Optics Considerations for eRHIC

ERL: Main-stream - 5-10 GeV e^-

Up-gradable to 20^+ GeV e^-

Vladimir N. Litvinenko

Collider Accelerator Department, Brookhaven National Laboratory, Upton, NY, USA

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Credits go to:

Ilan Ben-Zvi, Rama Calaga, Dmitry Kayran, Jörg Kewisch, Christoph Montag, Brett Parker, Vadim Ptitsyn, Thomas Roser, Bernd Surrow, Steven Tepikian, Dejan Trbojevic

eRHIC requires a very large tunability range for c.m. energies while maintaining very high luminosity up to **10^{34} cm^{-2} s^{-1}** per nucleon. The designs of this future polarized electron-hadron collider, eRHIC, based on a high current super-conducting energy-recovery linac (ERL) with energy of electrons up to 20 GeV, have a number of specific requirements on the ERL optics.

Three of the most distinctive features of this scheme are:
full spin transparency of the ERL optics at all operational energies,
the capability to support up to four interaction points and
preservation of 20 GeV e-beam parameters in the arcs.

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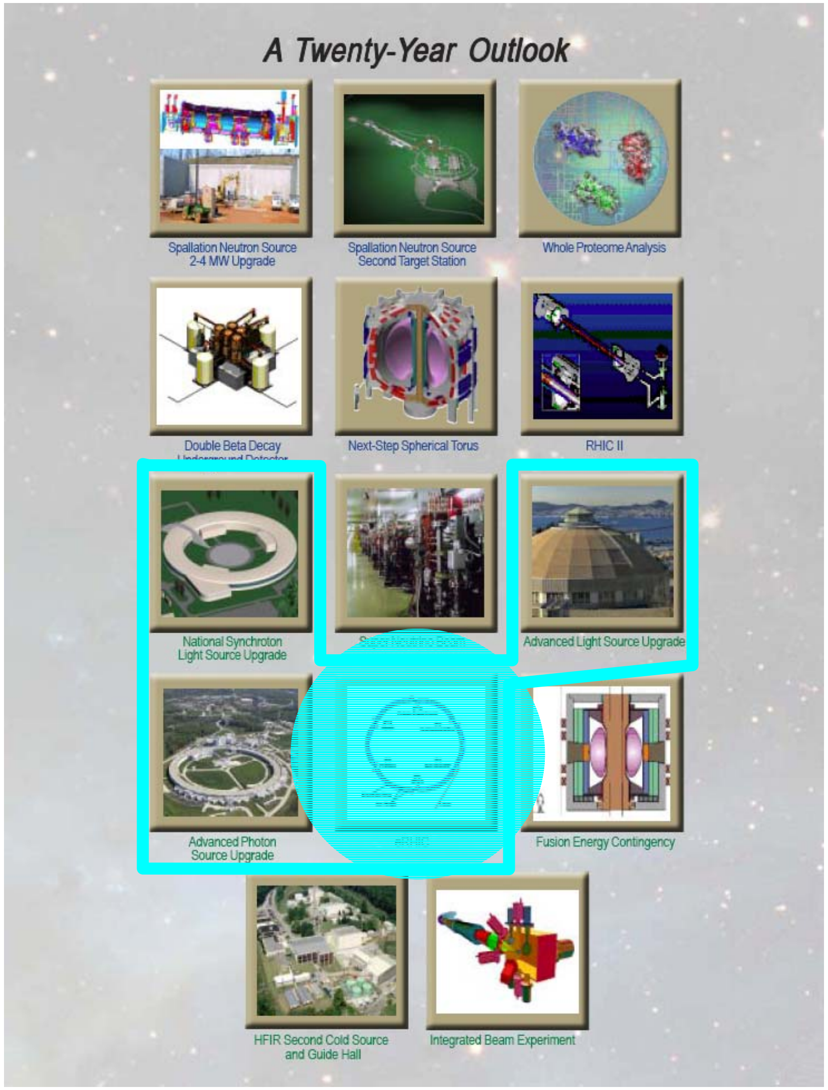
Considerations

- High current, very high energy (10-to-20+ GeV) ERL ⇨ Limitation on SR
- Polarization control at the IP ⇨ Polarization transparency of the lattice
- Potential light source and FEL application ⇨ Preservation of emittance and energy spread
- IP optics - ⇨ Support of (multiple) IP(s) with large disrupion parameter for the e-beam

Work is supported by DoE

eRHIC - electron-ion colliders



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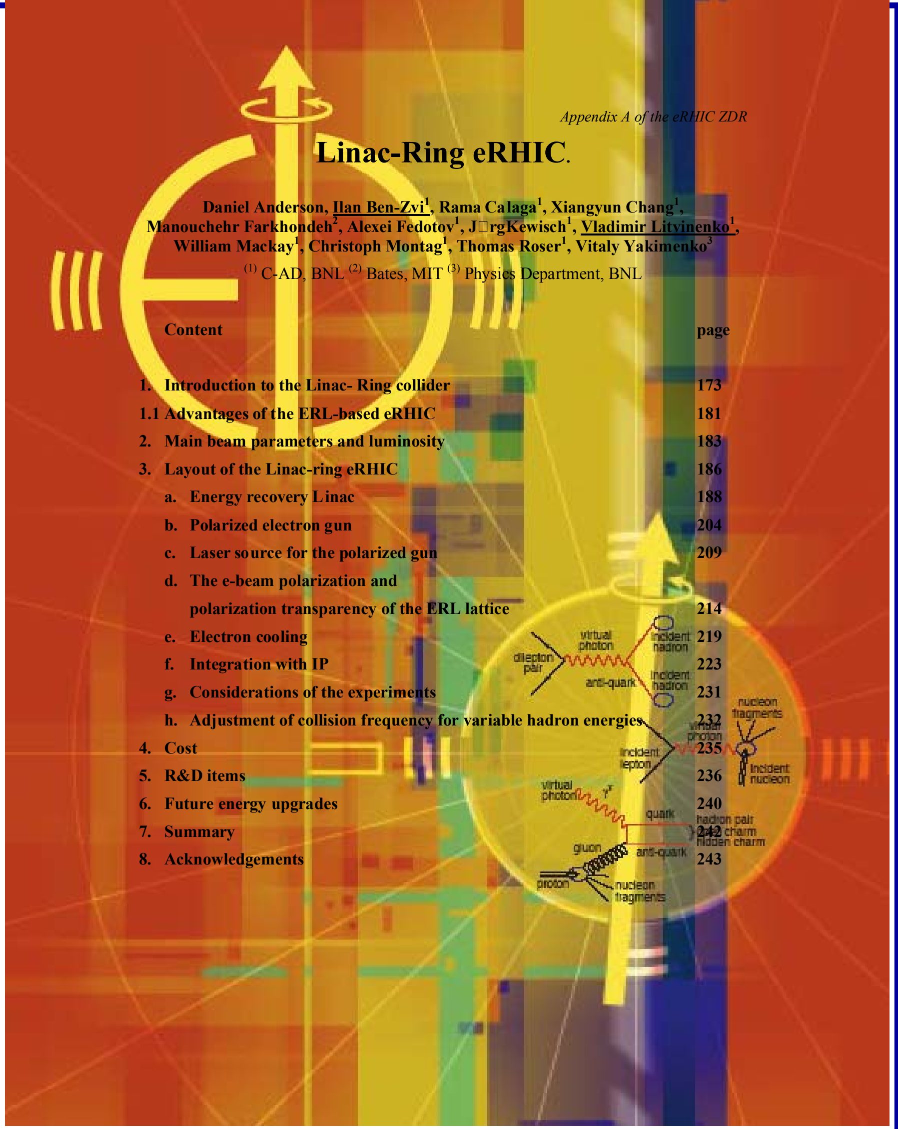
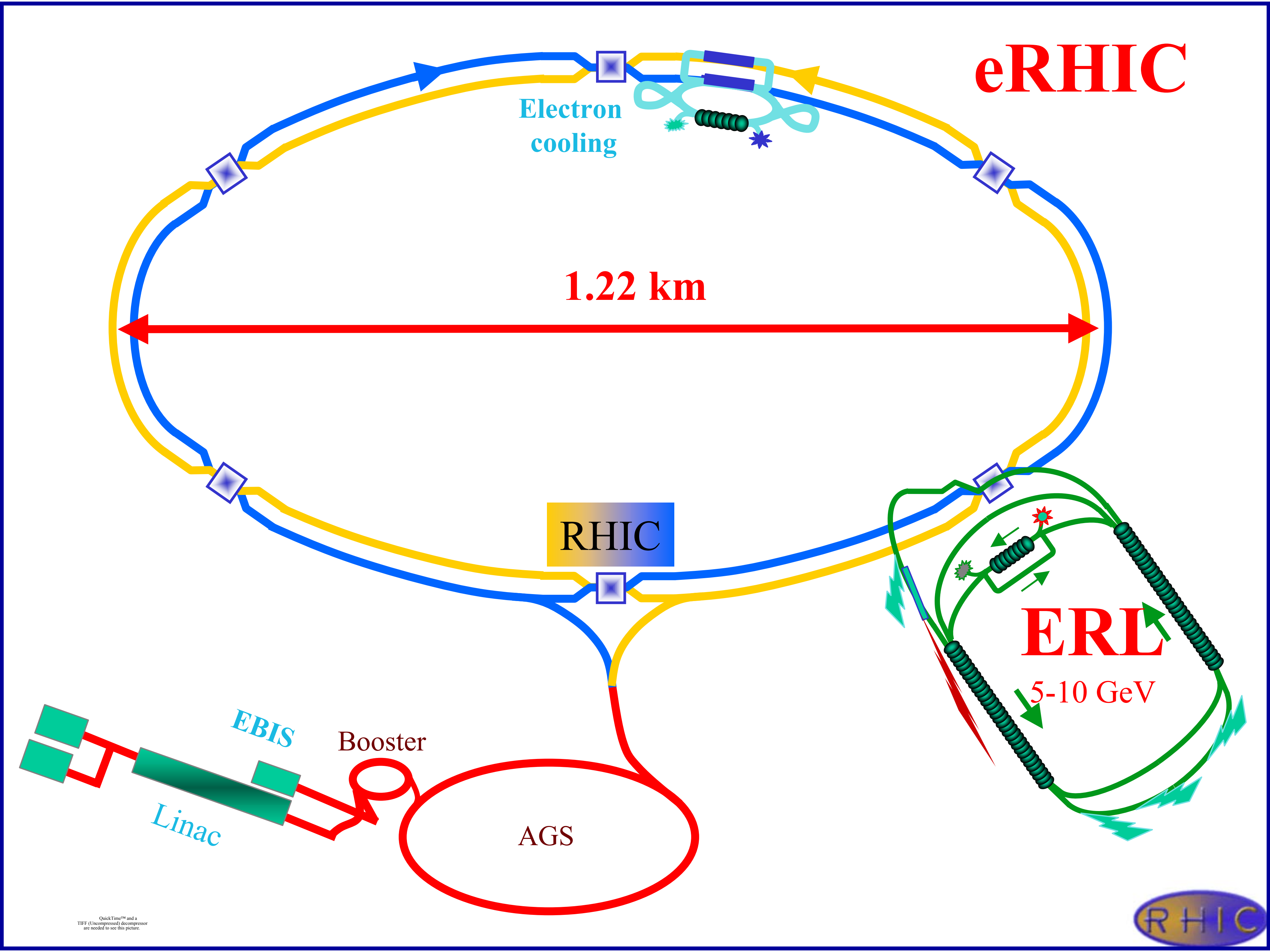
Linac-ring eRHIC

Daniel Anderson[1], Ilan Ben-Zvi[1,2,4], Rama Calaga[1,4], Xiangyun Chang[1,4], Manouchehr Farkhondeh[3], Alexei Fedotov[1], Jörg Kewisch[1], Vladimir Litvinenko,[1,4], William Mackay[1], Christoph Montag[1], Thomas Roser[1], Vitaly Yakimenko[2]

[(1)] Collider-Accelerator
[(2)] Physics Departments of BNL,
[(3)] Bates Lab, MIT ,
[(4)] Department of Physics and Astronomy, SUNY @ Stony Brook

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




eRHIC
Electron cooling
1.22 km
RHIC
ERL
5-10 GeV
EBIS
Booster
Linac
AGS
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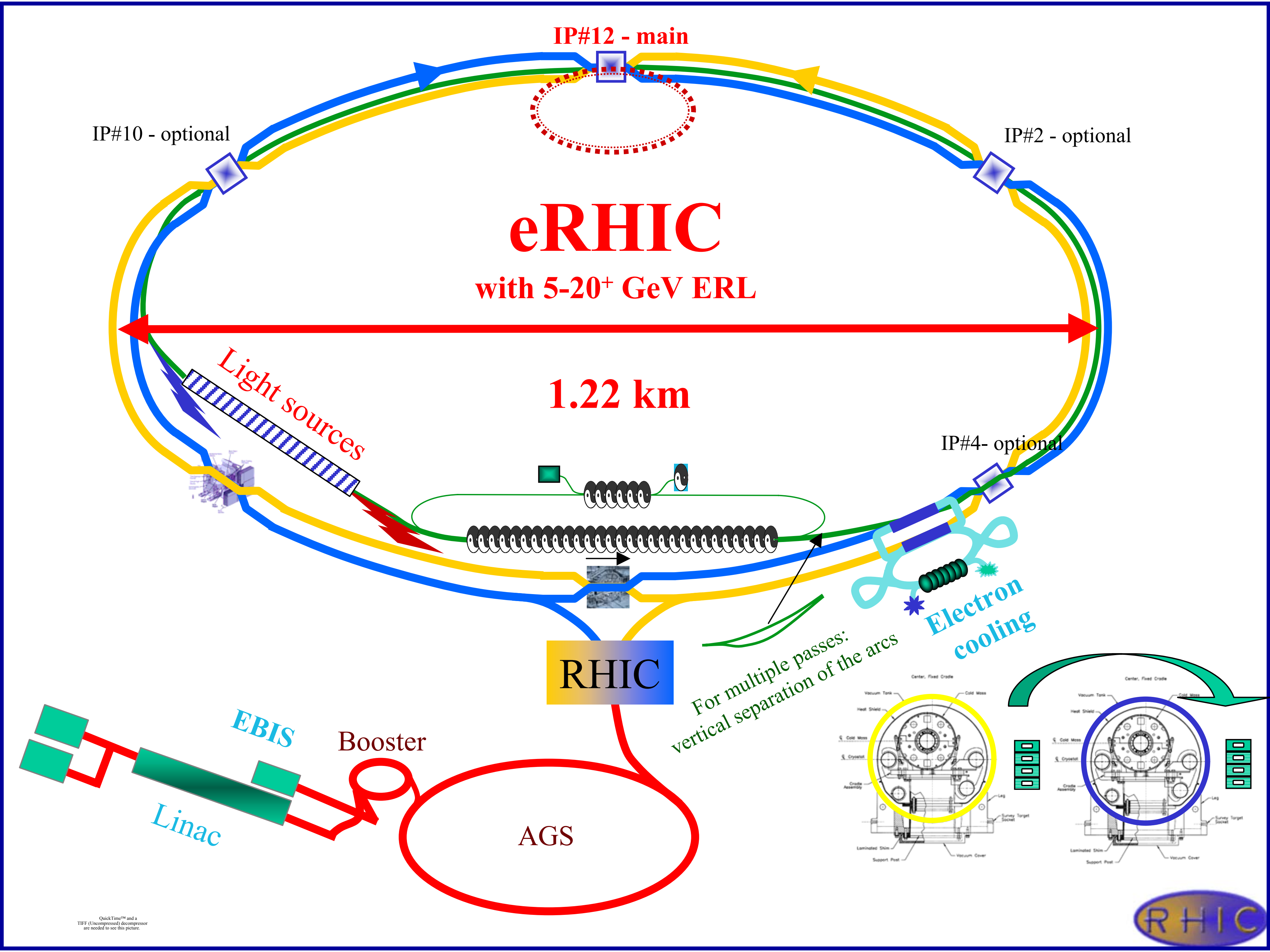
RHIC


IP#12 - main
IP#10 - optional
IP#2 - optional
eRHIC
with 5-20+ GeV ERL
1.22 km
Light sources
IP#4- optional
Electron
cooling
For multiple passes:
vertical separation of the arcs
RHIC
EBIS
Booster
Linac
AGS
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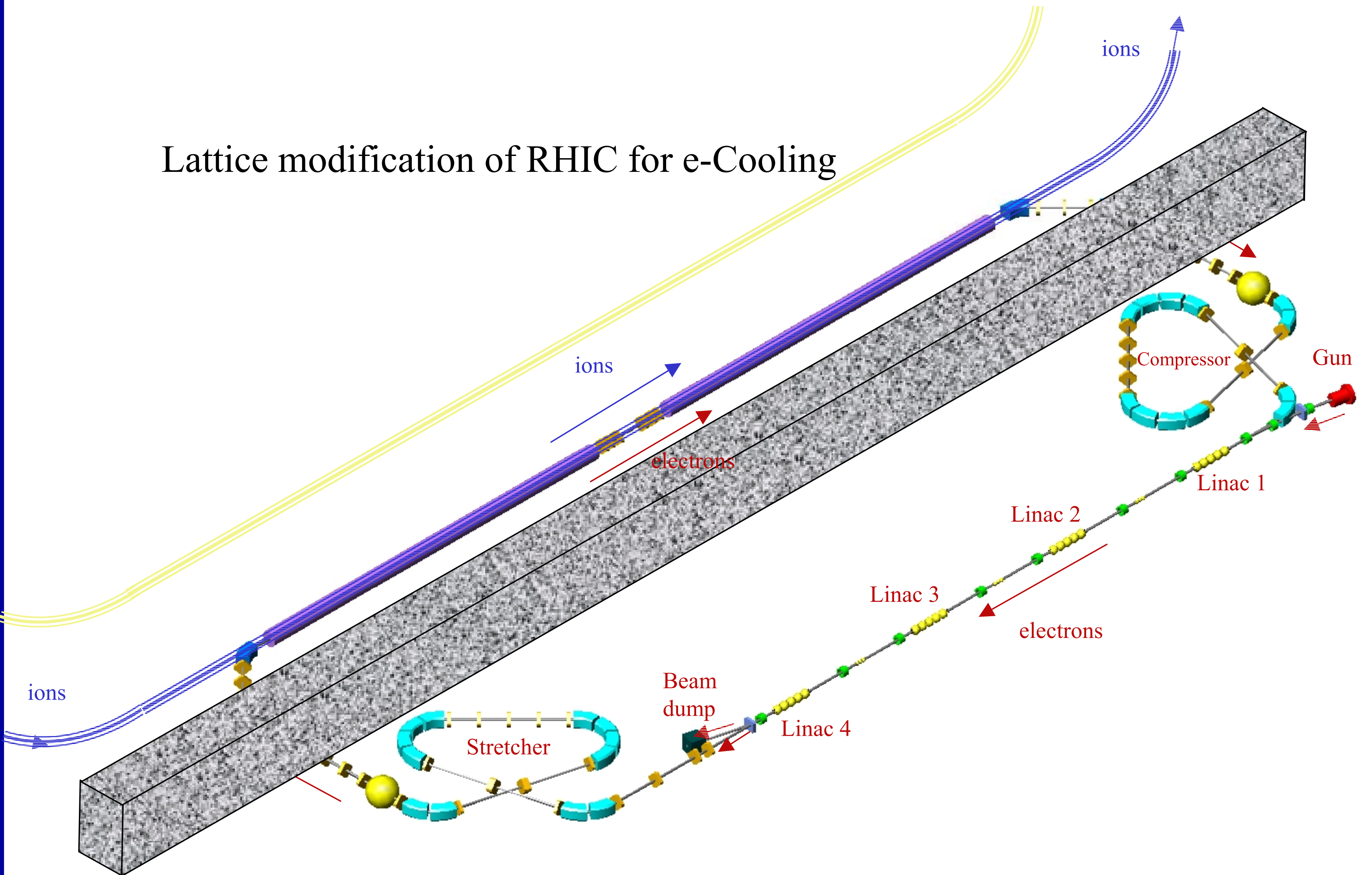
RHIC

Lattice modification of RHIC for e-Cooling



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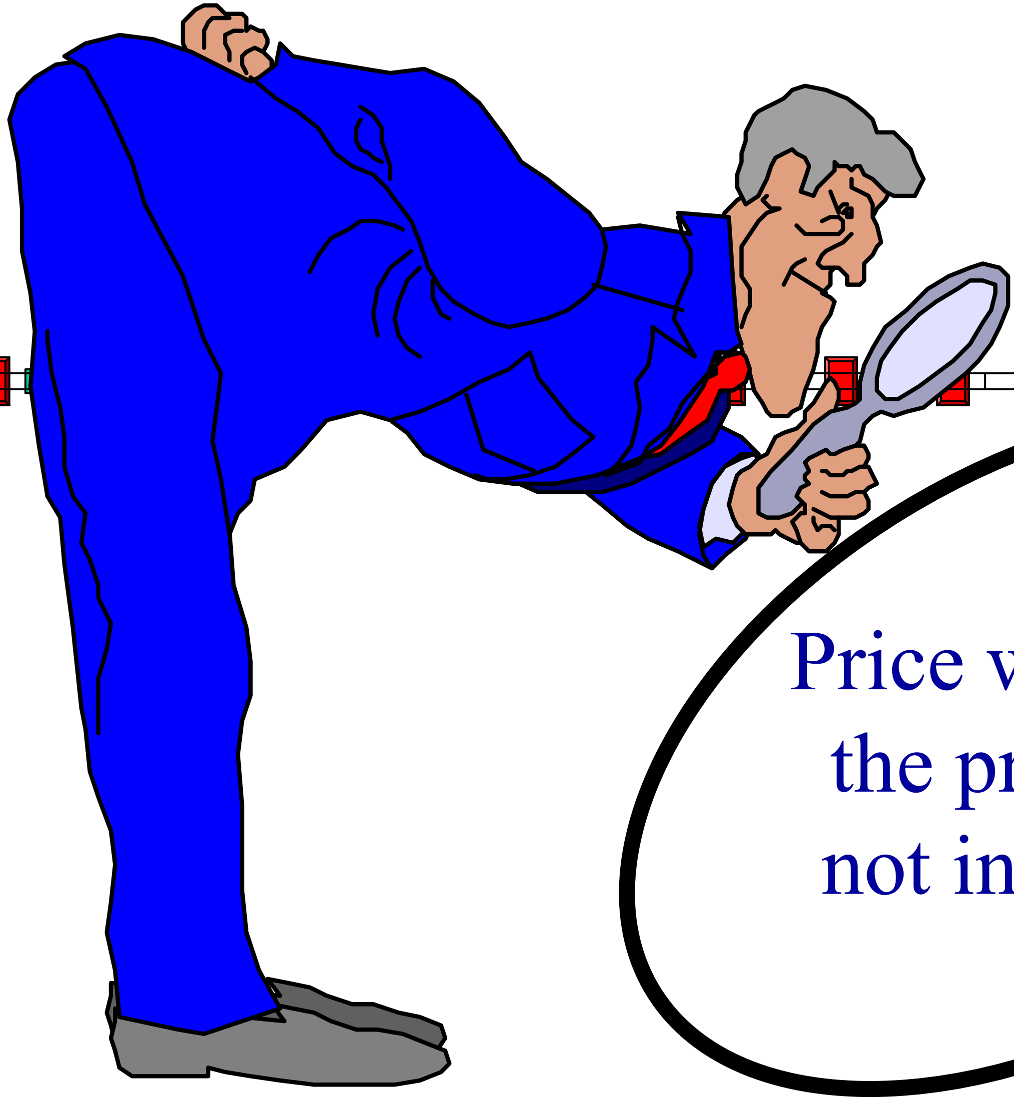

Price will be in
the precision
not in the size

RHIC

Goals and Targets

- This scheme meets or exceeds the requirements for the collider specified in the physics program for eRHIC [1]:

✓ **Electron beams colliding with beams of protons or light and heavy nuclei**

✓ **Wide range of collision energies (E_{cm}/nucleon from 15 GeV to 100 GeV)**

✓ **High luminosity $L > 10^{33}$ cm^{-2} s^{-1} per nucleon**

✓ **Polarization of electron and proton spins**

✓ **Preferably, two interaction regions with dedicated detectors.**

[1] Physics performance requirements for eRHIC, A.Deshpande et al.,

RHIC

Center-of-mass energies for linac-ring eRHIC

Energy, GeV **proton** **electons** c.m.	**26**	**50**	**100**	**250**
1	10.20	14.14	20.00	31.62
2	**14.42**	20.00	28.28	44.72
5	22.80	31.62	44.72	70.71
10	32.25	44.72	63.25	**100.00**
20	**45.61**	**63.25**	**89.44**	**141.42**
30	55.86	77.46	109.54	173.21

Energy, GeV **Au/u** **e** c.m.	**50**	**100**
1	14.14	**20.00**
2	**20.00**	28.28
5	31.62	44.72
10	44.72	**63.25**
20	63.25	89.44
30	77.46	109.54

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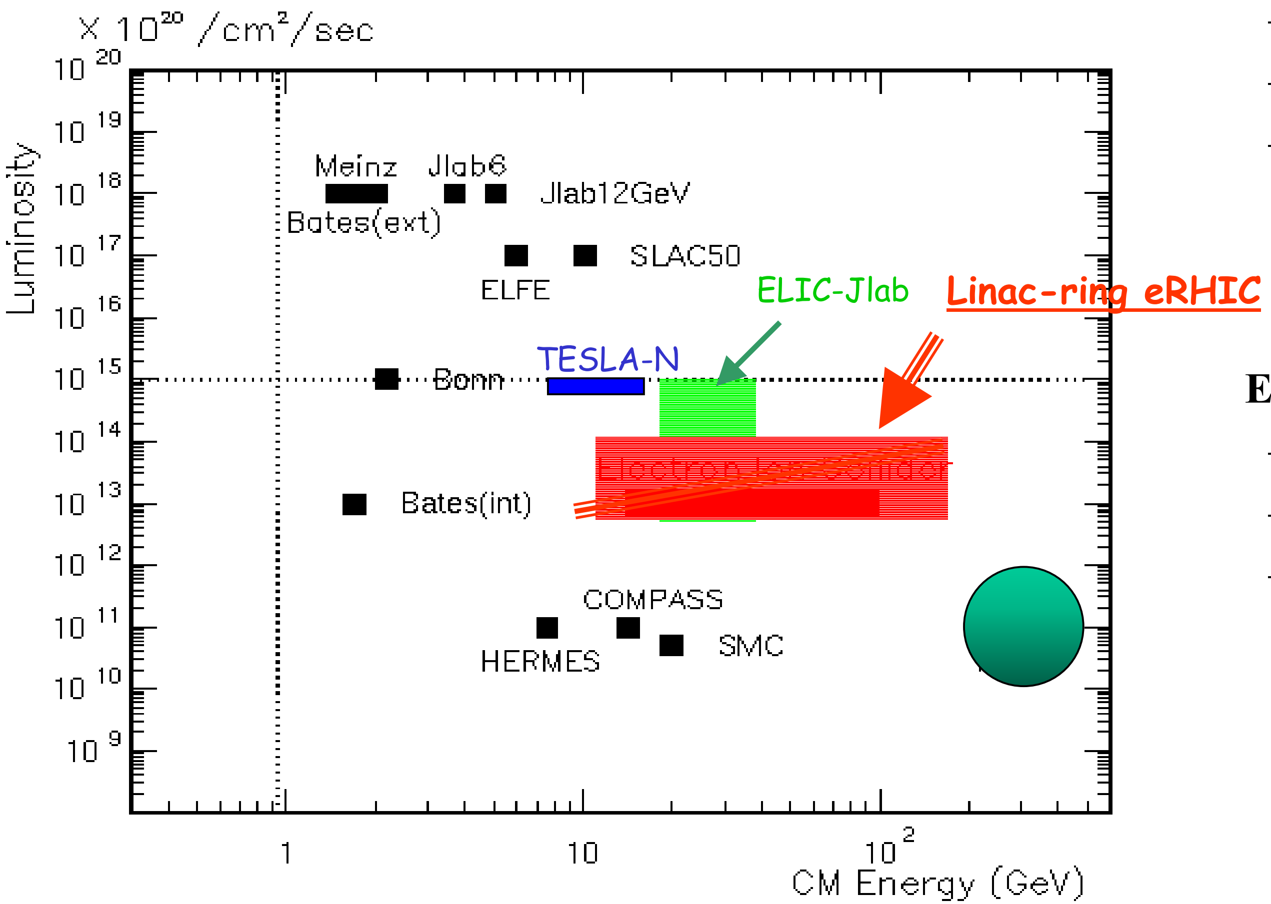
CM vs. Luminosity

Modified: original is from Abhay Deshpande's talk at at EIC2004



- **eRHIC**
  - Variable beam energy
  - P-U ion beams
  - Light ion poalrization
  - Large luminosity

ELIC
- Variable beam energy
- Light ion polarization
- Large luminosity

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Beam parameters

RHIC	eRHIC	*Light source option*
Ring circumference [m]	3834	
Number of bunches	360	
Beam rep-rate [MHz]	28.15	
Protons: number of bunches	360	
Beam energy [GeV]	26 - 250	
Protons per bunch (max)	2.0 ¿ 10^{11}	
Normalized 96% emittance [μm]	14.5	
RMS Bunch length [m]	0.2	
Gold ions: number of bunches	360	
Beam energy [GeV/u]	50 - 100	
Ions per bunch (max)	2.0 ¿ 10^{9}	
Normalized 96% emittance [μm]	6	
Electrons:		
Beam rep-rate [MHz]	28.15	*703.75*
Beam energy [GeV]	2 Š 20	
γ, Relativistic factor	**3.9 10^{3} - 3.9 10^{4}**	
RMS normalized emittance [μm]	5- 50	*0.9*
Beam emittance @ 20 GeV [□]	***1.25-12.5***	***0.18***
Full transverse coherence λ[□]		*1.13*
photon energy [keV]		*11*
RMS Bunch length [psec]	30	*0.03 - 3*
Electrons per bunch	0.1 - 1.0 ¿ 10^{11}	
Charge per bunch [nC]	1.6 -16	*0.7*
Average e-beam current [A]	0.45	*0.5*

Presently, RHIC operates for ~ 28 weeks/year
The rest of the year the RHIC ion rings do not work
Time for dedicated LS run

Spin motion

Bargman, Mitchel,Telegdi equation

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

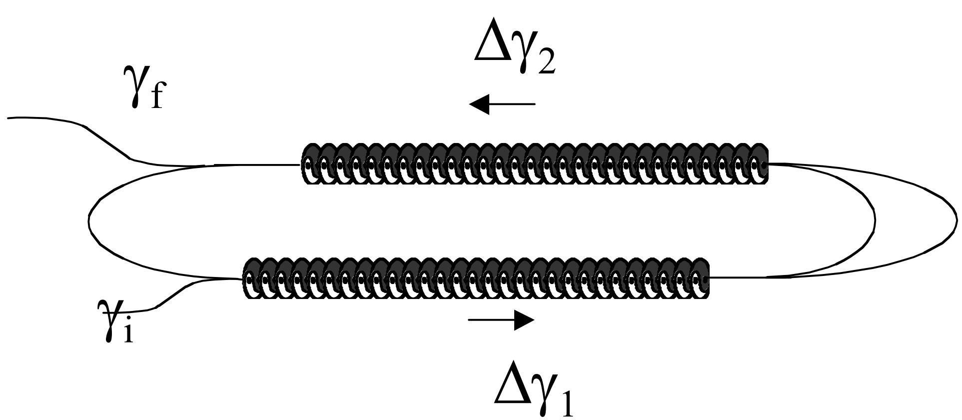
$a = g/2-1 = 1.1596521884\cdot 10^{-3}$

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

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

in a θ-arc

For *n*-passes in ERL $\quad \varphi = \pi a\cdot\left(\gamma_i(2n-1)+n(\Delta\gamma_1\cdot n+\Delta\gamma_2(n-1))\right)$



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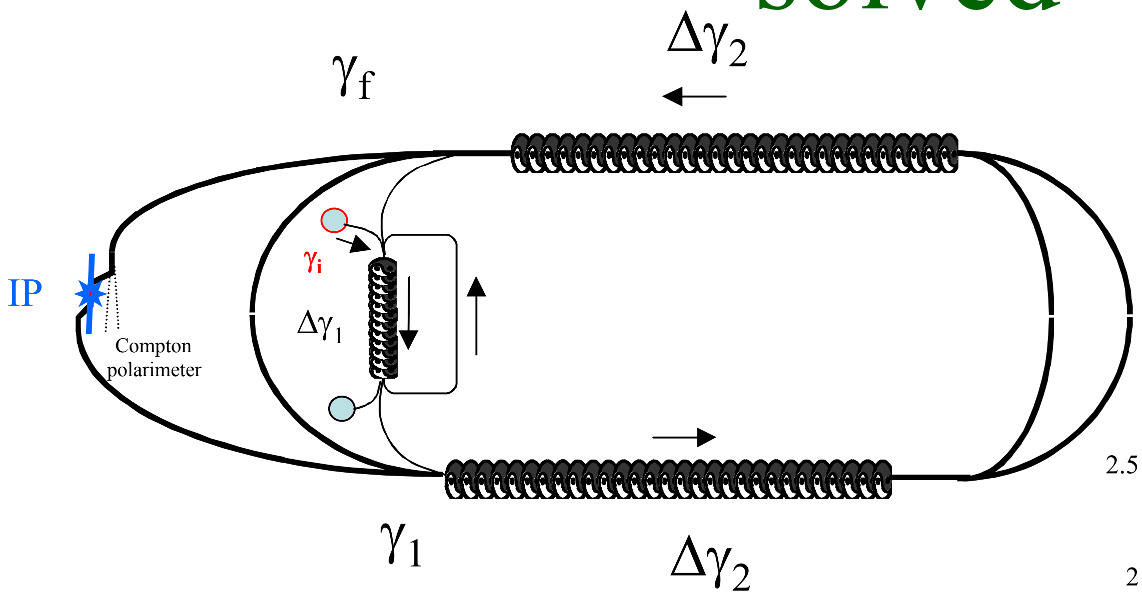
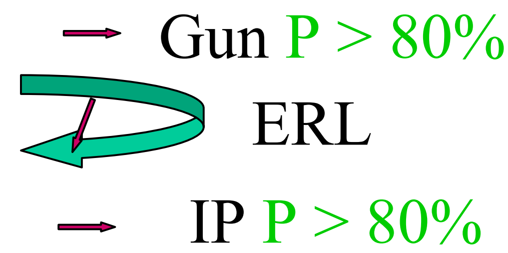
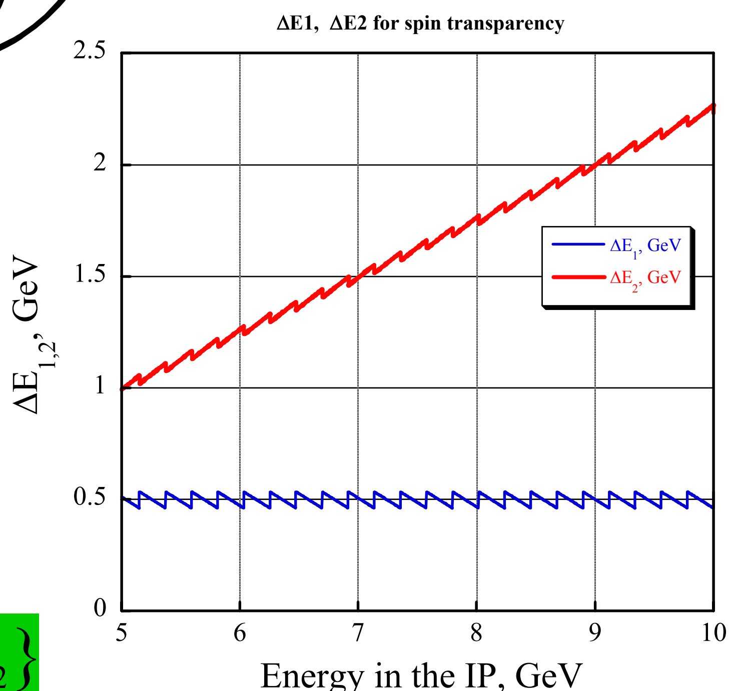
Energy independent spin control - solved





$\Delta\theta/\pi$	γ
-1/12	γ_i
2	$\gamma_i + \Delta\gamma_1$
1/2	$\gamma_i + 2\,\Delta\gamma_1$
1	$\gamma_i + 2\,\Delta\gamma_1 + 1\,\Delta\gamma_2$
1	$\gamma_i + 2\,\Delta\gamma_1 + 2\,\Delta\gamma_2$
1	$\gamma_i + 2\,\Delta\gamma_1 + 3\,\Delta\gamma_2$
1/2	$\gamma_i + 2\,\Delta\gamma_1 + 4\,\Delta\gamma_2$

$$\varphi = a\sum \Delta\theta_k \gamma_k = \pi a\{(6-1/12)\gamma_i + 10\Delta\gamma_1 + 8\Delta\gamma_2\}$$



TBBU for eRHIC?

- The circumference of RHIC provides $T_o \sim 13\mu s$
- The BNL cavity HOM Q's is 10^2 to 10^4
- The typical frequencies are >1 GHz
- $\tau = Q/\omega \sim 10^{-8}$ to 10^{-6} seconds,

or attenuation between e^{20} to e^{2000}

Interaction region design requirements

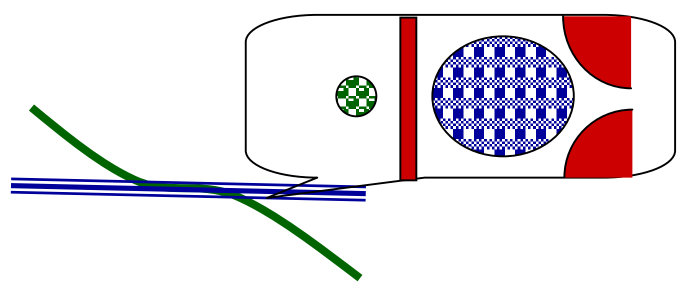
- Head-on collisions due to long ion bunches
- Equal beam sizes at interaction point to avoid emittance degradation
- ± 3m machine-element free region for detector installation
- Sufficient beam separation at entrance of first ion septum quadrupoles at ± 5m

  $(12\,\sigma_e + 12\,\sigma_i + d_{septum})$
- Accommodation of synchrotron radiation fan

Integration with IP

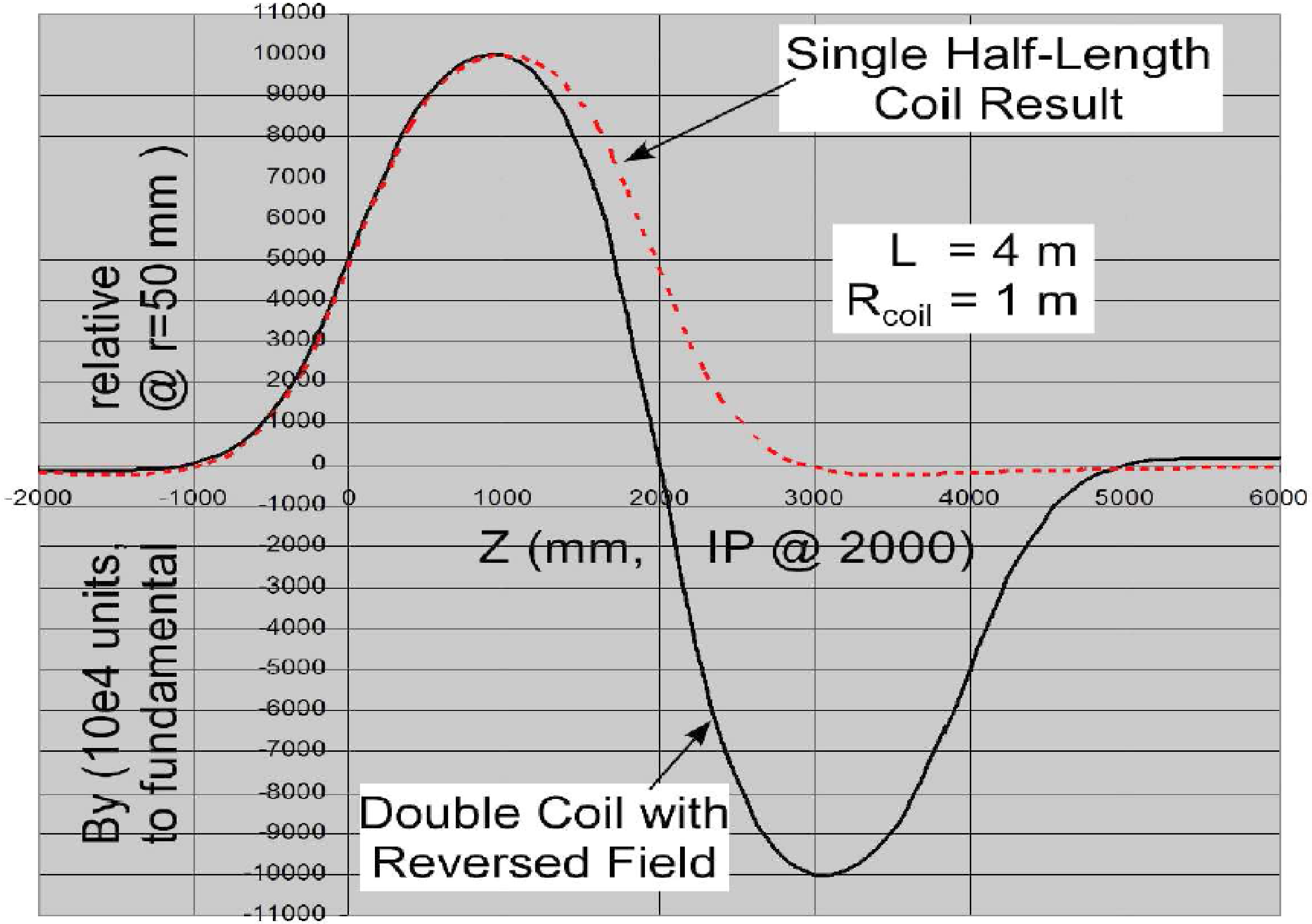
Ȩ$x = 12\sigma_{p,x} + \mathbf{5\sigma_{e,x}} + d$septum= 12¿ 0.93mm + **5 ¿ 0.25mm**+ 10mm = 22.4mm.

- 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



* C.Montag - IP lattice for linac-ring

Detector-integrated Dipole (DID) for beam separation



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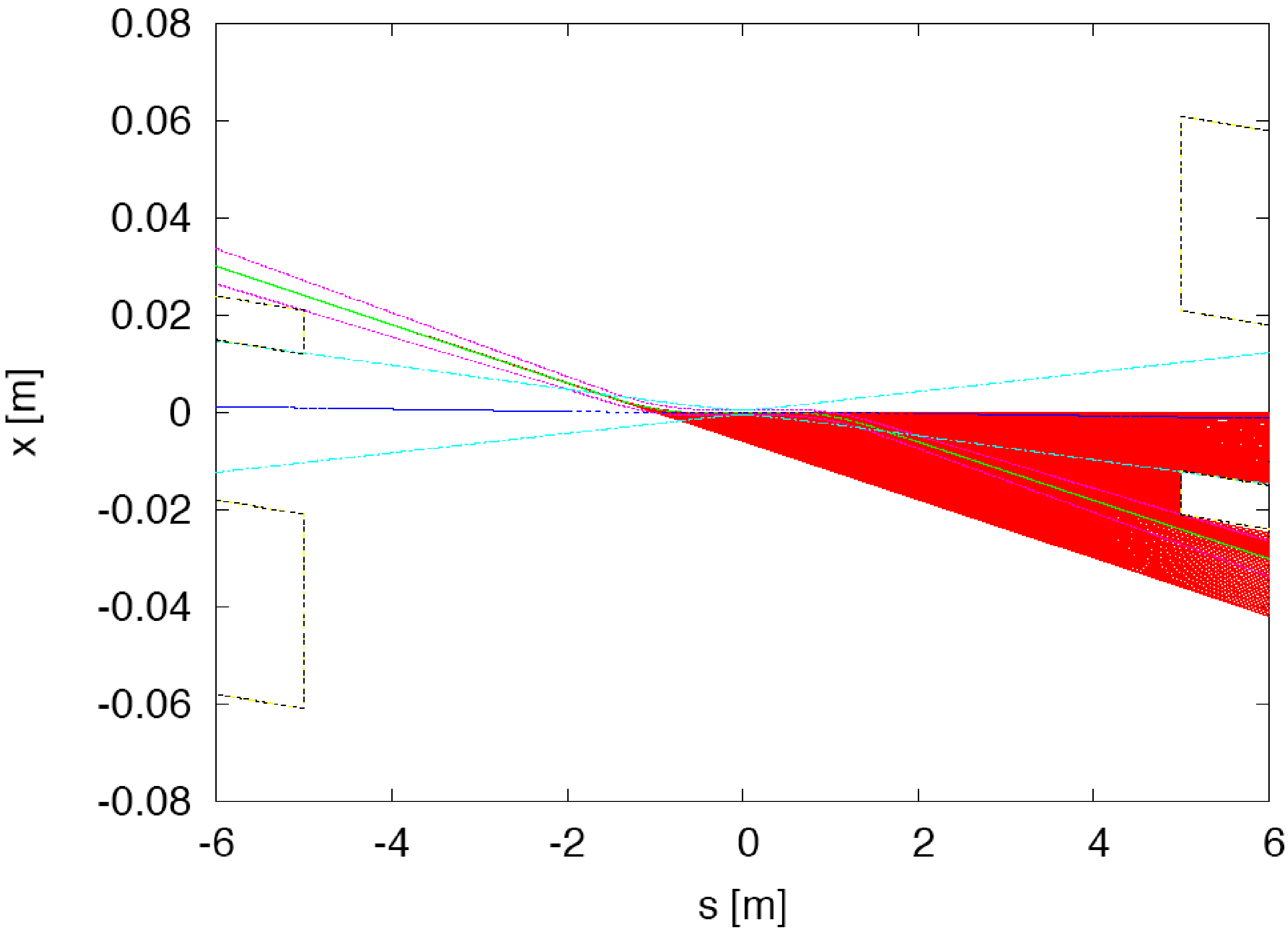
Interaction region (top view) with 12σ beam envelopes and synchrotron radiation fan



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Detector Design --- HERA like…

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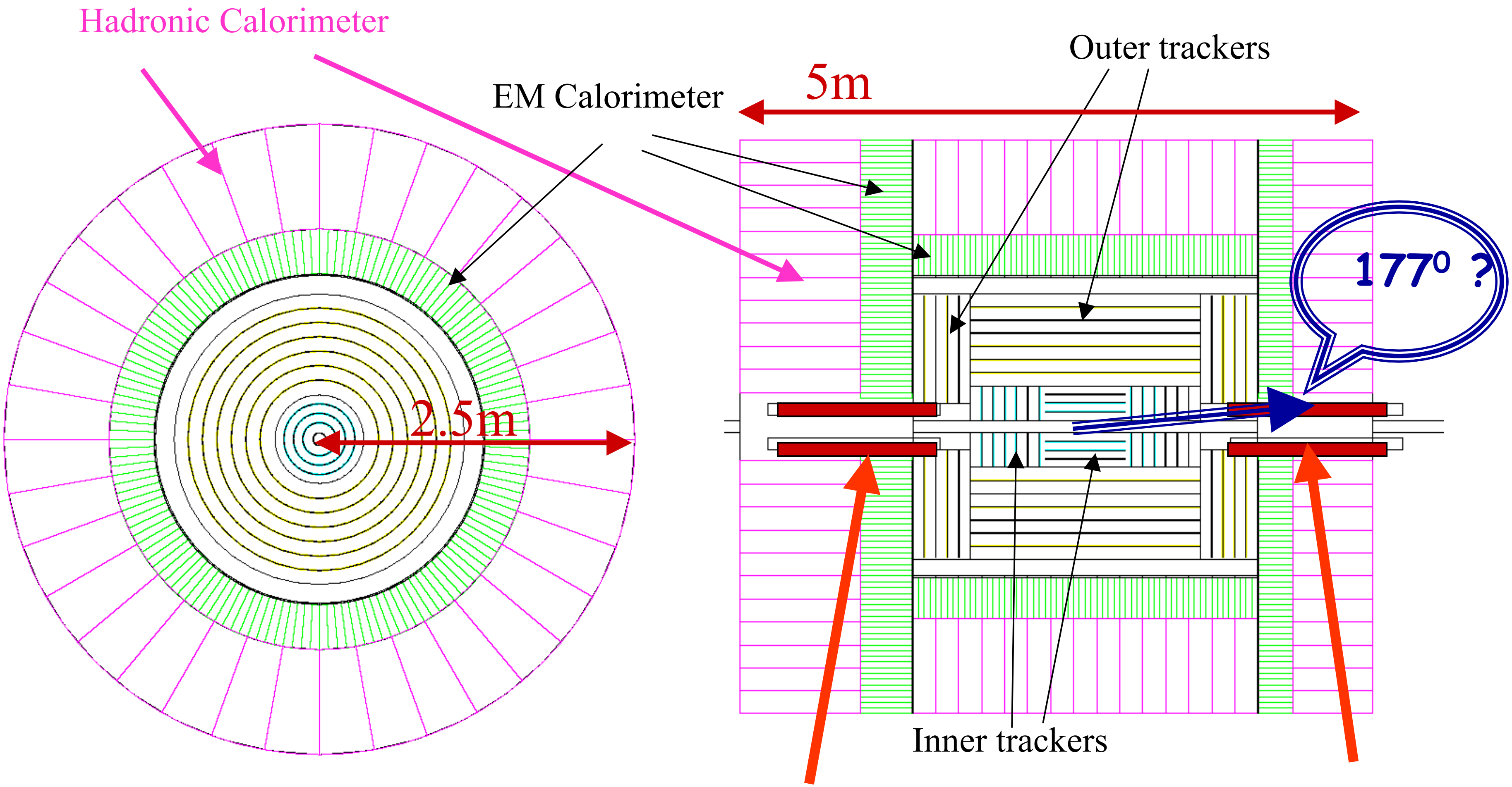

Nearest ring quadrupole: 1m ring-ring

5 m - linac-ring

Where do electrons and quarks go?

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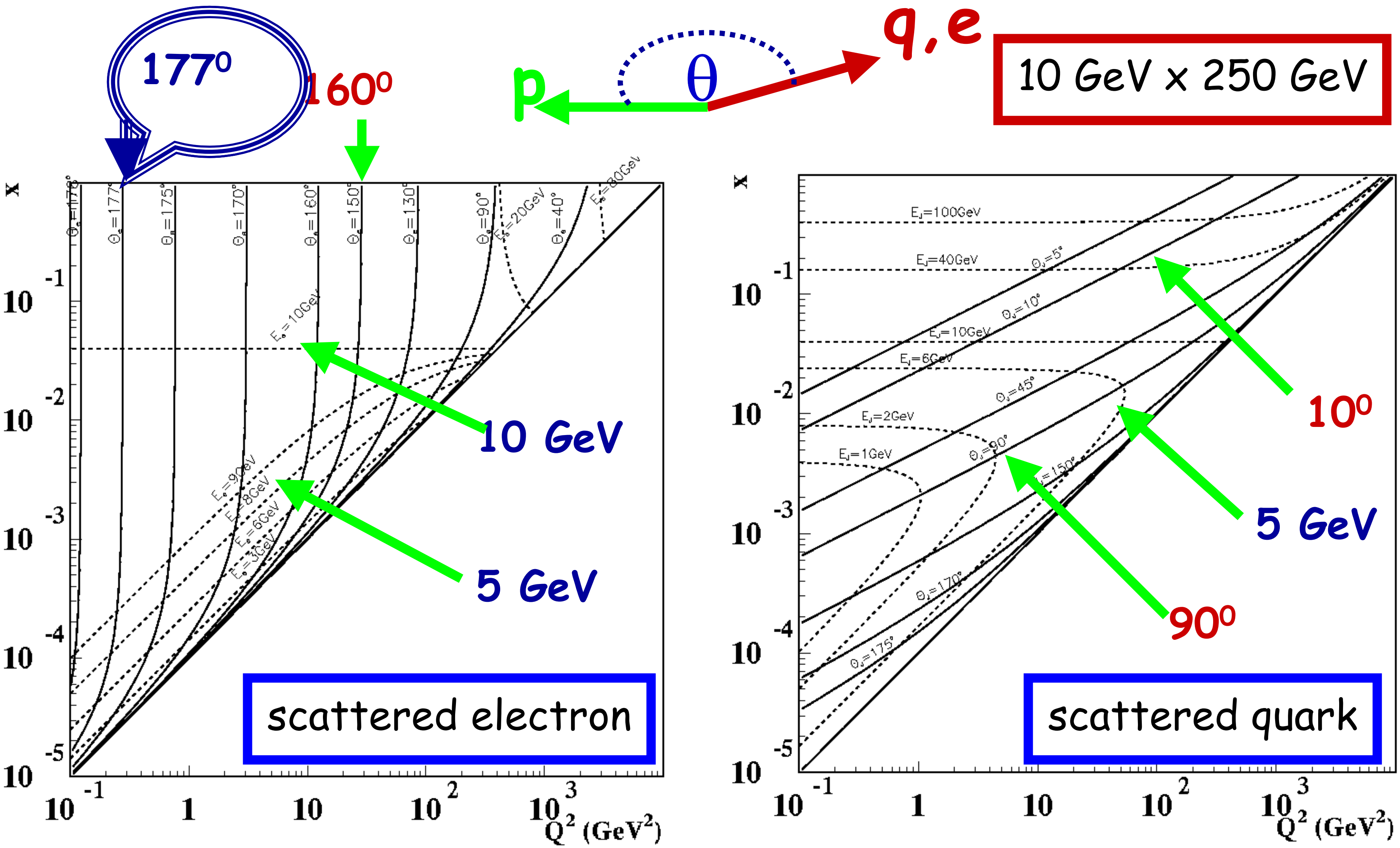
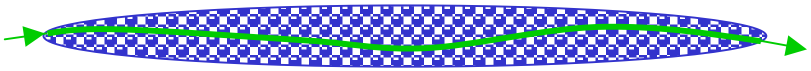
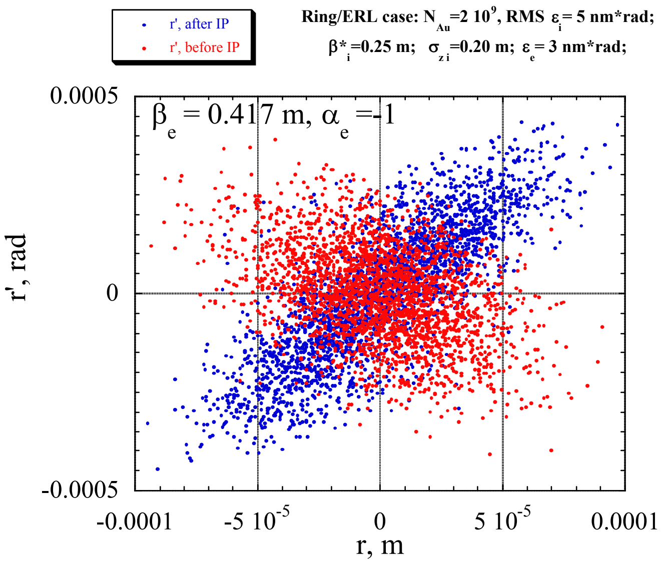


IP issues

$$D = \frac{Z_h N_h}{\gamma_e} \frac{r_e}{\sigma^2_{r(h)}} \sigma_{s(h)}$$

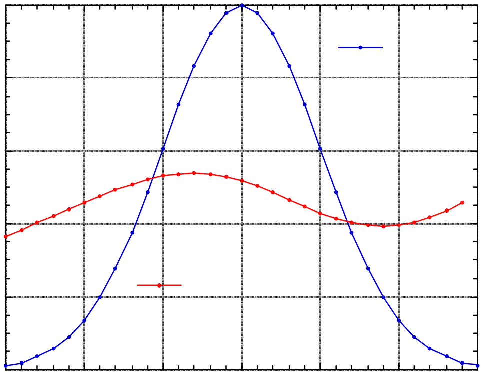
For the linac-ring collider, the beam-beam effect on the electron beam is better described not by a tune shift but by a disruption parameter, i.e. additional betatron phase advance





Does e-beam survives?

YES



Round 10 GeV electron beam from ERL with initial transverse RMS emittance of 3 nm·rad passes through the IP with the disruption parameter 3.61 (**tune shift ξ_e = 0.6**). Poincare plots for e-beam distribution before (red) and after (blue) the IP. After removing the *r-r'* correlations, the emittance growth is only 11%.

Matching the beam's size with the ion beam and a negative α=-1 at *z*=-0.3m. The e-beam's size does not shrink below the matched value and the hadron tune shift does not exceed ξ_h = **0.005**

Luminosity is determined by the hadron beam!

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

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

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

$$\xi_h = \frac{N_e}{\gamma_h} \frac{r_h}{4\pi Z \varepsilon_h} = 0.005$$

Luminosity 10^{33} cm^{-2}sec^{-1}	*Protons 26 GeV*	*Protons 50 GeV*	*Protons 100 GeV*	*Protons 250 GeV*
Electrons 5(2)-10 GeV	**0.201**	**0.395**	**0.791**	**1.98**

Luminosity (per nucleus) 10^{31} cm^{-2}sec^{-1}	*Au 50 GeV/u*	*Au 100 GeV/u*
Electrons 5(2)-10 GeV	**1.02**	**2.05**

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

$$\xi_h \to 0.024 \quad \Leftrightarrow \quad L_{p\ e} \to 1 \cdot 10^{34}$$

eRHIC - spontaneous radiation

Very few facts

Energy	**20**	10	GeV
Bρ	666.67	333.33	kGs m
Loss per turn	35.40	2.21	MeV
Power	**17.70**	**1.11**	**MW**
λc (reg. bend)	0.28	2.24	□
E ph critical (reg. bend)	44.35	5.54	KeV
λc (2T bend)	0.02	0.09	□
E ph c (2T bend)	**532**	133.05	**KeV**
λc (10 T bend)	0.0047	0.0186	□
E ph c (10T bend)	**2661**	665.24	**KeV**
Wiggler K=1			
Period	**1**	1	**cm**
λo	**0.049**	0.196	□
E ph	**253.3**	63.3	**KeV**
Wiggler K=2			
Period	**4**	4	**cm**
λo	**0.392**	1.567	□

Something New for High Flux Nuclear Physics

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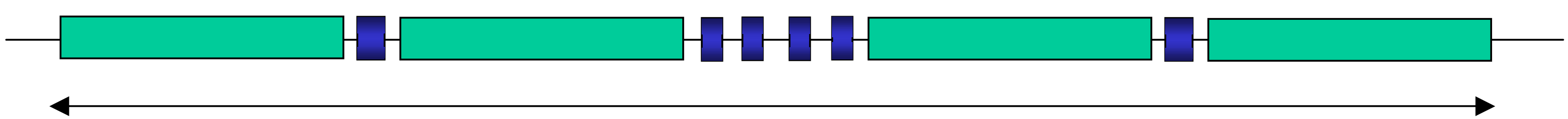
RHIC

Beam parameters

Energy	**20**	GeV		Energy	10	GeV	
γ	3.91E+04			γ	1.96E+04		
Circumference	**3834**	m		Circumference	*3834.00*	m	
R, average	610.20	m		R, average	*610.20*	m	
% fill	65.55%			% fill	*65.55%*		
R magnets	400.00	m		R magnets	*400.00*	m	
B	1.67	kGs		B	0.83	kGs	
N TBA cells	**150.00**			N cells	*150.00*		
ε_{norm}	9.50E-07	m rad		ε norm	*9.50E-07*	m rad	
ε	**0.243**	□ **rad**		ε	**0.485**	□	
Bunchlength	**from 0.1 to 2**	**psec**		Bunchlength	**from 0.1 to 2**	**psec**	
Damping time	1.45E-02	sec		Damping time	1.16E-01	sec	
Revolution time	1.28E-05	sec		Revolution time	1.28E-05	sec	
Δε (TBA)	***0.016***	□ ***rad***	***6.70%***	***Δε (TBA)***	***0.001***	□	***0.10%***
ε	**0.259**	□ **rad**		ε	**0.486**	□	
RMS energy spread	2.54E-05			RMS energy spread	4.49E-06		



25 meters TBA cell

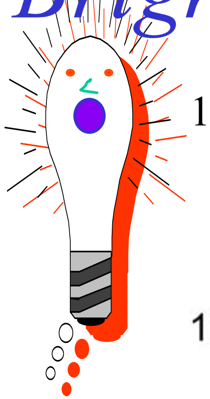
Single pass Ångstrom-class FELs at eRHIC

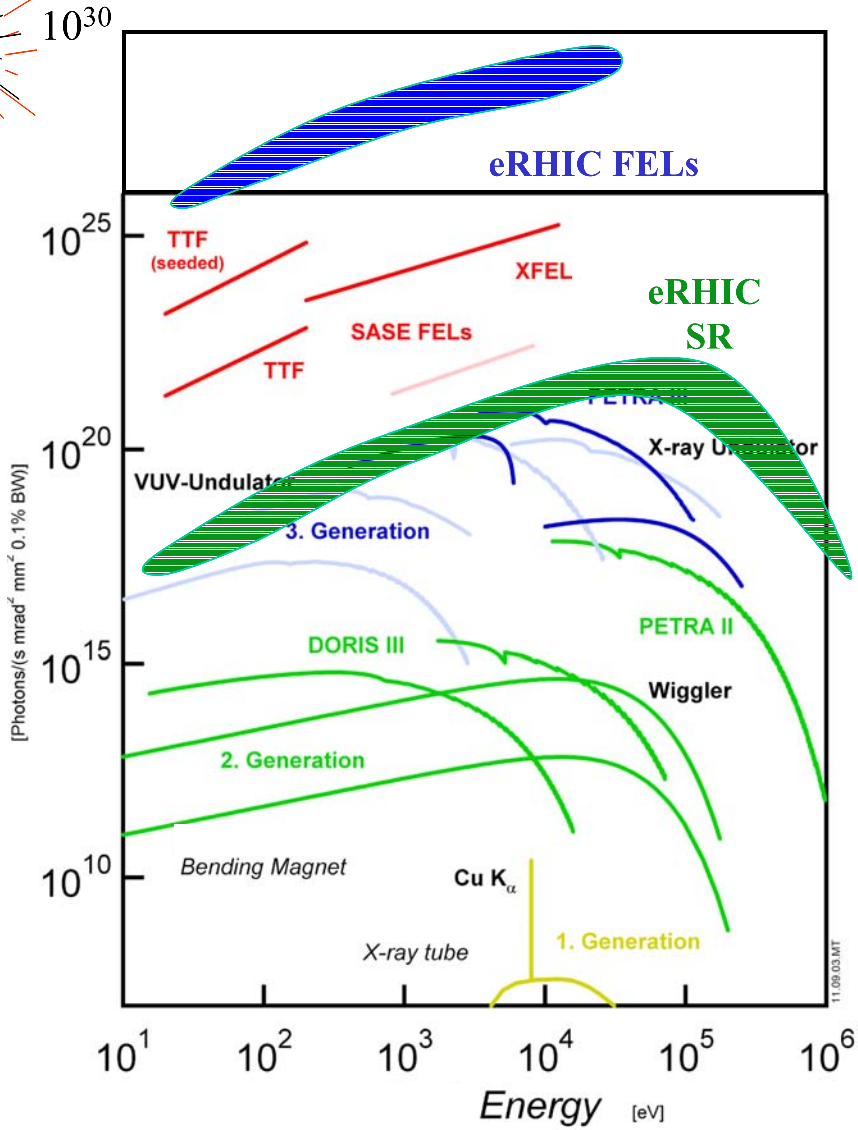
Average lasing power is a problem!

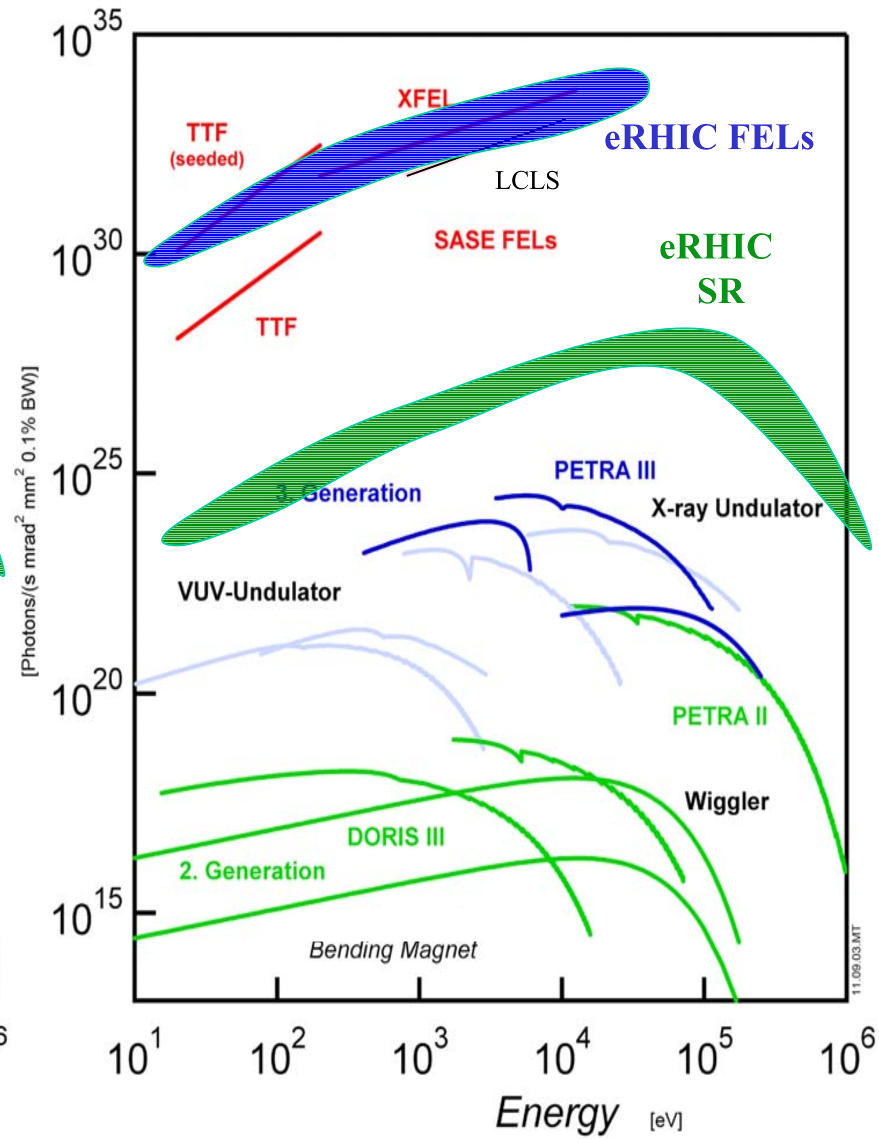
@ 1Å (12 keV) It is from 0.6 MW to 1.3 MW

Energy, GeV	20		15		10	
Wavelength, Å	**0.5**	**1**	**0.87**	**1.8**	**2**	**4**
Bunch length, psec	0.2	0.2	0.27	0.27	0.4	0.4
Peak Current, kA	5	5	3.75	3.75	2.5	2.5
Wiggler period, cm	**2.5**	**3**	**2.5**	**3**	**2.5**	**3**
SASE gain length, m	**7.5**	**4.3**	**5.5**	**3.3**	**3.7**	**2.4**
SASE Saturation length, m	100	60	76	47	51	34
Saturation power, GW	**7.7**	**19**	**6.4**	**14**	**4.5**	**9**
DOK, gain length, m	3.5	1.4	1.5	.65	.51	.25
DOK, saturation length, m	47	19	21	9	7	3.5

Brightness Average & Peak







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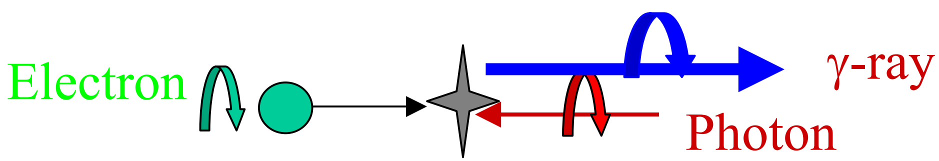
Polarized photon source - causes loss of few μA

- Wavelength [nm] — 300 - 900
- Polarization of photons — circular (left/right)
- Polarization of electrons — longitudinal, ~90%
- IC laser power [kW] — 50
- Mode of operation — CW



Wavelength, nm	300	900
γ-rays, Peak energy, GeV	11.17	5.93
Flux, γ-rays/sec	$2.13 \cdot 10^{13}$	$4.26 \cdot 10^{13}$
Power of γ-ray beam, kW	**2.5**	**2.7**

Note - potential source of polarized positrons

Conclusions

- Optics solutions for ERL-based eRHIC do require solid but conventional technologies ⇨ No cliff-hangers are expected
- ERL-based eRHIC has natural solution for Polarization transparency of the lattice and polarization control at the IP ⇨ No surprises
- ERL-based eRHIC has fantastic potential as light, FEL and γ-ray source and FEL application ⇨ Preservation of emittance and energy spread is well understood
- IP optics has challenges only for hadrons - ⇨ Support of multiple IP(s) looks possible
- Additional aspects of the optics: circumference adjustments, low energy arcs, switch-yard.

Work is supported by DoE