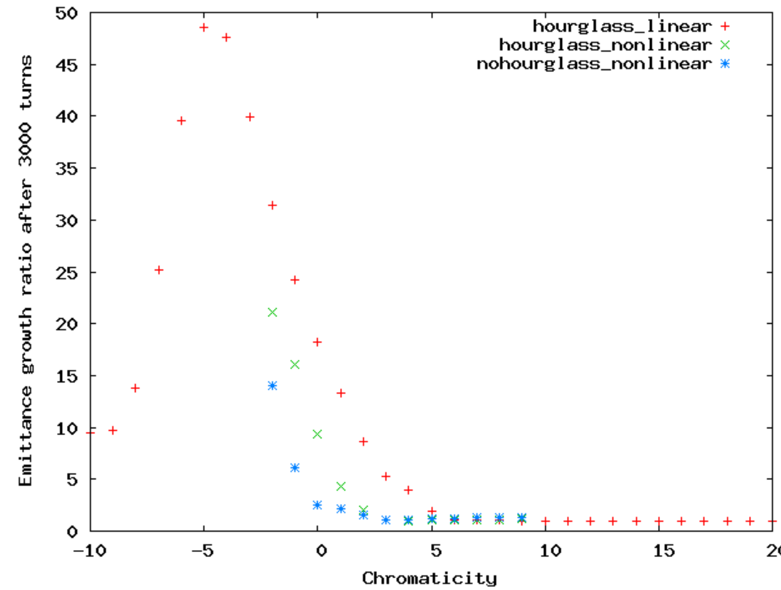




Courtesy of Y.Hao

Chromaticity suppresses kink instability





The optimum chromaticity is around ξ = +4

Courtesy of Y.Hao

Energy (GeV)	25
Number of bunches	10
Bunch spacing (ns)	7
Bunch intensity (10^{11})	2
Beam current (mA)	42
95% normalized emittance (π·mm·mrad)	6

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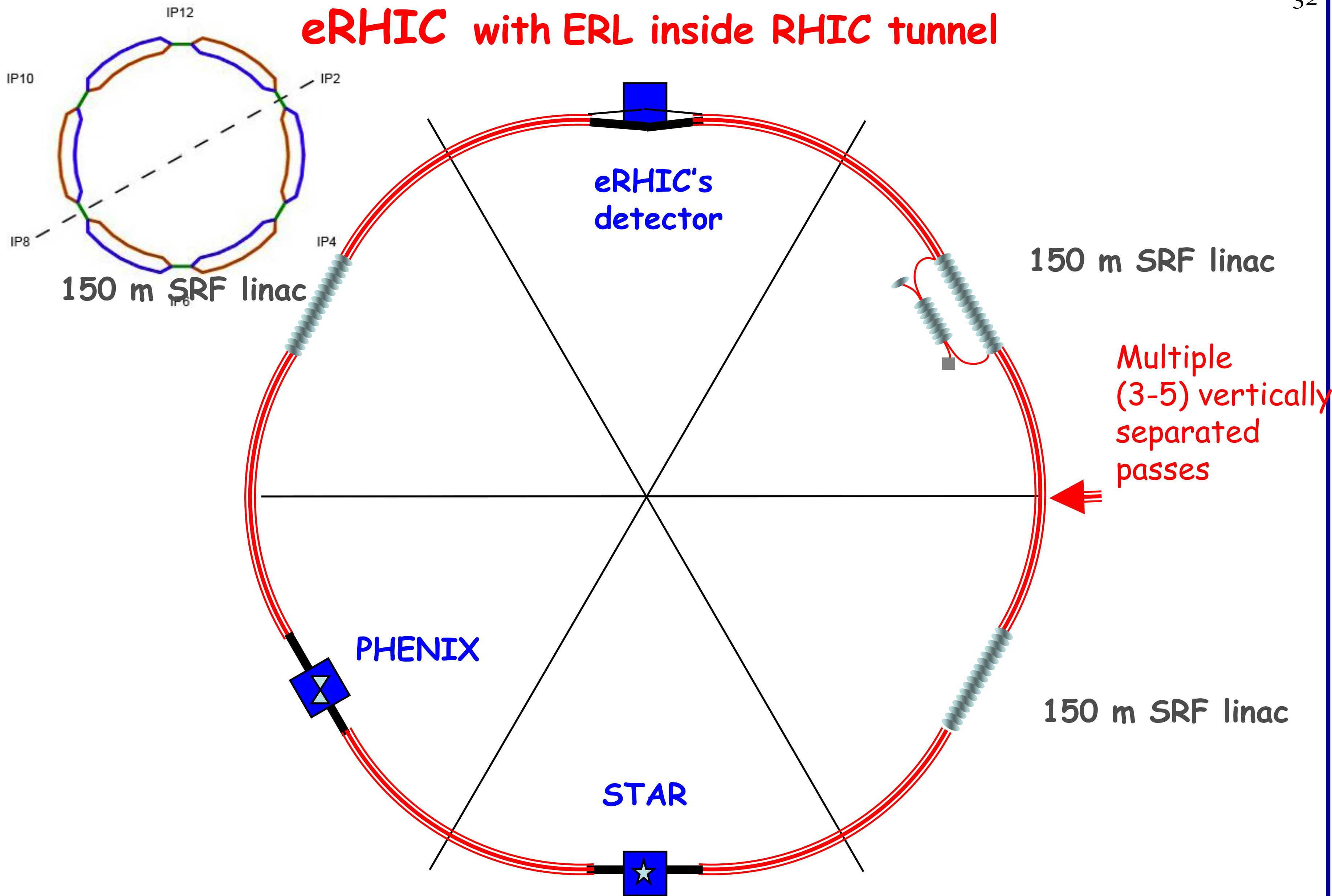
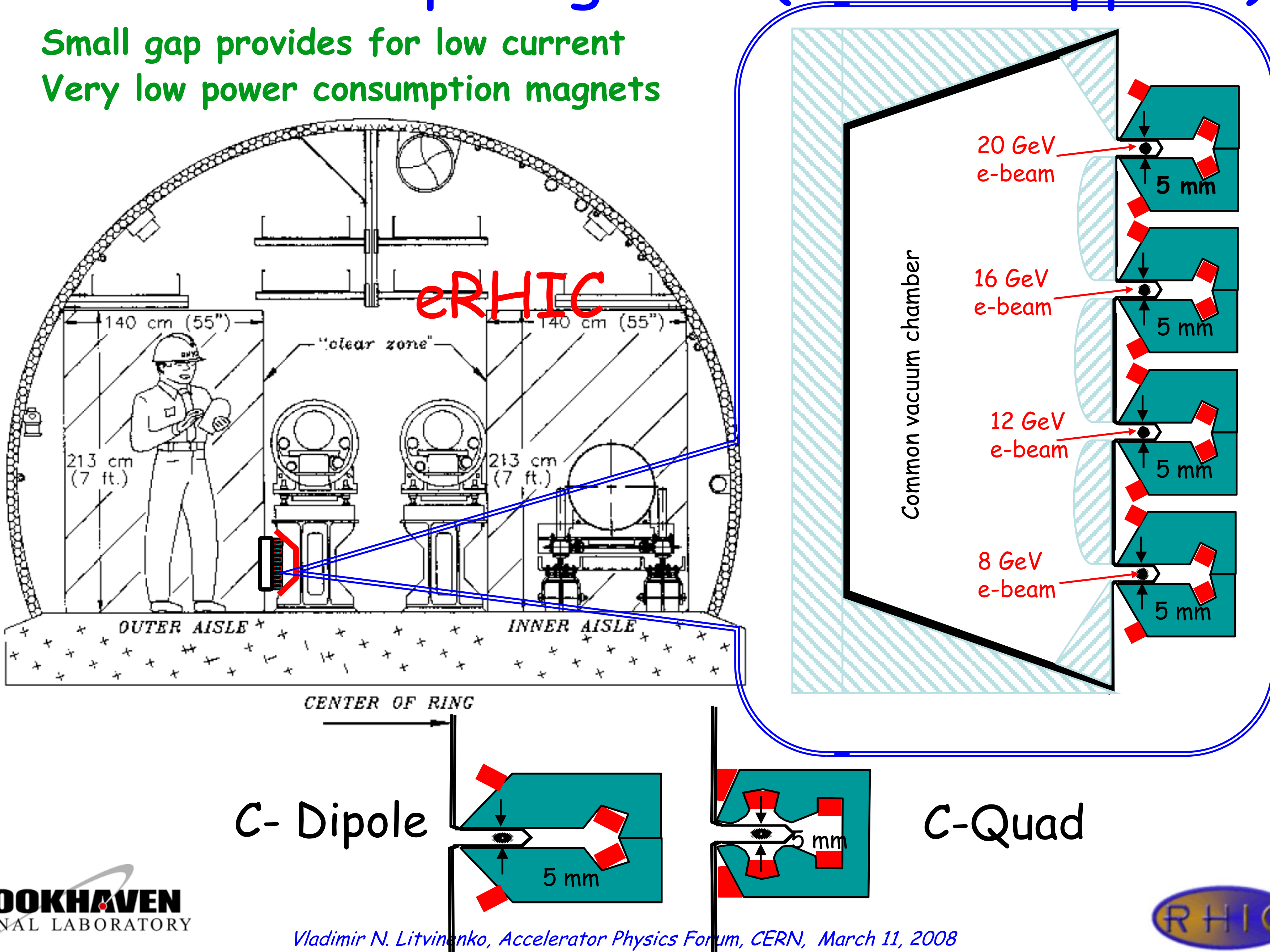
eRHIC with ERL inside RHIC tunnel



Similar configuration may be considered for LHeC

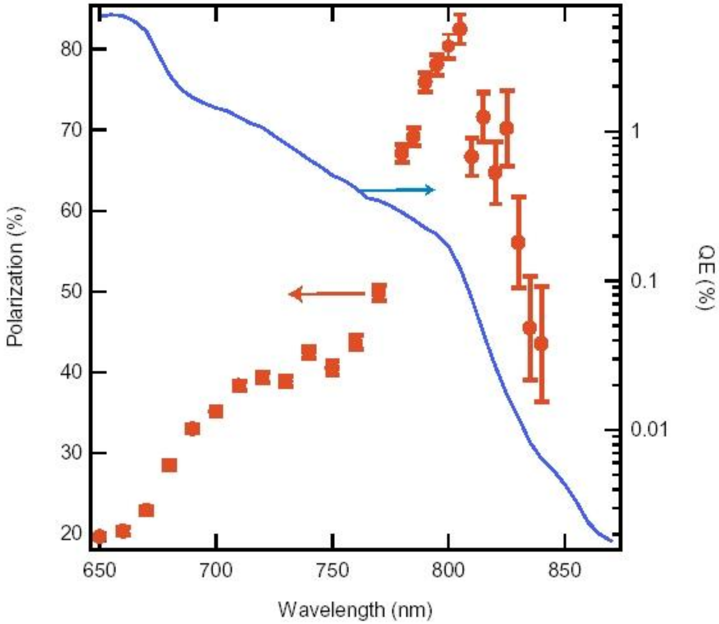
eRHIC loop magnets (LDRD support)

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



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

- eRHIC linac-ring requires several hundreds of mA with traditional e-cooling or tens of mA with coherent electron cooling to go to 10^{33}-10^{34} luminosity level

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

ERL spin transparency at all energies

Bargman, Mitchel,Telegdi equation

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

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

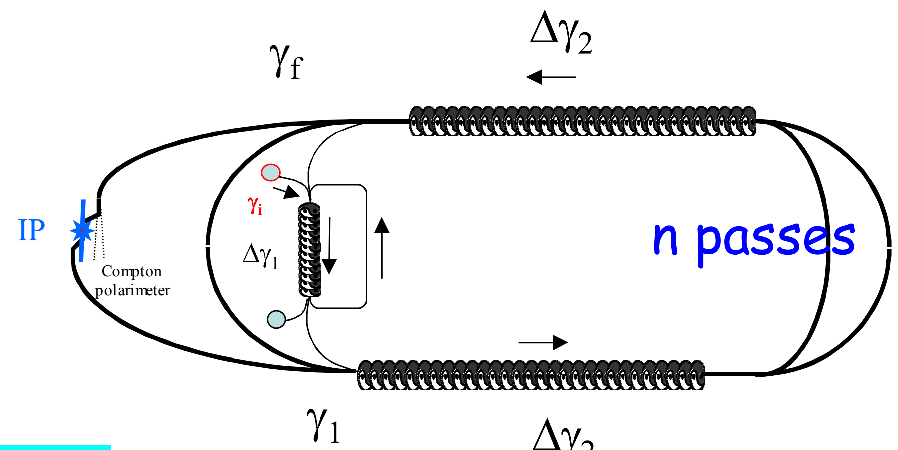
$$\hat{\mu} = \frac{g}{2}\frac{e}{m_o}\hat{s} = (1+a)\frac{e}{m_o}\hat{s}; \qquad \nu_{spin} = a\cdot\gamma = \frac{E_e}{0.44065[GeV]}$$

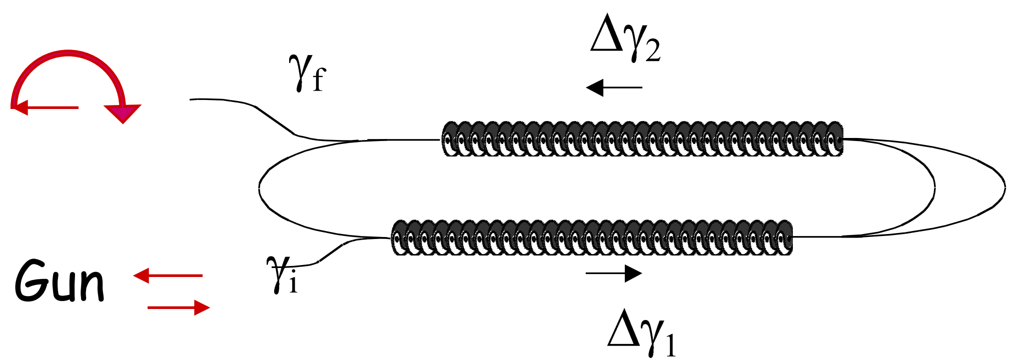
$$\Delta\varphi = a\cdot\gamma\theta$$

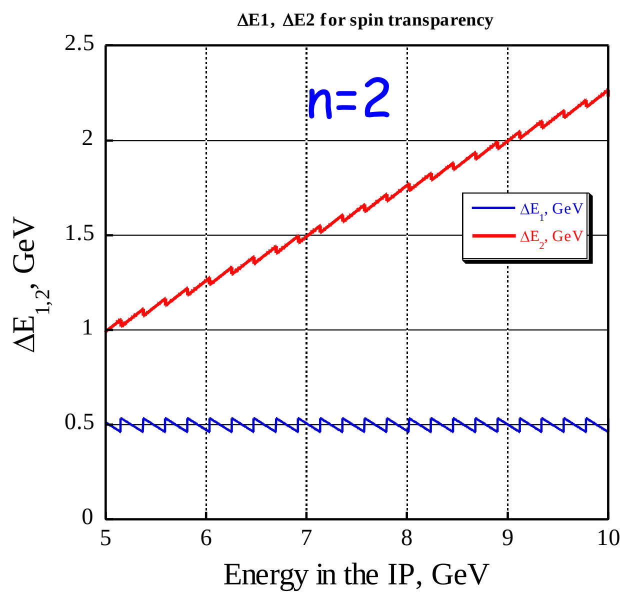
Total angle $\varphi = \pi a\cdot\left(\gamma_i(2n-1)+n(\Delta\gamma_1\cdot n+\Delta\gamma_2(n-1))\right)$

Has solution for all energies!

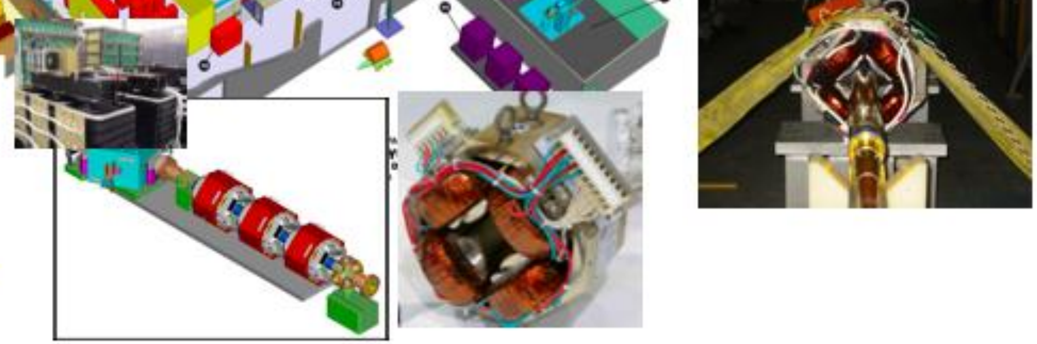
$$\begin{cases}\gamma_i + 2\cdot(\Delta\gamma_1+\Delta\gamma_2) = \gamma_f \\ a\cdot\left(\gamma_i(2n-1)+n(\Delta\gamma_1\cdot n+\Delta\gamma_2(n-1))\right) = N\end{cases}$$

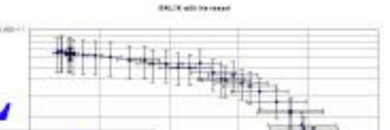






R&D ERL at BNL





E_{inj} =2.5-.3.5 MeV

E_{total} = 25 MeV, I_{max} = 0.5 A

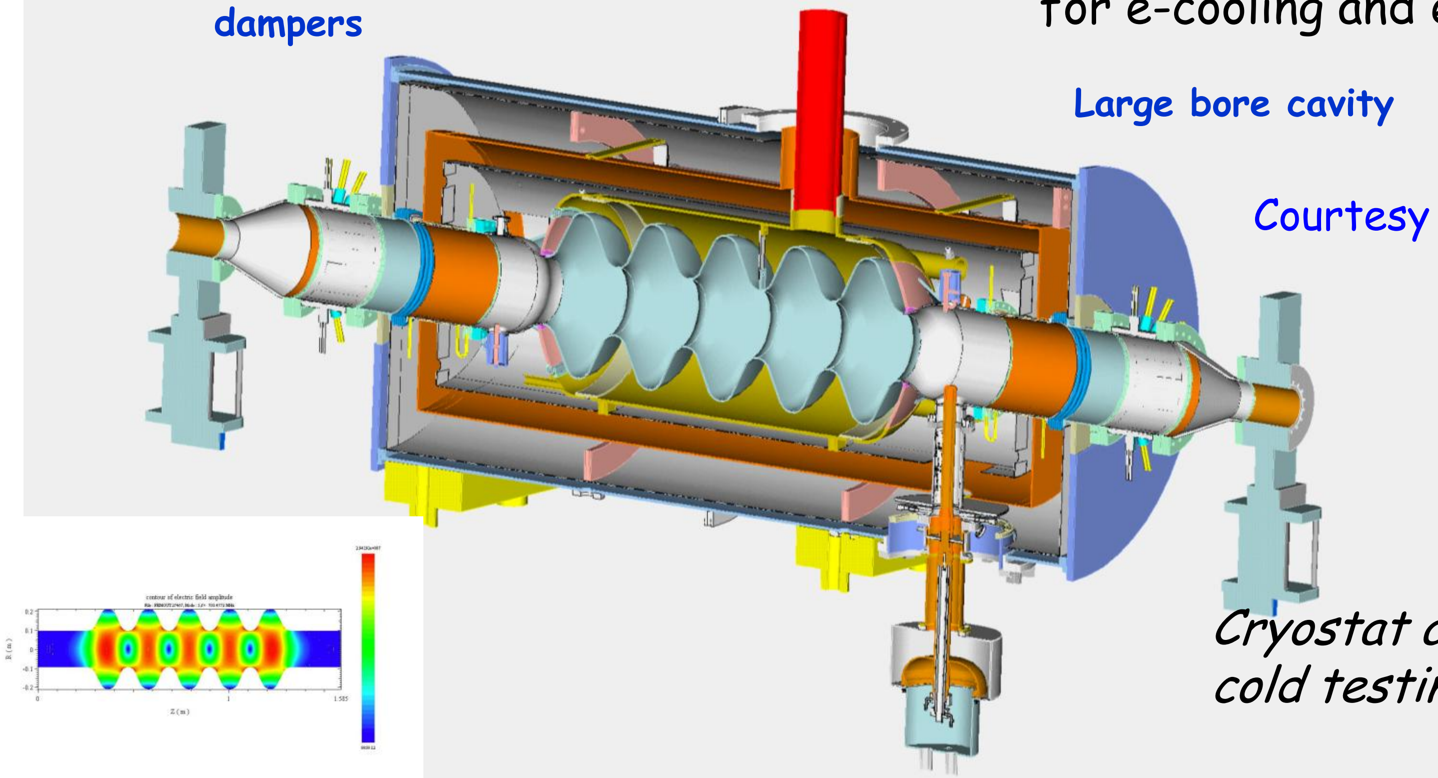
ε_n ~ 2 mm mrad @ 1.4 nC

Single Loop, SRF Gun

5 cell SRF linac, 703.75 MHz

BNL's 5-cell SRF Cavity

703.75 MHz 5-cell cavity designed in BNL and built by AES for e-cooling and eRHIC



Courtesy of I. Ben Zvi

Cryostat assembly and cold testing in 2007

State-of-the-art cavity engineering design to minimize and damp High Order modes of electromagnetic field.

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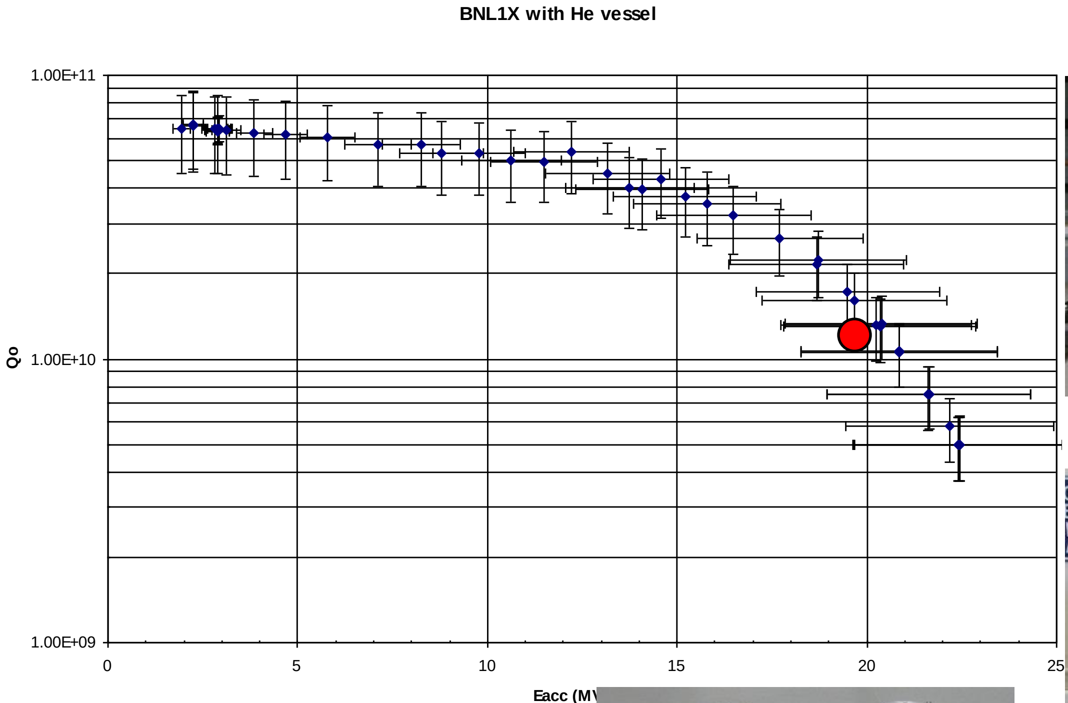
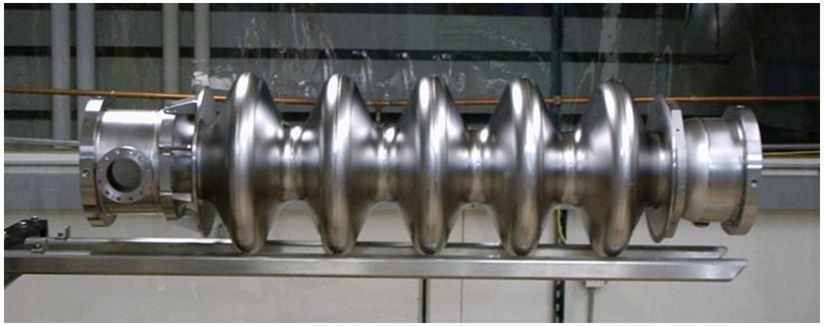
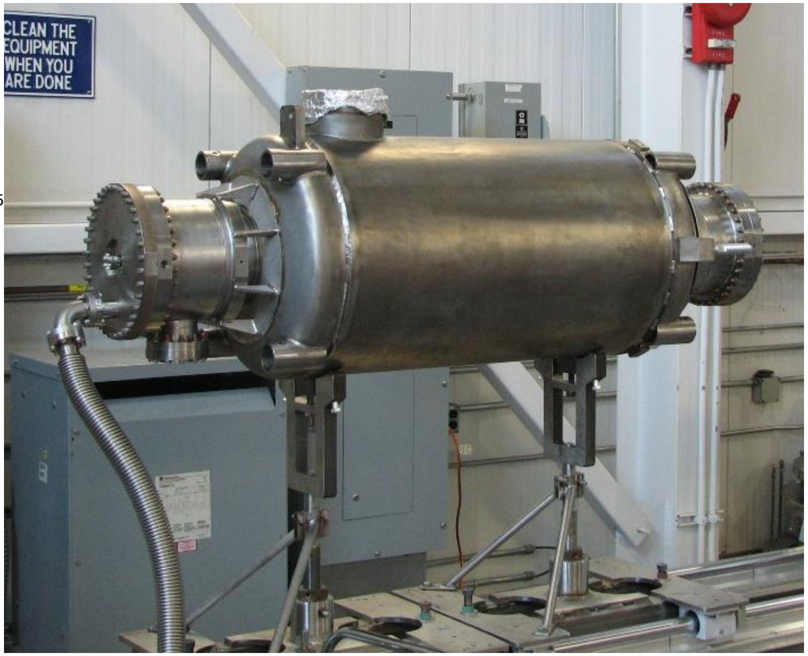
5 cell cavity successfully processed

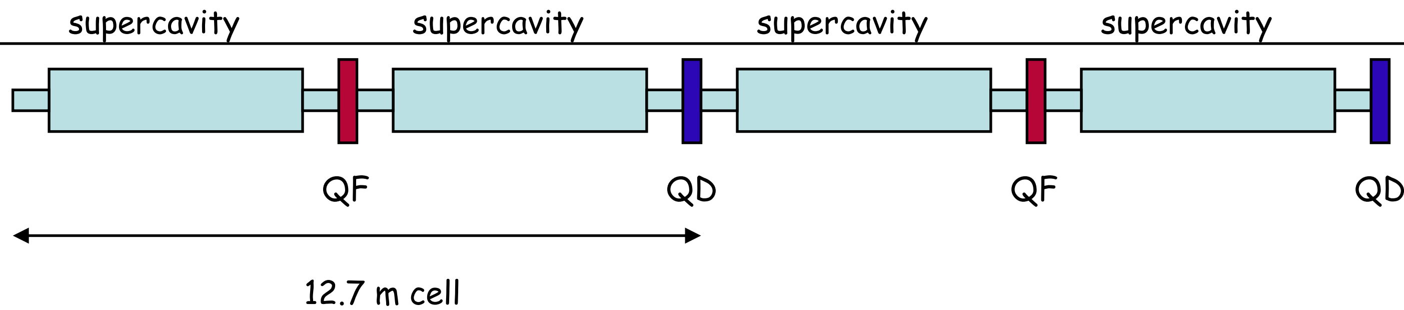




Courtesy of I. Ben Zvi

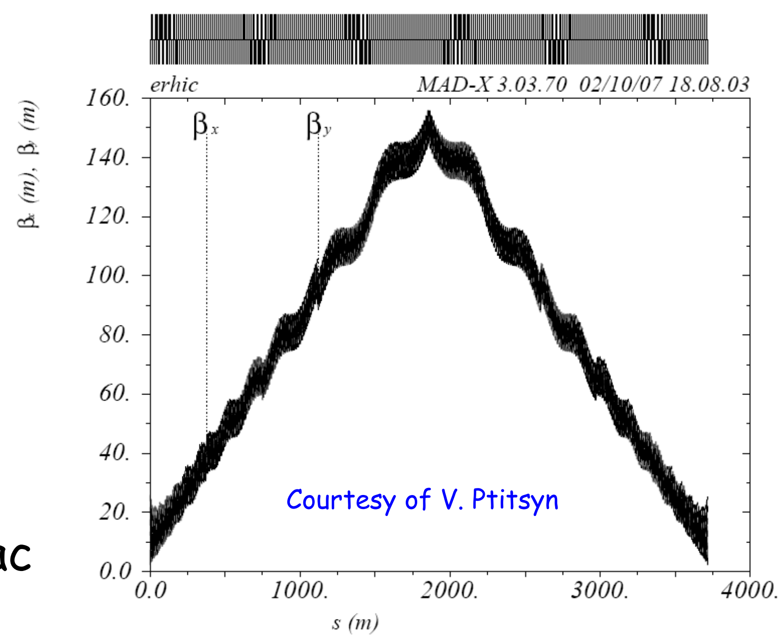


Linac optics



Based on the present design of super-cavity:
two 700 MHz cavities with up to 19 MeV gain/cavity + 2.1 GHz cavity
Total energy gain per super-cavity ~ 34 MeV
Average accelerating gradient ~ 5.4 MeV/m
We are developing plan to reach ~10 MeV/m average gradient

Optics solution
with constant gradient
linac lattice with 500 m linac



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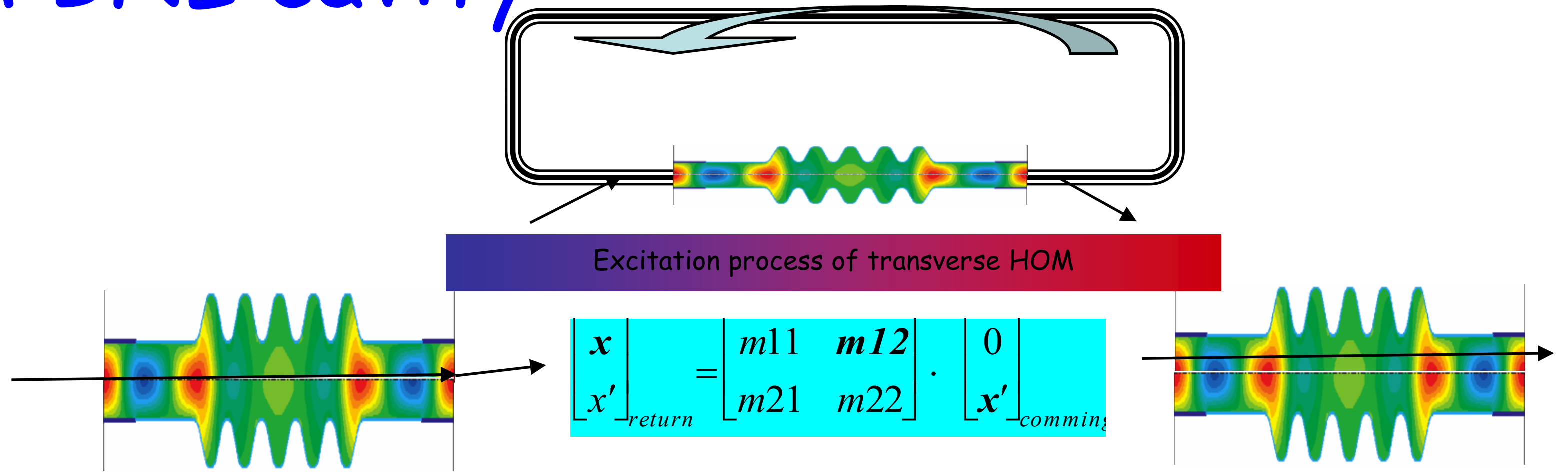
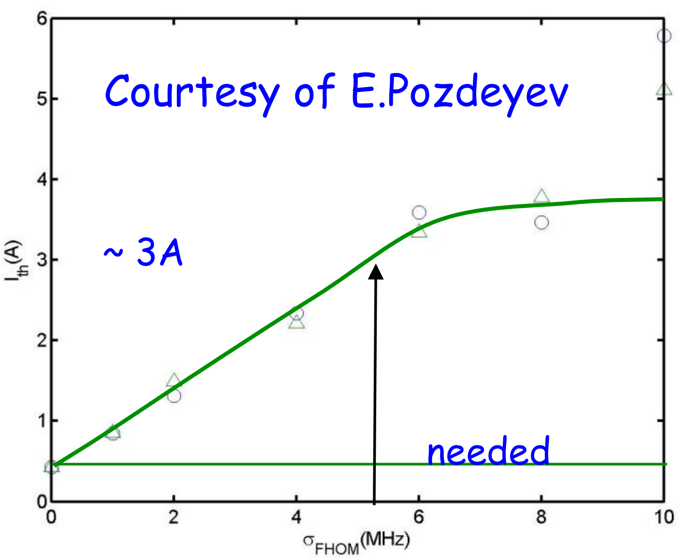
TBBU stability with BNL cavity

$$I_{th}^{(1)} = \frac{-2 p_r c}{e(R/Q)_m Q_m k_m M_{ij} \sin(\omega_m t_r + l\pi/2)}$$



$$\begin{bmatrix} x \\ x' \end{bmatrix}_{return} = \begin{bmatrix} m11 & \boldsymbol{m12} \\ m21 & m22 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ x' \end{bmatrix}_{comming}$$

- Single pass R&D ERL - I_{th} = 23 A
- eRHIC Linac Parameters (preliminary):
  - 200x16MeV/pass cavities (3.2 GeV gain), measured Cu-model HOM spectrum
  - 50 focusing and 50 defocusing quadrupoles, G=±1.262 T/m
  - **3 2.8 km loops around RHIC**
  - 28 MHz bunch rep.rate



Scaling from eRHIC

In the ERL-based eRHIC we collide two round beams with equal size (see section 3.f). The main distinct feature of the ERL-based eRHIC is that the attainable luminosity is completely defined by the energy and intensity of protons or ion beam in RHIC:

$$L = f_c \cdot \xi_i \cdot \frac{\gamma_i}{\beta_i^*} \cdot \frac{Z \cdot N_i}{r_i} \qquad \xi_h = \frac{N_e}{\gamma_h} \cdot \frac{r_h / Z}{4\pi\varepsilon_h}$$

i.e. by the intensity N_i, rep-rate f_c, the energy of the ion/proton $\gamma_i = E_i / Mc^2$, its charge $q = Ze$ and classical radius $r_i = Z^2 e^2 / Mc^2$ and allowable beam-beam tune shift ξ_i. The *ERL based eRHIC* luminosity is independent of the electron beam energy and linearly proportional to the energy of the proton or ion beam. It means that that the same center of mass energy, (given no preference of the energy ratio), can be reached using higher energy protons (ions) and lower energy electrons, hence the high luminosity.

$$L_{LHeC} = \frac{f_{c\ \ LHeC}}{f_{c\ \ eRHIC}} \cdot \frac{\xi_{p\ \ LHeC}}{\xi_{p\ \ eRHIC}} \cdot \frac{\gamma_{p\ \ LHeC}}{\gamma_{p\ \ eRHIC}} \cdot \frac{\beta^*_{p\ \ eRHIC}}{\beta^*_{p\ \ LHeC}} \cdot \frac{N_{p\ \ LHeC}}{N_{p\ \ eRHIC}} =$$

$$= 2.6 \cdot 10^{33} \cdot \frac{40\ \ MHz}{14\ \ MHz} \cdot \frac{0.024}{0.015} \cdot \frac{7000}{250} \cdot \frac{0.25\ \ m}{0.5\ \ m} \cdot \frac{1.7\ \ 10^{11}}{2\ \ 10^{11}} = 1.4 \cdot 10^{35}$$

i.e. in LHeC practical limit is the power of RF system to compensate synchrotron radiation of electrons

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Why Linac-Ring for LHeC looks so grim?

Comparison Linac-Ring and Ring-Ring

	Linac-Ring	Ring-Ring
Energy / GeV	40-140	40-80
Luminosity / 10^{32} cm^{-2} s^{-1}	0.5	10
Mean Luminosity, relative	2	1 [dump at L_{peak} /e]
Lepton Polarisation	60-80%	30% [?]
Tunnel / km	6	2.5=0.5 * 5 bypasses
Biggest challenge	CW cavities	Civil Engineering Ring+Rf installation
Biggest limitation	luminosity (ERL,CW)	maximum energy
IR	not considered yet one design? (eRHIC)	allows ep+pp 2 configurations [lox, hiq]

Plenary ECFA, LHeC, Max Klein, CERN 30.11.2007

Why predicted LHeC luminosity is below that of eRHIC and ELIC, which operate at much lower energies?

V. Ptitsyn's talk at PAC 2007

	HERA		eRHIC ring-ring		eRHIC ERL-based		ELIC		LHeC	
	p	e	p	e	p	e	p	e	p	e
Energy, GeV	920	27.5	250	10	250	10	225	9	7000	70
Bunch frequency, MHz	0.75		14		14		1500		40	
Bunch intensity, 10^{11}	0.72	0.29	1	2.3	2	1.2	0.04	0.075	1.7	0.14
Beam current, A	0.1	0.04	0.21	0.48	0.42	0.26	1	1.8	0.54	0.07
Rms emittance, nm	5.1/5.1	20/3.4	9.5/9.5	53/9.5	3.8	1.0	5.1/0.2	5.1/0.2	0.5/0.5	7.6/3.8
β*, x/y, cm	245/18	63/26	108/27	19/27	26	100	0.5/0.5	0.5/0.5	180/50	13/7
Beam size at IP, x,y, μm	112/30		100/50		32/32		5/1		31/16	
Max beam-beam parameter per IP	0.001	0.037	0.015	0.08	0.015	2.3	0.0064	0.086	0.0008	0.05
Bunch length, cm	19	1	20	1.2	20	1	0.5	0.5	7.6	0.7
Polarization, %	0	50	70	80	70	>80	>70	80	0	0
Distance of first quad from the IP, m	2		1		3		3		1.2	
Crossing Angle, mrad	0		0		0		30		2	
Peak Luminosity, 10^{33} $cm^{-2}s^{-1}$	0.04		0.47		2.6		75		1.1	

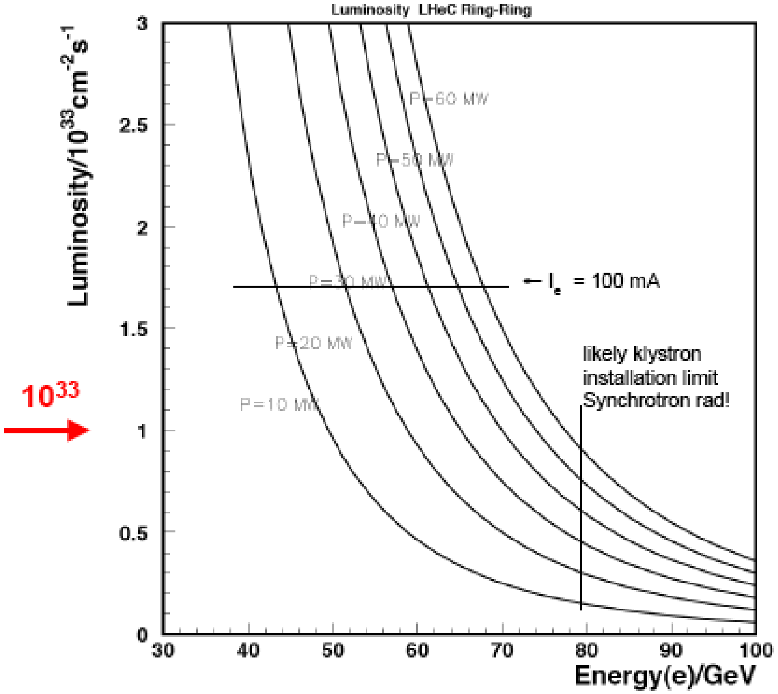
Ring-Ring LHeC is limited by power of synchrotron radiation from the e-beam!

Luminosity: Ring-Ring

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}} = 8.3 10^{32} \cdot \frac{I_e}{50mA} \frac{m}{\sqrt{\beta_{px}\beta_{pn}}} cm^{-2}s^{-1}$$

$\varepsilon_{pn} = 3.8\mu m$
$N_p = 1.7 \cdot 10^{11}$
$\sigma_{p(x,y)} = \sigma_{e(x,y)}$
$\beta_{px} = 1.8m$
$\beta_{py} = 0.5m$

$$I_e = 0.35mA \cdot \frac{P}{MW} \cdot \left(\frac{100GeV}{E_e}\right)^4$$



10^{33} **can be reached in RR**
E_e = 40-80 GeV & P = 5-60 MW.

HERA was 1-4 10^{31} cm^{-2} s^{-1}
huge gain with SLHC p beam

F.Willeke in hep-ex/0603016:
Design of interaction region
for 10^{33} : 50 MW, 70 GeV

May reach 10^{34} with ERL in bypasses, or/and reduce power.
R&D performed at BNL/eRHIC

cf also A.Verdier 1990, E.Keil 1986

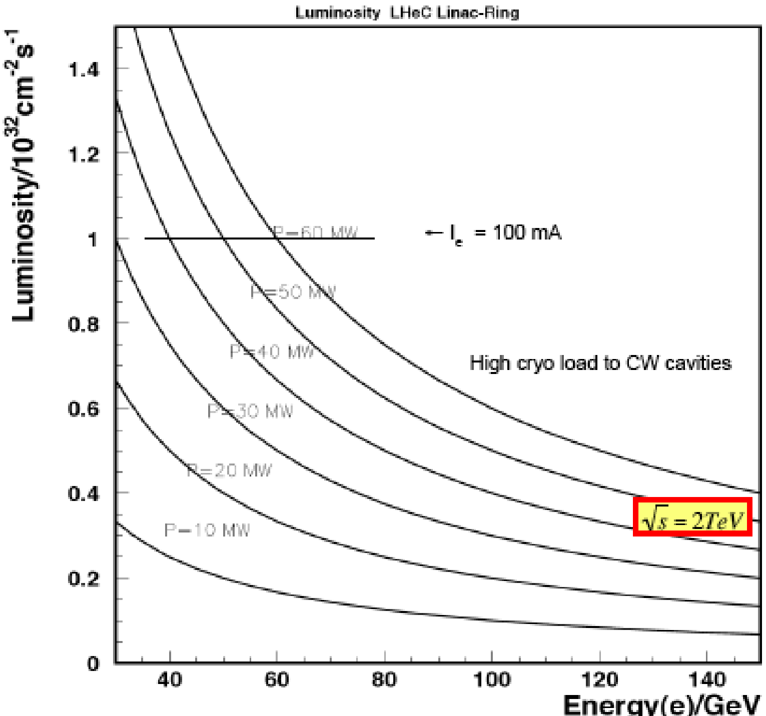
M.Klein, ecfa07 talk

For linac-ring LHeC a pulsed linac with 0.5% duty factor (1 msec, 5 Hz(without energy recovery was considered

Luminosity: Linac-Ring

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn} \beta^*} \cdot \frac{P}{E_e} = 1 \cdot 10^{32} \cdot \frac{P/MW}{E_e/GeV} cm^{-2} s^{-1}$$

$\varepsilon_{pn} = 3.8 \mu m$
$N_p = 1.7 \cdot 10^{11}$
$\beta^* = 0.15 m$



$$I_e = 100 mA \cdot \frac{P}{MW} \cdot \frac{GeV}{E_e}$$

LHeC as Linac-Ring version can be as luminous as HERA II:

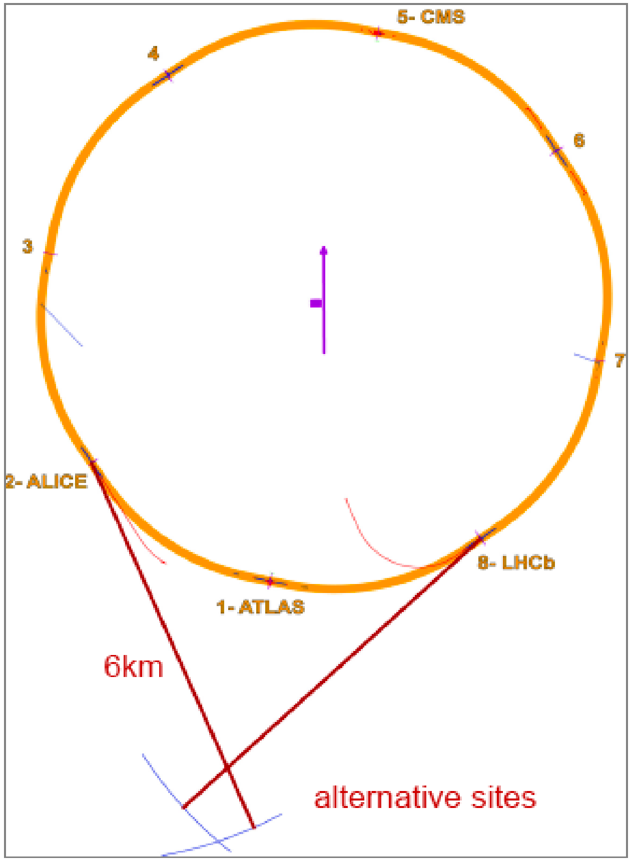
4 10^{31} can be reached with LR:
E_e = 40-140 GeV & P=20-60 MW
LR: average lumi close to peak

140 GeV at 23 MV/m is 6km +gaps

Luminosity horizon: high power: ERL (2 Linacs?)

M.Klein, ecfa07 talk

e$^{\pm}$ Linac - p/A Ring



	units	ring-linac pulsed		ring-linac, cw , ~99% energy recovery	
		e-	p	e-	p
energy	GeV	70	7000	70	7000
punch population	10^{10}	2	17	2	17
σ_z	cm	0.03	7.55	0.03	7.55
beam current (pulsed)	mA	101	858	101	858
emittance $\varepsilon_{x,y}$	nm	0.5, 0.5			
$\beta^*_{x,y}$	cm	15, 15			
spacing	ns	25			
e-linac/ring length	km	3.5		7 (2 linacs)	
e- pulse length		1 ms		cw	
repetition rate		5 Hz		continuous	
e- beam power	MW	35		7000	
peak luminosity	**10^{32} $cm^{-2}s^{-1}$**	**0.6**		**2x110**	

S. Chattopadhyay (Cockcroft), F.Zimmermann (CERN), et al.

Plenary ECFA, LHeC, Max Klein, CERN 30.11.2007

Nobody can afford a regular full energy linac for a high luminosity e-H collider!

In eRHIC ERL 20GeV, 500mA beam will have reactive power of 10 GW !

Regular linac - RF transmitter alone will cost $5/W -> $50,000M

Hence - ENERGY RECOVERY IS THE MUST

ERL based LHeC with cooling: 30 x luminosity

	Electrons	Protons
Energy	70 GeV	7 TeV
N per bunch	0.14 10^{11}	1.7 10^{11}
Rep rate, MHz	40	
Beam current, mA	90	1090
Norm emittance, μm	3	0.3
β*, m	0.92	0.5
ξ* D	12.7 6.52	**0.0057**
Luminosity, x 10^{34} cm^{-2} sec^{-1}	**3.77**	
Loss for SR, MW	67	-

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ERL based LHeC with cooling 100 GeV electrons

	Electrons	Protons
Energy	100 GeV	7 TeV
N per bunch	$0.033\ 10^{11}$	$1.7\ 10^{11}$
Rep rate, MHz	40	
Beam current, mA	20	1090
Norm emittance, μm	3	0.3
β*, m	1.3	0.5
ξ* D	12.7 4.56	**0.00137**
Luminosity, x 10^{34} cm^{-2} sec^{-1}	**0.9**	
Loss for SR, MW	67	-

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ERL based LHeC

- Luminosity $3 \cdot 10^{34}$ cm^{-2} sec^{-1}
  at all energies of e-beam (probably will be limited by burn-off of the proton beam)
  - *Or "ring-ring" luminosity of 10^{33} cm^{-2} sec^{-1} with 3 mA electron beam current and 2.2 MW loss for SR*
- e-beam current is low (because of the cooling!)
- If further reduction of β^* is possible, L~ 10^{35} is feasible
- Higher energies of electrons are possible
- e-Beams with very low emittance are possible -> larger β^* for electron - easier optics, longer detectors, less modulation effects by synchrotron oscillations….
- 100 GeV e-beam with luminosity up to $9 \cdot 10^{33}$ cm^{-2} sec^{-1}

Lower current of e-beam

$$\xi_p = \frac{N_e}{\gamma_p} \cdot \frac{r_p}{4\pi\varepsilon_p} = \frac{N_e \cdot r_p}{4\pi\varepsilon_{p\ norm}};$$

- Normalized emittance of electrons ~ 3 μm is possible - no problems to match the proton beam
  - @ 100 GeV, γ_e=2 10^5 ~ 300 γ_p , i.e. proton normalized emittance can be as low a 0.01 μm
- N_e ~ ε_{norm}; ε_{norm} : 3.8μm -> 0.1μm -> N_e=4 10^9
- E_e=100 GeV, I_e= 20 mA, SR_{loss}=57 MW (the same as Ring-Ring with 100 x luminosity)
- This case requires additional studies of beam stability (e-beam disruption + kink instability)

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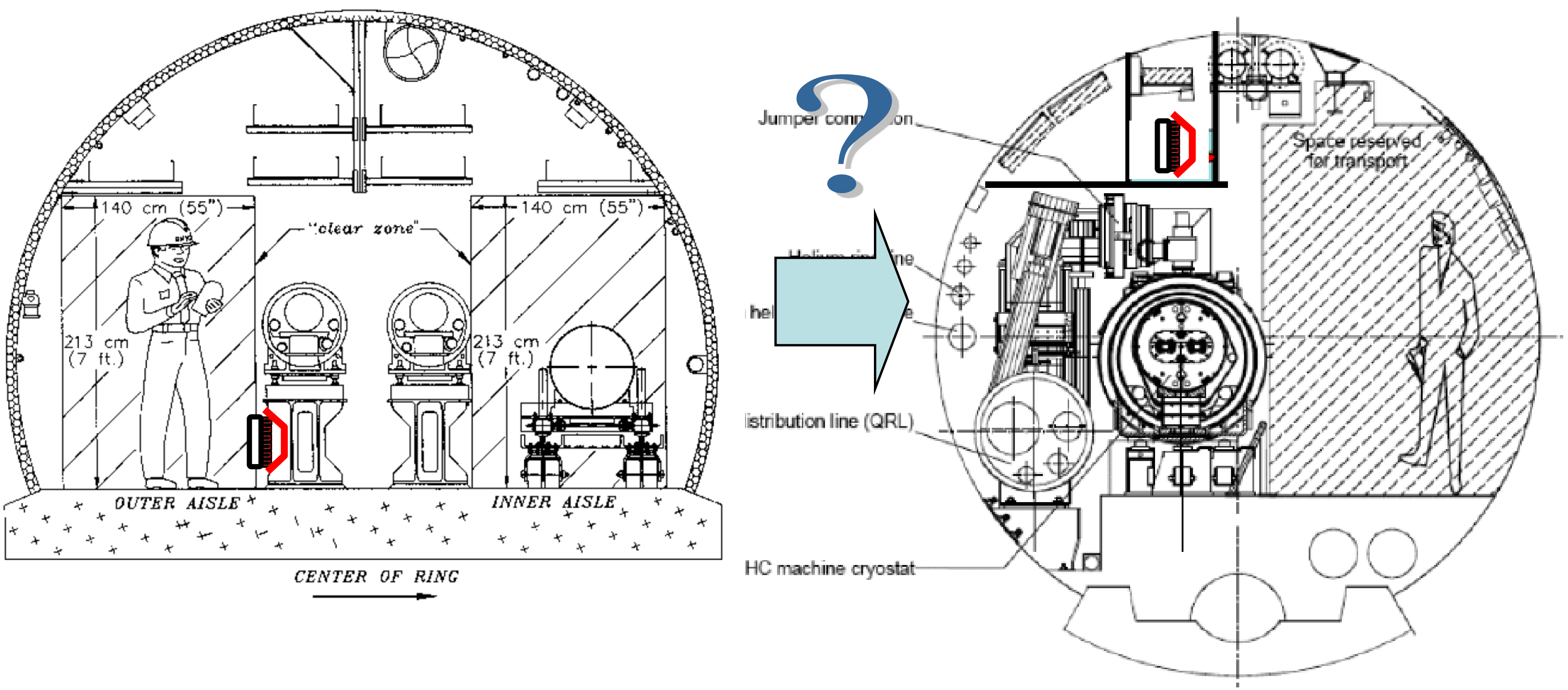
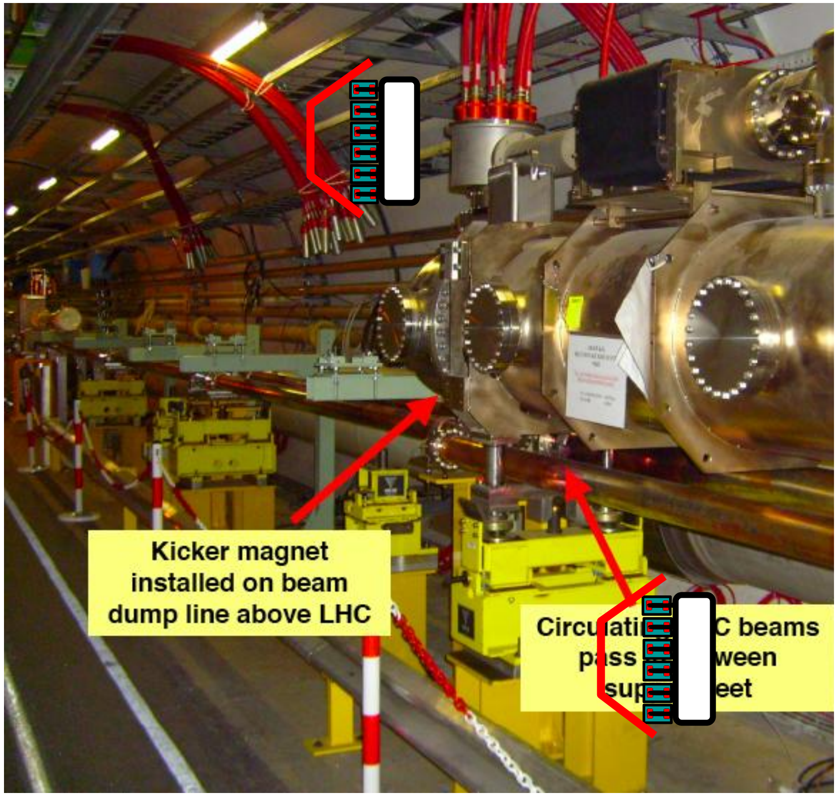
Other considerations

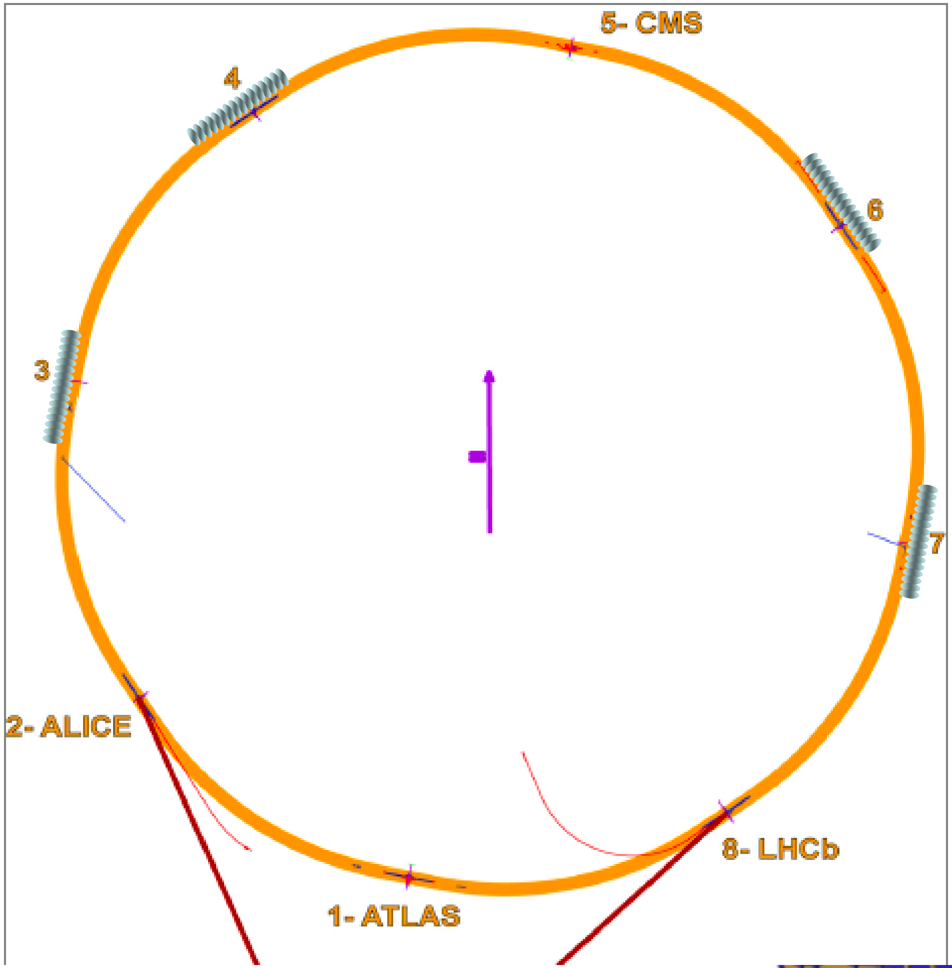
- May (for the most part) fit inside the LHC tunnel.



Other considerations

- Is there room for linac in the straights?





Conclusions

- ERL seems to be the most promising approach for high energy, high luminosity electron-ion and polarized electron-proton collider
- It can take advantage of any ring-ring concept and go further
- Presently there is no show-stoppers but a significant amount of R&D
- At BNL the 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.
- LHeC based on this principle reach 10^{34}-10^{35} level of luminosity