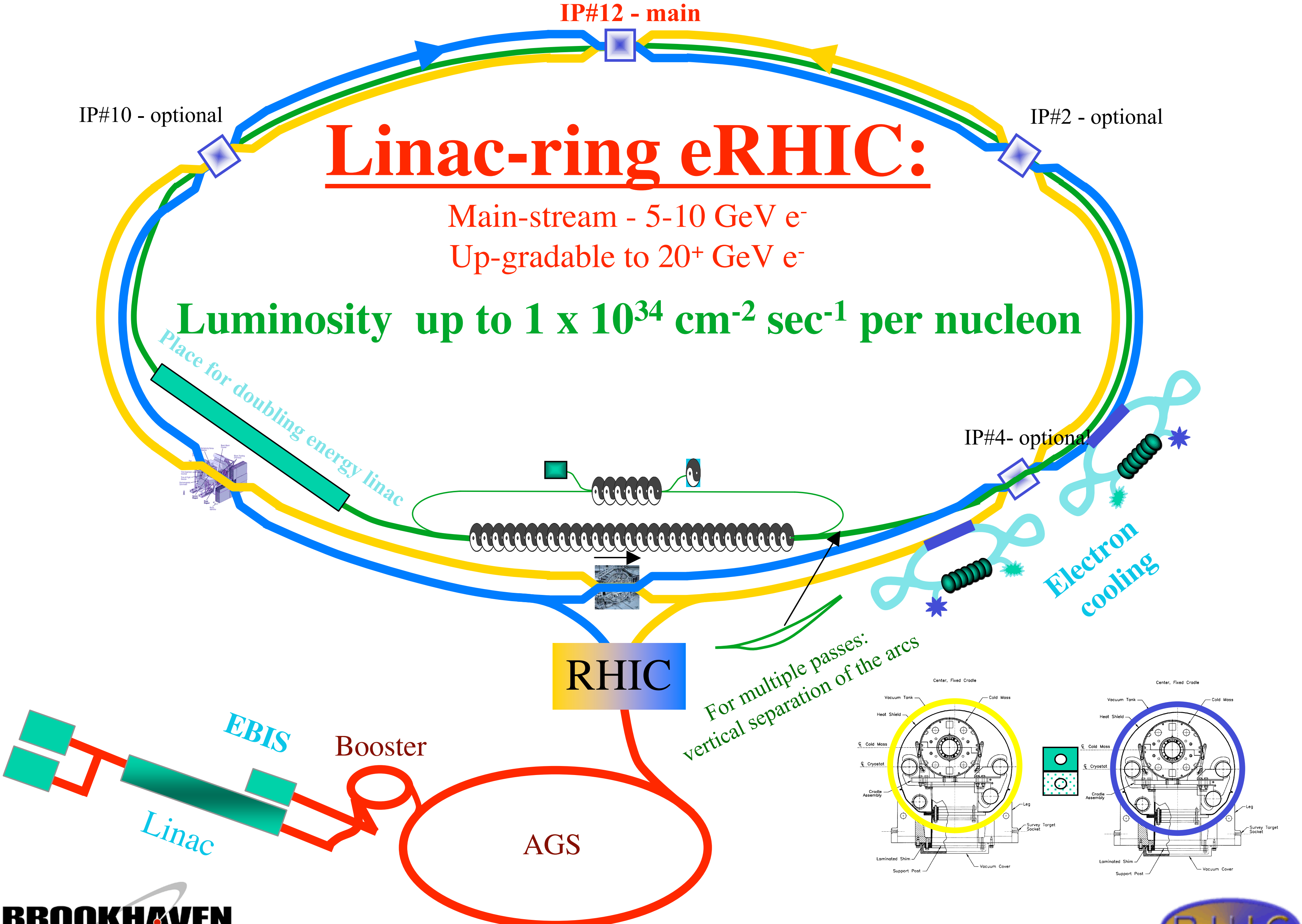
Linac-ring eRHIC:

Main-stream - 5-10 GeV e^-

Up-gradable to 20^+ GeV e^-

Luminosity up to 1×10^{34} cm^{-2} sec^{-1} per nucleon



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RHIC

Linac-ring eRHIC

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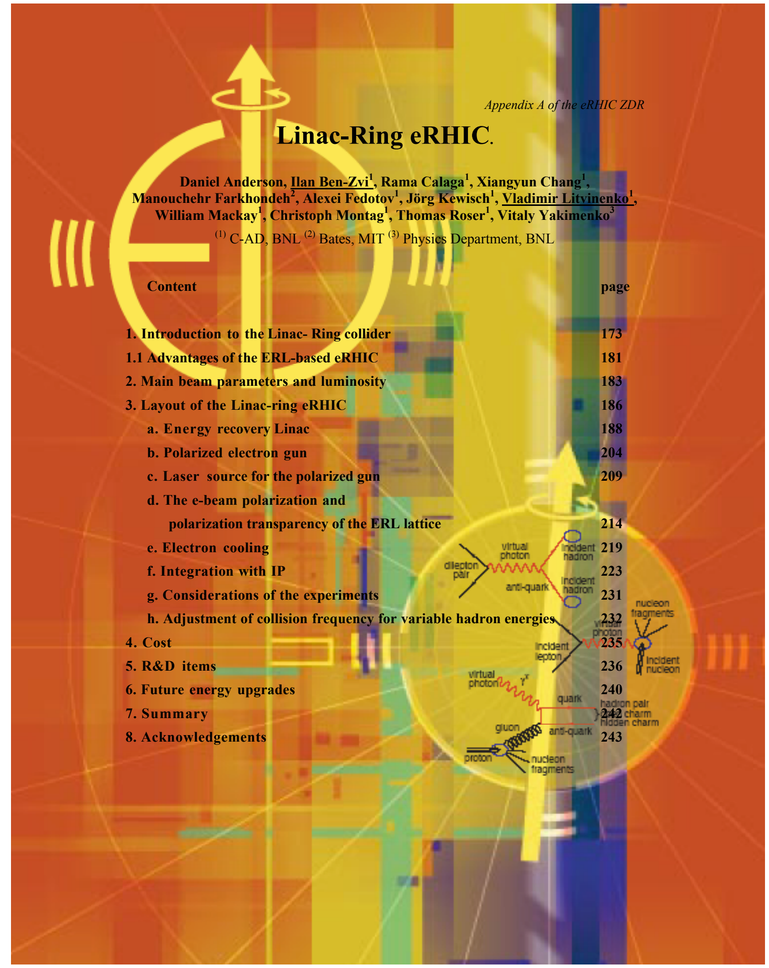
Jörg Kewisch[1], Vladimir Litvinenko,[1,4],
William Mackay[1], Christoph Montag[1],
Thomas Roser[1], Vitaly Yakimenko[2]


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], Jörg Kewisch[1], Vladimir Litvinenko[1], William Mackay[1], Christoph Montag[1], Thomas Roser[1], Vitaly Yakimenko[3]

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Content **page**

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RHIC

Outline: unique features

- Layout(s), ERL
- Beam parameters
- Luminosity : the values and the limits
- CM energies
- Polarization: the gun and spin dynamics
- Conclusion

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**

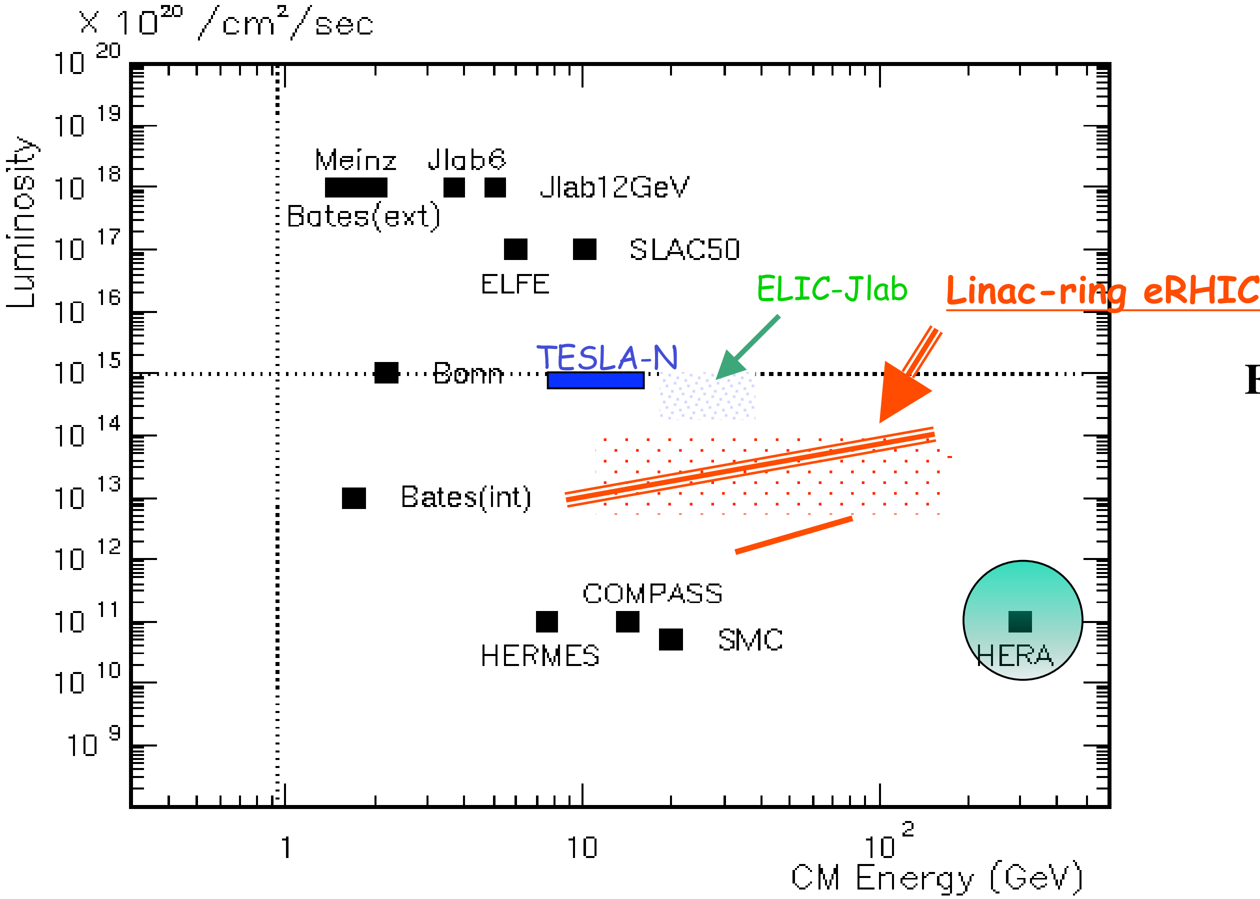
✓ **Polarization of electron and proton spins**

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

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

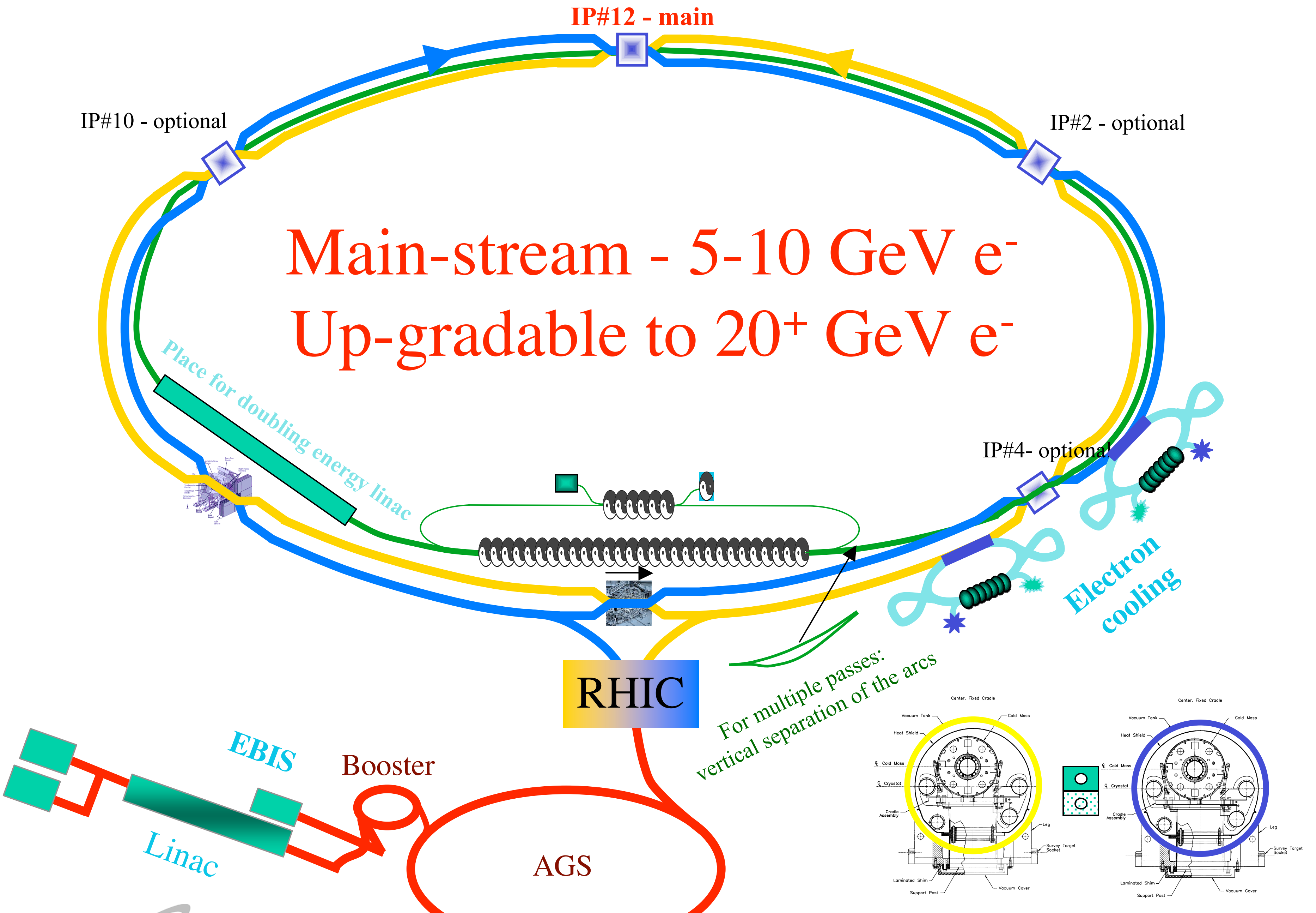
CM vs. Luminosity

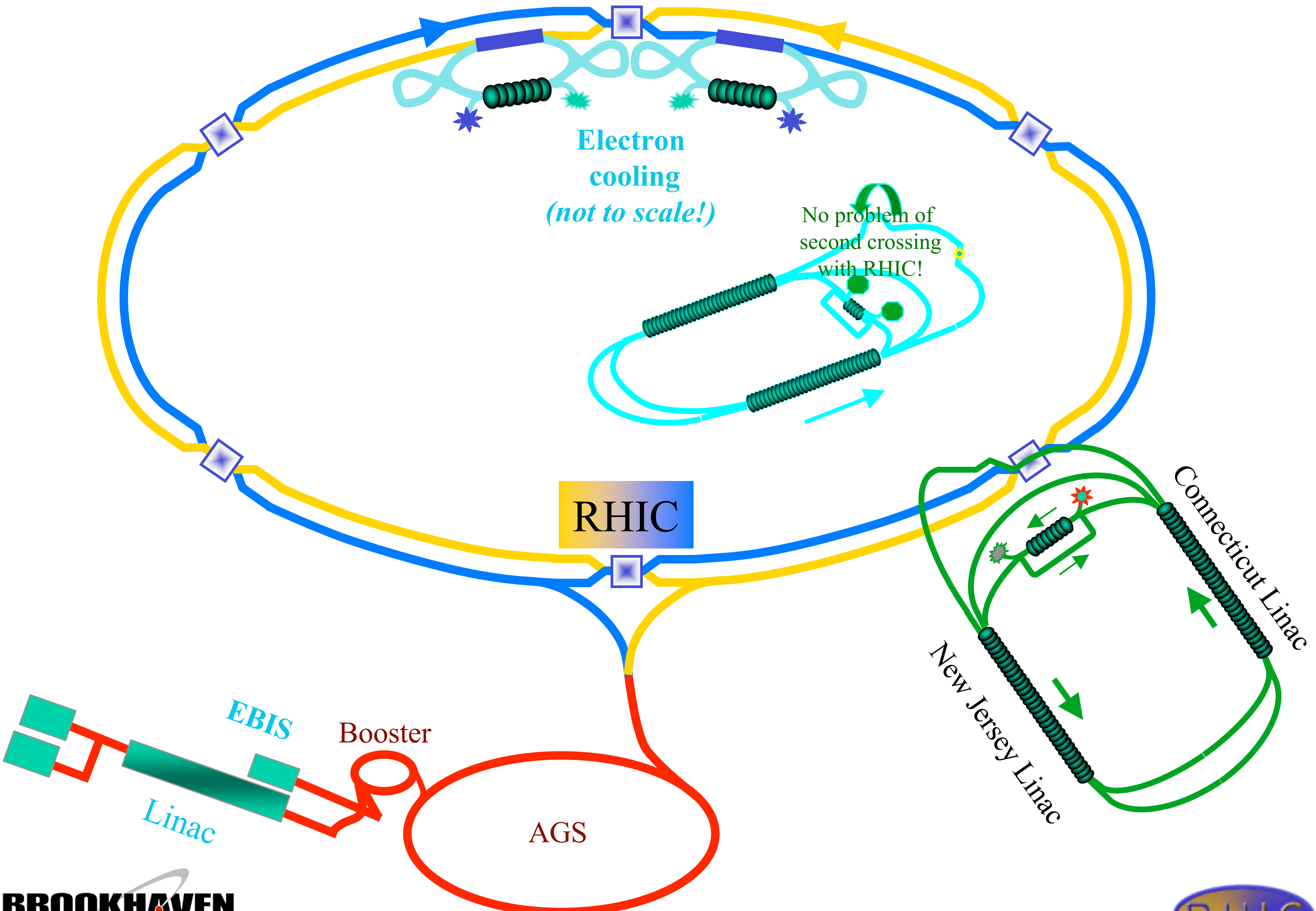
Modified: original is from Abhay Deshpande's talk at at EIC2004



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

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


IP#12 - main
IP#10 - optional
IP#2 - optional
Main-stream - 5-10 GeV e-
Up-gradable to 20+ GeV e-
Place for doubling energy linac
IP#4- optional
Electron cooling
For multiple passes: vertical separation of the arcs
RHIC
EBIS
Booster
Linac
AGS



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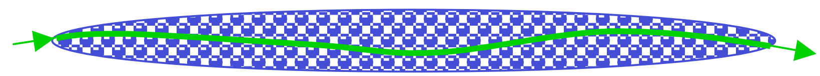
Beam parameters

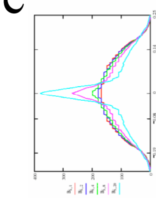
RHIC	main case	*option*
Ring circumference [m]	3834	
Number of bunches	360	
Beam rep-rate [MHz]	28.15	
Protons: number of bunches	360	*120*
Beam energy [GeV]	26 - 250	
Protons per bunch (max)	$2.0 \cdot 10^{11}$	*$6 \cdot 10^{11}$*
Normalized 96% emittance [μm]	14.5	
β* [m]	0.26	
RMS Bunch length [m]	0.2	
Beam-beam tune shift in eRHIC	0.005	
Synchrotron tune, Qs	0.0028 (see [2.4])	
Gold ions: number of bunches	360	*120*
Beam energy [GeV/u]	50 - 100	
Ions per bunch (max)	$2.0 \cdot 10^{9}$	*$6 \cdot 10^{9}$*
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]	28.15	*9.38*
Beam energy [GeV]	2 - 10	
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 – 0.45	*0.015 – 0.15*

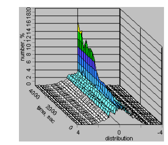
IP issues

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

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

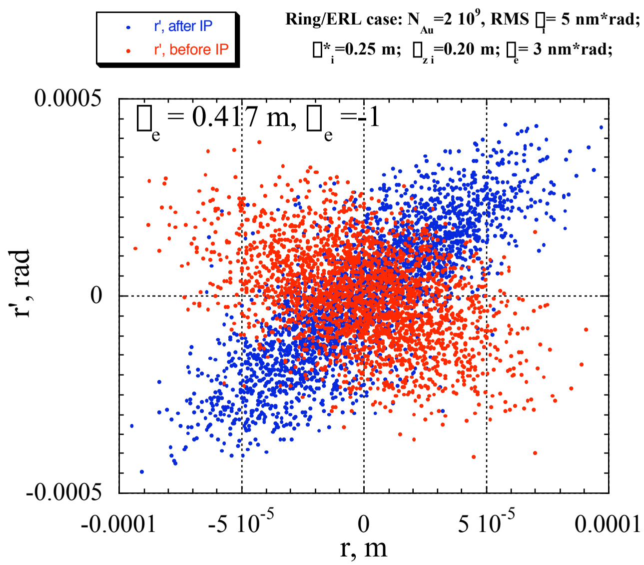






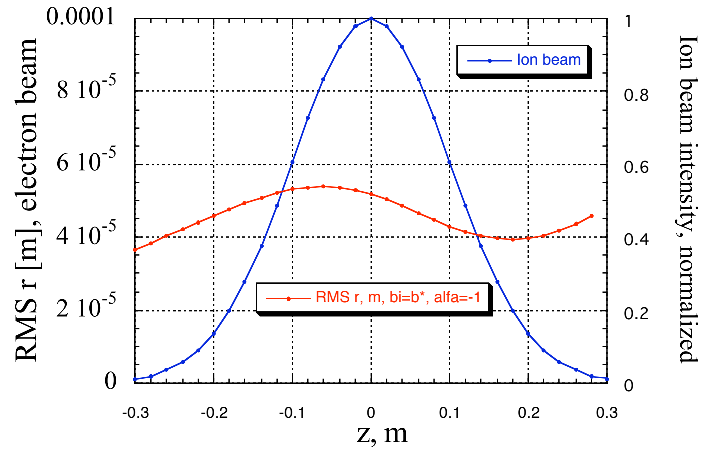
Does e-beam survives?

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

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

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

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

$$\xi_h \approx 0.024 \quad \Rightarrow \quad L_{p\,e} \approx 1 \cdot 10^{34}$$

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Luminosity is determined by the hadron beam!

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

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

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Linac-ring eRHIC

with present intensity of proton beam

RHIC	**Present Performance**	
Ring circumference [m]	3834	✔
Number of bunches	360	✔
Beam rep-rate [MHz]	4.69	✔
Protons: number of bunches	**60**	✔
Beam energy [GeV]	**250**	
Protons per bunch (max)	**$1.8 \cdot 10^{11}$**	✔
Normalized 96% emittance [μm]	14.5	✔
or	*5 (with e-cooling)*	
β* [m]	0.26	
RMS Bunch length [m]	0.2	✔
Beam-beam tune shift in eRHIC	**0.024**	dedicated mode*
Synchrotron tune, Qs	0.0028	✔
Electrons:		
Beam rep-rate [MHz]	4.69	
Beam energy [GeV]	2 - 10	
β*	0.8 m	
RMS Bunch length [m]	0.01	
Electrons per bunch	$4.7 \cdot 10^{11}$ (57 mm mrad)	
or	*$1.6 \cdot 10^{11}$ (19 mm mrad)*	
Average e-beam current [A]	0.36	
or	*0.12*	

$$L = \gamma_h \cdot \left(f_c \cdot N_h\right) \cdot \frac{\xi_h \cdot Z_h}{\beta_h^* \cdot r_h} = 1.41 \times 10^{33}$$

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Center-of-mass energies for linac-ring eRHIC

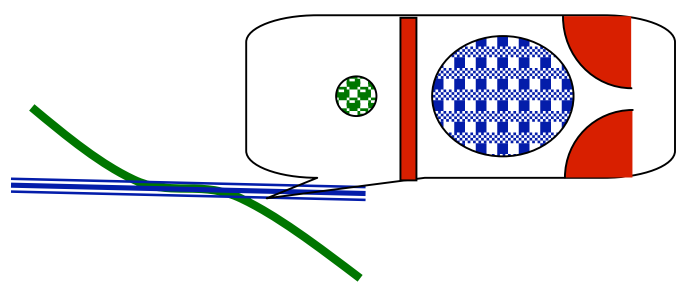
Energy, GeV **proton** **electons** c.m.	**26**	**50**	**100**	**250**
1	10.20	14.14	20.00	31.62
2	**14.42**	20.00	28.28	44.72
5	22.80	31.62	44.72	70.71
10	32.25	44.72	63.25	**100.00**
20	45.61	63.25	89.44	141.42
30	55.86	77.46	109.54	173.21

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

Integration with IP

$\Delta x = 12\sigma_{p,x} + \mathbf{5\sigma_{e,x}} + d\text{septum} = 12 \cdot 0.93\text{mm} + \mathbf{5 \cdot 0.25\text{mm}} + 10\text{mm} = 22.4\text{mm}.$

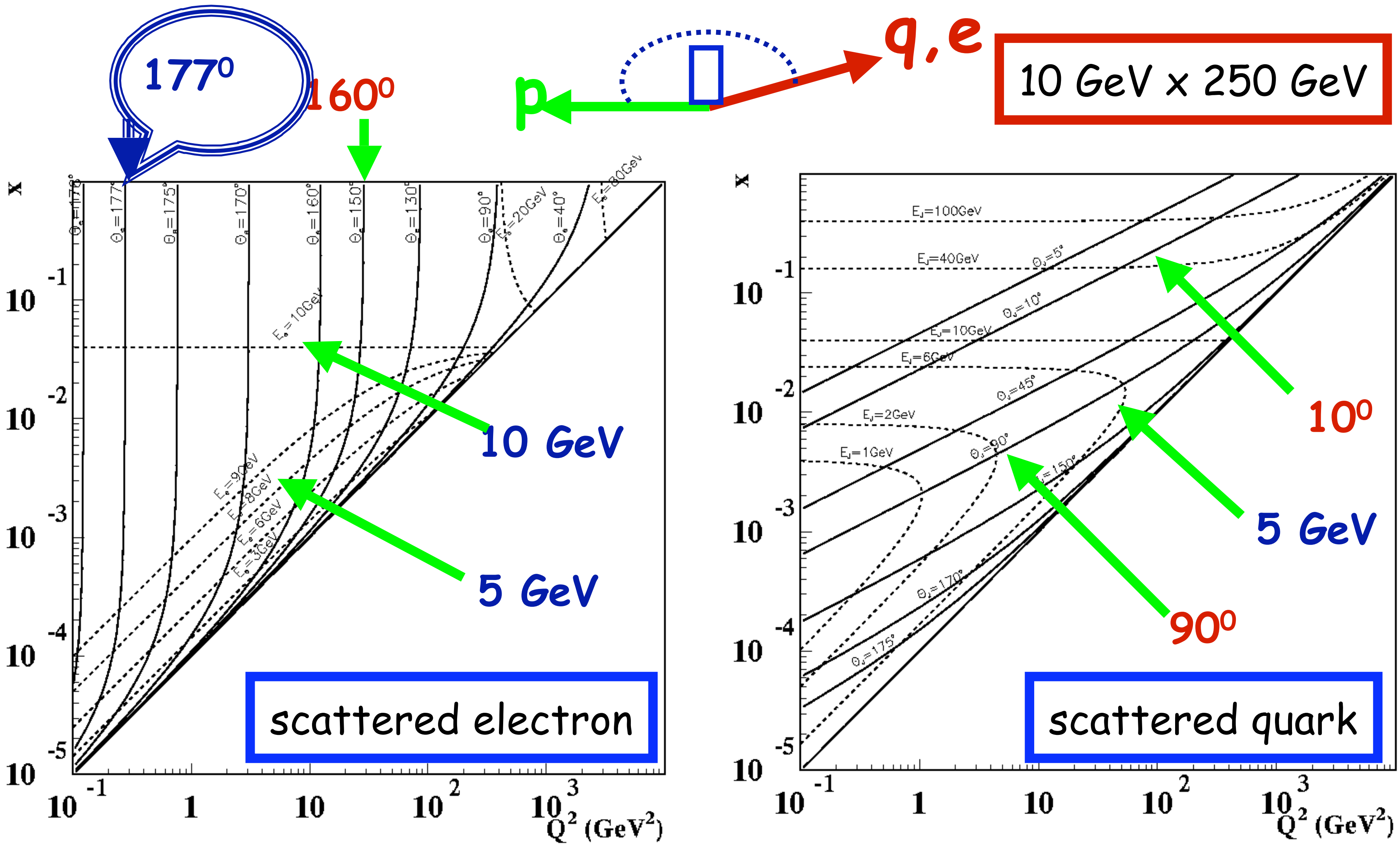
- Round-beam collision geometry to maximize luminosity
- Smaller e-beam emittance resulting in 10-fold smaller aperture requirements for the electron beam*
- Possibility of moving the focusing quadrupoles for the e-beam outside the detector and the IP region, while leaving the dipoles used for separating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



* C.Montag - IP lattice for linac-ring

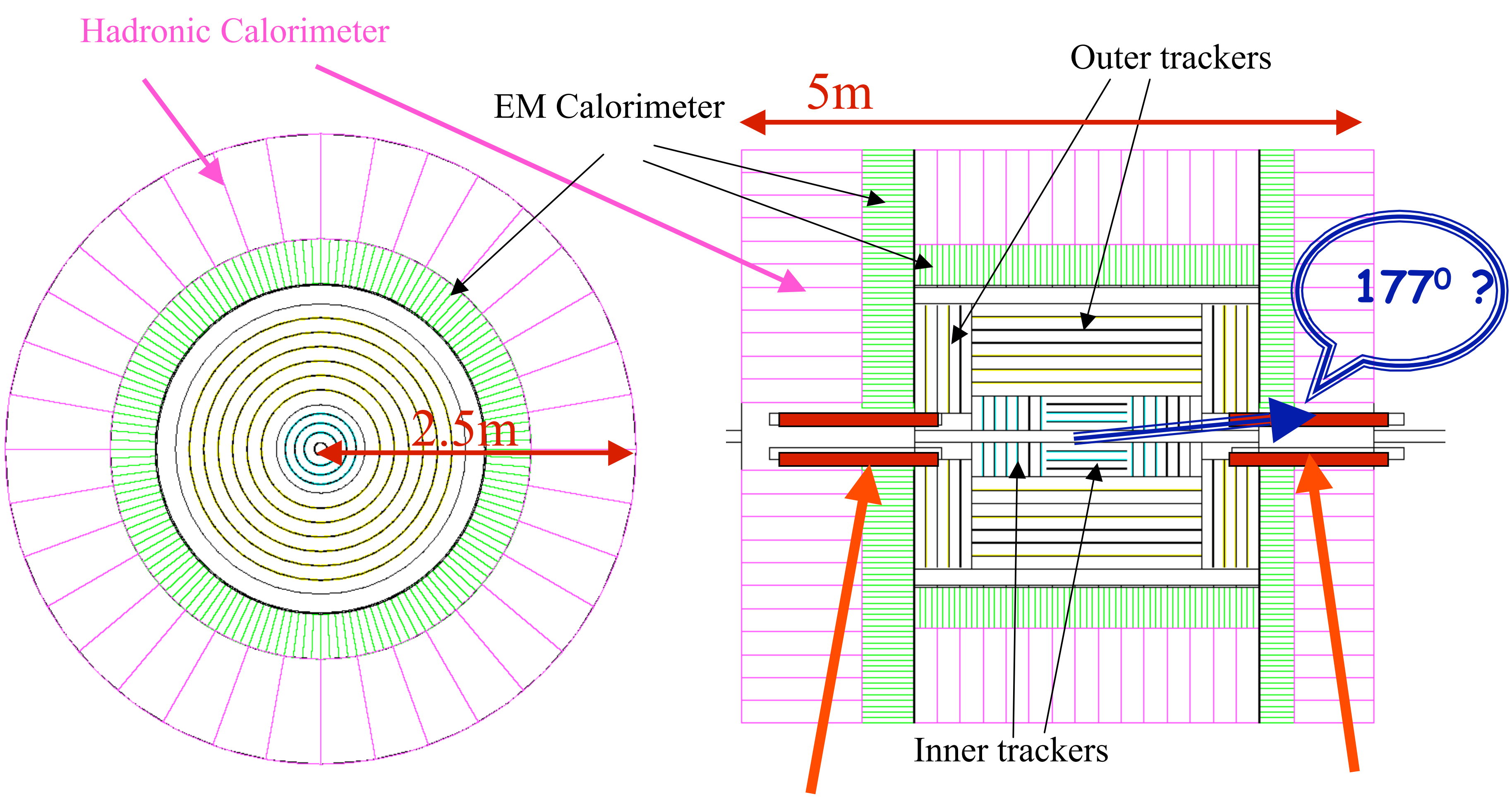
Where do electrons and quarks go?

© from Abhay Deshpande's talk at at EIC2004



Detector Design --- HERA like…

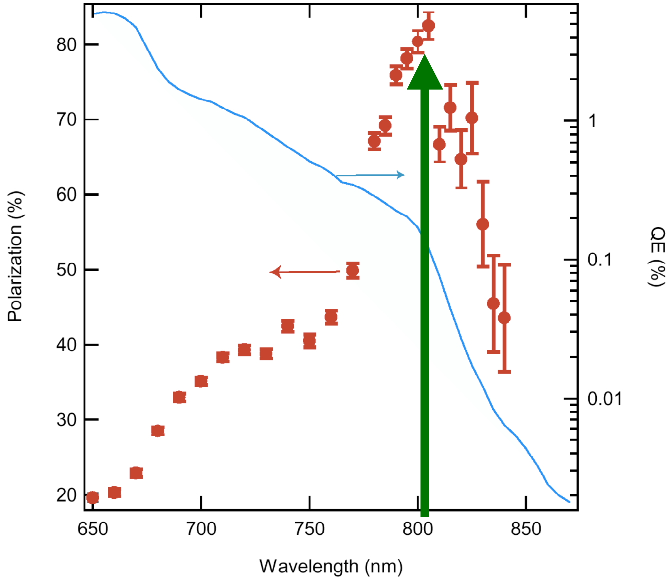
© from Abhay Deshpande's talk at at EIC2004

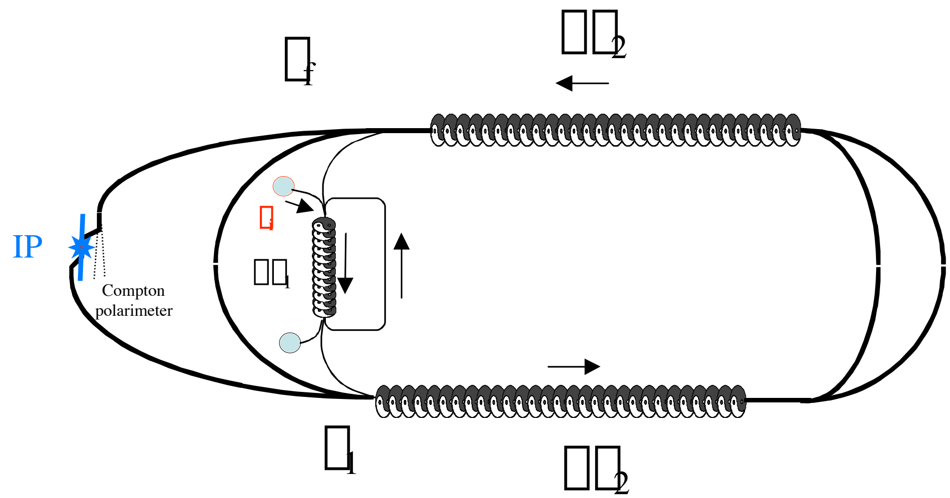


Nearest ring quadrupole: 1m ring-ring

5 m - linac-ring

Polarized electron gun and ERL spin dynamics





	NLC	JLC	TESLA	CLIC
Number of bunches/train	95	95	2820	154
Bunch spacing (ns)	2.8	2.8	337	0.66
DR energy GeV	1.98	1.98	5	1.98
Charge per bunch (nC)	2.56	1.9	3.2	1.0
Injected emittance (mm-mrad)	100	100	10	7
Damped beam emittance (h)	3	2.6	8	.43
Damped beam emittance (v)	0.03	0.004	0.02	0.003
Damped beam bunch length (ps rms)	13.3	16.6	20	10
Damping time (ms)	5.2	3.9	50	21
Damping cycles	4.8	4.8	4	6
Bunch trains per ring	3	3	1	12
Repetition rate (Hz)	120	150	5	100

- Wavelength [nm] — 815 ± 15
- Photon energy [eV] — 1.52
- Polarization — circular (left/right)
- Laser power [W] — 475 for 0.15% QE; 2,283 for 0.03% QE
- Mode of operation — CW
- Rep-rate — 28.15 MHz
- Energy per pulse [□J] — 17 - 844
- □-Pulse duration [psec] — 100 - 200
- Peak power [kW] — 170 – 8,440
- Stability
  - Pulse-to-pulse — < 0.1%
  - Long term — < 1%

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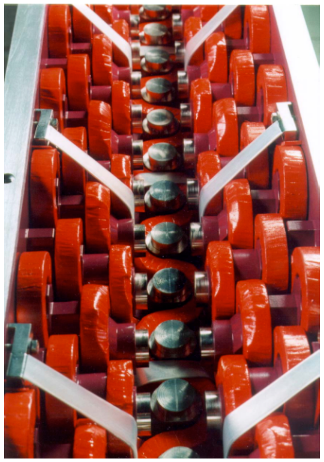
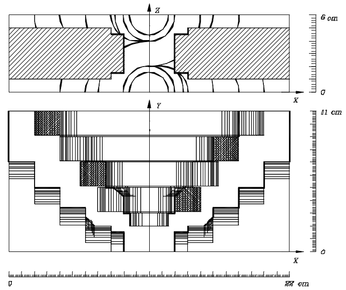
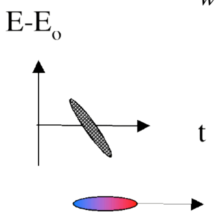
FEL for polarized gun:

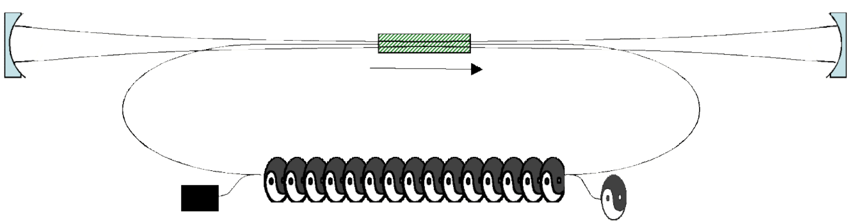


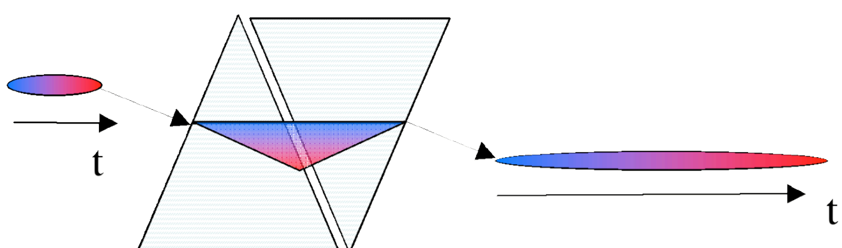


$$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1 + K_w^2\right)$$

$$K_w = \frac{eB_w\lambda_w}{2\pi mc^2}$$







Electron beam	
Energy [MeV]	**160**
Beam current (mA)	**5**
Beam Power (kW)	800
FEL ext. efficiency	up to 0.75%
FEL power (kW)	**up to 6, nominal - 2**
Charge/bunch (pC)	180
Rep. Rate (MHz)	28.15
Wiggler	
Type	helical with switchable helicity
Length [m]	2 x 0.9
Period, λ_w [cm]	6
Aperture [cm]	1
Wiggler parameter, K_w	1.29 - nominal (tunable within 0-1.5)
Peak magnetic field [T]	0.230 (tunable within 0-0.265)
Laser light	
Wavelength, λ [nm]	815, nominal, (tunable within 400 – 1000 nm
Chirp [nm/psec]	5
Polarization	**100% circular (left/right)**
Spot-size in FEL[cm^2]	0.0020
that the mirror [cm^2]	2.08
□-Pulse duration [psec]	5 (chirped)
Optical cavity	
Length [m]	31.8926
Radius of curvature [m]	15.962
Rayleigh range [m]	0.5
Out-coupling	10%
Intracavity power [kW]	60
CW Power density [kW/cm^2]	30 at the mirror
Peak Power density [MW/cm^2]	205 at the mirror
Laser pulse stretcher	
Input pulse duration [psec]	5, chirp 5 nm/psec
Wavelength [nm]	*815*
Chrip [nm/psec]	*5*
Dispersion section [psec/nm]	20 –40
Input pulse duration [psec]	100 -200

Spin motion

Bargman, Mitchel,Telegdi equation

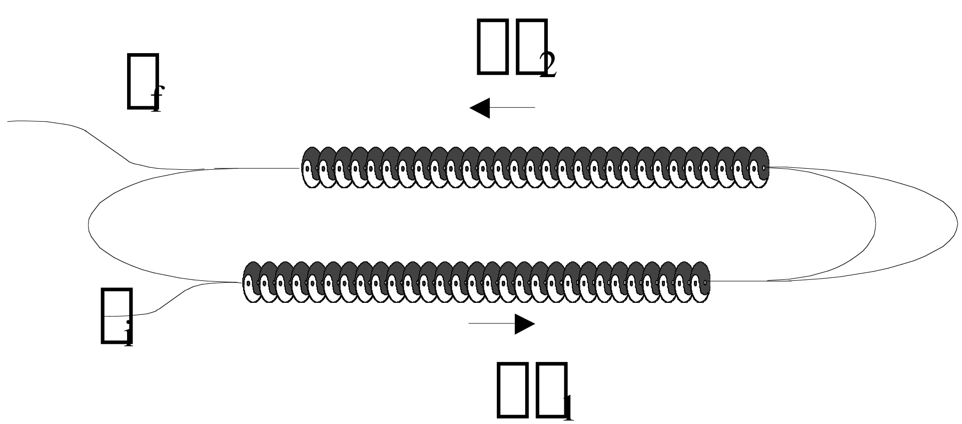
$$\frac{d\hat{s}}{dt} = \frac{e}{mc}\hat{s} \times \left[\left(\frac{g}{2} - 1 + \frac{1}{\gamma}\right)\vec{B} - \frac{\gamma}{\gamma+1}\left(\frac{g}{2} - 1\right)\vec{\beta}\left(\vec{\beta}\cdot\vec{B}\right) - \left(\frac{g}{2} - \frac{\gamma}{\gamma+1}\right)\left[\vec{\beta} \times \vec{E}\right]\right]$$

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

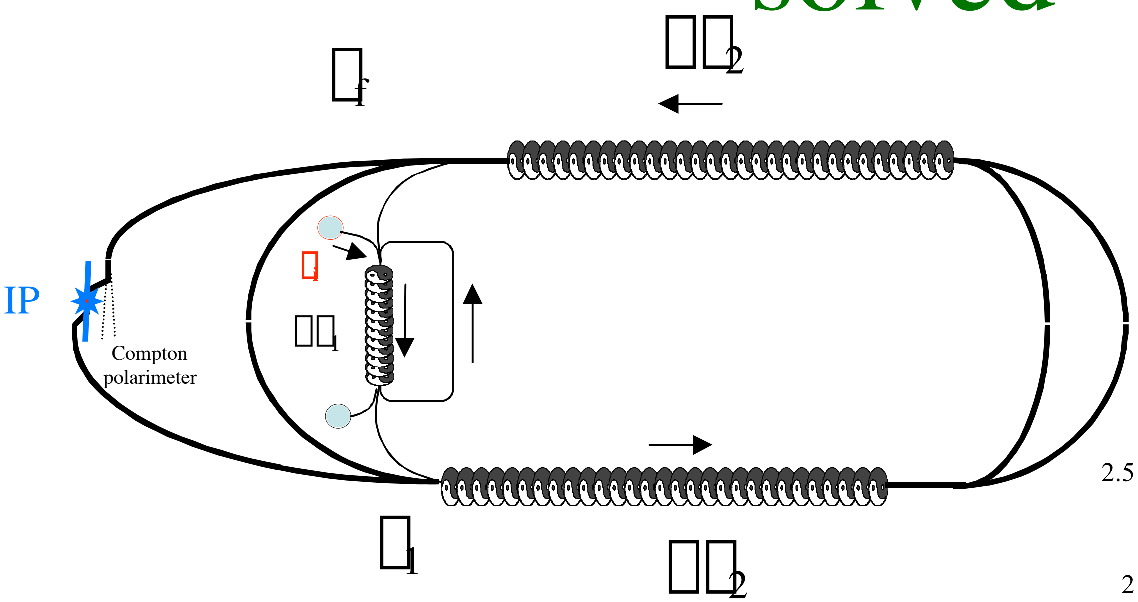
$$\vec{\Omega} = \frac{g}{2}\frac{e}{m_o}\hat{s} = (1+a)\frac{e}{m_o}\hat{s}; \qquad \nu_{spin} = a\cdot\gamma = \frac{E_e}{0.44065[GeV]}$$

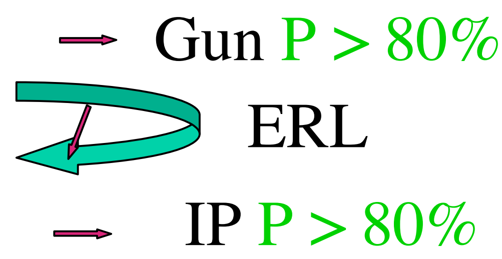
$$\Delta\varphi = a \cdot \pi\gamma$$ in a π-arc

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



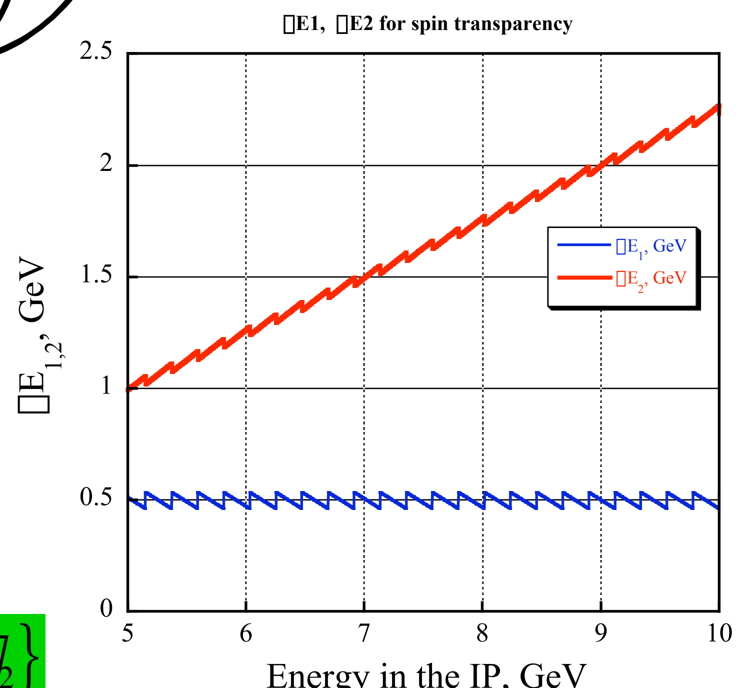
Energy independent spin control - solved





□□/□	□
-1/12	□□
2	□□ + □□1
1/2	□□ + 2 □□1
1	□□ + 2 □□1 + 1 □□2
1	□□ + 2 □□1 + 2 □□2
1	□□ + 2 □□1 + 3 □□2
1/2	□□ + 2 □□1 + 4 □□2

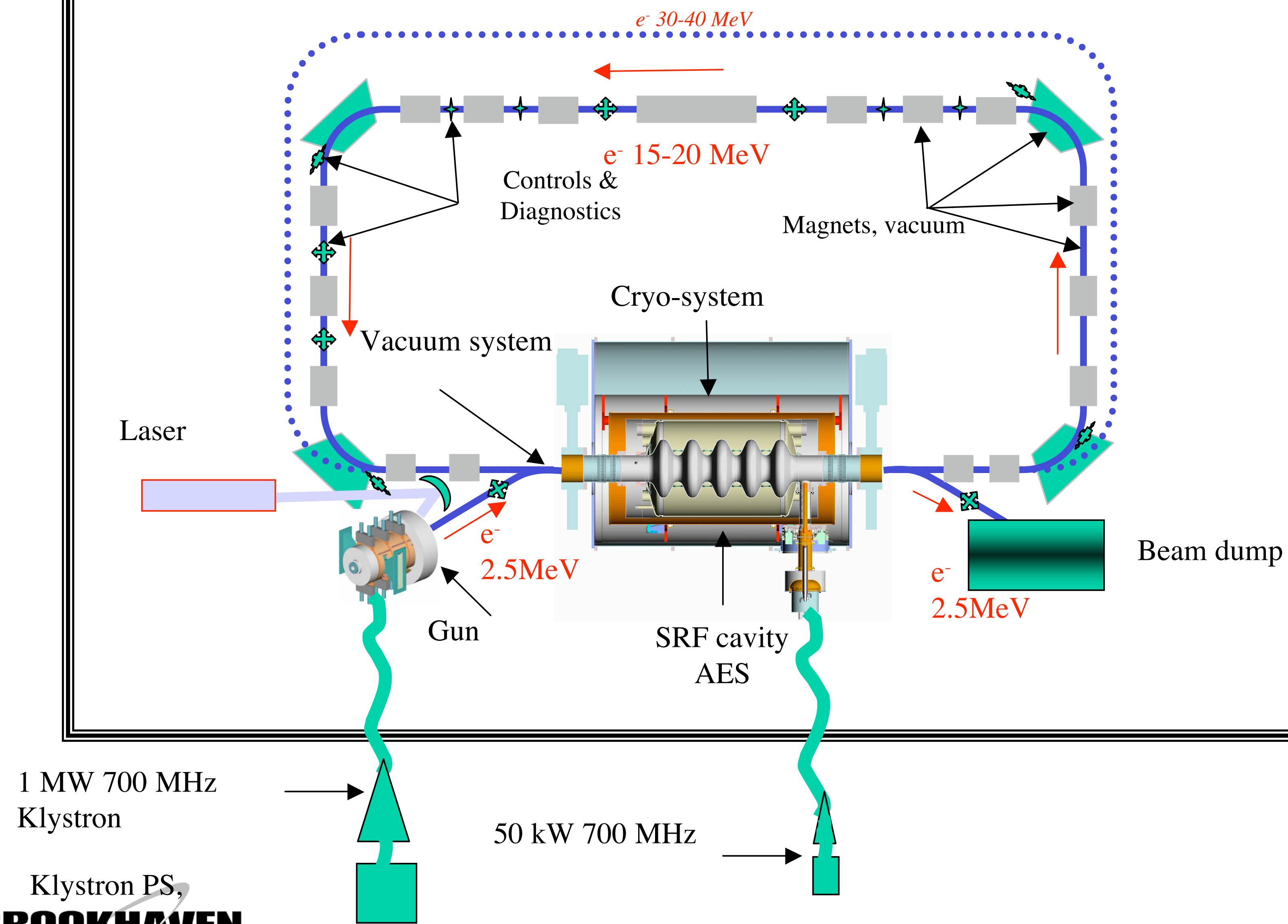
$$\square = a \square \square\square_k \square_k = \square a\left\{(6 \square 1/12)\square_i + 10\square\square_1 + 8\square\square_2\right\}$$



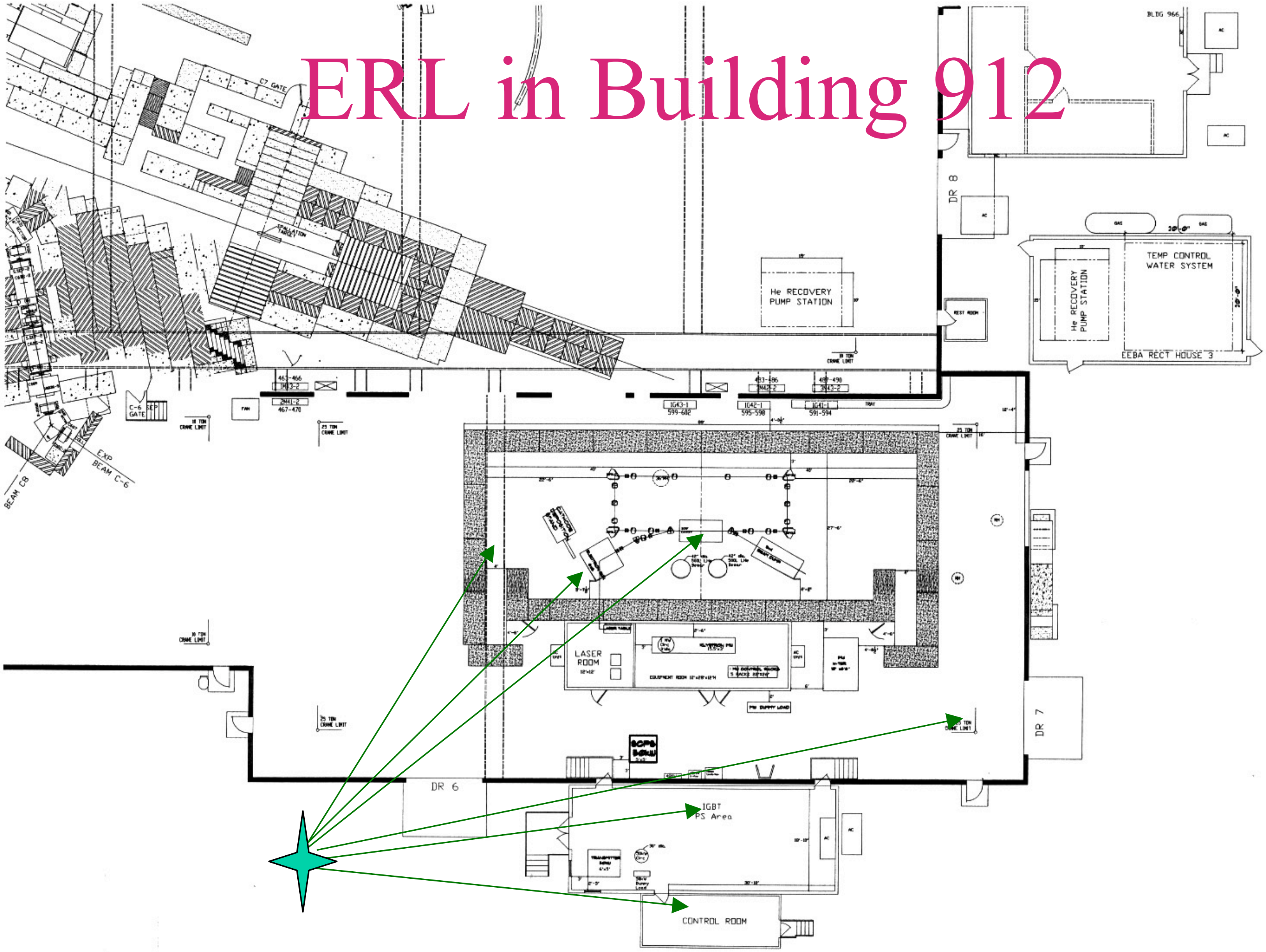
Limitations and challenges

- No positron-ion collisions (*in present state…*)
- Need for intense R&D program on
  - High intensity, high current polarized electron source
  - High current ERL (on-going program)

R & D item #1 - Bldg. 912



ERL in Building 912



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Milestones of the ERL prototype projects

Task Name	Start	Finish	2004 H1	2004 H2	2005 H1	2005 H2	2006 H1	2006 H2	2007 H1
e-CX/ERL Project	3-Feb-03	15-Mar-07							
Develop the 5-cell RF cavity shape	3-Feb-03	30-Nov-05							
Assemble SRF Cavity & Associated Components	3-Oct-05	4-Dec-05							
Electron Gun Procurement	3-Feb-03	6-Jan-06							
Photocathode System Procurement	3-Feb-03	23-Mar-06							
Assemble & Test of RF Gun & Associated Systems	2-Feb-04	4-Apr-06							
Design & Procurement of ERL Vacuum System	10-Jan-05	8-Mar-06							
Beam Dump Procurement	1-Oct-03	25-Aug-05							
Assemble Photocathode, RF Gun, Cavity & Beam Dump for test	24-Aug-05	25-Sep-06							
Design & Procurement of ERL Magnetic System	8-Jan-04	2-Nov-06							
ERL installation	26-Sep-06	15-Mar-07							
Building 912 Facility modifications for ERL	3-Feb-03	15-Feb-06							
ERL commissioning	1-Mar-07								

Conclusions: It is feasible - Needs R&D

- Wide range of collision energies (E_{cm}/nucleon from 15 GeV to 100+ GeV. e^- energy as low as 1 GeV as high as 25 GeV).
- High luminosity ➡ 10^{34} cm^{-2} s^{-1} for high energy protons,
  ➡ 10^{32} cm^{-2} s^{-1} for high energy Au ions.
- High degree of polarization (>80%) of the electrons at any energy, **no forbidden energies**.
- One, two, three … interaction regions with dedicated detectors
- Energy of electron is simply upgradeable.
- Reduction of synchrotron radiation in detector by cooling ions.
- **No quadrupoles in detector.**
- Simple compensation for ion velocity.
- Possibility of □-ion collider.