A QUARTER CENTURY OF RHIC – PERFORMANCE FAR BEYOND DESIGN*

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Abstract

As a cornerstone of US Nuclear Physics, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) concluded operations this year, marking the end of a remarkable 25-year era of colliding beam research. Originally designed to deliver ion-ion collisions over a broad range of energies, including species of unequal mass, RHIC's capabilities were later expanded to support a unique and highly successful polarized proton program. Sustained technological innovation and continuous performance optimization significantly enhanced the collider's flexibility, efficiency, and scientific reach. Major advances included bunched-beam stochastic cooling and injector upgrades, which enabled nearly a 50-fold increase in luminosity over the original design; RF-based electron cooling, which extended the accessible energy range; and head-on beam-beam compensation using electron lenses. For the polarized proton program key developments included the deployment of Siberian Snakes, resonance mitigation techniques, and precision beam control that enabled high proton polarization at high beam energies. In the following, we review the evolution of RHIC performance, summarize major advances in accelerator science achieved at RHIC, and highlight selected, highly impactful improvements that contributed to sustained high-performance operation.

RHIC PERFORMANCE HISTORY

Soon after a Relativistic Heavy Ion Collider was identified in 1983 by the DOE/NSF Nuclear Science Advisory Committee as the highest-priority next major facility, a formal proposal was published in 1984 [1] utilizing the existing 3.8 km tunnel. The RHIC Conceptual Design Report [2] released in 1986 outlined collider operations for ion species ranging from light ions (e.g., protons) to heavy ions (e.g., Uranium). The design featured two independent collider rings and included the capability for "asymmetric collisions" between beams of different mass. Construction of RHIC began in 1991, with collider installation starting in 1994. This phase included commissioning of a new AGS Booster pre-injector synchrotron [3] in 1991, RHIC commissioning late 1999, and first ion-ion collisions in 2000.

An aerial view of the facility is shown in Fig. 1. The pre-injectors consist of multiple ion sources, with ion beams from EBIS or the Tandem Van de Graaff, and polarized protons accelerated in the 200 MeV LINAC. The AGS Booster, which accelerates protons to 1.4 GeV or 100-400 MeV/u for ions, serves as the injector to the AGS. From there, beams are accelerated to 23-28 GeV for protons or up to 10-15 GeV/u for ions before being injected into RHIC, where they are further accelerated to maximum energies of 100 GeV/u for ions and 255 GeV for protons.

RHIC was originally configured to support four experiments: STAR, PHENIX, PHOBOS, and BRAHMS. PHOBOS and BRAHMS concluded data taking in 2005 and 2006, respectively, after which the physics program continued with continuous upgrades at STAR and PHENIX. In the final three years of RHIC operation, a completely new detector, sPHENIX, replaced PHENIX.

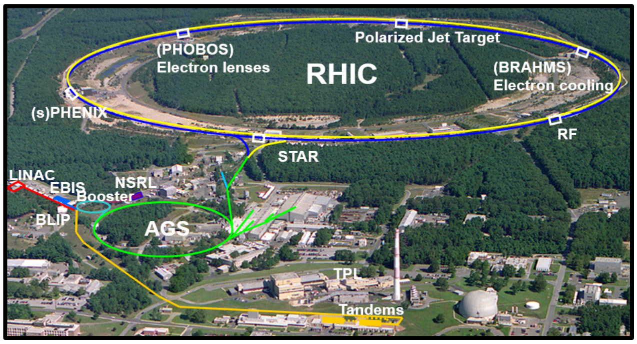

Figure 1: RHIC and the pre-injector complex.

Achieved performance parameters for the final Au+Au run (Run-25) and last highest-energy $\vec{p}+\vec{p}$ run (Run-22) are summarized in Table 1. For Au+Au collisions, sPHENIX operated with a 1 mrad crossing angle (θ^*), while collisions at STAR (not shown) initially used $\theta^*=0$ yielding nearly twice the peak luminosity, albeit "levelled" to avoid detector pile-up. The fourfold decrease in emittance over each store resulted from stochastic cooling. For $\vec{p}+\vec{p}$ collisions, the beta-functions were reduced ('squeezed') once permitted by the extent of the beam-beam tune footprint.

Table 1: RHIC Parameters for Au+Au and $\vec{p}+\vec{p}$

	Au+Au	**$\vec{p}+\vec{p}$**	**Unit**
Energy (c.o.m)	200	510	GeV
Ions/p (per bunch)	2.0	200	$\times 10^9$
No. of bunches	111	111	
ε (rms, normalized)	$2.15 \rightarrow 0.55$	2.5	π μm
β*	0.7	$1.5 \rightarrow 1.2 \rightarrow 1.0$	m
L, peak	4.2×10^{27}	2.0×10^{32}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
<L>	1.9×10^{27}	1.6×10^{32}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$

An overview of RHIC operating modes is presented in Fig. 2, showing weeks of operation for physics runs lasting at least two weeks. Highlighted cases (in boldface, blue) mark several milestones: commissioning with Au+Au in (Run-1), first polarized protons collisions (Run-2), the first asymmetric, collisions with d+Au (Run-3), first high-energy polarized proton run (Run-9), U+U collisions (Run

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† minty@bnl.gov on behalf of the very many scientists, engineers, and technicians whose collective efforts are presented here.

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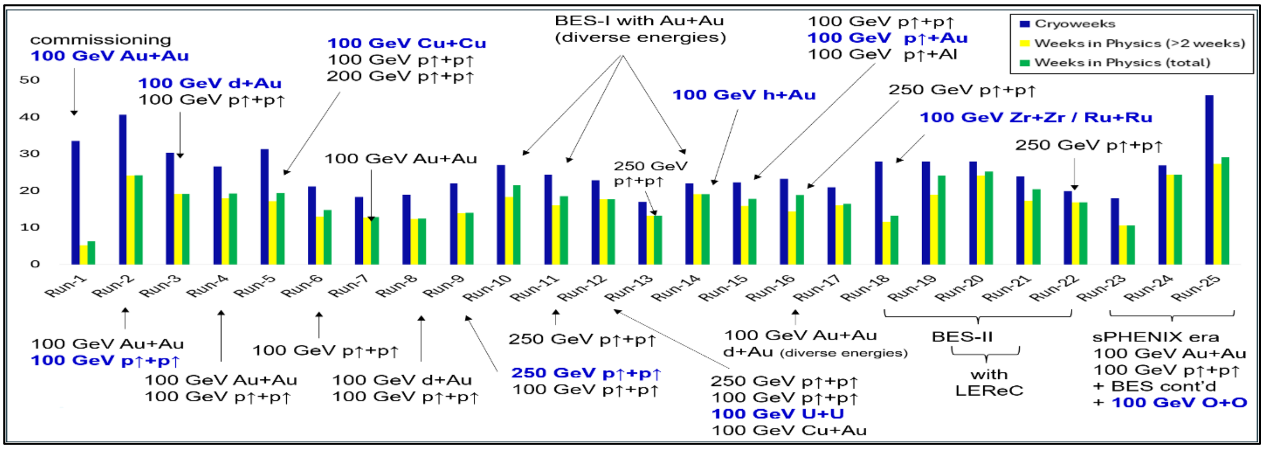

Figure 2: Synopsis of a quarter-century of colliding beams at RHIC - weeks of operation versus time.

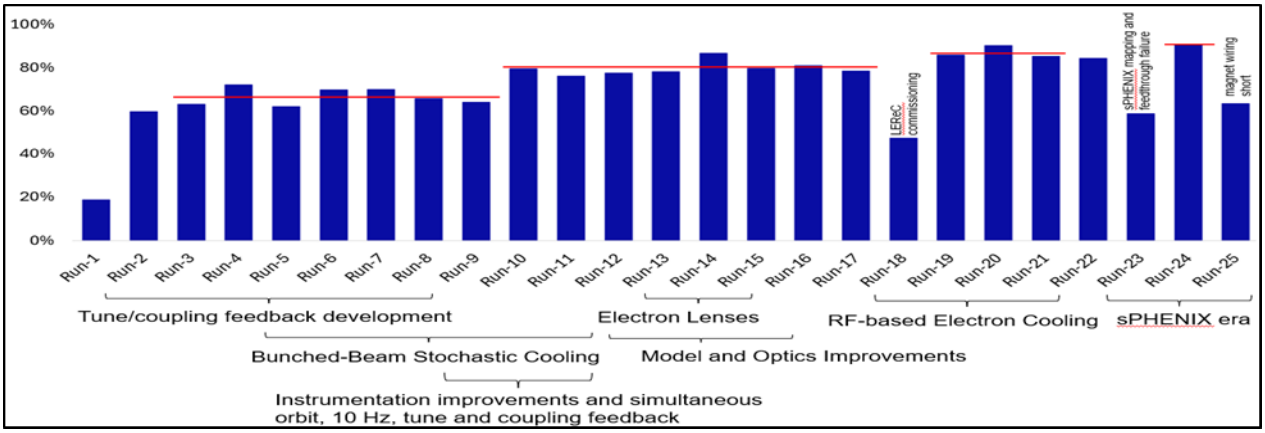

Figure 3: Ratio of calendar time in physics to cryo – weeks versus time.

12), asymmetric polarized $\vec{p}$+Au collisions (Run-15), the the isobar run with Zr+Zr and Ru+Ru (Run-18), and O+O (Run-25). The isobar run featured daily machine "mode switching" between species to minimize experimental uncertainties demonstrating the high automation, flexibility, and reliability of the entire hadron accelerator complex. The figure also indicates years with Au+Au collisions with Low Energy RHIC electron Cooling (LEReC) and the final three years of RHIC running in the sPHENIX era. Figure 3 shows the ratio of physics calendar time to cryo-weeks, highlighting key technological and operational developments. The following sections discuss these developments and their impact on overall facility performance.

ADVANCES IN ACCELERATOR SCIENCE

At RHIC, three-dimensional (3D) **bunched beam stochastic cooling** (SC) [4,5] was developed primarily to counteract intrabeam scattering (IBS), while also helping to relax emittance preservation tolerances of beams from the injectors and from high-current beam instabilities at transition crossing. Key innovations included new pickups detecting Schottky signals at high frequencies (~10 GHz) in the presence of coherent collective motion; high feedback gain enabled using free-space microwave transmitters and receivers; sub-ns timing precision, and high-precision closable kicker cavities that were open during injection and closed after acceleration to store energy.

This 3D stochastic cooling, applied at unprecedented energies and intensities, dramatically increased RHIC performance as illustrated in Fig. 4, which shows the delivered luminosity during Au+Au collisions at 200 GeV c.o.m. in 2007 before SC, and in 2014 with full 3D SC applied. The higher start-of-store luminosity reflects increased injected beam intensities achieved over the intervening years through improvements in the hadron injector complex. After reaching full energy, the SC systems were engaged, producing a rapid rise in early-store luminosity and sustaining high luminosity throughout the store. SC also increased the total integrated luminosity by extending physics-store duration.

RF-based electron cooling (EC) [6] was developed and implemented at RHIC to mitigate strong intrabeam scattering (IBS) in the ion beams and to provide cooling during collisions well below the nominal RHIC injection energy. Key innovations included the production of non-magnetized electron bunches with low emittance, low energy spread, and high-current [7] as well as their RF-acceleration while preserving beam quality (e.g., momentum spread and angular divergence) throughout transport and within the cooling sections. Equally critical was the precise matching of the electron and ion beam positions and energies in the cooling regions [8].

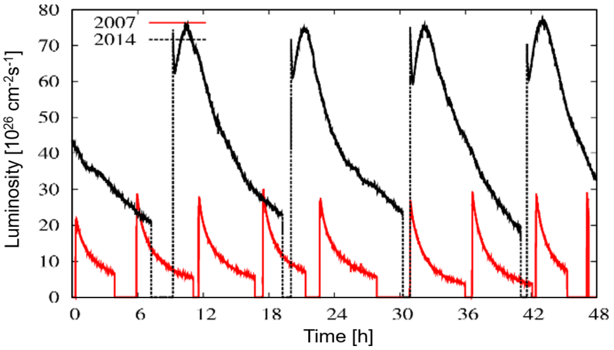

Figure 4: Luminosity versus time without (red) and with (black) bunched-beam SC. Courtesy W. Fischer (2026).

Figure 5 compares the average luminosity achieved during the first phase of the Beam Energy Scan (BES-I) physics program from 2007-2014 (blue squares) with that of the second phase (BES-II) during 2019-2021 (red circles), clearly demonstrating significant performance gains in the later period, particularly at the two lowest energies where RF-based EC was applied. Higher beam intensities and longer beam lifetimes were enabled by improved injector performance, implementation of a third harmonic rf system to reduce the beam peak current, optimization at lower-tune working point, and enhanced mitigation of flux pinning and associated persistent currents in RHIC's superconducting magnets using tailored demagnetization cycles [9]. These advances – supported by improved accelerator modelling and implementation (see below) – enabled highly reproducible magnetic fields even at below-design operating currents. This technology – based on RF-accelerated electron bunches - extends the applicable energy range of electron cooling beyond that achievable with conventional approaches and is planned for implementation in the future Electron Ion Collider (EIC).

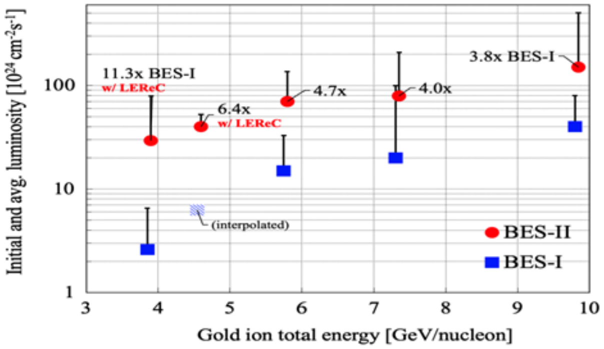

Figure 5: Luminosity as a function of Au beam energy highlighting performance enhancement at lowest beam energies, with strongest IBS, achieved with rf-based EC [9].

The **polarized proton program** at RHIC [10] several key technological advances, including a high-intensity polarized source [11,12], the first use of **full Siberian Snakes** [13-15], diverse polarimetry [16-18], and enhanced spin tracking simulations in the AGS pre-injector and in RHIC [19]. In 2006, an additional **partial snake** [20,21] was installed in the AGS [22] to mitigate the polarization dependence on bunch intensity observed earlier, providing a foundation for subsequent operation at higher AGS bunch intensities. In 2011, the implementation of **horizontal tune jumps** [23] in the AGS preserved the extracted polarization at even higher intensities. In RHIC, a 9 MHz RF system was installed to improve longitudinal matching at injection enabling higher injected beam intensities. Advances in beam control also contributed to improved polarization transmission efficiency in RHIC. These yielded, with 100 GeV $\vec{p}$ beams an average polarization, averaged over all physics stores and over each individual store, as measured by the hydrogen jet polarimeter, of nearly 60% in 2012.

The average polarization for highest energy (250 and 255 GeV) $\vec{p}+\vec{p}$ runs is shown in Fig. 6. The above-mentioned enhancements, together with an extensive campaign of enhanced instrumental resolution, correction of BPM electronic offsets, and operation with **simultaneous orbit, tune/coupling, and beam-centering feedback** [24] yielded an approximately 50% relative increase in proton beam polarization from 2009 to 2012. The realization of tune/coupling feedback [25,26] built on earlier advances in high-sensitivity tune measurements [27] and theory [25, 28]. The new orbit feedback system leveraged existing orbit correction infrastructure, deterministic BPM data delivery, and pre-computed beam-response matrix elements, enabling corrections at a 1 Hz rate with up to ~40 million referenced matrix elements during acceleration of polarized protons to full energy [29,30]. A global "10 Hz feedback" system [31,32], designed to suppress the effects of triplet magnet vibrations, was implemented at fixed energies in 2011, and during beam acceleration in 2012. These developments enabled acceleration with betatron tunes close to the 2/3 orbit resonance and far from the 7/10 spin resonance, reference Fig. 7 [33]. The continued increase in polarization from 2013 to 2015 resulted from improved accelerator modelling and more accurate lattice implementation (see below). More recently, a novel scheme using betatron coupling to suppress resonances driven by partial snakes in the AGS was developed [34] and implemented [35].

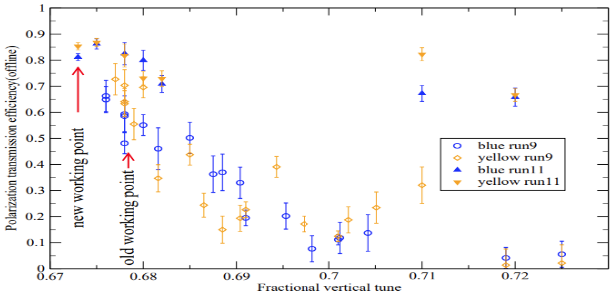

Figure 6: Polarization transmission efficiency in RHIC versus vertical betatron tune [33].

Head-on beam-beam compensation [36] using electron lenses was implemented for the 2015 200 GeV c.o.m. $\vec{p}+\vec{p}$ run. Each of the two lenses (one in each RHIC ring) comprised a low-noise DC electron beam, a magnetized transport system - including a 6T superconducting solenoid - that guided the oppositely directed 5 keV electrons into collinearity with the proton beam, and an electron collector. Precise overlap of the electron and proton beams was achieved using novel 'back-scattered electron detectors'[37], which detected Coulomb-scattered electrons and overcame limitations encountered elsewhere in aligning beams with significantly different bunch lengths (i.e., frequency content). In combination with a lattice optimized to compensate resonance-driving terms and more accurate lattice implementation (see below), the electron lenses enabled nearly a doubling of both peak and average luminosities at 200 GeV c.o.m.

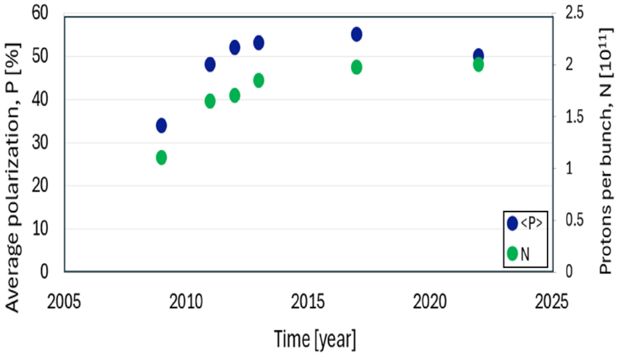

Figure 7: Store- and run- averaged polarization and bunch population versus time. Courtesy H. Huang (2026).

FURTHER OPTIMIZATIONS

RHIC performance was further improved through enhanced beam control including implementation of carefully sequenced control actions with attention to preserving data integrity, and advances in accelerator modelling and lattice implementation.

Chromaticity and optical functions during acceleration were measured with orbit, tune/coupling and beam-centering feedback enabled [38]. The measurement sequence proceeded as follows: beam orbit data were first acquired for orbit feedback, allowing 200 ms for data delivery; the beam was then excited ("pinged"), and turn-by-turn (TBT) data were delivered over the subsequent 800 ms. Including TBT data transfer, this cycle was repeated every 2 s for single-beam and every 4 s – alternating between beams – for dual-beam measurements. These measurements enabled chromaticity correction during acceleration and showed that the dominant uncertainty in IPM-based emittance measurements arose from differences between modelled and actual beta functions.

To calibrate the analyzing powers of the RHIC p-Carbon polarimeters [33], **chromaticity feedback** was added to the suite of feedback systems to enable controlled deceleration from 250 GeV to 100 GeV. This was achieved by synchronizing a sinusoidal RF frequency modulation with a 1 Hz period, with the zero crossings aligned to the BPM sampling used for the orbit feedback. The chromaticity was determined from the corrections applied by the tune feedback system in conjunction with the RF frequency modulation. Figure 8 shows polarized proton bunch intensities (a) and the main dipole current (b) for three acceleration-deceleration cycles. During deceleration, persistent currents required chromaticity corrections of up to 25 units.

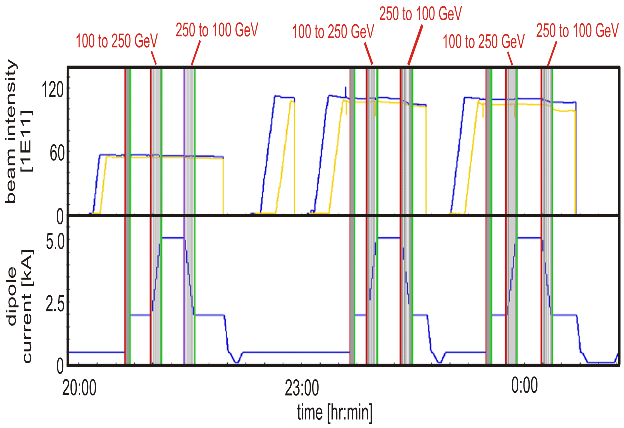

Figure 8: Simultaneous orbit, tune/coupling, energy, and chromaticity feedback.

In 2012-2013 **coupling corrections** [39] in RHIC were revisited [40] after determining that the observed residual dispersion arose from the global coupling correction compensating for uncorrected local coupling in the interaction regions (IRs) [41], due primarily to triplet magnet roll errors. The local coupling was therefore re-evaluated in 2012 using more efficient measurement procedures and higher-precision BPM measurements resulting in a reduction of the local skew quadrupole strengths by a factor of ~5 in the blue ring and ~3 in the yellow ring, thus reducing the interplay between local (IR) and global coupling corrections. Orbit response matrices (ORMs) acquired before (a) and after (b) these corrections are shown in Fig. 9.

Significant **advances in accelerator modelling and lattice implementation** benefitted both the heavy-ion and polarized-proton programs at RHIC with far-reaching consequences. A discrepancy between design and measured beta functions observed during nominally benign spin rotators ramps – emergent when the lattice symmetry was relaxed to accommodate local betatron phase shifters – revealed that optics optimizations were not applied self-consistently, with subsequent optimizations altering previously optimized parameters. To resolve this, OptiCalc – the code used for lattice design and implementation – was brought into alignment with MADX, incorporating cubic splines for magnet strength evolution during acceleration, improving transition-crossing quadrupole modelling, and correcting previously unrecognized legacy code issues. By 2014, these improvements substantially reduced required "trim corrections" (aligning measurements with model), and, for the first time at RHIC, excellent agreement between modelled and measured optics was attained. Removal of legacy empirical correction factors in 2016 further reduced trim correction strengths.

The result of the improved optics modelling and implementation greatly increased operational flexibility. In addition to enabling the demagnetization cycles noted above, these developments enabled abort kicker "pre-fire protection bumps", better linear optics correction, nonlinear chromaticity control, and multiple mid- to late-store beta squeezes using telescopic optics [43].

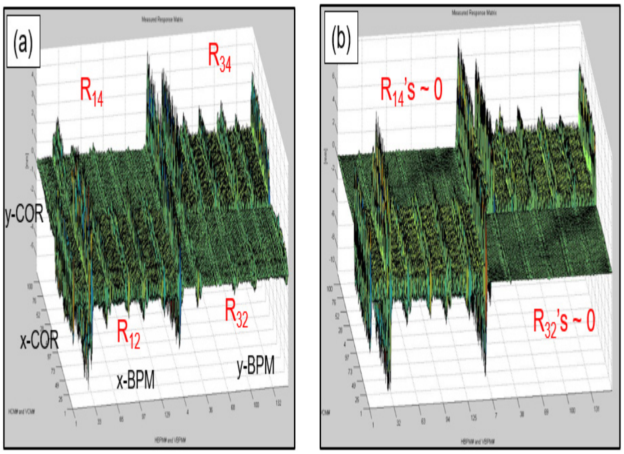

Figure 9: ORM elements before (a) and after (b) renewed correction of local and global coupling [42].

These modifications, together with feedback-based beam control enabled efficient operations supporting multiple beam species and/or energies each year. In addition, they were essential to several proof-of-principle demonstrations relevant to the EIC, including acceleration of flat hadron beams with an emittance ratio of 11:1 [44] and stable operation with radial offsets of up to +/-20 mm [45], a capability required for achieving the highest c.o.m. collisions energies in the EIC.

OTHER IMPROVEMENTS

Many additional studies and optimizations further improved RHIC operational efficiency. For example, a race condition in the "beam sync encoder", used to generate a phase-locked timing signal synchronized with the beam revolution frequency, was identified and corrected. As a beneficial byproduct, a **new timing setup procedure** was established in 2011, which significantly reduced the need for expert intervention by streamlining the initialization of timing across systems, including instrumentation, pulsed devices, and the experimental detectors.

A multi-year issue of **spontaneous emittance blow-up**, which caused inoperable conditions in 2011, was localized and resolved within a week-long effort. Automatically generated waterfall displays from a dynamic signal analyzer using tune monitor inputs revealed the disturbance's presence at injection energy. Subsequent monitoring of both transverse planes in both RHIC rings further localized the effect to the horizontal plane. Systematic equipment disconnections traced the source to a broken wire between an abort kicker thyratron and magnet feedthrough.

PERFORMANCE SUMMARY

The integrated luminosity as a function of time for Au+Au collisions at 200 GeV c.o.m. energy, with zero crossing angle, and for all $\vec{p}+\vec{p}$ runs is shown in Figs. 10 and 11, respectively. The figures demonstrate the substantial improvements in both luminosity and operational efficiency achieved over the course of the RHIC physics programs.

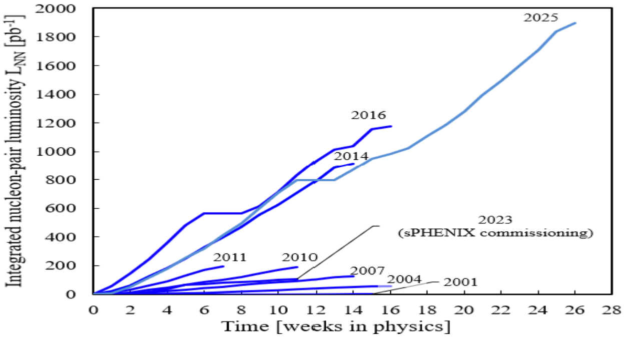

Figure 10: Integrated luminosity for 200 GeV c.o.m. Au+Au runs. Courtesy W. Fischer (2026).

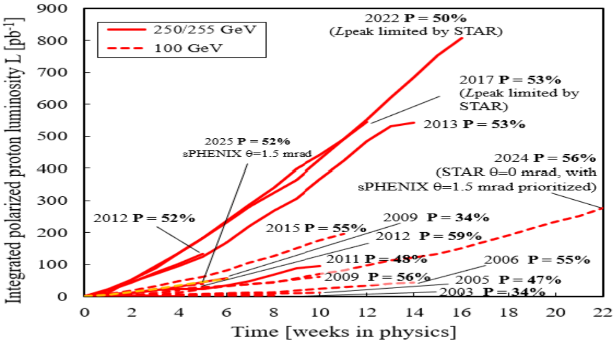

Figure 11: Integrated luminosity for $\vec{p}+\vec{p}$ runs. Courtesy W. Fischer (2026).

CONCLUSION

This report reviewed the operational history of RHIC, a major U.S. nuclear physics facility, that recently concluded a highly productive quarter-century of operations. RHIC's success reflects sustained technological innovations in accelerator science, precise beam control, and advances in accelerator modelling and implementation. Collectively, these developments resulted in enhanced operational flexibility which enabled further optimizations as well as support of multiple different accelerator configurations each year. RHIC's legacy includes major advances in collider technology and operational methodologies that inform the design and development of next-generation facilities, including the future Electron-Ion Collider.

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