eRHIC Design and R&D

From RHIC to eRHIC

- Performance requirement for 1st stage and full EIC
- eRHIC design
- R&D for eRHIC

For the eRHIC design team (V. Litvinenko et al.)

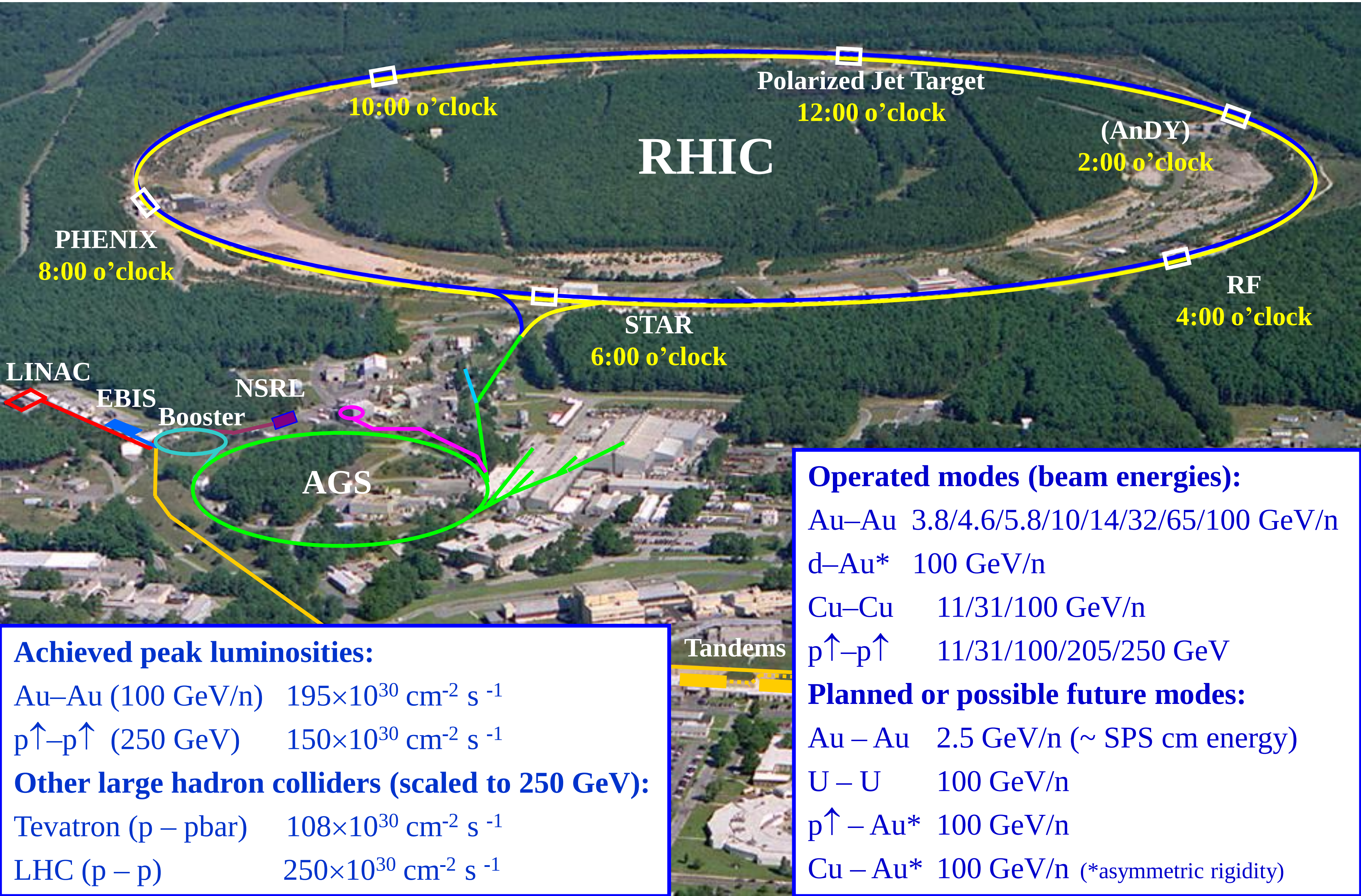
BROOKHAVEN NATIONAL LABORATORY

Thomas Roser
Workshop on Future Directions in High Energy QCD
October 20-22, 2011

Performance requirement for 1st stage and full EIC (INT)

- Highly polarized (> 70%) electron and nucleon beams
- Ion beams from deuterium to the heaviest nuclei (uranium)
- Center of mass energy range: ~ 20 GeV to ~ 150 GeV
- Peak collision luminosity up to 10^{34} cm^{-2} s^{-1}
- Non-zero crossing angle without loss of luminosity (crab crossing)
- Strong cooling of the proton and ion beams for high luminosity
- First stage of EIC to reach CM energy of ~ 70 GeV
- Possibility to have multiple interaction regions
- Ground breaking new QCD probe with ~ 10^{33} cm^{-2} s^{-1} for 10 yrs (~ 50 fb^{-1})
- Precision imaging and EW experiments need ~ 10^{34} cm^{-2} s^{-1}

RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities:

Au–Au (100 GeV/n) 195×10^{30} cm^{-2} s^{-1}

p↑–p↑ (250 GeV) 150×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 250 GeV):

Tevatron (p – pbar) 108×10^{30} cm^{-2} s^{-1}

LHC (p – p) 250×10^{30} cm^{-2} s^{-1}

Operated modes (beam energies):

Au–Au 3.8/4.6/5.8/10/14/32/65/100 GeV/n

d–Au* 100 GeV/n

Cu–Cu 11/31/100 GeV/n

p↑–p↑ 11/31/100/205/250 GeV

Planned or possible future modes:

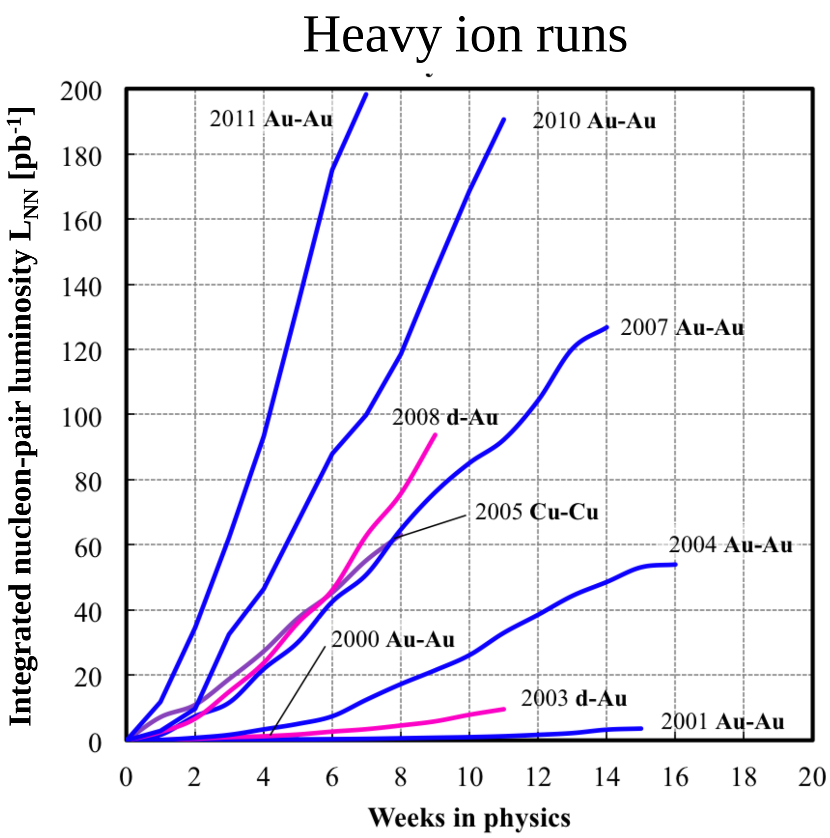
Au – Au 2.5 GeV/n (~ SPS cm energy)

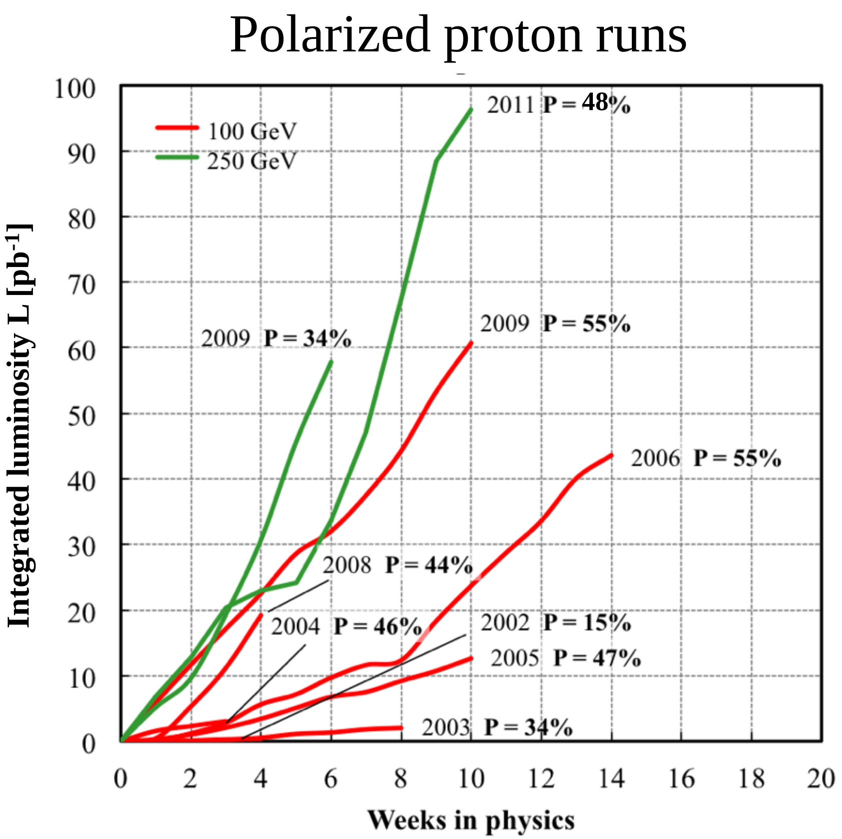
U – U 100 GeV/n

p↑ – Au* 100 GeV/n

Cu – Au* 100 GeV/n (*asymmetric rigidity)

Delivered Integrated Luminosity and Polarization





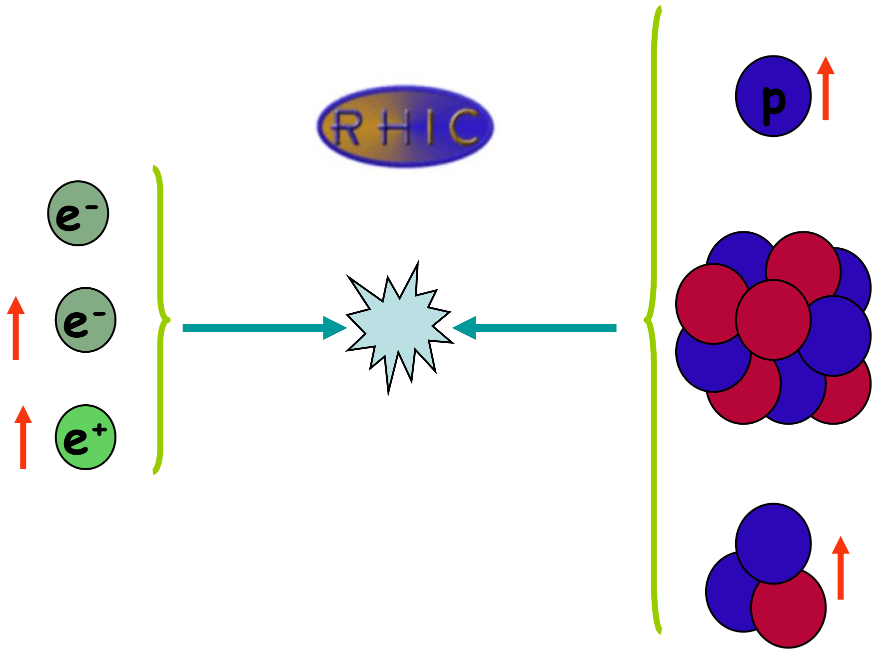
- Luminosity upgrades underway increase luminosity by additional factor 2.

Nucleon-pair luminosity: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.

eRHIC: QCD Facility at BNL

Add an electron accelerator to the existing $2B RHIC

Unpolarized and
80% polarized leptons
5 - 30 GeV

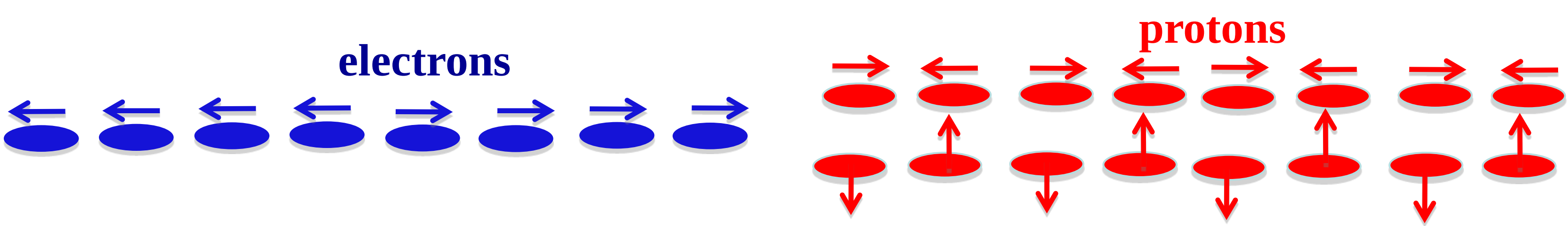


70% polarized protons
50 - 250 (275*) GeV

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

Pol. light ions (He-3)
50 - 167 (184*) GeV/u

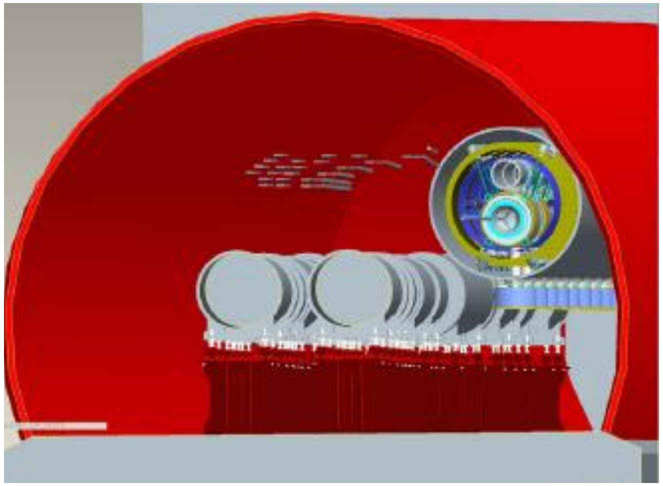
Center-of-mass energy range: 30 - 175 GeV
Any polarization direction in lepton-hadrons collisions

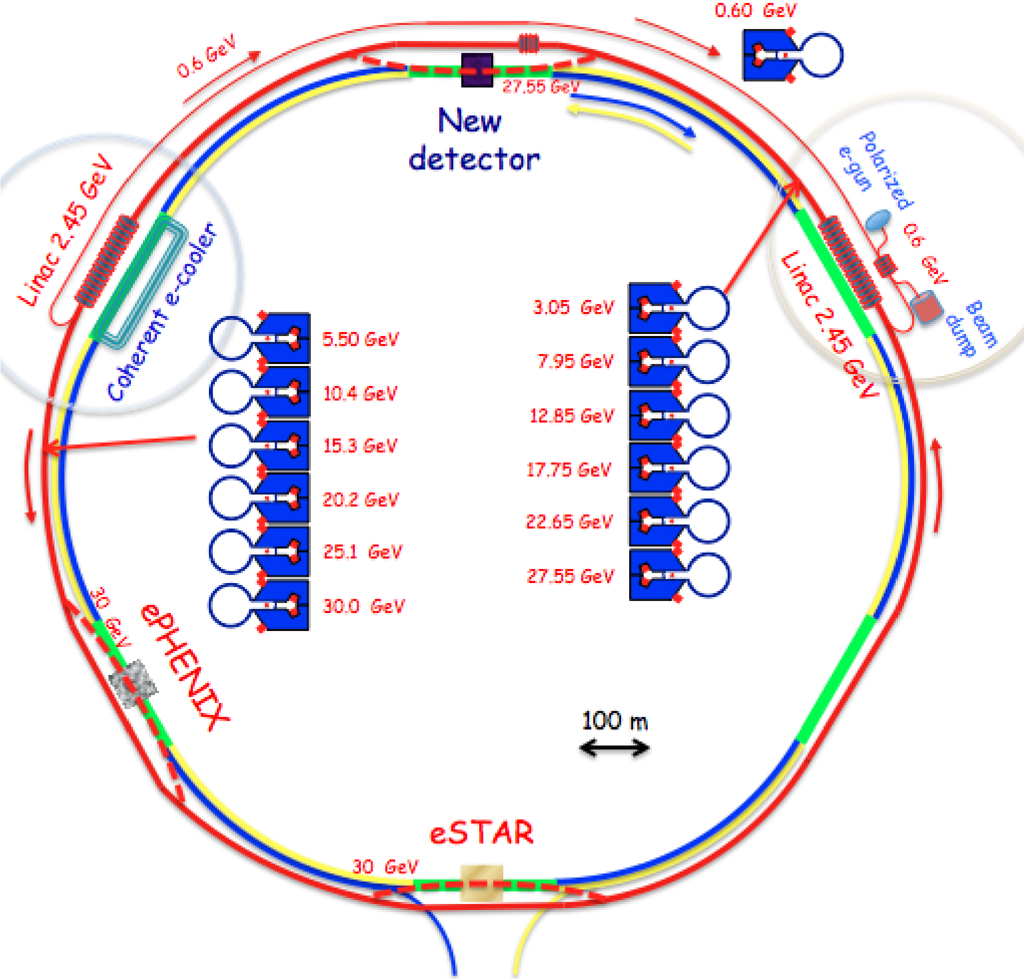


*** We are exploring a possibility of increasing RHIC ring energy by 10% - 30%**

eRHIC design

- 5 – 30 GeV electron beam accelerated with Energy Recovery Linac (ERL) inside existing RHIC tunnel collides with existing 250 GeV pol. protons and 100 GeV/n HI RHIC beams
- Single pass allows for large collision disruption of electron bunch and high luminosity ($L \sim 10^{34}$ cm^{-2} s^{-1}) and full electron polarization transparency
- Accelerator R&D:
  - High current (50 mA) pol. electron gun
  - Multi-pass high average current ERL
  - Coherent electron cooling of hadron beam
  - Polarized He-3 in RHIC
- 1st stage: 5 GeV electron beam
  - All arc magnets installed for 1st stage
  - Staged Linac length (2 x 0.4 GeV)
  - 1st stage similar to CEBAF 12 GeV upgrade



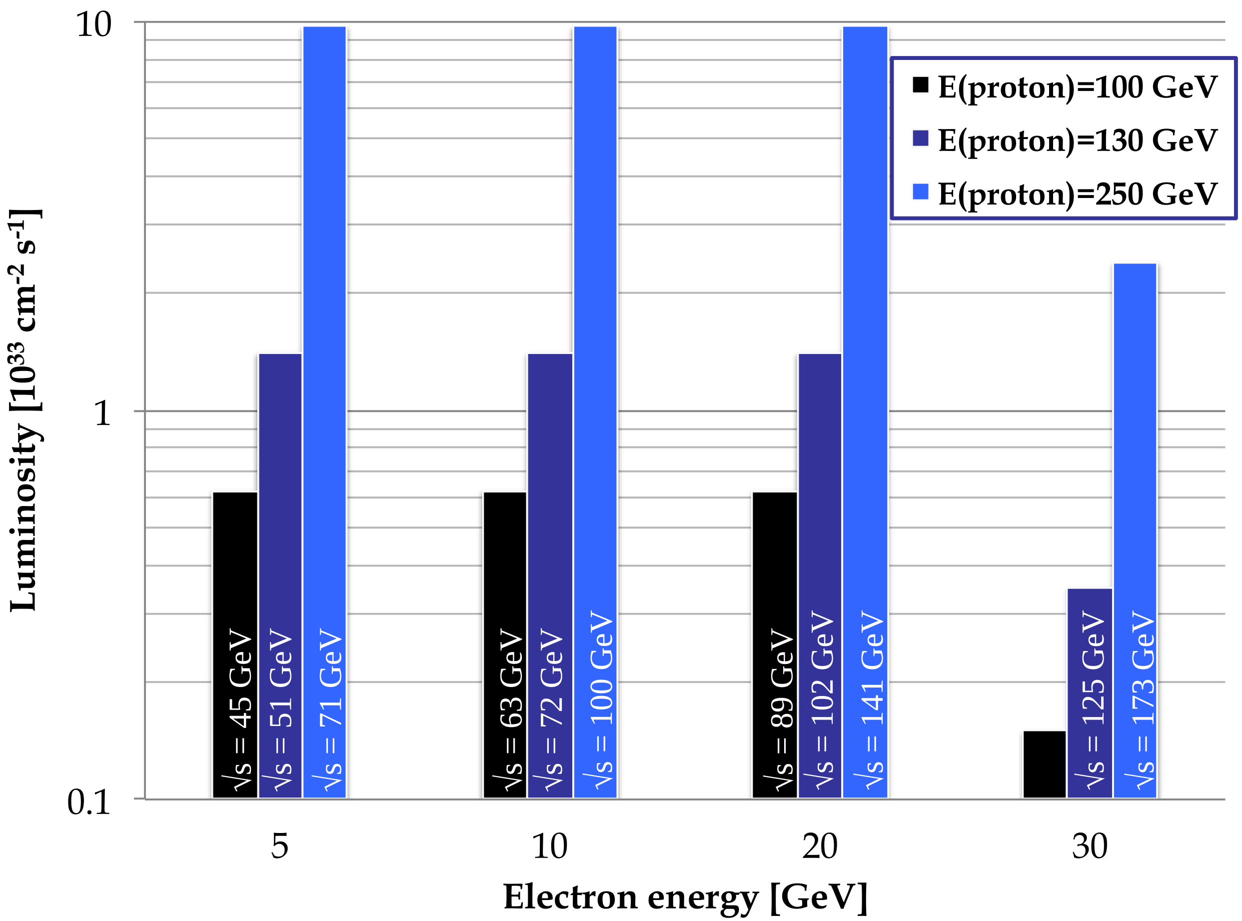


Main elements of the concept

- Single pass ERL for electrons allows for large collision disruption of electron bunches and high luminosity and full electron polarization transparency
- Strong cooling of hadron beam (÷10 emittance) in both longitudinal and transverse directions using coherent electron cooling
- Small electron beam size allows for small magnets with gaps of 5 mm (and 10 mm at the two lowest energy orbits)
- Unique solution for linac-ring colliders, which allows energy change of colliding hadrons from 50 GeV to 250 GeV
- Using recent advances in super-conducting quadrupole technology allows design IR with $\beta^* = 5$ cm
- Crab-crossing with large crossing angle following success at KEK-B
- Need 50 mA of polarized electron beam current
- Together results in eRHIC top luminosity of 10^{34} cm^{-2} s^{-1}

- If polarized positrons are needed for the program, build positron ring and use ERL for generating and accelerating positrons. Luminosity of these collisions will be much lower, i.e. ~ 10^{32} cm^{-2} s^{-1} and not all energies of hadrons could be used in the collisions

eRHIC Luminosity



- Hourglass effect is included
- Luminosity falls as the cube of hadron energy E_h^3 because of space charge limit
- Luminosity is the same at electron energies from 5 GeV to 20 GeV
- e-beam current and luminosity fall as E_e^{-4} for electron energies > 20 GeV

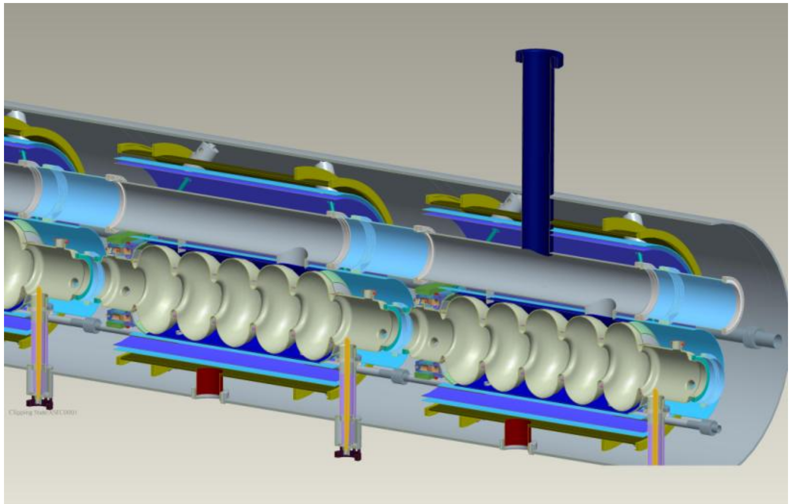
e – p Luminosities

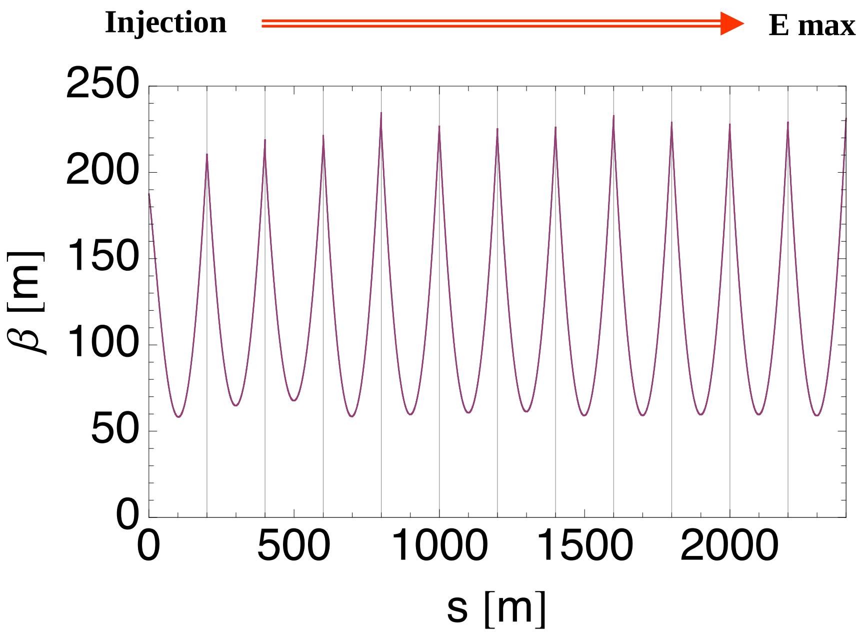
	First stage		Second stage (highest luminosity)		Second stage (highest electron energy)	
	p	e	p	e	p	e
Energy, GeV	250	5	250	20	250	30
Number of bunches/ Bunch frequency, MHz	166	14.07	166	14.07	166	14.07
Bunch intensity, 10^{11}	2	0.22	2	0.22	2	0.056
Bunch charge, nC	32	3.5	32	3.5	32	0.9
Beam current, mA	420	50	420	50	420	12.6
Rms normalized emittance, 1e-6 m	0.18	6.6	0.18	26.4	0.18	39.7
β^*, cm	5	5	5	5	5	5
Beam size at IP, 1e-6 m	5.8	5.8	5.8	5.8	5.8	5.8
Beam angular spread at IP, mrad	0.11	0.11	0.11	0.11	0.11	0.11
rms bunch length, cm	8.3	0.2	8.3	0.2	8.3	0.2
Polarization, %	70	80	70	80	70	80
Luminosity, x 10^{33}, $cm^{-2}s^{-1}$ (with hourglass reduction)	9.7		9.7		2.4	

e – Au Luminosities

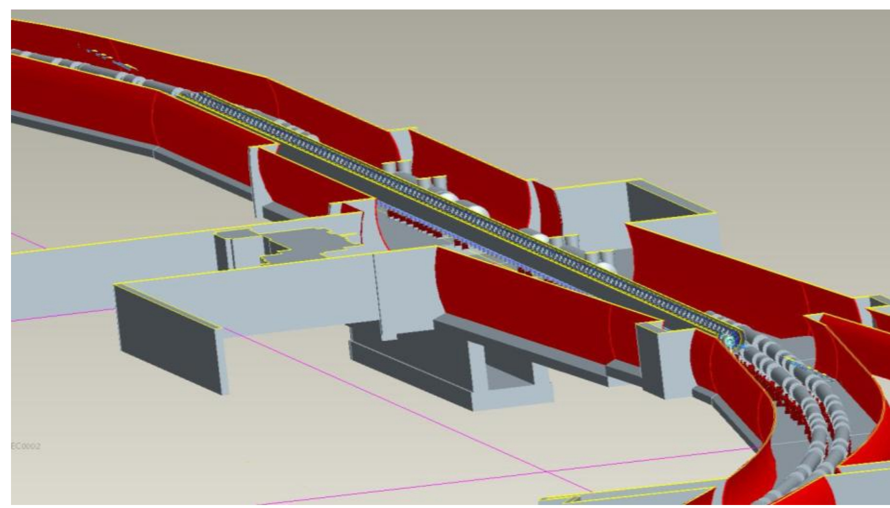
	First stage		Second stage (highest luminosity)		Second stage (highest electron energy)	
	Au	**e**	**Au**	**e**	**Au**	**e**
Energy, GeV	100	5	100	20	100	30
Number of bunches/ Bunch frequency, MHz	166	14.07	166	14.07	166	14.07
Bunch intensity, 10^{11}	0.004	0.22	0.004	0.22	0.004	0.056
Bunch charge, nC	5.2	3.5	5.2	3.5	5.2	0.9
Beam current, mA	67	50	67	50	67	12.6
Rms normalized emittance, 1e-6 m	0.072	6.6	0.072	26.2	0.18	39.4
β*, cm	5	5	5	5	5	5
Beam size at IP, 1e-6 m	5.8	5.8	5.8	5.8	5.8	5.8
Beam angular spread at IP, mrad	0.11	0.11	0.11	0.11	0.11	0.11
rms bunch length, cm	8.3	0.2	8.3	0.2	8.3	0.2
Polarization, %	70	80	70	80	70	80
Luminosity, x 10^{33}, $cm^{-2}s^{-1}$ (with hourglass reduction)	3.9		3.9		1.0	

eRHIC Linac

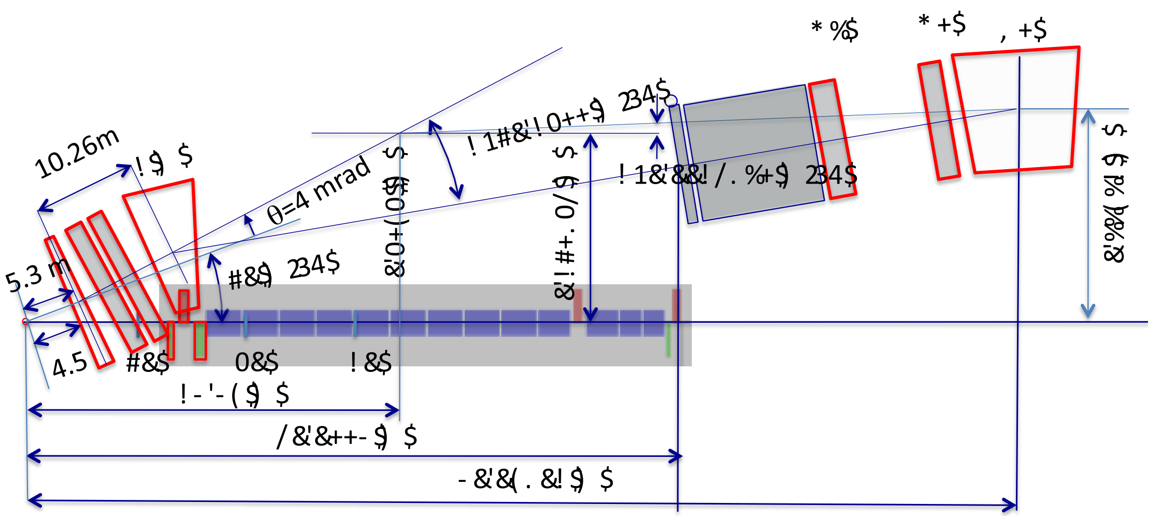


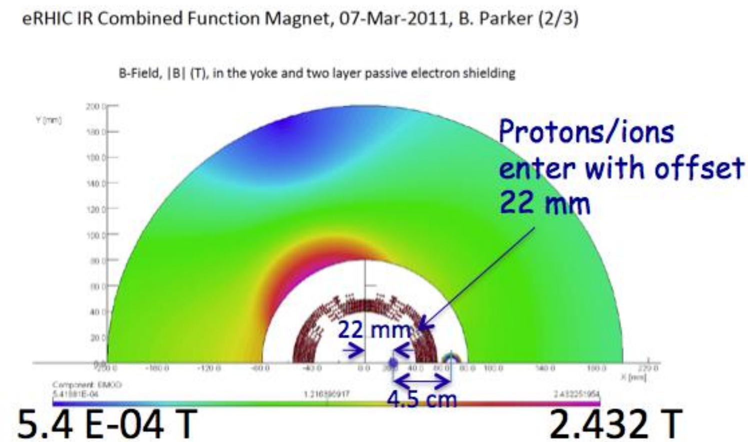


- Total Linac length: ~ 200 m
- Warm-to-cold transitions only at the ends
- No quadrupoles in Linac
- Maximum energy gain per pass: 2.45 GeV
- Accelerating gradient: 19.2 MV/m
- Based on BNL SRF cavity with fully suppressed HOMs, critical for high current multi-pass ERL
- eRHIC cavity & cryostat designs are still evolving

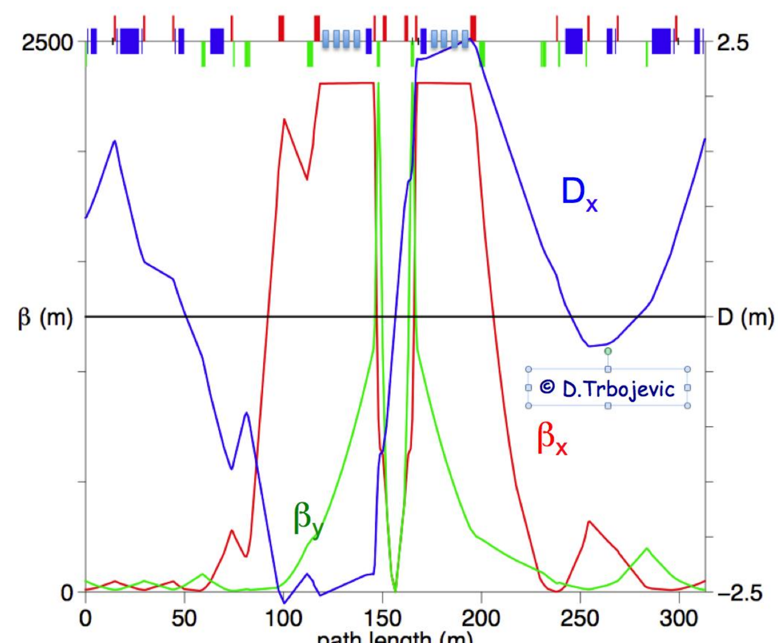


eRHIC high-luminosity IR with β* = 5 cm

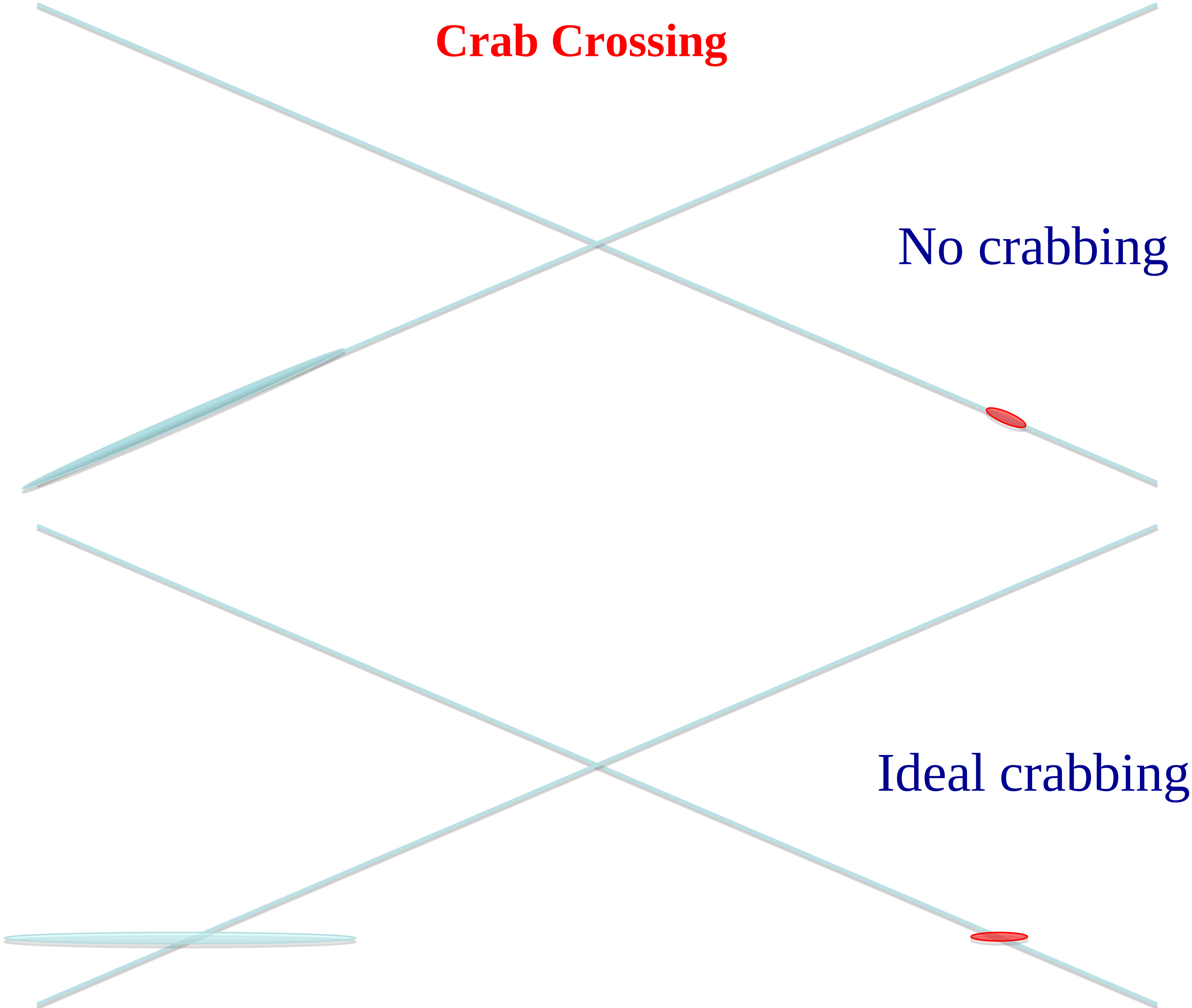




- 10 mrad crossing angle and crab-crossing
- High gradient (200 T/m) large aperture Nb3Sn focusing magnets
- Free-field electron pass through the hadron triplet magnets
- Integration with the detector: efficient beam separation and detection of low angle collision products
- Gentle bending of the electrons to avoid SR



Crab Crossing



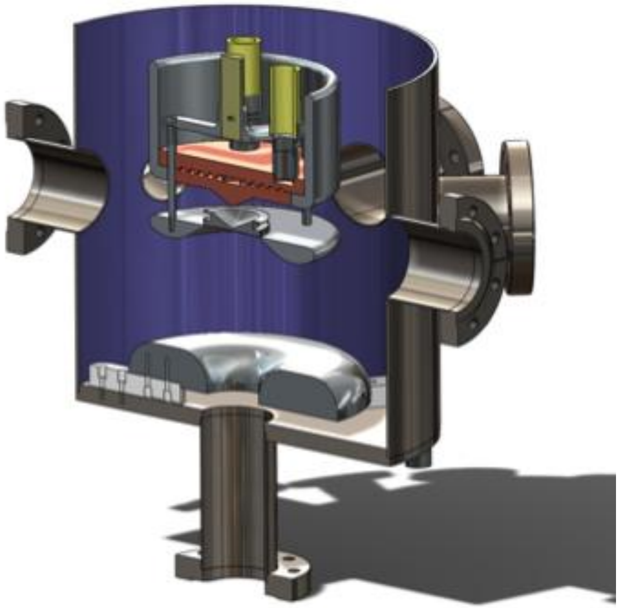
Main accelerator R&D items for eRHIC

- High current (50 mA) polarized electron gun
- Multi-pass high average current ERL
- Polarized He-3 in RHIC
- Coherent electron cooling of hadron beams

High CW current polarized electron gun

- Matt Poelker (JLab) achieved 4 mA with good lifetime
- More current with (effectively) larger cathode area

Single large area cathode



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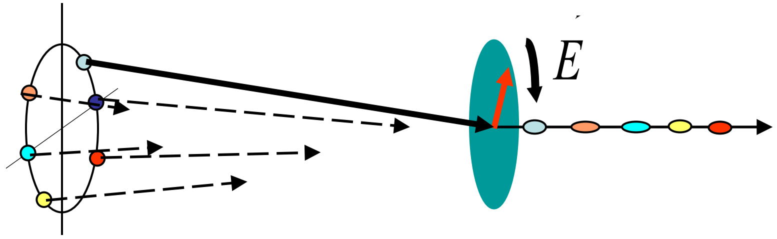
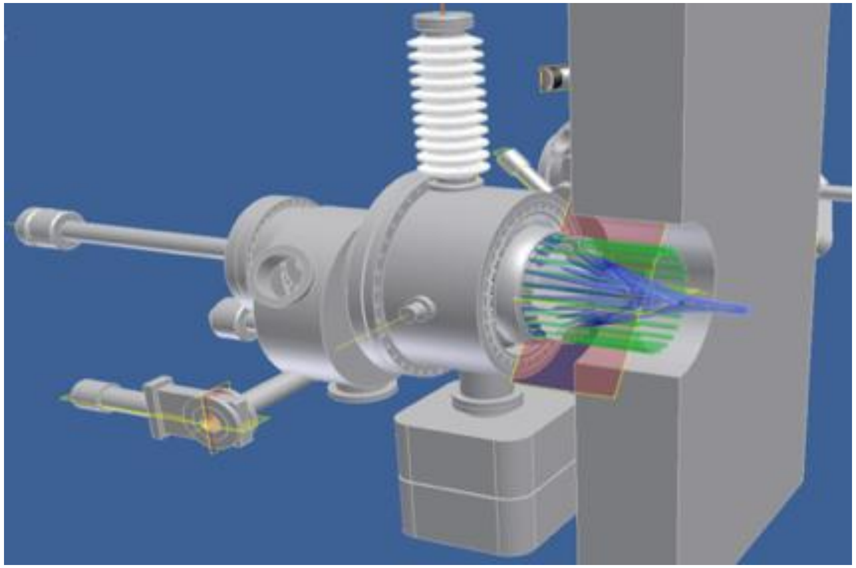
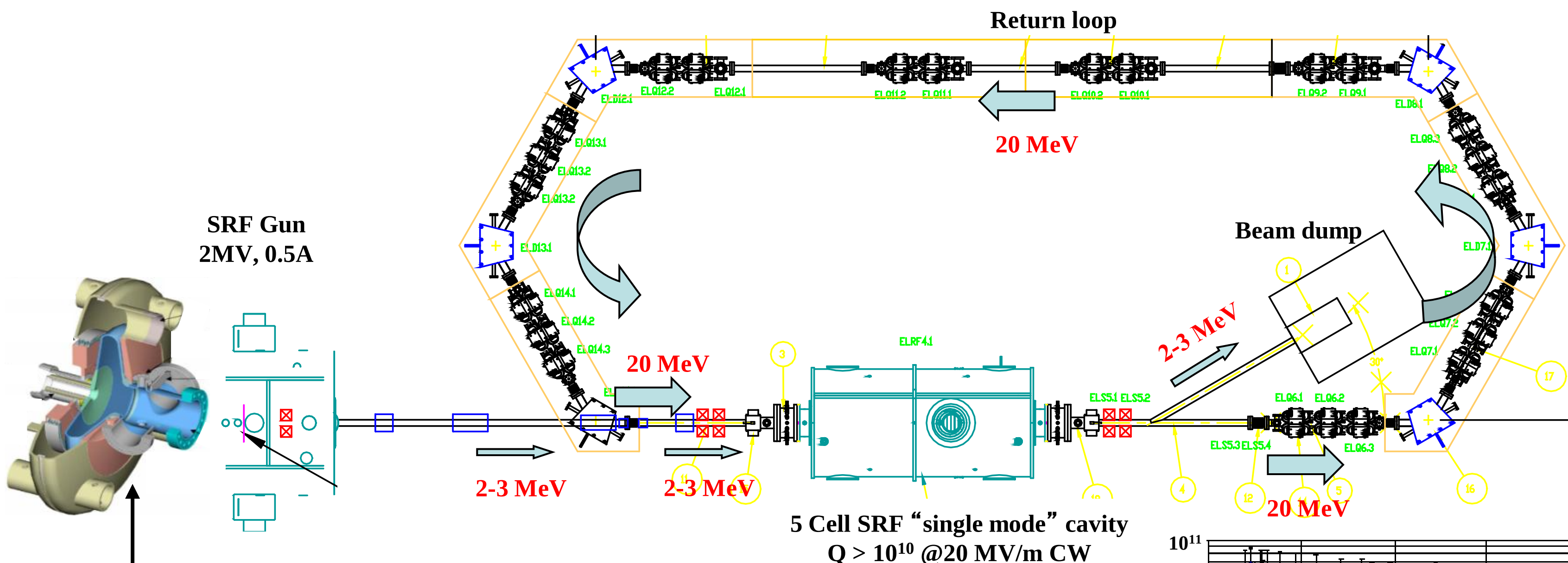
Gatling electron gun: many smaller cathodes



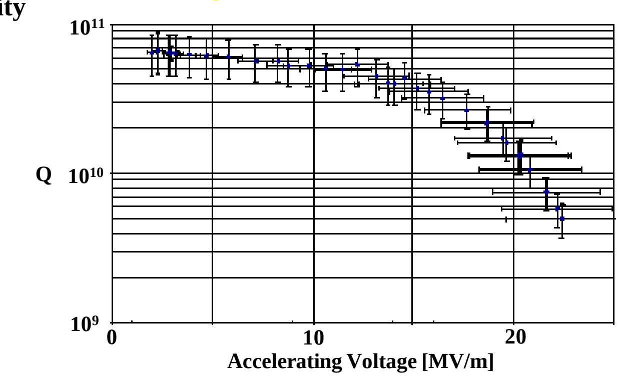


Energy Recovery Linac (ERL) Test Facility

- Test of high current (0.5 A), high brightness ERL operation
- Highly flexible return loop lattice to test high current beam stability issues
- Allows for addition of a 2nd recirculation loop
- Same beam current in cavity as for 6-pass eRHIC ERL

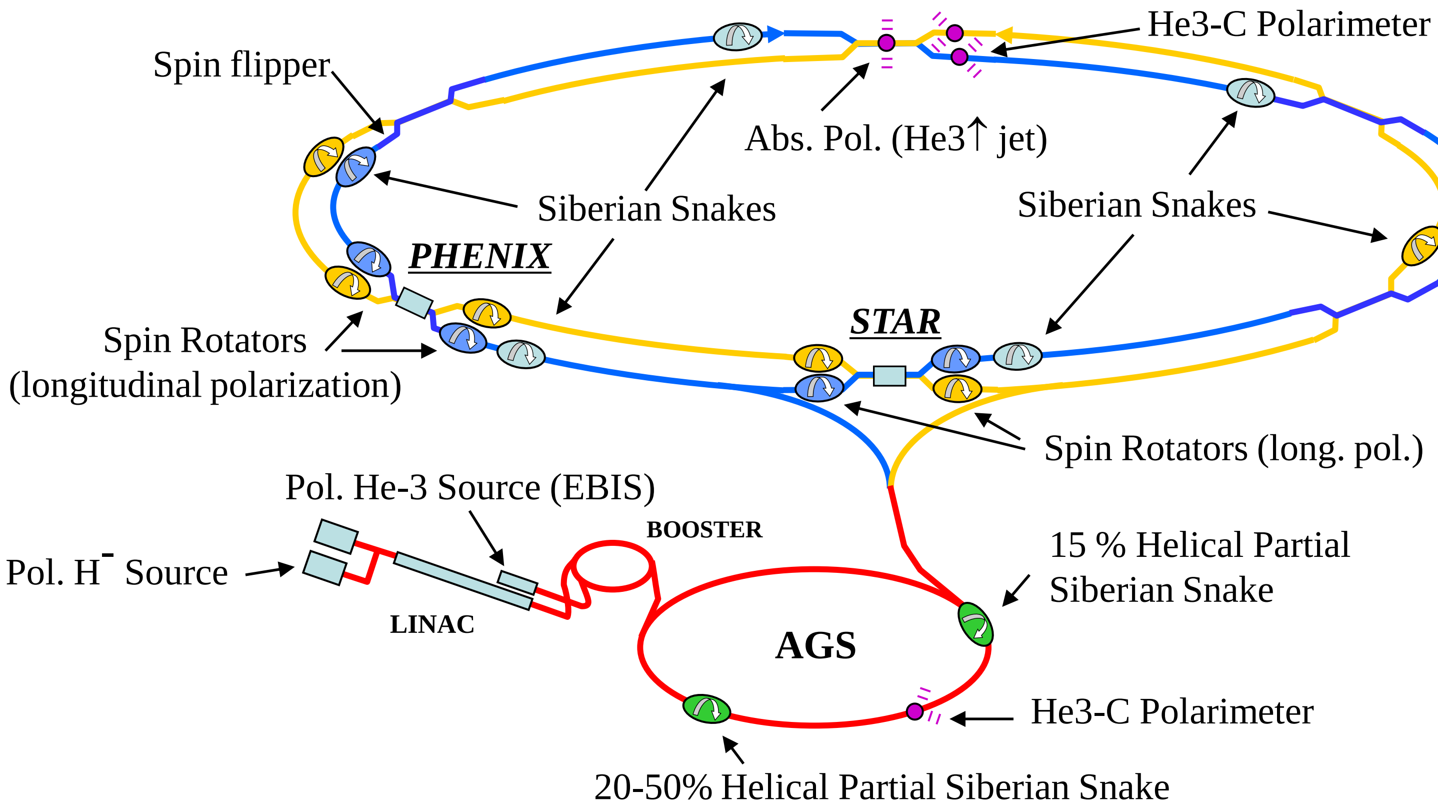


1 MW, 703.75 MHz CW Klystron



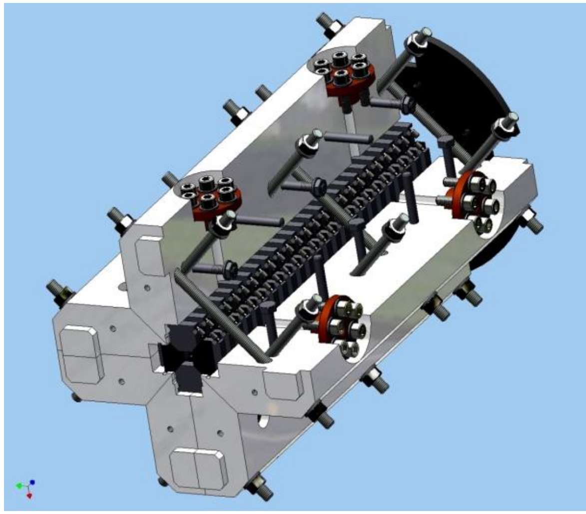
Polarized He-3 in RHIC

- Resent workshop to review status and R&D needs for polarized He-3 acceleration
- Polarized He-3 from new EBIS; test soon possibly starting with unpolarized He-3
- Polarimetry:
  - Relative: He3-C CNI polarimeter;
  - Absolute: He3-He3 CNI polarimeter using polarized He-3 jet
- Depolarizing resonances are stronger; no depolarization expected with six snakes in RHIC
- Physics from polarized p-He3? High luminosity may be possible (see below)



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 □ 10x reduced proton emittance gives high eRHIC luminosity at much reduced electron current
- Proof-of-principle demonstration planned with 40 GeV/n Au beam in RHIC (~ 2014)

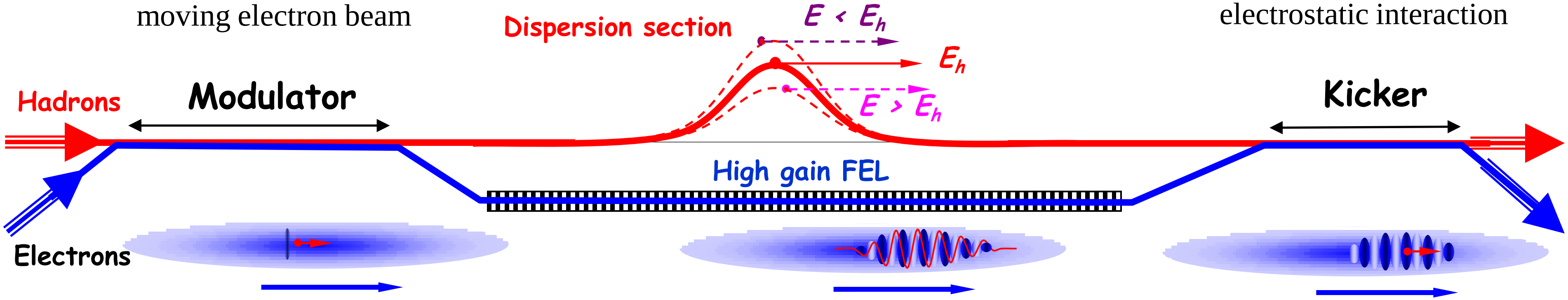


Helical wiggler prototype

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

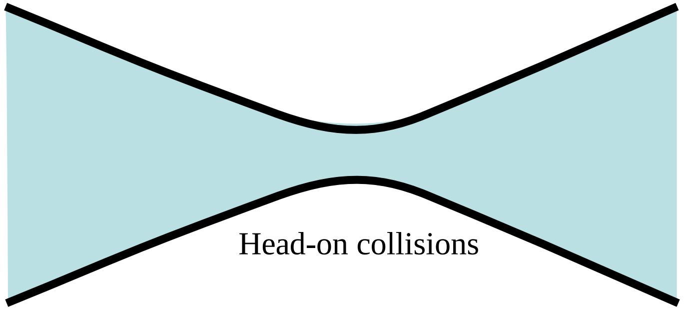
Amplifier: Free Electron Laser (FEL) with gain of 100 -1000 amplifies density variations of electron beam, energy dependent delay of hadron beam

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

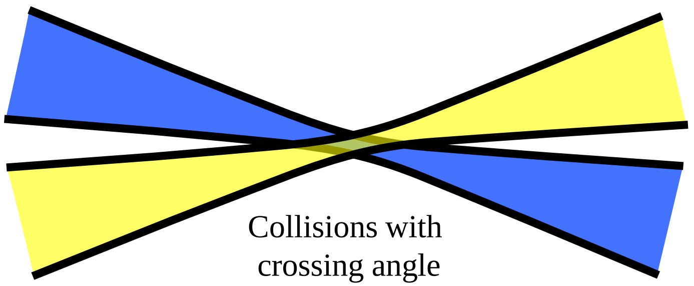


Symmetric collisions with large crossing angle

- Head-on collisions:
  - Luminosity loss from hour-glass effect requires shorter bunch length for smaller beta-star
  - Reducing bunch length limited by peak current, momentum acceptance and/or instabilities
  - Difficult to reduce beta-star without reducing emittance and momentum spread



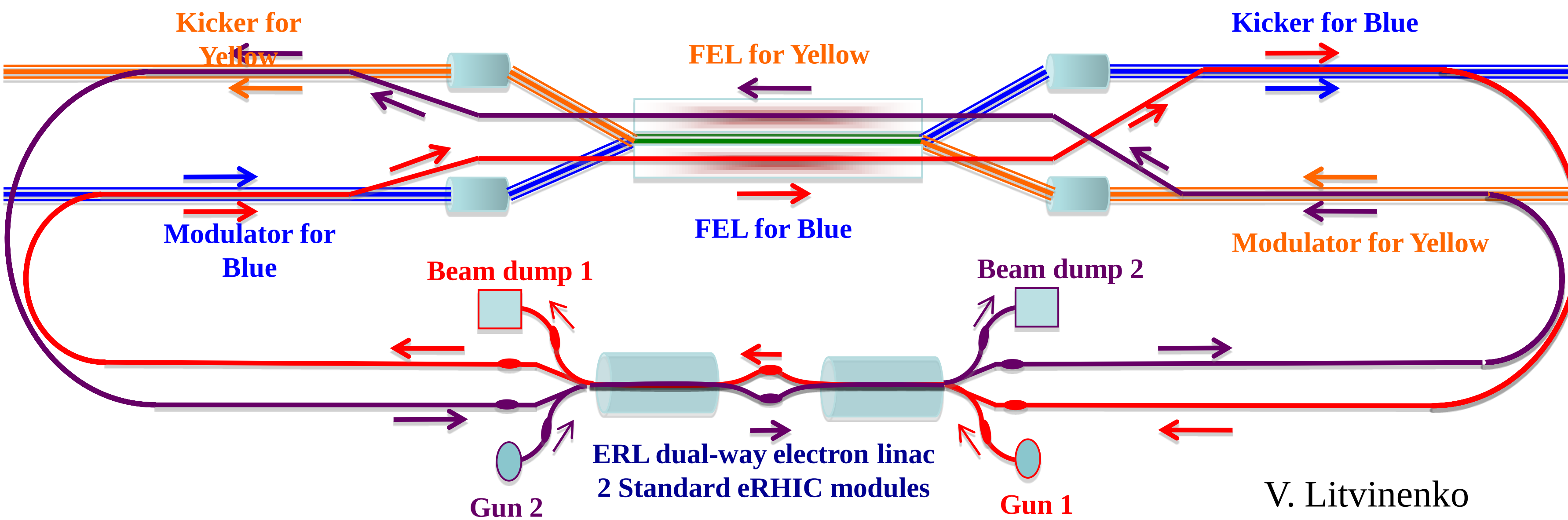
- Large crossing-angle collisions (Piwinski angle):
  - To be beneficial needs low emittance beams (strong cooling: synchrotron rad. or CeC)
  - Separate bunches outside high luminosity region to avoid beam-beam effect from low luminosity region.
  - Reducing beam emittance back to beam-beam limit
  - Smaller emittance and shorter overlap region allows for smaller beta-star
  - For N_b/k particles colliding (k ~ 10, ε = ε^0/k):



$$\frac{L}{g} = \frac{1}{4p}\frac{N_b}{ke_n}\frac{N_b}{t_b}\frac{R}{b^*} = \frac{1}{4p}\frac{N_b}{ke_n}\frac{N_b}{t_b}\frac{Rgs'^2}{e_n} = \frac{1}{4p}\frac{N_b}{e_n^0}\frac{N_b}{t_b}\frac{Rgs'^2}{e_n^0/k} = k\frac{L^0}{g}$$

Coherent electron Cooling for RHIC

- RHIC: overlap length ~ 10 cm, ε_n (95%) ~ 1 π μm , β^* ~ 10 cm □ ~ x10 luminosity increase
- Together with eLens beam-beam compensation 5 $\times 10^{33}$ cm^{-2} s^{-1} might be possible for 500 GeV pp (~ 25 interactions per crossing)
- LHC demonstrated 30 interactions per crossing is OK, planning for 200!
- Effect of long range beam-beam?
- Possible layout in RHIC IP of CeC driven by a single linac:



V. Litvinenko

Summary

- Linac-ring design of eRHIC reaches high luminosity (10^{34} cm^{-2} s^{-1}) at high energy
- Use existing RHIC facility ($2B replacement value)
- Maximum total synchrotron radiation power loss ~ 10MW [$E_e \geq 20$ GeV]
- Advanced technologies used:
  - 6-pass 30 GeV ERL - coherent electron cooling - crab-crossing - Nb3Sn super-conducting quadrupole - small gap magnets and strong focusing isochronous arc lattice - gun with 50 mA of polarized electrons
- External eRHIC design review (8/1-3/2011):
  - "The committee is highly satisfied with the material presented, covering most of the relevant subjects. The committee did not see any significant holes in the concept. For the project success it is crucial to experimentally demonstrate feasibility of a 50-mA polarized electron gun with reasonable lifetime and coherent electron cooling."
- Cost & schedule review planned for ~ January 2012
- R&D projects relevant to eRHIC design at BNL, Bates, JLab and beyond:
  - HOM damped SRF linacs - SRF crab cavities - CeC test - R&D ERL - polarized gun small gap magnets - beam-beam and beam dynamics studies - SC magnets technology.