Making RHIC Possible: Reflections on the Machine

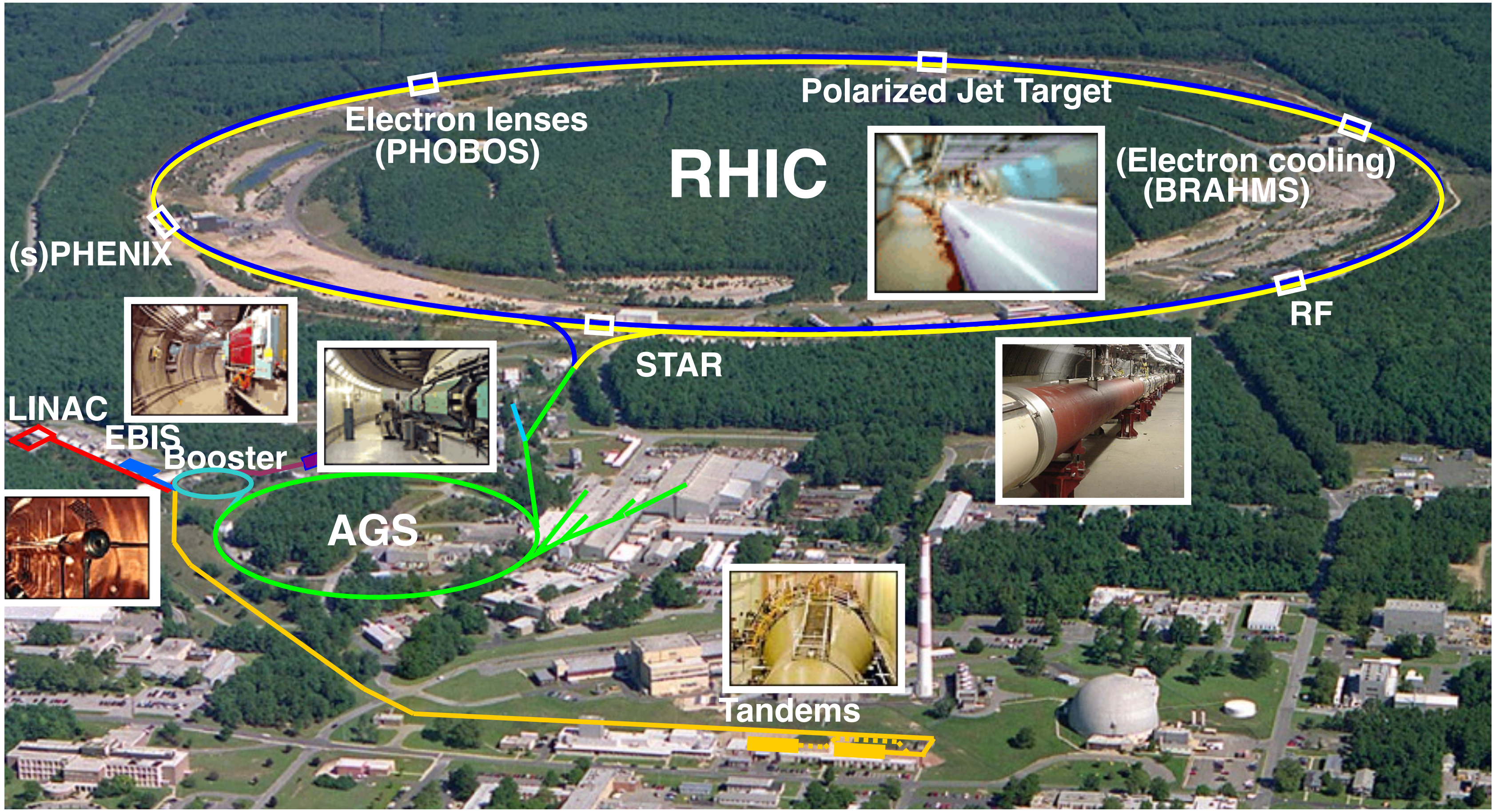
Thomas Roser

RHIC Science Symposium

May 14, 2026

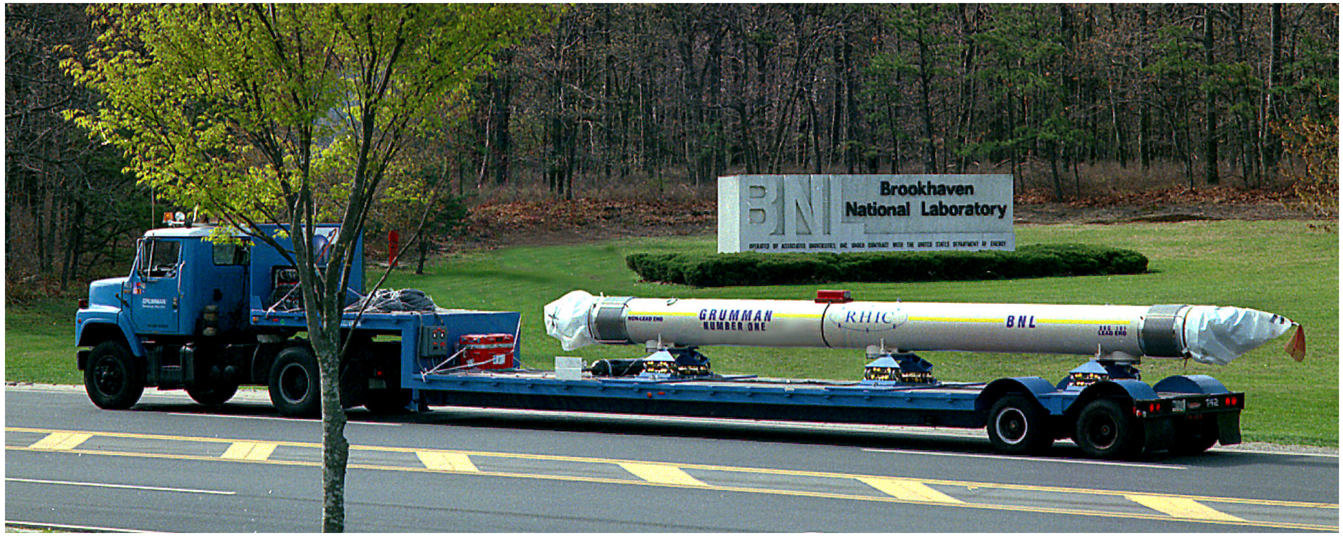
RHIC – a uniquely flexible collider

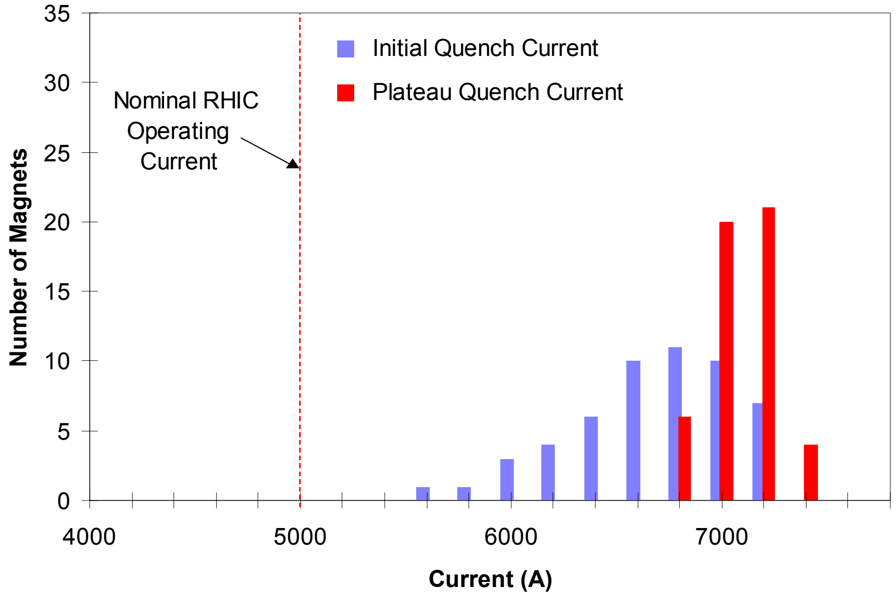
- Collider with two independently powered 3.8 km superconducting rings that allows gold-gold, proton-gold, and proton-proton collisions at equal energies up to 100 GeV.
- High luminosity polarized proton-proton collisions up to 250 GeV.
- Six independently powered interaction regions, initially instrumented with four detectors: STAR, PHENIX, PHOBOS, BRAHMS.



The superconducting magnets – the centerpiece of RHIC

- Conservative design developed at BNL
- Manufactured at Grumman based on prints from BNL
- Large quench margin and excellent quench performance
- The two RHIC rings are independent and can operate at a current ratio of 2.5:1
- No RHIC dipole magnet failed over the 26-year operating time.





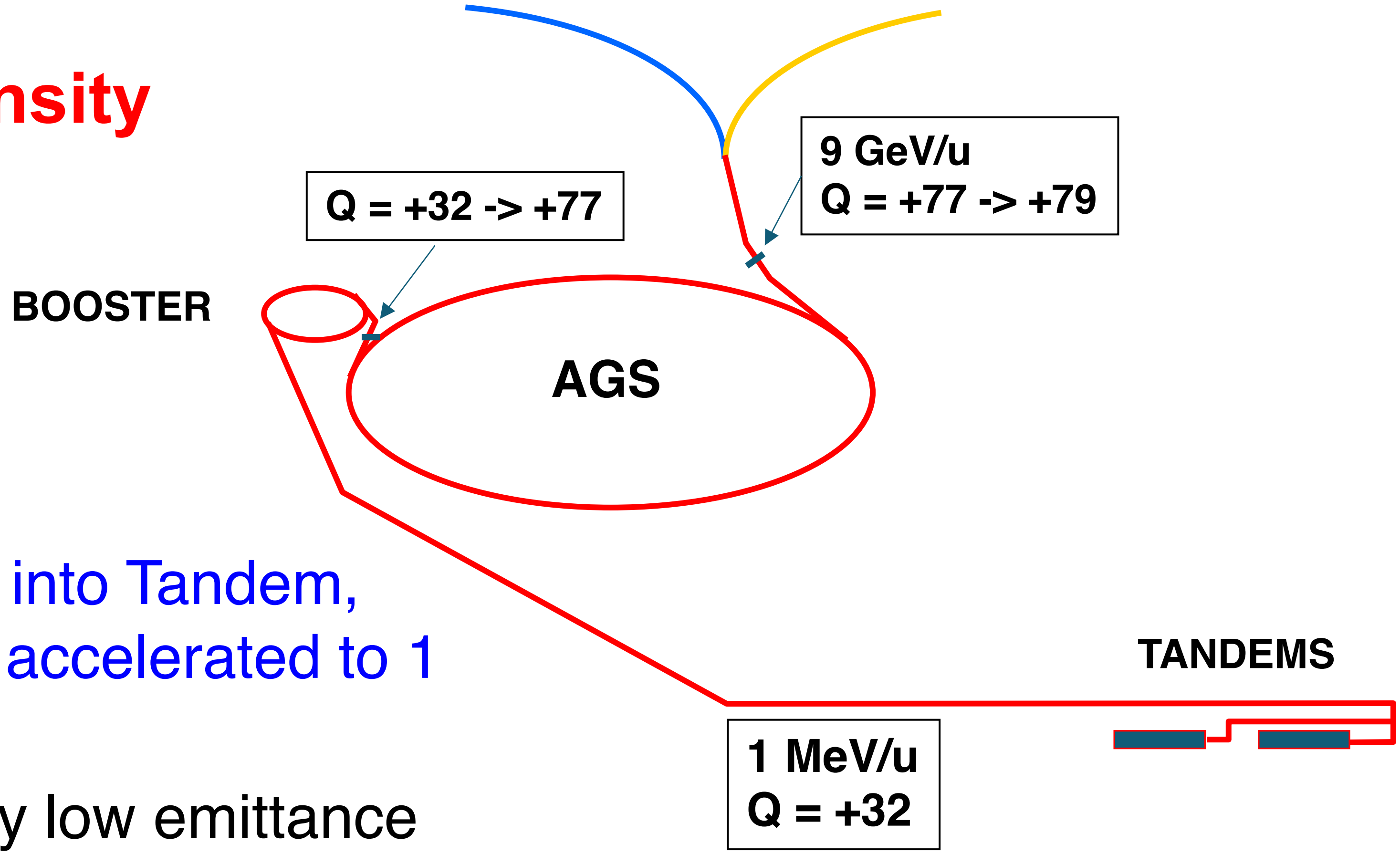
A brief timeline of RHIC

- The 1983 NSAC Nuclear Physics Long Range Plan included a relativistic heavy ion collider as the highest priority new facility
- It would use the tunnel and a 25-kW helium refrigerator from the ISABELLE/CBA project (it's good to have a tunnel!)
- First idea of a polarized proton collider was discussed at the 1990 Polarized Collider Workshop at Penn State
- RHIC construction started in 1991
- First beam in RHIC tunnel (sextant test) in 1997
- RHIC commissioning started in 1999
- First gold-gold collisions on June 12, 2000
- Reached RHIC gold-gold design luminosity in 2001
- First polarized proton collisions in RHIC in 2001

Known unknowns: Risks at start of RHIC construction

- When RHIC construction started 1991 some critical performance parameters had not been demonstrated:
  - Probably the most important issue was the production of the very high bunch intensity of 10^9 gold ions.
  - The lifetime of colliding high energy gold beams was unknown. Electron-positron pairs produced in the collisions followed by electron capture could lead to fast beam loss. This turned out not to be a problem.

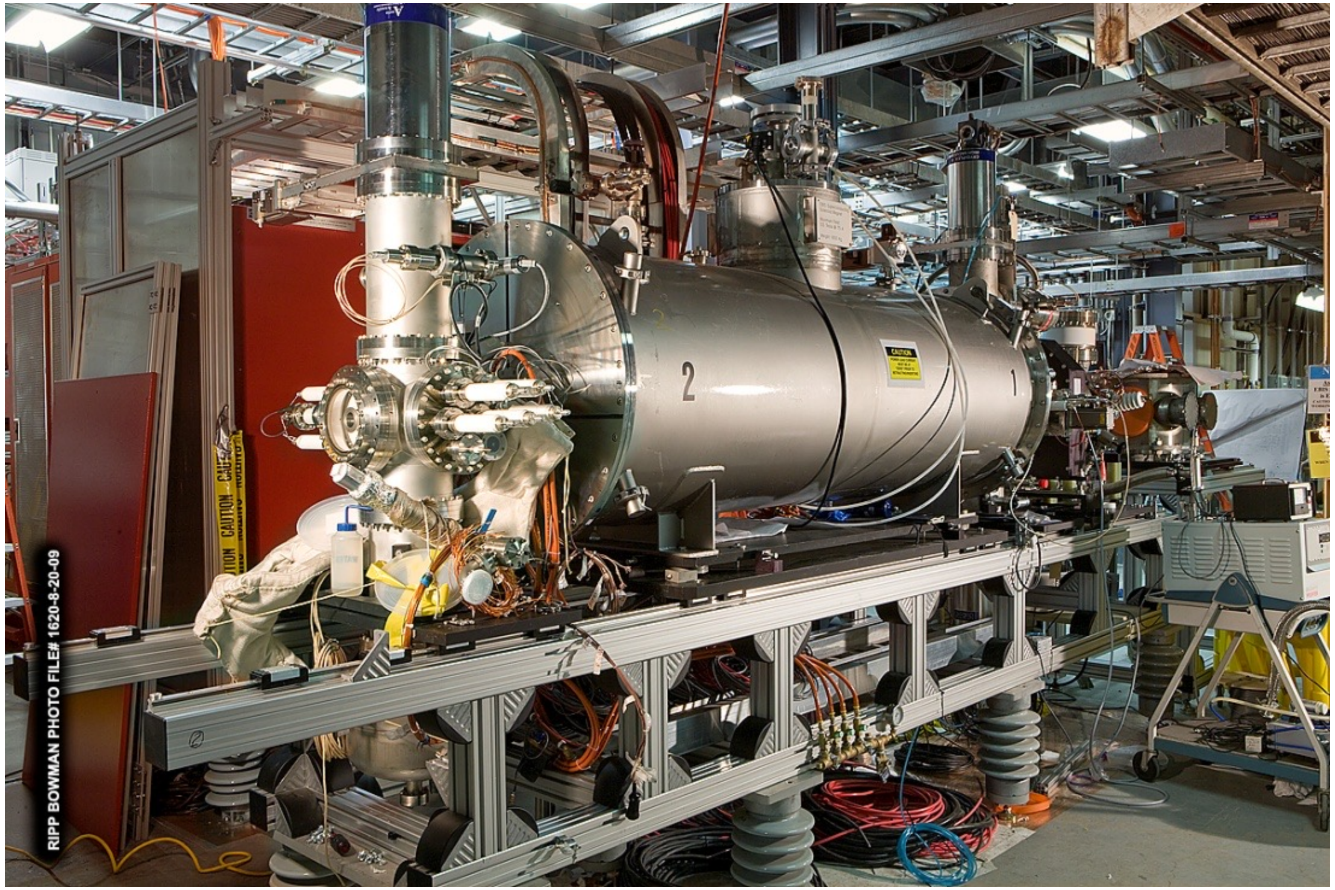
The quest for high gold intensity



- Negative gold ion source injected into Tandem, stripped in terminal to Au32+ and accelerated to 1 Mev/u.
- 700 micro sec long pulse with very low emittance injected into Booster over about 100 turns painting both in horizontal and vertical directions.
- Stripped to Au77+ on the way to AGS.
- Accelerated in AGS to 9 GeV/u and stripped to Au79+ on the way to RHIC.

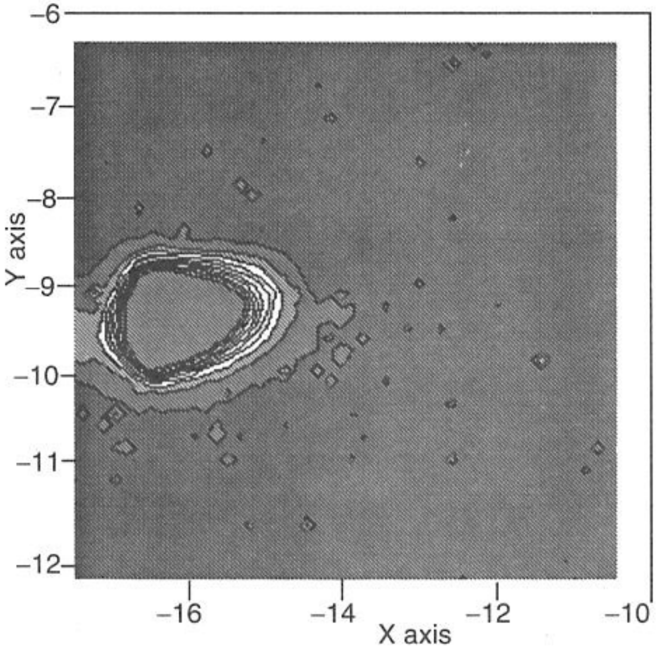
The race for high heavy ion bunch intensity

- C-AD developed a high intensity Electron Beam Ion Source (EBIS), where an intense electron beam provides space charge compensation to accumulate high intensity Au32+ at low energy.
- EBIS was developed in friendly competition with CERN, where a laser ion source was developed for the LHC. At the end, BNL successfully developed both the EBIS and a Laser ion Source (LION).



RHIC Sextant test, January 26, 1997

In the main control room at the Alternating Gradient Synchrotron (AGS), where the gold-ion beam was guided from the AGS to the end of the first sextant of the Relativistic Heavy Ion Collider, are: (clockwise from far left) James Rose, Robert Frankel, Peter Wanderer, Waldo McKay, Michael Brennan, Michael Harrison, Ted Robinson, Michael Anerella, Tom Shea; (center, from left) Thomas Roser and Steve Peggs.



First image of the first gold-ion beam to reach the end of the first RHIC sextant, as seen on a beam-profile monitor, at 2:08 p.m., on Sunday, January 26.

First circulating beam, summer 1999

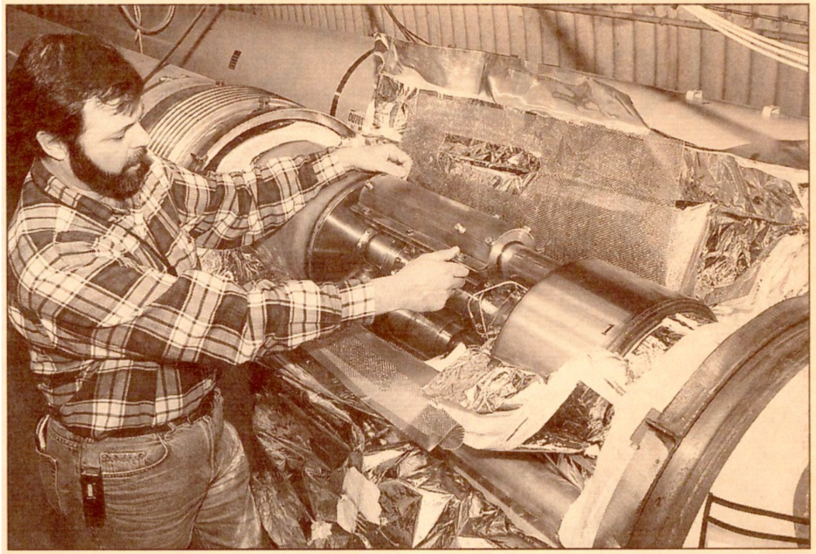
- Beam circulated in blue (45 minutes) and yellow (few thousand turns) despite major obstacles
- Beam pipe bellows distorted at all dummies! They were twisted during a pressure test.192 bellows needed to be replaced over a 6 months period.

Newsday Photo / John Paraskevas

Scientists Todd Satogata, seated left, Dejan Trbojevic, Vadim Ptitsin, standing left, and Andreas Lehrach gather around their computers Friday as they tweak the high-energy beam making its way around Brookhaven Lab's new super-collider ring.

BNL Breakthrough

Successful step in start-up of ion collider



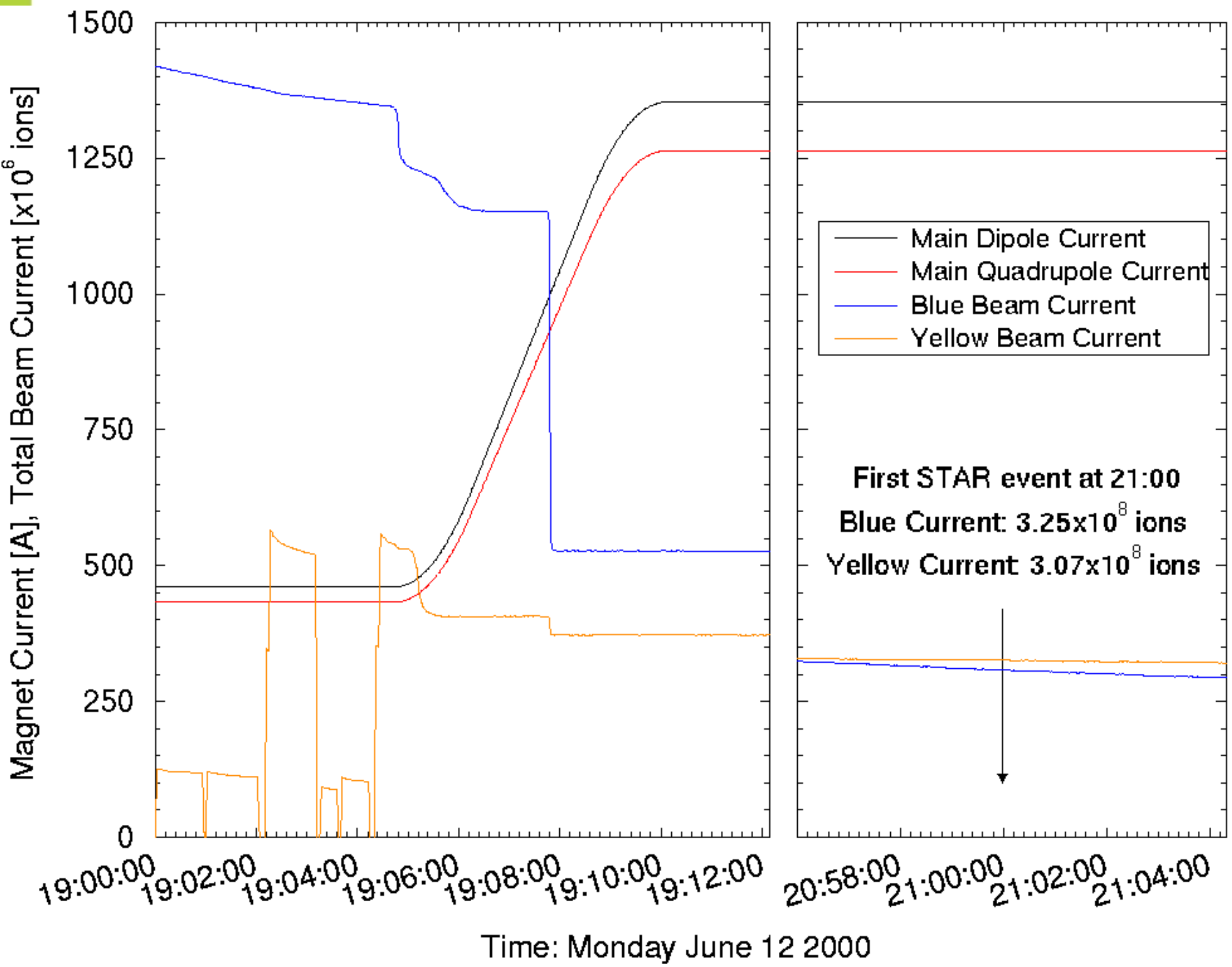
Newsday Photo / John H. Cornell Jr.

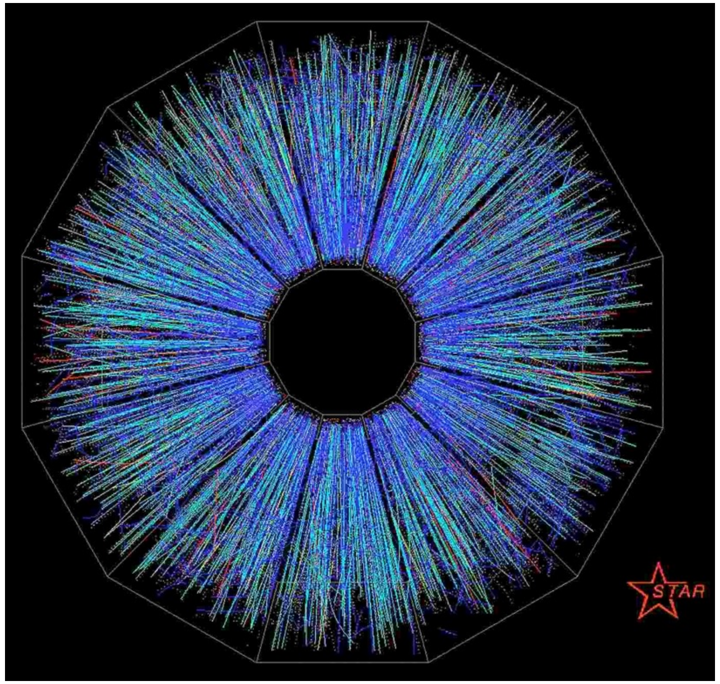
Gary McIntyre, head of the mechanical support group, examines a finished bellows on the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. Project managers decided to replace 200 of the bellows, which took two months.

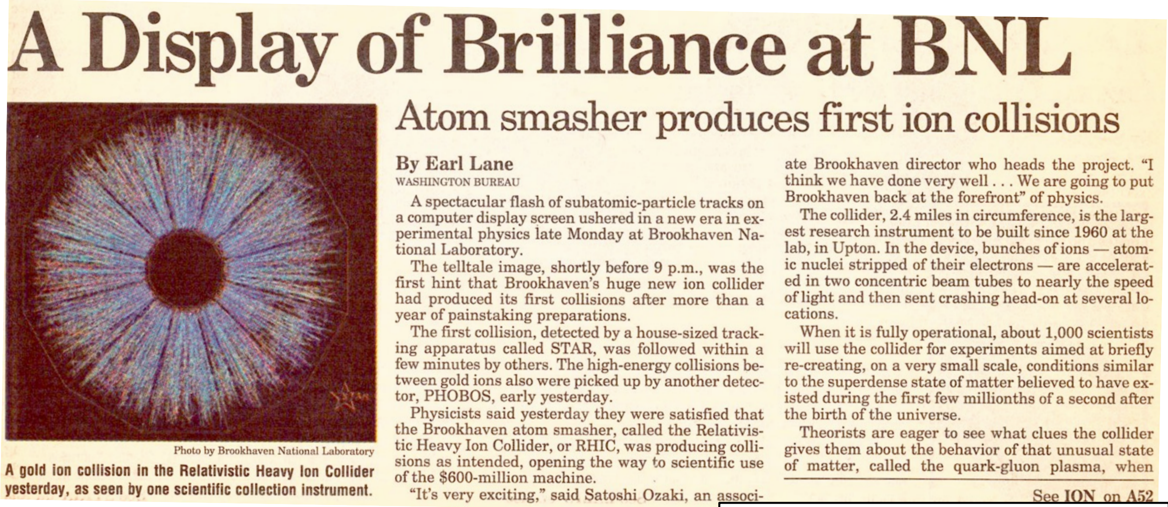
Collider's Start Delayed 6 Months

Newsday, January 9, 2000

Ramp to First Collisions in RHIC, June 12, 2000







A Display of Brilliance at BNL

Atom smasher produces first ion collisions

Photo by Brookhaven National Laboratory

A gold ion collision in the Relativistic Heavy Ion Collider yesterday, as seen by one scientific collection instrument.

By Earl Lane
WASHINGTON BUREAU

A spectacular flash of subatomic-particle tracks on a computer display screen ushered in a new era in experimental physics late Monday at Brookhaven National Laboratory.

The telltale image, shortly before 9 p.m., was the first hint that Brookhaven's huge new ion collider had produced its first collisions after more than a year of painstaking preparations.

The first collision, detected by a house-sized tracking apparatus called STAR, was followed within a few minutes by others. The high-energy collisions between gold ions also were picked up by another detector, PHOBOS, early yesterday.

Physicists said yesterday they were satisfied that the Brookhaven atom smasher, called the Relativistic Heavy Ion Collider, or RHIC, was producing collisions as intended, opening the way to scientific use of the $600-million machine.

"It's very exciting," said Satoshi Ozaki, an associate Brookhaven director who heads the project. "I think we have done very well . . . We are going to put Brookhaven back at the forefront" of physics.

The collider, 2.4 miles in circumference, is the largest research instrument to be built since 1960 at the lab, in Upton. In the device, bunches of ions — atomic nuclei stripped of their electrons — are accelerated in two concentric beam tubes to nearly the speed of light and then sent crashing head-on at several locations.

When it is fully operational, about 1,000 scientists will use the collider for experiments aimed at briefly re-creating, on a very small scale, conditions similar to the superdense state of matter believed to have existed during the first few millionths of a second after the birth of the universe.

Theorists are eager to see what clues the collider gives them about the behavior of that unusual state of matter, called the quark-gluon plasma, when

See ION on A52

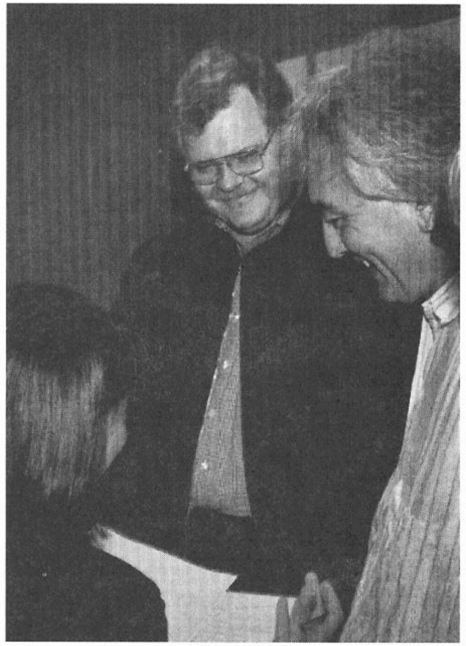
Newsday, June 14, 2000

And then there was rejoicing…

Celebrating the good news are Mike Butler, U.S. Department of Brookhaven Group; Derek Lowenstein, Collider-Accelerator Departme Nicholas Samios, Physics Department and former BNL Director; and Ozaki, Associate Laboratory Director for RHIC.

Howard Wieman, Bill Christie, Spiros Margetis

Thomas Ludlam, Satoshi Ozaki



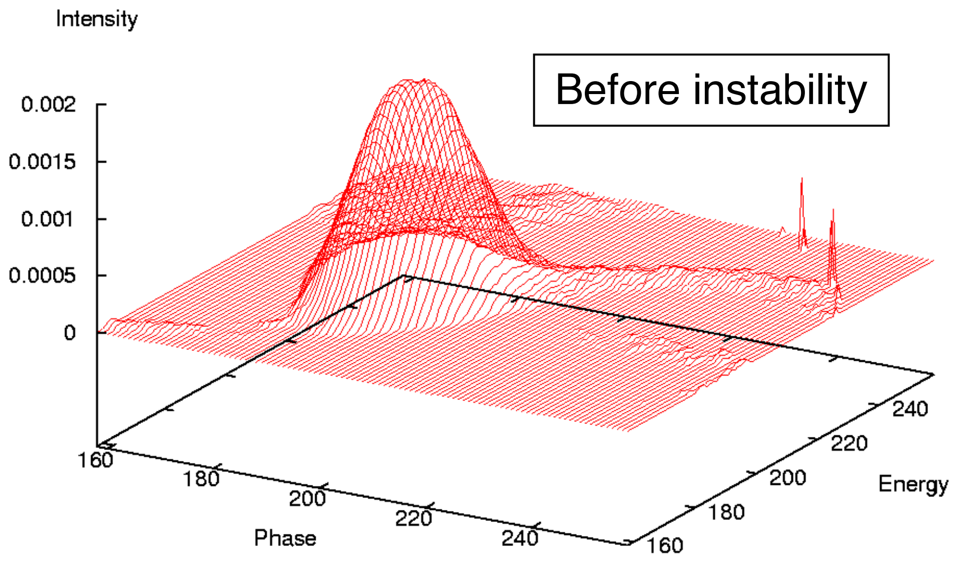
Tim Hallman, John Harris

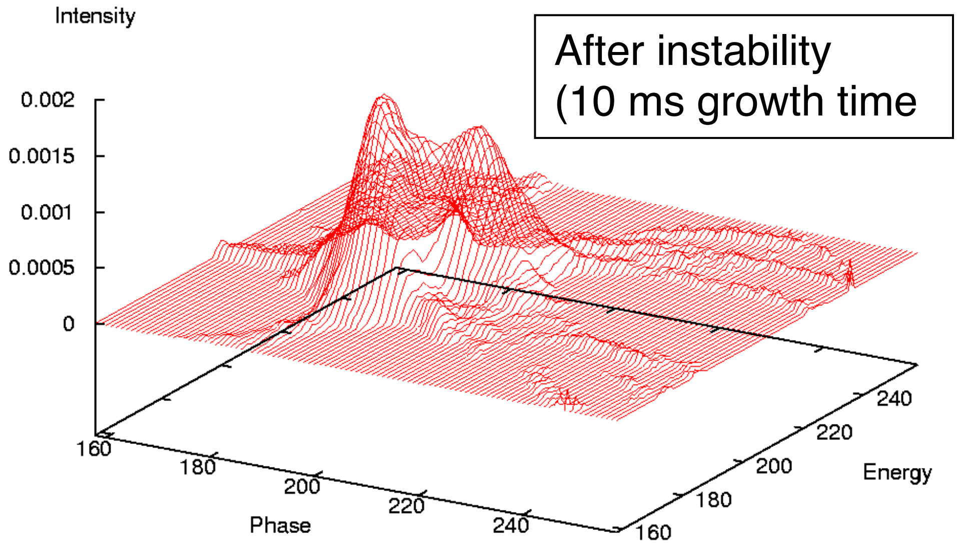
Mei Bai, Dejan Trbojevic, Leif Ahrens

Thomas Roser, Fulvia Pilat, Satoshi Ozaki, Derek Lowenstein

Unknown unknowns: Electron Clouds in RHIC

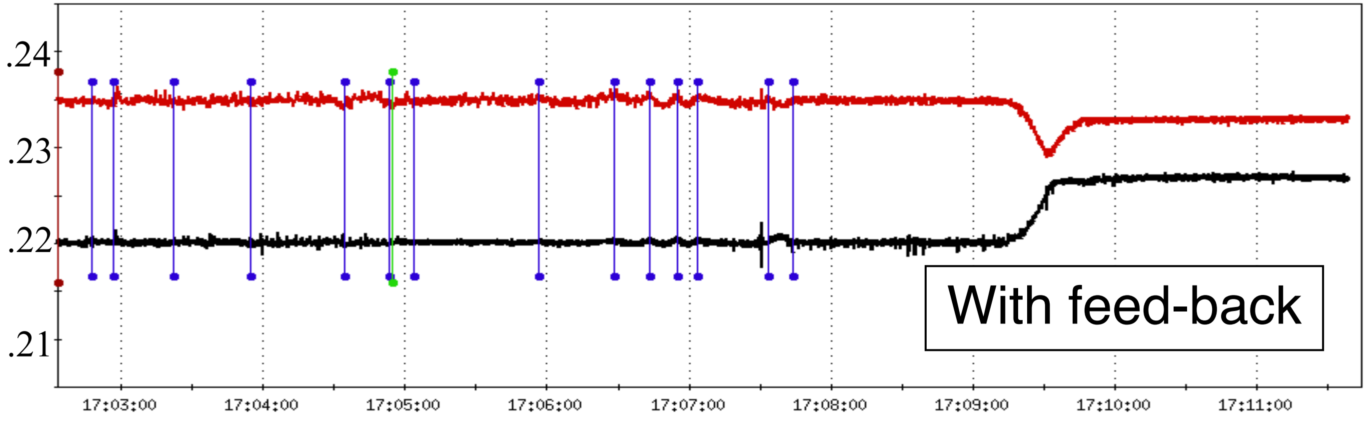
- RHIC beam intensity was limited by rapid dynamic pressure rise in warm beam pipes.
- Also identified an ultra-fast transverse instability.
- Both issues were caused by electron clouds in the room temperature sections of RHIC, an emerging realization at many accelerators at the time.
- NEG coating and scrubbing resolved this issue over the next ~ 5 years.

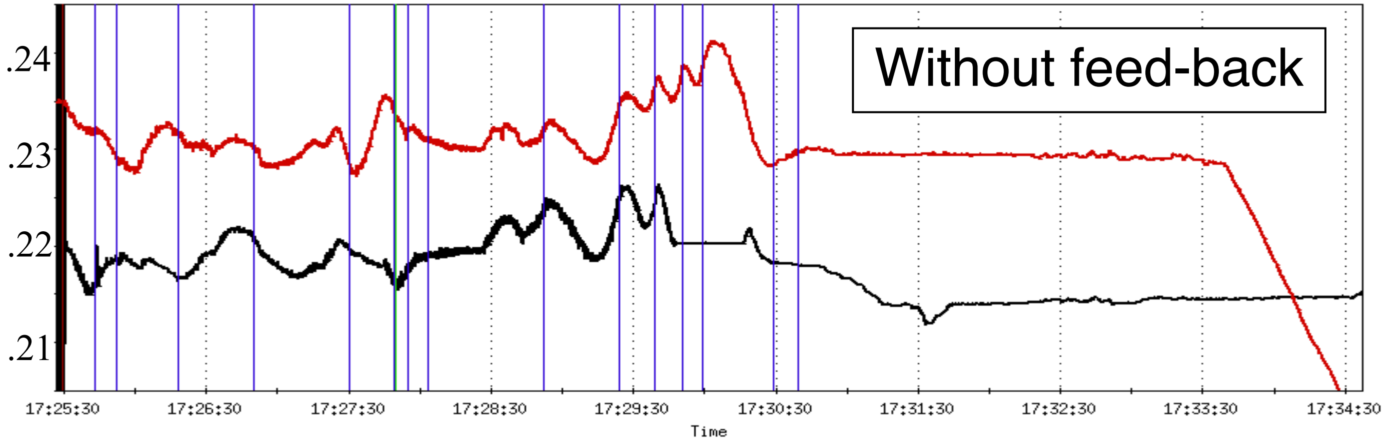




Development at RHIC: Beam-based tune and coupling feedback

- Instantaneous and continuous tune measurements through phase lock to the beam and fast feedback
- High precision control of tune and coupling. Particularly important for polarized proton acceleration.
- Stable operation in the presence of persistent current variations

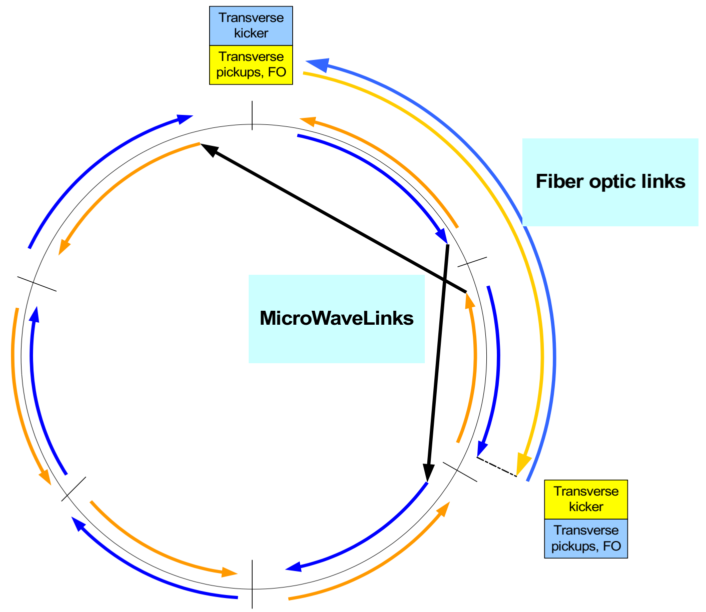


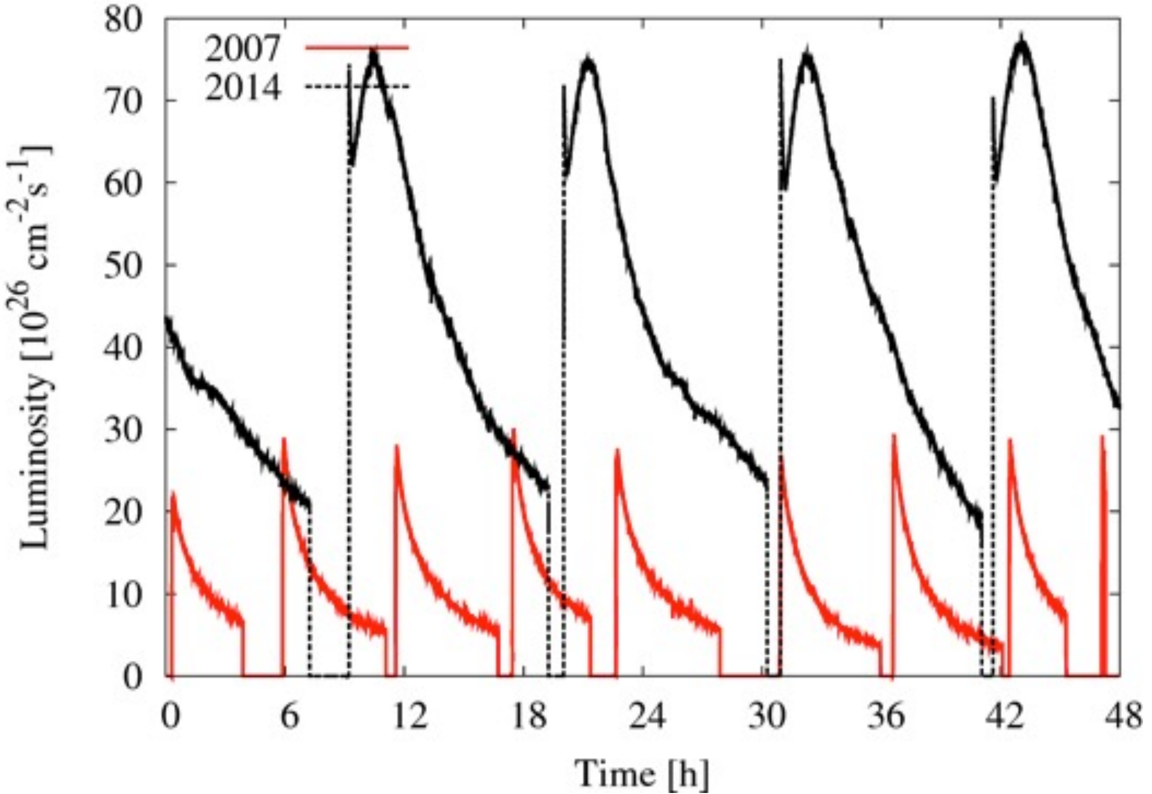


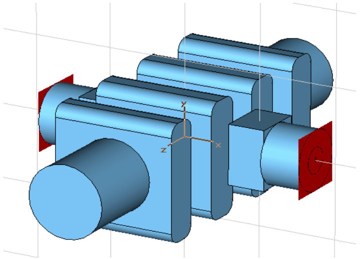
Peter Cameron, "Closed-loop technology speeds up beam control" CERN Courier, May 2006

Development at RHIC: 3-D Stochastic Cooling in RHIC

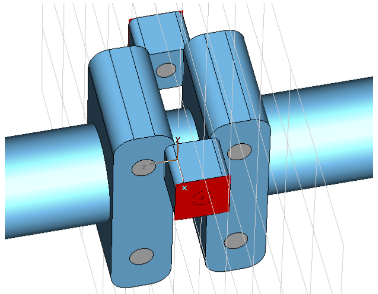
- High charge of Gold ions blows up bunches and causes rapid luminosity loss.
- First high energy, bunched beam longitudinal and transverse stochastic cooling (3-D) in both rings to counteract Intra-Beam scattering.
- Bunch structure of RHIC beams allowed for powerful high-Q cavity kickers







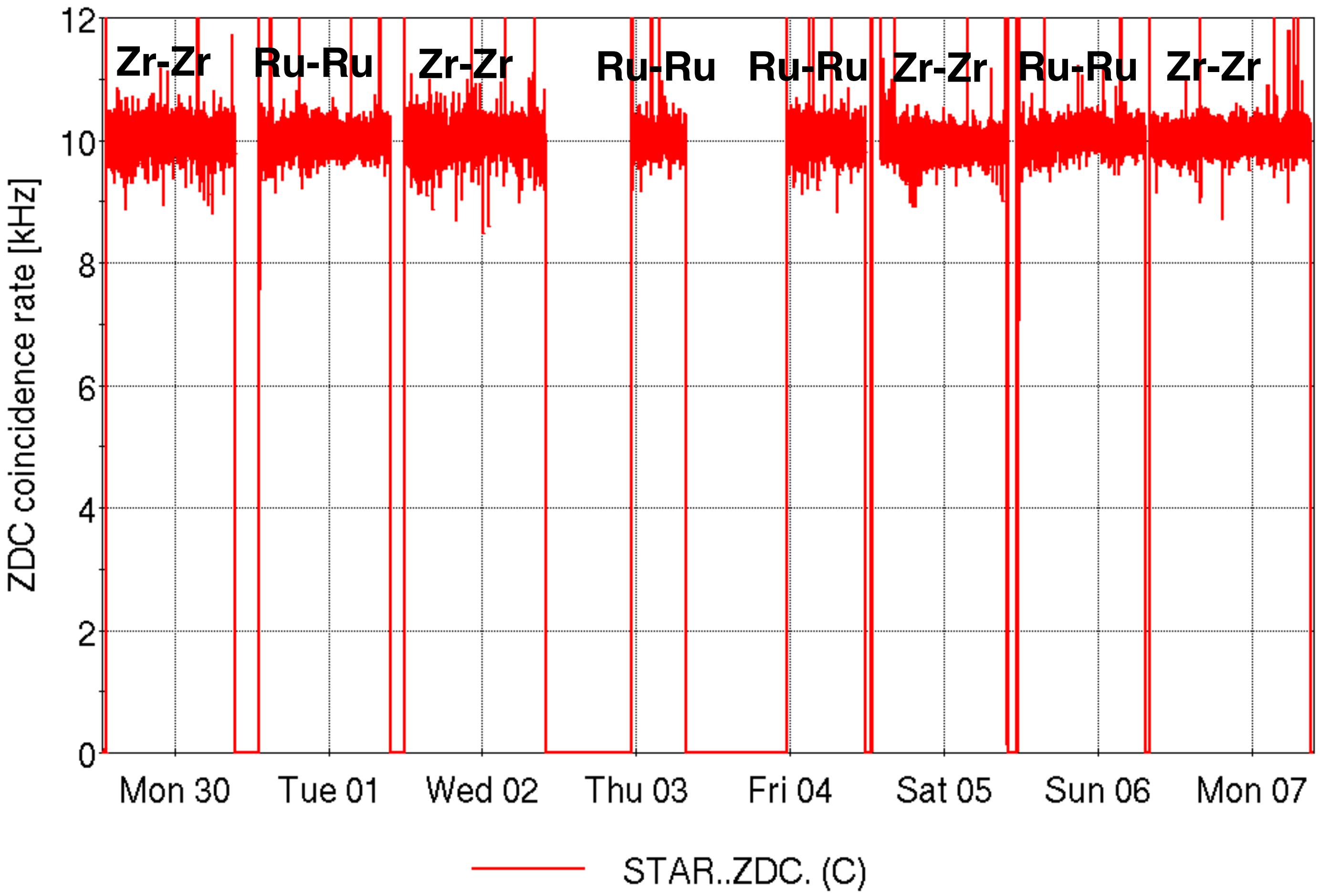
Longitudinal kickers



Transverse kickers

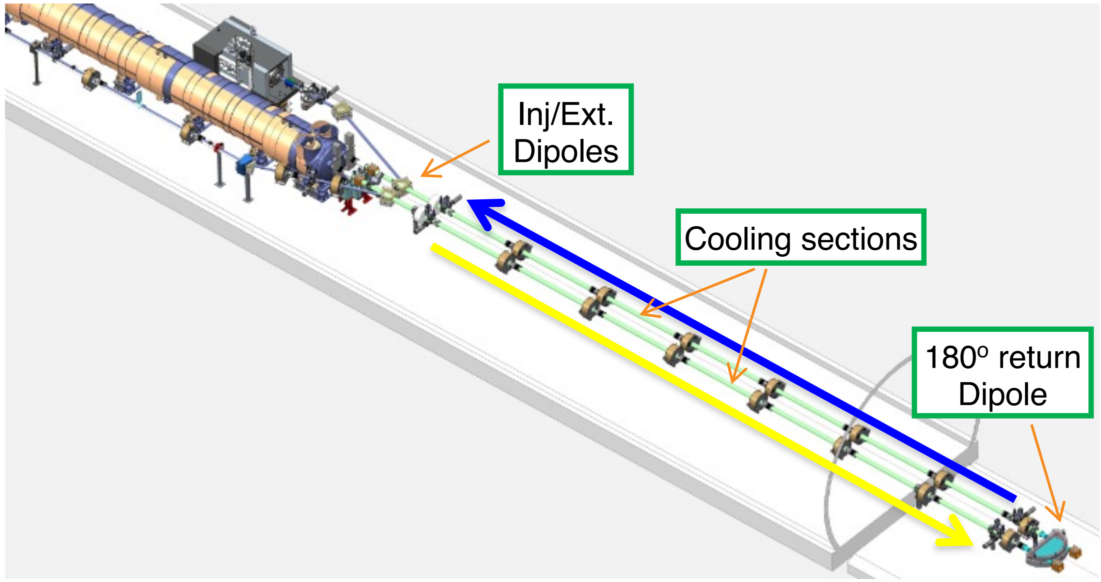
Development at RHIC: Fast alternating of species

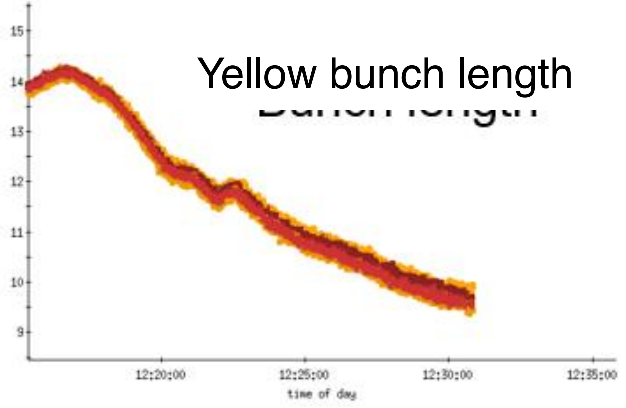
- For an accurate comparison of Ru-Ru and Zr-Zr collisions fast and automatic configuration switching was developed.
- Store-by-store species change
- With stochastic cooling: flat luminosity and 20-hour nominal store length

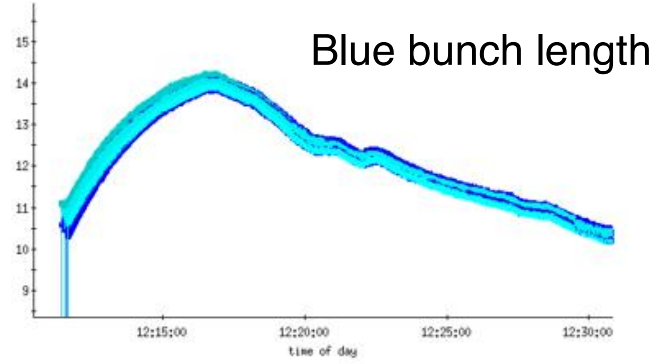


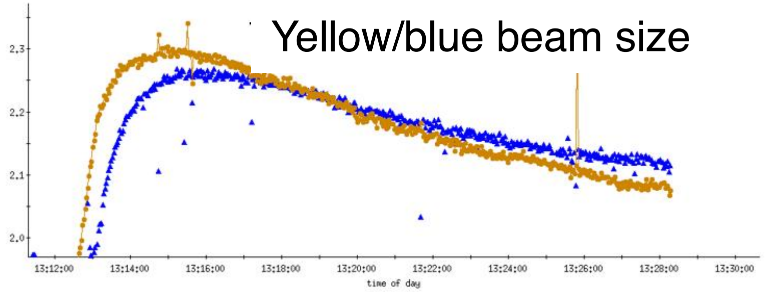
Development at RHIC:
Low Energy RHIC electron Cooling

- First non-magnetized electron cooling with bunched electron beam.
- Successfully cooled 4.6 GeV gold beams in both rings simultaneously
- Longitudinal and transverse cooling demonstrated



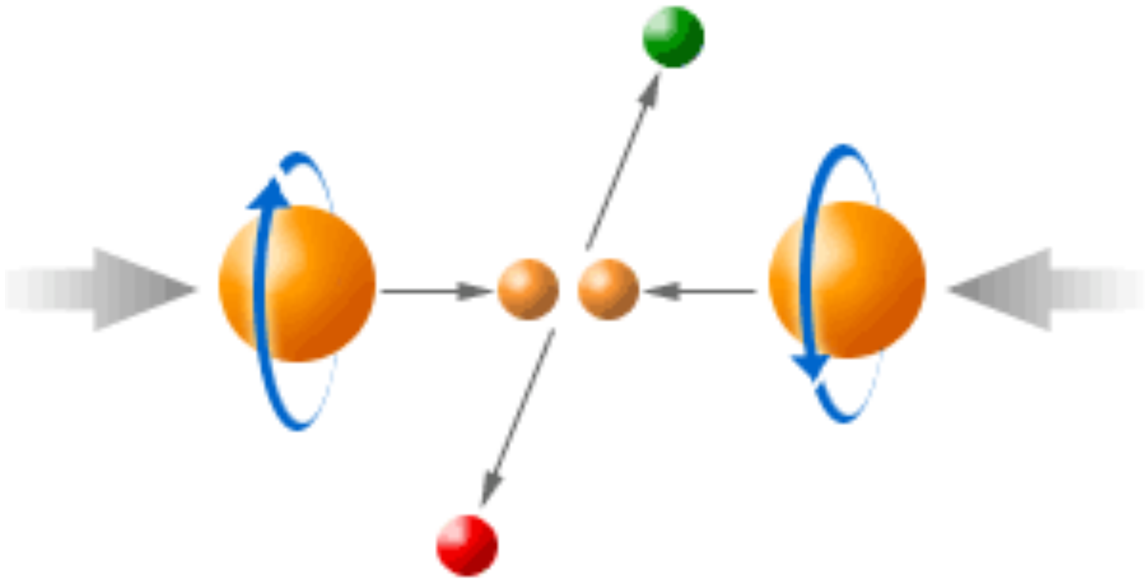






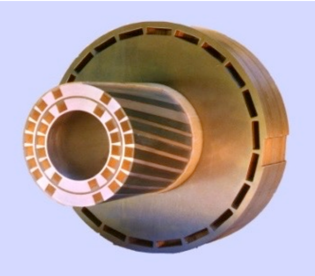
Development at RHIC: Polarized proton acceleration and collisions

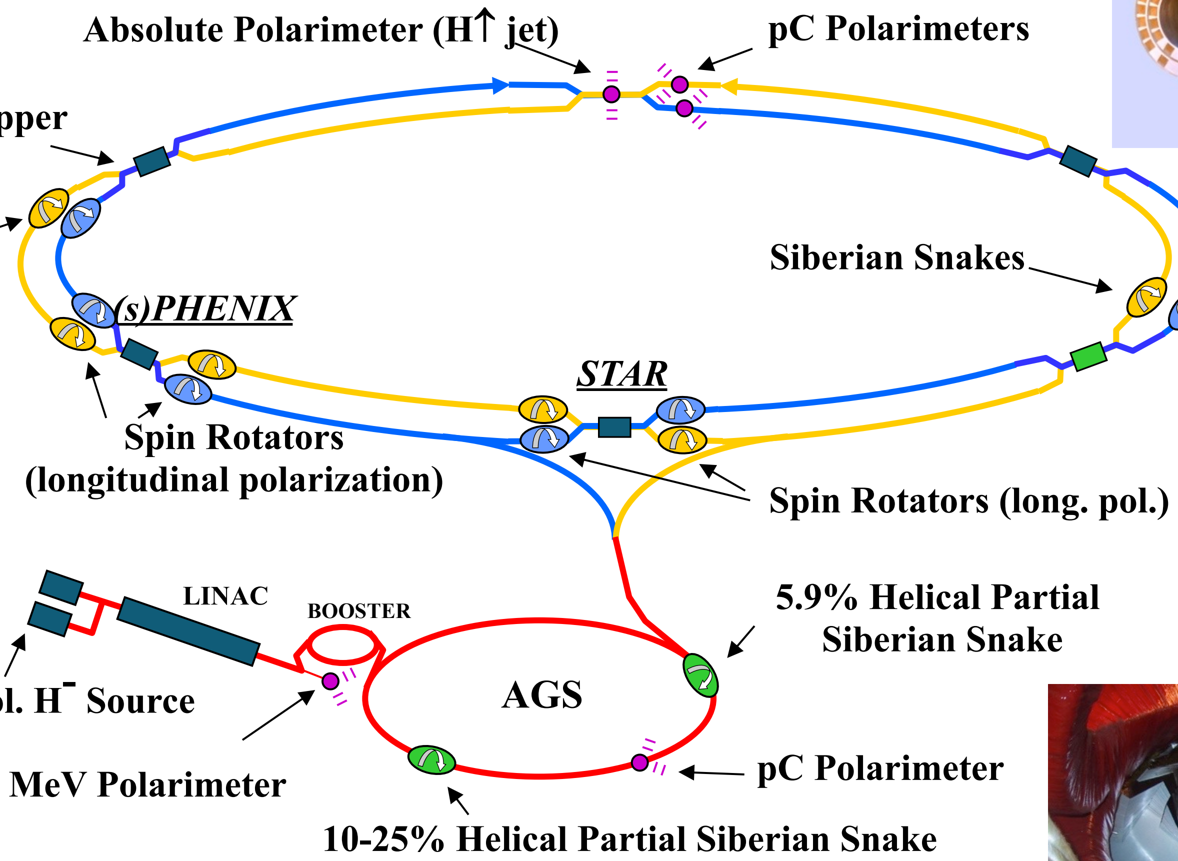
- Although not part of the initial design, polarized proton collisions became an essential part of RHIC's success. Many aspects of a polarized collider were never demonstrated and RHIC became both the demonstrator as well as the first operational polarized collider. Much of the spin hardware was funded by Riken, Japan.
  - High intensity polarized Hminus source
  - Polarized proton acceleration in AGS without a full Siberian snake
  - Polarized proton acceleration in RHIC with two full Siberian snakes
  - Lifetime of beam polarization with high luminosity collisions

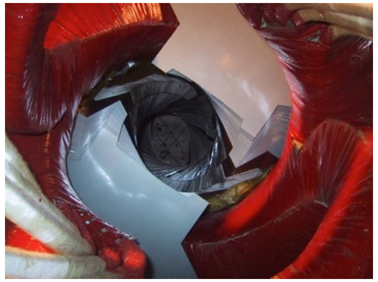


RHIC – First Polarized Hadron Collider

- Two full Siberian snakes per ring preserve proton polarization to 255 GeV
- Spin direction control at detectors with spin rotators
- Minimally invasive polarimeters; also measure polarization profiles
- Absolute polarimeter using world's most intense polarized H jet





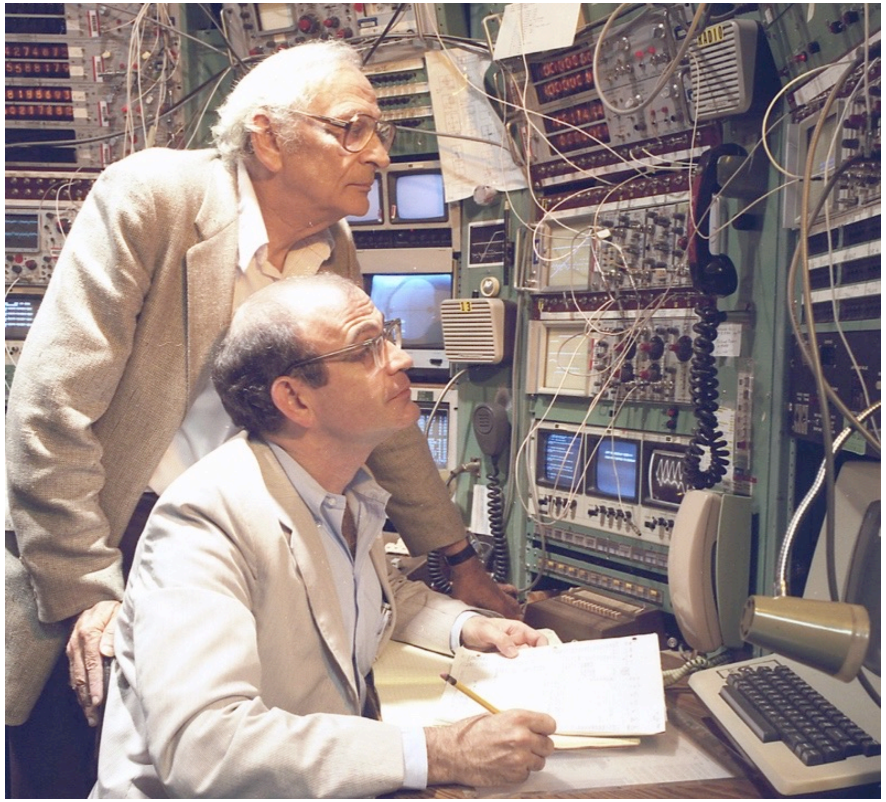


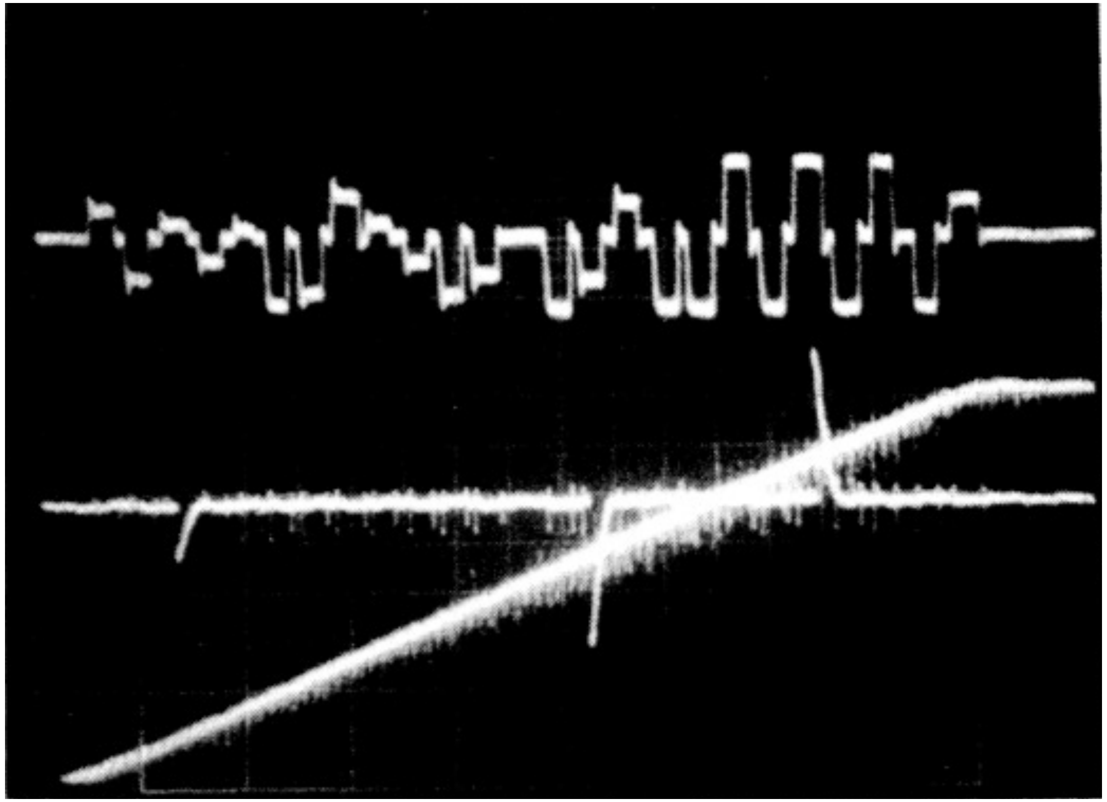
High intensity polarized H- source

- Developed as BNL, TRIUMF, KEK, INR collaboration
- 1.0 mA in 300 μs (1.8 x 10^{12} protons per pulse); 83% polarization
- One source pulse is captured and accelerated for one bunch in RHIC
- With inefficiencies and scraping to lower emittance and higher polarization bunch intensity in RHIC is 2.5 x 10^{11} polarized protons

First Effort to Accelerate Polarized Protons in AGS

- In the 1980s, Alan Krisch and Larry Ratner led the first effort to polarize the AGS by correcting the approximately 50 imperfection and intrinsic depolarizing resonances. This was a truly heroic effort!

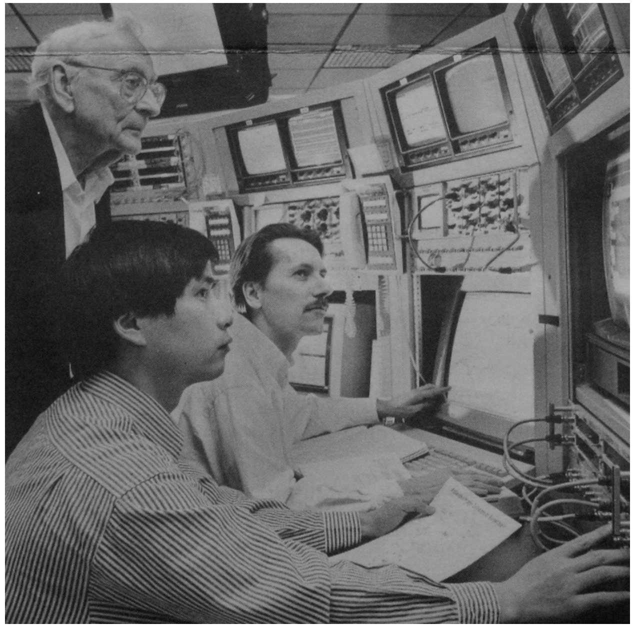




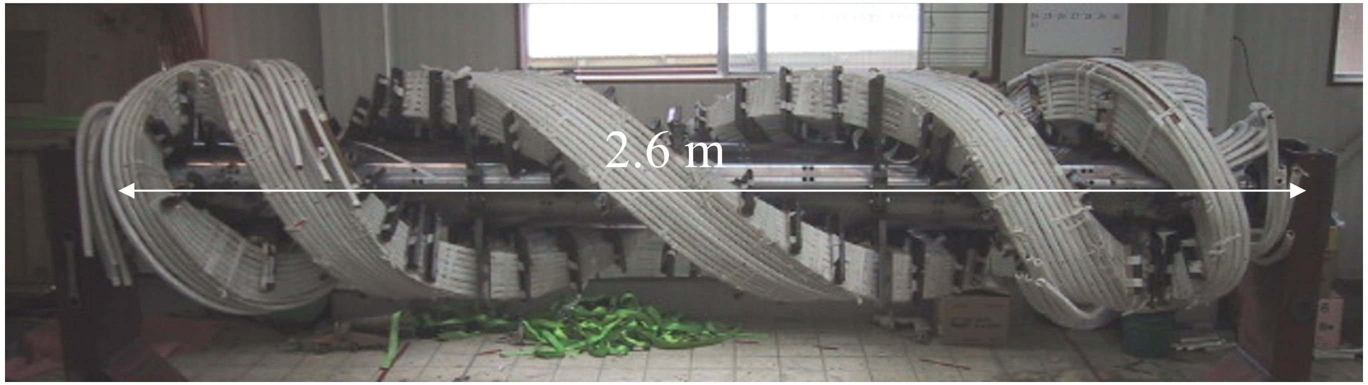
1/95 correction dipole; 1/10 pulsed quadrupole; main field

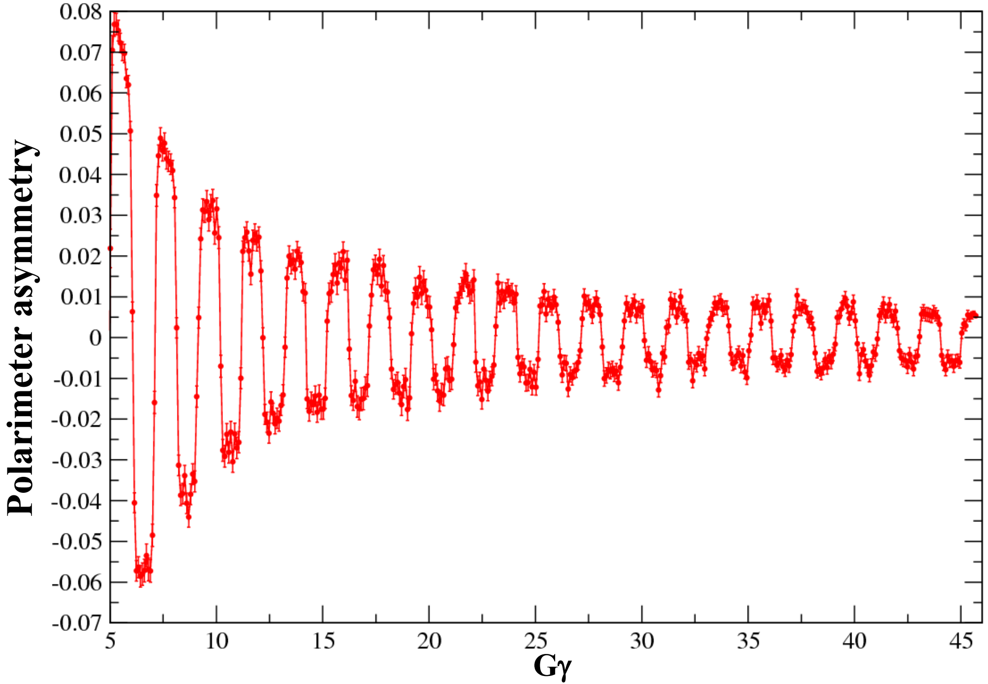
Polarized Protons in the AGS

- Two strong partial Siberian snakes using variable-pitch helical dipoles
- Vertical betatron tune at 8.98!
- Pulsed quadrupoles to jump across the many weak horizontal spin resonances driven by the partial snakes.



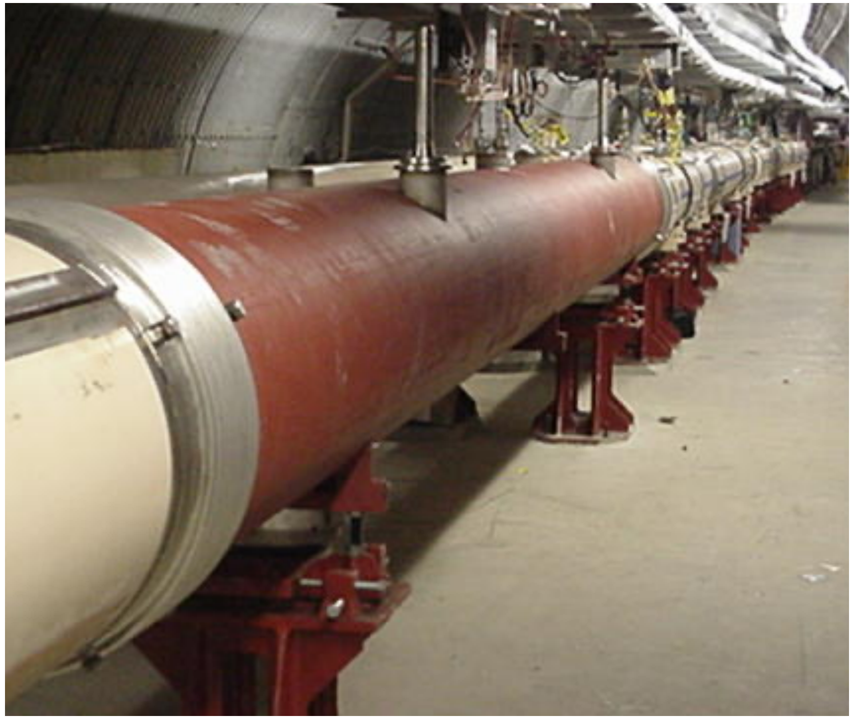
Larry Ratner, Haixin Huang and TR in AGS MCR.

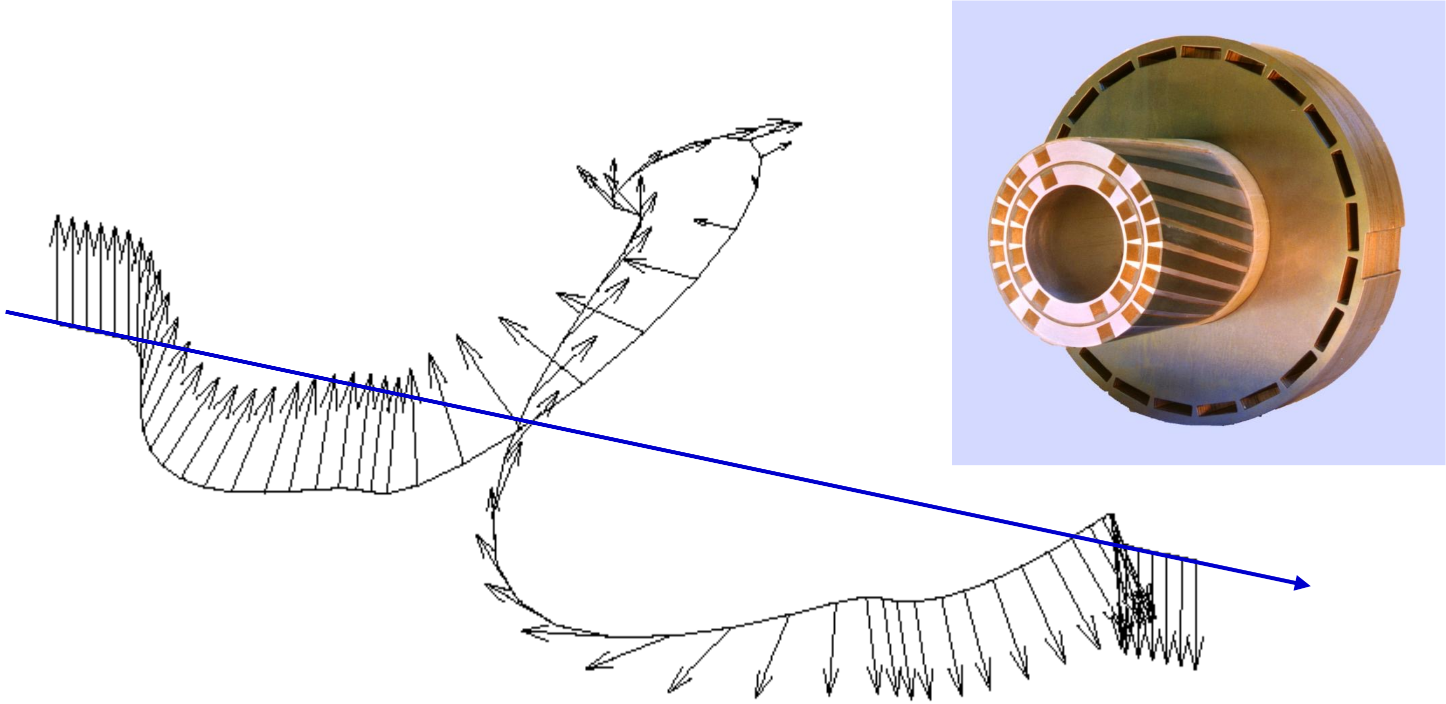




Polarized protons in RHIC

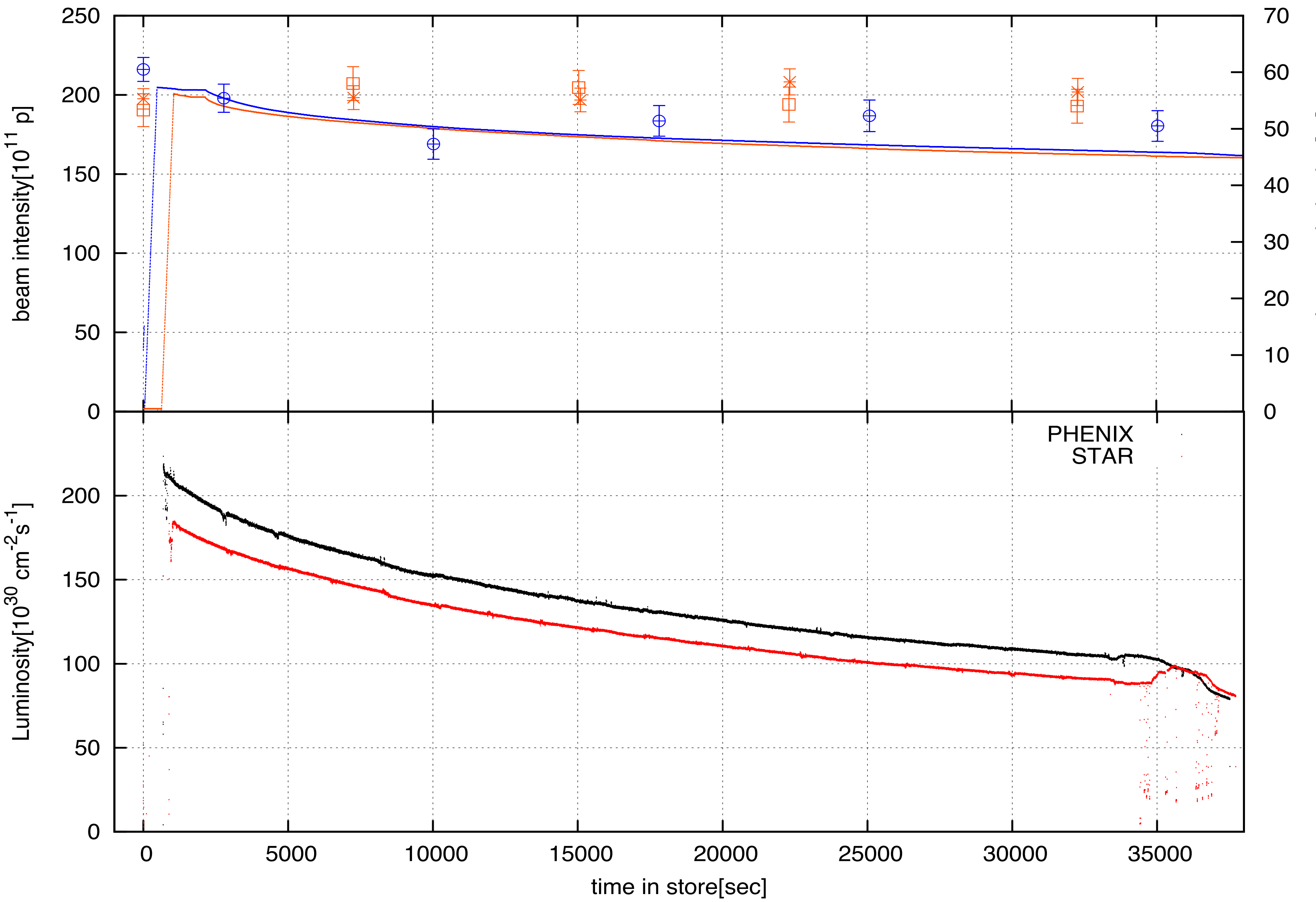
- 2+2 RHIC Siberian Snakes: four 4 Tesla superconducting helical dipoles, each 2.4 m long and with full 360-degree twist
- 4+4 RHIC spin rotators: four 4 Tesla superconducting helical dipoles, two right- and two left-handed, each 2.4 m long and with full 360-degree twist





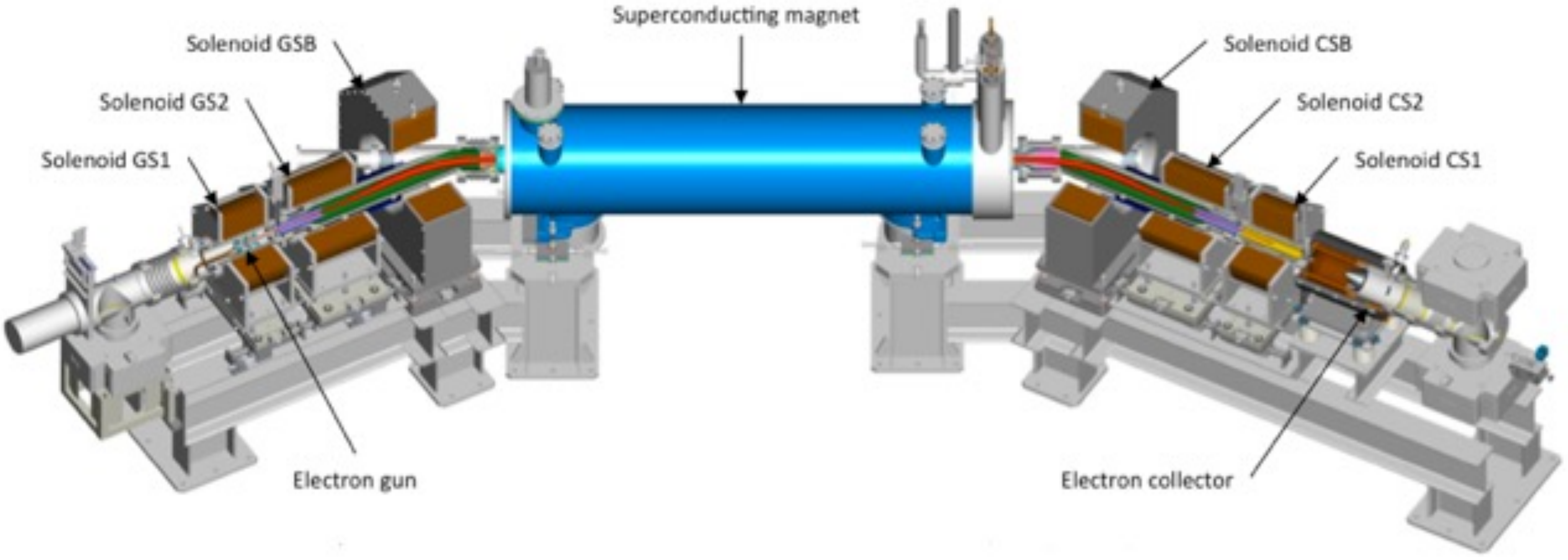
Polarized Proton Collisions at 255 GeV Beam Energy

- Reached ~ 57% average polarization in 14 best stores
- Little polarization loss on ramp and during store
- Peak luminosity: $2.5 \times 10^{32}\ cm^{-2}\ s^{-1}$
- Requires excellent control of orbit, tune and coupling

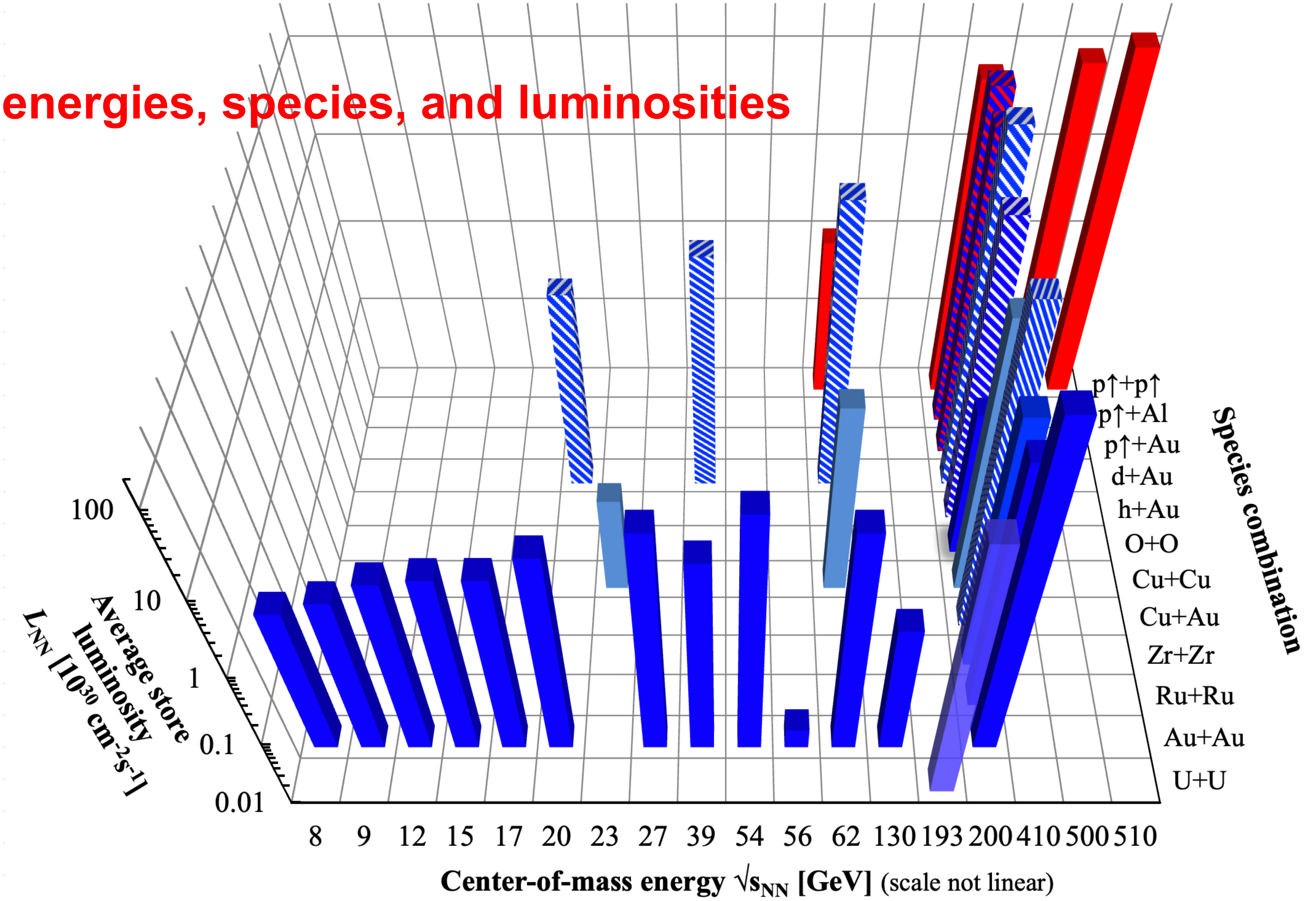


Development at RHIC:
Beam-beam compensation with electron lenses

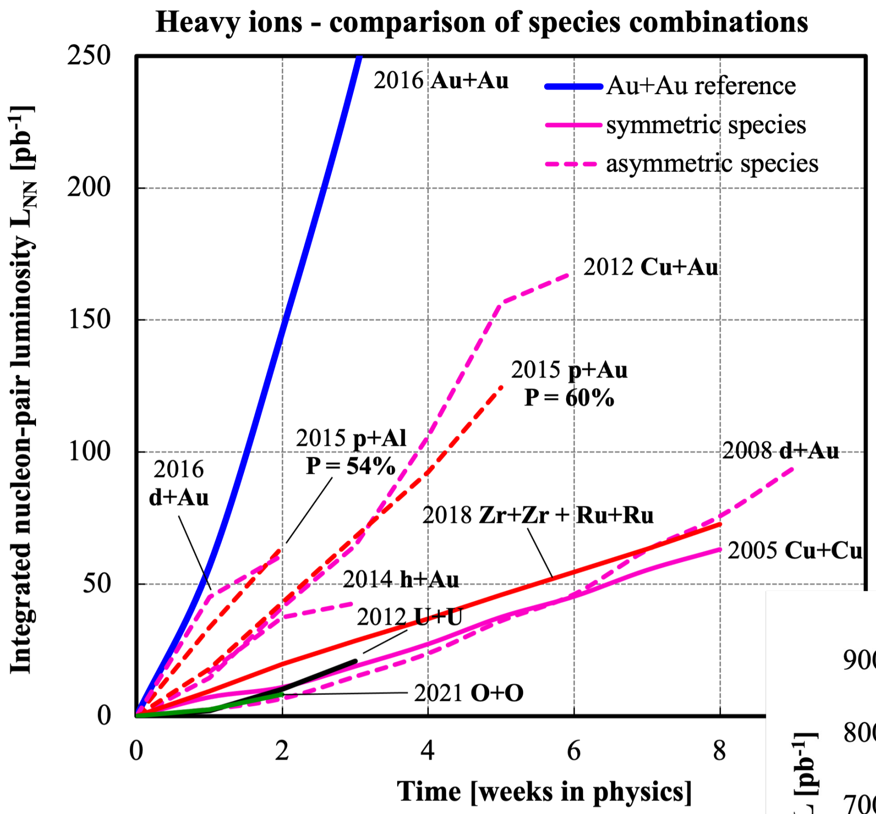
- Proton-proton collisions in RHIC are limited by beam-beam tune spread.
- First successful head-on beam-beam compensation by colliding with a low energy electron beam.

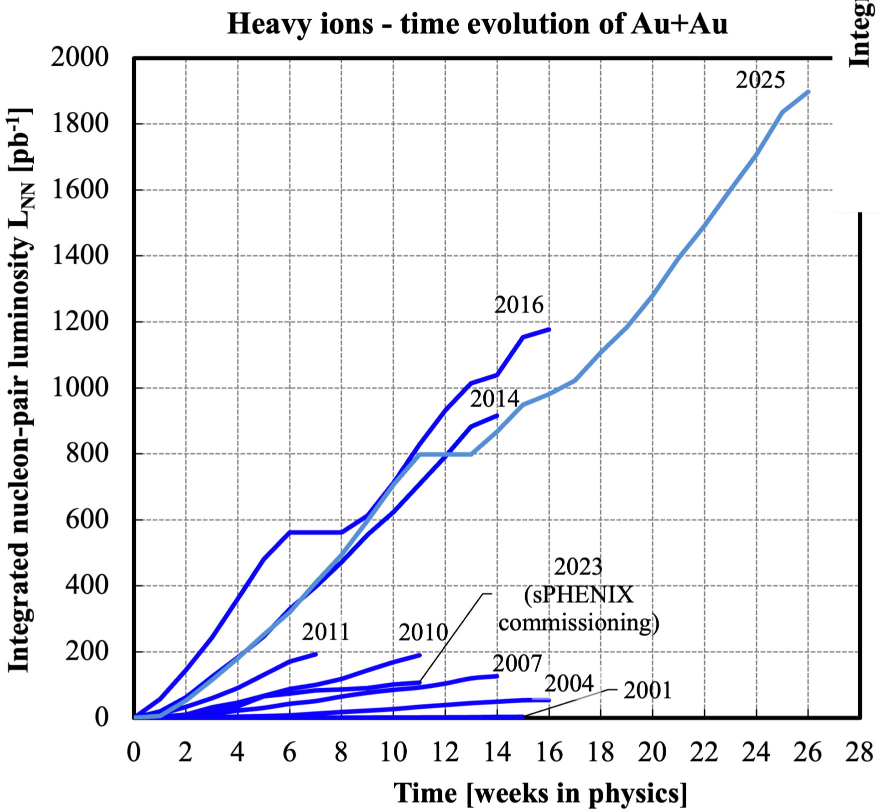


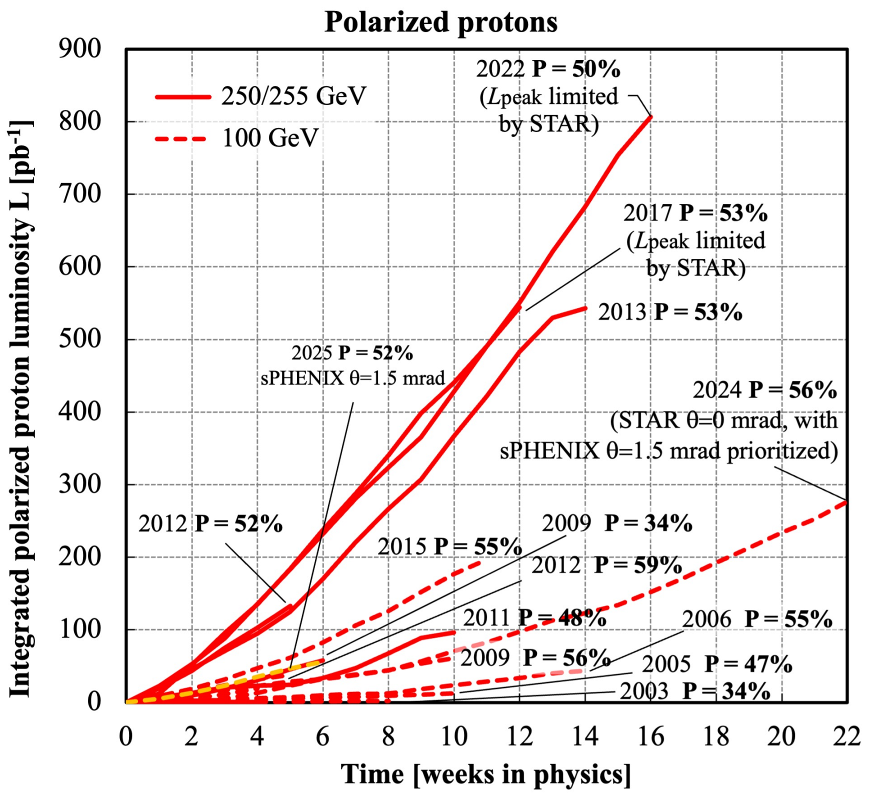
RHIC energies, species, and luminosities



RHIC evolution







Summary

- RHIC is the first heavy collider and reached record luminosities over a wide energy range with advanced beam cooling techniques
- RHIC is also the first polarized proton collider establishing the feasibility of accelerating polarized proton beams to high energy using Siberian snakes and demonstrating head-on beam-beam compensation
- Over the last 26 years RHIC has operated with unparalleled flexibility of collision energy from 7 to 510 GeV and ion species from protons to Uranium.
- The fantastic achievements of RHIC form the basis for the polarized Electron Ion Collider.