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RHIC MACHINE STUDIES TOWARDS IMPROVING THE PERFORMANCE AT 2.5 GEV *

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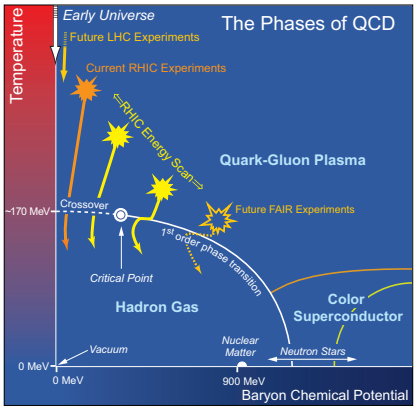

Figure 1: The QCD phase diagram, with the critical point expected in the center-of-mass energy range between $\sqrt{s_{\rm NN}} = 5$ and $30\,\rm GeV$.

Abstract

To search for the critical point in the QCD phase diagram, Au-Au collisions at beam energies between 2.5 and 15 GeV/n are required. While RHIC has successfully operated at 3.85 and 5.75 GeV/n, the performance achieved at 2.5 GeV/n is not sufficient for a meaningful physics program. We report on dedicated beam experiments performed to understand and improve this situation.

INTRODUCTION

During the next 5 - 10 years, one of the major RHIC physics programs will be the search for the critical point in the QCD phase diagram, shown in Figure 1. This search requires a gold beam energy scan in the range between 2.5 and 15 GeV/nucleon, which extends well below the RHIC design energy range from 10 GeV/n at injection to 100 GeV/n at store.

Operating RHIC below its design energy range is very challenging for a number of reasons. First of all, beam emittances are large, resulting in a lower limit on the β-function at the interaction point, and therefore in low luminosity. Large space charge tune shifts are encountered even with moderate beam intensities. Last but not least, the multipole errors in the accelerator magnets are optimized at full energy, while they are an order of magnitude larger below the nominal injection energy.

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Table 1: Beam parameters achieved at three different energies during the physics runs of the first phase of the beam energy scan.

	3.85 GeV	5.75 GeV	9.8 GeV
γ	4.1	6.1	10.7
σ_s [m]	1.5	1.5	1.5
ϵ_n [μm]	3	2.5	2.5
ϵ [μm]	0.73	0.41	0.23
$I_{\rm bunch}$ [10^9]	0.5	1.1	0.9
$N_{\rm bunches}$	111	111	111
β^* [m]	6.0	6.0	2.5
$\Delta Q_{\rm bb}$	$1.2 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$
$\Delta Q_{\rm sc}$	0.035	0.047	0.012
$\tau_{\rm beam}$ [sec]	1000	1500	3000

In the first phase of the beam energy scan in FY2010 and FY2011, RHIC operated at three different energies at and below its nominal injection energy [1, 2]. During these runs, beam lifetimes of roughly 15 minutes to one hour were achieved at gold bunch intensities of $0.5 \cdot 10^9$ to $1.1 \cdot 10^9$ ions per bunch; at the lower energies these intensities were limited by the space chage tune shift. Table 1 lists the beam parameters achieved during these runs.

In FY2012, RHIC operated for the first time successfully at a quarter of its nominal injection energy, namely at 2.5 GeV/nucleon [3]. During that test, beam lifetimes of approximately 4 minutes were achieved, see Figure 2. The bunch intensity was limited at $4 \cdot 10^7$ Au ions per bunch because of an injection efficiency of only 10 percent. Due to this short beam lifetime, only 27 bunches per ring were injected, since filling 110 bunches takes about two minutes per ring.

At these low bunch intensities, most of the RHIC beam instrumentation does not work properly, making it virtually impossible to understand and improve the machine performance. Most importantly, the transverse beam size and therefore the emittance were unknown because the ionization profile monitor (IPM) could not operate reliably.

EXPERIMENTS

In an effort to understand the single particle performance of the RHIC lattice at 2.5 GeV/nucleon Au beam energy, protons with the same rigidity of 19.3 Tm were injected and stored at an energy of 5.86 GeV. Due to the different charge-to-mass ratio Z/A of protons compared to gold ions, the relativistic Lorentz factor γ is about a factor 2.5

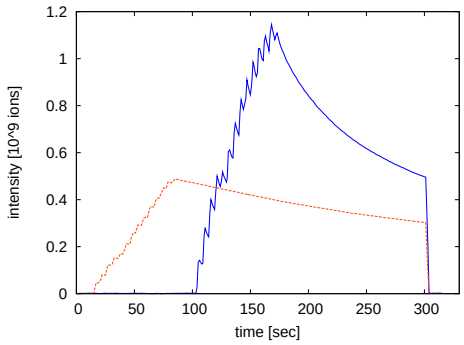

Figure 2: A typical Au-Au store at 2.5 GeV/n beam energy during a test run in 2012. While 27 bunches are being injected into the Blue ring, the intensity in the Yellow ring decreases by some 25 percent due to the short beam lifetime.

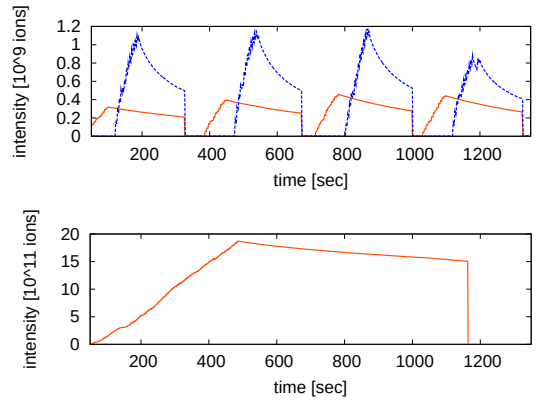

Figure 3: Comparison of the lifetime performance of typical Au-Au stores at 2.5 GeV/n in the Blue and Yellow ring (top) with a typical proton store at 5.86 GeV (bottom) in the Yellow ring.

Table 2: Beam parameters during the 5.86 GeV proton test experiment.

ramp	pp13-6GeV
$B\rho$	19.3 Tm
E	5.86 GeV
E_{kin}	4.92 GeV
γ	6.25
p	5.79 GeV/c
f_{rev}	77.187 kHz
h	363

higher than for gold ions at the same rigidity. Assuming identical normalized emittances ϵ_N for the two species, this results in smaller transverse beam sizes. Furthermore, the space charge tune shift

$$\Delta Q_{\mathrm{sc}} = -\frac{Z^2 r_p}{A} \frac{N}{4\pi\beta\gamma^2\epsilon_N} \frac{C}{\sqrt{2\pi}\sigma_s} \tag{1}$$

for protons is also reduced by a factor $Z/(A\cdot\gamma^2) = 2.5^3$ as compared to gold ions with identical bunch charge $Z \cdot N$, normalized emittances ϵ_N, and bunch lengths σ_s.

After some tuning, intensities of $4 \cdot 10^{10}$ protons per bunch were routinely injected and stored, with beam lifetimes of approximately one hour, as shown in Figure 3. Compared to the experience with gold ions in the same RHIC lattice, this was a huge improvement.

To characterize the single-particle performance of the lattice, we measured the dynamic aperture by two different methods. In the first attempt, we injected proton bunches with intentionally mis-steered orbits and measured the resulting beam emittances using the RHIC polarimeter target as a slow wire scanner. Mis-steering the injection orbit resulted in a drop of the injection efficiency and therefore the resulting stored beam intensity, Figure 4, thus indicating that an aperture limit was reached. During injection, losses were observed only in the RHIC abort kicker area, which is geometrically the tightest aperture at injection. Applying orbit bumps in an effort to reduce the losses in that location proved unsuccessful, which indicates that the beam orbit was well centered in the 2" $\times$ 3" aperture. However, regardless of the mis-steering efforts, the RMS beam sizes measured by the polarimeter target, at $\beta_x = \beta_y = 25\,\mathrm{m}$, remained constant at $\sigma_x = 2.4\,\mathrm{mm}$ and $\sigma_y = 2.0\,\mathrm{mm}$ which indicates that the beam already filled the available aperture even when it was injected without any intentional mis-steering, see Figure 6. At the abort kickers with $\beta_x = 41\,\mathrm{m}$, $\beta_y = 119\,\mathrm{m}$, this corresponds to RMS beam sizes of $\sigma_x = 3.1\,\mathrm{mm}$ and $\sigma_y = 4.4\,\mathrm{mm}$. These values are small compared to the abort kicker aperture, so it is safe to assume that the measured acceptance is limited by the dynamic aperture rather than the physical aperture.

This observation was confirmed by a second experiment in which the stored beam was transversely blown-up by the RHIC tunemeter. Again, this experiment resulted in RMS beam sizes of 2.4 mm horizontally and 2.0 mm vertically at the polarimeter. Furthermore, we observed a shrinking bunch length while the tunemeter was exciting the beam transversely, see Figure 5. We therefore conclude that the dynamic aperture is smallest for particles with large momentum deviation $\Delta p/p$.

The measured beam sizes of 2.4 mm horizontally and 2.0 mm vertically at the IPM with $\beta = 25\,\mathrm{m}$ correspond to RMS geometric emittances of $\epsilon_x = 0.23\,\mathrm{mm\,mrad}$ and $\epsilon_y = 0.16\,\mathrm{mm\,mrad}$. In contrast to this, Au beams with an RMS geometric emittance of $\epsilon = 0.73\,\mathrm{mm\,mrad}$ have been routinely stored at 3.85 GeV/nucleon. This indicates a dynamic aperture that is at least a factor 3 larger at the 50 percent higher rigidity of $29.7\mathrm{Tm}$ at 3.85 GeV/nucleon compared to $19.3\,\mathrm{Tm}$ at 2.5 GeV/nucleon Au, or 5.86 GeV protons. The root cause of this large difference is not

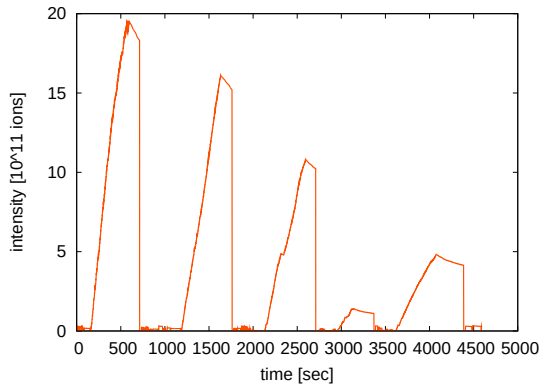

Figure 4: Total intensities of 110 bunches during the dynamic aperture measurement with mis-steered injection.

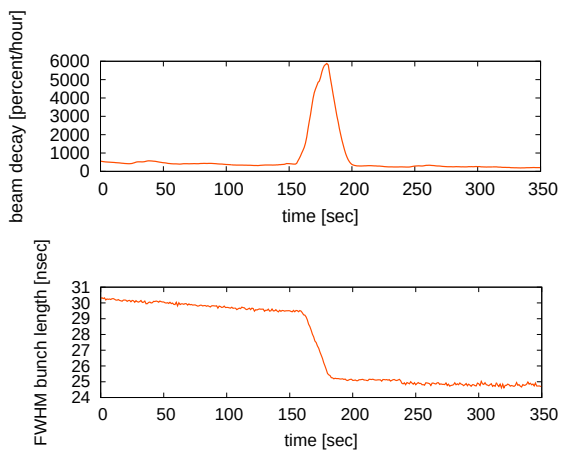

Figure 5: Hourly beam decay (top) and average bunch length during the dynamic aperture measurement using transverse emittance blow-up via the RHIC tunemeter.

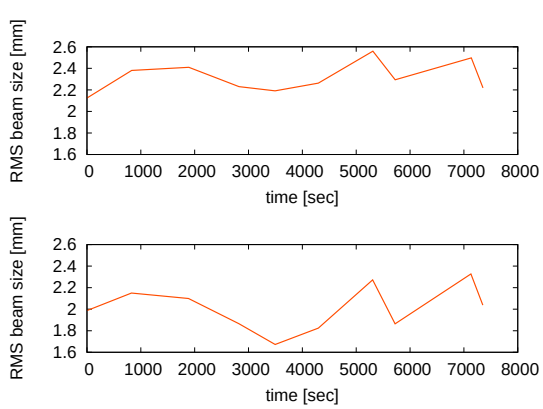

Figure 6: RMS beam sizes measured by using the RHIC polarimeter target as a wire scanner during the dynamic aperture studies.

yet understood. Tracking studies are currently being performed in an affort to understand and improve the dynamic aperture at 2.5 GeV/nucleon Au.

SPACE CHARGE

Based on the measured emittance $\epsilon = 0.16\,\mathrm{mm\,mrad}$, corresponding to a normalized emittance of $\epsilon_n = 1\,\mathrm{mm\,mrad}$, an RMS bunch length of $\sigma_s = 3\,\mathrm{m}$, and a bunch intensity $N = 4 \cdot 10^{10}$ protons/bunch, the space charge tune shift achieved during our experiments with 5.86 GeV protons can be computed as

$$\Delta Q_{\mathrm{sc}} = -0.065, \tag{2}$$

which is consistent with the space charge tune shift limit of $\Delta Q_{\mathrm{sc}} \approx -0.05$ observed with Au beams at 3.85 and 5.75 GeV/nucleon.

Assuming the same geometric emittance of $\epsilon = 0.16\,\mathrm{mm\,mrad}$ for 2.5 GeV/nucleon gold, corresponding to a normalized emittance of $\epsilon_n = 0.4\,\mathrm{mm\,mrad}$, and a bunch length of $\sigma_s = 3\,\mathrm{m}$, this same space charge tune shift would be reached at a bunch intensity of $N_{\mathrm{Au}} = 8 \cdot 10^7$ gold ions per bunch, which is a factor 5 less than what was achieved at 3.85 GeV/nucleon. With 111 bunches per ring, this would result in a luminosity of $L = 2 \cdot 10^{22}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

CONCLUSION

Measuring the dynamic aperture of the 2.5 GeV/nucleon Au lattice by injecting and storing protons at the same rigity resulted in a dynamic aperture that is at least 3 times smaller than that for 3.85 GeV/nucleon Au. Improving this is the key to a higher beam intensity at the space charge limit, and therefore to higher luminosity. Tracking studies, including a frozen space charge model, are currently under way to understand and improve the dynamic aperture. However, multipole errors at these low energies are only known for a single dipole and a single quadrupole, which limits the predictive power of these simulations somewhat. As the next step, it is planned to inject gold beams with emittances taylored to the measured dynamic aperture to study the beam lifetime under these conditions.

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