Overview of Electron-Ion Collider Initiatives

- **eRHIC** **RHIC, BNL, Upton, NY, USA**
- **ELIC** **CEBAF, Jefferson Lab, Newport News, VA, USA**
- **LHeC** **LHC, CERN, Geneva, Switzerland**
- **ENC** **FAIR, GSI, Darmstadt, Germany**

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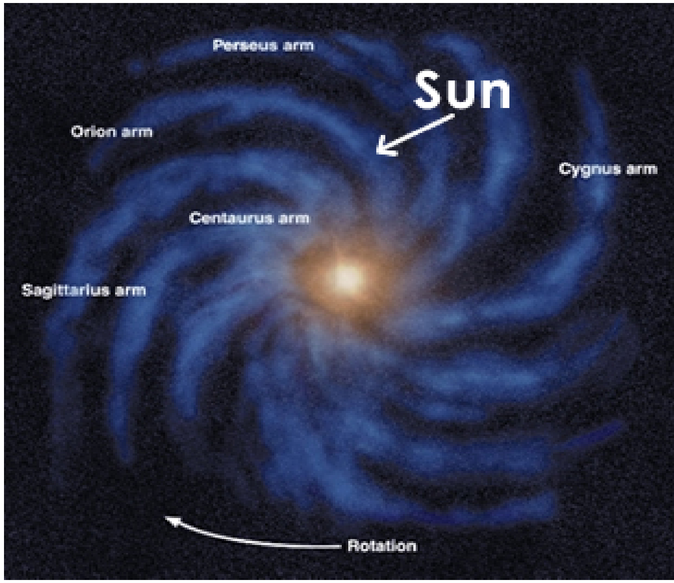
Max Klein, Andreas Jankowiak, and other colleagues

Richard Milner
PAC09 Conference
May 4 – May 8, 2009

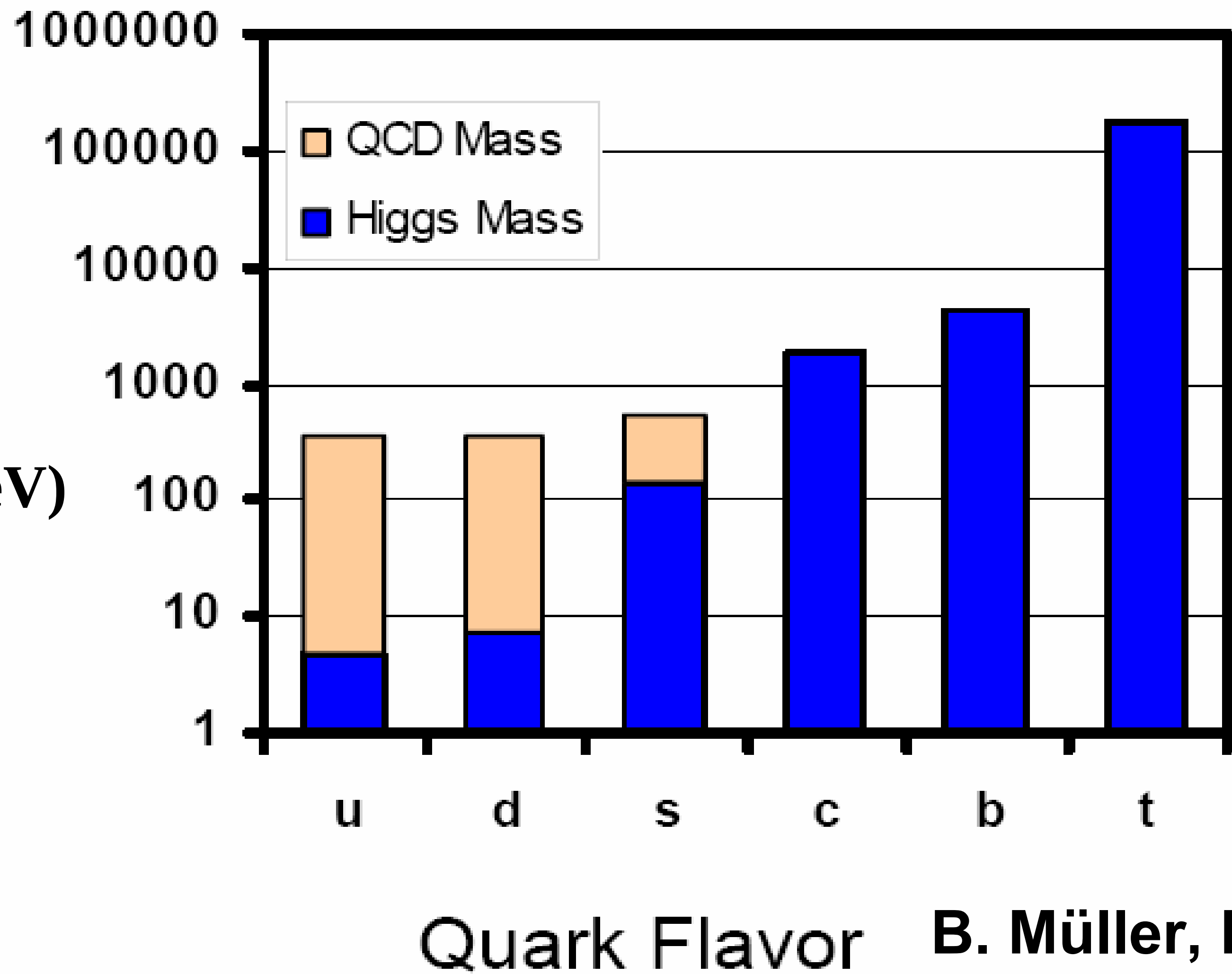
The Fundamental Structure of Matter



- Essentially all of the observable matter is made of protons and neutrons
- QCD describes these building blocks in terms of pointlike quarks and gluons.
- *Up* and *down* quarks and gluons dominate hadron structure in the physical world
- It has been a major goal of physicists to understand the structure and properties of the nucleon.
- Recent work has brought our understanding to a new level of precision.

Baryonic mass is dominated by QCD

Mass (MeV)



B. Müller, Nucl. Phys. A 750 (2005) 84

QCD is unique

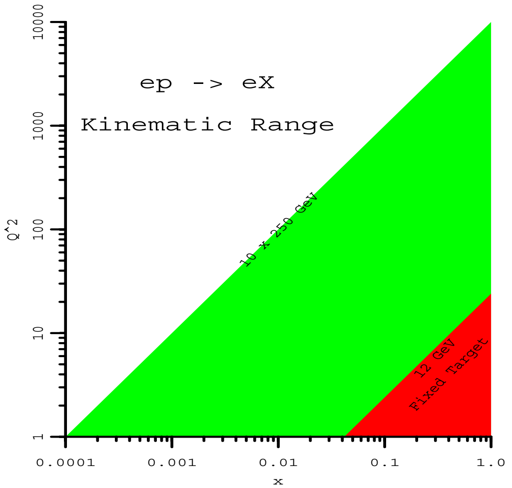
- It is the only fully consistent theory that we are certain that describes the real world: in the limit $m_q \rightarrow 0$, there are no free parameters
- All the interactions are a consequence of deep symmetry principles like gauge invariance and chiral symmetry
- Most of the visible phenomena are emergent: quarks and gluons are not seen
- This makes QCD the only laboratory for exploring the dynamics of a non-trivial, consistent relativistic theory
- The dominant virtual components (gluons and sea quarks) of QCD are largely unexplored and poorly understood

Why a high luminosity lepton-ion collider ?

- The lepton probe provides the precision of the electroweak interaction but requires high luminosity to be effective
- Lepton scattering on hadron targets in new regimes has consistently yielded new insights, e.g. DIS, EMC effect, Glue
- High $E_{cm} \Rightarrow$ large range of x, Q^2 **$Q_{max}^2 = E_{CM}^2 \bullet x$**

  x range: valence, sea quarks, glue

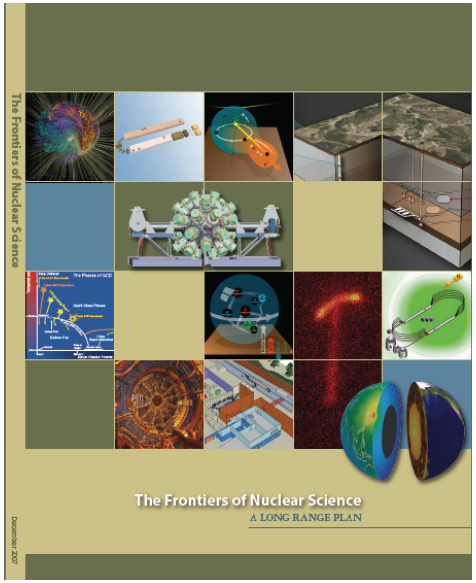
  Q^2 range: utilize evolution equations of QCD
- High polarization of lepton, nucleon achievable
- Complete range of nuclear targets
- Collider geometry allows complete reconstruction of the final state



An electron-ion collider is needed to complete the study of the fundamental structure of matter

NSAC 2007 Long Range Plan

- “An ***Electron-Ion Collider (EIC)*** *with polarized beams has been* ***embraced by the U.S. nuclear science community*** *as embodying the vision for* ***reaching the next QCD frontier****. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia. In support of this new direction:*



- **We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton.”**

- “*The detailed requirements for the machine complex and detectors at an EIC are driven by the need to access the relevant kinematic region that will allow us to explore gluon saturation phenomena and image the gluons in the nucleon and nuclei with great precision. These considerations constrain the basic beam parameters to be:*
  - *Ee = 3 to at least 10 GeV* — *Polarized electrons (and positrons)*
  - *Ep = 25 to 250 GeV* — *Polarized protons, light ions*
  - *EA = 25 to 100 GeV* — *Heavy ions A at least as high as Au”*

High luminosity
~ L(ep) ~$10^{33\text{-}34}$ cm^{-2} s^{-1}
~ 50 fb^{-1} over 10 years
~ 100 times luminosity of HERA

The Initiatives

- At RHIC: add electron beam facility to the existing hadron complex

- At JLab: add hadron/nuclear beam facility to the existing electron beam complex

- Other Electron Ion Collider proposals:

  - LHeC: 70 x 7000 GeV, unpolarized beams, L ~ 10^{33} cm^{-2} s^{-1}

  - ENC@FAIR: 3 x 15 GeV, polarized beams, L ~ 2 x 10^{32} cm^{-2} s^{-1}

ELIC Design Goals

- Colliding beam energy e × p (ion): 3 × 30 (15) GeV to 10 × 250 (100) GeV
- Luminosity: $0.1 - 3 \times 10^{34}$ cm^{-2} s^{-1} *per* interaction point
- Ion Species: Polarized H, D, ^{3}He, possibly Li
  Up to heavy ion A = 208, fully stripped
- Polarization: Longitudinal polarization at the IP for both beams
  Transverse polarization of ions
  Spin-flip of both beams
  All polarizations >70% desirable
- Positron Beam *desirable*
- Plans for ultra high energy (325x20 GeV) and very low energy (5 x 5 GeV)
- Ring-Ring (R-R) collider design
  - takes advantage of CEBAF as a full energy polarized electron injector
  - Modest requirements for polarized electron source

ELIC Conceptual Design

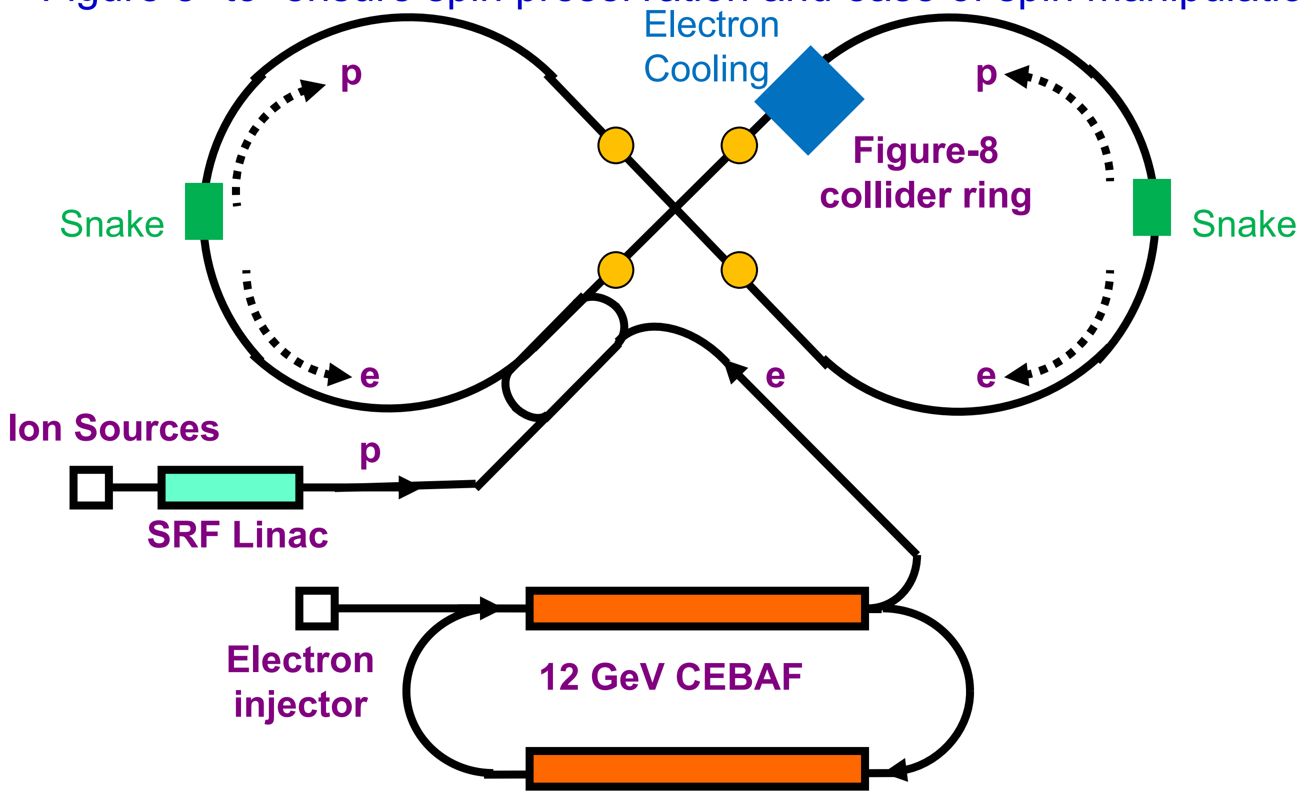
ELIC Design Luminosity: $L \sim 3 \times 10^{34}\ cm^{-2}\ sec^{-1}$ (250 GeV protons x 10 GeV electrons)

ELIC Luminosity Concepts: High bunch collision frequency (f = 0.5 GHz)
Short ion bunches ($\sigma \sim 5$ mm)
Super strong final focusing ($\beta^* \sim 5$ mm)
Large beam-beam parameters (0.01/0.1 per IP)
Equidistant phase advance between four IPs so total bb equal IP bb shift (?)
Large synchrotron tunes to suppress synchro-betatron resonances

ELIC Polarization: "Figure 8" to ensure spin preservation and ease of spin manipulation

ELIC R&D needs:

- High energy electron cooling of ion beams
- Crab cavities
- Stability of intense ion beams
- Detector R&D for high repetition rate

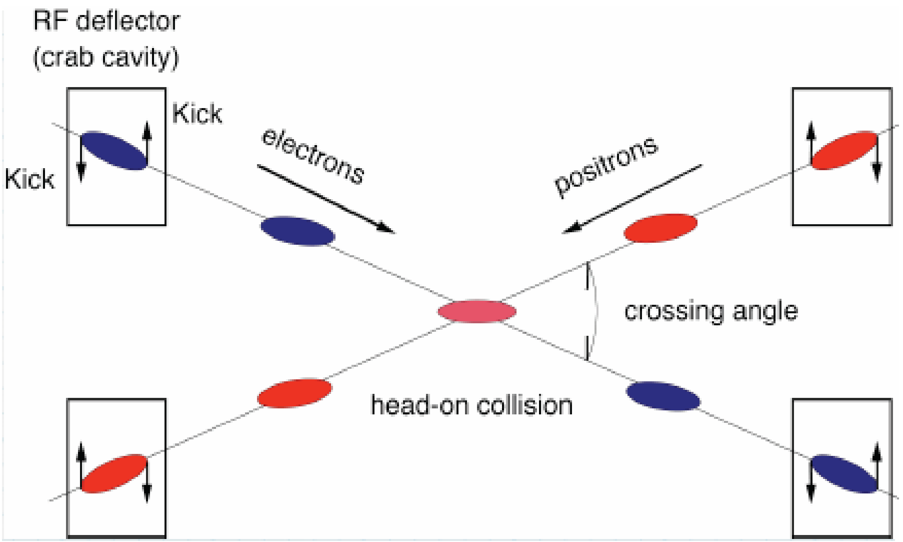


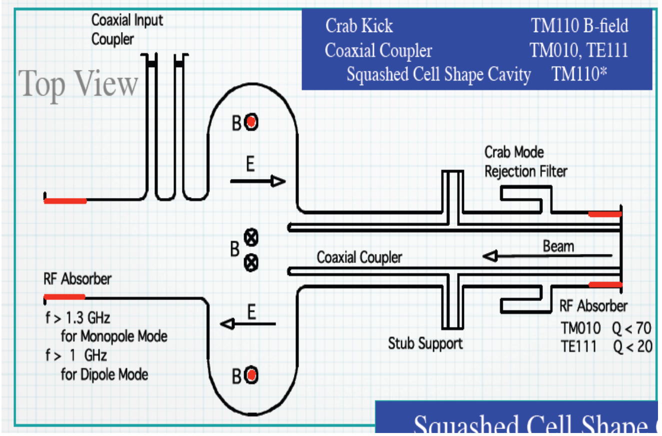
ELIC (e/p) Design Parameters

Beam energy (p/e)	GeV	250/10	150/7	50/5
Figure-8 ring	km	2.5		
Collision freq	MHz	499		
Beam current (p/e)	A	0.22/0.55	0.15/0.33	0.18/0.38
Particles/bunch (p/e)	10^9	2.7/6.9	1.9/4.1	2.3/4.8
Energy spread (p/e)	10^{-4}	3/3		
Bunch length, rms (p/e)	mm	5/5		
Hori. emit., norm. (p/e)	µm	0.70/51	0.42/35.6	.28/25.5
Vertical emit., norm. (p/e)	µm	0.03/2.0	0.017/1.4	.028/2.6
β^* (p/e)	mm	5/5		
Vert. b-b tune-shift (p/e)		0.01/0.1		
Peak lum. per IP	10^{33} cm^{-2}s^{-1}	29	12	11
Luminosity lifetime	hours	24		

ELIC R&D: Crab Crossing

- High repetition rate requires crab crossing colliding beam to avoid parasitic beam-beam interaction
- Crab cavities needed to restore head-on collision & avoid luminosity reduction
- Minimizing crossing angle reduces crab cavity challenges & required R&D





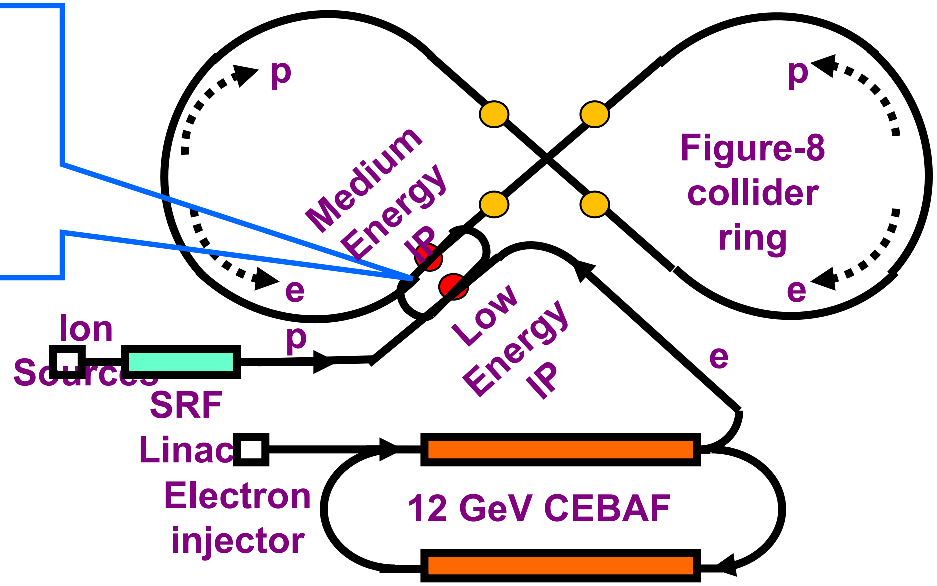
KEKB cavity: angle: 11 mrad, V_{kick}:1.4 MV

ELIC: angle: 22 mrad, V_{kick}:1.2 MV (e), 24 MV (ions)

R&D: Multi-cell SRF crab cavity design capable for high current operation.

Possible Staging of ELIC

The tunnel houses 3 rings:
Electron ring up to 5 GeV/c
Ion ring up to 5 GeV/c
Superconducting ion ring
for up to 30 GeV/c



Stage		Maximum Momentum (GeV/c)		Ring Size (m)		Ring Type	
		Proton	Electron	Ion	Electron	Ion	Electron
1	Low Energy	5	5	400	400	Warm	Warm
2	Medium Energy (MEIC)	30	5	400	400	SC	Warm
3	Medium Energy	30	10	400	1800	SC	Warm
4	High Energy (ELIC)	250	10	1800	1800	SC	Warm

Parameter for ELIC Stages

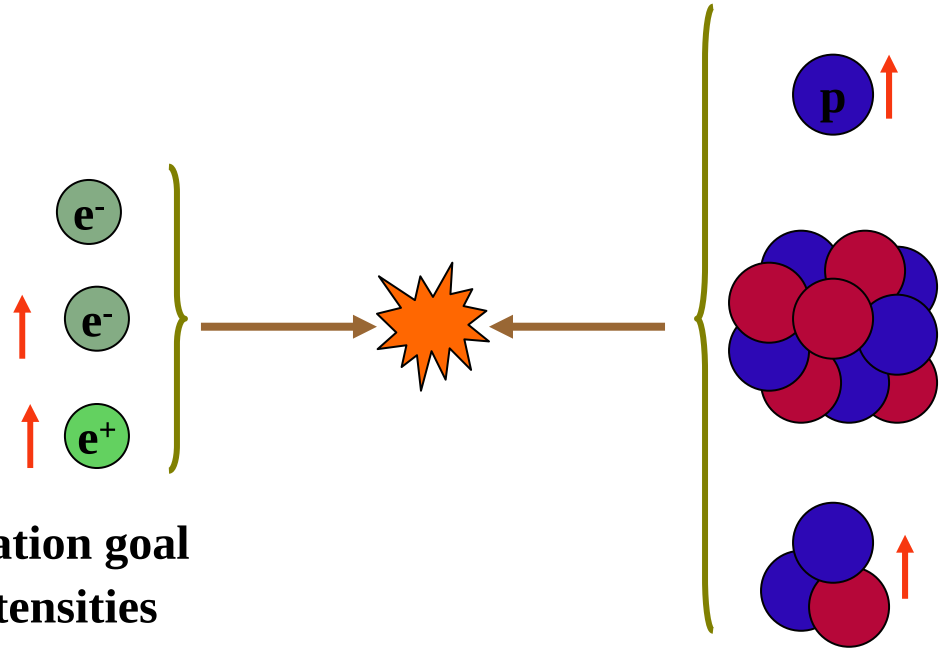
Beam Momentum (p/e)	GeV/c	5/5	10/5	30/5
Circumference	m	407	407	407
Beam Current (p/e)	A	0.16/1	0.42/1	0.43/1
Repetition Rate	GHz	0.5	0.5	0.5
Particles per Bunch (p/e)	10^{10}	0.2/1.25	0.52/1.25	0.54/1.25
Bunch Length (p/e)	cm	5/0.25	5/0.25	5/0.25
Normalized Hori. Emittance (p/e)	mm mrad	0.27/120	0.26/120	0.39/120
Normalized Vert. Emittance (p/e)	mm mrad	0.27/12	0.26/12	0.39/12
Horizontal β^* (p/e)	cm	0.5/2	0.5/1	0.5/0.5
Vertical β^* (p/e)	cm	0.5/20	0.5/10	0.5/5
Beam Size at IP (p/e)	μm	15.7/15.7	11/11	7.8/7.8
Horizontal B-B Tune Shift (p/e)		0.006/0.004	0.006/0.006	0.004/0.01
Vertical B-B Tune Shift (p/e)		0.006/0.37	.01/0.1	0.004/0.1
Laslett Tune Shift (p/e)		0.1/small	0.07/small	0.05/small
Luminosity	$10^{33} s^{-1} cm^{-2}$	0.4	2.1	4.4

eRHIC

Electron accelerator

RHIC

Unpolarized and polarized leptons
3 - 10 (30) GeV



Polarized protons
25 - 250 (325) GeV

Heavy ions (Au)
20 - 100 (130) GeV/n

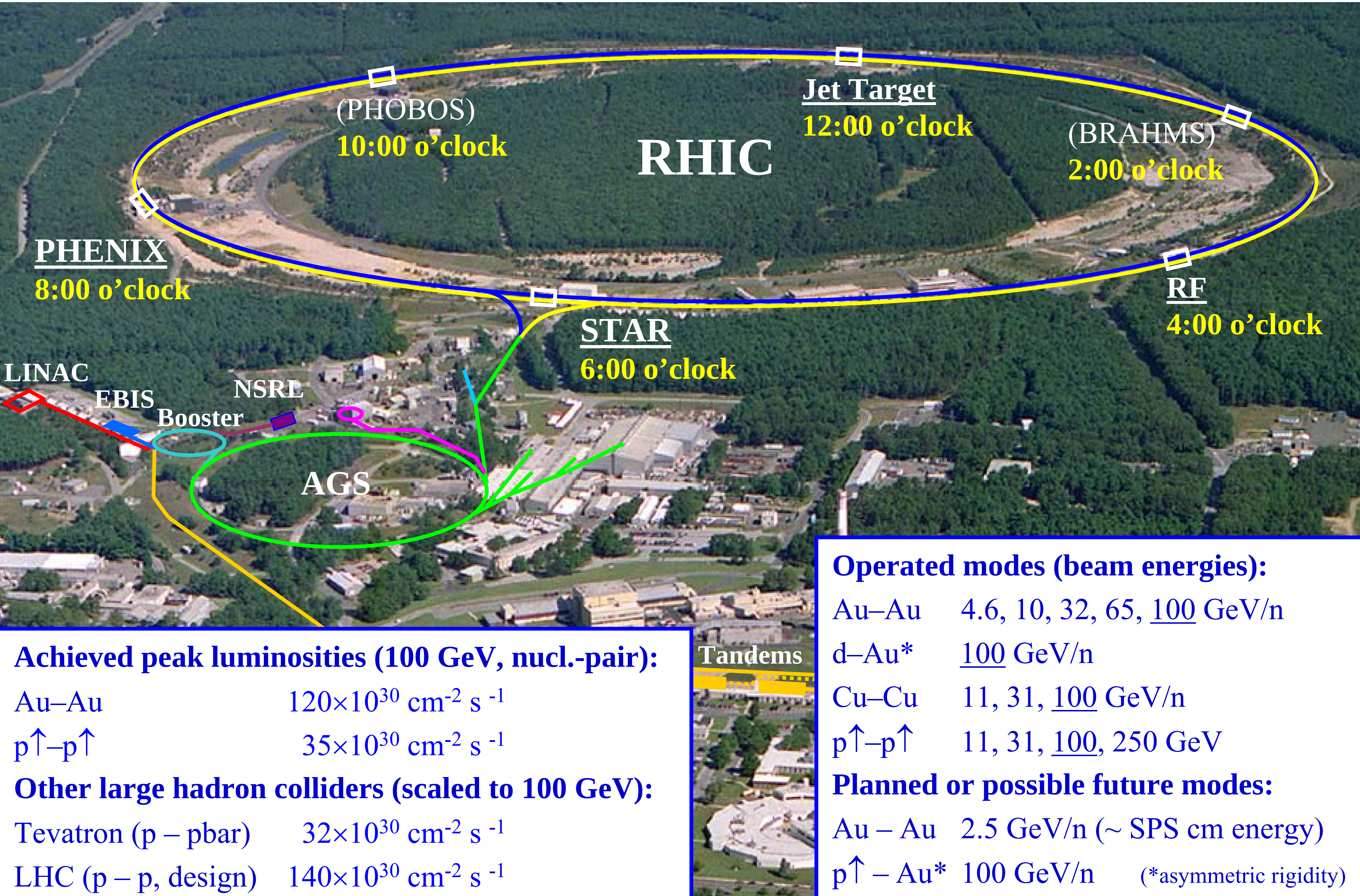
Polarized light ions
d,He^3: 125,167 GeV/n

70% beam polarization goal
Positrons at low intensities

Center mass energy range: 15 - 100 (200) GeV

Note: eA program for eRHIC needs as high an electron energy as possible even with a trade-off for the luminosity: up to 30 GeV would be possible.

RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities (100 GeV, nucl.-pair):

Au–Au	120×10^{30} cm^{-2} s^{-1}
p↑–p↑	35×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 100 GeV):

Tevatron (p – pbar)	32×10^{30} cm^{-2} s^{-1}
LHC (p – p, design)	140×10^{30} cm^{-2} s^{-1}

Operated modes (beam energies):

Au–Au	4.6, 10, 32, 65, <u>100</u> GeV/n
d–Au*	<u>100</u> GeV/n
Cu–Cu	11, 31, <u>100</u> GeV/n
p↑–p↑	11, 31, <u>100</u>, 250 GeV

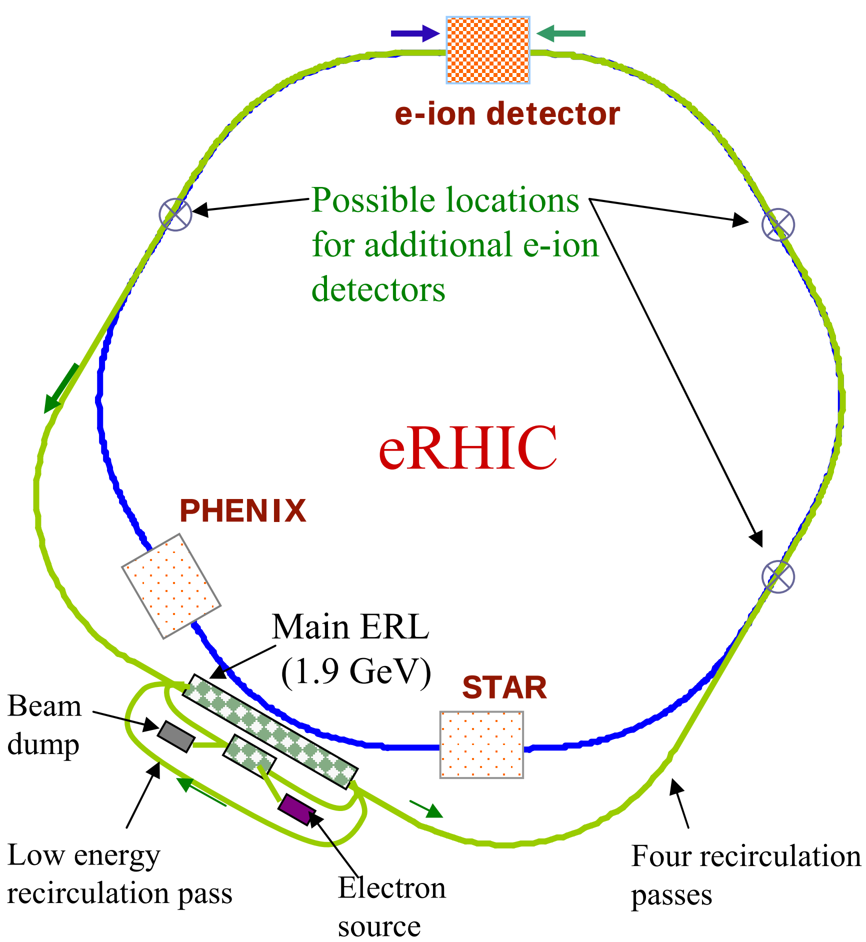
Planned or possible future modes:

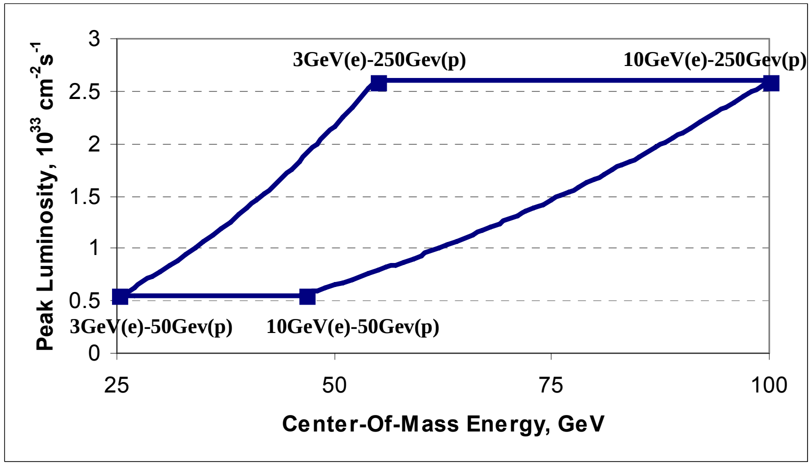
Au – Au	2.5 GeV/n (~ SPS cm energy)
p↑ – Au*	100 GeV/n (*asymmetric rigidity)

eRHIC Design

- Integrated electron-nucleon luminosity of ~ 50 fb^{-1} over about a decade for both highly polarized and intense nucleon and nuclear (A = 2-208) beams existing at RHIC :
  - 25 - 250 GeV polarized protons
  - up to 100 GeV/n gold or uranium ions)
  - up to 167 GeV/n polarized ^3He or up to 125 GeV/n polarized deuterons possible
- Two accelerator design options, developed for high brightness 10 GeV electron beams:
  - Ring-Ring option:
    - Electron storage ring for polarized electron or positron beam.
    - Technologically more mature with peak luminosity of 0.5×10^{33} $cm^{-2}s^{-1}$
  - Linac-Ring option (provides higher luminosity and possibly higher energy):
    - Superconducting energy recovery linac (ERL) for the polarized electron beam.
    - Peak luminosity of 2.6×10^{33} $cm^{-2}s^{-1}$ with potential for even higher luminosities.
    - R&D for a high-current polarized electron source needed to achieve the design goals.

ERL-based Linac-Ring eRHIC





- 10 GeV electron design energy. Possible upgrade to 20 – 30 GeV.
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) and detectors;
- Full polarization transparency at all energies for the electron beam;
- Ability to take full advantage of transverse cooling of the hadron beams;
- Possible options to include polarized positrons at lower luminosity: compact storage ring or ILC-type polarized positron source

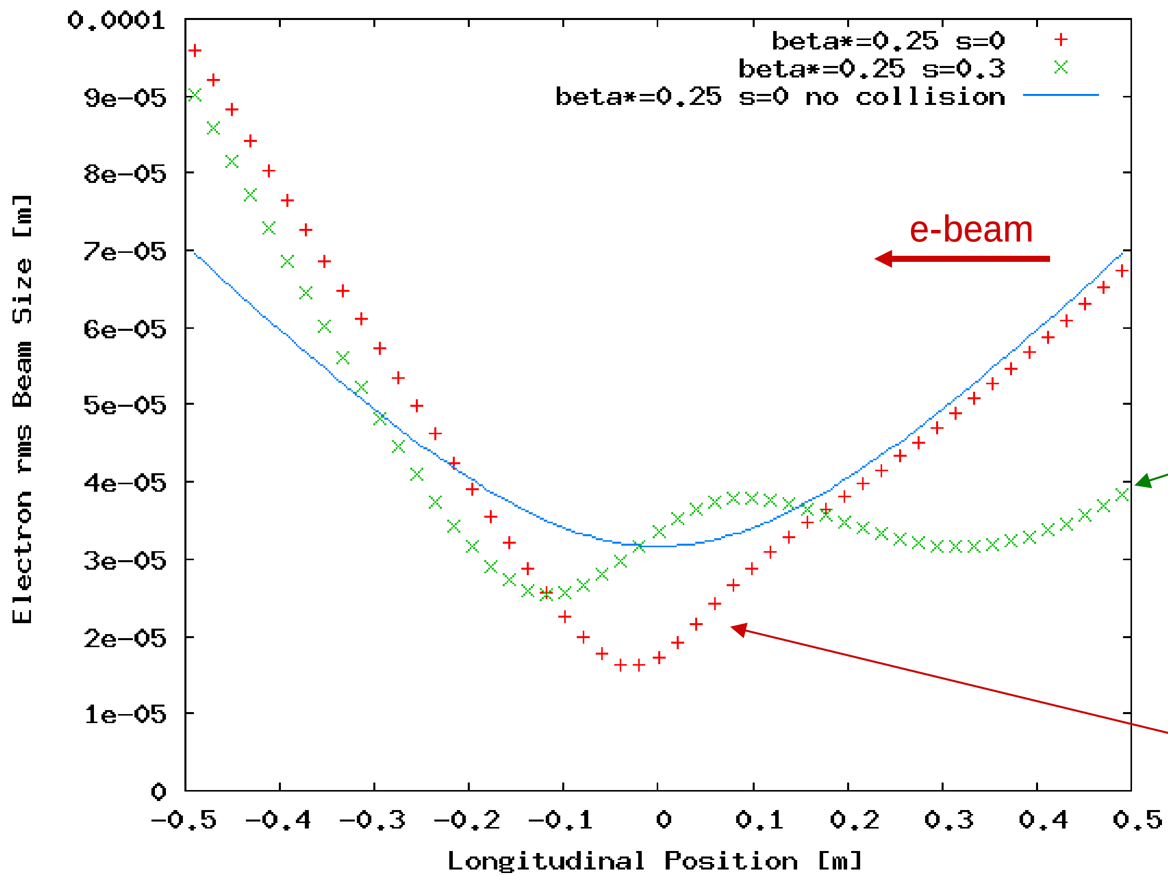
ERL-based eRHIC Parameters

	Electron-Proton Collisions				Electron-Au Collisions			
	High energy		Low energy		High energy		Low energy	
	p	e	p	e	Au	e	Au	e
Energy, GeV	250	10	50	3	100	10	50	3
Number of bunches	166		166		166		166	
Bunch spacing, ns	71	71	71	71	71	71	71	71
Bunch intensity, 10^{11} (10^{9} for Au)	2.0	1.2	2.0	1.2	1.1	1.2	1.1	1.2
Beam current, mA	420	260	420	260	180	260	180	260
95% normalized emittance, πμm	6	460	6	570	2.4	460	2.4	270
Rms emittance, nm	3.8	4.0	19	16.5	3.7	3.8	7.5	7.8
β*, cm	26	25	26	30	26	25	26	25
Beam-beam parameters	0.015	0.59	0.015	0.47	0.015	0.26	0.015	0.43
Rms bunch length, cm	20	1.0	20	1.0	20	1.0	20	1.0
Polarization, %	70	80	70	80	0	0	0	0
Peak Luminosity/n, 10^{33} $cm^{-2}s^{-1}$	**2.6**		**0.53**		**2.9**		**1.5**	
Aver.Luminosity/n, 10^{33} $cm^{-2}s^{-1}$	**0.87**		**0.18**		**1.0**		**0.5**	
Luminosity integral /week, pb^{-1}	**530**		**105**		**580**		**290**	

If effective high energy transverse cooling becomes possible the required electron beam current can be reduced to 50 mA, maintaining the same luminosity.

Effect of Electron Pinching on the Proton Beam

The electron beam is focused by strong beam-beam force leading to larger proton beam-beam parameter



Proper selection of the IP β and β-waist is important to minimize the proton beam-beam parameter

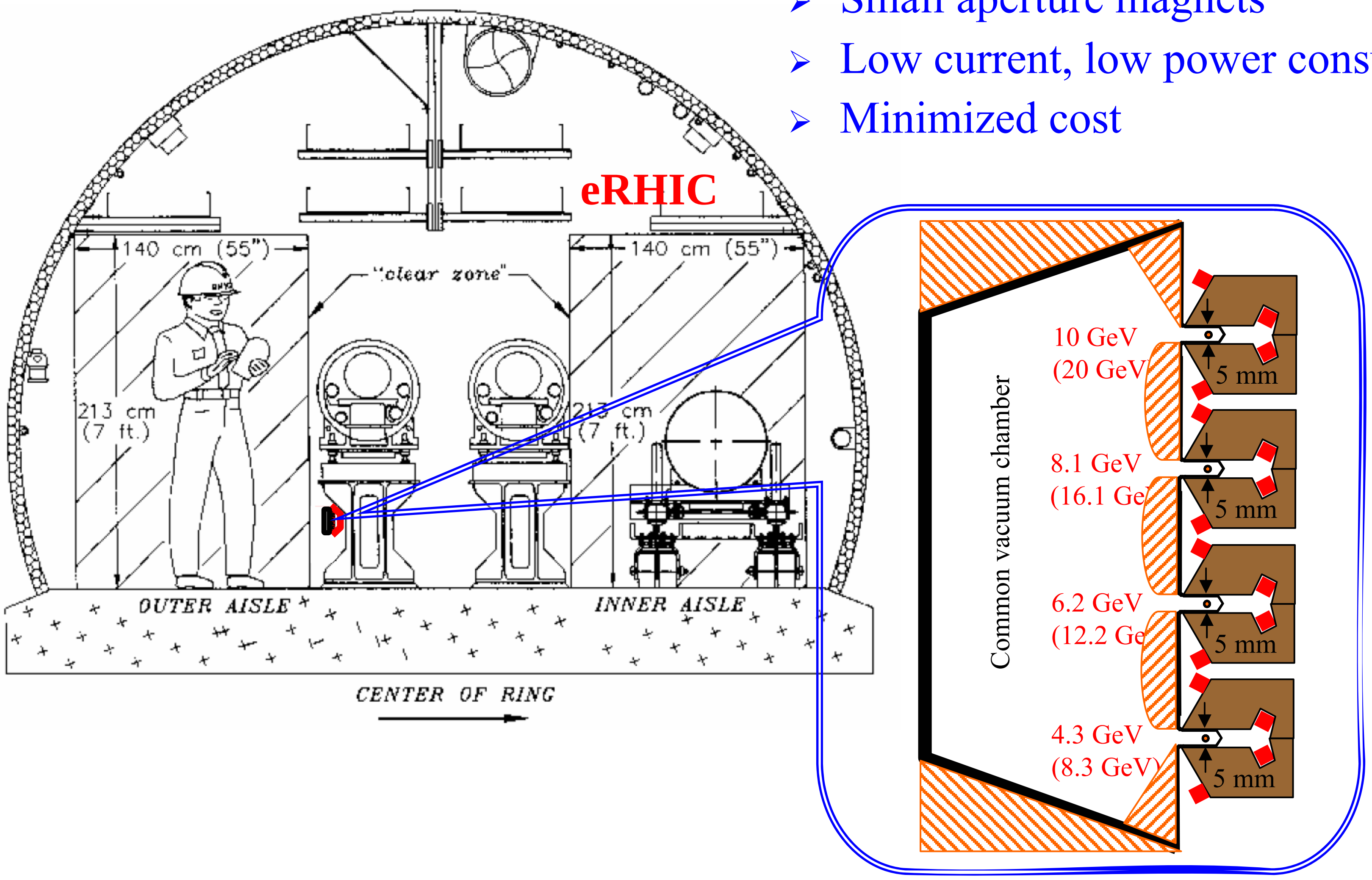
$$\xi_{\max} = 0.022 \qquad \xi_{ave} = 0.014$$

$$\xi_{\max} = 0.054 \qquad \xi_{ave} = 0.031$$

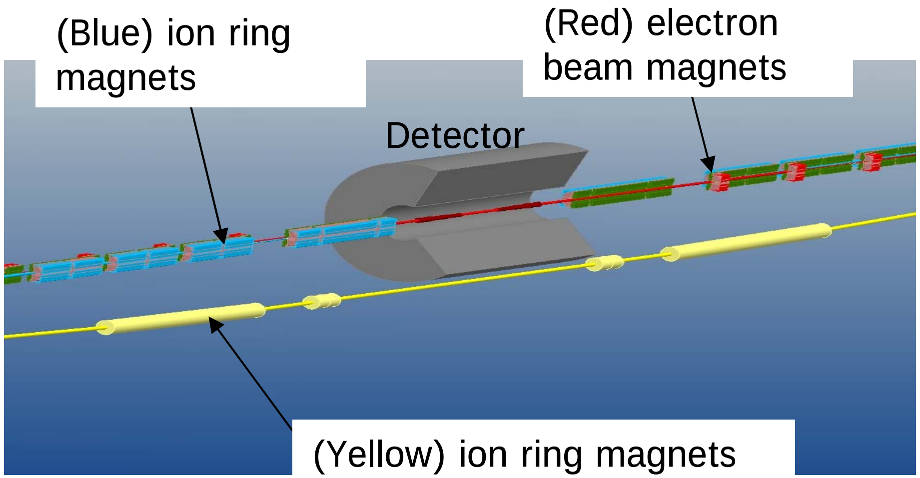
More investigations are underway for incoherent proton beam emittance growth in the presence of electron pinch, including the optimal choice of the working point.

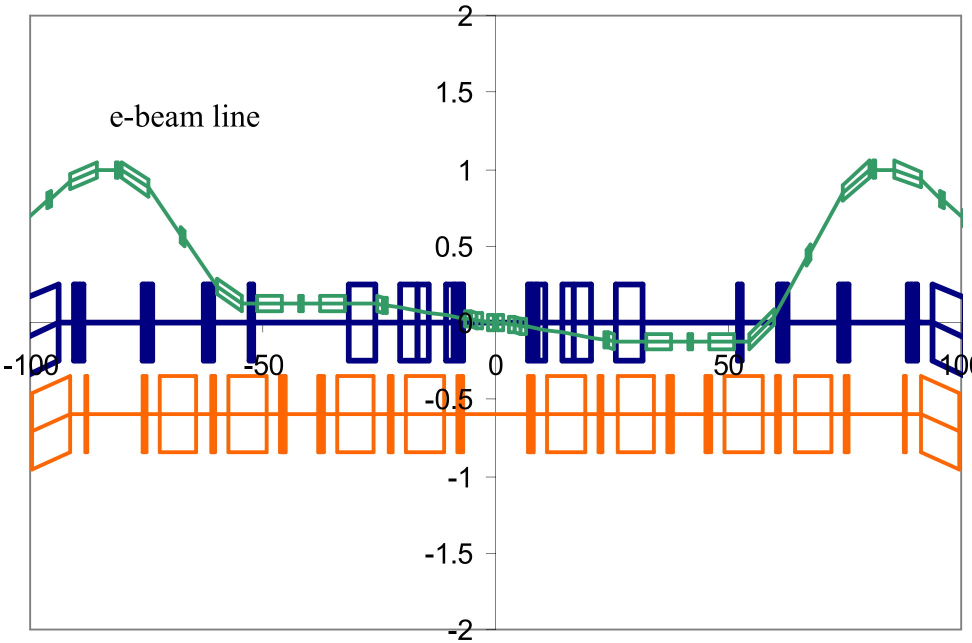
Compact Magnets for Recirculation Passes

- Separate recirculation loops
- Small aperture magnets
- Low current, low power consumption
- Minimized cost



Interaction Region Design (example for Ring-Ring case)





IR design features:

- No crossing angle at the IP
- Detector integrated dipole: dipole field superimposed on detector solenoid.
- No parasitic collisions.
- Round beam collision geometry with matched sizes of electron and ion beams.
- Synchrotron radiation emitted by electrons does not hit surfaces in the detector region.
- Blue ion ring and electron ring magnets are warm.
- First quadrupoles (electron beam) are at 3m from the IP
- Yellow ion ring makes 3m vertical excursion.
- Linac-Ring option can accommodate longer detector region

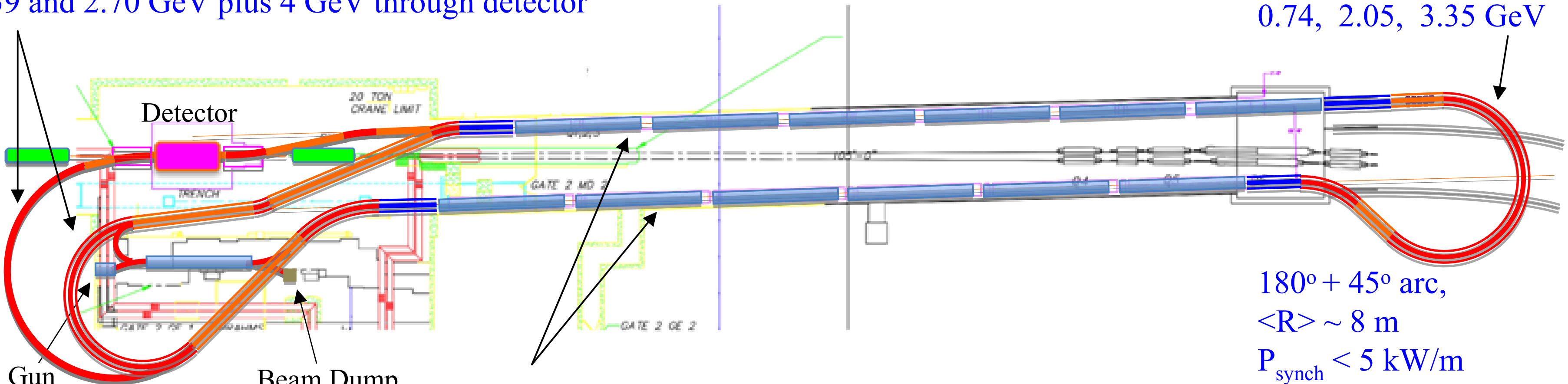
HERA type half quadrupole used for proton beam focusing

Staging of eRHIC

- **Medium Energy eRHIC**
  - Both accelerator and detector are located in RHIC at 2 o'clock IR
  - 90% reuse of components for eRHIC
  - 4 GeV ↑e^- x 250 GeV ↑p (63 GeV c.m.), L ~ 10^{32}-10^{33} cm^{-2} sec^{-1}
  - 4 GeV e^- x 100 GeV/n Au (40 GeV c.m.), L/n ~ 10^{32}-10^{33} cm^{-2} sec^{-1}
- **eRHIC**
  - High energy and luminosity, possibly also inside RHIC tunnel
  - 10 (20) GeV ↑e^- x 250 GeV ↑p (140 GeV c.m), L ~ 2.6 x 10^{33} cm^{-2} sec^{-1}
  - 10 (20) GeV e^- x 100 GeV/n Au (89 GeV c.m.), L/n ~ 2.9 x 10^{33} cm^{-2} sec^{-1}
- **Possible eRHIC extensions and upgrades**

  Higher energy and/or higher luminosity. For example:
  - 10 GeV ↑e^- x 325 GeV ↑p, L ~ 10^{34} cm^{-2} sec^{-1} (high energy proton cooling, high e-beam intensity)
  - 30 GeV e^- x 120 GeV/n Au (120 GeV c.m.), L/n ~ 10^{32}-10^{33} cm^{-2} sec^{-1} (extended linac, reduced e-beam intensity to limit synchrotron radiation power)

Medium Energy eRHIC in RHIC tunnel at 2 o'clock IR



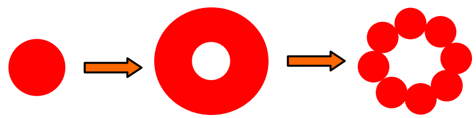
- IR2 region:
  - Asymmetric detector hall matches asymmetric detector for e-p collisions
  - Long, wide (7.3m) tunnel can accommodate the two linacs of the ERL
- Injector system (polarized gun, bunching system, pre-accelerator ERL) and the beam dump in detector hall
- Recirculation passes extend outside of the existing tunnel to allow for warm magnets and acceptable synchrotron radiation power. Minimal civil construction costs.

Medium Energy eRHIC parameters for e-p collisions

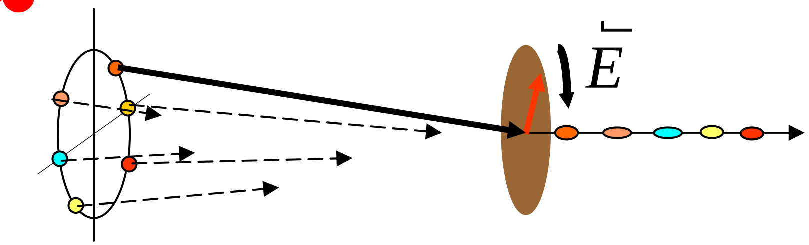
	no cooling of protons; parallel to RHIC ops		pre-cooled proton beam		high energy cooling of proton beam	
	p	e	p	e	p	e
Energy, GeV	250	4	250	4	250	4
Number of bunches	111		111		111	
Bunch intensity, 10^{11}	2.0	0.31	2.0	0.31	2.0	0.31
Beam current, mA	320	50	320	50	320	50
95% normalized emittance, $\pi\mu m$	15	440	6	175	1.5	44
Rms emittance, nm	9.4	9.4	3.8	3.8	0.94	0.94
β^*, cm	50	50	50	50	50	50
rms bunch length, cm	20	0.2	20	0.2	5	0.2
beam-beam parameter	0.002	0.44	.004	0.69	0.015	0.69
disruption parameter		3.1		7.7		7.7
Peak Luminosity, 10^{32} cm^{-2}s^{-1}	**0.93**		**2.3**		**9.3**	

R&D: High Intensity Polarized Electron Gun

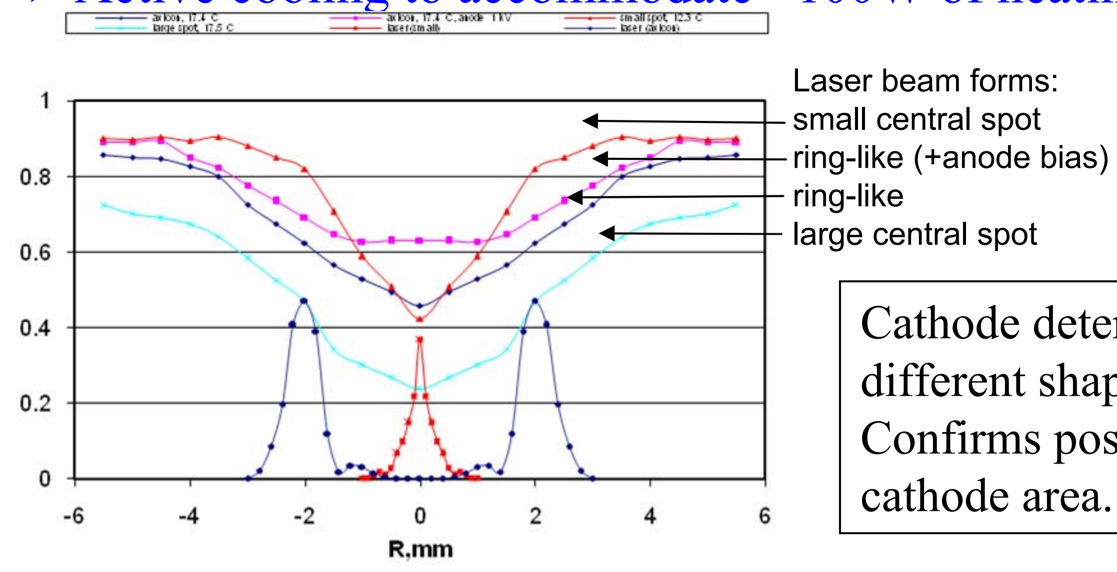
- ERL eRHIC design needs ~ 250 mA or 20 nC/bunch
- 50 mA from large cathode (diameter > 1cm) with ~ 50 mA/cm^2
- Development of a source with large (ring like) cathode area (MIT-Bates, E.Tsentalovich) to minimize ion bombardment damage.



- Multiple guns with rf-combiner to reach 250 mA:



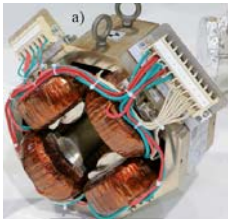
- Active cooling to accommodate ~100W of heating load from laser power

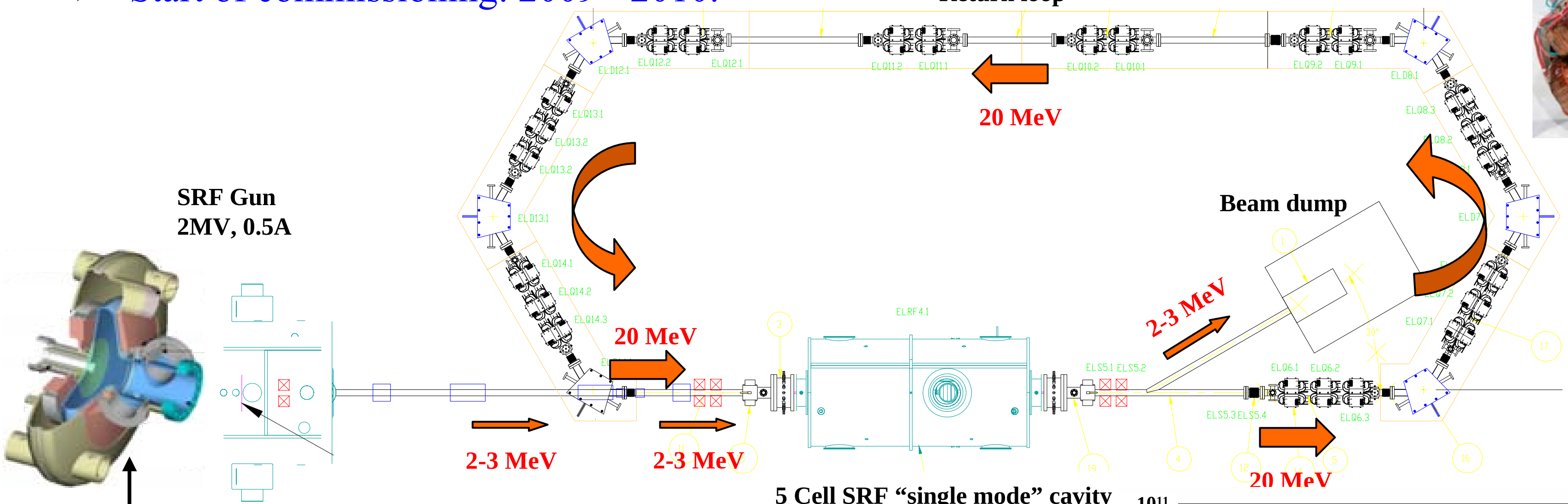


Cathode deterioration measured with different shapes of laser spot on the cathode. Confirms possible advantage of ring-like cathode area.

R&D: Energy Recovery Linac Test Facility

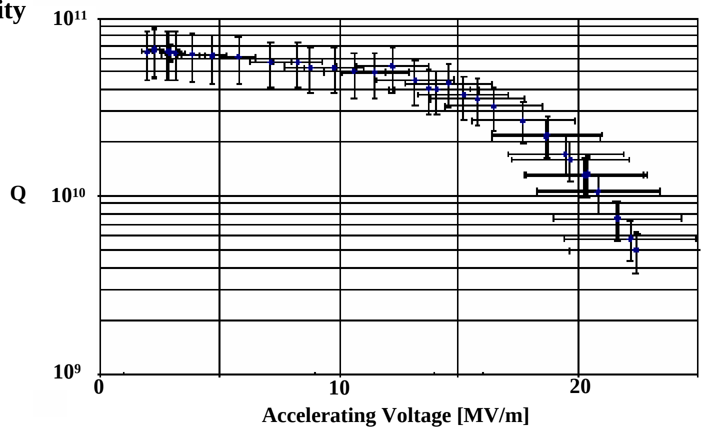
- Test of high current (0.5 A), high brightness ERL operation
- Electron beam for RHIC (coherent) electron cooling (54 MeV, 10 MHz, 5 nC, 4 μm)
- Test for 10 – 20 GeV high intensity ERL for eRHIC
- Test of high current beam stability issues, highly flexible return loop lattice
- Allows for addition of a 2nd recirculation loop
- Start of commissioning: 2009 - 2010.





5 Cell SRF "single mode" cavity
Q > 10^{10} @20 MV/m CW

SRF Photocathode gun powered by
1 MW, 703.75 MHz CW Klystron



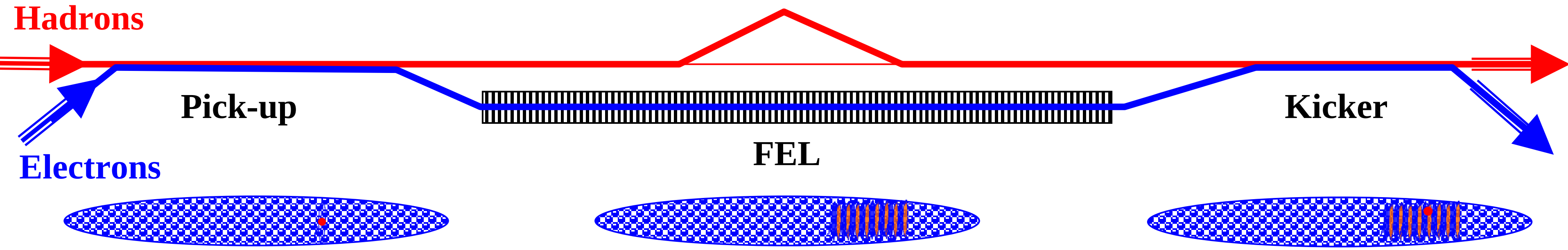
R&D: Coherent Electron Cooling

- Idea proposed by Y. Derbenev in 1980, novel scheme with full evaluation developed by V. Litvinenko
- Fast cooling of high energy hadron beams
- Made possible by high brightness electron beams and FEL technology
- ~ 20 minutes cooling time for 250 GeV protons → much reduced electron current, higher eRHIC luminosity
- Proof-of-principle demonstration possible in RHIC using Test-ERL.

Pick-up: electrostatic imprint of hadron charge distribution onto co-moving electron beam

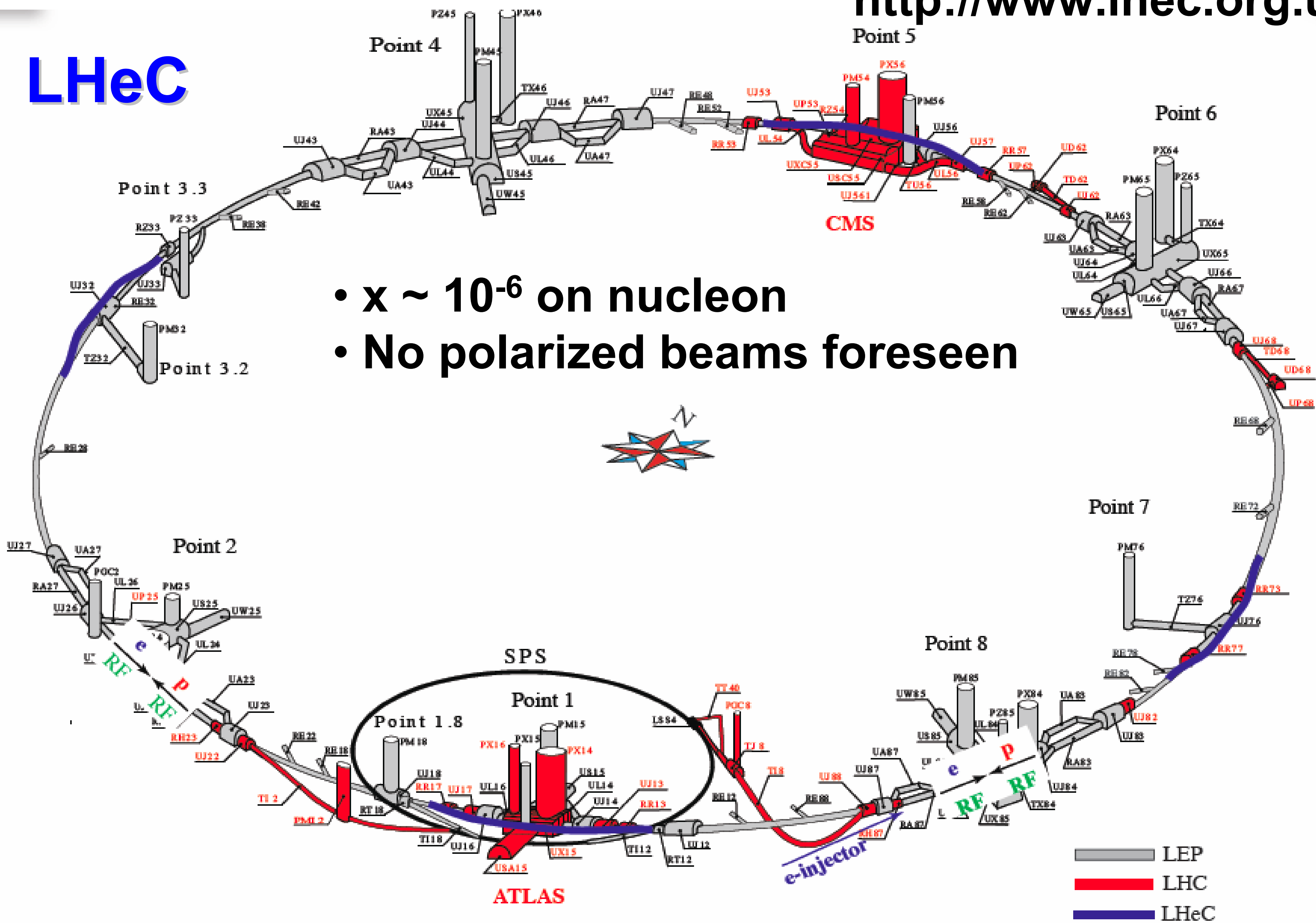
Amplifier: Free Electron Laser (FEL) with gain of 100 -1000 amplifies density variations of electron beam, energy dependent delay of hadron beam

Kicker: electron beam corrects energy error of co-moving hadron beam through electrostatic interaction



LHeC

- $x \sim 10^{-6}$ on nucleon
- No polarized beams foreseen



PAC09 Conference
May 4 – May 8, 2009

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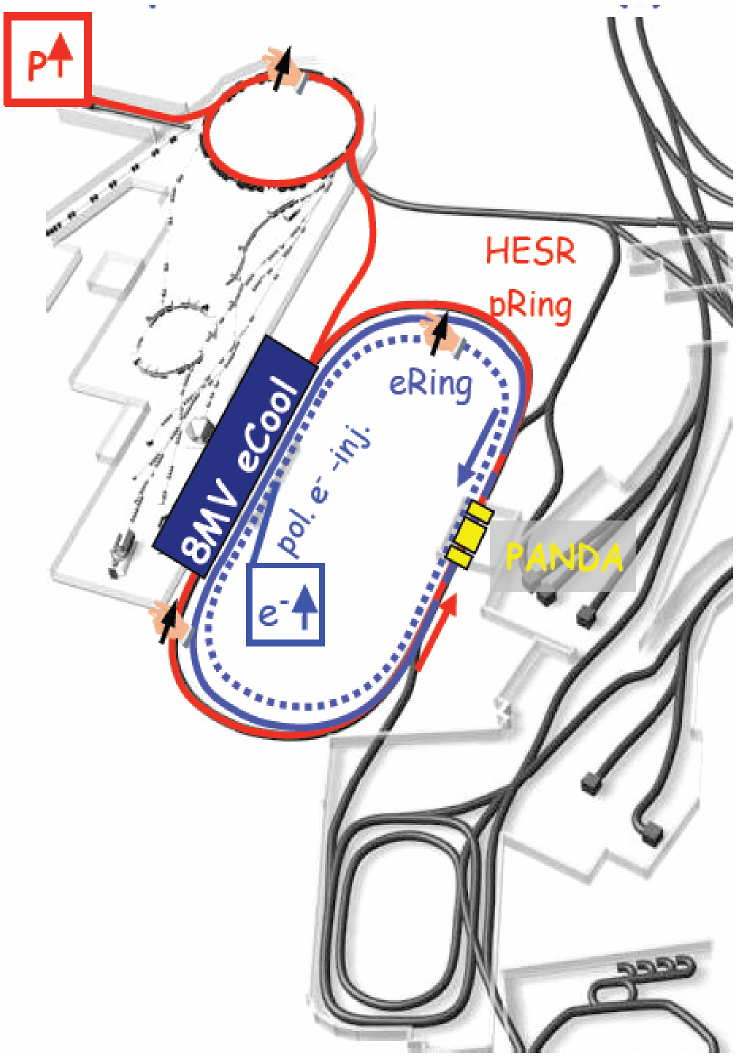

- $L \sim 10^{33}\ cm^{-2}s^{-1}$
- $E_{CM} \sim 13$ GeV
- polarized e-/e+
- polarized p/d
- possible utilization of planned PANDA detector
- Physics focus: study of nucleon structure down to $x \sim 10^{-3}$

Summary

- ELIC:
  - New ion accelerator and collider and existing CEBAF electron beam
  - High luminosity ring-ring collider using very high collision frequency, short ion bunches, super strong final focusing and high energy hadron cooling.
  - R&D on crab cavity scheme, production of intense ion beams and beam-beam effects
  - Staging options being developed

- eRHIC;
  - New high intensity electron beam colliding with existing RHIC heavy ion and polarized proton beams
  - High luminosity ERL-ring collider using high electron beam disruption parameter (beam-beam parameter) and could benefit from high energy hadron cooling
  - R&D on high intensity polarized electron gun and high intensity Test-ERL.
  - Staging option: 4 GeV $\uparrow e^-$ x 250 GeV $\uparrow p$ (63 GeV c.m.), L ~ 10^{32}-10^{33} cm^{-2} sec^{-1}

- LHeC and ENC: Focus on high E_{CM} (without polarization) and lower E_{CM} (with polarization), respectively – see talks

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