RHIC's Quarter-Century of Colliding Beam Operations

RHIC Overview and Operations History
Advances in Accelerator Science
Further Optimizations
Performance Summary and Legacy

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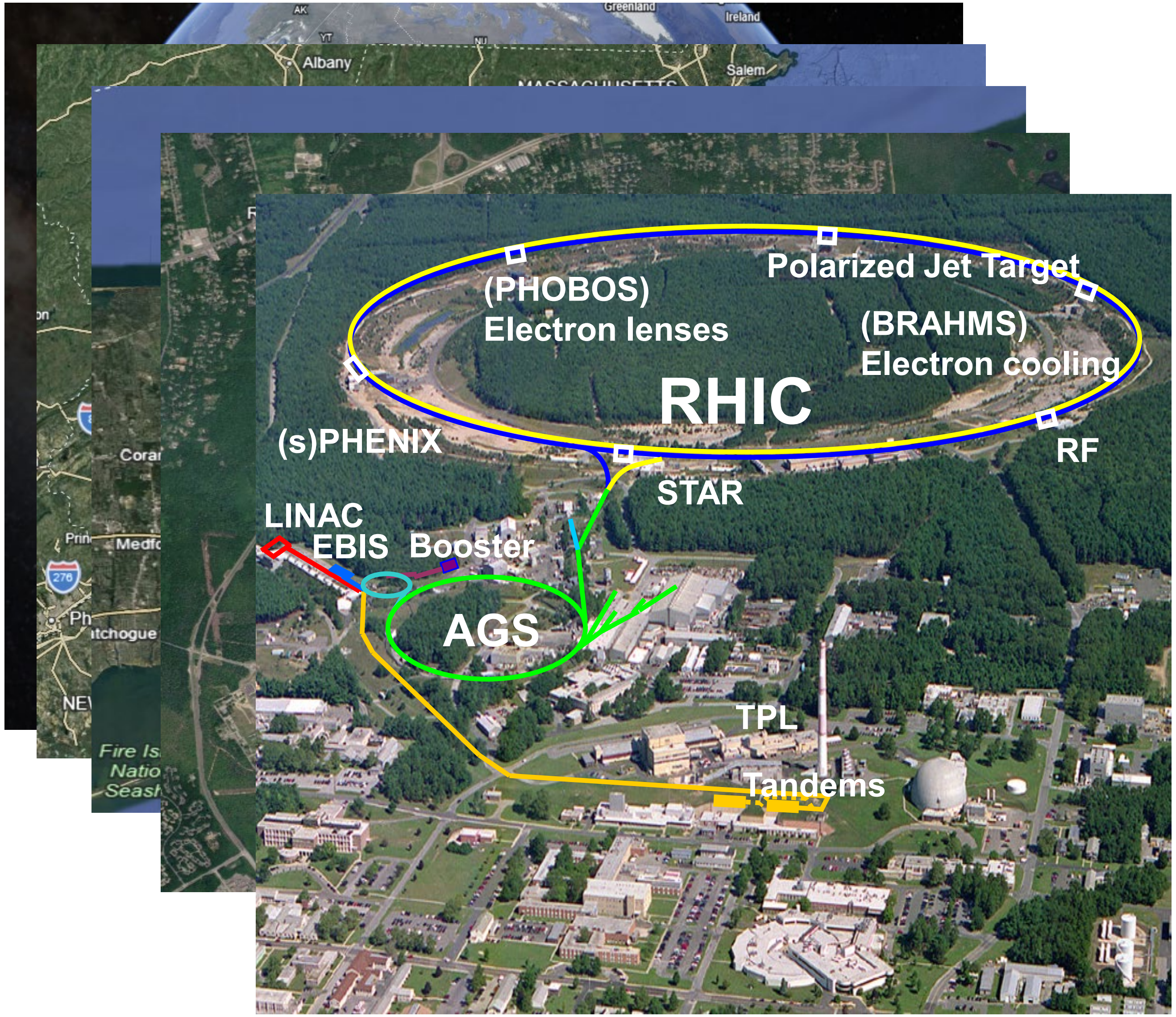
U.S. DEPARTMENT of ENERGY

RHIC Overview and Operations History

Relativistic Heavy Ion Collider (RHIC)



1983 DOE/NSF NSAC: identified a **Relativistic Heavy Ion Collider** as highest priority next major facility

1984 proposal for RHIC at BNL

1986 RHIC CDR

1991 RHIC construction start

1993 RHIC spin program added (RIKEN, Japan)

1994 RHIC collider installation start

achieved parameters (symmetric modes)

	Au+Au	$\vec{p}+\vec{p}$	unit
energy (c.o.m)	200	510	GeV
ions/p (per bunch)	2.0	200	$\times 10^9$
# bunches	111	111	
ε (rms, normalized)	2.15→0.55	2.5	π μm
β*	0.7	1.5→1.2→1.0	m
L, peak	4.2×10^{27}	2.0×10^{32}	$cm^{-2}s^{-1}$
<L>	1.9×10^{27}	1.6×10^{32}	$cm^{-2}s^{-1}$

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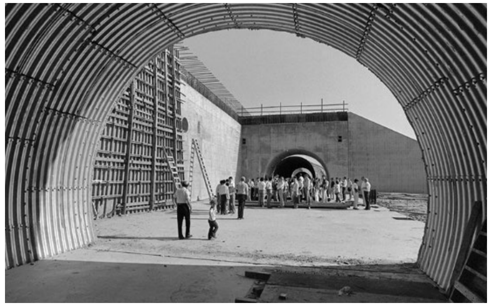
RHIC timeline

1991

start of RHIC construction



1994

collider installation begins

1995

groundbreaking for STAR

1999

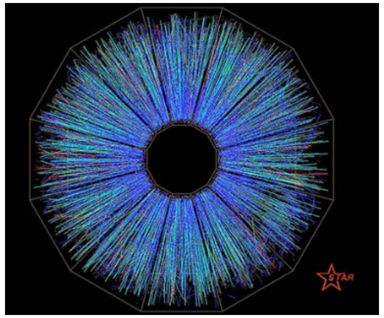
first Siberian snake magnet

2000

RHIC dedication ceremony

SC magnet cold

first Au+Au collisions

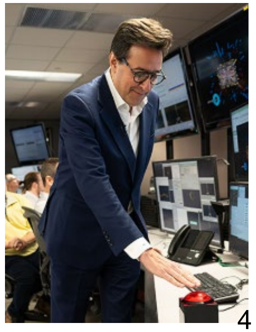


2001

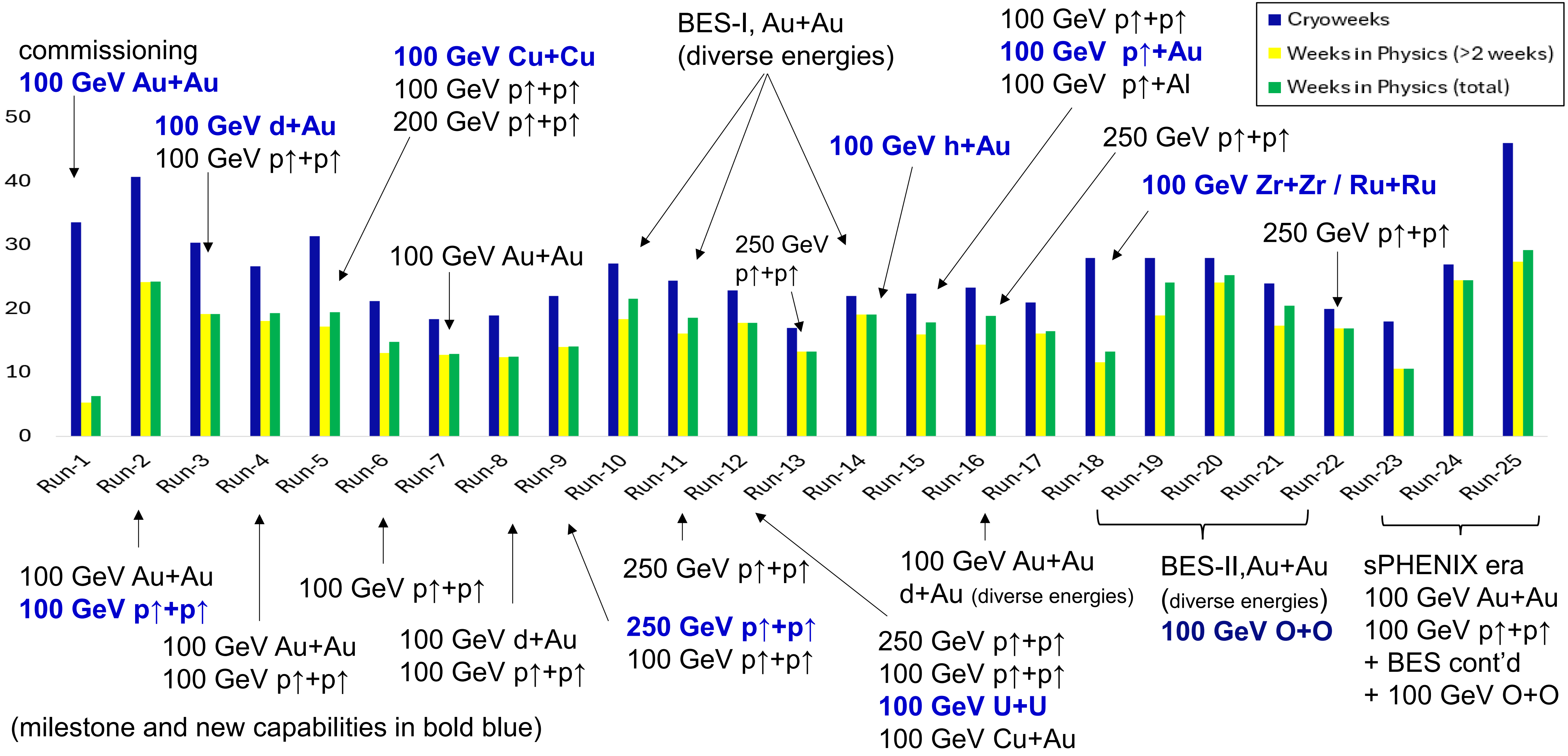
first p↑+p↑ collisions

2026

RHIC operations conclude

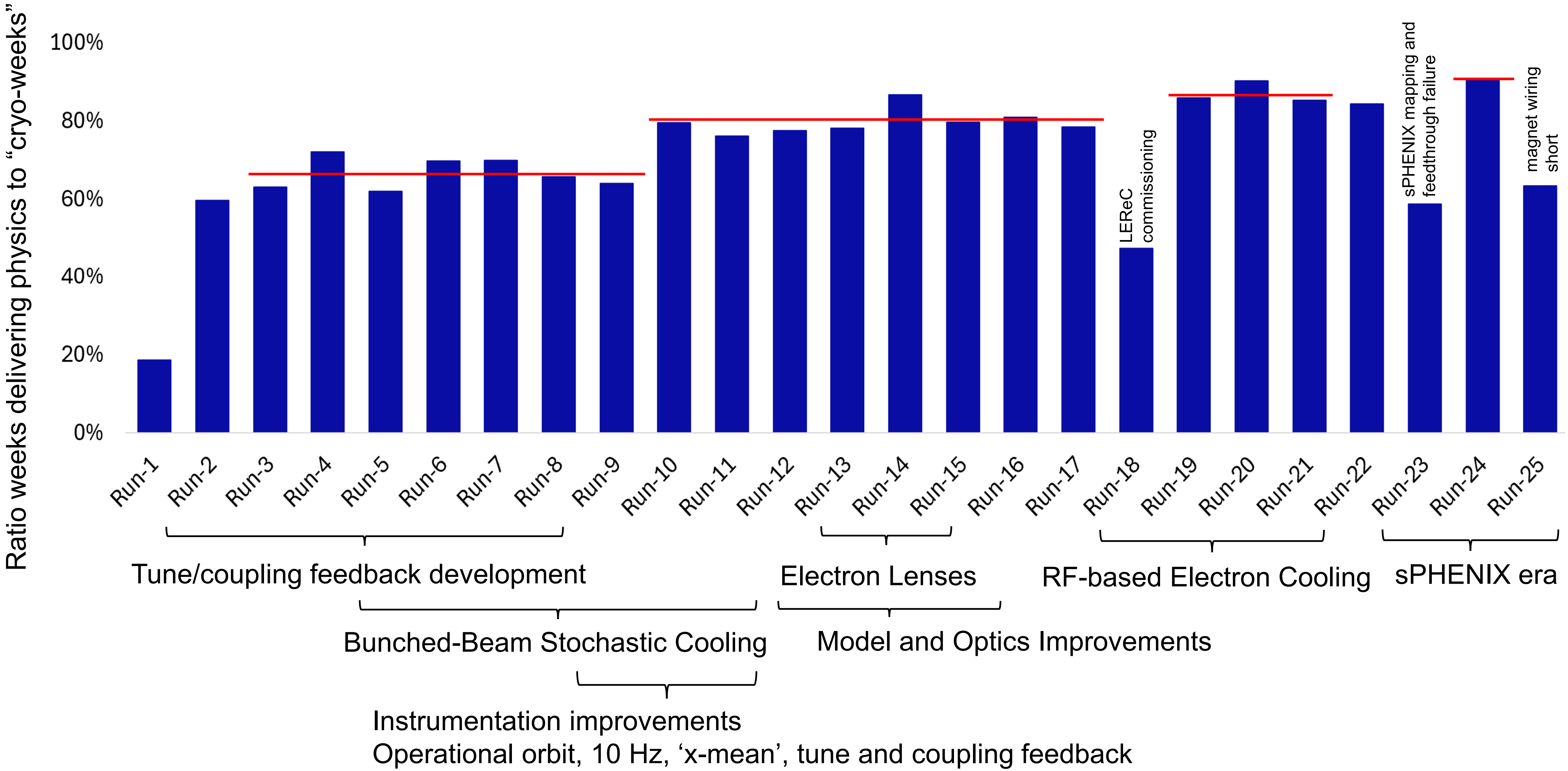


A quarter-century of collisions at RHIC



(milestone and new capabilities in bold blue)

Timeline of Accelerator Science Innovations at RHIC



Advances in Accelerator Science

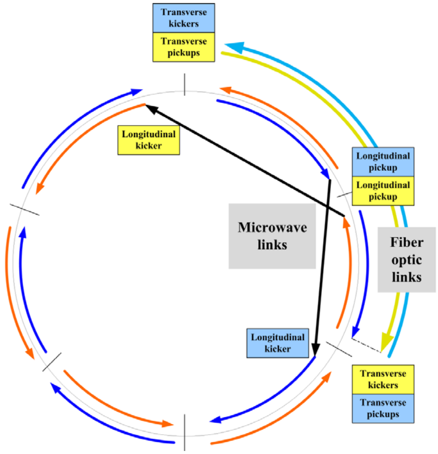
Three-dimensional (3D) bunched-beam stochastic cooling

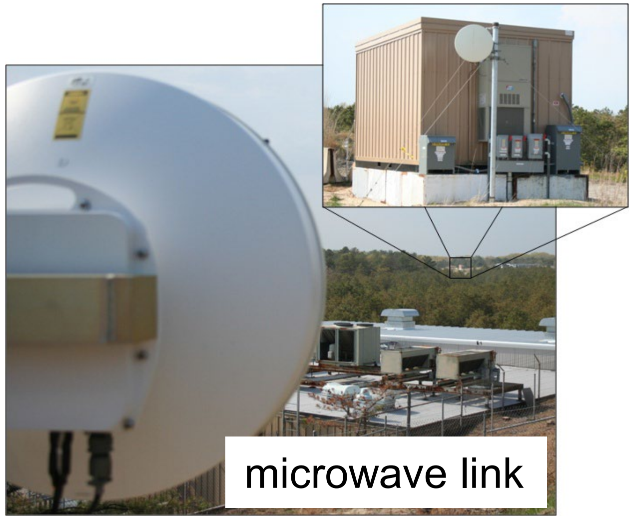
Purpose — counteract intrabeam scattering and cool beams' emittances

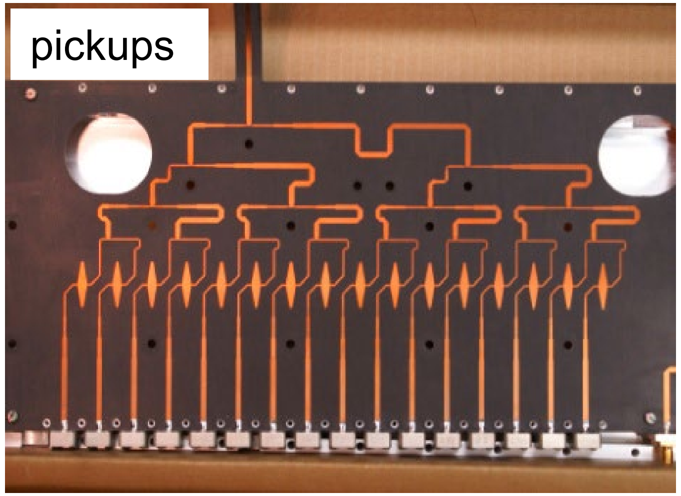
Key innovations

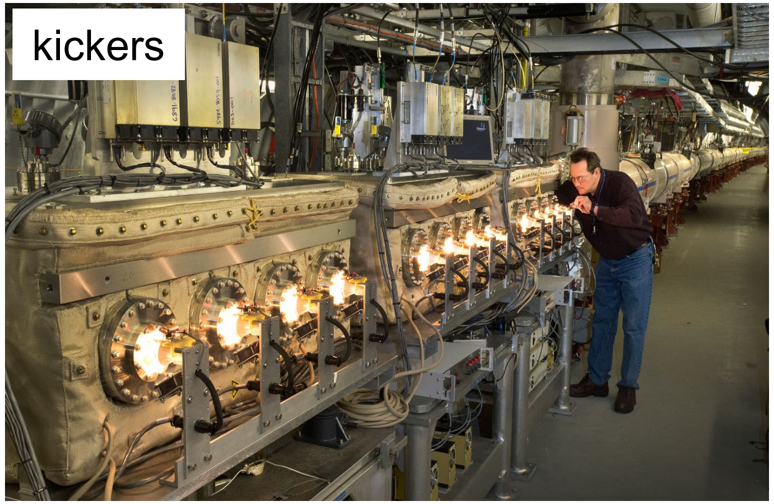
- high-frequency Schottky signal detection (in the presence of signals from coherent collective motion)
- free-space microwave transmitters and receivers for high feedback gain
- high-precision 'variable-aperture' kickers

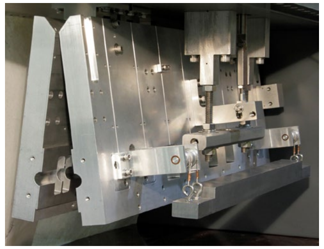
layout

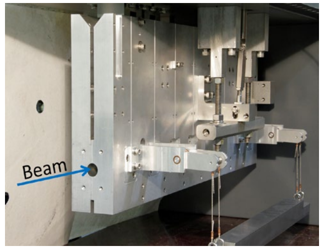








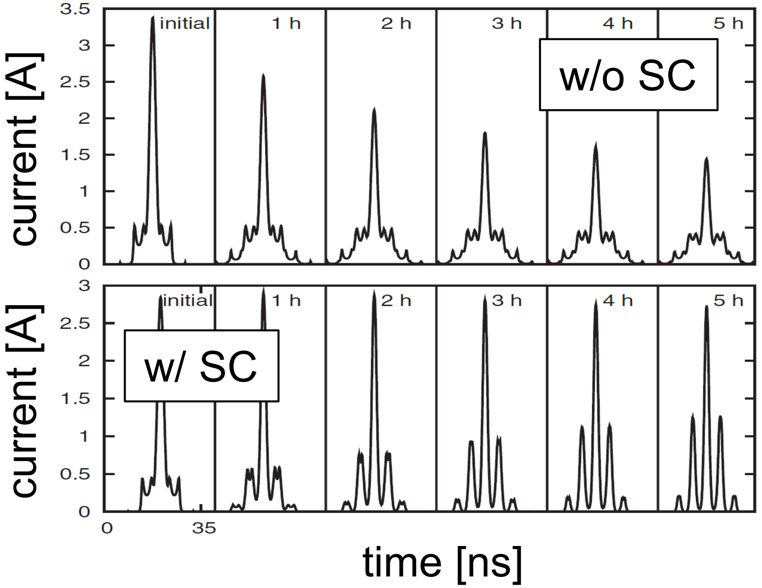




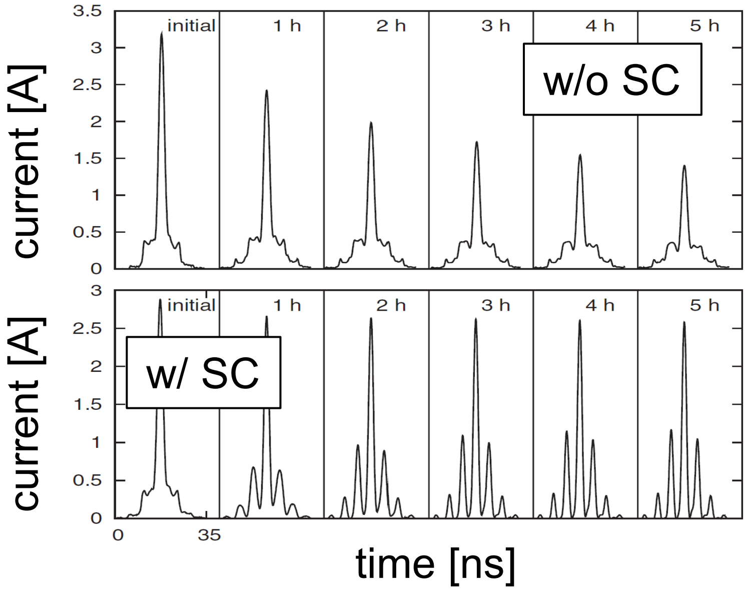
M. Blaskiewicz, J.M. Brennan, K. Mernick, "Three-dimensional stochastic cooling in [RHIC]", *PRL* (2010)

First proof-of-principle with longitudinal stochastic cooling

simulations, 100 GeV/n Au



measurements, 100 GeV/n Au

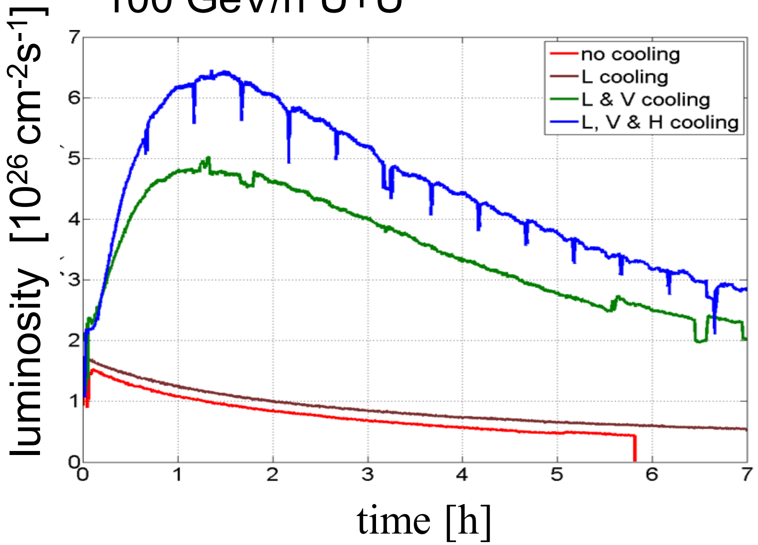


M. Blaskiewicz, J.M. Brennan, F. Severino, “Operational stochastic cooling in [RHIC]”, *PRL* (2008).

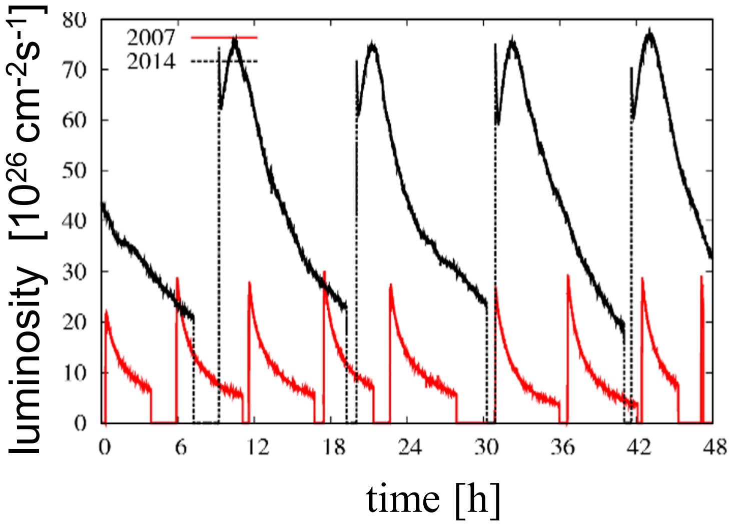
Full 3D bunched-beam stochastic cooling

Y. Luo et al., “Burn-off dominated uranium and asymmetric copper-gold operation in RHIC”, PAC (2103).

100 GeV/n U+U



100 GeV/n Au+Au



M. Blaskiewicz, J.M. Brennan, K. Mernick, “Three-dimensional stochastic cooling in [RHIC]”, *PRL* (2010).

Full-energy Au+Au average luminosity almost 50 times design

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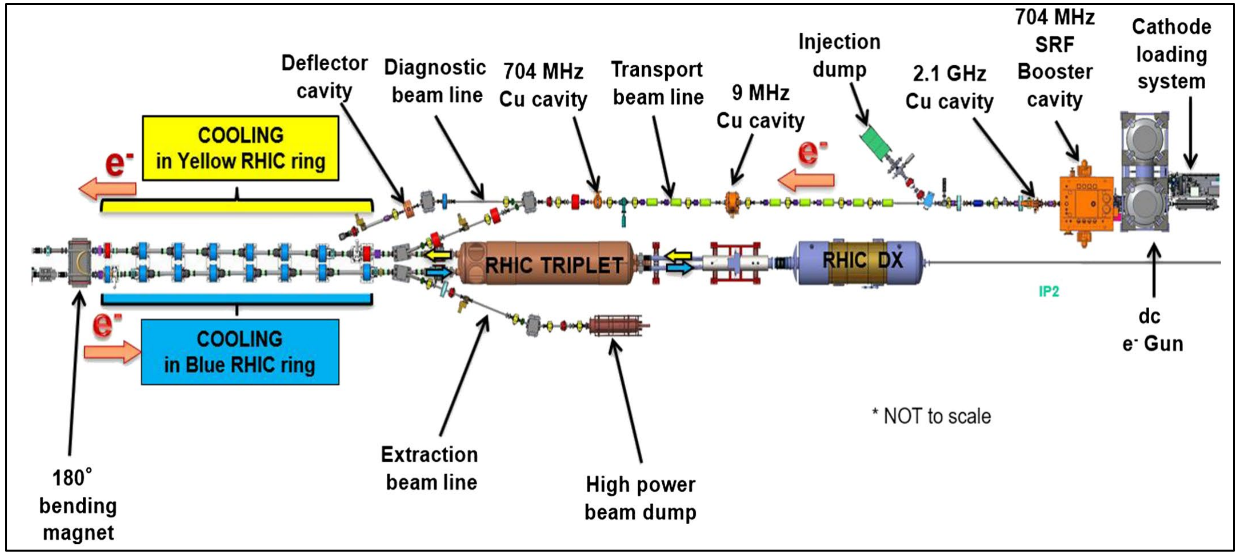
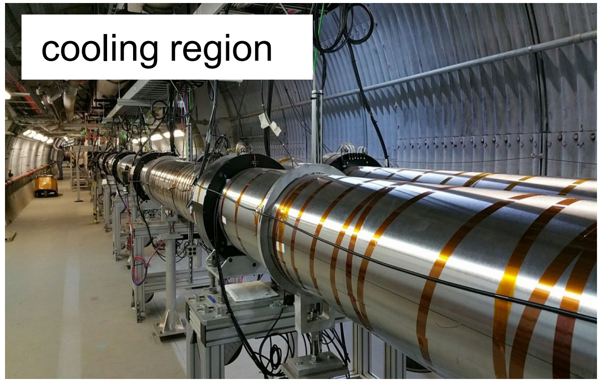
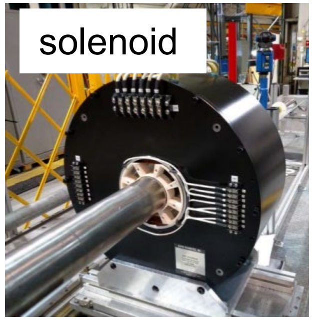
RF-Based Electron Cooling

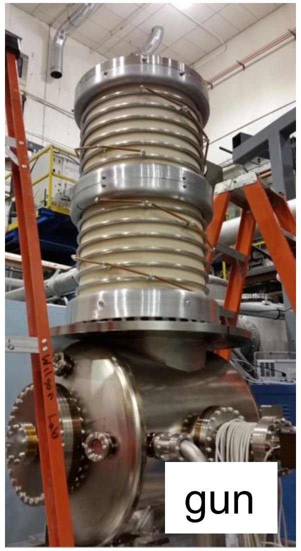
Purpose	mitigate strong intrabeam scattering and cool beams' emittances at low energy including during collisions
Key innovations	• RF-accelerated electron bunches • non-magnetized electron beam (~30 mA) with low emittance, low energy spread, and high current • single electron beam cools both (counter-rotating) ion beams • electron cooling with colliding beams



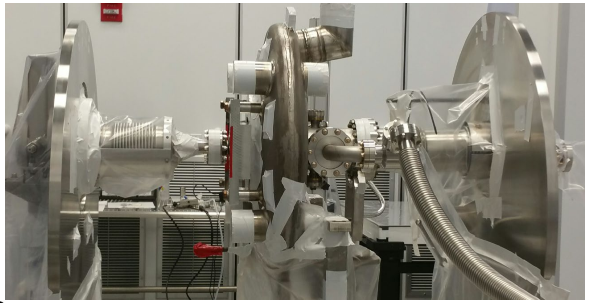




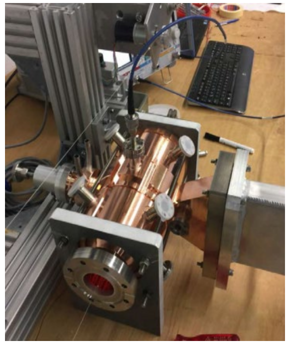
A. Fedotov et al., "Experimental demonstration of hadron beam cooling using radio-frequency accelerated bunches", *PRL* (2020)



704 MHz SC booster



2.1 GHz NC cavity



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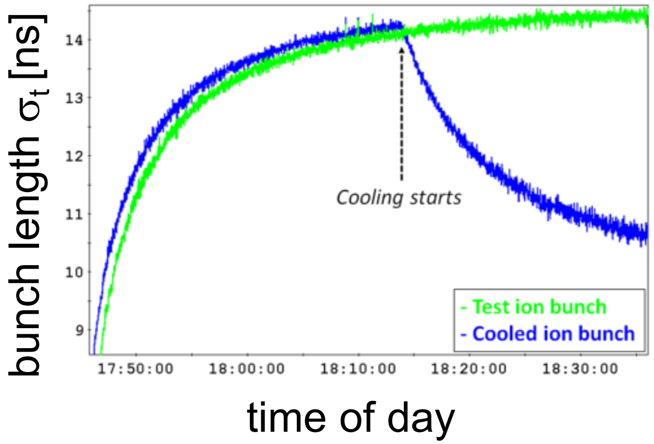
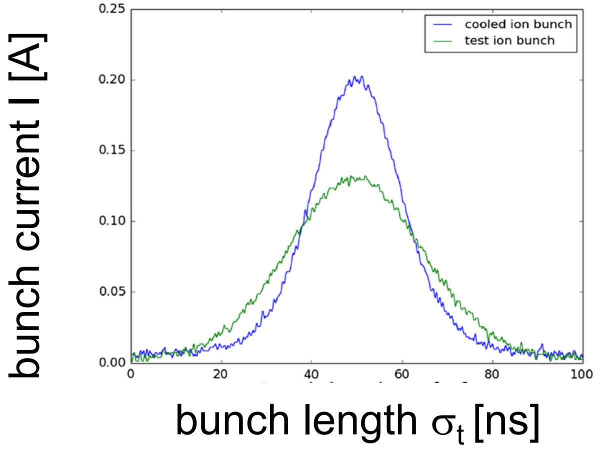
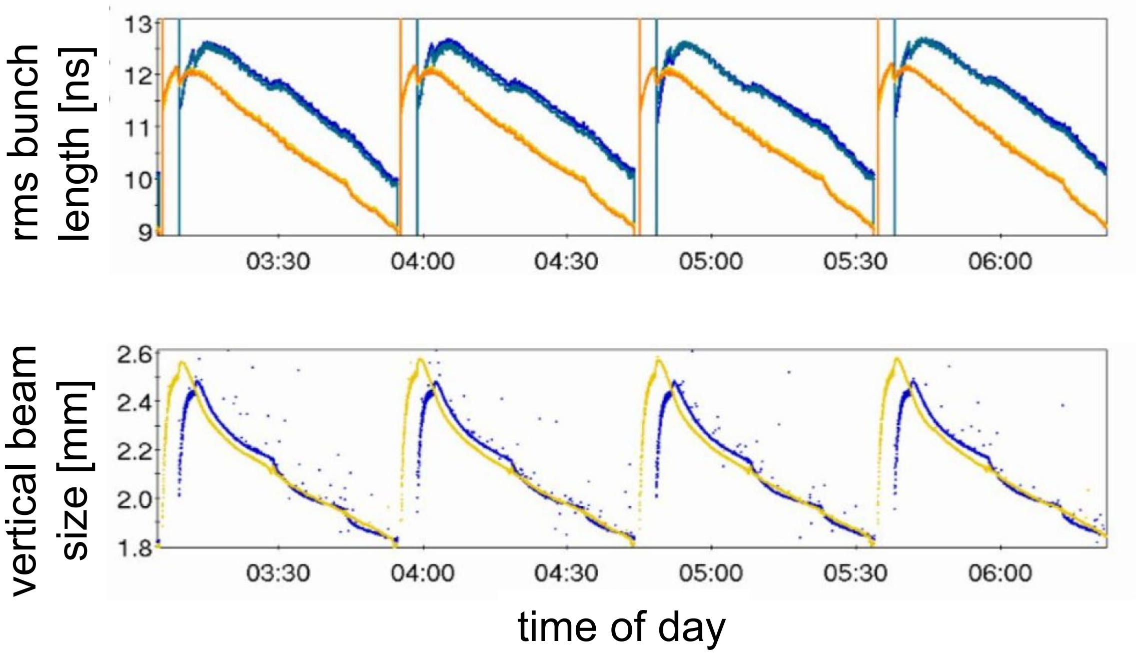
First proof-of-principle with RF-based electron cooling



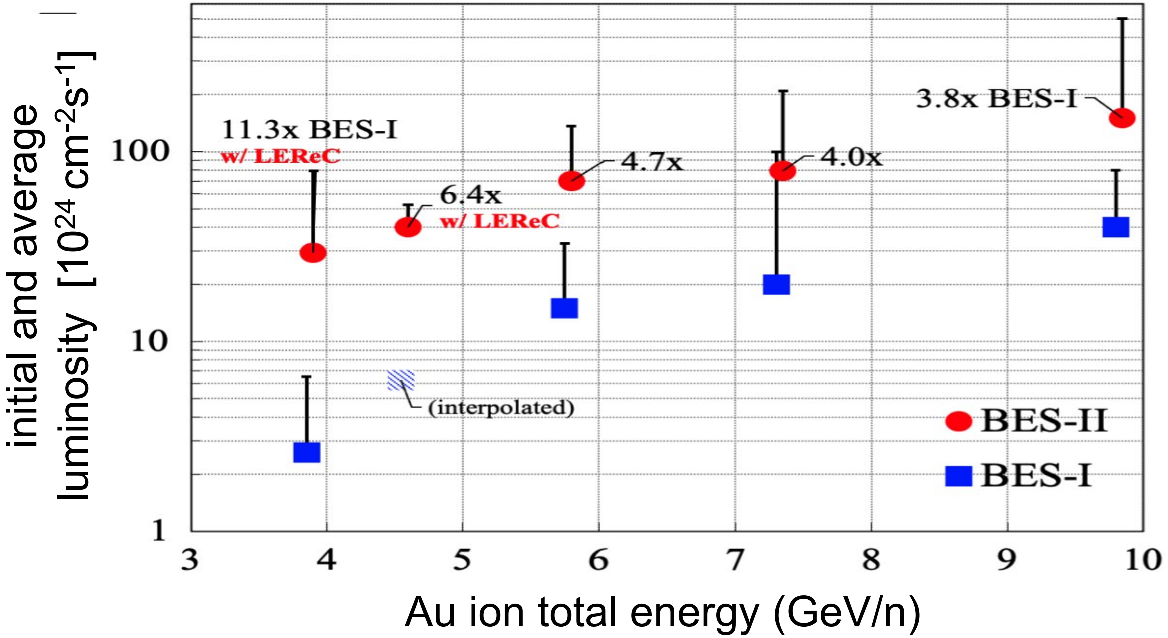


S. Seletskiy *et al.*, “Accurate setting of electron energy for demonstration of first hadron beam cooling with RF accelerated electron bunches”, *PRAB* (2019).

Routine operations: 2 MeV electrons, Au 4.6 GeV/n Au ions



Luminosity w/ and w/o cooling (2010 - 2021)



RF-based electron cooling extends applicability to high energies; planned for the future Electron-Ion Collider (EIC)

Polarized Protons

Purpose — Generate, accelerate, and collide protons with highest polarization

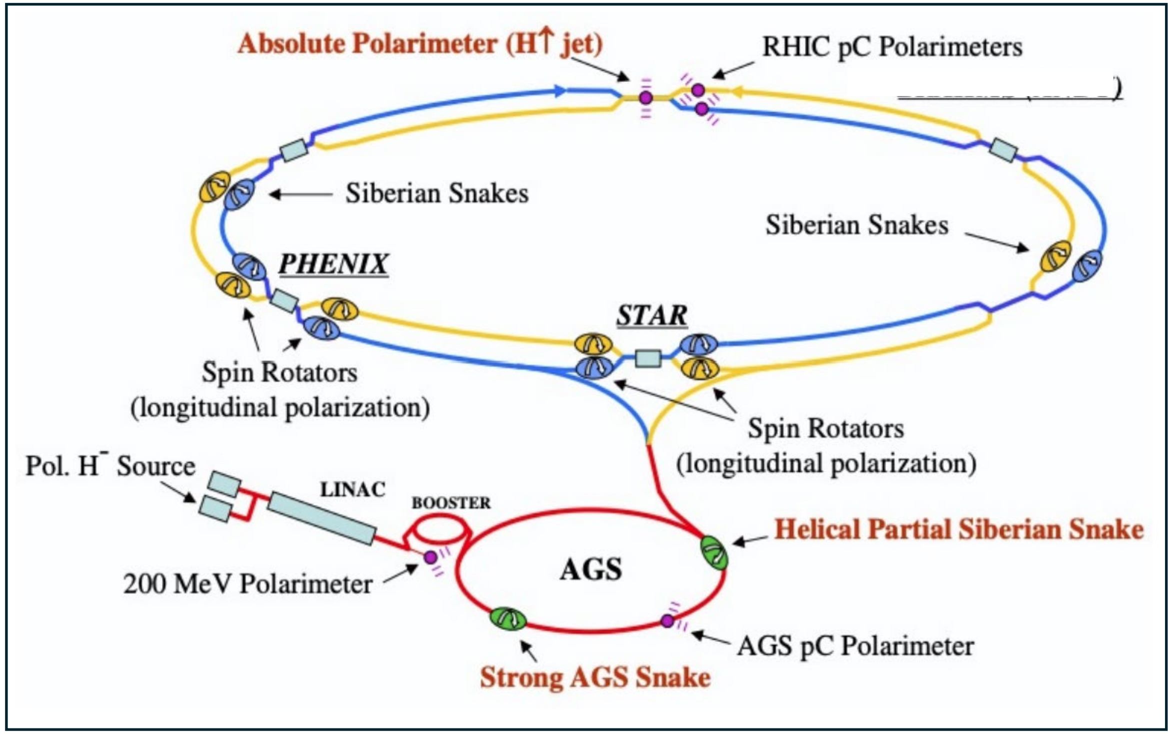
Key innovations
- high-intensity polarized source
- full and partial Siberian Snakes
- diverse polarimetry
- enhanced spin tracking simulations

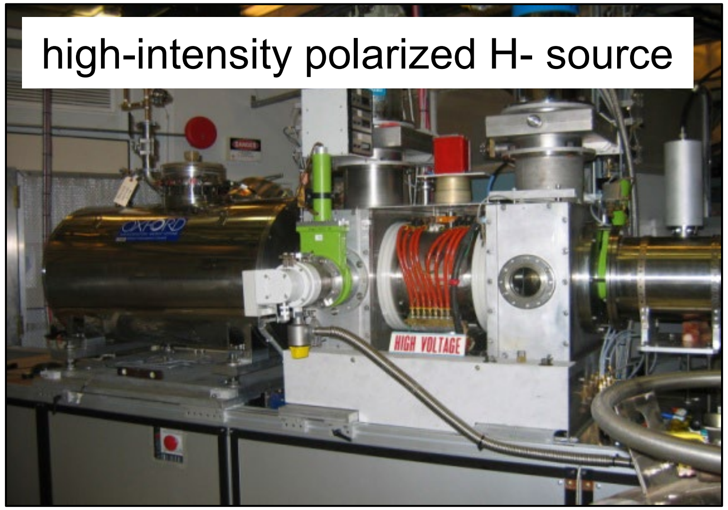
T. Roser *et al.*, "Polarized proton collider at RHIC (BNL, 2006).

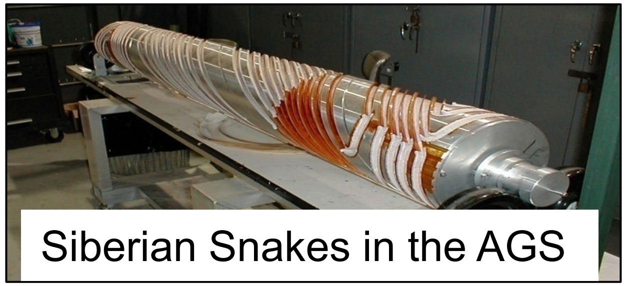
A. Zelinski *et al.*, "The RHIC polarized H- source", Rev. Sci. Instrum. (2016).

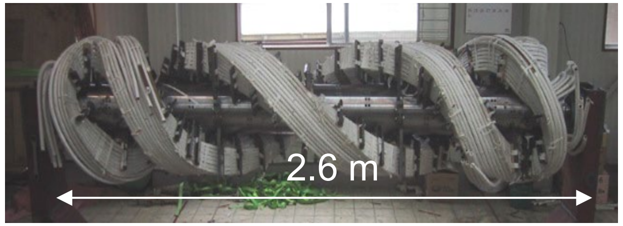
E. Willen *et al.*, "A helical magnet design for RHIC", PAC (1997).

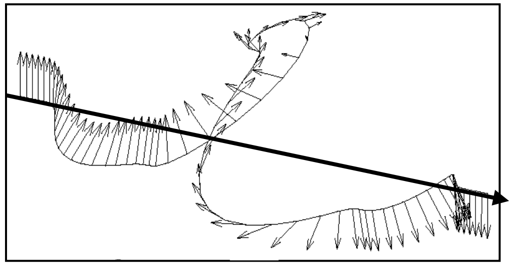
F. Méot *et al.*, "RHIC optics and spin dynamics with snakes and rotators", PRAB (2022).





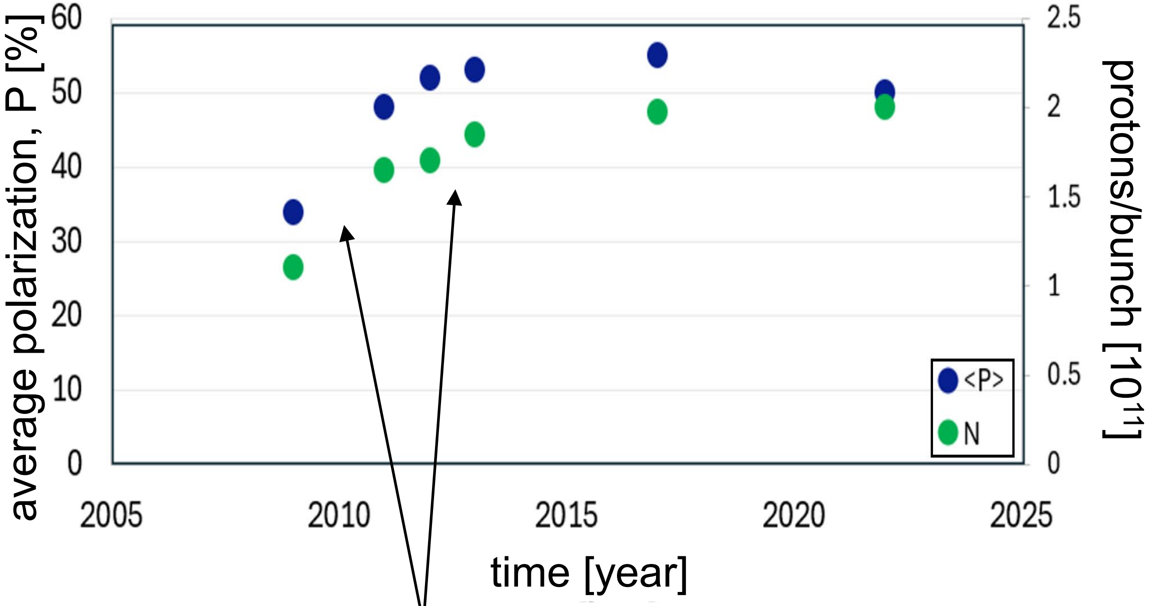


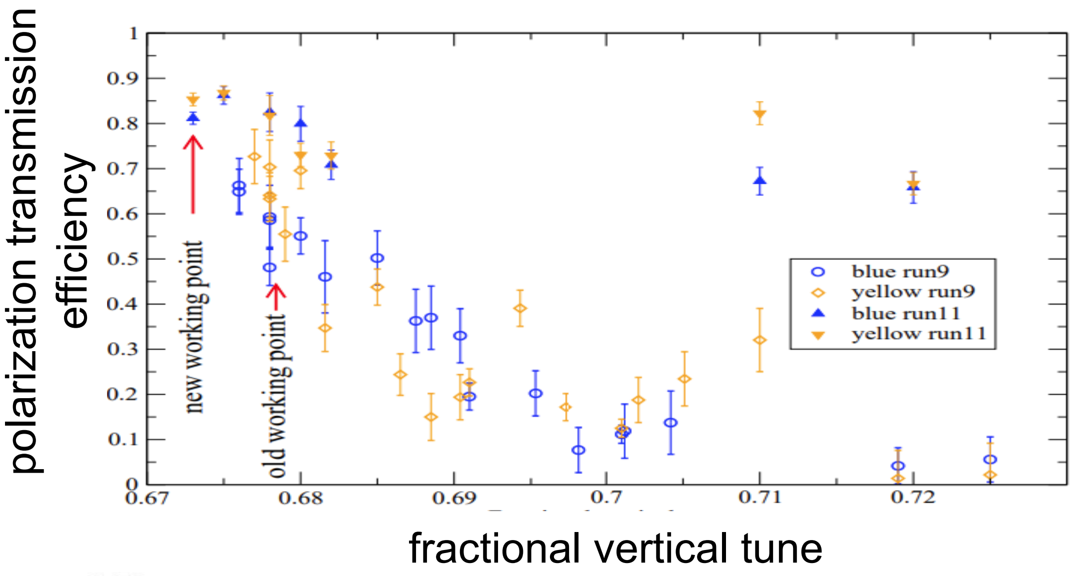




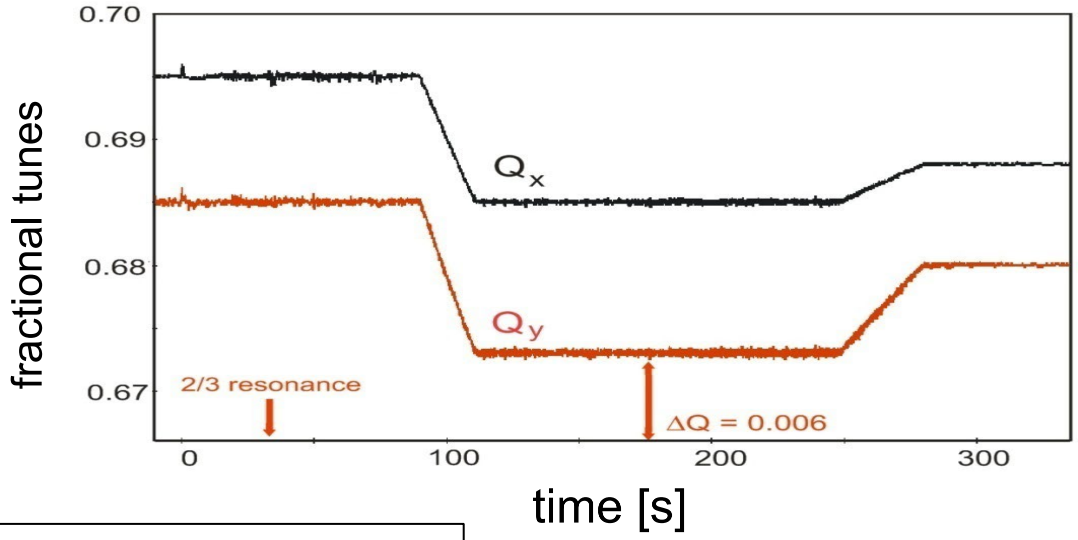
M. Bai *et al.*, "First polarized proton collisions at a beam energy of 250 GeV in RHIC", PAC (2009)

Polarization evolution in RHIC at 250 GeV





Key advances
- 2006: additional partial Siberian Snake in the AGS
- 2011: horizontal “tune jumps” in the AGS
- 2008 – 2012: advances in beam control
- 2013 – 2015: advances in lattice modelling and implementation



Highest proton polarizations ever achieved in a collider

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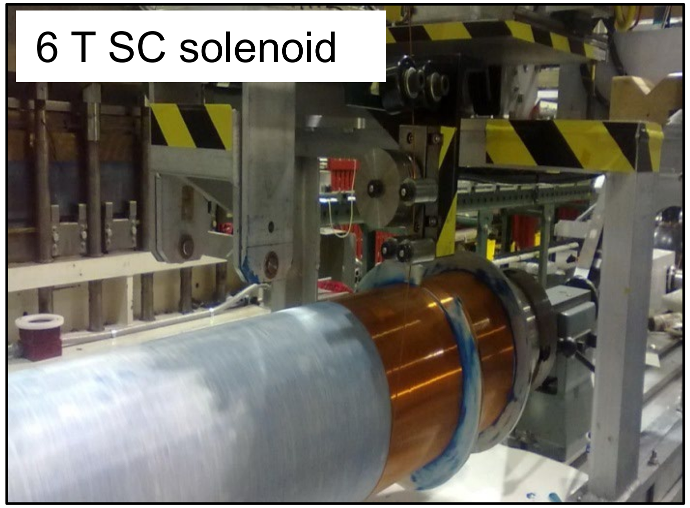
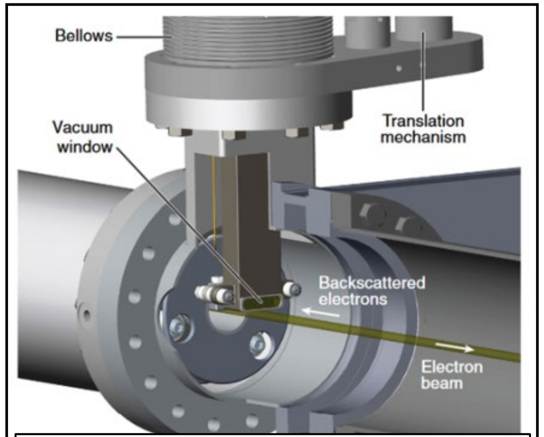
Head-on Beam-Beam Compensation with Electron Lenses

Purpose Beam-beam tune spread compensation

Key innovations

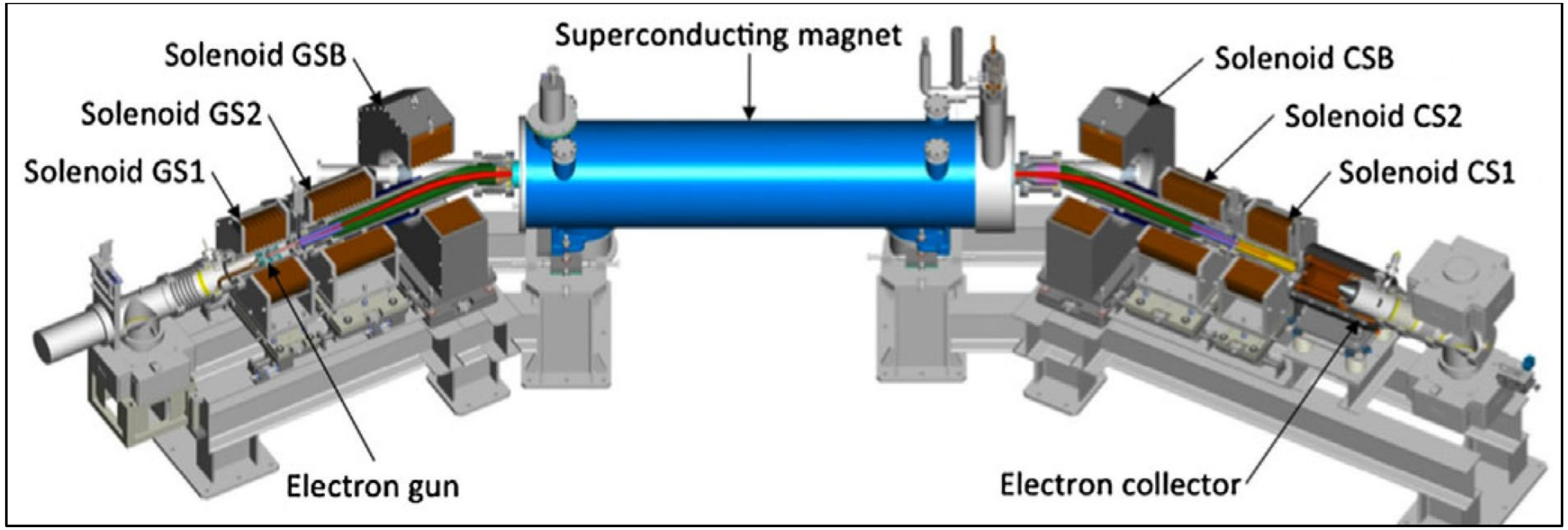
- large thermionic cathode, high DC current (1A), low-noise electron beam
- magnetized transport with high-field SC solenoids
- precision alignment between beams
- operation in a high-energy collider

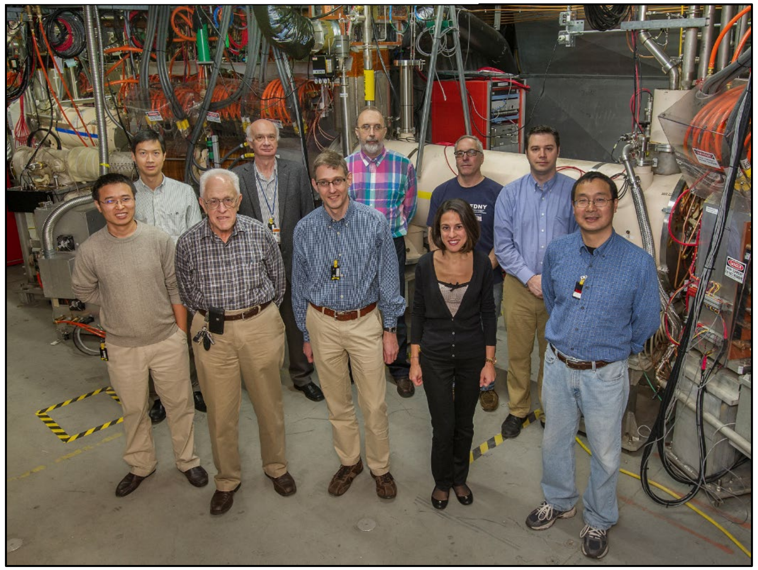

6 T SC solenoid



Novel alignment detector

W. Fischer et al., "Operational Head-on Beam-Beam Compensation with Electron Lenses in [RHIC], PRL 115, 264801 (2015)





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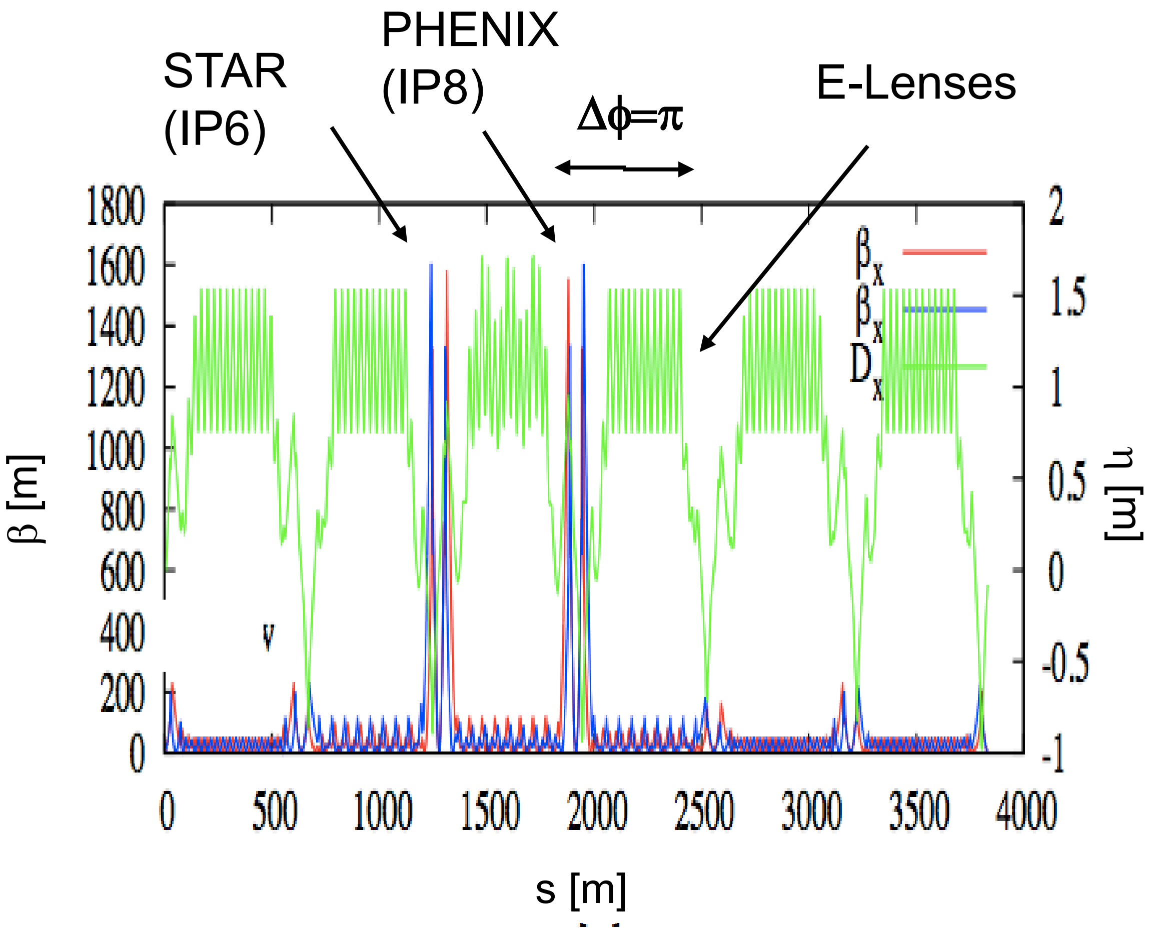
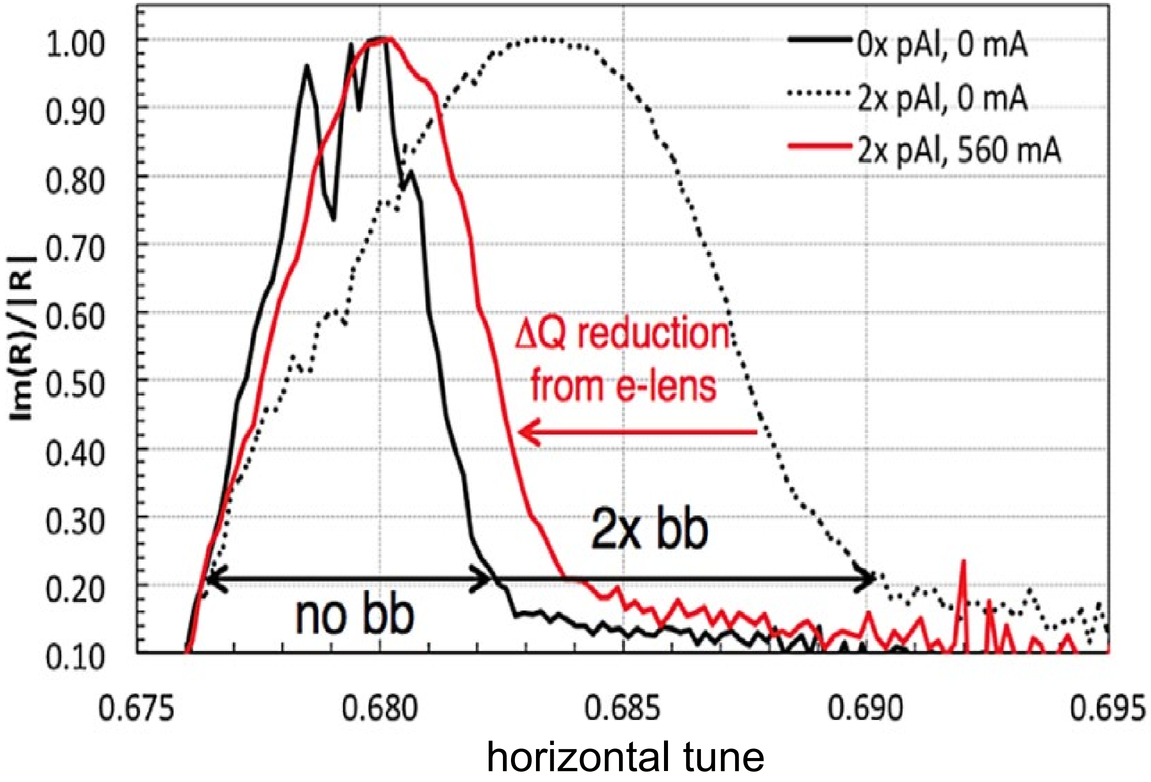
S. White, W. Fischer, Y. Luo, "Optics solutions for pp operation with electron lenses at 100 GeV", BNL-105550-2014-IR (C-A/AP/519)

W. Fischer et al., "Operational Head-on Beam-Beam Compensation with Electron Lenses in [RHIC], PRL 115, 264801 (2015)





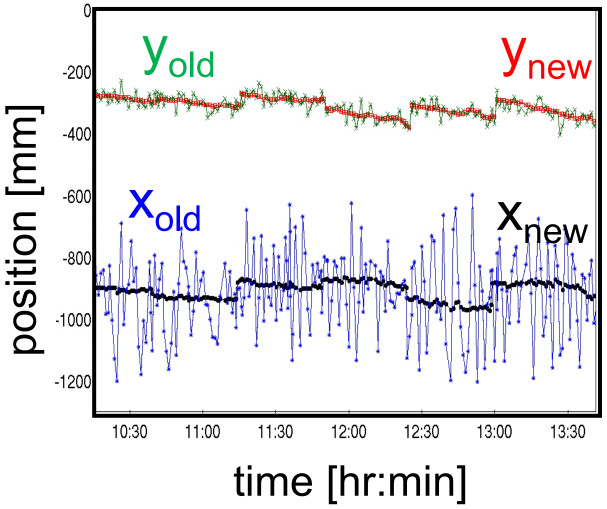
Lenses, lattice and lattice implementation, and high beam intensities nearly doubled the peak and average luminosities in p↑+p↑ collisions at 100 GeV.

Further Optimizations

Instrumentation

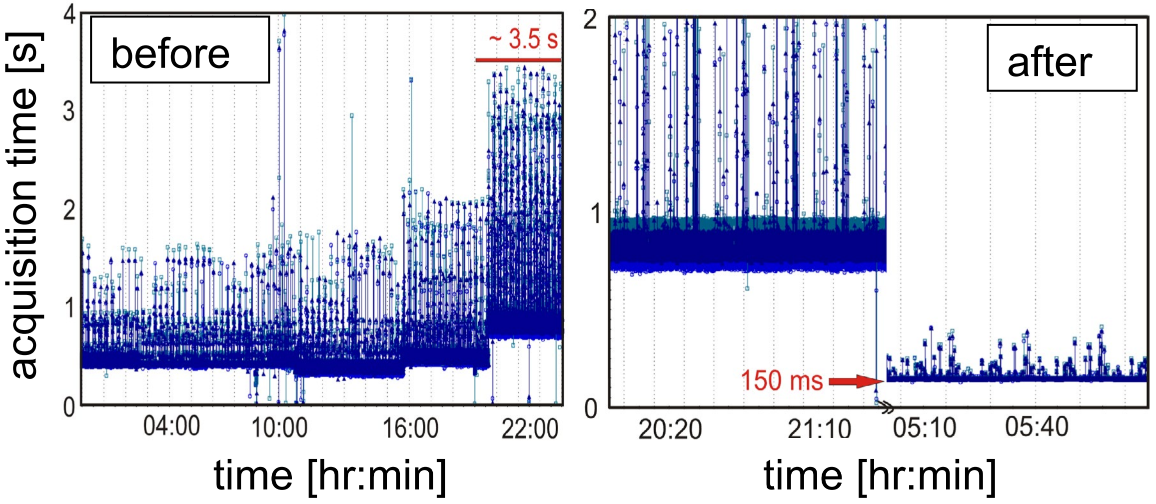
Beam Position

suppression of variations due to 10 Hz mechanical vibrations

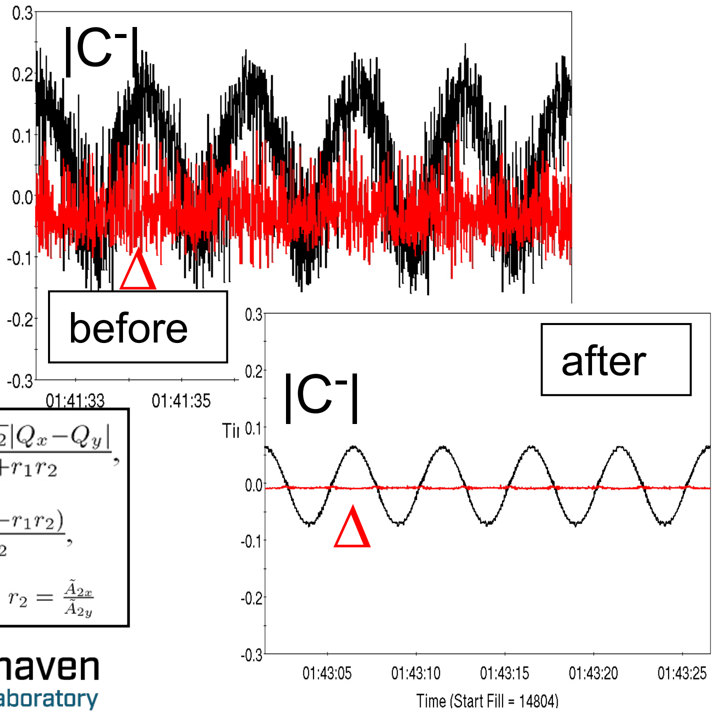


BPM Data Delivery

faster and deterministic data delivery from BPMs



Tune and Coupling



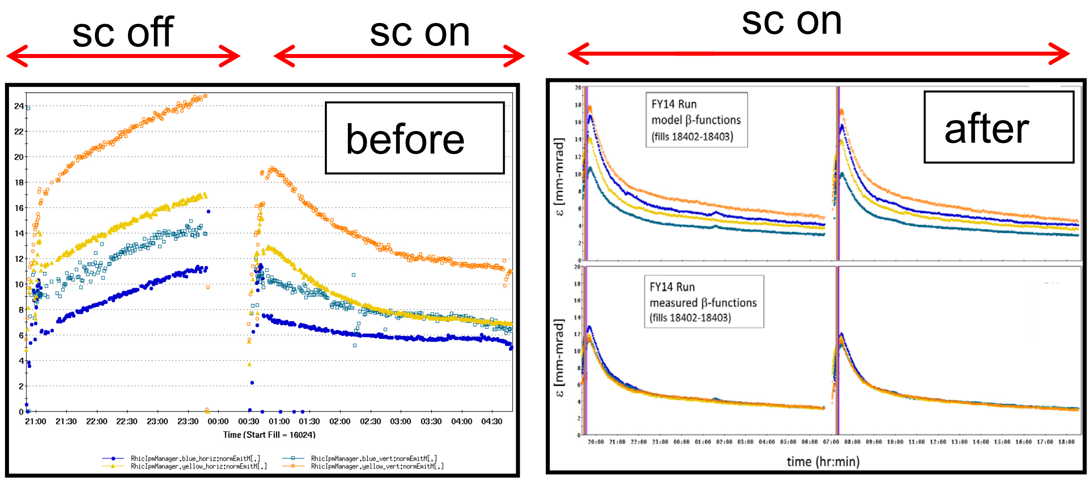
$$|C^-| = \frac{2\sqrt{r_1 r_2}|Q_x - Q_y|}{1 + r_1 r_2},$$

$$\Delta = \frac{|Q_x - Q_y|(1 - r_1 r_2)}{1 + r_1 r_2},$$

$$r_1 = \frac{\tilde{A}_{1y}}{\tilde{A}_{1x}} \quad \text{and} \quad r_2 = \frac{\tilde{A}_{2x}}{\tilde{A}_{2y}}$$

Emittances

channel by channel calibrations implemented



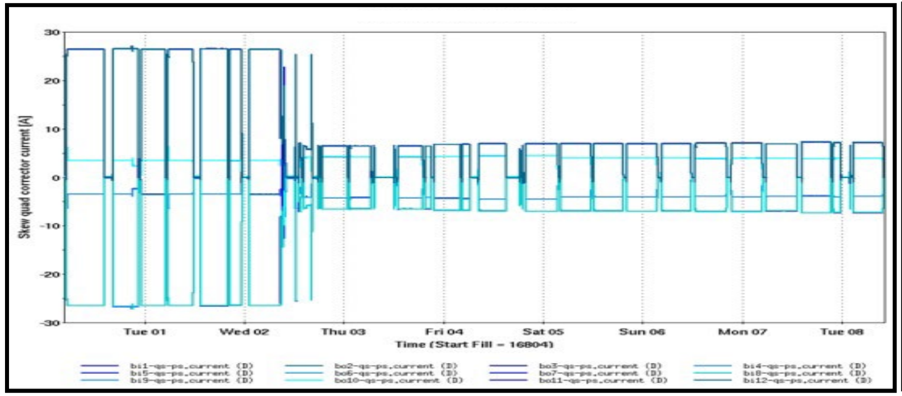
beam emittances
(top) after calibration
(bottom) and with measured beta functions

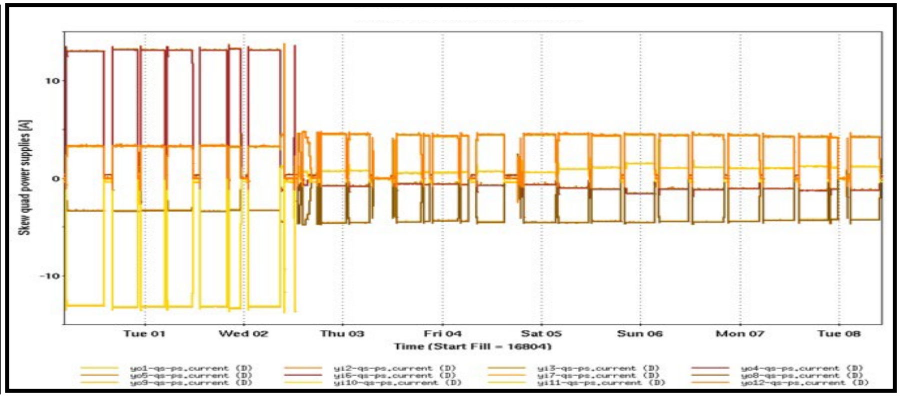
Local and global coupling

Purpose	(initial motivation) improve polarization using dispersion-free steering; secondary, localized coupling correction
Key elements	accuracy in BPM average orbit measurement, accelerator reproducibility (from feedbacks), coding

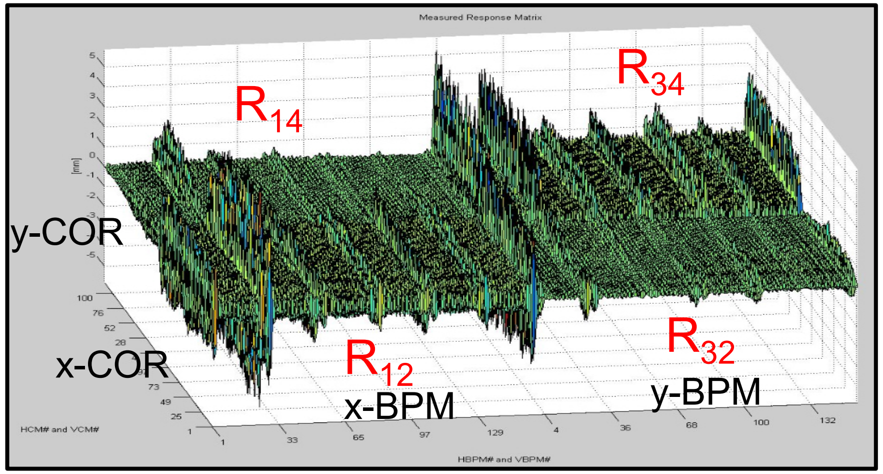
C. Liu et al, "Simultaneous global coupling and dispersion correction in RHIC", NIM (2014)

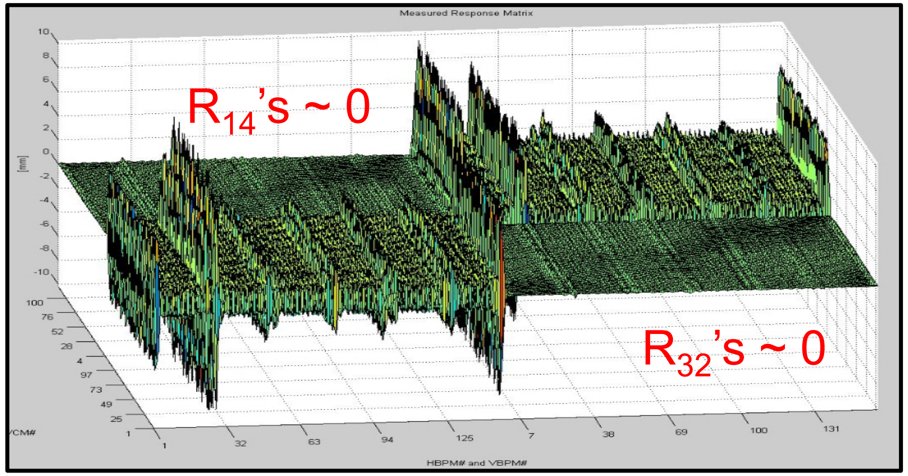
local skew quad strengths, courtesy A. Marusic (Run-12)





measured orbit response matrix, courtesy T. Summers (Run-10)





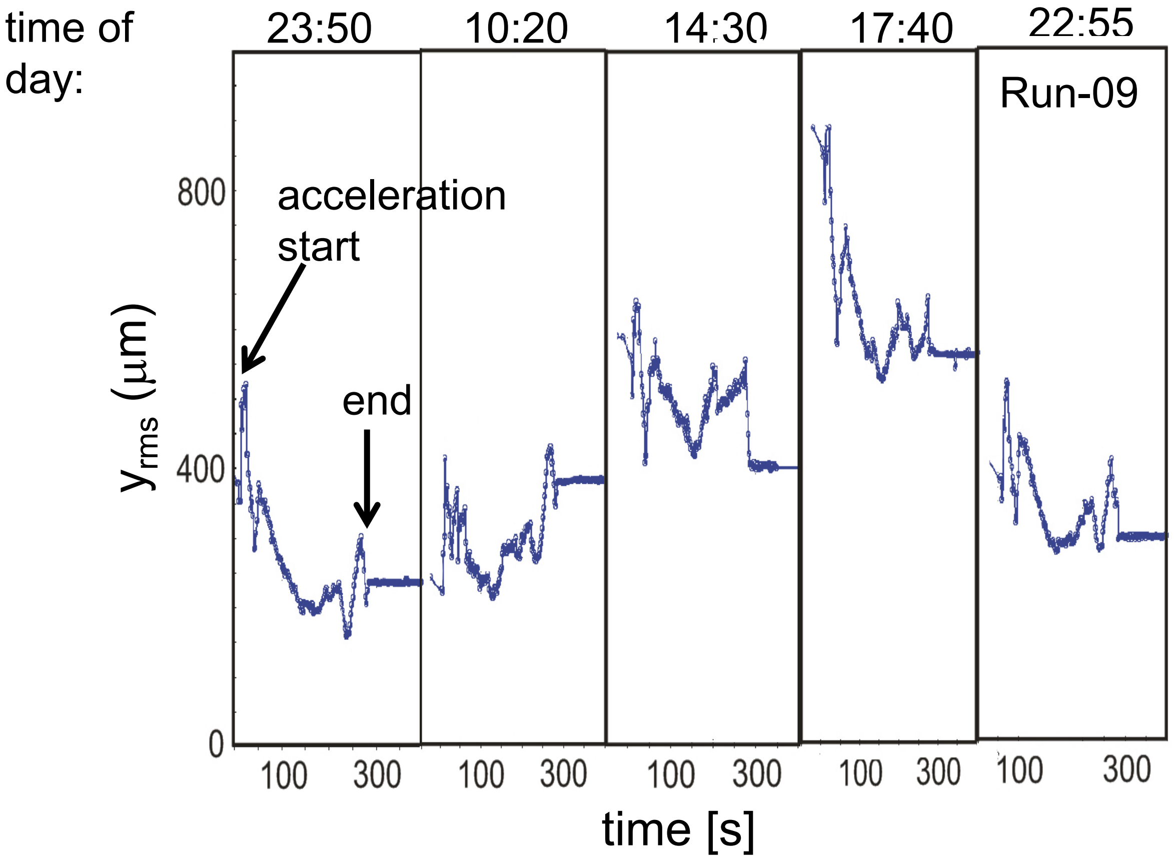
measured orbit response matrix, courtesy T. Summers (Run-12)

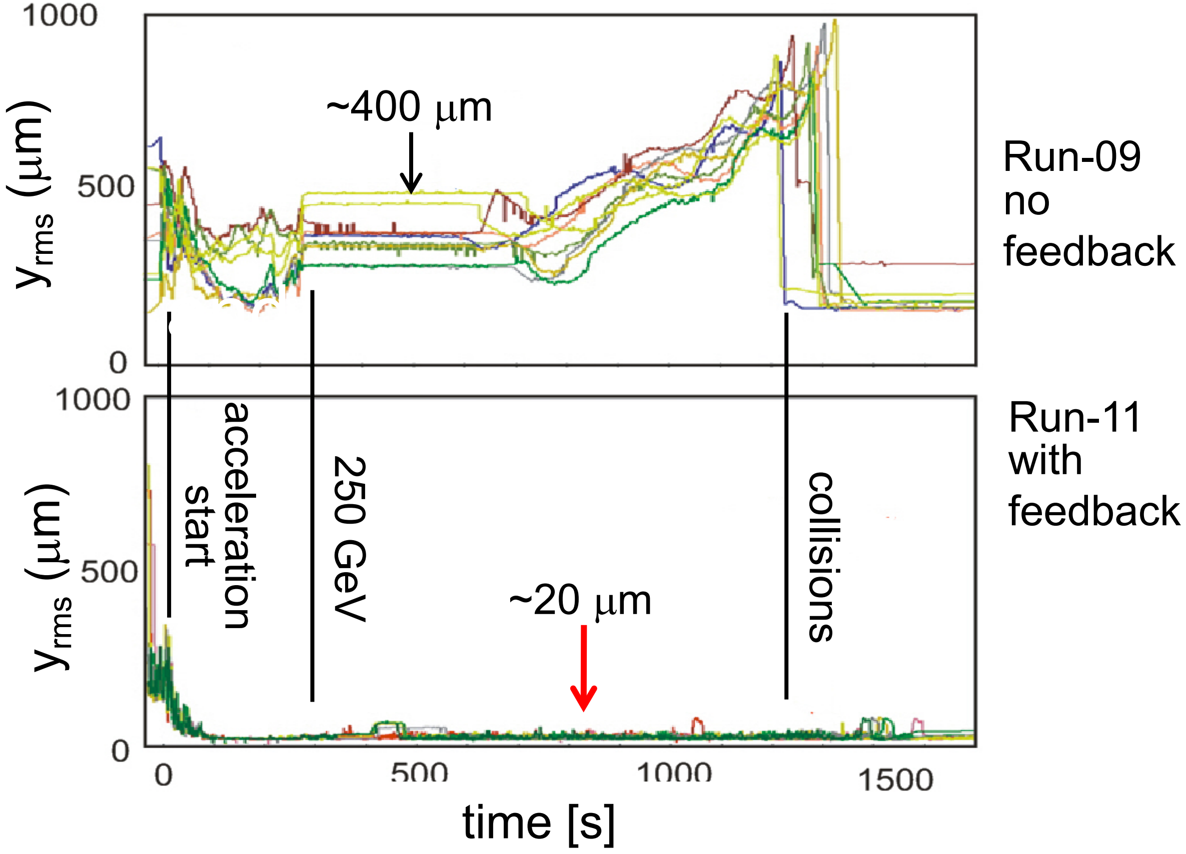
Local (IR) and global coupling improved and independent.

Orbit Feedback

Purpose: reduce actions of tune/coupling feedbacks, improve reproducibility

Key elements: accuracy in BPM average orbit measurements, data delivery, coding





Significant reduction in time needed to establish new modes of operation (species and/or energies) of operation and improved operational reproducibility

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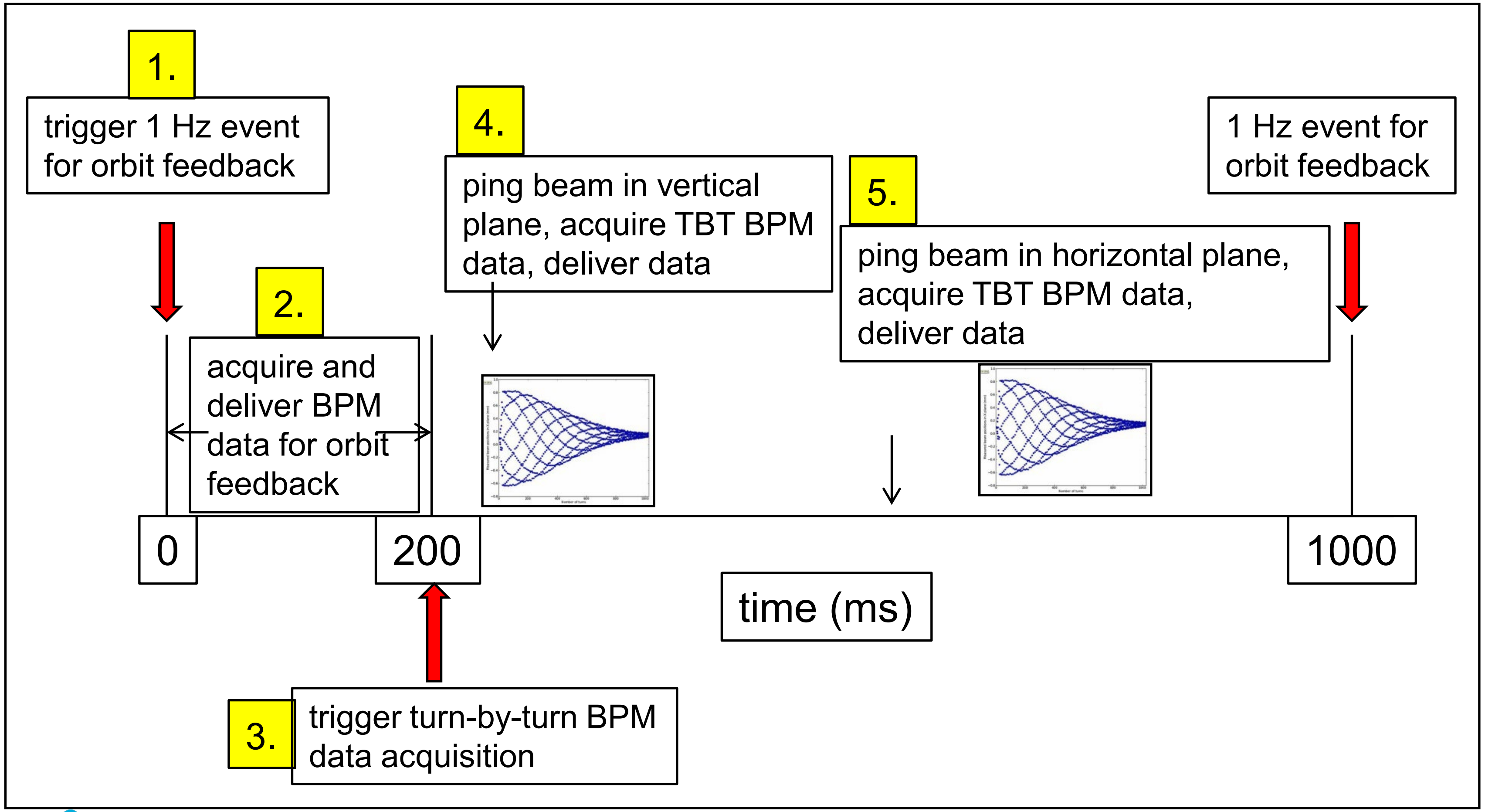
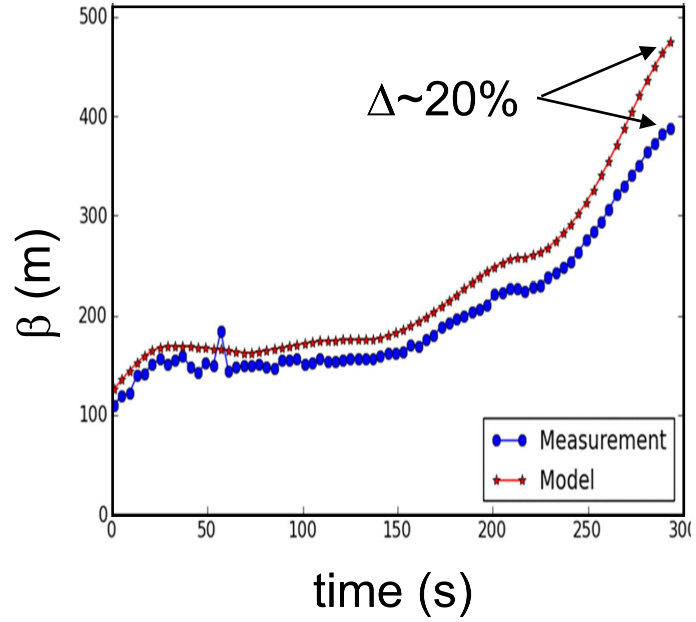
Optics Measurement and Correction during Beam Acceleration

Purpose investigate discrepancies between emittances measured at injection and store energies

Key elements careful orchestration of data acquisitions and data delivery using interleaved
average orbit BPM measurements (for orbit feedback)
turn-by-turn BPM measurements (for optics measurements)

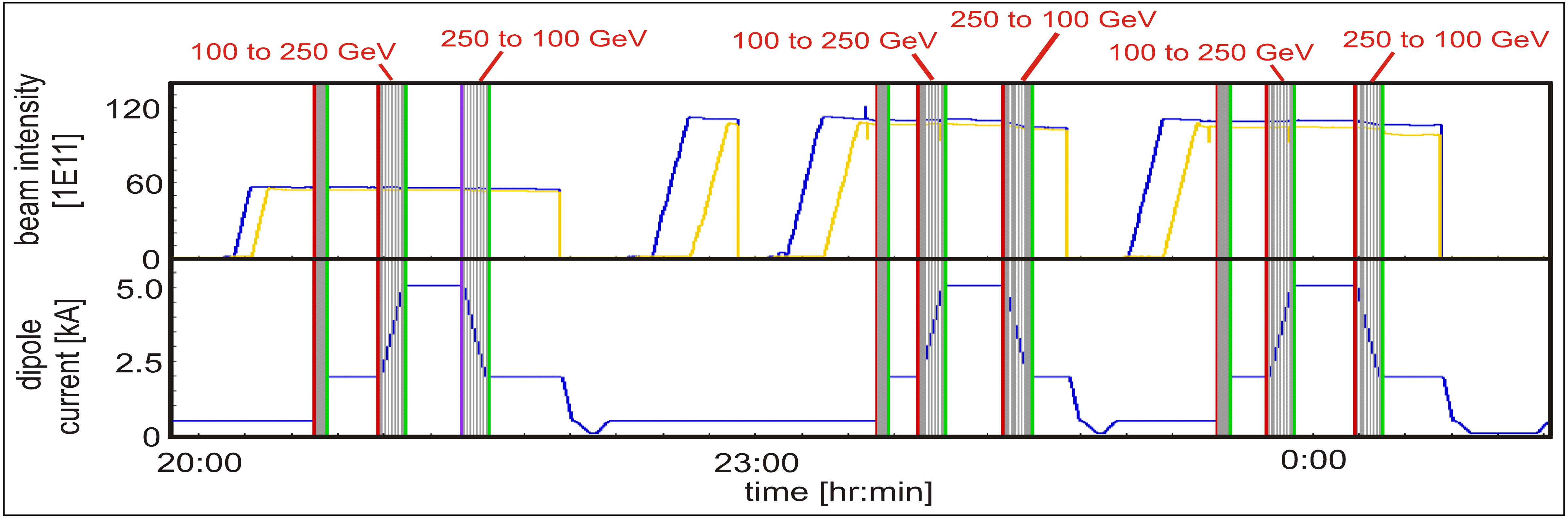




Error in emittance measurement dominated by knowledge of beta-functions

Orbit, tune/coupling, beam-centering + (new) chromaticity feedback

Purpose	absolute polarimeter calibration
Key elements	sinusoidal rf frequency modulation with zero crossings aligned with time of BPM acquisition for orbit feedback action of tune/coupling feedback used to infer chromaticity



~25 units of chromaticity correction during deceleration (compare with catastrophic beam loss tolerance – during acceleration – of typically 2-3 units)

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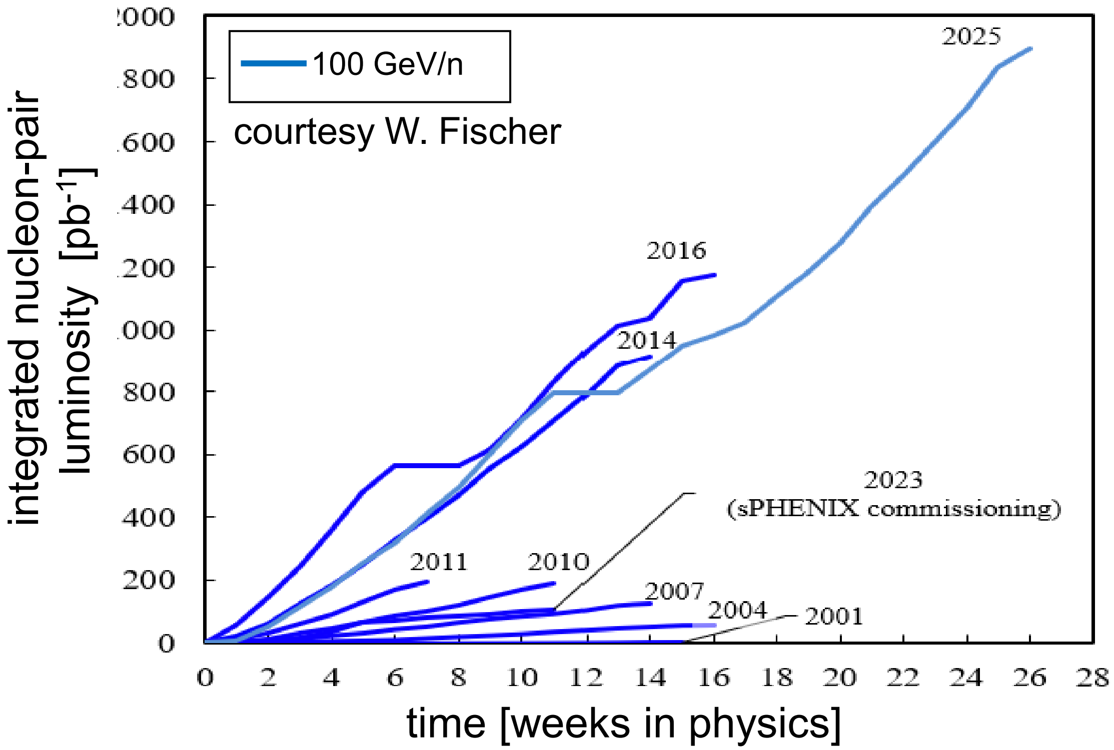
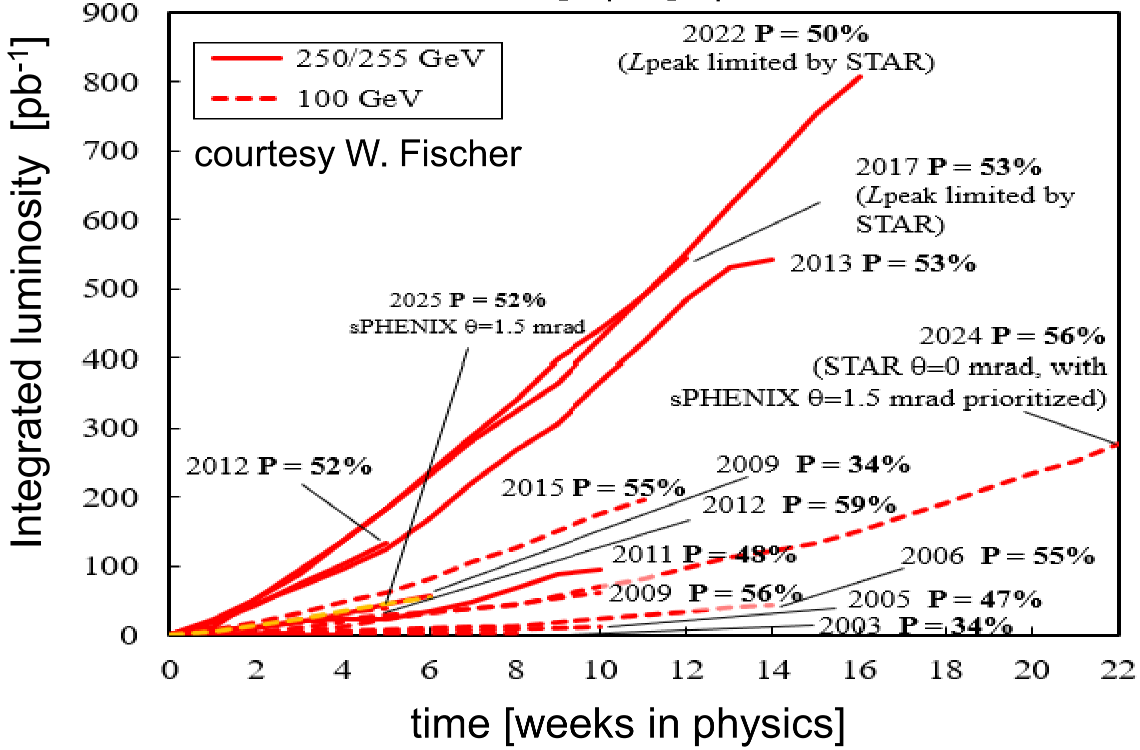
Performance Summary and Legacy

Au + Au



p↑+p↑



RHIC was the first heavy ion collider and first polarized proton collider.
Collider technologies developed and used operationally:

ions	3D bunched-beam stochastic cooling	supplemented by precise beam control and advances in accelerator modeling
	RF-based electron cooling	
p↑	sources, Siberian Snakes and rotators, polarimetery, resonance mitigation, and codes	
	head-on beam-beam compensation with electron lenses	

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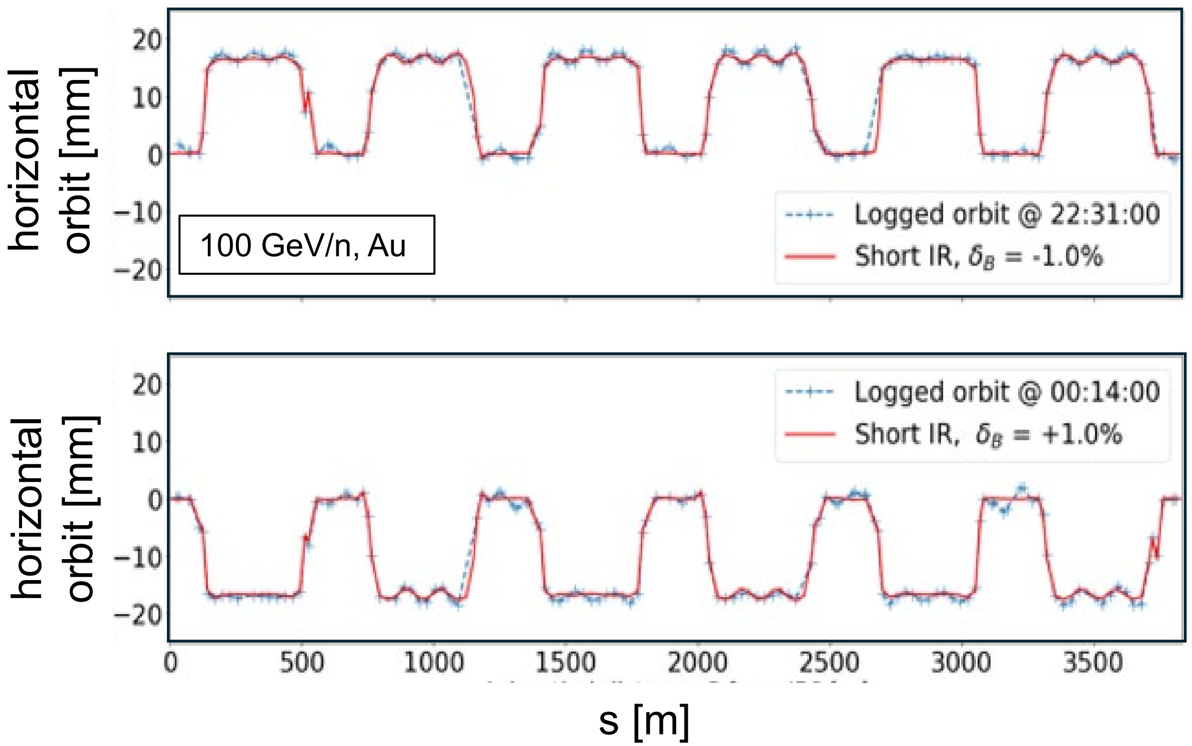
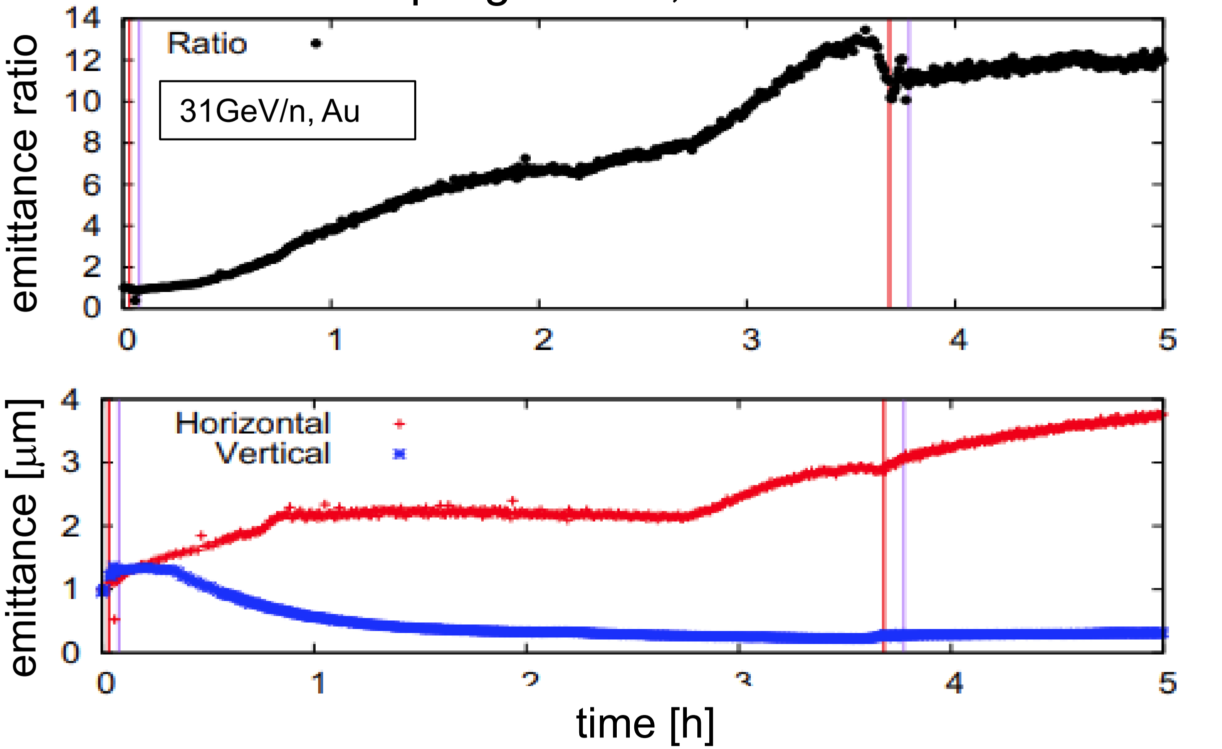
Two examples from recent Accelerator Physics Experiments

purpose extend the energy reach of the EIC
challenges off-momentum linear optics correction



G. Robert-Demolaize *et al.*, "Large radial shift experiments in RHIC and their implications for EIC design", NIMA (2025).

purpose enable collisions with flat beams
challenges generation (with stochastic cooling), coupling control, and acceleration



Y. Luo *et al.*, "Experimental demonstration of accelerating a beam with large transverse emittance ratio in the [RHIC] for the [EIC]", PRL (2026).

RHIC's legacy includes major advances in collider technology and operational methodologies which also inform the design and development of next-generation facilities, including the future Electron-Ion Collider.

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