Status of EIC Machine Studies

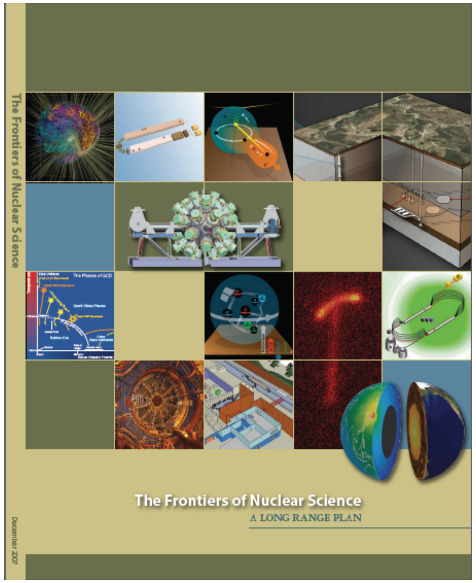
BROOKHAVEN NATIONAL LABORATORY

Thomas Roser
EIC Collaboration Meeting
December 11 - 13, 2008

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”*

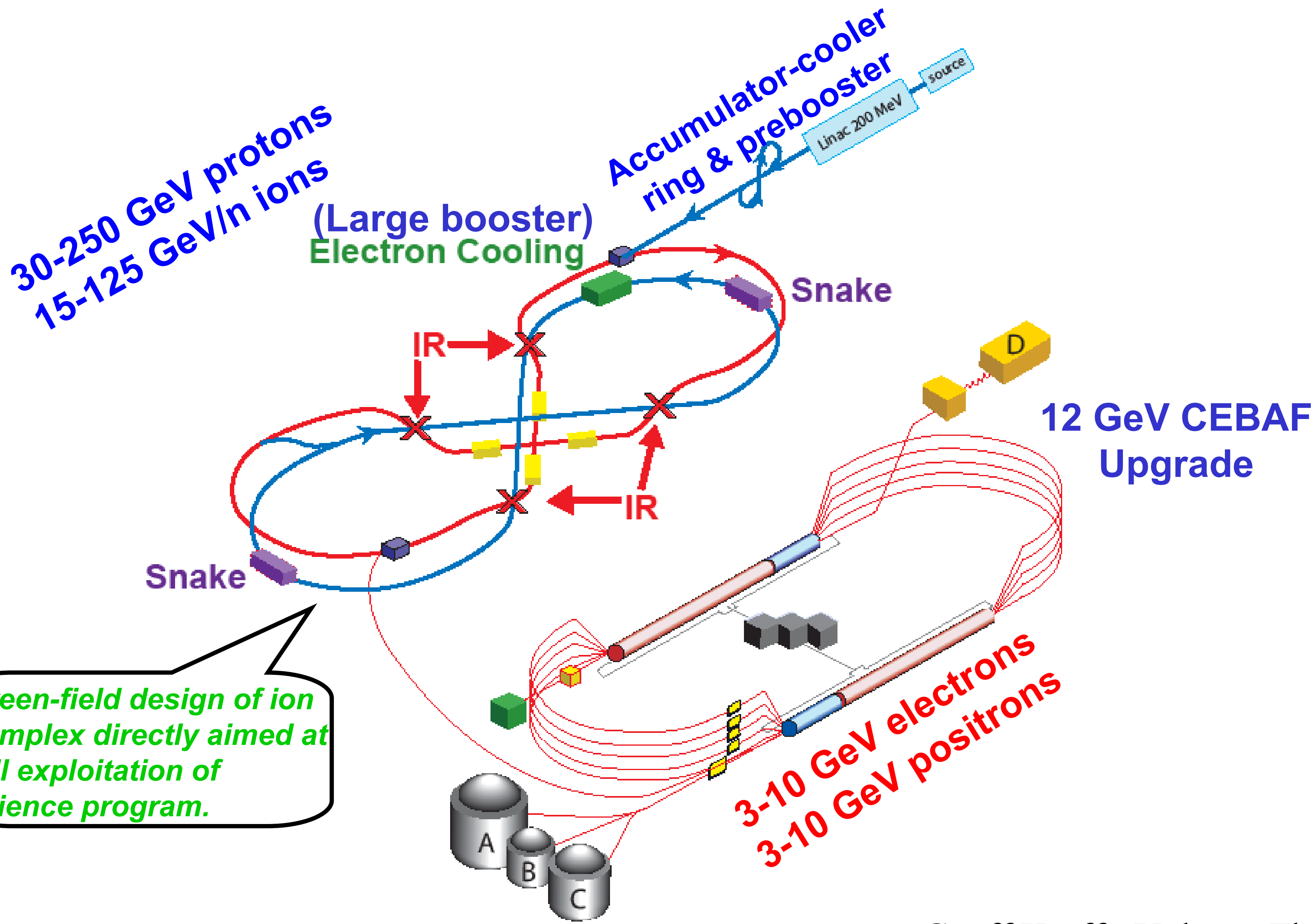
High luminosity
~ L(ep) ~$10^{33\text{-}34}$ cm^{-2} s^{-1}
~ 50 fb^{-1} over 10 years
~ 100 times luminosity of HERA

The Proposals

- 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 EIC proposals address different physics and parameter space:
  - LHeC: 70 x 7000 GeV, unpolarized beams, L ~ 10^{33} cm^{-2} s^{-1} (see talk of Ferdi Willeke (BNL) at Hampton meeting)
  - ENC@FAIR: 3 x 15 GeV, polarized beams, L ~ 2 x 10^{32} cm^{-2} s^{-1} (see talk of Andreas Jankowiak (Mainz) at this meeting)

BROOKHAVEN NATIONAL LABORATORY

ELIC Conceptual Design (Updated)



Green-field design of ion complex directly aimed at full exploitation of science program.

Geoff Krafft, Yuhong Zhang

ELIC Design Goals Including Recent Updates

- Expanding nominal design to cover whole CM energy range (20 to 100 GeV CM) required by NSCA LRP
  - Colliding beam energy 30x3 GeV to 250x10 GeV
- Luminosity
  - ~ 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)

ELIC (e/p) Design Parameters (Updated)

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

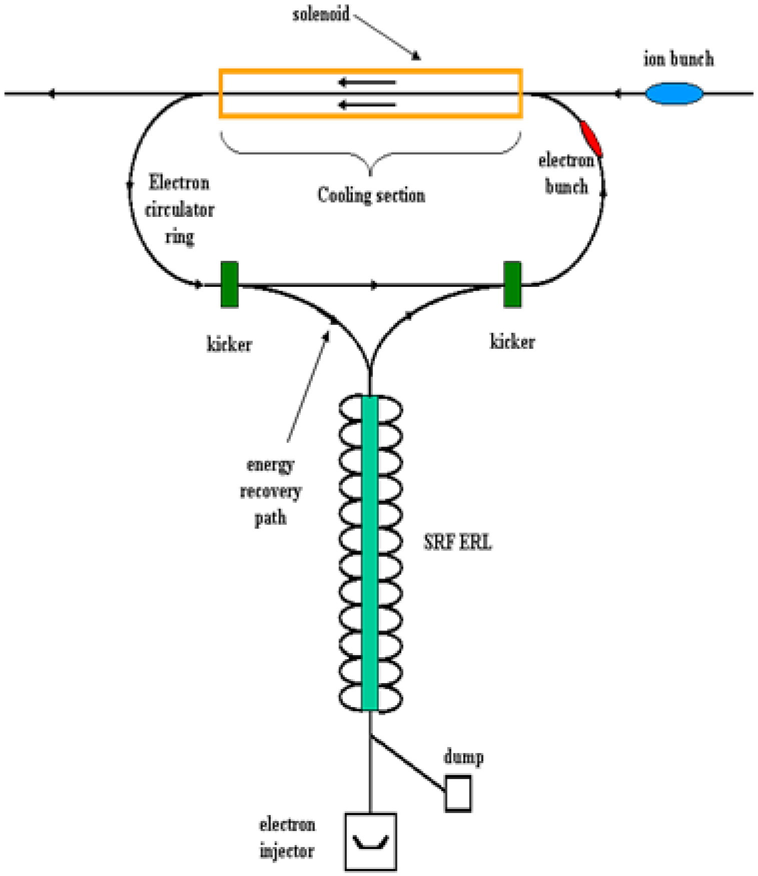
BROOKHAVEN NATIONAL LABORATORY

Main ELIC R&D Issues

- To achieve luminosity of ~ 10^{34} cm^{-2} sec^{-1} need:
  - High bunch collision frequency (f=0.5 GHz)
  - Crossing angle (~ 22 mrad)
  - Short ion bunches (~ 5 mm)
  - Super strong final focusing (β^* ~ 5 mm)
  - Large beam-beam parameters (0.01/0.1 per IP)
  - High brightness ion beams
- R&D issues:
  - High energy electron cooling using circulator
  - Crab cavity
  - Stability of intense ion beams
  - Detector R&D for high repetition rate

ELIC R&D: Electron Cooling

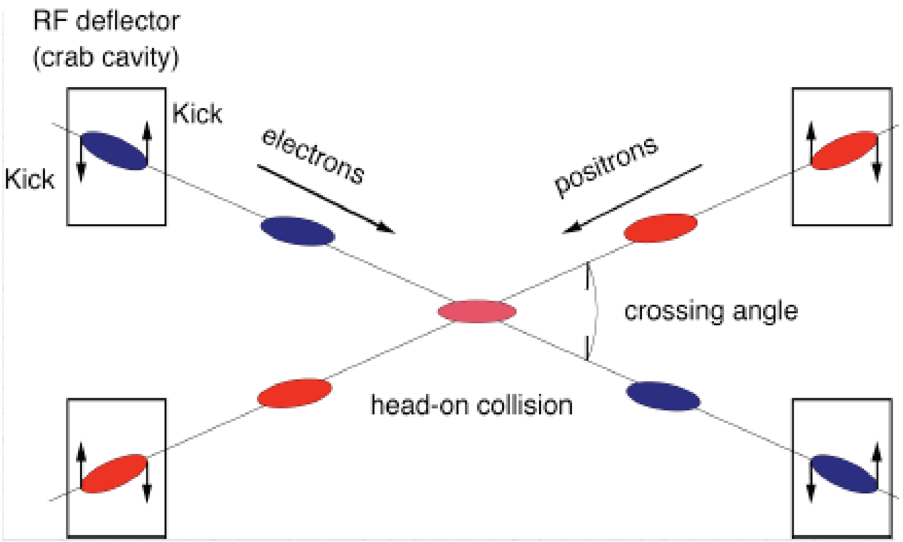
- Required to suppress IBS, reduce emittances, and provide short ion bunches
- Effective for heavy ions (higher cooling rate), difficult for protons
- State-of-Art: Fermilab demonstration (4.34MeV, 0.5A DC)
- ELIC ERL Based Circulator Cooler:
  - 3 A CW electron beam, up to 125 MeV
  - Circulator (100 turns) cooler for reducing average current from source/ERL
- R&D:
  - Bunched e beam cooling
  - Kicker rise time
  - SRF ERL for high current CW beam (see JLab and BNL ERL R&D)

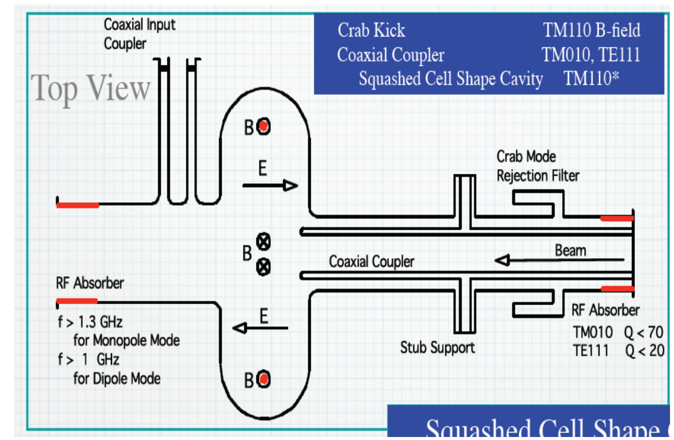


BROOKHAVEN NATIONAL LABORATORY

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.
Also LARP effort (BNL lead) for LHC upgrade

BROOKHAVEN NATIONAL LABORATORY

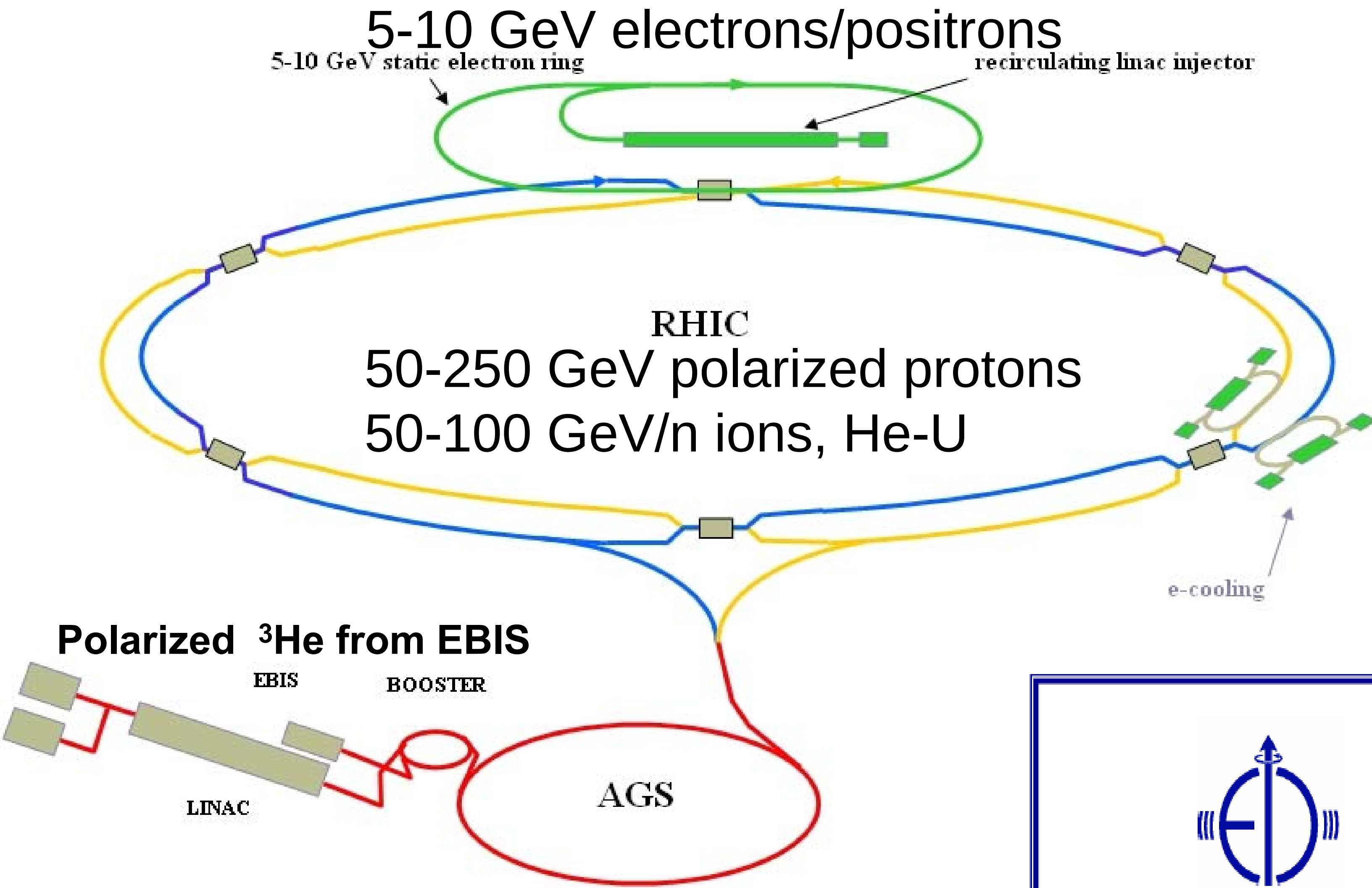
ELIC R&D Goals for Next Two Years

- Electron cooling: optimization and simulation
- Beam-beam and IBS simulation
- Forming intensity ion beam with stochastic cooling
- Electron spin dynamics simulation (with DESY)
- Crab cavity prototype (with JLab SRF Institute)
- Final focusing magnet (with JLab Physics division)
- Fast kicker (with JLab Engineering Division)
- Electron sources (with JLab Source & Injector group)
- Complete ZDR !

eRHIC

- Integrated electron-nucleon luminosity of ~ 50 fb^{-1} over about a decade for both highly polarized nucleon and nuclear (A = 2-208) RHIC beams.
  - 50-250 GeV polarized protons
  - up to 100 GeV/n gold ions
  - up to 167 GeV/n polarized ^3He ions
- Two accelerator design options developed in parallel (2004 Zeroth-Order Design Report):
  - ERL-based design (“Linac-Ring”; presently most promising design):
    - 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.
  - Ring-Ring option:
    - Electron storage ring for polarized electron or positron beam.
    - Technologically more mature with peak luminosity of 0.5×10^{33} $cm^{-2}s^{-1}$.

Ring-Ring eRHIC layout




C-A/AP/142
March 2004

eRHIC

Zero[th]-Order Design Report

BROOKHAVEN
NATIONAL LABORATORY

Ring-Ring eRHIC

- Electron/positron storage ring 5-10 GeV
- 1.2 km circumference (1/3 RHIC) optimized for: cost, synchrotron light power, e^+ polarizing time (5-20 min)
- “Super-bends” for optimal emittance and polarizing time at all energies
- Full-energy injection using re-circulating linac or figure-8 fast synchrotron
- Polarized injection: optimized ring; top-off mode
- “Spin transparent” lattice including IR and spin rotators
- Ring circumference adjustable to ion energy (RHIC orbital frequency) with a “Trombone”

Ring-Ring eRHIC Parameters

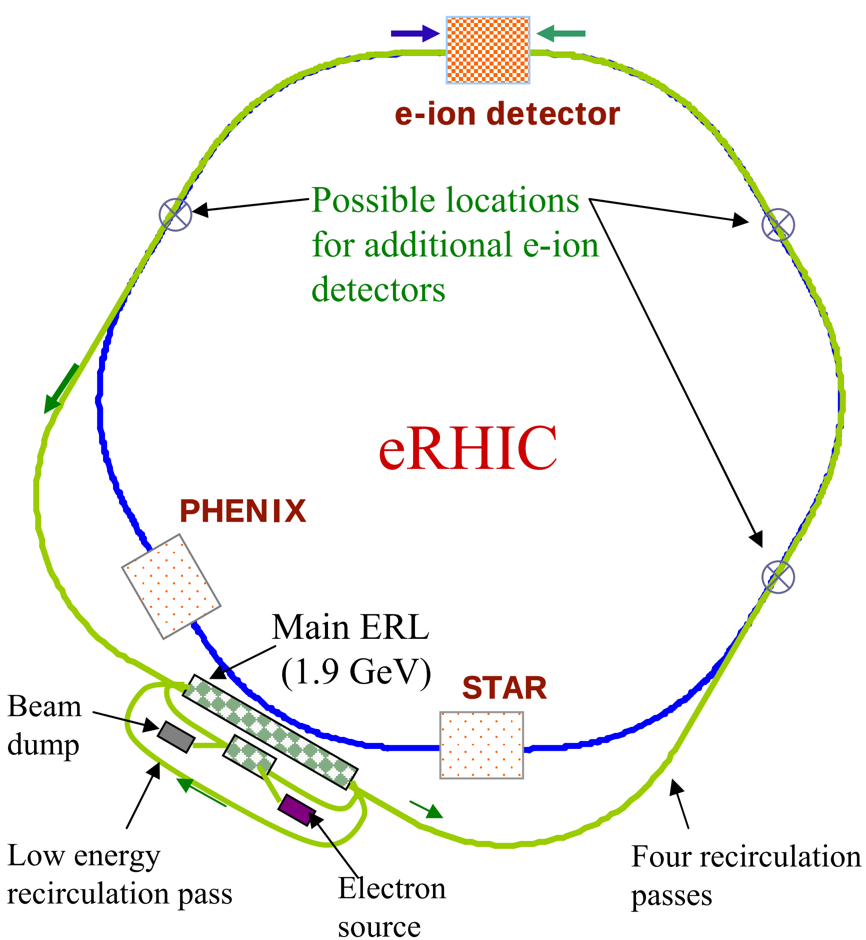
		High energy setup		Low energy setup	
		p	e	p	e
Energy, GeV	GeV	250	10	50	5
Number of bunches		165	55	165	55
Bunch spacing	ns	71	71	71	71
Particles / bunch	10^{11}	1.00	2.34	1.49	0.77
Beam current	mA	208	483	315	353
95% normalized emittance	π mm·mrad	15		5	
Emittance ε_x	nm	9.5	53.0	15.6	130
Emittance ε_y	nm	9.5	9.5	15.6	32.5
βx^*	m	1.08	0.19	1.86	0.22
βy^*	m	0.27	0.27	0.46	0.22
Beam-beam parameter ξ_x		0.015	0.029	0.015	0.035
Beam-beam parameter ξ_y		0.0075	0.08	0.0075	0.07
Bunch length σ_z	m	0.20	0.012	0.20	0.016
Polarization	%	70	80	70	80
Peak Luminosity	**10^{33}, cm^{-2}s^{-1}**	**0.47**		**0.082**	
Average Luminosity	**10^{33}, cm^{-2}s^{-1}**	**0.16**		**0.027**	
Luminosity Integral /week	**pb^{-1}**	**96**		**17**	

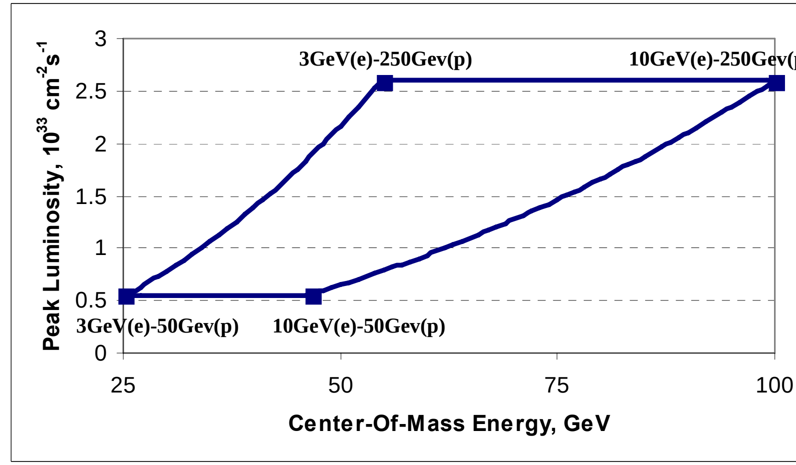
BROOKHAVEN
NATIONAL LABORATORY

Ring-Ring eRHIC Status

- Lattice design concept finalized, spin tracking, beam-beam effects studied
- Injection concept studied with cost optimization
- Interaction point concept developed and optimized with preliminary detector designs
- No major R&D
- Project reviewed by the RHIC Machine Advisory Committee (MAC)
- **Solid basis for cost estimate**
  - Could be built and made operational in a short time pending only availability of funds
- Recent development: electron lens in e-ring could increase beam-beam parameter on electron beam at IP. (e –lenses are studied for RHIC pp luminosity increase)

ERL-based eRHIC





- 10 GeV electron design energy. Possible upgrade to 20 GeV by doubling main linac length.
- 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

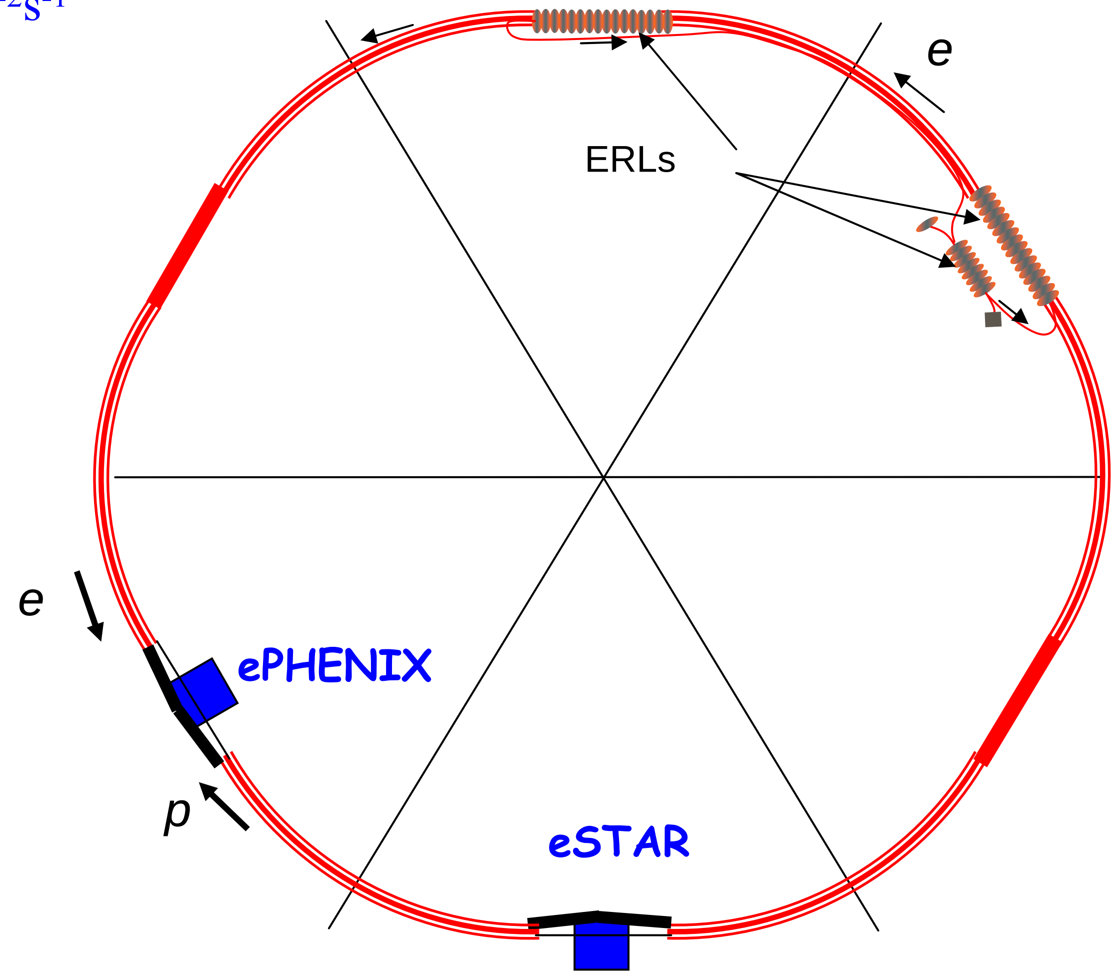
	Electron-Proton Collisions				Electron-Au Collisions			
	High energy setup		Low energy setup		High energy setup		Low energy setup	
	p	e	p	e	Au	e	Au	e
Energy, GeV	250	10	50	3	100	10	50	3
Number of bunches	166		166		166		166	
Bunch spacing, ns	71	71	71	71	71	71	71	71
Bunch intensity, 10^{11} (10^9 for 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*, x/y, cm	26	25	26	30	26	25	26	25
Beam-beam parameters, x/y	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, 1.e33 $cm^{-2}s^{-1}$	**2.6**		**0.53**		**2.9**		**1.5**	
Aver.Luminosity/n, 1.e33 $cm^{-2}s^{-1}$	**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 proton emittance and electron beam current can be reduced simultaneously, maintaining the luminosity.

BROOKHAVEN NATIONAL LABORATORY

Lower cost option with Linacs in RHIC tunnel

- High energy (up to 20-30 GeV) ERL-based design with all accelerating linacs and recirculation passes placed in the RHIC tunnel.
- Considerable cost savings
- Luminosity exceeds 10^{33} $cm^{-2}s^{-1}$



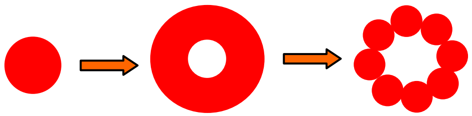
BROOKHAVEN NATIONAL LABORATORY

Main eRHIC R&D Items

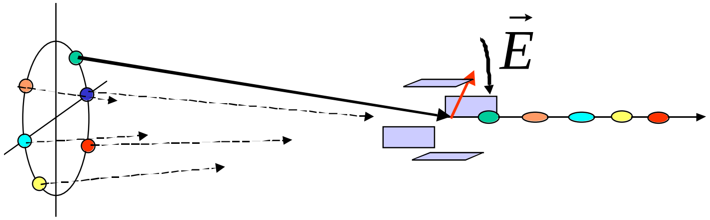
- **Electron beam R&D for ERL-based design:**
  - High intensity polarized electron source
    - Development of large cathode guns with existing current densities ~ 50 mA/cm^2 with good cathode lifetime.
  - Energy recovery technology for high power beams
    - Multi-cavity cryo-module development; high power beam ERL, BNL ERL test facility; loss protection; instabilities.
  - Development of compact recirculation loop magnets
    - Design, build and test a prototype of a small gap magnet and its vacuum chamber.
  - Beam-beam effects: e-beam disruption
- **Main R&D items for ion beam:**
  - Beam-beam effects: electron pinch effect and kink instability
  - Polarized ^{3}He acceleration
  - 166 bunches
  - High precision ion beam polarimeter to 1-2 %
- **General EIC R&D item**:
  - Proof of principle of Coherent Electron Cooling

eRHIC R&D - Polarized Electron Gun Development

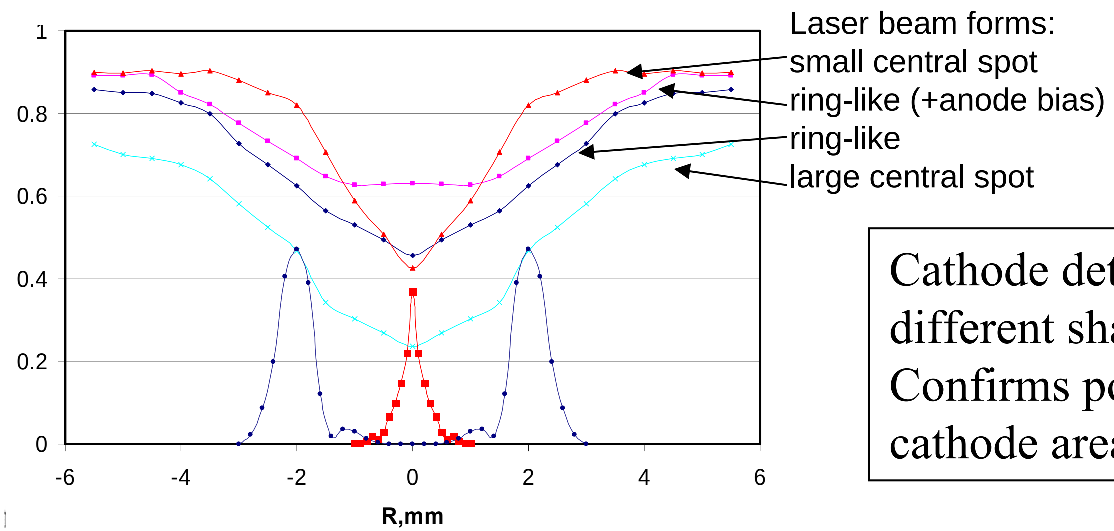
- ERL eRHIC design needs ~ 250 mA or 20 nC/bunch
- 50 mA from large cathode (diameter > 1cm) with ~ 50 mA/cm^2
- Development of a source with large (ring like) cathode area (MIT-Bates, E.Tsentalovich) to minimize ion bombardment damage.



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



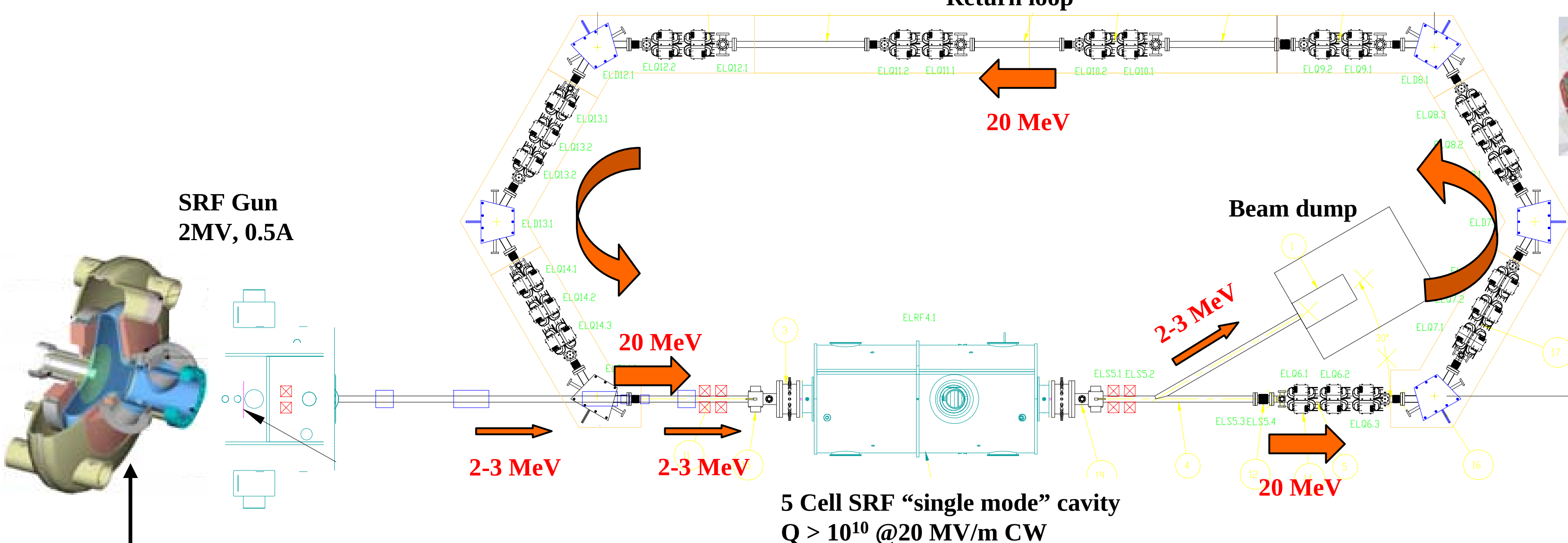
- Active cooling, to accommodate ~100W of heating load from laser power



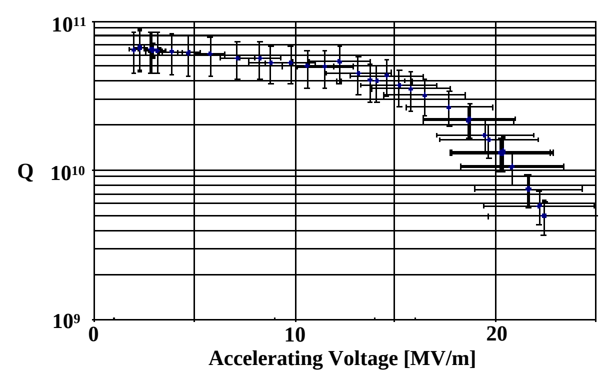
Cathode deterioration measured with different shapes of laser spot on the cathode. Confirms possible advantage of ring-like cathode area.

Energy Recovery Linac (ERL) 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
- Start of commissioning: 2009 - 2010.



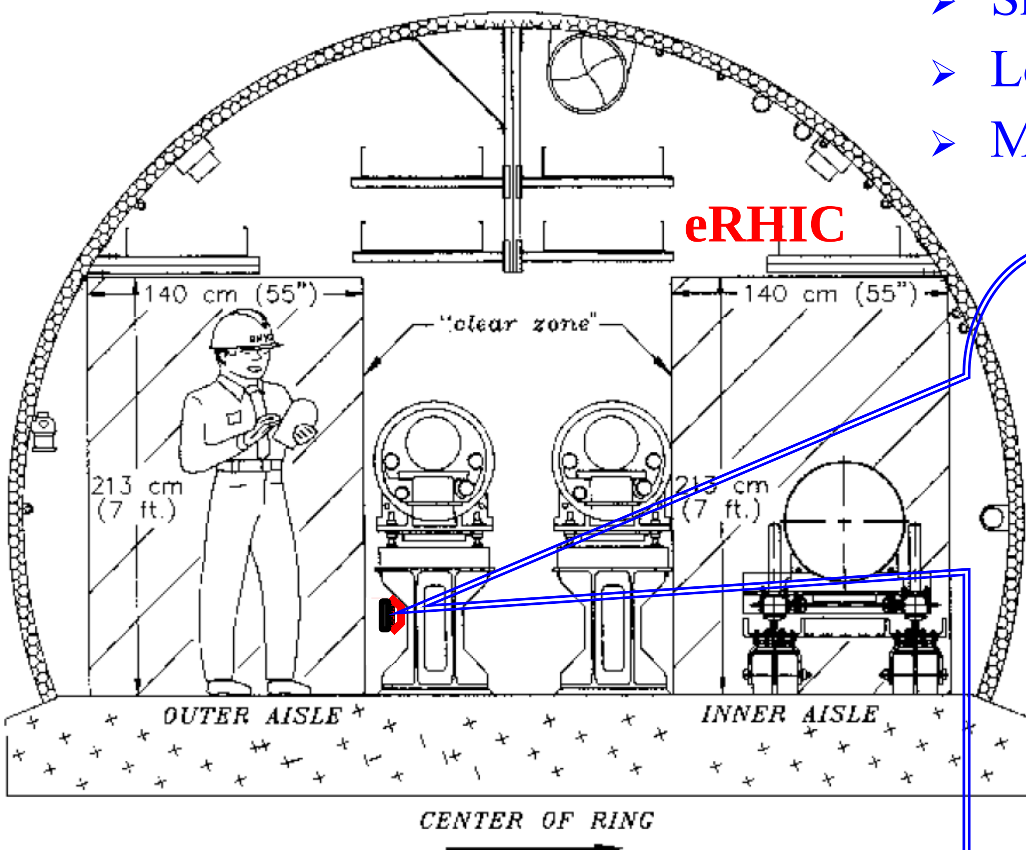
1 MW, 703.75 MHz CW Klystron

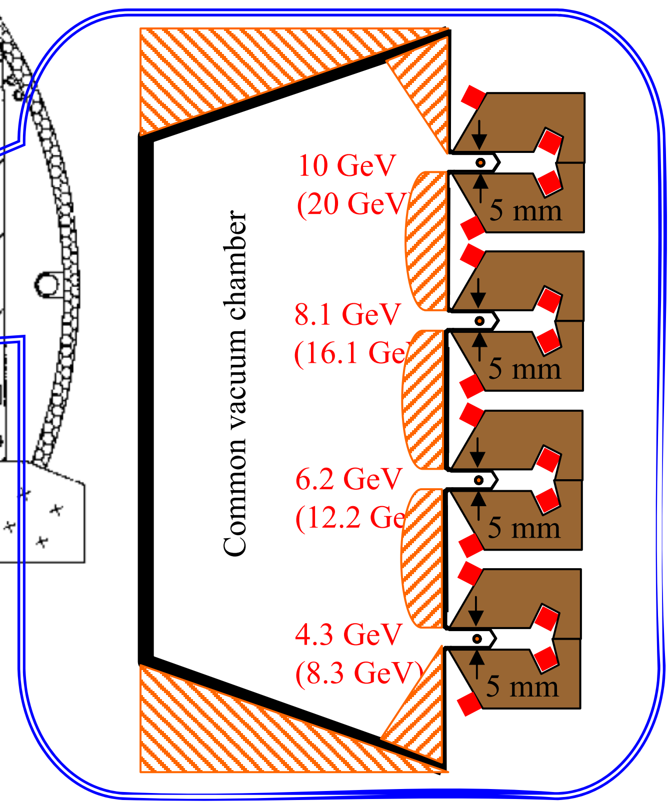


BROOKHAVEN NATIONAL LABORATORY

eRHIC R&D - Recirculation Passes

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



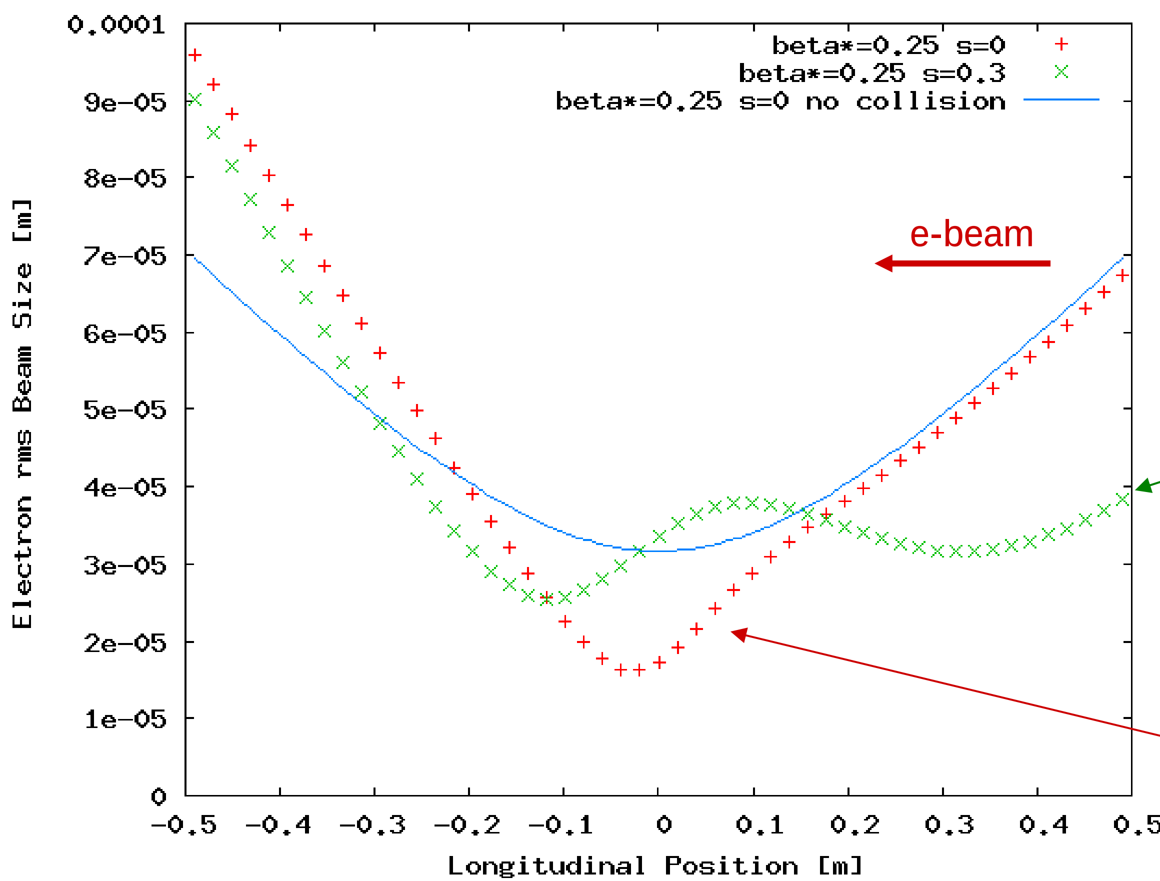


Development of prototype magnets is underway (BNL LDRD, V.N.Litvinenko)

BROOKHAVEN NATIONAL LABORATORY

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

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

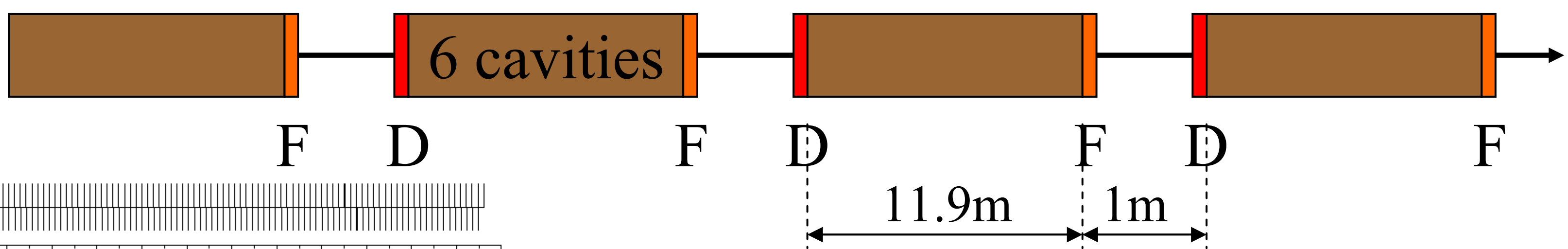
$$\xi_{\max} = 0.054$$
$$\xi_{ave} = 0.031$$

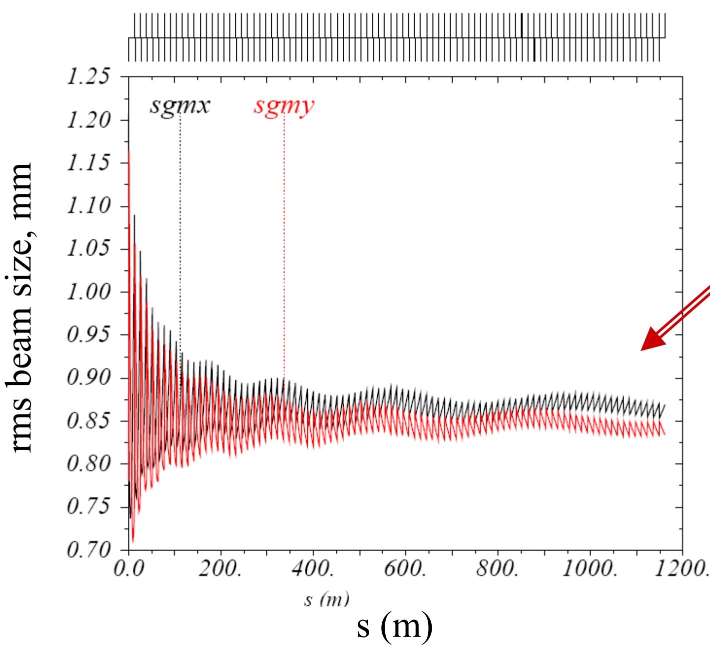
More investigations are underway for incoherent proton beam emittance growth in the presence of electron pinch, including the optimal choice of the working point.

BROOKHAVEN NATIONAL LABORATORY

eRHIC R&D - Compact linac design

- Increased number of 700MHz cavities inside one cryostat to 6 cavities.
- 3rd harmonic cavities to reduce momentum spread; may not be needed
- Cavity gradient: 19.5 Mev/m; average acceleration rate: 8.2 MeV/m
- Total length of 1.9 GeV linac: 232m   (instead of ~ 360m in the previous design)

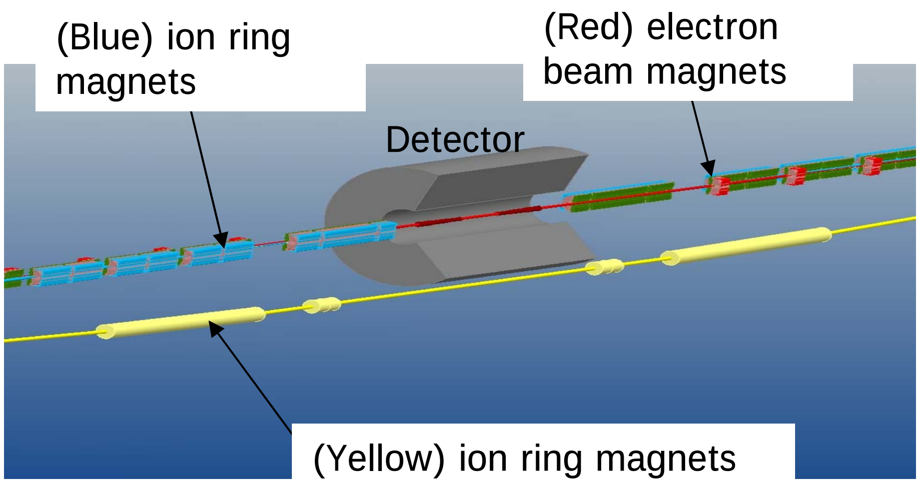


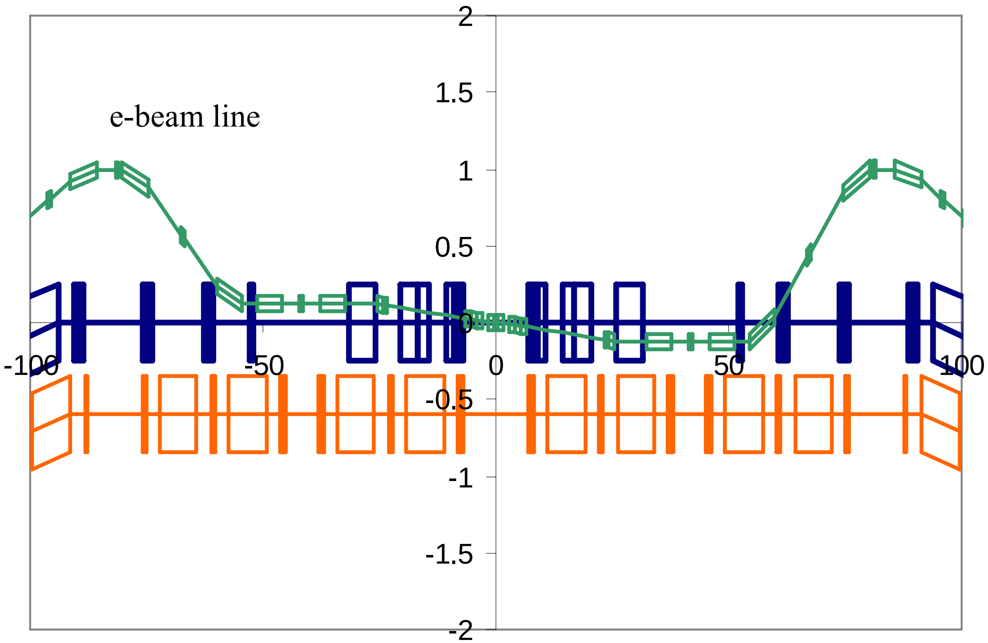


- Evolution of rms beam sizes along the linac on all acceleration passes.
- Recirculating passes are Unit matrix.
- Doublet focusing (90º phase advance per cell)
- Constant quadrupole gradient.

Compact linac design allows for linac(s) to be placed inside the RHIC tunnel

Interaction Region Design





Present 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.

HERA type half quadrupole used for proton beam focusing

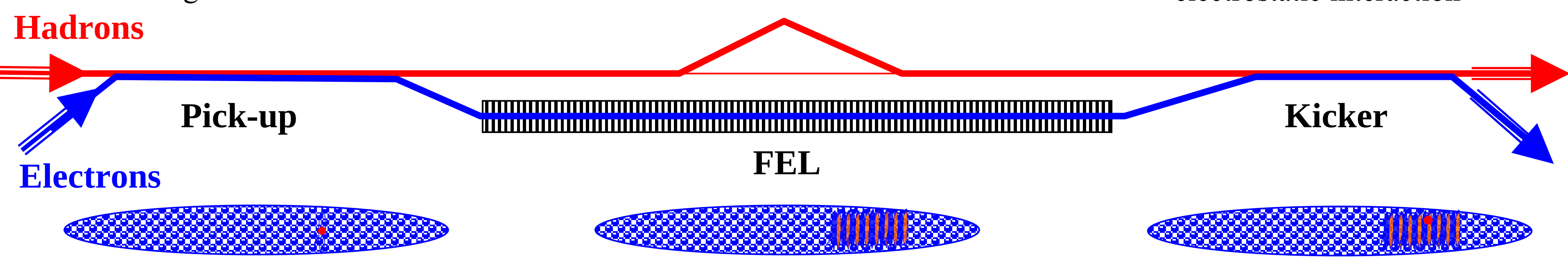
Coherent Electron Cooling

- 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



Summary

- **Awaiting specific EIC R&D funds in response to LRP recommendation.** In the meantime:
- ELIC:
  - Significant update of parameters: reduced bunch rate, increased energy and circumference
  - Conceptual design of complete ring and IP beam optics, electron cooling and circulator cooler
  - Continued study of crab cavity scheme (KEK, prototype at JLab, also LARP [BNL lead]), production of intense ion beam and beam-beam effects
- eRHIC;
  - Accelerator design work on aspects of the ERL-based design of eRHIC, including linac design, recirculating pass optics, and beam-beam effects.
  - Some funding available for polarized electron source development (NP Accel. R&D), ERL test facility (NP Accel. R&D, NAVY) and compact magnet design (BNL LDRD). Expect significant advances during the next two years.
  - Other design options under consideration: ERL-based designs with linac(s) in the tunnel and Ring-Ring design.
- R&D for both ELIC and eRHIC:
  - Coherent Electron Cooling can be developed and tested at RHIC
  - Polarized ^{3}He source development at the BNL EBIS