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The Relativistic Heavy Ion Collider *
Project at Brookhaven

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Abstract

The Relativistic Heavy Ion Collider (RHIC) facility will provide collision energies of 100 GeV/nucleon per beam for heavy ions as massive as gold. RHIC will use the existing Brookhaven AGS and Tandem Van de Graaff as injector. The new accelerator facility, which is a nuclear physics initiative, will utilize the existing facilities of the partially completed CBA project. This report discusses the physics motivation for such a facility, the status of the machine design, R&D work and preparations for experiments at RHIC.

I. Introduction

At this conference we have seen some of the first results[1] from experiments with high energy nuclear beams at Brookhaven and CERN. These experiments, which began within the past year, use fixed targets at the AGS and SPS. These programs have begun with relatively light ions ($A \lesssim 32$ amu) to explore states of compressed nuclear matter in which high energy density is achieved in an environment of high baryon density at energies near the maximum for nuclear stopping.

The widespread interest and excitement which these experiments have generated is due in large part to the fact that they are providing the first glimpse of what is expected to be a whole new regime of physical phenomena,

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[1]Presentations at this conference by O. Hansen, D. Lissauer, W. Willis.

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

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and that these experiments will be followed in the near future by measurements with much higher beam masses and much higher collision energies.

In the next 2-3 years it will be possible to extend the mass range of the AGS beams, with a Booster Synchrotron, to cover essentially the entire periodic table up to $A \simeq 200$. The next goal is then to reach much higher energies with colliding beams of heavy ions, creating the thermodynamic conditions of high temperature and energy density at which the formation of a deconfined plasma of quarks and gluons is predicted.[2]

The essential motivation for colliding heavy nuclei at high energies is the production of nuclear matter at extreme conditions of temperature and baryon density: extended volumes of hadronic matter with energy densities greater than 10 times that of the nuclear ground state should be realizable. The specific motivation from the theory of quantum chromodynamics (QCD) is the belief that macroscopic volumes of nuclear matter can be assembled at such extreme thermodynamic conditions as to overcome the forces that confine constituents in normal hadrons, resulting in a phase transition creating a new form of matter in an extended confined plasma of quarks and gluons. The physics issues underlying the production and detection of this new state of matter have been the subject of a series of recent conferences.[3] Studies with a variety of theoretical methods have led to the basic expectation that

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[2]See, for example, H. Satz, Ann. Rev. of Nuclear and Particle Science, 5, 245 (1985).

[3]M. Gyulassy and L. Schroeder (eds.), Fifth Int'l Conf. on Ultra-Relativistic Nucleus-Nucleus Collisions (Quark Matter '86), Asilomar, CA, USA, April 13-17, 1986. Proc. Nuclear Physics Vol. A461 (1987).

at an energy density of approximately 1 GeV/fm^3 nuclear matter must undergo a change of phase to a state in which quarks become free to move about within a confinement volume much larger than hadronic sizes. These theoretical expectations are illustrated on the phase diagram of nuclear matter shown in Fig. 1.

Such high energy densities are conjectured to have prevailed in the very early universe, a few microseconds after the Big Bang. They may exist today within the cores of neutron stars. The possibility of creating these conditions for investigation in the laboratory is one of the great challenges for modern experimental physics.

Calculations based on the measured properties of high energy hadron-hadron and hadron-nucleus interactions,[4] as well as information from high energy nucleus-nucleus collisions observed in cosmic ray data, show that energy densities of this order can be reached, over the range of temperature and density conditions exhibited in Fig. 1, in accelerator-produced collisions of heavy nuclei.

Recent theoretical results[5] indicate a second phase transition, coupled to the deconfinement transition, possibly at somewhat higher energy density, in which chiral symmetry is restored. Inducing this transition would bring us yet closer to the elementary states of matter, as it is the

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[4]See, for example, J.D. Bjorken, Phys. Rev. D27, 140 (1983); J. P. Blaizot and A. H. Mueller, "The Early Stage of Ultra-Relativistic Heavy Ion Collisions," Saclay PhT/87-022 (1987).

[5]See, for example, H. Satz, Ann. Rev. of Nuclear and Particle Science, 5, 245 (1985).

spontaneous breaking of chiral symmetry in ordinary hadronic states which gives the pion a nonzero mass.

With ion collisions at very high beam energies we expect to achieve not only extreme baryon density (moving out along the horizontal axis of Fig.1) but also produce the case of extremely high temperature at near-zero baryon density (moving along the vertical axis of Fig. 1). The latter conditions approximate those of the very early universe, as the cooling cosmos condensed from one of quarks to one of hadrons. Such conditions are expected to be achieved in the central rapidity regions of high energy heavy ion collisions; the energies required to do so call for a colliding beam facility, as illustrated in the kinematic diagram of Fig. 2.

II. The RHIC Design

The concept of a heavy ion collider facility, which would reach center-of-mass collision energies at least 10 times higher than the fixed target experiments, has been identified as a high priority need in the Long Range Plan for basic nuclear research as outlined by the U.S. Department of Energy and National Science Foundation[6]. At Brookhaven the Relativistic Heavy Ion Collider (RHIC) project has been designed[7] to provide this facility, utilizing the AGS accelerator complex as injector to a dedicated

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[6] "A Long-Range Plan for Nuclear Science," report of DOE/NSF Nuclear Science Advisory Committee (Dec. 1983).

[7] "Conceptual Design of the Relativistic Heavy Ion Collider (RHIC)", Brookhaven National Laboratory Report BNL 51932 (May, 1986).

heavy ion collider in the CBA tunnel with its existing experimental halls, support buildings and liquid helium refrigerator.

The system of accelerators which comprise the Brookhaven heavy ion program is illustrated in Fig. 3. Ions are injected into the AGS through a long transfer line from the Tandem Van de Graaff accelerator. The commissioning of ion beams accelerated in the AGS took place during this past year, and marks the first step in a long term plan for heavy ion physics at BNL, a summary of which is given in Table I.

Table 1. Heavy Ion Facilities at BNL

1986 Begin AGS Fixed Target Experiments

Beam Energy: Up to 28 $(\frac{Z}{A})$ GeV/amu

Ion Species: ^{1}H to ^{32}S

Flux: $\approx 10^{9}$ ions/pulse

Running Time: 5-10 weeks/year

1989* AGS Experiments with Booster Synchrotron

Extend ion mass to A ≈ 200 (Au)

1992* Begin RHIC Collider Experiments

Beam Energy: Up to 250$(\frac{Z}{A})$ GeV/amu per beam in collider mode

Ion Species: ^{1}H to ^{197}Au

Total c.m. collision energy:

500 GeV (protons) 40,000 GeV (Au)

Luminosity: $10^{31}cm^{-2}sec^{-1}$ $5x10^{26}cm^{-2}sec^{-1}$

*(indicates proposed dates)

In 1986 Brookhaven received the first construction funds from the U.S. Department of Energy for the Booster Synchrotron as part of a general program to improve the AGS performance[8]. Present plans forsee completion in 1990. In addition to increased proton intensity for the high energy physics experimental program, the Booster will extend the heavy ion mass range to gold nuclei.

The basic parameters of the RHIC facility are illustrated in Fig. 4. The design calls for a top beam energy of 100 GeV/nucleon for ions of mass A=200, and the acceleration of ion masses spanning the full periodic table. The complete accelerator complex, consisting of Tandem, Booster, AGS and RHIC will provide c.m. collision energies for gold beams ranging from 1.5+1.5 GeV/nucleon to 100+100 GeV/nucleon. This energy range is covered with no inaccessible gaps, and adequate beam intensities throughout. Because operation in the collider mode at very low energy would require very large aperture (and therefore very costly) magnets--much more so than is required at the top energies--the energy range is covered in three segments: As shown in Fig. 4, the range between fixed target AGS experiments and high energy collider operation is spanned by using one of the RHIC beams striking a fixed target. For this operation an internal gas jet target would be used.

The layout of the RHIC collider is shown schematically in Fig. 5. The circumference of the collider is 3833 meters. It consists of two accelerator rings with six crossing regions (insertions) where the counter-rotating beams are brought into collisions and experiments carried out. Particle bunches

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[8]"Design and Status of the AGS Booster Accelerator", E. B. Forsyth and Y. Y. Lee, Brookhaven National Laboratory Report BNL 39298 (1987).

accelerated in the AGS to top energy (28 GeV for protons; 11 GeV/amu for gold) are transferred to the collider by a magnet system installed in the existing transfer line tunnels. Single bunches of ions are injected 57 times into each ring in boxcar fashion. Filling time per ring will be about 1 minute. For gold, as an example, there will be ~ 1.1×10^{9} ions/bunch, or 6×10^{10} ions in 57 bunches in each ring. For the lightest ions, hydrogen and deuterium, approximately 10^{11} ions/bunch can be stored in the machine. Acceleration will take approximately 60 seconds. Bending and focussing of the ion beams is achieved with superconducting magnets. Given that the machine will be built in the existing CBA tunnel, a cost optimization is achieved by filling the circumference with relatively low field magnets. The maximum energy of 100 GeV/amu for gold ions (250 GeV for protons) is reached with a magnetic field of 3.4 Tesla. Maximum operational flexibility is obtained with the magnets of each ring in separate vacuum vessels, with the beams in the arcs separated by 90 cm. Figure 5 illustrates a half-cell of the arc magnet lattice, consisting of a dipole, two quadrupoles, and lumped corrector coils.

The six beam crossing regions are designed to accommodate a range of configurations to fulfill the needs of experiments. As illustrated in Fig. 6, these include head-on collisions of beam bunches as well as a range of crossing angles. The free space available for experimental equipment in each crossing region is 9 meters on either side of the intersecting point. For head-on collisions with gold ion beams at top energy, a luminosity of 4.4×10^{26} cm^{-2} sec^{-1} averaged over a 10 hour beam lifetime is expected. For protons the expected luminosity is about 8×10^{30} cm^{-2} sec^{-1}. These maximum

values will be decreased by a factor of ~ 4 for a beam crossing angle of 2 mrad. Collisions of unequal species, e.g. protons in one beam and gold ions in the other will be possible as well.

III. 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 refrigerator has a capacity of 25 kilowatts at a temperature of 4.3K. The estimated heat load for RHIC is ~10 kilowatts at 4.6K.

The superconducting magnets for RHIC have been designed and they constitute the largest component of the construction cost. The arc dipole magnet cross section is shown in Fig. 7. The dipole magnets are of cosθ coil geometry with coil i.d. of 8.0 cm and yoke length 9.7 meters. These magnets will operate at relatively low fields (3.4 Tesla for the highest beam energy) and are designed for simplicity of manufacture using a single layer of superconducting coil. It is planned that most of the magnets for the RHIC machine will be industrially fabricated. Figure 8 shows a magnet assembly, consisting of a dipole, quadrupole and corrector coils, mounted in a cryostat.

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An R&D program is underway at Brookhaven to develop the final design and specification of these magnets. A series of half-length magnets has been built and tested. The laboratory is currently testing a series of full-size, pre-production dipole magnets, including some which have been manufactured in industry. Four full-length, field quality dipole magnets have been built during the past year, using coils wound at BNL. Three of these magnets have been assembled by the industrial firm Brown, Boveri Corp. (BBC) of Mannheim, West Germany, using tooling fixtures which are in place for the HERA project at DESY. An agreement has been reached between BNL and DESY whereby this tooling will become available for the manufacture of RHIC magnets in exchange for BNL assistance in the superconducting and cryogenic design for HERA. The first of the full-length magnets, assembled at BNL, was successfully tested in February, 1987. A second magnet in the series, industrially built, was tested two weeks prior to this conference. Both magnets reached fields of approximately 4.6 Tesla, or 35% higher than the operating field for RHIC.

The magnet R&D program is continuing, with work now in progress on quadrupoles, corrector coils and the specialized magnets needed for the beam crossing regions. A full cell of arc magnets, consisting of two dipoles, two quadrupoles and lumped corrector package, will be installed and tested prior to the production of final magnets.

The current planning calls for construction of the RHIC facility to begin in October 1988, with completion in the fall of 1993. The accelerator construction cost is roughly 200 million dollars, with an additional 70 million dollars budgeted for detectors (these figures are in FY 1988 U.S. dollars).

IV. Experiments and Detectors

Of the six crossing regions built into the RHIC rings, those at the 2, 4, 6 and 8 o'clock positions have completed experimental halls, including support buildings and (except in the 4 o'clock "open area") crane coverage. The RHIC plan calls for mounting experiments initially in these four areas, leaving the remaining two unfinished until some later time.

The nature of these experiments, and specific designs for detectors have been studied by a number of groups at workshops and conferences over the past several years[9,10,11,12]. The measurement capability required for such experiments is similar to that which exists in spectrometers for high energy elementary particle experiments, but there are important differences. The most striking is the extraordinary level of particle multiplicities which experiments must deal with in high energy nucleus-nucleus collisions:

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[9] W. Willis and C. Chasman, Quark Matter '83, Proc. 3rd Int. Conf. on Ultra-Relativistic Nucleus-Nucleus Collisions (T. Ludlam and H. Wegner, eds.), Nucl. Phys. A418, 413 (1984).

[10] L. Schroeder, ed., Proc. of the Workshop on Detectors for Relativistic Nuclear Collisions, Lawrence Berkeley Laboratory LBL-18225 (1984).

[11] P. Haustein and C. Woody, eds., Proc. of the Workshop on Experiments and Detectors for a Relativistic Heavy Ion Collider, Brookhaven National Laboratory, BNL 51921 (1985).

[12] T. Ludlam, Quark Matter '86 (Ref. 3), p. 443 (1987). In the same volume see also: C. Fabjan, p. 371; M. Albrow, p. 417; N. DiGiacomo, p. 403 H. Gordon, p. 395; C. Gruhn, p. 375; S. Lindenbaum et al., p. 431.

Estimates for RHIC reach up to ~10,000 particles per event. In addition, most of the essential measurements involve soft particles, with transverse momenta and pair masses characteristic of the kinetic energies in a thermalized plasma of quarks and gluons. This is in contrast with the elementary particle case where the focus is largely on rare processes produced in the high P_T tails of momentum distributions. In April 1985 a workshop involving about 100 nuclear and high energy physicists provided preliminary designs and cost estimates for a first-round suite of detectors for RHIC. The proceedings[13] from the workshop are available, and provide a detailed discussion of physics goals and conceptual designs for detector systems. This work was followed up in discussions at the 1986 Quark Matter meeting at Asilomar[14]. These efforts have continued, with individual working groups holding small meetings at BNL, CERN and elsewhere. In May of this year another week-long workshop will be held, at Lawrence Berkeley Laboratory. If funding authorization for the project proceeds according to the proposed schedule, it is anticipated that letters of intent for experimental proposals will be called for early in 1988, with the first completed proposals for RHIC experiments to be submitted in the spring of 1989.

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[13] P. Haustein and C. Woody, eds., Proc. of the Workshop on Experiments and Detectors for a Relativistic Heavy Ion Collider, Brookhaven National Laboratory, BNL 51921 (1985).

[14] T. Ludlam, Quark Matter '86 (Ref. 3), p. 443 (1987). In the same volume see also: C. Fabjan, p. 371; M. Albrow, p. 417; N. DiGiacomo, p. 403 H. Gordon, p. 395; C. Gruhn, p. 375; S. Lindenbaum et al., p. 431.

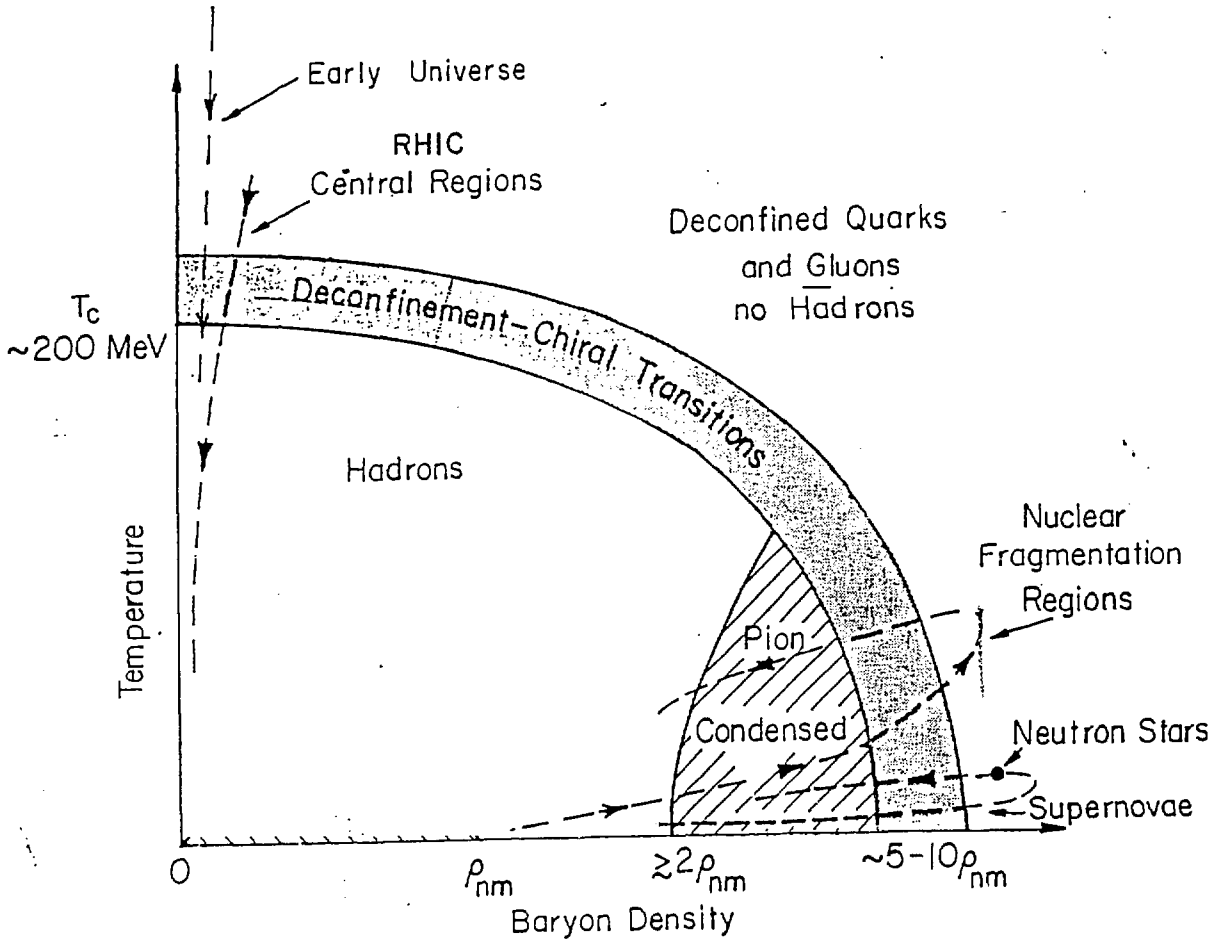

Fig. 1. Phase diagram of Nuclear Matter. Temperature is plotted vs. net baryon density for an extended volume of nuclear matter in thermal equilibrium. Normal nuclear matter appears at the point ρ_{nm} at zero temperature, and this is the neighborhood explored by low energy nuclear physics. The region of the phase transitions corresponding to deconfinement (at temperature T_C) and chiral symmetry restoration is indicated. The indicated trajectories show two avenues for probing the quark-gluon plasma with high energy nucleus-nucleus collisions: by reaching high baryon densities among the hot, compressed fragments of the colliding nuclei, and at very high temperatures in the central rapidity region among thermally produced particles where conditions may approximate those of the early universe.

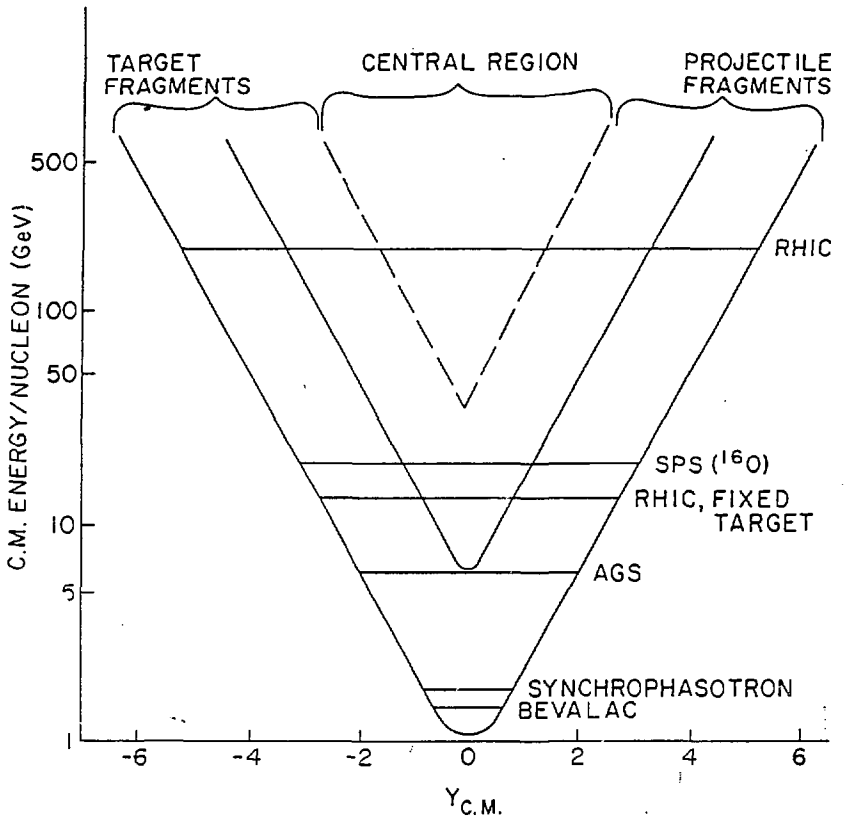

Fig. 2. The kinematic landscape available to the RHIC facility and some existing machines. The outer "vee" is the phase space limit--the rapidity of the incident nucleons. The inner, solid vee delineates fragmentation regions of width $\Delta y = 2$, as observed in proton-proton collisions. The dashed lines indicate the wider ($\Delta y = 4$) fragmentation regions--and hence narrower central region expected at a given energy for nucleus-nucleus collisions with $A = 200$. The horizontal lines indicate energies reached with the components of the AGS/RHIC complex, as well as in the facilities which presently exist (LBL Bevalac, Dubna Synchropasotron) and the oxygen and planned sulfur beams in the CERN SPS.

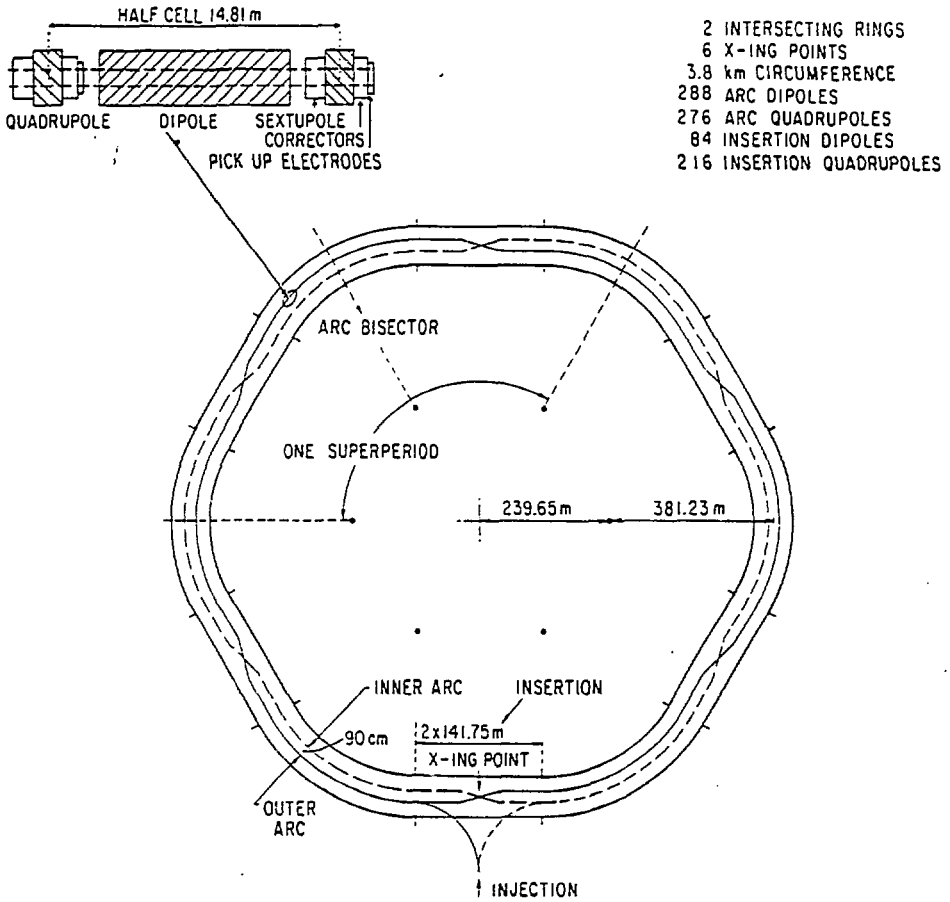

Fig. 3. Site map of present and proposed accelerators at Brookhaven. The Tandem Van de Graaff and the AGS with its linac injector are existing machines. The Booster Synchrotron for pre-injection to the AGS is currently under construction. The RHIC colliding beams accelerator to the north of the AGS complex is a proposed construction project.

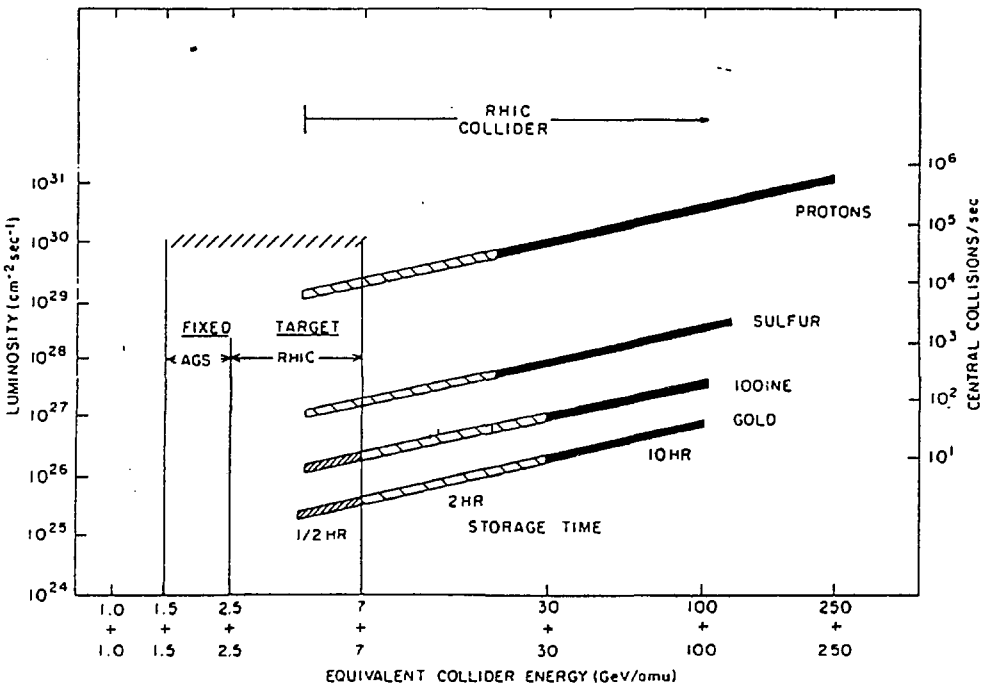

Fig. 4. The design luminosity, for various ion masses, as a function of collision energy over the full range accessible with AGS and RHIC. On the left-hand scale, central collisions correspond to impact parameter less than 1 fermi.

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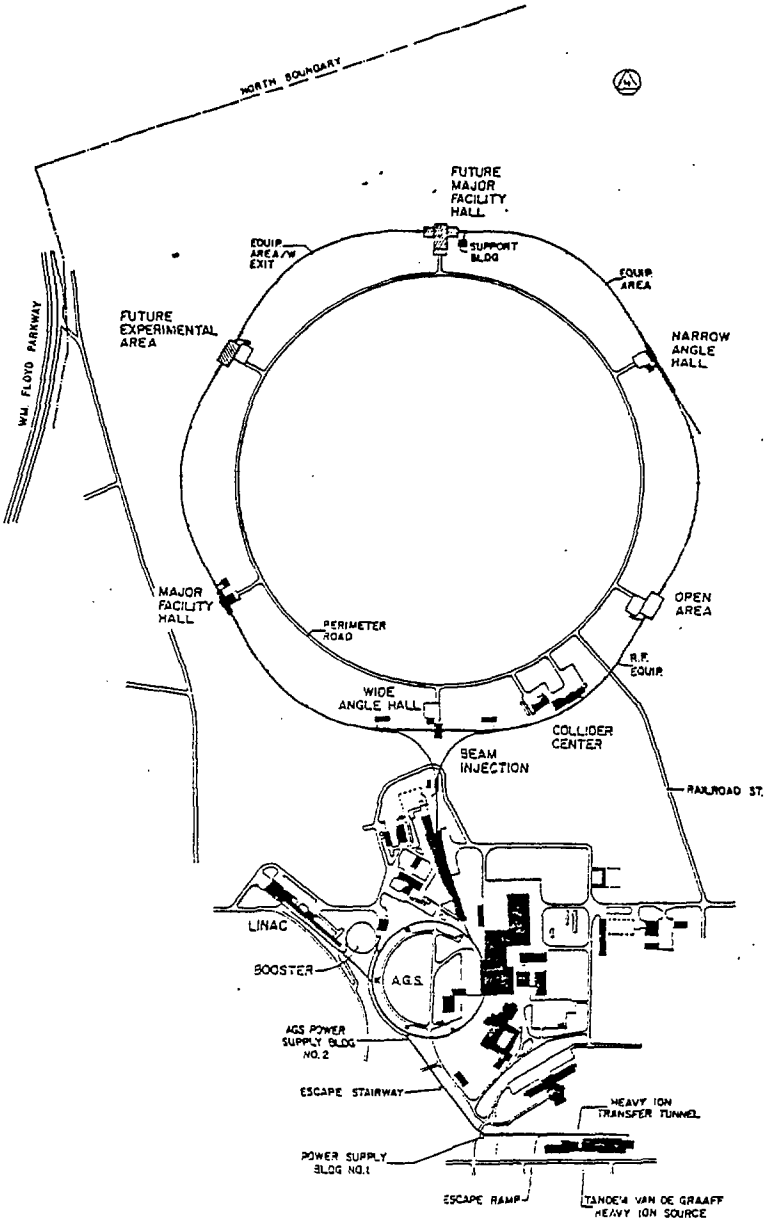

SITE MAP

Fig. 5. Layout of the Collider.

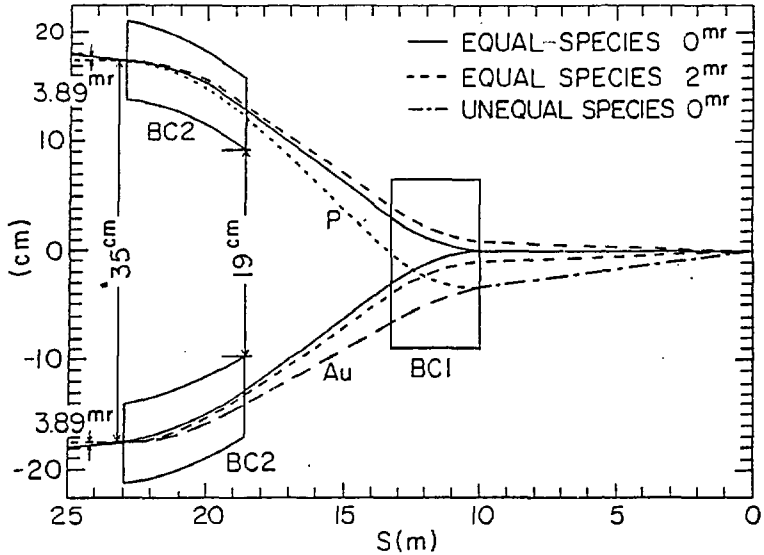

Fig. 6. Beam crossing geometry. BC1, BC2 are dipole magnets. The distance from the crossing point is denoted by S.

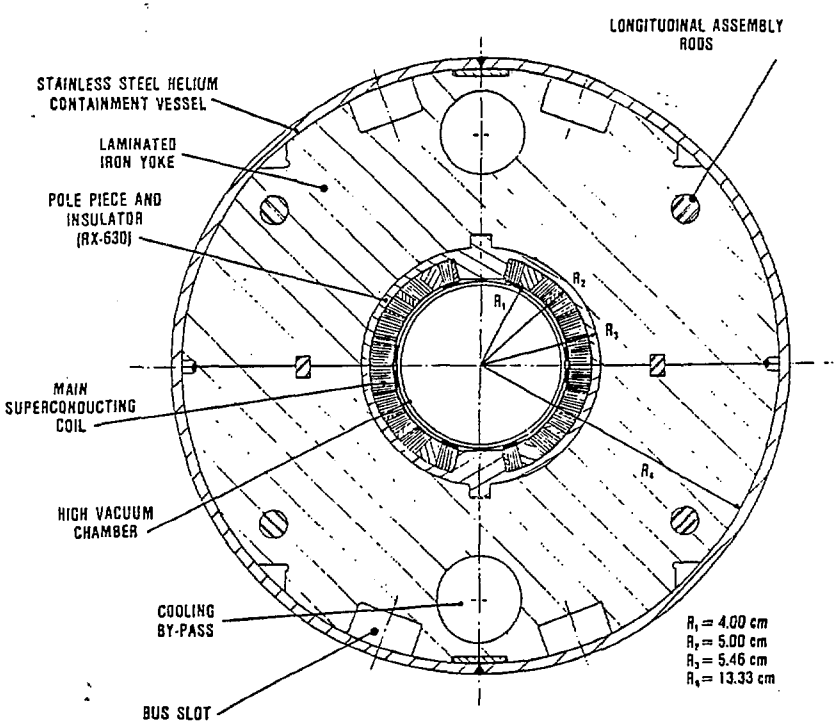

Fig. 7. Cross section of RHIC dipole magnet.

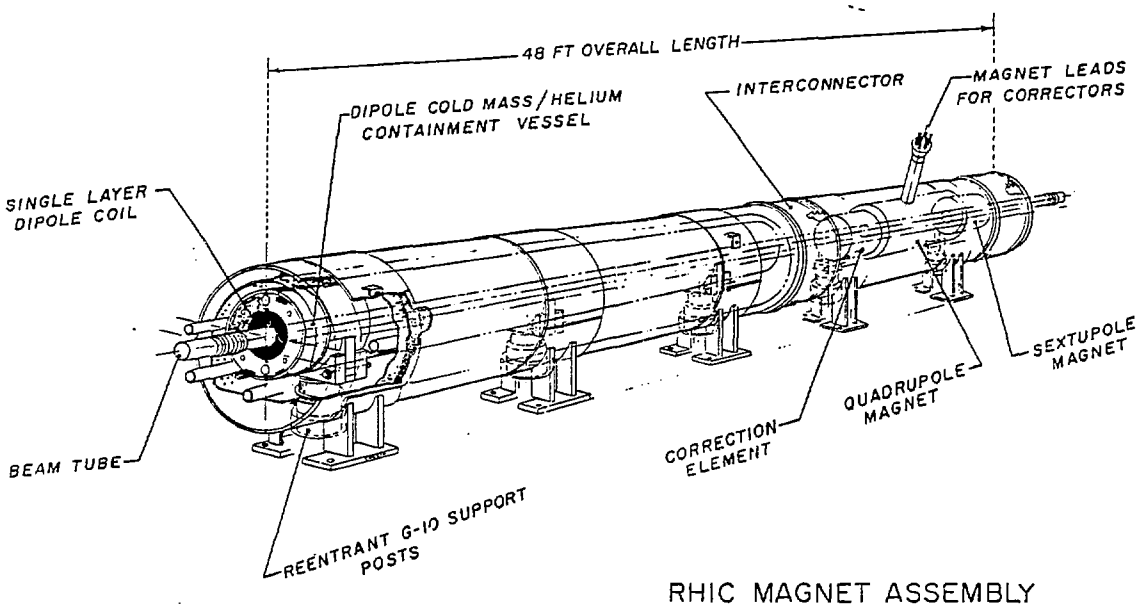

Fig. 8. RHIC magnet assembly: The drawing shows a half-cell of the arc magnet lattice, including a dipole, corrector package, quadrupole and sextupole magnets enclosed in their cryostat.