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The RHIC Project Overview and Status

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THE RHIC PROJECT: OVERVIEW AND STATUS*

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Introduction

The Relativistic Heavy Ion Collider at Brookhaven will extend the present heavy ion capabilities of the AGS into an energy domain not available at any other laboratory within the foreseeable future. The Brookhaven site map in Fig. 1 shows the accelerators and connecting beam tunnels involved in the heavy ion program, i.e. the Tandem Van de Graaff, the Heavy Ion Transfer Line, the AGS, the booster synchrotron presently under construction, and the existing ring tunnel for the proposed collider. Operation of the AGS for heavy ion experiments started in October 1986 with the delivery of O^{8+} beams. Subsequently, the mass range was extended with the AGS delivering typically 2×10^{8} Si^{14+} ions/pulse at a kinetic energy of 13.8 GeV/u.[1] Completion of the AGS booster synchrotron in 1991 will extend the mass range to the heaviest ions, typically ^{179}Au, with ^{238}U a definite possibility.

The acceleration of heavy ions to very high energies at Brookhaven was already considered for the ISABELLE/CBA project.[2] After its cancellation, the realization of a dedicated heavy ion collider in the vacant tunnel became feasible and the design objectives were defined in 1983 by a Task Force on Relativistic Heavy Ion Physics.[3] The study of such a heavy ion accelerator/collider was initially supported by generic R&D funds and later on as part of the Brookhaven Exploratory Research Program. The results of this multi-year R&D effort were presented in the May 1986 Conceptual Design Report (CDR).[4] This document remains valid in most respects but progress resulting from two years of intensive R&D work, now supported with direct DOE funds, in the areas of accelerator physics and superconducting magnet technology resulted in a few design improvements. The present paper summarizes the major features of the RHIC design with emphasis on those aspects of particular interest to the future user and it concludes with a short discussion of the superconducting magnet R&D program.

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*Work performed under the auspices of the US Department of Energy.
1. R.K. Reece et al., Proc. 1987 IEEE Particle Accelerator Conference, Washington, DC, p. 1600.
2. M.Q. Barton, Proc. 1982 Bielefeld Workshop on Quark Matter Formation and Heavy Ion Collisions, p. 237; and IEEE Trans. **NS 30**, 2020 (1983).
3. T. Ludlam and A. Schwarzschild, Nucl. Phys. **A418**, 657c (1984).
4. "*Conceptual Design of the Relativistic Heavy Ion Collider RHIC*", BNL Report 51932 (1986).

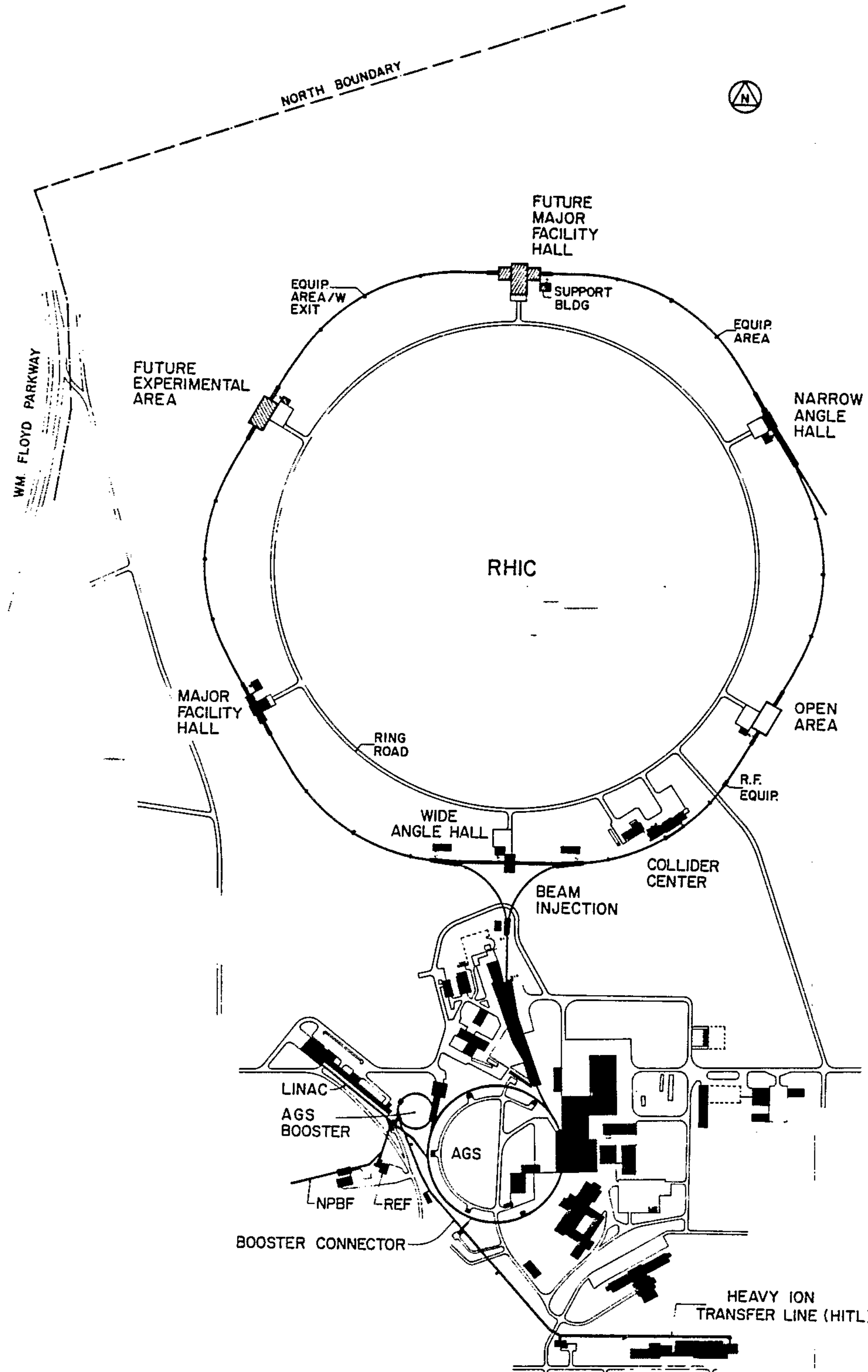

Fig. 1. Site map of accelerators at Brookhaven.

The RHIC Scenario and Major Parameters

The existence at Brookhaven of the AGS/Tandem Van de Graaff complex and the availability of the vacant ring tunnel provide a unique opportunity to construct the Relativistic Heavy Ion Collider at minimal cost. The layout of the two intersecting magnet rings in the tunnel is shown schematically in Fig. 2. Each ring consists of six arcs providing most of the bending and six insertions where the two rings intersect and the beams can be brought into collision. Of the six crossing regions built into the RHIC rings, those at the 2, 6, and 8 o'clock positions have completed experimental halls, including support buildings and crane coverage. The 4 o'clock region is an "open area" which allows considerable flexibility in the detector configuration. The magnets of each ring are cryogenically and electrically separate; they are located in the tunnel side-by-side with a 90-cm horizontal spacing as shown in Fig. 3.

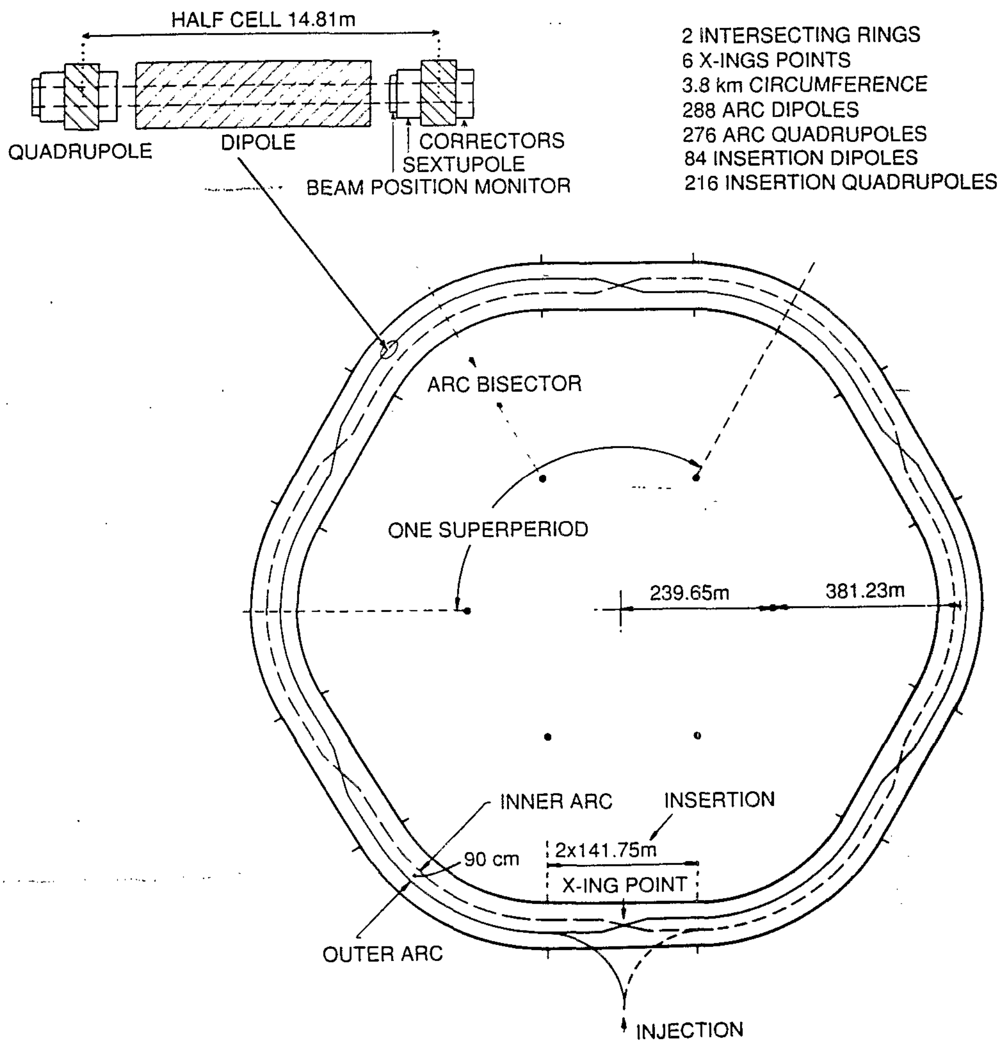

Fig. 2. Layout of the RHIC rings.

The RHIC design desiderata can be achieved in different ways. An 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. It was found that intrabeam scattering is one of the dominant design considerations in heavy ion machines, which require stronger focusing lattices and higher rf voltages then corresponding proton machines.

Given that the machine will be built in the existing 3.8-km long tunnel, a cost optimization is achieved by filling the circumference with relatively low-field magnets. The maximum energy for gold ions of 100 GeV/u is reached with a magnetic field of 3.45 T. The major parameters of the RHIC systems are listed in Table I.

The RHIC related R&D efforts have been concentrated on accelerator physics questions affecting performance and the construction 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 general comments need be made here.

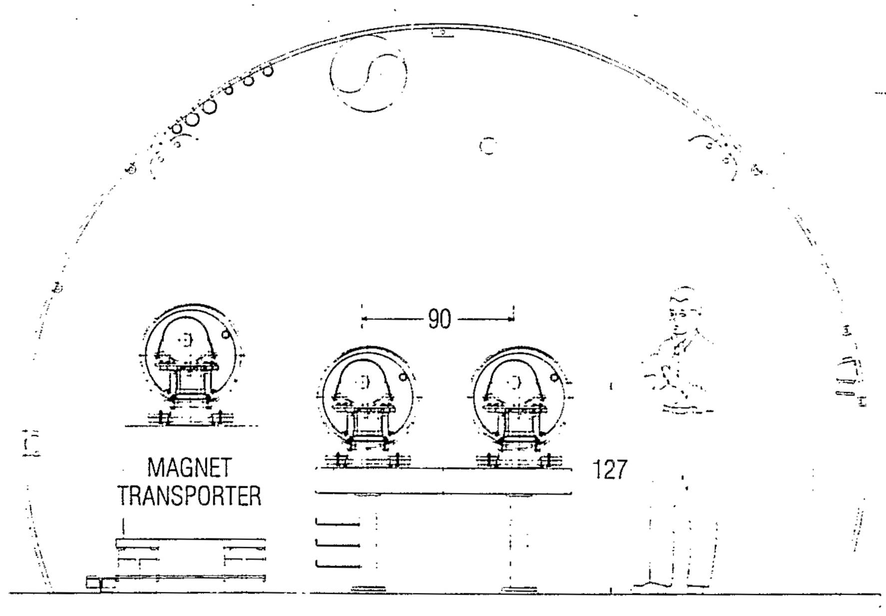

Fig. 3. RHIC tunnel cross section.

Table I. Major Parameters of RHIC Systems

Circumference, 4-3/4 C_{AGS}	3.834	km
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	72	T·m
Magnetic rigidity, $B\rho$: @ 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	400	kV
Storage rf, 160 MHz	11.4 (4.3)	MV
Acceleration time	1	min

Injector

The Tandem-Booster-AGS combination represents a very good injector for RHIC, capable of satisfying the beam parameters assumed for the collider design, e.g., Au bunches with 1×10^9 ions with normalized emittances of 10π 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 transferred to RHIC and is vertically injected by a sequence of septum and kicker magnets as shown in Fig. 4. The requirements for the injection kickers listed in Table I will allow injection of 114 bunches. The intensity of Au beams is source-limited. The May-86 CDR assumed acceleration of fully stripped ions in the AGS. Higher intensities can be obtained by omitting one stripping foil after the Tandem and accelerating partially stripped ions, Au^{77+}, in the AGS. It was decided to take advantage of this possibility in order to allow the booster operation with the presently planned h=3 rf system which is simpler but provides only 10^9 Au-ions per bunch for injection into RHIC. Adding a h=1 rf system in the booster represents a future option to increase the number of ions per bunch.

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. 4 and the beam dump kicker requirements are given in Table I. A 1-μsec gap in the bunch sequence, 13 μsec long, will be provided to minimize uncontrolled beam spill. Although acceptable at the design intensity, the internal beam dump may have to be replaced in the future by a beam extraction system in order to remove the constraints on beam intensity. Adding a septum magnet at the location of the beam dump would allow beam extraction, without requiring other changes to the ring.

rf Systems

The beam will be accelerated with an 26.7 MHz rf system operating on the $h = 6 \times 57$ harmonic. A voltage of about 400 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.

To limit the bunch length and thus the diamond length, a second 160 MHz storage rf system will be installed. The momentum spread of the beam grows in time due to intrabeam scattering; the rf voltage has to follow in order to keep the bunch length constant. The voltage requirements of the 160 MHz rf system for gold and proton beams are shown in Fig. 5 as function of storage time assuming a bucket half height Δ_B equal to twice the rms energy spread δ_E. The bucket half height is related to the voltage V by

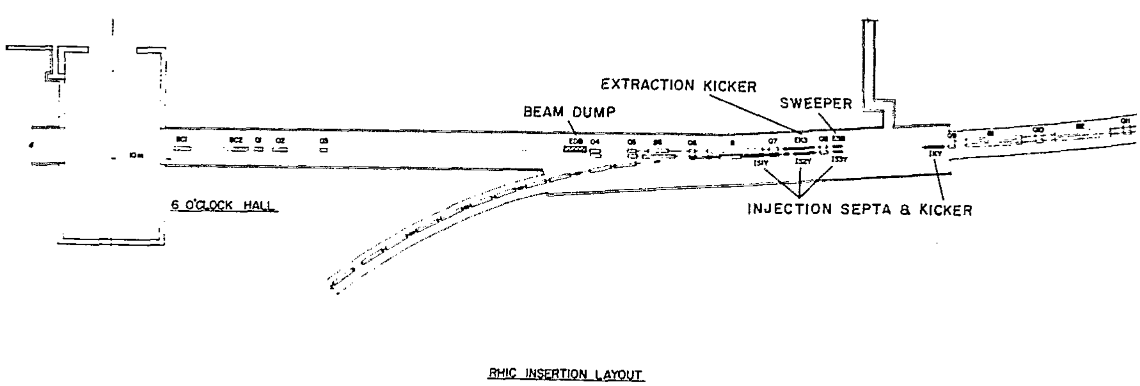

Fig. 4. Six o'clock insertion with injection and beam dump.

$$\Delta_B = \left(\frac{\Delta E}{E}\right)_B = \left(\frac{2}{\pi}\frac{\beta^2 \; e \; V}{h \; |\eta| \; \gamma \; E_o}\frac{Q}{A}\right)^{1/2}$$

with $\eta = \gamma_{tr}^{-2} - \gamma^{-2}$ and A the atomic mass unit, Q the charge state and h the rf harmonic ($h = 2052$ for 160 MHz). The energy spread of gold beams with 10^9 ions/bunch is computed to grow from $\delta_E = 0.25\times10^{-3}$ to 1.14×10^{-3} rms during the 10 h storage time. By continuously changing the rf voltage during this time, the rms bunch length remains constant at 31 cm. The minimal rf voltage at 100 GeV/u is then 11.4 MV, which requires a 160 MHz rf system with 16 cavities per ring.

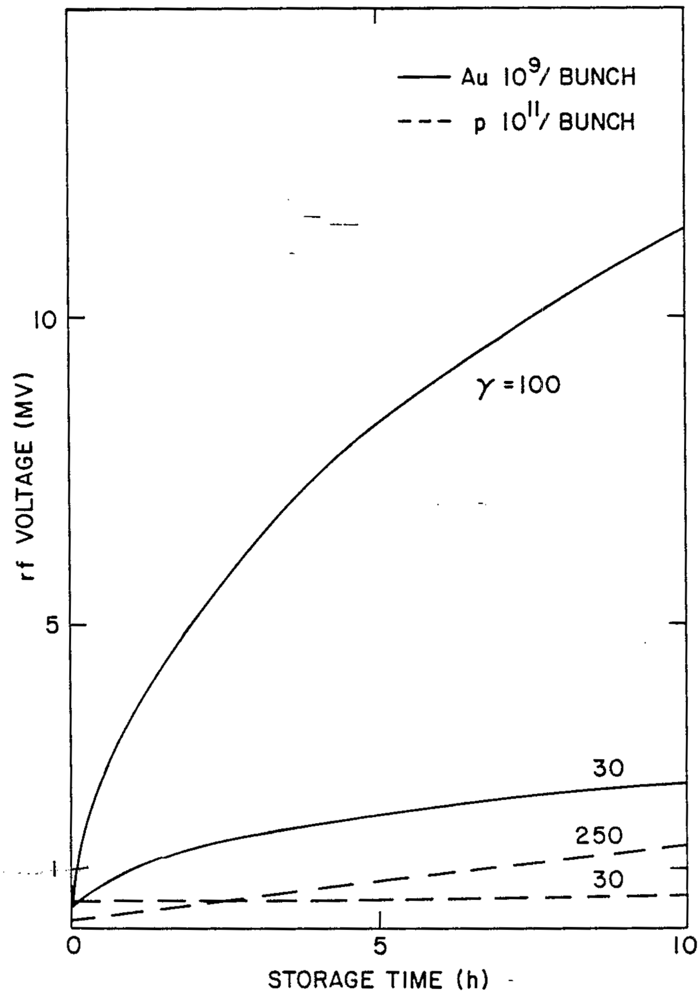

Fig. 5. Voltage requirements of storage rf system for nominal design parameters.

Intrabeam Scattering

The design and the performance of a heavy ion collider is strongly influenced by the beam growth due to intrabeam scattering. The choice of the arc-magnet aperture and of the voltage for the 160 MHz storage rf system depends directly on results from intrabeam scattering computations.[5]

The time dependence of the rms energy spread δ_E and of the transverse rms beam size σ is obtained by integrating the coupled intrabeam scattering differential equations, valid above transition and assuming full coupling ($\varepsilon_H = \varepsilon_V$)

$$\tau_E^{-1} = \frac{1}{\delta_E}\frac{d\delta_E}{dt} = \frac{27\pi}{2} L_g\, r_p^2\, E_o \frac{\langle X_p\rangle}{<\beta>} \frac{\left[\dfrac{<\sigma>}{\langle X_p\rangle\,\delta_E}\right]^2}{\left[1+\left[\dfrac{<\sigma>}{\langle X_p\rangle\,\delta_E}\right]^2\right]^{1/2}} \frac{N_B}{S\,\varepsilon_N^2}\left[\frac{Q^2}{A}\right]^2$$

and

$$\tau_H^{-1} = \frac{1}{\sigma}\frac{d\sigma}{dt} = \frac{1}{2}\left[\frac{<\sigma>}{\langle X_p\rangle\,\delta_E}\right]^{-2} \tau_E^{-1}$$

with the longitudinal bunch area

$$S = 6\pi\,\sigma_\ell\,\delta_E\,\gamma\,E_o/c$$

the normalized 95% transverse emittance

$$\varepsilon_N = 6\pi\,(\beta\gamma)\,<\sigma>^2\,/\,<\beta>$$

and

$$L_g \approx 20$$

where r_p is the classical proton radius, $<X_p>$ the averaged dispersion and $<\beta>$ the averaged betatron function.

[5] G.Parzen, Nucl. Instr. Meth., **A251**, 220 (1986) and **A256**, 231 (1987).

For typical RHIC parameters, intrabeam scattering evolves as follows: Within the first few minutes, the energy spread increases rapidly until equipartition is reached, i.e.,

$$<X_p> \delta_E \approx <\sigma_H>$$

Transverse beam size and beam size due to the energy spread then grow together. Since the bunch length is kept constant by the rf system, the appropriate scaling law is

$$\tau_E^{-1} = \tau_H^{-1} \propto \frac{N_B}{<\sigma>^5} \left(\frac{Q^2}{A}\right)^2$$

It follows that the aperture requirements depend only weakly on the number of particles/ bunch,

$$<\sigma> \propto (N_B)^{1/5} \left(\frac{Q^2}{A}\right)^{2/5}$$

and the voltage requirements follow as

$$\underline{V} \propto (N_B)^{2/5} \left(\frac{Q^2}{A}\right)^{4/5}$$

The differential equations governing intrabeam scattering are believed to be well-understood and reliable. There are, however, uncertainties resulting from the lack of knowledge as to the beam parameters in RHIC after injection and acceleration through transition. In view of these uncertainties which mostly impact the rf voltage requirements and the substantial cost attached to the high-frequency rf system, installation of a lower voltage rf system on day-one would seem advisable.

The impact of operating with an initial emittance larger than the nominal $\varepsilon_N = 10\pi$ mm·rad in order to reduce the rf voltage requirements were studied by Parzen.[6] The results are shown in Fig. 6 from which we conclude that a reduction of the rf voltage from 11.4 to 4.3 MV (6 instead of 16 cavities) is possible by intentionally increasing the initial emittances to 60π mm·mrad which would result in a luminosity reduction by a factor 2÷3 while maintaining the bunch length and the 10-hour lifetime.

[6] G. Parzen, private communication.

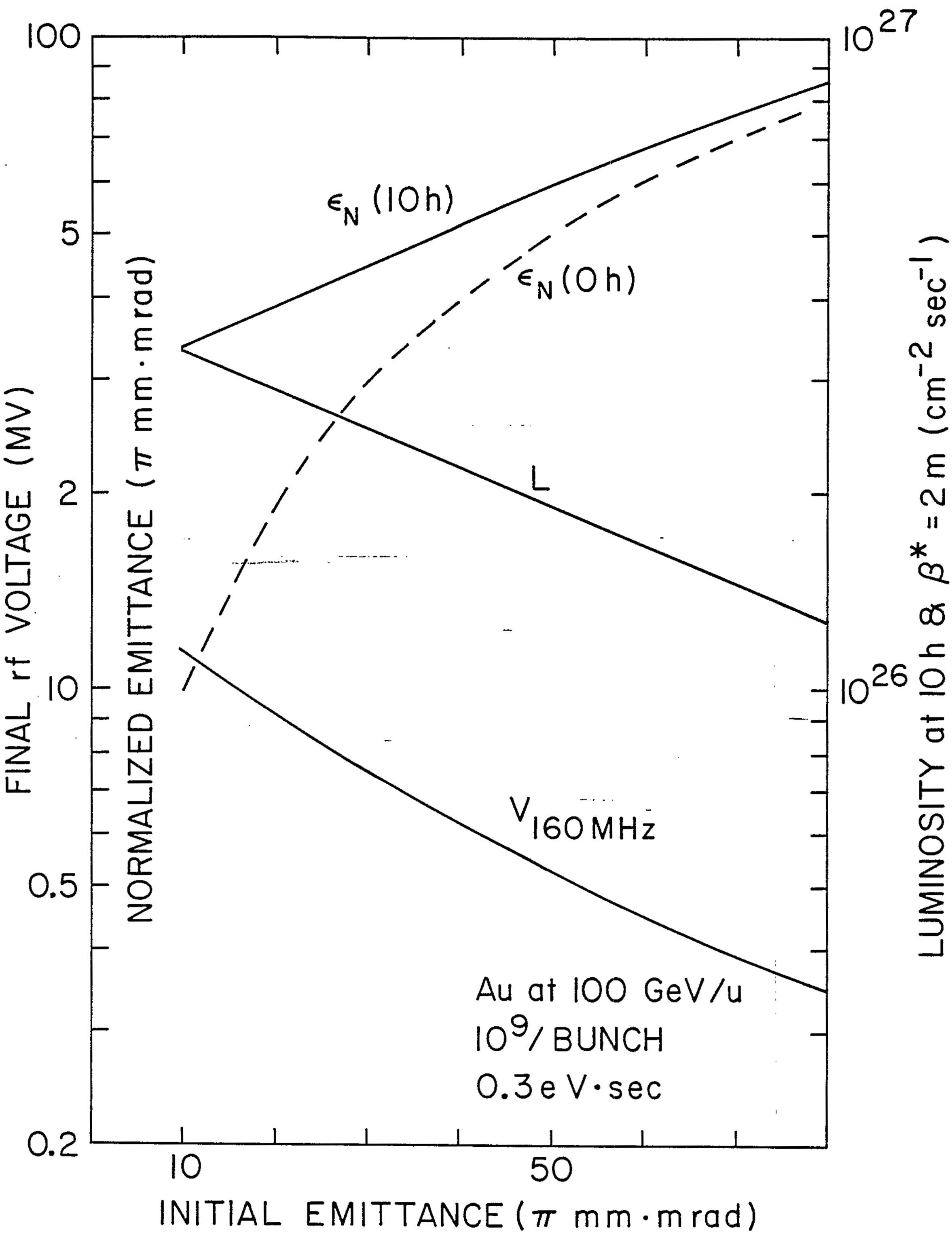

Fig. 6. Dependence of luminosity and rf voltage requirement on initial emittance.

Performance Estimates

The performance objectives for RHIC were first spelled out by a Task Force for Relativistic Heavy Ion Physics in a report[3] 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.

The quench field of the arc dipoles is about 4.6 T which is 30% higher than the 3.45 T required at the design energy of 100 GeV/u and higher operating energies should be achievable. However, the dipole configuration at the crossing point (Fig. 7) is field limited, BC1 to ~4.7 T, and head-on collisions cannot be obtained above design energy.

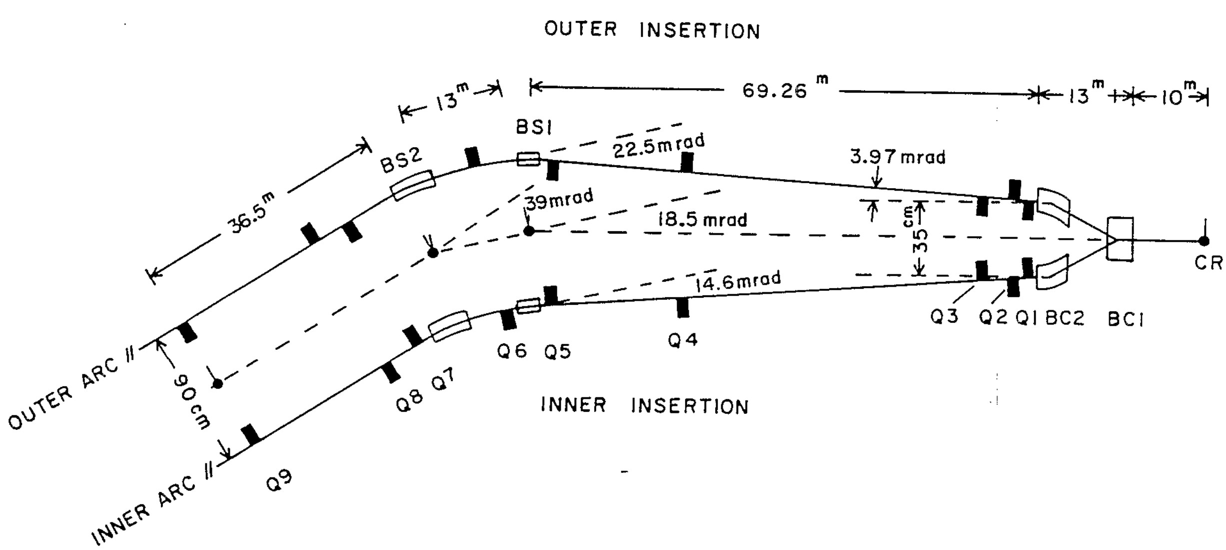

Fig. 7. Insertion magnet layout.

Range of Ion Masses

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

Head-on collisions of Au-p are possible as shown in Fig. 8. Operation with unequal species requires synchronization between the two beams, i.e., equal velocity and the operating field in the proton ring is lowered by the ratio $A/Q \approx 2.5$ for gold. The field in the common dipole BC1 is also lowered resulting in a change of the beam direction at the intersection point by about 3.4 mrad.

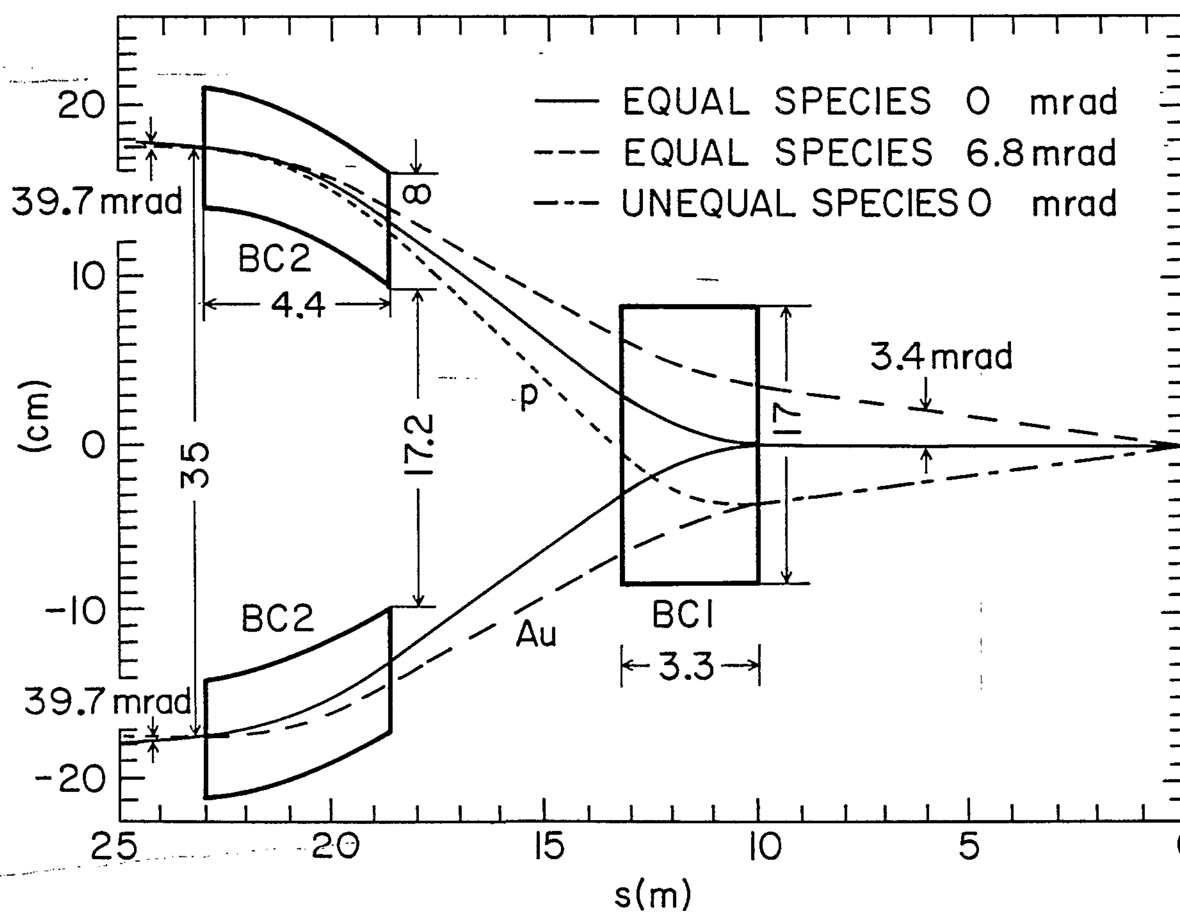

Fig. 8. Beam path at crossing point for Au-Au and Au-p collisions.

Luminosity

The luminosity requirements for initial experiments are rather modest, about 10^{25} cm^{-2} sec^{-1}. The machine is designed for Au-Au collisions with a luminosity of 3×10^{26} cm^{-2} sec^{-1} at top energy while maintaining the option for future upgrades to 2×10^{27} cm^{-2} sec^{-1}.

The maximum luminosity is obtained with head-on collisions of very short bunches, for which one has

$$L_o = \frac{3}{2} f_{rev} \; B \; \frac{(\beta\gamma) \; N_B^2}{\varepsilon_N \; \beta^*}$$

where N_B is the number of particles per bunch, B the numbers of bunches per beam, f_{rev} the revolution frequency, ε_N the invariant transverse 95% emittance, and β^* the beta-function at the crossing point. The design performance parameters for RHIC are given in Table II.

Taking into account a finite bunch length σ_ℓ and crossing angle α, the luminosity is given by

$$L = L_o / \sqrt{1+q^2}$$

with

$$q^2 = \left(\frac{1}{2} \; \frac{\alpha \; \sigma_\ell}{\sigma_H^*}\right)^2 + \left(\frac{\sigma_\ell}{\beta^*}\right)^2$$

where the horizontal rms beam size at the crossing point

$$\sigma_H^* = \left(\frac{\varepsilon_N}{6\pi \; (\beta\gamma)} \; \beta^*\right)^{1/2}$$

The ultimate performance of hadron colliders is limited by beam-beam effects. The experience from the CERN Sp$\bar{\text{p}}$S suggests that the important parameter for long-term stability is the beam-beam tune spread which is given by the sum of the beam-beam tune shifts per crossing

$$\Delta\nu_{BB} = \sum_i \frac{3}{2} \; r_p \; \frac{N_B}{\varepsilon_N} \; \frac{Q^2}{A}$$

with the quantities as previously defined. The observational limit is $\Delta\nu_{BB} < 0.02$, which is not exceeded for the nominal RHIC design.

The beam-beam tune shift is independent of the number of bunches stored as well as of the β^* at the crossing point. Increasing the number of bunches and lowering β^* yields higher luminosities without exceeding the beam-beam limit.

Table II. RHIC Performance Parameters

Revolution frequency	78.2		kHz
No bunches	57		
Bunch spacing	224		nsec
	Au	p	
β^* @ top energy	2	2	m
No particles/bunch	1×10^{9}	1×10^{11}	
Top momentum, $\beta\gamma$	108	268	
Emittance, initial	10	20	π mm·mrad
@ 10 h	34	24	π mm·mrad
Luminosity, initial	11×10^{26}	1.4×10^{31}	cm^{-2} sec^{-1}
@ 10 h	$\sim3\times10^{26}$	$\sim10^{31}$	cm^{-2} sec^{-1}
Beam-Beam tune spread, max	0.014	0.02	
Luminosity expectation†	2×10^{27}	3×10^{32}	

†B = 114, N_B(Au) = 2×10^{9}; N_B(p) = 2×10^{11}, β^*(p) = 0.5 m

Doubling the number of bunches from 57 to 114 requires faster injection kickers, and is an obvious future improvement. Tripling the number of bunches, on the other hand, is incompatible with zero-angle crossing if the present free space from crossing point to BC1 is retained; furthermore, the collision frequency would require improved detector capabilities and this option is not under consideration at present.[7]

Lowering β^* is limited by the aperture of the low-beta quadrupoles. The limit is found from the following approximation

$$\beta^* > (2\ \mathrm{m}) \left(\frac{\varepsilon_N}{34\pi\ \mathrm{mm\cdot mrad}}\right)\left(\frac{100}{\gamma}\right)$$

For gold beams at top energy, $\beta^* \approx 2$ m represents the minimum with the present insertion configuration. For protons at top energy, β^* could be lowered to about $\beta^* \approx 0.5$ m resulting in a luminosity gain of a factor 4 over the nominal design. This upgrade involves new power supplies for the insertion quadrupoles and, possibily, new cryogenic current leads. A further reduction of β^* has little merit due to the $\beta^* > \sigma_\ell$ limit.

By installing additional quadrupoles, common to both rings, a mini-beta insertion with $\beta^* = 1$ m for gold beams could be created.[8] However, the free space available for detectors is reduced to ±5 m and the use of common quadrupoles prevents operation with unequal species. Furthermore, the quadrupoles require larger apertures and higher

[7] W. Willis and T. Ludlam, Proc. Workshop on RHIC Performance, March 88, BNL 41604, p. 239.
[8] S.Y. Lee, "*Mini-Beta Insertion for the RHIC Lattice*", RHIC Technical Note, RHIC-34.

gradients for which no conceptual design has been developed so far. A reduction of the beam life time due to the desired beam-beam nuclear reaction also sets a lower limit on $\beta^* > 1.9$ m.[9] Clearly the mini-beta insertion represents no option for day-one.

The most direct method of increasing the luminosity above the nominal design valve is by way of a larger number of particles per bunch. The beam-beam limit is avoided by reducing the number of collision points used. The maximum N_B is probably limited by collective instabilities, with the transverse single-bunch mode-coupling instability imposing the most severe constraint.[10] Increasing the number of ions/bunch by a factor 2 is quite realistic. Higher intensities impact the accelerator system requirements, in particular the rf system and the beam dump, but are well within the range of available technical solutions.

In summary, one can expect luminosities higher than the design by a factor of

$$2 \times 2^2 \times 4 = 32 \text{ for protons}$$
$$2 \times 2^2 = 8 \text{ for gold–ions.}$$

By using other techniques to improve performance, in particular stochastic cooling, even higher luminosities are possible, but obviously quite uncertain.

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 the crossing angle should be possible.

The rms diamond length σ_I is determined by the rms bunch length σ_ℓ to be for head-on collisions

$$\sigma_I = \sigma_\ell / \sqrt{2}$$

In order to obtain $\sigma_I \leq$ 20 cm, a bunch length of $\sigma_\ell \approx 28$ cm is required. The rms length of the bunches injected from the AGS is about 98 cm for gold and 72 cm for protons. At the end of the acceleration cycle to top energy and transfer into the storage rf system, the rms bunch length is 31 cm for Au and 24 cm for protons. Due to intrabeam scattering the bunch length tends to grow. The bunch length is kept constant by appropriate growth of the rf voltage. The maximum bunch length, which the bunch can assume, depends on the bucket length which is set by the rf frequency. Very short bunches are possible, but a practical limit is given by the voltage requirement and thus

[9] G. Young, Proc. Workshop on RHIC Performance, March 1988, BNL 41604, p. 255.
[10] M.S. Zisman, Proc. Workshop on RHIC Performance, March 1988, BNL 46104, p. 371.

by the cost of the rf system. The choice of a 160 MHz (h = 2052) storage rf system, in addition to the 26.7 MHz (h = 342) acceleration rf system, assures an rms bunch length of

$$\sigma_\ell = \frac{2\ R}{h} \arcsin \frac{\delta_E}{\Delta_B}$$

where R = average machine radius, h = rf harmonic, δ_E = rms energy spread, and Δ_B = bucket height. For the design value of δ_E/Δ_B = 0.5, follows σ_ℓ = 31 cm.

Operation with a finite crossing angle, α, further reduces the diamond length

$$\sigma_I = \frac{\sigma_\ell}{\sqrt{2}\ (1+q^2)^{1/2}}$$

with q as defined above.

However, it may well be that operation with large, finite crossing angles is prohibited by beam-beam excited synchro-betatron resonances if[11]

$$\alpha > \alpha_{SB} = 2\ \sigma_H^* \ /\ \sigma_\ell$$

The maximum acceptable crossing angle is encountered at 30 GeV/u for gold where one finds $\alpha_{SB} \approx 6.8$ mrad. The diamond length at the synchro-betatron limit is $\sigma_I = \sigma_\ell / 2 \approx$ 15 cm rms. In order to provide such a short diamond length, the common dipole BC1 must have an aperture of at least 17 cm. By coincidence, this is also the aperture required for operation of unequal species.

A cost-efficient detector design requires the luminosity in a short diamond length, i.e. a large luminosity density

$$L \ /\ \sigma_I \propto L_o \ /\ \sigma_\ell$$

which is independent of the crossing angle but which can be enhanced by reducing the bunch length. In other words, it is more desireable to reduce the diamond length by shortening the bunch length than by adjusting the crossing angle.

[11] A. Piwinski, CERN Accelerator School, Oxford, England, 1985, CERN report 87-03, p. 187.

Superconducting Magnet System

The superconducting magnet system for RHIC is the one hardware system for which the R&D efforts have advanced beyond the conceptual design stage. The superconducting arc magnets, dipoles, quadrupoles, sextupoles and corrector units 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. Three of these magnets were assembled by an industrial firm using coils wound at BNL. The first of the full-length magnets, assembled at BNL, has been successfully tested in February, 1987. Subsequently the remaining, industrially built magnets in this series have been tested. Two each dipoles (#5 & 6) and quadrupoles were built in 1987/88, of which one dipole and both quadrupoles have been tested individually. Preparations for the in-house construction of two dipoles (#7 & 8) with their folded-post cryostats are in progress. They will then be combined with the existing quadrupoles for a full-cell system test in FY 1989. Preparations for a series of six industrial prototype dipoles are in progress. The major items in the ongoing magnet R&D effort are summarized in Table III.

The first four full-size R&D magnets 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. Dipole #5 & 6 were built with a new coil geometry, increased yoke-coil gap to reduce saturation b_4, and with a ratio of Cu:SC = 2.25 in the superconductor to improve the quench behavior. The quench curve of dipole #5 is shown in Fig. 9. The quench data for the first quadrupole is shown in Fig. 10.

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. The existence of the RHIC tunnel, of course, had a profound impact on the cost optimization, leading to the selection of single-layer, cold-iron, cold-bore arc magnets. 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. The dipole cross section is shown in Fig. 11. The quadrupoles design concepts follow directly the dipole solution as shown in Figure 12. The cross section of the sextupole and trim/corrector magnet models are shown in Figures 13 and 14. Insertion magnets may have special requirements as to aperture and field or gradient, which led to different solutions.

Table III. RHIC Superconducting Magnet R&D

- 4 Full-size arc dipole models with HERA-type cryostats
  DRA001 – DRA004: Tested in FY 87
- 2 Arc dipoles with post-type cryostats
  DRB005: Tested in June 88;
  DRB006: Test in Nov. 88
- 2 Full-size quadrupoles with cryostats
  QRA001: Tested in June 88
  QRA002: Tested in Sept. 88
- 2 Sextupoles: First test in July 88
- 2 Correctors: Test in Nov. 88
- Preparations for 2 prototype dipoles (#7 & 8) with improved post-type cryostat
  Test in Apr. 89 / June 89
- Full-cell system test
  (FY 89)
- Preparations for 6 industrial arc dipole prototypes
  (FY 89 & 90)

The major arc magnet parameters are listed in Table I. 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.

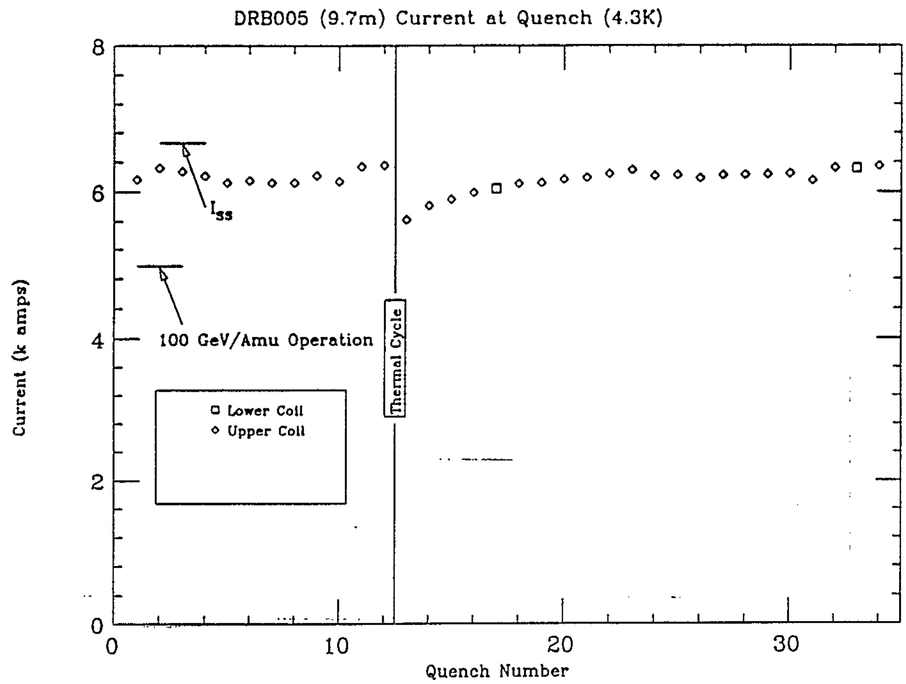

Fig. 9. Quench curve of RHIC dipole prototype.

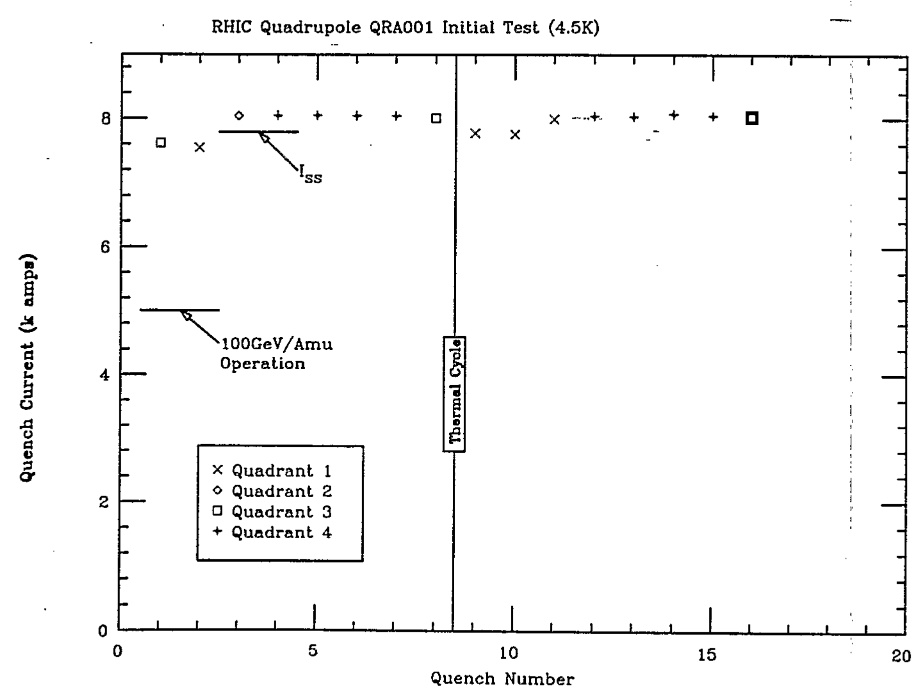

Fig. 10. Quench curve of RHIC arc quadrupole.

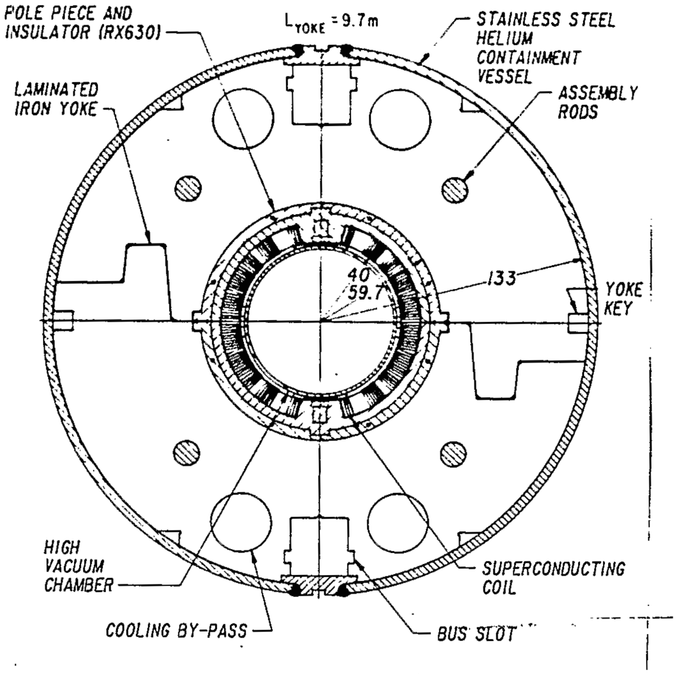

Fig. 11. RHIC arc dipole cross section.

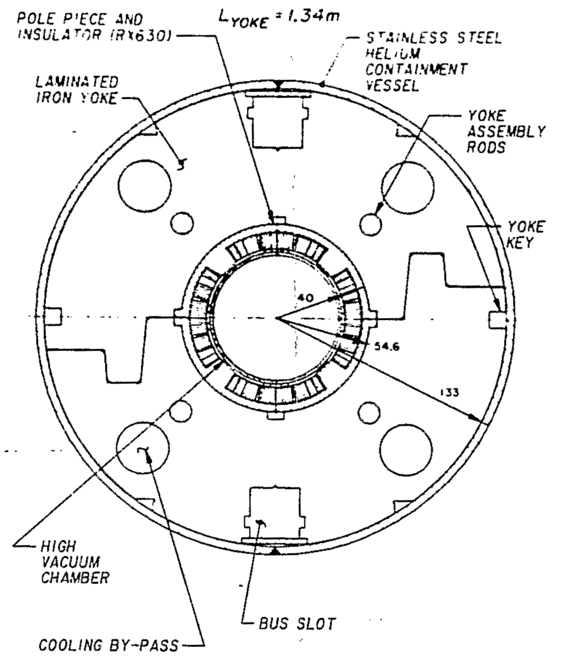

Fig. 12. RHIC arc quadrupole cross section.

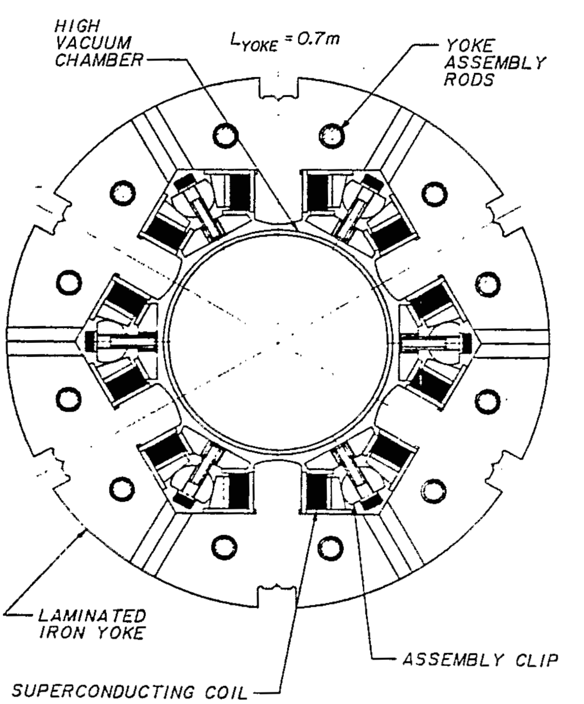

Fig. 13. RHIC arc sextupole cross section.

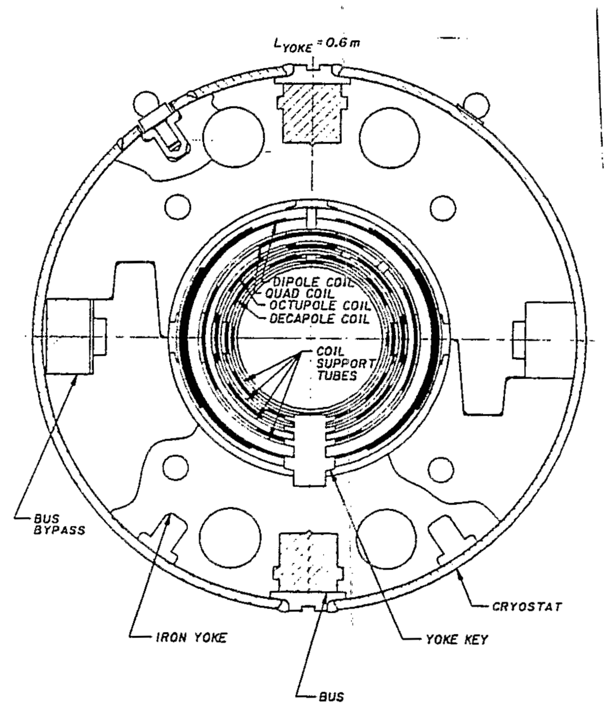

Fig. 14. RHIC arc corrector cross section.

The cross section of the RHIC dipole cryostat is shown in Fig. 15. The design follows largely the concepts developed for SSC cryostats, in particular in the use of a folded-post support. 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, recooler units are installed in each sextant. The total estimated heat load is about 10 kW, which is sufficiently lower than the 25 kW @ 4.3 K capability of the operational CBA refrigerator.

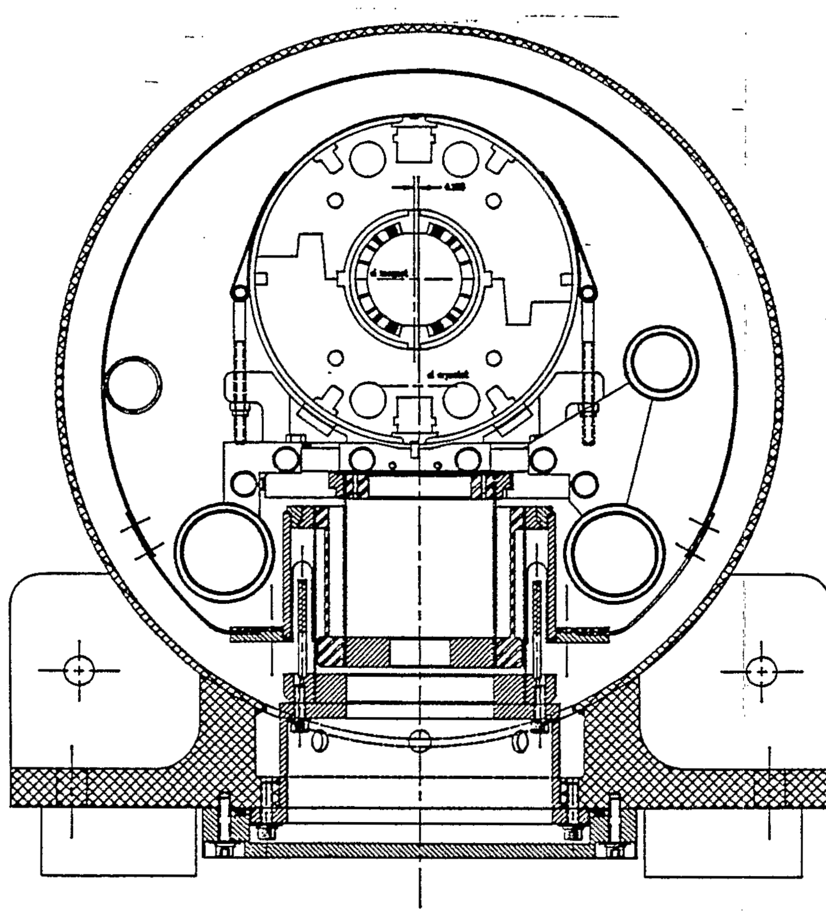

Fig. 15. RHIC dipole cryostat.

The Present Status

As noted above, a large fraction of the RHIC facility already exist. 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, and preparations for a series of six industrial prototype dipoles are in progress. The project has been reviewed and validated by the U.S. Department of Energy. The construction of this accelerator/collider which is planned to start in Fiscal Year 1990 would take about six years and allow the start of an experimental program in 1996.

Acknowledgements

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