eRHIC Design Status and Plans

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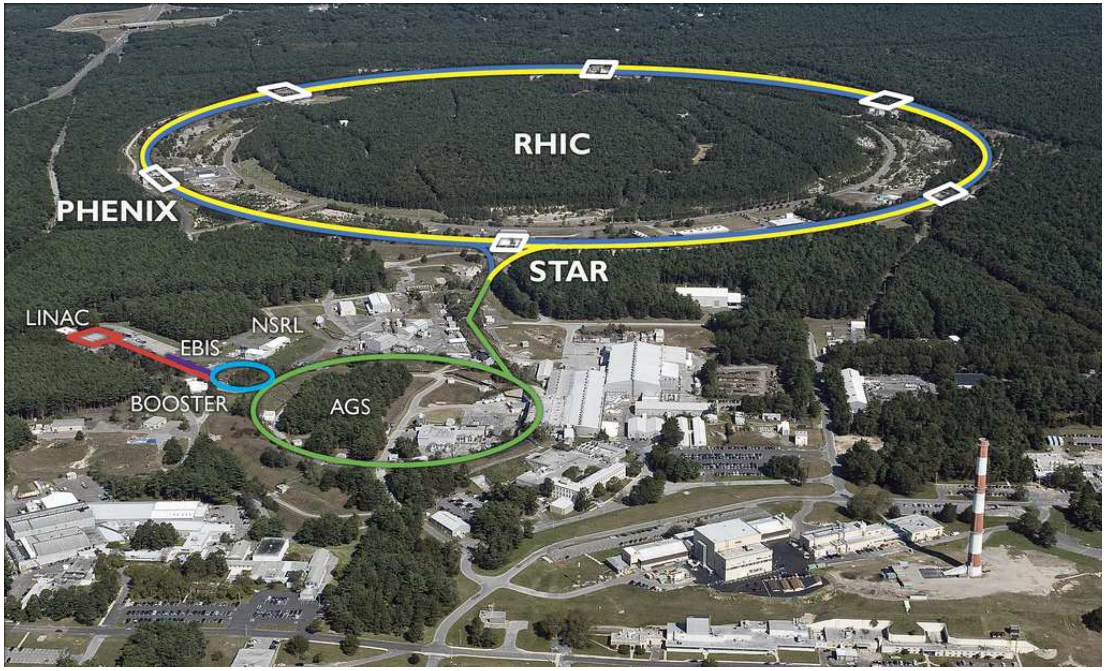


The Relativistic Heavy Ion Collider RHIC

- Two superconducting storage rings
- 3833.845 m circumference
- Energy range 25 - 250 GeV polarized protons, or 10 - 100 GeV/n gold
- Virtually all ion species, from (polarized) protons to uranium
- Two collider experiments, STAR and PHENIX
- Siberian snakes to preserve proton polarization on the ramp
- Spin rotators to manipulate spin orientation at IPs
- Operating since 2000

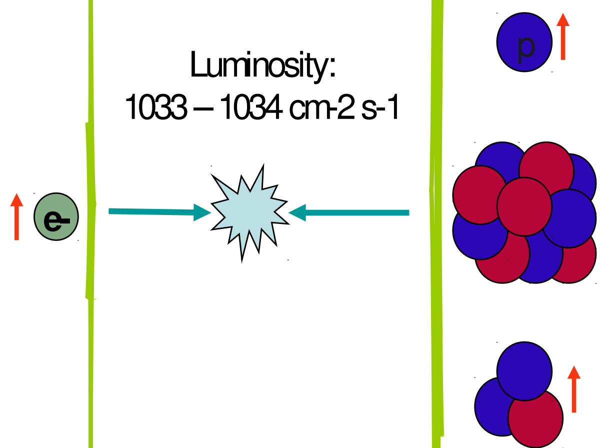
Electron-ion collider physics

eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing $2.5B RHIC
including existing RHIC tunnel, detector buildings and cryo facility

Luminosity:
1033 – 1034 cm-2 s-1

80% polarized electrons:
1.3 – 21.2 GeV

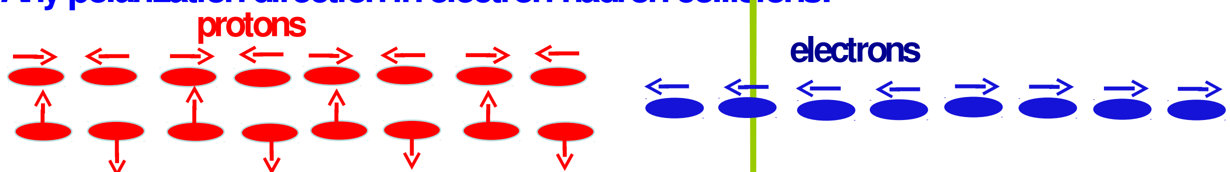


70% polarized protons
25 - 250 (275*) GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u

Pol. light ions (He-3)
17 - 167 (184*) GeV/u

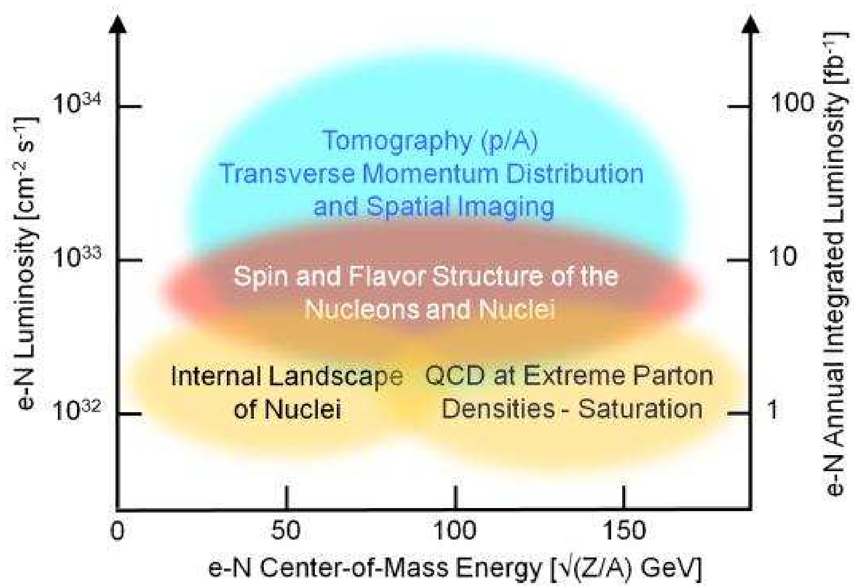
- **Center-of-mass energy range: 20 – 145 GeV**
- **Full electron polarization at all energies**
  Full proton and He-3 polarization with six Siberian snakes
- **Any polarization direction in electron-hadron collisions:**



* It is possible to increase RHIC ring energy by 10%

eRHIC Design Requirements
based on EIC White Paper

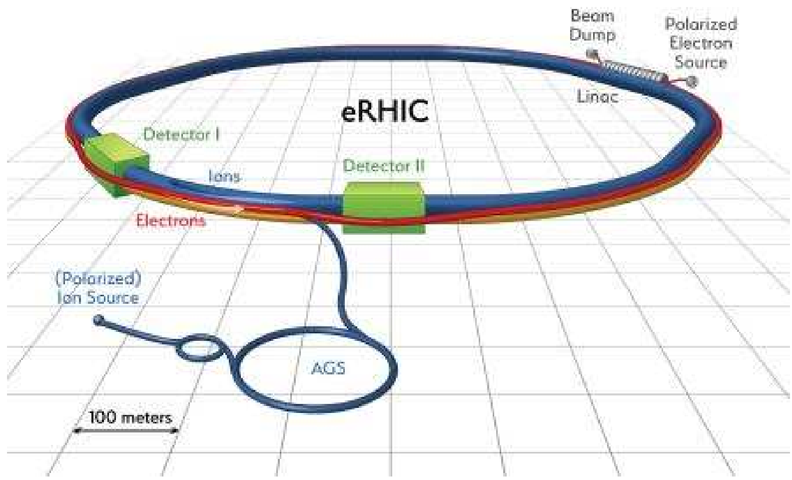
- High luminosity, $10^{33} - 10^{34}\,\text{cm}^{-2}\text{sec}^{-1}$
- Large center-of-mass energy range, $20 - 140\,\text{GeV}$
- Longitudinal spin polarization of both beams
- Arbitrary spin patterns in both beams
- Large acceptance for forward scattered protons with $200\,\text{MeV/c} < p_\perp < 1.3\,\text{GeV/c}$, and a 4 mrad forward neutron cone



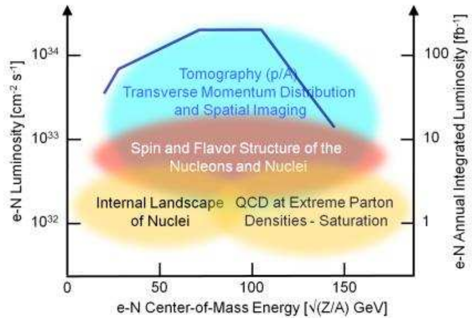
eRHIC Design Concept

Based on RHIC with
- 275 GeV polarized proton ring
- large circumference tunnel with long straights

By adding an 18 GeV electron accelerator (either linac or storage ring) in the same tunnel:
- high energy reach
- moderate synchrotron radition losses
- high luminosity



Ultimate eRHIC Design



- Meets all requirements of EIC White Paper
- Luminosity $10^{33} - 10^{34}\,\text{cm}^{-2}\text{sec}^{-1}$ over entire center-of-mass energy range 20 - 140 GeV

However:

- Based on high-risk, novel technologies:

– high current Energy-Recovery Linac (ERL),

– 50 mA polarized electron gun,

– Coherent electron Cooling (CeC),

– Fixed-Field Alternating Gradient (FFAG) focusing

$\Rightarrow$ To move forward, start with a low-risk design at lower luminosity ($10^{32} - 10^{33}$) that can later be upgraded

Acceptable Risk Design

Requirements for an initial phase:

- CM energy: 20 - 140 GeV
- Luminosity: $0.1 - 1 \times 10^{33}$; upgradable to $1 - 10 \times 10^{33}$ with modest upgrades depending on R&D progress for ion cooling
- Frequent changes to the spin-sign assignment of the electron beam as determined by the Physics requirements
- Beam divergencies at the IR not exceeding the experimental requirements

Requirements can be met with either a linac-ring or a ring-ring design

Ring-Ring vs. Linac-Ring

Ring-Ring:

Many bunches, ampere-level beam currents

Limited by beam-beam effect on electrons, $\xi \leq 0.1$

Main challenge:

Interaction region with focusing of both beams near IP, plus masking of synchrotron radiation

Linac-Ring:

Low emittance bunches

No beam-beam limit on electrons

Relatively large electron β^* allows large l^*

Main challenges:

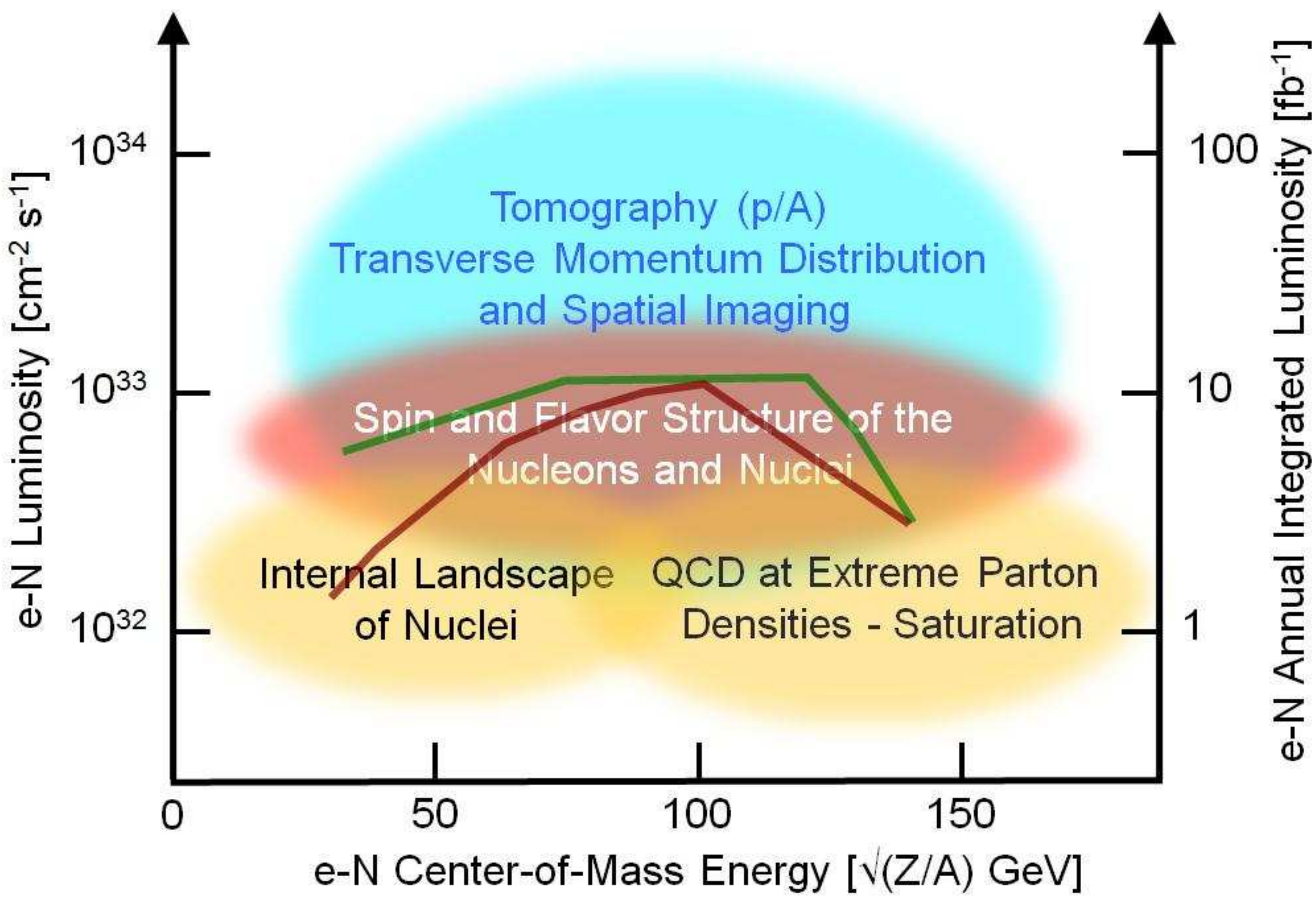
High intensity polarized electron gun

HOM power in ERL linac

Parameters at Highest Luminosity

	Ring-Ring		Linac-Ring	
Parameter	e	p	e	p
Energy [GeV]	10	250	13	250
$\sqrt{s}$ [GeV]	100		105	
No. of bunches	330		110	
Bunch freq. [MHz]	28.2		9.4	
Bunch intensity [10^{10}]	31	12	3.3	30
Beam current [mA]	1300	500	50	415
Emittance h/v [nm]	24.2/3.86	17.7/6.7	2.5/2.5	3.4/3.4
Vertical β^* [cm]	7.4	4.2	17.5	13
Horizontal β^* [cm]	417	567	35	26
IP rms beam size h/v [μm]	318/17		30/21	
rms beam div. at IP h/v [μrad]	80/230	56/400	85/120	115/163
max. beam-beam parameter	0.1	0.015	1	0.004
e-beam disruption parameter	neglig.		6	
rms bunch length [cm]	0.8	8	0.3	16
Polarization [%]	80	70	80	70
Luminosity [10^{33} cm^{-2}sec^{-1}]	1.1		1.2	

Luminosity vs. Center-of-Mass Energy



Main Features of the Linac-Ring Design

• Superconducting multi-turn energy-recovery linac (ERL)
3 GeV superconducting linac with 6 return loops to 18 GeV

• High current polarized electron source
Eight individual guns in parallel, each delivering 6.25 mA, with bunch-by-bunch switching between them

• Low-emittance RHIC protons and stochastically cooled heavy ions
Reliable generation and preservation of low emittance proton beams to be demonstrated

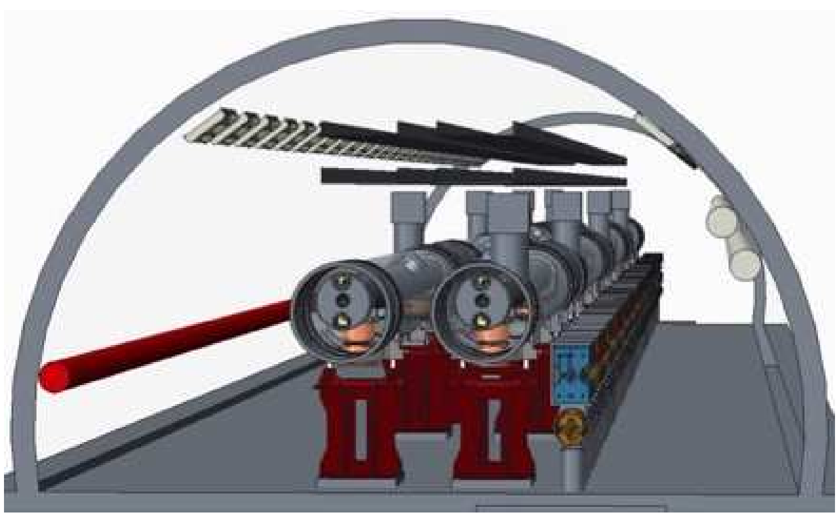
• 14 mrad crossing angle requiring crab cavities

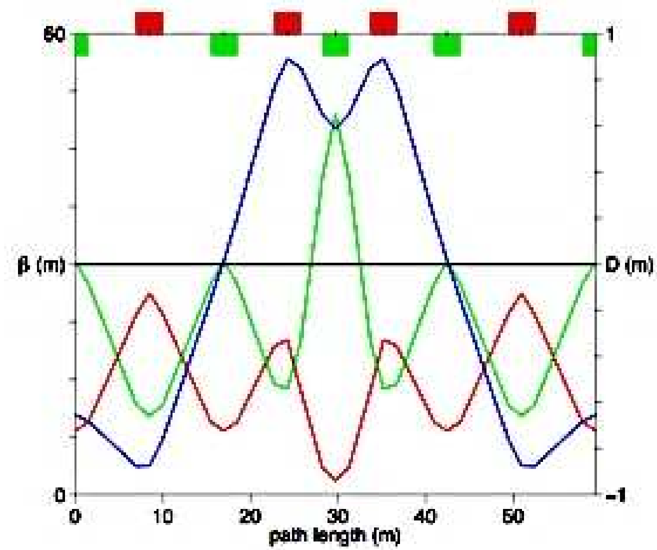
• Spin rotators after injector and before IP

Superconducting Multi-Pass ERL

• Two 200 m long linacs, 1.5 GeV each, 36 cryo modules with 18 MV/m

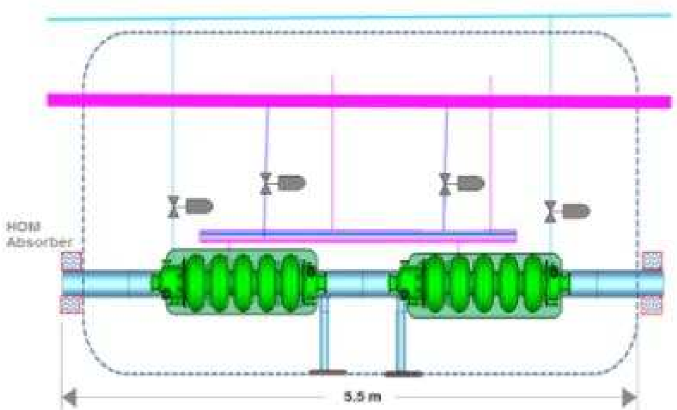
• 6 vertically stacked isochronous recirculating loops in the RHIC tunnel to reach 18 GeV





Cryo module

- Two 647 MHz 5-cell cavities (JLab/FNAL design) per module
- 72 modules total (36 per linac)
- 18 MV/m, CW, $Q = 3 \times 10^{10}$
- RF power 26.7 kW, HOM power 12-30 kW per module
- Total length 5.5 m, $U = 42\,\text{MV}$



- Beampipe HOM dampers (demonstrated at KEKB and Cornell)

Polarized Electron Source

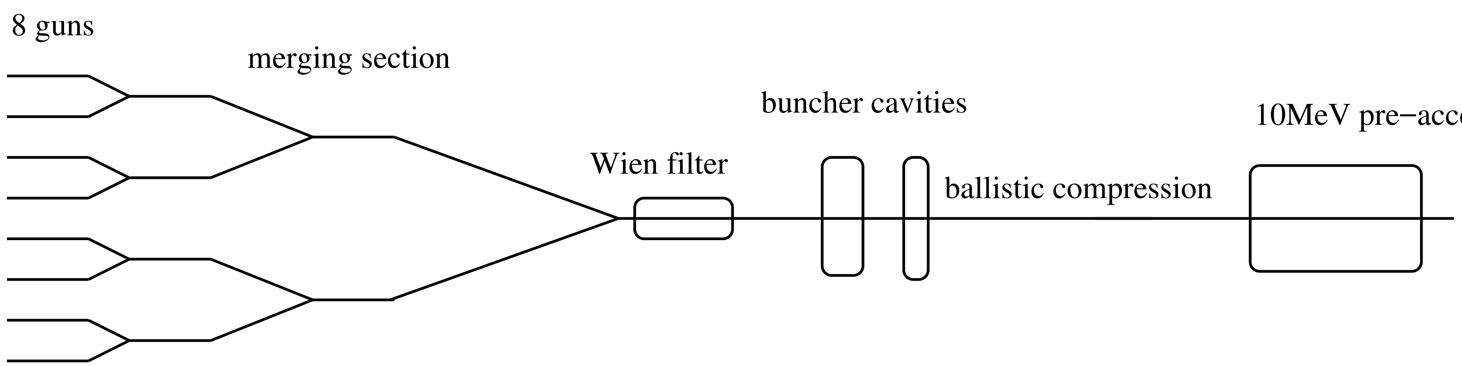
Need 3×10^{10} electrons/bunch at 9.4 MHz (50 mA), with 80% polarization

Meet this requirement using 8 guns in parallel, each providing 5.3 nC bunches at 1.2 MHz

• Beam current similar to JLab polarized gun (4 mA), but 5 A peak current is more than factor 10 higher (0.3 A)
• 5 A peak current is similar to SLC polarized gun (2.7 A), but average current of 6.25 mA is much larger
• eRHIC gun needs combination of both

Experimental verification required, in progress

High-Intensity Electron Injector



10 MeV injector consisting of 8 individual eletron guns, combiner section, buncher and pre-accelerator

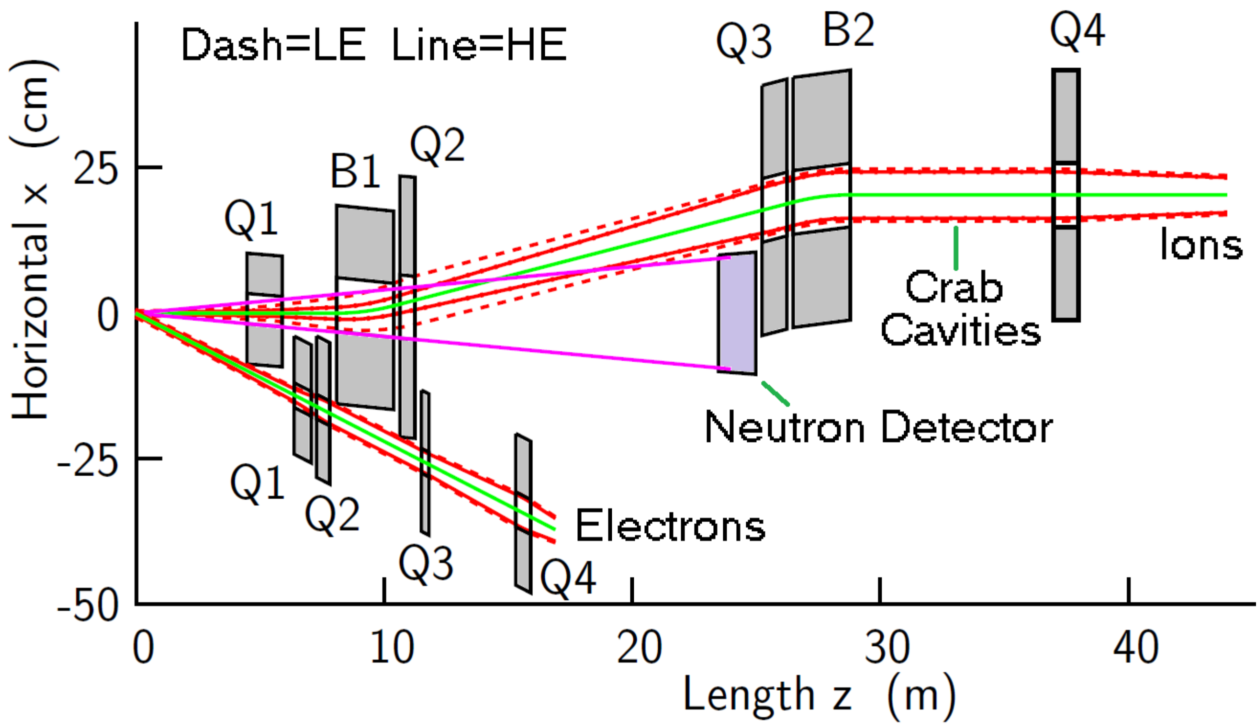
Ongoing studies:

- Develop test gun and laser system with eRHIC parameters
- Finalize technicalities of combiner section
- Detailed 3D-studies of high charge beam transport
- Experimental studies of cathode lifetime

Main Features of the Ring-Ring Design

- Full energy polarized electrons injected and stored in storage ring
- Many bunches, high electron beam current, flat beams
- IR geometry and detector capable of accepting large electron beam emittance
- 22 mrad crossing angle requiring crab cavities
- Bunch-to-bunch spin sign control by full energy injection and frequent bunch replacement
- RHIC hadron beams
- Electron beam current limited by 10 MW synchrotron radiation power

Interaction Region

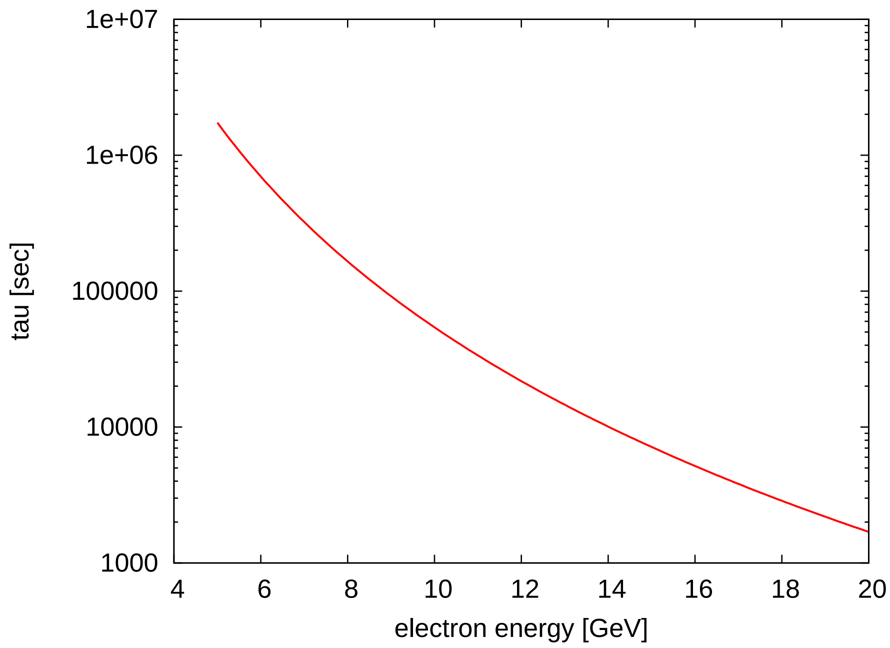


- Interleaved arrangement of electron and hadron quadrupoles
- 22 mrad total crossing angle
- Beam size in crab cavity region independent of energy - crab cavity apertures can be rather small, thus allowing for high frequency

Electron polarization

Ramping would destroy electron polarization

Electrons self-polarize at store due to synchrotron radiation:



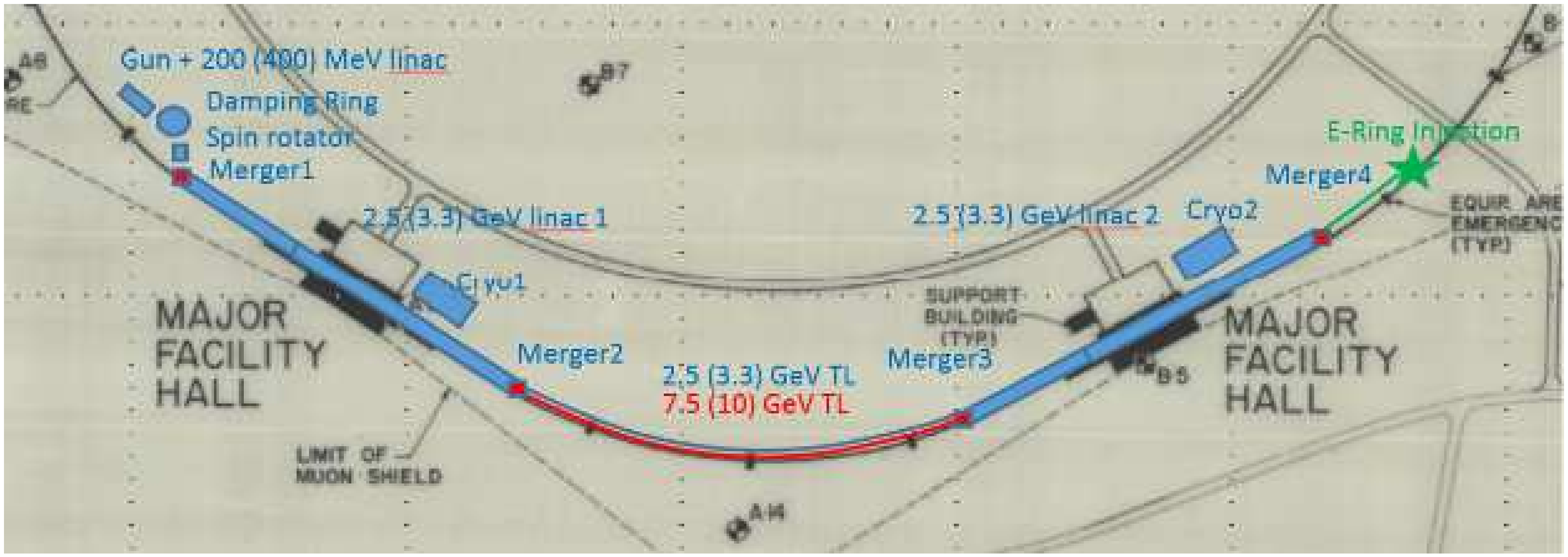
Self-polarization is not viable except at highest energies

$\Rightarrow$ Need a full-energy polarized injector

Advantage of a full-energy polarized injector:

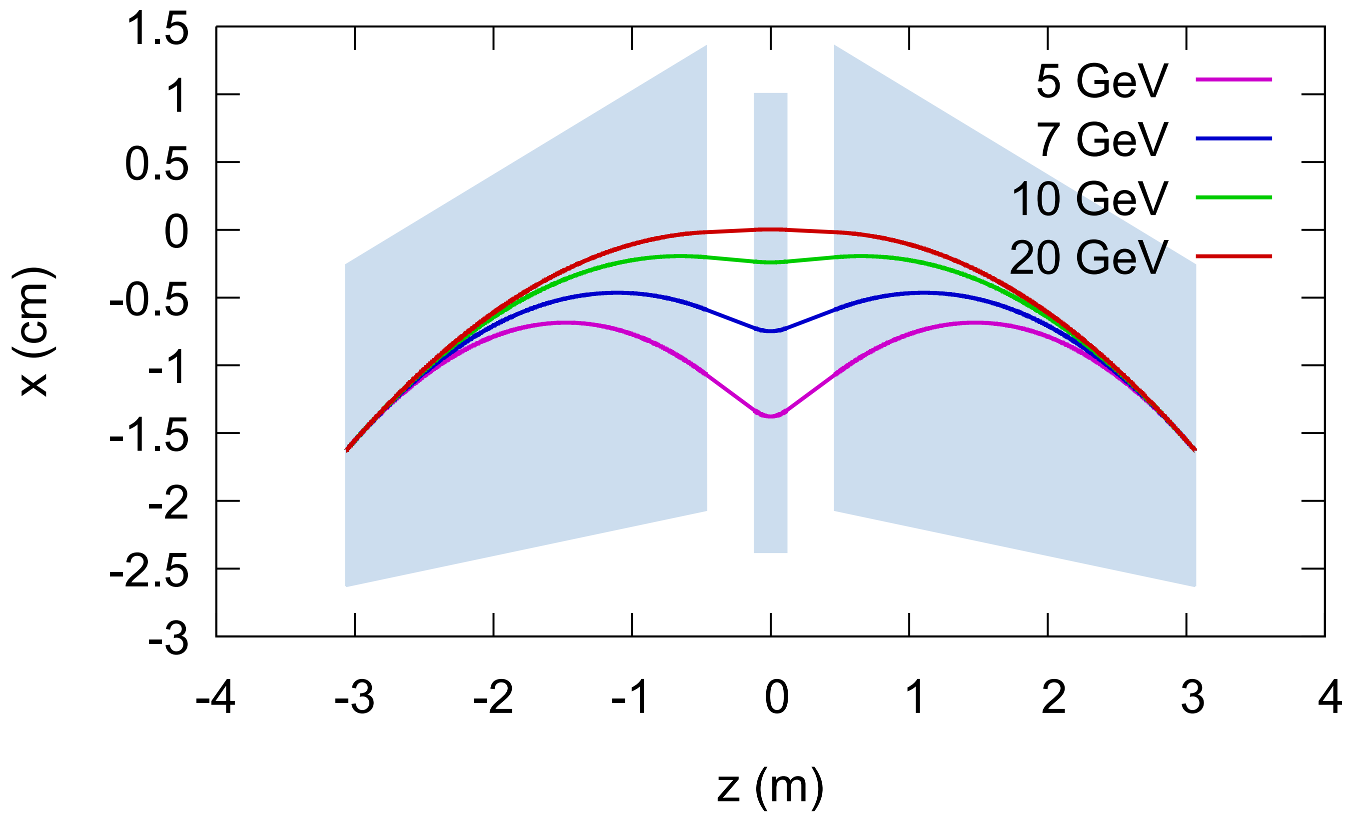
- Electron spin patterns with alternating polarization (as in RHIC proton fills) are required for single-spin physics
- Such fill patterns can be generated by a full-energy polarized injector
- Bunches with the “wrong” (unnatural) polarization direction will slowly flip into the “right” orientation. Time scale given by Sokolov-Ternov self-polarization time
- Bunch-by-bunch replacement at 1 Hz (360 bunches in 6 min) yields sufficient polarization even at full energy with $\tau_{S-T} = 30\,\text{min}$
- Requires good intensity lifetime $> 1\,\text{h}$ to limit beam-beam effect of electron bunch replacement on proton bunches

Electron Injector



- Recirculating linac based on XFEL/LCLS-2 cryomodules, or 650 MHz SRF cavities identical to those in Linac-Ring scheme
- With two 3 GeV linacs in two adjacent RHIC straights, two recirculations to 18 GeV

Superbends



Short, sharp bends to increase damping decrement at low energies, thus allowing high electron beam-beam parameter $\xi = 0.1$

Studies and R&D Items

- Linac-Ring R&D items:

- High-current polarized electron gun
- HOM damping for $12 \times 50\,\mathrm{mA}$ total current
- Multi-pass high current ERL
- FFAG prototype (cost savings)

- Ring-Ring Studies:

- Beam-beam simulations
- Electron polarization studies
- Multi-turn off-energy injection to eliminate need for accumulator ring

- Common R&D items:

- Crab cavities
- In-situ beampipe copper coating

Strategy Towards eRHIC Design

- Study linac-ring and ring-ring concepts simultaneously

- Carry out common R&D items (crab cavities) in parallel

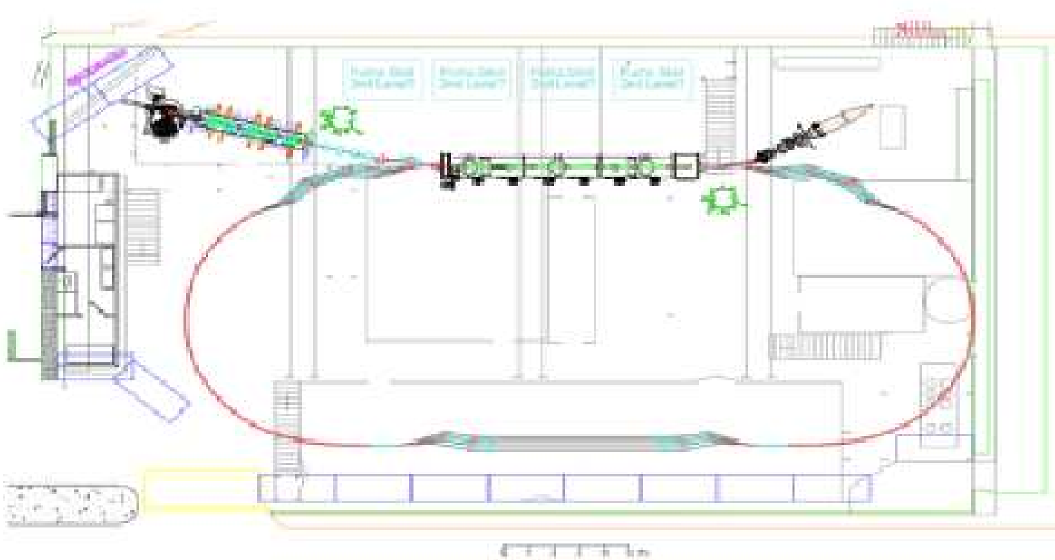
- Work towards experimental verification of critical design items (electron source for linac-ring)

- Continue work on cost-savings R&D (FFAG, Waveguide HOM damper, Gatling Gun)

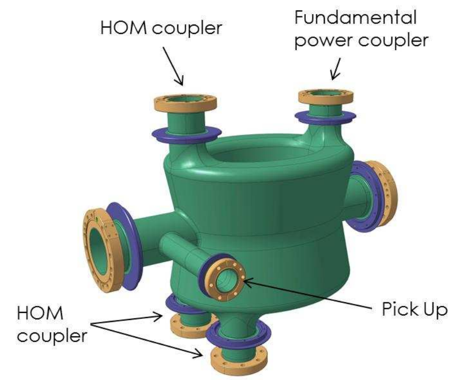
Multi-Pass Test ERL at Cornell

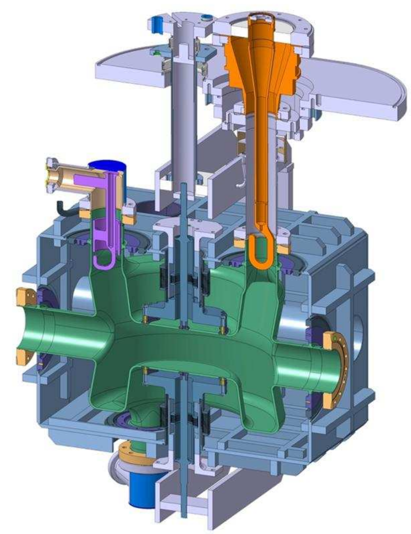
eRHIC linac-ring prototype

- Four-pass ERL with FFAG arcs
- 48.5 MeV CW SRF linac
- Permanent magnets used for recircultion arcs
- Test of spreader/combiner sections, and adiabatic transition from arcs to straights



Crab Cavity Development





• Both linac-ring and ring-ring IRs are based on a crossing angle
• Need crab cavities to restore luminosity, and avoid synchro-betatron resonances
• Prototypes being developed in collaboration with CERN, needed for LHC luminosity upgrade

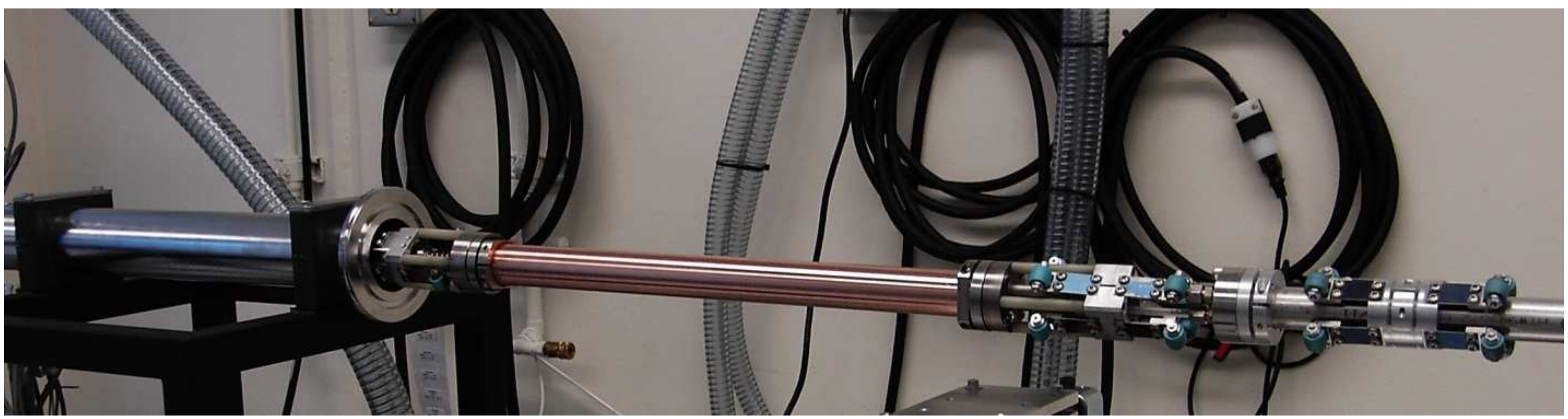
Critical R&D effort for any EIC

In-situ Beampipe Copper Coating

• Resistive wall losses in stainless steel beampipes due to increased number of bunches in ring-ring design and short bunch length in ultimate linac-ring design exceed allowable cryo load

• Need copper coating to increase conductivity

• In-situ beam pipe coating of an entire machine has never been done, but successful coating of 20 m combination of cold-bore RHIC tubing & bellows having room temperature conductivity 85% of solid copper was achieved.



50 cm long cathode magnetron being inserted into a RHIC-type beam pipe

- RHIC cryo capacity limit corresponds to heat load of 0.5-1 W/m from resistive wall and electron cloud

- Using a resistivity of $2.7 \cdot 10^{-8}\,\Omega \cdot$ m (room temperature copper - at 4 K it's 100 times better), 360 proton bunches with $N = 1.5 \cdot 10^{11}$/bunch and $\sigma_s = 8$ cm generate 0.37 W/m - well below the limit

- Caveat:
  Increase in effective resistivity due to magneto-resistance - to be quantified by putting a copper resonator in a high field magnet and measuring the change in Q as function of magnetic field. Resonator capable of operating at cryogenic temperatures is about to be setup
  Heat load from electron clouds still needs to be evaluated

- Could use mole to add layer of amorphous carbon to reduce SEY for e-cloud if necessary. E-cloud simulation results for Cu-coated eRHIC are slightly better than for present LHC with 25 nsec, $1.2 \cdot 10^{11}$

- Estimated time to coat full ring: 120 days in 3 shifts

- eRHIC construction may be only opportunity for coating

Luminosity Upgrade

- Luminosities in $10^{34}\,cm^{-2}sec^{-1}$ range require strong hadron cooling
- Both linac-ring and ring-ring designs allow luminosity upgrade
- Ring-ring upgrade requires increased number of bunches - 1320 instead of initial 330
- Alternatively, ring-ring scheme can be converted to linac-ring by operating full-energy injector in ERL mode
- Intermediate luminosity upgrade for ring-ring can be achieved at all but the highest electron energies by doubling the initial number of bunches, to 660
- Proof-of-principle of very strong Coherent electron Cooling (CeC) in progress at RHIC

Summary

• eRHIC design covers the entire EIC White Paper physics case, with $10^{32} - 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ luminosities

• Two initial design options under study:

- ERL-based linac-ring design with high performance at relatively low technical risk
- ring-ring design with high preformance, based on existing technology

• Need to carry out critical R&D on crab cavities, 50 mA polarized electron source

• Cost effective upgrade to $10^{34}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ possible for both design schemes, using strong hadron cooling

• Crucial R&D underway to mitigate risk of strong hadron cooling (CeC Proof-of-Principle)