THE RELATIVISTIC HEAVY ION COLLIDER RHIC AT BROOKHAVEN*

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Abstract

The progress in the status of the RHIC project and R&D for the project is presented. Also presented are the salient design features of the RHIC collider which make it unique as a dedicated heavy ion physics machine.

Introduction

The Relativistic Heavy Ion Collider (RHIC) project at Brookhaven National Laboratory (BNL) has made significant progress this past year. With a well-advanced accelerator design and superconducting magnet R&D, RHIC is ready for construction. An initiation of the RHIC construction was included in the Presidential budget proposal to Congress for FY 1991. Needless to say, this budget proposal is based on the continued support of the nuclear physics community as exemplified by the conclusion of the NSAC Long Range Plan Working Group, urging an immediate start of RHIC construction. Two DOE review committees have also concurred with that conclusion. With Congressional approval, construction of the collider can be started in the fall of 1990, with a goal of performing a colliding beam experiment in the spring of 1997.

This budget proposal includes a total estimated construction cost of \$397 M including \$90 to 100 M for the initial complement of major detectors. The funding will be distributed over 6 years, with the following profile:

FY 1991	1992	1993	1994	1995	1996
\$15 M	\$50 M	\$80 M	\$90 M	\$90 M	\$72 M

In addition, the project will continue to receive funding for accelerator and detector R&D at the level of about \$7 M through FY 1994, and envisages pre-operation funding starting in FY 1995.

The "RHIC Project" organization was established as a new entity within the Laboratory at the beginning of FY 1990 to manage the collider and detector construction. Under this project organization, a number of task forces are finalizing the details of the accelerator design and preparing for the industrial production of the standard superconducting magnets.

The preparation for the RHIC construction has been directed mainly at two technical areas. The first is to generate a viable accelerator design and to solve accelerator physics questions so that a reliable performance estimate can be made. After intensive studies during the past several years, and with a number of reviews and workshops which evaluated and suggested some improvements, we believe that we have a definitive machine design on hand. Major expected performances and parameters of the RHIC collider are given in Tables 1 and 2, respectively. The second area is to develop a suitable design of superconducting magnets which matches the requirements from the machine design. Although the modest magnetic field strength required for this accelerator allows the magnet design to be simple and less demanding, a careful development was necessary to prove its mass producibility.

Utilizing the existing 3.8 km tunnel and 4 experimental halls which were built for the CBA project (~95% complete), the series of accelerators, from the Tandem Van de Graaff to the AGS (which are in operation), have lowered the cost of the project considerably. The Booster Synchrotron, which will become operational in 1991, will provide a capability for ions as heavy as gold. In addition, on-going experimental programs with heavy ion beams at the AGS will provide the scientific infrastructure for the effective execution of the physics program at RHIC.

RHIC Acclerator Configuration

The RHIC plan calls for the construction of two intersecting storage rings which are capable of accelerating, storing, and colliding ions as heavy as gold at the beam energy of 30-100 GeV/u. The overall accelerator configuration of the RHIC facility is shown in Fig 1. The existing accelerator complex which consists of the Tandem Van de Graaff, Heavy Ion Transfer Line, the Alternating Gradient Synchrotron (AGS), and the new Booster Synchrotron will be used as the injector. Taking the gold ion as an example, negative ion beams from a pulsed sputter ion source (200 μA, >120 μsec, $Q = -1$) are accelerated by the first stage of the Tandem Van de Graaff, stripped of atomic electrons to $Q \sim +14$ by a foil at the high voltage terminal, and accelerated by the second stage to ~1 MeV/u. The beams are then transported through a 540 m-long transfer line to the Booster without further stripping of atomic electrons. A test performed for the gold beam indicated that ~2×10^{10} gold ions can be delivered to the Booster in 120 μsec. After multi-turn injection, beams are grouped into 3 bunches and accelerated to 72 MeV/u. A foil at the Booster exit strips all atomic electrons except for two tightly bound K-shell electrons. The AGS, with its improved vacuum, can accelerate 3 bunches of $Q = +77$ gold ions to 10.4 GeV/u with only a few percent loss. Ions are fully stripped at the exit of the AGS and injected into the RHIC storage rings. Beam stacking is done in box-car fashion by repeating this acceleration cycle 19 times to establish 57 bunches for each ring. The overall filling time of both rings should be about 1 min.

Table 1: 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})	$\sim 2 \times 10^{26}$	1.4×10^{31}
Lifetime (hr)	~10	>10
Beam-beam tune spread/crossing	3×10^{-4}	4×10^{-3}

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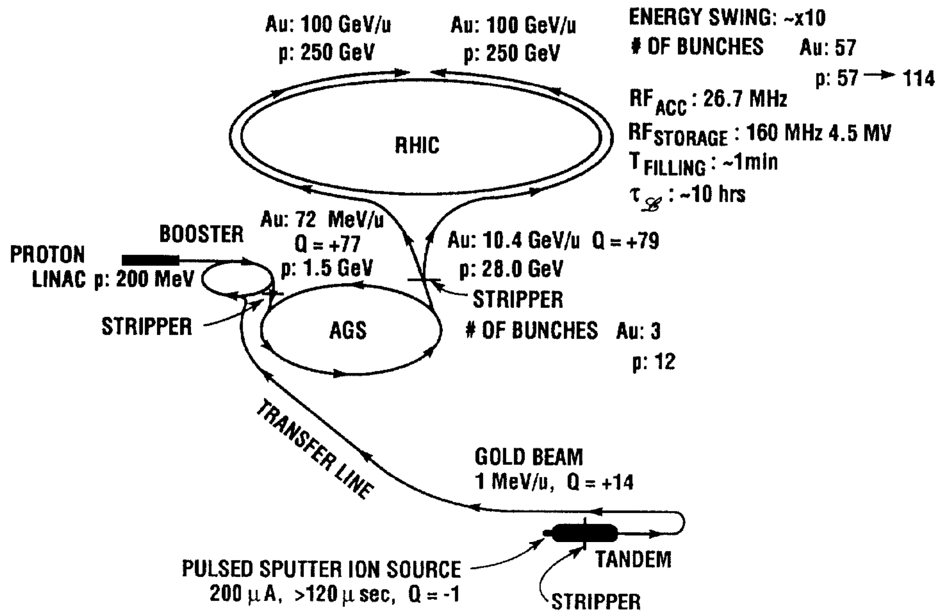

Fig. 1. Overall configuration of the accelerator complex for RHIC. An accelerator chain which consists of Tandem Van de Graaff, the Booster Synchrotron, and the AGS serves as the injector to the RHIC collider. The sequence of the operation of this accelerator system is described in the text.

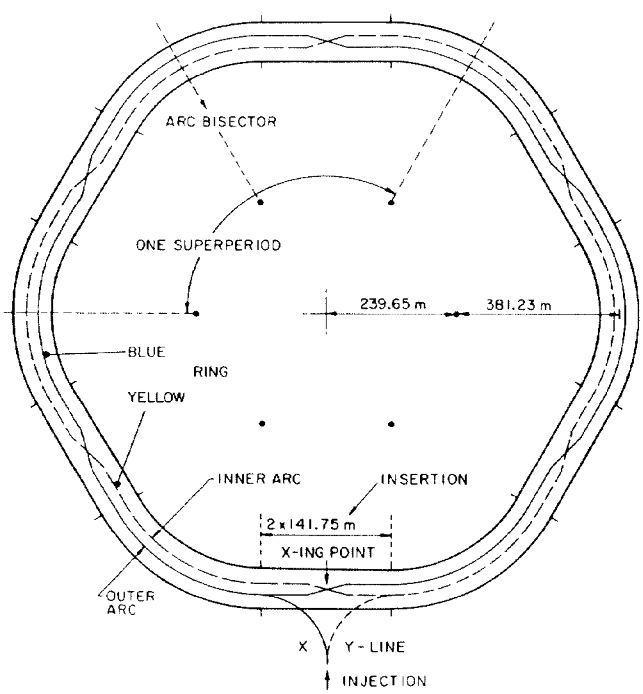

Fig. 2. General layout of the RHIC collider. Each ring consists of a pair of inner and outer arc sections which repeat 3 times along the ring forming 3-fold symmetry. There are 6 arc sections and 6 insertion sections. Each arc consists of 12 FODO cells.

The bunches are captured in stationary buckets of the so-called acceleration rf system operating at ~26.7 MHz, corresponding to a harmonic $h = 57 \times 6$. This rf frequency was chosen to match the bucket shape to the bunch shape determined by the AGS rf system so as to avoid bunch area dilution. With the exception of protons, all ion species must be accelerated through the transition energy. In order to avoid bunch area dilution at the transition, a γ-transition jump will be executed. After reaching the operating beam energy in the range 30 GeV to 100 GeV/u (which takes about 1 min), the bunches are transferred to the so-called storage rf at 160 MHz ($h = 57 \times 6 \times 6$). This 6 times higher frequency was chosen to limit the growth of the bunch length due to intrabeam scatterings to ~31 cm (or collision diamond rms length ~22 cm).

The design luminosity of the collider is $\sim 2 \times 10^{26}$ cm^{-2} sec^{-1} for gold at the beam energy of 100 GeV/u ($\sim 1.4 \times 10^{31}$ cm^{-2} sec^{-1} for protons at 250 GeV) with the collision of 57 bunches in each beam. The luminosity lifetime of ~10 h is expected for gold beams and somewhat longer for lighter ions.

A general layout of the collider is shown in Fig. 2. It is composed of two identical, non-circular concentric superconducting magnet storage rings (3.8 km in circumference) in a common horizontal plane, oriented to intersect with one another at 6 locations along the ring. Having 3-fold symmetry, each ring consists of three inner and three outer arcs (each ~355.5 m long) and six insertions (each 283.5 m long) joining the inner and outer arcs. Each arc is composed of 12 FODO cells, i.e., 24 half cells each with a 9.46 m long dipole, a 1.13-m long quadrupole, a 0.75 m-long sextupole, and a 0.58-m long assembly for decapole, octupole, quadrupole, and dipole correctors. The arc magnets have an 80-mm coil inner diameter to provide enough aperture for enlarged beam emittance caused by intrabeam scattering. The

Table 2: Major Parameters for the Collider

Energy range (each beam), Au	7-100 GeV/u
protons	28-250 GeV
Luminosity, Au-Au @ 100 GeV/u & 10 h av.	2×10^{26} cm^{-2} sec^{-1}
Operational lifetime Au @ $\gamma > 30$	>10 h
Diamond length	±22 cm rms
Circumference, 4-3/4 C_{AGS}	3833.852 m
Number of crossing point	6
Free space at crossing point	±9 m
Beta @ crossing, horizontal/vertical	6 m
low-beta insertion	2 m
Crossing angle, maximum	7 mrad
Betatron tune, horizontal/vertical	28.824
Transition energy, γ_T	24.7
Filling mode	Box-car
No. of bunches/ring	57
No. of Au-ions/bunch	1×10^9
Filling time (each ring)	<1 min
Magnetic rigidity, $B\rho$: @ injection	96.7 T·m
@ top energy	839.5 T·m
Bending radius, arc dipole	243.241 m
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 field strength, $\int B d\ell$	32.62 T·m
Dipole current	~5 kA
Dipole yoke length	9.70 m
Quadrupole gradient	71.8 T/m
Arc quadrupole strength, $\int G d\ell / B\rho$	0.09665 m^{-1}
Coil i.d. arc magnets	8 cm
Beam tube i.d.	7.29 cm
Beam separation in arcs	90 cm
Injector kicker strength (95 nsec)	0.132 T·m
Beam dump kicker (1 μsec)	1.2 T·m
Beam stored energy	300 kJ
rf voltage, $h = 342$	400 kV
rf voltage, $h = 2052$	4.5 MV
Acceleration time	1 min

spacing of the two beams in the arc section is 90 cm. The insertion sections shown in Fig. 3 provide the low-beta and dispersion suppression required at the crossing points.

RHIC Superconducting Magnet R&D

An intensive research and development program on superconducting magnets has been carried out over the last several years. Having a requirement of relatively modest dipole field strength of 3.45 T, the dipole magnet as shown in Fig. 4 has a simple one-layer cosθ coil design with low carbon iron lamination, also acting as the collar. A high-precision injection-molded spacer of mineral-loaded phenolic (RX 630) is used as the insulator and space material between the coil assembly and the iron yoke lamination. This material was tested extensively and had been proven to have an excellent dimensional stability and good radiation resistance. The eight R&D magnets which have been tested to date (Fig. 5) show that all magnets exceeded the field strength required for RHIC, the most recent units having as much as ~30% margin. The field quality measurement of the most recent 4 dipoles gave (1) random variations in all multi-pole terms much smaller than the tolerances required; (2) average values of all unallowed multipole terms and of the allowed b_6, which are within systematic tolerances; and (3) average values of b_2 and b_4, which are small enough to be easily adjusted in an iteration of coil cross section in the industrial process.

Two R&D units of quadrupole-sextupole-corrector assemblies were also built and tested. They consist of arc quadrupoles with a design similar to the dipole, of sextupoles with superconducting wire coils, and a corrector assembly with multiple concentric cylinders of 4 different multipole correction windings. The results showed that they all meet the RHIC requirements with a 50 to 100% margin. For some of the insertion quadrupoles with required coil i.d. of 130 mm, a design developed for CBA will be adapted. All insertion dipoles with 80 mm coil i.d. will have the same design as the arc dipoles.

All superconducting magnets for RHIC, except for a final beam steering dipole with 170 mm coil i.d., are ready for mass production. Our intention is that all arc magnets and some 80 cm bore insertion section magnets will be manufactured by industry.

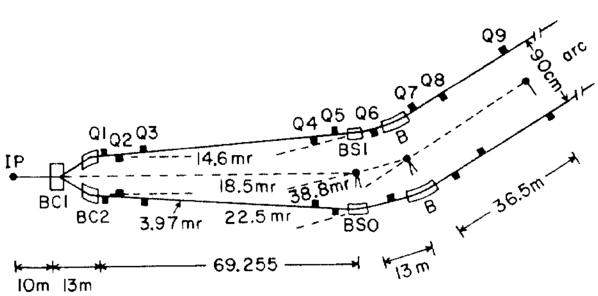

Fig. 3. Layout of one half of the insertion section connecting inner and outer arcs of a ring. Each half insertion contains 9 quadrupoles, 2 dipoles for dispersion suppression, and the remaining dipole BC2 closest to the intersection point plus a dipole BC1 common to both rings for beam manipulation to achieve head-on collisions.

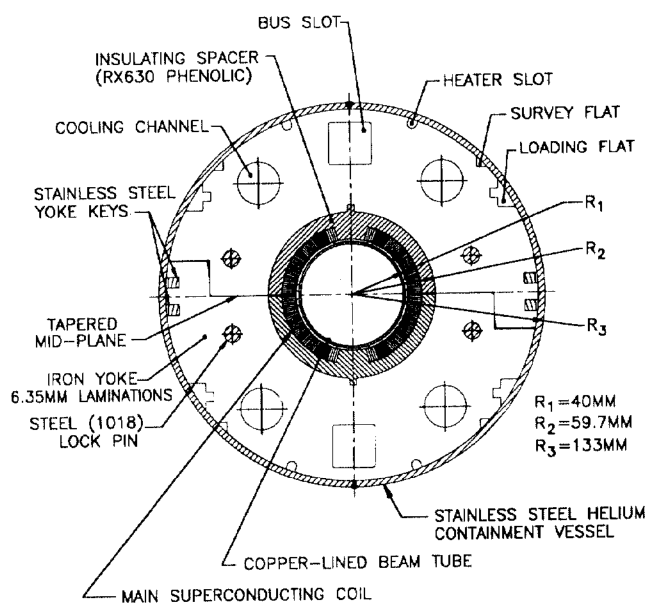

Fig. 4. Cross section of RHIC arc dipole magnet.

Expected Performance of RHIC

The design luminosity for various species of ions as a function of collision energy over the RHIC collider energy range is shown in Fig. 6. On the right-hand scale, the frequency of central collisions corresponding to an impact parameter < 1 Fermi is indicated. Also shown is the energy range covered by the RHIC collider accessible with a shorter luminosity lifetime, and by fixed-target experiment at RHIC and AGS. One important aspect of the RHIC collider is its operational flexibility resulting from having two independent rings for two counter rotating beams. This allows collisions of any unequal species including the range from gold on gold to protons on gold in an equivalent kinematical regime. This flexibility seems to be essential to untangle such complex phenomena as the production of quark matter expected in collisions of relativistic heavy ions. In this sense also, RHIC is a unique collider dedicated to the research of heavy ion collisions.

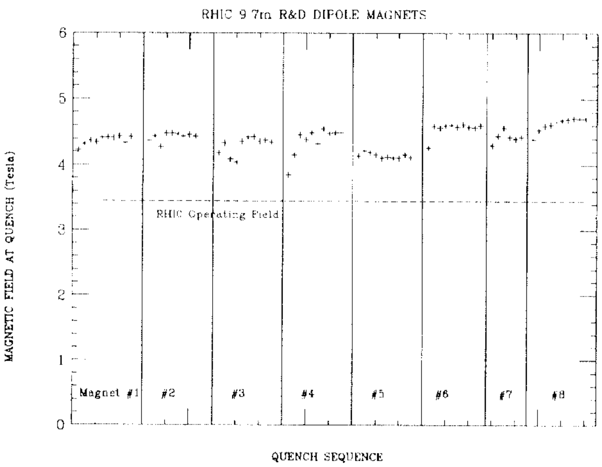

Fig. 5. Quench performance of 8 RHIC dipole R&D units. In all cases, the first quench exceeded the operating magnetic field of RHIC. The latest prototype units demonstrated that there is about 30% of margin in the field strength.

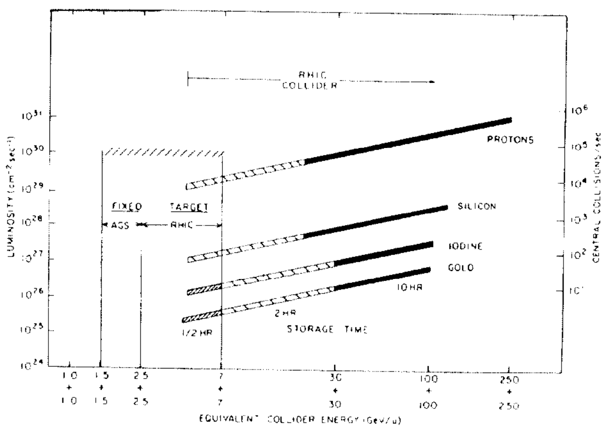

Fig. 6. Design luminosity for various ion masses as a function of collision energy over the full range accessible with the AGS and RHIC.