eRHIC Design Status

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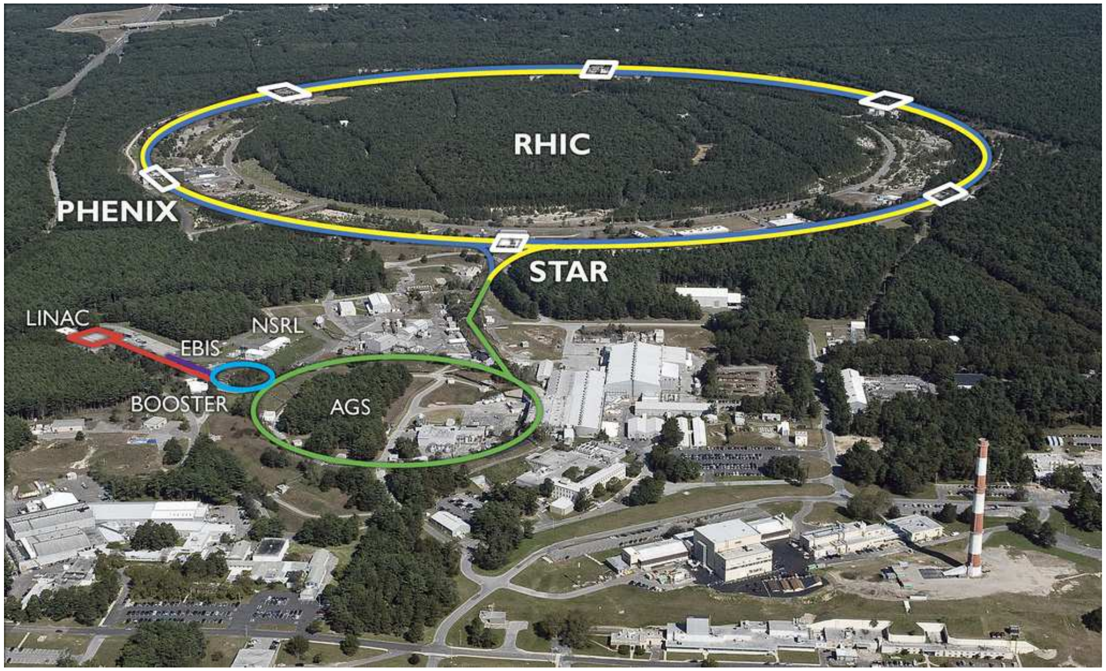
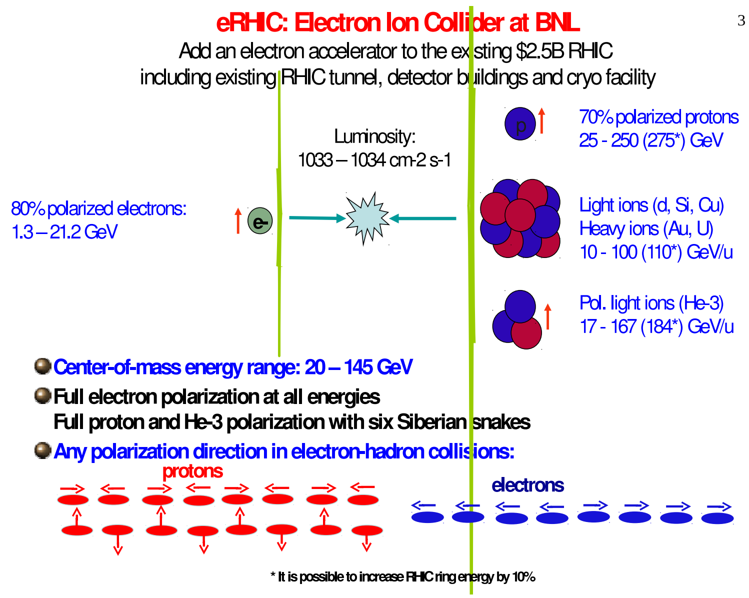


The Relativistic Heavy Ion Collider RHIC

- 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

- How is the nucleon spin of 1/2 composed of its constituents?
- How are gluons spatially distributed in the nucleon?
- How does the gluon density saturate?

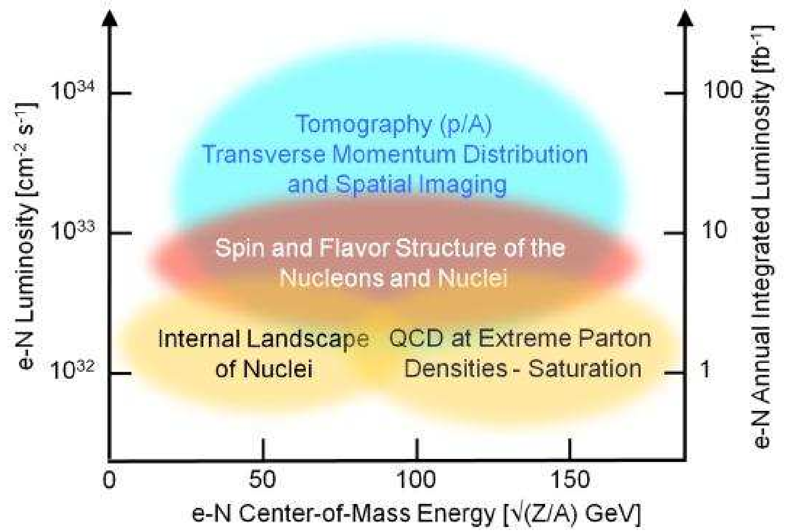


An electron-ion collider (EIC) will provide enhanced access to the nucleon's "inner landscape"

eRHIC Design Requirements

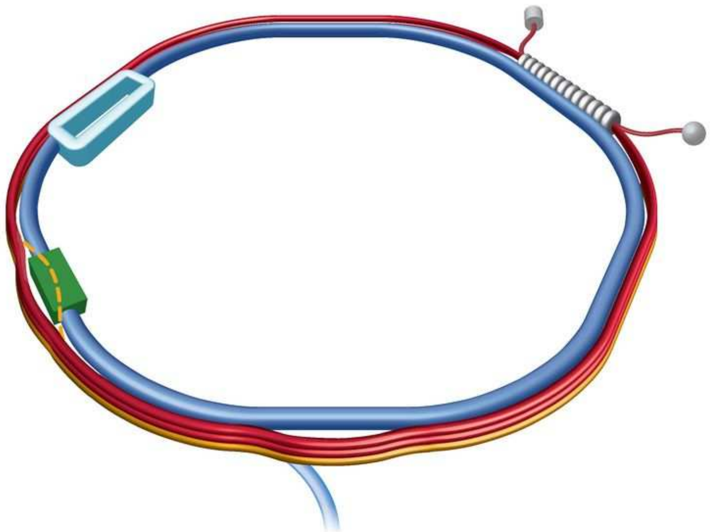
based on EIC White Paper

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

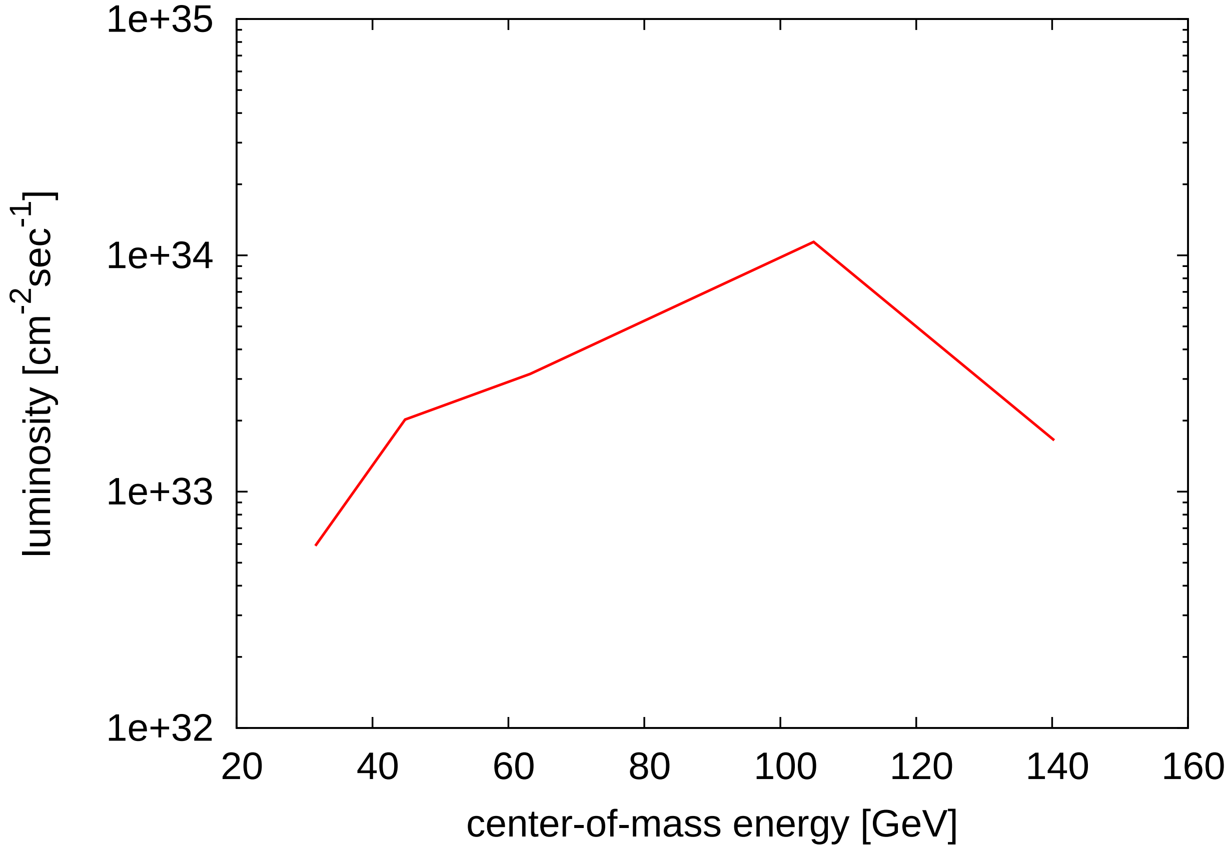


Design Concept

- Based on RHIC with 275 GeV polarized protons
- Electron storage ring with 5 - 18 GeV
- 1320 bunches per ring
- Up to 2.7 A electron current
- Very flat normalized proton emittances, 2.4 μm hor., 0.1 μm vert., achieved by strong hadron cooling
- Low proton bunch intensities, $0.75 \cdot 10^{11}$
- Full energy polarized electron injector



Luminosity vs. center-of-mass energy



$1.14 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ peak luminosity

Staged Approach

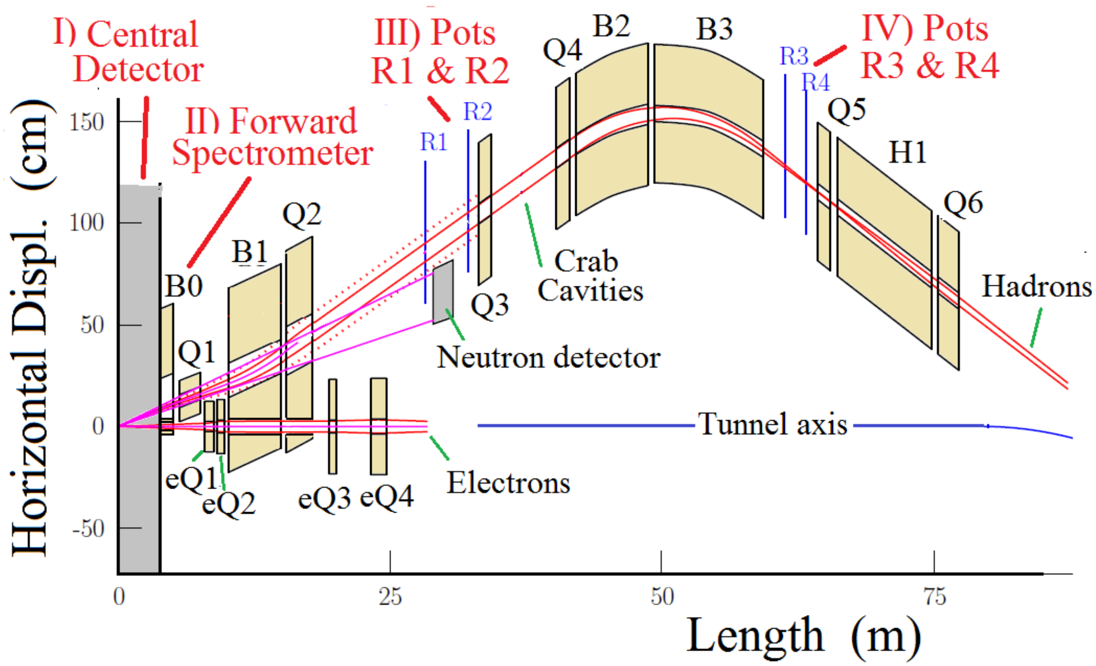
- Bunched beam electron cooler for eRHIC is very challenging due to high energy and large number of bunches
- BNL is developing electron cooler for low energy gold beams - first bunched beam electron cooler in the world
- To mitigate this risk, start with a design that does not need cooling
- Upgrade to full luminosity performance once cooling becomes available

Proton Beam Parameters for Initial Phase

		eRHIC	RHIC
N_b		330	110
max. N_p	$[10^{11}]$	1.5	2.5
ϵ_N hor./vert.	$[\mu\text{m}]$	4.7/1.8	2.5/2.5
min. σ_s	[cm]	8	20
max. $\Delta p/p$	10^{-4}	14	5
min. β_p^*	[cm]	4.4	60
max. $\hat{\beta}_p$	[km]	1.2	3
min. τ_{IBS}	[h]	7.3	4.8
max. $\mathcal{L}$	$[10^{33}\,\text{cm}^{-2}\text{sec}^{-1}]$	2.9	

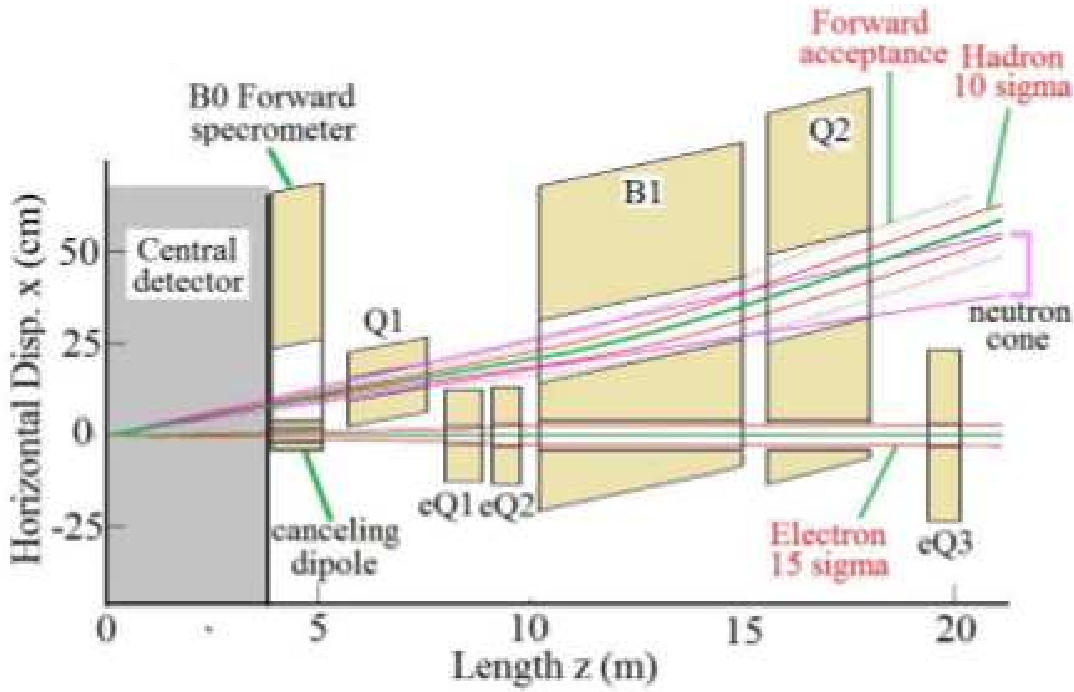
- Only most extreme parameters are listed - complete list in Backup Slides
- Proton emittances can be achieved by slight shaving (vertical, 25 percent reduction) and noise injection (horizontal) - long IBS growth time requires no cooling whatsoever while ensuring high average luminosity
- Necessary decoupling required for flat beams demonstrated at RHIC during 31.2 GeV d-Au run

Interaction Region Layout



- Interleaved arrangement of electron and hadron quadrupoles
- 22 mrad total crossing angle, using crab cavities
- Beam size in crab cavity region independent of energy - crab cavity apertures can be rather small, thus allowing for higher frequency
- Forward spectrometer (B0) and Roman Pots (R1-R4) for full acceptance

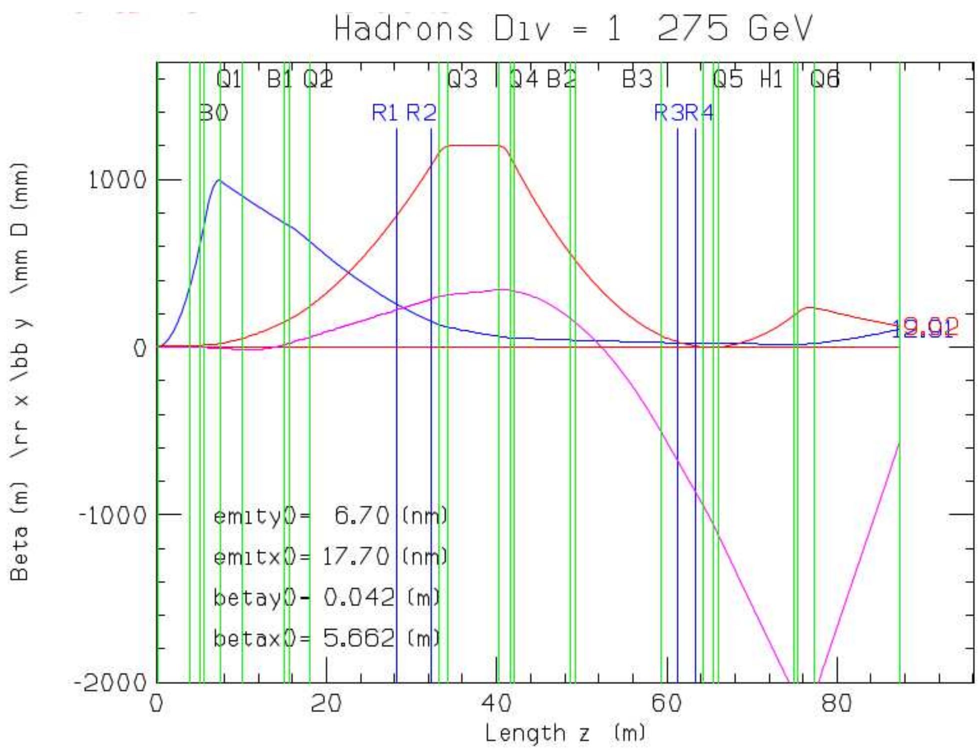
IR Detail



Actively shielded electron beampipe through superferric hadron spectrometer B0

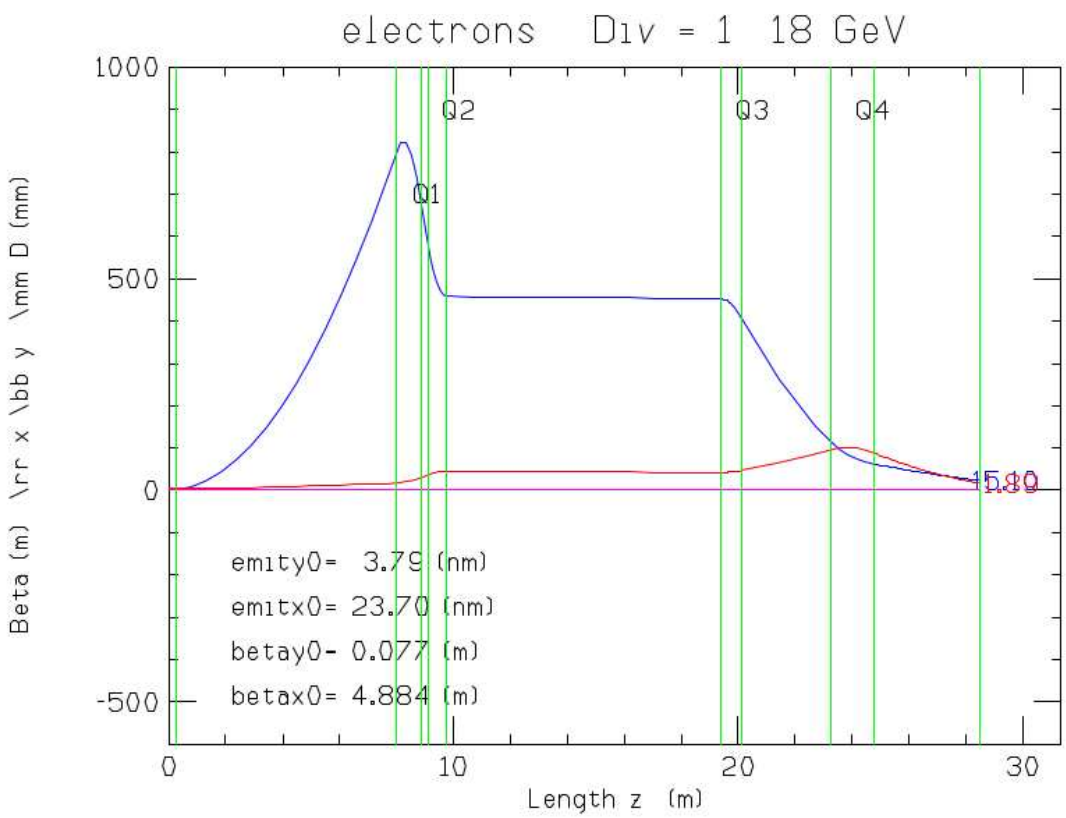
Hadron quadrupole Q1 with anti-quadrupole to create field-free region for electrons

Proton β-Functions at 275 GeV



- Maximum β around 1200 m, keeping chromaticities small (10 units horizontally, 12 vertically for half IR - similar to present RHIC)

Electron β-Functions at 18 GeV



- Small chromaticities (10/15 units) due to early focusing

- corresponding number for KEKB is 38

IR Hadron Magnet Parameters

	s_{upstream} m	L m	IR cm	OR cm	B_{pole} T	gradient T/m
B0	3.90	1.20	15.0	40.0	-1.70	0
Q1	5.70	1.86	3.2	10.1	3.39	-105.8
B1	10.20	4.80	8.5	38.5	3.52	0
Q2	15.60	2.40	12.0	33.0	3.57	29.79
Q3	33.12	1.20	5.0	35.0	1.35	26.93
Q4	40.32	1.20	5.0	35.0	1.59	31.83
B2	42.12	6.60	5.0	35.0	-4.40	0
B3	49.32	10.00	4.0	34.0	-4.40	0
Q5	64.32	1.20	4.0	34.0	0.51	-12.73
H1*	66.12	8.75	4.0	34.0	0.0	0.0
Q6	75.37	2.00	4.0	34.0	2.20	55.0

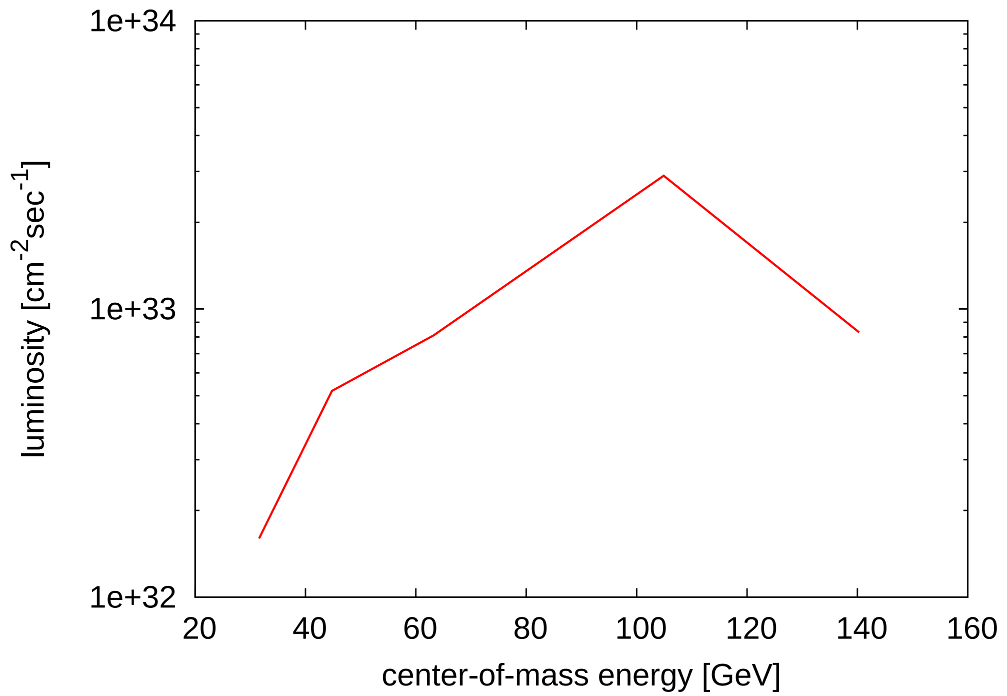
*: Helical dipoles as RHIC spin rotator

IR Electron Magnet Parameters

	s_{upstream} m	L m	IR cm	OR cm	B_{pole} T	gradient T/m
Qe1	7.99	0.86	2.5	12.5	0.73	-29.20
Qe2	9.11	0.67	3.2	13.2	1.06	33.20
Qe3	19.38	0.75	3.2	23.2	0.37	-11.56
Qe4	23.25	1.50	3.7	23.7	0.36	9.63

- Inner radii determined by maximum 10σ proton, 15σ electron size over entire energy range
- Outer radii determined by space available between beams
- Developed conceptual designs for the most challenging magnets, B0 and Q1

Luminosity vs. $\sqrt{s}$ in Initial Phase

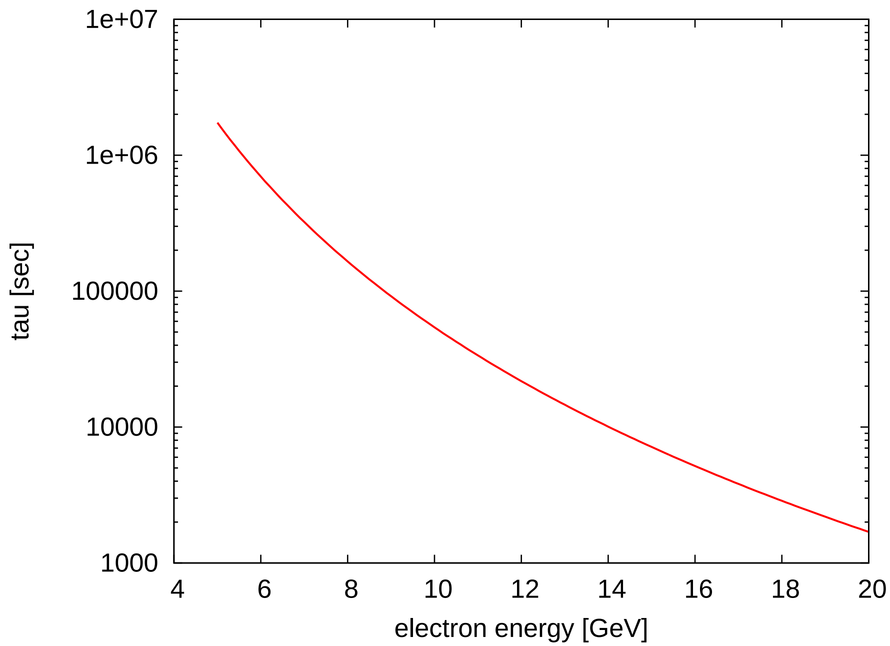


- $2.9 \cdot 10^{33}\,cm^{-2}sec^{-1}$ peak luminosity with 10 GeV electrons, 250 GeV protons, including hourglass, crab crossing, and abort gap
- Electron energy 5 GeV or higher, as suggested by detector designers

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

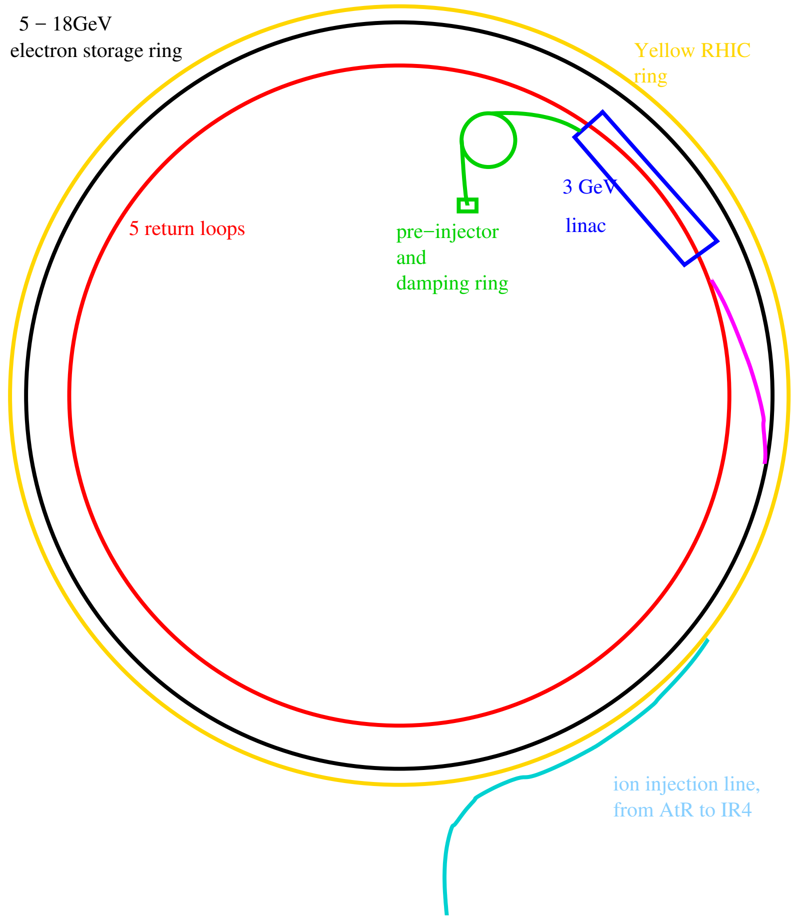
$\Rightarrow$ Need a full-energy polarized injector

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 $\tau_{S-T} = 30\,\mathrm{min}$
- Requires good intensity lifetime $> 1\,\mathrm{h}$ to limit beam-beam effect of electron bunch replacement on proton bunches
- Damping ring to reach 50 nC bunch charge. SLC gun produces 16 nC

1. Recirculating linac injector

- Recirculating linac, based on pulsed 650 MHz cavities
- 3 GeV linac seems feasible in 200 m straight section
- 5 return loops to reach 18 GeV



2. Highly symmetric rapid-cycling (or rapid-ramping) synchrotron (RCS)

- At 20 GeV, electron $G \cdot \gamma = 45.4$
  ($G = 0.00115965219$: anomalous gyromagnetic ratio)

- Assume a circular RCS, made up of identical periods

- Superperiodicity $P = 48$ and a tune of $\nu = 48.2$ results in depolarizing resonances at $G\gamma = k \cdot P \pm l \cdot \nu$

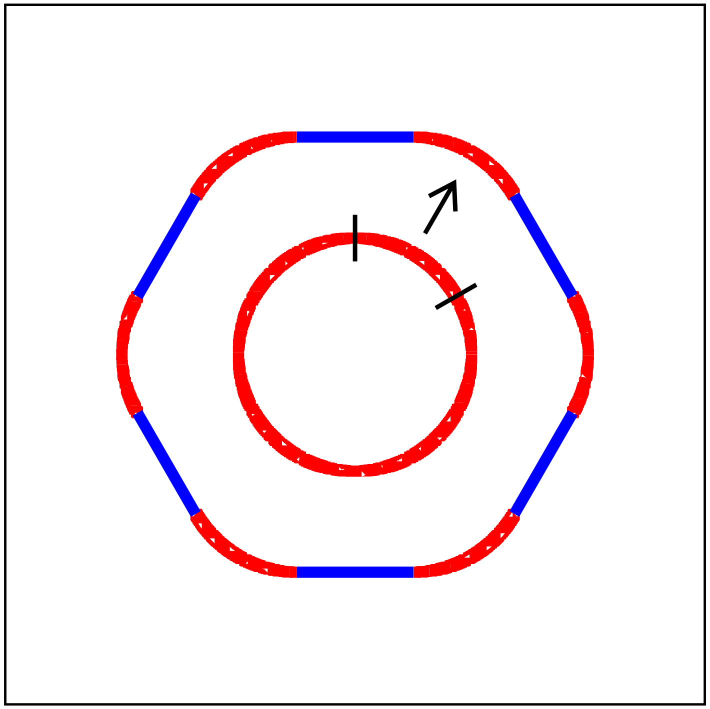
- Resonance condition fulfilled at $G\gamma = 2 \cdot P - \nu = 47.8$
  - outside the energy range

- High superperiodicity requires a circular ring, unlike the RHIC tunnel with its six straights

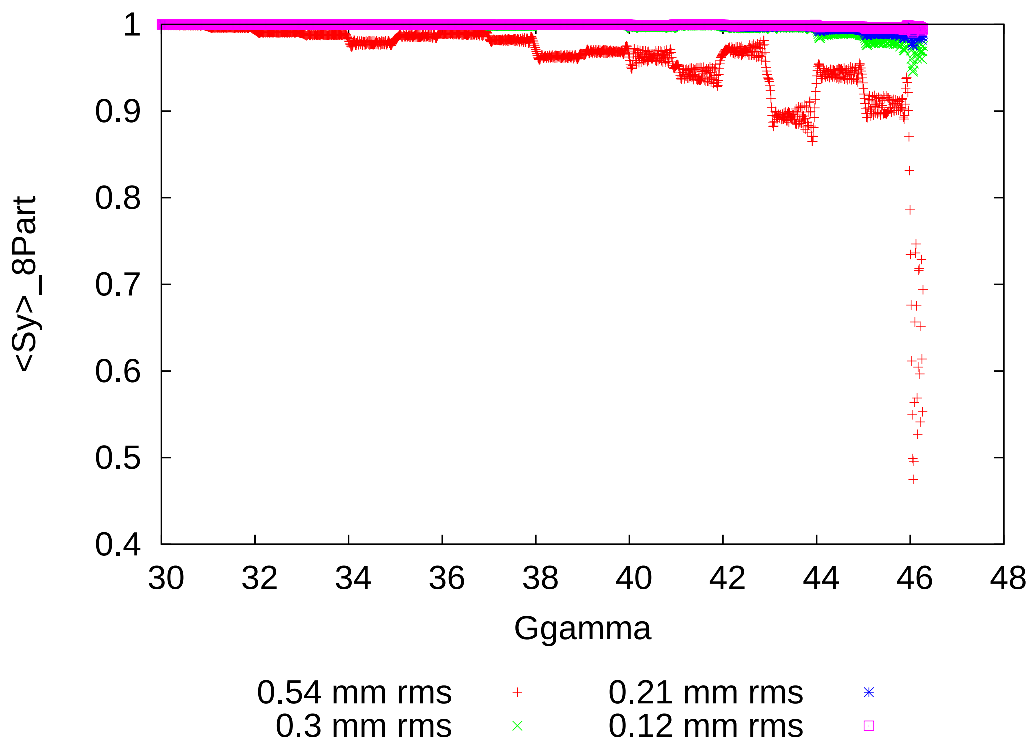
- However, if transfer matrices of straights are unit matrices

$$M_{\text{straight}} = I,$$

energy range remains resonance free

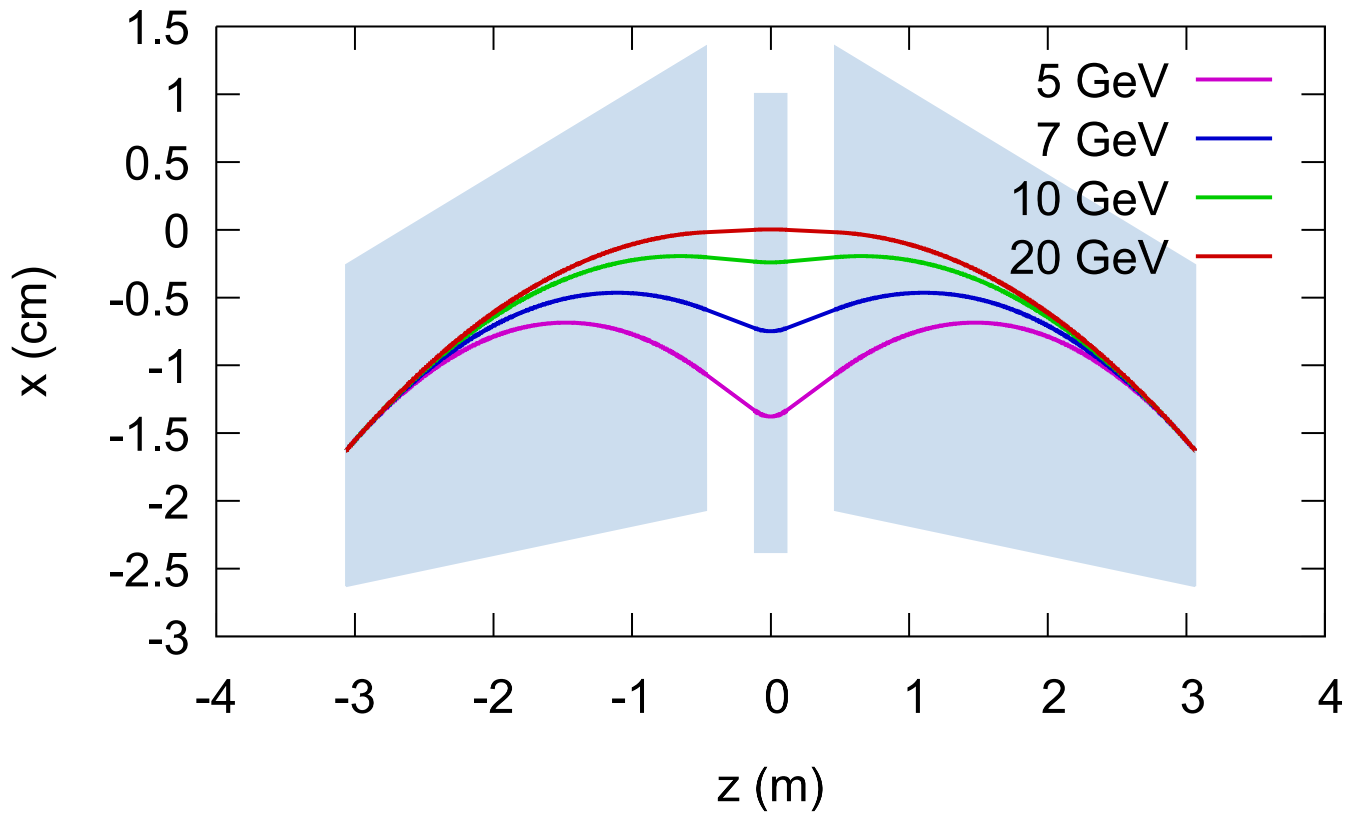


Polarization in RCS with orbit errors



- Spin tracking confirms validity of RCS concept
- 4000 turns used in simulation
- Faster ramping in only 400 turns technically feasible, further improving polarization preservation

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

- Beam-beam simulations

- Electron polarization studies

- Multi-turn off-energy injection to eliminate need for accumulator ring

- Crab cavities

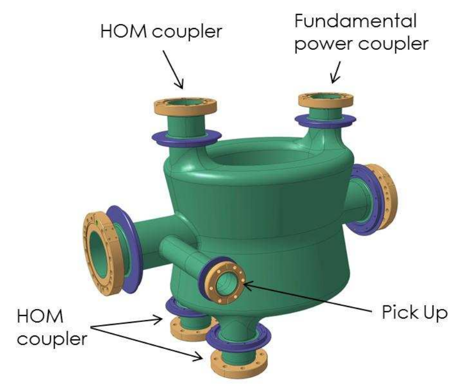
- In-situ beampipe copper coating

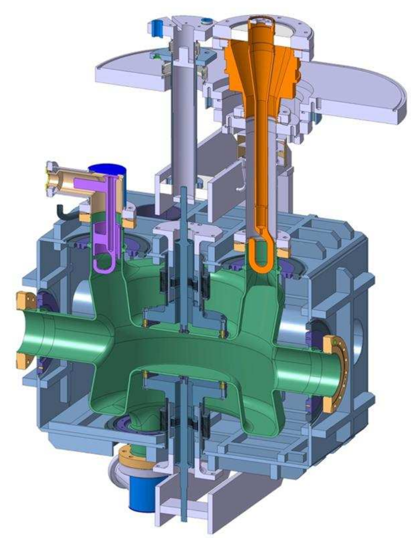
Crab Cavity Development

• IR design is based on a 22 mrad crossing angle; separator dipole would severely restrict Physics capabilities

• Need crab cavities to restore luminosity, and avoid synchro-betatron resonances

• Prototypes being developed in collaboration with CERN, needed for LHC luminosity upgrade





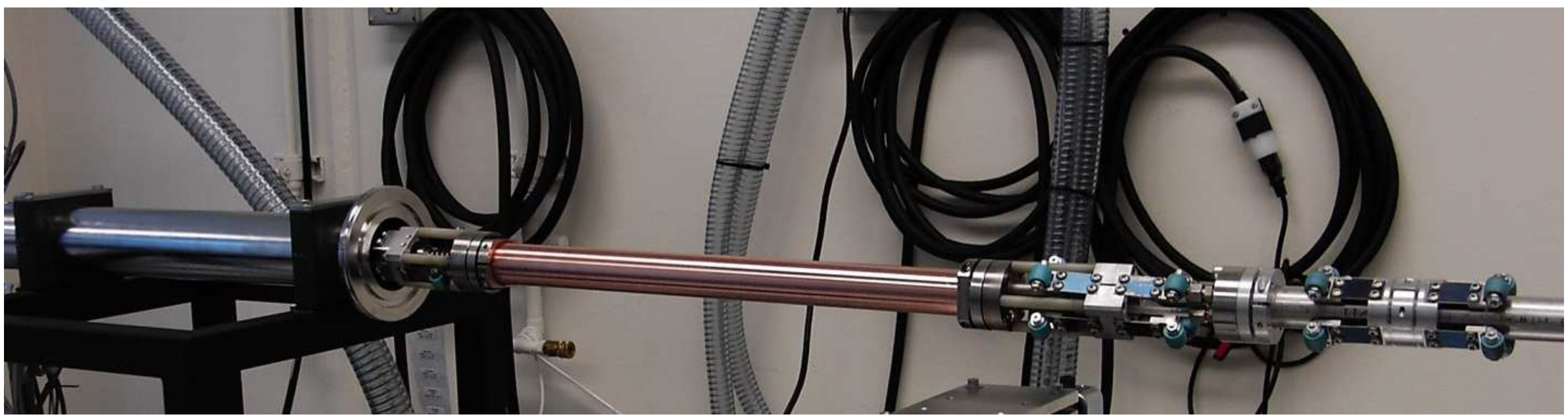
Critical R&D effort

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

Luminosity Upgrade

- Upgrade requires increased number of bunches - 1320 instead of initial 330 - and hadron cooling

- Alternatively, if recirculating linac is chosen as full-energy injector, ring-ring scheme can be converted to linac-ring by operating full-energy injector in ERL mode. Requires strong hadron cooling as well, but only 110 bunches

- Intermediate luminosity upgrade 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 $10^{32} - 10^{33}\,\text{cm}^{-2}\text{sec}^{-1}$ luminosities

- Need to carry out critical R&D on crab cavities, in-situ beam pipe coating, and cooling

- Cost effective upgrade to $10^{34}\,\text{cm}^{-2}\text{sec}^{-1}$ possible, using strong hadron cooling

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