Relativistic Heavy Ion Collider Status and Plans

RHIC overview

Luminosity and polarization evolution

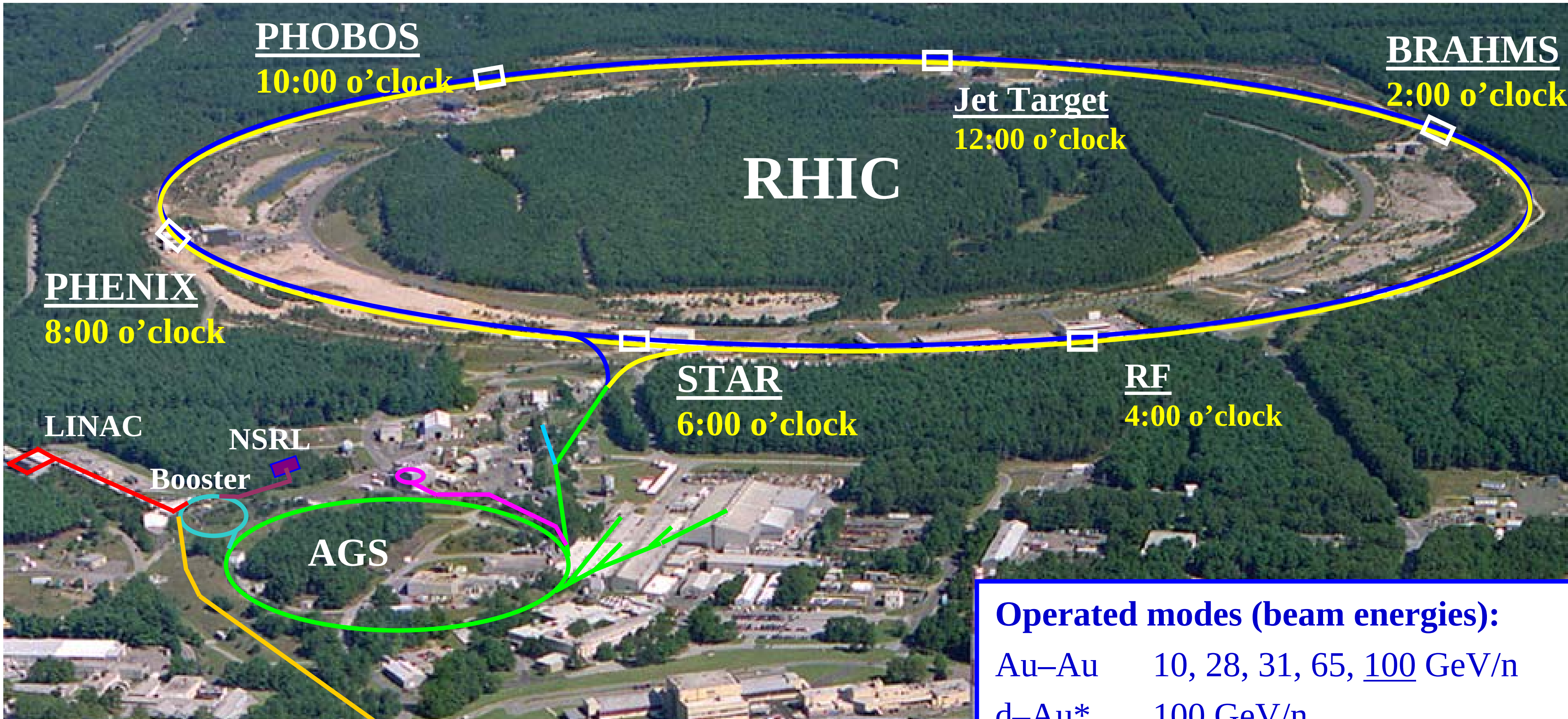
Performance limitations

RHIC II luminosity upgrade

BROOKHAVEN NATIONAL LABORATORY

Thomas Roser
APAC 2007
January 30, 2007

RHIC – a High Luminosity (Polarized) Hadron Collider



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

Au–Au	58×10^{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)	28×10^{30} cm^{-2} s^{-1}
LHC (p – p, design)	140×10^{30} cm^{-2} s^{-1}

Operated modes (beam energies):

Au–Au	10, 28, 31, 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>, 205, 250 GeV

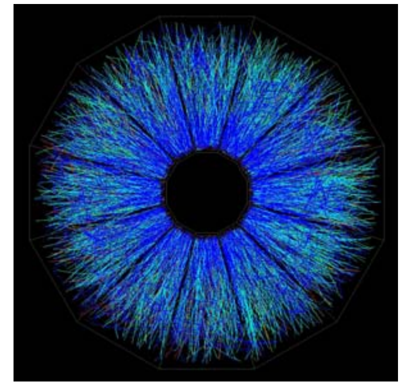
Possible future modes:

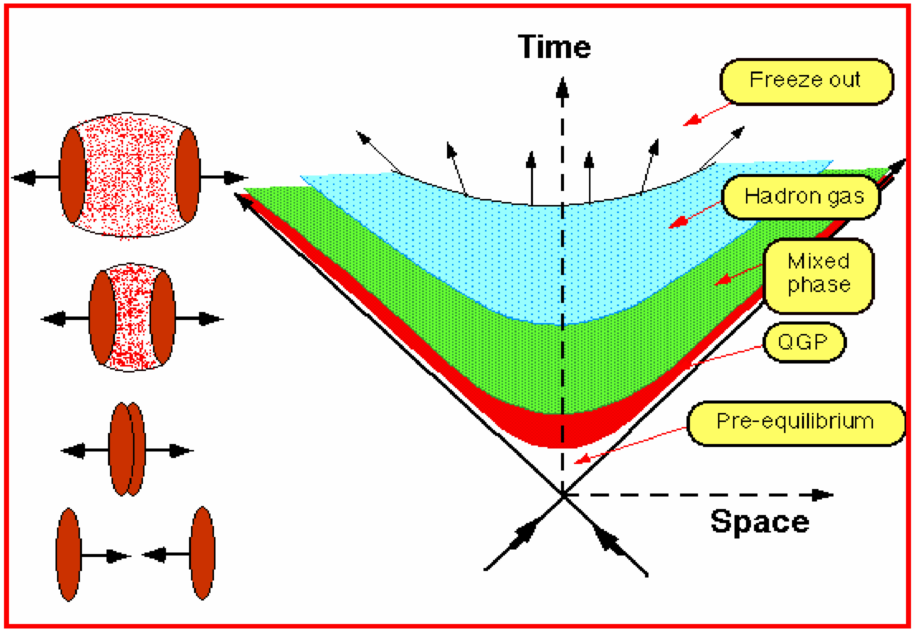
Au – Au	2.5 GeV/n (AGS, SPS c.m. energy)
p↑ – Au*	100 GeV/n (*asymmetric rigidity)

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)





a. **Formation phase -**
parton scattering

b. **Hot and dense phase -**
→ strongly interacting hot dense material (sQGP, "perfect liquid")

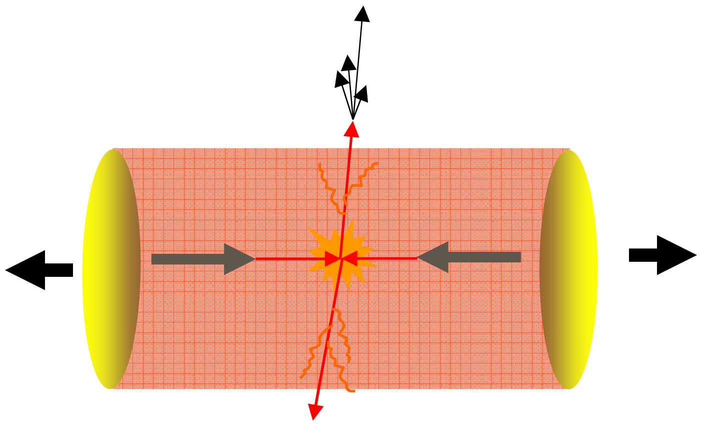
c. **Freeze-out –**
emission of hadrons

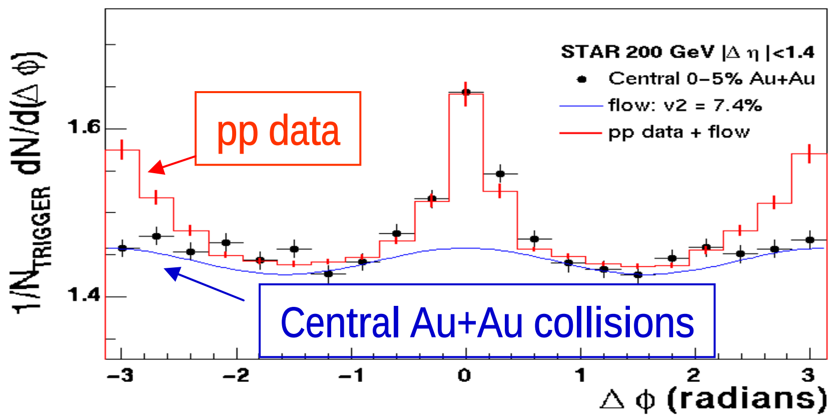
Produce and explore a new state of matter

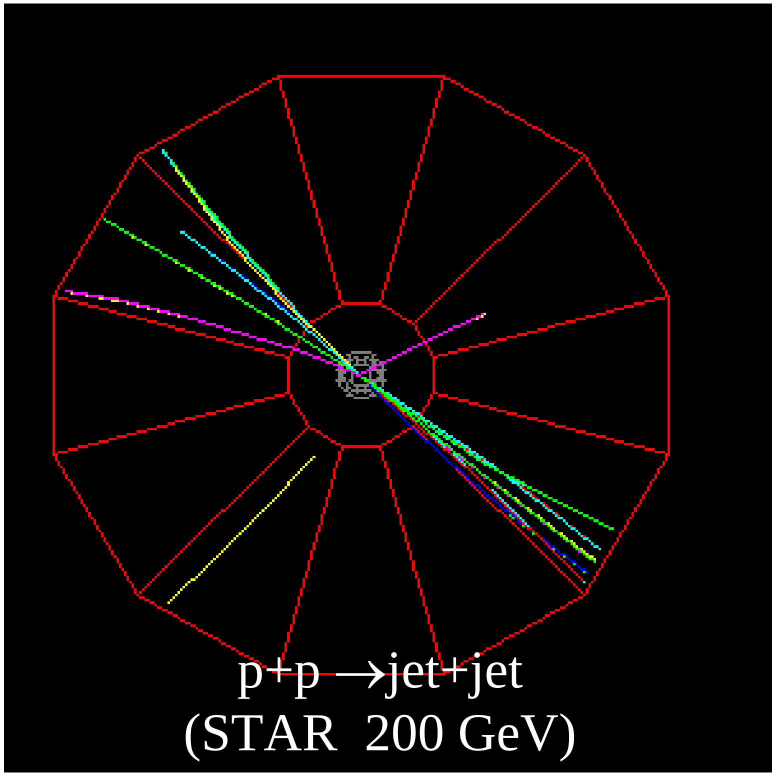
Animation by Jeffery Mitchell (Brookhaven National Laboratory). Simulation by the UrQMD Collaboration

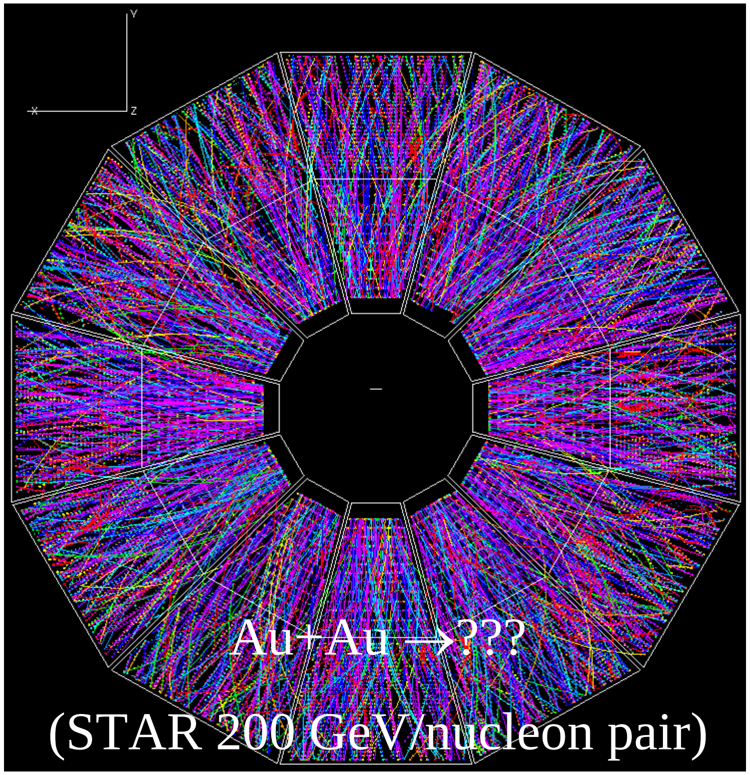
BROOKHAVEN NATIONAL LABORATORY

Hard Scattering at RHIC

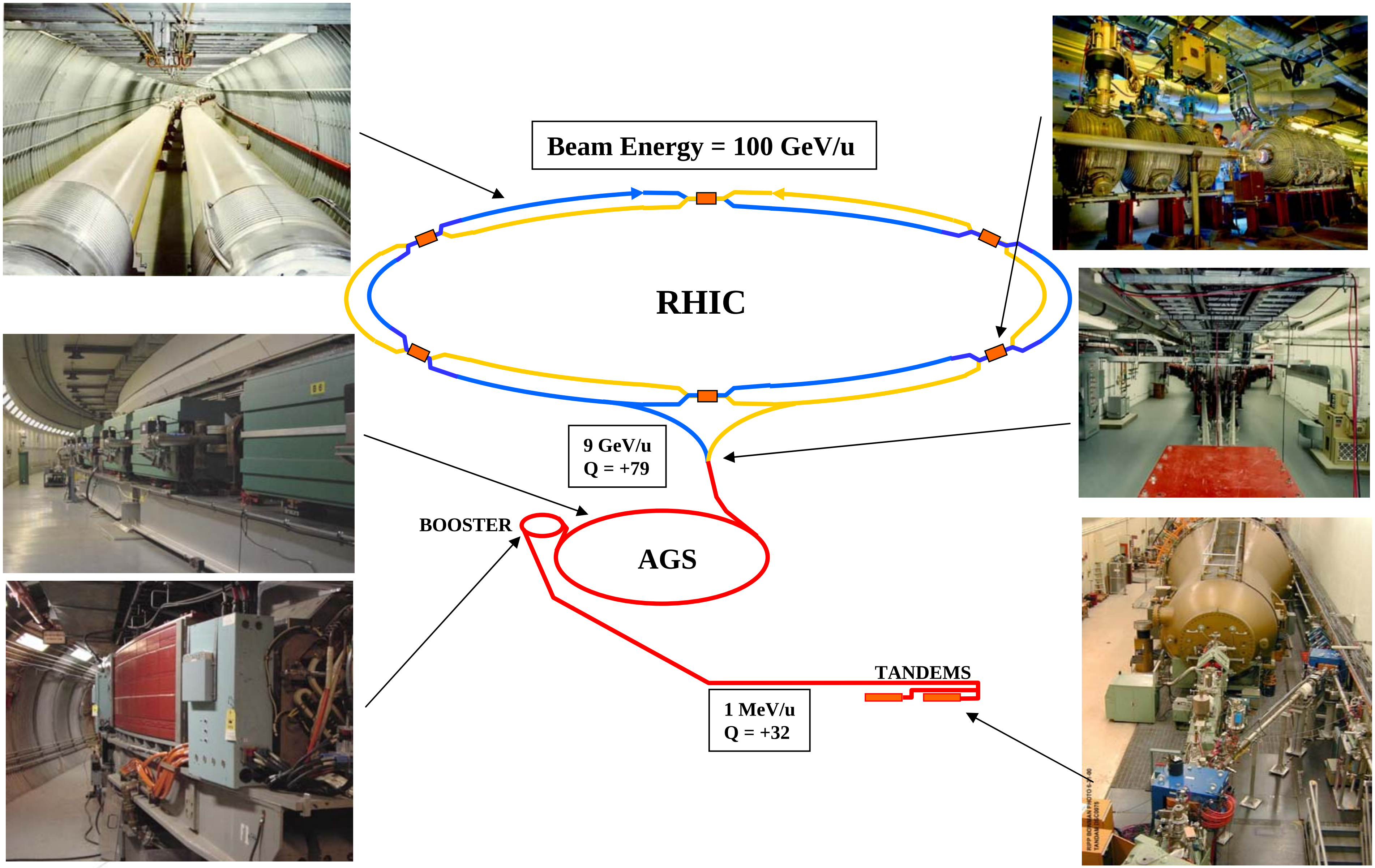








Gold Ion Collisions in RHIC



RHIC Design and Achieved Parameters

Mode	No of bunches	Ions/bunch [10^9]	β* [m]	Beam pol.	$\mathcal{L}_{store\ ave}$ [$cm^{-2}s^{-1}$]	$A_1A_2\mathcal{L}_{store\ ave}$ [$cm^{-2}s^{-1}$]	$A_1A_2\mathcal{L}_{peak}$ [$cm^{-2}s^{-1}$]
Design values (1999)							
Au – Au	56	1.0	2		2×10^{26}	8×10^{30}	31×10^{30}
p – p	56	100	2		4×10^{30}	4×10^{30}	5×10^{30}
Achieved values (up to 2006)							
Au – Au	45	1.1	1		4×10^{26}	16×10^{30}	58×10^{30}
d – Au	55	120/0.7	2		2×10^{28}	8×10^{30}	28×10^{30}
Cu – Cu	37	4.5	0.9		80×10^{26}	32×10^{30}	79×10^{30}
p↑ – p↑	111	130	1	65%	20×10^{30}	20×10^{30}	35×10^{30}
Enhance design values (2009)							
Au – Au	111	1.1	0.9		8×10^{26}	31×10^{30}	155×10^{30}
p↑ – p↑	111	200	0.9	70%	60×10^{30}	60×10^{30}	90×10^{30}

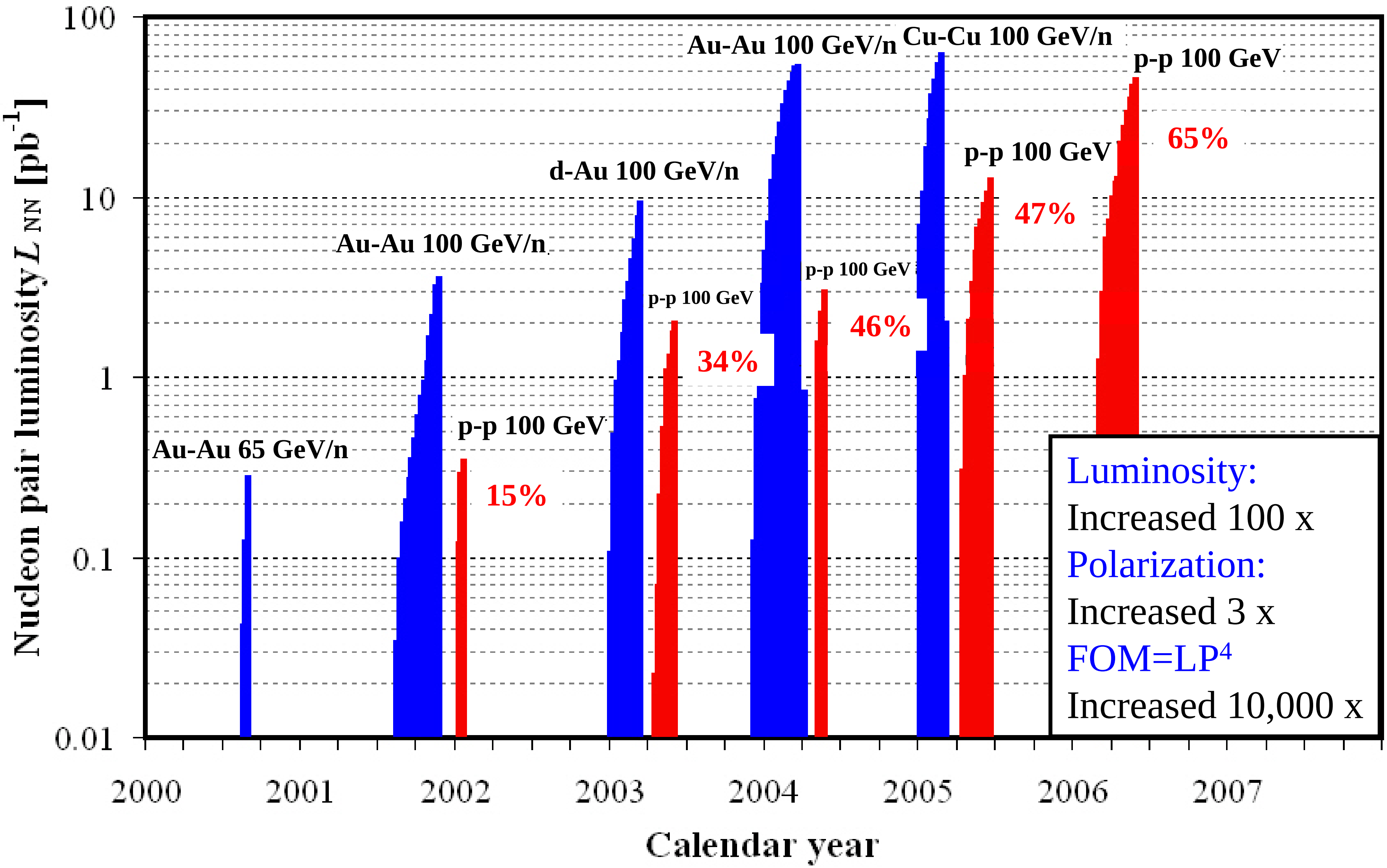
$$\mathcal{L} = \frac{3 f_{rev}\gamma}{2}\frac{N_B N_{Ion}^2}{\varepsilon\beta^*}$$

Other high luminosity hadron colliders:

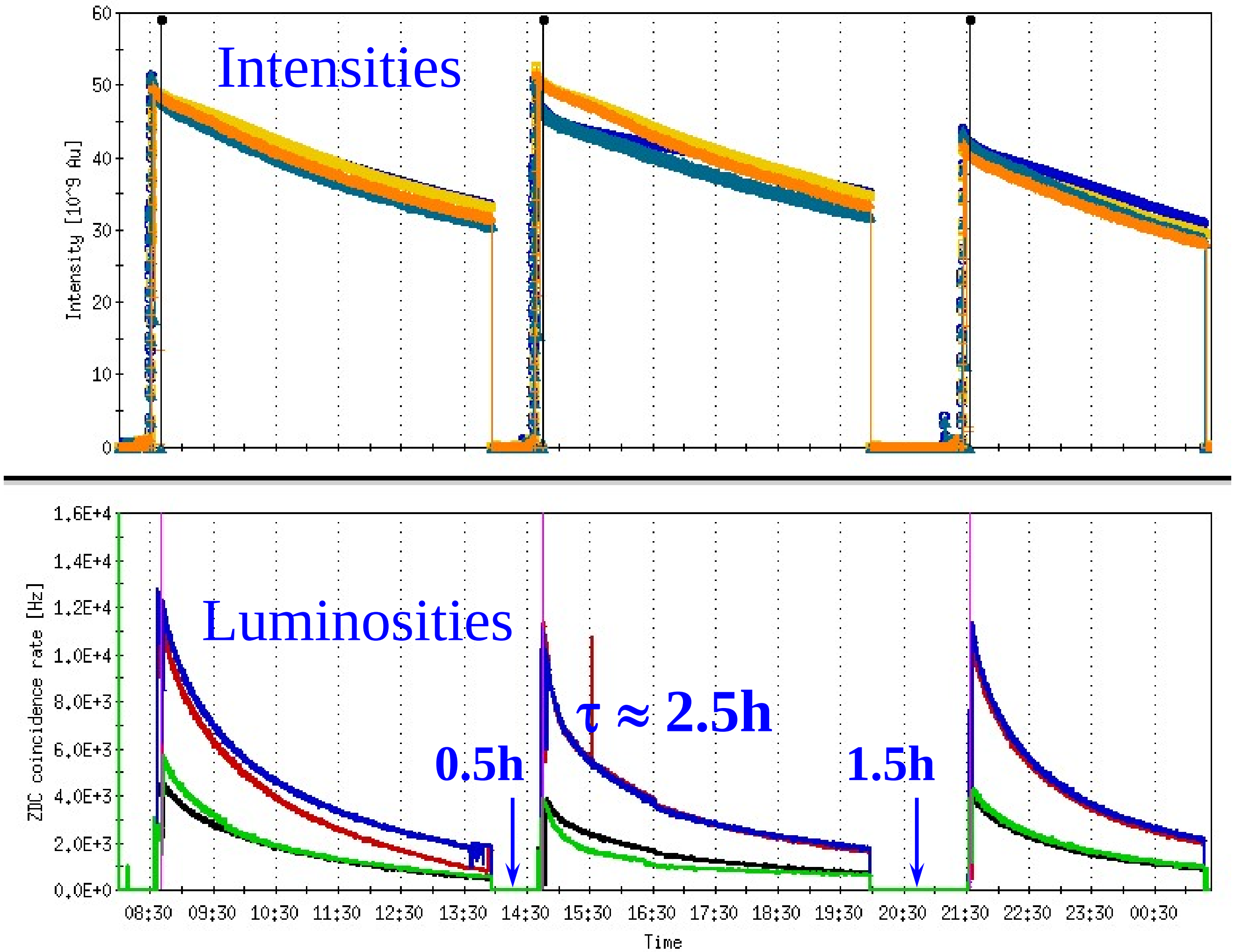
	achieved	goal	scaled to 200 GeV
Tevatron (2 TeV)	280×10^{30}	200×10^{30}	28×10^{30}
LHC (14 TeV)		10000×10^{30}	140×10^{30}

BROOKHAVEN NATIONAL LABORATORY

Delivered Luminosity and Polarization during Last 5 Years



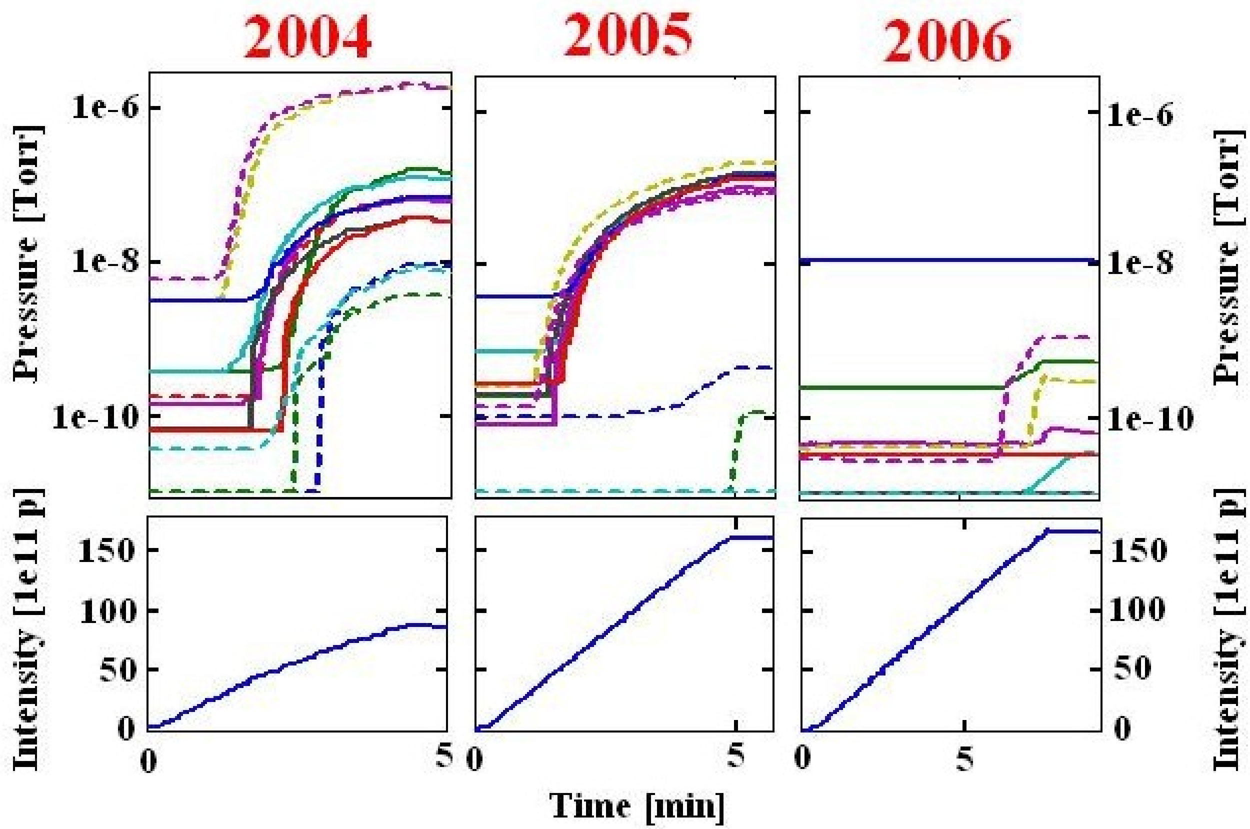
Luminosity Limit – Intra-Beam Scattering (IBS)



- Debunching requires continuous gap cleaning
- Luminosity lifetime requires frequent refills
- Ultimately need cooling at full energy

BROOKHAVEN NATIONAL LABORATORY

Luminosity Limit: Dynamic Pressure Rise



Dynamic pressure rise caused by electron clouds

Upgraded warm and cold vacuum system:

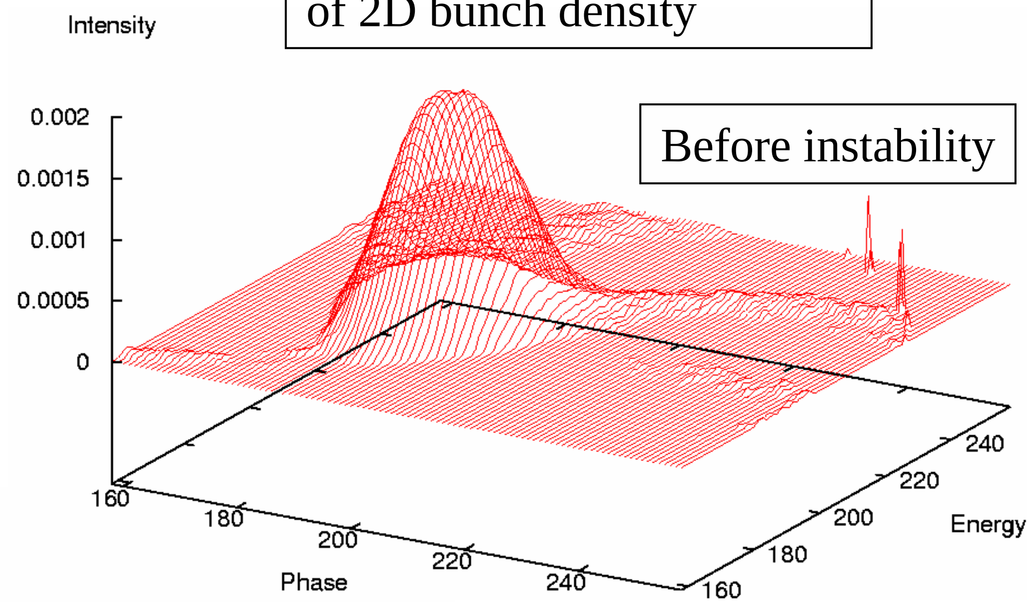
- installed 430m of NEG-coated pipes (~700m warm sections)
- reduced pressure in cold section to 10^{-7} Torr before cool-down

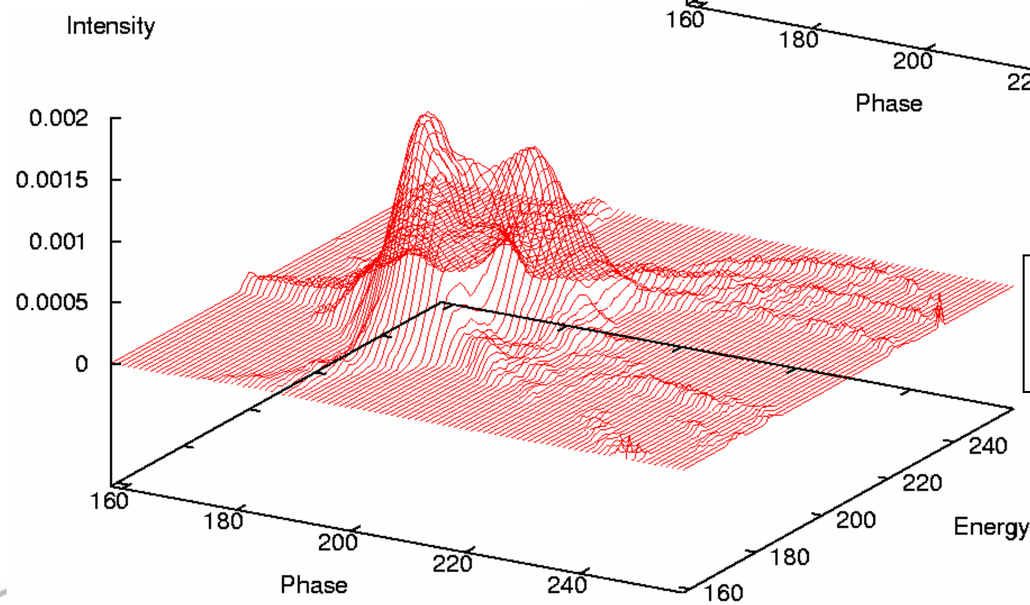
Dynamic pressure currently not a concern during operation

Luminosity Limit – Fast Instability Near Transition

- Fast transverse instability (~ GHz)
- High sensitivity around transition
- Effect of broadband impedance and electron clouds
- Cures: beam-beam tune spread, octupoles, adjust crossing of zero-chromaticity, suppress electron clouds

Tomographic reconstruction of 2D bunch density



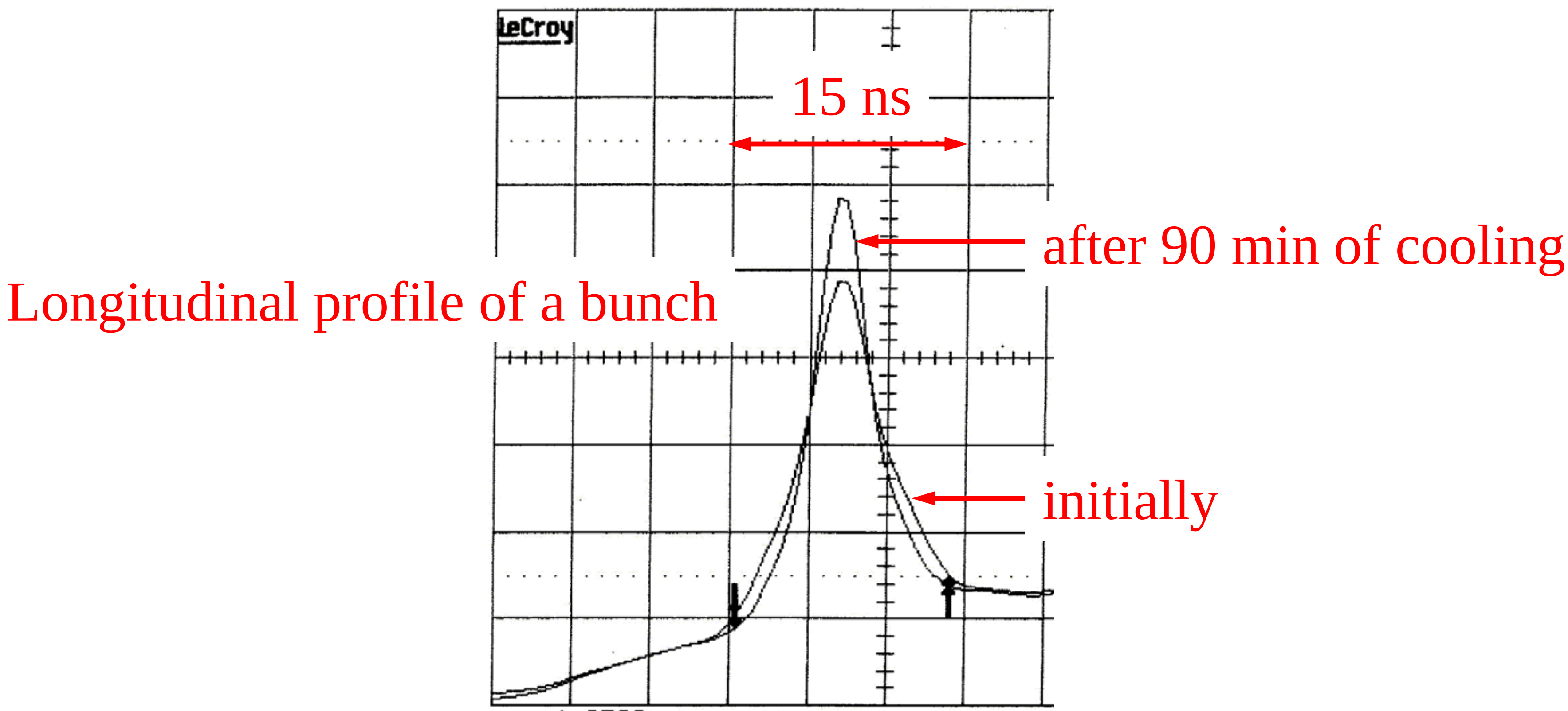


After instability with ~ 10 ms growth rate

BROOKHAVEN NATIONAL LABORATORY

High Energy Bunched Beam Stochastic Cooling

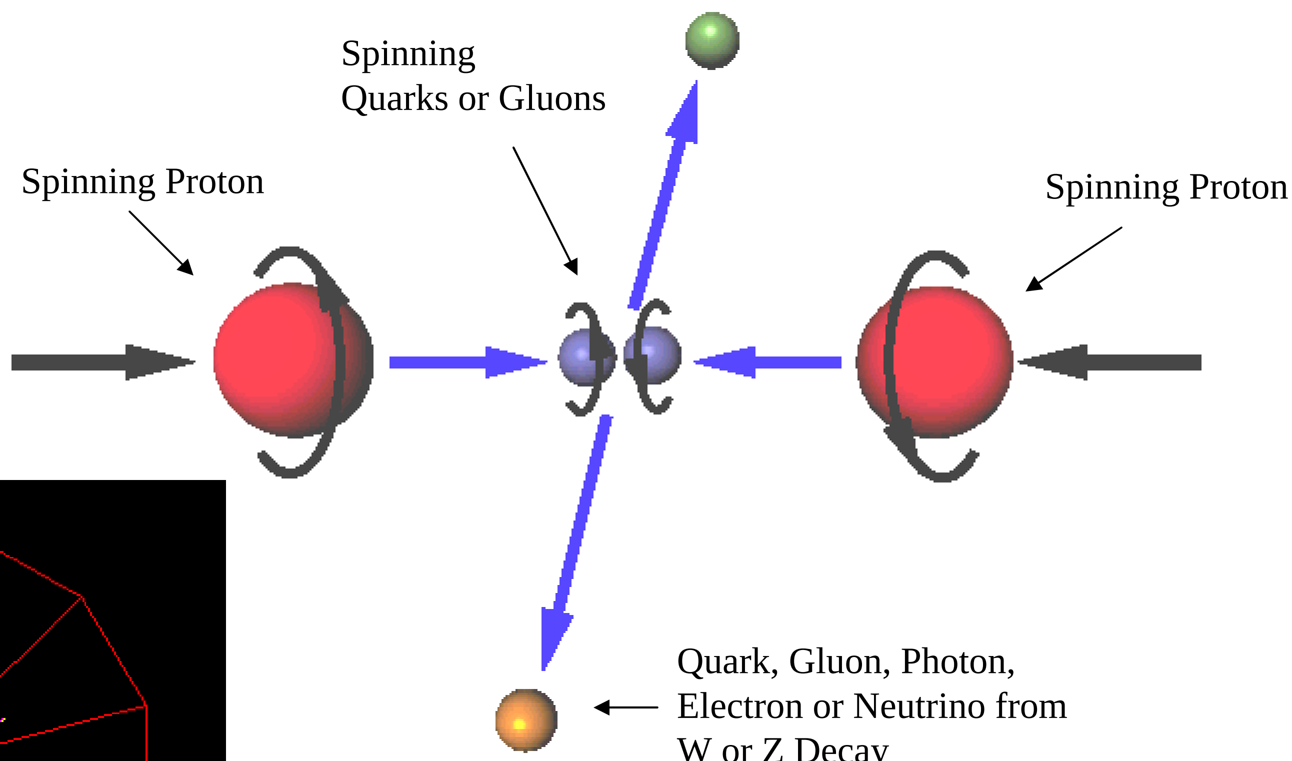
Recently demonstrated longitudinal stochastic cooling in bunch of 2×10^9 protons at 100 GeV (~1% of normal p intensity, ~ normal Au intensity)
[M. Brennan, M. Blaskiewicz]

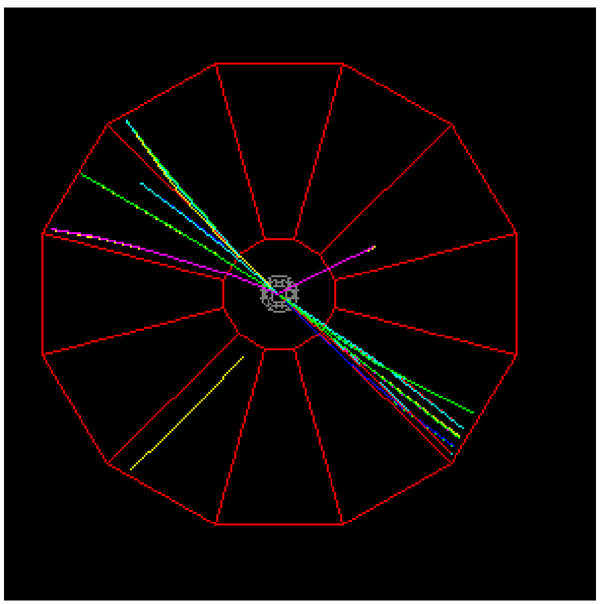


Expect to stop debunching of Au beams → 20-50% more luminosity

BROOKHAVEN
NATIONAL LABORATORY

RHIC Spin Physics

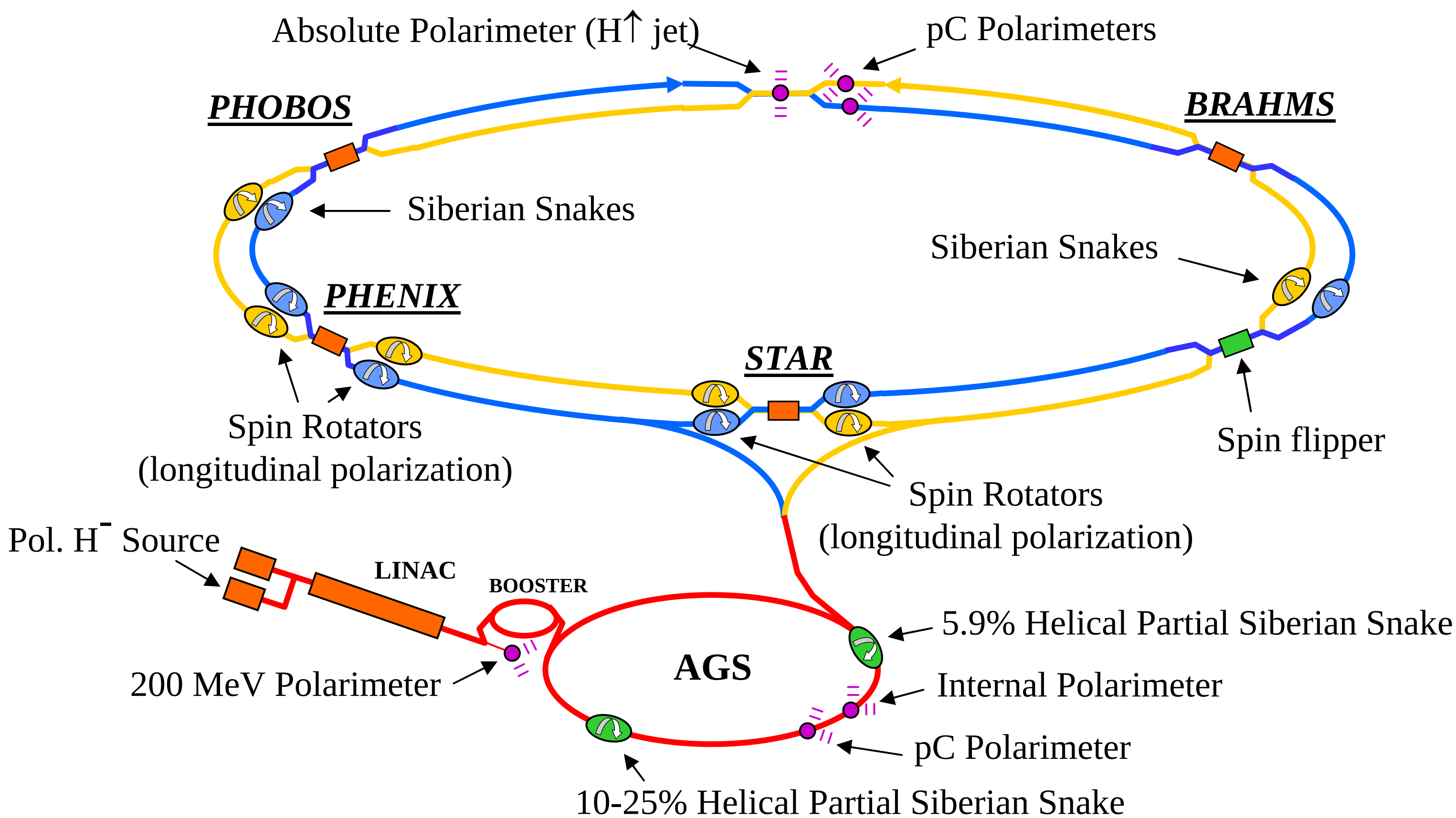




- Spin structure functions of gluon and anti-quarks
- Parity violation in parton-parton scattering
- Requires high beam polarization and high luminosity

BROOKHAVEN
NATIONAL LABORATORY

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

BROOKHAVEN NATIONAL LABORATORY

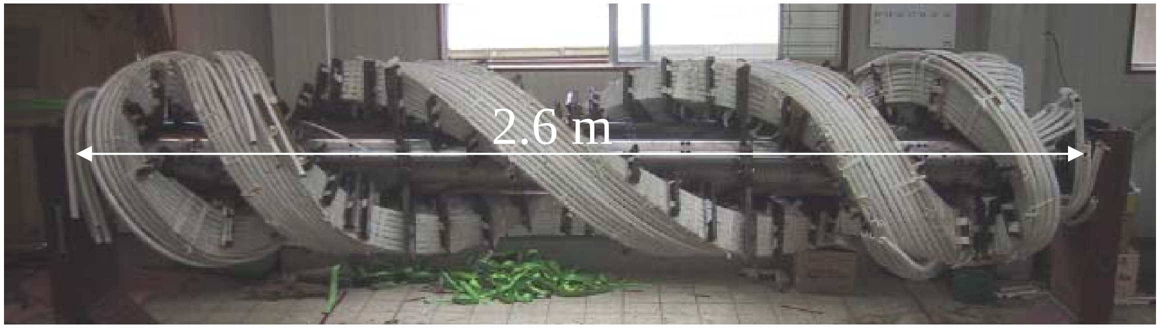
(Naïve) Requirements for Siberian Snake Strengths

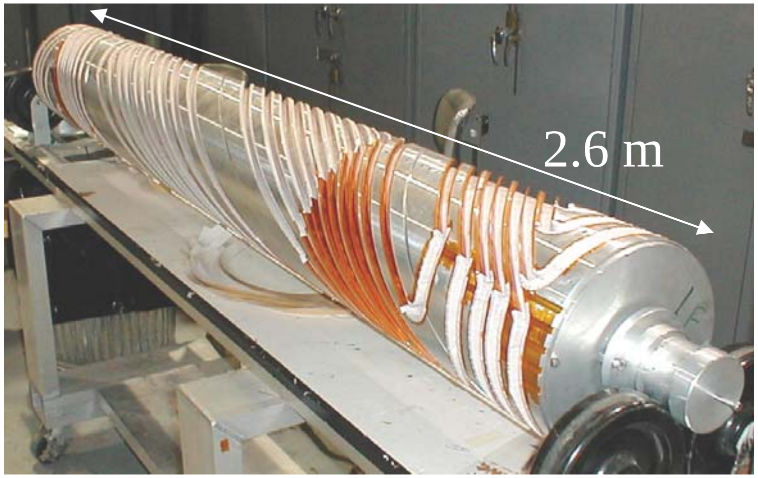
Total spin rotation of Siberian snakes (δ)

> Spin rotation of resonance driving fields per turn (ε)

Intrinsic spin resonances	$\varepsilon \propto \sqrt{\text{Energy}}$
Partial Siberian snakes in AGS ($\delta = 38°$)	$\varepsilon < 0.1$
One full snake ($\delta = 180°$)	$\varepsilon < 1/2$
Two full snakes in RHIC ($\delta = 360°$)	$\varepsilon < 1$
N full snakes (LHC? $N \approx 16$)	$\varepsilon < N/2$

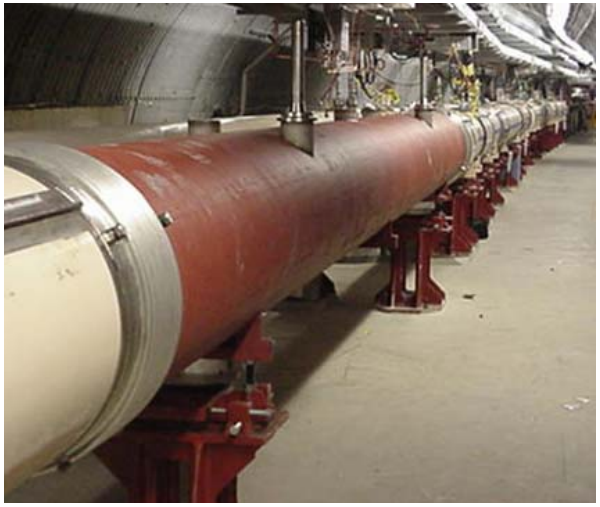
Siberian Snakes

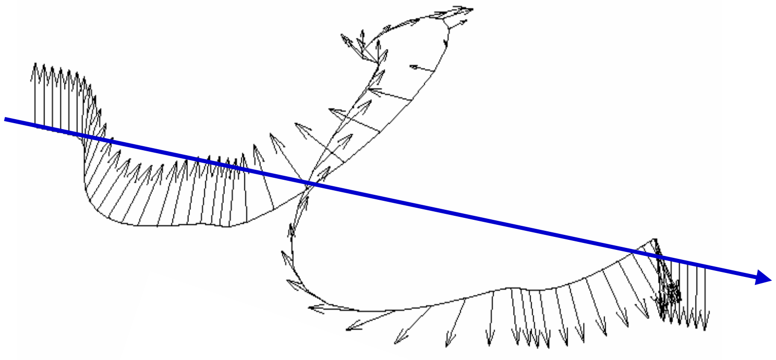


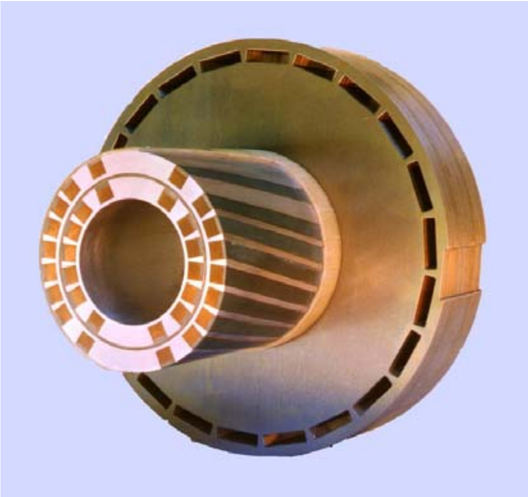


Major funding by RIKEN, Japan
RT helical dipole constructed at Tokano Ind., Japan
SC helical dipoles constructed at BNL

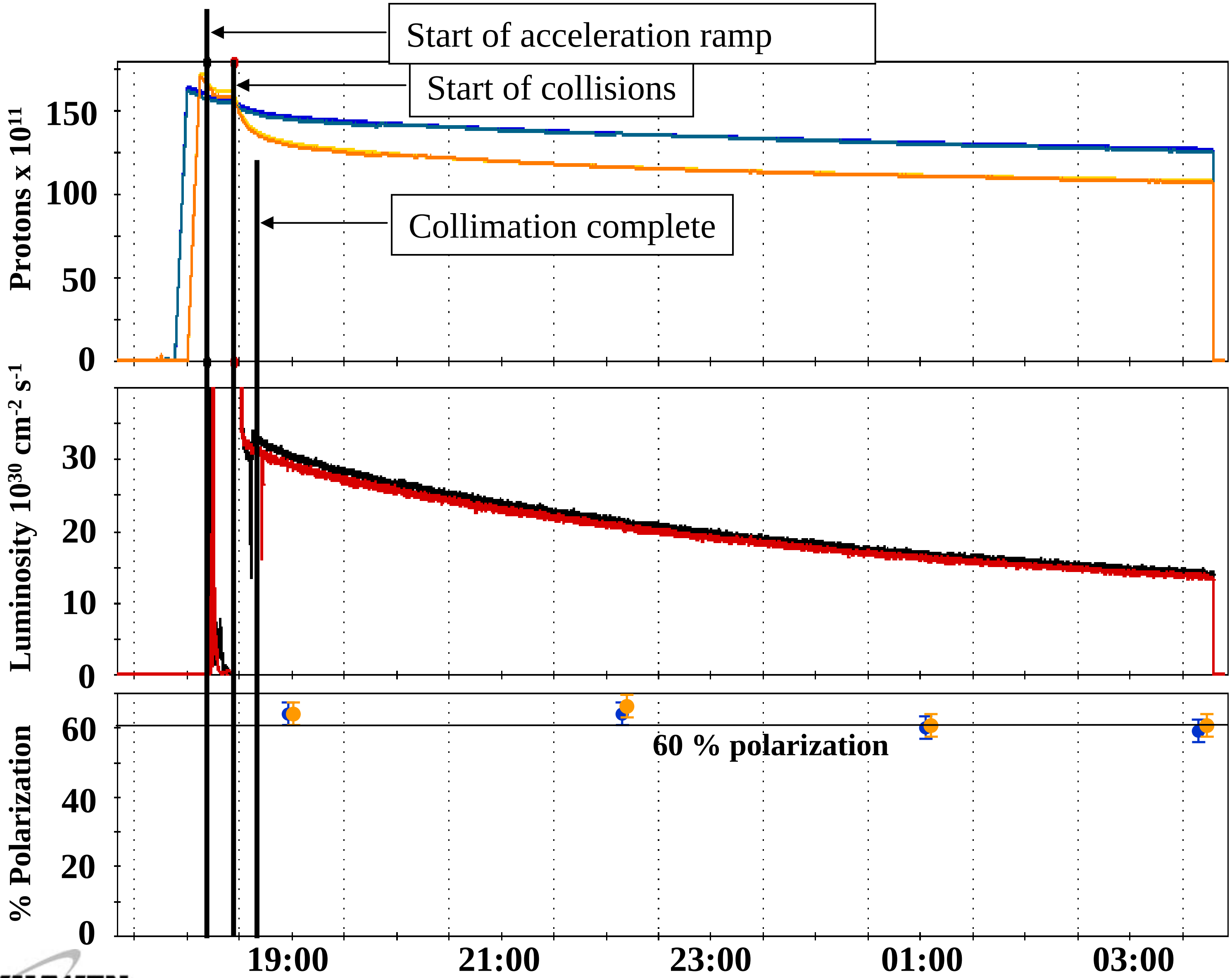
AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m
RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist







Luminosity and Polarization Lifetimes in RHIC



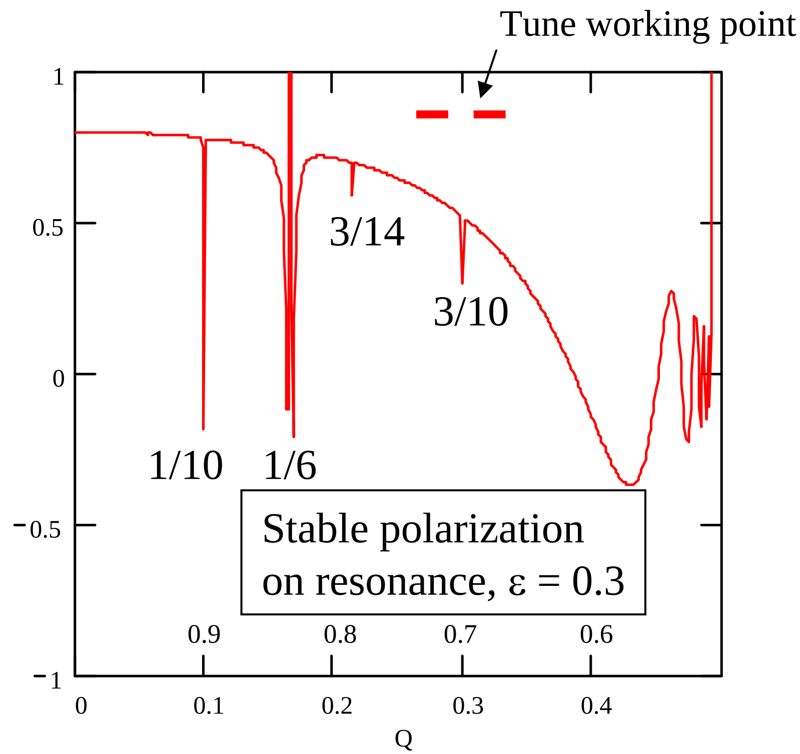
BROOKHAVEN
NATIONAL LABORATORY

Polarization with Snakes – Snake Resonances

$\nu_{sp} + (2m+1)Q_y = k$ (m, k = integer)

$\nu_{sp}=1/2 \rightarrow Q_y = (2k+1)/2(2m+1)$

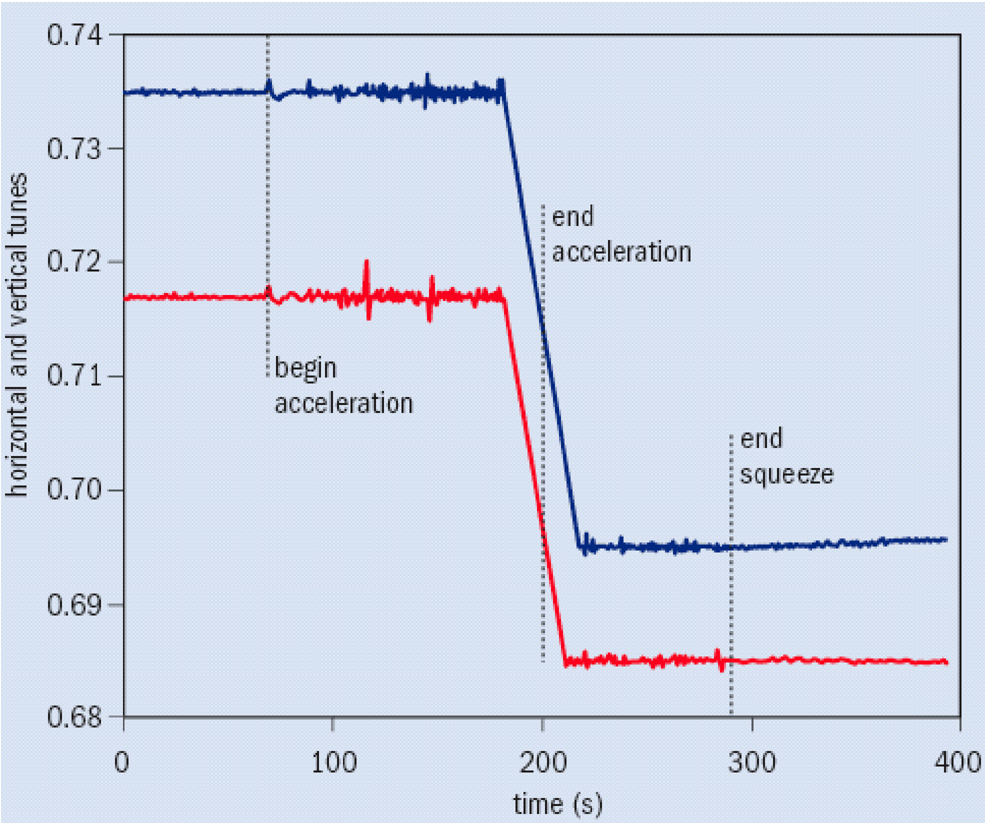
Subset of orbit resonance conditions



First analytical solution of isolated resonance with snakes
S.R. Mane, NIM A 498 (2003) 1

BROOKHAVEN NATIONAL LABORATORY

Beam-Based Tune and Coupling Feed-Back

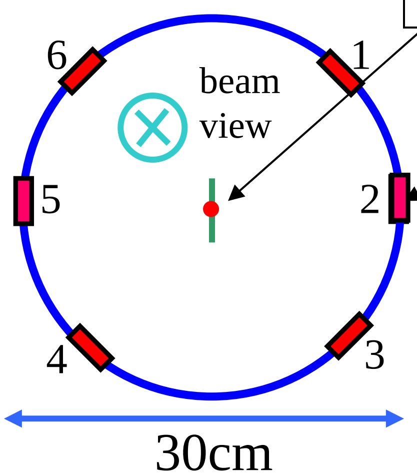


- High precision control of tune and coupling
- Controlled crossing of 7th order orbit resonance and 5th order snake resonance (10th order orbit resonance)
- All settings are recorded and can be played back on future ramps (feed-forward)
- Stable operation in the presence of persistent current variations

- Plan to implement chromaticity feed-back

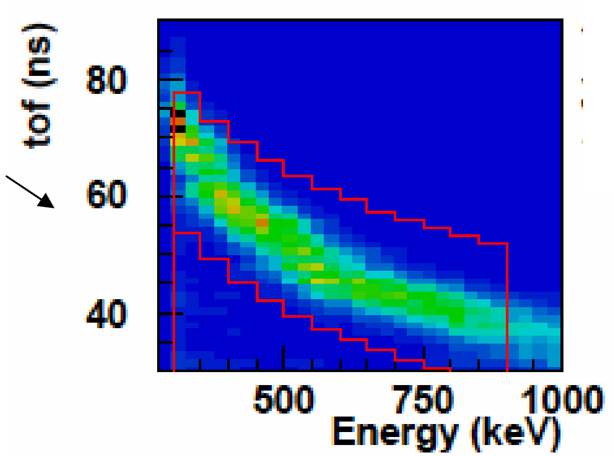
Peter Cameron, "Closed-loop technology speeds up beam control"
CERN Courier, May 2006

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)



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

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

$\mathbf{A_N \approx 0.015}$ originates from anomalous magnetic moment of $\boldsymbol{p}$

- Negligible emittance growth per polarization measurement
- Carbon target survives beam heating due to radiation cooling!

BROOKHAVEN
NATIONAL LABORATORY

Future Plans for RHIC

Machine goals for next three years with upgrades in progress:

- **Enhanced RHIC luminosity (112 bunches, $\beta^* = 1$m):**
- **Au – Au: 8×10^{26} cm^{-2} s^{-1} (100 GeV/nucleon)**

2 × achieved

- **For protons also 2×10^{11} protons/bunch (no IBS):**
- **p↑ – p↑: 60×10^{30} cm^{-2} s^{-1}; 70 % polarization (100 GeV)**
  150×10^{30} cm^{-2} s^{-1}; 70 % polarization (250 GeV)

3 × achieved

(luminosity averaged over store delivered to each of 2 IRs)

EBIS (low maintenance linac-based pre-injector; all species incl. U and pol. He3)

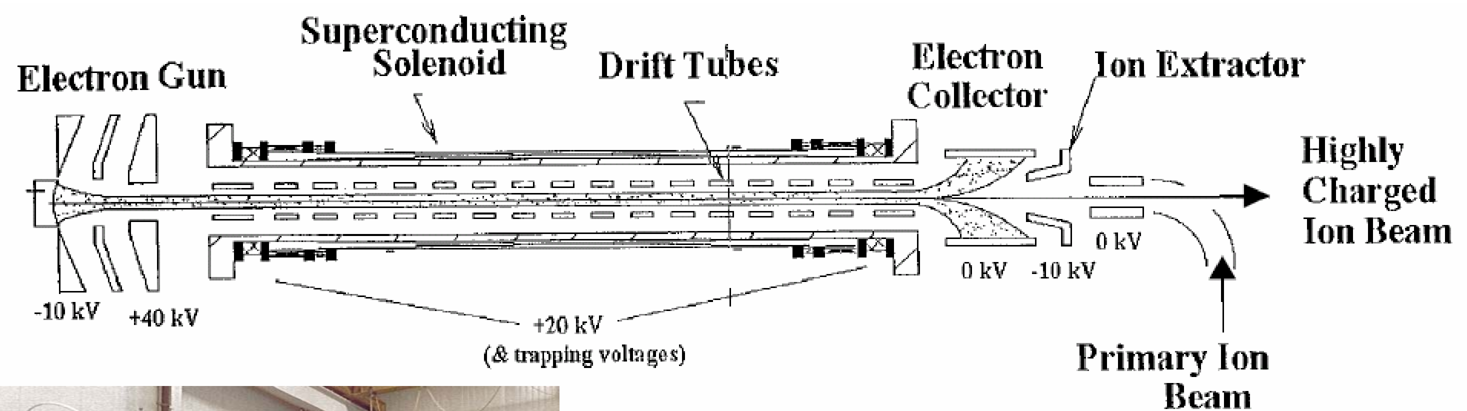
RHIC II luminosity upgrade (e-cooling, ~10 × more luminosity, R&D in progress)

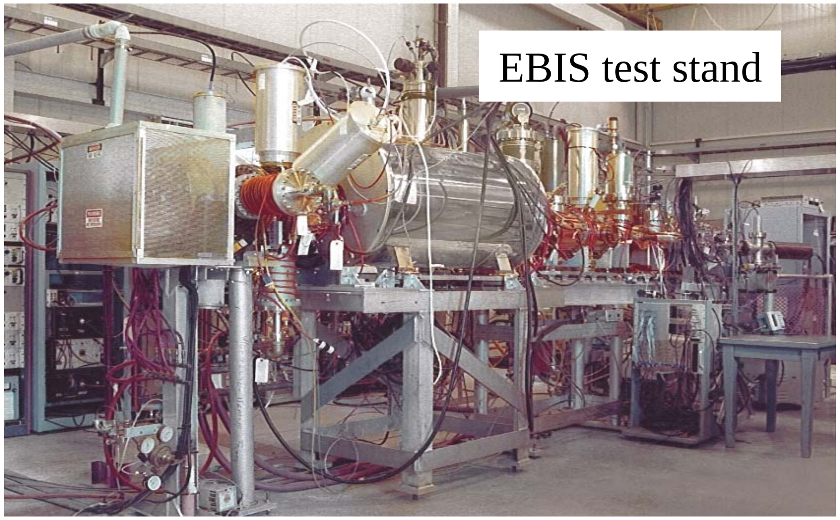
eRHIC (high luminosity (1×10^{33} cm^{-2} s^{-1}) eA and pol. ep collider)

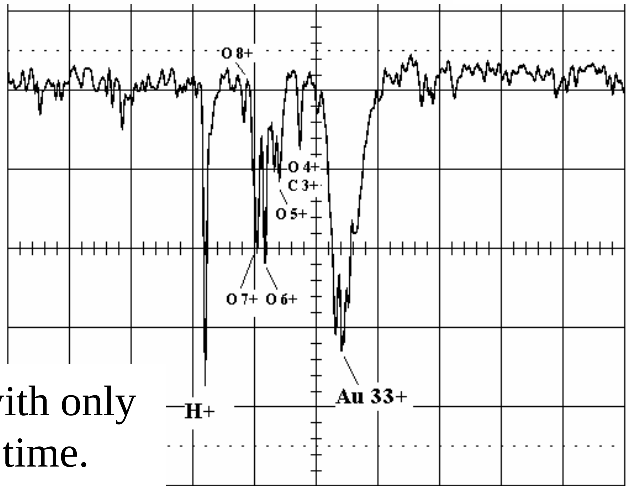
BROOKHAVEN NATIONAL LABORATORY

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)
- Achieved 1.7×10^9 Au^{33+} in 20 μs pulse with 8 A electron beam (60% neutralization)
- Construction schedule: FY2006 – 09







Gold charge state with only 40 ms confinement time.

RHIC II Luminosity Upgrade - Electron Cooling of Au Beams

Objectives

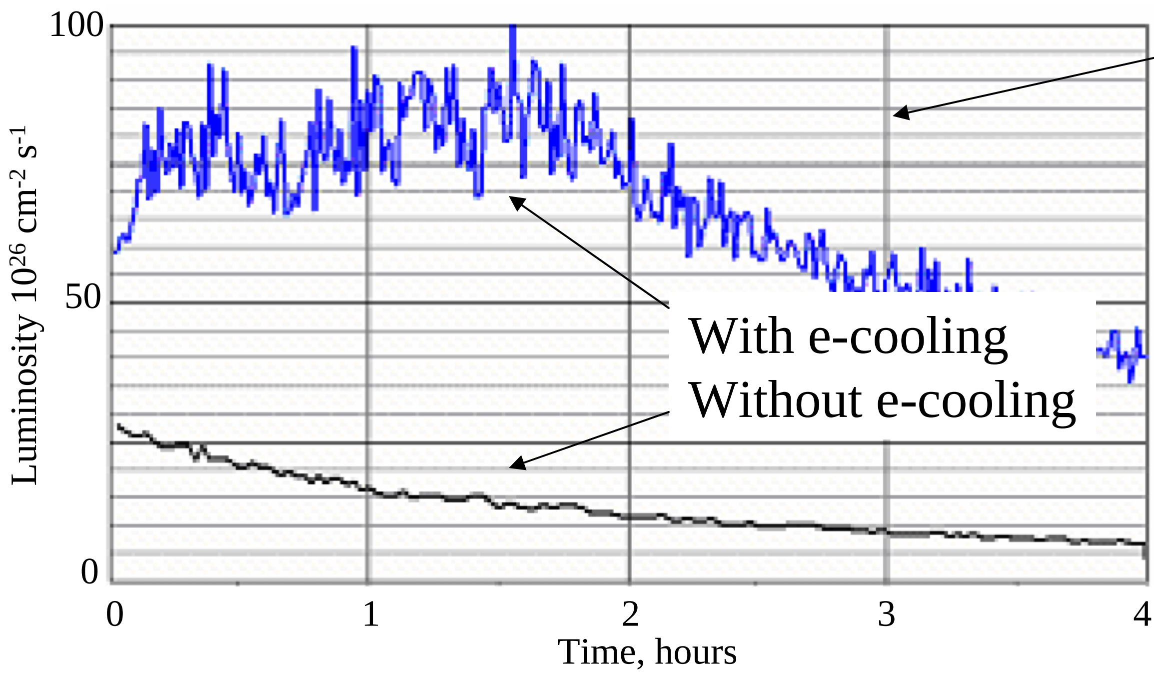
- Eliminate beam blow-up from intra-beam scattering at 100 GeV
- Increase RHIC luminosity: For Au-Au at 100 GeV/A by ~10
- Cool polarized p at injection
- Reduce background due to beam loss
- Allow smaller vertex

Challenges

- Cooling rate slows in proportion to $\gamma^{7/2}$. (10^7 for $\gamma = 100$)
- Energy of electrons 54 MeV, well above DC accelerators, requires bunched electrons.
- Need exceptionally high electron beam brightness (high bunch charge with low emittance)

BROOKHAVEN NATIONAL LABORATORY

Electron Cooling Simulations

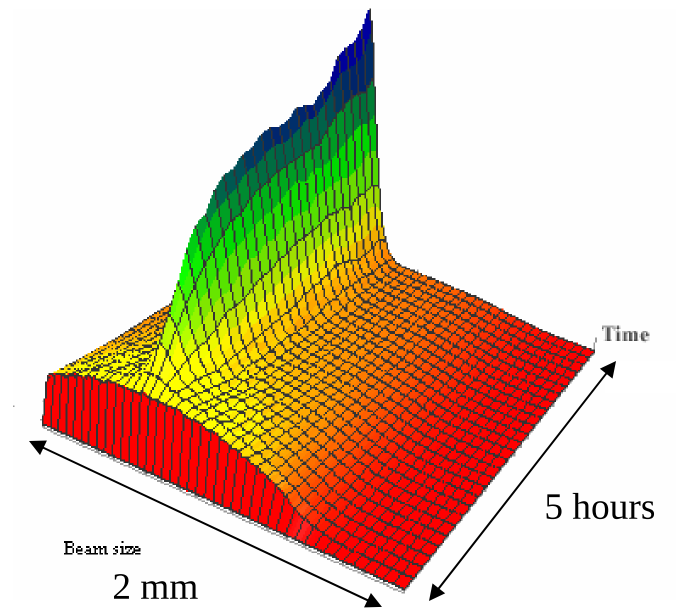


Luminosity leveling through continuously adjusted cooling

Store length limited to 4 hours by "burn-off"

Four IRs with two at high luminosity

Transverse beam profile during store



BROOKHAVEN
NATIONAL LABORATORY

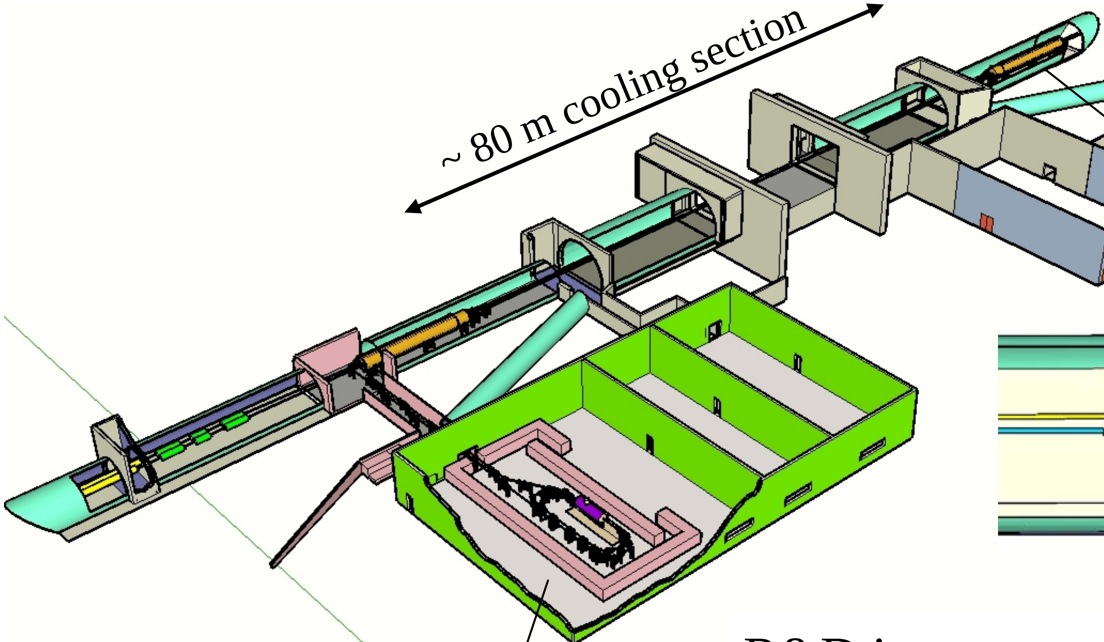
RHIC II Luminosities with Electron Cooling

Gold collisions (100 GeV/n x 100 GeV/n):	**w/o e-cooling**	**with e-cooling**
Emittance (95%) $\pi\mu m$	15 $\rightarrow$ 40	15 $\rightarrow$ 3
Beta function at IR [m]	1.0	1.0 $\rightarrow$ 0.5
Number of bunches	111	111
Bunch population [10^9]	1	1 $\rightarrow$ 0.3
Beam-beam parameter per IR	0.0016	0.004
Ave. store luminosity [10^{26} cm^{-2} s^{-1}]	8	70

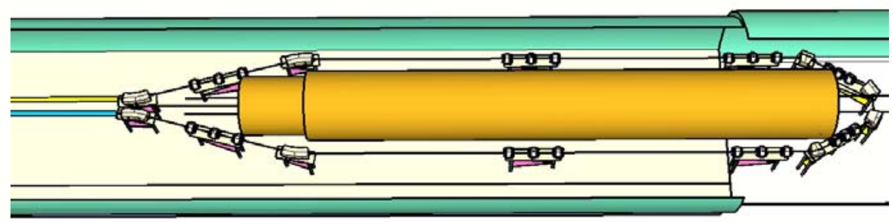
Pol. Proton Collision (250 GeV x 250 GeV):		
Emittance (95%) $\pi\mu m$	20	12
Beta function at IR [m]	1.0	0.5
Number of bunches	111	111
Bunch population [10^{11}]	2	2
Beam-beam parameter per IR	0.007	0.012
Ave. store luminosity [10^{32} cm^{-2} s^{-1}]	1	5

BROOKHAVEN NATIONAL LABORATORY

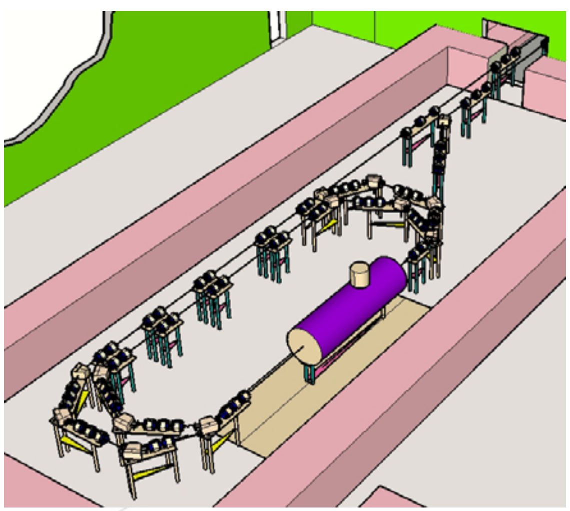
RHIC Electron Cooler



Electron beam return



2 turn
Energy Recovering Linac



R&D issues:

- Benchmarking of IBS and cooling simulation codes (non-magnetized e-cooler at FNAL) ✓
- Development of 5 - 10 nC, 703.8 MHz CW SCRF electron gun (10 MHz rep. rate)
- Development of 703.8 MHz CW superconducting cavity for high intensity beams
- Construction of Test Energy Recovering Linac (ERL) at high electron beam current

Summary

Since 2000 RHIC has collided, for the first time,

- Heavy ions
- Light on heavy ions
- Polarized protons (with up to 65 % beam polarization)

Heavy ion luminosity increased by factor 100

For next 3 years planned:

- Factor 2 increase in heavy ion luminosity
- Factor 3 increase in proton luminosity with 70 % polarization

Future upgrades:

- RHIC luminosity upgrade (~10x) using electron cooling at store
- Electron-ion collider eRHIC