ERL-based electron-hadron colliders: 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.

e-RHIC
(V. Litvinenko), Head
(V. Ptitsyn), Deputy
(A. Petway), Secretary

Beam Dynamics
(V. Ptitsyn), GL
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)

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Content

- What eRHIC is about
- <u>Choosing the focus: ERL or ring for electrons?</u>
  - Advantages and challenges of ERL driver
  - R&D items for ERL-based eRHIC
  - New developments
    - 5-cell SRF cavity
    - Small magnets for eRHIC loops
    - Kink instability
    - Electron beam disruption during the collision
    - Simulations of the beam-beam effects
    - Coherent electron cooling
    - Staging
- <u>Relevance to LHeC - some results & number</u>
- Conclusions

Appendix A of the eRHIC ZDR

Linac-Ring eRHIC.

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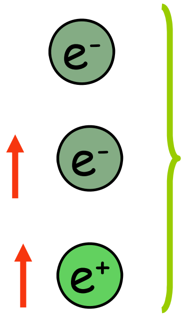
Conclusions first

- 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
- There is a clear possibility for eRHIC (LHeC?) staging
- Presently there is no show-stoppers but a significant amount of R&D
- At BNL the R&D ERL tests start in 2009, MIT's progress with developing high current polarized gun, prototyping of small gap magnets are in progress .....
- **LHeC based on this principle reach 10^{34}-10^{35} level of luminosity -natural topic for collaborating with BNL**

eRHIC Scope -QCD Factory

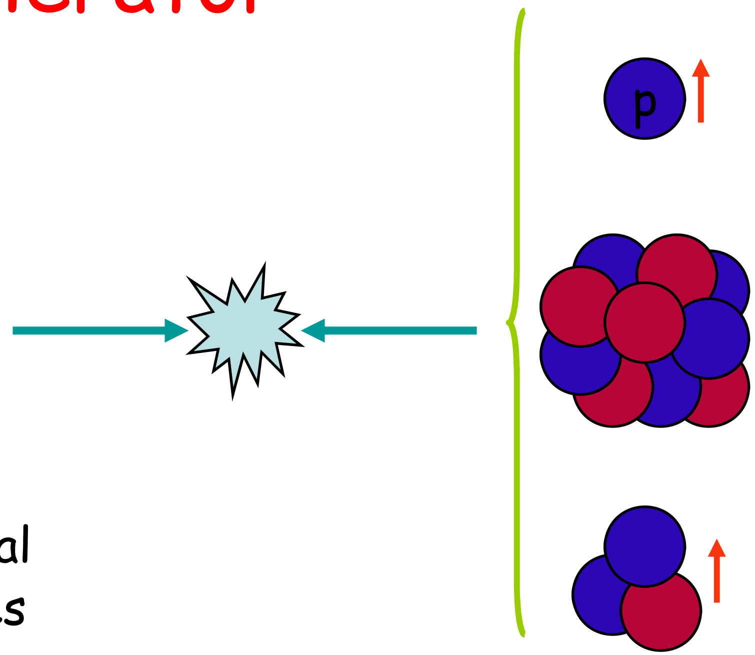
Electron accelerator

Unpolarized and polarized leptons 2-20 (30) GeV



70% beam polarization goal
Positrons at low intensities

RHIC



Polarized protons
25↓ 50-250 (325) GeV

Heavy ions (Au)
50-100 (130) GeV/u

Polarized light ions
(He^3) 215 GeV/u

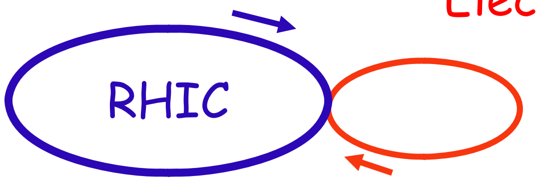
Center mass energy range: 15-200 GeV

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

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

View from 2004: How eRHIC can be realized?

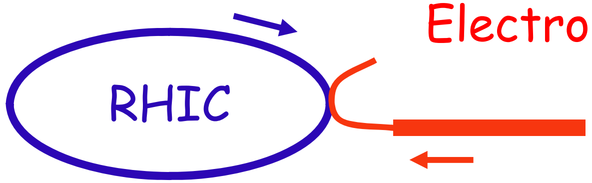
- Ring-ring:



Electron storage ring

$$L = \left(\frac{4\pi\gamma_h\gamma_e}{r_h r_e}\right)(\xi_h\xi_e)(\sigma_h^{'}\sigma_e^{'})f$$

- Linac (ERL)-ring:



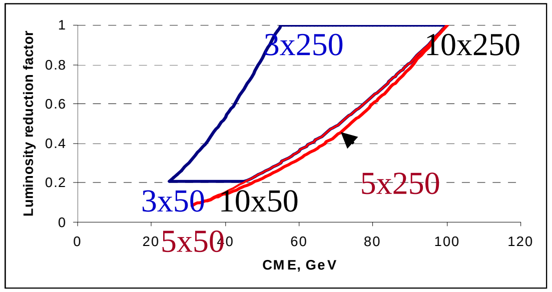
Electron linear accelerator

$$L = \gamma_h f N_h \frac{\xi_h Z_h}{\beta_h^* r_h}$$

Advantages & Challenges of ERL based eRHIC

- Allows use of RHIC tunnel
- 2-3 fold higher energy of electrons
- Higher luminosity up to 10^{34} cm^{-2} sec^{-1}
- Multiple IPs
- Higher range of CM-energies + high luminosities
- Full spin transparency at all energies
- No machine elements inside detector(s)
- No significant limitation on the lengths of detectors
- ERL is simply upgradeable
- eRHIC can be staged

- Novel technology
- Need R&D on polarized gun
- May need a dedicated ring positrons

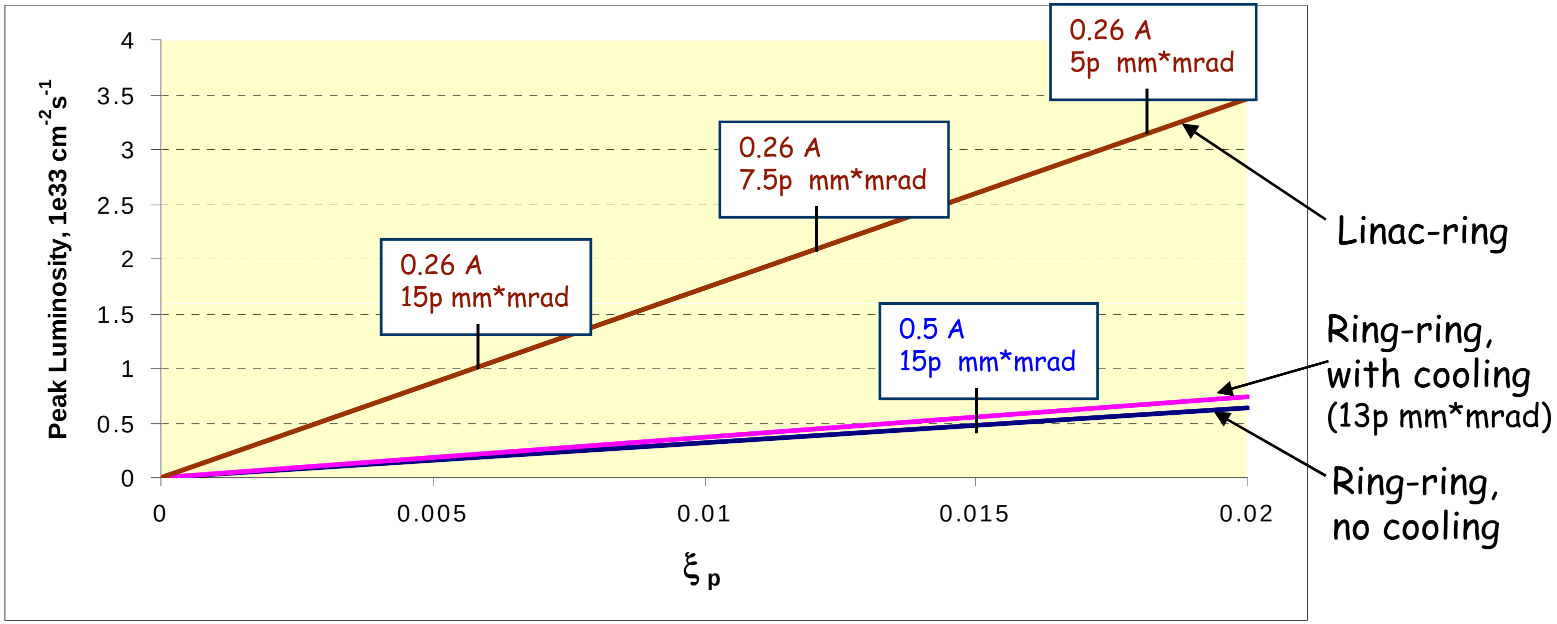


In Ring-ring luminosity reduces 10-fold for 30 GeV CME.
Required norm.emittance (for 50 GeV protons) ~3 mm*mrad

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

Luminosity

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

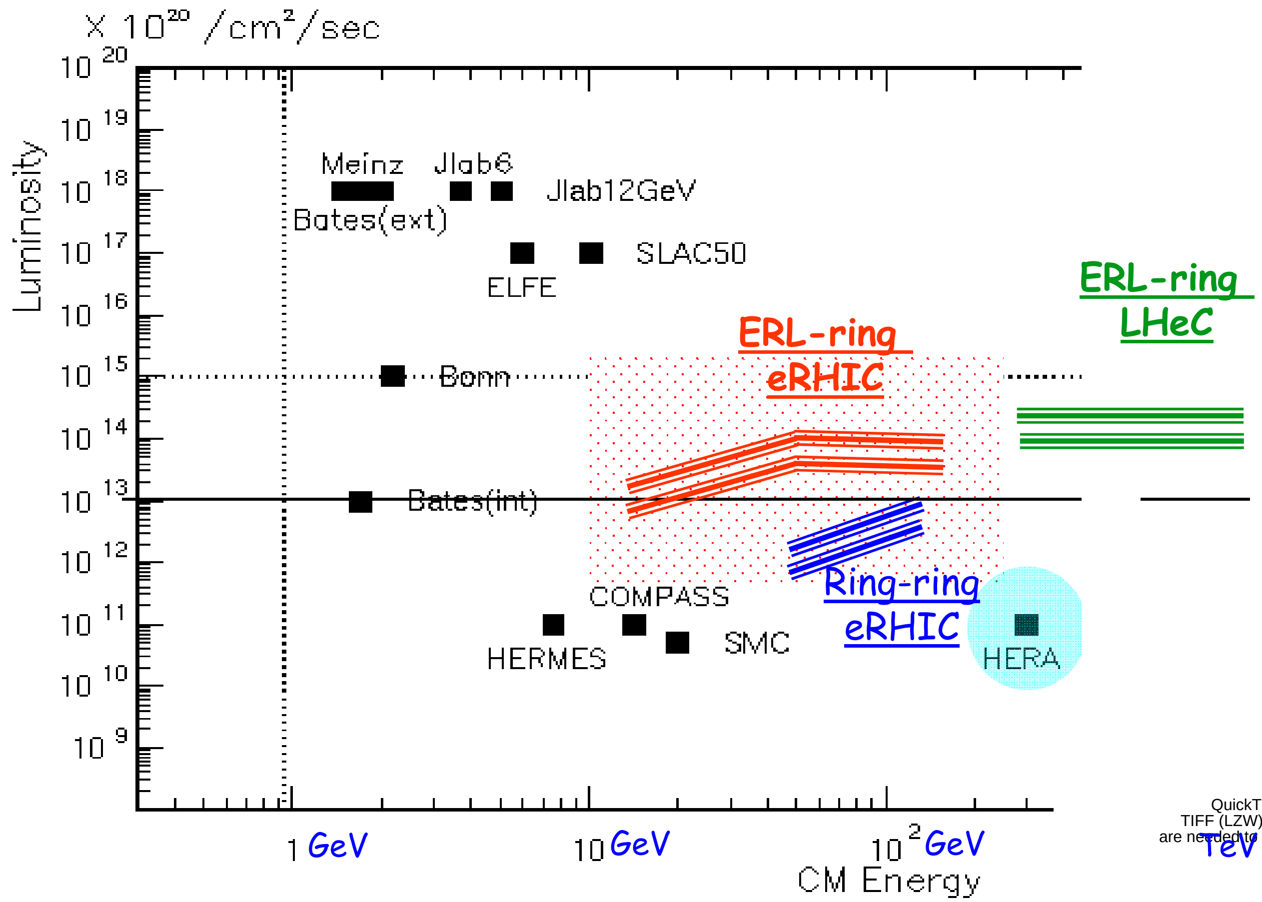


Markers show electron current and (for linac-ring) normalized proton emittance.
In dedicated mode (only e-p collision): maximum ξ_p~0.016-0.018;

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

CM vs. Luminosity



eRHIC

- Variable beam energy
- Polarizes electrons and protons
- p-He^3-U ion beams
- Light ion polarization
- Large luminosity

ERL spin transparency at all energies

Bargman, Mitchel,Telegdi equation

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

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

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

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

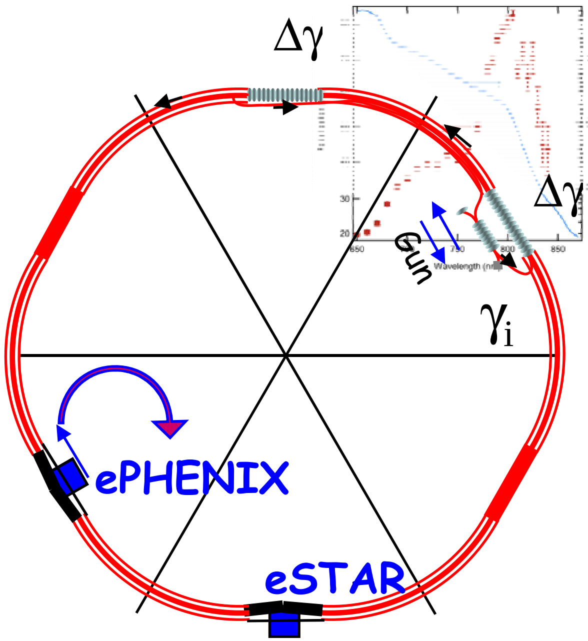
Total angle

$$\varphi = 2\pi a\cdot\left((n-1/2)\gamma_i + \{2n(n-2)-1/6\}\Delta\gamma\right)+\varphi_i$$

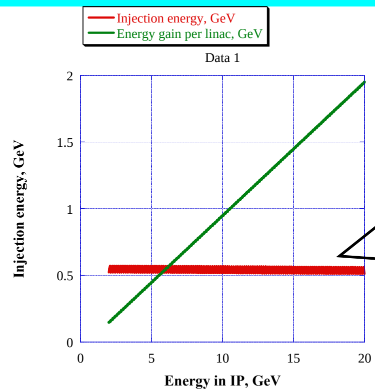
Has solution for all energies!

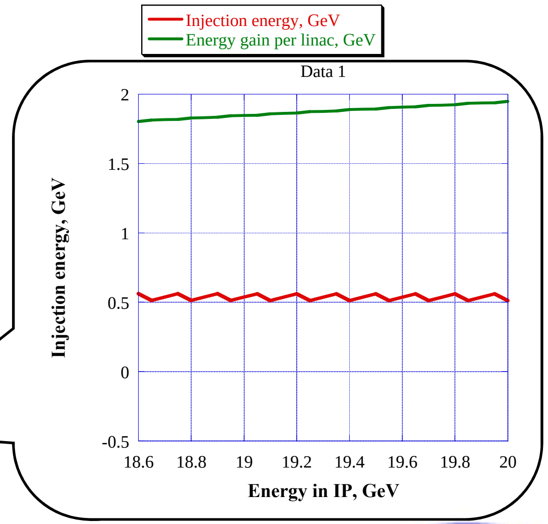
$$\begin{cases}\Delta\gamma = (\gamma_f-\gamma_i)/2n \\ 2\pi a\cdot\left((n-1/2)\gamma_i + \{n(n-2)-1/3\}\Delta\gamma\right)+\varphi_i \quad = \theta + N\pi\end{cases}$$

$$E_i = \frac{0.44065[GeV]}{n+1+1/3n}\operatorname{mod}\left(\varphi_f-\varphi_i-\left(n-2-\frac{1}{3n}\right)\frac{E_f}{0.44065[GeV]},\pi\right)$$

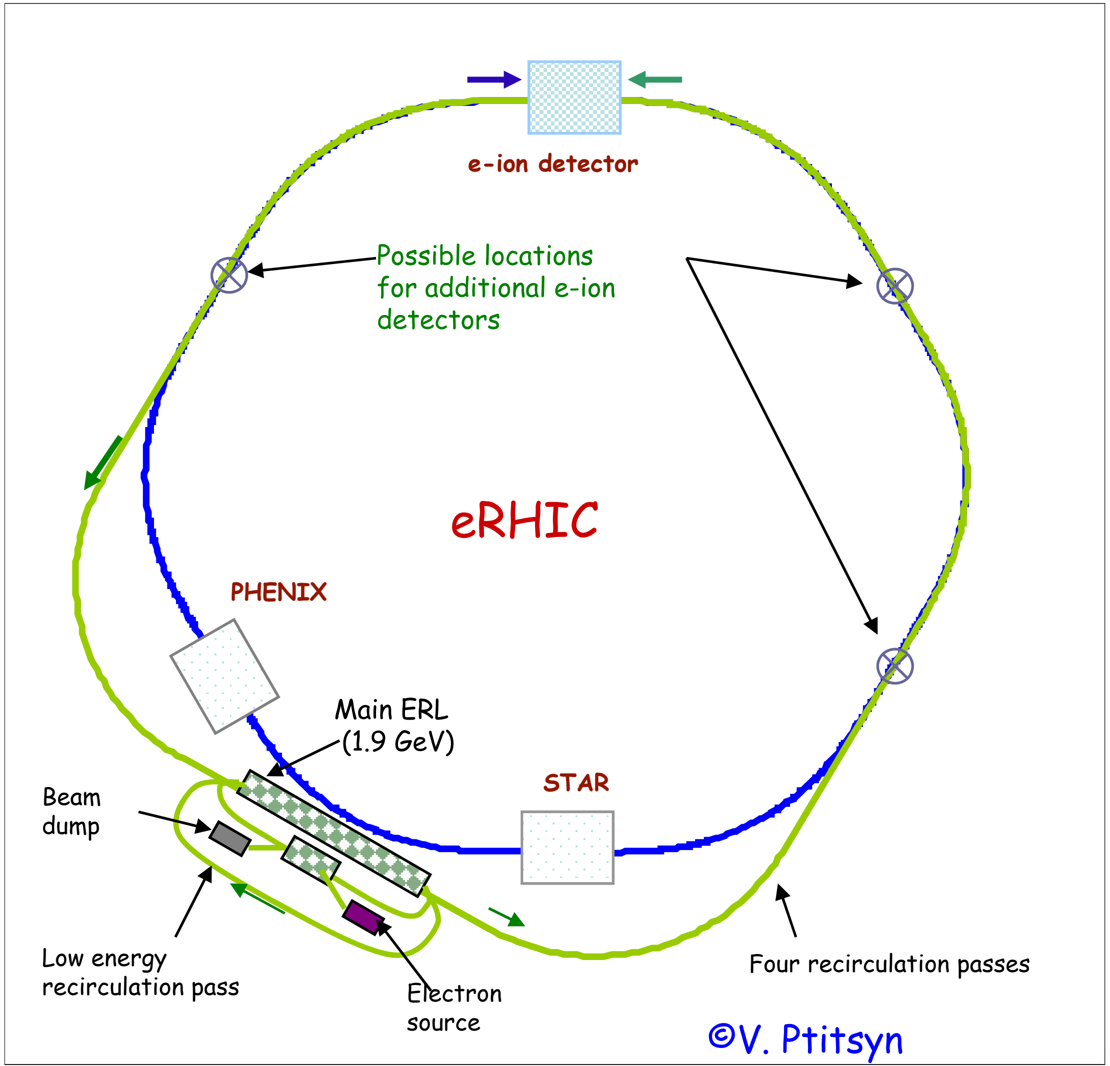


$$\delta E_{i\,\max} = \pm 37 \;\; MeV \;\; \vee n = 5$$





Baseline: ERL-based eRHIC



- 10 GeV electron beam energy, upgradeable to 20 GeV by doubling the main linac
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) and detectors
- 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 (compact storage ring; Compton backscattered) - Though at lower luminosity

Baseline: ERL-based eRHIC Parameters

	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	2.0	1.2
Beam current, mA	420	260	420	260
Normalized 95% emittance, p 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	

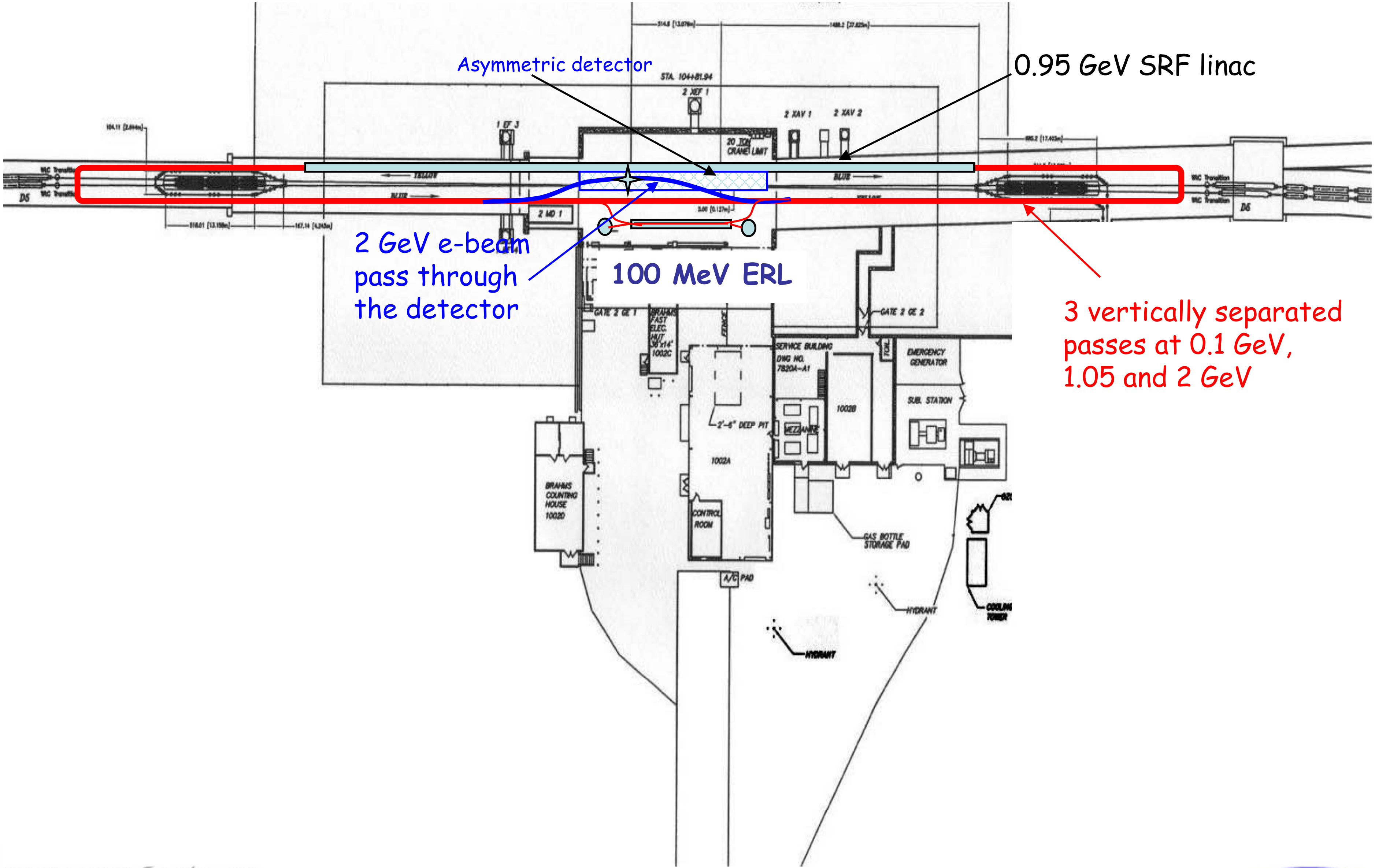
©V. Ptitsyn

Current vision of eRHIC:

Increased the Energy Reach and Luminosity
Effective use of cooling
Staging

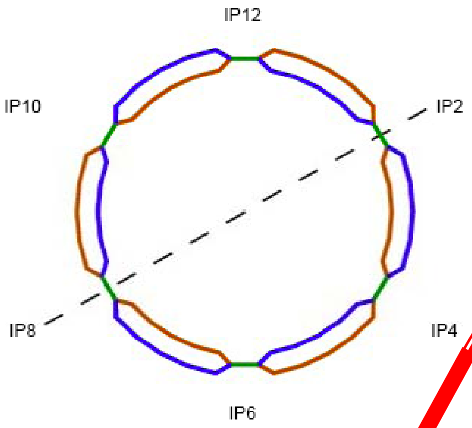
- **MEIC**: Medium Energy Electron-Ion Collider
  - Located at IP2 (with a modest detector)
  - 2 GeV e^- x 250 GeV p (45 GeV c.m.), L ~ 10^{32} cm^{-2} sec^{-1}
- **eRHIC - Full energy, nominal luminosity ,** inside RHIC tunnel
  - 30% increase of RHIC energy is possible with replacing DX magnets
  - Polarized 20 GeV e^- x 325 GeV p (160 GeV c.m), L ~ $4 \cdot 10^{33}$ cm^{-2} sec^{-1}
  - 30 GeV e x 130 GeV/n Au (120 GeV c.m.), L ~ 10^{31} cm^{-2} sec^{-1}
  - Based on present RHIC beam intensities
  - With coherent electron cooling the electron beam current is 25 mA
  - 1.92 MW total for synchrotron radiation.
  - Power density is 1 kW/meter and is well within B-factory limits (8 kW/m)
- **eRHIC - High luminosity at reduced energy,** inside RHIC tunnel
  - Polarized 10 GeV e^- x 325 GeV p, L ~ 10^{35} cm^{-2} sec^{-1}
  - Polarized positrons (with lower luminosity)
- Potential for replacing RHIC lattice with 8T, 0.8 TeV ring
  - i.e. potential for HERA with tow-three orders higher luminosity

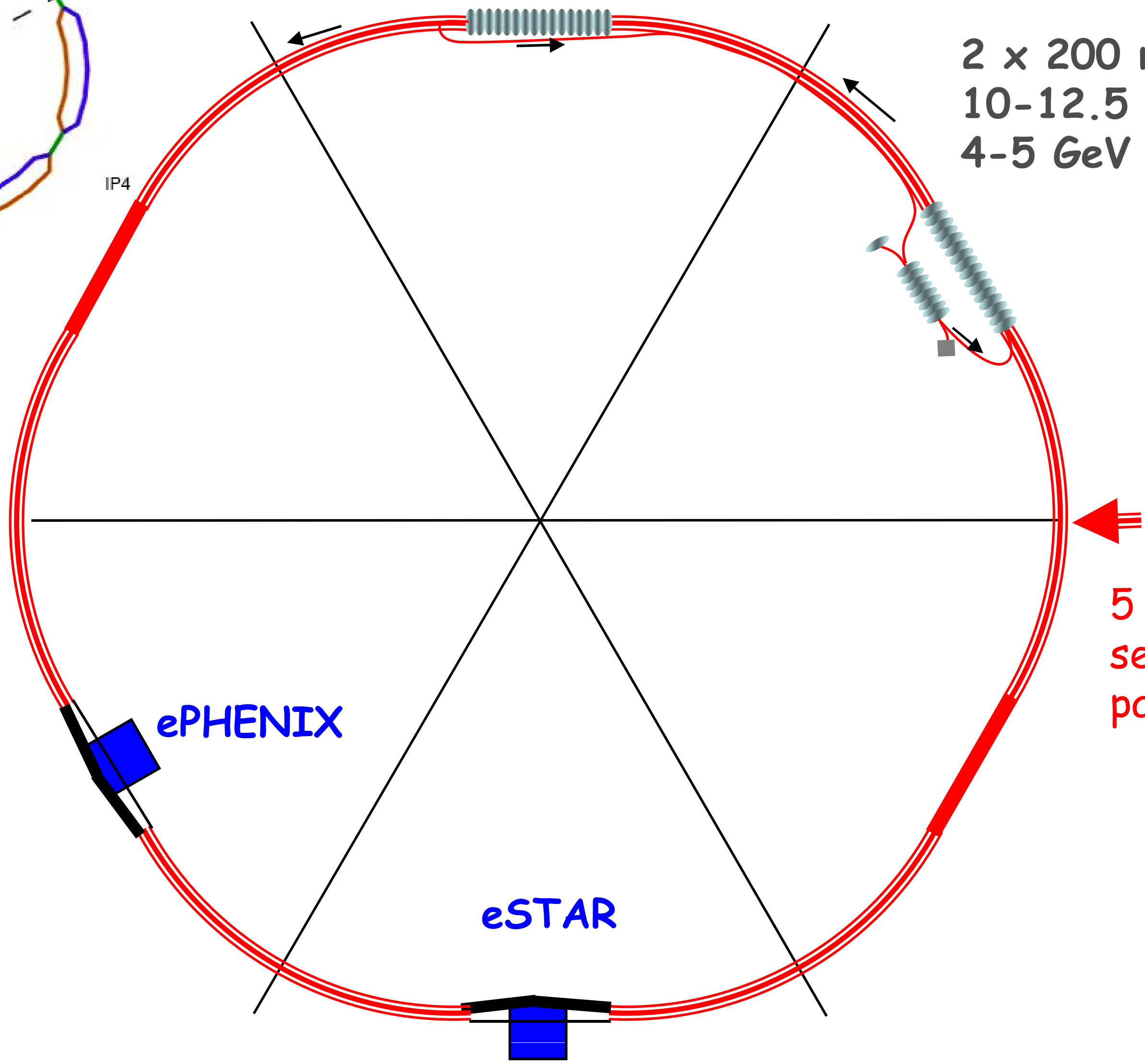
MEIC with 2 GeV ERL @ IP2



20 GeV e x 325 GeV p eRHIC

with ERL inside RHIC tunnel





2 x 200 m SRF linac
10-12.5 MeV/m
4-5 GeV per pass

5 (6) vertically separated passes

Main advantages of ERL + cooling

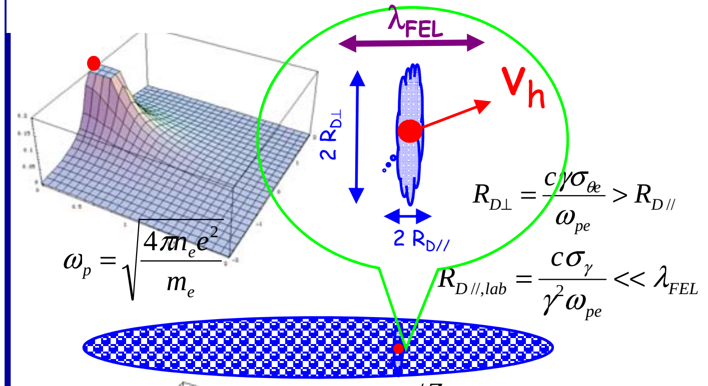
$$L = \gamma_p \frac{f_{col} N_p}{\beta_p^* r_p} \xi_p \qquad \xi_p = \frac{r_p}{4\pi} \cdot \frac{N_e}{\varepsilon_{p\ norm}};$$

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

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

- 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….

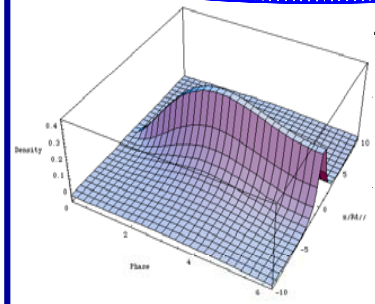
Coherent electron cooling

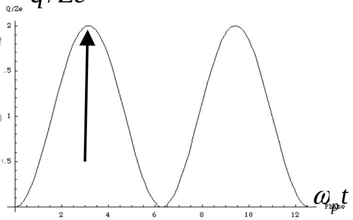


$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{m_e}}$$

$$R_{D\perp} = \frac{c\gamma\sigma_{\theta e}}{\omega_{pe}} > R_{D//}$$

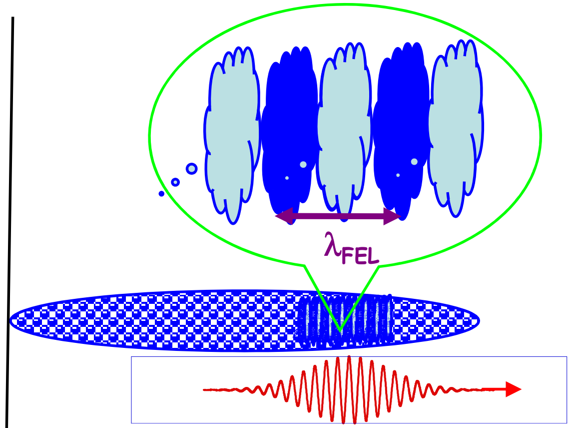
$$R_{D//,lab} = \frac{c\sigma_\gamma}{\gamma^2\omega_{pe}} << \lambda_{FEL}$$





$$q = -Ze\cdot(1-\cos\omega_p t)$$

$$\varphi_1 = \omega_p L_1 / c\gamma$$



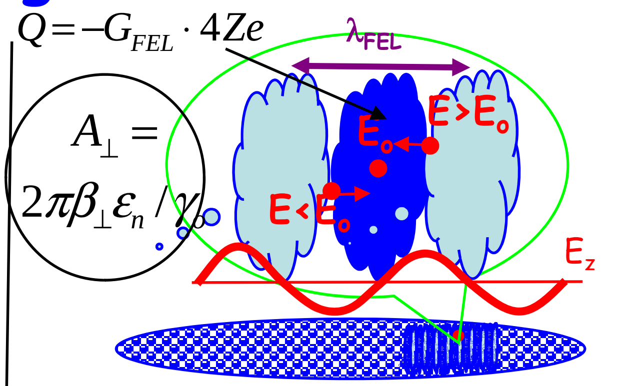
$$\lambda_{FEL} = \frac{\lambda_w}{2\gamma^2}(1+a_w^2) \qquad L_{Go} = \frac{\lambda_w}{4\pi\rho\sqrt{3}}$$

$$L_G = L_{Go}(1+\Lambda) \qquad \Delta\varphi = \frac{L_{FEL}}{\sqrt{3}L_G}$$

$$G_{FEL} = e^{L_{FEL}/L_G}$$

$$Q = -G_{FEL}\cdot 4Ze$$

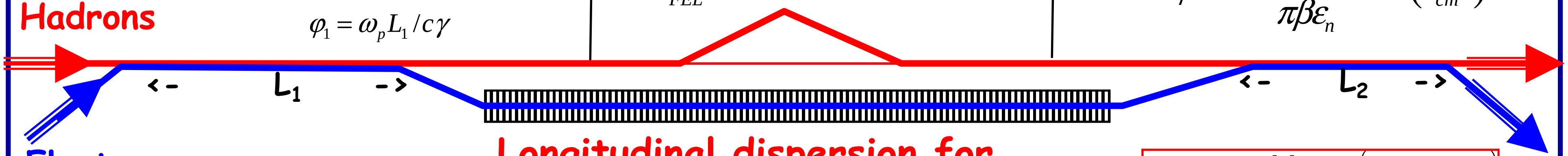
$$A_\perp = 2\pi\beta_\perp\varepsilon_n/\gamma_o$$



$$k_{cm} = \frac{\pi}{\gamma_o\lambda_{FEL}} \qquad \rho_{amp} = \frac{G\cdot Ze}{2\pi\beta\varepsilon_n}\cdot\frac{4k_{cm}}{\pi}\cos(k_{cm}z)$$

$$\Delta\varphi = 4\pi\rho \Rightarrow \varphi = -\frac{8G\cdot Ze}{\pi\beta\varepsilon_n k_{cm}}\cdot\cos(k_{cm}z)$$

$$\vec{\mathbf{E}} = -\vec{\nabla}\varphi = -\hat{z}\frac{8G\cdot Ze}{\pi\beta\varepsilon_n}\cdot\sin(k_{cm}z)$$



$$Q_{\lambda_{FEL}} \approx \int_0^{\lambda_{FEL}} \rho(z)\cos(k_{FEL}z)dz$$

$$Q_{\lambda_{FEL}}(\max) \approx -2Ze;\ \rho_k = -Ze\frac{4k}{\pi A_\perp}$$

Modulator: region 1
a quarter to a half of plasma oscillation

Longitudinal dispersion for hadrons

$$\Delta t = -D\cdot\frac{\gamma-\gamma_o}{\gamma_o};\ D = D_{free} + D_{chicane};$$

$$D_{free} = \frac{L}{\gamma^2};\ D_{chicane} = l_{chicane}\cdot\theta^2$$

Amplifier of the e-beam modulation via FEL with gain G_{FEL}~10^2-10^3

$$\Delta E_i = -\frac{8G\cdot Z^2e^2}{\pi\beta\varepsilon_n}L_2\cdot\sin\left(k_{FEL}D\frac{E-E_o}{E_o}\right)\cdot\left(\frac{\sin\varphi_2}{\varphi_{p2}}\right)\cdot\left(\sin\frac{\varphi_1}{2}\right)^2$$

Kicker: region 2, less then a quarter of plasma oscillation

Transition to a stationary state:

Coherent Electron Cooling vs. IBS

$$X = \frac{\varepsilon_x}{\varepsilon_{xo}};\ S = \left(\frac{\sigma_s}{\sigma_{so}}\right)^2 = \left(\frac{\sigma_E}{\sigma_{sE}}\right)^2;$$

$$\frac{dX}{dt} = \frac{1}{\tau_{IBS\perp}} \frac{1}{X^{3/2}S^{1/2}} - \frac{\xi_\perp}{\tau_{CeC}} \frac{1}{S};$$

$$\frac{dS}{dt} = \frac{1}{\tau_{IBS//}} \frac{1}{X^{3/2}Y} - \frac{1-2\xi_\perp}{\tau_{CeC}} \frac{1}{X};$$

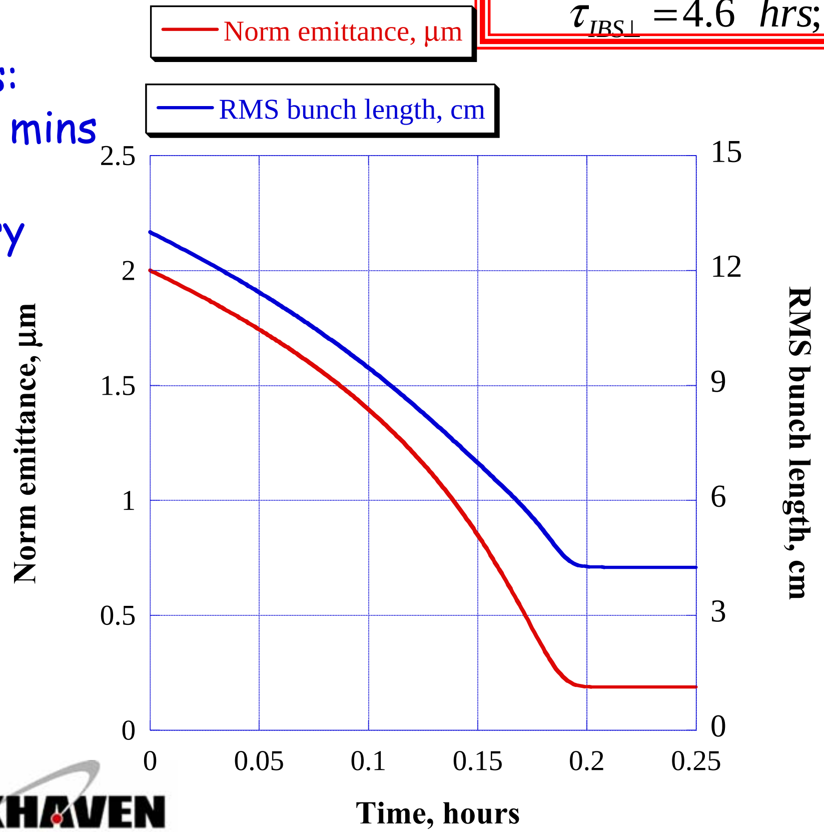
$$X = \frac{\tau_{CeC}}{\sqrt{\tau_{IBS//}\tau_{IBS\perp}}} \frac{1}{\sqrt{\xi_\perp(1-2\xi_\perp)}};\quad S = \frac{\tau_{CeC}}{\tau_{IBS//}} \cdot \sqrt{\frac{\tau_{IBS\perp}}{\tau_{IBS//}}} \cdot \sqrt{\frac{\xi_\perp}{(1-2\xi_\perp)^3}}$$

$$\varepsilon_{xn0} = 2\,\mu m;\ \sigma_{s0} = 13\ cm;\ \sigma_{\delta 0} = 4\cdot 10^{-4}$$

$$\tau_{IBS\perp} = 4.6\ \ hrs;\ \tau_{IBS//} = 1.6\ \ hrs;$$

IBS in RHIC for eRHIC, 250 GeV, $N_p=2\cdot 10^{11}$
Taken from Beta-cool, ©A.Fedotov

Dynamics:
Takes 12 mins to reach stationary point



$$\varepsilon_{xn} = 0.2\,\mu m;\ \sigma_s = 4.9\ \ cm$$

This allows

a) keep the luminosity as it is
b) reduce polarized beam current down to 25 mA (5 mA for e-I)
c) increase electron beam energy to 20 GeV (30 GeV for e-I)
d) increase luminosity by reducing β* from 25 cm down to 5 cm

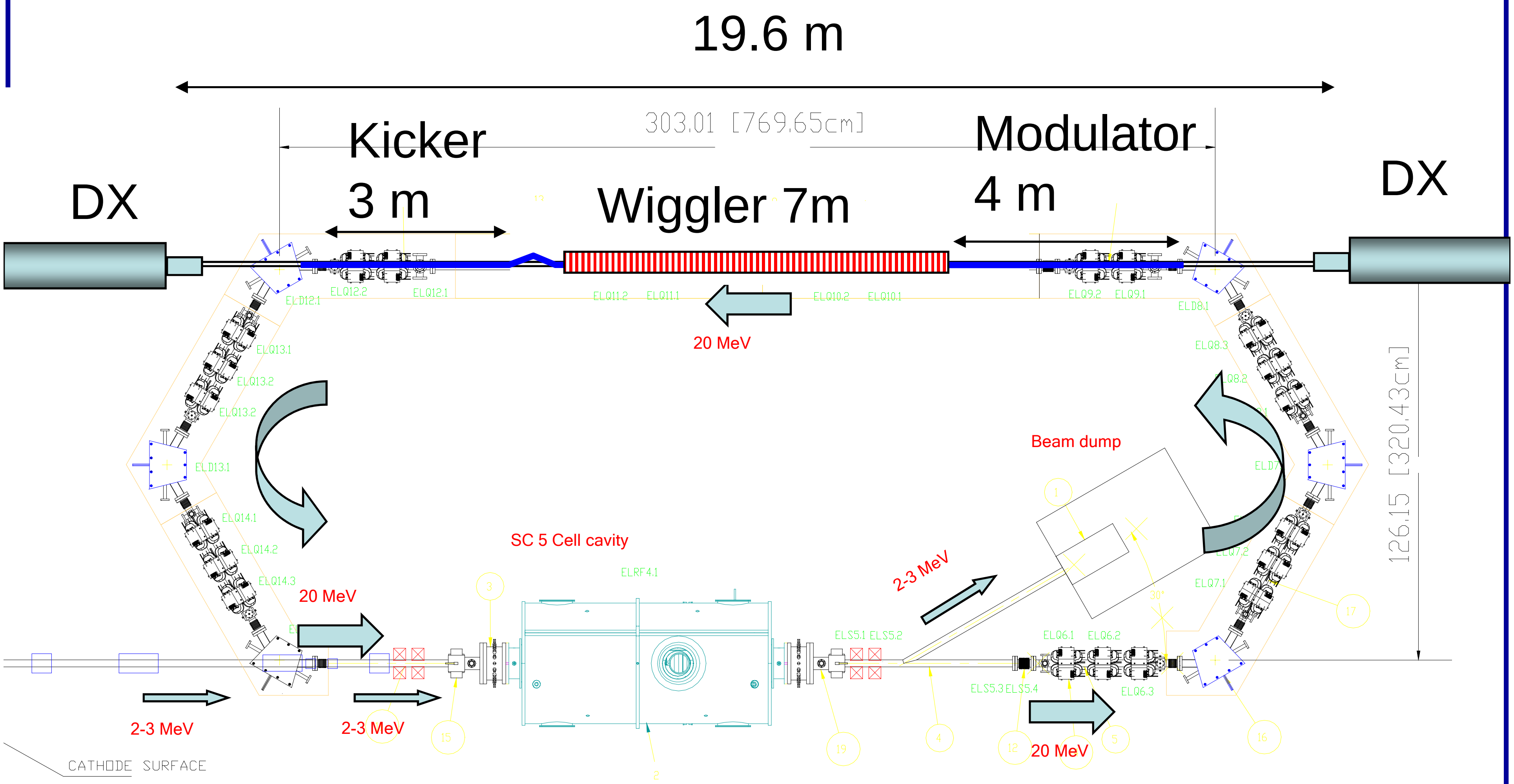
Decrements for hadron beams with coherent electron cooling

Machine	Species	Energy GeV/n	Trad. Stochastic Cooling, hrs	Synchrotron radiation, hrs	Trad. Electron cooling hrs	Coherent Electron Cooling, hrs 1D/3D
RHIC PoP	*Au*	*40*	-	-	-	*0.02/0.06*
eRHIC	Au	130	~1	20,961 ∞	~ 1	0.015/0.05
eRHIC	**p**	**325**	**~100**	**40,246 ∞**	**> 30**	**0.1/0.3**
LHC	p	7,000	~ 1,000	13/26	∞ ∞	0.3/<1

Main R&D Items

- **Electron beam R&D**
  - Energy recovery technology for high power beams (BNL)
    - R&D ERL - high current, low emittance beams, stability, low losses
    - Multi-cavity cryo-module development
  - High intensity polarized electron source (MIT & BNL)
    - Development of large cathode DC guns
      existing current densities ~ 50 mA/cm^2, good cathode lifetime.
    - Development of SRF polarized gun
  - Development of compact recirculating loop magnets (LDRD @ BNL)
    - Design, build and test a prototype of dipole and quadrupole
    - Design, build and test a prototype vacuum chamber
- **Main R&D items for hadron beams (BNL)**
  - Polarized ^{3}He production (EBIS) and acceleration
  - 166 bunches (50% more bunches in RHIC)
  - Proof-of-Principle of the Coherent Electron Cooling

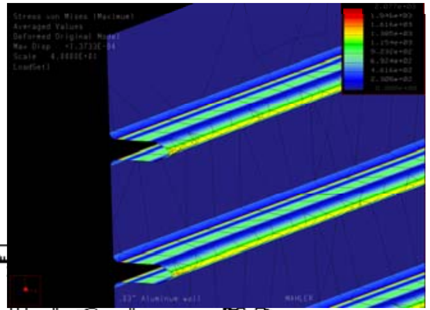
IR-2 layout for Coherent Electron Cooling proof-of-principle experiment

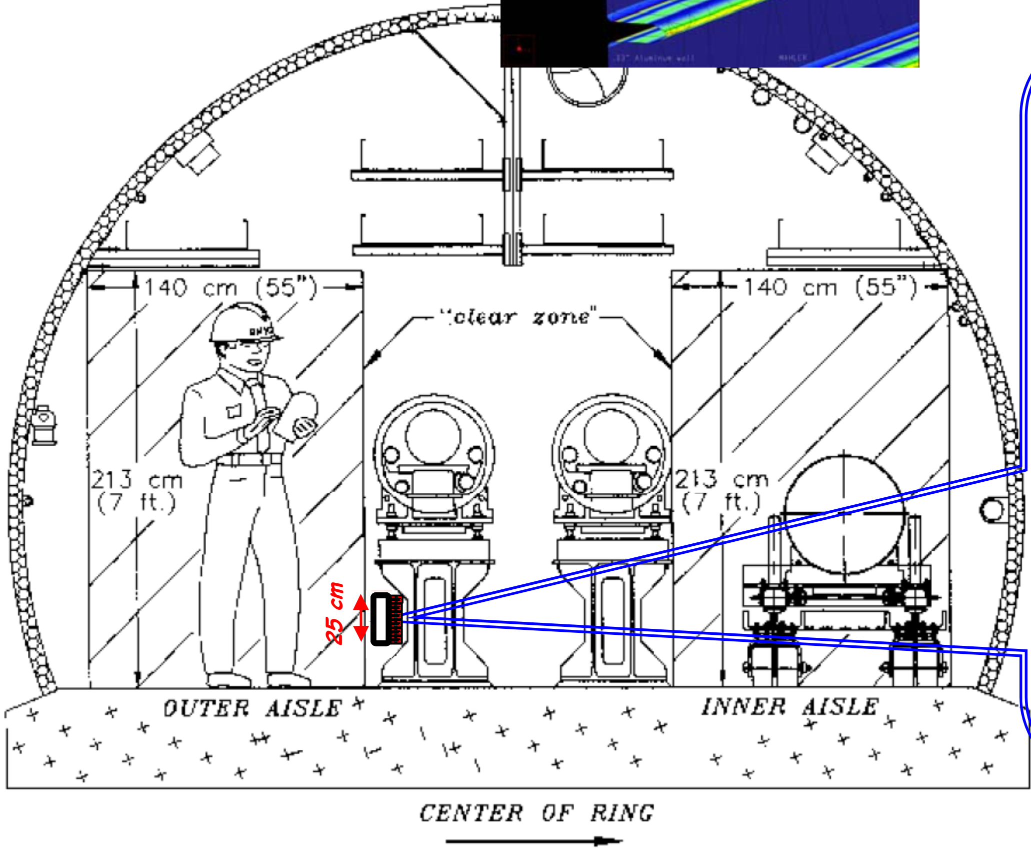


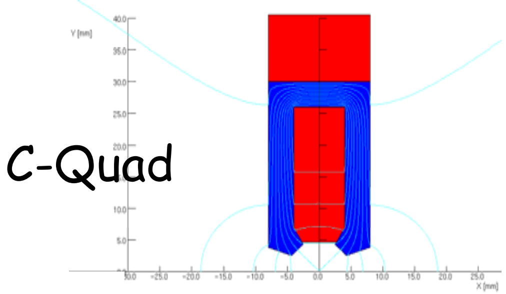
eRHIC loop magnets and vacuum chamber: LDRD project

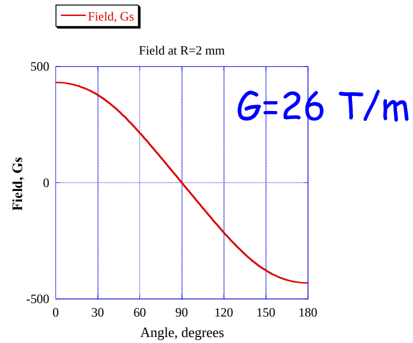
- Small gap provides for low current, low power consumption magnets
- Magnetic design - W.Meng, mechanical engineering - G.Mahler
- Starting studies of the acceptable field errors and of the alignment tolerances
- First dipole prototype is in hands

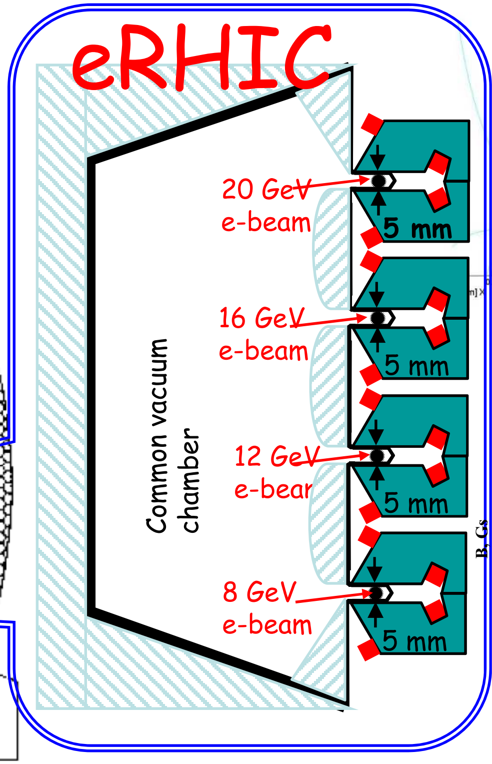
All vacuum chamber
Thickness - 0.75 mm
Sag - 3.6 microns

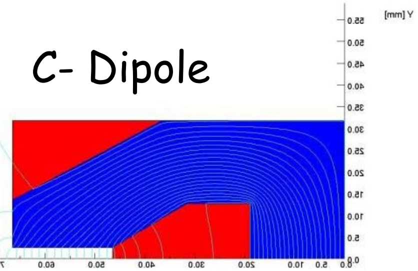


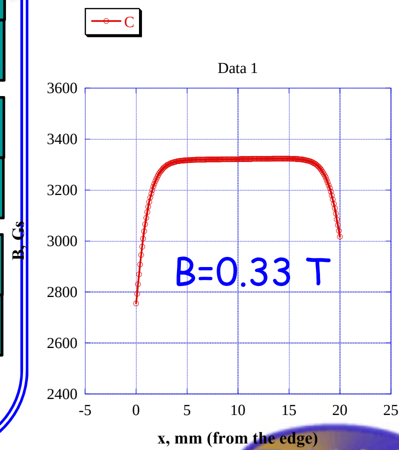




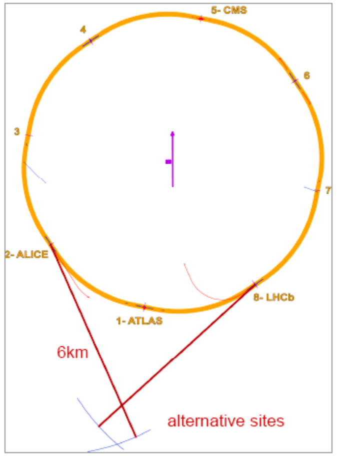








Why Linac-Ring for LHeC looks not as strong?



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

		ring-linac pulsed		ring-linac, cw , ~99% energy recovery	
	units	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

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

Nobody can afford a regular full-energy linac for a full-luminosity electron-hadron 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

Scaling for ERL based LHeC

In the ERL-based eRHIC we collide two round beams with equal size 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.

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

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

Thus, in LHeC practical limit is the power of RF system to compensate synchrotron radiation of electrons

ERL based LHeC with cooling: 20 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	27	1090
Norm emittance, μm	5.5	0.3
β*, m	0.25	0.25
ξ* D	12.7 6.52	**0.0057**
Luminosity, x 10^{33} cm^{-2} sec^{-1}	**22.4**	
Loss for SR, MW	**20**	-

ERL based LHeC with cooling: additional considerations

	Electrons	Protons
Energy	70 GeV	7 TeV
Angular spread, μrad	4.83	9.26
Distance to parasitic collision point,m	3.5	
Crossing angle, μrad	±100	
Separation (in sigma)	15.1	28.2

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	6	1090
Norm emittance, μm	7.8	0.3
β*, m	0.25	0.25
ξ* D	12.7 4.56	**0.00137**
Luminosity, x 10^{33} cm^{-2} sec^{-1}	**5.4**	
Loss for SR, MW	**20**	-

ERL based LHeC with cooling: higher energy

	Electrons	Protons
Energy	140 GeV	7 TeV
N per bunch	$0.088\ 10^{11}$	$1.7\ 10^{11}$
Rep rate, MHz	40	
Beam current, mA	1.7	1090
Norm emittance, μm	16	0.3
β*, m	0.25	0.25
ξ*	6.3	**0.0006**
Luminosity, x 10^{33} cm^{-2} sec^{-1}	**1.5 / 0.12**	
Loss for SR, MW	**20**	Kink Λ=0.03

Hard radiation may be a problem
Without cooling - luminosity is 13 times lower

ERL based LHeC: lower current e-beam

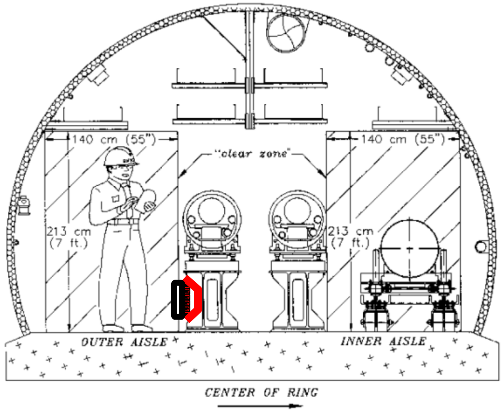
$$\xi_p = \frac{N_e}{\gamma_p} \cdot \frac{r_p}{4\pi\varepsilon_p} = \frac{N_e \cdot r_p}{4\pi\varepsilon_{p\ norm}};$$

- 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}

- 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
- $N_e \sim \varepsilon_{norm;}$ 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 disruption and kink instability

Other considerations

- Is there room for linac in the straights?
- Would ERL (for the most part) fit inside the LHC tunnel.



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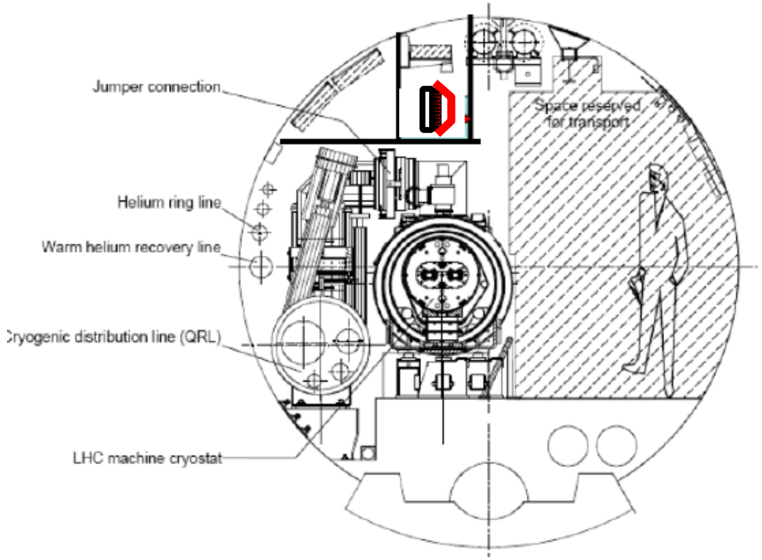

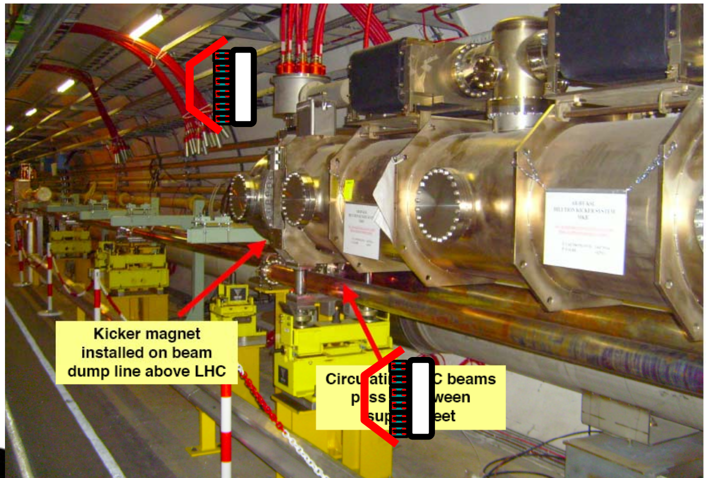

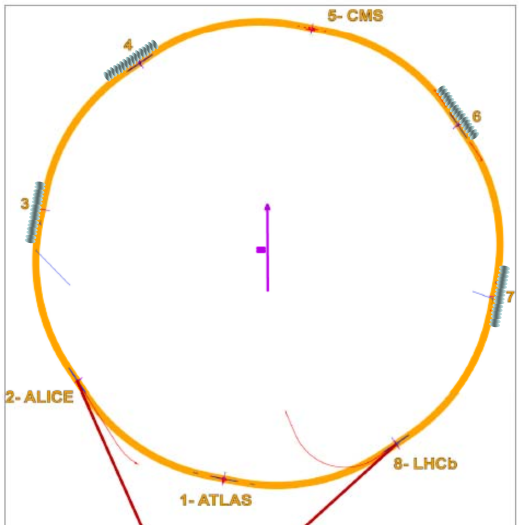

Conclusions

- 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
- There is a clear possibility for eRHIC (LHeC?) staging
- Presently there is no show-stoppers but a significant amount of R&D
- At BNL the R&D ERL tests start in 2009, MIT's progress with developing high current polarized gun, prototyping of small gap magnets are in progress .....
- **LHeC based on this principle reach 10^{34}-10^{35} level of luminosity -natural topic for collaborating with BNL**

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Inputs

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- S.Vigdor
- D. Lowenstein

C. Montag - following talk