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STATUS OF THE RHIC* and BNL/CERN HEAVY ION PROGRAMS

Satoshi Ozaki
Brookhaven National Laboratory
Upton, New York 11973 USA

With the gold beam operation at the Brookhaven AGS started in 1992, and with the lead beam operation at the CERN SPS planned for 1994-1995, investigation of high nucleon density states through high energy heavy ion collisions is becoming a reality. In addition, the Relativistic Heavy Ion Collider (RHIC) at BNL, which is dedicated to the study of ultra-high energy heavy ion collisions, is under construction with a target completion date in 1997. There also is a plan to run the proposed CERN LHC for a few months a year for the heavy ion program. These colliders should provide opportunities to extend our knowledge of nuclear matter to the extraordinary states of extreme high temperature and high density, thus opening the way to the creation and study of quark-gluon plasma. The lattice gauge calculation based on the theory of strong interactions (QCD) predicts that, at such states, quarks and gluons are deconfined from individual nucleons and form a hot plasma.

In this paper, the status of heavy ion stationary target programs at the BNL AGS and the CERN SPS, the progress of RHIC construction, and heavy ion research potential at LHC will be presented. The status of the CERN LHC will be covered elsewhere in these Proceedings.

GOLD BEAM OPERATION AT AGS

In 1991, a 1 GeV synchrotron (AGS Booster) was added to the AGS injection line to facilitate an increase of the AGS proton beam intensity by a factor of 2 to 3. With additional improvements being made, the AGS proton beam intensity should reach the target value of 6×10^{13} per pulse with a repetition cycle of 1.8 to 2.5/sec in a year or two. In addition, this Booster provides the AGS with the additional capability to accelerate heavy ions, as heavy as gold.

The experimental program with heavy ions at the AGS began in 1986, first with oxygen beams and then with silicon beams in 1987. In both cases, ions were directly injected into the AGS from the Tandem Van de Graaff in fully stripped form. The 14.5 GeV/nucleon (GeV/u) beams were extracted from the AGS for fixed target experiments. For heavier ions such as gold, a boost of energy beyond that of the Tandem was needed to strip atomic electrons more tightly bound to the nucleus.

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

A schematic diagram of the AGS accelerator complex and the operating scenario for the gold beam is shown in Fig. 1. For the initial gold beam operation in 1992, 1 MeV/nucleon (MeV/u) beams from the Tandem with an average charge of +12.5/ion were sent through

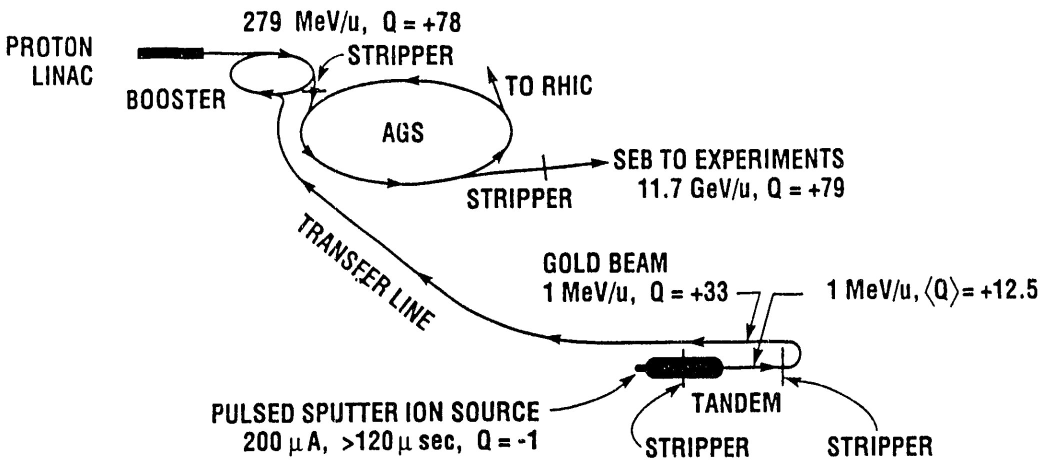

Fig. 1. The AGS accelerator complex and operating scenario for the gold beam run.

$20\mu g/cm^2$ carbon foil and stripped to the charge state of +33. The Booster accelerated them to 279 MeV/u, the energy which was high enough for efficient stripping of the remaining atomic electrons to the charge state of +78 or +79. The injection to the Booster was multi-turn for the duration of the Tandem beam length, 350 μsec, accumulating 2.5 $\times$ 10^8 gold ions in 3 bunches. The final energy reached with the AGS was 11.7 GeV/u with an intensity of 7 $\times$ 10^7 ions per beam, sufficient for initial experiments. In the initial operation, there was a significant loss of beam in each step of beam transfer and acceleration, resulting in the overall loss of beam by 3 to 4 orders of magnitude. The cause of these losses is being identified and remedied to improve the performance for coming experimental runs and also for the planned injection into RHIC.

Approved gold beam experiments are listed in Table 1. Most of them address the search for the formation of quark-gluon plasma in high baryon density states produced by gold beams. They are also in the most part the continuation of silicon and oxygen beam experiments at the AGS, but with some modification of set-ups to handle very high multiplicity from gold beam reactions. Experiment E892 addresses somewhat different aspects of the heavy ion collision. This atomic physics experiment investigates electron capture processes from the e^+e^- pair created by the electro-magnetic interaction of heavy ions. This is an important investigation which may yield information on the beam lifetime in heavy ion colliders.

Table 1: AGS Heavy Ion Experiments with Au Beam (Approved)

E863	I. Otterlund/ F. Wilkes	Particle Production and Nuclear Fragmentation: Emulsion
E866	C. Chasman/ H. Hamagaki (E802)	Inclusive Particle Production: Small Acceptance Spectrometer
E877	P. Braun-Munzinger (E814)	Baryon Rapidity Dist., p-p/$\pi-\pi$ Correlations, E_T Production: 4 π Calorimeter/Forward Tracking and Particle ID
E882	B. Price	Exotic Particle Production (|Z| $\geq$ 3, high A/Z, etc.)
E891	E. Platner (E810)	Search for QGP: MPS with Large Aperture Tracking with TPC
E892	H. Gould	Electron Capture from Pair Production

CERN LEAD BEAM PLAN WITH SPS AND LHC

Presently, the CERN-SPS provides the heavy ion program with sulphur beams with an intensity of 1.8 $\times$ 10^9 ions/pulse (or 3 $\times$ 10^{10} charge/pulse). The SPS operating schedule includes up to 8 weeks of heavy ion runs in the coming years. The Pb beams are expected in late 1994, with the first full production run in early 1995. This lead beam project is a collaboration of laboratories in France, Italy, Germany, and India (they are responsible for the construction of the Pb ion source as well as the pre-acceleration and beam transport system), and CERN (who is responsible for the upgrade of rings).

The CERN lead beam operation scenario is shown in Fig. 2. The ECR ion source which can produce 80 μA of Pb^{25+} beams is being developed by GANIL. The lead beams from the ECR source at an energy of 2.5 keV/nucleon (keV/u) are transported through the Low Energy Beam Transport (LEBT) to the RFQ acceleration unit for further pre-acceleration. The LEBT and RFQ are the responsibility of INFN, Legnaro. The heavy ion linac contributed by GSI takes 250 keV/u beams from the RFQ and accelerates them to 4.2 MeV/u. After going though the first stripping foil where about half of the remaining atomic electrons are removed, lead ions at the charge state of +53 will proceed to the PS Booster through the High Energy Beam Transport (HEBT) which is being built by INFN, Torino. Lead beams will then be fed into the existing chain of accelerators, reaching an energy of 94 MeV/u by the PS Booster, 3.11 GeV/u by the PS, and, after being fully stripped by the second stripping foil, finally will reach the energy of 50 to 160 GeV/u by the SPS. The vacuum in the PS Booster and PS will have to be improved by a factor of $\sim$10 to assure a minimal beam loss for the Pb beam operations. The straightforward estimate based on the intensity from the ECR source, a realistic transmission efficiency up through the PS ($\eta = 0.02$), and no losses from the PS through the SPS gives an expectation of the beam intensity greater than 10^8 ions/SPS pulse, about a factor of 2 above the intensity requested by experiments.

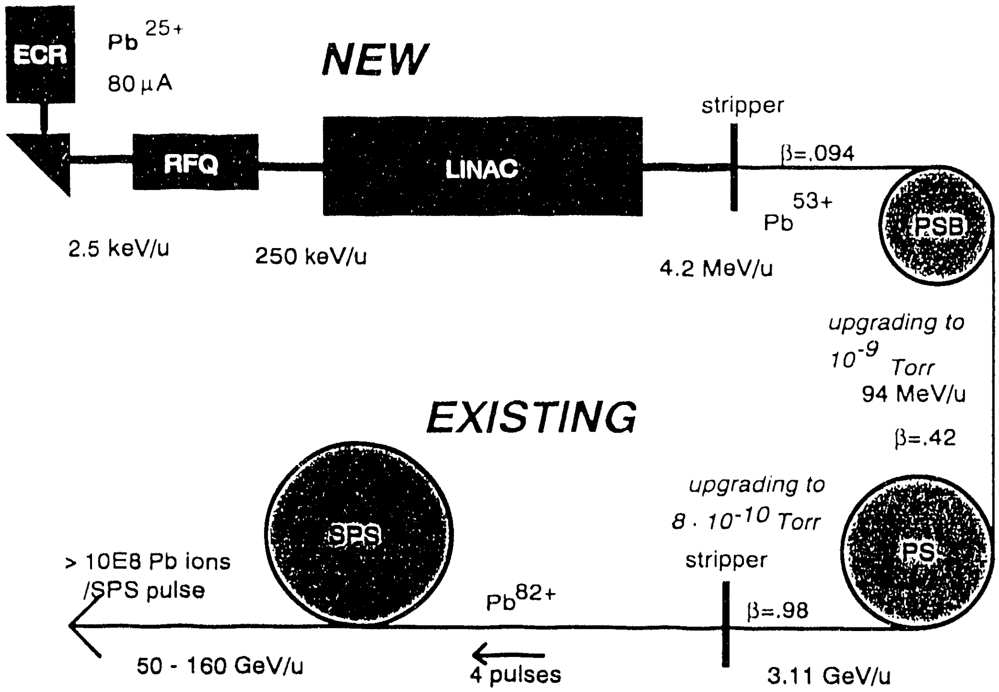

Fig. 2. The CERN lead beam acceleration scenario.

The approved experiments with SPS lead beam operation are given in Table 2. The program covers a range of physics including searches of quark-gluon plasma in the projectile domain through hadronic and electromagnetic probes, HBT measurements, and search of strangelets. In addition, a number of emulsion experiments are also planned to explore phenomena in newly opened frontier.

The plan to construct the LHC using the LEP tunnel will be presented elsewhere in these Proceedings. Although the principal purpose of the LHC is the search of Higgs and other ultra-high energy phenomena from p-p collisions in the multi-TeV region, the lead beam capability of the SPS will make it possible to run the LHC for ultra-high energy heavy ion collision experiments at least for a part of the time. The 2-in-1 geometry of the ring magnet design proposed for the LHC, however, will not allow it to collide unequal ion species like protons with lead which are deemed desirable to study the formation of quark-gluon plasma. The current estimate of the luminosity for lead-lead collisions based on the anticipated SPS performance is in the range of 10^{24} to 10^{25} cm^{-2} sec^{-1}. The final goal for the luminosity is proposed to be 2×10^{27} cm^{-2} sec^{-1} with an improved ion source and/or cooling and stacking.

The plan is to dedicate one interaction area at the LHC to a detector designed for the heavy ion experiment. Recently, the ALICE collaboration submitted a Letter of Intent to build such a detector. The collaboration plans to reuse part of the L3 detector and to add a silicon tracker, Time Projection Chamber, Time of Flight/Ring Imaging Cherenkov detector, Zero Degree Calorimeter, Single Arm EM Calorimeter, Multiplicity Array, etc. This detector will be more or less a general purpose detector for the heavy ion physics experiments, and it will cover many aspects of phenomena which are expected from the quark-gluon plasma formation in extreme energy density states. In addition, collaborations planning detectors for the p-p operation of LHC, such as ATLAS, CMS, and L3P have expressed their interest to join the heavy ion program also, addressing specific aspects of the heavy ion collisions such as high mass di-muon production (or Υ suppression) and jets.

Table 2: CERN Heavy Ion Experiments with Pb Beam (Approved)

WA97	E. Quercigh (WA85/94)	Hyperons (Λ, Ξ, Ω): Ω Magnet + RICH, Si Telescope
WA98	H. Gutbrod (WA80/93)	Prompt γ's, π^o, η: pb-Glass E.M. Calorimeter, γ counting Array, ZDC, Plastic Ball
NA44	H. Boggild (NA44)	HBT, Inclusive Particle Spectra: Small Acceptance Spectrometer
NA49	R. Stock (NA35)	HBT, Particle Ratios, p_t- Spectra: Large Acceptance Spectrometer
NA50	L. Kluberg (NA38)	Thermal Di-muons, J/Ψ Suppression, p, ω, ϕ at High p_t
NA51	K. Pretzl (New)	Strangelets: Beamline Spectrometer, TOF, Cherenkov
EMU11/12/13/14 - P.L. Jain (EMU08)/ I. Otterlund (EMU01)/ W. Wolter/D. Gosh		

STATUS OF RHIC CONSTRUCTION

The RHIC Project is an ongoing construction activity at BNL. The mission of the Project is to construct a superconducting, high energy heavy ion collider. An existing 3.8 km ring tunnel (95% complete), four experimental areas, and a 25 kW liquid He refrigerator will be used in the construction. In addition, an existing chain of accelerators consisting of the Tandem Van de Graaff, the AGS Booster, and the AGS will be used as the injector. The Project mission also includes construction of a complement of detectors for the initial phase of experimentation.

The Project Overview

The collider performance objectives are given in Table 3. The collider is to accelerate and store beams of ions, ranging from gold ions to protons, with a top energy of 100 GeV/u for gold (250 GeV for proton) and a beam lifetime of ~10 hr. The lower bound of energy for the colliding beam operation is envisaged to be about 30 GeV/u, determined by a faster emittance growth by the intra-beam scattering of heavy ions at lower energies. The luminosity for gold-gold collisions of 2×10^{26} cm^{-2} s^{-1} is expected at each beam crossing point for an operation with 57 bunches for each of the two rings and 1×10^9 gold ions per bunch. The wide energy range provided by this collider is expected to cover the transition from the confined nucleon phase to the deconfined quark-gluon plasma phase of nuclear matter. Having two rings independent of each other, the colliding beams can be of unequal species of ions, like protons on gold ions. This feature is unique to RHIC and is considered vital for understanding complex heavy ion collision phenomena, such as the onset of the quark-gluon plasma formation.

Table 3: The Collider Performance Objectives

Ion Types: A ~ 200 (Au) – A = 1 (p)

Ring Operation: Independent for two rings → unequal ion species

	Au-Au	p-p
Beam Energy	100 GeV/u - 30 GeV/u	250 GeV - 30 GeV
Luminosity	2×10^{26} cm^{-2} sec^{-1}	1.4×10^{31} cm^{-2} sec^{-1}
Number of Bunches	57	57
Particles/Bunch	1×10^9	1×10^{11}
Luminosity Lifetime	~10 hrs	>10 hrs
β^*	10 m → ~2 m	10 m → 2m

In 1983, a long-range plan, prepared by the U.S. nuclear science community for the U.S. Department of Energy (DOE) and the National Science Foundation, cited RHIC as the highest priority new facility in the field of nuclear physics. That recommendation was repeated in the 1989 long-range plan. The Project's seven-year funding for construction began in FY 1991 with the total estimated cost of $406.6 M, and the target completion date in 1997. After the final review, the full-scale construction of the collider was approved by DOE in January 1992. About one quarter of the construction funding is reserved for detectors. The new Presidential Budget recently submitted for FY 1994, however, reduces the funding for FY 1994 by \$20 M from \$90 M planned, and also places a cap on the total RHIC funding at the present level of \$76 M for subsequent years. If this funding scenario prevails, the completion of RHIC will be delayed by about one and a half years.

To date, the RHIC Project has made a good progress towards the original goal of the completion in 1997. The project has been fortunate in acquiring top level staff members to fill all of the key positions of the Project organization. An extensive value engineering was carried out on the design of the collider to minimize the cost of the construction, while maintaining the simplicity and reliability of the operation. The accelerator lattice was reviewed and small modifications in its insertion optics were made in early 1992. This lattice (RHIC92) provides a wide range of β functions at collision points, accommodating a large dynamic aperture for the injection with $\beta^* = 10$ m and high luminosity collisions with $\beta^* = 1{\sim}2$ m. The procurement of accelerator components is also going very well, completing the contract award for $\sim$ 70% (or $\sim$\$77 M) of total major procurements for the collider.

In addition, there is a high level of activity at BNL. The in-house production of special magnets and corrector assemblies is about to start; the tunnel is being surveyed and survey monuments and magnet stands are being installed; and the detail engineering, design, and prototype work of the remaining accelerator systems is in progress.

Significant progress was also made in the RHIC detector program. Two major detector systems (PHENIX and STAR) which will occupy two large experimental halls are well defined and approved by the Laboratory. STAR is already in the construction phase and PHENIX will enter into the construction phase this summer. Two small-scale experiments (PHOBOS and Forward Angle Hadron Spectrometer) received preliminary approval to proceed with formal proposals and conceptual designs for construction. From a technical viewpoint, the completion of the collider construction and the start of the heavy ion collision physics program as originally scheduled in 1997 is realistic.

The Collider Configuration and Status

Figure 3 shows the accelerator configuration of the RHIC facility and the operation scenario taking gold ions as an example. Similarly to the AGS gold beam operation, negative ion beams from a pulsed sputter ion source are accelerated to a higher energy as they go through stages of the accelerator chain, i.e., the first and the second stages of the Tandem Van de Graaff, the Booster Synchrotron, and finally the AGS. The scenario for stripping of the atomic electrons is somewhat different from the case described previously for the AGS gold beam operation. The stripping is done first with a foil at the high voltage terminal of the Tandem to the electric charge (Q) of $\sim$+14, and then by the foil at the exit of the Booster to +77, i.e., all atomic electrons except for the two K-shell electrons. The AGS, with its improved vacuum of 10^{-8} Torr, can accelerate three bunches of Q =

+77 gold ions from the Booster to 10.8 GeV/u with only a few percent loss. Ions are fully stripped at the exit of the AGS and injected into the RHIC collider rings, one bunch at a time (three times for each AGS cycle).

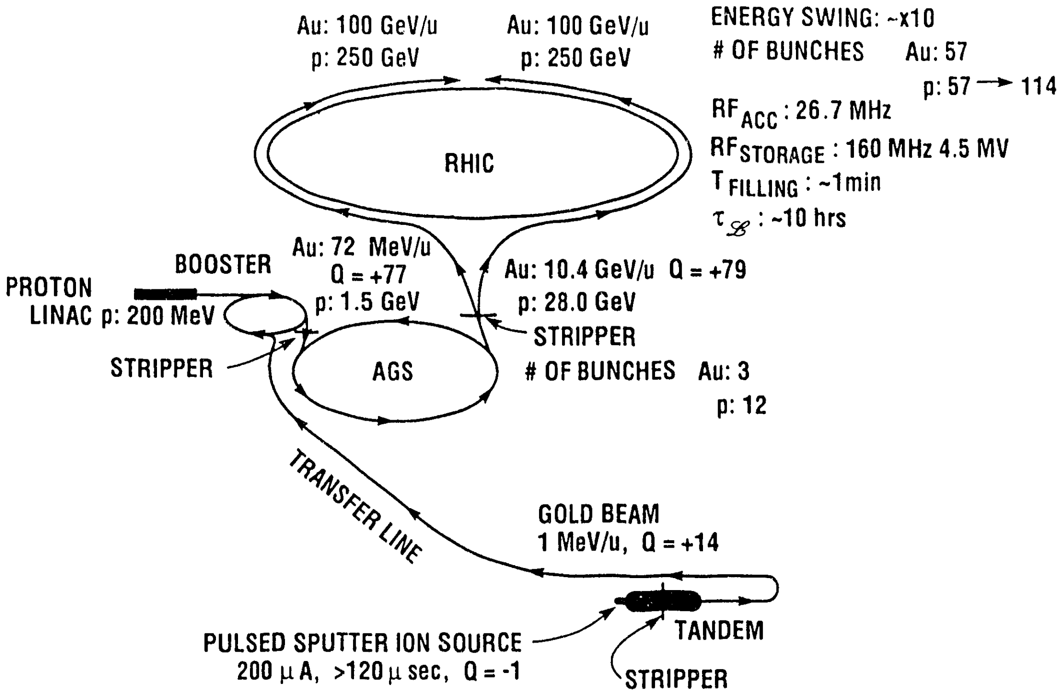

Fig. 3. RHIC accelerator configuration and operating scenario for gold beams.

Beam stacking is done in the boxcar fashion by repeating the above injection cycle 19 times for each ring until 57 bunches are captured in stationary buckets of the "acceleration rf system" operating at ~26.7 MHz, corresponding to a harmonic $h = 57 \times 6$. The time it takes to fill two rings is ~1 min and acceleration to the top energy takes about 1 min. After reaching the operating energy, the bunches are transferred to the "storage rf system" at 196 MHz ($h = 57 \times 44$). This higher frequency for beam storage was chosen to compress and hold the bunch length to ~25 cm (or collision diamond length ~20 cm rms), as required from the experimental consideration. The Project was fortunate in being able to acquire the CERN SPS 200 MHz standing wave rf system for the RHIC storage rf system.

The collider is composed of two identical, quasi-circular concentric superconducting magnet rings (3,833.85 m in circumference), arranged to intersect with one another at six locations (Fig. 4). In the arc section, the rings are placed side-by-side, with the beam-to-beam spacing of 0.9 m. Therefore, each ring consists of three inner and three outer arcs (each ~355 m long), and six insertion sections (each ~283 m long) joining the inner and outer arcs. Each arc is composed of 11 standard arc FODO cells (see inset in Fig. 4) and a modified half cell at each end. The standard cell consists of two dipole magnets

(9.45 m) and two combined magnet units each consisting of one quadrupole (1.11 m), one sextupole (0.75 m), and one assembly of multipole corrector windings (0.58 m). The dipole magnet in the modified cell is 2.95 m long. The crossing point of the beams is located at the middle of the insertion sections (Fig. 5). Two dipole magnets in each beam near the crossing point steer circulating beams to head-on collisions.

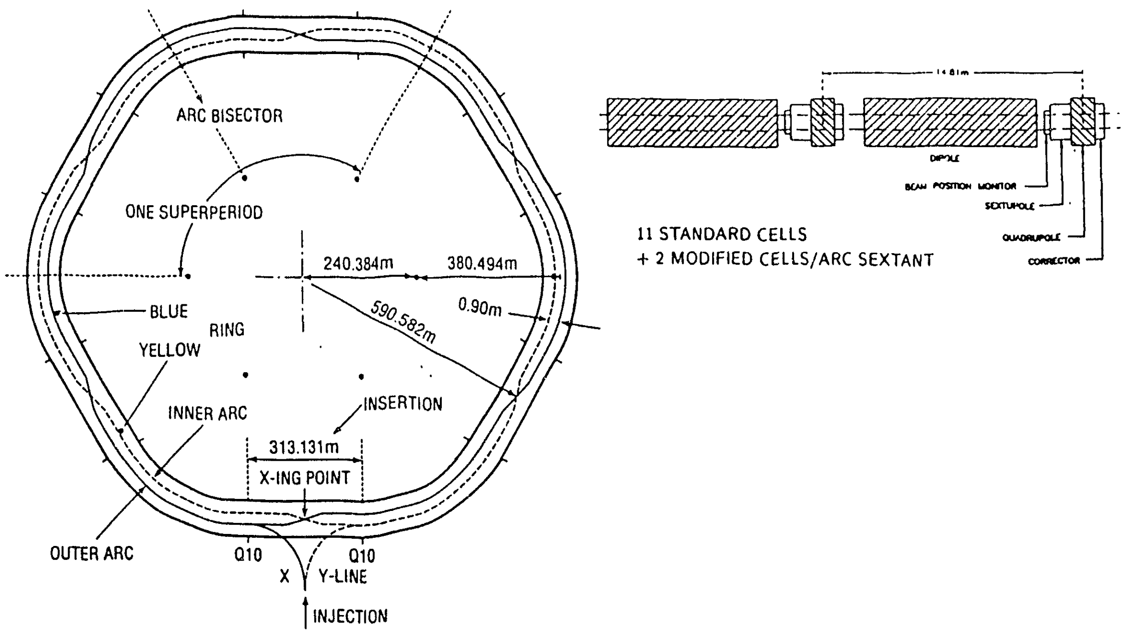

Fig. 4. Layout of the RHIC collider rings. The inset shows a standard arc cell.

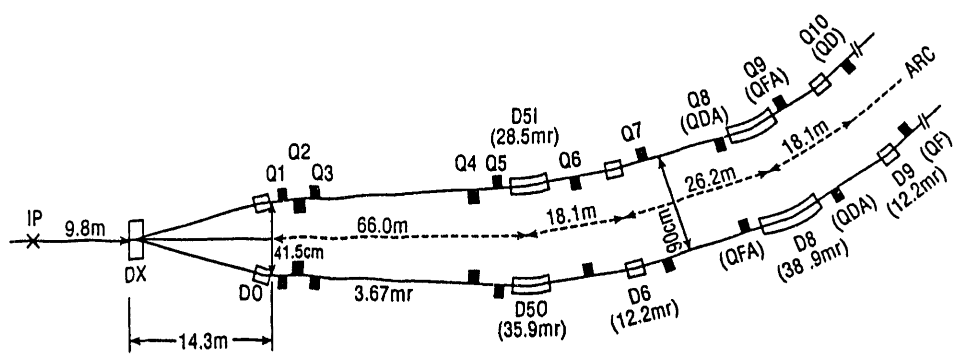

Fig. 5. Layout of one half of the insertion section.

Arc magnets and most of the insertion magnets have an 80 mm coil bore diameter to provide enough aperture for emittance growth caused by intrabeam scattering. Five magnets in each beam near the crossing point have larger bore diameters (110 ~ 200 mm) for improved dynamic aperture of the collider even for the lowest β^* operation.

The operating magnetic field of arc dipoles is 3.45 T. This relatively low field allows the simple design which calls for a single layer cosθ coil, approximated by four coil blocks separated by precisely shaped wedges (Fig. 6). Since the outward force of the coil is relatively modest, low carbon iron yoke lamination (6 mm thick) can also serve as the collar. High precision, injection molded, mineral loaded phenolic insulating spacers also define the geometry of the coil. The magnets are cooled to a temperature of <4.6 K by supercritical helium.

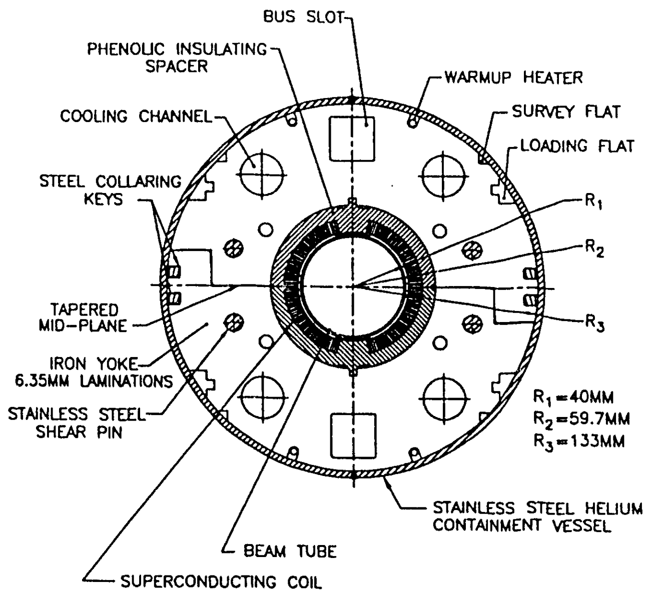

Fig. 6. Cross section of RHIC arc dipole magnet. Supercritical helium for cooling flow through the gap between the beam tube and superconducting coil as well as through four cooling channels

The design of the quadrupoles is similar to that of the dipoles but with four coils, each made of two coil blocks. The design of the sextupoles is of the superferric type with six poles of the iron yoke lamination determining the magnetic field property. A similar design is used for the trim-quadrupoles which will supplement insertion region quadrupoles to control the optical parameters (β functions) at the crossing points. The technology used for the corrector windings was developed by BNL in collaboration with industry for this specific purpose. This technology, which is based on the "Multi-Wire Process" precisely lays and firmly bonds insulated superconducting wires on plastic substrates. The substrates, each designed for intended multipole correction, are wrapped around stainless steel tubes of varying diameters, and are nested together in a concentric manner to form the multipole corrector assembly.

Superconducting cables used for 80 mm bore dipoles and quadrupoles are the "Rutherford type," consisting of 30 strands of 0.648 mm superconducting wire. Each wire is a composite of 6 μm NbTi filaments (~3600 filaments) and pure copper with a copper-to-superconductor ratio of 2.25:1, a conservative design for the present technology. The minimum J_c of 2600 A/mm^2 specified can easily be achieved with current industrial technology. An order to produce 1.8 million feet of cable, the total requirement for the Project, was placed with one firm with a hope of ensuring product uniformity. This perhaps is the largest single lot manufacuring of superconducting cables under a strict quality control to date. It should be noted that the expertise on superconducting materials and test facilities within the Project have been very valuable in establishing a cooperative partnership with industry. Insertion quadrupoles and dipoles with large bore use 36 strand cables similar to that developed for the new SSC 50 mm dipoles. Manufacturing of these cables as well as superconducting wires for sextupoles, trim-quadrupoles, and correctors is proceeding very well. In all, industrial manufacturing of superconductors needed for the Project will be completed during 1993, well in advance of magnet fabrication.

To date, ten R&D full-length dipoles have been built and tested. In all cases, the magnetic field at the first quench exceeded the required field of 3.45 T with a comfortable safety margin, and reached values in the range of 4.3~4.7 T after a few quenches. A number of quadrupoles, sextupoles, and corrector assemblies were also built and tested. All satisfied RHIC requirements with a very comfortable margin of greater than 50%. Through iterative processes, the coil cross section designs for 80 mm dipoles and quadrupoles were optimized for the field quality. Preproduction dipole magnets built with this optimized design show the field quality well acceptable to RHIC. The field qualities of 8 preproduction quadrupoles are also acceptable and the randam variation among them is found to be smaller than anticipated.

The RHIC rings use 1240 superconducting magnets and approximately 500 corrector units. Of these, 1132 magnets will be produced by industry. They are 360 dipoles, 412 quadrupoles, 288 sextupoles, and 72 trim-quadrupoles, all with 80 mm bore. Three contracts to manufacture these magnets were awarded to industry in the latter half of 1992. Each contract includes technology transfer, design and fabrication of tooling, and manufacturing of the respective magnets. The delivery of the dipole and quadrupole magnets is expected to begin in late 1993, and the entire production completed by mid 1996. The production of sextupole magnets will begin in mid 1993.

The remainder of the magnets, namely, 72 each of 130 mm bore quadrupoles, 24 each of 110 mm bore dipoles, and 12 each of 200 mm bore dipoles, and correctors, will be assembled at BNL using its magnet fabrication facility.

The main feature of the cryogenic system is the 25 kW helium refrigerator, with a primary capacity of 24.8 kW at about 4 K and a secondary capacity of 55 kW at about 55 K. This refrigerator was fabricated, installed, and, after testing, was accepted by BNL in March 1986. With some minor changes, this system can produce the refrigeration required by RHIC with ~100% reserve capacity. Cold centrifugal compressors will be used to circulate single-phase, supercritical pressure helium in a closed loop through the magnets of each ring and through a distributed network of heat exchangers for recooling by the primary flow of liquid helium from the refrigerator.

The Physics Program at RHIC

There are a number of signatures which are predicted to signify the formation of quark-gluon plasma. Typically, an observation of a global feature of hadron production from the heavy ion collisions, such as multiplicity, spatial and energy distributions of emerging hadrons, and the production of specific types of particles can reveal the plasma formation. Contrary to hadrons which are strongly absorbed by the nuclear matter and thus convey information only of the surface of the plasma, leptons and photons are penetrating probes and can give an insight on the inner making of the plasma. A change in the global feature as a function of energy can signify an onset of the plasma formation. The RHIC detector program consists of two complementary major detector systems (PHENIX and STAR) and two small-scale experiments (PHOBOS and Forward Angle Hadron Spectrometer). These detectors collectively cover all of the predicted signatures. At present, a total of ~500 physicists from ~80 institutions worldwide are involved in this program.

STAR (Spokesperson: J. Harris, LBL/Proj. Manager: J. Marx, LBL). The STAR[1] collaboration plans to use the large solid angle tracking and particle identification capability of a cylindrical Time Projection Chamber, placed in a large solenoidal magnet. The design emphasizes detection of a global feature of the hadrons (soft processes) and jets (hard scattering processes) as the signature of the quark-gluon formation. The basic configuration of the detector for the initial stage of the experiment is estimated and determined to meet the funding plan of the Project for a major detector. This detector was approved by the HE/NP Program Advisory Committee of the Laboratory (PAC) and Technical Advisory Committee (TAC) of RHIC, and was baselined to enter into the construction phase in January 1993.

PHENIX (Spokesperson: S. Nagamiya, Columbia/Proj. Manager: S. Aronson, BNL). The PHENIX[2] collaboration focusses on the detection of leptons, photons, and hadrons in selected solid angles, with a high rate capability. The central part of the PHENIX detector consists of an axial field magnet and two detector arms each covering the rapidity region ± 0.35 and 1/4 of full azimuth. Each arm will be equipped with a Drift Chamber, Pad Chambers, RICH, Time Expansion Chamber, TOF, and EM Calorimeter for tracking, particle identification, and EM calorimetry. In addition, an array of silicon detectors closer to the beam pipe gives a close to 4π coverage for particle detection. The collaboration also

[1] CDR - LBL Pub-5347

[2] CDR - BNL Pub (in press)

intends to incorporate a muon arm in the forward direction to enable di-muon detection. This collaboration is a large-scale international collaboration of more than 275 physicists from more than 10 countries. This detector proposal was approved by the PAC and TAC in February 1993 and is expected to enter into the construction phase after the cost and schedule baselining in August of this year.

PHOBOS (Spokesperson: W Busza, MIT). Coined from a small satellite of Mars, PHOBOS is a true tabletop experiment. This double arm spectrometer with a pair of small high field magnets and high spatial resolution silicon detector planes will make it possible to fit the entire detector on a table of ~1 m in diameter. This detector focusses on hadronic lepton signatures for the investigation of the quark-gluon plasma with some sensitivity to electrons as well. With encouragement from PAC, the collaboration is preparing a formal proposal.

The Forward Angle Hadron Spectrometer (Spokesperson: F. Videbaek, BNL). This spectrometer is designed for inclusive spectroscopic measurement with particle identification over a limited solid angle, but at various rapidity settings.

The RHIC Project is making excellent progress toward the original goal of starting relativistic heavy ion collision studies in 1997. Most of the technical issues associated with the collider are resolved, procurement of magnets and other accelerator components are well underway, and a realistic picture of the experimental program is taking shape.

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