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THE RELATIVISTIC HEAVY ION COLLIDER AT BROOKHAVEN*

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Abstract The conceptual design of a collider capable of accelerating and colliding heavy ions and to be constructed in the existing 3.8 km tunnel at Brookhaven has been developed. The collider has been designed to provide collisions of gold ions at six intersection points with a luminosity of about 2×10^{26} cm^{-2}sec^{-1} at an energy per nucleon of 100 GeV in each beam. Collisions with different ion species, including protons, will be possible. The salient design features and the reasons for major design choices of the proposed machine are discussed in this paper.

INTRODUCTION

The experimental program at the Brookhaven Alternating Gradient Synchrotron has been expanded, starting in 1986, to include the acceleration of light ions, oxygen and silicon, to kinetic energies of 13.6 GeV/u.[1,2] The completion of the AGS Synchrotron Booster, expected in 1991, will add the capability of accelerating heavy ions with atomic masses up to $A \approx 200$, e.g. gold and possibly uranium.[3] The logical next step in Brookhaven's heavy–ion program is the construction of the Relativistic Heavy Ion Collider. RHIC would be a dedicated heavy–ion machine capable of colliding gold beams at 100 × 100 GeV/u and with a luminosity of 2×10^{26} cm^{-2}sec^{-1}, opening up an energy domain not available at any other laboratory within the foreseeable future.

The performance objectives for this collider were determined to satisfy the requirements of a relativistic heavy ion collider identified as the highest–priority next construction project in the 1983 Long Range Plan of the DOE/NSF Nuclear Science Advisory Committee.[4] Brookhaven National Laboratory has submitted a proposal for the construction of RHIC to the US Department of Energy and, since Fiscal Year 1987, has received funding for R&D efforts preparing for the construction of the collider. Present plans foresee a five–year construction schedule starting in October 1990.

Brookhaven National Laboratory has distinct advantages for the construction of a dedicated heavy ion collider facility in the 100 GeV/u per beam energy range

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at a low cost, not possible at any other site. This is due to the existence of essentially all conventional constructions originally intended for the defunct ISA/CBA project, i.e. a main ring tunnel, central control and office building, three completed experimental halls (plus one open experimental area), support buildings, the beam transfer tunnels from the AGS. In addition, the heavy-ion injector complex will be operational and a Helium refrigerator system which has the capacity to meet RHIC requirements is complete. Taking into account the existing resources, the construction cost to complete the collider was estimated at $\sim$ 300 M\$, excluding detectors.

The ongoing R&D effort for RHIC has been directed on one hand at producing a viable conceptual design and solving accelerator physics questions so that reliable performance estimates can be made and on the other hand at building prototypes of superconducting arc magnets.[5,6] A definite conceptual design for the collider has been completed.[7] Full size prototypes of arc dipoles, quadrupoles, sextupoles and corrector magnets have been built and successfully tested.[8,9] A full cell is presently being assembled and its cooldown is scheduled for the end of this year.

In this paper, the salient design features and the reasons for major design choices of the proposed machine are discussed. Performance estimates are given and the dominant limitations are addressed. The accelerator physics questions having a direct impact on the magnet design are summarized and the resulting dipole design is presented. Finally, possible future upgrades and expected performance improvements are discussed.

THE RHIC SCENARIO AND MAJOR PARAMETERS

The RHIC conceptual design follows in many ways the examples of existing major proton colliders, notably the SPS and the Tevatron, by utilizing short bunches to enhance the luminosity while keeping the average current and stored beam energy low. However, it was found that intrabeam scattering[10] is one of the dominant design considerations in heavy-ion machines, which require stronger focusing lattices and higher rf voltages than corresponding proton colliders. The constraint of fitting RHIC into an existing tunnel imposed a lattice with six intersection points and fixed the length of the insertion regions but presented few if any design problems. In fact, the circumference of the existing tunnel ($\sim$ 3.8 km) results in a conservative magnetic bending field of 3.45 T. This relatively low field, for a superconducting dipole, allows a simple single-layer design at minimum cost.

Injector Complex

The design specifications of RHIC call for the injection of 57 bunches per ring each comprising 10^9 fully–stripped $^{197}Au^{79+}$ ions with a normalized emittance (95%) of 10 π mm·mrad and a phase space area of 0.3 eV·sec.

The existing accelerator complex at Brookhaven consisting of the Tandem Van de Graaff, the Heavy Ion Transfer line, the Alternating Gradient Synchrotron and the Booster Synchrotron, presently under construction, will serve as the injector of heavy ions for RHIC. Using a pulsed negative–ion sputter source and a thin carbon stripping foil at the high voltage terminal, the Tandem will deliver 1.2×10^{10} Au^{14+} ions in a 110 μsec long pulse. Multiturn injection into the Booster and capture by the rf system gives 3 bunches which will be accelerated to 72 MeV/u and stripped in a second foil resulting in 2×10^9 Au^{77+} ions per bunch. The 3 bunches are then accelerated in the AGS to 10.4 GeV/u and fully stripped, which occurs essentially without losses due to the high energy, before their transfer to and injection into RHIC.[11]

The Tandem source can deliver many other elements. Since the acceleration and storage of very heavy ions represents the most demanding task, gold ions are given here as the prototypical example. The present AGS with direct injection from the linac can already provide the required intensity of 10^{11} protons/bunch.

Lattice

RHIC will have two interlaced rings in a common horizontal plane. Each ring is composed of six arc sextants and six experimental insertions. The ring spacing in the arcs is 90 cm in order to allow separate cryostats considered desirable during operation. The side–by–side configuration eliminates the need for vertical dispersion suppressors. The polarity sequence of all quadrupoles is anti–symmetric with respect to the crossing points to simplify dispersion matching of the insertion and to assure zero horizontal dispersion at the crossing point. The crossing angle is adjustable from 0 to 6.8 mrad, although head–on collisions are considered standard. The beta function at the crossing point is $\beta^*_H = \beta^*_V = 6$ m during injection and acceleration, but it can be reduced to 2 m during storage.[12]

In the arcs a simple separated function FODO structure with $\pi/2$ phase shift/cell has been adopted. In order to minimize the aperture requirements very strong focusing is necessary, but a limit is imposed so as to keep the transition energy below $\gamma = 30.9$, i.e. the proton injection energy. A cell length of $\sim$ 30 m was chosen resulting in $\gamma_T = 24.8$. Heavy ion beams are accelerated through transition; in order to avoid bunch dilution, a γ_T jump is required with $\Delta\gamma_T = 0.6$ in 60 msec. Using 2 families of quadrupole correctors at QF in the arcs, separated by π phase shift, the transition energy is changed without tune change.

The RHIC lattice has a natural chromaticity of -49 for $\beta^* = 6$ m and more with the low–beta insertions activated. Correction of chromatic effects over the momentum aperture of $\pm$ 0.5% is achieved with a 3 family sextupole scheme.[13]

Beam Transfer, Injection and Dump

Beam transfer from the AGS to RHIC involves the injection of 3 heavy ion bunches at a time into matched rf buckets in the collider. A transfer line brings the beam to the 6 o'clock insertion, where a sequence of three septum magnets and a kicker guide the beam vertically onto the injection closed orbit (Fig. 1). The kicker strength is 400 G with a risetime of 95 nsec; the kicker length is 3.25 m and its aperture 40 mm vertical by 20 mm horizontal.[14]

The stored beam energy is about 300 kJ, small enough to be aborted onto an internal dump without quenching of magnets, at the end of the storage period or in case of equipment malfunction. The beam will be dumped in a single turn (13 μsec) by activating the ejection kicker which deflects the beam vertically into a septum magnet and onto a dump block. The strength of the full aperture kicker is about 12 kG·m with a risetime of 1 μsec. A gap of 1.1 μsec (or 3 missing bunches) is required to avoid uncontrolled beam loss. A properly designed dump block can stand the thermal impact of a single bunch but subsequent ones must be displaced with the aid of a sweeper magnet.[15]

Acceleration and Storage rf Systems

The RHIC rf system must capture, accelerate, and store the nominally 57 bunches for many hours. Capture and acceleration will be performed by the h=342 system operating at 26.7 MHz. To maintain short bunches with an rms bunch length of σ_ℓ = 31 cm during storage (i.e. the colliding mode), the bunches will be transferred to the h=2052 rf system operating at 160 MHz. Transfer of the bunches will be done using the bunch rotation method.[16]

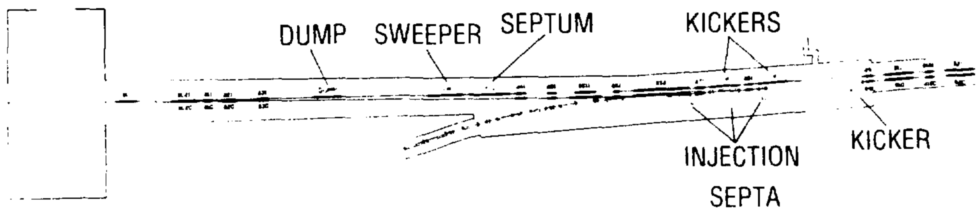

FIGURE 1 Insertion at 6 o'clock with injection and beam dump magnets.

TABLE I RHIC Performance Estimates

No. bunches	57	
Bunch spacing (nsec)	224	
Collision angle	0	
Free space at crossing point (m)	±9	
	Au	p
No. particles/bunch	1×10^9	1×10^{11}
Top energy (GeV/u)	100	250
Emittance (π mm·mrad)	60	20
Diamond length (cm rms)	22	20
Beta* (m)	2	2
Luminosity ($cm^{-2}sec^{-1}$)	$\sim2\times10^{26}$	1.4×10^{31}
Lifetime (h)	~10	> 10
Beam beam tune spread/crossing	3×10^{-4}	4×10^{-3}

The acceleration rf system has 2 cavities per ring capable of 400 kV. Matched injection of gold ions requires 215 kV and their acceleration a constant 300 kV. The acceleration time of $\sim$ 1 min is given by the requirements of the quench protection system. The storage rf system has 6 cavities capable of 4.2 MV. The initial voltage requirement for Au–ions of $\gamma = 100$ is $\sim$ 290 kV which is raised to full voltage after 10 h storage, in step with the increasing energy spread due to intrabeam scattering.

PERFORMANCE

The major performance criteria for a heavy ion collider have been formulated as early as 1983 and were subsequently confirmed by advisory committees representing the nuclear physics user community.[17] The performance estimates for RHIC are summarized in Table I.

Intrabeam scattering has been observed to limit the luminosity lifetime in the CERN Sp$\bar{p}$S collider.[18] In view of its Z^4/A^2 dependence, intrabeam scattering of Au–beams has been a major consideration in establishing RHIC design parameters such as magnet aperture and voltage for the storage rf system. For typical injected beams, the energy spread of the beam increases rapidly until equipartition is reached, i.e. $\sigma_H = \sqrt{2}X_p\delta_E$. The longitudinal and transverse beam dimensions then grow together until the magnet or rf aperture limits are reached. For example, at injection the longitudinal phase space area doubles in about 6 min.

The experience with hadron colliders suggest an upper limit on the beam–beam tune spread of $\Delta\nu_{BB}$ <0.02 in order to avoid resonances of 10^{th} or lower order.[19] At design intensities, the beam–beam limit will not be reached. However, it may well be that operation with large finite crossing angles is prohibited by beam–beam excited synchro–betatron resonances, suggesting head–on collisions as the standard operating mode.[20]

The luminosity depends quadratically on bunch intensity which will be limited by single–beam collective effects. The longitudinal microwave instability is expected to represent the most serious limit, especially for protons at top energy where the tolerable coupling impedance is $Z/n < 2\ \Omega$.

One of the experimental requirements is a luminosity lifetime of at least 10 h. The lifetime of a single beam could be limited by nuclear scattering between the ion beam and the residual gas, but this effect is negligible at the design pressure of $< 10^{-10}$ Torr. In contrast, beam–beam interactions due to nuclear scattering, which is of course the reason for building RHIC, and in the case of gold beams, the single nucleon breakup due to Coulomb excitation of giant dipole states[21] as well as capture of electrons from pair production[22] will result in beam loss and reduced luminosity lifetime.

Luminosity improvements by an order of magnitude can be expected by doubling the number of bunches and the number of ions per bunch and by a further reduction of β^*.[23]

MAGNET SYSTEM

The existence of a ring tunnel with ~ 3.8 km circumference, originally built for a 400 GeV proton machine, allowed the choice of conservatively designed superconducting magnets. Operation at 250 GeV protons (100 GeV/u Au ions) requires a dipole field of 3.45 T which can be achieved with single–layer coils, made of Rutherford type superconducting NbTi cable. However, the requirement of operation with unequal ion species, e.g. p–on–Au, ruled out cost–saving 2–in–1 magnets. Most of the bending is done by the arc dipoles each of which has an effective length of 9.46 m and is curved with a radius of 243 m to reduce its aperture (4.8 cm sagitta). The low field permits the use of a cold–iron yoke serving as collar to provide the prestress.

In order to enhance the operational flexibility, cryogenically separate arc magnets were adopted. The cryostat follows the design concepts developed for the SSC magnets, in particular in the use of the folded–post design. However, the RHIC cryostat is simpler since only one intermediate heat shield at ~ 55 K is required.

The expected heat load per dipole is 3.5 W at 4.6 K and 20 W at 55 K. Heating of the stainless beam tube by image currents is estimate at $\sim$ 0.3 W/dipole but could increase by an order of magnitude if the number of bunches and the number of ions/bunch would be doubled. In order not to preclude future upgrades, the beam tube will be plated with a 10–20 μm thick copper layer.[24]

The superconducting magnets have a cold–bore beam tube with an aperture of 7.29 mm. The coil aperture was determined to accommodate the dimensions of a gold beam at 30 GeV/u after 10 h, when $\epsilon_N = 33\times10^{-6}\pi$m and $\Delta p/p = \pm5.6\times10^{-3}$. Experience with hadron colliders has shown that in order to minimize radiation background a 6σ safety factor is required leading to a good–field aperture requirement of $a_\delta + a_\beta = \pm26.7$ mm. By applying the 2/3 rule, a coil i.d. of 80 mm was found. This choice was confirmed by tracking studies[25,26] to provide adequate dynamic aperture taking into account the expected random field errors due to 50 μm mechanical errors.[27,28]

Long–term storage of the beam will require that the operating tune remains in a range which is free from 10^{th} and lower resonances. With the nominal tune at 28.826, the useable tune range between the 5^{th} and 6^{th} order resonance is 33×10^{-3}. Limiting the tune spread due to a single field harmonic to $\sim3\times10^{-3}$ results in severe tolerance requirements and consequently octupole and decapole correction coils will be provided, in addition to the standard closed–orbit, chromaticity, and linear–coupling correction systems. The strong chromaticity sextupoles are built as separate units. All other correction coils are combined in the corrector magnets separate from dipoles and quadrupoles.

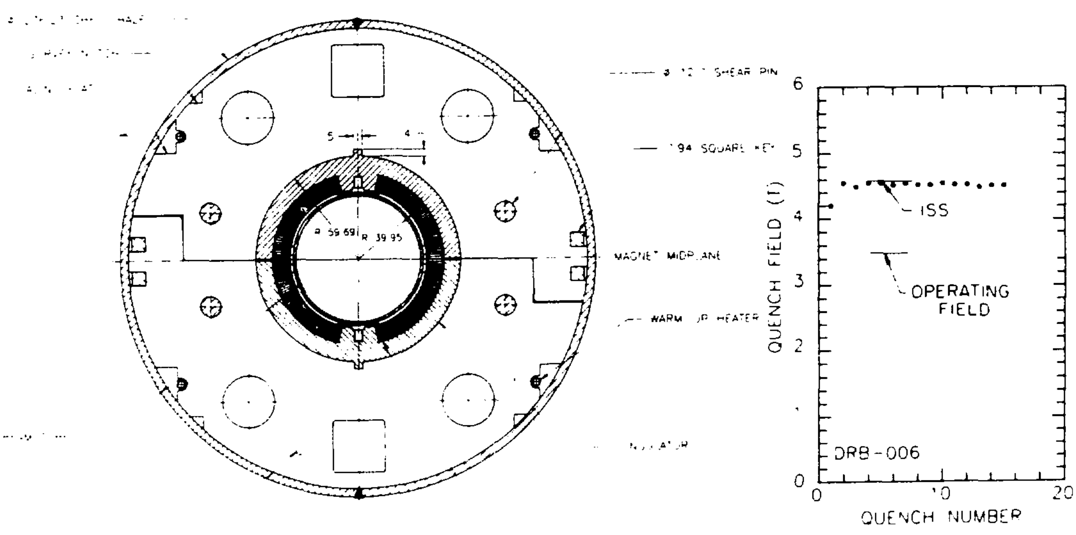

FIGURE 2 Cross section and quench curves of RHIC dipoles.

In the two rings of the collider, there are 372 dipoles, 492 quadrupoles, 288 sextupoles, 24 skew quadrupoles and 492 magnets for correction of field perturbations. The superconducting magnet system for RHIC is the one hardware system for which the R&D efforts have advanced beyond the conceptual design stage. Full-size arc magnets, dipoles, quadrupoles, sextupoles and corrector units have been built and tested. All units reached design specifications. The six dipoles achieved fields of ~ 4.6 T, or 35% higher than the operating field for RHIC, with virtually no training (Fig. 2). Measurement of field quality indicated adequate rms errors, but the need for adjustment of systematic harmonics. It is intended that the arc magnets will be industrially fabricated and plans for technology transfer are being developed.

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