RHIC PERFORMANCE AND PLANS TOWARDS HIGHER LUMINOSITY AND HIGHER POLARIZATION *

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Abstract

The Relativistic Heavy Ion Collider (RHIC), the first hadron accelerator and collider consisting of two independent rings, has completed its fourth year of operation since commissioning in 1999. RHIC is designed to provide luminosity over a wide range of beam energies and species, including heavy ions, polarized protons, and asymmetric beam collisions. RHIC has produced physics data at four experiments in runs that include gold-on-gold collisions at various beam energies (9.8, 31, 65, and 100 GeV/u), high-energy polarized proton-proton collisions (100 GeV), and deuteron-gold collisions (100 GeV/u). We review recent machine performance for high-luminosity gold-gold operations and polarized proton operations, including causes and solutions for known operational limits. Plans and progress for luminosity and polarization improvements, electron cooling, and the electron-ion collider eRHIC are discussed.

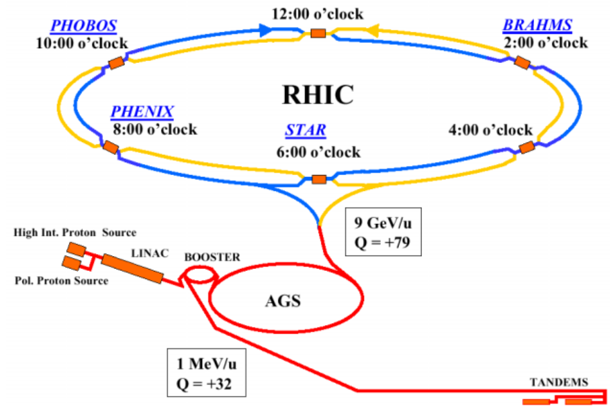

Figure 1: The layout of RHIC and its injection chain, including Tandems for ion injection and a linac for polarized proton injection.

THE RHIC COMPLEX

RHIC consists of two independent superconducting 3.8 km rings, intersecting at six interaction points (IPs) (Fig. 1) and providing luminosity to four concurrent experiments. With these two independent rings and a variety of injectors, the RHIC complex is a highly flexible hadron collider capable of colliding intense beams ranging from fully stripped gold ions down to polarized protons.

RHIC has completed four successful physics runs since commissioning in 1999. In Run-1, RHIC collided gold nuclei at 65 GeV/u with modest luminosity to commission detectors and produce first physics data. In Run-2, RHIC collided gold nuclei at the design energy of 100 GeV/u, producing first results of nuclear jet quenching and indications of the creation of a new form of nuclear matter. In Run-3, RHIC ran with asymmetric species for the first time, colliding deuterons and gold nuclei at 100 GeV/u to confirm jet-quenching observations. In Run-4, RHIC collided gold nuclei at 100 GeV/u and 31 GeV/u with much higher luminosities to provide the first substantial data set with rare probes and larger p_t reach. Each run has also included 6–10 weeks of 100 GeV polarized proton commissioning and operations[1]. Table 1 shows design, achieved, and upgrade machine parameters.

Each change of species for a RHIC run typically requires a 1–3 week setup period where initial ramping and collisions are established, followed by a 1–2 week ramp-up period where detectors are set up and luminosity production is maximized. This is a substantial piece of the typical 27–31 weeks of annual RHIC operation. Setup and ramp-up periods are shorter during planned mid-run species changes, as injector development can often occur during RHIC physics stores; optimum run planning has included a heavy ion run and a polarized proton run for each RHIC operating period.

For all species, injection is performed with $\beta^\star$=10 m at all IPs. For ions, acceleration ramps squeeze to $\beta^\star$=5 m at all IPs to optimize transition jump optics, and then squeeze to final collision optics during the remainder of the acceleration ramp. Collision optics are typically $\beta^\star$=5 m at non-experimental IPs, and $\beta^\star$=1–3 m at experimental IPs, depending on experiment background issues and presence of nonlinear correctors. Through the acceleration ramp, beams are vertically separated with $\pm$5 mm bumps and RF-locked in an "anti-cogged" position to avoid all beam-beam effects including tune modulation[2].

The annual RHIC Retreat[3] was held in June 2004, reviewing Run-4 performance and issues and determining Run-5 planning. Run-5 begins in October 2004, and will likely be evenly divided between a symmetric light ion physics run at 100 GeV/u and a polarized proton physics run at 100 GeV. There are several suitable light ion species available such as Si^{14+}, Fe^{26+}, Ni^{28+}, and Cu^{29+}, and expected peak luminosities range from $3\text{–}11\times10^{28}\ \mathrm{cm^{-2}s^{-1}}$. Building on Run-4 successes, polarizations of up to 50% and peak luminosities up to $25\times10^{30}\ \mathrm{cm^{-2}s^{-1}}$ are expected for the Run-5 polarized proton run.

RUN-4 GOLD OPERATION

In late 2003, RHIC returned to 100 GeV Au-Au operation for an 16-week running period. This period consisted of two weeks of setup, two weeks of ramp-up, and a 12-week physics production run where RHIC delivered 15 times more integrated luminosity to major experiments than the Run-2 Au-Au run. Luminosity evolution for all RHIC Au-Au runs is shown in Fig. 2, with a total lu-

* Work performed under the auspices of the U.S. Department of Energy
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Table 1: RHIC performance evolution. The Run-# parameters shown provided the highest experiment luminosities.

Species [Run]	Max energy [GeV/u]	No of bunches	Ions/bunch [10^9]	$\beta^\star$ [m]	Emittance [$\pi\mu$rad]	$\mathcal{L}_{peak}$	$\mathcal{L}_{store,ave}$ [$\times10^{26}$ cm^{-2}s^{-1}]	L_{week}
Au-Au (Design)	100	56	1.0	2	15-40	9	2	50 μb^{-1}
p-p (Design)	250	56	100	2	20	50000	40000	1.2 pb^{-1}
d-Au (Run-3)	100	55	110d/0.7Au	2	15	700	200	4.5 nb^{-1}
Au-Au (Run-4)	100	45	1.1	1	15-40	15	4	160 μb^{-1}
$\vec{\mathrm{p}}-\vec{\mathrm{p}}$ (Run-4)	100	28	170	1	20-30	150000	100000	0.9 pb^{-1}
Au-Au (Enhanced)	100	112	1.1	1	15-40	36	9	350 μb^{-1}
$\vec{\mathrm{p}}-\vec{\mathrm{p}}$ (Enhanced)*	250	112	200	1	20	900000	720000	26 pb^{-1}

*with 70% average store polarization

minosity of over 1300 μb^{-1} delivered to PHENIX and STAR (at $\beta^\star$=1m), and 550 μb^{-1} delivered to BRAHMS and PHOBOS (at $\beta^\star$=3m). The average luminosity of 4×10^{26} cm^{-2}s^{-1}(at PHENIX), twice design luminosity, was achieved early and maintained through the run. The best week delivered 179 μb^{-1} to PHENIX [4]; previous best operation in Run-2 was 24 μb^{-1}/week.

Previous RHIC Au runs had bunch intensity limited by the injectors, with peak intensity near the design value of 1.0×10^9 Au/bunch and typical intensity closer to 0.7×10^9 Au/bunch. The Booster injection septum was repaired in late 2003, before the Run-4 Au Au run; this increased typical bunch intensities at RHIC injection to 1.1–1.2×10^9 Au/bunch. Additional RF bunch merging techniques in the Booster may lead to even larger ion beam intensities in the future[5].

For Au operations, vacuum issues — particularly pressure increases within the IR region beam pipes[6] associated with electron clouds and ion desorption[7] — now limit the total RHIC beam intensity to 105×10^9 (Au equivalent) in both rings. This curently limits the RHIC instantaneous luminosity. Instantaneous luminosity was maximized within this constraint by increasing single-bunch intensity, reducing bunch numbers, and optimizing bunch train patterns [8]. Before Run-4, 60 m of NEG-coated beampipes were installed in warm sections to evaluate pumping speed and secondary emission yield reduction; studies indicate that NEG coating improved vacuum conditions, and detailed analyses are underway[6].

The luminosity lifetime of gold ions in RHIC is limited to 2.5 h due to the effects of intrabeam scattering (IBS), which creates longitudinal and transverse emittance growth and scatters ions out of the RF buckets. Longitudinal emittance growth times are consistent with IBS prediction, while transverse emittance growth times are faster than IBS prediction by a factor of two[9]. With an average refill time of 1–2 h, optimum integrated luminosity was achieved with store times of approximately 4 h.

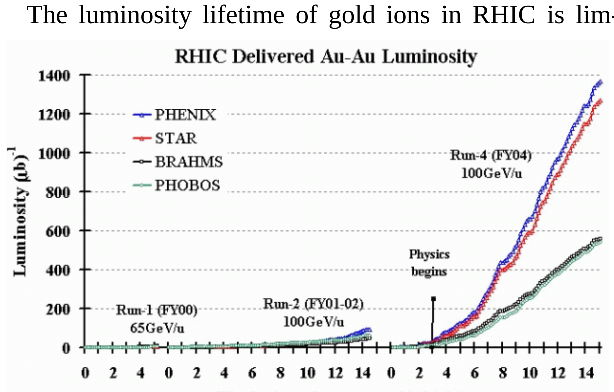

Figure 2: Integrated gold-gold luminosity delivered to the four RHIC experiments during RHIC Runs 1, 2, and 4.

Overall machine operational efficiency and uptime have improved every year since facility commissioning, with careful attention to several efforts that reduce facility downtime and minimize experimental program interruptions. The average percentage of calender time producing physics rose from 25% at the end of the Run-2 Au-Au run to 30% at the end of the Run-3 d-Au run, to 53% in the Run-4 Au-Au run[4].

With the success of high Au bunch intensities, high luminosity, and reliable operation, RHIC experiments requested a short 31 GeV/u Au-Au run at the end of the normal 100 GeV/u run. The setup time for this lower-energy configuration was less than 2 days, followed by 9 days of operation that delivered a total of 22 μb^{-1} to experiments located at $\beta^\star$=3m, an integrated luminosity comparable to the whole of Run-2 Au-Au operations.

RUN-4 POLARIZED PROTON OPERATION

For six weeks, from April 2 to May 15 2004, RHIC accelerated and collided polarized protons at 100 GeV for an engineering development run. The layout of RHIC for polarized proton operations is shown in Fig. 3. The main objectives of this run were to to evaluate the performance of the warm 5% AGS helical snake (installed in January 2004), evaluate the limitations fo high-intensity operation with protons in the beam-beam limit, and to commission the absolute polarimeter with a hydrogen jet target. Though this was an engineering run, physics stores were provided with average luminosity of 5×10^{30} cm^{-2}s^{-1} and beam polarizations from 40–45%, and unpolarized high-luminosity development achieved peak luminosities in excess of 10×10^{30} cm^{-2}s^{-1} with collisions at two experiments. A typical store is shown in Fig. 4.

Previous polarized proton operations in RHIC were limited by working point and beam-beam tune spread

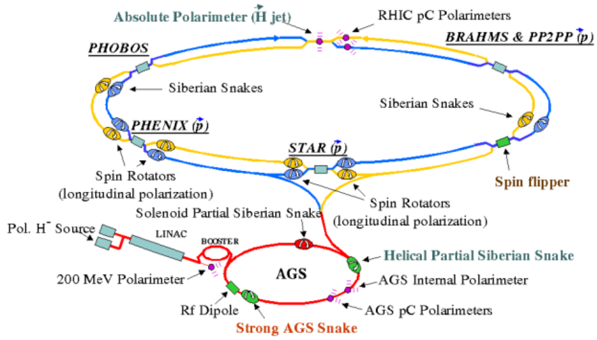

Figure 3: Layout of RHIC, injectors, and components for polarized proton operations.

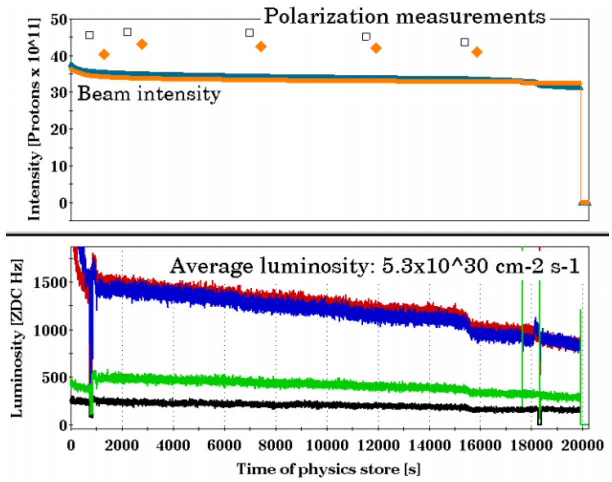

Figure 4: A typical Run-5 polarized proton store, with 45 bunches of $0.8\times10^{11}$and 40–45% beam polarizations. Polarization and beam intensity are roughly constant throughout the store; luminosity degrades due to transverse emittance growth driven by beam-beam forces.

issues[1]. After exploration of other possible working points, the RHIC working point was moved from (0.22,0.23) to (0.68,0.69)[10]. This working point optimized luminosity lifetime and polarization at store, but was not acceptable for injection because of the strong 2/3 resonance. We therefore injected at (0.72,0.73), and moved the tunes to the new working point during the acceleration ramp as shown in Fig. 5. The total beam-beam tune shift achieved at collisions was 8×10^{-3} with 28 bunches per ring, two collisions, and bunch intensities of 1.7×10^{11}as measured by a phase-locked loop tunemeter; the total beam tune spread achieved was 1.6×10^{-2}.

Vacuum issues also limited instantaneous luminosity and total RHIC beam intensity. A total proton intensity of 144×10^{11} (45 bunches, 1.5-2.0$\times10^{11}$/bunch) produced vacuum pressures in warm straight sections of up to 3×10^{-7} Torr. Physics runs during this period used bunch intensities of 1.4×10^{11} and 28–45 bunches/ring to maximize luminosity and avoid vacuum degredation. During high-intensity tests at injection energy near the end of the run, pressure rises of $\Delta P/P_0 \approx 10^3$ were observed in two blue ring cold bore regions with blue beam intensity of 108×10^{11}[11]. As with Au, these pressure rises are likely driven by electron clouds, and are thus highly dependent on fill pattern.[8]

A dedicated polarized hydrogen gas jet target with two Si recoil spectrometers was installed in the RHIC 12 o'clock interaction region in March 2004[12]. This jet was operated through the Run-4 polarized proton run to calibrate the RHIC proton-carbon CNI relative polarimeters. The jet density exceeded $10^{12}\mathrm{p/cm}^2$, and jet polarization typically exceeded 95%. 700k events at 100 GeV and 120k events at 24 GeV were acquired at the peak of the system analyzing power in a dedicated multi-day run, and these statistics will allow absolute calibration of the CNI polarimeters to <10% at 100 GeV and <20% at 24 GeV. The desired goal is to calibrate the relative polarimeters to about 5% at the respective running energies.

Superconducting helical spin rotators are located on each side of the two low-beta experiments to provide longitudinally polarized beam collisions[1, 13]. These spin rotators ramp to maximum field in 430 seconds, and create substantial orbit distortions at injection energies. Attempts to tune injection and ramps with the spin rotators on, which would save 15 minutes of unproductive time per physics ramp and increase integrated luminosity, failed because injection orbit distortions were not tolerable.

With careful orbit correction, polarization transmission through RHIC magnet ramps was 90–100%. Both CNI polarimeters worked well, allowing polarization measurements through acceleration and spin rotator ramps to permit localization of polarization losses during ramping.

The polarized beam source[14] reliably produced 70% beam polarizations, and beam polarizations at AGS extraction were routinely 45%. A warm helical partial 5% Siberian snake was installed in the AGS in January 2004; this snake eliminates all depolarizing imperfection resonances up to RHIC transfer energy of 24 GeV without coupling issues created by the old solenoidal snake. Some depolarizing intrinsic spin resonances were avoided by spin flipping with a vertical RF dipole that created large coherent vertical betatron oscillations[15]. The remaining ≈20% polarization losses in the AGS are due to coupling and weak intrinsic resonances.

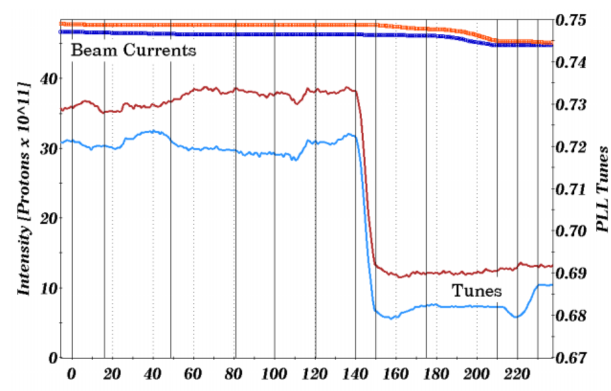

Figure 5: A typical Run-5 polarized proton acceleration ramp, showing no beam loss as tunes are moved from injection to store values.

UPGRADE PLANS

Polarization

The highest priority of the spin program is to raise RHIC beam polarization P, since the figure of merit for spin collisions scales as $\mathcal{L}P^4$. Depolarization in the AGS will be minimized with a superconducting partial 20% helical partial snake due to be installed in January 2005. First commissioning of this snake will occur during AGS setup for the Run-5 polarized proton run, though it is uncertain if this snake will be available for routine operations in that run. The existing 5% warm helical snake will be used to for spin matching at AGS injection and extraction[16].

The OPPIS polarized proton source currently provides 70–75% beam polarization. A new solenoid for this source is planned within two years; this will permit delivery of 80% beam polarization with beam intensities of twice the present value at RHIC injection.

Vacuum Improvements and Stochastic Cooling

At present, RHIC instantaneous luminosity is limited by total intensity, which is in turn limited by vacuum and electron cloud effects in warm beampipes. 60 m of solenoids have been installed and tested in some warm sections, and have been used to lower local pressure rise by a factor of 4 with a 5 G solenoidal field. We are installing new solenoids on the stainless common sections of the BRAHMS and PHOBOS experiments; the STAR and PHENIX experiment solenoids are sufficient to eliminate multipacting and pressure rise on their own.

We are also implementing a two-year program to NEG coat and activate most of the RHIC warm beampipes, to provide extra linear pumping and reduce secondary electron yield (SEY) and electron stimulated desorption (ESD). Linear pumping for activated NEG is about 10^2 l/s/m, SEY is reduced by a factor of two, and ESD is reduced by two orders of magnitude over stainless steel. 260 m of NEG-coated beampipes are being installed before Run-5; however, coating of the PHOBOS experiment beampipes (three 4 m long fragile Be pipes) has been deferred until 2006. We expect that this upgrade will allow operation of heavy ions to near the observed cold bore pressure rise limit of 100–120$\times 10^9$ Au total intensity.

Further RHIC luminosity upgrades require that emittance growth from IBS is reduced or eliminated. Stochastic cooling and electron cooling are under active investigation for RHIC beam cooling. Longitudinal stochastic cooling is under active development as longitudinal IBS scattering out of the RF buckets is the dominant contributor to heavy ion beam lifetime in collisions at RHIC. A single low-power longitudinal test assembly will be installed for Run-5 testing[17]. Optical stocahstic cooling using optical parametric amplifiers with higher signal to noise is also under study[18].

Electron Cooling

Electron cooling of 100 GeV/u gold beams with 10^9ions per bunch in RHIC requires a 54 MeV electron beam with an average current of 100–200 mA[19]. This electron beam has a high power of 5–10 MW, necessitating the use of an superconducting energy-recovery linac (ERL). ERL technology with superconducting cavities has been successfully demonstrated at Jefferson Lab with a 100 MeV 10 mA electron beam[20].

The electron beam must also be magnetized (have high angular momentum) throughout its transport[23], and encounter the ion beam within a 26 m long 2–5 T solenoidal field to avoid ion-electron recombination. This solenoid may be split into two 13 m opposing sections to limit coupling effect on the circulating RHIC ion beam yet maintain full cooling length; magnetized electron beam matching between these solenoids will be accomplished with a set of intermediate quadrupoles[24].

Table 2: RHIC luminosities with electron cooling

Au-Au (100 GeV/u)	w/o e-cool.	with e-cool
Emittance (95%) [$\pi\mu$rad]	15→40	15→10
$\beta^\star$ [m]	1.0	1.0→0.5
Number of bunches	112	112
Bunch intensity [10^9]	1.0	1.0→0.3
Beam-beam param. per IR	0.0016	0.004
$\mathcal{L}_{peak}$ [10^{26} cm^{-2}s^{-1}]	32	90
$\mathcal{L}_{store,ave}$ [10^{26} cm^{-2}s^{-1}]	8	70
$\vec{p}-\vec{p}$ (250 GeV/u)		
Emittance (95%) [$\pi\mu$m]	20	12
$\beta^\star$ [m]	1.0	0.5
Number of bunches	112	112
Bunch intensity [10^11]	2.0	2.0
Beam-beam param. per IR	0.007	0.012
$\mathcal{L}_{store,ave}$ [10^{30} cm^{-2}s^{-1}]	150	500

Table 2 shows the parameters for future RHIC luminosity upgrades without and with electron cooling. Electron cooling has the most dramatic effect on the luminosity of gold collisions, where beam burn-off due to collisions becomes the dominant source of particle loss. Electron cooling may also improve operation with polarized protons, as the proton beam can be pre-cooled at injection energy before acceleration, resulting in lower beam emittance; however, cooling effects on proton polarization need to be studied. Electron cooling of RHIC beams also extends beyond presently operating electron cooling facilities in other regards: the use of bunched electron beam accelerated by a energy recovery linear accelerator, and beam cooling during collider operation.

Vigorous R&D is underway to develop the critical components of the RHIC electron cooling system. A high-brightness, high-current electron source consisting of an RF photo-cathode gun operating at 703.75 MHz, capable of providing 2.5 MeV and about 100 mA current is currently being fabricated[21]. A 703.75 MHz five-cell high-current superconducting Niobium RF cavity for the ERL is also being fabricated; this cavity has an iris size of 17 cm with an enlarged beampipe of 24 cm, and includes two ferrite absorbers for higher order mode damping to avoid multi-bunch instabilities. Beam breakup thresholds of 1.4–2.4 A have been calculated. In the final configuration, four cavi-

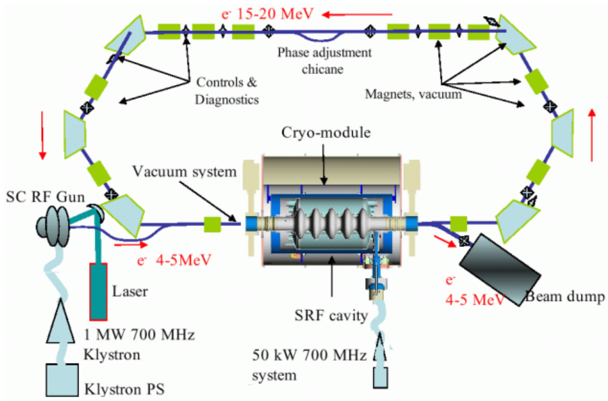

Figure 6: Layout of the 15-20 MeV 703.75 MHz ERL test system currently under construction at BNL, including the SCRF cavity in a cryo module and the 2.5 MeV CW photoinjector.

ties will accelerate the electron beam to 54 MeV[22].

The test setup layout for these components, including a single SCRF cavity for ERL tests up to 20 MeV, is shown in Fig. 6; this setup is expected to be in operation at BNL in 2006. Prototype design is underway for a 2–5 T superconducting solenoids, including testing of correction systems that will provide the required 10^{-5} field precision along their full length.

eRHIC

A low-emittance cooled gold beam is also essential for a future electron-ion collider at RHIC. This facility is being designed to collide a variety of ions (50–250 GeV polarized protons to 100 GeV/u Au) with 10 GeV polarized electrons or polarized positrons (5–10 GeV). Luminosities of 10^{32-33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ are achievable for e-p collisions with 70% longitudinal polarization of both beams; luminosities of 10^{30-31} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for e-Au collisions are achievable. The lepton beam will be provided by a polarized electron source and a recirculating 5–10 GeV linac, which then injects the leptons into a storage ring; positrons self-polarize in the storage ring with a polarization time of about 20 minutes[25, 26].

A preliminary design for the eRHIC interaction region has been developed, including spin rotators for both rings. Preliminary issues related to the integration of a detector into the IR design have also been considered, anticipating regions of intense synchrotron radiation generated by the bends in the electron beam[27].

ACKNOWLEDGEMENTS

These highly successful RHIC runs and promising upgrade paths are made possible by the dedicated efforts of the RHIC design, operations, and upgrade teams. Special thanks go to the RHIC Run-4 run coordinators, Wolfram Fischer (Au-Au) and Mei Bai (polarized protons).

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