eRHIC: High-Energy, High-Luminosity Electron-Ion Collider at BNL

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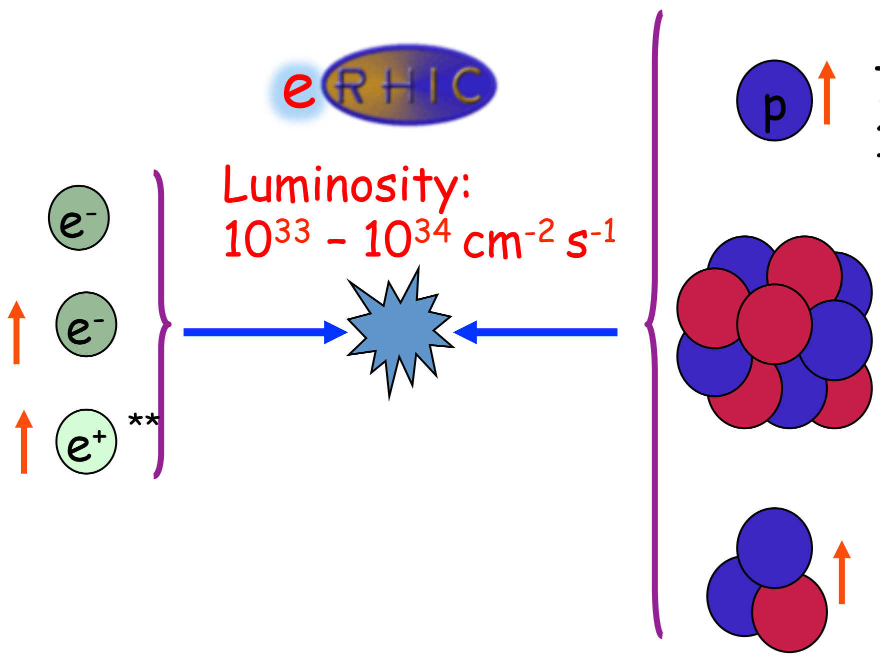
BNL Approach to EIC

- At BNL we are pursuing design of electron-ion collider, **eRHIC**, which covers all CM range of interest indicated in EIC white paper from day one
- As a cost-effective strategy, we selected luminosity up-grade path towards ultimate eRHIC performance
- Our eRHIC design is base on linac-ring scheme, which offers ultimate eRHIC performance.
- As a back-up option, we are reviewing one more time the ring-ring option
- Both versions have their own challenges and risks – we are pursuing extensive R&D program to mitigate and retire risks for both designs

eRHIC: QCD Facility at BNL

Add electron accelerator to the existing $2B RHIC

80% polarized electrons, 2.6-21.2 GeV

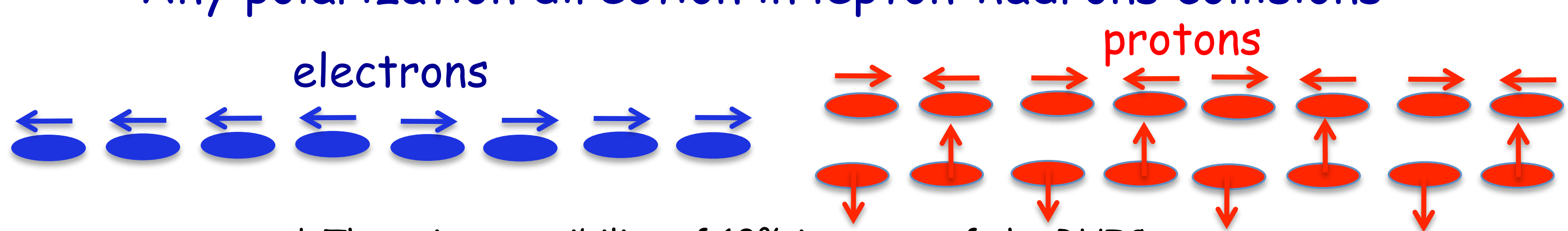


70% polarized protons
100-250 (275*) GeV

Light ions (d,Si,Cu)
Heavy ions (Au,U)
50-100 (110*) GeV/u

Polarized light ions
(He^3) 167 (184*) GeV/u

Center of mass energy range: 30-145 GeV
Any polarization direction in lepton-hadrons collisions



* There is a possibility of 10% increase of the RHIC energy
** Positrons can be added as an up-grade but at lower luminosity

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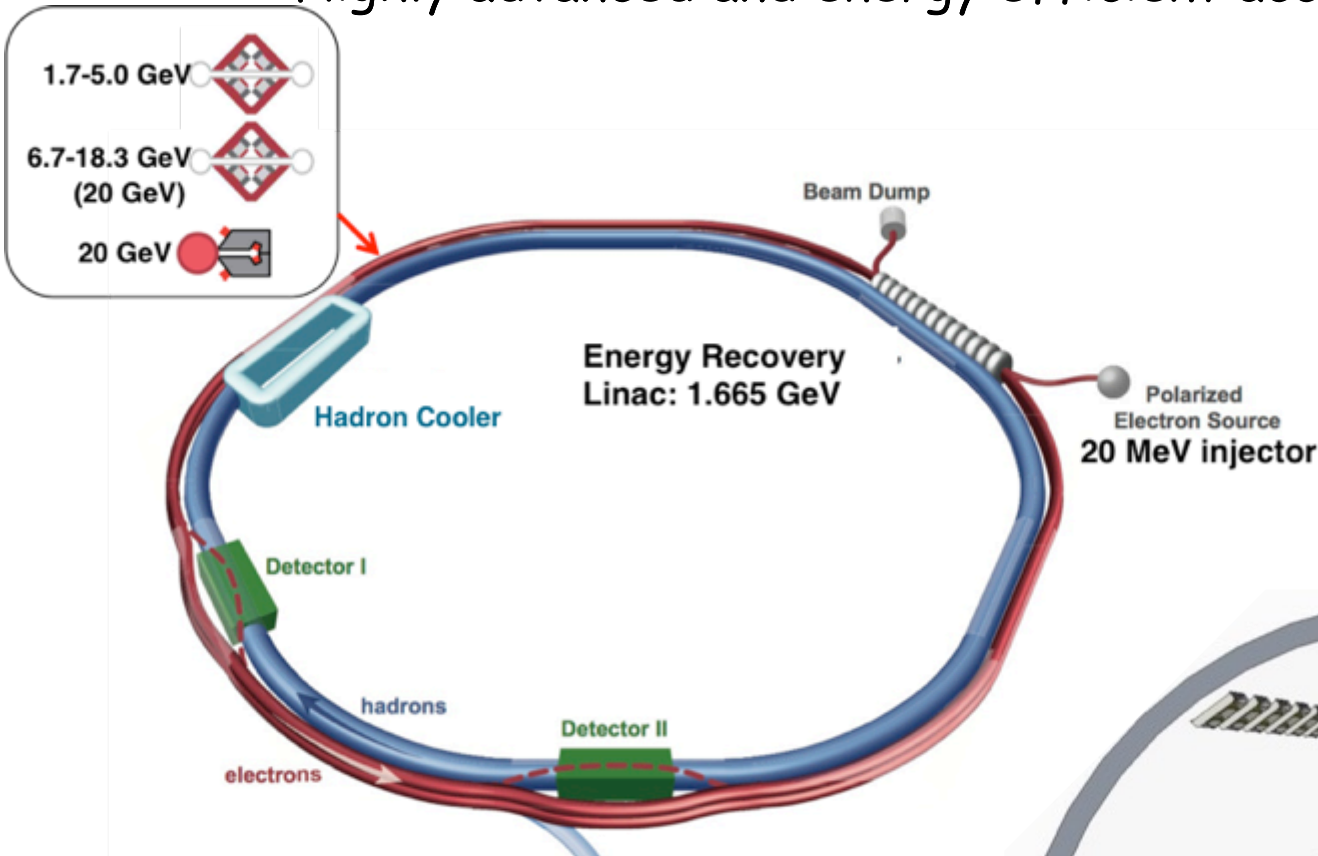
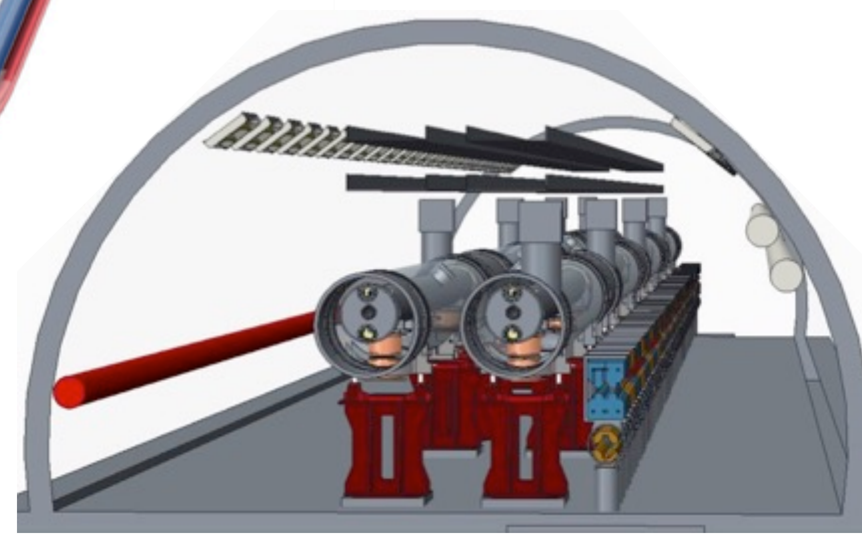
eRHIC design

Highly advanced and energy efficient accelerator





- Peak luminosity: 2×10^{34} cm^{-2} s^{-1}
- ERL, permanent magnet arcs and strong cooling of proton beam reduce electric power consumption from ~ 1 GW to about 15 MW!

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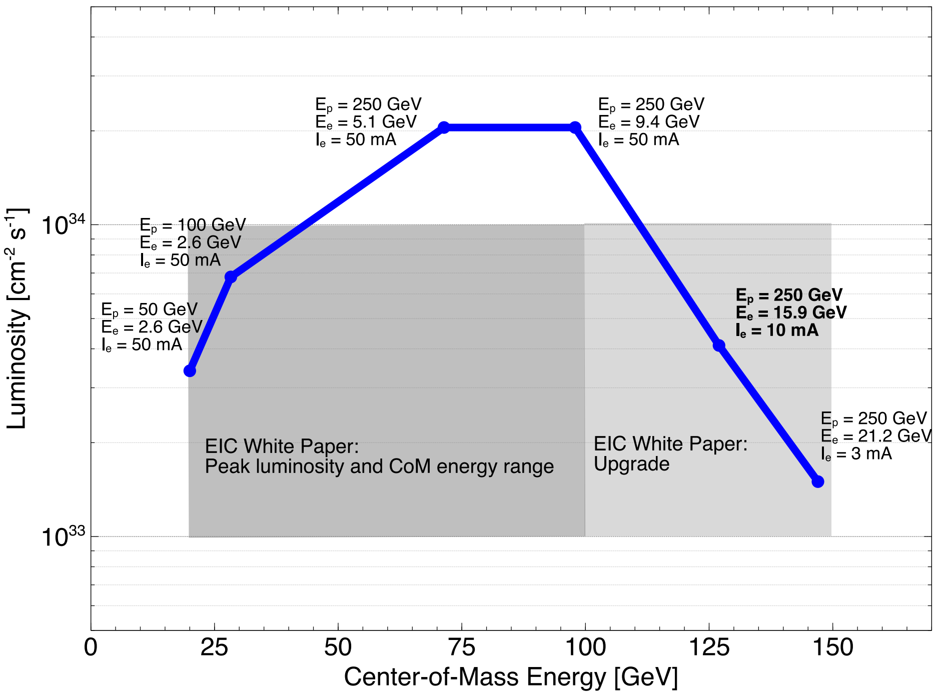
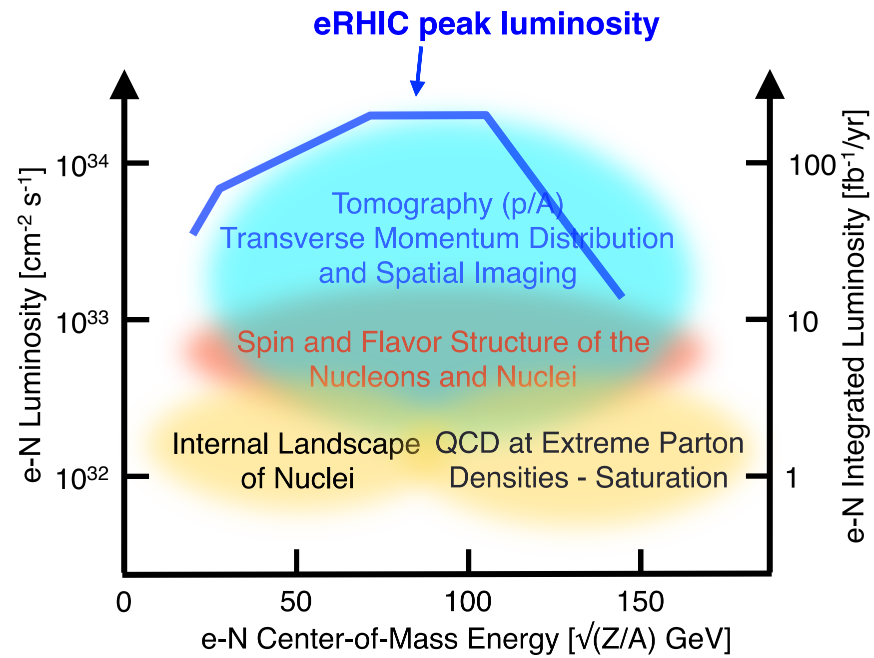
eRHIC peak luminosity vs. CoM energy





- eRHIC design covers whole Center-of-Mass energy range, including "EIC White Paper Upgrade" region
- Small beam emittances and IR design allows for full acceptance detector at full luminosity

Ring - ring vs. ERL - ring

$$L = f_b\left(\frac{4\pi\gamma_p\gamma_e}{r_p r_e}\right)(\xi_p\xi_e)(\sigma'_p\sigma'_e) \qquad \xi_p = \frac{r_p\beta^*_p}{4\pi\gamma_p}\frac{N_e}{\sigma^2_e} \qquad \xi_e = \frac{r_e\beta^*_e}{4\pi\gamma_e}\frac{N_p}{\sigma^2_p}$$

$$\frac{4\pi\gamma_p\gamma_e}{r_p r_e} = 2.7\cdot 10^{36}\ cm^{-2} \qquad \sigma'_p = \sigma'_e \le 0.15 mrad \quad \xi_p \le 0.015 \qquad \xi_e \le 0.1$$

for ring - ring

E_p=250 GeV, E_e=20 GeV

- Ring - Ring
  - For bunch rep. rate f_b = 10 MHz: L ≤ 9 x 10^{32} s^{-1} cm^{-2}
  - Increase luminosity by increasing f_b (and electron current and synchrotron radiation power)
  - Decrease electron current (and synchrotron power) by **cooling proton beam** and use low emittance electron storage ring
  - High power of SR losses
  - High synchrotron radiation in detector (e.g. back-ground) is the main challenge
- ERL - Ring
  - For bunch rep. rate f_b = 10 MHz (or any rate) the luminosity is not limited; eRHIC design study had ξ_e=1.5: L = 1.4 x 10^{34} s^{-1} cm^{-2}
  - Increase luminosity and/or decrease electron current by **cooling proton/ion beam**
  - Source with high polarized electron current is the main challenge

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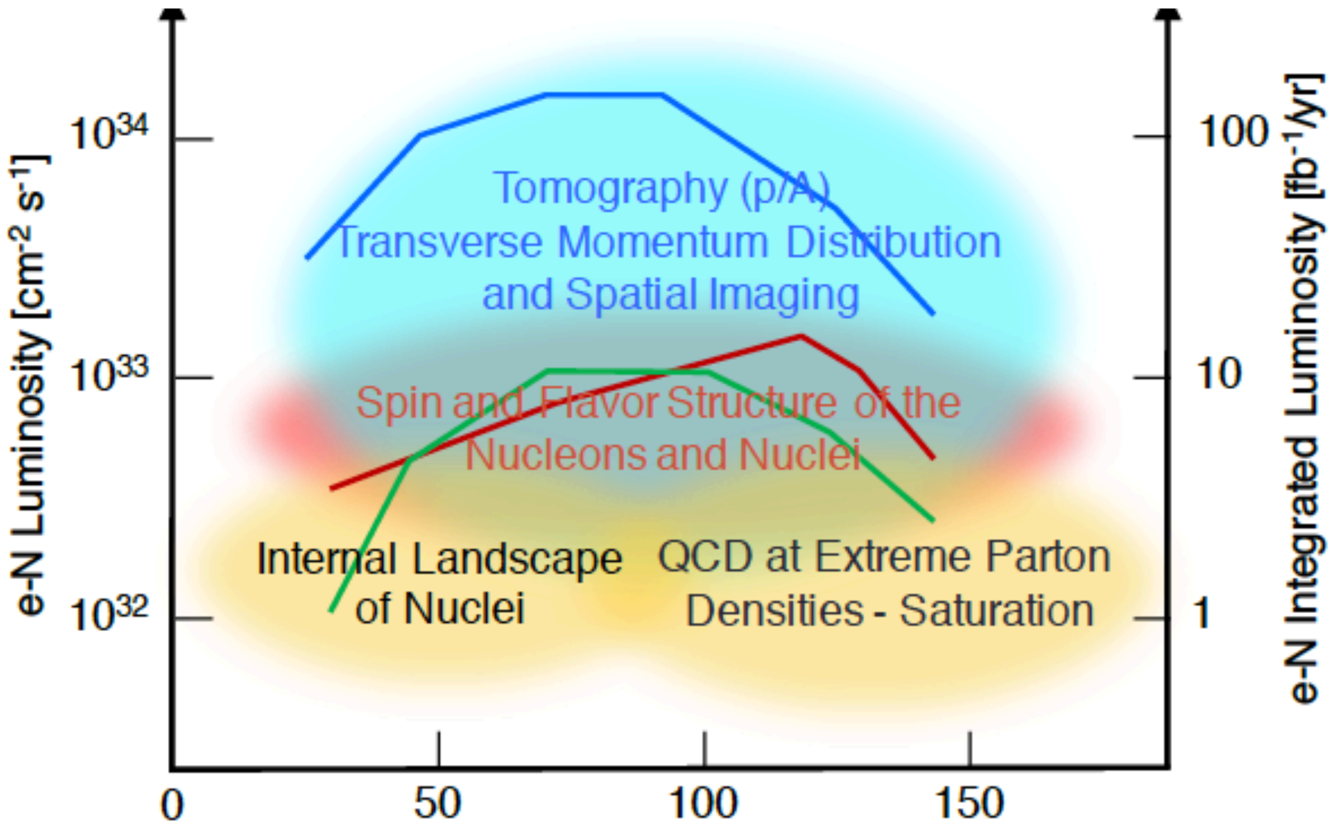
Staging Luminosity



$\vec{e}$-$\vec{p}$

Table 1-1: Beam parameters for highest luminosity of e-p collisions for the three design options.

	RR Nominal design		LR Nominal design		LR Ultimate design	
	e	p	e	p	e	p
Energy [GeV]	13.7	250	10	250	8.3	250
CM energy [GeV]	117		100		91	
Bunch frequency [MHz]	28.2		9.4		9.4	
Bunch intensity [10^{10}]	21	22	1.7	20	3.3	30
Beam current [mA]	935	990	26	277	50	415
rms norm.emittance h/v[um]	1430/250	2.5/2.5	36.7/36.7	0.5/0.5	16.5/16.5	0.27/0.27
rms emittance h/v [nm]	53/9.4	9.4/9.4	1.9/1.9	1.9/1.9	1.0/1.0	1.0/1.0
beta*, h/v [cm]	38/27	216/27	12.5/12.5	12.5/12.5	7/7	7/7
IP rms beam size h/v [um]	142/50		15.3/15.3		8.4/8.4	
IP rms ang. .spread h/v [urad]	375/186	66/186	120/120	120/120	120/120	120/120
max beam-beam parameter	0.1	0.015	1.2	0.004	4.1	0.015
e-beam disruption parameter			20		36	
max space charge parameter	4e-5	0.001	1.4e-4	0.006	8.6e-4	0.058
rms bunch length [cm]	1	20	0.3	16.5	0.3	5
Polarization [%]	80	70	80	70	80	70
Peak luminosity [$10^{33}cm^{-2}s^{-1}$]	1.4		1.0		14.4	

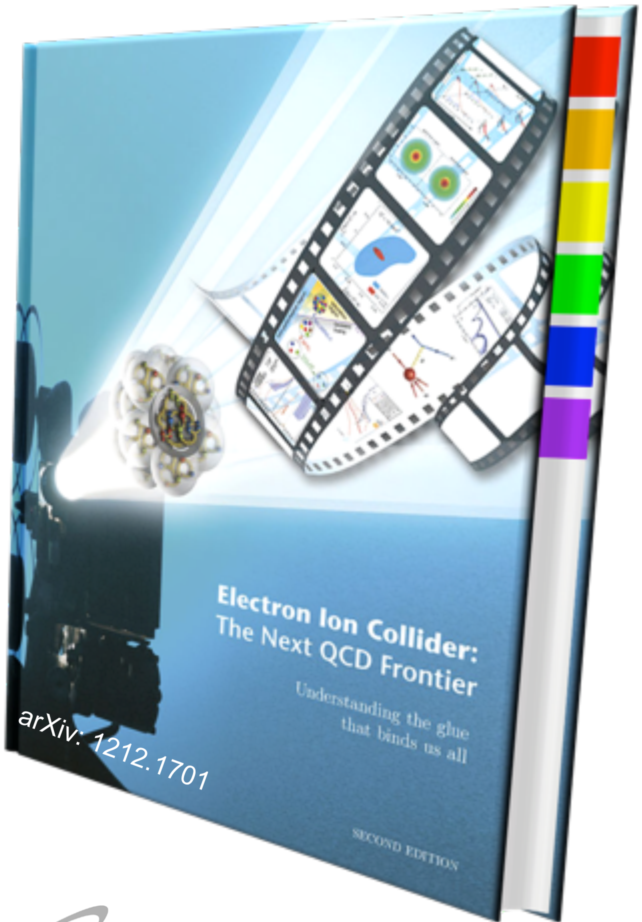
$\vec{e}$-A

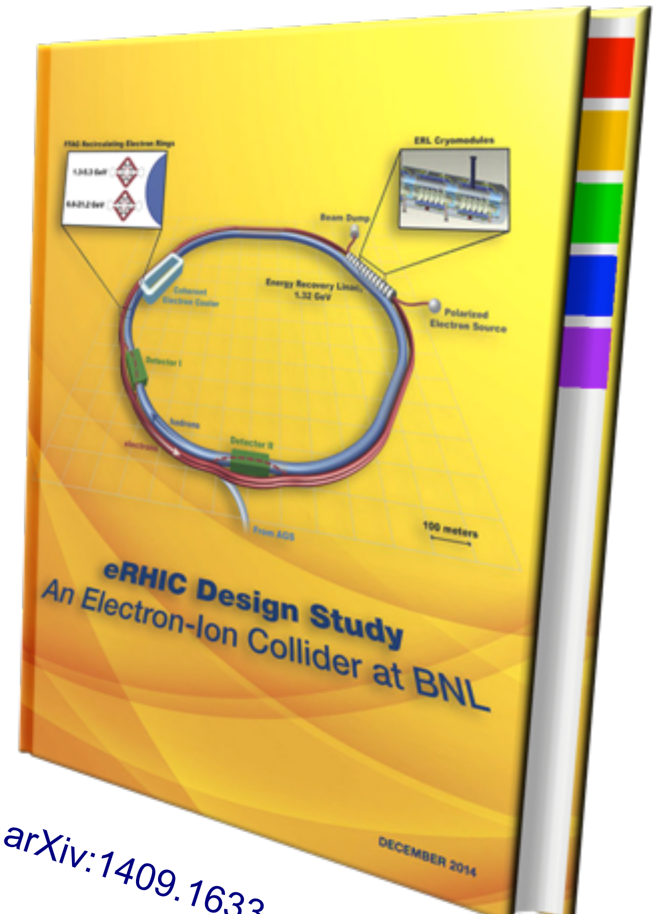
Table 1-2: Beam parameters for highest luminosity of e-Au collisions for the three design options.

	RR Nominal design		LR Nominal design		LR Ultimate design	
	e	Au	e	Au	e	Au
Energy [GeV/u]	13.7	100	10	100	8.3	100
CM energy [GeV]	74		63		58	
Bunch frequency [MHz]	28.2		9.4		9.4	
Bunch intensity [10^{10}]	21	0.2	1.7	0.2	3.3	0.2
Beam current [mA]	935	710	26	219	50	219
rms norm.emittance h/v[um]	1420/	1.0/1.0	29/29	0.16/0.16	24/24	0.16/0.16
rms emittance h/v [nm]	53/9.4	9.4/9.4	1.5/1.5	1.5/1.5	1.5/1.5	1.5/1.5
beta*, h/v [cm]	38/27	216/27	12.5/12.5	12.5/12.5	7/7	7/7
IP rms beam size h/v [um]	142/50		13.6/13.6		10.2/10.2	
IP rms ang. .spread h/v [urad]	375/186	66/186	109/109	109/109	146/146	146/146
max beam-beam parameter	0.073	0.015	1.2	0.0053	1.5	0.01
e-beam disruption parameter			20		29	
max space charge parameter	4e-5	0.005	1.5e-4	0.039	6e-4	0.058
rms bunch length [cm]	1	20	0.3	16.5	0.3	11
Polarization [%]	80	0	80	0	80	0
Peak luminosity [$10^{33}cm^{-2}s^{-1}$]	2.5		2.5		8.0	

EIC Main Detector Requirements

E.C. Aschenauer, A. Kiselev and R. Petti





arXiv:1409.1633

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Global Requirements

Requirements from Physics:

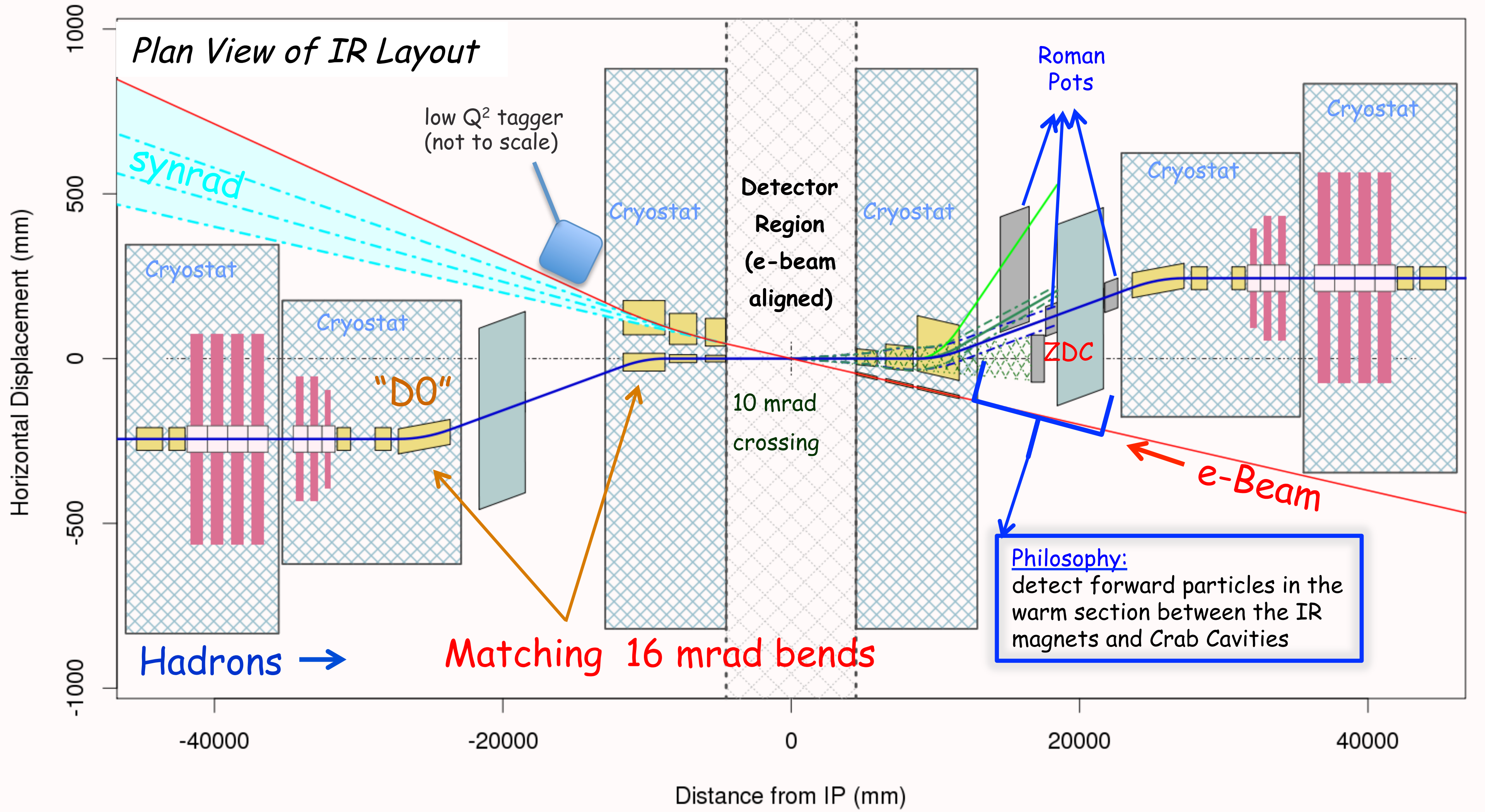
- High Luminosity > 10^{33} $cm^{-2}s^{-1}$ and higher → nucleon/nuclei imaging
- Flexible center of mass energy → wide kinematic reach
- Electrons (0.8) and protons/light nuclei (0.7) highly polarized → study spin
- Wide range of nuclear beams (D to U) → high gluon densities
- room for a wide acceptance detector with good PID (e/h and p, K, p)
- wide acceptance for protons from elastic reactions and neutrons from nuclear breakup

EIC physics reqs

- Requirements for detector and IR clearly defined and documented
- AP and EIC groups work together to integrate the main and auxilliary detectors into the machine and IR-design

	Hadron	Lepton
Polarization	0.7	0.8
Bunch spin orientation	flexible from bunch to bunch	flexible from bunch to bunch
scattered neutron acc.	+/- 4 mrad	
scattered proton acc.	+/- 5 mrad @ 250 GeV $0.18 < p_t$ (GeV) < 1.3	
Machine free region	+/- 4.5 m for detector	
Luminosity	$> 10^{33}$ cm^{-2}s^{-1}	
Luminosity monitor acc.		+/- 1-2 mrad $dL/L < 1\%$
Relative Luminosity	$L^{++/--}/L^{+-/-+} \sim 10^{-4}$ to 10^{-5}	
wide kinematic range	$\sqrt{s}$: 45 (30) to 140 GeV	
wide range of nuclei	p to Uranium	

eRHIC: IR Design is join venture of accelerator and EIC physicists



E.C. Aschenauer, B. Parker, D. Trbojevic, Y. Jing.....

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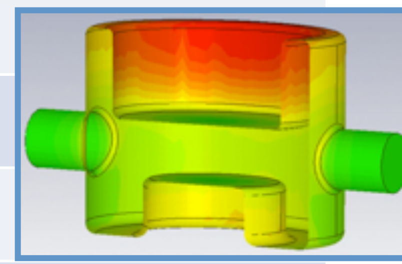
Accelerator R&D for eRHIC

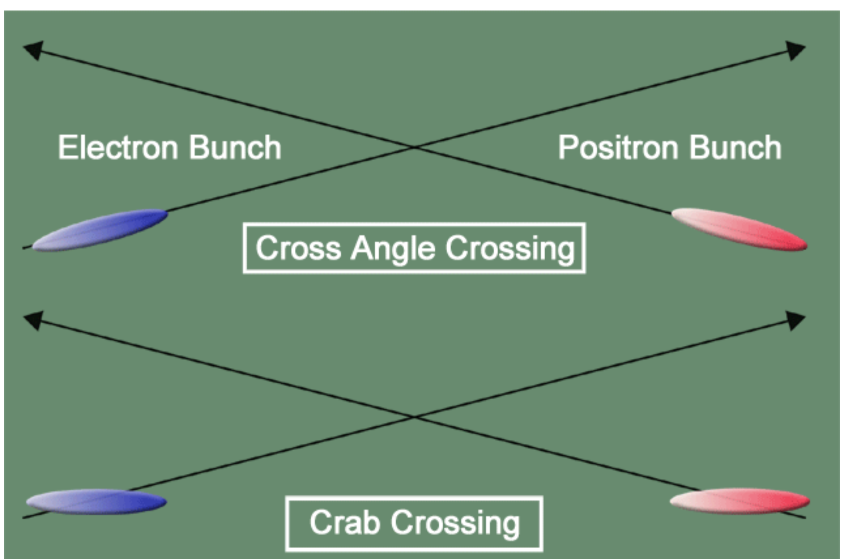
Polarized electron gun
Coherent Electron Cooling
Multi-pass SRF ERL with FFAG arcs – C-beta
Crab cavities
Polarized ^{3}He production
Linac-ring beam-beam affects
β^*=5 cm
HOM damped SRF cavities

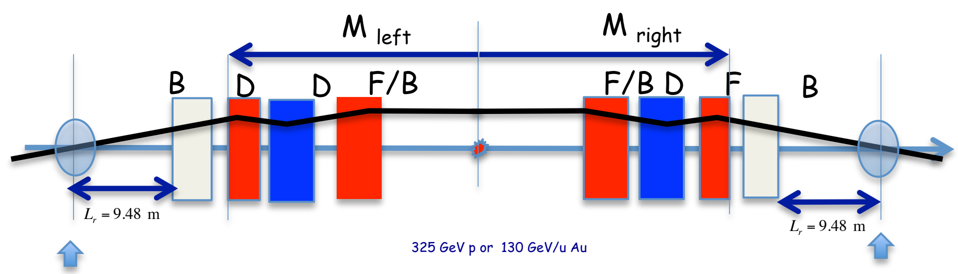


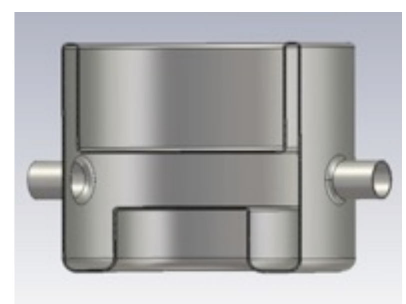
Crab-crossing in all scenarios

- We have to separate colliding beams.
- To avoid synchrotron radiation by 20 GeV electrons in the IR – one of serious backgrounds at HERA, we can not use separating dipoles.
- To separate beams without applying magnetic field, we need a crossing angle
- This also allows bringing the hadron triplet closer to the IR – hence lower β*
- Crossing angle reduces luminosity ~100-fold
- The crabbing (tail up, nose down) is needed to restore luminosity

Idea Introduced by R. B. Palmer SLAC PUB 4832



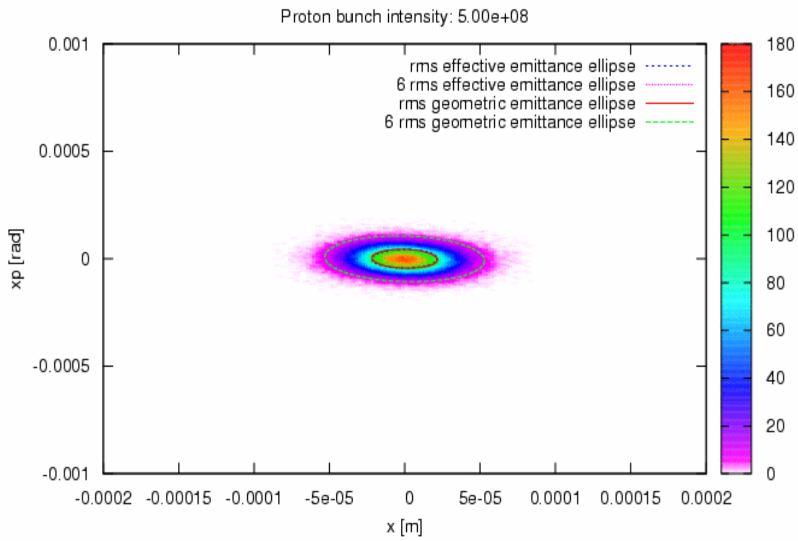




Original BNL crab-cavity design

High luminosity with a Linac-Ring collider

- For Linac-Ring collider the single collision of electron bunch removes the limitation of the beam-beam effect of the high energy hadron beam on the lower energy electron beam
- Can reach high luminosity with high intensity, low emittance hadron beam and lower intensity electron beam (and less synchrotron radiation power)
- Disruption of electron beam by hadron beam is large (similar to ILC) but emittance growth is limited to about 2x
- Need strong hadron beam cooling (10 times in transverse and longitudinal direction) for highest luminosities, small vertex distribution, and small forward divergence
- Novel cooling method:
  - Coherent electron Cooling (CeC)
  - Required performance demonstrated in extensive simulations
  - Proof-of-Principle test underway at RHIC



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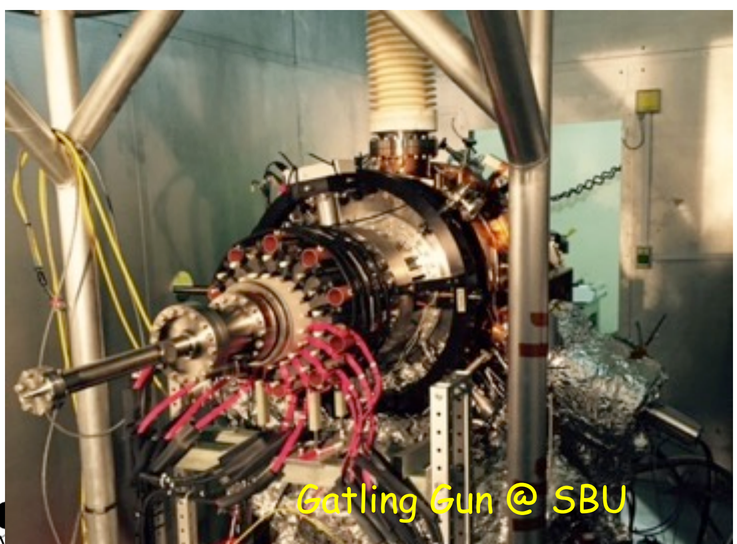
High CW current polarized electron gun

- Matt Poelker (JLab) achieved 4 mA polarized e-beam with 6 hours charge lifetime
- More current with effectively larger cathode area and laser spot
- Tests started at MIT with very large cathode area
- Gatling gun principle: multiple guns/cathodes with same charge lifetime
  - Requires fast switching between guns/cathodes
- Gatling Gun Test-stand at SBU:
  - Tests with beam from two cathodes started
- Backup to single Gatling gun: Fast switching between four 12.5 mA guns
- Backup to high current gun: Fast switching between ten 12.5 mA guns

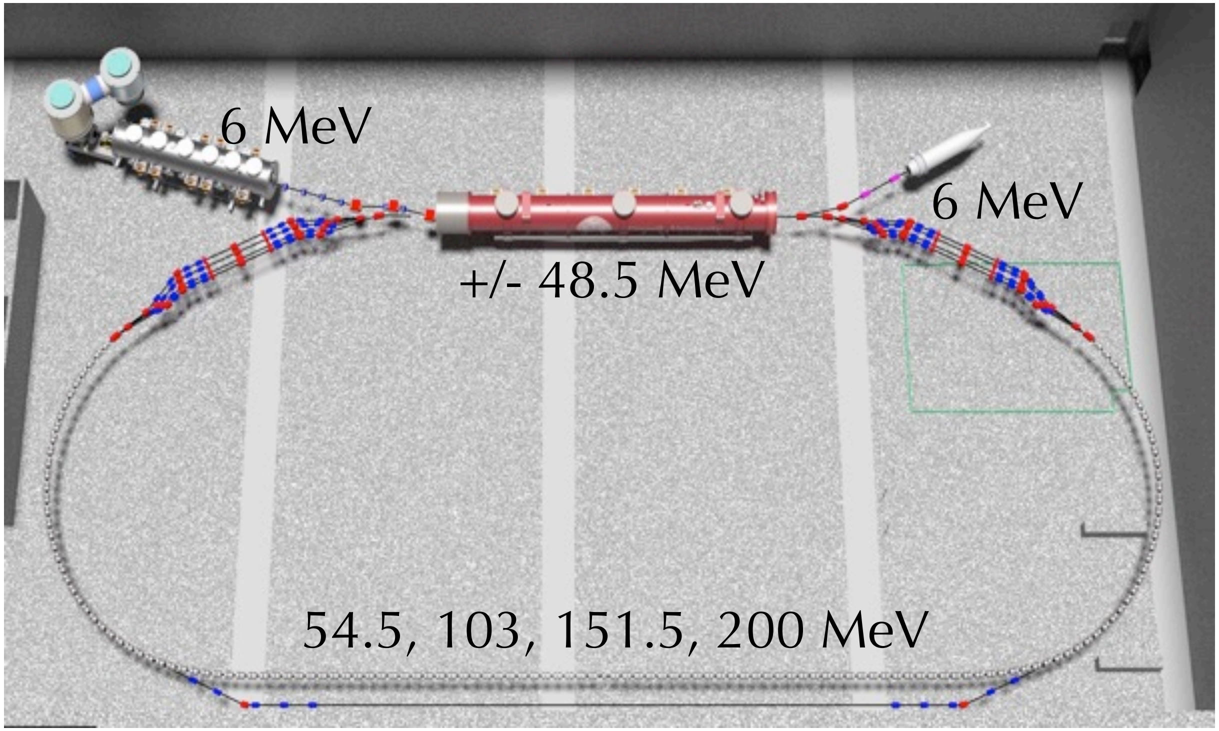


Gatling Gun @ SBU

Large cathode gun @ MIT

Multi-pass test-ERL at Cornell – an eRHIC prototype

- Uses existing 6 MeV low-emittance and high-current injector and 48.5 MeV CW SRF Linac
- ERL with single four-pass recirculation arc with x4 momentum range
- Permanent magnets used for recirculation arc
- Adiabatic transitions from curved to straight sections
- Test of spreader/combiner beam lines
- High current can be used to test HOM damping by replacing Linac with eRHIC Linac cryostat



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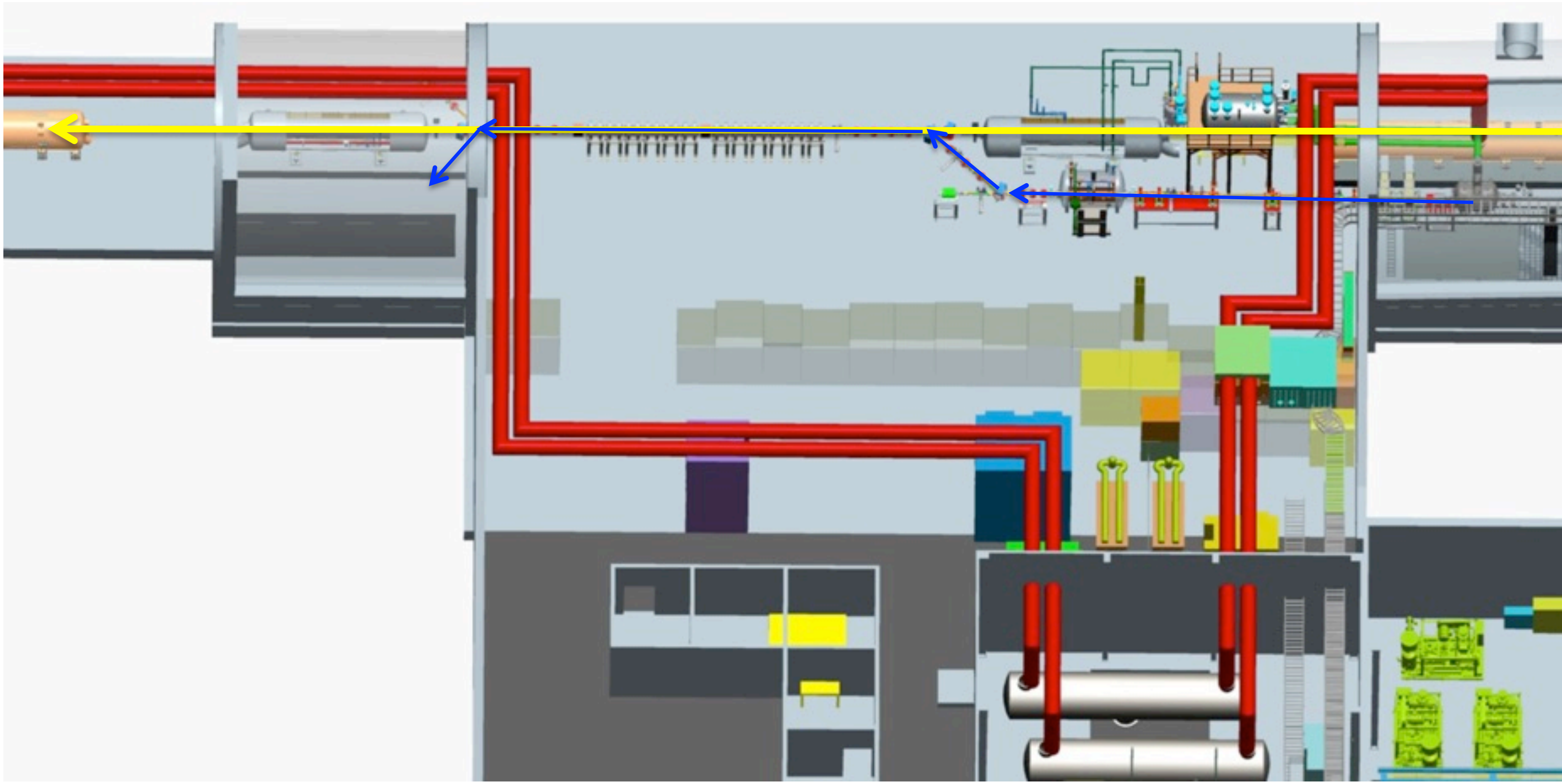
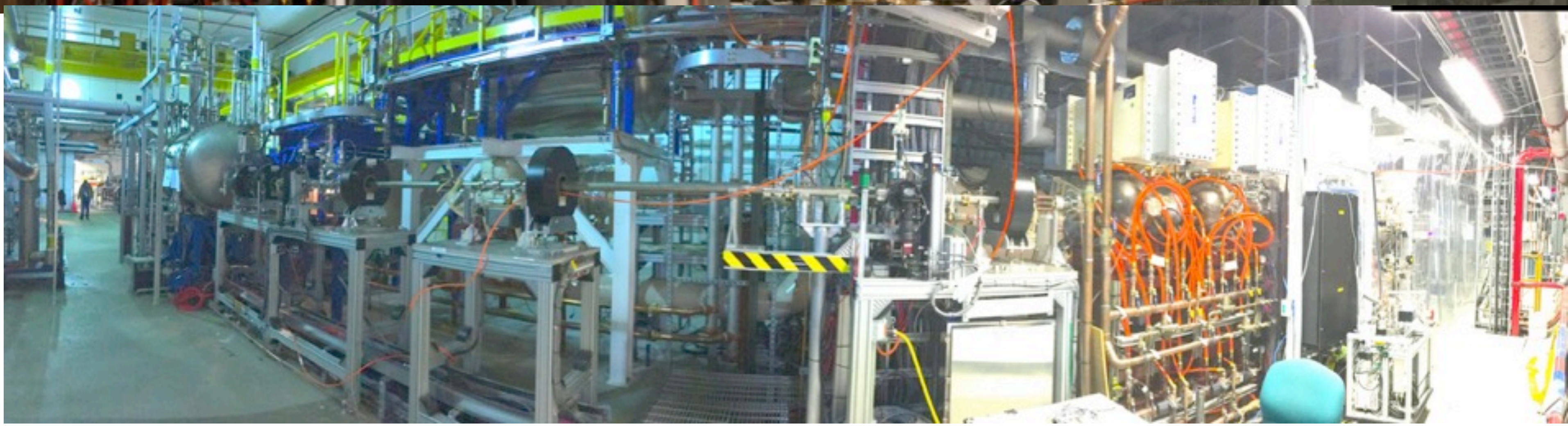
Coherent electron Cooling Proof-of-Principle Experiment



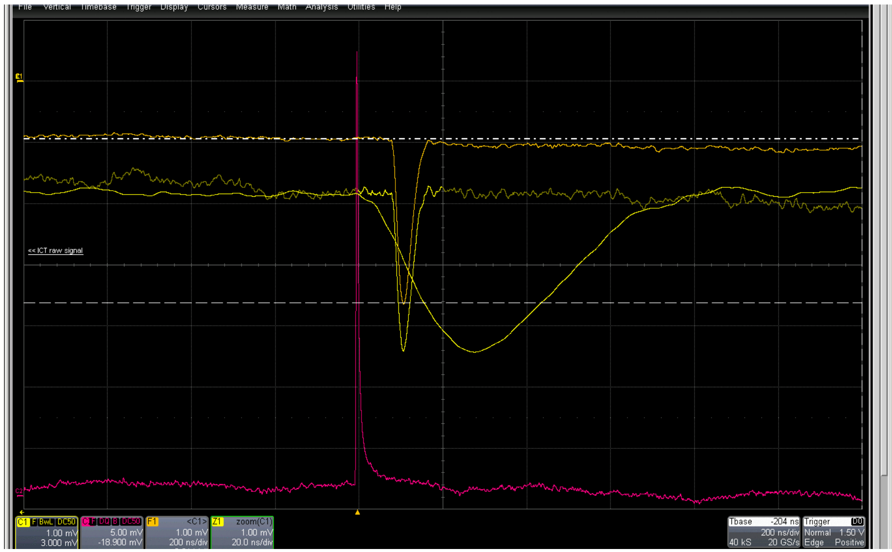
Coherent electron Cooling (CeC) demonstration experiment

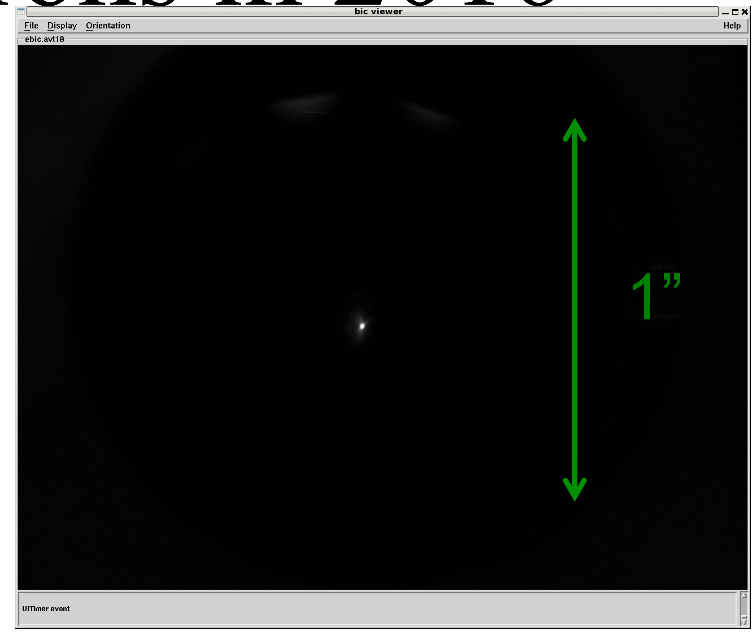
- DOE NP R&D project aiming for demonstration of CeC technique is in progress since 2012
- All equipment and infrastructure had been installed into RHIC's IP2, including 20 MeV SRF linac and helical wigglers for FEL amplifier,beam transported to low energy dump
- First beam from SRF gun (3 nC/bunch, 1.7 MeV) on 6/24/2015; exceeds performance of all operating CW electron guns
- Proof-of-principle demonstration with 40 GeV/n Au beam scheduled during RHIC Run 16 and 17. Micro-bunching test also planned with same set-up

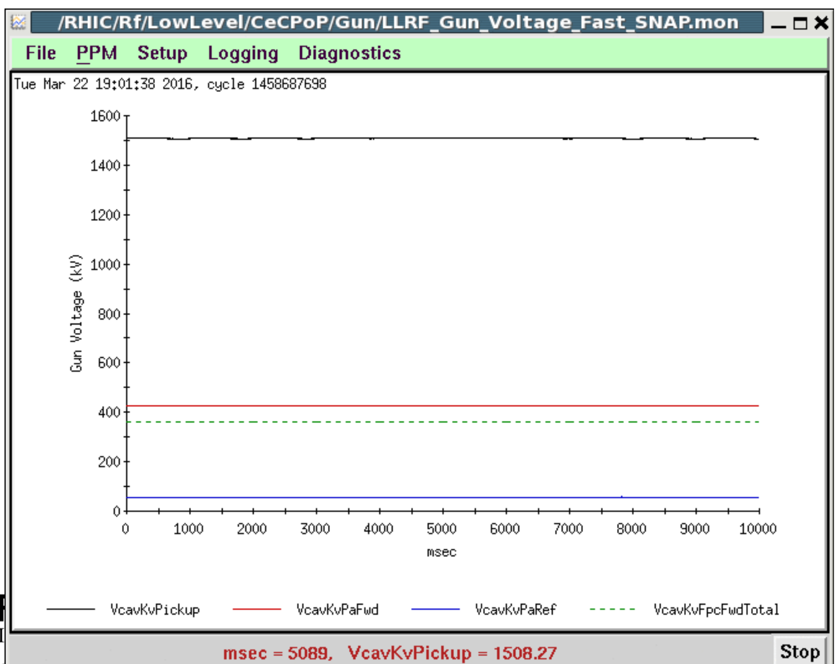
Coherent electron cooler: in commissioning

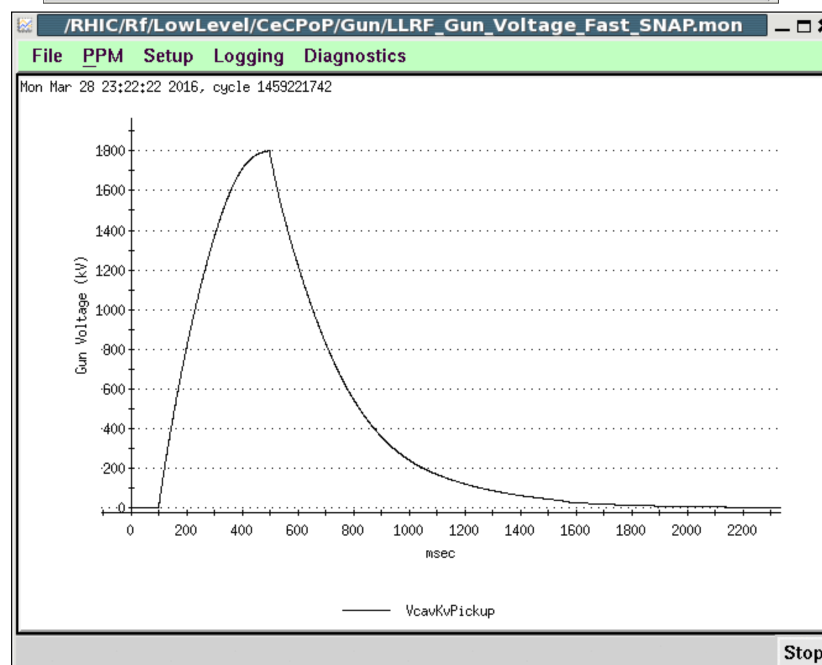


First photo-electrons in 2016









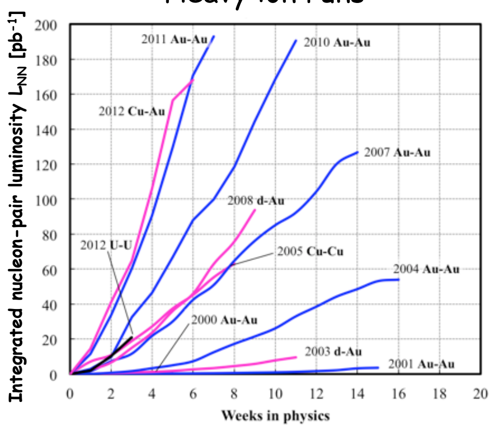
Collaboration network

- We are collaborating with a number of institutions on various aspects of eRHIC R&D. We intend to expand this network.
  - SBU – all R&D items
  - BINP, Daresbury Lab – Coherent electron cooling
  - Cornell – FFAG multi-pass ERL experiment, high intensity electron source
  - MIT – polarized gun R&D
  - JLab – CEBAF ERL experiment, possible collaboration on polarized electron gun
  - CERN – crab cavities for HL-LHC and eRHIC (ERL-Ring or Ring-Ring), test-ERL
  - Berkeley – numerical simulations of beam-beam interactions, discuss collaboration on a number of items
  - ANL – discuss collaboration on HOM damper design, possible collaboration on low-energy injector cavities
  - FNAL – possible collaboration on 650 MHz SRF ERL cavities
  - Various SBIR projects – high-efficiency RF amplifiers (completed), in-situ RHIC beam pipe coating (only stage 1), eRHIC permanent magnet development, high intensity electron beam transport

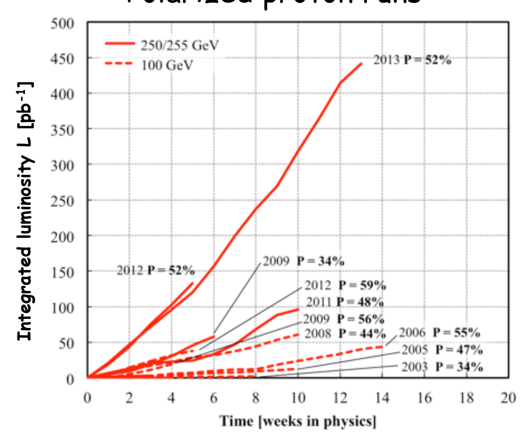
Conclusions

- We are considering multi-pass ERL with two FFAG arcs as a cost effective solution for full-energy 21.15 GeV ERL for eRHIC
  - All energies will be available from the day one
  - Initial luminosity of 1.5x 10^{33}, will be increased above 10^{34} using AIPs (accelerator improvement projects) – this strategy worked extremely well for RHIC

Heavy ion runs



Polarized proton runs



- The design is complete and undergoing the cost estimate
- We studied most of collective effects & did not find any showstoppers
- We are developing various risk mitigation scenarios – albeit with lower luminosities - including more conventional cooling techniques and ring-ring back-up option