From HERA to future electron-ion colliders

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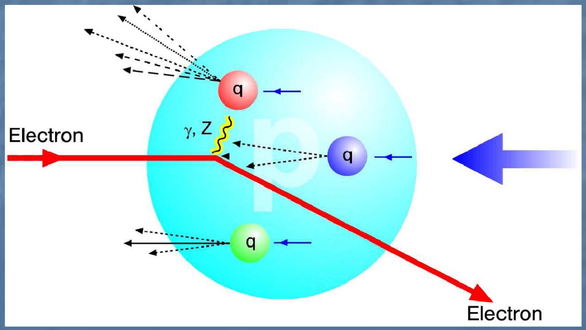
HERA – first lepton-proton collider

- Double ring collider (6.3 km)
- Completing its operation this year
- 920 GeV (p) X 27.5 GeV (e^-, e^+)
- 320 GeV center0f-mass energy
- Longitudinal lepton polarization
- Superconducting proton ring



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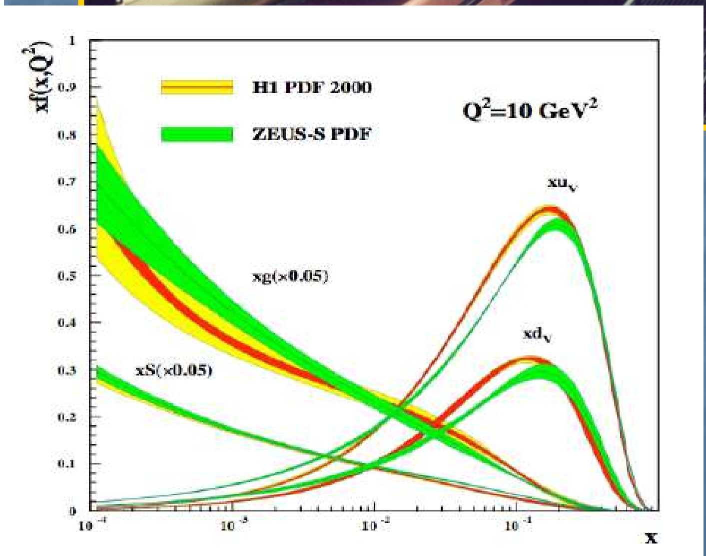


Selection of physics results:

- **precise data on details of the proton structure**
- **the discovery of very high density of sea quarks and gluons present in the proton at low-x**
- **detailed data on electro-weak electron-quark interactions**
- **precision tests of QCD (α_s measurements)**

Physics scope of lepton-ion colliders after HERA

Different Center-of-Mass Energy -> Different kinematic regions

Higher Luminosity -> Precision data

Polarized beams -> Spin structure of nucleons (still a puzzle!)

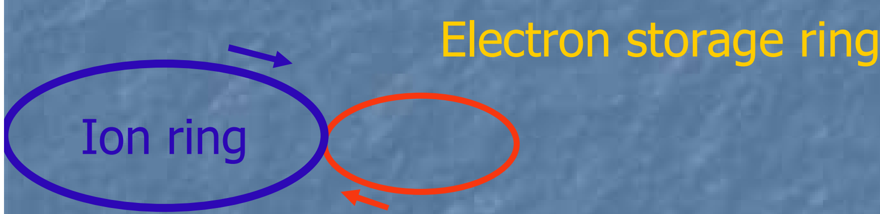
Ions up to large A -> Color Glass Condensate (state of extreme gluon densities)

QCD dynamics in much greater details

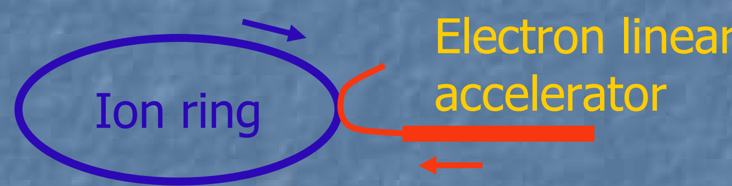
Also, search for new physics: leptoquarks … (high CME)

Future collider designs

Ring-ring



Linac-ring



	CME	On the base of
eRHIC ring-ring	30-100 GeV	RHIC (BNL)
ELIC	20-90 GeV	CEBAF (JLab)
LHeC	1.4 TeV	LHC (CERN)

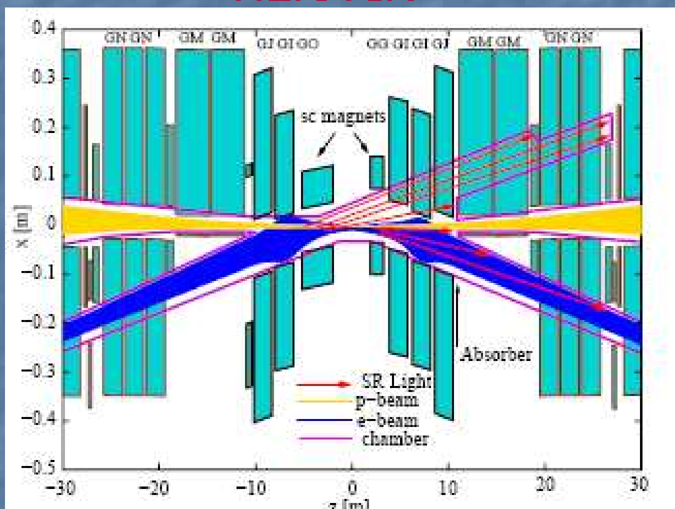
	CME	On the base of
eRHIC ERL-based	25-100 GeV	RHIC (BNL)

Parameter table

	HERA		eRHIC ring-ring		eRHIC ERL-based		ELIC		LHeC	
	p	e	p	e	p	e	p	e	p	e
Energy, GeV	920	27.5	250	10	250	10	225	9	7000	70
Bunch frequency, MHz	10.4		14.1		14.1		1500		40	
Bunch intensity, 10^{11}	0.72	0.29	1	2.3	2	1.2	0.04	0.075	1.7	0.14
Beam current, A	0.1	0.04	0.21	0.48	0.42	0.26	1	1.8	0.54	0.07
Rms emittance,x/y, nm	5.1/5.1	20/3.4	9.5/9.5	53/9.5	3.8	1.0	5.1/0.2	5.1/0.2	0.5/0.5	7.6/3.8
β*, x/y, cm	245/18	63/26	108/27	19/27	26	100	0.5/0.5	0.5/0.5	180/50	13/7
Beam size at IP, x/y, μm	112/30		100/50		32/32		5/1		31/16	
Max beam-beam parameter per IP	0.0012	0.037	0.015	0.08	0.015	2.3	0.0064	0.086	0.0008	0.05
Bunch length, cm	19	1	20	1.2	20	1	0.5	0.5	7.6	0.7
Polarization, %	0	45	70	80	70	>80	>70	80	0	0
Peak Luminosity, 10^{33} $cm^{-2}s^{-1}$	0.04		0.47		2.6		75		1.1	

IR design

HERA IR



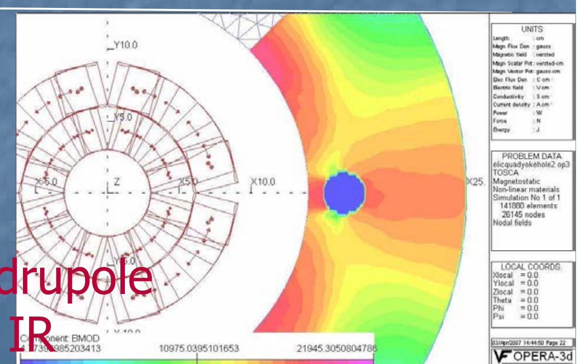
Taking into account HERA (and B-factories) experience to resolve IR design issues:

- Strong beam focusing
- Fast separation *(avoiding parasitic beam-beam)*
- Managing synchrotron radiation fan *(absorbers, collimators, masks locations; precise orbit control)*
- IR Vacuum *(beam conditioning, adequate pumping, avoiding HOM heating)*
- Detector integration

Special IR magnet designs

HERA type half quadrupole used in eRHIC and LHeC designs

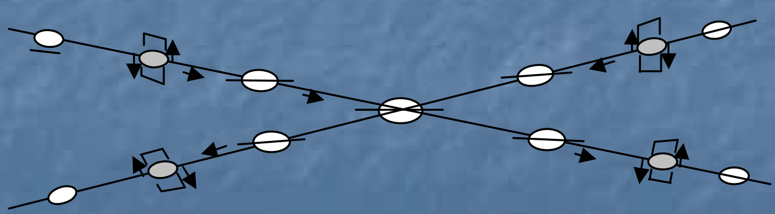
Lambertson quadrupole is a part of ELIC IR



IR design features

	Distance to nearest magnet from IP	Beam separation	y/x beam size ratio
eRHIC ERL-based	3 m	Detector integrated dipole	1
eRHIC ring-ring	1 m	Combined field quadrupoles	0.5
ELIC	3 m	Cross. Angle 30 mrad	0.2
LHeC	1.2 m	Cross. Angle 2 mrad	0.5

ELIC and LHeC:
Crossing Angle + Crab Crossing ⟹



20-25 MV transverse voltage (for protons)
R&D for crab cavities:

- Cavity design for high current operation
- Phase and amplitude stability tolerances
- Evaluation of beam dynamics effects

KEKB Crab Cavity Commissioning this year

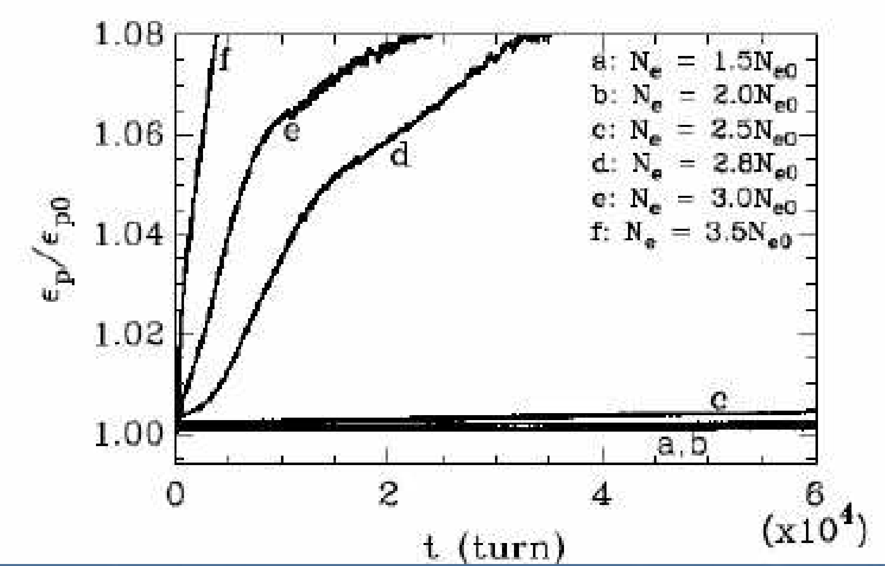
Beam-beam interactions

eRHIC and ELIC designs aim at considerably higher beam-beam parameters than achieved at HERA (ξ_p = 0.0012, ξ_e = 0.04).

ξ_p = 0.012 achieved in RHIC polarized proton operation
ξ_e > 0.08 in e+e- factories

ELIC e-ring:
- **large synchrotron tune -> eliminating nonlinear synchro-betatron resonances**
- **equidistant betatron phase advance between IPs**

eRHIC ring-ring: 2-D strong-strong simulation confirmed feasibility of design parameters *(J. Shi et al.)*



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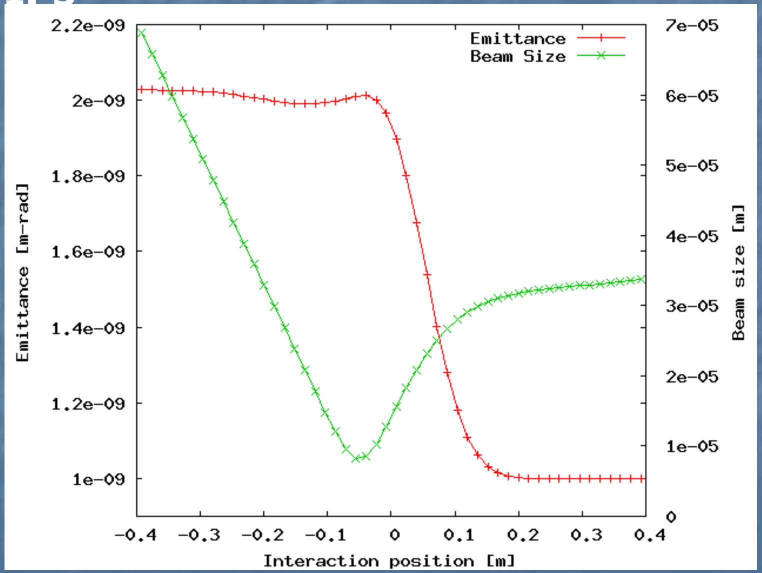


eRHIC ring-ring: 2-D strong-strong simulation confirmed feasibility of design parameters *(J. Shi et al.)*

eRHIC ERL-based: e-beam disruption, kink instability, e-beam parameter fluctuations have been studied *(Y. Hao et al, this conference)*

Further beam-beam simulations are planned.

Specific design issues

➢Matching beam cross sections at the IP for different collision energies.

eRHIC ERL-based: variable β^*
eRHIC ring-ring : variable electron emittance + variable β^*
ELIC: variable ion normalized transverse emittance (e-cooling)

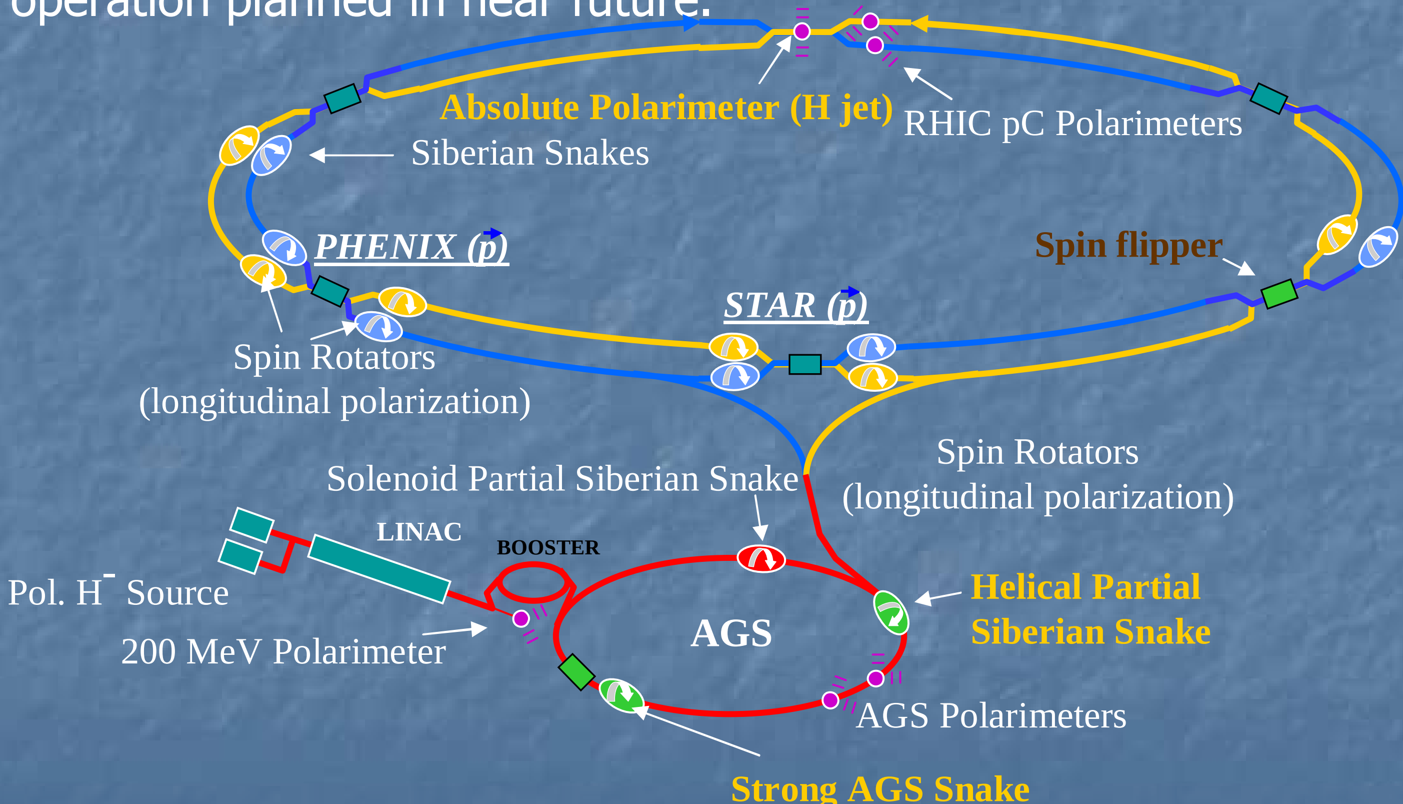
➢Matching bunch frequencies for various ion energies.
Ion revolution frequency varies with the energy.

eRHIC ERL-based: within tuning range of linac RF cavities ($\Delta f/f < 10^{-3}$)
eRHIC ring-ring: e-ring circumference lengthening (by 20cm) by mechanically moving arcs ("trombone")
ELIC: "clocking" -> variation of ion RF harmonic number; ~1.2cm maximum orbit offset in the arcs.

eRHIC, ion beam

RHIC -> 7 years of operation involving polarized protons, d, Cu and Au ions

Only polarized proton collider in the world. 100 GeV operation so far. 250 GeV operation planned in near future.



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For eRHIC:

- Increase of number of bunches: 111 -> 166 -> (332?) (Injector system; e-cloud)
- Polarized ^{3}He production (EBIS) and acceleration.
- Possibility of parallel operation with ion-ion and lepton-ion collisions

eRHIC luminosity will benefit from ion beam cooling techniques:

- Longitudinal stochastic -> used in the heavy ion operation this year
- RHIC-II electron cooling facility under design

eRHIC ZDR (2004); "eRHIC Accelerator Design Position Paper" for LRP (2007)
BNL and MIT-Bates collaboration

eRHIC ERL-based design

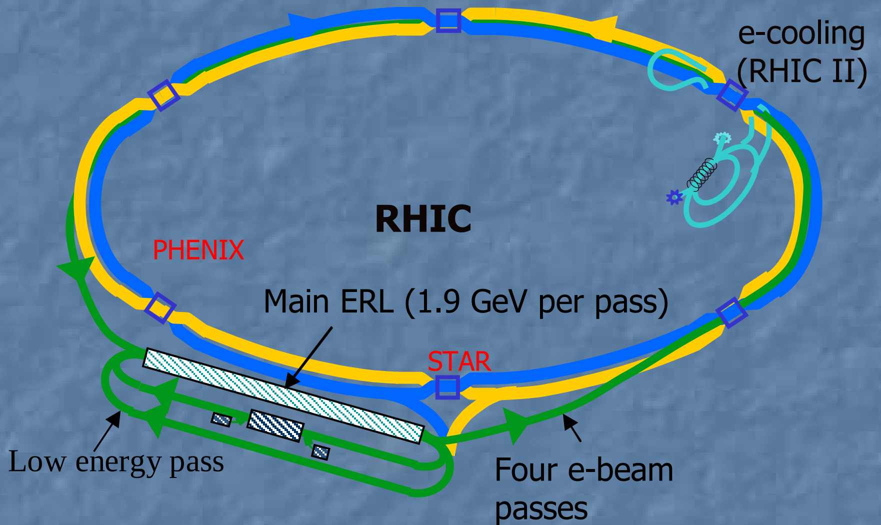
3-10 GeV polarized electrons (with possible upgrade to 20 GeV)

~300m long energy recovery linac

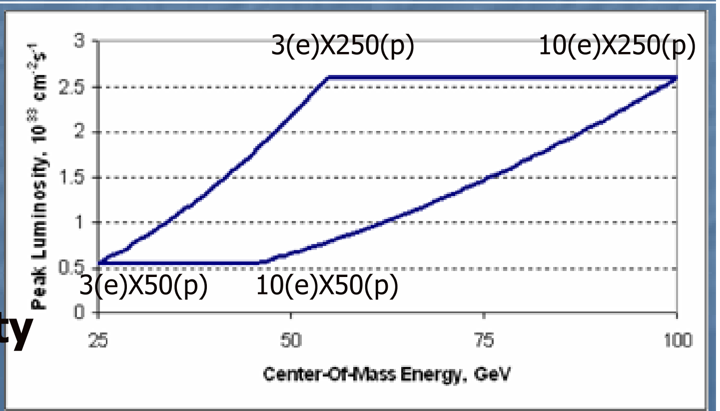
Recirculation passes in the RHIC tunnel

Advantages:

- Much higher electron beam-beam limit
- Multiple working points
- Polarization transparency (at all energies)
- No spin rotator needed
- IR design (small emittance, round beam)
- Full advantage of cooling techniques



Peak Luminosity vs CME



ERL-based eRHIC R&D

➢Energy recovery technology for high energy (10 GeV) and high current (0.25A) beams.
Acceleration structure is based on 704 MHz 5-cell SRF cavity, designed for RHIC electron cooling.
Energy recovery, beam loss tolerances, cavity protection system, beam recirculation issues.
ERL test facility at BNL under construction.

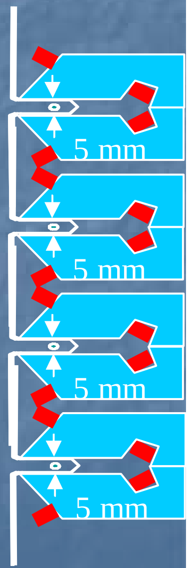
➢High intensity polarized electron source
Development of large cathode guns with existing current densities ~ 50 mA/cm^2 and acceptable cathode lifetime. (MIT-Bates)

Positron design options:
•**compact self-polarized ring**
•**ILC type positron production**
•**recirculating pass as storage ring**

Design of recirculation passes:

➢Small aperture magnets (V.Litvinenko)

➢FFAG type pass (D.Trbojevic, this confer.)



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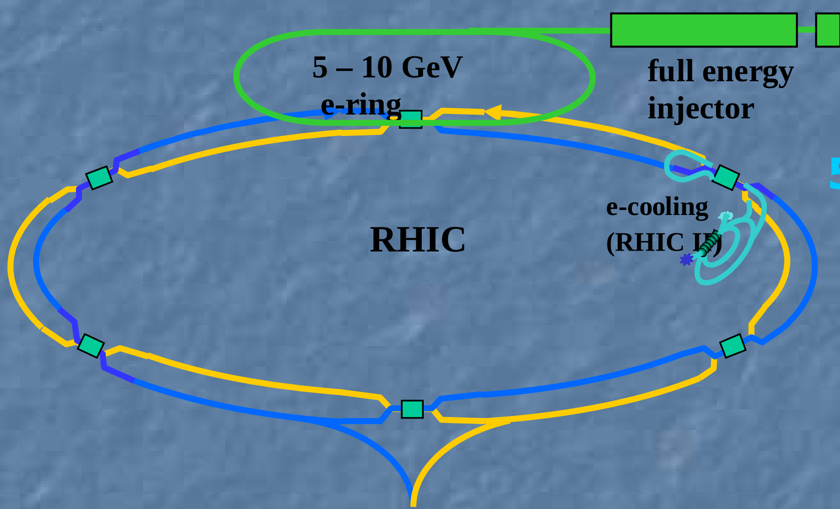
eRHIC ring-ring



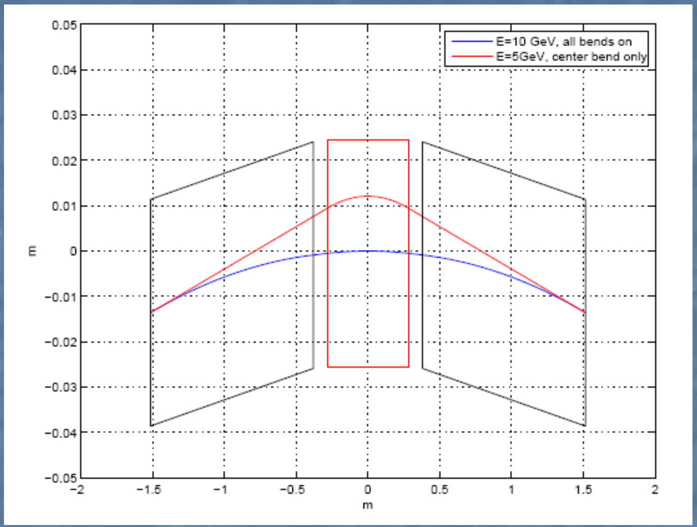
5-10 GeV polarized electrons (positrons)

Peak L = 4.7 10^{32} cm^{-2} s^{-1} (10(e) X 250(p) Gev)

Peak L = 0.8 10^{32} cm^{-2} s^{-1} (5(e) X 50(e) GeV)

- **10 GeV, 0.5 A e-ring with 1/3 of RHIC circumference (1278m)**
- **Injector variants: recirculating linac (warm or cold), figure-8 booster.**
- **Polarized e^- (from the source) and e^+ (self-polarized, 20min at 10 GeV)**
- **Polarization is not available at all lepton energies because of spin resonances**
- y_{co} rms < 150 μm : **closed orbit (and misalignment) tolerances for 80% polarization level**

eRHIC ring-ring features



e-ring lattice based on superbends (triplet dipole):

- Improves luminosity at lower electron energies.
- Polarized positrons down to 5 GeV (self-polarization time ~5min)

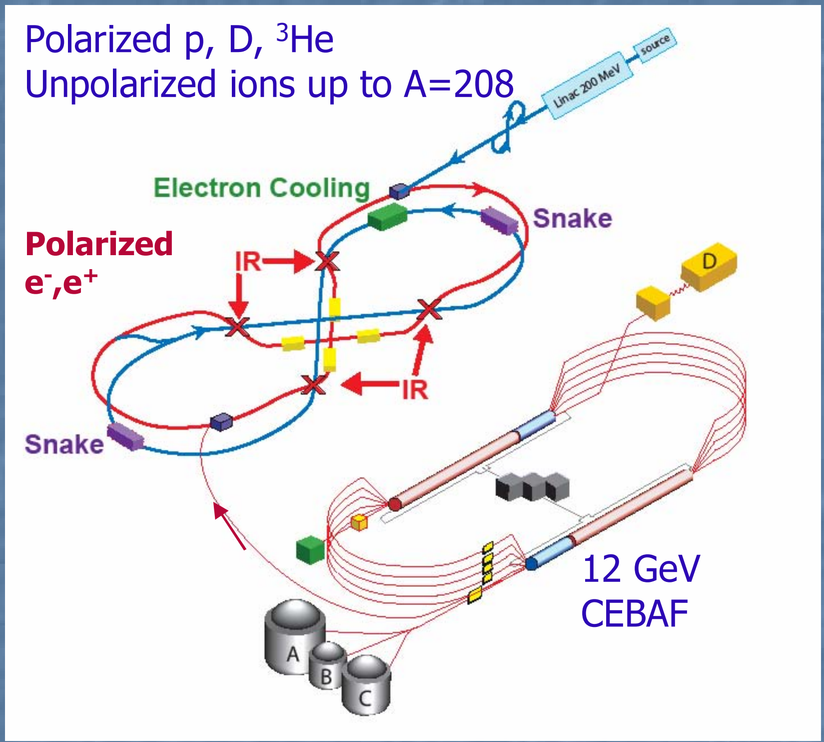
Electron emittance variation:

~60 nm for 10(e)x250(p) GeV -- ~160 nm for 5(e)x50(p) GeV.
Realized by superbend field variation and FODO cell phase adjustments.

Engineering developments:

- High-heat load vaccum chamber. (Linear radiation power exceeds 15 kW/m)
- Electron ring circumference adjustments
- Design of superbend magnets

ELIC



E_p = 30-225 GeV; E_{ions} = 15-100 GeV/n

E_e = 3-9 GeV

Peak L ~ 7.5 10^{34} cm^{-2} s^{-1} (9 (e) X 225 (p) GeV)

Peak L ~ 8. 10^{33} cm^{-2} s^{-1} (3 (e) X 30 (p) GeV)

- **"Figure-8" design of ion and lepton storage rings: polarization preservation at ll energies.**
- **Snakes, solenoids and control vertical orbit distortions for the manipulation of spin orientation at IPs.**
- **Very high luminosity approach: moderate bunch intensity, short ion bunches, strong focusing and high bunch repetition rate.**
- **Four interaction regions**
- **The operation compatible with 12 GeV CEBAF operation for fixed target program.**

ELIC ZDR (Draft) and
Y. Zhang's talk

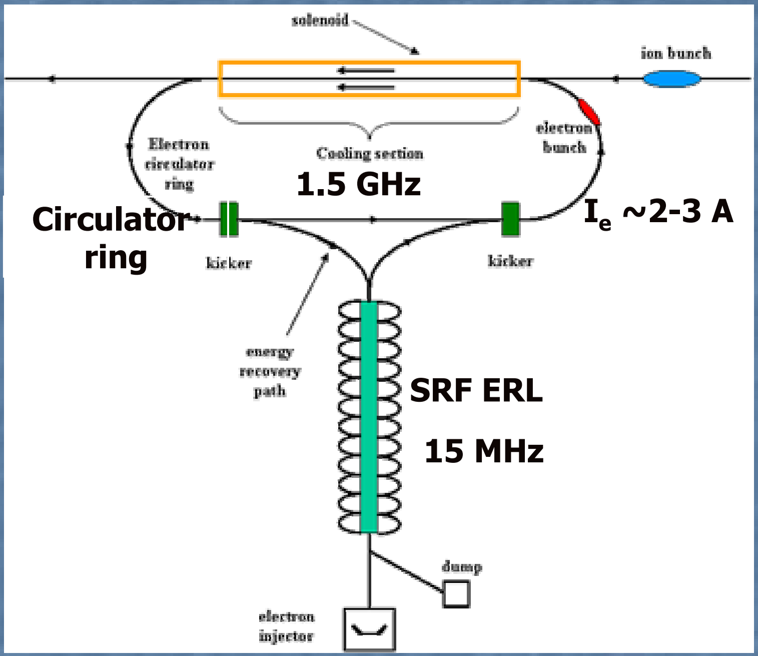
ELIC R&D items

- ➢High energy electron cooling
(for efficient longitudinal and transverse cooling of protons up to 225 GeV)

- ➢Detector data acquisition and triggering for high bunch rate (1.5 GHz)

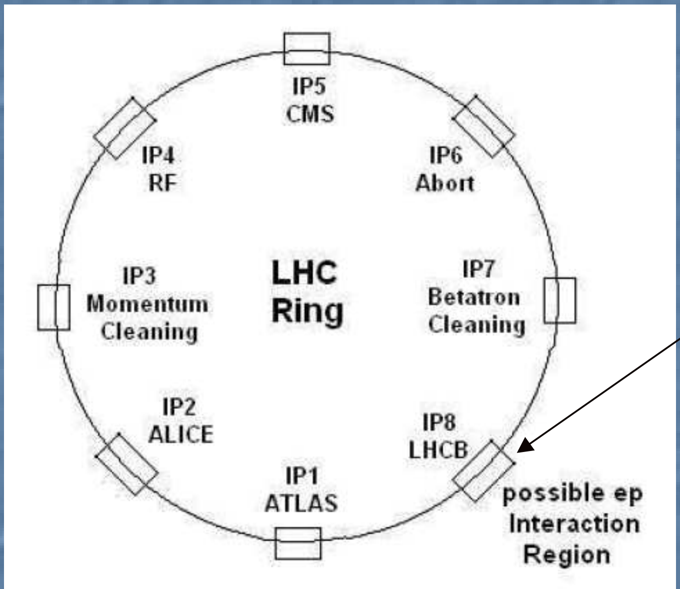
- ➢Crab Crossing

- ➢Stability of intense ion beams



e-cooling design based on circulator ring

LHeC



- 70 Gev (e) X 7 TeV (p) -> 1.4 TeV CME
- Peak L = 1.1 10^{33} cm^{-2} s^{-1}
- e-ion collisions at IP8 (after completion of LHCB experiment)
- Proton (ion) beam parameters -> same as for LHC
- Lepton (e-, e+) ring above existing LHC rings
- Injection system identical to LEP
- No major technological developments needed

Luminosity limitation:
large RF Power to replenish synchrotron radiation loss
50MW -> 70 mA maximum lepton current

Conceptual design presented in DESY 06-006, Cockroft 06-05 report by J.B. Dainton, F. Willeke, et al.

Summary

- Several designs of the lepton-ion colliders are under development, including eRHIC at BNL, ELIC at JLab and LHeC at CERN.

- The collider designers are using the experience obtained during years of HERA operation.

- In the same time new ideas and technologies are applied in the accelerator design which should allow to achieve considerably higher luminosities.

- At the end the cost and the importance of the physics that can be explored at a particular collider will be important factors for a success of one or another design.

Acknowledgements to: I. Ben-Zvi, J.B. Dainton, A. Fedotov, J. Keil, Y. Hao, V.N. Litvinenko, L. Merminga, C. Montag, T. Roser, D. Trbojevic, Y. Zhang.