RHIC and its Upgrade Programs

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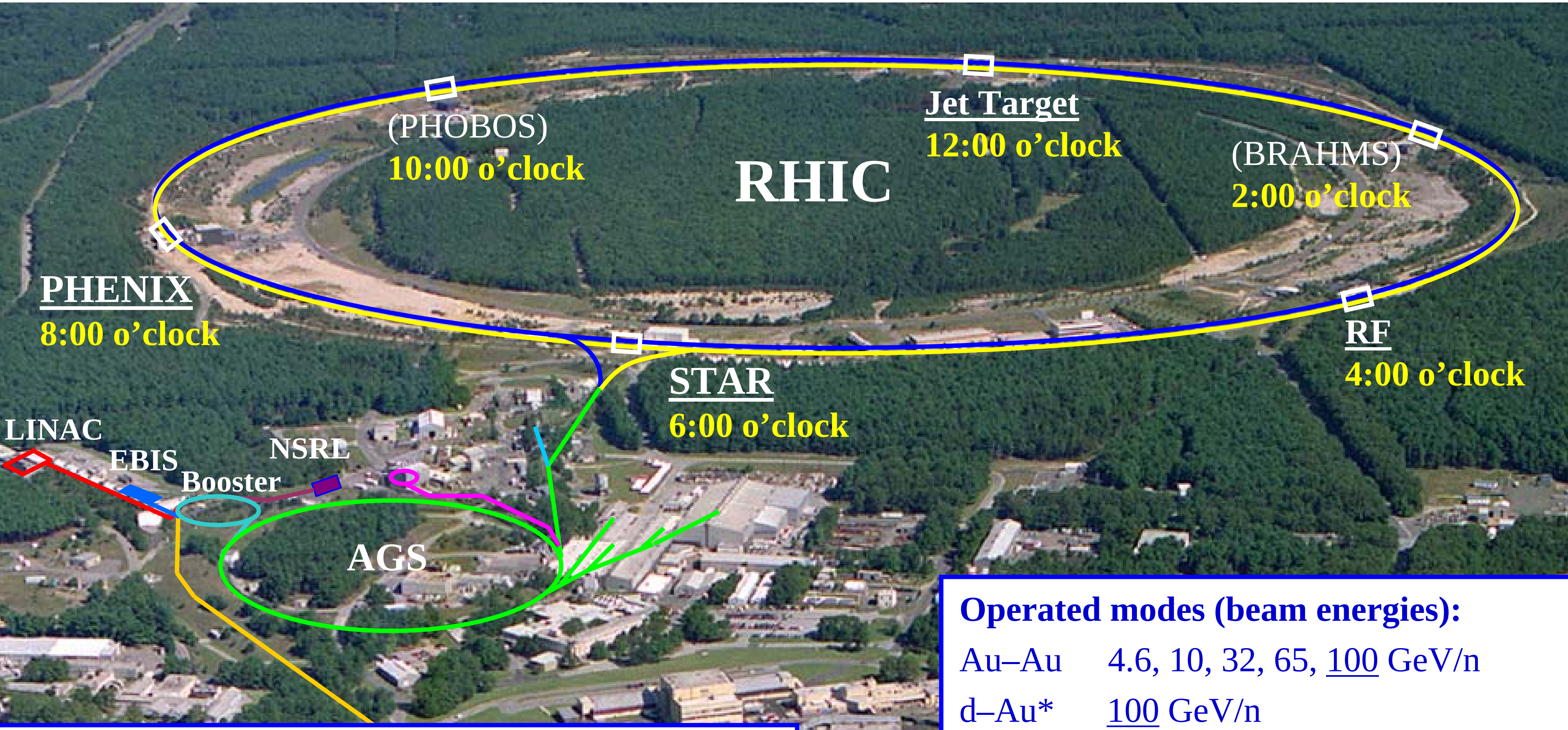
RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities (100 GeV, nucl.-pair):

Au–Au	120×10^{30} cm^{-2} s^{-1}
p↑–p↑	35×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 100 GeV):

Tevatron (p – pbar)	32×10^{30} cm^{-2} s^{-1}
LHC (p – p, design)	140×10^{30} cm^{-2} s^{-1}

Operated modes (beam energies):

Au–Au	4.6, 10, 32, 65, <u>100</u> GeV/n
d–Au*	<u>100</u> GeV/n
Cu–Cu	11, 31, <u>100</u> GeV/n
p↑–p↑	11, 31, <u>100</u> GeV

Planned or possible future modes:

p↑–p↑	250 GeV
Au – Au	2.5 GeV/n (~ SPS cm energy)
p↑ – Au*	100 GeV/n

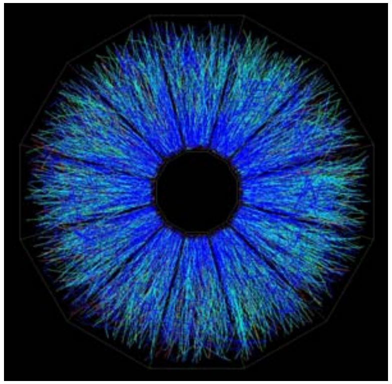
(*asymmetric rigidity)

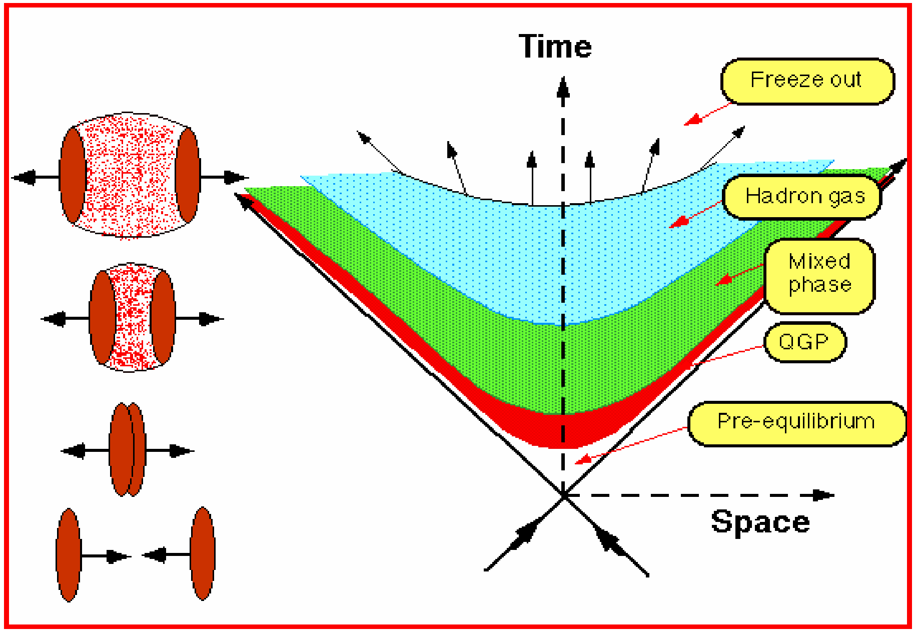
A Mini-Bang:

Nuclear matter at extreme temperatures and density

Colliding gold at 100 + 100 GeV/nucleon (40 TeV total cm energy)

Plus: other species (p-p, Cu-Cu, …)
asymmetric collisions (d-Au, [p-Au])
several energies (100+100, 65+65, 32+32, 10+10, 4.6+4.6)





a. **Formation phase -**
parton scattering

b. **Hot and dense phase -**
→ strongly interacting hot dense material (“perfect liquid”)

c. **Freeze-out –**
emission of hadrons

Produce and explore a new state of matter

Animation by Jeffery Mitchell (Brookhaven National Laboratory). Simulation by the UrQMD Collaboration

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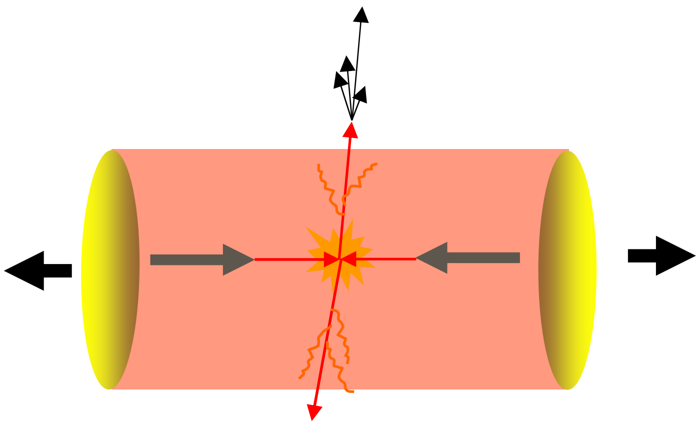
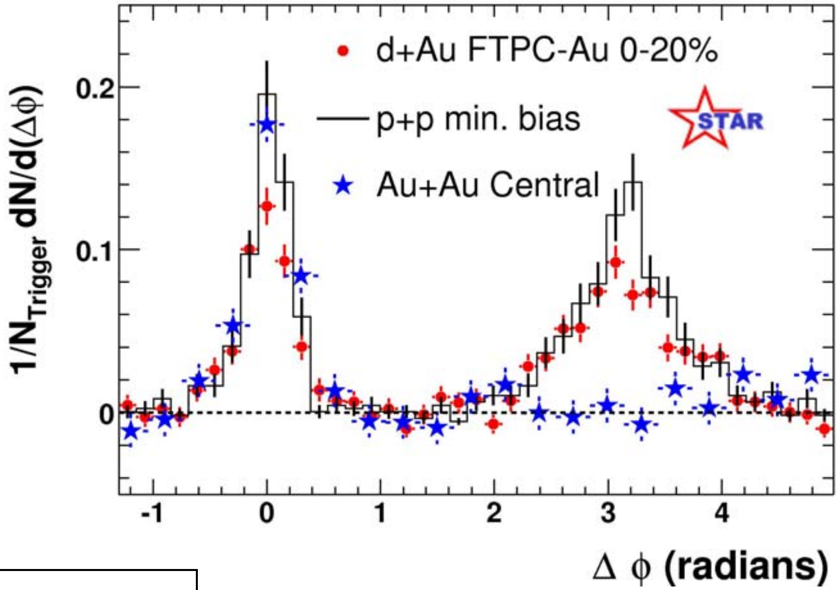
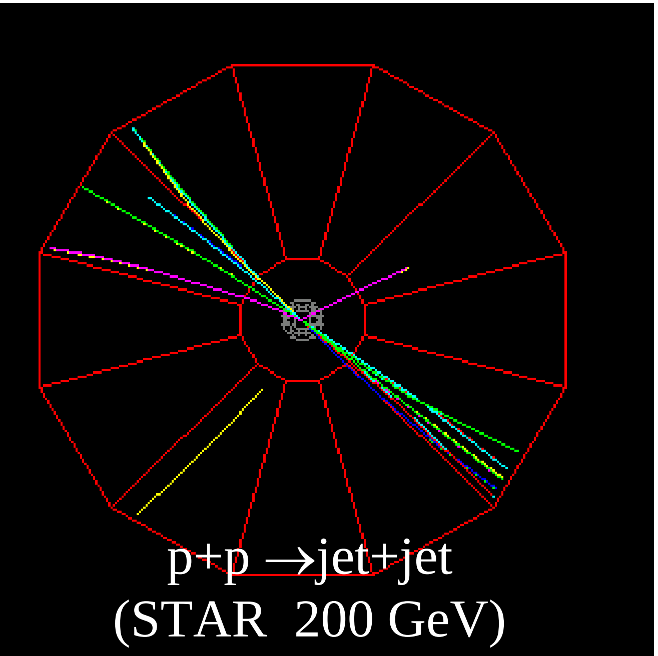
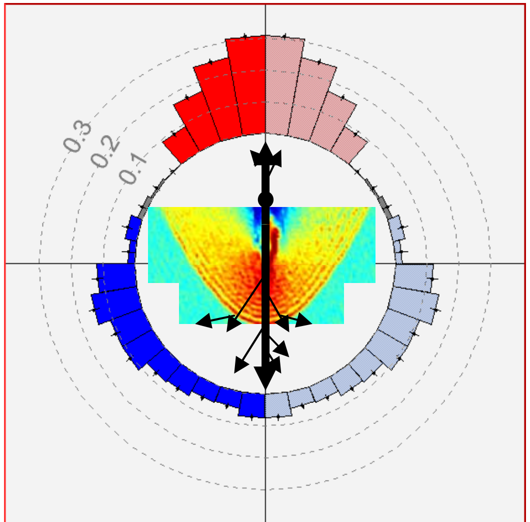
Hard Scattering at RHIC

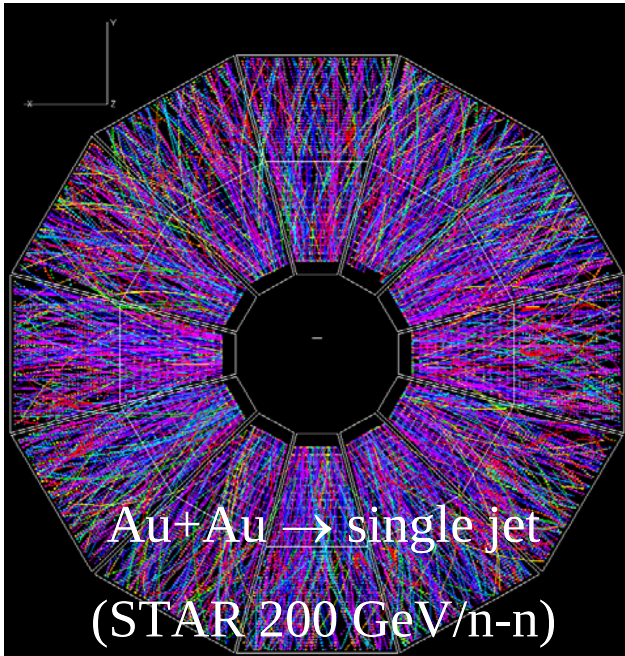




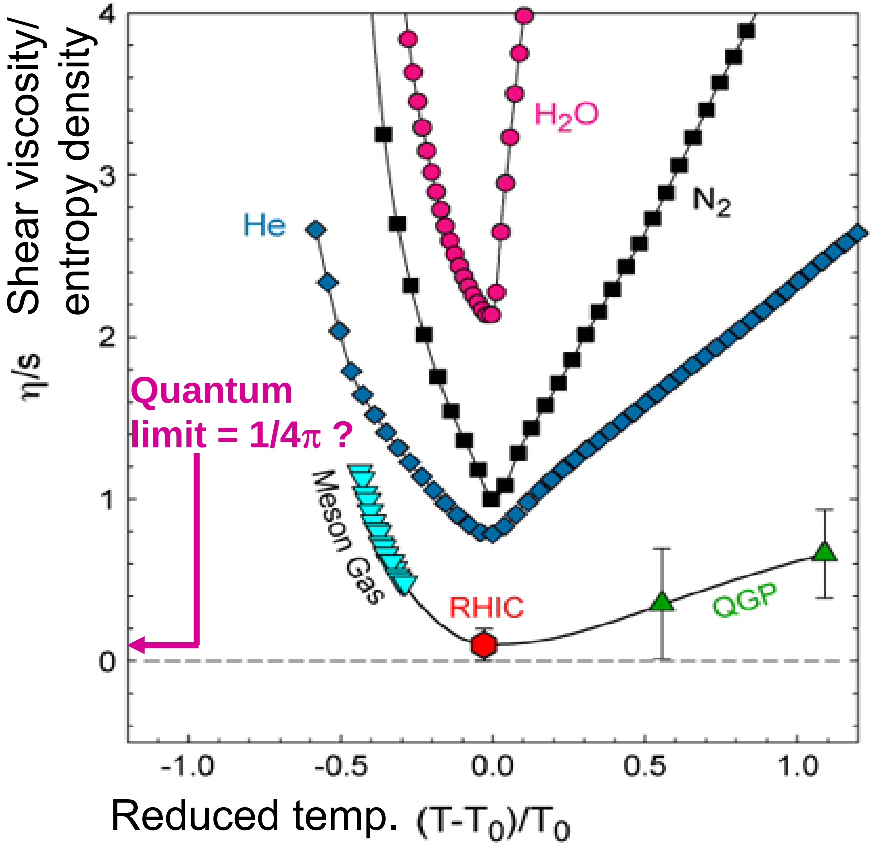


softer fragments emitted along Mach-like cone





A "Perfect Liquid"



- The matter produced in near-central ion-ion collisions at RHIC flows as a more nearly perfect (very low shear viscosity) liquid than any previously known.
- RHIC probes matter in the very strong coupling limit of QCD.
- Qualitative insight provided through mathematical duality with string theory that includes gravity.

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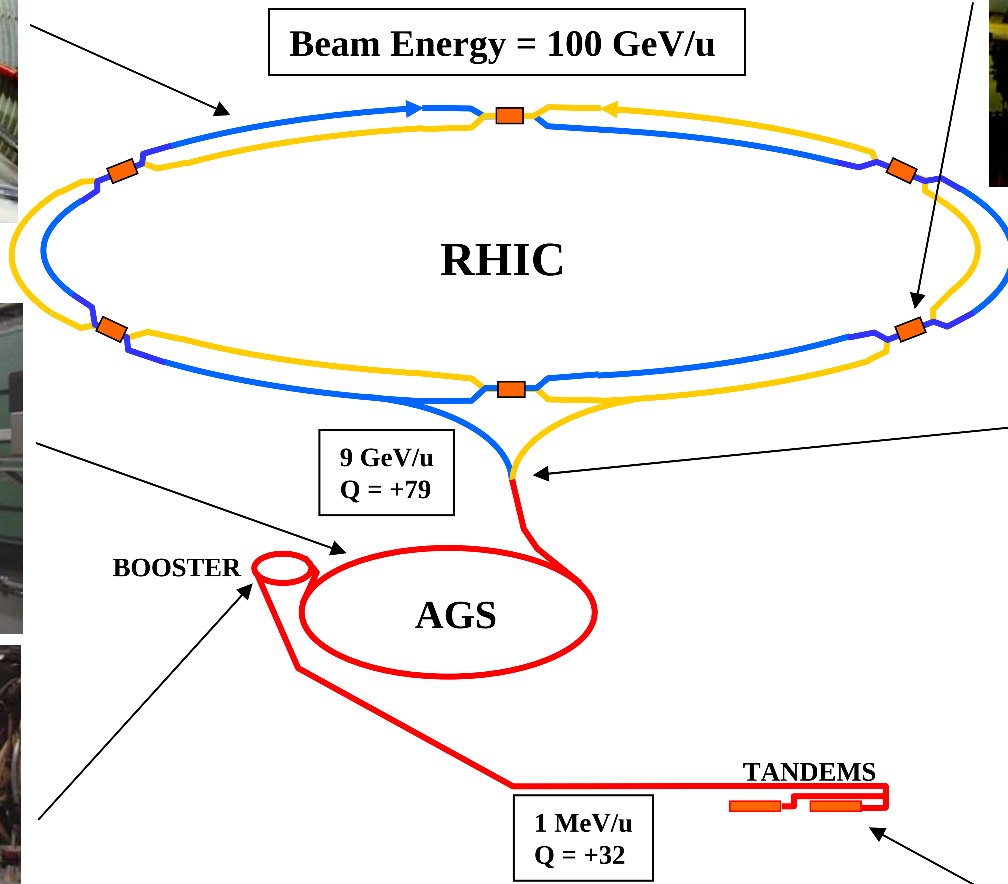
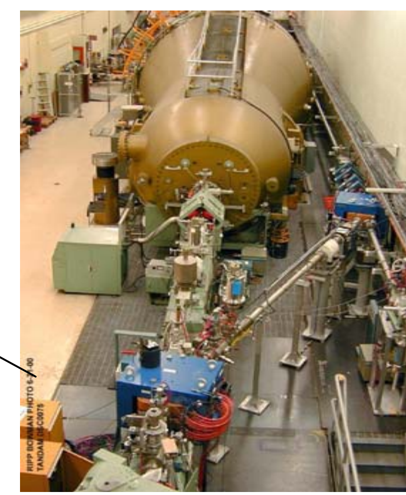
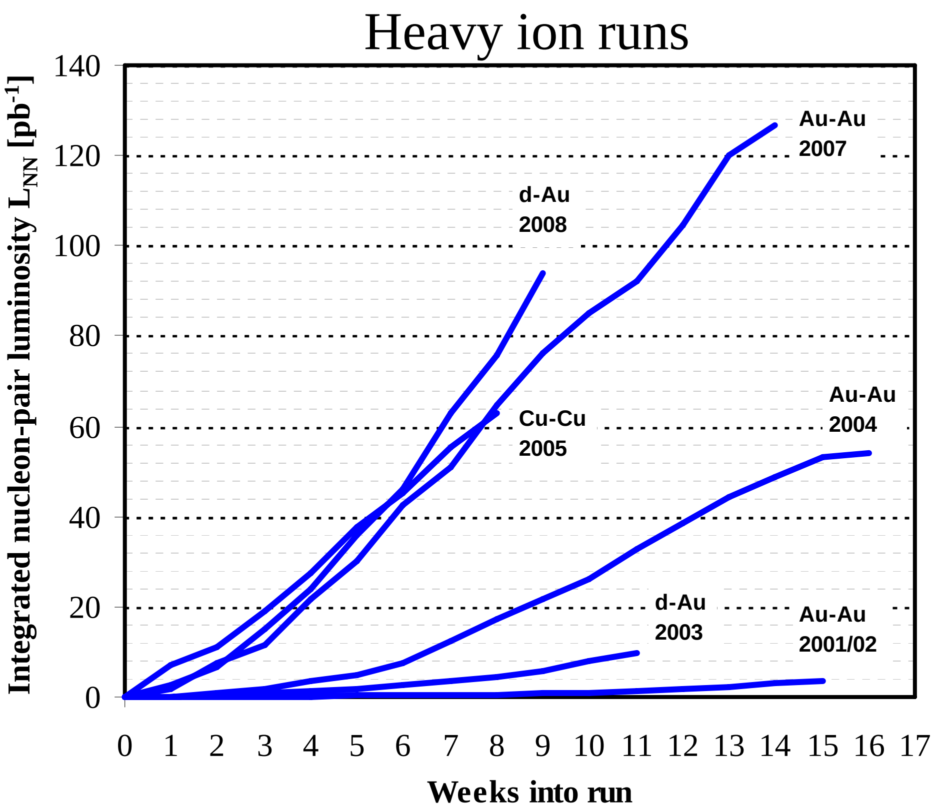
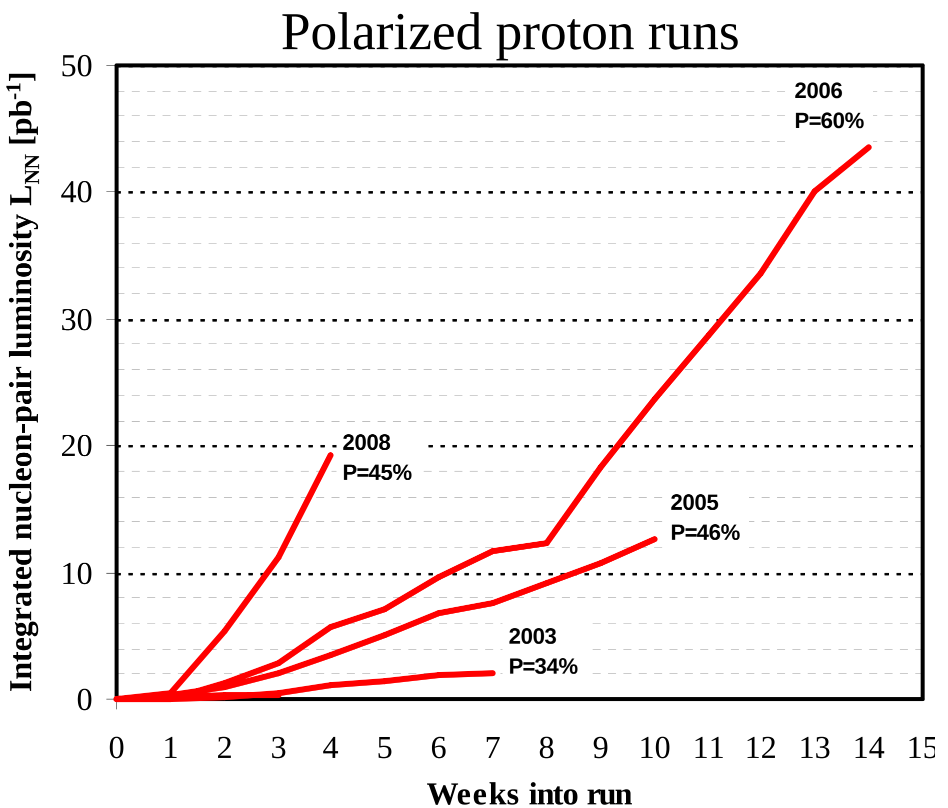
Gold Ion Collisions at RHIC





Delivered Integrated Luminosity and Polarization





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

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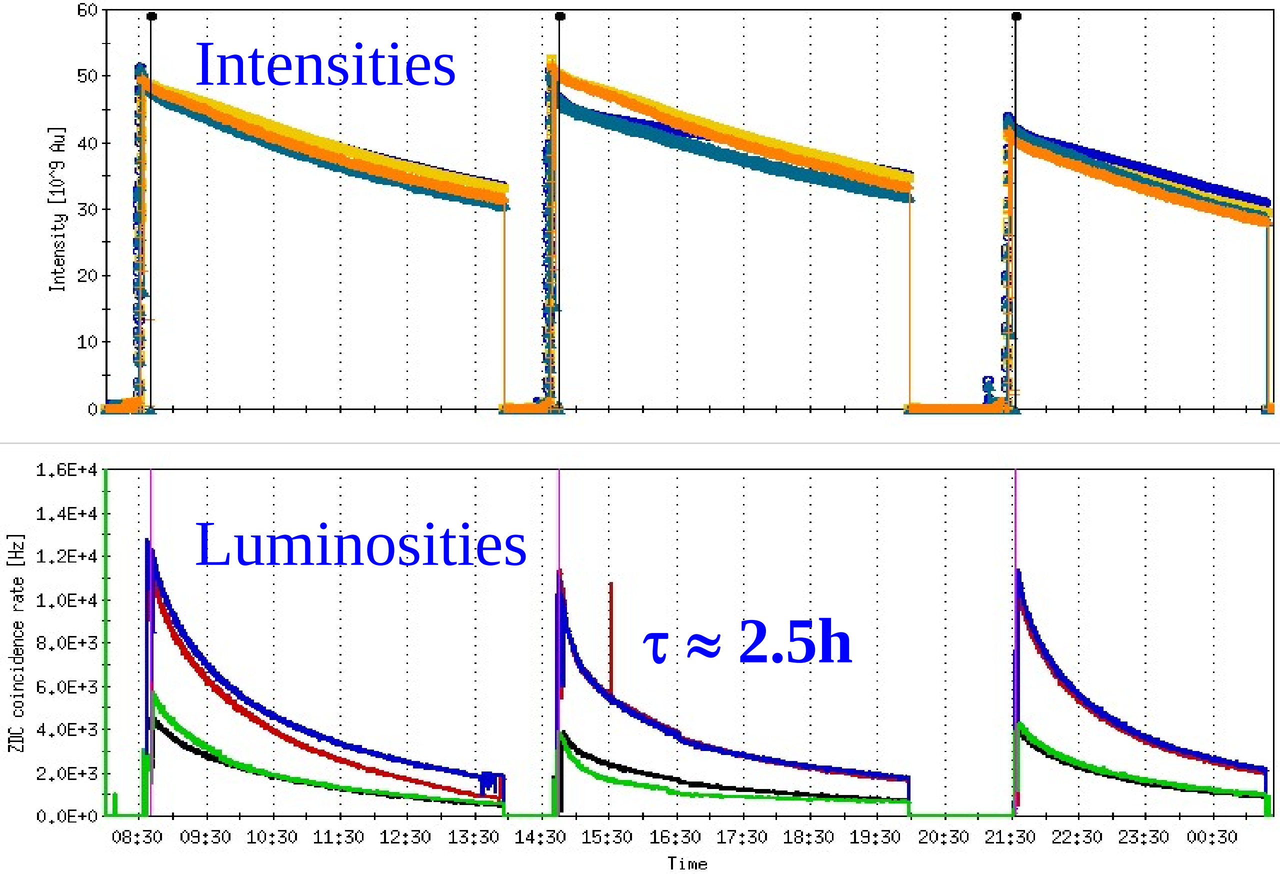
Luminosity Limit – Intra-Beam Scattering (IBS)



- IBS causes debunching, which requires continuous abort gap cleaning
- Short luminosity lifetime requires frequent refills
- Increased focusing decreases IBS (“IBS suppression” lattice)
- IBS requires cooling at full energy: stochastic and electron cooling

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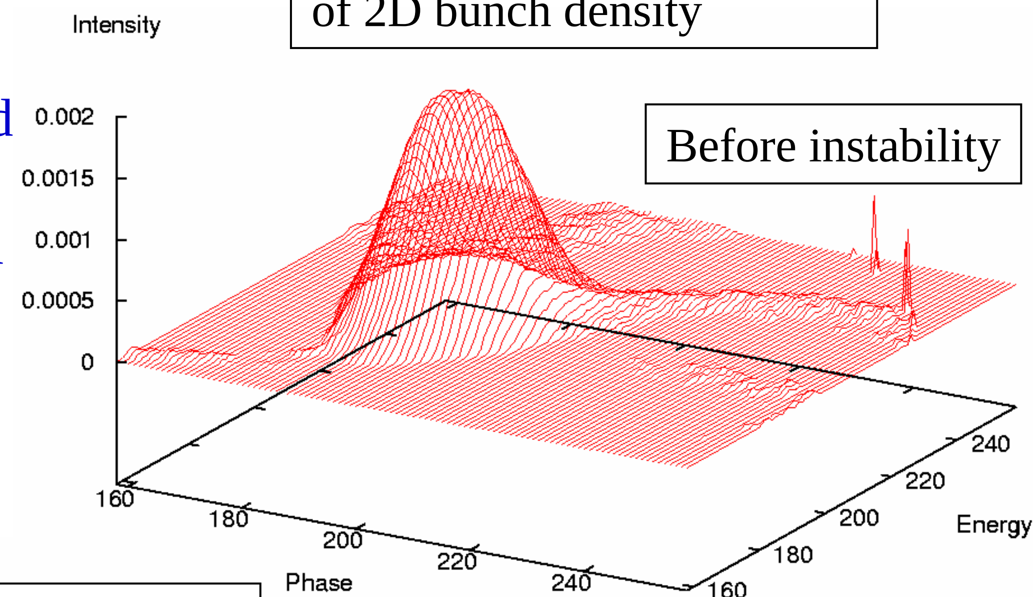
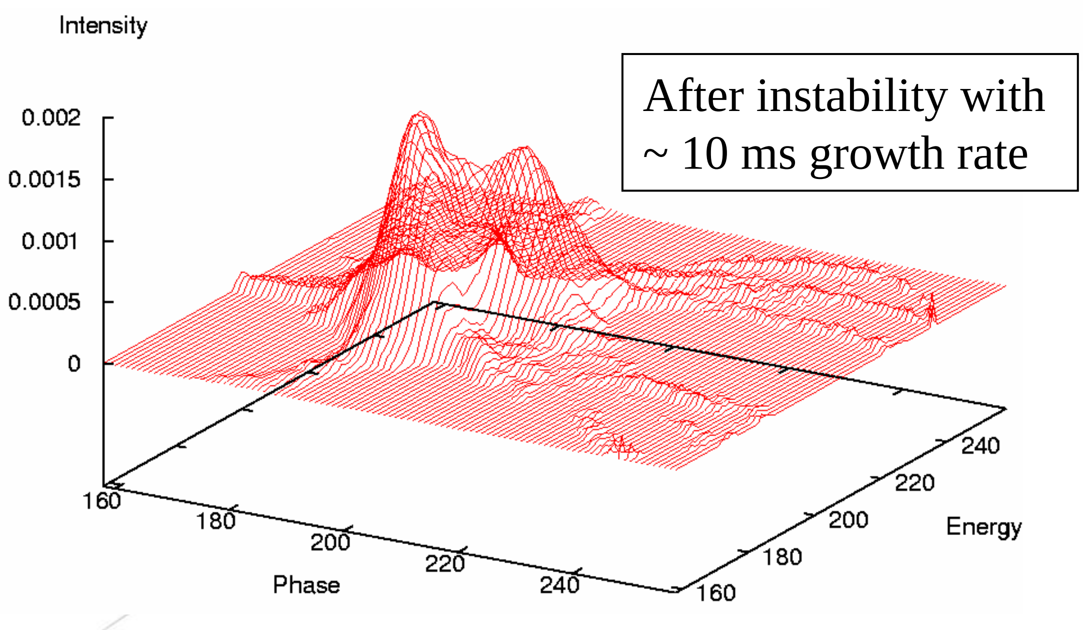
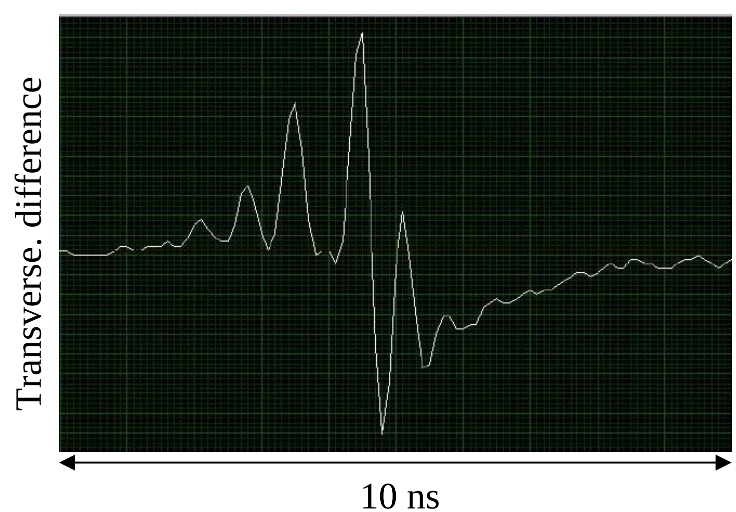
Luminosity Limit – Fast Instability Near Transition

- Fast transverse instability (~ GHz)
- High sensitivity around transition
  (high peak current, zero chromaticity)
- Effect of broadband impedance and electron clouds
- Cures: octupoles, suppress electron clouds, chromaticity jump, active damper (?)

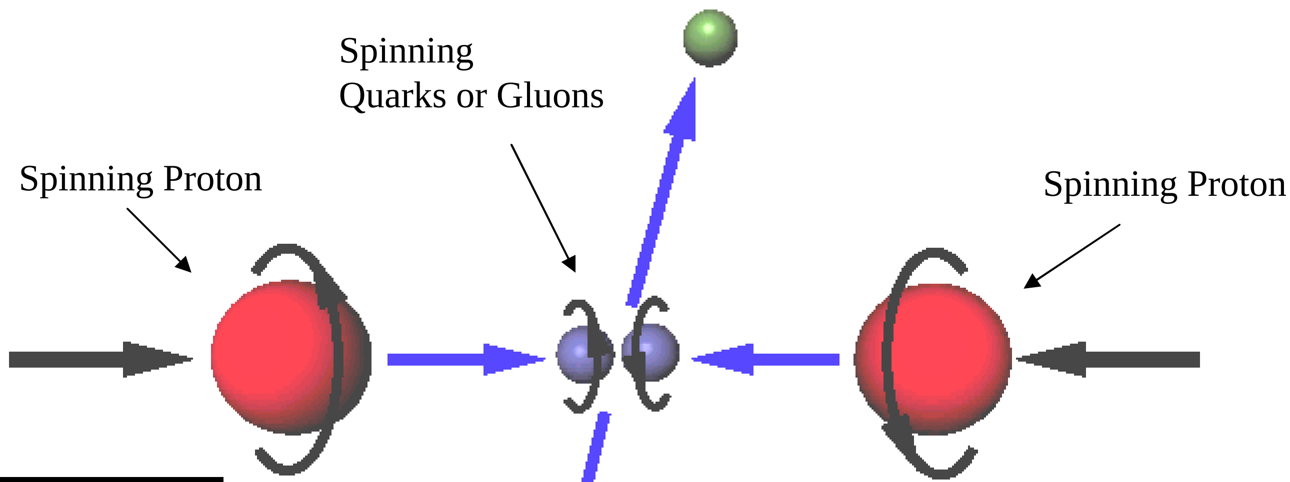
Tomographic reconstruction of 2D bunch density

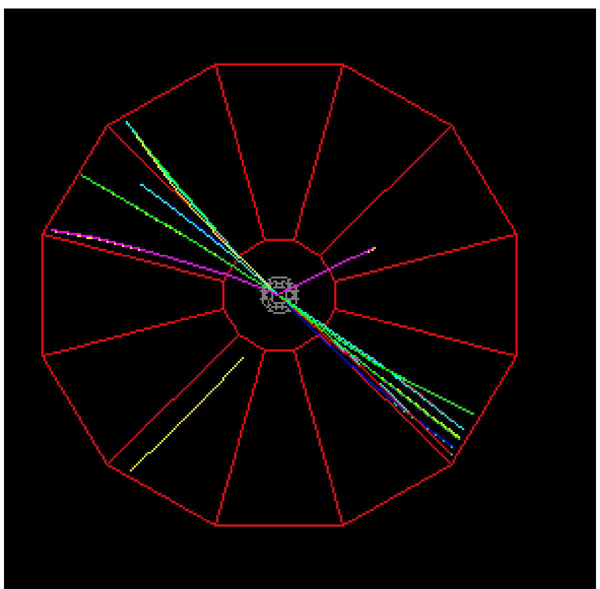






RHIC Spin Physics





- Spin structure functions of gluon and anti-quarks
- Parity violation in parton-parton scattering
- Requires high beam polarization and high luminosity

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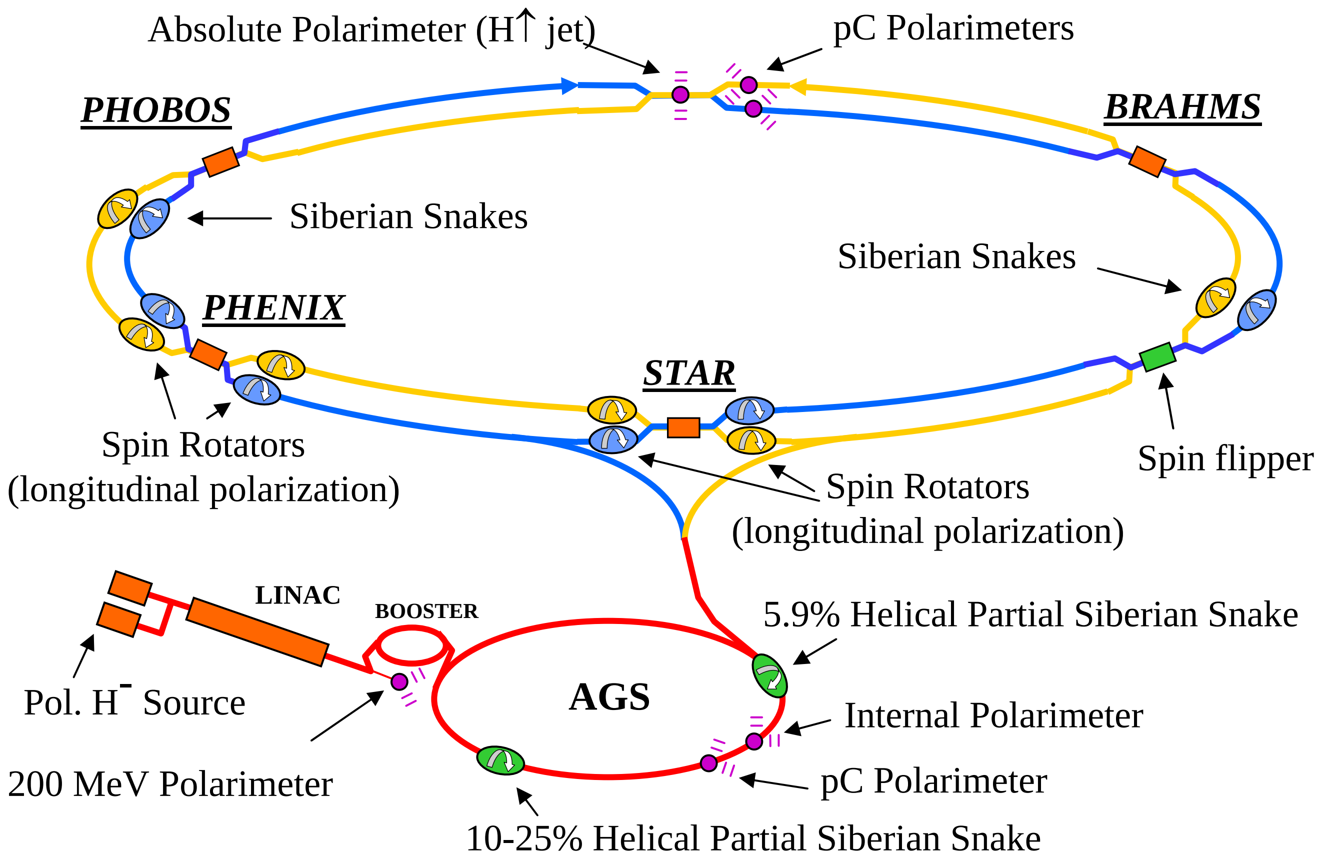
RHIC – First Polarized Hadron Collider



Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79\ E/m \rightarrow$ ~1000 depolarizing resonances
With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½ \rightarrow$ no first order resonances
Two partial Siberian snakes (11° and 27° spin rotators) in AGS

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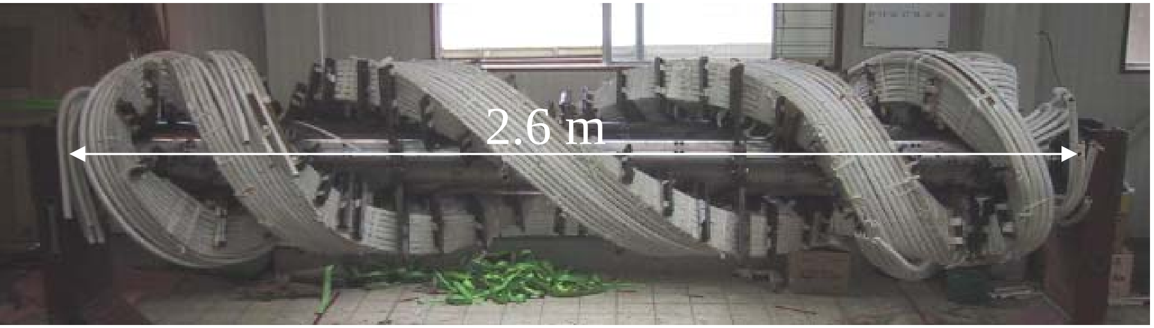
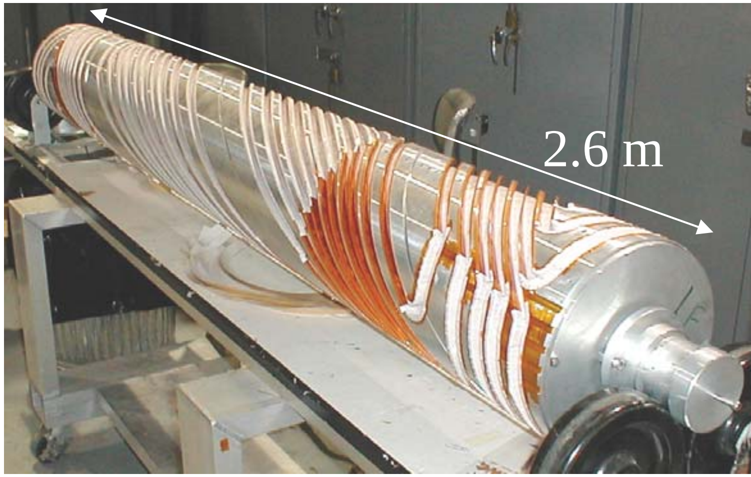
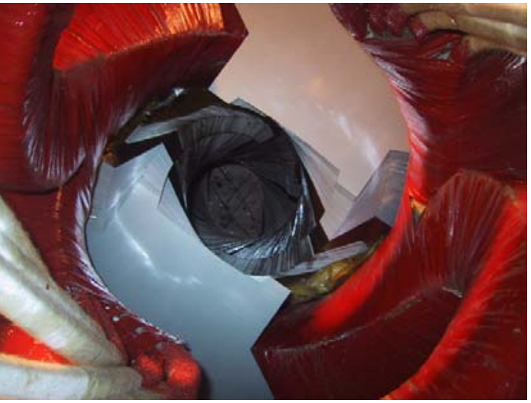
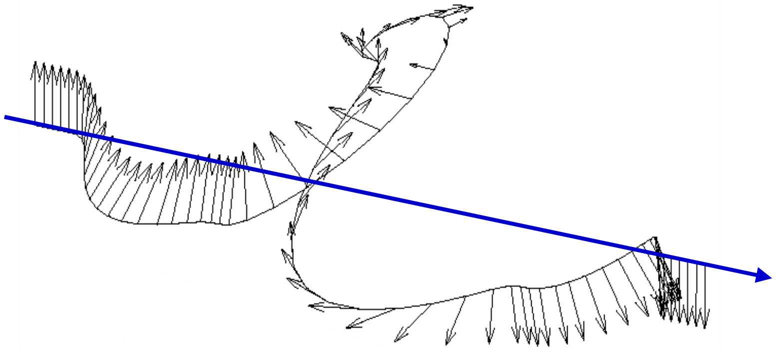
Siberian Snakes

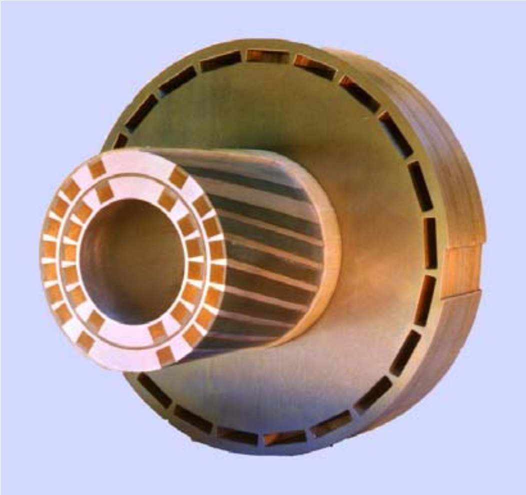




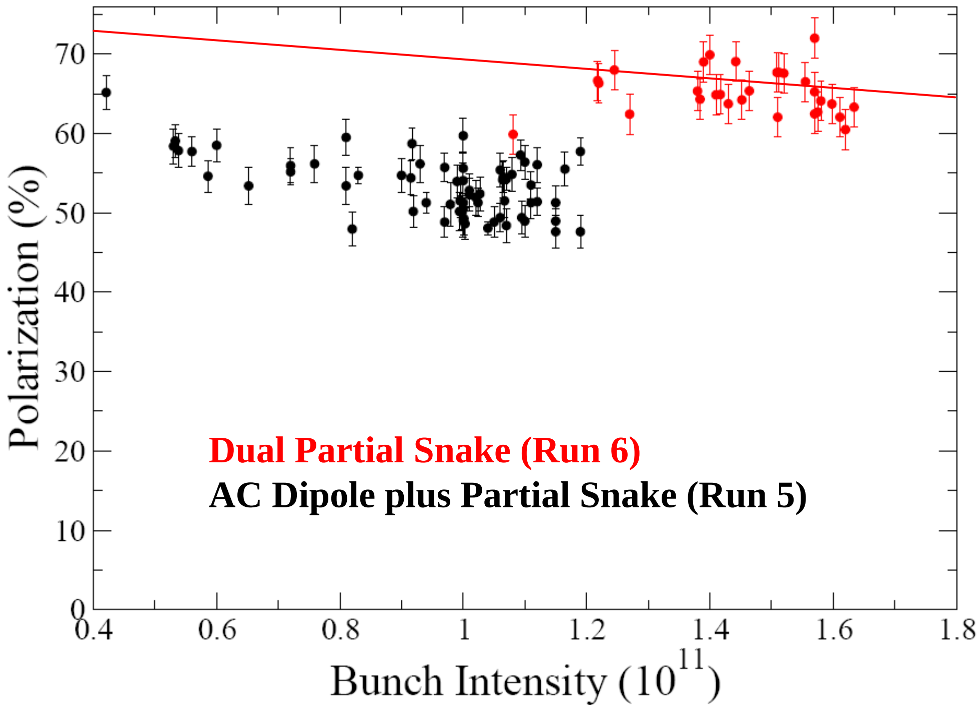


- AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m long
- RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist





AGS Polarization



$\varepsilon_{N,rms} \sim 2\ \mu m$

- Dual Partial Snake in AGS avoided depolarization from all vertical depolarizing resonances. Strong partial snakes also drive weak horizontal depolarizing resonances. (~ 5-10% polarization loss)
- Plan to use tune jump for weak horizontal resonances

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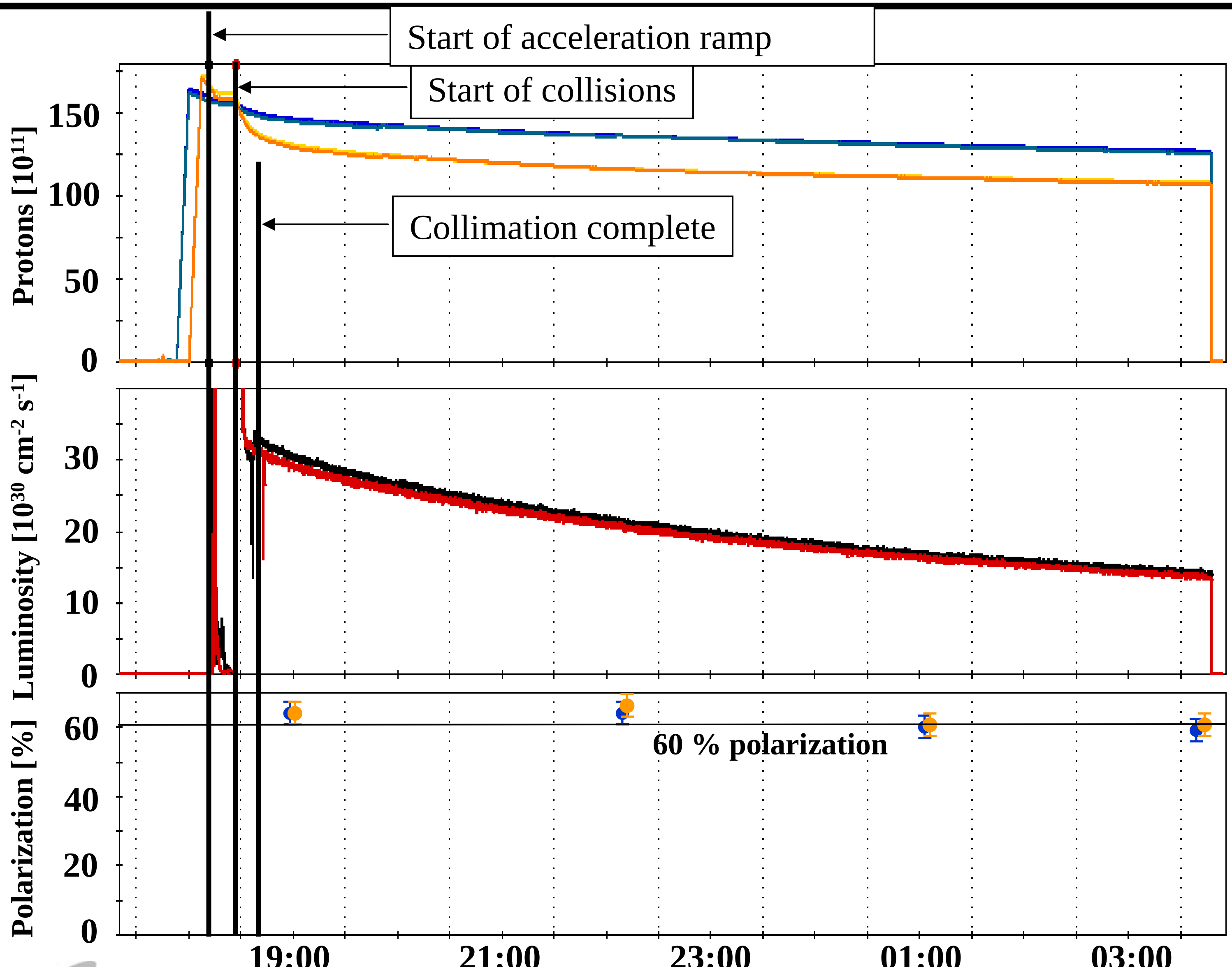
Luminosity and Polarization Lifetimes in RHIC at 100 GeV



45 % polarization on first acceleration to 250 GeV!

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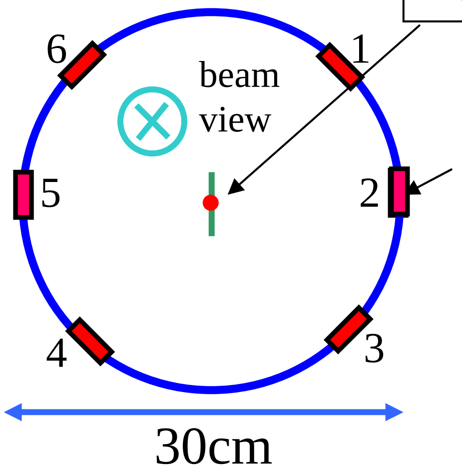
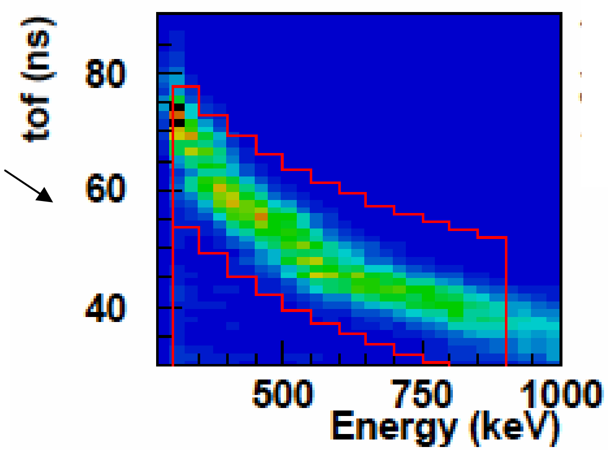
Proton-Carbon Coulomb-Nuclear Interference Polarimeter

Ultra-thin carbon ribbon target
~ 100 mono-layers think, 10μm wide

Si strip detectors for recoil carbon
(TOF, E_C)





$$p^{\uparrow}C \rightarrow p^{\uparrow}C$$

$$P_B = \frac{\varepsilon_{LR}}{A_N}, \quad \varepsilon_{LR} = \frac{N_L - N_R}{N_L + N_R}$$

- $A_N \approx 0.015$, originates from anomalous magnetic moment of proton
- Negligible emittance growth per polarization measurement
- Due to radiation cooling carbon target survives beam heating
- Measures polarization and beam profile

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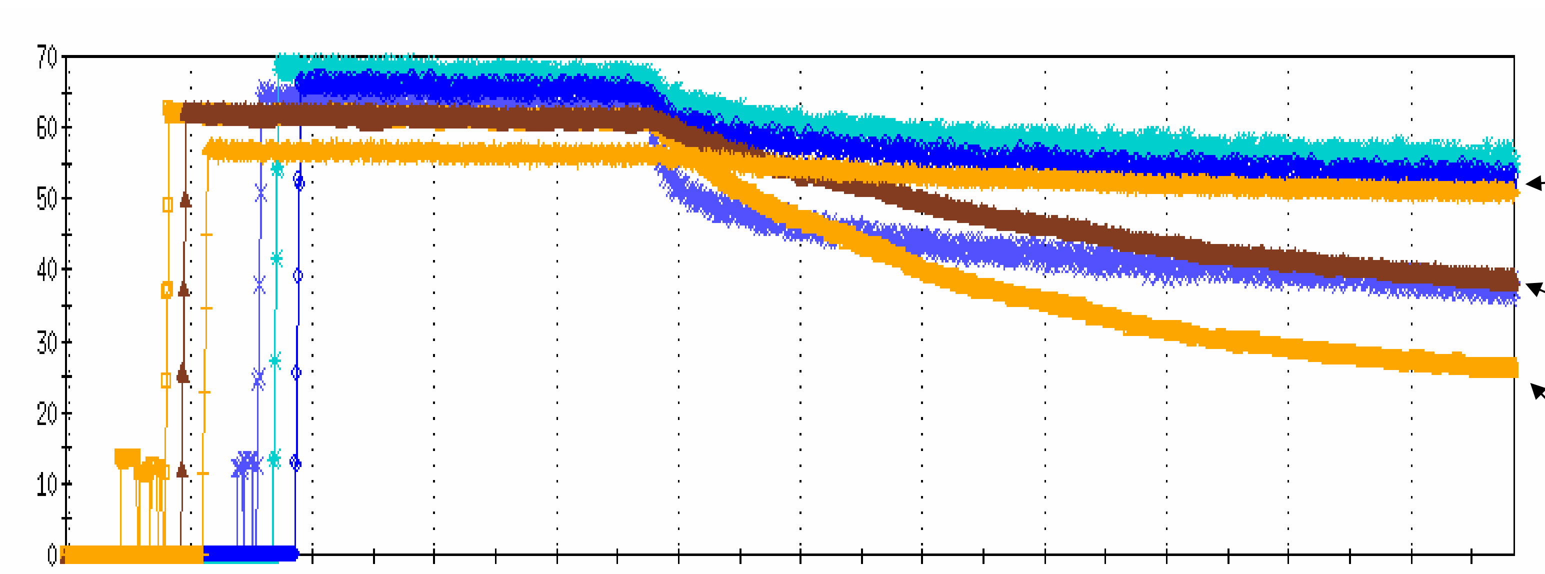
Luminosity Limit – Head-on Beam-Beam Interaction

- First strong-strong hadron collider (after ISR)
- Limits high luminosity pp operation (beam-beam tune spread ~ 0.01)
- Cures: Non-linear (chromaticity) corrections, better working point, electron lens



Current of bunches with 2, 3, or 4 collisions

RHIC Facility Upgrade Plans

- RHIC luminosity upgrade:
  - 0.5 m β^* for Au – Au and p↑ – p↑ operation
  - Stochastic cooling in RHIC of Au beams
  - New storage rf system in RHIC (56 MHz SRF cavity)
  - Electron lens in RHIC for beam-beam compensation (R&D)
- EBIS (low maintenance linac-based pre-injector; all species including U and polarized ^3He)
- eRHIC: high luminosity ($\geq 1 \times 10^{33}$ cm^{-2} s^{-1}) eA and pol. ep collider using 10 - 20 GeV electron driver, based on Energy Recovering Linac (ERL), and strong cooling of hadron beams

  Exploring gluons at extreme density!

RHIC Luminosity and Polarization Goals

Parameter	unit	Achieved	Luminosity upgrade
Au-Au operation		(2007)	(~ 2011)
Energy	GeV/nucleon	100	100
No of bunches	…	103	111
Bunch intensity	10^9	1.1	1.0
Average Luminosity	10^{26} $cm^{-2}s^{-1}$	12	40
p↑- p↑ operation		(2006/08)	(~ 2012)
Energy	GeV	100	100 (250)
No of bunches	…	111	111
Bunch intensity	10^{11}	1.5	2.0
Average Luminosity	10^{30} $cm^{-2}s^{-1}$	23	80 (200)
Polarization	%	60	70

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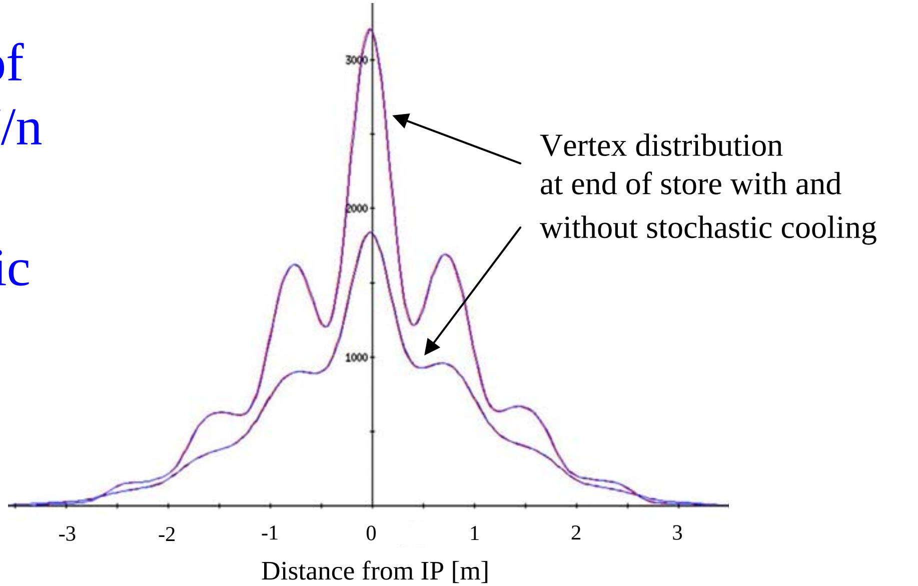
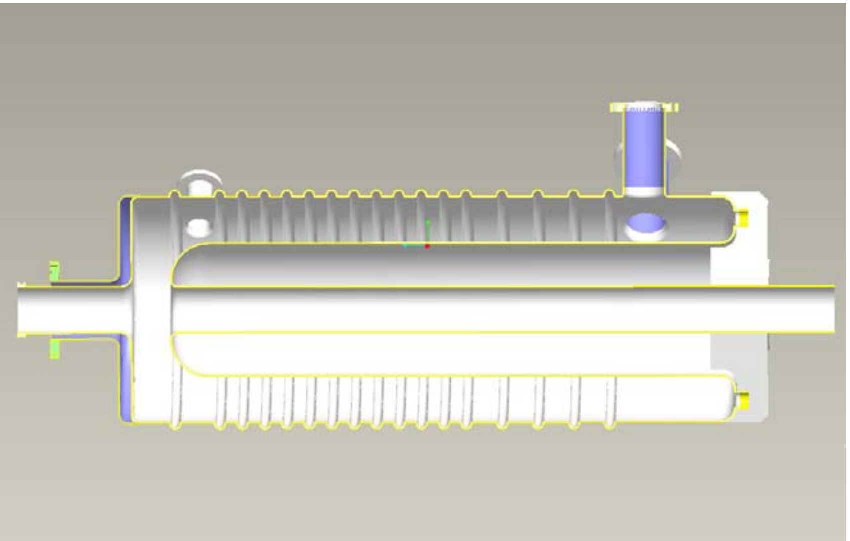
Stochastic Cooling and 56 MHz SRF cavity

- Longitudinal stochastic cooling of core of bunched beam demonstrated at 100 GeV/n in RHIC counteracting longitudinal IBS.
- Full longitudinal and transverse stochastic cooling under construction

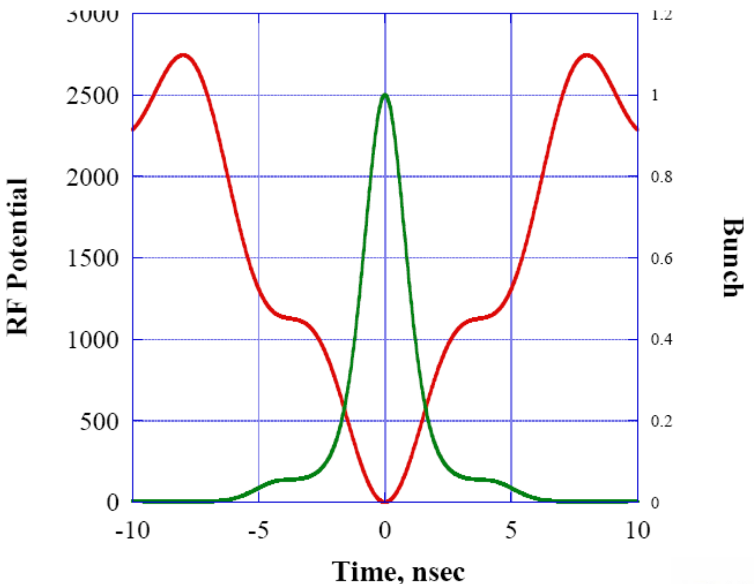


56 MHz SRF storage cavity:

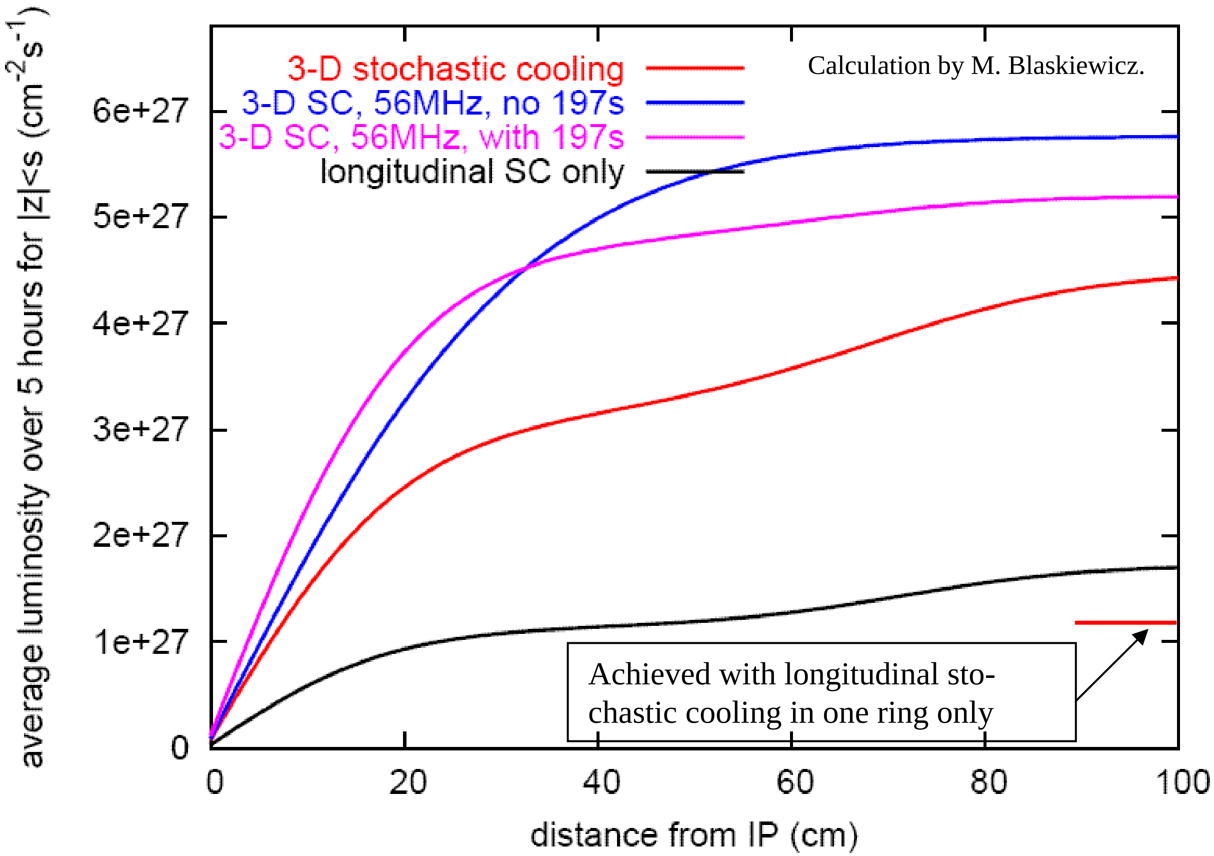
- Avoid rebucketing operation.
- Greatly reduces satellite bunches
- Re-entrant quarter wave resonator



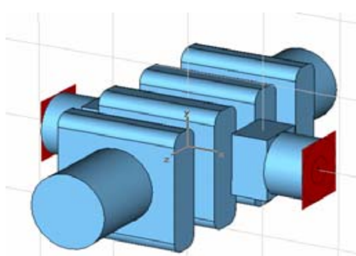
V_{28MHz}= 0.3MV; V_{SRF}= 2 MV; V_{197MHz}= 2 MV



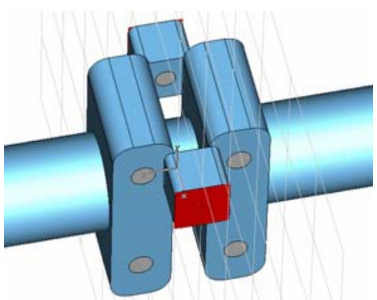
Luminosity Increase with Full Stochastic Cooling



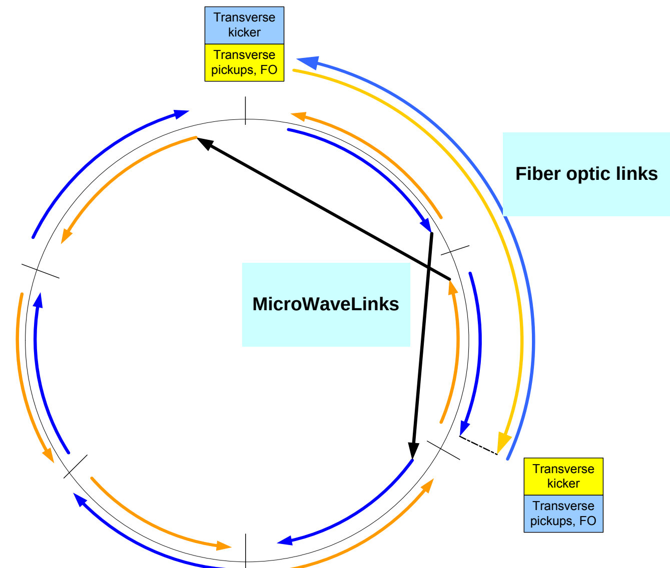
- Transverse stochastic cooling in one plane only
- Second plane cooled through x-y coupling
- 5 – 8 GHz bandwidth split up into 16 frequency bands
- Each frequency has its own cavity kicker



Longitudinal kickers



Transverse kickers



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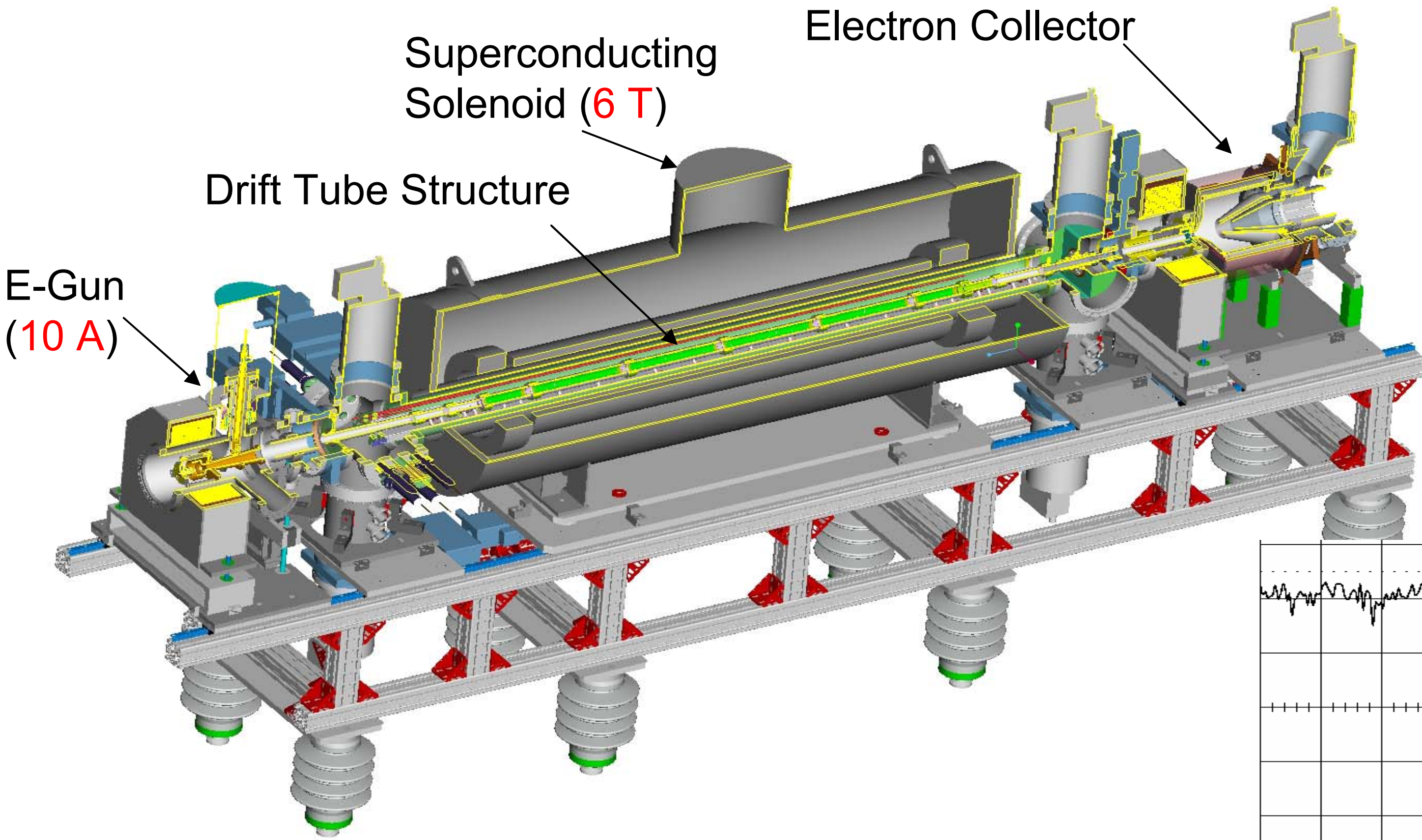
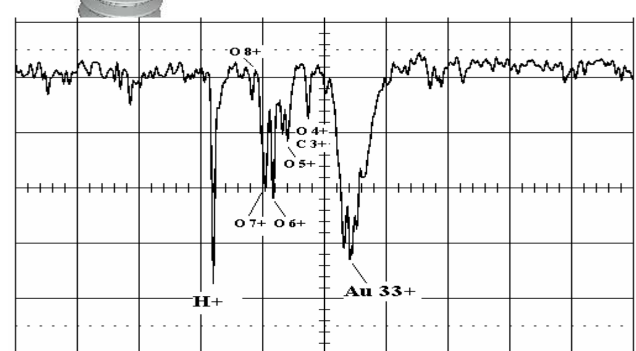
Electron Beam Ion Source (EBIS)

- New high brightness, high charge-state pulsed ion source, ideal as source for RHIC
- Produces beams of all ion species including noble gas ions, uranium (RHIC) and polarized He^3 (eRHIC) (~ 1-2 × 10^{11} charges/bunch with $\varepsilon_{N,rms}$ = 1-2 μm)
- Achieved 1.7 × 10^9 Au^{33+} in 20 μs pulse with 8 A electron beam (60% neutralization)
- Construction of EBIS, RFQ and IH Linac complete by 2010

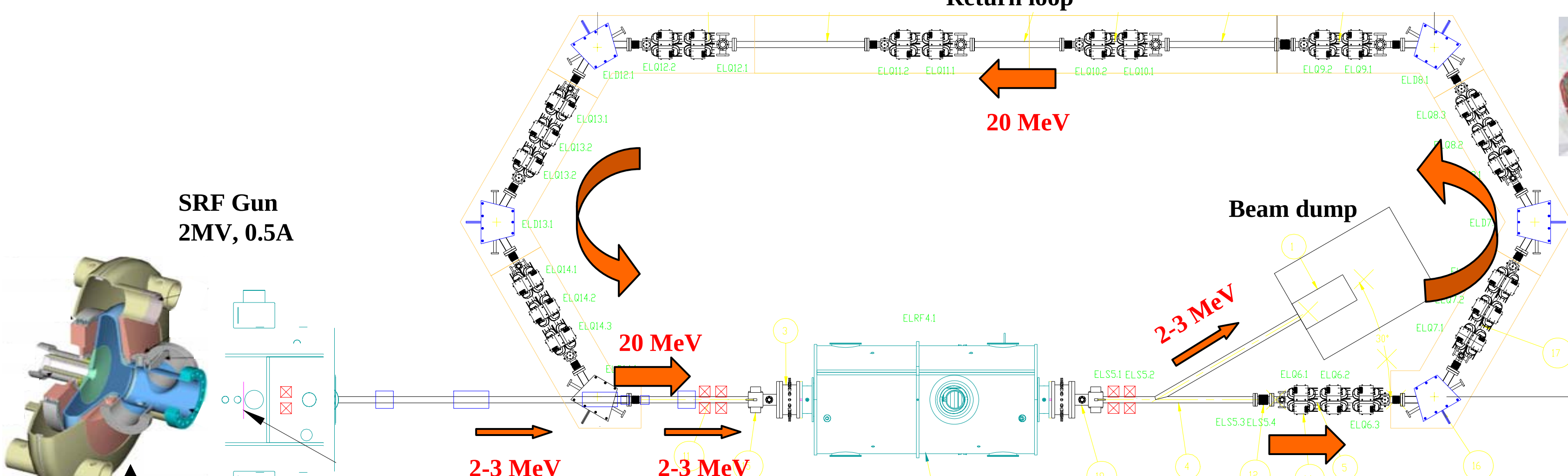


Gold charge state with only 40 ms confinement time.



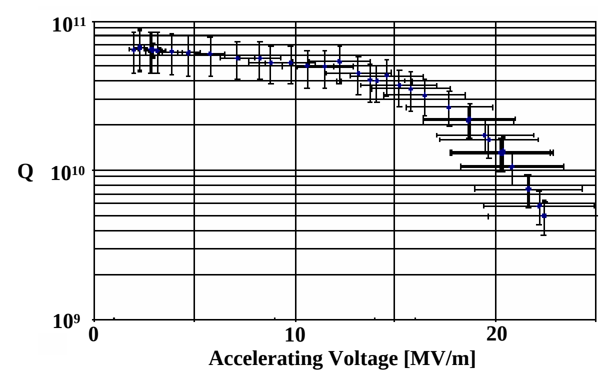
Energy Recovery Linac (ERL) Test Facility

- Test of high current (0.5 A), high brightness ERL operation
- Electron beam for RHIC (coherent) electron cooling (54 MeV, 10 MHz, 5 nC, 4 μm)
- Test for 10 – 20 GeV high intensity ERL for eRHIC.
- Test of high current beam stability issues, highly flexible return loop lattice
- Start of commissioning: 2009 - 2010.



5 Cell SRF "single mode" cavity
Q > 10^{10} @20 MV/m CW

1 MW, 703.75 MHz CW Klystron



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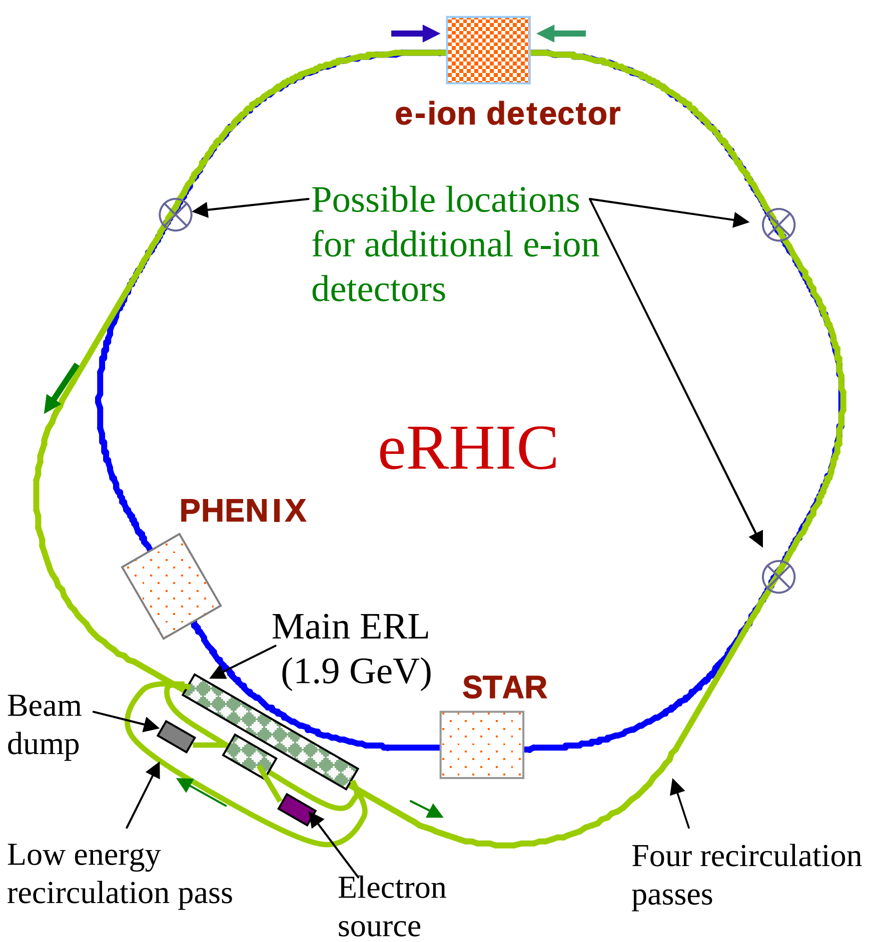
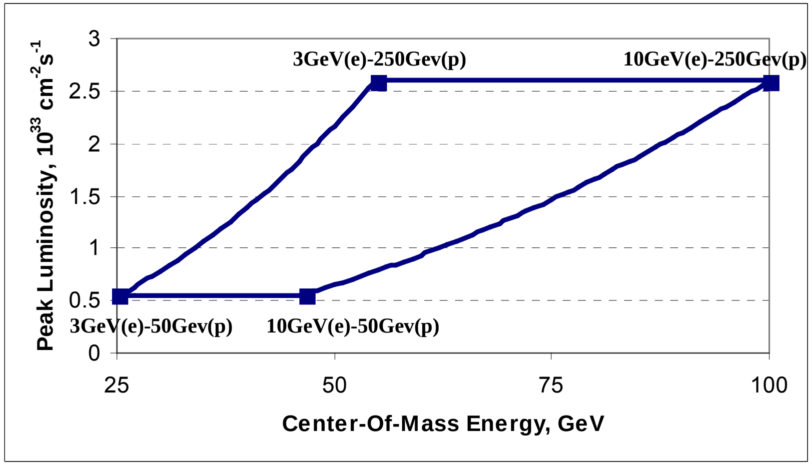
ERL – Based Electron-Ion Collider (eRHIC)





- 10 GeV electron design energy. Possible upgrade to 20 GeV by doubling main linac length.
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) and detectors;
- Full polarization transparency at all energies for the electron beam;
- Ability to take full advantage of transverse cooling of the hadron beams;
- Possible options to include polarized positrons at lower luminosity: compact storage ring or ILC-type polarized positron source

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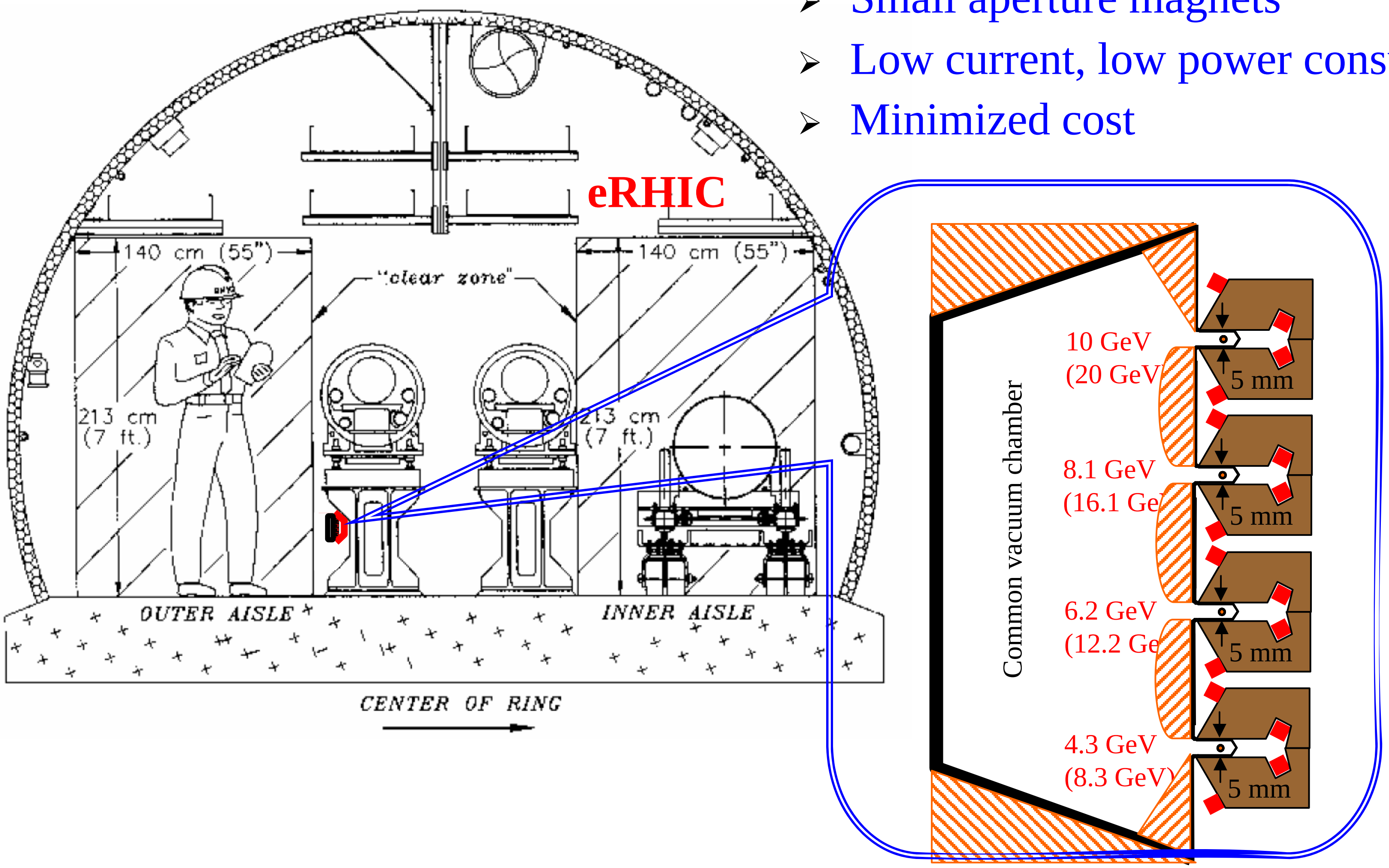
Recirculation Passes

- Separate recirculation loops
- Small aperture magnets
- Low current, low power consumption
- Minimized cost



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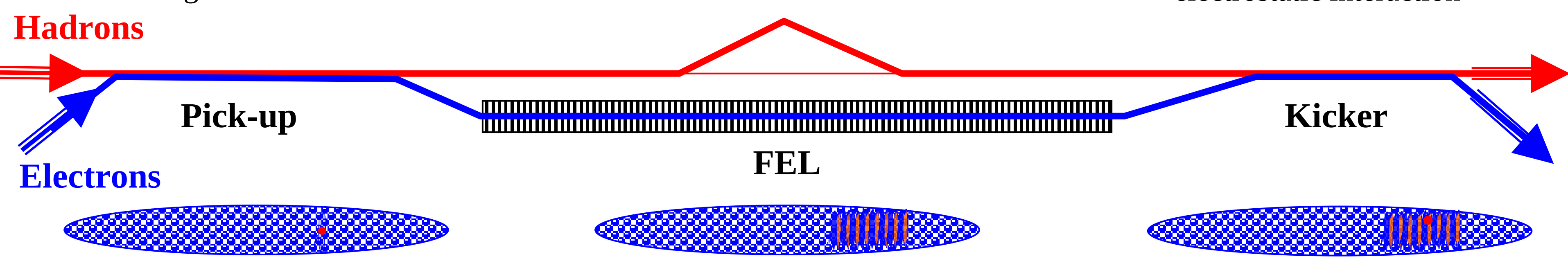
Coherent Electron Cooling

- 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 → much reduced electron current, higher eRHIC luminosity
- Proof-of-principle demonstration possible in RHIC using test ERL.

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



Summary

Since 2000 RHIC has collided, at many different collision energies,

- Gold on gold with luminosity exceeding design luminosity by factor of six
- Asymmetric ions at high luminosity
- Polarized protons with 60 % beam polarization

Upgrade plans:

- Luminosity upgrade to 40×10^{26} cm^{-2} s^{-1} through high energy beam cooling
- Uranium beams from EBIS
- High luminosity polarized electron ion collider - eRHIC