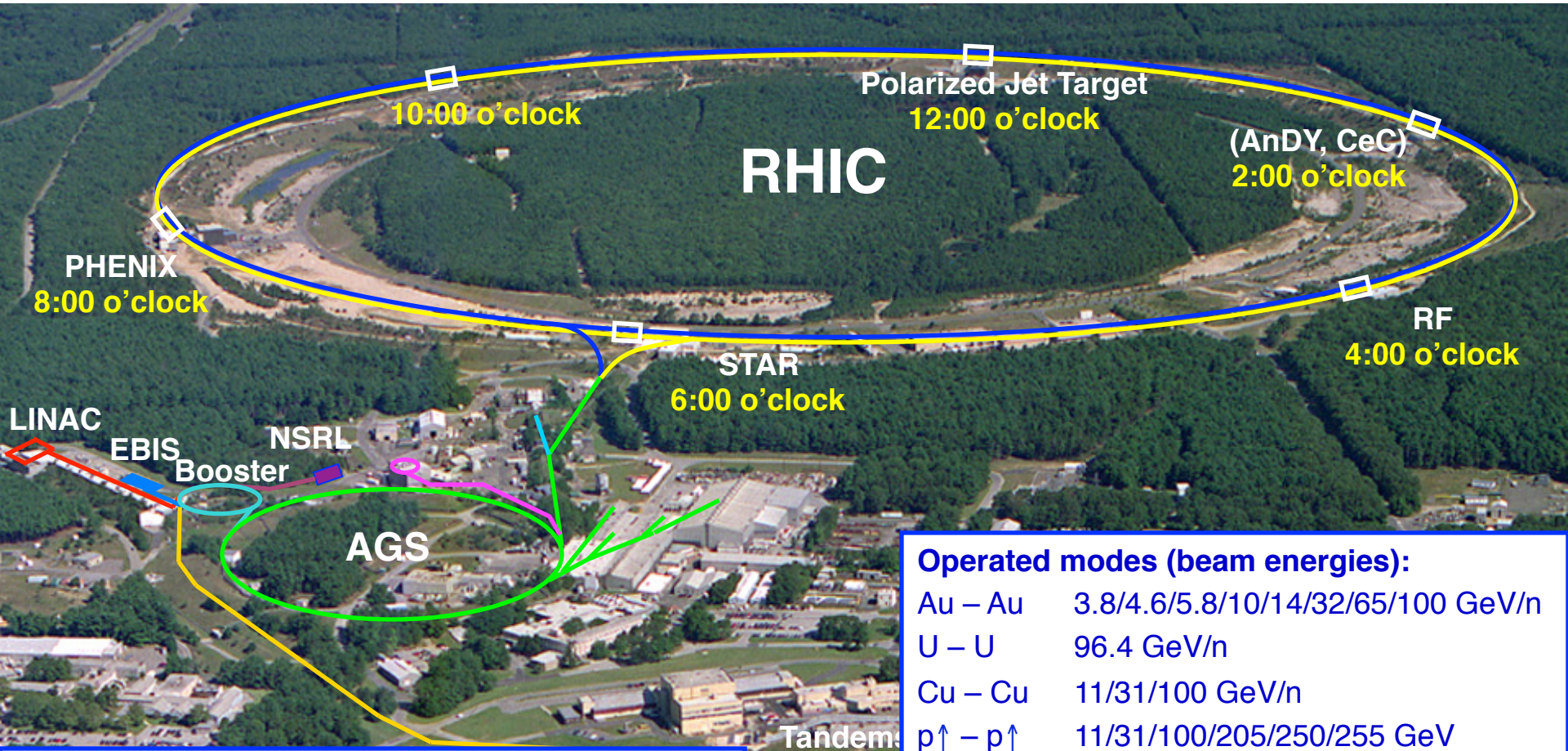
RHIC Polarized Collider and eRHIC

- Recent performance of RHIC
- Future plans for polarized beams at RHIC
- Accelerator R&D towards eRHIC
- The next machine: eRHIC, a polarized electron-polarized proton collider

BROOKHAVEN NATIONAL LABORATORY

Thomas Roser, BNL
SPIN2012
September 18, 2012

RHIC – a High Luminosity Polarized Hadron Collider



Achieved peak luminosities:

Au – Au (100 GeV/n)	195×10^{30} cm^{-2} s^{-1}
p↑ – p↑ (255 GeV)	165×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 255 GeV):

Tevatron (p – pbar)	110×10^{30} cm^{-2} s^{-1}
LHC (p – p)	430×10^{30} cm^{-2} s^{-1}

Operated modes (beam energies):

Au – Au	3.8/4.6/5.8/10/14/32/65/100 GeV/n
U – U	96.4 GeV/n
Cu – Cu	11/31/100 GeV/n
p↑ – p↑	11/31/100/205/250/255 GeV
d – Au*	100 GeV/n
Cu – Au*	100 GeV/n

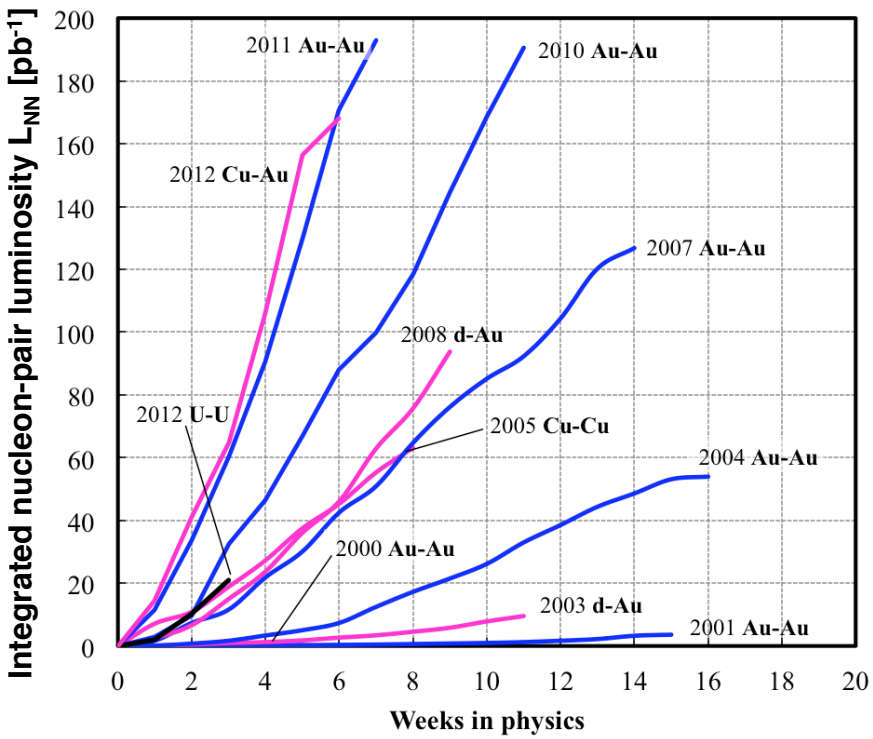
Planned or possible future modes:

Au – Au	2.5 GeV/n
p↑ – Au*	100 GeV/n
p↑ – ^{3}He↑*	166 GeV/n

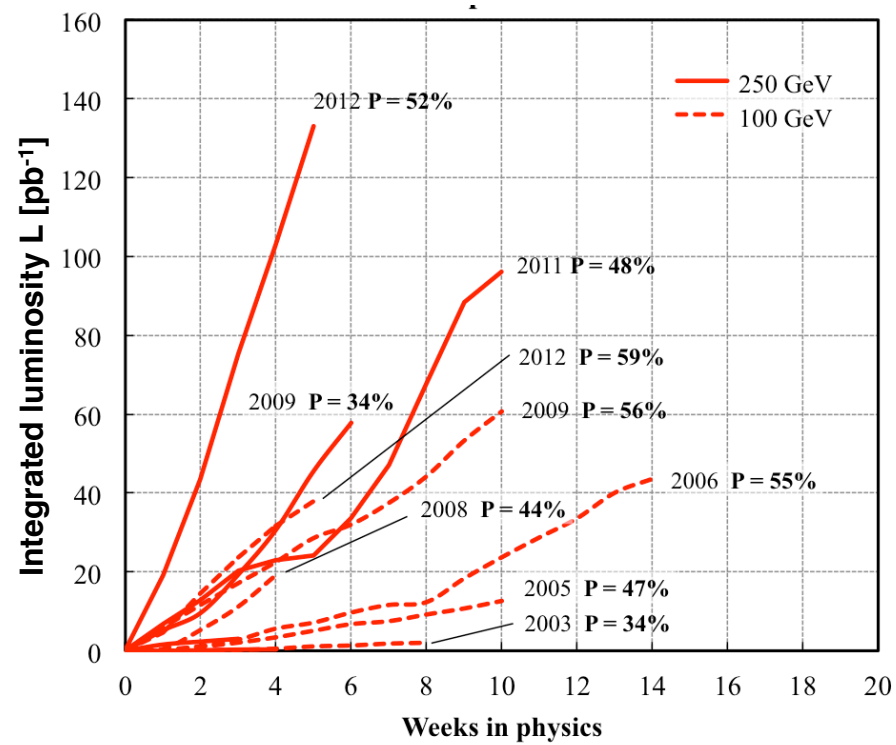
(*asymmetric rigidity)

RHIC Integrated Luminosity and Polarization (RHIC II performance!)

Heavy ion runs



Polarized proton runs



- Further upgrades:
  - 56 MHz SRF system to reduce vertex length
  - Electron lenses to ~ double pp luminosity
  - Polarization goal: 70 %

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

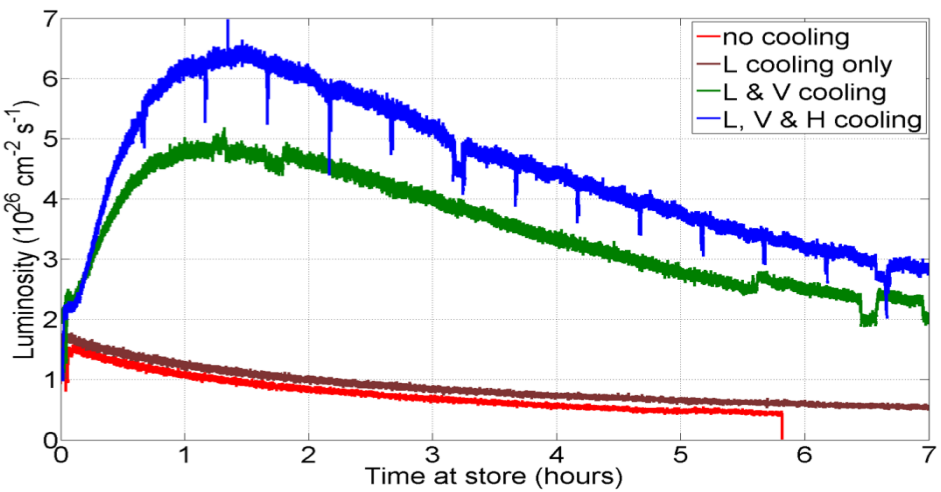
RHIC Facility Upgrade Plans

- EBIS (2012) (low maintenance linac-based pre-injector; all species including U and polarized ^{3}He)
- RHIC luminosity upgrade (RHIC II) (≥ 2012):
  [Au-Au: 40×10^{26} cm^{-2} s^{-1}; 500 GeV p-p: 1.5×10^{32} cm^{-2} s^{-1}]
  - 0.5 m β^* for Au – Au and p↑ - p↑ operation
  - Stochastic cooling of Au beams and 56 MHz storage SRF system in RHIC
- Further luminosity upgrade for p↑ - p↑ operation (≥ 2014):
  [500 GeV p-p: ~ 3×10^{32} cm^{-2} s^{-1}]
  - Electron lens in RHIC for head-on beam-beam compensation (× 2)
- Low energy ($\sqrt{s}$ = 5…30 GeV) Au-Au collisions for critical point search
  - ~ 1…5 MeV electron cooling of Au beams at injection (≥ 2017)
- eRHIC: high luminosity (~ 1×10^{34} cm^{-2} s^{-1}) eA and pol. ep collider using 5-10 GeV and later up to 30 GeV electron driver, based on an Energy Recovering Linac (ERL), and strong cooling of hadron beams (> 2020)
  Exploring gluons at extreme density!

RHIC Run 12 Performance

- Record luminosities and beam polarizations (61.8% (B); 56.6% (Y)) at 100 GeV
- Record luminosities and beam polarizations (50.3% (B); 53.5% (Y)) at 255 GeV
- First acceleration of ^{3}He (unpolarized) in AGS during short test run; Operation of ^{3}He-C CNI polarimeter demonstrated

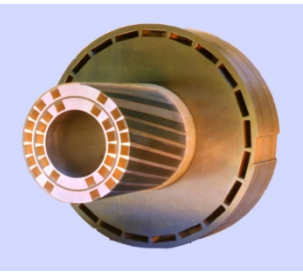
- First U-U collisions; x 5 luminosity from 3-D stochastic cooling
- First Cu-Au collisions; exceeding max. luminosity predictions with record EBIS/ injector performance and 3-D stochastic cooling
- 2.5 GeV Au-Au test with decent beam lifetime
- Very short set-up time due to flawless operation of beam-based feed-back system
- First hadron collider with increasing luminosity!

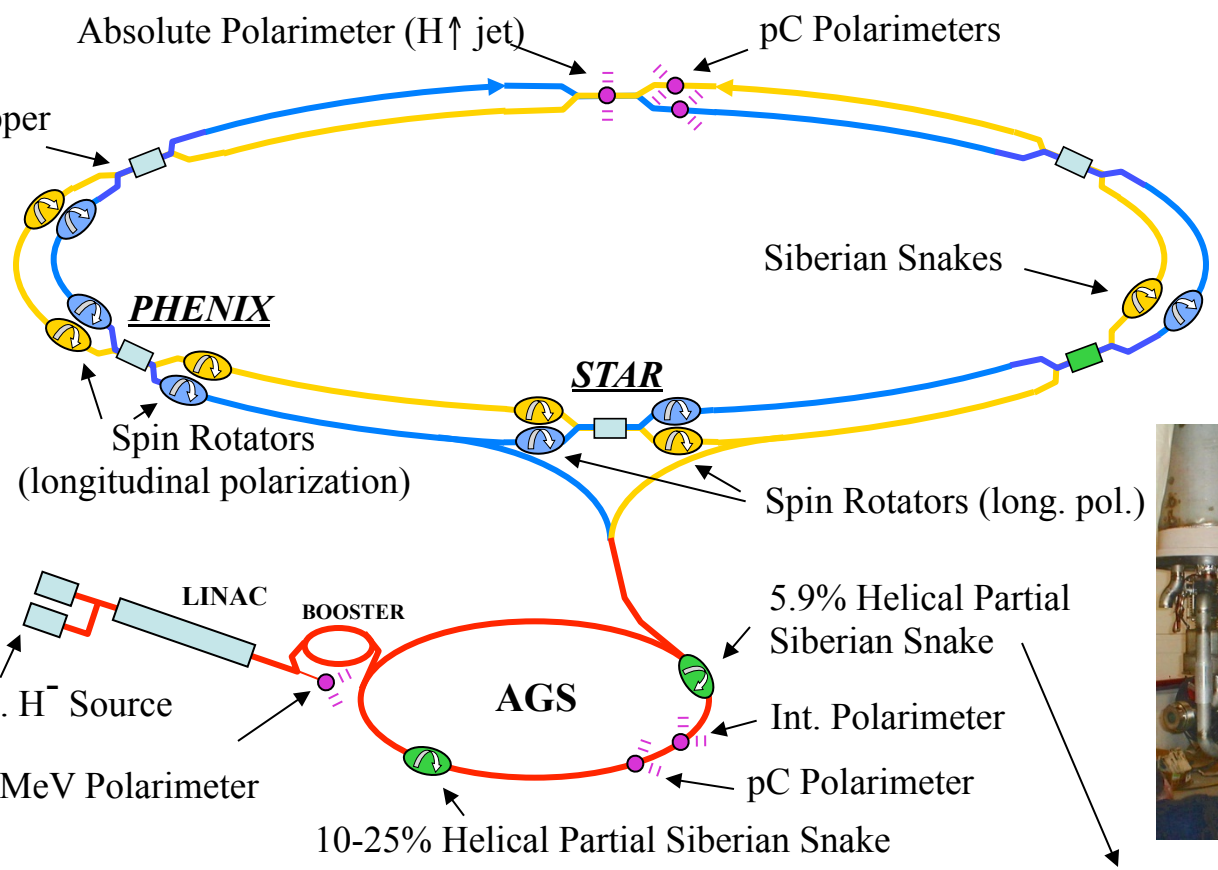


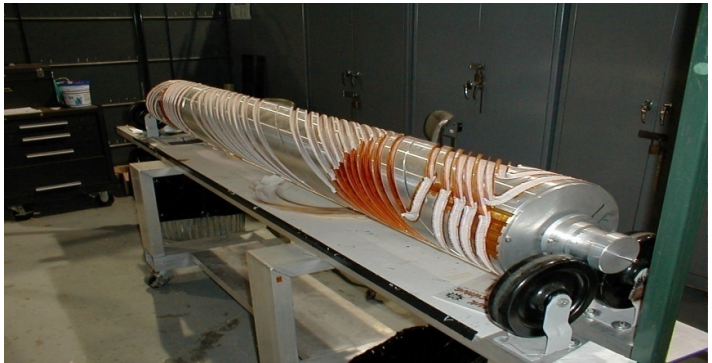
Luminosity in U-U store

Beams cooled to $\varepsilon_{rms,norm} = 0.4\ \mu m$

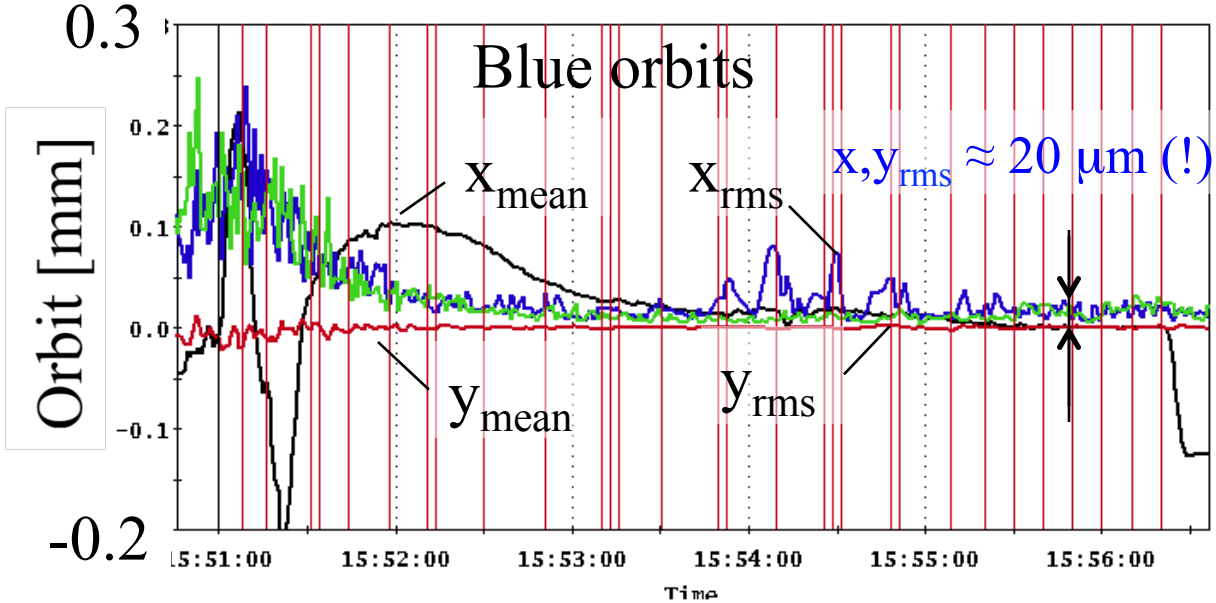
RHIC – First Polarized Hadron Collider

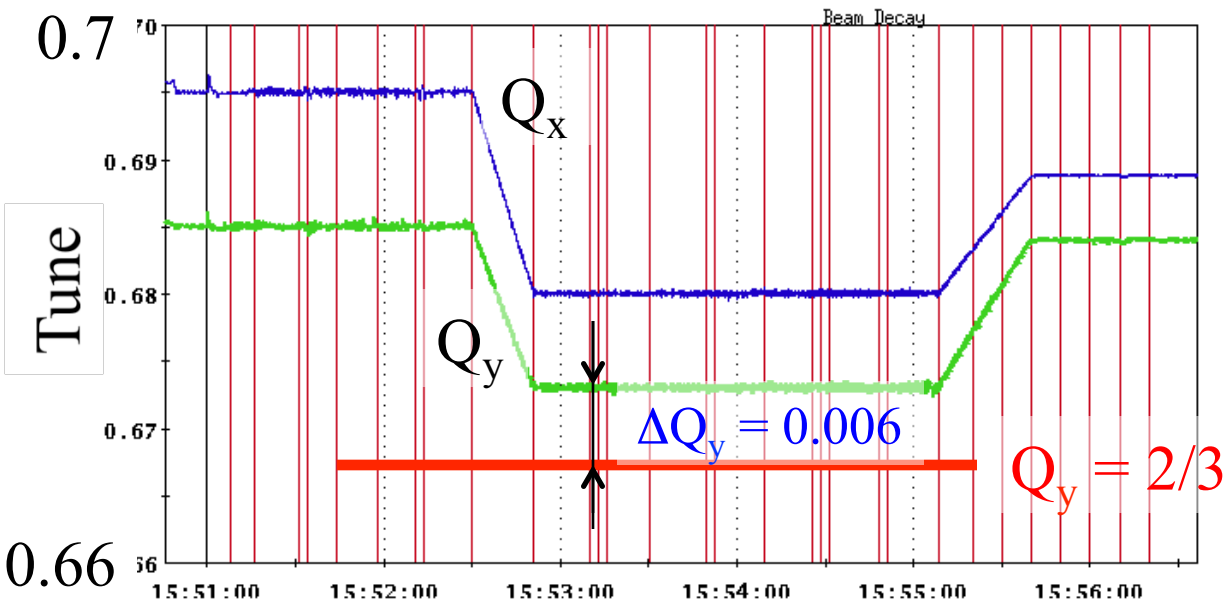






Beam control improvement – feedbacks on ramp





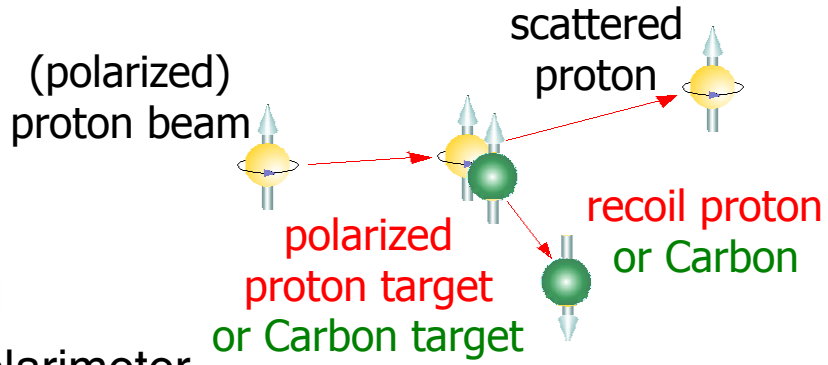
- Slow orbit feedback on every ramp allows for
  - Smaller y_{rms} (smaller imperfection resonance strength)
  - Ramp reproducibility (have 24 h orbit variation)
- Continues fast 10 Hz orbit feedback eliminates effect of vibrating triplets
- Tune/coupling feedback on every ramp allows for
  - Acceleration near $Q_y = ⅔$ with better polarization transmission

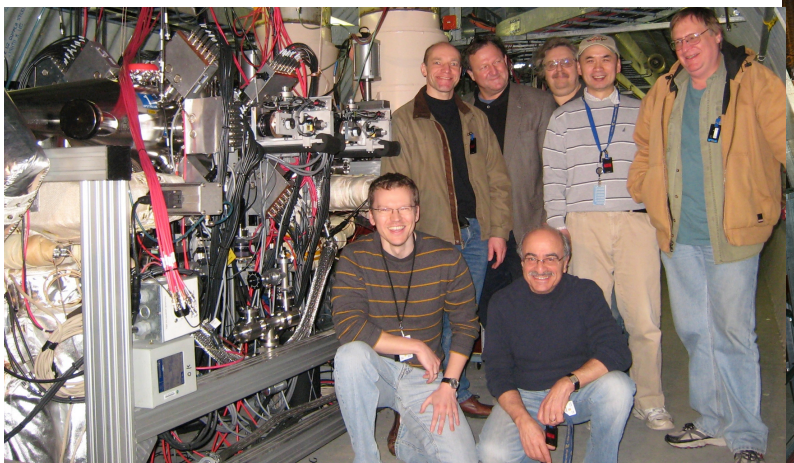
RHIC polarimetry

- Absolute polarimeter (Pol. Hjet)
  - Polarized hydrogen jet target allows for absolute beam polarization measurement:

$$P_{\text{Beam}} = P_{\text{Target}} \frac{\varepsilon_{\text{Beam}}}{\varepsilon_{\text{Target}}}$$

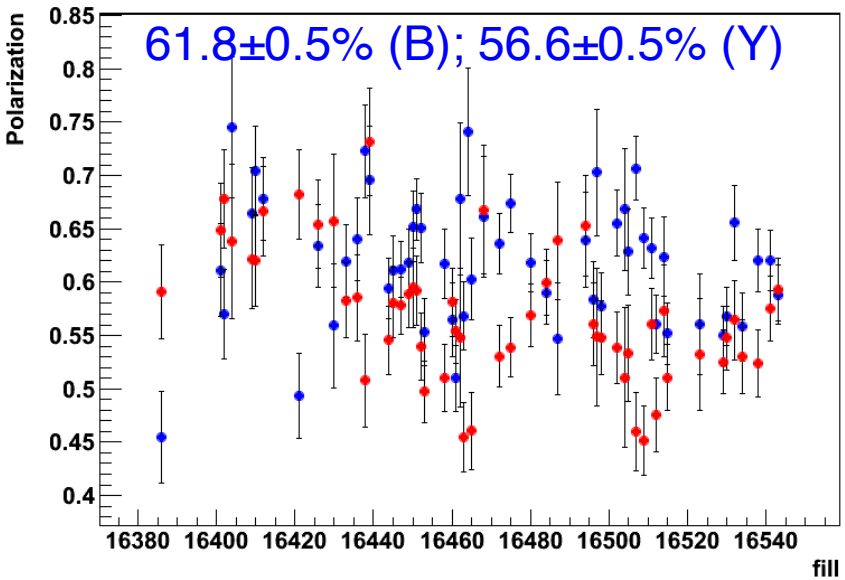
  - Jet target thickness of ~ 1×10^{12} cm^{-2} achieved
  - Jet pol. 92 ± 2 % measured with Breit-Rabi polarimeter
  - Analyzing power A_N ~ 0.044 (24 – 255 GeV)
- Relative polarimeters (proton-carbon)
  - Measure horizontal and vertical polarization profiles
  - Fast measurements (~ 2 minutes)
- Local polarimeters (forward neutron production)
  - Significant asymmetry, calibrated with Hjet
  - Used to adjust transverse polarization component to zero



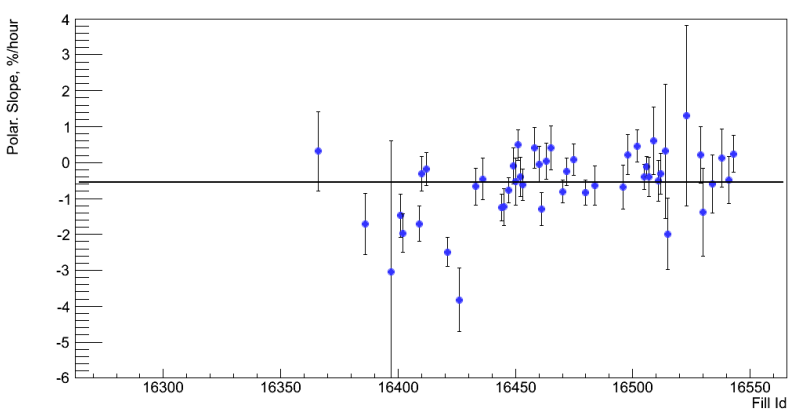


Results from Run 12

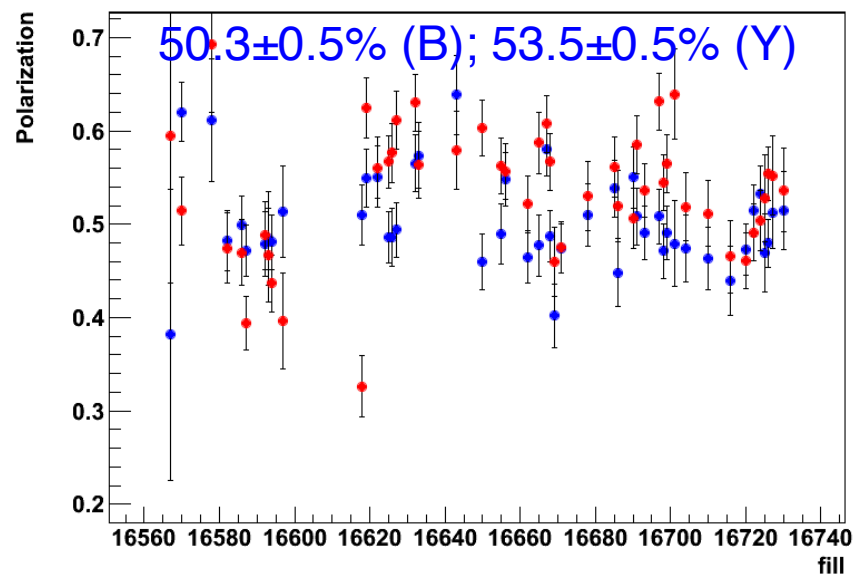
- 100 GeV
  - Average store pol. from Hjet



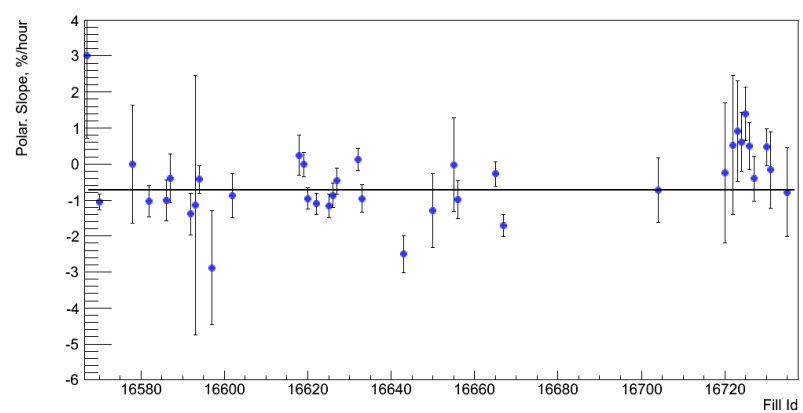
  - Pol. decay from pC polarimeters



- 255 GeV beam
  - Average store pol. from HJet



  - Pol. decay from pC polarimeters



Depolarization in AGS and RHIC

- Polarization loss from intrinsic resonances: polarization lost at edge of beam → polarization profile (A. Bazilevsky, Thu., 5:20 pm)
  - Impact of polarization profile on beam polarization at collisions $P_{coll.}$:

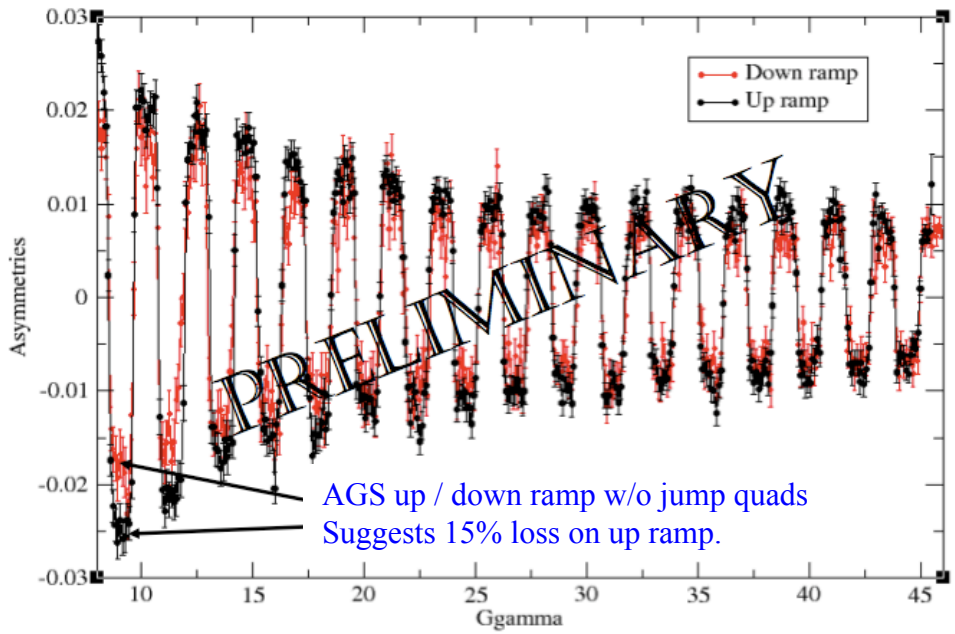
$$P(x,x',y,y') = P_0 e^{-\frac{x^2+x'^2}{2\sigma_{x,P}^2}} e^{-\frac{y^2+y'^2}{2\sigma_{y,P}^2}}; \quad I(x,x',y,y') = I_0 e^{-\frac{x^2+x'^2}{2\sigma_{x,I}^2}} e^{-\frac{y^2+y'^2}{2\sigma_{y,I}^2}}; \quad R_H = \frac{\sigma_{x,I}^2}{\sigma_{x,P}^2}; \quad R_V = \frac{\sigma_{y,I}^2}{\sigma_{y,P}^2}$$

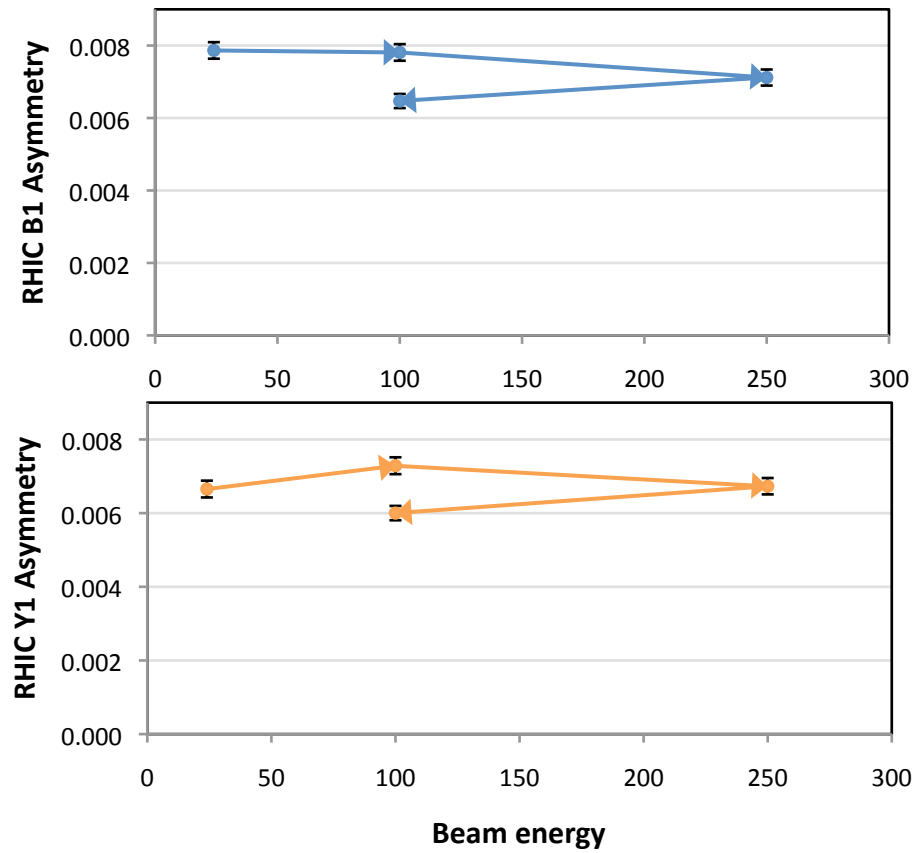
$$\langle P \rangle = P_0 \frac{1}{(1+R_H)(1+R_V)}; \quad P_{coll.} = P_0 \frac{1}{\sqrt{1+\frac{1}{2}R_H}\sqrt{1+R_H}\sqrt{1+\frac{1}{2}R_V}\sqrt{1+R_V}} = \langle P \rangle \frac{\sqrt{1+R_H}\sqrt{1+R_V}}{\sqrt{1+\frac{1}{2}R_H}\sqrt{1+\frac{1}{2}R_V}}$$

  - For $R_H \approx R_V$ and small: $P_0 = \langle P \rangle (1+\langle R \rangle)^2$; $P_{coll.} = \langle P \rangle (1+\frac{1}{2}\langle R \rangle)$
- Note that P_0, the polarization of the core particle, should be equal to the maximum achievable polarization.
- Loss of average polarization is compatible with development of polarization profiles → all remaining polarization loss in AGS and RHIC is due to vertical and horizontal intrinsic resonances. (no coherent polarization loss)

Depolarization measurements using up/down ramps

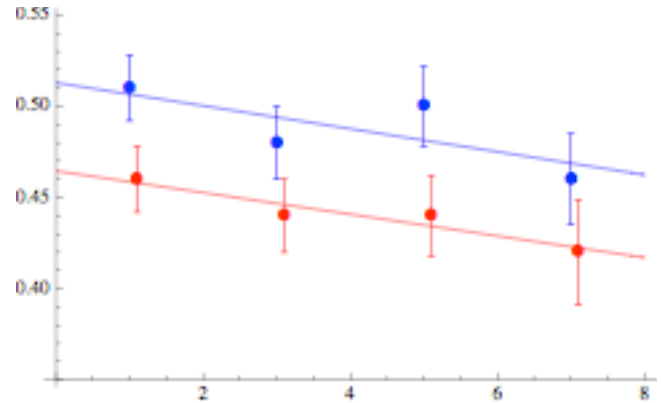
- Asymmetry measurements before acceleration and after identical deceleration determines all sources of depolarization
- AGS up/down measurement gives ~ 10–15 % residual depolarization
- No depolarization up to 100 GeV in RHIC
- RHIC up/down measurements between 100 and 250 GeV give ~ 10–15% depolarization
- Consistent with pol. profiles

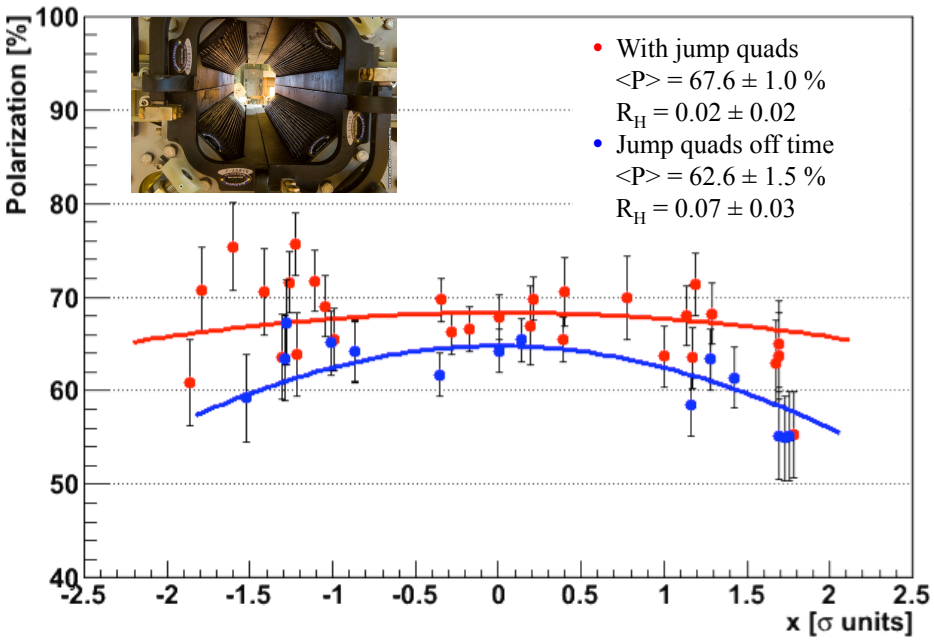


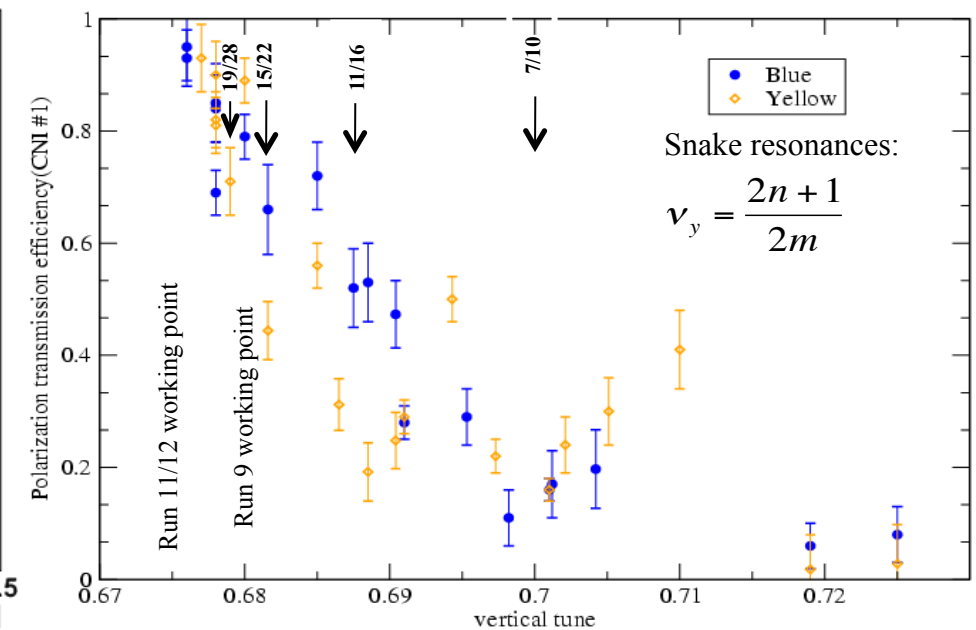


Polarization improvements

- New high intensity OPPIS (A. Zelenski, Tue., 3 pm) (+5%)
- 80 horizontal tune jump in AGS operational with high intensity beam
- AGS loss before extraction -> fast, on-the-fly extraction (+ 5%)
- Acceleration near Q_V = ⅔ in RHIC operational
- Reduce spin tune spread by matching dispersion at the snake locations (+?%)
- 0.5 – 1.0 % polarization loss during 100 and 255 GeV stores: not understood, shorter stores?

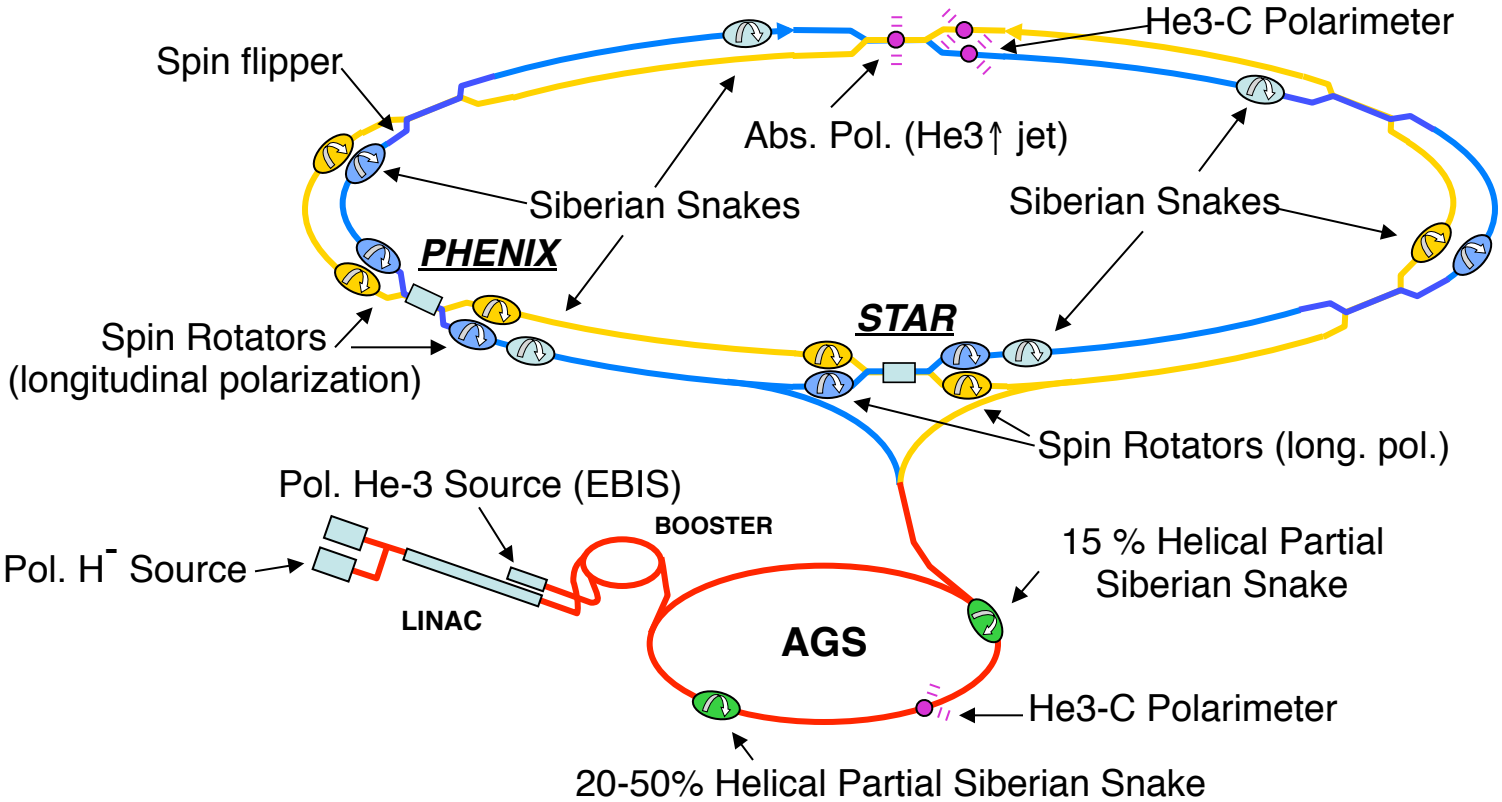






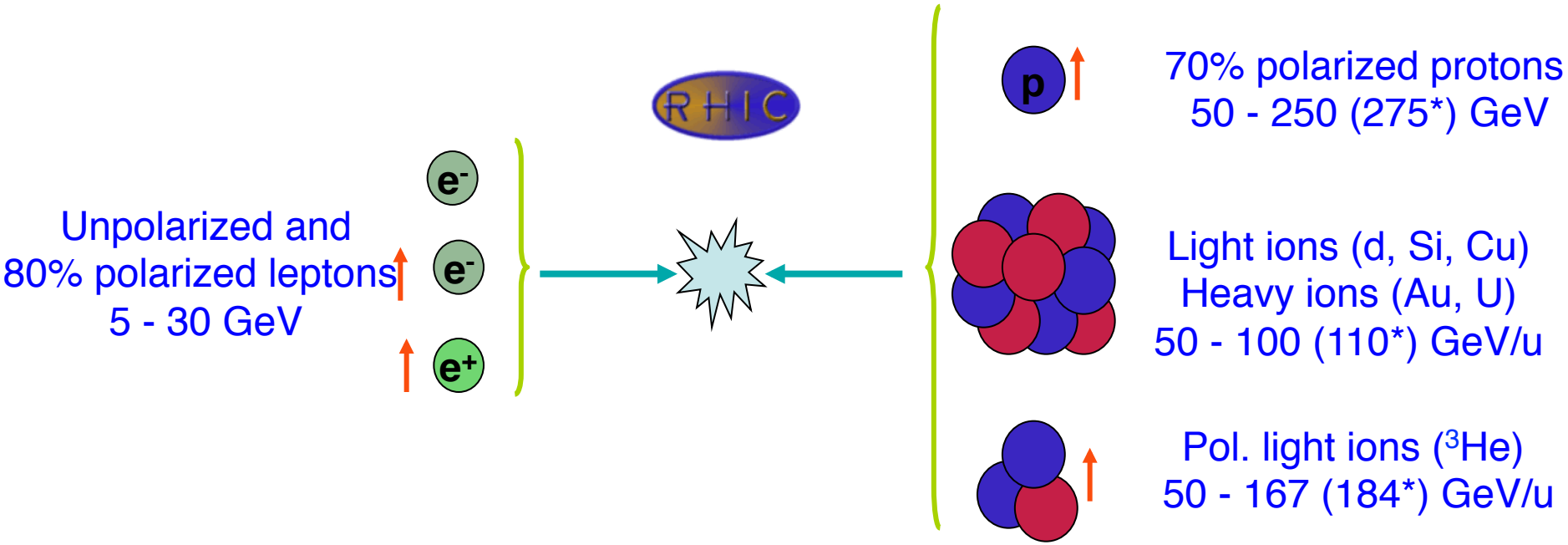
Polarized ^{3}He in RHIC

- Polarized ^{3}He possible from new EBIS (J. Maxwell, Tue., 3:30 pm)
- Max. energy in RHIC: 170 GeV/n
- Depolarizing res. are stronger, however no depolarization expected with six snakes in RHIC
- Accelerated unpolarized ^{3}He from EBIS in AGS
- Relative pol.: ^{3}He-C CNI polarimeter; successfully tested with unpolarized ^{3}He
- Absolute pol.: ^{3}He-^{3}He CNI polarimeter using polarized ^{3}He jet?



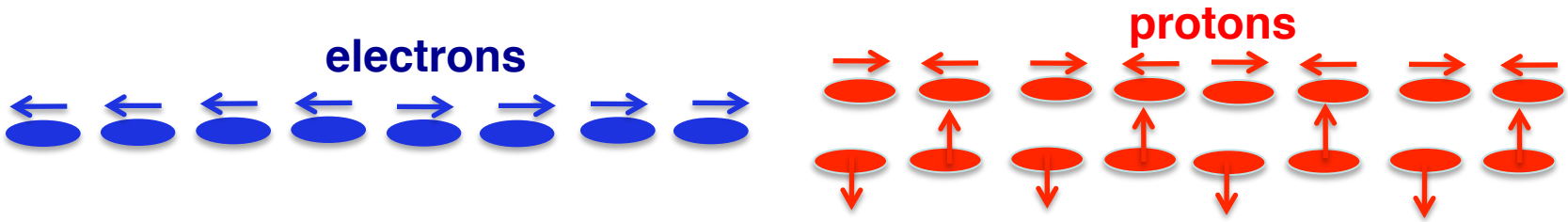
eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing RHIC



Center-of-mass energy range: 30 - 175 GeV

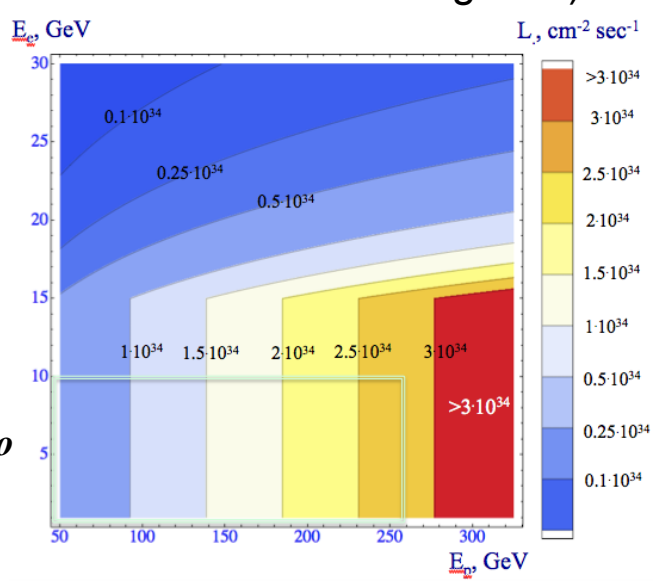
Any polarization direction in lepton-hadrons collisions



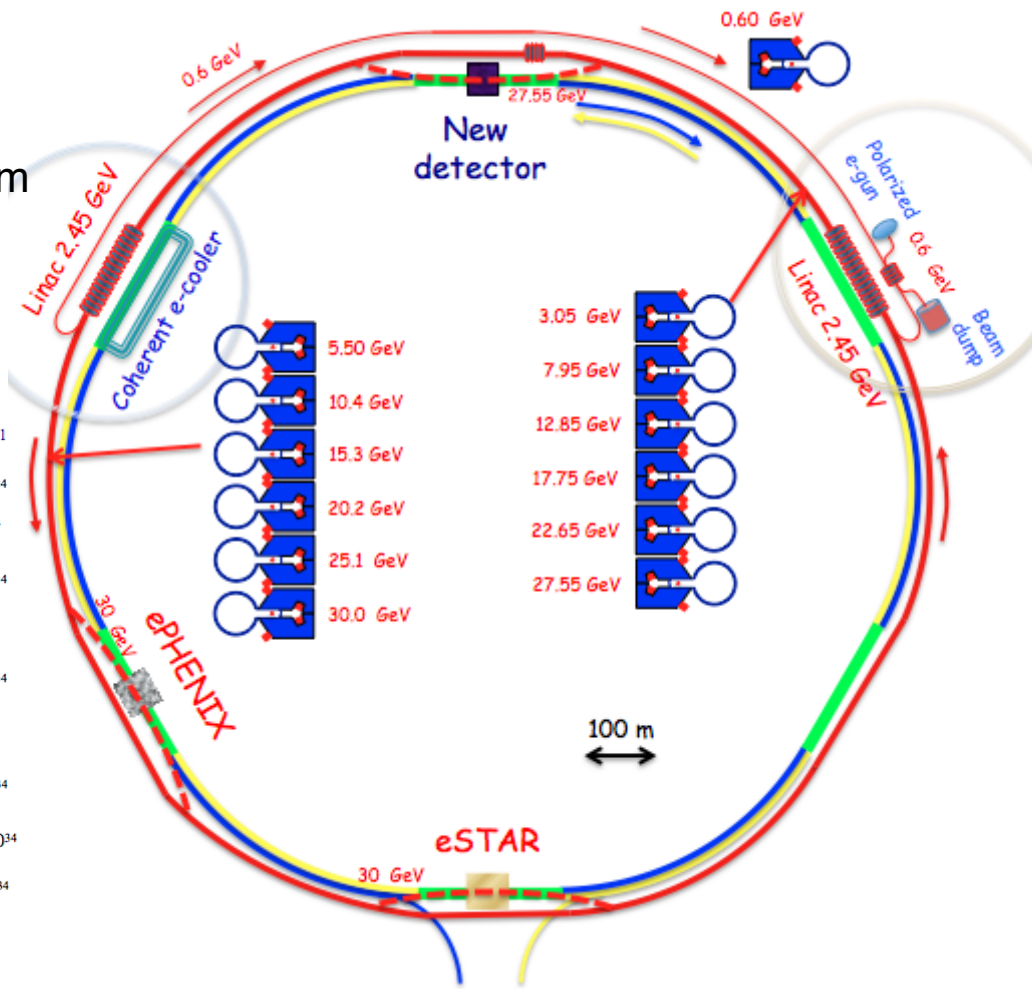
*** We are exploring a possibility of increasing RHIC ring energy by 10% - 30%**

eRHIC design status

- 10 – 30 GeV electron beam accelerated with Energy Recovery Linac (ERL) inside existing RHIC tunnel collides with existing 250 GeV polarized 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 ^{3}He in RHIC
- 1st stage: 5-10 GeV electron beam
  - Similar to CEBAF 12 GeV upgrade (1 GeV SRF linac + recirculating arcs)



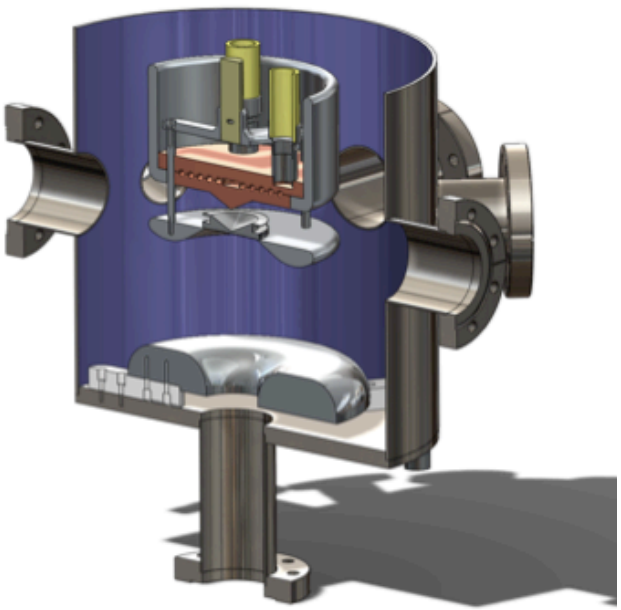
Box area corresponds to the first stage



High CW current (50 mA) polarized electron gun

- Matt Poelker (JLab) achieved 4 mA with good lifetime (Tue., 5:20 pm)
- More current with (effectively) larger cathode area

Single large area cathode
(Development at MIT)



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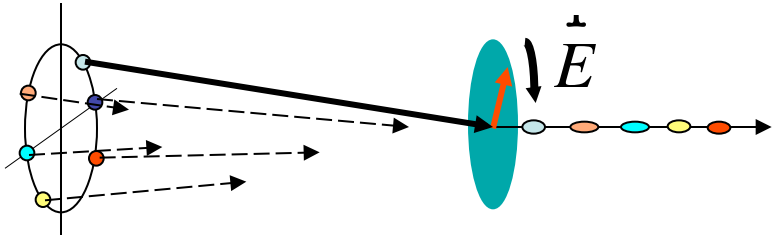
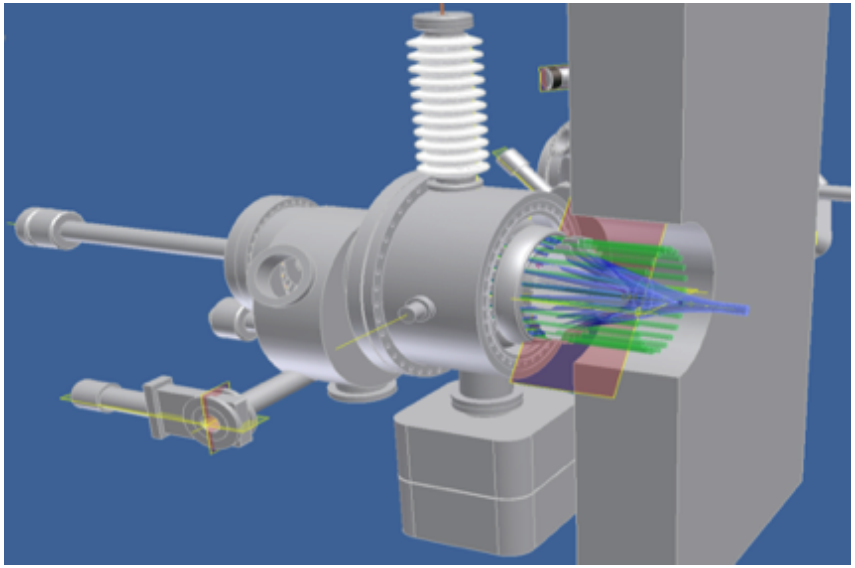
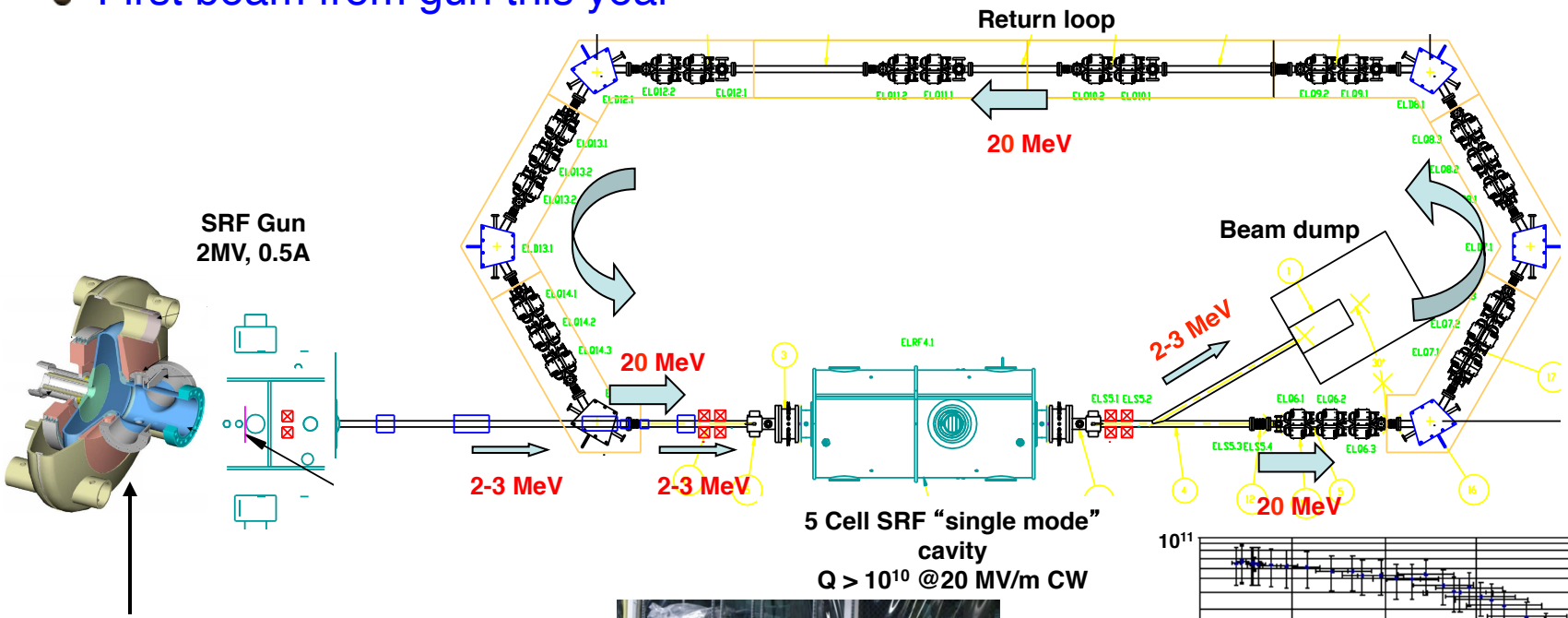
Gatling electron gun: many smaller cathodes
(Development at BNL)

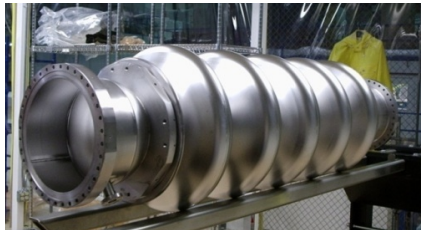


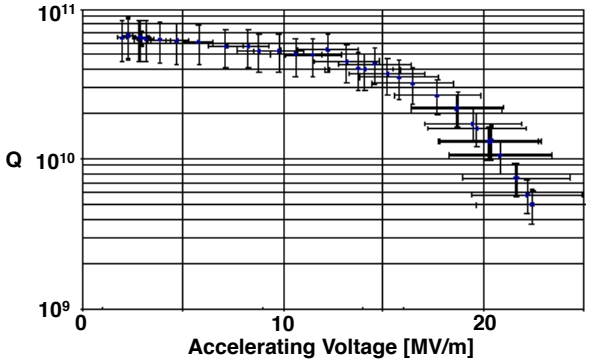


Energy Recovery Linac (ERL) Test Facility

- 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
- Similar beam current in cavity as for multi-pass eRHIC ERL
- First beam from gun this year

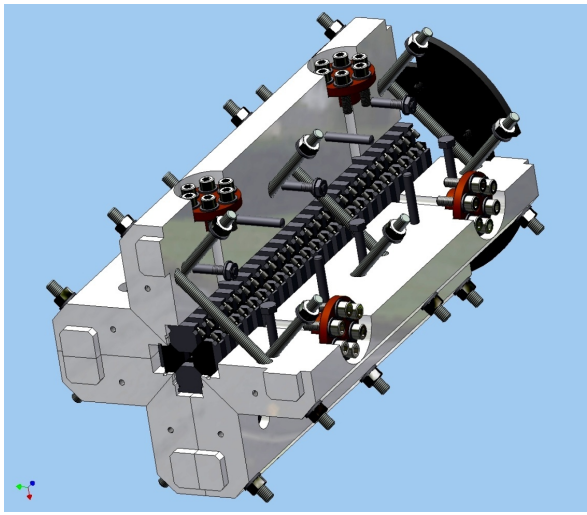






Coherent electron Cooling (CeC)

- 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 (commissioning during run 15)

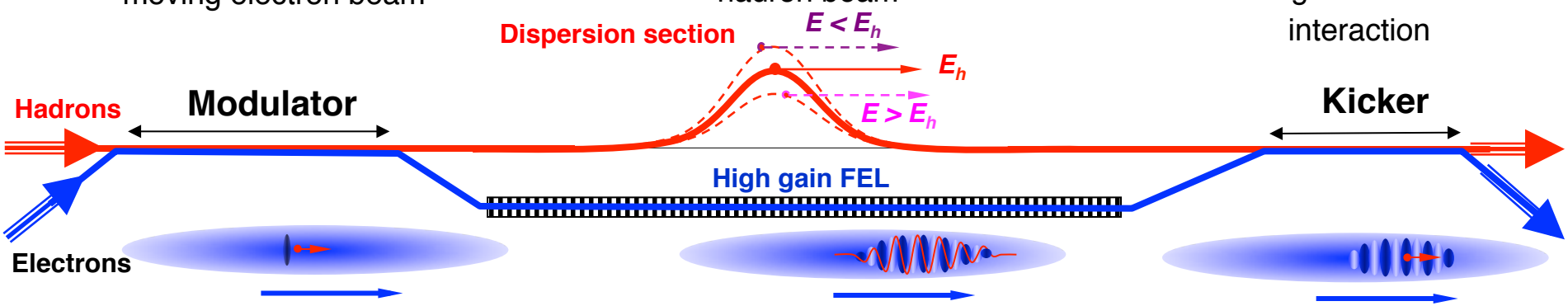


Helical wiggler prototype

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

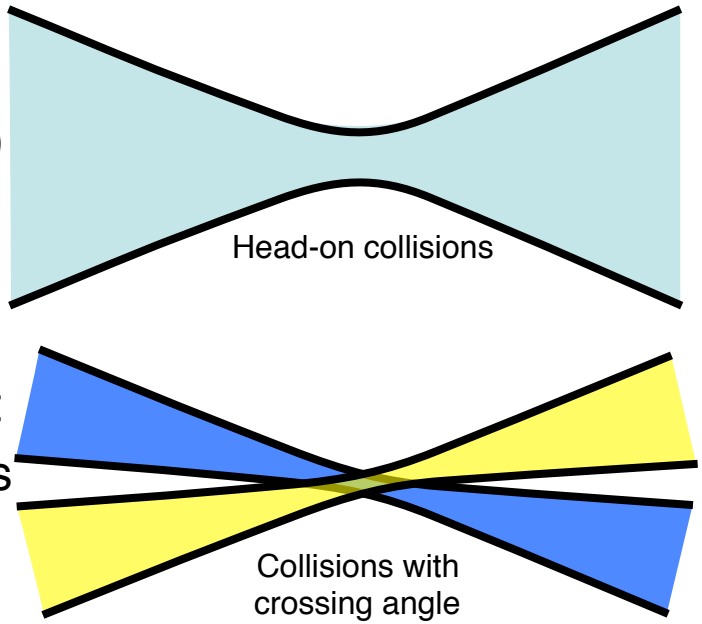
Amplifier: Free Electron Laser (FEL) with gain of 100 -1000 amplifies density variations of electron beam, energy dependent delay of hadron beam

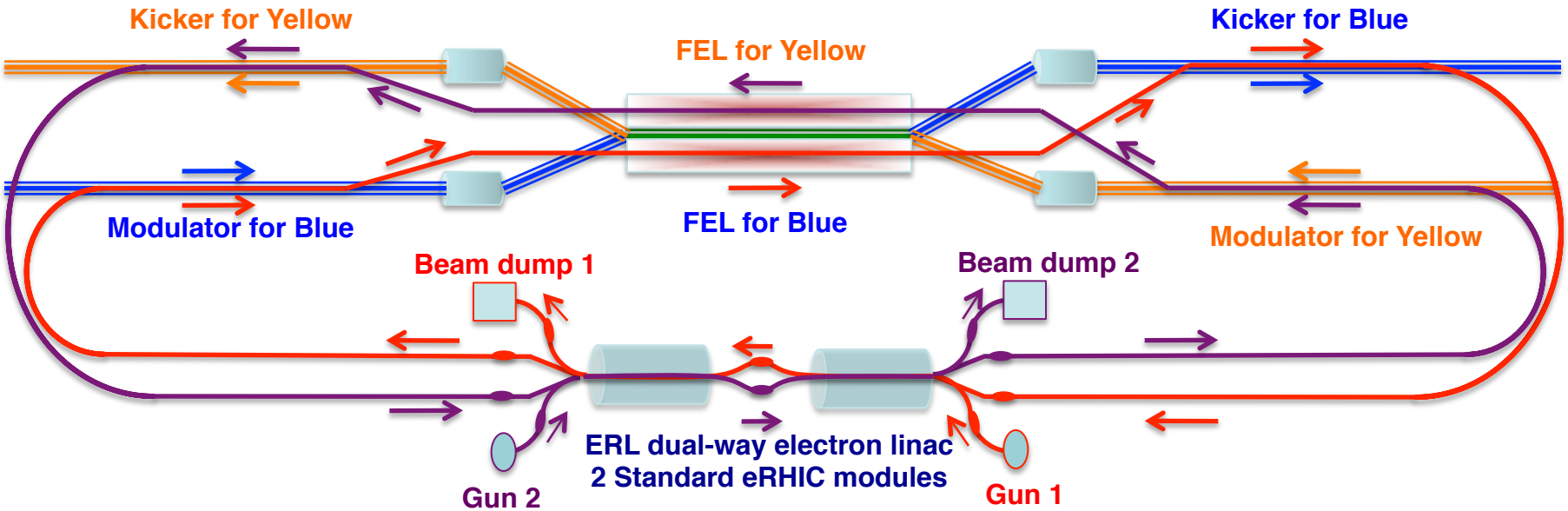
Kicker: electron beam corrects energy error of co-moving hadron beam through electrostatic interaction



CeC for RHIC: High Luminosity with large Piwinski angle

- If head-on collisions are at beam-beam limit large Piwinski angle collisions with very small emittance can increase luminosity (Super B factory)
- Needs strong cooling: synchrotron rad. or **CeC**
- Separate bunches outside high luminosity region to avoid beam-beam from low luminosity region.
- Reducing beam emittance back to beam-beam limit
- Smaller emittance and shorter overlap region allows for smaller beta-star
- RHIC: overlap length ~ 10 cm, ε_n (95%) ~ 1 π μm , β^* ~ 10 cm → ~ x10 luminosity increase (~ 5 x10^{33} cm^{-2} s^{-1} !)





Summary

- Exceptionally successful RHIC Run-12 with record luminosities and polarization
- Additional upgrades for increased luminosity and polarization (new OPPIS, e-lenses) on track
- Accelerator R&D towards high energy beam cooling and high luminosity electron-ion collider: eRHIC