BNL Particle Physics Facilities Performance and Planned Upgrades

RHIC luminosity and polarization evolution

Electron Beam Ion Source (EBIS) pre-injector

Plans for luminosity upgrades

Low energy Au – Au collisions (Critical point search)

Electron-Ion Collider @ BNL (eRHIC and MeRHIC)

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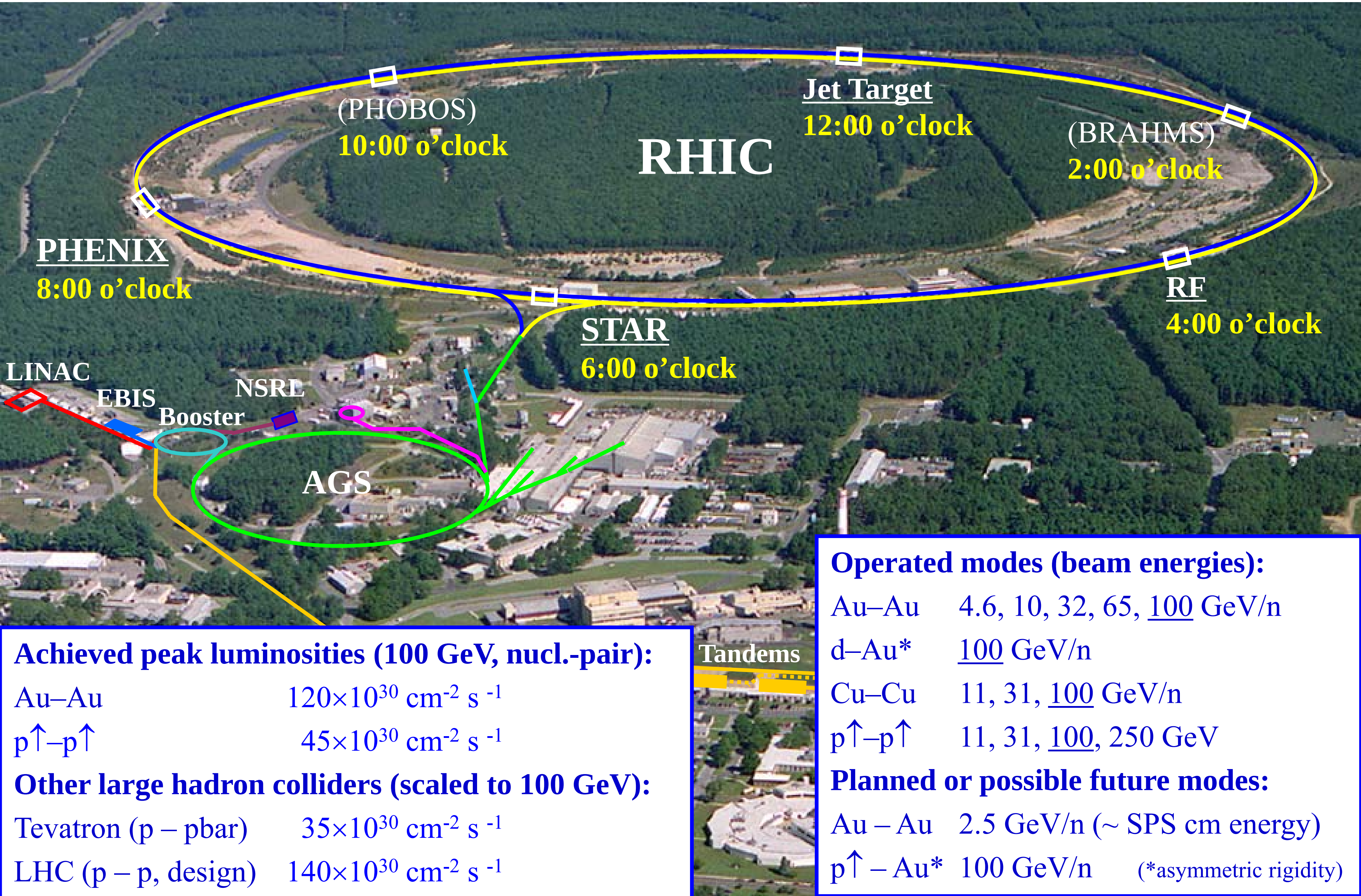
Thomas Roser
New Opportunities @ CERN
May 13, 2009

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↑ 45×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 100 GeV):

Tevatron (p – pbar) 35×10^{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>, 250 GeV

Planned or possible future modes:

Au – Au 2.5 GeV/n (~ SPS cm energy)

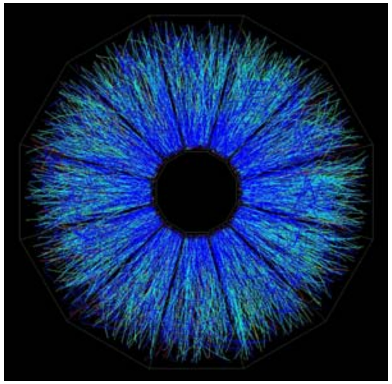
p↑ – Au* 100 GeV/n (*asymmetric rigidity)

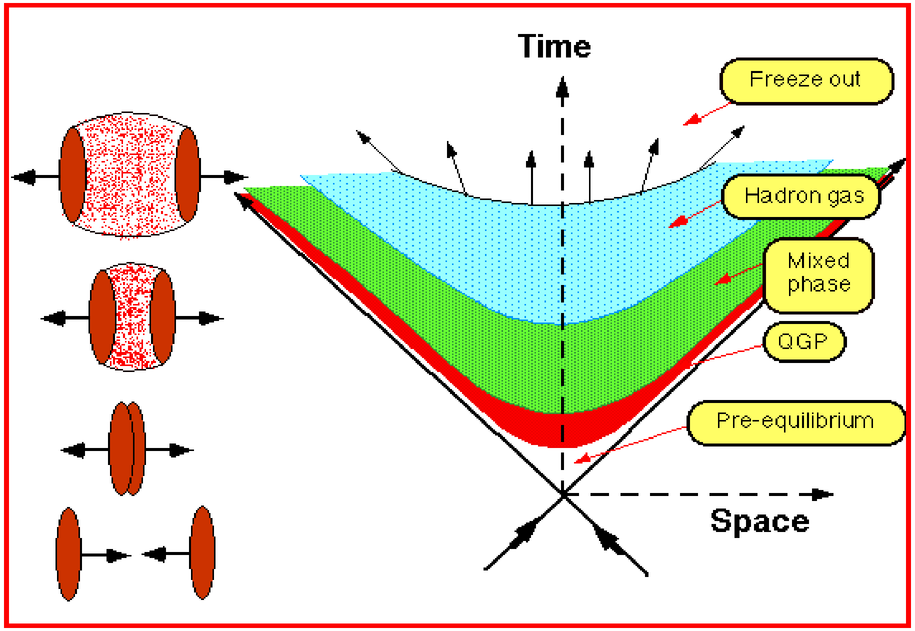
A Mini-Bang:

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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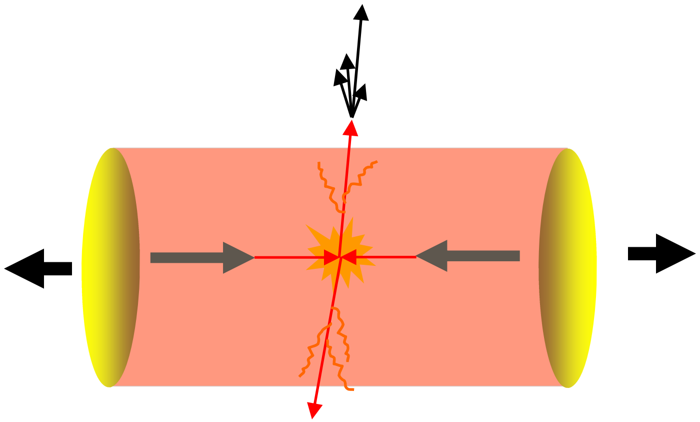
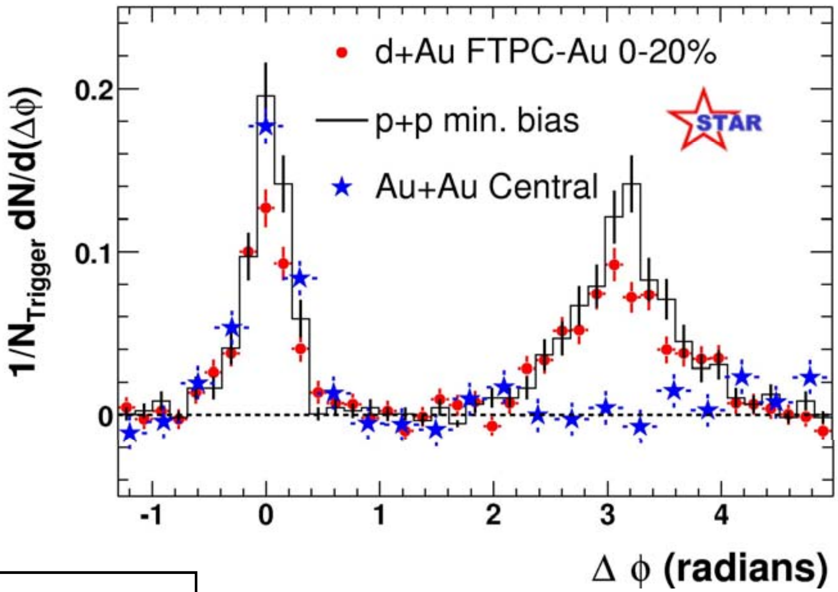
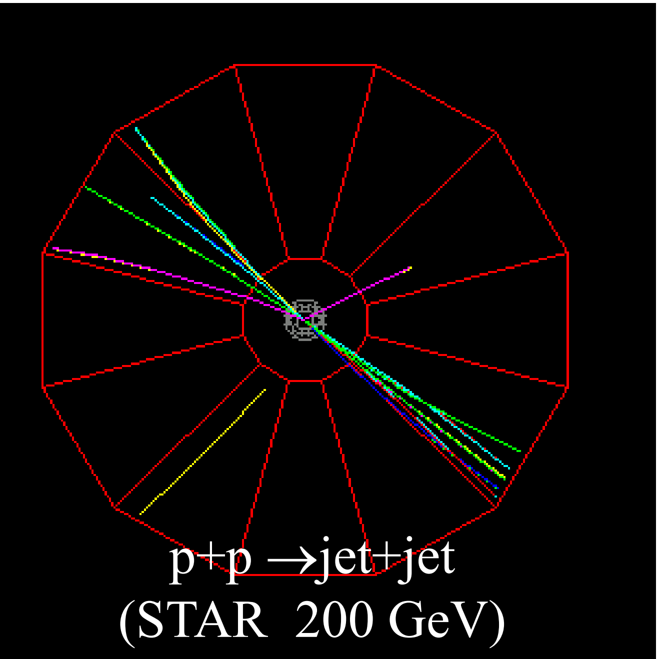
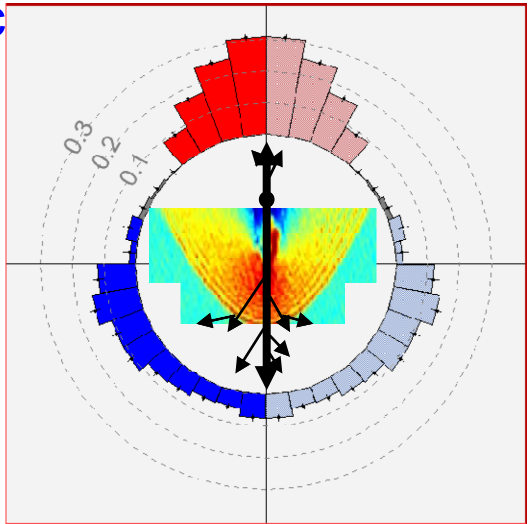
Hard Scattering at RHIC

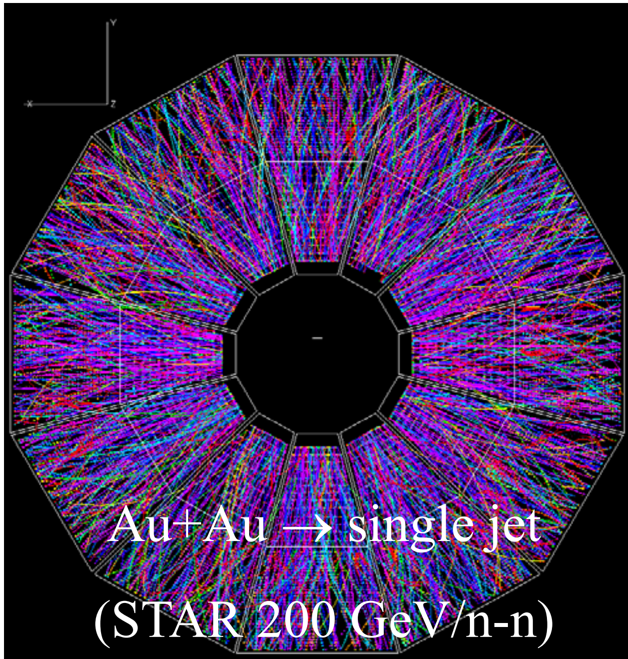




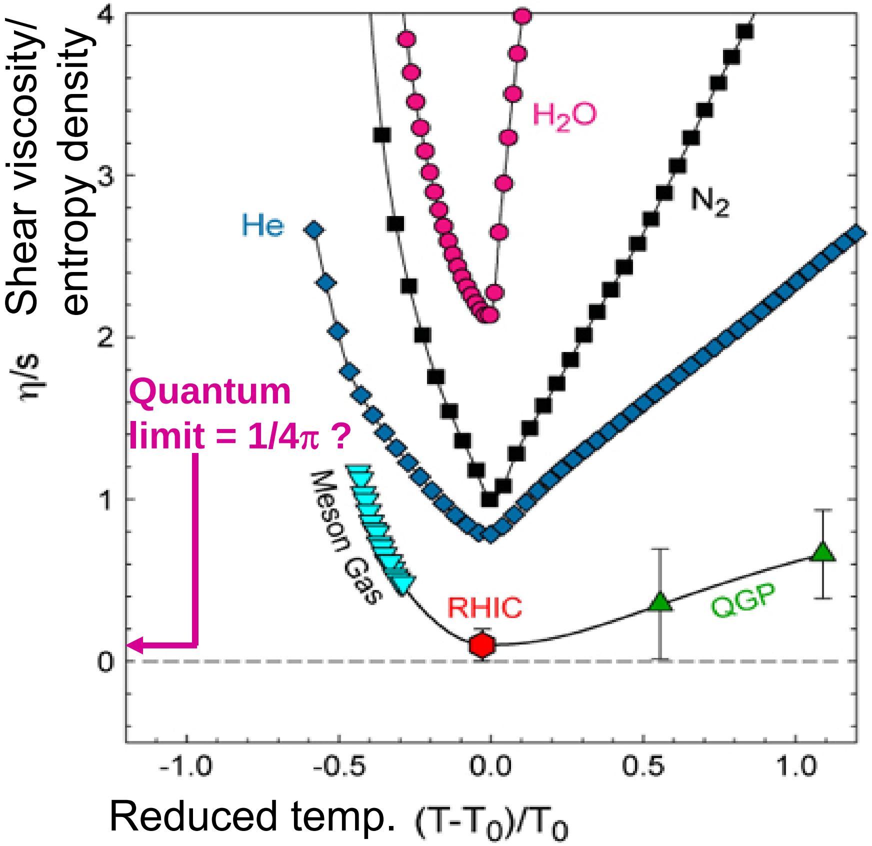


softer fragments
emitted along Mach-like
c





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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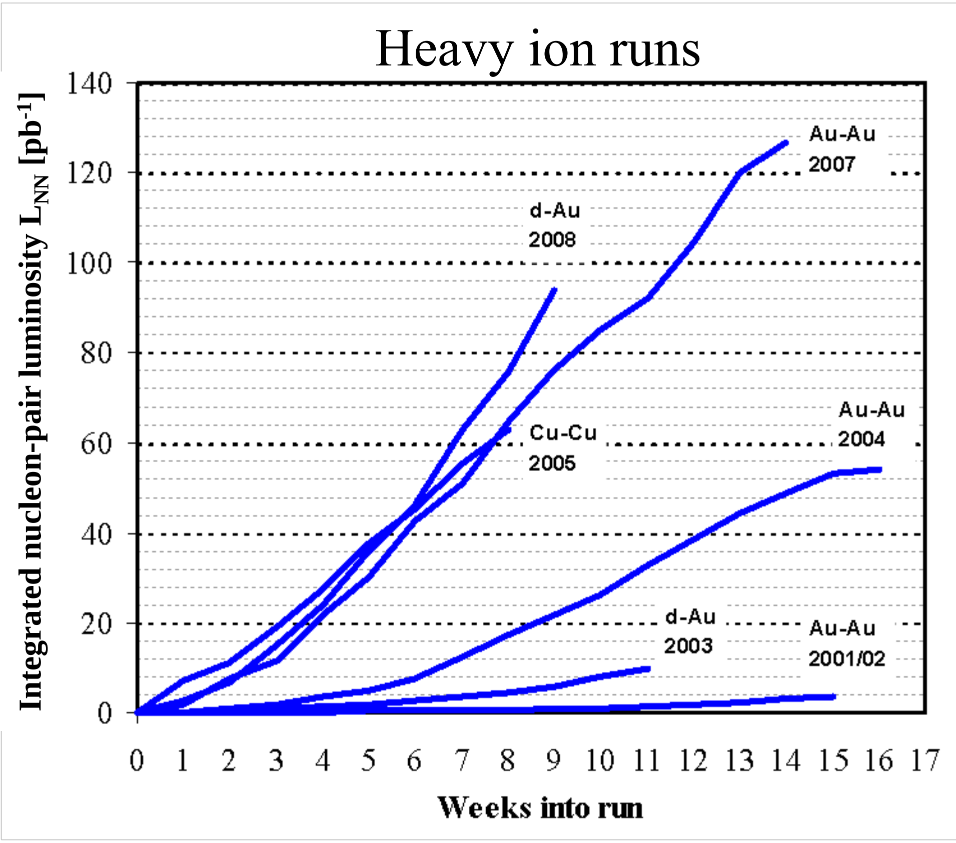
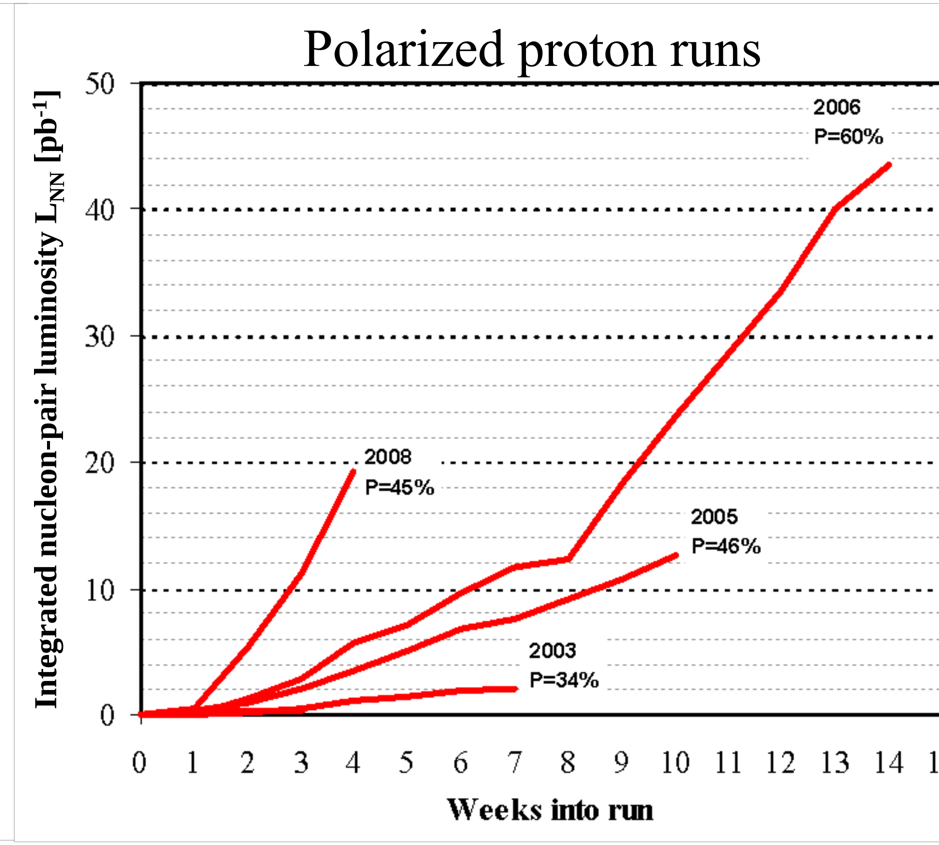
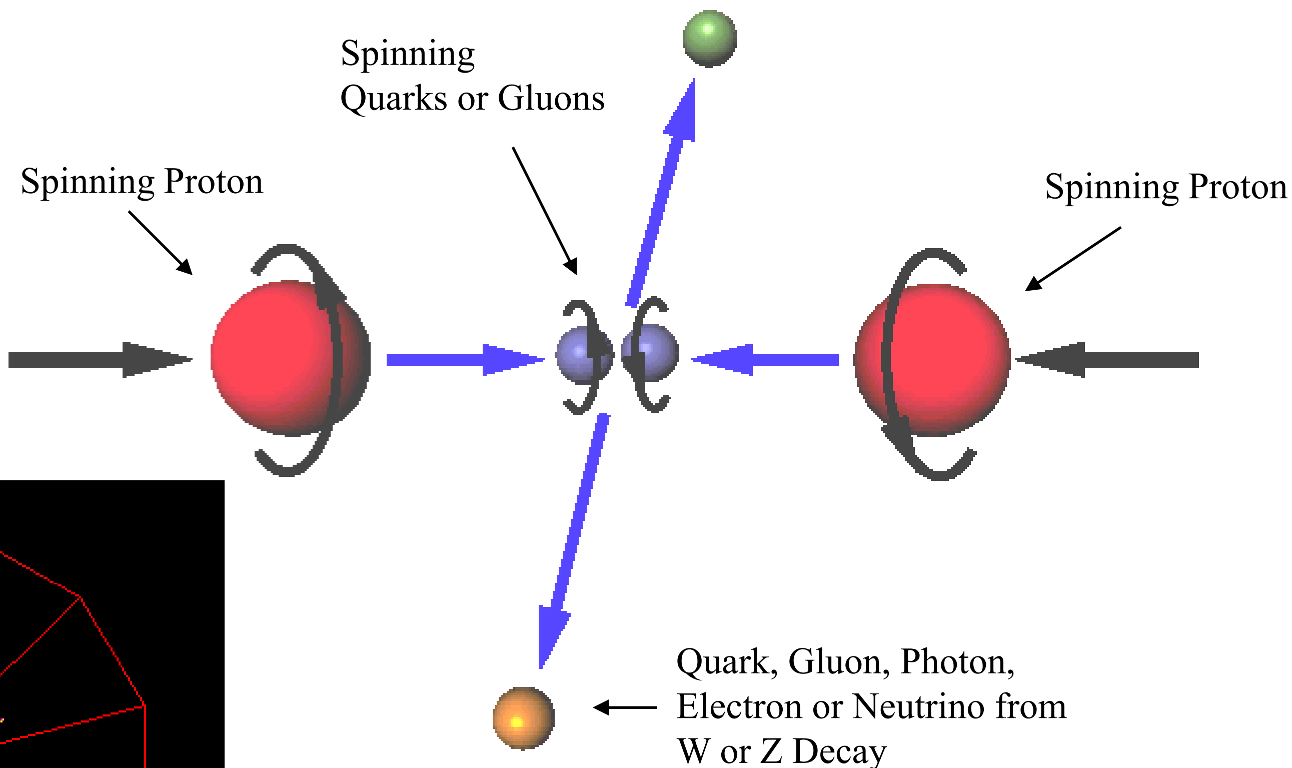
Delivered Integrated Luminosity and Polarization

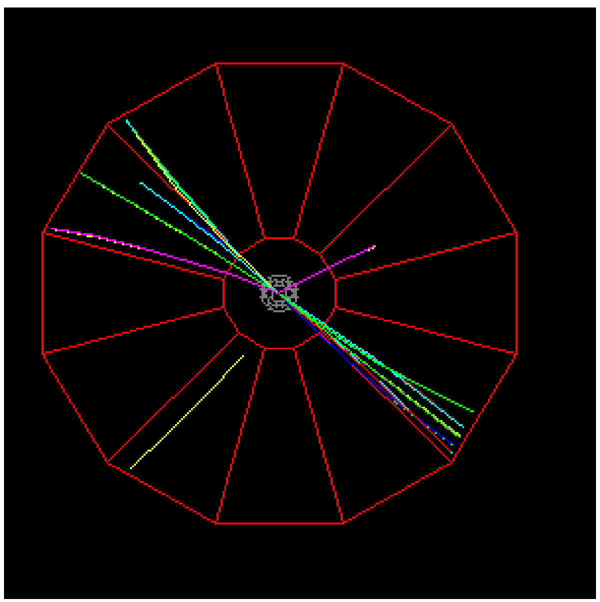




Nucleon-pair luminosity: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.

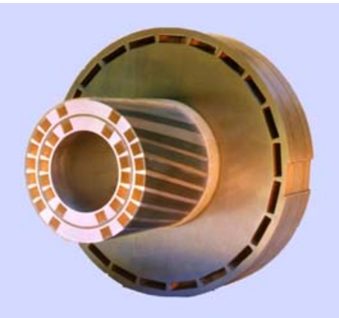
RHIC Spin Physics

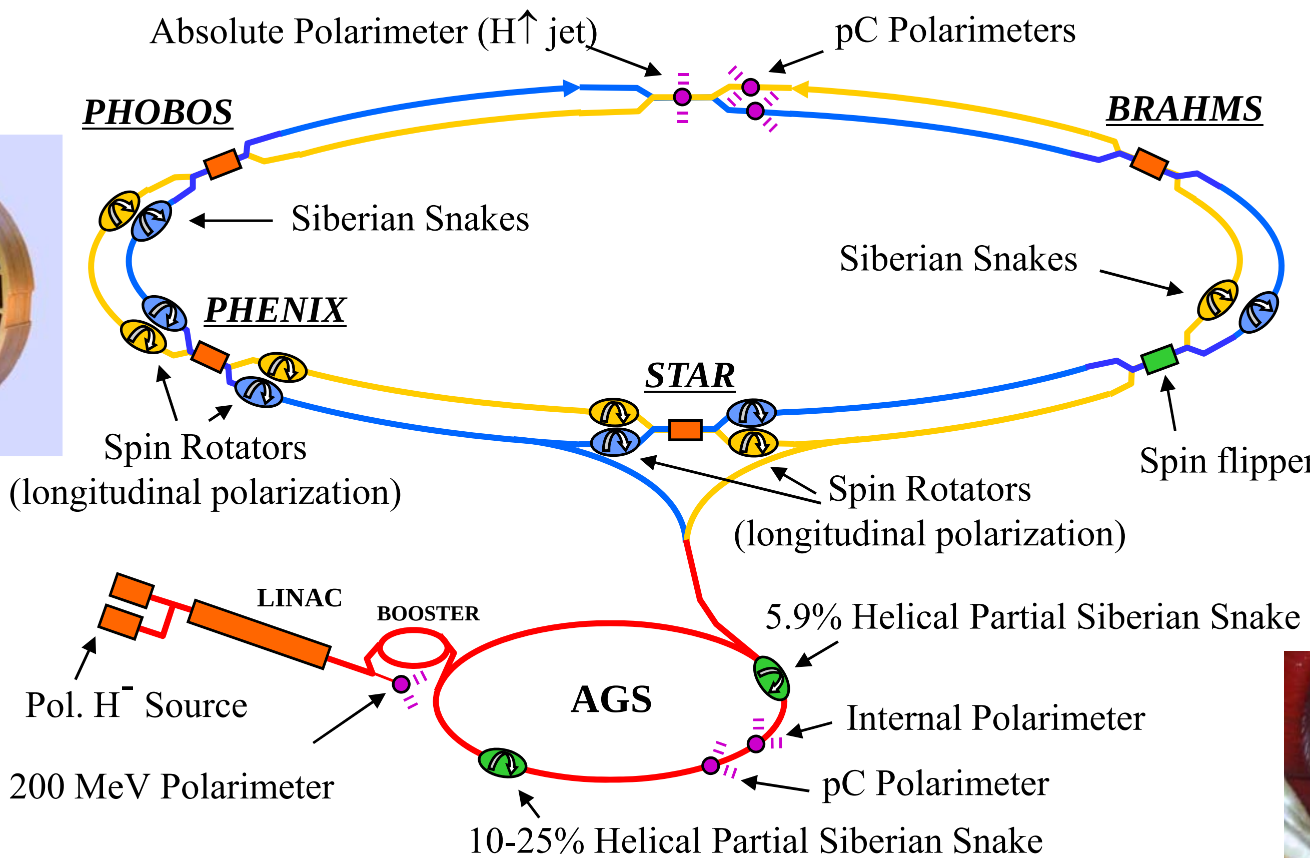




- Spin structure functions of gluon and anti-quarks
- Parity violation in parton-parton scattering
- Requires high beam polarization and high luminosity

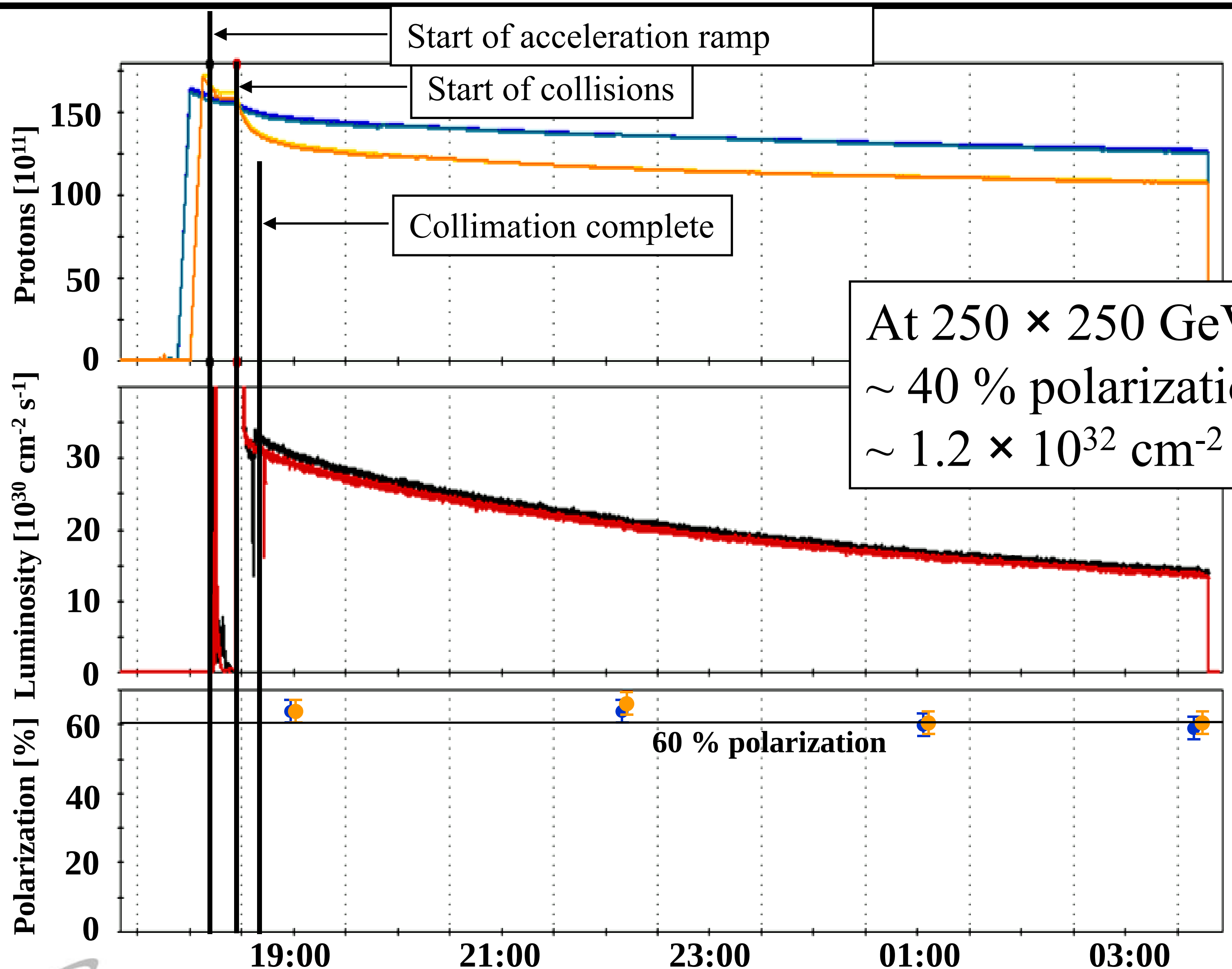
RHIC – First Polarized Hadron Collider





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

Luminosity and Polarization Lifetimes in RHIC at 100 GeV



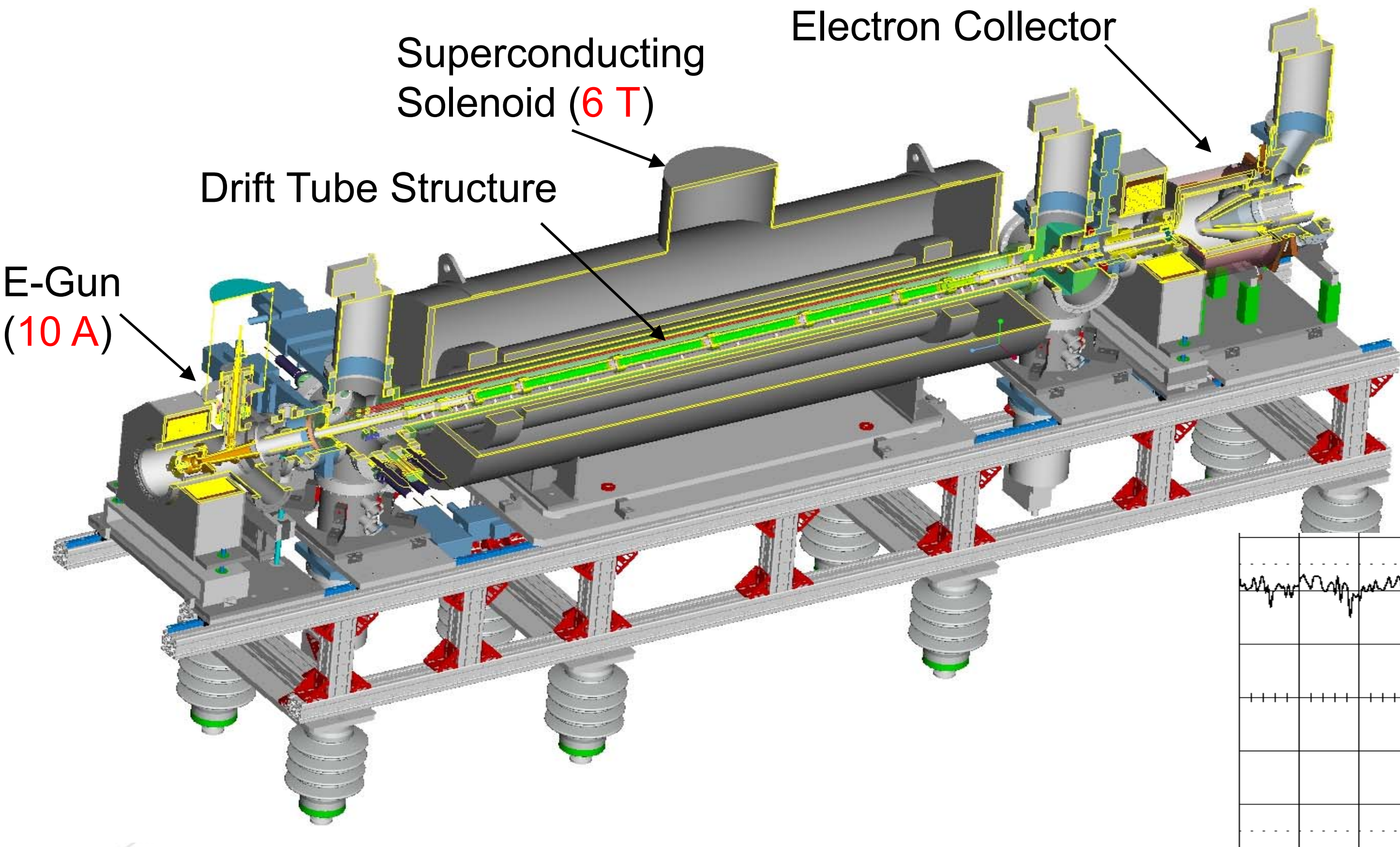
At 250 × 250 GeV:
~ 40 % polarization
~ 1.2×10^{32} cm^{-2} s^{-1}

RHIC Facility Upgrade Plans

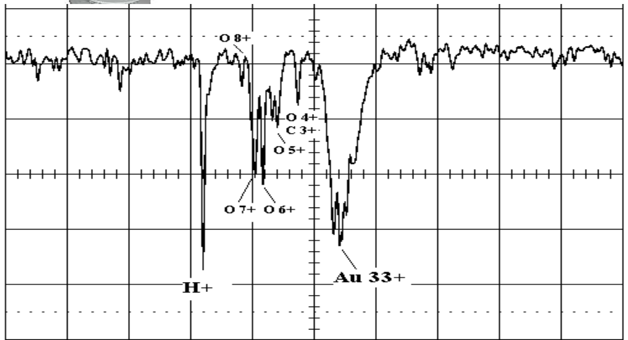
- EBIS (~ 2011) (low maintenance linac-based pre-injector; all species including U and polarized ^{3}He)
- RHIC luminosity upgrade (~ 2012):
  [Au-Au: 40 × 10^{26} cm^{-2} s^{-1}(× 4); 500 GeV p-p: 2 × 10^{32} cm^{-2} s^{-1}]
  - 0.5 m β^* for Au – Au and p↑ – p↑ operation
  - Stochastic cooling of Au beams and 56 MHz storage rf system in RHIC
- Further luminosity upgrade for p↑ – p↑ operation (~ 2014):
  [500 GeV p-p: 6 - 12 × 10^{32} cm^{-2} s^{-1}]
  - 0.3 m β^* for 500 GeV p↑ – p↑ operation (× 1.6)
  - Electron lens in RHIC for head-on beam-beam compensation (× 2-4)
- Low energy ($\sqrt{s}$=5…30 GeV) Au-Au collisions for critical point search
  - ~ 1…5 MeV electron cooling of Au beams at injection
- eRHIC: high luminosity (≥ 1 × 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 (~ 2020)
  Exploring gluons at extreme density!

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

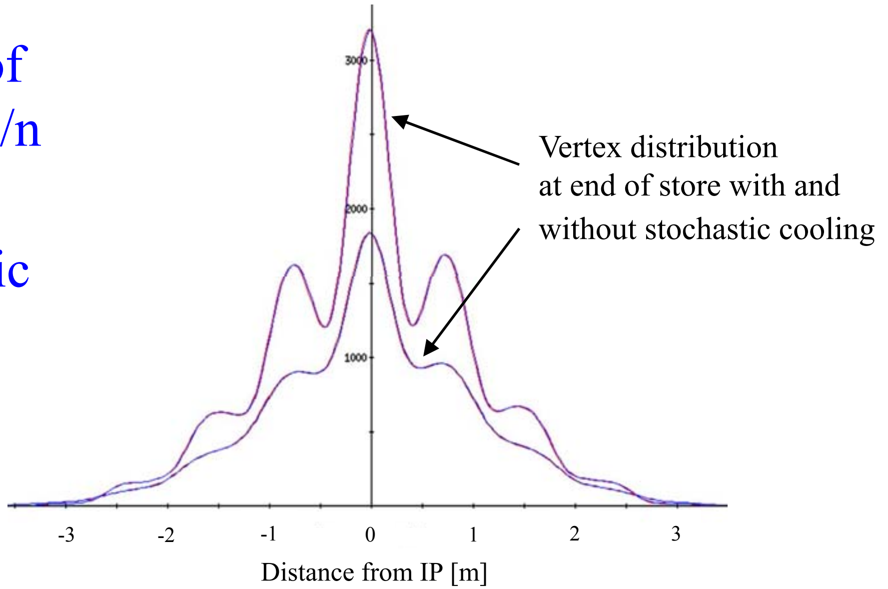


Gold charge state with only 40 ms confinement time.



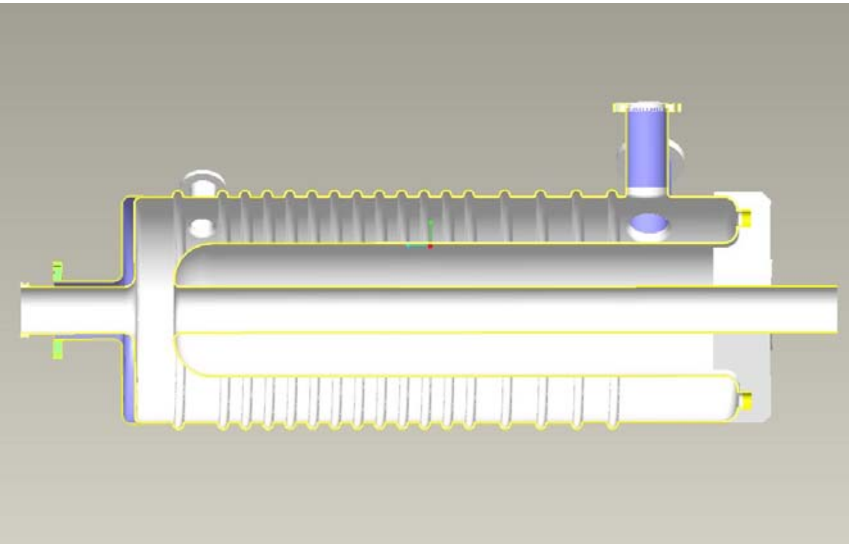
Stochastic Cooling and 56 MHz SRF cavity

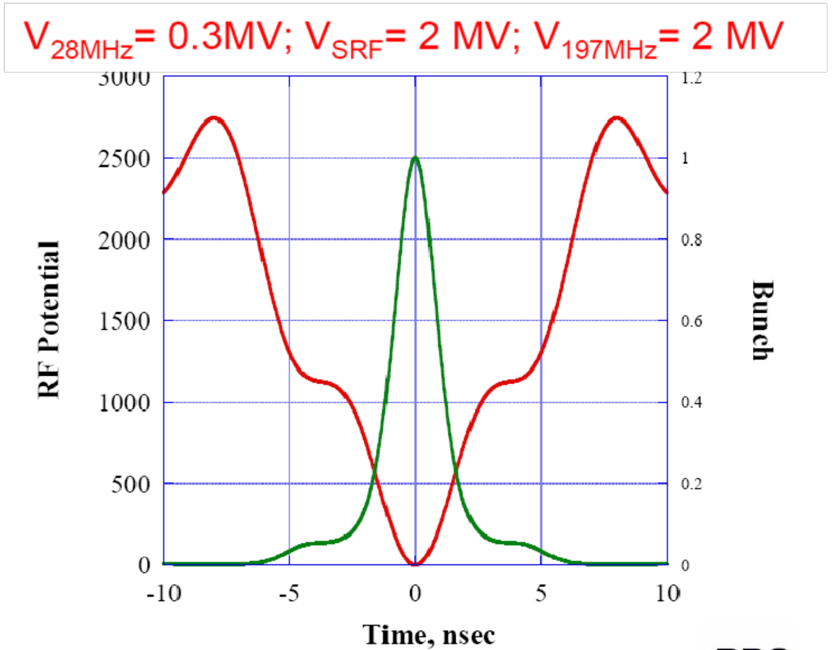
- Longitudinal stochastic cooling of core of bunched beam demonstrated at 100 GeV/n in RHIC counteracting longitudinal IBS.
- Full longitudinal and transverse stochastic cooling under construction



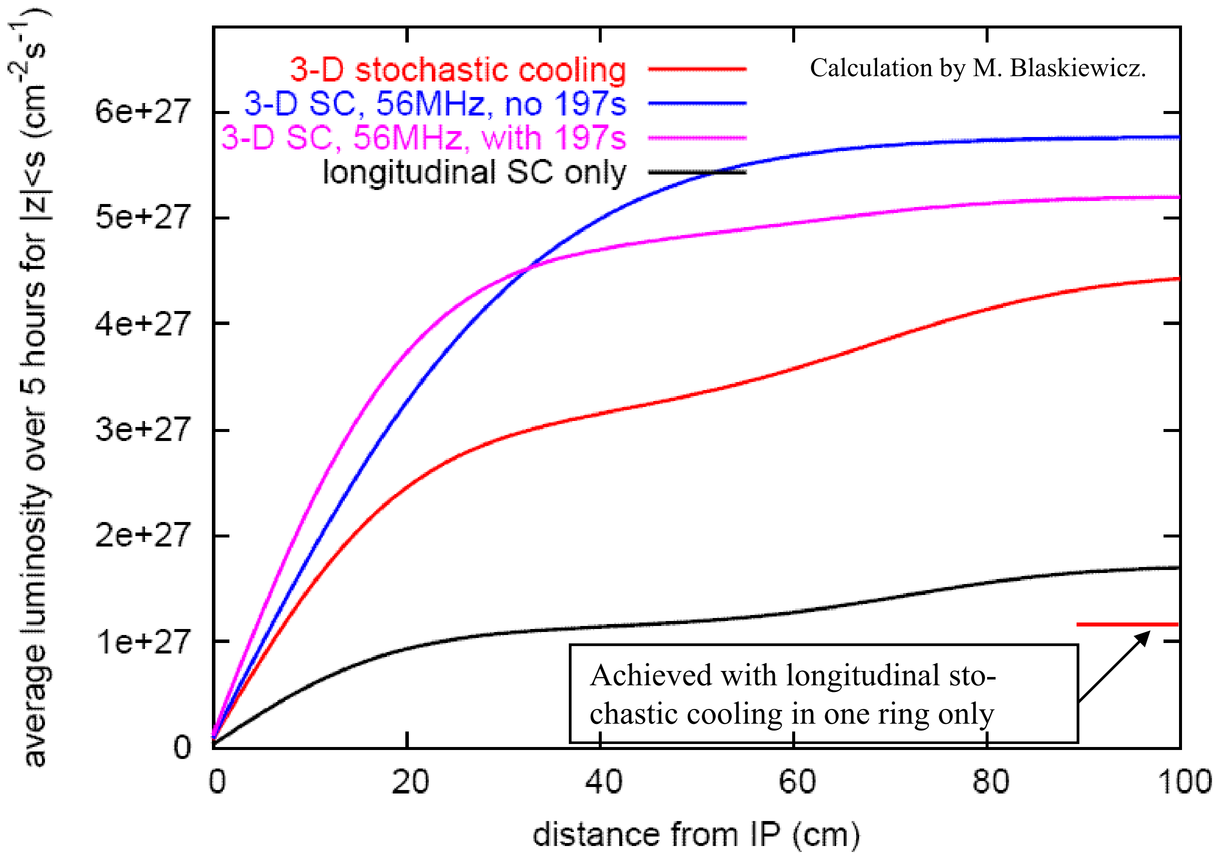
56 MHz SRF storage cavity:

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

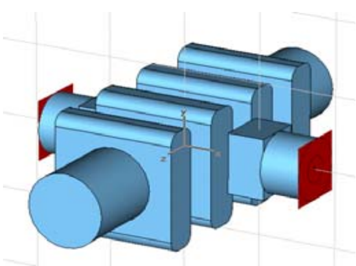


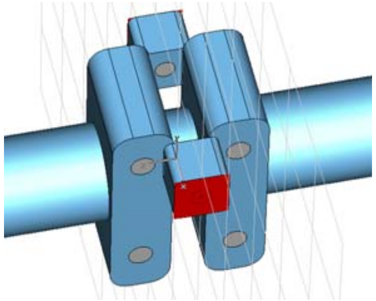


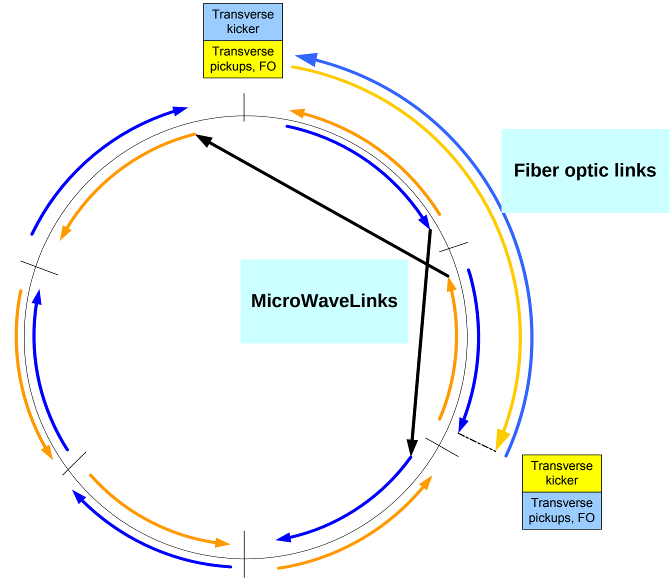
Luminosity Increase with Full Stochastic Cooling



- 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







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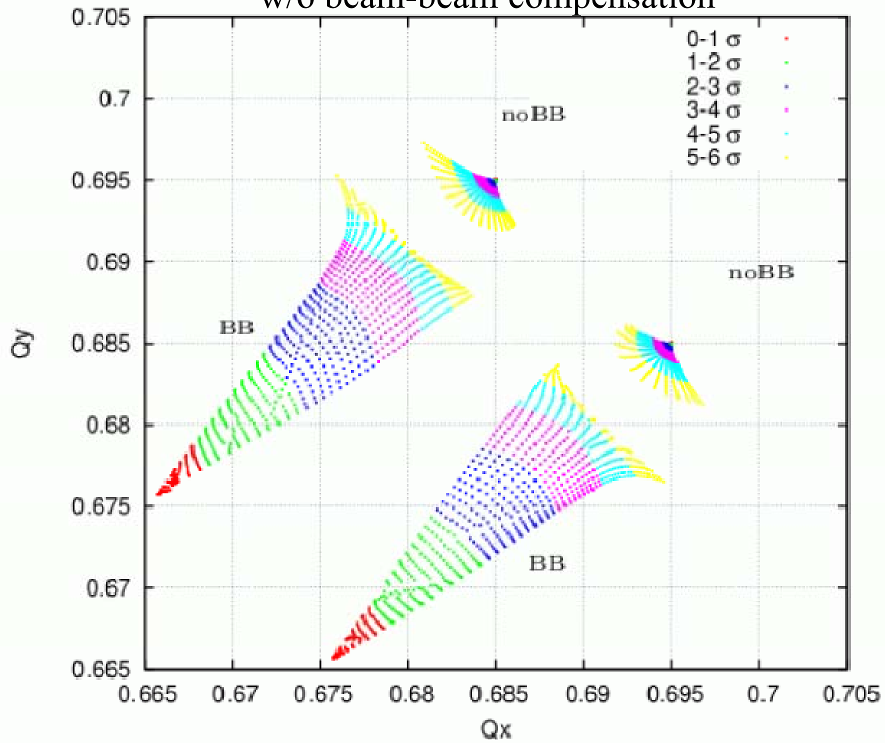
Longitudinal kickers Transverse kickers

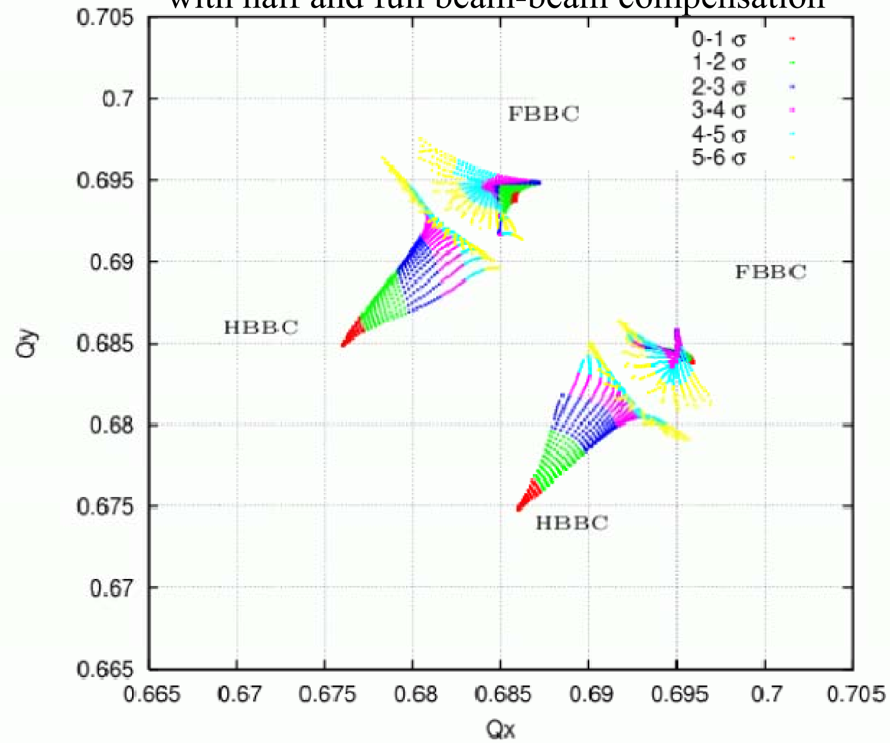
Electron Lenses for pp Operation

- Polarized proton luminosity is limited by head-on beam-beam tune spread
- Low energy electron beam interacting with proton beam can compensate head-on beam-beam tune spread (× 2 - 4 luminosity?)
- Single and multi particle simulation underway

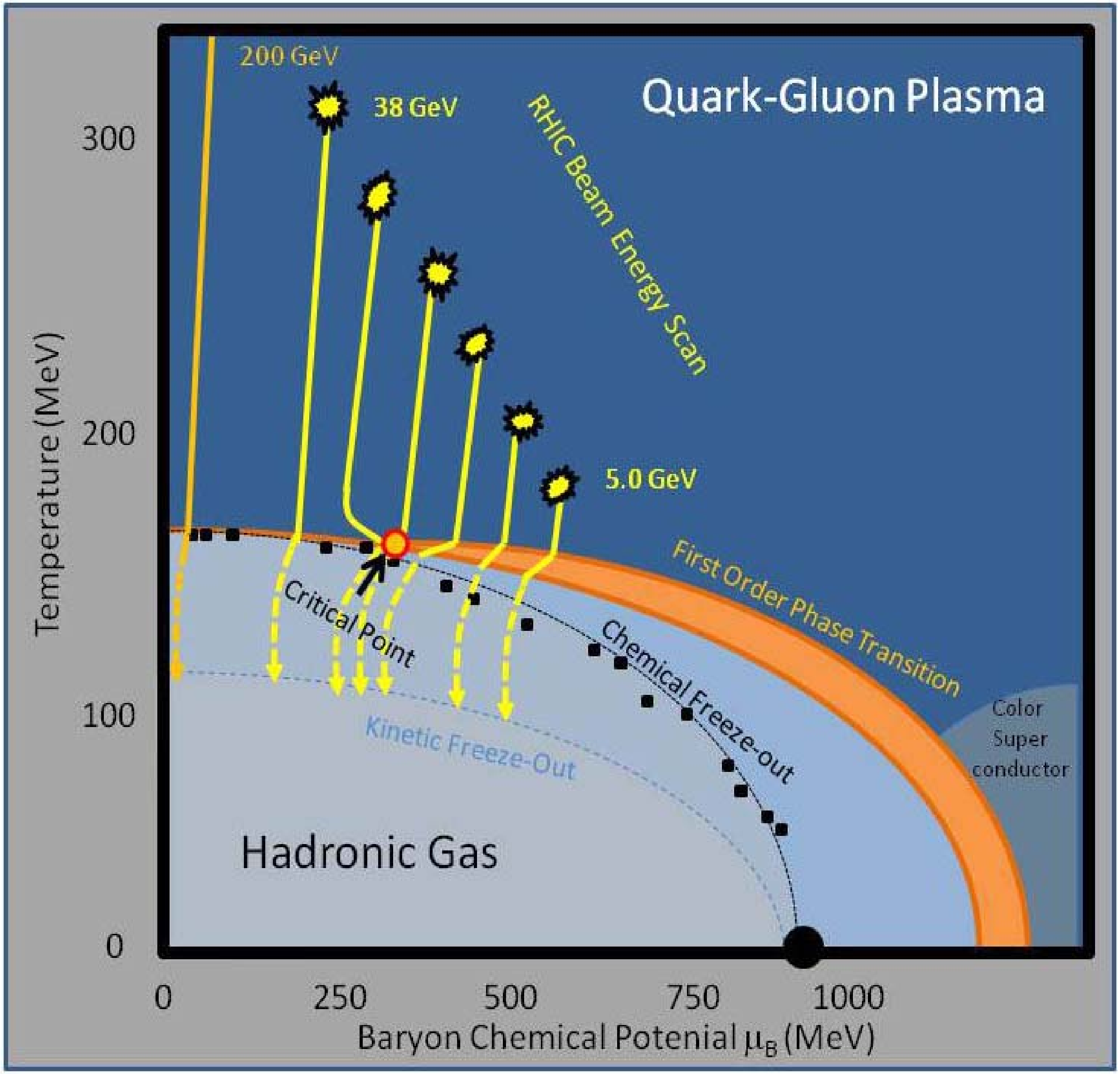
w/o beam-beam compensation



with half and full beam-beam compensation



QCD Critical Point Search



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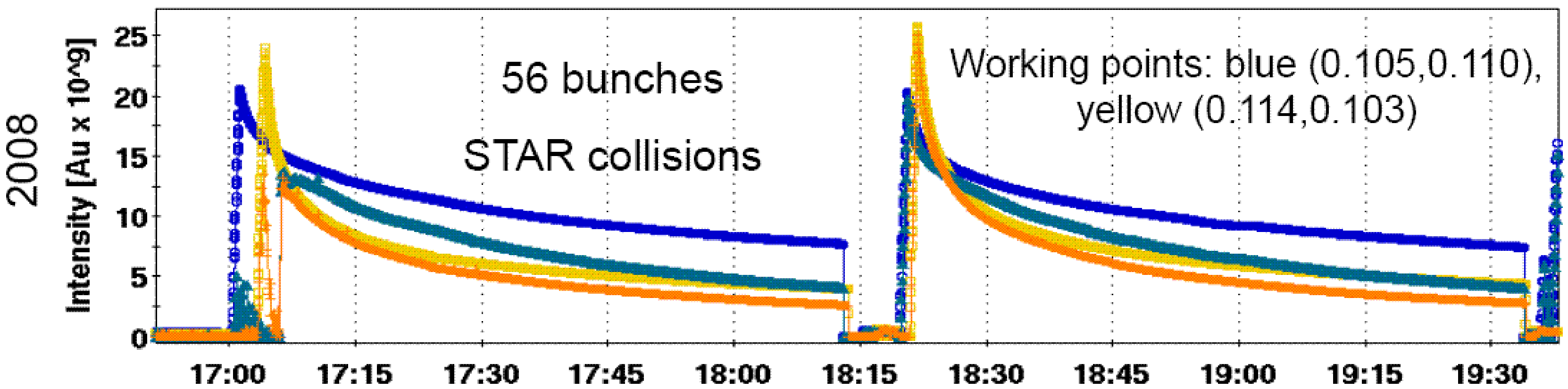
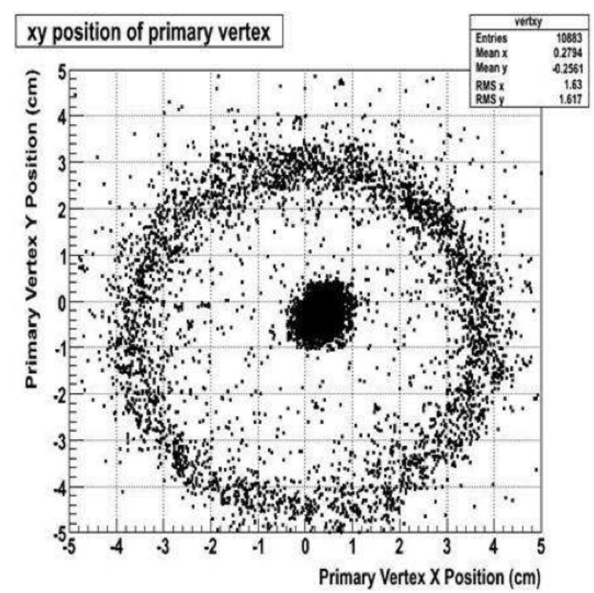
Tests of √s = 9 GeV Au - Au operation in RHIC

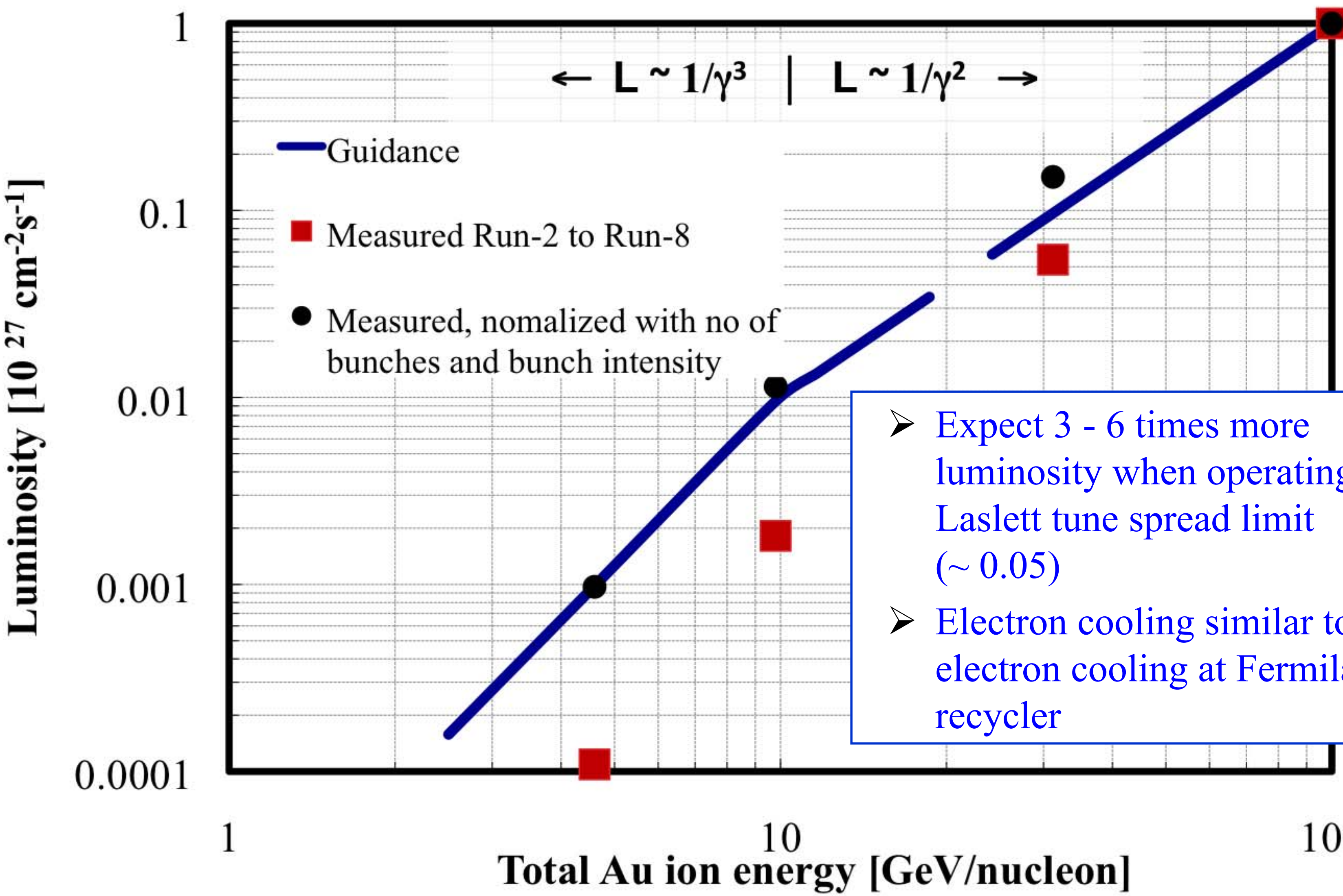


- Operation below regular injection energy with large b2 corrections
- Collisions clearly identifiable in detectors
- Luminosity as expected



Vertex reconstruction at STAR

Au – Au luminosity scaling with energy



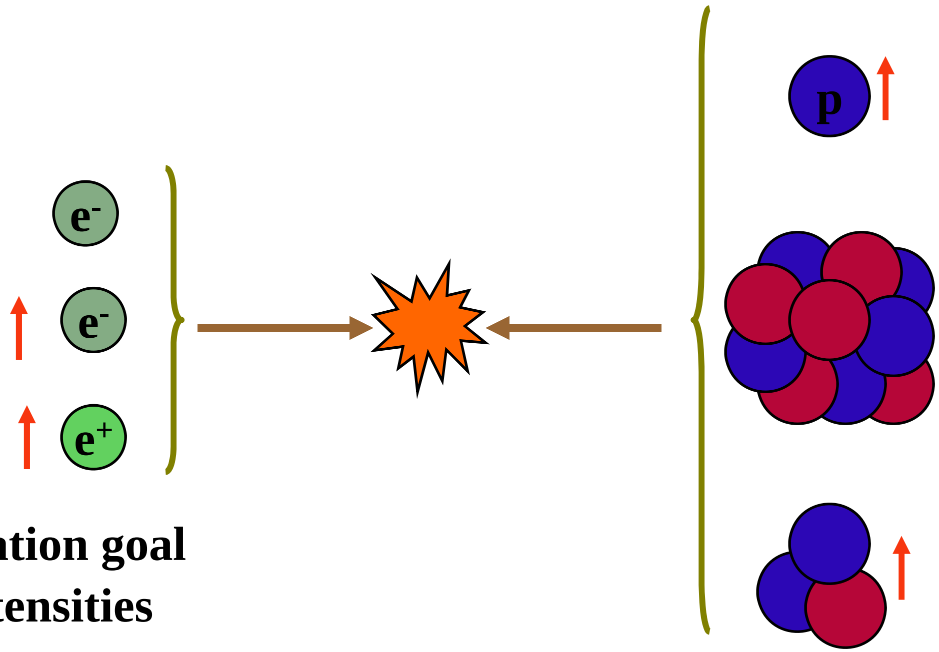
- Expect 3 - 6 times more luminosity when operating at Laslett tune spread limit (~ 0.05)
- Electron cooling similar to electron cooling at Fermilab recycler

eRHIC

Electron accelerator

RHIC

Unpolarized and polarized leptons
3 - 10 (30) GeV



Polarized protons
25 - 250 (325) GeV

Heavy ions (Au)
20 - 100 (130) GeV/n

Polarized light ions
d,He^3: 125,167 GeV/n

70% beam polarization goal
Positrons at low intensities

Center mass energy range: 15 - 100 (200) GeV

Note: eA program for eRHIC needs as high an electron energy as possible even with a trade-off for the luminosity: up to 30 GeV would be possible.

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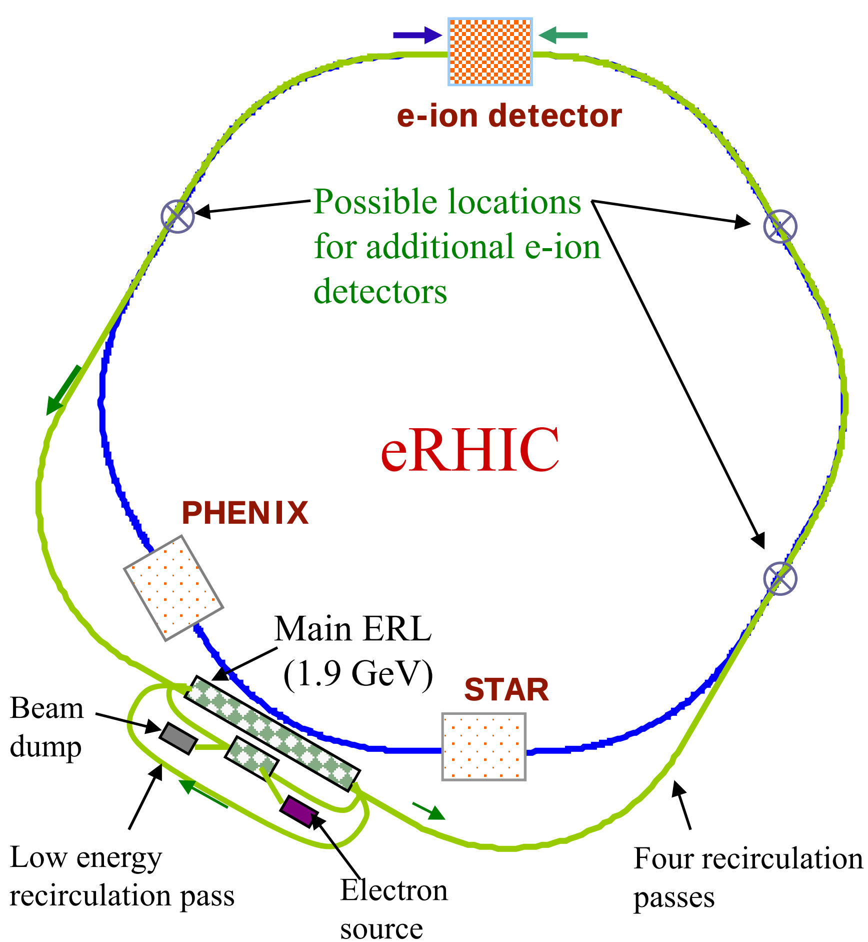
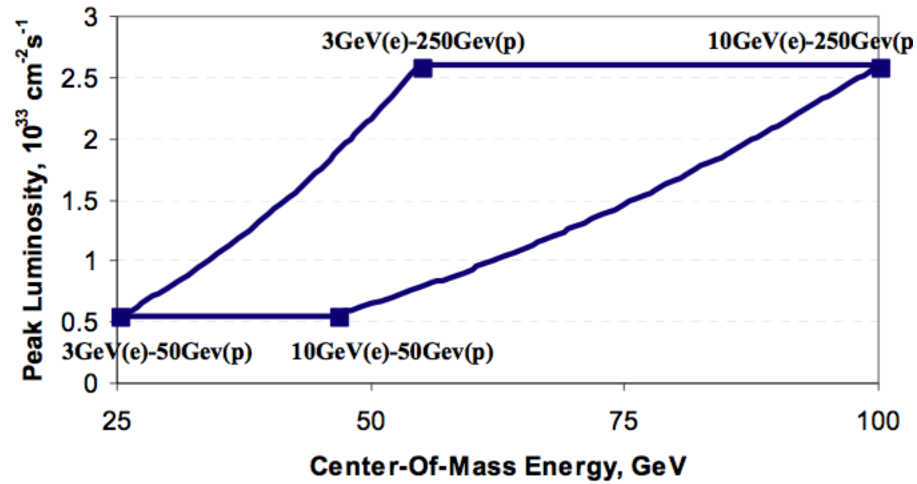
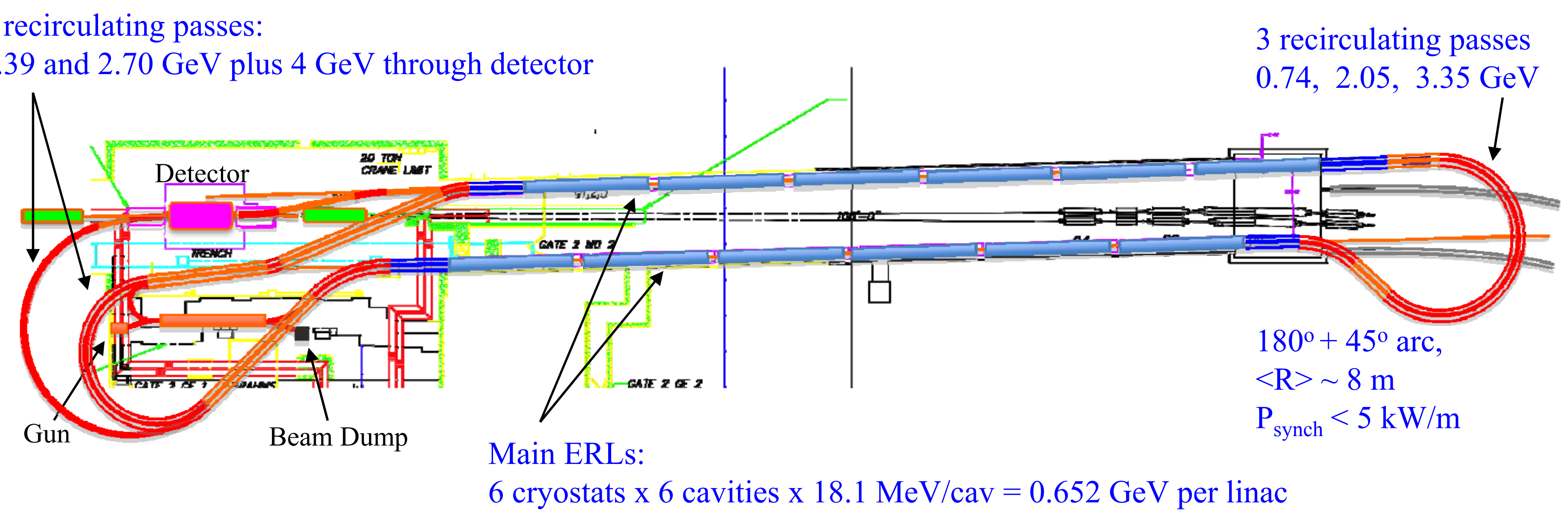
ERL-based Linac-Ring eRHIC





- 10 GeV electron design energy. Possible upgrade to 20 – 30 GeV.
- Peak luminosity: 3×10^{33} cm^{-2} s^{-1}
- 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

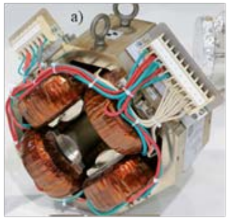
1. stage: Medium Energy eRHIC in RHIC tunnel

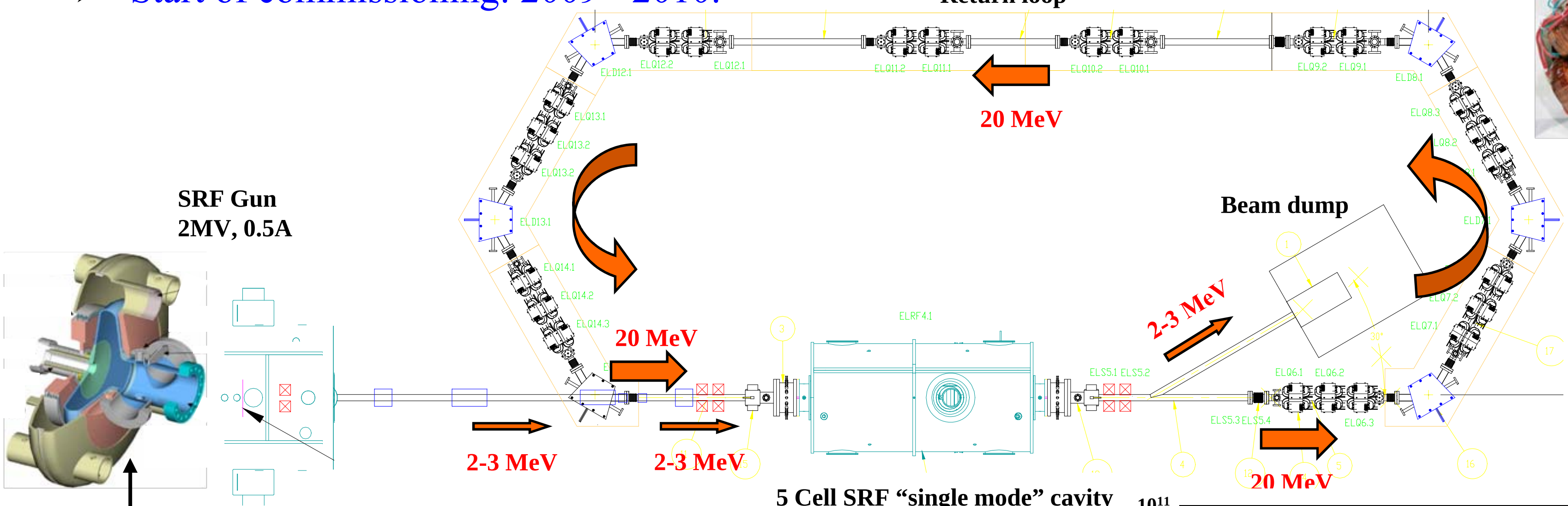


- 250 GeV p↑ × 4 GeV e↑ or 100 GeV Au × 4 GeV e
- Peak luminosity: 1×10^{32} cm^{-2} s^{-1}

Energy Recovery Linac Test Facility

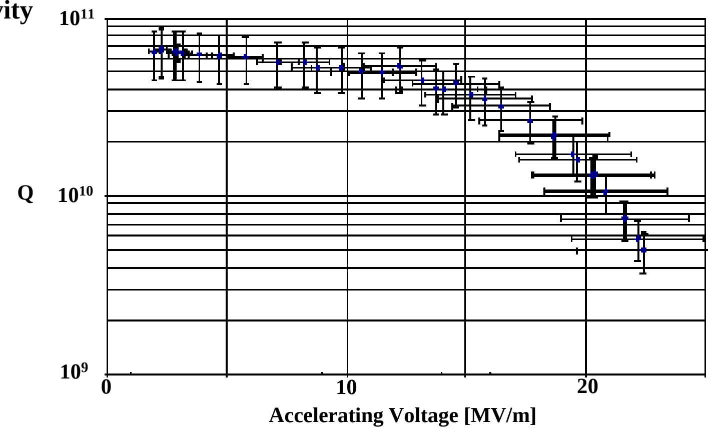
- Test of high current (0.5 A), high brightness ERL operation
- Electron beam for RHIC (coherent) electron cooling (54 MeV, 10 MHz, 5 nC, 4 μm)
- Test for 10 – 20 GeV high intensity ERL for eRHIC
- Test of high current beam stability issues, highly flexible return loop lattice
- Allows for addition of a 2nd recirculation loop
- Start of commissioning: 2009 - 2010.





SRF Photocathode gun powered by 1 MW, 703.75 MHz CW Klystron

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



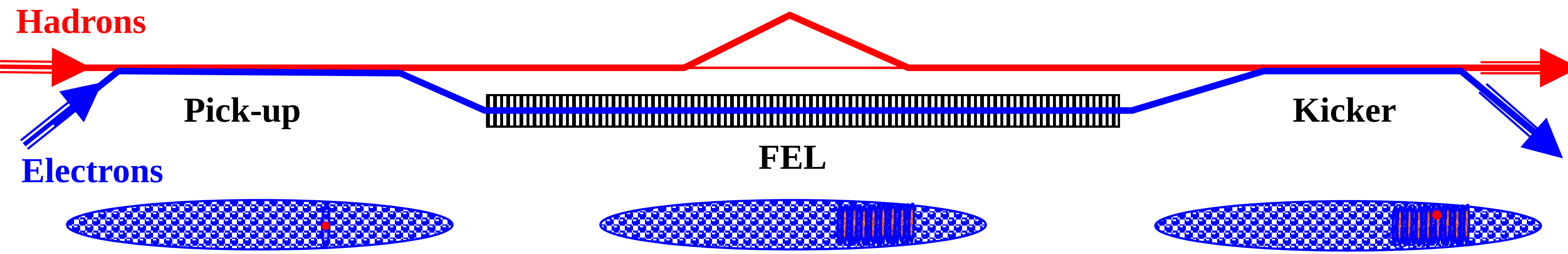
Coherent Electron Cooling

- 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 % average beam polarization

Future runs / upgrade plans:

- Uranium beams from EBIS
- Luminosity upgrade to 40×10^{26} cm^{-2} s^{-1} through high energy beam cooling
- High luminosity 250 x 250 GeV polarized proton run at 2×10^{32} cm^{-2} s^{-1} and later at $6 - 12 \times 10^{32}$ cm^{-2} s^{-1}
- Low energy Au-Au collisions for critical point search
- High luminosity polarized electron ion collider
  - MeRHIC: 250 GeV p↑ x 4 GeV e↑ ; 1×10^{32} cm^{-2} s^{-1}
  - eRHIC: 250 GeV p↑ x 10 GeV e↑ ; 3×10^{33} cm^{-2} s^{-1}

Back-up Slides

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
Ave. delivered 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
Ave. delivered luminosity**	10^{30} cm^{-2}s^{-1}	23	80 (200)
Polarization	%	60	70

* 5 × 'enhanced' luminosity and 20 × design luminosity
** without vertex cuts

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ERL-based eRHIC Parameters

	Electron-Proton Collisions				Electron-Au Collisions			
	High energy		Low energy		High energy		Low energy	
	p	e	p	e	Au	e	Au	e
Energy, GeV	250	10	50	3	100	10	50	3
Number of bunches	166		166		166		166	
Bunch spacing, ns	71	71	71	71	71	71	71	71
Bunch intensity, 10^{11} (10^{9} for Au)	2.0	1.2	2.0	1.2	1.1	1.2	1.1	1.2
Beam current, mA	420	260	420	260	180	260	180	260
95% normalized emittance, πμm	6	460	6	570	2.4	460	2.4	270
Rms emittance, nm	3.8	4.0	19	16.5	3.7	3.8	7.5	7.8
β*, cm	26	25	26	30	26	25	26	25
Beam-beam parameters	0.015	0.59	0.015	0.47	0.015	0.26	0.015	0.43
Rms bunch length, cm	20	1.0	20	1.0	20	1.0	20	1.0
Polarization, %	70	80	70	80	0	0	0	0
Peak Luminosity/n, 10^{33} $cm^{-2}s^{-1}$	**2.6**		**0.53**		**2.9**		**1.5**	
Aver.Luminosity/n, 10^{33} $cm^{-2}s^{-1}$	**0.87**		**0.18**		**1.0**		**0.5**	
Luminosity integral /week, pb^{-1}	**530**		**105**		**580**		**290**	

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If effective high energy transverse cooling becomes possible the required electron beam current can be reduced to 50 mA, maintaining the same luminosity.

Medium Energy eRHIC parameters for e-p collisions

	no cooling of protons; parallel to RHIC ops		pre-cooled proton beam		high energy cooling of proton beam	
	p	e	p	e	p	e
Energy, GeV	250	4	250	4	250	4
Number of bunches	111		111		111	
Bunch intensity, 10^{11}	2.0	0.31	2.0	0.31	2.0	0.31
Beam current, mA	320	50	320	50	320	50
95% normalized emittance, $\pi\mu m$	15	440	6	175	1.5	44
Rms emittance, nm	9.4	9.4	3.8	3.8	0.94	0.94
β^*, cm	50	50	50	50	50	50
rms bunch length, cm	20	0.2	20	0.2	5	0.2
beam-beam parameter	0.002	0.44	.004	0.69	0.015	0.69
disruption parameter		3.1		7.7		7.7
Peak Luminosity, 10^{32} $cm^{-2}s^{-1}$	**0.93**		**2.3**		**9.3**	

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