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at 2.5 GeV beam energy*

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FIRST RHIC COLLIDER TEST OPERATION AT 2.5 GEV BEAM ENERGY *

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Abstract

To search for the critical point in the QCD phase diagram, RHIC needs to operate at a set of low gold beam energies between 2.5 and 20 GeV per nucleon. During run 12, first successful collider operation at the lowest energy of 2.5 GeV per nucleon was achieved. We present the challenges and achieved results, and discuss possible future upgrades and improvements.

INTRODUCTION

The Relativistic Heavy Ion Collider RHIC consists of two superconducting storage rings with a circumference of 3.8 km. These two rings intersect at six locations around the circumference; two of these interaction regions are equipped with the detectors STAR at the 6 o’clock location and PHENIX at the 8 o’clock position. For nominal high energy collider operation, fully stripped gold ions are injected into the two rings from the Alternating Gradient Synchrotron AGS at a beam energy of 10 GeV/nucleon and accelerated up to 100 GeV/nucleon.

As a new major physics program for the next 5-10 years, RHIC will be searching for the critical point in the QCD phase diagram. As schematically indicated in Figure 1, the nominal collision energy of colliders such as RHIC and the LHC corresponds to a region above the critical point where the baryon chemical potential, or net baryon density, is low and the temperature high. Studying the critical point and the onset of deconfinement therefore requires Au-Au collisions at much smaller center-of-mass energies, namely in the region between $\sqrt{s_{NN}} = 5$ and 20 GeV.

Operating RHIC at these low energies is particularly challenging for a number of reasons. Due to the large machine circumference, space charge tune shifts reach values as large as $\Delta Q_{sc} = 0.1$, which is more than five times larger than the highest beam-beam parameters achieved in RHIC at full beam energy. Operational experience at 3.85 and 5.75 GeV/nucleon beam energy in RHIC has shown that the beam lifetime suffers significantly for space charge tune shifts beyond $\Delta Q_{sc} = 0.05$. Bringing such space charge dominated beams into collision proved to reduce the beam lifetime even further [2].

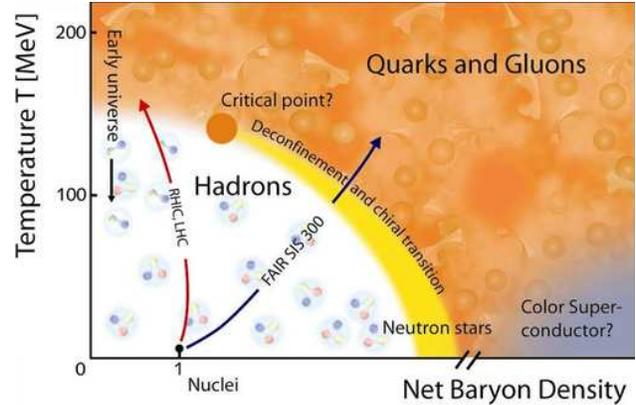


Figure 1: The QCD phase diagram [1]. A lower center-of-mass energy $\sqrt{s_{NN}}$ corresponds to a higher net baryon density. the critical point is expected to in the energy range between $\sqrt{s_{NN}} = 5$ and 20 GeV.

Since RHIC was designed and built to provide heavy ion collisions at relativistic energies up to 100 GeV/nucleon Au, its superconducting magnets are optimized at high fields as well. At the low magnetic field required for low energy operation below the nominal injection energy, multipole errors in those magnets are comparatively large. As an example, Figure 2 shows the measured sextupole component in a RHIC dipole as a function of magnet current during a full hysteresis cycle. The multipole data for 10-poles in the dipoles and 12- and 20-poles in the quadrupoles look qualitatively similar, with a characteristic maximum at magnetic fields corresponding to 2.5 to 10 GeV/nucleon Au beam energy, and an asymptotic approach of small values at high fields.

OPERATIONAL EXPERIENCE

During a first test at 2.5 GeV/nucleon beam energy in 2010, lifetimes of only 4 sec for 65 percent of the beam and 40 sec for the remaining 35 percent were achieved [3]. A careful analysis of measured multipole errors later revealed that the sextupole component in the main dipoles was not correctly represented in the RHIC online model, resulting in a chromaticity error of about 100 units [4]. A second test

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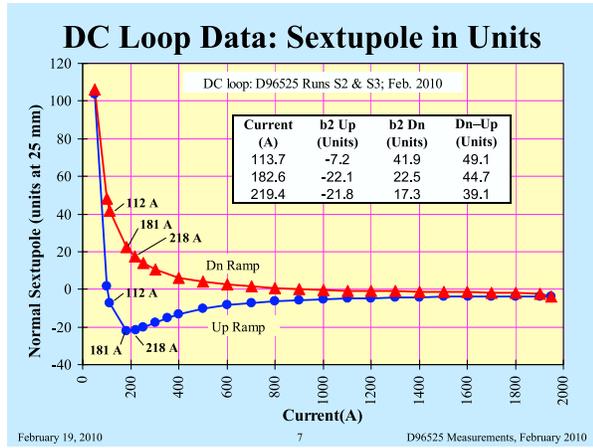


Figure 2: Measured sextupole component in one RHIC dipole, for a full hysteresis cycle. Regular injection energy corresponds to 471 A magnet current, while at 2.5 GeV/nucleon the dipole current is 113 A.

run was therefore performed during two days in June 2012 to evaluate the performance after correcting the chromaticity error.

The RHIC 28 MHz RF cavities have a tuning range from 27.92 to 28.18 MHz. Operation at the regular harmonic number $h = 360$ is therefore not possible at 2.5 GeV/nucleon beam energy. Instead, the harmonic number was changed to $h = 387$, which provides collisions at both STAR and PHENIX [5].

The β -function at the two interaction points was set to $\beta^* = 8$ m. This ensures that the 4 cm ID detector beam pipes are in the shadow of the low- β triplet quadrupoles to reduce beam induced detector background without overly limiting the aperture in the triplets [6].

The 2.5 GeV/nucleon test run was scheduled right after the full energy Cu-Au run [7]. Except for the beam energy, the injector setup was identical. Au beams were produced in the BNL Electron Beam Ion Source [8] and injected into the Booster. There, during each Booster cycle, four bunches were merged into one bunch and transferred into the AGS. During each AGS cycle, eight of those bunches received from the booster were first merged into four bunches, and then those four bunches into two. However, this resulted in very long bunches that had a poor capture efficiency of only 30 percent when injected into RHIC. The final AGS bunch merge from four into two bunches was therefore removed, which reduced the bunch length from 90 to 50 nsec at AGS extraction, and increased the capture efficiency in RHIC to 50 percent.

The injection efficiency into RHIC turned out to be poor. Bunch intensities of $6 \cdot 10^8$ Au ions/bunch in the AGS-to-RHIC transfer line (AtR) resulted in only $2 \cdot 10^7$ Au ions/bunch in RHIC. This can be partially attributed to the long bunches out of the AGS which were slightly longer than the RHIC injection kicker pulse. However, the trans-

Table 2: Comparison of measured multipole coefficients at different Au beam energies in RHIC, in units of 10^{-4} .

	2.5 GeV/n	3.85 GeV/n	9.8 GeV/n	100 GeV/n
sextupole	-7.2	-22.1	-10	-3
10-pole	6.1	3.9	0.4	0.7
12-pole	4.9	-9.5	-7	-3
20-pole	-2.1	-1.2	-1.9	-2.1

verse beam sizes during the test run are unknown, and may well have contributed to the poor injection efficiency.

Once beams were injected into RHIC, beam lifetimes of 4 min were achieved, see Figure 3. This improvement over the 2010 test run confirmed the chromaticity at that earlier test run had indeed been the root cause of the poor performance. However, with 4 bunches per 5 sec AGS cycle being injected into RHIC, filling one ring with the standard 111 bunches would have taken about 2 minutes, so filling both rings would have taken one beam lifetime. Therefore, a filling pattern with only 27 bunches per ring was applied. During a couple of hours of luminosity operation, several hundred event candidates have been identified by the STAR detector [9]. Figure 4 shows the bunched and unbunched beam intensities in the two RHIC rings during the 2-day test run.

The root cause of the short beam lifetime is still unknown. Assuming a 95 percent normalized emittance of $\epsilon_n = 20\pi$ mm mrad, the direct space charge tune shift, calculated as

$$\begin{aligned} \Delta Q_{sc} &= -\frac{Z^2 r_p}{A} \frac{N}{4\pi\beta\gamma^2\epsilon_N} \frac{C}{\sqrt{2\pi}\sigma_s} \\ &= -0.005, \end{aligned} \quad (1)$$

is much smaller than at other low energies where RHIC successfully operated with lifetimes exceeding 15 min, as listed in Table 1. Here, $Z = 79$ and $A = 197$ denote the charge state and atomic mass number of the beam ions, r_p is the classical proton radius, N the bunch intensity, C the accelerator circumference, ϵ_N the RMS normalized emittance, and σ_s the RMS bunch length. β and γ are the Lorentz parameters.

The measured multipole errors in the RHIC main magnets at 2.5 GeV/nucleon Au beam energy are comparable to those at other energies where RHIC operated successfully [4], see Table 2. One might therefore conclude that these lattice nonlinearities are not responsible for the short beam lifetime. However, multipole errors at low energies have only been measured in one spare main dipole and one spare main quadrupole, while the low energy multipole errors in other magnets, in particular the triplet quadrupoles, are unknown.

Table 1: Low energy beam parameters achieved in RHIC so far. At the lowest energy of 2.5 GeV/n, the actual beam emittance is unknown due to lack of reliable instrumentation at the tiny beam intensities. Luminosity signals and lifetime are also questionable at this energy due to high backgrounds.

		2.5 GeV/nucleon	3.85 GeV/nucleon	5.75 GeV/nucleon
Lorentz factor	γ	2.68	4.1	6.1
RMS bunch length	σ_s [m]	2.5	1.5	1.5
norm. emittance	ϵ_n [π mm mrad]	20	20	15
bunch intensity	I_{bunch} [$1e9$]	0.05	0.5	1.1
no. of bunches	N_{bunches}	27	111	111
IP β -function	β^* [m]	8.5	6.0	6.0
beam-beam tunes shift	ΔQ_{bb}	-1.2e-4	-1.2e-3	-1.7e-3
space charge tunes shift	ΔQ_{sc}	-0.005	-0.035	-0.047
beam lifetime	τ_{beam} [sec]	250	1000	1500
luminosity lifetime	τ_{lumi} [sec]	unknown	400	1500
peak luminosity	L_{peak} [$\text{cm}^{-2}\text{sec}^{-1}$]	> 0	$3.1e24$	$3.3e25$
avg. store luminosity	$L_{\text{store avg.}}$ [$\text{cm}^{-2}\text{sec}^{-1}$]	> 0	$1.25e24$	$1.5e25$

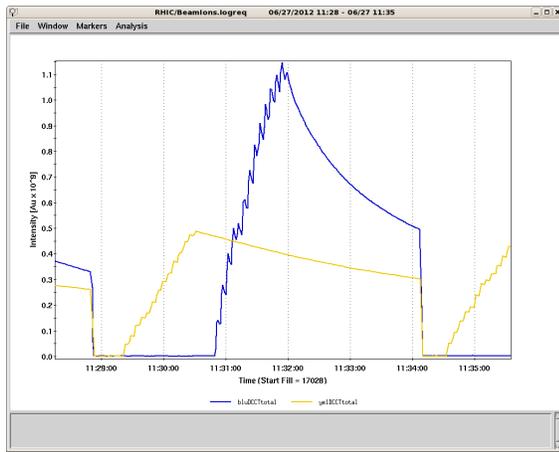


Figure 3: A typical RHIC store at 2.5 GeV/nucleon beam energy. After the “Yellow” ring is filled with 27 bunches, 27 bunches are injected into the “Blue” ring. Since there is no separation of the two beams at the IPs during the injection process, bunches collide as soon as they are injected.

SUMMARY

RHIC successfully provided first Au-Au collisions at a beam energy of 2.5 GeV/nucleon. Due to improved understanding of the sextupole errors in the superconducting dipoles, beam lifetimes of 4 min were achieved, compared to 40 sec in an earlier test in 2010. Beam intensities were two orders of magnitude smaller than at full energy due to a very poor injection efficiency. The root cause of this is being studied in dedicated experiments.

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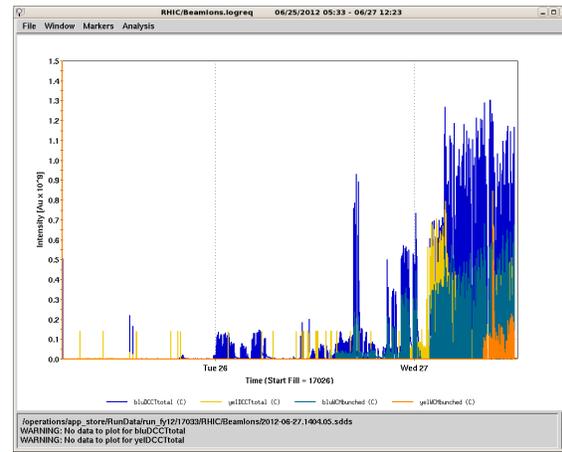


Figure 4: History of beam intensities in the two RHIC rings during the entire 2.5 GeV/nucleon test run. Collisions were provided to the two RHIC experiments on Wednesday morning from 9:30 to noon.

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