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RHIC PERFORMANCE DURING THE 7.5 GeV LOW ENERGY RUN IN FY 2014 *

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Abstract

As the last step of phase 1 of the beam energy scan (BES-I), aimed at the search for the critical point in the QCD phase diagram, RHIC collided gold ions at a beam energy of 7.3 GeV/nucleon during the FY 2014 run. While this particular energy is close to the nominal RHIC injection energy of 9.8 GeV/nucleon, it is nevertheless challenging because it happens to be close to the AGS transition energy, which makes longitudinal beam dynamics during transfer from the AGS to RHIC difficult. We report on machine performance, obstacles and solutions during the FY 2014 low energy run.

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) consists of two superconducting storage rings with 3.8 km circumference. During regular heavy ion operations with Au beams, fully stripped gold ions are injected from the Alternating Gradient Synchrotron (AGS) at 9.6 GeV/nucleon and accelerated in RHIC to energies up to 100 GeV/nucleon.

To search for the onset of deconfinement and the critical point in the QCD phase diagram, Fig. 1, Au beam collisions with beam energies in the range from 2.5 to 10 GeV are required. Operationally this is realized by injecting beams of the desired energy into RHIC, which acts as a constant-energy storage ring. To minimize the turnaround time between stores, no separation between the two beams is provided at the two experiments STAR and PHENIX during the injection process. In this energy range, which extends far below the nominal RHIC injection energy, the luminosity performance is severly limited by several energy-dependent effects. RHIC has successfully provided low energy collisions with Au beam energies of 3.85, 5.75, and 9.6 GeV/n in past runs. For FY2014, the two experiments PHENIX and STAR requested a beam energy of or around 7.5 GeV/n.

ENERGY CHOICE

In previous low energy runs during the first phase of the beam energy scan (BES-I), RHIC has been providing gold-gold collisions at center-of-mass energies of $\sqrt{s_{\mathrm{NN}}} = 7.7$, 11.5, and and 19.6 GeV [1]. For the low energy run in FY2014, the experiments requested an additional energy around $\sqrt{s_{\mathrm{NN}}} = 15$ GeV, or 7.5 GeV/n beam energy.

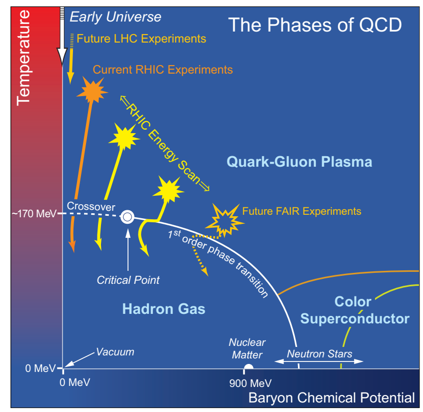

Figure 1: The QCD phase diagram, with the critical point expected in the center-of-mass energy range between $\sqrt{s_{\mathrm{NN}}} = 5$ and 30 GeV.

With the transition energy in the AGS, the injector synchrotron for RHIC, being at $\gamma_t = 8.5$, extracting at an energy of 7.5 GeV/n, or $\gamma = 8.05$, would result in very short bunches with a large momentum spread that could not be longitudinally matched upon injection into RHIC. Lowering the beam energy significantly improves this situation due to the $1/(\gamma - \gamma_t)^4$ scaling of the bunch length in the vicinity of γ_t. However, due to the limited frequency range of the 28 MHz RF system in RHIC, the beam energy cannot be lowered below 7.3 GeV/n without having to change the harmonic number [2]. At this energy, longitudinal matching from the AGS into RHIC is feasible, so the energy for the FY2014 run was chosen to be 7.3 GeV/n instead of the originally requested 7.5 GeV/n.

WORKING POINT

During earlier low energy runs significant deterioration of the beam lifetime was observed as a result of the beam-

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beam interaction in conjunction with the space charge force [1, 3, 4]. With the tunes set to $(Q_x, Q_y) = (.13, .12)$ during those runs in FY2010, the beam decay rate more than doubled when the beams collided, though the total beam-beam tune shift was a factor 5 to 10 smaller than the space charge tune shift. This was especially surprising since both forces are similar in nature and - assuming Gaussian beams - have the same functional dependence on particle coordinates. As was clearly demonstrated in FY2010, the beam lifetime deterioration due to the beam-beam interaction could not be attributed to the increased overall tune spread, because the lifetime of one beam immediately recovered even at the end of a store when the other beam was dumped.

Based on dedicated beam experiments as well as tracking studies aimed at finding a better working point, the tunes for the FY2014 low energy run were chosen as $(Q_x, Q_y) = (.095, .085)$. At these near-integer tunes, which could not be used in FY2010 due to the 10 Hz orbit jitter, the spacing between nonlinear resonances is largest, resulting in an increased dynamic aperture in the presence of the strongly nonlinear beam-beam force.

To confirm the superiority of these new near-integer tunes during FY2014 operations, the working point was set to the FY2010 tunes of $(Q_x, Q_y) = (.13, .12)$ for a single store. After the Yellow ring was filled, the Blue beam was injected. The resulting beam-beam collisions significantly reduced the beam lifetime of the Yellow beam, as depicted in Fig. 2. To confirm this behavior, the Blue beam was dumped, which led to an immediate increase of the Yellow beam lifetime. Re-filling the Blue beam again caused a similar lifetime deterioration.

In contrast to this, no effect on the Yellow beam lifetime was observed due to the Blue beam injection when the working point was set to $(Q_x, Q_y) = (.095, .085)$, as shown in Fig. 2. This test confirms that the near-integer working point optimizes the beam lifetime and therefore maximizes the integrated luminosity.

ORBIT CORRECTION AND COLLISION STEERING

Orbit corrections, especially collision steering in the interaction regions, turned out to be particularly challenging during this low energy run. The dipole correctors in RHIC provide a maximum field integral of $\int B\,\mathrm{d}l = 0.5\,\mathrm{Tm}$ at a power supply current of 50 A. Since these bi-polar corrector power supplies are controlled via 12-bit digital electronics, the orbit angle resolution of each of these correctors at a Au beam energy of $E = 7.3\,\mathrm{GeV/n}$ is approximately $\Delta\phi = 2.4\,\mu\mathrm{rad}$. With the IR steering bumps constructed of dipole correctors in the triplets as well as the arcs, the orbit angle resolution achievable at the interaction point is thus about $\Delta\phi_{\mathrm{IP}} = 25\,\mu\mathrm{rad}$. This translates to an orbit offset of about $\Delta x = 0.5\,\mathrm{mm}$ at the nearest beam position monitors in the triplets.

When an orbit correction at the IP was attempted using 4-bumps across the interaction region to maximize the col-

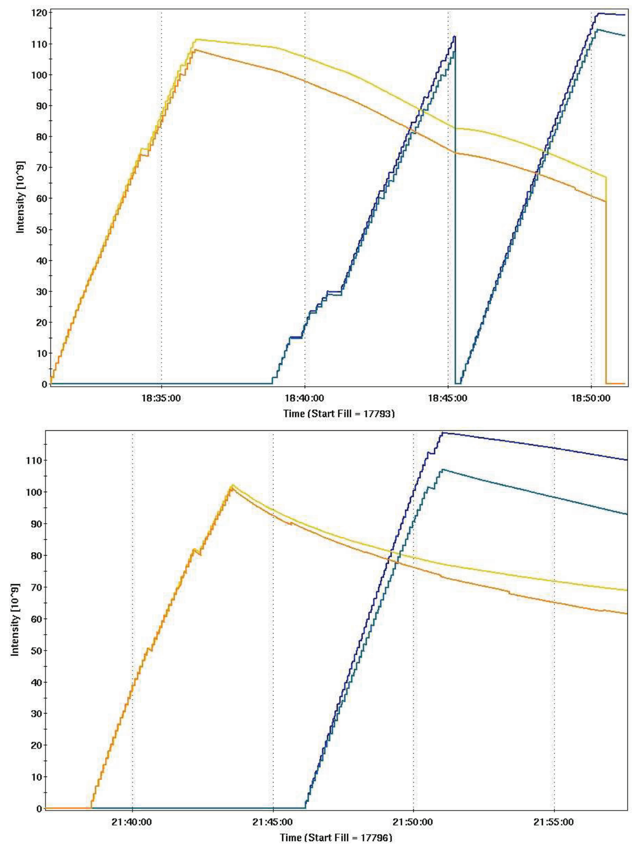

Figure 2: Beam intensities in the Yellow ring during injection of the Blue beam, at the FY2010 working point of $(Q_x, Q_y) = (.13, .12)$ (top) and the FY2014 near-integer working point $(Q_x, Q_y) = (.095, .085)$ (bottom).

lision rate, this limited resolution of the corrector power supplies resulted in unpredictable behavior of the orbit because the orbit angles provided by the individual dipole correctors were no longer proportional to each other. This resulted in difficult background conditions at the experiments throughout the entire low energy run.

To improve this situation in future low energy runs, it is planned to utilize a set of less efficient correctors that require larger field changes for the same orbit changes at the interaction point, which will therefore make the limited resolution of these correctors less pronounced. Alternatively, the 12-bit controllers of those power supplies could be upgraded.

LUMINOSITY PERFORMANCE

During RHIC operation at the highest energy of $100\,\mathrm{GeV/n}$ Au the limiting aperture is given by the low-β triplet quadrupoles around the interaction regions. At energies below $100\,\mathrm{GeV/n}$ the geometric beam emittance is larger. To maintain the maximum beam size in the triplets, the β-function in the triplets therefore has to be reduced. This is accomplished by increasing the β-function at the interaction point accordingly. As a net effect, the luminosity L scales as a function of beam energy E, with $L(E) \propto E^2$.

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Table 1: Machine Parameters Achieved During the FY2014 Low Energy Run at 7.3 GeV/n Beam Energy

no. of bunches/ring	111
ions per bunch	$1.1 \cdot 10^9$
β^*	3.5 m
rms emittance	1.7 μm
$L_{\rm peak}$	$1 \cdot 10^{26}$ cm^{-2}sec^{-1}
$L_{\rm store\ avg}$	$0.2 \cdot 10^{26}$ cm^{-2}sec^{-1}
integrated luminosity per week	8.1 μb^{-1}
time in store	57% of calendar time

For the FY2014 low energy run at $E = 7.3\,\mathrm{GeV/n}$, the β-function at the two experiments STAR and PHENIX was therefore chosen as $\beta^* = 3.5\,\mathrm{m}$.

The STAR and PHENIX collaborations set their integrated luminosity goals at $\int L = 20\,\mu\mathrm{b}^{-1}$. Based on the RHIC collider projection document [5], the duration of the low energy physics run was therefore scheduled to be three weeks.

After the cryo cool-down, which took three days, low-energy beam collisions were set-up within 9 days, which marked the beginning of the 3 week physics program in the afternoon of February 16, 2014. The store duration was initially set to 1 h; once turn-around time between stores had reached its minimum the store duration was re-optimized to 45 min to maximize the integrated luminosity for the run. Each day, a 30 min period without beam was scheduled to allow for pedestal runs at PHENIX.

Due to the low energy, intrabeam scattering led to fast debunching of the beams. These unbunched Au ions spread around the ring and filled the abort gap. When the beams were dumped at the end of each store, this unbunched beam in the abort gap led to background spikes at STAR that could potentially damage the silicon vertex detector. Continuous gap cleaning [6] using the tunemeter kickers was therefore established to reduce the unbunched beam in the abort gap to levels that became tolerable for STAR.

During the course of the run, one major equipment failure occured. On February 20, the cyclo-converter of the Siemens motor generator, the main magnet power supply for the AGS, failed. After 24 hours, the Westinghouse motor generator was operational, and physics running in RHIC resumed. Due to this failure, the duration of the low energy run was extended by one day to allow the STAR collaboration to reach their integrated luminosity goal. When the low energy run ended on March 11, 23 μb^{-1} had been delivered to PHENIX, and 21.2 μb^{-1} to STAR, thus meeting the integrated luminosity goal for the run. Table 1 lists the main machine parameters achieved during the run.

OTHER ACCOMPLISHMENTS

As an alternative method to study Au-Au collisions at very low center-of-mass energies around $\sqrt{s_{\rm nn}} = 5\,\mathrm{GeV/n}$, where beam operation in collider mode becomes exceedingly difficult [7], the STAR collaboration had pro-

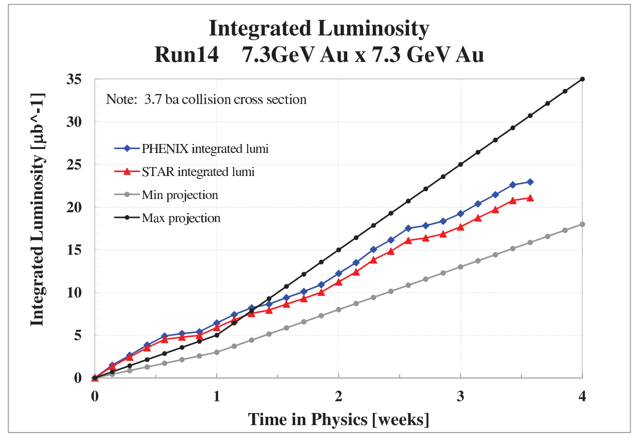

Figure 3: Integrated luminosity delivered to the two detectors STAR and PHENIX during the FY2014 low energy RHIC run, together with the minimum and maximum projections for the run.

posed the installation of an internal target 2.05 m from the interaction point [8]. For Run-14, a first prototype of such a target was installed. This Au target has an aperture of 2 cm, which equals the aperture of the beryllium beam pipe inside the STAR detector. The aperture of this target was intentionally chosen such that it cannot be hit by any circulating beam ions to ensure that such hits do not have any detrimental effects on the silicon vertex detector. This target was successfully used to set up the STAR trigger system, using target hits by the beam halo, which consists of ion fragments due to interactions with the upstream aperture limitation in the triplets.

The lattice for this low energy run was designed with a special high-β insertion optics in IR2 that would be suitable for low-energy cooling [9] in the future. The β-functions in IP2 were chosen as (β_x, β_y) = (34 m, 14 m) in the Blue ring, and (β_x, β_y) = (13 m, 49 m) in the Yellow ring.

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