Novel Features in eRHIC

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for eRHIC group

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RHIC

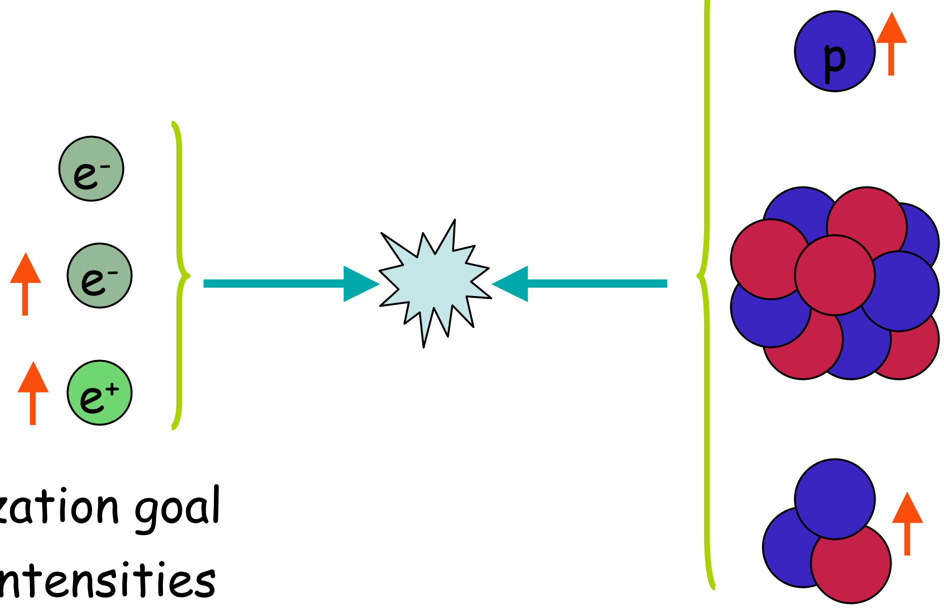
Novel features

- *Coherent electron cooling - the key for many novel features in eRHIC*
- Choosing the focus: ERL for electrons
  - Advantages and challenges of ERL driver
    - spin transparency
  - R&D items for ERL-based eRHIC
- eRHIC is the future of RHIC: eRHIC staging
  - Energy challenge
  - 20 GeV e x 325 GeV $\vec{p}$ and 30 GeV $\vec{e}$ x 125 GeV/n heavy ions
  - Loss on synchrotron radiation
  - Polarized beam current
- Luminosity challenge:
  - Can eRHIC deliver 10^{35} cm^{-2} sec^{-1} luminosity?
  - *High rep-rate, crab cavities, coating RHIC arc vacuum chambers and more*
- Other novelties and oldies
  - *Low (350 MHz) RF frequency, no 3rd harmonic, higher real estate gradient*
  - Small magnets for re-circulating passes, resistive-wall losses
  - e-lens or fast a quads for matching ERL beam
  - *compact and flexible separators and combiners*
  - Possibility of eRHIC II up-grade

eRHIC Scope -QCD Factory

Electron accelerator

Unpolarized and
polarized leptons
2-30 GeV



RHIC

Polarized protons
$_{25}\downarrow$ 50-325 GeV

Heavy ions (Au)
50-130 GeV/u

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

70% beam polarization goal

Positrons at low intensities

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.

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

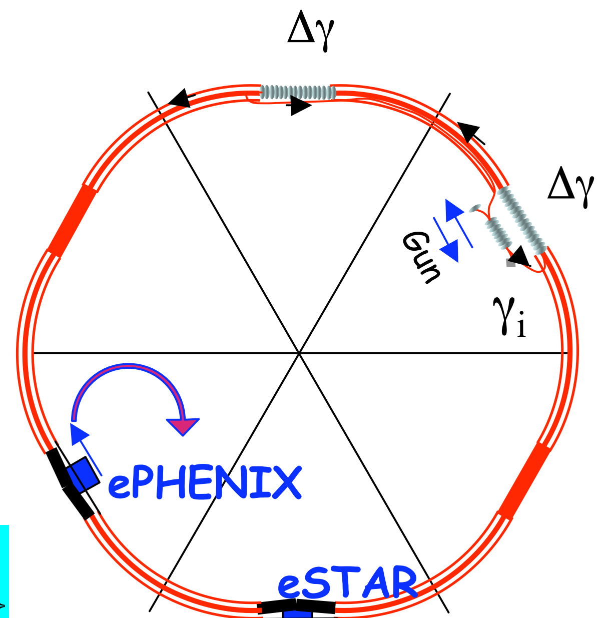
$$\varphi = 2\pi a\cdot\left((n-1/2)\gamma_i + \{2n(n-2)-1/6\}\Delta\gamma\right) + \varphi_i$$

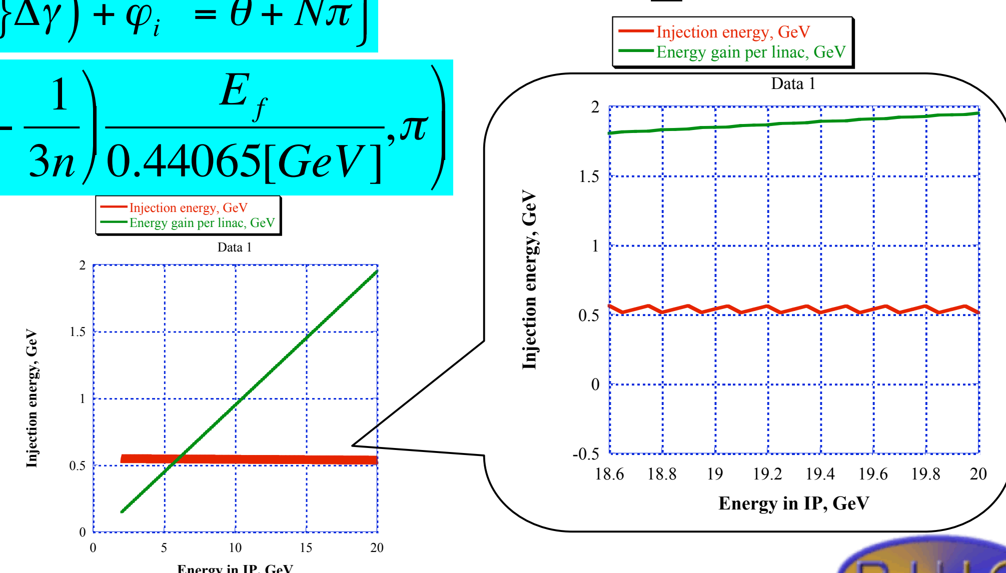
Has solution for all energies!

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

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

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





Main advantages of ERL + cooling

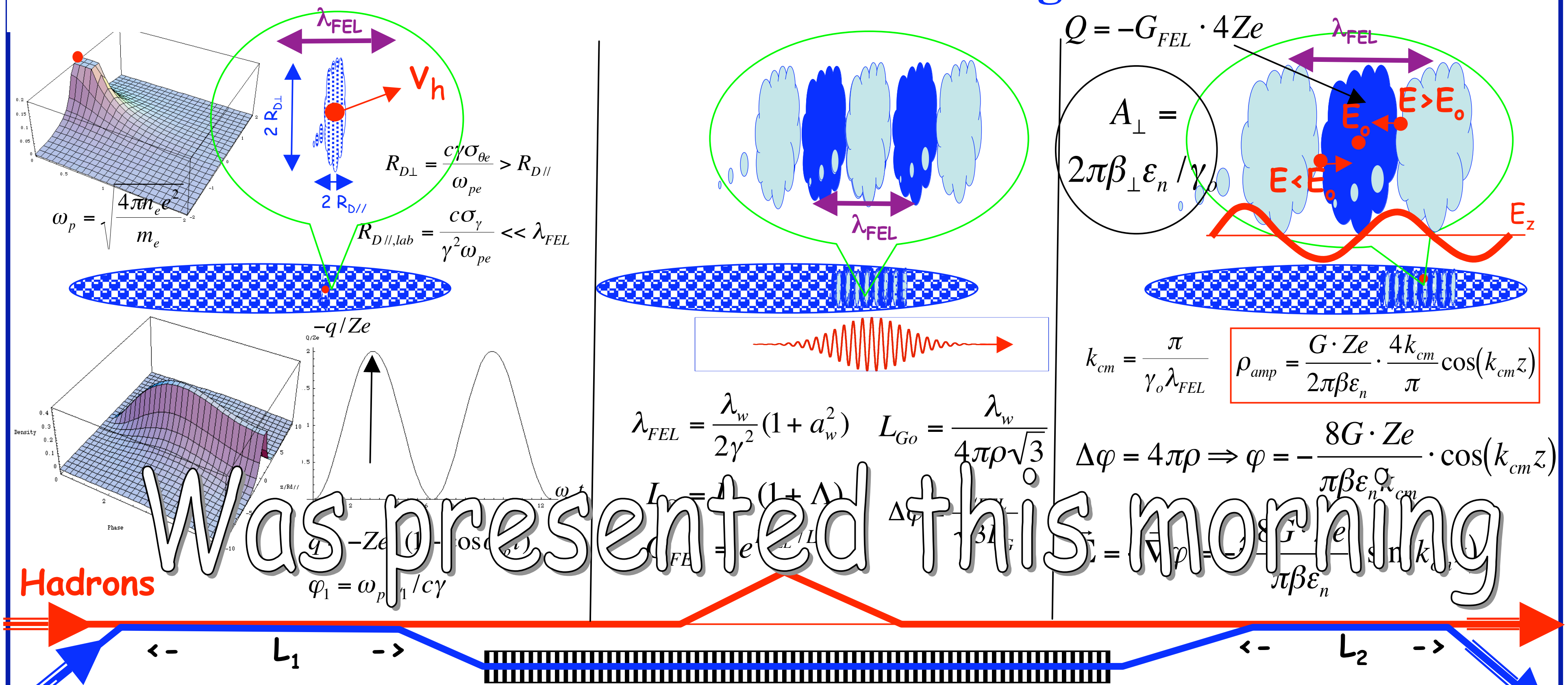
$$L = \gamma_p \frac{f_{col} N_p}{\beta_p^* r_p} \xi_p \qquad \xi_p = \frac{r_p}{4\pi} \cdot \frac{N_e}{\varepsilon_{p\ norm}};$$

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

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

- 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 or 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 -> relaxed gun!, losses for synchrotron radiation going down, X-ray background in the detectors goes down….

Coherent electron cooling



Electrons

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

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

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

Most versatile option

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

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

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Coherent e-Cooling for eRHIC

(protons are the main challenge)

Main Parameters	CeC	
Modulator Length	15	m
Kicker length	5	m
Peak current, e	100.0	A
Amplification	200.00	
Wavelength	500	nm
λ_w	5	cm
FEL bandwidth	0.1	

Cooling time		
Emittance, Full bunch	0.086	hrs
Ampl, Full bunch	0.171	hrs
Local	50.23	sec
Length of the system	32.49	m
FEL length	12.49	m
FEL gain length	0.99	m

Hadrons		
Z	1	
A	1	
Energy per nucleon	325	GeV
Energy per nucleon	3.250000E+11	eV
γ	346.38	=
N, part/bunch	2.00E+11	
Charge	32.04	nC
Bunch length	0.433	nsec
Bunch lengt, RMS	0.130	m
Peak current	29.50	A
Emmitance, norm	2	mm mrad
Emmitance, m rad	5.77398E-09	
$\sigma E/E$	4.00E-04	

Electrons		
	1	
Energy	0.177	GeV
Energy	1.770E+08	eV
γ	346.38	
N, part/bunch	3.12E+10	
Charge	5.0	nC
Bunch length	0.050	nsec
Bunch lengt, full	0.015	m
Peak current	100.0	A
Emittance, norm, RMS	5	mm mrad
Emittance, RMS	1.443E-08	m rad
$\sigma E/E$	2.26E-04	
σ_E	4.00E+04	eV
Long emittance	2.000E-06	eV sec

Stationary state: IBS vs. CeC

$$\frac{\sigma_\varepsilon^2}{\tau_{IBS//}} = \frac{N r_c^2 c}{2^5 \pi \gamma^3 \varepsilon_x^{3/2} \sigma_s}\left\langle \frac{f(\chi_m)}{\beta_y v}\right\rangle; \quad \frac{\varepsilon_x}{\tau_{IBS\perp}} = \frac{N r_c^2 c}{2^5 \pi \gamma^3 \varepsilon_x^{3/2} \sigma_s}\left\langle \frac{H}{\beta_y^{1/2}} f(\chi_m)\right\rangle; \kappa = 1$$

$$f(\chi_m) = \int_{\chi_m}^{\infty} \frac{d\chi}{\chi} \ln\left(\frac{\chi}{\chi_m}\right) e^{-\chi}; \; \chi_m = \frac{r_c m^2 c^4}{b_{\max} \sigma_E^2}; b_{\max} \cong n^{-1/3}; \; r_c = \frac{e^2}{mc^2}; \quad (e->Ze; m->Am)$$

J.LeDuff, "Single and Multiple Touschek effects", Proceedings of CERN Accelerator School, Rhodes, Greece, 20 September - 1 October, 1993, Editor: S.Turner, CERN 95-06, 22 November 1995, Vol. II, p. 57

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

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

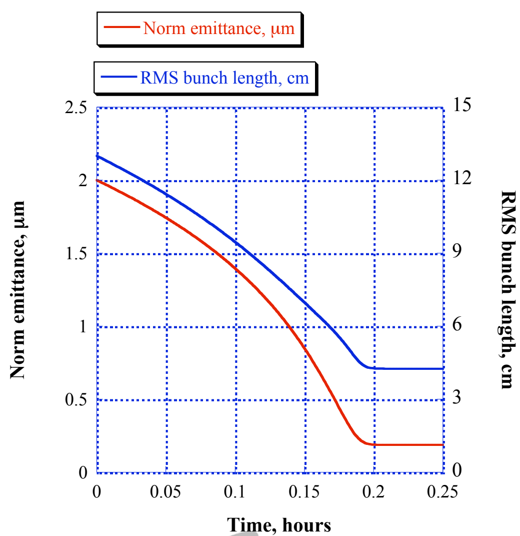
$$\frac{dS}{dt} = \frac{1}{\tau_{IBS//}} \frac{1}{X^{3/2} Y} - \frac{1-2\xi_\perp}{\tau_{CeC}} \frac{1}{X};$$

$$\varepsilon_{xn0} = 2\,\mu m; \; \sigma_{s0} = 13\ cm; \; \sigma_{\delta 0} = 4 \cdot 10^{-4}$$
$$\tau_{IBS\perp} = 4.6 \;\; hrs; \; \tau_{IBS//} = 1.6 \;\; hrs;$$

IBS in RHIC for eRHIC, 250 GeV, N_p=2·10[11]
Beta-cool, ©A.Fedotov

Stationary solution:

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



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

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

Staging of eRHIC: Energy Reach and Luminosity

- **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
  - 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 120 GeV/n Au (120 GeV c.m.), L ~ 10^{31} cm^{-2} sec^{-1}
  - 20 GeV e x 120 GeV/n Au (120 GeV c.m.), L ~ $5 \cdot 10^{31}$ cm^{-2} sec^{-1}
- **eRHIC - High luminosity at reduced energy**, inside RHIC tunnel
  - Polarized 10 GeV e^- x 325 GeV p, L ~ 10^{35} cm^{-2} sec^{-1}
  - Smaller improvements (3-4 fold) in e-Ion collisions

More detail during discussion on staged eRHIC, Today 5:25 p.m.

Staging of eRHIC: Cost, Re-use, Beams and Energetics

- **MEIC**: Medium Energy Electron-Ion Collider
  - **Cost estimate - $150M** *(in 2007 $)*
  - 90% of ERL hardware will be use in the phase I (and will reduce cost of eRHIC)
  - Possible use of the detector components for eRHIC detectors
- **eRHIC - phase I**
  - **Based on present RHIC beam intensities**
  - With coherent electron cooling requirements on the electron beam current is 25 mA
  - 20 GeV, 25 mA electron beam losses 1.92 MW total for synchrotron radiation*.
  - 30 GeV, 5 mA electron beam loses 1.98 MW for synchrotron radiation
  - Power density is 1 kW/meter and is well within B-factory limits (8 kW/m)
- **eRHIC - phase II**
  - **Requires crab cavities, new injections, Cu-coating of RHIC vacuum chambers, new level of intensities in RHIC**
  - Polarized electron source current of 400 mA
  - 10 GeV, 400 mA electron beam losses 1.96 MW total for synchrotron radiation, power density is 1 kW/meter

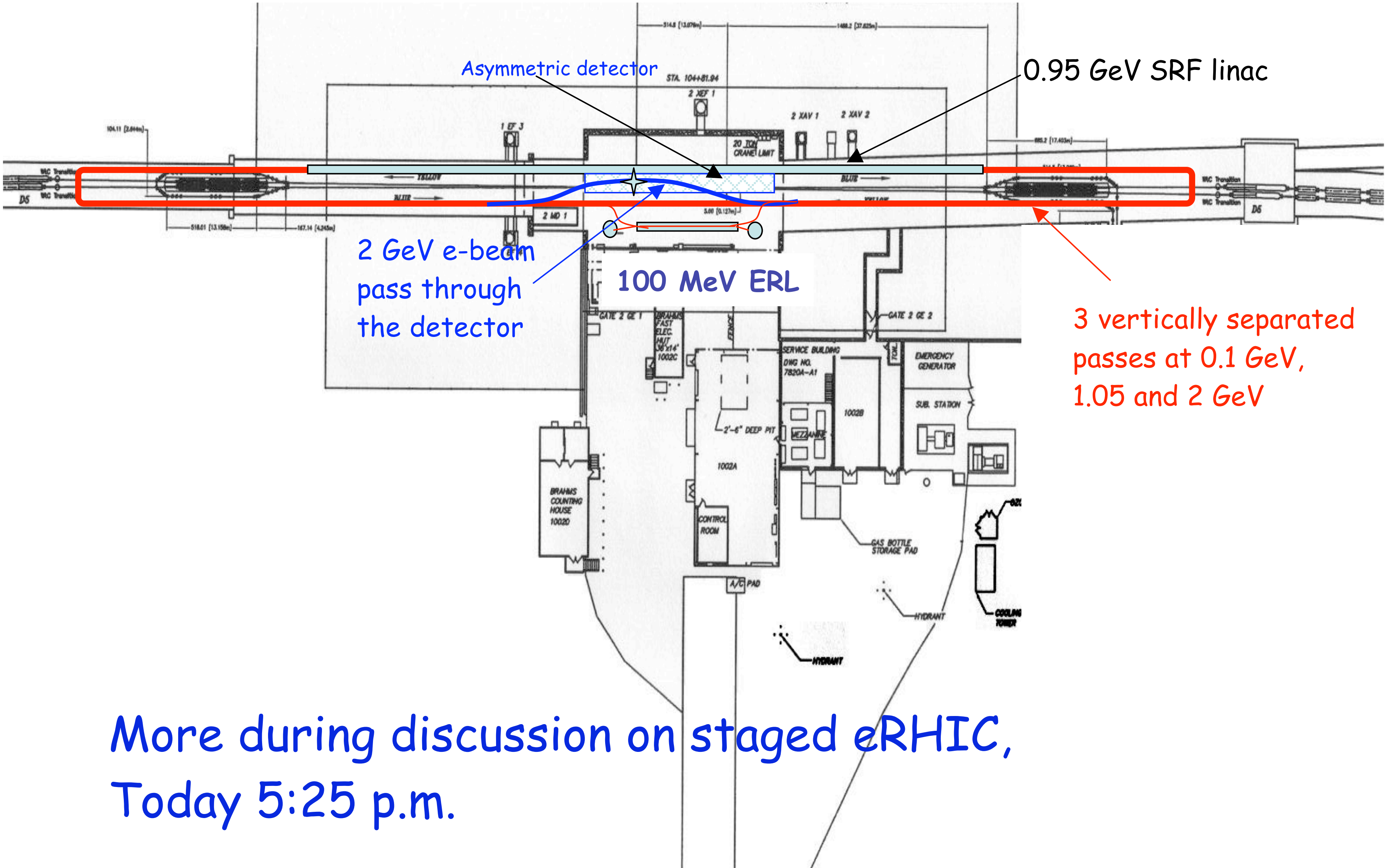
**Compare it with 15 MW power loos for 10 GeV electrons in ELIC!*

More detail during discussion on staged eRHIC, today 5:25 p.m.

Possible future up-grade - eRHIC II
c.m. Energy of HERA with 100x Luminosity

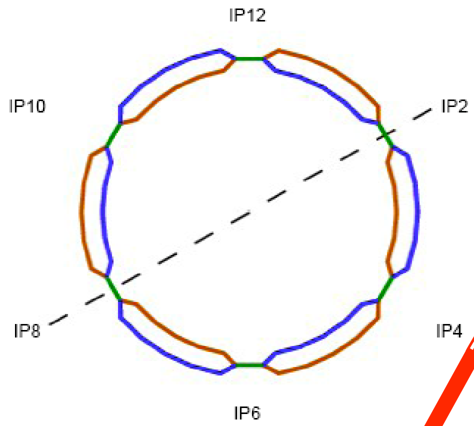
- **eRHIC II:** replacing RHIC-ring magnets by 8 T
  - proton energy in RHIC to ~ 800 GeV
  - will require more snakes for polarized proton operation
  - heavy ions with ~300 GeV/n
- **eRHIC II - Full energy, nominal luminosity**
  - inside RHIC tunnel
  - Polarized 20 GeV e^- x 800 GeV p (~300 GeV c.m), L ~ 10^{34} cm^{-2} sec^{-1}
  - 30 GeV e x 300 GeV/n Au (~200 GeV c.m.), L ~ 10^{32} cm^{-2} sec^{-1}

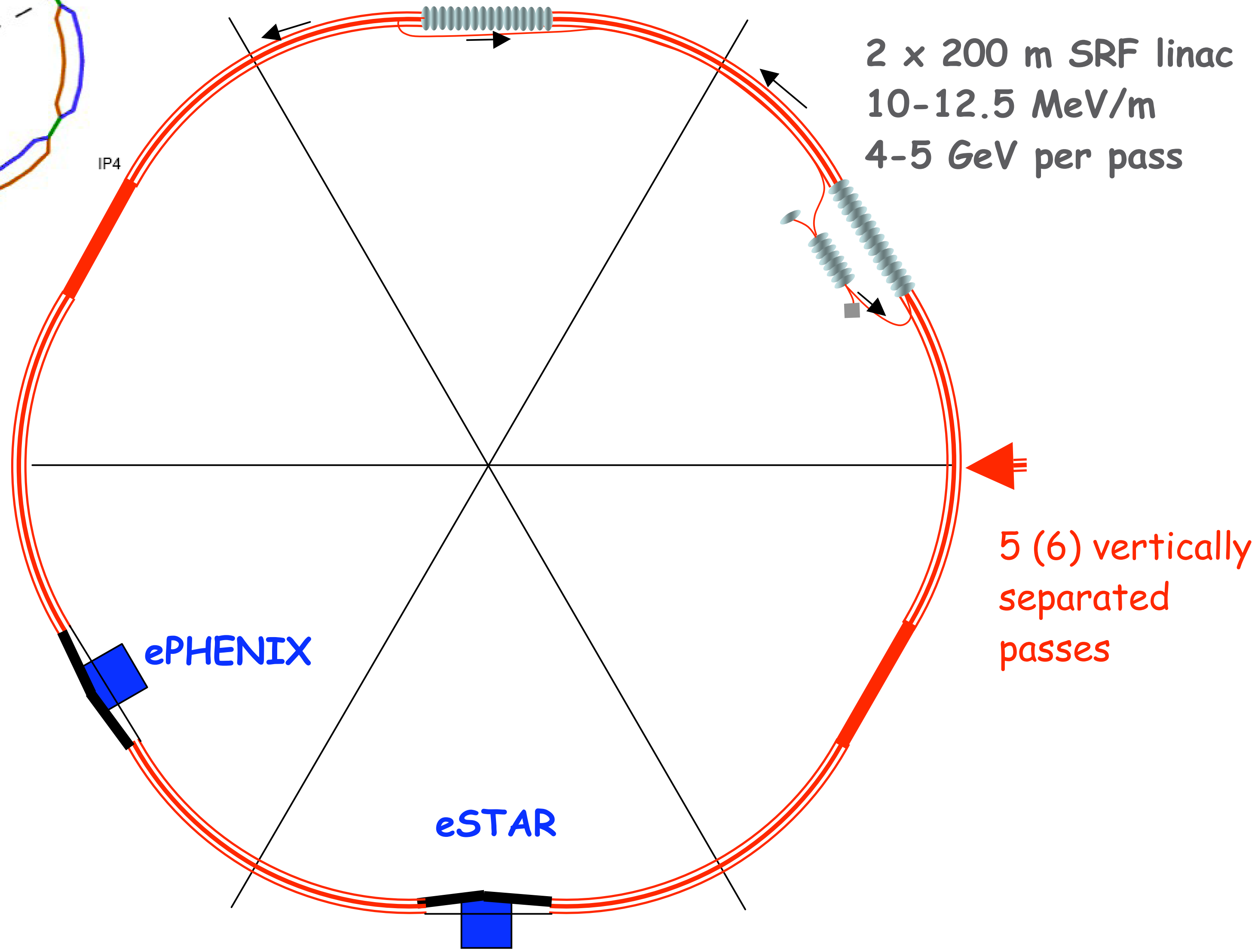
MEIC with 2 GeV ERL @ IP2



More during discussion on staged eRHIC, Today 5:25 p.m.

20 GeV e x 325 GeV p eRHIC
with ERL inside RHIC tunnel





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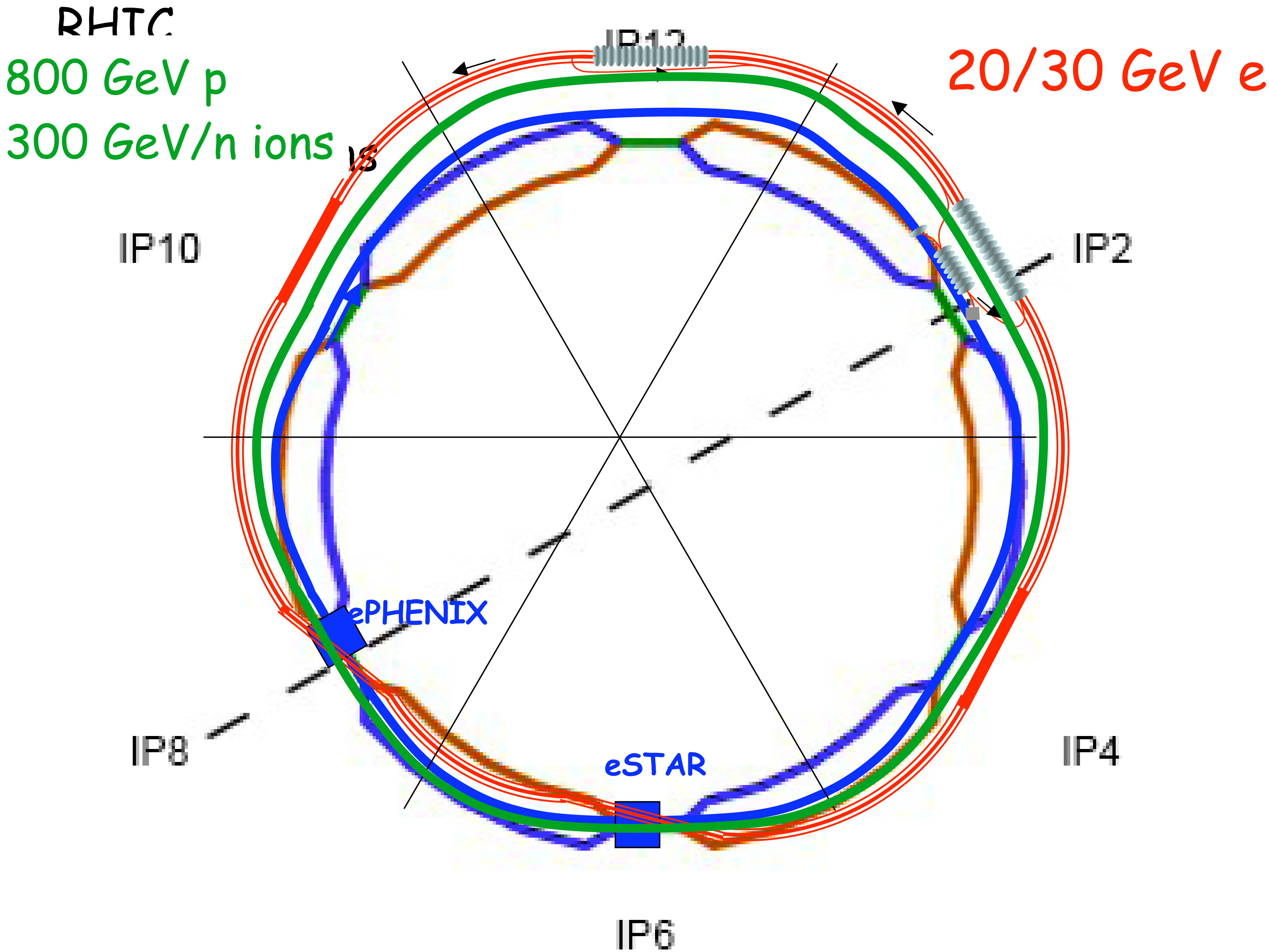
Staging of eRHIC with ERL inside RHIC tunnel

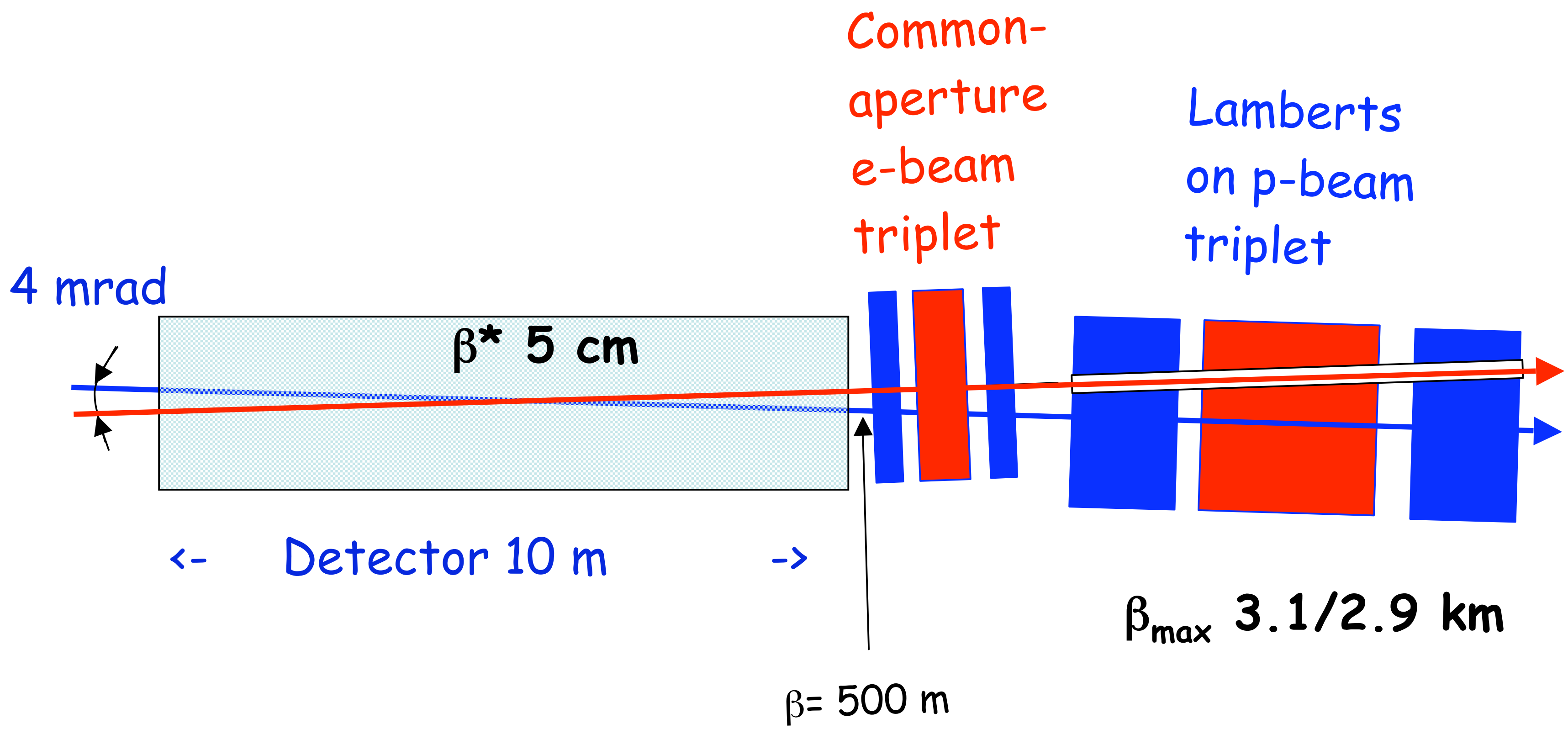


Borrowing ideas: B-factory, KEK, JLab's ELIC and LHeC

- **We are considering possibility of IP's with crossing angle and crab cavities**
  - **MAIN REASON - There will be no synchrotron radiation background problem in the detector and we can afford 10 m + of element-free IR for the detectors**
  - **β^* 5 cm for both protons and electrons**
  - **Hadron bunch length < 5 cm**
  - Emittance ~ 0.8 nm (normalized ~0.2 μm for protons and 30 μm for electrons)
  - RMS angular spread 0.1 mrad
  - Crossing angle ~ 2 mrad (per beam - 40 RMS sizes of hadron beam) - angle mostly required for separating beams in triplets
- **We are considering possibility of using rather small-aperture Lambertson-quads for such a scheme**
  - At 5 m, electron and proton beam will be separated ~ 2 cm and beam-sizes will be only 0.5 mm RMS

Straw-man IR lay out

no bending of electron trajectory in IR -> no X-rays



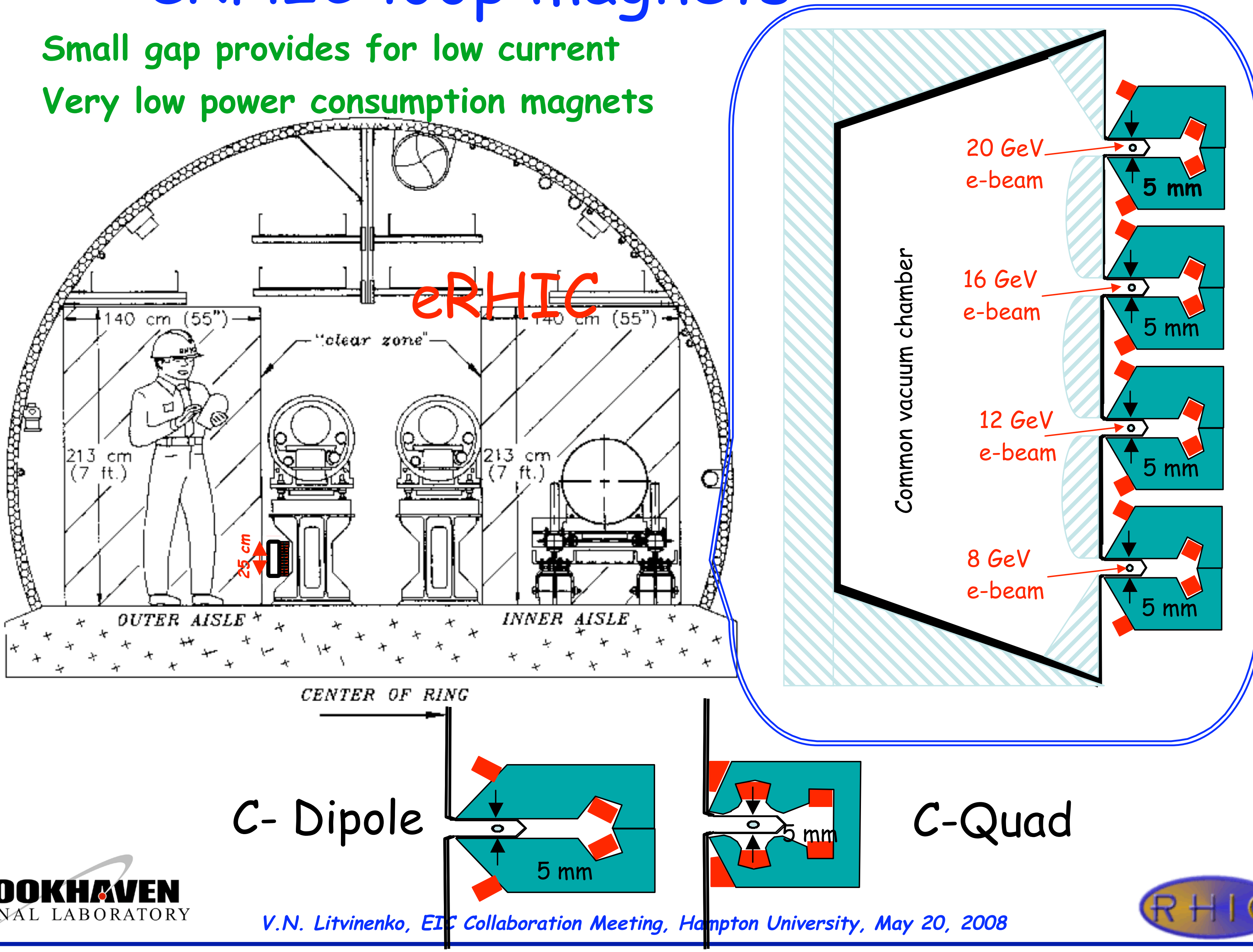
Displacement - 2 cm, RMS
RMS beam sizes - 0.5 mm

Can eRHIC deliver luminosity ~10^{35} cm^{-2} sec^{-1}?

- The answer is Yes. With coherent electron cooling eRHIC it can reach luminosity of $0.2*10^{35}$ cm^{-2} sec^{-1} with β^* = 5 cm with presently designed proton intensities
  - The question is what will be compromises?
  - Another question is what additional modification of RHIC it will require → →
- Compromises
  - Lower electron beam energy (~10 GeV) to keep power bill (for loss of synchrotron radiation
  - 5-10 times higher collision rate (~100 MHz)
- Additional developments
  - New injection system supporting higher rep-rate
  - Coating RHIC arc's vacuum chamber
  - Crossing angle and crab cavity

eRHIC loop magnets

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



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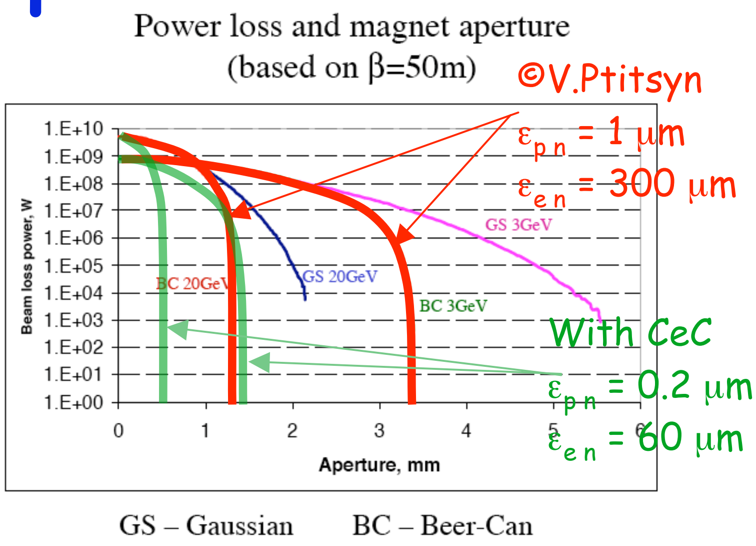
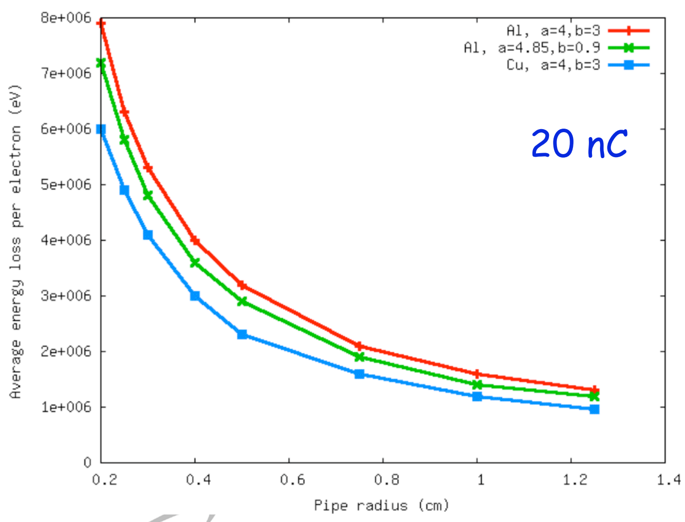
Limitations on the aperture for electron beam

- Magnetic field quality
- Alignment accuracy
- e-beam loss
- resistive-wall induced energy spread and energy loss





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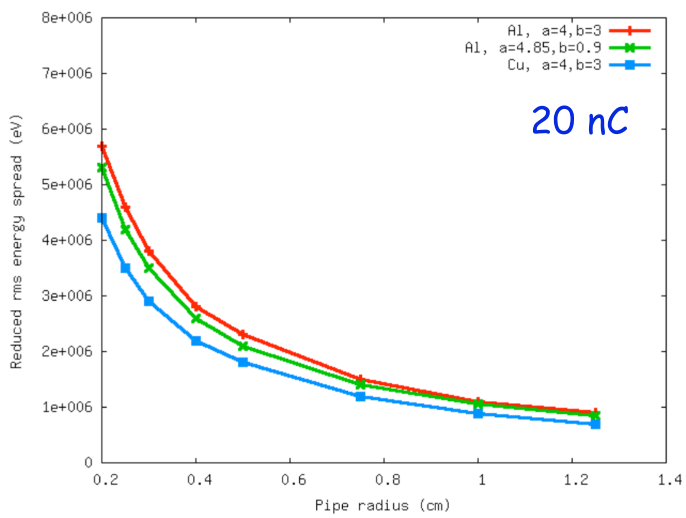
N_e = 20 nC/bunch/e

Loss ~1MW with 5 mm aperture

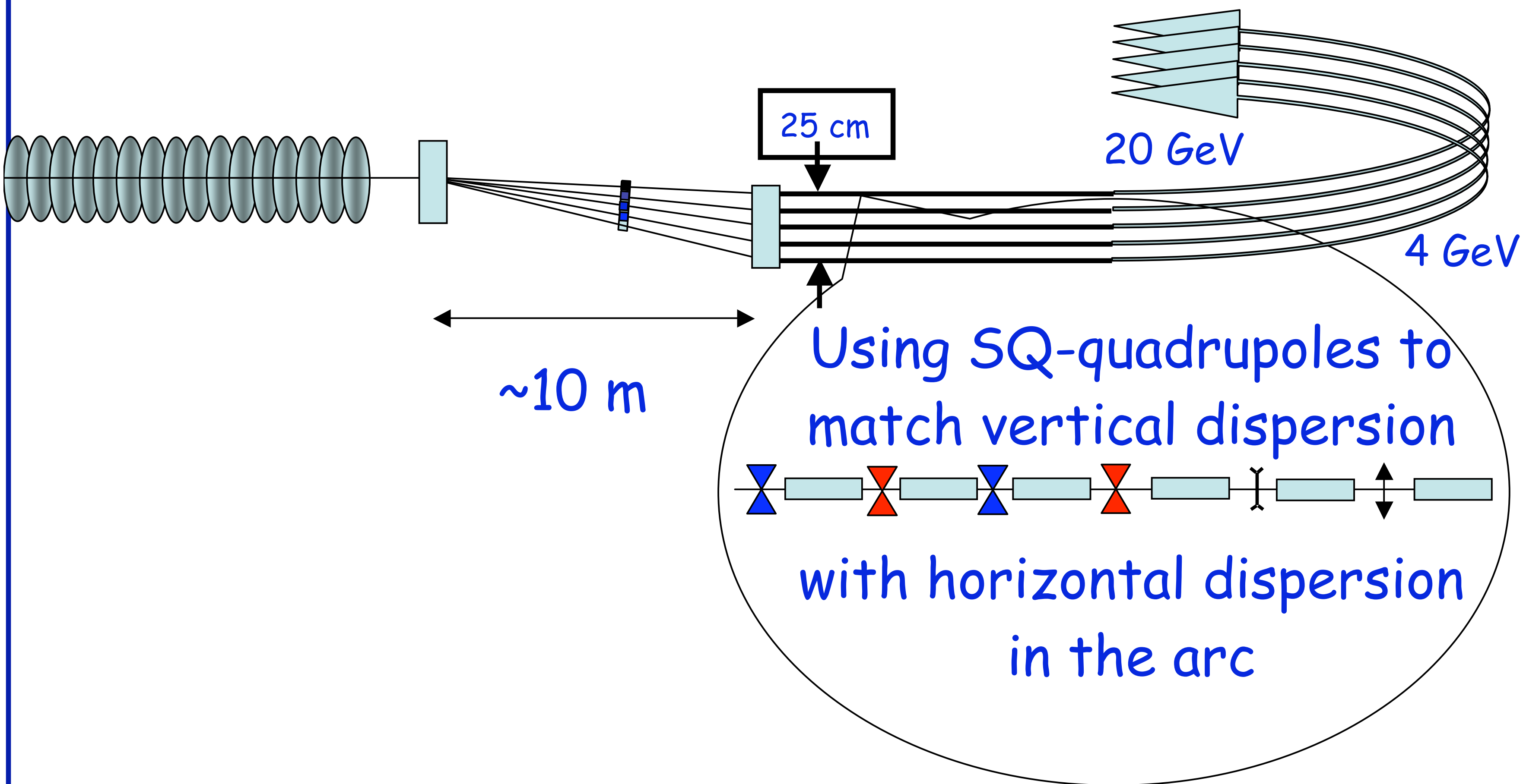
With CeC -

N_e -> 2 nC/bunch/e

Loss ~10kW with 5 mm aperture



Compact spreaders/combiners



This concept allows to use most of the RHIC straight sections for SF linacs and to use part of the arcs for matching

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
- There is a clear possibility for eRHIC staging (will be discussed later today)

Back-up slides

Advantages & Challenges of ERL based eRHIC

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

- **This scheme takes full advantage of cooling of the hadron beams**
- **Allows use of RHIC tunnel for the return passes and thus allow much higher energy of electrons compared with the storage ring.**
- **High luminosity up to 10^{34} - 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**
- Relatively novel technology
- Needs R&D on polarized gun
- Needs completion of e-cooling R&D (CeC and conventional)

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In eRHIC luminosity is determined by the hadron beam!

$$L = f_c \frac{N_e N_h}{4\pi\beta_h^* \varepsilon_h} \cdot h\left(\frac{\sigma_s}{\beta_h^*}\right)$$

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

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

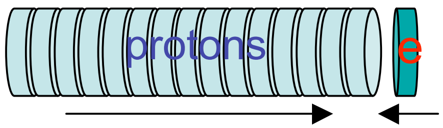
$$\xi_h = \frac{N_e}{\gamma_h} \frac{r_h}{4\pi Z \varepsilon_h}$$

$$\xi_h \to 0.02 \quad \Leftrightarrow \quad L_{p\ e} \to 0.3 \cdot 10^{34}$$

Thus, reducing (cooling) emittance of hadron beam, ε_h, allows to proportionally reduce electron beam current ($Ne \sim \varepsilon_h$). This in return reduces strain on photocathode, loss on synchrotron radiation -> means higher energy!, X-ray back-ground in detectors…. In combination with reduction of the bunch length, this also allows reduction of β* and an increase of the luminosity.

Thus, strong cooling makes eRHIC a perfect EIC!

Beam mismatch - e-lens or ferrite lens for compensation



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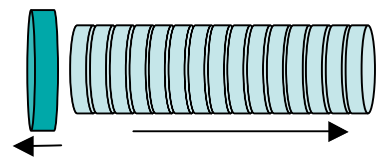
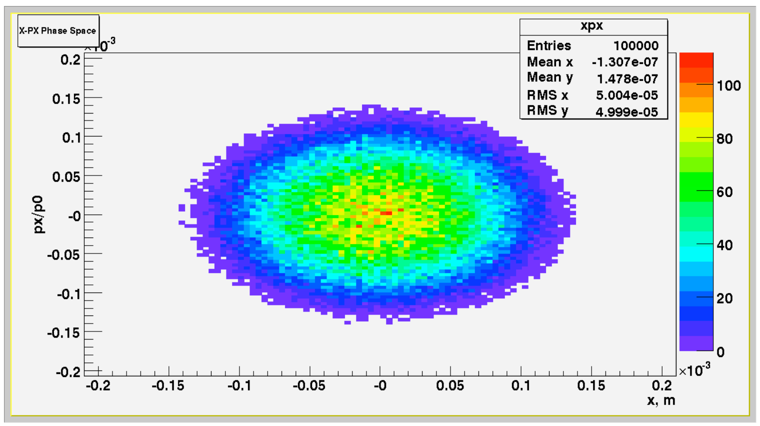
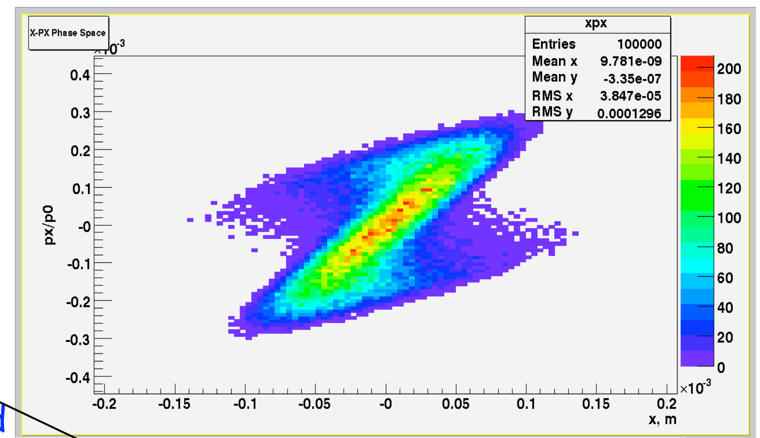
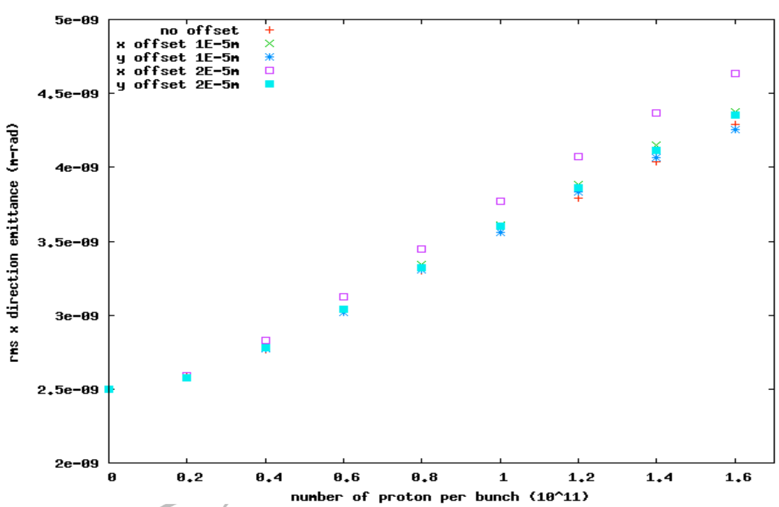


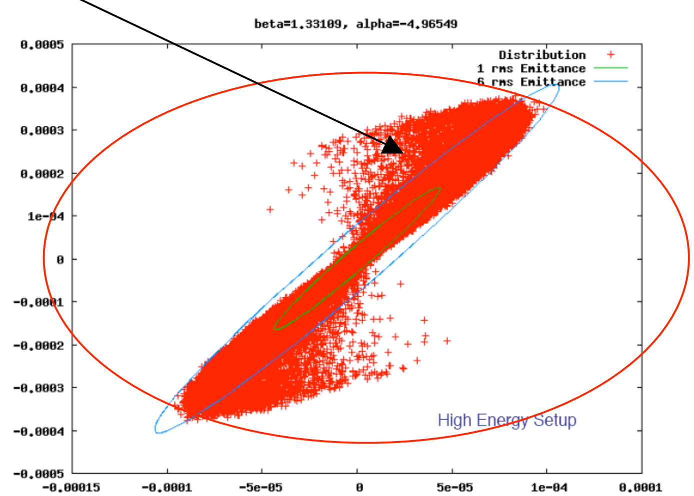


Interaction



Optimized





Main advantages of ERL + cooling (cont..)

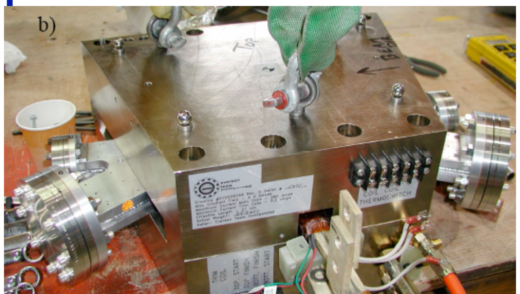
- Where is the limit?

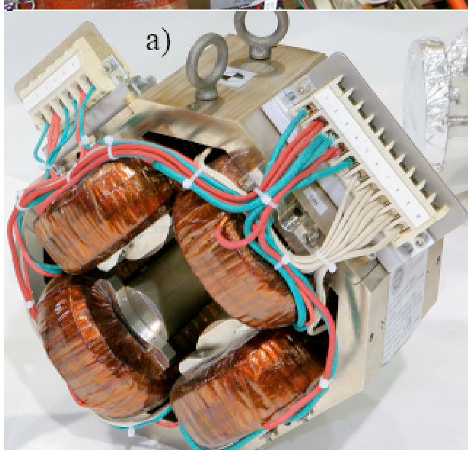
$$D = \frac{Z_h N_h r_e}{\gamma_e \beta_h^* \varepsilon_h} \sigma_{s\ h}$$

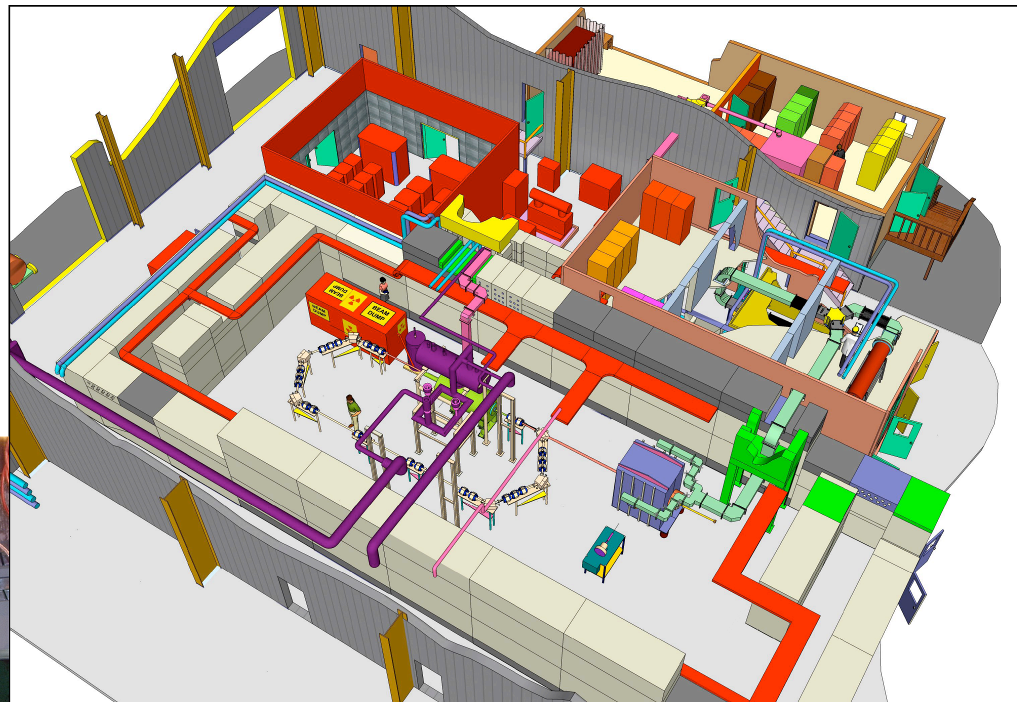
- Electron beam disruption (which better describes affect on electron beam in linac case) can cause emittance growth and kink instability of the hadron beam

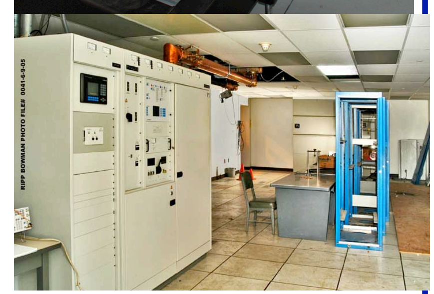
$$\Lambda = D \cdot \xi_h / Q_{s\ h}$$

R&D ERL Commissioning start 2/09









PoP of coherent electron cooling

- Use existing R&D ERL
- Design & simulations - 2008-2010
- RHIC modification for PoP - 2011
- Moving R&D ERL and installing it at RHIC - 2012
  - ? - should we speed it up to be ahead of NP LRP ?

- Total budget - $9M-$10M

Topics 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

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**