The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is a colliding beam research facility that is capable of colliding heavy ion beams as heavy as gold initially and uranium recently at a beam energy of 100 GeV/nucleon for ultra-high-energy nuclear physics research. It is also capable of colliding polarized proton beams up to a beam energy of 250 GeV for the spin-physics program. The construction of this facility was completed in initial configuration in 1999, and highly productive experimental programs have been in progress to date. This article describes the construction and initial configuration and performance of the facility, and upgrades of the collider in recent years as well as the variance of the operations mode developed in response to the evolving physics interests. These improvements include a more sophisticated arrangement to improve the proton beam polarization, introduction of a new heavy ion source based on the Electron Beam Ions Source technology, introduction of stochastic cooling of the beams to enhance the collision luminosity, and collisions of heavy ion beams at a beam energy significantly lower than the nominal injection energy.

Subject Index G00, G02

1. Introduction

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) is the US Department of Energy’s largest research facility for the nuclear physics program. The initial layout of the facility, shown in Fig. 1, includes the existing Alternating Gradient Synchrotron (AGS) and its injector complex as the heavy ion and polarized proton injector to RHIC, the new beam transfer line from the AGS, and the collider complex with and a complementary set of four detectors: BRAHMS, PHENIX, PHOBOS, and STAR.

From QCD theory, it was conjectured that extreme thermodynamic conditions created by collisions of heavy ions at ultra-high energy could overcome the forces that confine the constituents in normal hadrons. Such de-confinement should lead to a transition from the hadronic state of matter to a new state of matter, namely a plasma of quarks and gluons that would present in a microscopic volume for a fleeting moment. The physics issues underlying this transition to the so-called “Quark Gluon Plasma” (QGP) and the study of its properties were topics of interests in the early 1980s. The primary objective of RHIC, therefore, is to investigate this phase transition and to study the formation and properties of QGP.

With the addition of Siberian Snakes, which was made possible by the Spin Physics Collaboration with the RIKEN Laboratory of Japan, the scientific objective of RHIC was expanded to include the
Fig. 1. Layout of the RHIC Research Facility that includes the AGS complex as the injector, the AGS to RHIC beam transfer line, Collider Ring, and the initial set of four detectors. Operation of two of these detectors, PHOBOS and BRHMUS, was discontinued after their early physics objectives were successfully completed.

study of the spin structure of nucleons, and other spin physics studies at a range of collision energies never before possible. With RHIC, nuclear physics is entering into the “high-energy” domain in which the QCD structure of matter should be directly manifested in terms of the dynamics of quarks and gluons.

2. The RHIC facility

The idea to build RHIC dates back to 1983, when it was conceived as part of the long-range plan for nuclear science. The Nuclear Science Advisory Committee (NSAC), an advisory body to the US Department of Energy (DOE) and the National Science Foundation (NSF), made a declaration that “the United States should proceed with the planning for the construction of this relativistic heavy ion collider facility expeditiously; and we see it as the highest priority new scientific opportunity within the purview of our science” [1]. Based on this recommendation, DOE began supporting the R&D effort for the RHIC collider in 1987. The R&D was directed mainly toward a very focused developmental program on the superconducting magnets for the collider ring, but also included development of a conceptual design of the collider and studies of associated accelerator physics issues [2]. Allocation of funding for generic R&D of detectors suitable for heavy ion collision experiments began in FY 1990, and that was later converted to cover RHIC-specific detector R&D. Funding for the RHIC Construction Project began in 1990 and actual construction began in 1991.

The scope of the RHIC collider included design and construction of a two-ring superconducting hadron collider in an existing tunnel 3.8 km in circumference, and the beam transport lines from the
existing AGS to the RHIC collider. An existing chain of hadron accelerators at BNL, i.e., the Tandem Van de Graaff, the Booster, and the AGS, was used as the heavy ion injector. The existing proton linac was used as the source of polarized protons. The collider rings were installed in the tunnel enclosure that had five of six sextants completed for an earlier ISABELLE/CBA Project before the project was cancelled in 1983. Also utilized was a large helium refrigerator with a cooling capacity of 25 kW at a temperature of 4.2 K that was completed in 1986. The construction of the collider was completed in 1999, and the physics program in the newly opened energy domain for heavy ion collision began in 2000, 17 years after its conception.

Following the initial engineering test runs of the Collider, collisions of Au ions and preliminary physics runs took place during the subsequent period in the year 2000, first at a beam energy of 28 GeV/nucleon on June 12, 2000, and later at 65 GeV/nucleon. One of the first Au–Au collision events detected by the STAR detector without its solenoid magnet turned on is shown in Fig. 2.

Global properties of the collision results were presented at the Quark Matter 2001 Conference on January 15, just about four months after the run ended. Collisions of Au ions at the design beam energy of 100 GeV/nucleon were achieved on July 18, 2001. All four detectors were also commissioned at the same time and collected significant amounts of data during the four-week first physics run, opening a new frontier of nuclear matter research. The most significant achievement at RHIC to date is the discovery of a new state of matter created by the Au–Au collision at the top energy of RHIC. As announced at the April 2005 meeting of the American Physical Society, and published in *Nuclear Physics*, this matter is hot, dense, and behaves like a “perfect fluid,” flowing freely without viscosity [3–6].

The total line-item budget for the RHIC project was $616.6M in 1999 dollars, which consisted of $486.8M for the construction of the collider and a complementing set of detectors in their baseline configuration, $51.8M for the accelerator and detector technology R&D, and $77.8M for pre-operations including the verification of the functionality of the collider and some of the special process spares of RHIC-collider-specific equipment. From the beginning, $115M of the construction funds was set aside to support the construction of a set of baseline detectors. In order to further enhance the physics capability of the detectors, the decision was made in 1996 to add several detector sub-systems to the baseline configuration of PHENIX and STAR with the Additional Experimental
Table 1. Design performance specifications of RHIC

|                         | for Au–Au       | for p–p          |
|-------------------------|-----------------|------------------|
| Beam energy             | 100 → 30 GeV/u  | 250 → 30 GeV     |
| Luminosity              | $2 \times 10^{26}$ cm$^{-2}$ s$^{-1}$ | $1.4 \times 10^{31}$ cm$^{-2}$ s$^{-1}$ |
| Number of bunches/ring  | 60 (→120)       | 60 (→120)        |
| Luminosity lifetime     | ~10 h           | >10 h            |
| Beta function at collision points | 10 m → 2 m (1 m) | 10 m → 2 m (1 m) |

Equipment (AEE) program funds from DOE. This program also established the RHIC Computing Facility (RCF) that provides the computing support with a large-scale data storage system and CPU farm for simulation, data recording, event reconstruction, and data mining. The total AEE funding that started in 1996 was $38.2M. Provision of funding from NSF through the collaborating universities was instrumental in many ways, including support for the participation of university staff and students in the RHIC experimental program and the contribution of additional important hardware to the baseline detector. Lastly, the RHIC Project received many sizable contributions in the form of cash, equipment, manpower, and technical expertise from foreign countries and institutions, in addition to the intellectual participation of their scientists and students in the scientific mission of RHIC. The size of the total contributions from foreign sources is estimated to be equivalent to $50M, though it is rather difficult to make an accurate assessment because the mode of contribution varied case by case.

3. RHIC collider

The basic design parameters of the collider are given in Table 1. The top energy for heavy ion beams (e.g., for gold ions) is 100 GeV/u, and that for protons is 250 GeV.

The schematic layout of the collider ring, the configuration of arc lattice elements, and the inventory of magnets used are shown in Fig. 3. The ring consists of two quasi-circular concentric rings on a common horizontal plane, one (“Blue Ring”) for clockwise and the other (“Yellow Ring”) for counter-clockwise beams. The rings are oriented so that the counter-rotating beams intersect with one another at six locations along their 3.8 km circumference with equal distance from one to the next, and collide head-on at intersections where detectors are located.

Each ring consists of six arc sections (each ~356 m long) and six insertion sections (each ~277 m long) with a collision point at their center. Each arc section is composed of 11 FODO cells with a modified half-cell on each end. Each full cell consists of two 9.45 m-long dipoles and two composite units, each containing one 0.75 m-long sextupole, one 1.11 m-long quadrupole, and one 0.50 m-long corrector assembly. In the arc sections, the counter-rotating beams are separated by 90 cm horizontally.

A pair of dipole magnets, DX and D0, located at ~10 m and at ~23 m from the collision point, respectively, steers beams to a co-linear path for head-on collisions. Three quadrupole magnets, Q1–Q3, located outside the steering dipole D0, form the final focus triplet for high-luminosity collisions. Fig. 4 gives the horizontal and vertical $\beta$ functions and dispersion $\eta$ as a function of distance from the collision point. As shown, the initial configuration of the collision lattice gave $\beta_X = \beta_Y = 1$ m, and $\eta = 0$. However, this collision lattice leads to a rapid increase in the $\beta$ function with distance from the collision point. In addition, because of the intense intra-beam scattering caused by the high charge of heavy ions, the transverse beam emittance of the gold beams grows rapidly. In order to provide a sufficiently large dynamic aperture, the bore diameters of the RHIC collider magnets are relatively large, e.g., 180 mm for DX, 100 mm for D0, 130 mm for Q1–Q3, and 80 mm for all...
Fig. 3. The schematic layout of the collider ring. Also shown are a typical FODO lattice of arc sections (top left), and at top right a list of superconducting magnets used in the collider ring.

other magnets. Superconducting magnets are used exclusively for both rings. Altogether, 1740 superconducting magnets were required for the RHIC collider, of which 1200 units were manufactured by industry. As an example, a cross section of the dipole magnet as developed by BNL’s superconducting magnet team and manufactured by industry through the technology transfer process is shown in Fig. 5. The special feature of this magnet is that a straight cold mass was manufactured using high quality magnetic steel laminations with high tensile strength as the collar to hold the Rutherford cable and Cu spacer assembly in place, and bent to match the ring radius, while the upper and lower half cells were welded on to form the cold mass.

Unlike the case of proton beams, producing fully stripped high intensity and high brightness heavy ion beams, such as the Au beams, that are suitable for a collider is rather complex. The complexity arises from the fact that electrons are more tightly bound to a heavy nucleus, and effective stripping of the final k-shell electrons requires the acceleration of the partially stripped ions to tens of GeV/u. As shown in Fig. 6, this process, for the RHIC acceleration scenario for Au ion beams, for example, takes three accelerators in the injector chain, namely the Tandem Van de Graaff, the Booster, and the AGS itself. Negatively charged gold ion beams from the pulsed sputter ion source at the frontend of the Tandem (100 µA in a 700 µs pulse) are partially stripped of their electrons with a foil at the Tandem’s high voltage terminal, and then accelerated to the energy of 1 MeV/u by the second stage
of the Tandem. After further stripping at the exit of the Tandem and charge selection by bending magnets, beams of gold ions with a charge state of +32 are delivered to the Booster Synchrotron and accelerated to 95 MeV/u. The ions are stripped again at the exit from the Booster to reach a charge state of +77, a helium-like ion, and injected to the AGS for acceleration to the RHIC injection energy of 10.8 GeV/u. Gold ions, injected into the AGS in 24 bunches, are debunched and then re-bunched to four bunches at the injection front porch prior to acceleration. These four bunches are ejected at the top energy, one bunch at a time, and transferred to RHIC through the AGS-to-RHIC Beam Transfer Line. Gold ions are fully stripped to a charge state of +79 at the exit from the AGS. The stacking in the RHIC rings is done in a boxcar fashion. Fig. 7 shows the two RHIC rings in the tunnel.

In the initial configuration, acceleration and storage of beam bunches at RHIC uses two RF systems, one operating at 28 MHz to capture the AGS bunches and accelerate them to the top energy, and the other operating at 197 MHz to provide short-collision diamond ($\sigma_L \sim 25$ cm) for a more reasonable detector design. The synchrotron phase transition of the RHIC lattice is at $\gamma_T = 24.7$; thus all ions, except protons, must go through this transition. The RHIC collider, indeed, is the first superconducting accelerator (hence slow ramp rate) that passes through the synchrotron phase transition and the associated beam instability. It is important to cross this transition rapidly in order to minimize the beam loss and the emittance growth. This can be accomplished either by rapid acceleration through it with a resultant orbit jump to a larger radius or by a "$\gamma_T$-jump", where sets of quadrupoles are pulsed to change the tune of the machine and thus move the transition energy momentarily. For the year 2000 operation, the former method was used due to the lack of pulsed power supplies, while for the year 2001 run, the latter method has been implemented.

Polarized protons are injected from the existing 200 MeV linac for the spin physics program with collisions of polarized protons. During acceleration in the AGS, polarization is preserved with two helical dipoles that act as partial Siberian snakes. Figure 8 shows the windings of the normal-conducting helical dipole. A second helical dipole is a super-conducting magnet. Polarized beams become increasingly difficult to maintain with increasing energy due to the increased density and
Fig. 5. Cross-sectional view of a superconducting arc dipole magnet.

strength of the spin resonances. RHIC is by far the highest-energy polarized beam facility yet envisaged and a different approach was necessary. The use of Siberian Snakes to preserve beam polarization has been postulated for a long time, and has been implemented at RHIC. A Snake providing a full $180^\circ$ spin flip was designed and fabricated as part of this program. Each Snake is constructed from four 2 m helical dipole modules. Four such Siberian Snakes, built as part of the RIKEN–BNL Spin Physics Collaboration and with RIKEN funding, are installed in the collider rings (two in each ring, $180^\circ$ apart), as shown in Fig. 9. These Snakes [7] will make it possible to accelerate and store polarized proton beams for collisions, providing a unique opportunity to carry out the spin physics program at ultra-high center of mass energies. Other hardware that was built for the spin physics program under this collaboration includes two sets of four spin rotators that are installed on both sides of the collision points for the PHENIX and STAR detectors, respectively, and polarimeters.

4. RHIC operations and improvements

During its 14 years of operation RHIC has greatly exceeded the design parameters for gold–gold collisions, has successfully operated in an asymmetric mode of colliding deuteron on gold with both
beams at the same energy per nucleon, and thereby at different rigidities, and successfully completed a comparison run of colliding copper beams with record luminosities. Operation at unequal rigidities of the two colliding beams is a unique feature of RHIC with its two independent rings. The interaction regions are designed to separate the two beams first before they go through their separate final focus triplets.

For most of the heavy ion runs RHIC was operating with beam energies of 100 GeV/nucleon—the gold beam design energy. Additional running at lower beam energy was also accomplished, again demonstrating the high level of flexibility of RHIC. Gold collisions at energies much below the RHIC injection energy of 10 GeV/nucleon is allowing the study of the critical point in the quark–gluon phase diagram. Figure 10 shows the achieved integrated nucleon-pair luminosities for the many modes of operation of RHIC since its start of operation in 2000. Using nucleon-pair luminosity, which is calculated as the ion–ion luminosity times the number of nucleons in each of the two beam ions,
allows the comparison of the different modes of operation properly reflecting the relative statistical relevance of the data samples and also the degree of difficulty in achieving high luminosity.

The high charge and the low number of gold ions made it possible to contemplate stochastic cooling of the 100 GeV/nucleon bunched beam. A 6–9 GHz longitudinal and a 5–8 GHz vertical and horizontal stochastic cooling system was installed using novel high power multi-cavity kickers and the high-energy bunched beam was successfully cooled [8]. With the three planes of stochastic cooling operational in both rings, a peak luminosity at PHENIX and STAR of up to $50 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$ is possible, with an average store luminosity of $30 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$, which is 15 times the original RHIC design average store luminosity [9]. The large luminosity increase was accomplished with the novel application of stochastic cooling to high energy and bunched beams and through a number of inexpensive upgrade projects.

To make full use of the stochastic cooling a 56 MHz SRF quarter-wave cavity (Fig. 11) is being added to the RHIC rings that can provide 2 MV RF voltage in a large bucket during the beam storage. The large RF bucket, in combination with the existing 197 MHz RF system, will allow the longitudinal...
stochastic cooling to reduce the RMS bunch length to less than 1 ns and therefore minimize the length of the region where the beam bunches collide.

With the addition of the new Electron Beam Ion Source (EBIS), which replaces the Tandem pre-injectors, all ions, including uranium beams, can be delivered to and collided in RHIC. During a first run with uranium beams the stochastic cooling was so effective that, during a store, the collision rate would increase for about an hour before reaching a peak and then decline due to the “burn up” of ions in the two collision points [10].

A new polarized ion source providing H-minus beams with high intensity and polarization, a new resonance jumping system in the AGS, and carefully adjusted spin tune control in RHIC led to record average store polarization of 55% and average store luminosity of $160 \times 10^{30}$ cm$^{-2}$ s$^{-1}$ for 250 GeV on 250 GeV polarized proton collisions [11]. The interaction region beta$^*$ was reduced to 0.65 m with good dynamic aperture. This is three times smaller than the design value.
5. Conclusions

Since the year 2000, when experimental studies of collisions of relativistic heavy ion collisions became the reality after the 17-year incubation period, RHIC has run well, only limited by the facility’s operations funding. The scientific outputs from the years since then have been phenomenal. In the early years four complementary detectors, BRAHMS, PHENIX, PHOBOS, and STAR, gave outstanding looks at the global properties of matter that was produced by Au–Au collisions at relativistic energies. Of particular interest was that they discovered that the hot and dense matter produced by Au–Au collisions at the top energy of RHIC behaves like a dense and strongly coupled perfect fluid that flows freely with no viscosity. It was very gratifying that the creation of such a state of matter was confirmed later by the Pb–Pb collisions at much higher energy by LHC at CERN. To date, four experimental groups have published over 360 refereed papers, which have together received over 37,000 citations.

Another point that must be mentioned is that with the flexibility that was built into the design of RHIC, with the additional ability to accelerate and collide polarized proton beams, and with the ingenuity of the scientists, engineers, and operations staff, RHIC has been able to provide various operation modes requested for promising physics objectives. In particular, with the success of the stochastic cooling of bunched heavy ion beams, the increase of luminosity by ten times or more, which was the aim of the RHIC-II project, is within reach soon, much sooner than anticipated and with a lot less investment of funds. With these achievements, the future of RHIC is bright, leading to the realization of the next upgrade, namely e-RHIC for collisions of polarized electrons, polarized protons, and heavy ions.

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