REPORT FROM BNL

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PREFACE

Brookhaven National Laboratory (BNL) is a multidisciplinary laboratory, which is operated by Brookhaven Science Associates under contract with the U.S. Department of Energy since March 1998. As such, BNL has a number of electron and hadron accelerator facilities, and does engage in many advanced accelerator R&D activities. In the electron sector, there is the National Synchrotron Light Source (NSLS) which consists of a 2.5 GeV electron storage ring for X-rays and a 850 MeV (1A) ring for UV light. The Accelerator Test Facility (ATF), with a 50 MeV electron linac, is a very active R&D center for experimental studies of advanced acceleration methods. NSLS and ATF also are involved in an intensive R&D effort for the construction of a Deep-UV FEL facility.

In the hadron sector, there is the Alternating Gradient Synchrotron (AGS) complex (the AGS, Booster, the 200 MeV Linac) that has been the workhorse of high-energy physics for the last four decades, and now commands the position of being the highest intensity high-energy proton synchrotron in the world. Using the Tandem Van de Graaff as the source of ions, the AGS now operates with 11 GeV/u gold beams for the heavy ion program. The construction of the Relativistic Heavy Ion Collider (RHIC) is well underway, with the commissioning of the facility scheduled in 1999.

In other areas, BNL is a core participant in the inter-laboratory muon collider R&D efforts, and is one of the key members of the U.S. collaboration for the CERN-LHC that provides special superconducting magnets for IR and RF insertions of the ring. BNL also continues its active R&D efforts on advanced superconducting magnets for future accelerators (e.g., the muon collider and the very large hadron colliders).

In this presentation, the status of the hadron accelerator systems at BNL will be presented.

1. HIGH INTENSITY PERFORMANCE OF THE AGS

The AGS, a 30 GeV proton synchrotron, has been the workhorse of the high-energy physics program at BNL since 1961, supporting many important experiments. These experiments include Nobel Prize winning experiments such as the discovery of the two neutrinos, the CP violation, and the J particle, which made very significant contributions to the establishment of the Standard Model. In the early 1990's, the acceleration of light ions began and, since 1996, ions as heavy as gold, have been accelerated.

Fig. 1 shows a steady increase in the AGS proton beam intensity since its commissioning in 1961. Also shown are various improvements introduced to the AGS accelerator systems. The most dramatic increase in the intensity occurred during the last several years with the introduction of the new Booster. The circumference of the Booster is one quarter of the AGS. Therefore, it allows four Booster beam pulses to be stacked in the AGS at the injection energy of 1.5 to 1.9 GeV, i.e., a higher energy where the space charge effects are much reduced and, in turn, allows for the dramatic increase in the AGS beam intensity.

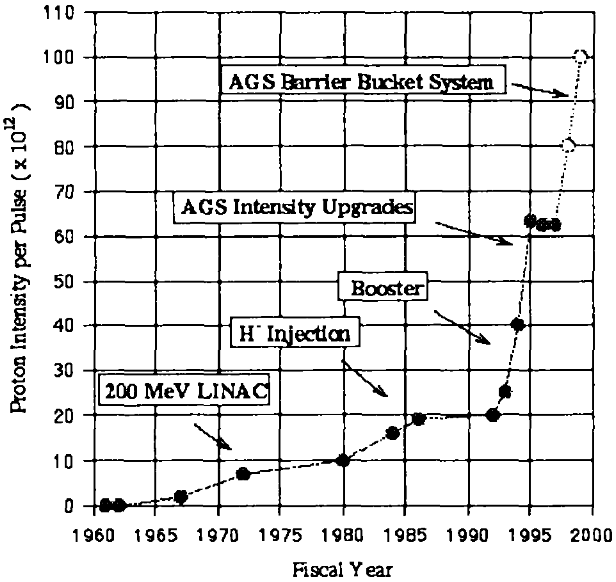

Fig. 1: Increase in the AGS proton beam intensity and accelerator upgrades since the commissioning

The 200 MeV linac supplies H^- beams to the Booster. With the recent upgrade of the Linac rf system, an average H^- current of 150 μA, and a maximum of 12 x 10^{13} H^- per 500 μsec pulse has been achieved. The normalized beam emittance is about 2π mm mrad for 95% of the beam, and the beam energy spread is about ±1.2 MeV. A magnetic fast chopper, installed at the 750 keV point, allows the shaping of the beam, injected into the Booster, to avoid excessive beam loss. The Booster beam intensity achieved surpassed the design goal of 1.5 x 10^{13} protons per pulse, and reached a peak value of 2.2 x 10^{13} protons per pulse. This was accomplished by the very careful correction of all important nonlinear orbit resonances, especially at the injection energy of 200 MeV, and by establishing a second harmonic rf system, using the extra set of rf cavities that were installed for the heavy ion operation. With the second harmonics, the rf bucket can be flattened to elongate the bunches in a further effort to reduce the space charge effects. The beam emittance growth and beam loss, which arise from a large tune shift of high intensity bunches, can be minimized by beginning to accelerate rapidly during and after injection.

The peak beam intensity reached at the AGS, at its normal operating energy of 24 GeV was 6.3×10^{13} protons per pulse, exceeding the design goal (6.0×10^{13} protons per pulse) of the latest upgrade with the Booster. This represents world record beam intensity for a proton synchrotron. In order to achieve this record intensity, the AGS itself must also be upgraded. It takes about 0.4 seconds to fill the AGS with four Booster cycles. During this period, bunches stored in the AGS are exposed to the coupled bunch instabilities caused by the resistive wall of the vacuum chamber. A very strong feedback with a transverse damper was introduced to minimize this effect. In order to further reduce the space charge effects, the injected bunches are lengthened by the mismatched bunch-to-bucket transfer from the Booster, as well as by the use of dilution rf cavities. The AGS proton beams must cross the synchrotron phase transition. In order to control bunches through this potentially unstable point during the acceleration cycle, and thus minimizing the beam loss, a new powerful transition energy jump system was introduced.

Aiming at a further intensity upgrade, a provision is being established to introduce a barrier bucket for beam stacking in the AGS. This work is in collaboration with KEK of Japan where the high intensity Japan Hadron Facility is being planned. In this provision, beams are debunched in the AGS, after the beam transfers from the Booster, in order to minimize the space charge effect. An isolated sine wave in the barrier cavity, installed in the AGS, will produce a gap in an otherwise continuous distribution of the beam. This gap will be expanded to receive another transfer from the Booster. This process will be repeated several times to achieve the goal of stacking 1×10^{14} protons per pulse. It should be noted that, with 1×10^{14} ppp and at the present repetition rate, the AGS can deliver 240 kW of beam power to a target, either for production of spallation neutrons and/or of muons.

2. THE RHIC PROJECT

The RHIC Project is the flagship research facility construction project of the U. S. Department of Energy, Nuclear Physics Division, which began in January 1991 and is expected to be completed in June 1999. The mission of this Project is to build a two-ring superconducting hadron collider, with two rings intersecting at six locations along their 3.8-km circumference. The top energy for heavy ions is 100 GeV/u and that for protons is 250 GeV. These counter-rotating beams will be steered to collide head-on at six intersection points. As shown in Fig. 2, an existing chain of accelerators; i.e., the Tandem Van de Graaff, the Booster, and the AGS will be used as the injector. Ion species that can be accelerated, stored, and collided at RHIC range from A=1 (proton) to A~200 (gold), at present. Subject to the development of a suitable ion source, collisions of heavier ions can be realized. Having two completely independent rings, collisions of unequal ion species, such as protons on gold ions can also be studied at RHIC. Performance specifications of the collider are listed in Table 1 below.

TABLE 1: Performance Specifications of RHIC

	for Au-Au	for p-p
E_{BEAM}	100 - 30 GeV/u	250 - 30 GeV
$<\mathcal{L}>$	2×10^{26} cm^{-2}sec^{-1}	1.4×10^{31} cm^{-2}sec^{-1}
N_{BUNCH}/Ring	60 ($\rightarrow$120)	60 ($\rightarrow$120)
$\tau_{LUMINOSITY}$	~10 hrs	>10 hrs
β* at IP	10m $\rightarrow$ 2m (1m?)	10m $\rightarrow$ 2m (1m?)

With an expectation that gold-gold collisions at RHIC will create states of nuclear matter that reach the temperature above 10^{13} degrees Kelvin, the physics objective of RHIC is to recreate a micro-cosmos of matter that is believed to have existed at the beginning of the universe. Thus, the principal physics objective of RHIC is to verify that the quark-gluon plasma (QGP) phase of matter exists. When verified, RHIC will provide physicists with the tool to study properties of QGP (nuclear physics interests), to study the strong interactions (QCD) between deconfined quarks (particle physics interests), and to obtain insights on how the universe was cooled down to form the present state (Cosmology and Astrophysics interests).

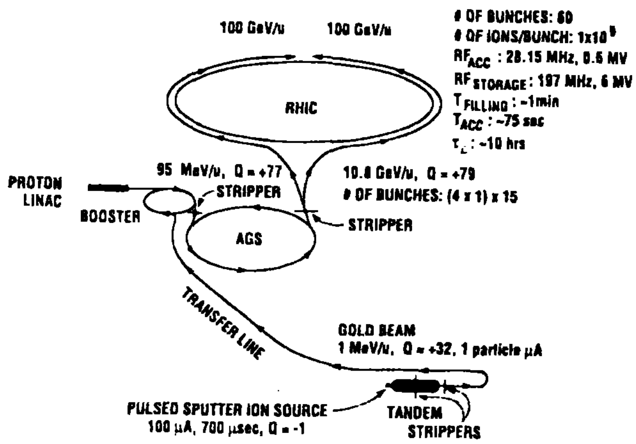

Fig 2: RHIC Acceleration Scenario for Au Beams

The RHIC acceleration scenario for Au ion beams is shown in Fig. 2. Three accelerators in the injector string will successively boost the energy of ions, and strip electrons from atoms in four stages, in order to attain fully stripped gold ions for injection to the RHIC rings. The high charge of ions will result in a strong intra-beam scattering of ions, and contribute to a rapid growth of both the longitudinal and transverse emittance of beams. For this reason, both the time it takes to fill the rings with bunches from the AGS ($T_{Filling}$), as well as the time it takes to accelerate to the top energy (T_{Acc}) are kept as short as ~1 min. The magnetic lattice design is based on a strongly focusing FODO cell. The storage RF voltage planned is higher than normal for ordinary proton storage rings. These are to control the rapid transverse and longitudinal growth of emittance caused by the intra-beam scattering. Another concern is the loss of ions from the stable orbit by capturing electrons either through collisions with residual gas in the beam tubes or through the pair-production process in the beam-beam collisions.

The collider consists of two quasi-circular concentric rings on a common horizontal plane, one for clockwise and the other for counterclockwise beams. Rings are oriented to intersect with one another at six locations along their 3.8 km circumference. Superconducting magnets are used exclusively for the storage rings. Each ring consists of six arc sections (each ~355.5 m long), 12 insertion sections (each ~118.75 m long), and six interaction regions with a collision point at their center (each ~46 m long). Each arc is composed of 11 FODO cells with a modified half cell on each end. Each standard half cell consists of a dipole unit (9.45 M long) and a unit that combines three magnetic elements, i.e., a sextupole (0.75 m long), a quadrupole (1.11 m long), and a corrector assembly (0.50 m long). In the arc sections, the counter rotating beams are separated by 90 cm horizontally. Each insertion section contains six quadrupoles and two dipoles for dispersion matching and β-function manipulations for the collision optics. Although the geometry of the interaction region allows beam crossings at an angle of 7 mrad, head-on collisions will be used as the standard mode of operation to minimize the beam instability, which might arise from coherent bunch-bunch interactions. Three dipoles, namely a DX magnet located at ~10 m and a pair of D0 magnets located at ~23 m from the collision point, steer beams to a co-linear path for collisions. Three quadrupoles (Q1-Q3) next to the D0 magnets form the final focus triplet for high luminosity collisions. All superconducting magnets in the arc and insertion sections have a coil bore diameter of 80 mm. In order to provide sufficient aperture in the collision mode of operation, the coil bore of the triplet quadrupoles is as large as 130 mm, and that of DX and D0 is 180 mm and 100 mm, respectively. Altogether, 1,740 superconducting magnets are used for the RHIC collider.

After the completion of technical development, design, fabrication of pre-production units, and verification of performances of each type of magnet, the technology to build dipole magnets and quadrupole and sextupole coil-yoke assemblies were transferred to industry. All magnets delivered to BNL showed excellent performances. This is due to the very tight control on dimensional and performance tolerances imposed on superconducting cables, iron yoke lamination, and other parts. The tight quality control on the manufacturing process by industry also played an important role. For example, as shown in Fig. 3, the quench performance of all dipole magnets tested at the cryogenic temperature of 4.2 K was excellent. No magnet quenched below the design operating current of 5,000A, and all reached a quench plateau which exceeded a value 30% above the operating current. The magnetic field qualities of the first 30 dipoles and quadrupoles produced by industry were also found to meet the stringent specifications for the RHIC optics. Since quench performances of these magnets were excellent, the field qualities met our stringent requirements, and the magnetic performances were very uniform from one magnet to the other. Only about 10% of dipoles and quadrupoles were sample-tested at the cryogenic temperature. The field qualities of all magnets, however, were tested at room temperature with the current of about 2% of the operating current, in order to verify that a magnet was assembled with proper material and according to proper procedures. All sextupole magnets and corrector assemblies were tested at the cryogenic temperature and with a full current, since they were built using a single wire strand conductor and have a higher risk of manufacturing damage.

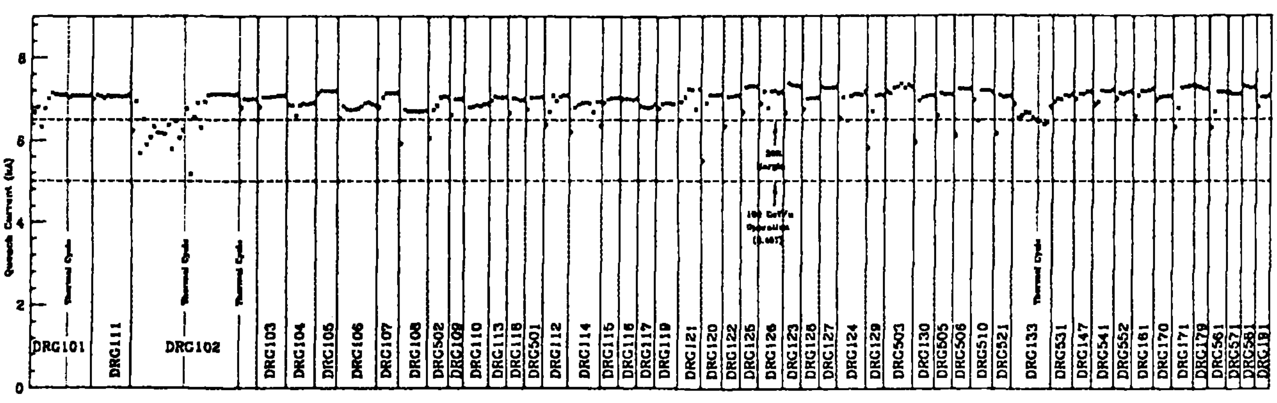

Fig. 3: Quench performance of RHIC production dipole magnet. Data from all 30 magnets tested are shown

Acceleration and storage of beam bunches at RHIC require two rf systems; namely, one operating at 28.15 MHz (the rf bucket length of 11m), to capture the AGS bunches and accelerate to the top energy, and the other operating at 197.05 MHz, to provide short collision diamonds (σ~25 cm) for a more reasonable detector design. The long bucket length of the acceleration rf system comfortably matches the length of the AGS beam bunches. The synchrotron phase transition of the RHIC lattice occurs at γ_T=24.7. Therefore, all ions, except protons, must go through this transition. In order to minimize the emittance growth at the transition, RHIC is equipped with a γ_T-jump, where sets of quadrupoles will be pulsed to change the tune of the machine quickly.

3. COLLIDER CONSTRUCTION STATUS

The collider construction is well underway and is more than 95% complete as of this writing (September 1998). Manufacturing of all superconducting magnets for the entire RHIC collider is complete, and all but a few of the magnets have already been installed in the tunnel. Interconnection of these magnets is more than 90% complete. The remaining interconnections to be completed are only those for interaction region dipoles and quadrupoles.

Beam injection lines are completed for both clockwise and counter-clockwise beams. Installation of the cryogenic distribution piping is completed in four out of six sextants. All of ten 197 MHz storage mode rf cavities, as well as four 28 MHz acceleration cavities, are on hand and six of the former and two of the latter are installed on the beam line. Good progress was also made in the fabrication and installation of other accelerator components for the collider. Presently, major mechanical assembly efforts are focused in and around the interaction regions with the expectation that the installation of ring components will be completed in December 1998. Work on power supplies, access controls, beam-dump, etc. is also well underway.

One of the most significant milestones achieved recently is the first sextant test that was undertaken in January and February of 1997. For this test, one sixth of the ring, i.e., one sextant of the actual collider was completed and cooled to the operating temperature of 4.5 K and gold beams from the AGS were transported to a temporary beam dump placed at the end of the sextant. The major goals of this test were:

1) to verify cryogenic system performances and evaluate motions of ring components during the cool down
2) to verify power supply ramping and quench protection system performances
3) to study injection conditions, e.g., apertures, matching and pulse-pulse stability, and
4) to verify the low level rf control including bucket selection, multi-bunch injection, and injection stability.

Another important objective of this test was to help focus the attention of the Project staff members on an intermediate milestone during this nine-year long construction project.

This sextant test was very successful on all accounts. The gold beams were sent through this sextant on January 21, 1997, several days ahead of the scheduled milestone date set in 1994. In fact, it took only seven days from the beginning of the cool-down of the ring to the successful transportation of the gold beams to the temporary beam dump. All of the goals outlined above were met with relative ease, demonstrating that the hardware and software developed for RHIC work. This sextant test also verified that the AGS could provide gold beams with beam parameters, such as emittance and stability, which are acceptable for the RHIC operation. The beam bunch intensity achieved is close to RHIC specifications, and will be improved during the course of the next few years.

4. COLLISIONS OF POLARIZED PROTONS AT RHIC

With the help of a partial snake solenoid and a vertical rf dipole, the AGS has successfully accelerated polarized proton beams, overcoming a number of depolarizing resonances. Results from the recent experiment are compared with simulations in Fig. 4. The simulation with $\varepsilon_y = 9\pi$, $\varepsilon_x = 40\pi$ predicted the measurement of polarization with the rf dipole quite well, showing the predicting power of simulation. As can be seen in the other simulation in the figure, further improvement of the polarization to the level of 75% in the RHIC transfer energy range can be expected by replacing the solenoid with a helical snake.

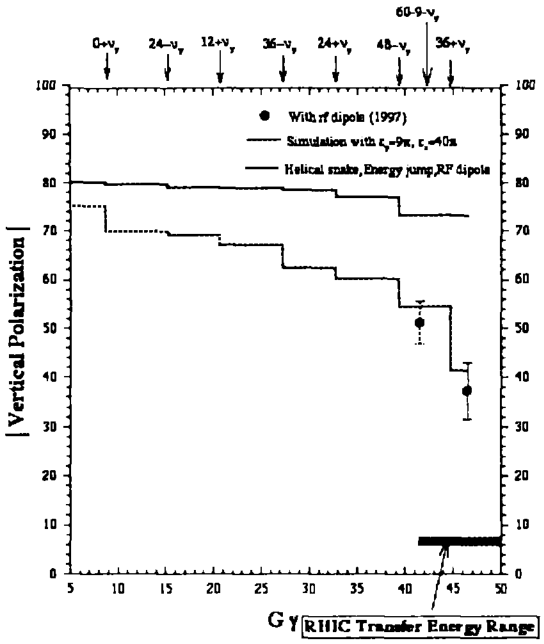

Fig. 4: AGS polarized proton experiment.

Having a high-energy source of polarized protons in the AGS, there is a great opportunity to realize collisions of polarized proton beams with the total collision energy of 500 GeV at RHIC. Such collisions will open the frontier for the studies of spin and gluon structure functions of nucleons, and possibly allow an observation of spin dependent $W^{\pm}$ production. To preserve the polarization of protons in the RHIC collider, however, a pair of Siberian snakes, each consisting of four superconducting helical dipole magnets, will have to be added to each ring. In addition, two pairs of spin rotators, also consisting of four superconducting helical dipole magnets, are needed at two major experiments for the collisions of longitudinally polarized protons. Beginning in 1995, the Institute for Physical and Chemical Research (RIKEN) of Japan and BNL entered into collaboration on the spin physics program at RHIC. Japanese Science and Technology Agency, through RIKEN, funds hardware needed for the polarized beams at RHIC.

The development of helical dipole magnets for the snakes and spin rotators is done, and the manufacture of 50 of these units will begin shortly. The accelerator physics studies on the spin dynamics in the RHIC rings have been completed, showing that the system, as designed, should work without difficulties. An extensive study to optimize the polarization measurement of beams is in progress. It is anticipated that the spin physics program at RHIC will begin in the year 2000, about one year after the beginning of the heavy ion program.

5. DETECTORS AND THEIR CONSTRUCTION STATUS

The scope of the RHIC Project also includes construction of detectors for the first round of experiments. The principal objective of these detectors is to investigate phenomena from collisions of relativistic heavy ions, and to search for quark-gluon plasma. It is anticipated that these collisions include events with 5,000 to 10,000 particles. There are two major detectors (STAR and PHENIX) and two small-scale detectors (PHOBOS and BRAHMS). Construction of these detectors is funded mostly by the RHIC Project, but with significant foreign contributions from Japan, Russia, some European countries and others. In order to broaden the physics reach, a decision was made recently to supplement the baseline configuration of the STAR and PHENIX detectors with additional instrumentation. Also added is the second Muon Arm to the PHENIX detector, funded by RIKEN of Japan, to improve its capability for the spin physics program. As of this writing, the construction of detectors is 85% to 90% complete and is making tangible progress toward their completion in time for the collider commissioning in 1999. Participants in the four RHIC experiments consist of about 900 scientists, engineers, and students from 88 institutions in 19 countries.

6. CONCLUSION

RHIC is a world class colliding beam facility dedicated to the studies of relativistic heavy ion collision, and has a great potential to open new frontiers in our understanding of matter. Collisions of gold beams at top energies should allow us to enter into a new regime of nuclear matter, which existed only once in the very early history of our universe, giving us an opportunity for new discoveries. The addition of spin physics capabilities will expand the versatility of the collider to address fundamental issues involved in the theory of strong interactions.

Construction of this facility, both the collider and detectors, is proceeding well with the target date for the commissioning in June 1999. The mechanical assembly of the collider and tunnel personnel access security system will be completed during December of 1998. Cool down of the collider ring and test of subsystems will be carried out during January and February of 1999, followed by tests with beams in March. The installation of detectors at collision points will take place during April and May of 1999 in preparation for the commissioning run during June and July. Our objective is to look forward to the exciting heavy ion physics program starting at RHIC in the fall of 1999.

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