# The RHIC Project*

M.A. Harrison
Brookhaven National Laboratory
Upton, NY 11973, USA

*Abstract*

The design of the first Relativistic Heavy Ion Collider, RHIC, is discussed. Particular attention is paid to those novel features of a heavy ion collider that are distinct from hadron colliders in general. These features are derived from the experimental requirements of operation with a variety of ion species over a wide energy range including collisions between ions of unequal energies.

## 1. INTRODUCTION

The overriding 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. At present the heavy ion fixed target programs at the AGS at BNL, and the SPS at CERN have not seen unambiguous evidence of this effect.

The performance objectives of a heavy ion collider were originally formulated in 1983 by a *Task Force for Relativistic Heavy Ion Physics* [1]. The main goal is collisions at energies up to 100 GeV/u per beam for very heavy ions, which for the RHIC project is defined to be gold ($^{197}Au^{79}$), but the program outlined also called for lighter ions all the way down to protons. Luminosity requirements for the heaviest ions were specified to be in the $10^{26-27}$ $cm^{-2}$ $s^{-1}$ range. The higher Au-Au total cross-section results in interaction rates comparable to p-p colliders although this luminosity is several orders of magnitude lower than those machines. A short interaction point length (< 20 cm rms) is desirable for optimum detector design. The final, though most influential, experiment requirerhent was the need for collisions of different ion species (most notably p-Au) at the same center of mass energies per nucleon. This necessitates accommodating charge to mass ratios (A/Z) in the range of 1 (p) to ~2.6 (Au). Stabilizing the collision point involves equalizing the rotation frequencies of the two beams which in turn requires the two rings to operate at different magnetic fields. The complications in the interaction region where the beams must pass through common magnets dictate a lattice design different from conventional hadron colliders.

Based on these general requirements the detailed RHIC machine parameters were derived and are outlined in Table 1. The difficulties associated with the production of the dense beams needed for RHIC are the subject of the previous talk [2] and will not be discussed further. Operation of the RHIC collider at relatively low energies together with the enhanced intrabeam scattering, which scales as $Z^4/A^2$, result in beam of large transverse and longitudinal dimensions. This in turn has ramifications for the lattice (short cells, strong focusing), and magnet aperture. The rf system requirements are also determined by this consideration and the short interaction point. 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 and RHIC is a superconducting machine.

Table 1
Major Parameters for the Collider

| | | |
|---|---|---|
| Kinetic Ener., Inj.-Top (each beam), Au | 10.8-100 | GeV/u |
| protons | 28.3-250 | GeV |
| No. of bunches/ring | 57 | |
| Circumference, 4-3/4 $C_{AGS}$ | 3833.845 | m |
| Beam separation in arcs | 90 | cm |
| Number of crossing points | 6 | |
| Free space at crossing points | ±9 | m |
| Beta @ crossing, horizontal/vertical | 10 | m |
| low-beta insertion | 1 | m |
| Betatron tune, horizontal/vertical | 28.18, 29.18 | |
| Transition Energy, $\gamma_T$ | 23.60 | |
| Magnetic Rigidity, $B\rho$: @ injection | 97.5 | T·m |
| @ top energy | 839.5 | T·m |
| Bending radius, arc dipole | 242.781 | m |
| No. of dipoles (192/ring+12 common) | 396 | |
| No. quadrupoles (276arc+216insertion) | 492 | |
| Dipole field @ 100 GeV/u, Au | 3.45 | T |
| Arc dipole length, effective | 9.45 | m |
| Arc dipole length, physical | 9.728 | m |
| Dipole current | ~5 | kA |
| Arc quadrupole gradient | 71.2 | T/m |
| Arc quadrupole length, effective | 1.11 | m |
| Coil i.d. arc magnets | 8 | cm |
| Beam tube i.d. | 6.9 | cm |
| Operating temperature, Helium refrigerant | <4.6 | K |
| Refrigeration capacity @ 4 K | 24.8 | kW |
| Vacuum, warm beam tube sections | $5 \times 10^{-10}$ | Torr |
| Beam stored energy | ~200 | kJ |
| rf voltage, $h$=342 | 600 | kV |
| rf voltage, $h$=2508 | 6 | MV |
| Acceleration time | 1 | min |

## 2. MACHINE LAYOUT AND LATTICE

The complete RHIC facility will be a complex set of accelerators interconnected by beam transfer lines. The RHIC rings are shown schematically in figure 1. The collider is located in the existing ~3.8 km tunnel north of the AGS. It is comprised of two identical, quasi circular rings separated horizontally by 90 cm, and oriented to intersect

*Work performed under the auspices of the U.S. Department of Energy.

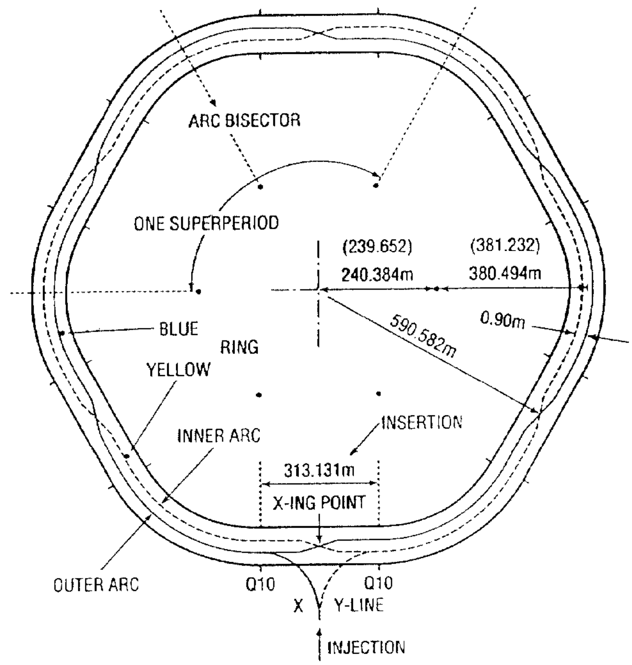


Figure 1. Layout of the collider and in parenthesis of the tunnel.

with one another at six locations. Having 3-fold symmetry each ring consists of three inner and three outer arcs and six insertion regions joining the inner and outer arcs. Each arc consists of 11 FODO cells with each half cell consisting of a single dipole together with a spool piece assembly containing a quadrupole, sextupole and concentric correction elements. The nominal design magnetic rigidity of the dipoles is 840 T·m which corresponds to a design field of ~ 3.5 T at 100 GeV/u. Injection takes place at 100 T·m. The lattice functions of the standard cell are shown in figure 2. The half-cells are ~ 15m long and have beta-functions in the

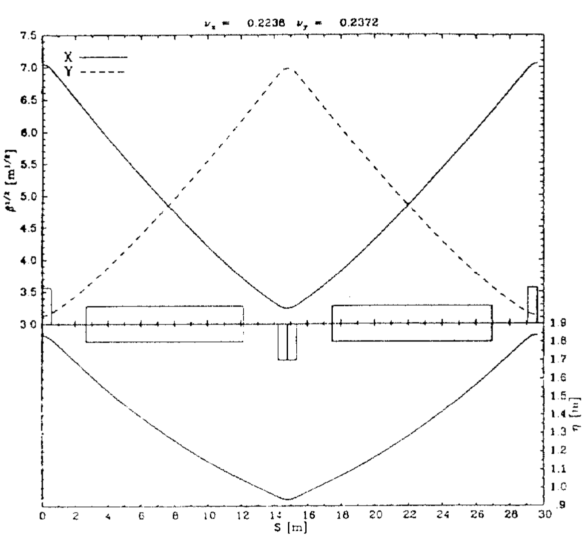


Figure 2. Lattice functions of RHIC regular arc cell.

range 10.5 -> 50 m with a dispersion maximum of 1.8 m. These relatively small values are dictated by the need to minimize the physical size of a beam (i.e. maximize dynamic aperture and thus intensity lifetime) with relatively large normalized emittances (40π mm-mrad 95%, 1.2 eV-s/u). The dipole coil i.d. of 8 cm is determined by the beam size at injection and also the projected emittance growth which occurs during a store at the lowest collision energy of 30 GeV/u. The quadrupoles run at a maximum gradient of 72 T·m and also have a coil i.d. of 8 cm. A cross-section of a dipole is shown in figure 3. The magnets are conceptually similar to the HERA dipoles with a 'cold-iron' design and cryogenic transfer lines located in the cryostat. Each dipole is ~ 10m long.

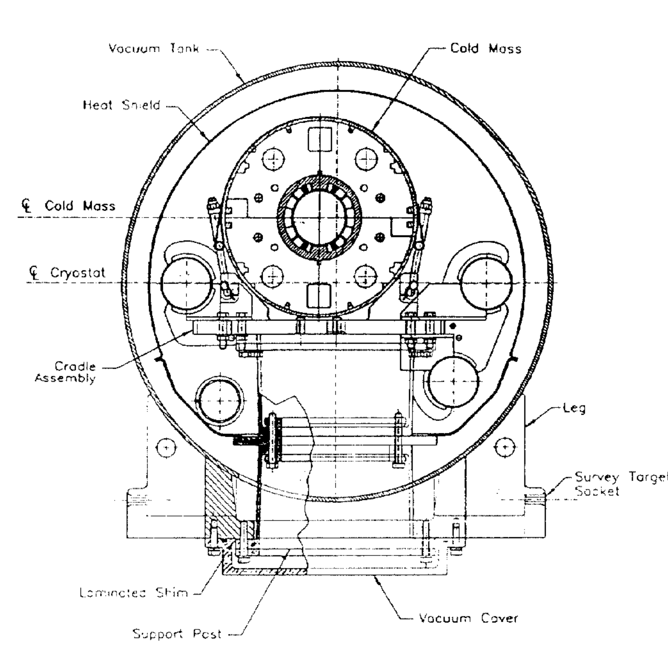


Figure 3. Arc dipole with cryostat cross section.

Collisions of the beams take place at the crossing point of the insertions. These regions contain the optics necessary for producing a small betatron amplitude function $\beta^*$, zero dispersion at the crossing point, and the bending magnets to bring the beams into head-on collisions. The 'non-arc' regions also contain the only warm regions of the machine where the machine utilities reside such as injection, beam abort, rf, collimators and specialized instrumentation. Locations available for these other devices are the 35m between Q3 and Q4, the missing dipole between Q7 and Q8, and the region adjacent to the short D9 dipole. The layout of an insertion, connecting the standard cells to the interaction point, is shown in figure 4. The magnetic elements in the Q10 -> Q4 region are identical in cross-section to the standard cell but with various lengths. The final focus triplet (Q1, Q2, & Q3 ), and bending magnets (D0 & DX) are non

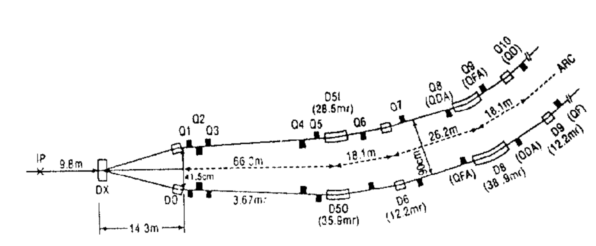

Figure 4. Expanded layout of RHIC half insertion.

standard magnets with apertures of 13cm, 10cm and 18cm respectively. The focusing is relaxed at injection with a $\beta^*$ value of 10 m. During collisions at top energy a $\beta^*$ of 1 m can be attained resulting a betamax of ~1400m in the triplet quadrupoles. The maximum focusing is determined by both the physical beam size in the triplet and the strength of the trim quadrupoles at Q4, Q5 and Q6. At lower energies focusing is determined by dynamic aperture considerations and lies within these two extremes. The lattice functions in the IR's are shown in figure 5. In other hadron colliders the maximum focusing is accomplished by first bringing the

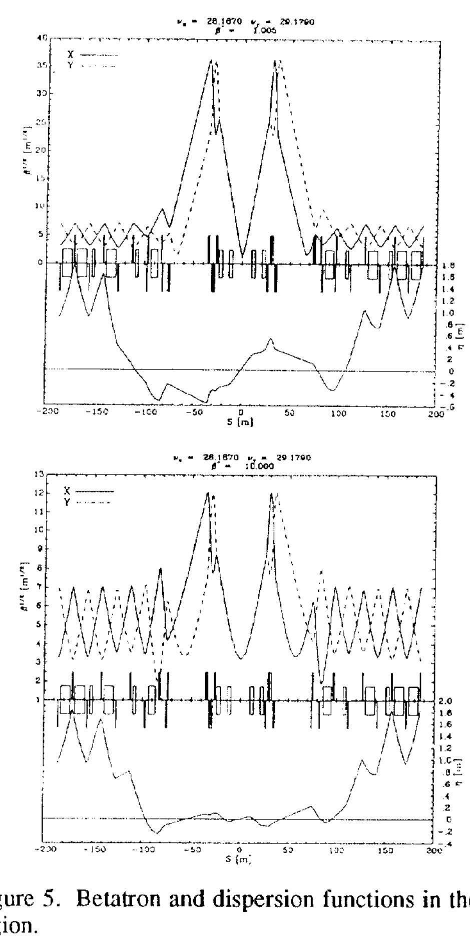

Figure 5. Betatron and dispersion functions in the insertion region.

beams together in a common vacuum chamber and focusing with a common triplet as close to the interaction point as possible to minimize the maximum beta functions. This standard technique cannot be used at RHIC which must accommodate particles of different species; the most extreme being p - Au collisions. Inverting the normal IR design results in a triplet separated by ~50m with only 18m available to the experiment. Each insertion is independently adjustable and can be matched over a machine tune range of ± 1 unit. The phase advance across the insertion is almost (but not completely) constant during the squeeze, as is the triplet excitation.

## 3. OPERATING CYCLE

The following cycle outlined below involves Au ions. Different ions species follow similar scenarios. The AGS accelerates three bunches at the nominal design intensity of $10^9$ ions per bunch to a top energy of 10.8 GeV/u. The bunches are transferred one at a time into individual RHIC 26 MHz accelerating system rf buckets. The bunches are matched to the RHIC buckets with a bunch rotation in the AGS 1/4 of a synchrotron period before transfer to alleviate the need for a very low RHIC matching rf voltage. The bunches are stacked in successive RHIC rf buckets giving a bunch separation of 67 m or 220 ns. The bunches are transferred at ~30 ms intervals and then the AGS recycles. A total of 19 such cycles is needed to fill each RHIC ring for a ~60 s filling time. Beam is transferred alternately to each ring on successive AGS cycles to equalize the dwell time. Space charge tune shifts at injection are a factor for the heavier ions and are estimated to result in a tune spread of ~0.023 for the gold bunches. While this value should not adversely affect operation some care will be necessary to avoid lower order resonances.

The beam is then accelerated at a rate of ~ 70 A/s which results in ~ 60s to flattop at maximum energy. All ions except protons will pass through transition energy at 23 GeV/u. In order to avoid bunch dilution and subsequent beam loss into the superconducting magnets a linear gamma-t jump is used to minimize the crossing time. The jump is executed by a series of pulsed quadrupoles and results in a dispersion wave through the insertion regions which is very nearly matched to the arc section. The residual betatron/dispersion wave around the arcs is less than a 15% mismatch and was designed to keep the physical beam size less than that expected at injection to avoid physical apertures and hence potential beam loss problems. The bipolar jump system nominally moves gamma-t in the range of ± 0.4 units but is capable of twice this value.

After reaching the collision energy the beam is transferred to the 196 MHz storage rf system. This transfer is accomplished by jumping the phase of the 26 MHz bucket by $\pi/2$ and allowing the beam to become unstable for a short period of time. The phase is then readjusted to the stable position and the bunch executes a $3\pi/4$ rotation in the bucket and is then captured in a quasi-matched fashion into the higher frequency bucket. In order to avoid beam losses in a high excitation regime of the magnets when they are most susceptible to beam induced quenching is it necessary limit the bunch area to < 0.5 eV-s/u. After this rebucketing process the beams are brought into collision and collision point $\beta^*$ is reduced to maximize the luminosity. It is anticipated that ultimately this refilling process will take less than 10 minutes with a total elapsed time between stores of ~ 30 minutes.

The maximum stored beam energy is ~ 200kJ per ring, small enough to be aborted onto an internal beam dump located on the 'away-side' of the interaction point in the warm 40m region between the Q3 and Q4 magnets. Beam will be ejected in a single turn when required by a kicker magnet system with a $1\mu s$ rise time which necessitates a missing 4 bunch gap for this purpose. Ions produce an energy deposition profile which is dominated by Coulomb losses resulting in very high initial energy densities on the first several cm of the dump. Beam sweeping across the dump face is necessary even at these relatively modest beam currents.

## 4. COLLIDER PERFORMANCE AND LUMINOSITY LIFETIME

The nominal RHIC bunch parameters range from Au ($10^9$ ppb, $10\pi$ mm-mrad) to protons ($10^{11}$ ppb, $20\pi$ mm-mrad) which together with 57 bunches in each ring and a $\beta^*$ of 2m result in initial luminosities for various ion species as shown in figure 6. The initial luminosity increases with the lighter ion species since the ion source maintains the electric current ($N_bZ$) per bunch roughly constant. In contrast to hadron colliders the beam-beam tune shift is relatively small (~ 0.012 maximum) and does not limit the performance.

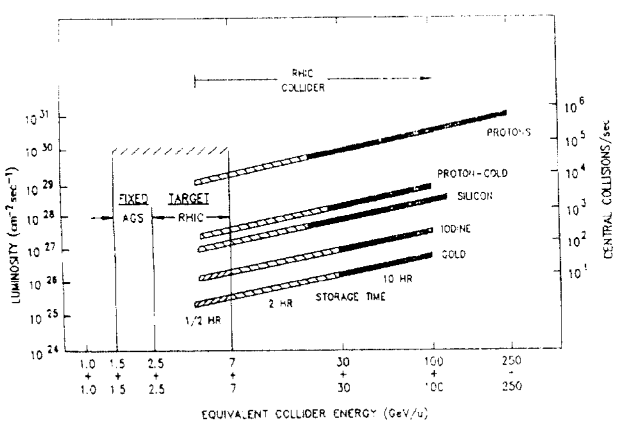


Figure 6. The initial luminosity, for various ion species, as a function of collision energy over the full range accessible with RHIC.

Limitations on the average luminosity arise from several effects. As previously mentioned intrabeam scattering growth rates scale as $Z^4/A^2$ which results in growth times for Au ions an order of magnitude larger than those for protons even though the bunch intensity is two orders of magnitude lower. This effect has been extensively studied in the RHIC scenario [3,4] and the calculations show some quite dramatic effects. Figure 7 shows the estimated emittance growth as a function of time during a store. The beam expands to fill the available bucket area during the first two hours and then beam starts to fall out of the bucket. During the nominal 10 hour store, ~40% of the circulating beam is estimated to be lost due to this effect. In addition, transverse emittance growth will also occur with an increase from 10 -> $40\pi$ mm-mrad expected. The initial luminosity lifetime is thus relatively short, 0.9 hr, rising to 11.1 hr by the end of 10 hours. Significant beam losses are also expected to provide enhanced background rates for the detectors which will require the protection of remote collimation devices. The large transverse emittances also have dynamic aperture implications in the triplet quadrupoles and have been used to define the desired field quality specifications in these elements.

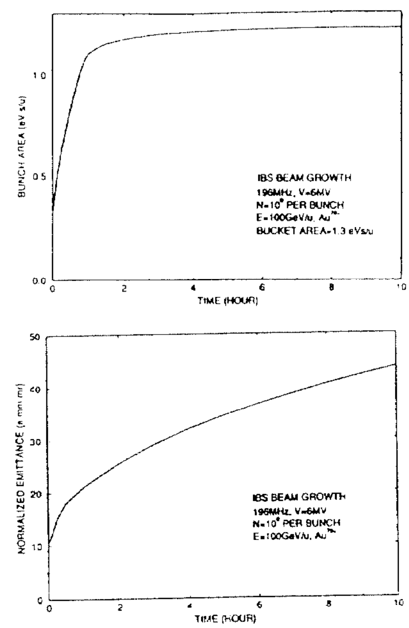


Figure 7. Longitudinal and transverse emittance growth from IBS v's time in the store.

In addition to IBS, significant beam depletion is also expected from the interactions at the crossing point from electro-magnetic interactions. The Lorentz contracted Coulomb field of the Au ions is sufficiently intense to produce large numbers of electron pairs (estimated cross-section 33,000 barns!) as the bunches pass through each other. These are relatively low energy electrons (a few 10's of KeV kinetic) so the pair production itself does not adversely affect the beam. Within this electron cloud however, an ion can capture an electron and change it's charge state by one. These particles will then be lost during the next several turns. Coulomb dissociation is also significant with the ions breaking up into several lighter fragments. Particle depletion cross sections from these effects (and the much smaller rate of nuclear interactions) have been estimated [5] to be ~250 barns per high luminosity

IR. The reduction in integrated luminosity during 10 hours arising from particle depletion is ~ 15% but becomes more significant for higher luminosity upgrade scenarios.

Compared to proton colliders the beam-gas cross section for Au ions is large (7 barns) which results in a stringent specification on the ring wide average beam tube vacuum in the warm regions of the machine of $5 \times 10^{-10}$ torr.

## 5. CONCLUSIONS

RHIC is the first facility where attributes of heavy ion operation have specifically influenced the design of the machine and operating philosophy in many areas. The more obvious ones have been outlined above. Operational flexibility to accommodate a diverse experimental program will be paramount. Future options involving high luminosity proton operation for b-physics and collisions involving polarized protons are also being actively pursued and require different scenarios and involve different issues again. The future promises to be interesting.

## 6. REFERENCES


[1] T. Ludlam and A. Schwarzchild, Nuc. Phys. A418, 657c (1984).

[2] T. Roser, "AGS Heavy Ion Operation with the New Booster", these proceedings.

[3] J. Wei, Proceedings of the XVth International Conference on High Energy Accelerators, Hamburg, 1992, p. 1028.

[4] J. Wei and A.G. Ruggiero, Proceedings of 1991 Particle Accelerator Conference, San Francisco, 1991, p. 1869.

[5] A.J. Baltz, M.J. Rhoades-Brown and J. Weneser, "Convergence of bound-electron-positron pair production calculations for relativistic heavy ion collisions", BNL Report 60532, June 1994.