PROCEEDINGS OF SCIENCE

RHIC Low-Energy Challenges and Plans

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, V. Schoefer, F. Severino, K. Smith, S. Tepikian, and N. Tsoupas**

Brookhaven National Laboratory

E-mail: satogata@bnl.gov, ahrens@bnl.gov, mbai@bnl.gov, brennan@bnl.gov, bruno@bnl.gov, jbutler@bnl.gov, drees@bnl.gov, fedotov@bnl.gov, wfischer@bnl.gov, pharvey@bnl.gov, hayes@bnl.gov, jappe@bnl.gov, rclee@bnl.gov, waldo@bnl.gov, malitsky@bnl.gov, gmarr@bnl.gov, michnoff@bnl.gov, oerter@bnl.gov, pozdeyev@bnl.gov, roser@bnl.gov, schoefer@bnl.gov, severino@bnl.gov, ksmith@bnl.gov, tepikian@bnl.gov, tsoupas@bnl.gov

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 the search for a possible 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 $\sqrt{s}$=19.6 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 these challenges during beam tests with gold beams in March 2008. This includes first operations at $\sqrt{s}$=9.18 GeV/n, first beam experience at $\sqrt{s}$=5 GeV/n, and luminosity projections for near-term operations.

PACS: 29.20.db, 29.27Eg

5th International Workshop on Critical Point and Onset of Deconfinement - CPOD 2009,
June 08 - 12 2009
Brookhaven National Laboratory, Long Island, New York, USA

[*]Speaker.

[†]Work supported by the US Deparment of Energy under Contract No. DE-AC02-98CH1-886.

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1. 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 range 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 the QCD phase diagram.

Future RHIC operations will explore Au-Au collisions in this energy range at both 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]. 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]. Determination of low energy collision rate scaling with γ is thus important for RHIC low-energy run planning.

A third test of the RHIC low energy program occurred from March 10–12 2008, just after the RHIC 2008 deuteron-gold 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. The STAR experiment acquired the first unambiguous $\sqrt{s}$=9.18 GeV/n Au-Au physics data during this run.

2. 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. At the lowest energy, 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 gold beam longitudinal emittance after AGS injection and RF merge 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

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. γ is the relativistic factor, $B\rho$ is the machine rigidity, $f_{\rm rev}$ is the beam revolution frequency, h is the RHIC RF harmonic number, $\beta^\star$ and $\beta_{\rm max}$ are the minimum and maximum beam envelope functions, and $\sigma^\star_{95\%}$ and $\sigma_{\rm max,95\%}$ are the minimum and maximum 95% beam sizes, which are calculated assuming normalized emittances of $\varepsilon_{\rm N}$(Au)=40$\pi\,\mu$m and $\varepsilon_{\rm N}$(p)=10$\pi\,\mu$m. The peak luminosity $L_{\rm peak}$ assumes γ^3 scaling below nominal injection energy.

Species	$\sqrt{s}$ [GeV/n]	γ	Bρ [T-m]	$f_{\rm rev}$ [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	77.88	360	10	147	2.3	9.5	$4{\cdot}10^{25}$
p (2006)	22.5	11.99	37.4	77.92	360	10	147	1.2	4.9	–
Au (2007–8)	9.18	4.93	37.4	76.57	366	10	147	3.7	14.2	$7.2\cdot10^{23}$
Au (2008)	5.0	2.68	19.3	72.57	387	8	180	4.6	21.9	$1.4\cdot10^{23}$

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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 and longitudinal quadrupole mode pumping in the AGS may improve this efficiency [6].

3. 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 lifetime 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 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. These constraints are detailed in Section 5.

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 $\varepsilon_{N,x,y}$ =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.

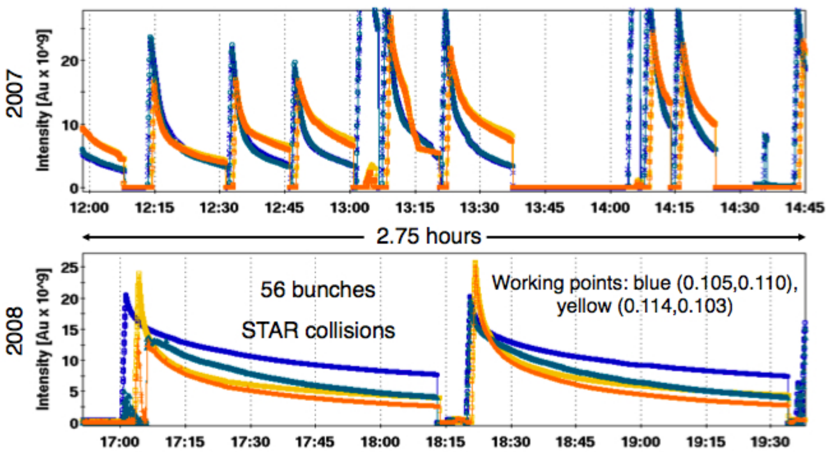

Figure 1: Comparison of 2007 (top) and 2008 (bottom) beam lifetimes at $\sqrt{s}$=9.18 GeV/n. Traces show circulating total and bunched beam intensities in correspondingly-colored RHIC rings. Sextupole reversal and elimination of strong octopoles clearly improved beam lifetime.

The achieved peak luminosity was about $3.5 \times 10^{23}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, while the average luminosity was about $1.2 \times 10^{23}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ with 56 bunches and 0.4-0.5$\times 10^9$ Au/bunch. First physics data was acquired by STAR at this energy. About 5000 good physics events of each type were acquired, and vertex reconstructions showed both beam-beam and beam-beampipe collisions [7]. The ratio of beam-beam to beam-beampipe collisions was about 1:1, consistent with vernier scan data (Fig. 2) but higher than expected. The source of the beam-beampipe background collisions is under investigation.

No collimation was performed during this physics run, as efforts were focused on evaluation of experiment clock triggers and cogging issues. Transverse collimation will be used in future runs, and should significantly improve experiment background issues.

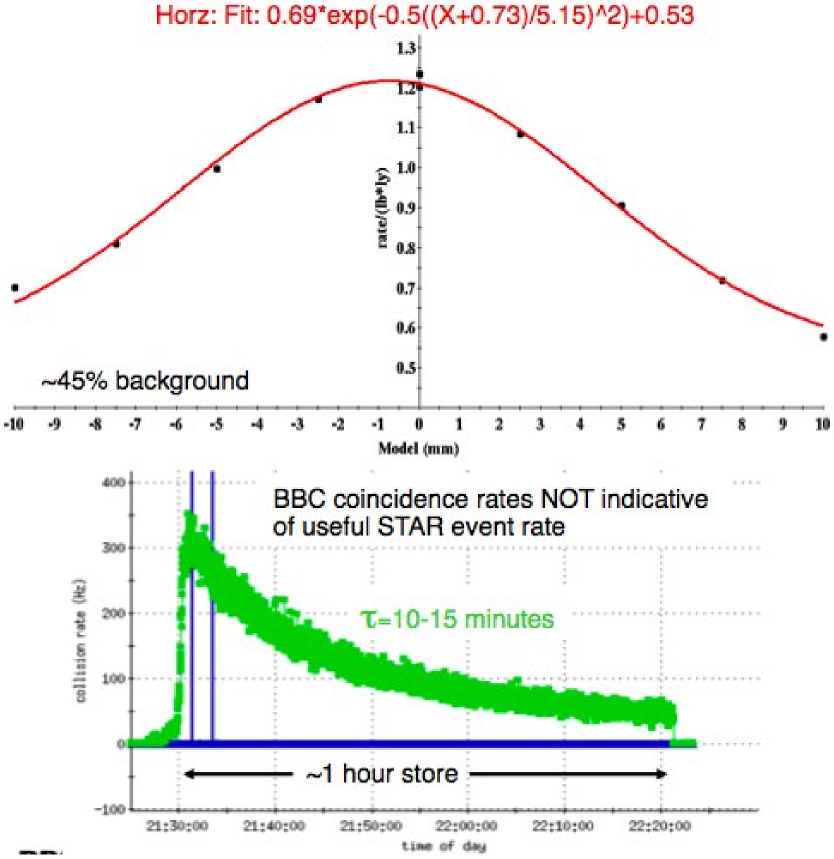

Figure 2: A horizontal vernier scan at the STAR detector during $\sqrt{s}$=9.18 GeV/n operations, and beam-beam counter (BBC) luminosity evolution during a typical store. Collision rate scaling was incorrect in this picture; actual event rates were on the order of 1 Hz.

4. 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 the RHIC yellow ring. The changeover to h=387 worked well, and there were no beam synchronous clock problems during this test. Injection efficiencies were less than 10%; Fig. 3 shows 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 quickly converge and showed amplitude-dependent orbit phase characteristic of a nonlinearity-dominated lattice. This observation 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. Future runs will also permit more careful orbit threading to establish circulating bunched beam.

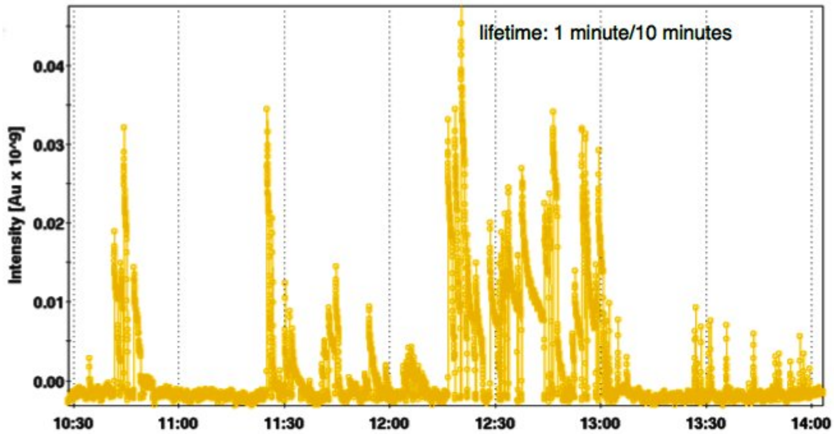

Figure 3: $\sqrt{s} = 5$ GeV/n injection test beam intensity in the RHIC Yellow ring.

5. HARMONIC NUMBER CONSTRAINTS

The RHIC injection and acceleration RF system operates in a frequency range of $f_{rf} = 28.0-28.17$ 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 $f_{rf} = 28.0847$ MHz. A summary of RHIC harmonic numbers and permissible energy ranges based on the RF tuning constraint is given in Table 2. It is particularly important to note that both experiments cannot have optimized collisions in the energy range $\sqrt{s}$ =8.6-18 GeV/n without major changes to DAQ triggers or RHIC RF. STAR and PHENIX experiment trigger clocks further constrain the harmonic number. The experiments currently require trigger 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.

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 only feasible for energies where $h$mod(9)=0 shown in Table 2 [9].

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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	*	*

There are other fill patterns with harmonic numbers not divisible by 9 that distribute low energy collisions between both experiments. However, all of these suboptimally redistribute collisions, do not create conditions where any bunches encounter collisions at both experiments, and do not increase the overall facility delivered luminosity. This operating condition would also require a change to the beam sync clock configurations so PHENIX and STAR would have different clock phases with respect to reference bunch crossings.

6. EXPERIMENT BEAMPIPE UPGRADES

Both RHIC experiments are planning upgrades in the 2011-12 timescale that will lower their beampipe apertures from ID=76mm to ID=40mm. With $\beta^\star$=10m to maximize triplet aperture, these upgraded beampipes become the local aperture limitation and would lead to excessive background for the low energy program [10].

A minor modification to lower $\beta^\star$ to 8m ensures that upgraded beampipes are shadowed by triplet magnet apertures. This is reflected in Table 1 and shown in Fig. 4. The beam size contours in this figure are for gold beam with normalized emittance $\varepsilon_{\mathrm{N}}(\mathrm{Au})=40\pi\,\mu$m at the lowest program energy of $\sqrt{s}$=5 GeV/n. The $3\sigma_{95\%}$ aperture is acceptable for expected short physics stores.

The RHIC abort kickers vertical apertures are 30% smaller than the triplet apertures under normal injection conditions. Losses at these apertures during the 2008 beam test indicate that they dominate low energy injection efficiency. The IR10 and abort region optics will be changed in future runs to optimize the balance between abort kicker and triplet apertures and maximize transverse injection efficiency.

7. PROJECTIONS

Table 3 shows some projections based on 2008 $\sqrt{s}$=9.18 GeV/n experience and expected tuning improvements in future runs. These projections assume a conservative 75% time in physics

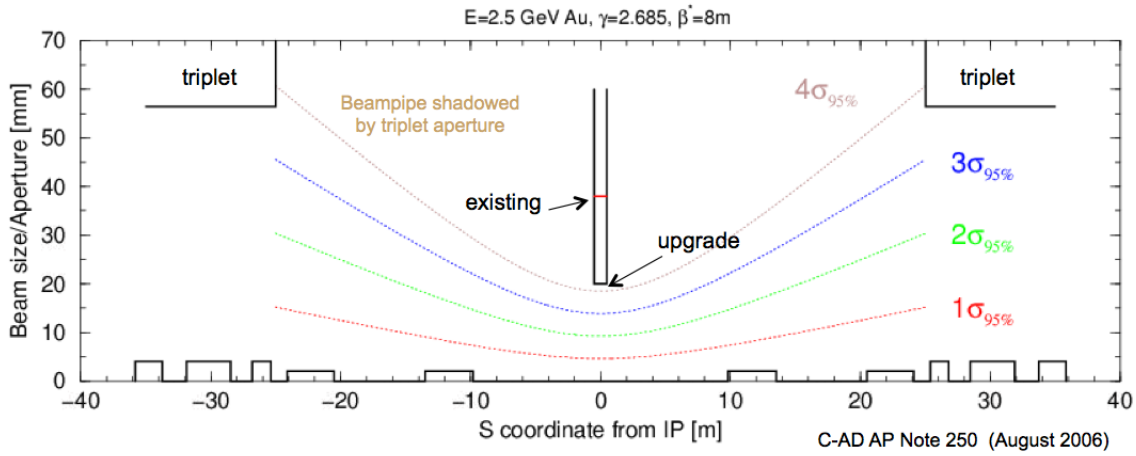

Figure 4: Beam size and aperture limitations in a RHIC IR, showing existing and upgrade beampipe apertures for gold beam with normalized emittance $\varepsilon_N(\mathrm{Au})=40\pi\,\mu$m at the lowest program energy of $\sqrt{s}$=5 GeV/n. Lowering $\beta^\star$ from 10m to 8m will create conditions where beampipe upgrades are shadowed by the triplet quadrupole apertures.

Table 3: Projections for RHIC low energy operations, without facility improvements such as permanent magnets and electron cooling, but including expected tuning improvements. This is based on an initial exploratory energy scan with 5M recorded events at each energy and 75% time in physics.

$\sqrt{s}$ [GeV/n]	μ_B [MeV]	<Event Rate> [Hz]	<Lumi> [cm^{-2} s^{-1}]	Days/ Mevent	# events	# beam days phys+setup
5.0	535	0.55	1.3×10^{23}	28	5M	140+5
6.1	470	1.0	2.4×10^{23}	15	5M	75+4
7.7	405	2.0	4.8×10^{23}	7.6	5M	38+3
8.6	370	3.0	6.9×10^{23}	5.0	5M	26+2
12	295	–	1.8×10^{24}	–	–	–
18	210	>30	6.2×10^{24}	0.5	5M	3+1
28	145	>60	2.5×10^{25}	<<1	5M	1+2(ramp)

and assume γ^3 luminosity scaling below injection. Note that sextupole leads must be swapped when operating below about $\sqrt{s}$=9.3 GeV/n. RHIC operates as a storage ring at all energies below $\sqrt{s}$=19.6 GeV/n. These projections show that a reasonable initial physics program, with reach to $\sqrt{s}$=7.7 GeV/n, can be run in about 10 weeks.

8. 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. More details and projections can be found in [11].

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At the lowest beam rigidities, the usual $\beta^{\star}$=10m optics may be modified with temporary permanent magnets between the DX and D0 dipoles in each IR. This would improve usable luminosity without sacrificing aperture in the triplets. These types of magnets can be installed and removed without breaking vacuum. This type of upgrade is only feasible for the lowest beam energies, but may provide 30% or more luminosity improvement at relatively low cost. This possible modification is currently under study.

We have also considered continuous injection as a way to improve integrated luminosity at the lowest beam energies. Here we continuously reinject beam, replacing the oldest single bunches in RHIC with new fresh bunches while dumping old bunches. Integrated luminosity is improved by a factor of 2–3. This requires development of a single-bunch extraction system and evaluation of experiment backgrounds, dump and collimator heating, and radiation safety issues within RHIC. Initial calculations show that chronic beam losses would be about five times higher than operations without continuous injection, which would require additional radiological controls and collimator work. Abort kicker modifications would also preclude a simple controlled abort of all stored beam in a single machine revolution. We therefore do not plan to operate RHIC with continuous injection.

9. CONCLUSIONS

RHIC heavy ion collisions at $\sqrt{s}$ =5-50 GeV/n are motivated by a search for the QCD phase transition critical point. Several test runs, with protons in 2006 and gold in 2007-8, have demonstrated program feasibility and first physics data at $\sqrt{s} = 9.18$ GeV/n. The RHIC RF system constrains the energy ranges where collisions optimally occur at one or both experiments. Anticipated experiment beampipe upgrades do not pose a significant challenge to machine aperture; we are investigating ways to improve abort kicker injection apertures with new optics. Electron cooling and IR optics upgrades have the potential to significantly improve low energy physics performance. Even without upgrades, projections indicate that a viable first physics program with reach to $\sqrt{s}$=7.7 GeV/n can run in about 10 weeks of machine time.

10. ACKNOWLEGEMENTS

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

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