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RHIC Low-Energy Challenges and Plans

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There is significant interest in RHIC heavy ion collisions at $\sqrt{s_{NN}}$ =5–50 GeV, motivated by a search for the QCD phase transition critical point. The lowest energies for this search are well below the nominal RHIC gold injection collision energy of $\sqrt{s_{NN}} = 19.6$ GeV. There are several operations challenges at RHIC in this regime, including longitudinal acceptance, magnet field quality, lattice control, and luminosity monitoring. We report on the status of work to address these challenges, including results from beam tests of low energy RHIC operations with protons and gold, and potential improvements from different beam cooling scenarios.

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1. BACKGROUND AND MOTIVATION

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 $\sqrt{s_{NN}}$ =5–50 GeV. Experimental identification of this critical point would be a major step towards the understanding of QCD at high temperatures and densities.

Experimental exploration of heavy ion collisions in this energy regime is feasible using the STAR and PHENIX detectors at RHIC. This data would complement existing fixed-target data from the AGS (2.5–5 GeV) and SPS (5–20 GeV). The required integrated luminosities for this search are low but challenging – approximately 5×10^6 min-bias events are needed at each of 6–7 energies to improve on existing NA49 statistics by a factor of 2–4 [2, 3].

Fig. 1 shows several scalings for RHIC Au-Au luminosity in the low-energy regime of interest. Above the nominal injection energy of 9.8 GeV/u, the beam size and aperture both scale with γ, so the event rate (or luminosity) scales as γ^2. Here RHIC runs as a ramping collider. Previous collider runs at several intermediate energies are consistent with prediction, with present peak luminosity $L_{peak} = 4.0 \times 10^{25}$ cm^{-2} s^{-1} at injection energy and $L_{peak} = 3 \times 10^{27}$ cm^{-2} s^{-1} at $\sqrt{s_{NN}} = 200$ GeV.

At and below nominal injection energy, RHIC runs as a colliding storage ring, and beam size, field quality, longitudinal acceptance, and intrabeam scattering (IBS) growth below an unknown threshold energy will conspire to make luminosity scaling worse. Fig. 1 shows γ^3 and γ^4 scalings as examples. The 2007 beam Au beam test, detailed in section 4 of this paper, demonstrated better than γ^2 scaling at $\sqrt{s_{NN}} = 9.18$ GeV. However, performance will certainly degrade at lower energies; an estimate of event rates for $\sqrt{s_{NN}} = 5$ GeV corresponding to $L_{peak} \approx 5 \times 10^{22}$ cm^{-2} s^{-1} is also shown.

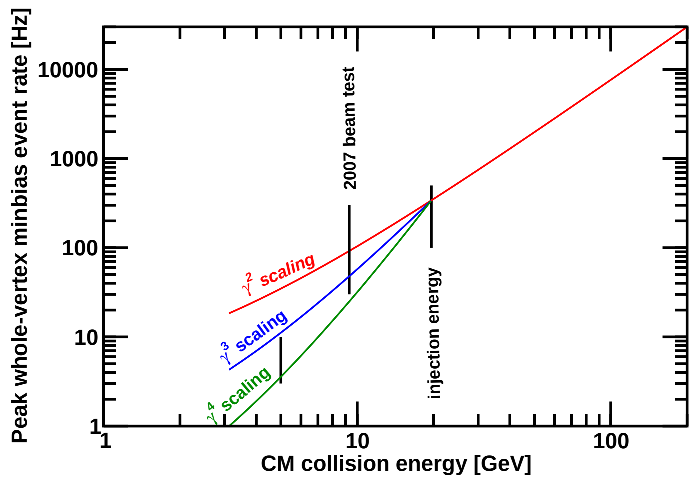

Figure 1: Scaling of RHIC minbias event rate (or luminosity) into the low energy regime. Energies of interest are $\sqrt{s_{NN}}$ =5–50 GeV, or beam kinetic energies of 1.6–24.1 GeV/u. Vertical lines are measured ($\sqrt{s_{NN}} = 19.2$ GeV at injection; $\sqrt{s_{NN}} = 9.18$ GeV in the 2007 beam test) and projected ($\sqrt{s_{NN}} = 5$ GeV) minimum to maximum event rates.

Table 1: Parameters for nominal RHIC Au injection, 2006 and 2007 low-energy test runs with protons and gold, and the lowest energy of interest for the QCD critical point search. Injection and 2007 test run peak luminosities are measured; the $\sqrt{s_{NN}}$ =5 GeV peak luminosity is estimated. Beam sizes are calculated assuming $\varepsilon_{\rm N}$(Au)=40π μm, $\varepsilon_{\rm N}$(p)=10π μm, $\beta^\star$=10m, and β_{max}=170m. L_{peak} assumes $\beta^\star$=10m.

Species	$\sqrt{s_{NN}}$ [GeV]	$KE_{\rm beam}$ [GeV/u]	γ	Bρ [T-m]	$f_{\rm rev}$ [kHz]	h	$\sigma^*_{95\%}$ [mm]	$\sigma_{max,95\%}$ [mm]	L_{peak} [cm^{-2} s^{-1}]
Au (inj)	23.47	10.80	12.6	97.3	77.95	360	2.3	9.5	400×10^{23}
p (2006)	22.5	10.31	11.99	37.4	77.92	360	1.2	4.9	–
Au (2007)	9.18	3.66	4.93	37.4	76.57	366	3.7	15.3	4×10^{23}
Au (low)	5.0	1.57	2.68	19.3	72.57	387	5.2	21.3	5×10^{22}

2. PARAMETERS

Table 1 compares some RHIC parameters that are relevant for low-energy operations, including two test runs that occurred in 2006 with protons and 2007 with gold. Summaries of these test runs are presented in the sections 3 and 4 of this paper.

For linear field response, power supply current scales with magnet rigidity Bρ. At the lowest requested collision energy, rigidity and power supply currents are only 20% of their values 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 and also show no serious issues at $B\rho$ =37.4 T-m.

At low energies, Au beam becomes less relativistic, and the ion beam velocity is lowered out of the RHIC RF tuning range of 28.0–28.17 MHz for the standard RHIC harmonic number $h = 360$.

Table 2: RF constraints for RHIC low-energy operations. Even harmonic numbers may be required for RHIC instrumentation and beam sync clock issues; RF software currently requires harmonic numbers divisible by 9 to generate simultaneous collisions at both experiments. Eliminating both these constraints would allow operation at any harmonic number divisible by 3.

Harmonic number h	$\sqrt{s_{NN}}$ range [GeV]	h(mod2)=0	h(mod3)=0	h(mod9)=0	h(mod18)=0
360	16.7–107	*	*	*	*
363	11.4–15.0		*		
366	9.0–10.5	*	*		
369	7.7–8.6		*	*	
372	6.9–7.4	*	*		
375	6.3–6.7		*		
378	5.8–6.1	*	*	*	*
381	5.45–5.7		*		
384	5.15–5.38	*	*		
387	4.91–5.1		*	*	

The harmonic number must therefore be raised for collision energies less than $\sqrt{s_{NN}} = 16.7$ GeV. RHIC is three-fold symmetric, so only harmonic numbers divisible by 3 can produce simultaneous collisions at both STAR and PHENIX experiments. RF software related to injection patterns currently requires harmonic numbers divisible by 9 to produce collisions at both experiments, and RHIC beam synchronous clock systems [4] currently require harmonic numbers divisible by 2 to operate properly. Work is underway to eliminate both these constraints and permit operation at any harmonic number divisible by 3, as shown in Table 2.

Longitudinal and transverse acceptance vs emittance is another challenge at low energies. RHIC Au beam typically has a longitudinal emittance of 0.2 eV-s/u at injection. This beam barely fits into the RHIC bucket RF with 400 kV at $\sqrt{s_{NN}} = 9$ GeV. At $\sqrt{s_{NN}} = 5$ GeV longitudinal acceptance is only 0.12 eV-s/u, and 30–50% of the beam immediately debunches even with perfect longitudinal injection. Transverse acceptance issues in the transfer line provide similar limitations, leading to expectations of only 20–40% injection efficiency at the lowest energy.

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3. 2006 PROTON TEST RUN

The first 24-hour test of RHIC at low energy occurred June 5–6 2006, during the 2006 RHIC polarized proton run. As Au beam was not available, the objective of this run was to evaluate setup time, power supply behavior, linear field quality, beam stability, and optics. The RHIC rigidity was $B\rho$=37.4 T-m, corresponding to beam kinetic energy of 10.31 GeV, less than half of the nominal proton injection kinetic energy of 22.87 GeV. This rigidity was chosen because it corresponds to a potentially interesting feature in the QCD phase diagram [3]; it is also about halfway between nominal injection and the lowest energy of interest. Protons are still highly relativistic at this energy so the RHIC harmonic number was unchanged.

After initial setup, first circulating beam was achieved in approximately 3 hours in both rings; another 3 hours were needed for RF setup and capture. Injection efficiencies were 70–80% with beam lifetimes of 5–10 hours at the normal polarized proton working point. Vernier scan attempts did not provide good data, due to lack of clean luminosity signal and high backgrounds from unstable beam.

Optics measurements were performed using difference orbits and orbit response matrices. These measurements indicated 10-15% beta waves in both planes compared to the design injection model, consistent with optics quality at nominal injection field in RHIC. This combined with excellent beam lifetimes indicated that field quality at these energies was not problematic. Beam ripple was also measured, and showed no deviation from nominal injection spectra; power supply ripple and regulation at this energy is therefore also not an issue.

Low-field extrapolation of RHIC magnet measurements shows that the RHIC main dipole sextupole component nearly doubles from -9 units to -16 units from nominal injection to this energy. This created additional chromaticity that was not fully compensated with the existing configuration of RHIC sextupoles. Vertical chromaticities could only be set to about +1 to +2 below transition energy instead of the desired value of -1; instabilities were damped with strong octupoles, though beams continued to be metastable. For physics runs at this and lower energy, defocusing sextupole power supplies will be reversed to allow proper chromaticity control without compromising dynamic aperture.

4. 2007 GOLD TEST RUN

The second 24-hour test of RHIC at low energy occurred June 6–7 2007, during the 2007 RHIC Au-Au run. The RHIC rigidity was $B\rho$=37.4 T-m, the same as the proton test run, to leverage the 2006 test run setup. This corresponded to an Au beam kinetic energy of 3.66 GeV/u. The objectives of this run were to use a new RHIC harmonic number, evaluate Au transverse and longitudinal acceptance, and measure Au-Au luminosity to place a measured low-energy point on Fig. 1.

$h = 366$ setup was straightforward for RHIC RF and AGS to RHIC synchro. The RHIC beam synchronous event system also relies on an RF clock to generate experiment trigger clocks and other beam-synchronous RHIC instrumentation timing [4]. Event generator hardware that generates its own $h = 360$ revolution fiducial event was bypassed and the beam synchronous links were reconfigured, but at the cost of priority of the fiducial event on the link. PHENIX could not lock to this clock, but STAR could, with trigger resets every few minutes.

Fig. 2 shows Au beam lifetime for three consecutive stores during this low-energy run. Injection efficiencies were 70–80%. Decomposition of the beam lifetime shows two main exponential components: a slow component of 20 minutes, and a fast component of 2 minutes. The slow component is consistent with an IBS growth time prediction at this energy. Measured transverse emittances were $\varepsilon_{N,x,y} = 15 - 25\ \pi\ \mu$m. Longitudinal injection efficiency was 100%; estimated longitudinal emittance was 0.14 eV-s/u, significantly smaller than the expected 0.2 eV-s/u, perhaps because AGS transition crossing was unnecessary.

Four vernier scans were acquired at the STAR experiment. Unfortunately none could be acquired with new PHENIX detectors due to trigger clock problems. Fig. 3 shows a STAR vernier scan over ± 9 mm in 15 minutes in the horizontal planes. Beams were longitudinally cogged out of collision early in the store, demonstrating only 5% backgrounds, though the gaussian baseline in the figure appears higher than this. The beam average σ of 5.98 mm is consistent with a minimum σ of 4 mm and an average normalized horizontal emittance of 25 $\pi\ \mu$m, giving a measured peak luminosity of 4×10^{23} cm^{-2} s^{-1} as listed in Table 1.

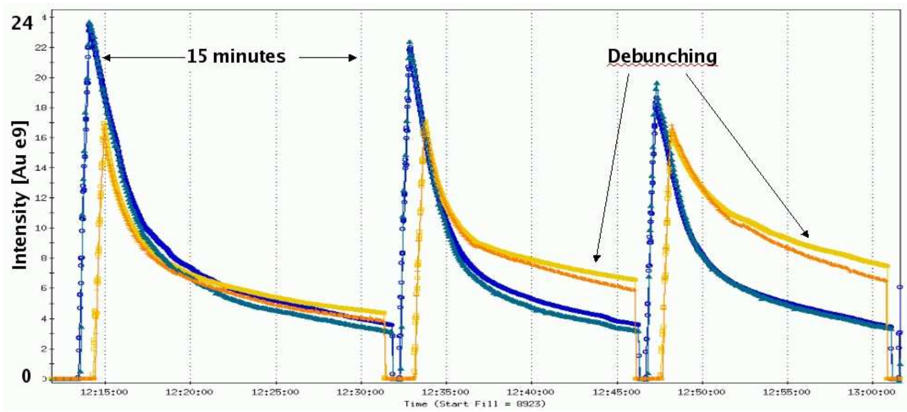

Figure 2: Au beam lifetime at $\sqrt{s_{NN}} = 9.18$ GeV (blue and yellow rings) during the 2007 gold test run, with a slow exponential decay component of 20 minutes and a fast exponential decay component of 2 minutes. Bunched and total beam currents are displayed; debunching is clearly visible, so momentum aperture is larger than the RF bucket size.

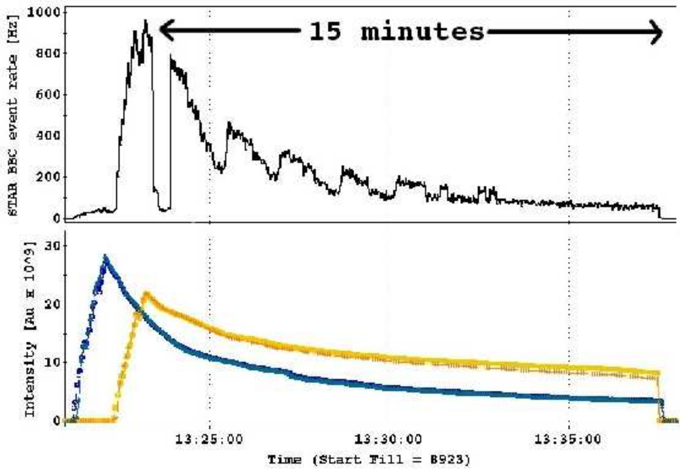

Figure 3: A 15-minute Au-Au store at $\sqrt{s_{NN}} = 9.18$ GeV, showing blue and yellow beam intensities and STAR BBC counter collision rates. Beams were uncogged and recogged at the start of the store; vernier scans in both planes were performed during the store.

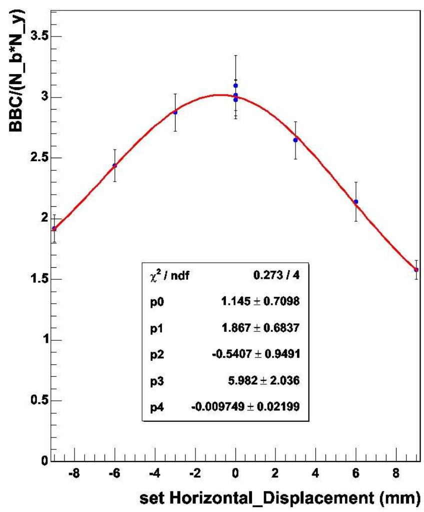

Figure 4: A STAR BBC vernier scan at $\sqrt{s_{NN}} = 9.18$ GeV, scanning beam horizontally over ± 6 mm. There was little background contamination, in contrast to the 2006 proton test run.

5. PROJECTIONS AND COOLING PROSPECTS

Table 3 shows a strawman proposal for a basic low-energy run exploring the energies from $\sqrt{s_{NN}} = 4.6$–28 GeV, or baryo-chemical potential $\mu_B = 150$–570 MeV as presented by T. Nayak at the 2006 RIKEN workshop [2]. The parenthesized values are modified projections based on 2007 test run results, which showed that 300 Hz average event rates were achievable at $\sqrt{s_{NN}} = 9$ GeV. Projections below $\sqrt{s_{NN}} = 8.8$ GeV have progressively larger uncertainties due to unknown dynamic aperture and luminosity lifetime. Even so, this indicates that a basic QCD critical point scan might be completed at RHIC in a six-week run.

Thorough measurements of K/π ratio fluctuations, jet quenching, and other possible critical

Table 3: A comparison of the STAR strawman low-statistic basic run proposal and extrapolations from the 2007 RHIC low energy test run (in parentheses). Beam days are expressed as run time plus setup time, assuming 50% combined detector/facility uptime. Whole-vertex average BBC rates are listed , and do not include detector vertex acceptance.

$\sqrt{s_{NN}}$ [GeV]	μ_B [MeV]	<Minbias BBC Rate> [Hz]	Days/ Mevent	# events $\times 10^6$	# beam days
4.6	570	3 ($\sim$5)	9 (4.6)	5	45 (23+2)
6.3	470	7 ($\sim$50)	4 (0.5)	5	20 (3+1)
7.6	410	13 ($\sim$150)	2 (0.2)	5	10 (1+1)
8.8	380	20 (300)	1.5 (<1)	5 (>5)	7.5 (1+1)
12	300	54 ($\sim$1000)	0.5 (<1)	5 (>50)	2.5 (1+1)
18	220	>100 (>1000)	0.25 (<1)	5 (>50)	1.5 (1+1)
28	150	>100 (>1000)	0.25 (<1)	5 (>50)	1.5 (1+2)

point signatures require larger data sets, on the order of 10-50M events per energy point. Run time in Table 3 is dominated by run time of the lowest energy; a ten- to twelve-week RHIC run would provide high statistics at all energies of interest. An optimal run plan starts at the highest energies, providing scheduling flexibility if promising signatures are measured at any intermediate energy.

Since the run time is dominated by the run time of the lowest energy, run planning is dominated by uncertainties in the machine performance at the lowest planned energy of $\sqrt{s_{NN}} = 5$ GeV. A test of gold collisions near this energy has been proposed for the 2008 RHIC run to determine luminosity and luminosity lifetime, and to evaluate requirements for potential AGS electron cooling. Injection efficiency of 20–50% and IBS lifetimes of a few minutes are expected, so vernier scans and luminosity measurement will be challenging. Beam synchronous clock issues for harmonic numbers other than 360 should be resolved during the 2007 shutdown and tested with experiment triggers.

RHIC low energy integrated luminosity is primarily constrained by IBS and field quality. Simulations indicate that initial gold beam IBS growth rates at $\sqrt{s_{NN}} = 5$ GeV are 250 and 100 s for transverse and longitudinal emittances, respectively [5]. In these conditions optimal RHIC store lengths are 3–5 minutes. Optimal normalized average luminosity $\langle L\rangle/L_{peak}$ strongly depends on the beam lifetime, ranging from 0.1–0.5 over beam lifetimes of 30–180 s.

Low-energy electron cooling in RHIC would counteract IBS beam loss, improve beam capture, and permit long low-energy stores. Electron cooling upgrades planned for the RHIC high-energy physics program cannot be used here, since electron and ion velocities must match. One possibility is ERL-based cooling, using a prototype half-cell superconducting RF gun delivering bunched 1 nC electrons with kinetic energies $E_k = 0.9 - 2.8$ MeV over a cooling length of 20 m. Another option is to use a DC electron beam, such as that from the Recycler cooler at Fermilab [6]. Preliminary simulations indicate that both systems would provide similar performance, improving peak luminosity by 15–30 and integrated luminosity by up to a factor of 100 [5].

For energies below $\sqrt{s_{NN}} = 9$ GeV in the 2007 test run, the AGS longitudinal emittance is likely too large to fit into the RHIC RF acceptance. At the lowest energy, this can result in immediate debunching of 50–80% of injected beam. One way to counteract this is with an AGS injection energy electron cooler. Simulations indicate that such a cooler could reduce gold beam longitudinal emittance by a factor of 5, improving peak and integrated luminosity by a factor of 5–15. Integrated luminosity would not dramatically improve since store lengths are still dominated by IBS lifetime in RHIC. This cooler requires a cooling section length of 1.5m, solenoidal field of 0.1 T, electron energy of 50 keV, and electron current of 0.5A. These parameters are easily achievable with existing technology and expertise, but IBS and space charge limitations require careful study [5]. Longitudinal dampers are also being considered to reduce longitudinal emittance growth at AGS injection.

6. CONCLUSIONS

RHIC heavy ion collisions at $\sqrt{s_{NN}}$ =5–50 GeV are motivated by a search for the QCD phase transition critical point. Two test runs, with protons in 2006 and gold in 2007, have demonstrated program feasibility at $\sqrt{s_{NN}} = 9.18$ GeV, and gold beam parameters are better than expected. RHIC harmonic number changes present minor problems; most, including experiment clocking problems, will likely be fixed during the 2007 summer shutdown. Projections estimate that a physics program with 10–50M minbias events at each of seven energies, ranging from $\sqrt{s_{NN}} = 4.6$–28 GeV and $\mu_{\rm B} = 150$–570 MeV, is feasible in a 10–12 week RHIC run with no further improvements. This estimate is dominated by uncertainties in the lowest energy performance. Optimal lowest energy store lengths are 3–5 minutes with predicted peak luminosity of 5×10^{22} cm^{-2} s^{-1}. Both RHIC and AGS electron cooling are being studied as possible upgrade paths to improve RHIC low-energy performance.

7. ACKNOWLEGEMENTS

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