RHIC LOW ENERGY TESTS AND INITIAL OPERATIONS*

T. Satogata†, L. Ahrens, M. Bai, J.M. Brennan, D. Bruno, J. Butler, A. Drees, A. Fedotov, W. Fischer, M. Harvey, T. Hayes, W. Jappe, R.C. Lee, W.W. MacKay, N. Malitsky, G. Marr, R. Michnoff, B. Oerter, E. Pozdeyev, T. Roser, F. Severino, K. Smith, S. Tepikian, and N. Tsoupas
Brookhaven National Laboratory, Upton, NY, 11973-5000 USA

Abstract

Future Relativistic Heavy Ion Collider (RHIC) runs, including a portion of FY10 heavy ion operations, will explore collisions at center of mass energies of 5-50 GeV/n (GeV/nucleon). Operations at these energies is motivated by a search for the QCD phase transition critical point. The lowest end of this energy range is nearly a factor of four below the nominal RHIC injection center of mass energy of $\sqrt{s}$=20.8 GeV/n. There are several operational challenges in the RHIC low-energy regime, including harmonic number changes, small longitudinal acceptance, lowered magnet field quality, nonlinear orbit control, and luminosity monitoring. We report on the experience with some of these challenges during beam tests with gold in March 2008, including first RHIC operations at $\sqrt{s}$=9.18 GeV/n and first beam experience at $\sqrt{s}$=5 GeV/n.

BACKGROUND

There is significant theoretical and experimental evidence that points to the existence of a QCD phase transition critical point on the QCD phase diagram. If this critical point exists, it should appear on the quark-gluon phase transition boundary in the range of baryo-chemical potential of 100–500 MeV [1]. This corresponds to heavy ion collisions at RHIC with $\sqrt{s}$ =5–50 GeV/n. Experimental identification of this critical point would be a major step in understanding QCD at high temperatures and densities.

Future RHIC operations will explore Au-Au collisions in this energy range at both the STAR and PHENIX detectors. The required integrated luminosities for this search are challenging since luminosity is expected to scale as γ^2 down to nominal injection energy, and at least γ^3 below [2]. Determination of low energy collision rate scaling with γ is important for RHIC low-energy run planning. Approximately 5×10^6 events are needed at each of 6–7 energies to improve on existing SPS and AGS results by a factor of 2–4 [3, 4].

A third test of the RHIC low energy program was scheduled from March 10–12 2008, just after the RHIC 2008 d-Au run. This run reproduced the 2007 Au-Au setup at $\sqrt{s}$=9.18 GeV/n, and explored initial injection and setup at the lowest program energy of $\sqrt{s}$=5 GeV/n. PHENIX and STAR acquired first unambiguous $\sqrt{s}$=9.18 GeV/n Au-Au collision data during this run.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.
† Author email: satogata@bnl.gov

PARAMETERS

Table 1 compares some RHIC parameters that are relevant for low-energy operations from a 2006 test with protons, and 2007-8 tests and operations with gold. Power supply current scales with rigidity Bρ for linear field response. At the lowest energy, rigidity and power supply currents are only 20% of those at nominal injection energy. Main power supply regulation has been tested in RHIC at these currents and shows no problems. Other field quality was experimentally investigated during the 2006 and 2007 test runs [2].

Longitudinal and transverse acceptances at low energies are challenging. The Au longitudinal emittance after AGS injection and merging is as low as 0.1 eV-s/n; it grows to about 0.2 eV-s/n after ramping to γ=2.68 [5]. This beam barely fits into the RHIC 28 MHz RF bucket with 500 kV at $\sqrt{s} = 9$ GeV/n. At $\sqrt{s}$=5 GeV/n longitudinal acceptance is only 0.1 eV-s/n, and a significant fraction of the beam will be injected outside the RF acceptance. Transverse acceptance issues in the transfer line provide similar limitations, leading to expectations of 20–50% injection efficiency at $\sqrt{s}$=5 GeV/n with the usual 28 MHz RF system. A future 56 MHz RF upgrade, combined with longitudinal quad pumping in the AGS, may improve this efficiency [6].

2008 9.18 GEV/N GOLD RUN

The main objectives of the $\sqrt{s}$=9.18 GeV/n run were to evaluate improvements in the RHIC beam synchronous clock and experiment triggers, to evaluate beam quality after reversal of defocusing chromatic sextupoles, and to acquire first physics data for the low energy program.

The RHIC beam synchronous clock system, used for all single-bunch timing, was modified between 2007 and 2008

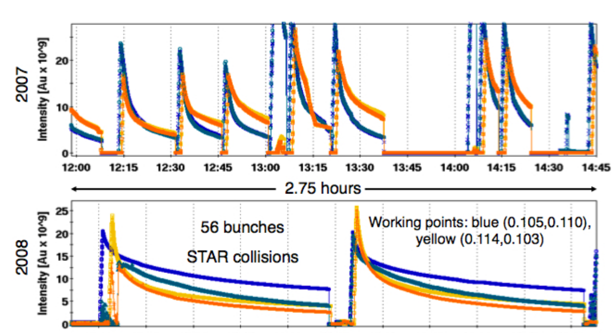

Figure 1: Comparison of 2007 and 2008 beam lifetimes at $\sqrt{s}$=9.18 GeV/n. Sextupole reversal and elimination of octopoles clearly improved beam lifetime.

Table 1: Parameters for nominal RHIC Au injection, 2006–8 low-energy test runs with protons and gold down to the lowest energy of interest for the QCD critical point search. Beam sizes are calculated assuming $\epsilon_{\rm N}$(Au)=40π μm and $\epsilon_{\rm N}$(p)=10π μm. $L_{\rm peak}$ assumes γ^3 scaling below nominal injection energy.

Species	$\sqrt{s}$ [GeV/n]	γ	Bρ [T-m]	$I_{\rm dipole}$ [A]	$f_{\rm rev}$ [kHz]	h	$\beta^\star$ [m]	$\beta_{\rm max}$ [m]	$\sigma^*_{95\%}$ [mm]	$\sigma_{\rm max,95\%}$ [mm]	$L_{\rm peak}$ [cm^{-2}s^{-1}]
Au (inj)	20.76	11.15	86.0	500.7	77.88	360	10	147	2.3	9.5	$4{\cdot}10^{25}$
p (2006)	22.5	11.99	37.4	217.7	77.92	360	10	147	1.2	4.9	–
Au (2007–8)	9.18	4.93	37.4	217.7	76.57	366	10	147	3.7	14.2	$7.2\cdot10^{23}$
Au (2008)	5.0	2.68	19.3	112.3	72.57	387	8	180	4.6	21.9	$1.4\cdot10^{23}$

to avoid phase problems that plagued earlier runs [2]. Tests in 2008 successfully triggered RHIC instrumentation and experiment DAQ clocks without major problems. However, RHIC operations at $\sqrt{s}$=9.18 GeV/n required h=366, which precluded simultaneous collisions at both experiments. This is detailed in the section "Harmonic Number Constraints" later in this paper.

Fig. 1 shows a comparison of $\sqrt{s}$=9.18 GeV/n Au beam lifetime for stores in the 2007 and 2008 test runs. Beam lifetime was substantially improved by reversing the hardware polarities of defocusing chromatic sextupole families. In the 2007 test run vertical chromaticity were positive even with zero strengths in these sextupoles, and beam stability was restored with strong octopoles at the expense of beam lifetime. This reversal is necessary for operations below about $\sqrt{s}$=9.3 GeV/n.

Injection efficiencies were 60-80%. Decomposition of the beam lifetime shows two main exponential components: a slow component of 50 minutes and a fast component of 3.5 minutes. The slow component is consistent with predicted growth rates [6]. Measured emittances from vernier scans were $\epsilon_{N,x,y}$ =15-25 π μm (Fig. 2). The longitudinal emittance was approximately 0.15 eV-s/n, consistent with AGS merge improvements [5]; this emittance fit inside the estimated RHIC RF bucket.

The achieved peak luminosity was about 3.5×10^{23}cm^{-2}s^{-1}, while the average luminosity was about 1.2×10^{23}cm^{-2}s^{-1} with 56 bunches and 0.4-0.5$\times 10^9$ Au/bunch. First physics data was acquired by STAR at this energy. Fig. 3 shows reconstructed vertex locations of collisions at the STAR detector during this run. The ratio of beam-beam to beam-beampipe collisions was about 1:1, consistent with a vernier scan (Fig. 2) but higher than expected. About 5000 good physics events of each type were acquired. The source of the beam-beampipe background collisions is under investigation.

2008 5 GeV/N GOLD TEST

A short test of Au beam injection at $\sqrt{s} = 5$ GeV/n was also performed following $\sqrt{s}$=9.8 GeV/n setup. A power supply failure limited this test to only one RHIC ring. The changeover to h=387 worked well, and there were no beam syncronous clock problems during this test. Injection efficiencies were less than 10%; Fig. 4 shows typical beam lifetime and tuning evolution during this test.

The objective of this test was to circulate any bunched beam. The bunched beam signal never exceeded 20 turns, and injection orbit oscillations were over 20 mm at peak. Traditional orbit threading did not converge and showed amplitude-dependent phase advances characteristic of a nonlinearity-dominated lattice. This data is consistent with large sextupole components measured in the RHIC dipoles at this energy. Work is underway to develop a fully nonlinear model that can be used for nonlinear orbit and chromaticity correction [7].

HARMONIC NUMBER CONSTRAINTS

The RHIC injection and acceleration RF system operates in a frequency range of $f_{\rm rf}$ = 28.0 − 28.17 MHz [8]. Below $\sqrt{s}$=9 GeV/n, the 28 MHz harmonic number h must be raised to keep the RF cavities within this frequency range. At the lowest energy of interest, $\sqrt{s}$ =5 GeV/n, h = 387 produces an accessible RF frequency of $f_{\rm rf}$ = 28.0847 MHz. A summary of RHIC harmonic numbers and permissible energy ranges based on the RF tuning con-

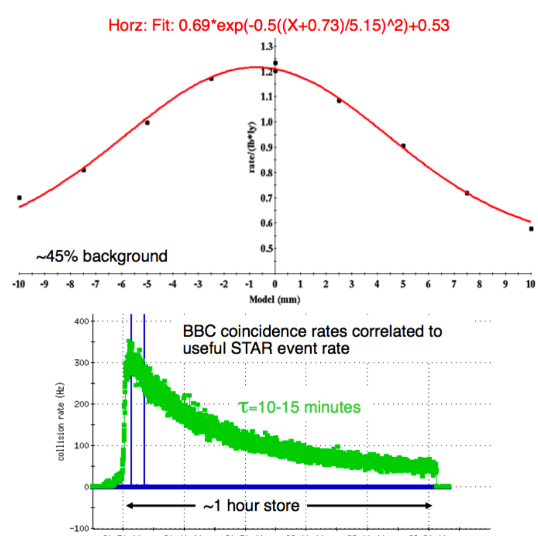

Figure 2: A horizontal vernier scan at the STAR detector during $\sqrt{s}$=9.18 GeV/n operations, and beam-beam counter (BBC) luminosity evolution during a typical store.

Table 2: Harmonic number choices for various collision energy ranges in the RHIC Low Energy program. These correspond to the acceptable RF frequency range of 28.0-28.17 MHz. Operations at other harmonic numbers reduce trigger luminosity by at least a factor of three due to precessing of experiment trigger clocks.

h	Allowed $\sqrt{s}$ [GeV/n]	h mod(3)=0	h mod(9)=0
360	18.0–107	*	*
363	11.34–15.15	*	
366	9.0–10.55	*	
369	7.71–8.60	*	*
372	6.87–7.47	*	
375	6.27–6.71	*	
378	5.81–6.15	*	*
381	5.45–5.72	*	
384	5.15–5.38	*	
387	4.91–5.10	*	*

straint is given in Table 2.

STAR and PHENIX experiment trigger clocks further constrain the harmonic number. The experiments currently require triggers clocks that are aligned to every third bucket. This enforces a requirement of $h$mod(3)=0 (i.e. the harmonic number is divisible by 3 with no remainder). Without this, experiment clocks precess from turn to turn.

PHENIX and STAR are also separated by 1/6 of the RHIC circumference. This implies that colliding bunch patterns are separated by 1/3 of the circumference. This, combined with the requirement that $h$mod(3)=0, produces a requirement that $h$mod(9)=0 for a fill pattern that gives a full complement of collisions at both experiments.

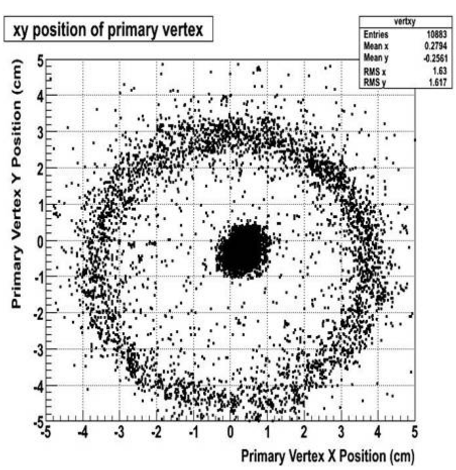

Figure 3: Reconstructed vertex locations of $\sqrt{s}$=9.18 GeV/n collisions at the STAR experiment during the 2008 run. Both beam-beam and beam-beampipe collisions are clearly visible, consistent with the beampipe inner diameter of 76mm. (Figure courtesy of the STAR collaboration, private communication.)

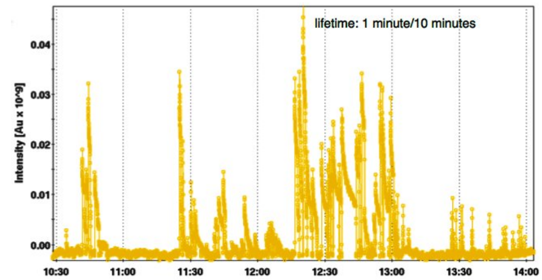

Figure 4: $\sqrt{s} = 5$ GeV/n injection test beam intensity in the RHIC Yellow ring.

This constraint was a limiting factor during the $\sqrt{s}$= 9.18 GeV/n run, where collisions could only be created at one experiment at a time. This in turn meant that collisions had to be tuned at each experiment individually, and each run was dedicated to collisions at one experiment or the other. Future operations are expected only for energies where $h$mod(9)=0 shown in Table 2 [9].

FUTURE PLANS

Electron cooling is an attractive option for the low energy program, as it counteracts IBS beam growth and can cool the beam in all dimensions. Electron beam energies of 0.8-5 MeV would be ideal, as this covers all energies up to RHIC injection energy. Several upgrades are being investigated. The preferred scheme is currently to transfer the Fermilab Pelletron to BNL after Tevatron shutdown, and to use this for DC non-magnetized cooling with an undulator in the cooling section to avoid recombination [10].

ACKNOWLEGEMENTS

The authors thank W. Christie of STAR and J. Haggerty of PHENIX for experiment liason support, and the RHIC/AGS operations staff for their continued support.

REFERENCES

[1] M. Stephanov, K. Rajagopal, and E. Shuryak, "Signatures of the Tricritical Point in QCD", Phys. Rev. Lett. **81**, 4816–4819 (1998).

[2] T. Satogata et al, "RHIC Challenges for Low Energy Operations", PAC 2007.

[3] RIKEN workshop proceedings, "Can We Discover the QCD Critical Point at RHIC", March 9–10 2006, `http://www.bnl.gov/riken/QCDRhic/`.

[4] G.S.F. Stephans, "critRHIC: the RHIC low energy program", J. Phys. G: Nucl. Part. Phys. **32** (2006) S447-S453.

[5] E. Pozdeyev, 2008 RHIC Retreat (March 31, 2008).

[6] A. Fedotov, WE6PFP005, this conference.

[7] T. Satogata et al., WE6PFP010, this conference.

[8] Alex Zaltsman, private communication.

[9] T. Satogata, BNL C-AD Tech Note: C-A/AP/309, March 2008.

[10] A. Fedotov et al., BNL C-AD Tech Note: C-A/AP/307, April 2008.