Unique features of linac-ring eRHIC

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Outline

- Layout(s), ERL ➜Detector without quads!
- CM energies
- Beam parameters
- Luminosity : the values and the limits
- Polarization: the gun and spin transparency
- 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.,

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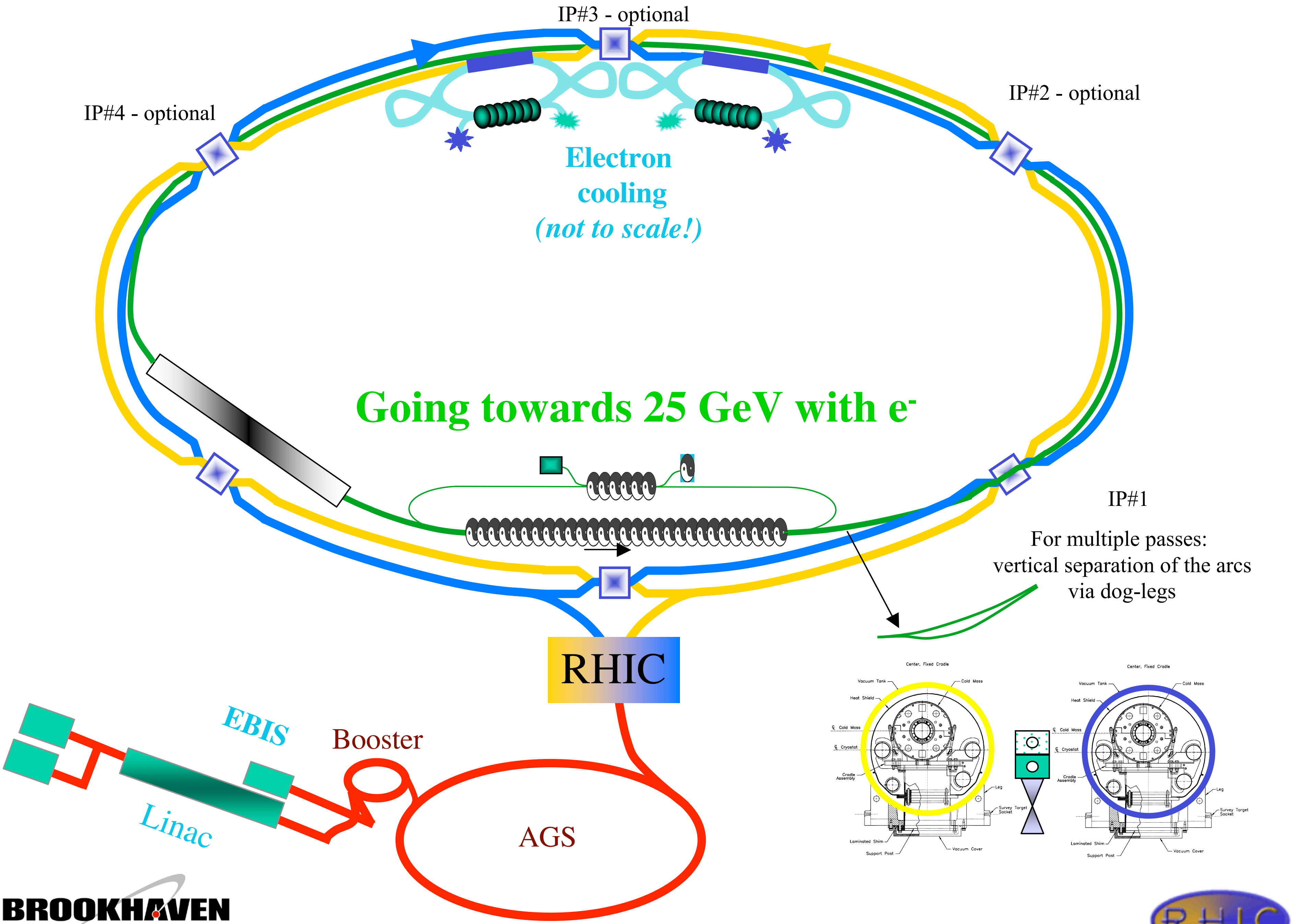
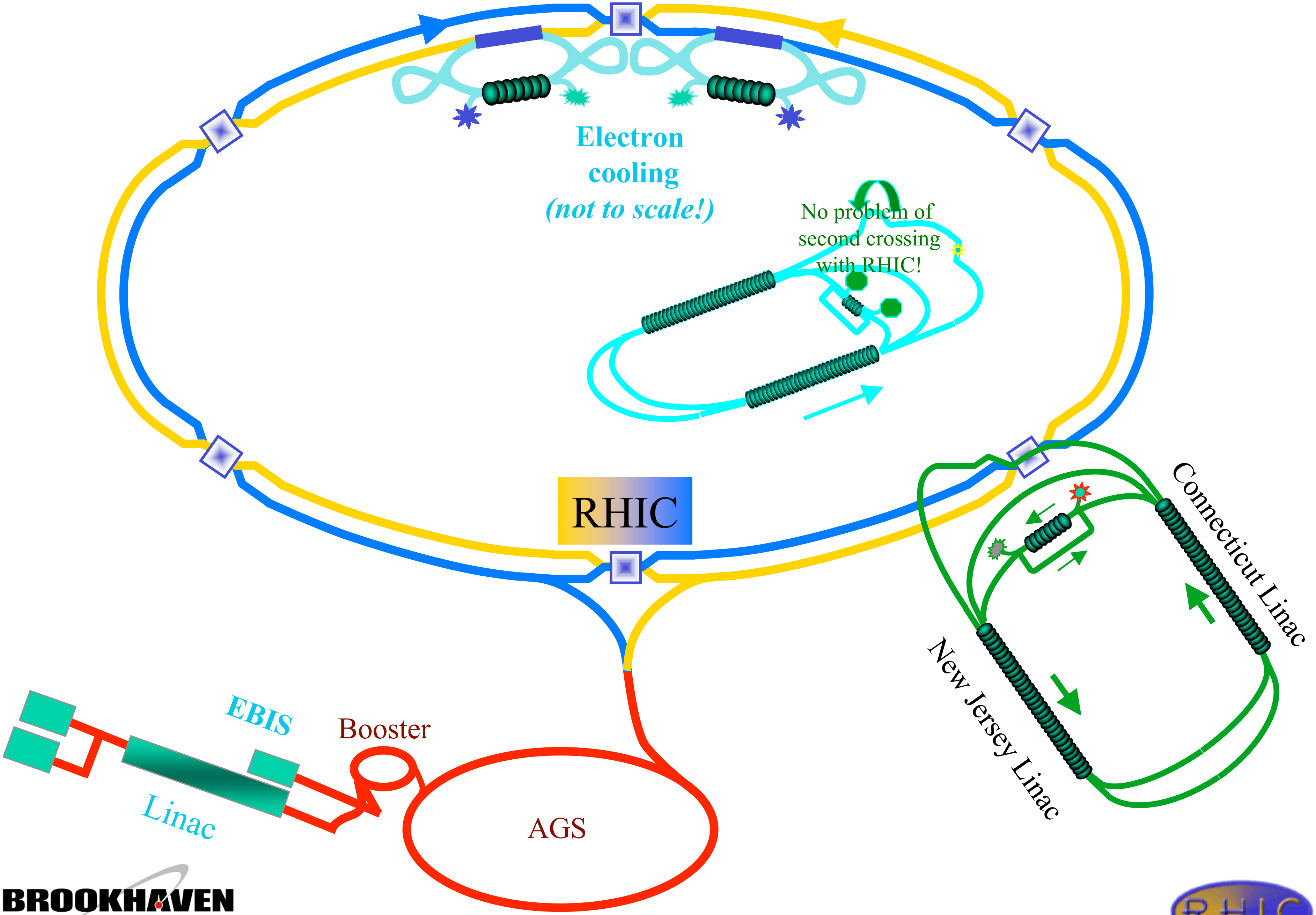
Going towards 25 GeV with e^-



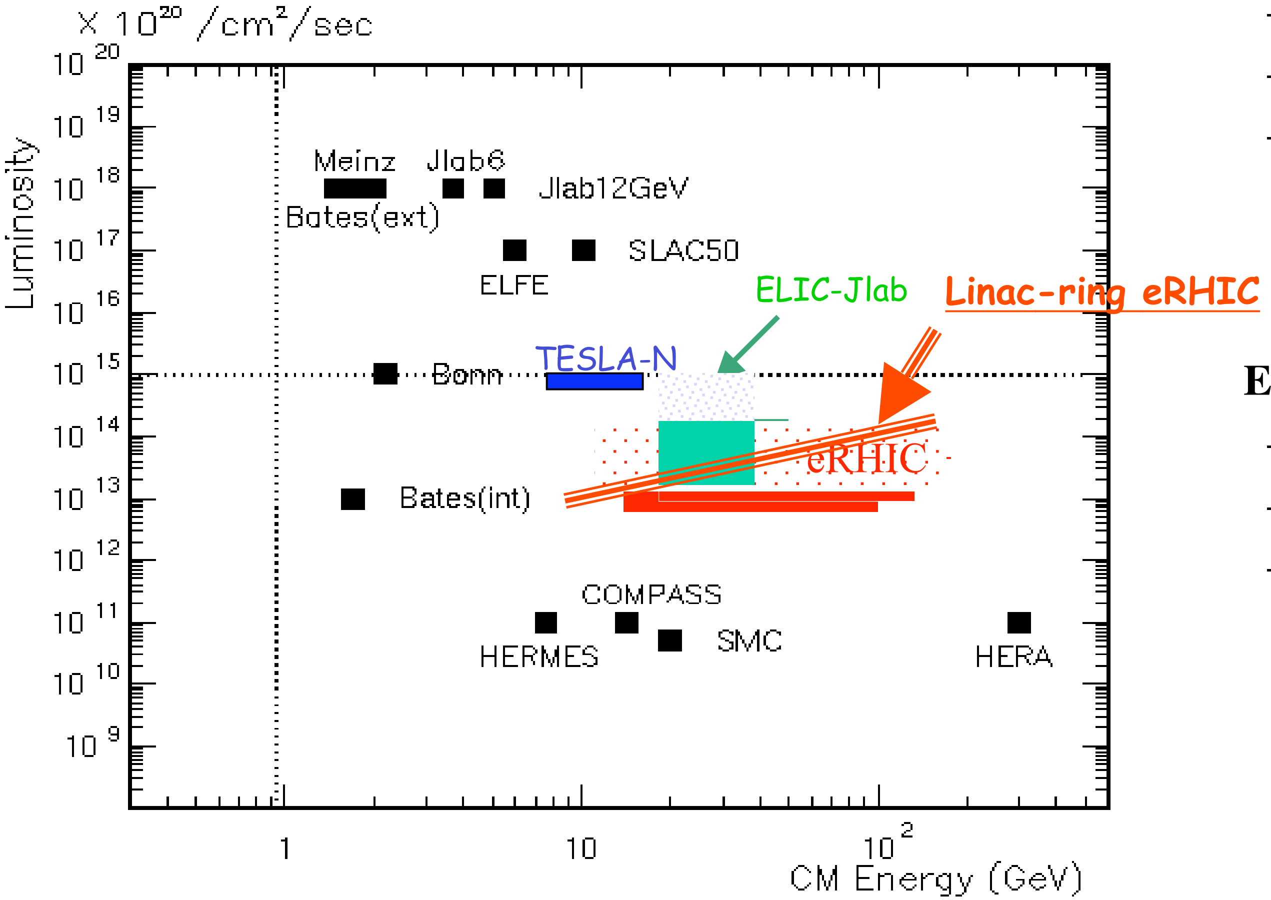
Electron cooling
(not to scale!)

For multiple passes:
vertical separation of the arcs
via dog-legs


Electron
cooling
(not to scale!)
No problem of
second crossing
with RHIC!
RHIC
Connecticut Linac
New Jersey Linac
EBIS
Booster
Linac
AGS

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

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*

Luminosity is determined by the hadron beam!

$$L = f_c \frac{N_e N_h}{4 \square \square_h^* \square_h}$$

Round beams $\square_e^* \square_e = \square_h^* \square_h$

$$L = \square_h \cdot \left(f_c \cdot N_h \right) \cdot \frac{\square_h \cdot Z_h}{\square_h^* \cdot r_h}$$

$$\square_h = \frac{N_e}{\square_h} \frac{r_h}{4 \square Z \square_h} = 0.005$$

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

$$\square_h \; \square \; 0.024 \quad \square \quad L_{p\;e} \; \square \; 1 \cdot 10^{34}$$

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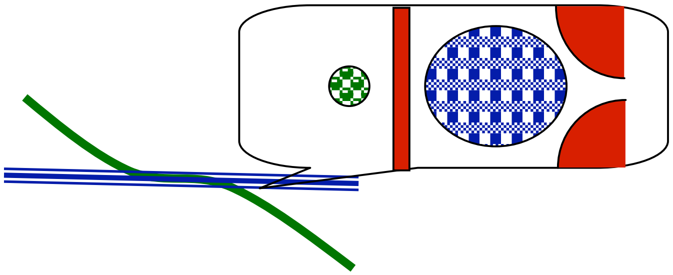
Integration with IP

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

- 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



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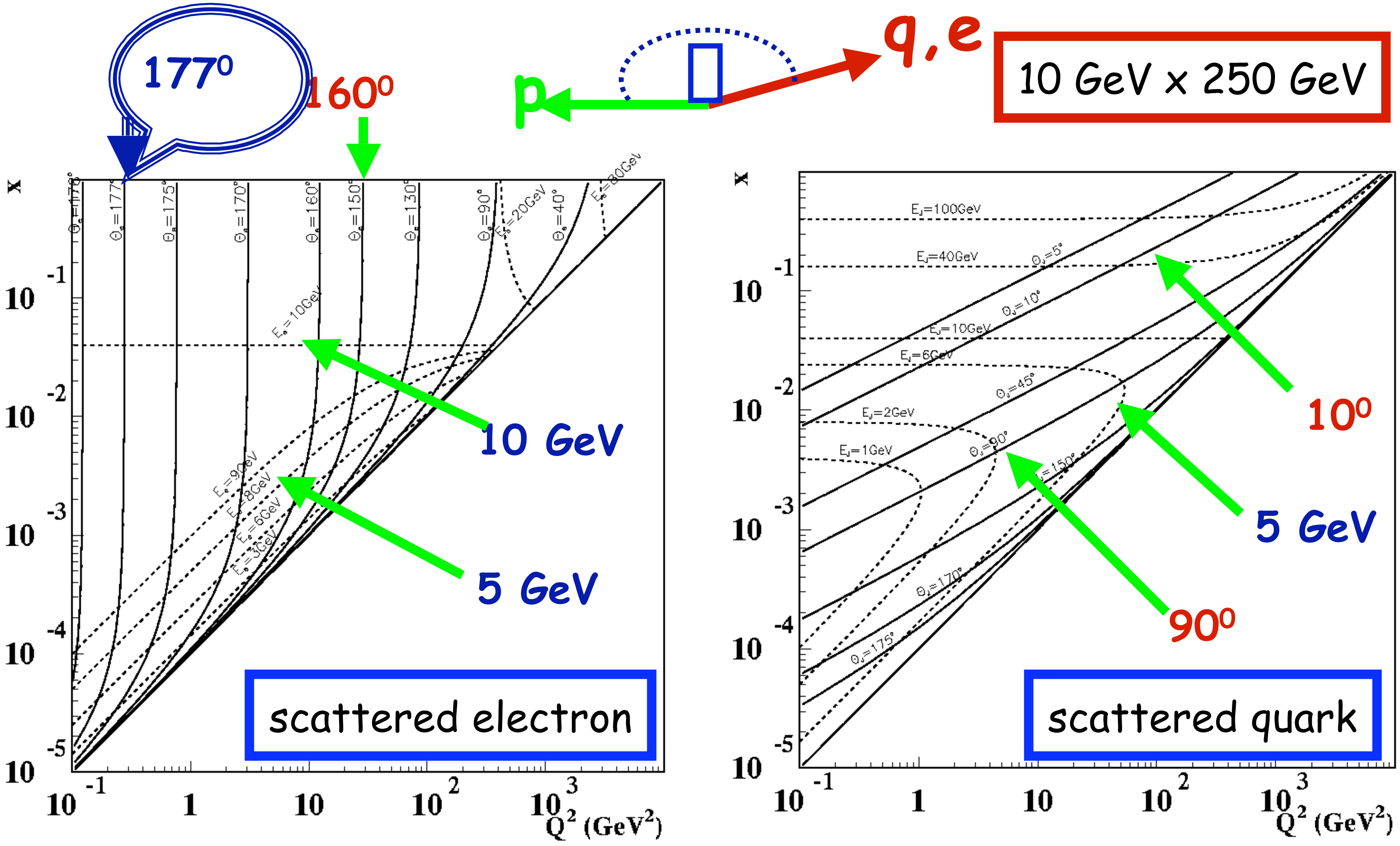
* C.Montag - IP lattice for linac-ring

Where do electrons and quarks go?

© from Abhay Deshpande's talk at at EIC2004

10 GeV x 250 GeV



Detector Design --- HERA like…

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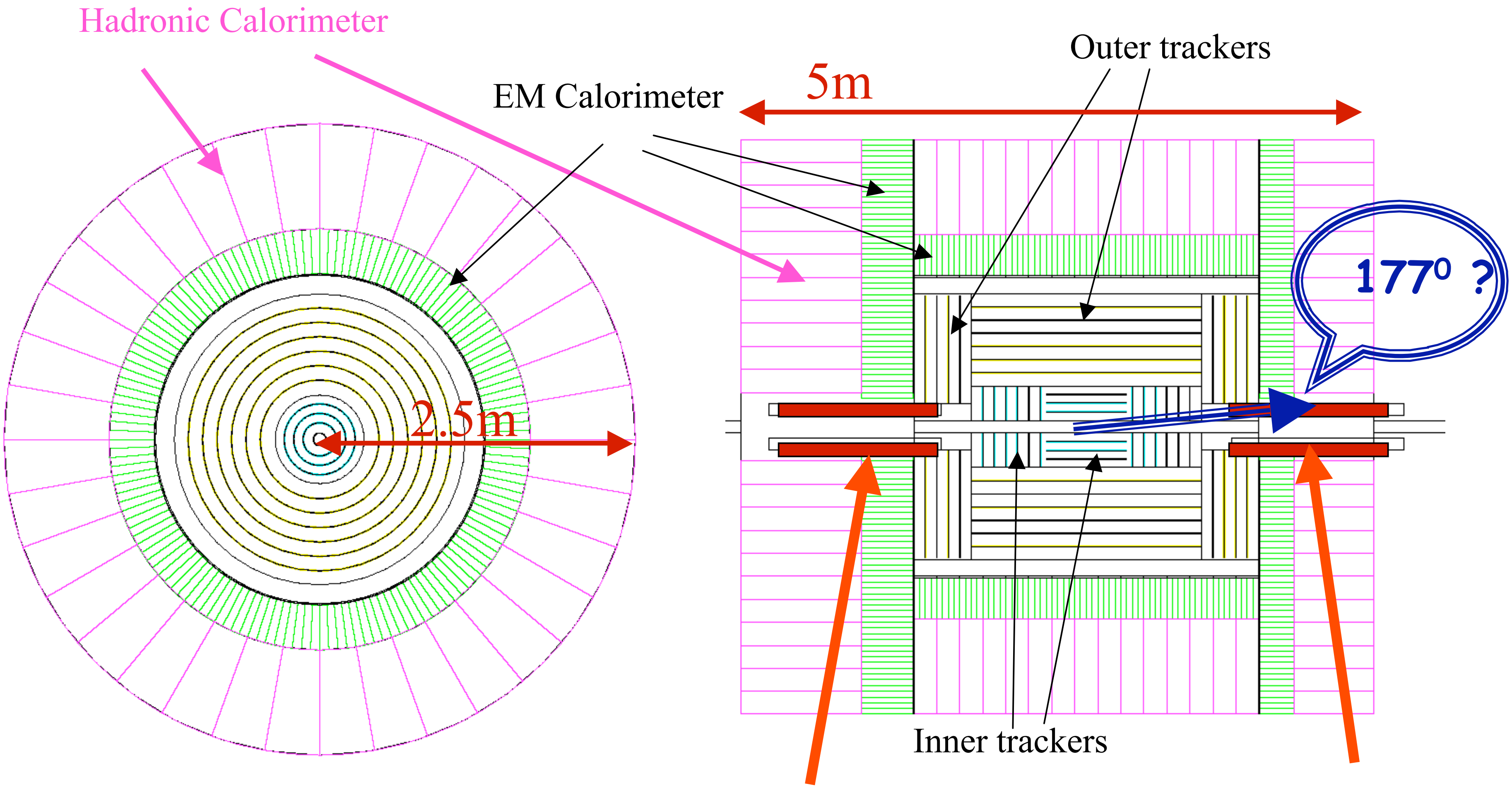


Hadronic Calorimeter

Outer trackers

5m

EM Calorimeter

177^0 ?

2.5m

Inner trackers

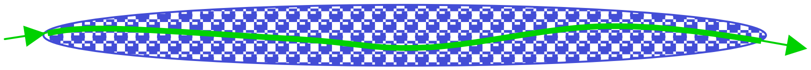
Nearest ring quadrupole: 1m   ring-ring

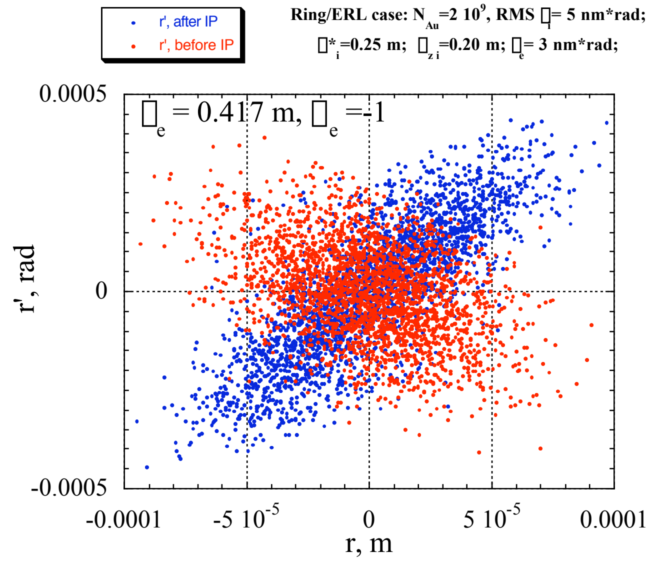
5 m - linac-ring

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



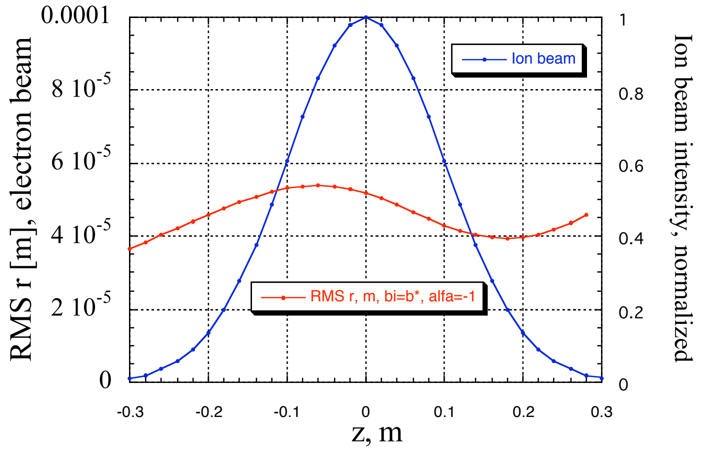


Round 10 GeV electron beam from ERL with initial transverse RMS emittance of 3 nm·rad passes through the IP with the disruption parameter 3.61 (**tune shift ξ_e = 0.6**). Poincare plots for e-beam distribution before (red) and after (blue) the IP.

After removing the *r-r'* correlations, the emittance growth is only 11%.

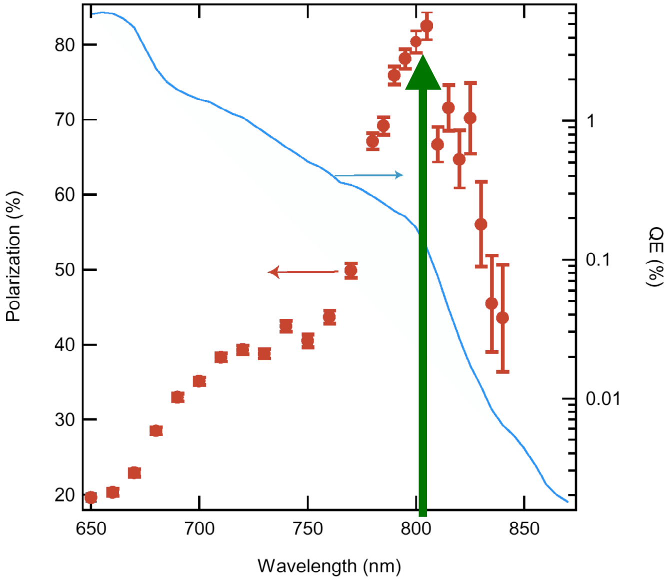
Does e-beam survives?

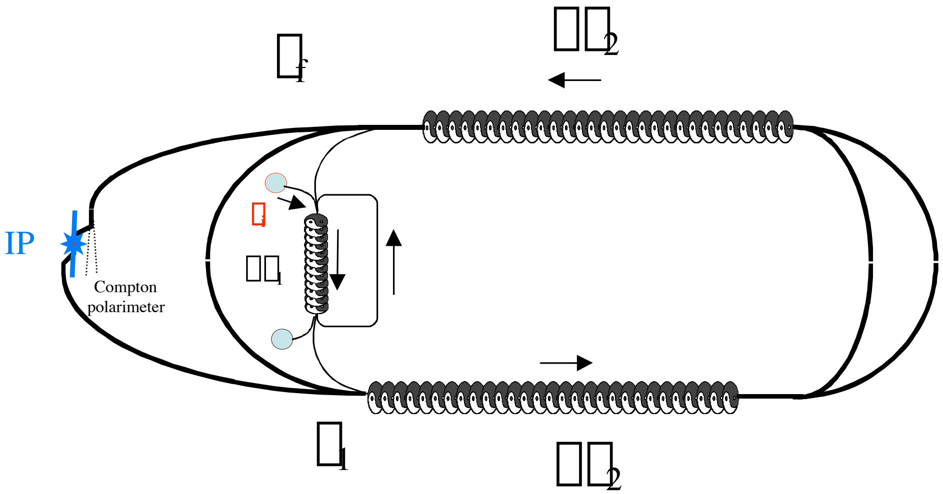
YES



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**

Polarized electron gun and ERL spin transparency

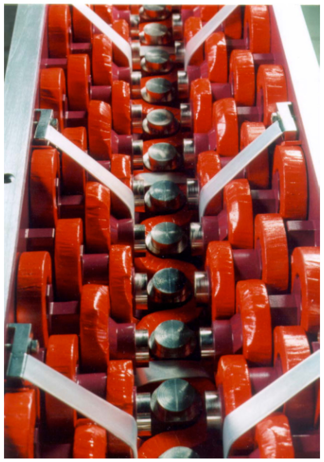


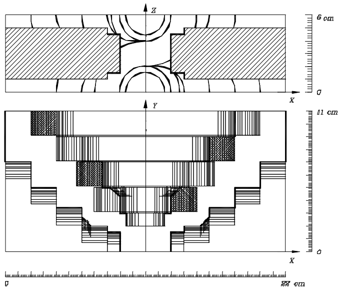


	NLC	JLC	TESLA	CLIC
Number of bunches/train	95	95	2820	154
Bunch spacing (ns)	2.8	2.8	337	0.66
DR energy GeV	1.98	1.98	5	1.98
Charge per bunch (nC)	2.56	1.9	3.2	1.0
Injected emittance (mm-mrad)	100	100	10	7
Damped beam emittance (h)	3	2.6	8	.43
Damped beam emittance (v)	0.03	0.004	0.02	0.003
Damped beam 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%	

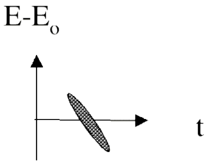
FEL for polarized gun:

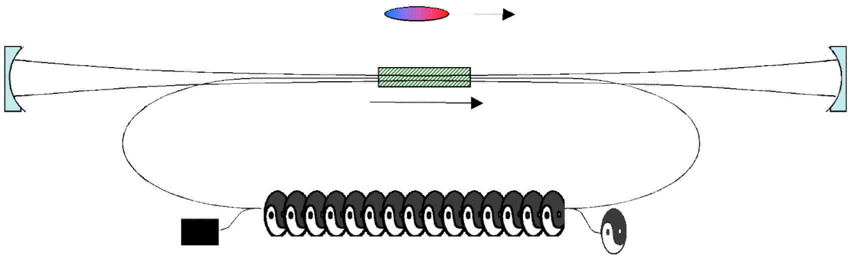


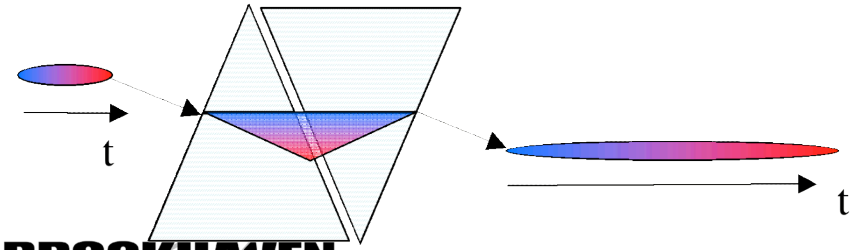


$$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1 + K_w^2\right)$$

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







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

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

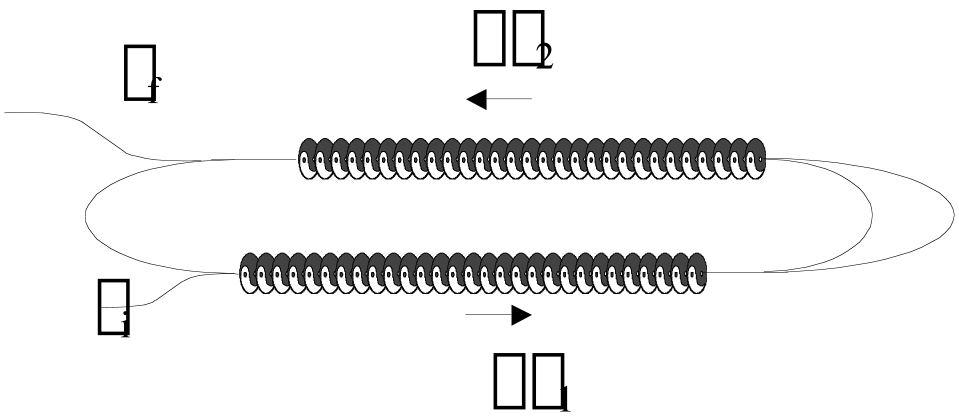
$a = g/2 - 1 = 1.1596521884 \cdot 10^{-3}$

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

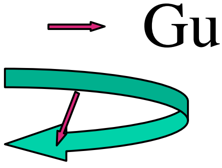
$$\Delta\varphi = a\cdot\pi\gamma$$

in a π-arc

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



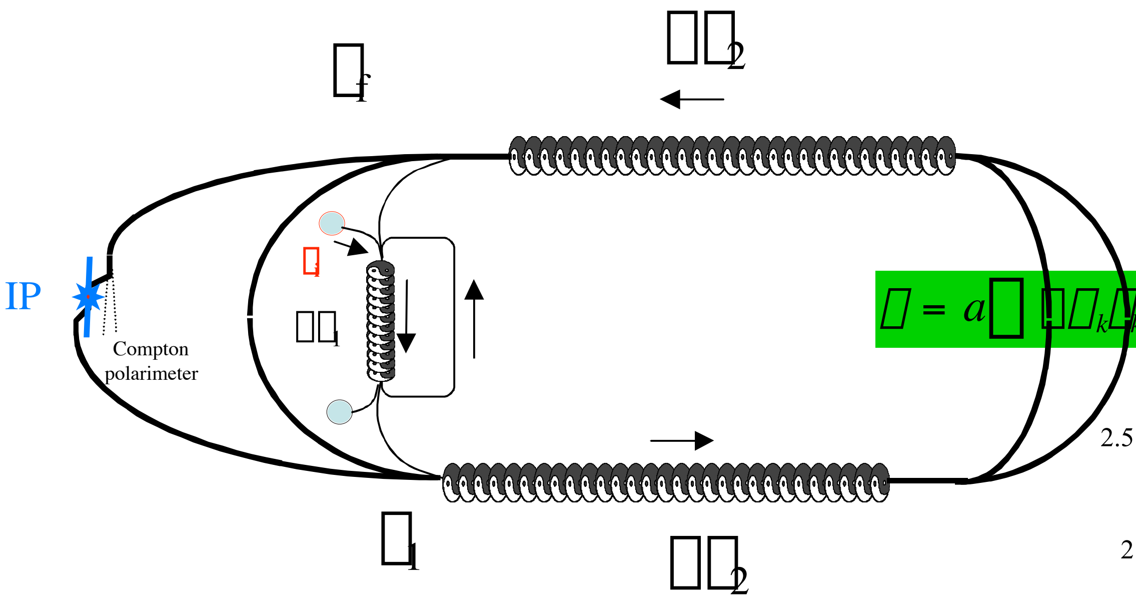
Spin transparency - solved



Gun P > 80%

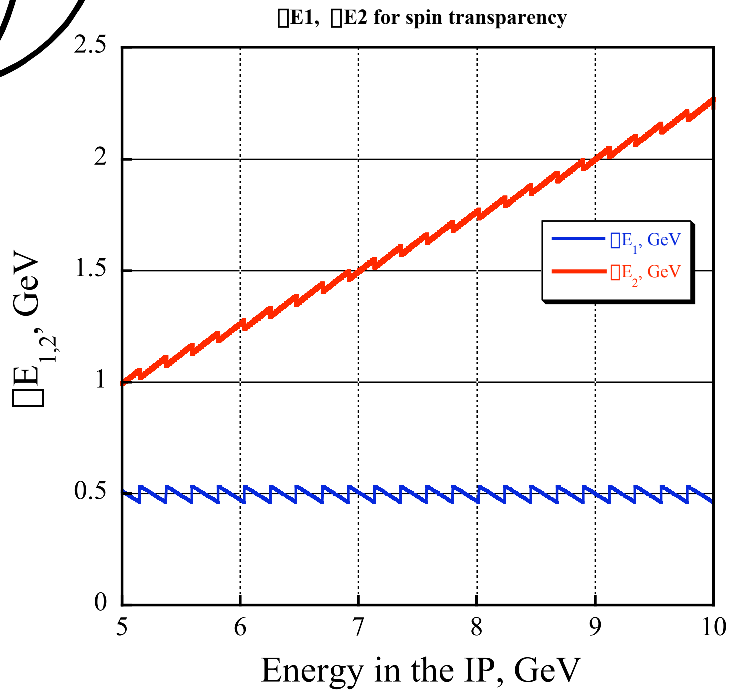
ERL

IP P > 80%



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

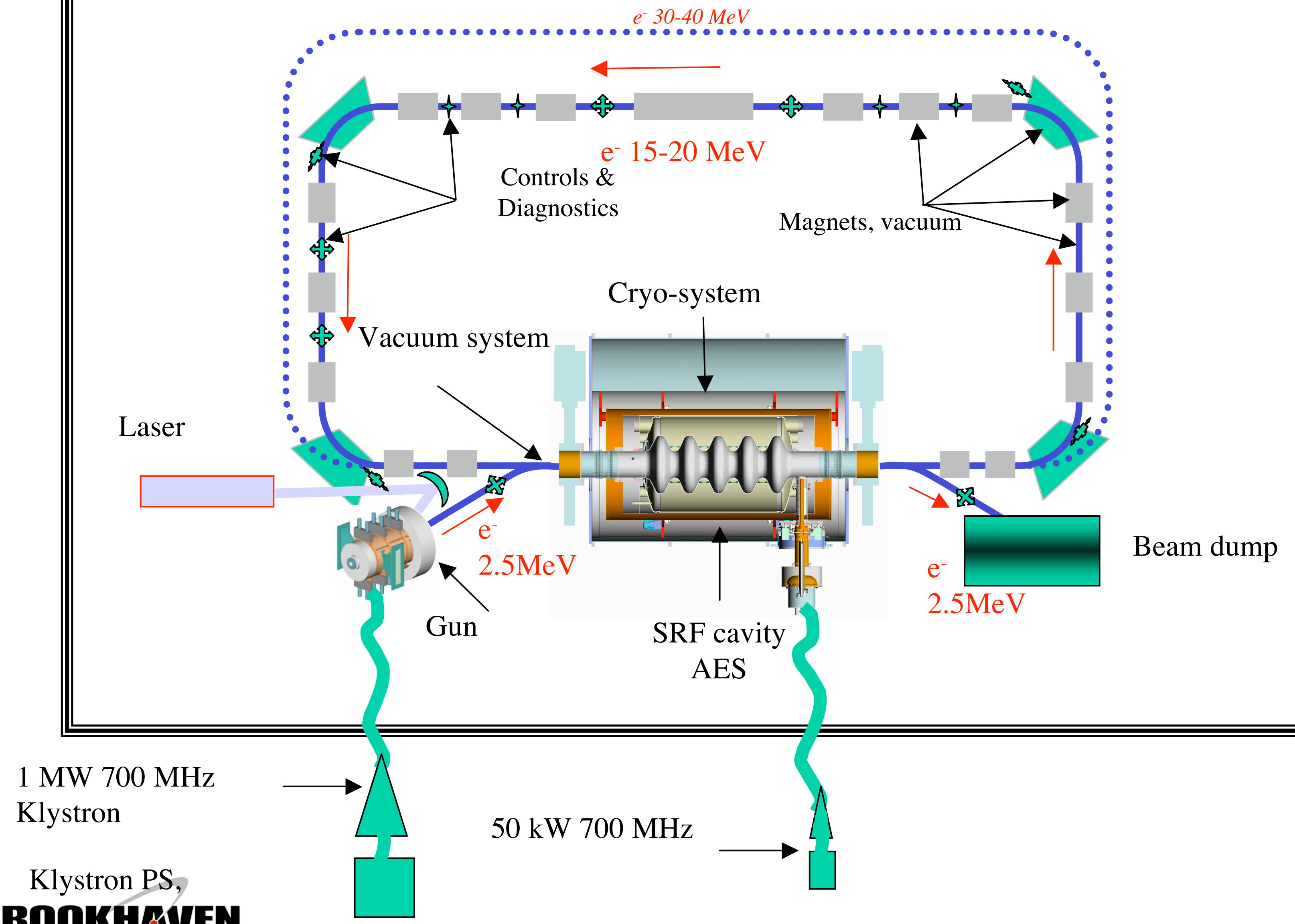
□□/□	□
-1/12	$\square_\square$
2	$\square_\square + \square\square_1$
1/2	$\square_\square + 2\,\square\square_1$
1	$\square_\square + 2\,\square\square_1 + 1\,\square\square_2$
1	$\square_\square + 2\,\square\square_1 + 2\,\square\square_2$
1	$\square_\square + 2\,\square\square_1 + 3\,\square\square_2$
1/2	$\square_\square + 2\,\square\square_1 + 4\,\square\square_2$



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



e$^-$ 30-40 MeV

e$^-$ 15-20 MeV

Controls & Diagnostics

Magnets, vacuum

Cryo-system

Vacuum system

Laser

e$^-$ 2.5MeV

Gun

SRF cavity AES

e$^-$ 2.5MeV

Beam dump

1 MW 700 MHz Klystron

Klystron PS,

50 kW 700 MHz

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.