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RHIC Low Energy Acceleration

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To search for the critical point and onset of deconfinement in the QCD phase diagram, the Relativistic Heavy Ion Collider has to collide beams of fully stripped gold ions in a beam energy range that extends well below the nominal injection energy. In this paper we discuss the scaling of key beam parameters with energy, present low energy beam parameters achieved at RHIC so far, and propose various scenarios to improve the luminosity performance in future low energy runs.

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1. Introduction

The Relativistic Heavy Ion Collider RHIC consists of two superconducting storage rings of 3.8 km circumference each that intersect at six equidistantly spaced locations around the machine circumference. Two of these interaction regions are equipped with the detectors STAR and PHENIX. Fully stripped gold ions are injected from the Alternating Gradient Synchrotron AGS at a nominal energy of 9.6 GeV/nucleon, and accelerated in RHIC to energies up to 100 GeV/nucleon. To search for the critical point and onset of deconfinement in the QCD phase diagram, Au beam collisions at beam energies between 2.5 and 10 GeV/nucleon are required. Since this energy range extends far below the nominal injection energy of RHIC, the resulting luminosity is severely limited by several energy dependent effects. In the next sections, we will discuss the energy dependence of these effects in some detail, before presenting the RHIC Au beam performance achieved at different energies below the nominal injection energy so far. Finally, we will present various measures aimed at improving the luminosity at these energies.

2. Scaling of beam parameters with energy

Operating a large machine like RHIC at very low energies is particularly challenging for a number of reasons. At any location s around the circumference of the accelerator, the transverse RMS beam size is given as

$$\sigma(s) = \sqrt{\varepsilon\beta(s)}, \tag{2.1}$$

with $\beta(s)$ and ε being the β-function and the beam emittance.

Introducing the normalized emittance ε_N, which is independent of the beam energy, the beam emittance ε scales with the Lorentz parameter γ as

$$\varepsilon = \frac{\varepsilon_N}{\beta\gamma}. \tag{2.2}$$

Therefore, the transverse beam size at low energies tends to be very large, which causes aperture restrictions, usually in the low-β triplets around the interaction points (IPs).

With the luminosity scaling as

$$L \propto \beta_{\mathrm{IP}}^{-1}, \tag{2.3}$$

and the product of the β-functions at the IP and the triplets being nearly constant,

$$\beta_{\mathrm{IP}}\beta_{\mathrm{triplet}} \approx \mathrm{const.}, \tag{2.4}$$

this limits the maximum allowable β-function in the triplets and therefore the luminosity.

The individual ions in a round beam with radius a and uniform charge density η repel each other due to their equal charge, with the electrical field at a radius $r < a$ inside the beam being

$$E_r = \frac{\eta}{2\varepsilon_0} r. \tag{2.5}$$

At the same time, the parallel currents of the individual co-moving ions result in a magnetic field

$$B_\Phi = -\frac{\beta\eta}{2\varepsilon_0 c} r \tag{2.6}$$

inside the beam, $r < a$. The resulting net space charge force can therefore be computed as

$$\vec{F} = q\cdot(\vec{E} + \vec{v}\times\vec{B}) \tag{2.7}$$

$$= \frac{q\eta}{2\varepsilon_0}(1-\beta^2)\vec{r} \tag{2.8}$$

$$= \frac{q\eta}{2\varepsilon_0\gamma^2}\vec{r}, \tag{2.9}$$

which increases rapidly at low energies due to the γ^{-2} scaling.

For Gaussian transverse and longitudinal beam profiles, this space charge force leads to a maximum tune shift

$$\Delta Q_{\rm sc} = -\frac{Z^2 r_p}{A}\frac{N}{4\pi\beta\gamma^2\varepsilon_N}\frac{C}{\sqrt{2\pi}\sigma_s}, \tag{2.10}$$

where Z and A are the atomic charge and mass number of the ion species, N the number of ions per bunch, β and γ the Lorentz parameters, C the accelerator circumference, and σ_s the RMS bunch length, respectively.

Due to the dependence of the space charge force on the transverse position of the test particle, the tune shift is not uniform for all particles, but results in a tune spread similar to the one caused by the beam-beam interaction. Particles near the center of the beam experience the full tune shift $\Delta Q_{\rm sc}$ according to Equation (2.10), while the tune shift for particles in the (Gaussian) tails of the bunch vanishes. The working point of the accelerator has to be chosen such that the entire tune space occupied by this space charge tune spread is free of low-order nonlinear resonances which would otherwise deteriorate the beam lifetime.

The transverse and longitudinal focusing forces cause individual beam particles to scatter off each other. This process, which is known as intrabeam scattering, leads to heating of the beam and therefore to emittance growth and luminosity degradation. Figure 1 shows calculated transverse emittance growth rates as a function of the Lorentz parameter γ, for a fixed 28 MHz RF voltage of 500 kV and a fixed longitudinal normalized emittance [1]. Intrabeam scattering can be compensated by electron cooling, which is planned to be installed in RHIC within the next couple of years.

Because RHIC was designed and built for heavy ion collisions at beam energies equivalent to 100 GeV/nucleon Au, the multipole errors of its superconducting magnets are minimized at high field strength. At the low magnetic fields necessary for the critical point search in RHIC, these multipole errors are largest (Fig. 2), leading to strong nonlinear resonances and therefore to a reduced dynamic aperture of the collider. This, in turn, may limit the beam lifetime.

Despite the challenges of low energy operation RHIC has been successfully operated well below its design injection energy. Achieved peak and average store luminosities for three different energies are listed in Table 1, together with key machine and beam parameters. While RHIC operated successfully for several weeks during physics runs at 3.85 and 5.75 GeV/nucleon, only a two-day test run was performed at the lowest energy of 2.5 GeV/nucleon. The tiny beam intensities during this test were not sufficient to measure beam parameters such as emittances reliably,

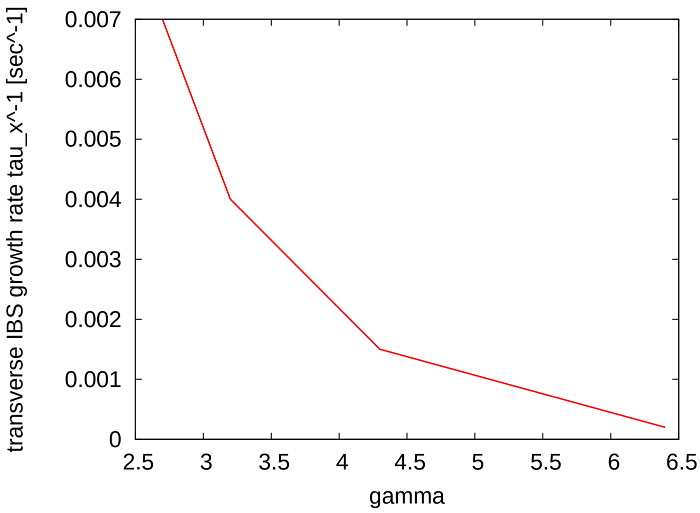

Figure 1: Transverse emittance growth rate due to intrabeam scattering, as a function of γ, for a fixed 28 MHz RF voltage of 500 kV and a fixed longitudinal normalized emittance.

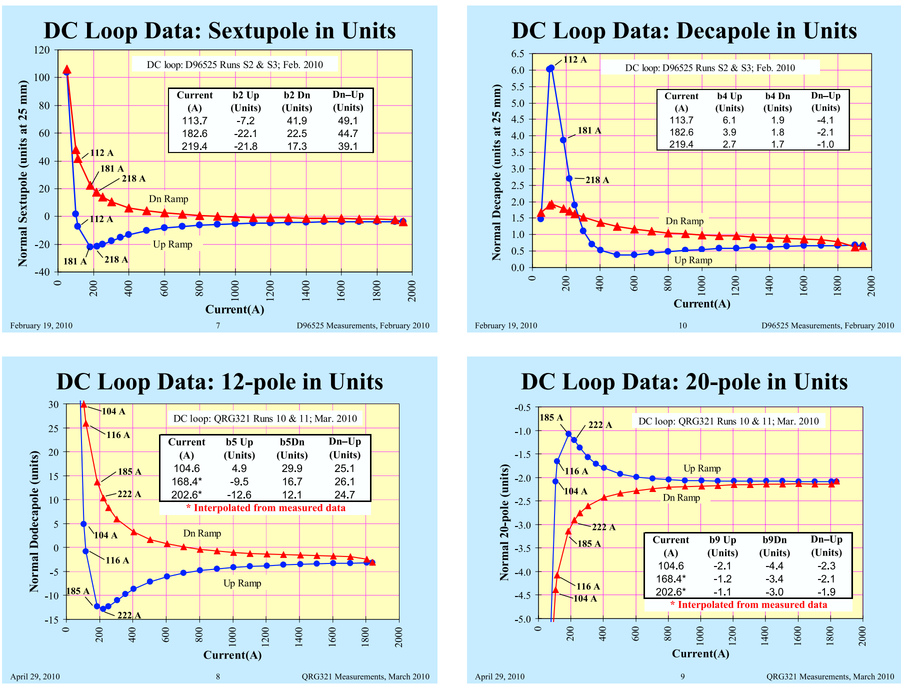

Figure 2: Multipole errors measured in one spare superconducting RHIC dipole and one spare quadrupole, as a function of magnet current during a hysteresis cycle. The blue data points correspond to the up ramp from the park current of 50 A, while the red data were taken during the down ramp of that hysteresis cycle.

	2.5 GeV	3.85 GeV	5.75 GeV
γ	2.68	4.1	6.1
σ_s [m]	2.5	1.5	1.5
ε_n [mm mrad]	20 (?)	20	15
I_{bunch} [1e9]	0.05	0.5	1.1
N_{bunches}	27	111	111
β^* [m]	8.5	6.0	6.0
ΔQ_{bb}	1.2e-4	1.2e-3	1.7e-3
ΔQ_{sc}	0.005	0.035	0.047
$\tau_{\mathrm{IBS}}(x/s)$ [sec]		475/525	4350/330
τ_{beam} [sec]	250	1000	1500
τ_{lumi} [sec]	?	400	1500
L_{peak} [cm^{-2}sec^{-1}]	>0	3.1e24	3.3e25
$L_{\mathrm{store\,avg.}}$ [cm^{-2}sec^{-1}]	>0	1.25e24	1.5e25

Table 1: Low energy beam parameters achieved in RHIC so far. At the lowest energy of 2.5 GeV/n, only a short test run was performed, during which only tiny beam intensities were injected that did not result in a meaningful luminosity signal.

but nevertheless led to a few hundred Au-Au events within a few hours that are presently being analyzed [2].

3. Operational experience and possible improvements

During the 2.5 GeV/n Au run in June 2012, only tiny bunch intensities of several 10^7 Au ions/bunch could be successfully injected and stored in RHIC due to an extremely poor injection efficiency of only about 10 percent from the end of the AGS-to-RHIC transfer line (AtR) into RHIC. This can be partially attributed to the bunch length out of the AGS being longer than the RHIC injection kicker pulse.

At these low intensities, the instrumentation in RHIC does not work reliably. For instance, transverse beam sizes are unknown. A possible unusually large transverse emittance may explain the poor injection efficiency.

Beam lifetimes at these tiny intensities were measured at approximately 4 min, which is a significant improvement compared to the 4 sec achieved in FY 2010 when the sextupole errors in the main dipole magnets were not modeled correctly [3]. However, it is yet unknown how beam lifetimes would scale with intensity once effects such as intrabeam scattering and space charge become significant.

Two key accelerator physics experiments (APEX) have been proposed and approved that aim at a further understanding of machine performance at this lowest energy. During long polarized proton stores in RHIC, Au ions at 2.5 GeV/nucleon will be set up in the AGS and extracted to the W-dump in the AtR transfer line, where beam emittances will be determined using photoluminescent screens. As a second experiment, protons at the same rigidity $B\rho$ as 2.5 GeV/n Au ions will be

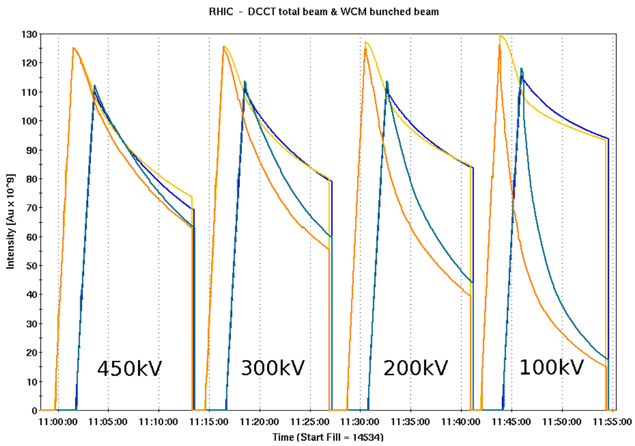

Figure 3: Au beam intensities in the Blue and Yellow RHIC rings during an RF voltage scan at a beam energy of 5.75 GeV/nucleon.

injected into RHIC to study the performance of the machine. Since protons at this rigidity will have a relativistic γ of 6.25 instead of 2.68, space charge effects will be significantly reduced.

At the other two low energy points, 3.85 GeV/n and 5.75 GeV/n, much higher bunch intensities were successfully injected and stored [4]. At 3.85 GeV/n, the space charge limit was reached at $\Delta Q_{sc} = 0.1$ for bunch intensities beyond $0.7 \cdot 10^9$ Au ions/bunch, resulting in poor lifetime [5]. For intensities below that limit, measured lifetimes agreed well with intrabeam scattering expectations.

At 5.75 GeV/n beam intensities of up to $1.1 \cdot 10^9$ Au ions per bunch were stored with a lifetime of 1600 seconds, increasing to 4200 sec for lower bunch intensities of $0.7 \cdot 10^9$ Au ions per bunch. As it was the case at 3.85 GeV/n, these lifetimes agree very well with expectations from intrabeam scattering simulations.

To study the beam lifetime dependence on the longitudinal momentum spread $\Delta p/p$, an RF voltage scan was performed, see Figure 3. While a lower RF voltage led to increased debunching, as indicated by the reduced lifetime of the bunched beam contribution, the lifetime of the total beam increased. Together with electron cooling, which would prevent debunching by counteracting intrabeam scattering, a lower RF voltage is therefore expected to significantly increase the beam lifetime.

During the low energy runs RHIC operated at a working point of $(Q_x, Q_y) = (28.13, 29.12)$, which was the result of a tune scan. At the time of the scan, the 10 Hz global orbit feedback [6] that suppresses orbit jitter introduced by mechanical vibrations of the IR triplet quadrupoles [7] was not yet operational, which prevented operating at near-integer tunes below $(28.10, 29.10)$.

Strong beam-beam effects were observed during the course of the low energy runs at 3.85 and 5.75 GeV/n, which reduced beam lifetimes by a factor of 3 to 5 once beams were brought in collision. As an illustration of these effects, Figure 4 shows the beam loss rate in percent per hour during a set of stores at 5.75 GeV/n beam energy. When the Yellow beam is dumped at the end of each store, the loss rate of the Blue beam improves dramatically due to the lack of beam-beam interaction. This effect was entirely unexpected, since the beam-beam tuneshift is about an order of magnitude smaller than the space charge tune shift. Since both effects are very

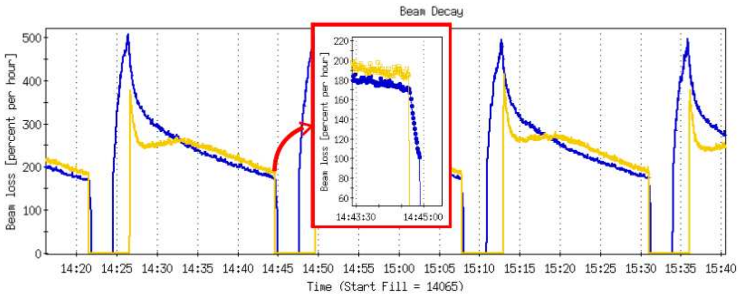

Figure 4: Beam decay rates during several Au beam stores at 5.75 GeV/n beam energy. The Blue beam decay rate improves dramatically as soon as the Yellow beam is dumped at the end of each store (see insert). Note that the algorithm to calculate the beam decay rate from the measured beam intensity has a time constant of 20 seconds. Hence, the actual drop in instantaneous beam decay is even more dramatic than suggested in this picture.

similar in nature, it was expected that the additional effect of the beam-beam interaction should be negligible. Simulation studies have in the meantime shown similarly strong effects of the beam-beam interaction in the presence of strong space charge forces [8].

Once the 10 Hz orbit feedback became operational, a beam experiment was performed to study the effect of beam-beam collisions in space charge dominated beams at near-integer tunes, where the spacing of nonlinear resonances is largest. Au beams at the nominal RHIC injection energy of 9.8 GeV were injected and subsequently brought into collision by collapsing the separation bumps. At a beam-beam tuneshift of $\xi_{\mathrm{beam-beam}} = 0.002$ and a space charge tune shift parameter of $\Delta Q_{\mathrm{sc}} = 0.03$ no discernable effect on the beam lifetime in the Blue ring was observed, while the Yellow beam lifetime still deteriorated. The reason for the different behavior of the two beams is not yet understood, but may be attributable to the different working points in the two rings, namely $(Q_x, Q_y) = (28.08, 29.07)$ in Blue and $(28.08, 29.09)$ in Yellow, or parameters such as betatron coupling or chromaticity that were less well controlled in Yellow than in Blue. However, this result is very encouraging for future low energy operations.

4. Electron cooling

Electron cooling is also capable of counteracting longitudinal as well as transverse emittance growth due to intrabeam scattering. This will enable RHIC to operate at or near the space charge limit of $\Delta Q_{\mathrm{sc}} = 0.05$, resulting in increased luminosity.

Since electron cooling prevents emittance growth and reduces the population of transverse tails, it may be possible to increase the physical aperture of the machine by retracting the collimators, which would result in improved beam lifetimes [9].

Besides reducing the longitudinal momentum spread $\Delta p/p$ by lowering the RF voltage, an even lower momentum spread can be achieved using a dedicated low-frequency RF system, either at 9 or at 4.5 MHz instead of the standard RHIC 28 MHz system [10]. However, the increased longitudinal intrabeam scattering rates resulting from the lower RF frequency are more challenging for the electron cooler design [11]. Even without such a dedicated RF system, luminosity improvements by a factor 2 or 3 at energies below 5.75 GeV/n may still be achievable. This factor increases with increasing beam energy, to an order of magnitude at 10 GeV/n [9].

5. Summary

RHIC has successfully operated for physics data taking at two low energies well below its nominal injection energy of 9.8 GeV/n, namely at 3.85 and at 5.75 GeV/n. At both energies, unexpectedly strong effects of the beam-beam interaction in conjunction with the large space charge tune spread were observed that severely limited the beam lifetime and therefore the luminosity performance. A beam experiment at near-integer tunes indicates that with the proper working point choice these effects can potentially be greatly reduced. To counteract intrabeam scattering, which is the dominating factor in limiting the beam lifetime without collisions, installation of an electron cooler is foreseen for the next couple of years. Operating with somewhat retracted collimators and a space charge tune spread of $\Delta Q_{\mathrm{sc}} = 0.05$ at near integer tunes is expected to result in a luminosity increase by a factor of 6 or higher at energies of 5.75 GeV/n and higher, while at lower energies the expected improvement factor is about 2 to 3 with the existing RF system.

Machine performance at 2.5 GeV/n beam energy is still being investigated. Beam experiments have been proposed and approved to study both the parameters of the injected Au beam and the RHIC lattice nonlinearities. These experiments will be conducted during Run-13.

With the improvements envisioned during the next few years, the estimated beam time to perform the second phase of the beam energy scan (BES-II) down to energies of 3.85 GeV/n can be reduced from about 70 to 20 weeks, which is the typical duration of a RHIC physics run during a given fiscal year.

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PoS(CPOD 2013)044