THE RELATIVISTIC HEAVY ION COLLIDER AT BROOKHAVEN*

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Abstract

The conceptual design of a Relativistic Heavy Ion Collider (RHIC) 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 5×10^{26} cm^{-2}sec^{-1} at an energy of 100 GeV/u in each beam. Collisions with different ion species, including protons, will be possible. The collider consists of two interlaced, but otherwise separate, superconducting magnet rings. The 9.7 m long dipoles will operate at 3.5 T. Their 8 cm aperture was determined by the dimensions of gold ion beams taking into account diffusion due to intrabeam scattering. Heavy ion beams will be available from the Tandem Van de Graaff/Booster/AGS complex. The salient design features and the reasons for major design choices of the proposed machine are discussed in this paper.

Introduction

Plans for the construction of a Relativistic Heavy Ion Collider (RHIC) at Brookhaven have been formulated and funding for a construction start in 1989 has been requested from the U.S. Department of Energy.[1] RHIC would represent the logical next phase in the ongoing heavy ion program at Brookhaven.

Acceleration of heavy ions in the AGS was studied as early as 1973/74.[2,3] The study concluded that ions with mass number around A ≈ 200 can be obtained provided that fully stripped ions would be available from the injector. The concept of using the existing Tandem van de Graaff as preinjector, connecting Tandem and AGS with a heavy ion transfer line, and adding a booster synchrotron to allow fully stripped very heavy ions anticipated the more recent developments of this Laboratory with remarkable foresight. Completion in 1984 of a beam transfer line joining the Tandem with the AGS permits acceleration of ions as heavy as sulfur.[4] During the latest AGS heavy ion run, $^{28}Si^{14+}$ beams with an intensity of 2×10^8 ions/pulse were delivered at a kinetic energy of 13.6 GeV/ nucleon for fixed target experiments.[5] Completion of the AGS Booster[6] scheduled for 1991 will permit acceleration of the heaviest ions, such as ^{197}Au and possibly ^{238}U.

The 1983 Long-Range plan of the nuclear physics community by the DOE/NSF Nuclear Science Advisory Committee called for the construction of an ultra-relativistic heavy-ion collider.[7] In response, Brookhaven developed plans for a 100 × 100 GeV/nucleon collider facility using the vacant tunnel which was intended for the aborted Isabelle/CBA machine. The design concepts for RHIC underwent several metamorphic phases,[8-10] which led to the May 1986 Conceptual Design Report (CDR).[11] This document remains valid in most respects, but progress resulting from 2 years of intensive R&D efforts in the areas of accelerator physics and superconducting magnet technology as well as ideas for improvements generated in the March 88 Workshop on RHIC performance[12] resulted in a few design changes. The present paper represents an up-to-date, but still tentative, summary of the expected collider performance and the conceptual design of the major accelerator systems.

Performance Estimates

The performance objectives for RHIC were first spelled out by a Task Force for Relativistic Heavy Ion Physics in a report[13] dated August 1983. The design requirements can be summarized in the following points.

Energy. Top energy will be about 100 × 100 GeV/u for heavy ions and 250 GeV for protons. This represents an order of magnitude increase over the SPS fixed target capabilities. It was pointed out that the collider should span a wide range of energies, down to 7 × 7 GeV/u and lower. The lower energies will be covered by internal target operation. In order to limit magnet aperture requirements, and thus cost, full luminosity requirements are limited to energies above 30 × 30 GeV/u.

Luminosity. The luminosity requirements for initial experiments are rather modest, about 10^{25} cm^{-2} sec^{-1}. The machine is designed for Au-Au with 5×10^{26} cm^{-2}sec^{-1} at top energy while maintaining the option for future upgrades to 10^{28} cm^{-2}sec^{-1}.

Range of Ion Masses. The expectations for interesting physics phenomena require a broad range of nuclei, from the heaviest (e.g., Au, Pb) to the lightest, including protons. Asymmetric operation, with heavy ion on protons, is considered to be crucial.

Intersection Regions. A minimum of 3 intersection regions is assumed and development of all available six regions is expected in the future. A free space at the crossing point of ±10 m is required. A number of experiments call for a diamond length of ≤ 20 cm rms. Furthermore, flexibility in adjusting β^* as well as crossing angle should be possible.

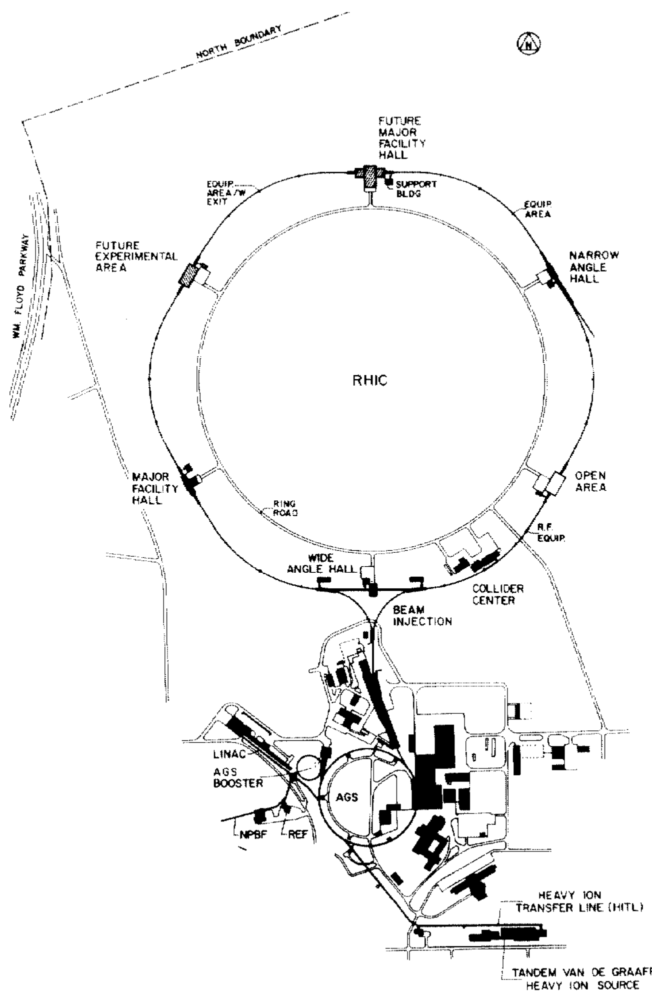

Fig. 1. Site map of accelerators at Brookhaven.

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Table I. RHIC Performance Estimates

	Au-Au	p-p	
Kinetic Energy	100 × 100	250 × 250	GeV/u
No. Bunches	57	57	
No. ions/bunch	1×10^9	1×10^{11}	
Inv. emittance @ 10 h	22	20	π mm·mrad
Bunch Area @ 10 h	1.5	1	eV·sec
β*	3	3	m
Luminosity	3.5×10^{26}	1×10^{31}	$cm^{-2}sec^{-1}$
Diamond length, rms	22	17	cm

The RHIC design desiderata can be achieved in different ways. It was found that intrabeam scattering is one of the dominant design considerations in heavy ion machines,[14] which require stronger focusing lattices and higher rf voltages then corresponding proton machines. Another important choice in the RHIC design was the utilization of short bunches colliding head-on to enhance the luminosity while keeping the average current and stored beam energy low.[15]

The site map in Fig. 1 shows present and proposed accelerators at Brookhaven. The 3.8 km long RHIC tunnel is located to the north of the AGS with its beam transfer tunnel connecting to the operational fast-ejection beam line (U-line). The existence of the tunnel imposed a lattice with six interaction points and fixed the length of the insertion regions, but overall represented no constraints on the design. In fact, the comparatively large circumference permitted significant cost savings in the magnet design. The tunnel cross section can accommodate two separate rings in the same horizontal plane, and this configuration was eventually adopted. Lattices with magnets above each other were ruled out from the start to avoid vertical dispersion suppressors. The design requirement for colliding unequal species eliminated lattices with common quadrupoles.

The final RHIC lattice is described in a companion paper at this conference.[16] The insertion lay out is shown in Fig. 2. During injection and acceleration, the insertion is adjusted for a $\beta^* = 6$ m in order to limit $\beta_{max} < 225$ m in the insertion quadrupoles. At top energy, the beta value at the crossing point will be reduced to $\beta^* =$ 3 m (and even 1 m in the case of protons).

The RHIC performance estimates are given in Table I. Luminosity and diamond length take into account the emittance and bunch area growth due to intrabeam scattering. The performance estimates are based on head-on collisions which are believed necessary to avoid limitations due to synchro-betatron resonances.[12] Thus in order to reduce the diamond length the addition of a high frequency (e.g. 160 MHz) rf system is assumed. The RHIC design now satisfies all design requirements stated above. Note that the initial Au-Au luminosity is larger by a factor of about 2 and the expected average luminosity over 10 h is about 5×10^{26} $cm^{-2}sec^{-1}$.

Superconducting Magnet System

The choice of the RHIC magnets was preceded by a detailed cost-benefit analysis comparing superconducting magnets of different configurations (e.g. large-aperture CBA, 3-inch FNAL, 2-in-1, window frame) as well as superferric magnets.[17,18] The existence of the RHIC tunnel had of course a profound impact on the cost optimization, leading to the selection of single-layer, cold-iron, cold-bore arc magnets.[19] The coil aperture of 8 cm i.d. (7.29 cm beam tube i.d.) accommodates the size of gold beams at 30 GeV/u after 10 h due to intrabeam scattering. The dipoles are bent to reduce the aperture requirements (4.8 cm sagitta). The beam tube in the dipoles is copper plated to limit beam heating.[20] The quadrupole design concepts follow directly the dipole solution. Insertion magnets may have special requirements as to aperture and field or gradient, which led to different solutions.

The major arc magnet parameters are listed in Table II. The design energy of 100 GeV/u is obtained with the relatively low field of 3.45 T. The quench field of these dipoles is expected to be about 4.6 T, providing ample safety margin and the possibility of higher operating fields. The cost analysis showed that lowering the design energy yields only minimal cost reduction due to the large fraction of field-insensitive items. Also, to minimize cost, the 9.7 m dipole length was the longest compatible with the lattice, i.e. one dipole per half cell.

Four full size R&D magnets were built and have been tested in horizontal dewars. All of these magnets reached fields of approximately 4.6 T, or 35% higher than the operating field for RHIC, with virtually no training. Measurement of field quality indicated adequate rms errors, but the need for adjustment of systematic harmonics.[21]

The design of the RHIC dipole cryostat follows largely the concepts developed for SSC cryostats, in particular in the use of a folded-post support.[22] It is however simpler because of the need for only a single 55 K heat shield. The main advantage of this cryostat design is derived from the possibility of 1) insulating the cold mass outside of the vacuum vessel and 2) referencing the magnet center to the ground plate prior to assembly.

The magnets of one ring are cryogenically in series. Supercritical helium at 5 atm arrives from the refrigerator at a temperature of 4.3 K, traverses the magnets of one ring and then returns. In order to keep the temperature below 4.6 K, two recooler units are installed in each sextant. The total estimated heat load is about 10 kW; which is sufficiently lower than the 25 kW at 4.3 K capability of the operational CBA refrigerator.

Other Accelerator Systems

The RHIC related R&D efforts have been concentrated on accelerator physics questions affecting performance and the con

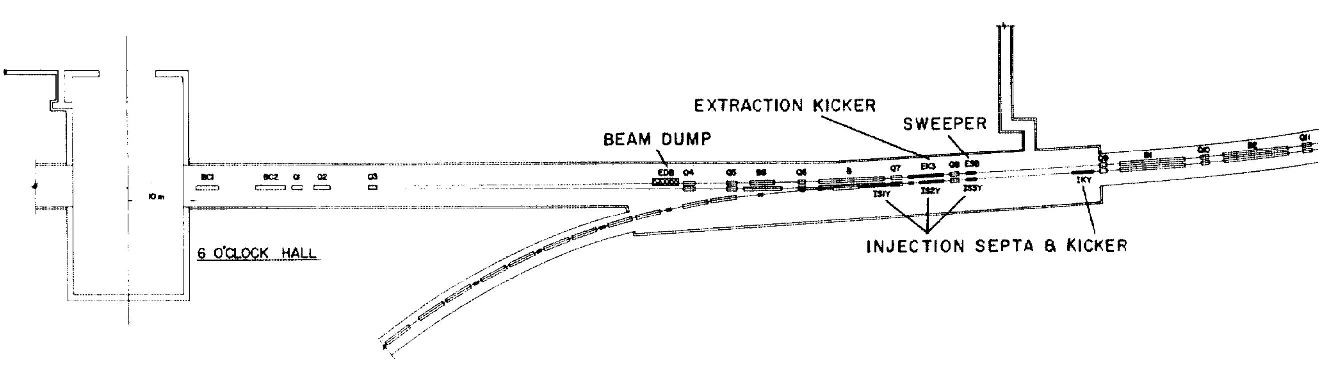

Fig. 2. RHIC insertion layout with injection and beam dump.

Table II. Major Parameters of RHIC Systems.

No. of dipoles (180/ring + 12 common)	372	
No. of quadrupoles (276 arc + 216 insertion)	492	
Dipole field @ 100 GeV/u, Au	3.45	T
Dipole magnetic length	9.46	m
Dipole yoke length	9.7	m
Coil i.d. arc magnets	8	cm
Beam tube i.d.	7.29	cm
Operating current	5	kA
Quadrupole gradient	67	T/m
Magnetic rigidity, Bρ: @ injection	96.7	T/m
@ top energy	839.5	T/m
No. of bunches/ring	57	
No. of Au-ions/bunch	1×10^9	
Filling time (each ring)	~1	min
Injection kicker rise time, 0.13 T·m	80	nsec
Stored energy, each beam	300	kJ
Beam dump kicker rise time, 1.7 T·m	~1	μsec
Acceleration rf, 26.7 MHz	300	kV
Storage rf, 160 MHz	6	MV
Acceleration time	1	min

struction of superconducting arc magnets. Other systems have received sufficient attention to come up with a conceptual design. In view of their status only a few comments need be made here.

Injector. The Tandem-Booster-AGS combination represents a very good injector for RHIC,[23] capable of satisfying the beam parameters assumed for the collider design, e.g., Au bunches with 1×10^9 ions with normalized emittances of 10 π mm·mrad and a bunch area of 0.3 eV·sec. The AGS will deliver a single bunch to RHIC, where nominally 57 bunches are accumulated in boxcar fashion. The AGS beam is transfered to RHIC and vertically injected by a sequence of septum and kicker magnets as shown in Fig. 3. The requirements for the injection kickers listed in Table II will allow injection of 114 bunches.

Beam Extraction. The stored energy per beam is about 300 kJ which should allow an internal beam dump. The configuration of beam extraction equipment is shown in Fig. 3 and the extraction kicker requirements are given in Table II. If necessary, the dump could be replaced by an ejection septum at a future date. A 1 μsec gap in the bunch sequence, 13 μsec long, will be provided to minimize uncontrolled beam spill.

rf Systems. The beams will be accelerated with an 26.7 MHz rf system operating on the $h = 6 \times 57$ harmonic.[24] A voltage of about 300 kV is required. The choice of this frequency accommodates the bunch length of the injected beam as well as passage through transition. The acceleration time of 1 min is relatively slow and provisions for a fast transition jump will be made. The momentum spread of the beam grows in time due to intrabeam scattering. To limit the diamond length to 20 cm rms and thus the bunch length to less than 28 cm rms, a second 160 MHz storage rf system with about 6 MV capability will be installed.

The Present Status

As noted above, a large fraction of the RHIC facility already exists. For the injector complex, the Tandem Van de Graaff, AGS, and heavy ion transfer line are already operational; the Booster Synchrotron is under construction. Most of the conventional construction for the collider is complete, including the ring tunnel, main service building and experimental halls for four of the six intersection regions. In addition, the liquid helium refrigerator, capable of cooling all of the superconducting magnets in the collider has been completed (as part of the CBA project) and successfully tested; the magnets for the AGS-to-RHIC beam transfer line are available.

The superconducting magnets for RHIC have been designed. The R&D work on these magnets is well along, and it is planned that a significant fraction of the magnets for the RHIC machine will be industrially fabricated. Four full-length, field-quality dipole magnets were built in 1986, using coils wound at BNL. Three of these magnets were assembled by an industrial firm. The first of the full-length magnets, assembled at BNL, has been successfully tested in February, 1987. Since then the remaining, industrially built magnets in this series have been tested as described above. Two each dipoles and quadrupoles were built in 1987/88, the first of these being presently tested individually. They will then be combined for a full-cell system test at the end of 1988. Work on two additional in-house dipoles with their folded-post cryostats as well as preparations for a series of six industrial prototype dipoles is in progress.

The Project has been reviewed and validated by the U.S. Department of Energy, and construction could begin in fiscal year 1989 if funds were made available. A five-year construction schedule is planned. The accelerator construction cost is roughly 200 M$ with additional funds budgeted for detectors and R&D.

Acknowledgements

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