RHIC STATUS

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Abstract

The design and construction status of the Relativistic Heavy Ion Collider, RHIC, which is in the seventh year of a nine year construction cycle, is discussed. Those novel performance features of a heavy ion collider that are distinct from hadron colliders in general are noted. These features are derived from the experimental requirements of operation with a variety of ion species over a wide energy range, including collisions between protons and ions, and between ions of unequal energies. Section 1 gives a brief introduction to the major parameters and overall layout of RHIC. A review of the superconducting magnet program is given in Section 2. Activities during the recent Sextant Test are briefly reviewed in Section 3. Finally, Section 4 presents the plans for RHIC commissioning in 1999.

1 INTRODUCTION

The primary motivation for colliding heavy ions at ultra-relativistic energies is the belief that it is possible to create macroscopic volumes of nuclear matter at such extreme conditions of temperature and energy density that a phase transition will occur from hadronic matter to a confined plasma of quarks and gluons. RHIC will provide head-on collisions at energies up to 100 GeV/u per beam for very heavy ions, nominally gold ($^{197}Au^{79+}$). The experimental program also calls for lighter ions all the way down to protons, including polarized protons. Luminosity requirements for the heaviest ions are in the 10^{26} - 10^{27} cm^{-2}s^{-1} range. Although these luminosities are several orders of magnitude lower than p-p colliders, the higher Au-Au total cross-section results in comparable interaction rates.

The most influential experimental requirement is the need for collisions of different ion species (most notably p-Au) at identical Lorentz γ's. This necessitates accommodating mass-to-charge ratios (A/Z) in the range from 1 (p) to 2.5 (Au). Stabilizing the collision point location involves equalizing the rotation frequencies of the two beams, which requires the two rings to operate at different magnetic fields. The need for such beams to pass through common magnets in the interaction region (IR) dictates a lattice design different from conventional hadron colliders. Beams with large transverse and longitudinal sizes are a natural consequence of collider operations at relatively low energies, with enhanced intra beam scattering (IBS), which scales as Z^4/A^2. This in turn has ramifications for the lattice (strong focusing short cells of 29.6 m length) and for the magnet aperture (80 mm in the arcs). The RF system requirements are also determined by these considerations, and by the desire for a short interaction diamond length (< 0.2 m rms), for optimum detector design. Colliders, unlike fixed target machines, are designed to operate for extended periods at high energies. The economics of power consumption argue strongly for superconducting magnets. RHIC is such a superconducting machine.

Kinetic energy range, Au	10.8-100	GeV/u
Kinetic energy range, p	28.3-250	GeV
Number of bunches per ring	60	
Circumference	3833.845	m
Number of crossing points	6	
β^*, injection, H/V	10	m
β^*, low-β insertion, H/V	2	m
Betatron tunes, H/V	28.19/29.18	
Transition energy, γ_T	22.89	
Magnetic rigidity, injection	97.5	Tm
Magnetic rigidity, top energy	839.5	Tm
Bending radius, arc dipole	242.781	m
Maximum arc dipole field	3.45	T
Maximum arc quad gradient	71.2	T/m
Arc magnet coil ID	80	mm
Triplet magnet coil ID	130	mm

Table 1: Major Parameters for the Collider.

The RHIC machine parameters outlined in Table 1 are derived from these general requirements. The complete RHIC facility, including its existing injector complex, is shown schematically in Fig. 1. The internal collider layout is shown schematically in Fig. 2.

1.1 Layout

RHIC consists of two identical, quasi-circular rings separated horizontally by 0.90 m, and oriented to intersect one another at six locations. Each ring consists of three inner and three outer arcs, separated by six insertion regions. Each arc consists of 11 FODO cells, with each half cell consisting of a single dipole and a CQS assembly containing a quadrupole, sextupole, and concentric correction elements. Beam collisions occur at a crossing point in each IR. These IRs contain the optics necessary for producing small collision betatron functions β^* and a zero dispersion at the crossing point, in addition to bending the beams into head-on collisions. The focusing is relaxed at injection with $\beta^* = 10$ m, but during collisions at top energy it is

* Operated by Associated Universities Incorporated, under contract with the U.S. Department of Energy.

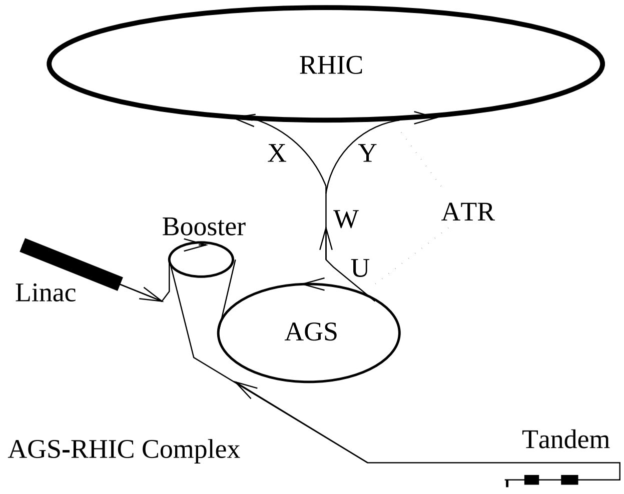

Figure 1: Schematic layout of the AGS-RHIC complex.

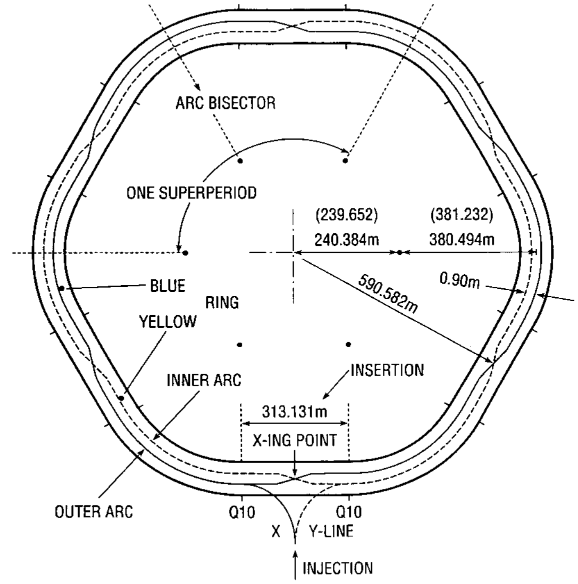

Figure 2: Layout of the collider and the tunnel.

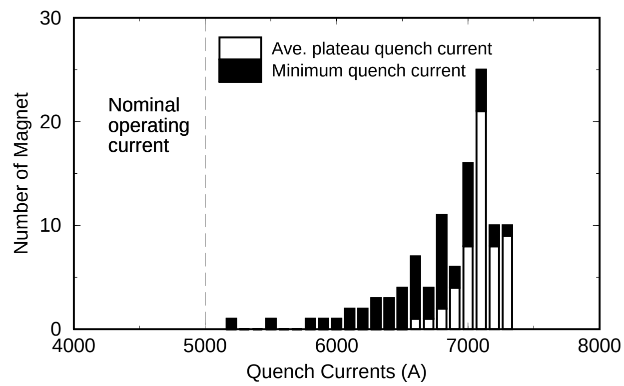

Figure 3: Arc dipole quench current distribution.

squeezed down to a value of 2 m, resulting in a maximum β of about 700 m in the triplet quadrupoles. The warm parts of each IR contain machine utilities such as injection, beam abort, RF stations, collimators, and specialized instrumentation.

2 MAGNETS

RHIC magnets are conceptually similar to the HERA dipoles, with a "cold-iron" design and cryogenic transfer lines located in the cryostat. The arc dipoles and quadrupoles have a coil inner diameter (i.d.) of 80 mm, and a nominal maximum field and gradient of 3.45 T and 72 T/m, respectively. Interaction region triplet quads have a coil i.d. of 130 mm, with a maximum focusing strength of about 48 T/m. Beam splitting dipoles D0 and DX have apertures of 100 mm and 180 mm, respectively. The industrial production of 80 mm arc magnets was completed in a two year period from 1994 to 1996, and the BNL assembly of CQS cryogenic modules has just been completed. Arc dipoles were produced by the Northrop-Grumman Corporation in a build-to-print contract, as complete cryogenic elements ready for immediate installation.

Field quality and quench threshold are both crucial aspects of superconducting magnet performance. The limited cold testing of only 20% of the magnets is justified by a healthy 30% quench current operating margin. Arc dipole statistics on minimum and plateau quench currents for a set of 60 magnets are shown in Fig. 3. None of the magnets tested to date have had an initial quench current less than the nominal operating level. Limited cold testing is also justified by the good correlation between warm and cold magnetic field quality measurements, confirmed by a careful analysis of the complete data set. All of the smaller number of IR magnets (which have a smaller quench margin) will be cold tested in a vertical dewar.

The distribution of field harmonics for the full set of dipole magnets, shown in Fig. 4, demonstrates excellent field quality with very small random multipole field components, by virtue of tight mechanical tolerances on the cable dimensions. The systematic component of the field harmonics is optimized for low-field performance at injection with yoke saturation apparent in the allowed harmonics at high field.

The dynamic aperture is determined by the triplet quadrupoles during collisions. For example, a maximum β of 1400 m would occur in the triplet under an upgrade scenario with $\beta^* = 1$ m. Under these conditions, the 5σ beam size is expected to increase from 35% to about 70% of the triplet magnet coil radius, due to strong IBS growth. Multiple sophisticated compensation techniques are used to optimize the field quality in triplet quadrupoles, including individual error correction with tuning shims, body-end harmonic compensation, magnet sorting, and lumped triplet multi-layer corrector packages. Especially tight alignment accuracies are required on these magnets [28]. Tuning shims are inserted into the eight empty slots of the IR

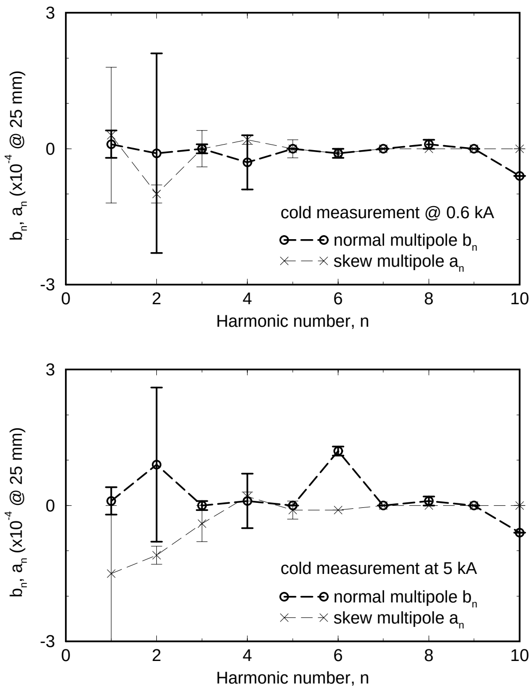

Figure 4: Arc dipole magnetic field multipole harmonics at injection (0.6 kA) and storage (5 kA) currents.

quadrupole body, as shown in Fig. 5, after the magnet is constructed and individually warm measured, in order to correct eight leading field harmonics. Recent experiments indicate that these multipole errors can be reduced to about 10% rms of their uncorrected values. The expected values for the mean and its uncertainty often become zero, while the final standard deviation is associated with a roll up of measurement errors, thermal cycling fluctuations, and quench fluctuations.

Continued production and assembly of IR magnets - correctors, triplet quadrupoles, and DX beam splitting dipoles - are the major items remaining on the RHIC magnet front. The first of the technically challenging DX beam splitting dipoles, with a field of 4.26 Tesla, is expected to finish construction in about October 1997. Prototype helical dipoles are being built at BNL and in industry, for use in Siberian snakes and spin rotators during polarized proton operations [2, 3, 4, 5, 6].

3 SEXTANT TEST

The Sextant Test was a full systems and beam test which occured from December 1996 through February 1997. Gold beam from the AGS was successfully passed through a single sextant in its final configuration, including injection kickers, RF cavities, et cetera. The only items missing were the DX beam splitting dipoles.

The BEAM test goals were to:
- transport beam through one cryogenic sextant to a dump

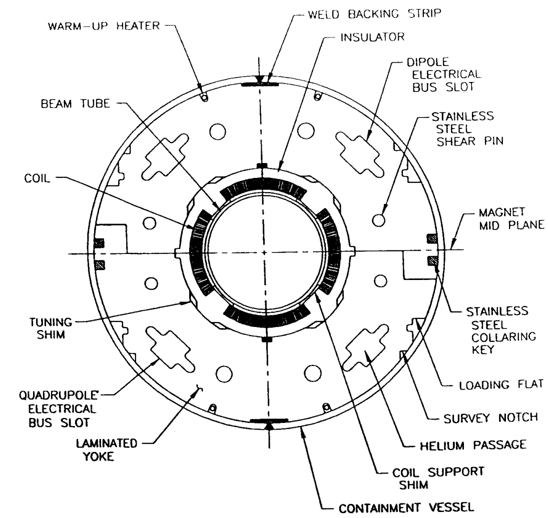

Figure 5: Triplet quadrupole cross-section showing empty slots for tuning shims.

- measure optical and dispersion functions
- study injection and establish nominal conditions
- commission beam diagnostic systems
- commission the low level RF controls
- perform radiation fault studies

The major SYSTEM test goals were to:
- verify cryogenic system performance
- verify the quench protection system
- test power supply ramping and storage
- observe mechanical motion during thermal cycles
- test the vacuum system performance

Beam operating conditions from the 1995 AtR Test were rapidly restored in late January, as beam was delivered 400 meters to the end of the straight part of the normal conducting AGS-to-RHIC (AtR) transfer line. Next, beam was maneuvered around a 90 degree bend, about 150 meters long, before encountering the Lambertson magnet. After the beam was steered through the Lambertson magnet and the injection kicker, gold ions immediately went through 400 meters of superconducting magnets, to a beam dump at the end of the sextant [7, 8, 9, 10].

Accelerator system tests continued after the end of the AGS gold run [11, 12, 13, 14]. During this time the sextant magnets were repeatedly ramped to 5,500 Amps, 10% beyond their nominal storage current, at a ramp rate 10% higher than nominal. This was the first time that many of the magnets had seen full current, since only approximately 20% of the industrially built magnets were cold tested. Tests and measurements of the vacuum, cryogenic, and quench protection systems were also performed. Finally, the magnets were taken through an additional complete thermal cycle.

With only minor caveats in some areas, the Sextant Test was a great success. Since there are several other papers in these proceedings discussing RHIC Sextant Test performance results, only a brief summary is presented here.

3.1 Test results

The Integral Transfer Function (ITF) of the arc dipoles, measured with beam, differed from the test stand measurements by only about 0.2%. Multiple measurements of the phase advance per FODO cell were made with different QF and QD current settings, with the results shown in Fig. 6. The beam-based arc quadrupole ITF, derived from these data, agrees with magnet test bench measurements within the 0.6% accuracy of the beam measurements. The optimum excitation level of the injection kicker was measured as 32.3 kV, very close to its design value [15, 16, 17].

Various RHIC instrumentation systems have been fully commissioned, from hardware through to high level application codes, in single pass injection line mode [18, 19, 20, 21]. These include beam position monitors, beam loss monitors, current transformers, and flag profile monitors. The prototype of an innovative ionization profile monitor, which collects electrons instead of positive ions, was also successfully tested [22]. Electron collection is made practical by applying parallel electric and magnetic fields.

Tomographical algorithms were used to reconstruct the distribution of beam in an RF bucket, starting from a set of wall current monitor profiles recorded over half a synchrotron period. This application software, currently used to observe beam coalescence in the AGS, will be deployed in RHIC in due course [23].

High power testing of some of the 200 Mhz (storage) cavities was performed, under vacuum [24]. Although one complete 28 MHz (acceleration) cavity has been assembled, it has not yet been high power tested. The digital low level RF system that controls the transfer of single bunches from the AGS into arbitrarily defined bunches in RHIC was also successfully commissioned.

4 COMMISSIONING AND THE YEAR ONE RUN

Full beam commissioning is scheduled to begin in January 1999 in a "Test" run that will begin as soon as full cool down has been completed, and the final beam pipe has been installed. First circulating beam is expected in this run. A spring shutdown for final collider installation of collimators [28] et cetera, and for detector roll-in will, be followed by a "Commissioning" run. First collisions and RHIC project completion are nominally expected to occur about half way through this run. Production running for the experiments, with gold ions, is scheduled to begin in fall 1999, and will last 37 weeks. Spin physics with polarized protons may start in 2000 [25, 26, 27].

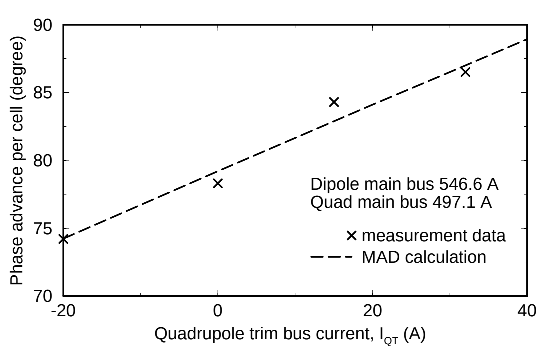

Figure 6: The horizontal phase advance per cell.

Goals for the end of the "Year One" production run include 50% uptime, a store set up time of less than 2 hours, and a luminosity of 10% of the design. This will require aggressive development of the luminosity parameters listed in Table 2, in particular the number of bunches and β^*, even with the more than satisfactory values of emittance and single bunch intensity that were measured in 1997. Based on Sextant Test experience, there is good reason to believe that it will be relatively easy to achieve design gold bunch intensities.

Approximately 40% of the bunch intensity is lost during the nominal gold storage time of 10 hours, mostly through IBS, but also with a significant contribution from Coulomb interactions. The cross sections for gold on gold at 100 GeV/u include:

$\sigma = 117$ barns for electron pair production and capture

$\sigma = 95$ barns for Coulomb nuclear dissociation

For example, if 2 experiments experience an instantaneous luminosity of $L = 8 \times 10^{26}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, the partial current lifetime due to nuclear interactions is approximately 49 hours. Figure 7 shows the expected "shot profile" performance for the beam parameters quoted in Table 2, using a beam dynamics model which, in addition to the above effects, includes emittance blow up due to IBS and beam losses to the dynamic aperture [29]. Emittance growth and beam loss lead to a factor of 8 loss in instantaneous luminosity during a nominal 10 hour store of gold ions.

	Gold 1997	Gold start	Gold end	Proton
No. of bunches		60	60	60
Bunch int., 10^9	.4	1.0	$\sim .6$	100.0
Lorentz gamma	12.1	108.4	108.4	268.2
Emittance, $\pi\mu$m	9.9	15.0	40.0	20.0
β^*, m		2.0	2.0	2.0
Lum., $\mathrm{cm}^{-2}\mathrm{s}^{-1}$		$8\ 10^{26}$	$1\ 10^{26}$	$1.5\ 10^{31}$

Table 2: Luminosity parameters in the Sextant Test, at the start and end of a 10 hour gold store, and in a proton store.

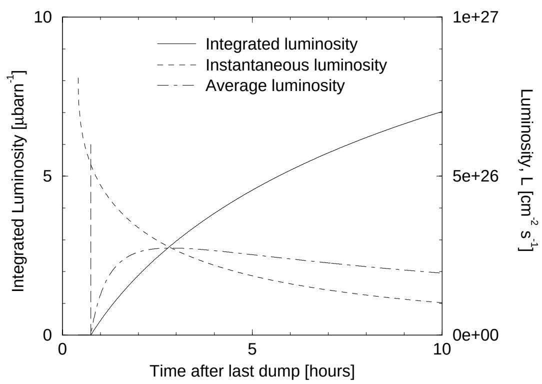

Figure 7: Integrated, instantaneous, and average luminosities during a nominal store of gold ions.

5 CONCLUSIONS

RHIC has two years of its nine year construction cycle to go before heavy ion operations begin in 1999. Industrial production of superconducting magnets has been completed, while in house production of specialized magnets continues. The major milestone of the Sextant Test was recently passed, successfully commissioning many of the beam and non-beam systems. Intra Beam Scattering is expected to be a dominant physical phenomenon limiting the ultimate performance of RHIC, with heavy ions. Polarized proton operations are scheduled to begin in 2000.

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