THE RELATIVISTIC HEAVY ION COLLIDER (RHIC)
PROJECT AT BROOKHAVEN*

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I. THE RHIC CONCEPT

High energy and nuclear physics have undergone extraordinary changes during the past fifteen years. The existence of quarks as the elementary constituents of hadronic matter has been confirmed, and the field of nuclear physics has embraced a wide-ranging program of research to study the structure of nuclear matter in terms of the quark degrees of freedom. As a result the characteristic energy of nuclear collision experiments is no longer confined to the few MeV range of traditional nuclear structure experiments, exploring a system of neutrons and protons, but extends into the many-GeV range which once was the exclusive domain of particle physics. This has led to a new generation of large accelerator facilities for nuclear physics. One example of these is the CEBAF 4 GeV electron beam facility now under construction in New Port News, Virginia.

The most spectacular of the new high energy approaches to nuclear physics is in the field of relativistic heavy ion collisions, for which it is anticipated that construction of the RHIC facility will begin soon. Here the goal is to subject large volumes of nuclear matter to such extreme conditions of temperature and pressure that a new form of matter is produced in which the recognizable components are not the familiar neutrons and protons, but are quarks.

The thermodynamic conditions required to bring about this phase transition from ordinary nuclear matter to a plasma of quarks and gluons can be estimated from the observed properties of quarks in high energy scattering experiments, and detailed theoretical studies can be carried out via quantum chromodynamics. The interesting temperatures are of the order of 100-200 MeV, and the corresponding densities about 10 times that of ordinary nuclear matter. These conditions are characteristic of the expanding universe a few microseconds after the Big Bang. The relevant densities might be attained in the cores of neutron stars. The possibility of exploring, in the laboratory, nuclear matter under such extreme conditions has sparked the recent widespread interest in colliding heavy nuclei at very high energies.

During the past two and a half years the first steps have been taken to carry out this kind of research. Ion beams have been accelerated in the Brookhaven AGS (14.5 GeV/u) and the CERN

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SPS (200 GeV/u). These beams, impinging on fixed targets, provide c.m. collision energies which are about an order of magnitude below the values which are ultimately desired. To date, the accelerated ion beams have been limited to nuclei of relatively low mass ($A \leq 32$). Nonetheless, important new data have resulted:¹ These experiments have established that states of compressed nuclear matter can be created and studied under laboratory conditions in which extreme values of energy density are achieved. The general characteristics of the observed events bear out the theoretical expectations for large thermal energy deposition in violent nuclear collisions, and they point the way for extending further the range of thermodynamic conditions over which to study new forms of dense hadronic matter. The most exciting results are the several indications that, indeed, when these extreme conditions are reached, there are new physical phenomena to be explored.

The planning for future facilities in both the U.S. and Europe call for a continued pushing back of the frontiers of this new field. Within a few years it will be possible to accelerate the heaviest nuclei (e.g., gold, lead, uranium) at both the SPS at CERN and the AGS at Brookhaven. The next step is the realization of RHIC in which high energy colliding beams will be available in a dedicated facility for heavy ion research.

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 an energy of 14.5 GeV/u. 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 collider² consists of two rings of superconducting magnets for accelerating and storing circulating beams of ions. The facility will have the flexibility of using the full range of ion species from protons to gold, and will cover the entire range of collision energies from those available at the Brookhaven Alternating Gradient Synchrotron (AGS) up to the top collider energy (100 GeV/AMU for gold beams). Average luminosities (particle fluxes) of $10^{26} - 10^{27} \text{ cm}^{-2} \text{ sec}^{-1}$ are predicted for gold-on-gold collisions at full energy, depending on the details of the experimental layout. Proton energies up to 250 GeV in each beam will be available at luminosities of about $10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$. The capability for collisions between different species will also be provided. The RHIC ring lattice has six crossing regions where the beams collide and experiments can be performed. Four of these

experimental areas will be utilized initially, with the remaining two available for future expansion of the research program. RHIC will use the existing AGS and Tandem Van de Graaff accelerator complex at Brookhaven as an injector. The new accelerator will be built in the existing CBA tunnel (3.8 km circumference), and will utilize the experimental halls, support building and liquid helium refrigerator from the partially completed CBA project. The RHIC project is proposed to begin construction in 1991, with the first collider experiments beginning in 1996.

II. INJECTORS AND MACHINE PERFORMANCE

The RHIC facility is designed to incorporate the flexibility to study collisions of all nuclei, from the lightest to the heaviest, and allow experiments to be carried out over the full range of energies, from a few GeV/u in the c.m. (AGS fixed target) up to the top collider energy, with no inaccessible gaps, and with adequate intensity for sensitive experiments. A plot of luminosity vs. energy for various ion species, with corresponding beam lifetime is shown in Fig. 2.

As discussed above, the AGS is presently capable of accelerating ions up to silicon with an energy of 14.5 GeV/u, using one of the two BNL Tandem Van de Graaff accelerators as injector. By the end of 1991, using the AGS Booster Synchrotron, which is presently under construction, the range of ion masses which will be available from the AGS will be extended up to Gold. The Tandem-Booster-AGS complex will then not only be available to provide beams for fixed-target heavy ion experiments, but will serve as injector for the RHIC collider.

The design specifications for RHIC call for 1.0×10^9 particles per bunch of fully stripped ^{197}Au ions, with normalized emittance 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 acceleration of heavy ions will be started using one of two existing Tandem Van de Graaff accelerators. The second tandem will be available as an alternate injector, providing an additional degree of operational reliability. A Tandem Van de Graaff accelerator is an attractive choice for starting the injection of heavy ions into a synchrotron. The ion source is conveniently located close to ground potential, and a wide variety of negative ions are available. Other important advantages are related to the excellent beam quality and stability. The transverse emittance at the exit of the accelerator is better than 1π mm·mrad and the energy stability is one part in 10^4 . Of particular importance for RHIC operation is the available ion-source output currents prior to stripping and acceleration in the Tandem. A pulsed mode of operating the source has been developed at Brookhaven, demonstrating that ten 300 μsec long pulses per second could be injected at maximum intensity without adverse effects on the performance or stability of the accelerator. Up to 240 μA of useable ^{197}Au are

reliably available from a sputter source. Larger currents are available for lighter ions, with up to 500 μA for ^{12}C . The design for injection to RHIC assumes a source current of 200 μA and a pulse length of 110 μs . The Tandem then delivers 1.2×10^{10} gold ions per pulse to the booster, in a charge state +14, with kinetic energy equal to 1.07 MeV.

The Booster Synchrotron, with a vacuum of 10^{-10} torr will be capable of accelerating the partially stripped ions, without significant beam loss, for final stripping before injection into the AGS. The final energy of Au^{+14} ions after acceleration in the Booster is 65.5 MeV/u. After extraction from the Booster, and on their way to the AGS, the ions pass through a stripping target which, for gold ions, consists of a copper foil 35 mg/cm^2 thick. The following table shows the number of ions per bunch and the normalized emittance for various ion species after acceleration in the Booster and stripping prior to injection into the AGS:

Species	^{16}O	^{127}I	^{197}Au	^{238}U
Charge State	8	53	77	90
Ions/bunch ($\times 10^9$)	8.3	2.3	2.0	0.6
Normal emittance ($\pi \cdot \text{mm} \cdot \text{mrad}$)	6.1	3.6	4.0	2.3

Inside the AGS all ions with $A \geq 127$ will be fully stripped. Heavier ions such as ^{197}Au (77^+) and ^{238}U (90^+) will be accelerated with 2 electrons in a filled K-shell.

After acceleration in the AGS, the buckets are transferred one at a time into RHIC. For the heaviest ions, it is necessary to pass through a final stripping foil to remove the last two electrons in the K-shell. At the top AGS energies (10.7 GeV/u kinetic energy for ^{197}Au), a design beta function value of 50, and a rms scattering angle of .046 mrad for a 100 mg/cm^2 copper foil, would correspond to an emittance growth of .033 $\pi \text{ mm} \cdot \text{mrad}$. Thus an insignificant increase in beam emittance is expected at these energies. At these energies, negligible losses in particle numbers per beam bunch are also expected during the final stripping process.

Single bunches of ions are injected 57 times into each ring in boxcar fashion. Filling time per ring will be about one minute. For gold, as an example, there will be $\sim 1.1 \times 10^9$ 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. The layout of the storage rings is shown in Fig. 3a.

The six beam crossing regions are designed to accommodate a range of detector configurations to fulfill the needs of experiments. 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 $2 \times 10^{26} \text{ cm}^{-2} \text{ sec}^{-1}$ averaged over a 10 hour beam lifetime is expected. For protons the expected luminosity is $1 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$. The r.m.s. length of luminous interaction region where the beams cross is ~ 20 cm. Collisions of unequal species, e.g., protons in one beam and gold in the other, will be possible as well. The Accelerator Physics group has considered possible future upgrades of the machine performance, and these were discussed in detail in a recent workshop on the ultimate performance of such a collider.³

III. PRESENT STATUS; OUTLOOK FOR EXPERIMENTS

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.

One of the most important elements of the RHIC proposal is the design of the superconducting magnets for the accelerator rings. These magnets are the largest component of the cost of the machine, and their fabrication and installation is the major determinant of the construction schedule. The design of these magnets is based on the cosine theta coil structure developed at Brookhaven for the Isabelle/CBA magnets, which has since been adopted for the Tevatron, HERA and SSC magnets as well. The RHIC dipole magnets are designed to operate at a relatively low field (3.5 T), and thus the coil can be wound in a single layer of superconductor. The dipole magnet cross section is shown in Fig. 4. Figure 5 shows a magnet assembly, consisting of a dipole, quadrupole and corrector coils, mounted in a cryostat. These magnets are fully designed, and have been the major component of an intensive RHIC R&D program which has been funded by the Department of Energy beginning in fiscal year 1987. Full-size, "machine quality" prototypes of dipoles, quadrupoles and sextupoles have been built and successfully tested. In the case of the dipoles, the largest component of the magnet system, three

of the prototypes built thus far have been assembled by an industrial manufacturer. All of the prototype dipole magnets (5 have been tested so far) have reached fields of approximately 4.6 T, or 35% higher than the operating field of RHIC with virtually no training. The RHIC magnets have been designed to be amenable to fabrication in quantity in industrial facilities, and it is planned that a significant fraction of the magnets for RHIC will be built by commercial manufacturers.

The magnet R&D program is continuing, with work now in progress to prepare a full cell of the machine magnet lattice (see Fig. 3) consisting of two dipoles, two quadrupoles, sextupoles and lumped corrector package, which will be installed and tested as a system prior to the production of final magnets.

The project has been reviewed and validated by the U.S. Department of Energy, and construction will begin in fiscal year 1991 if funds are made available. The accelerator construction cost is roughly 215 million dollars, with an additional 74 million dollars budgeted for detectors (these figures are in FY 1989 dollars).

Of the six crossing regions built into the RHIC rings, those at the 2, 4, 6 and 8 o'clock positions (see Fig. 1) 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 recording of events at RHIC, with sensitivity corresponding to the expected signals for new phenomena in nuclear matter under extreme thermodynamic conditions, will require the extension of known techniques for particle detection beyond the present ranges of application in elementary particle and nuclear physics. With beam energies up to 100+100 GeV/nucleon and ion masses up to ≥ 200 , the total energy in each collision can reach up to 40 TeV in the center-of-mass: a range far beyond that of any present accelerator or any existing detector system. Unlike the proposed SSC collider, which would accelerate elementary particles to such an energy and produce hundreds of very high energy particles in the final state, the most interesting events at the RHIC collider are expected to produce tens of thousands of final-state particles in each collision, with proportionately less energy carried away by each particle. Thus, while the basic detector technology will have much in common with the detector systems developed for colliding beams of elementary particles, the design of detector systems for the heavy ion collider must address a different set of problems.

In a series of workshops⁴⁻⁶ held since 1985, designs for large detector systems have been examined to study their technical feasibility and their impact on the design and modes of operation of the collider. These workshop studies also showed that the most useful improvements to the machine performance - from the point of view of extending the physics reach after, say, a first generation of experiments - would be those which increased the

luminosity of the machine, rather than extending the energy range. Subsequent accelerator physics studies have explored possible future upgrades of the machine which could increase the luminosity from all ion species by about a factor of ten beyond the current design values.

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Fig. 1 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-injector 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. 2 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.

Fig. 3 Layout of the storage rings for the RHIC collider.

Fig. 4 Cross section of RHIC dipole magnet.

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Fig. 5 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.