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HEAVY ION PROGRAM AT BNL: AGS, RHIC*

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Summary

With the recent commissioning of fixed target, heavy ion physics at the AGS, Brookhaven National Laboratory (BNL) has embarked on a long range program in support of relativistic heavy ion research. Acceleration of low mass heavy ions (up to sulfur) to an energy of about 14.5 GeV/nucleon is possible with the direct connection of the BNL Tandem Van de Graaff and AGS accelerators. When completed, the new booster accelerator will provide heavy ions over the full mass range for injection and subsequent acceleration in the AGS. BNL is now engaged in an active R&D program directed toward the proposed Relativistic Heavy Ion Collider (RHIC). The results of the first operation of the low mass heavy ion program will be reviewed, and future expectations discussed. The expected performance for the heavy ion operation of the booster will be described and finally, the current status and outlook for the RHIC facility will be presented.

Introduction

A growing community of nuclear and high energy physicists are pursuing a program of research into the properties of nuclear matter at high densities and temperatures [1,2]. Of particular interest, is the prediction from Quantum Chromodynamics (QCD),

New heavy ion research programs are being carried out at the AGS and at the CERN SPS, which has accelerated oxygen ions to 200 GeV/nucleon [3]. The first phase of the BNL program comprises direct injection of beams of low mass heavy ions from the Tandem Van de Graaff into the AGS for a fixed target program at about 14.5 GeV/nucleon [4]. Only fully stripped ions can be accelerated in the AGS because of the high rates of electron pick-up and loss for partially stripped ions in the residual gas. It is estimated that ions of mass up to sulfur can be fully stripped at Tandem energies with sufficient intensity for injection.

In the second phase of the program, the AGS booster [5] will accelerate partially stripped ions to energies at which they can be fully stripped for injection to the AGS. This will extend the accessible physics to that of ions from the full periodic table, with a top energy of about 11 GeV/nucleon for gold. Collisions at this energy on fixed targets are expected to produce rather low nuclear temperatures, but baryon densities of approximately 5 to 10 times nuclear density. The dashed trajectory labeled "Nuclear Fragmentation" in Fig. 1 illustrates a possible probe of the quark-gluon plasma at high baryon density in such collisions. These conditions may be similar to those found in neutron stars.

A growing community of nuclear and high energy physicists are pursuing a program of research into the properties of nuclear matter at high densities and temperatures [1,2]. Of particular interest, is the prediction, from Quantum Chromodynamics (QCD), of the formation of a quark-gluon plasma, a state analogous to an electronic (QED) plasma of free electrons and ions. Fig. 1 is a schematic representation of a phase diagram for nuclear matter with temperature (of nucleons and produced particles) plotted vs. baryon (nucleon) density. The region of deconfined quarks and gluons is the target of this research.

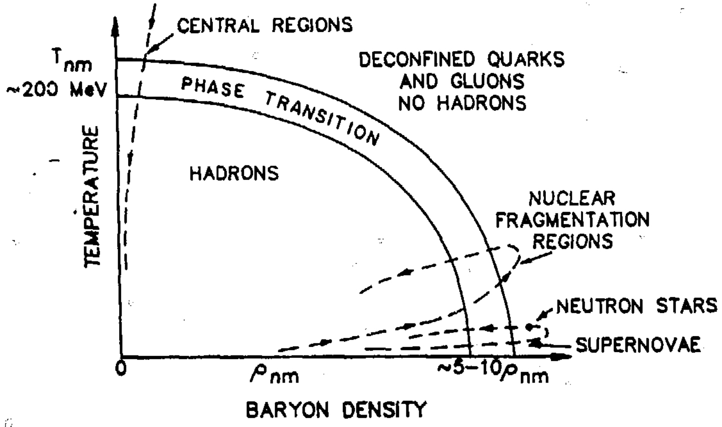

Fig. 1. Phase diagram showing nuclear temperature vs. baryon density. Band indicates transition between hadrons and the quark-gluon plasma. (after G. Baym, ref. 1)

"Nuclear Fragmentation" in Fig. 1 illustrates a possible probe of the quark-gluon plasma at high baryon density in such collisions. These conditions may be similar to those found in neutron stars.

The layout of the BNL site including the facilities comprising the heavy ion operation is shown in Fig. 2. Dominating the figure, and awaiting final project approval, is the proposed RHIC facility [6] which will extend the range of physics to energies of 100 Gev/nucleon in each ring. At these energies, the colliding nuclei are expected to be highly transparent to each other, leading to lower baryon density over much of the collision, but to high tempertures in the region of excitation and particle production. The trajectory in Fig. 1 labelled "Central Regions" indicates a possible probe of the quark-gluon plasma in heavy ion collisions in RHIC, under conditions which may closely parallel part of the early history of the universe.

Low Mass Heavy Ion Acceleration

The acceleration of oxygen ions in the AGS in Oct. 1986 initiated the program of relativistic heavy ion physics at BNL. This project encompassed the installation of pulsed negative ion sources at the two BNL Tandem machines, the construction of a 640 m beam transfer line, and the installation of injection equipment and new low frequency rf system components in the AGS [7].

Tandem as Preinjector

In serving as a pulsed preinjector for the AGS, the Tandem Van de Graaff facility operates in two modes. For the production of a fully stripped oxygen

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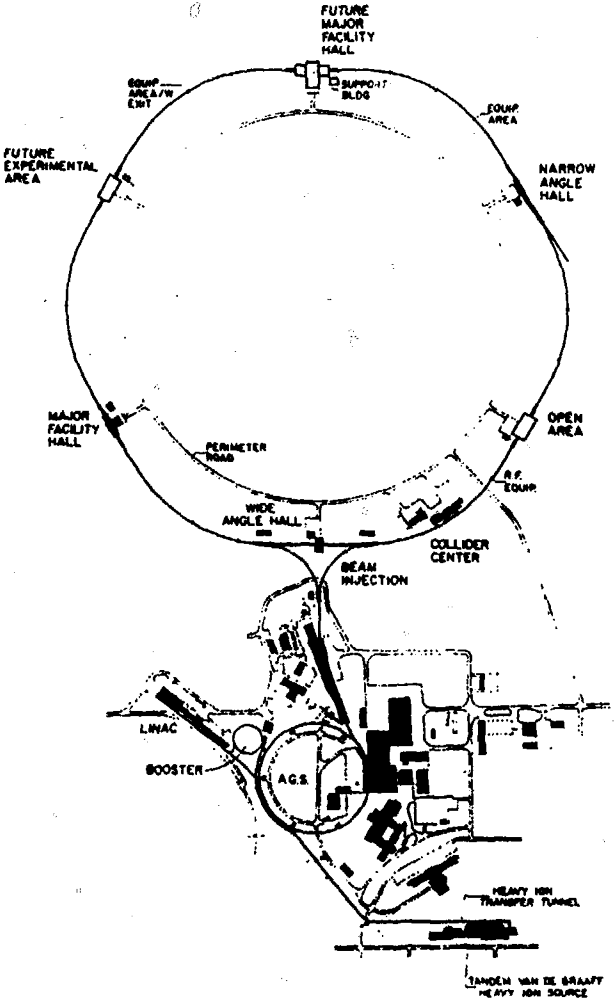


Fig. 2. The BNL accelerator site showing Tandem

turns (revolution period $\sim 22\ \mu s$). The injection takes place at a field of approximately 90 G on a slow ramp of about 0.1 T/sec.

The principal characteristics of the AGS acceleration cycle for low mass heavy ions are given in Table 1. The frequency range of the proton acceleration rf system in the AGS extends from 2.5 to 4.5 MHz, which is matched to the proton injection energy of 200 MeV. The capture and acceleration of heavy ions of 6-8 MeV/nucleon on the same 12th harmonic of the revolution frequency requires a range from 0.5 to 4.5 MHz. A separate ferrite-loaded cavity with a peak voltage of about 8 kV on each of two gaps [8] accelerates the beam to 200 MeV/nucleon, after which the proton system accelerates the beam to full energy. A new low-level rf system controls the low frequency sweep [9]. At 200 MeV/nucleon the control of the rf passes to the so-called "boot-strap" low-level system used for protons in which the beam pick-up signals drive both frequency and phase servos. The remainder of the acceleration cycle closely follows the proton cycle with the exception that transition energy occurs at twice the value of magnetic field because of the charge to mass ratio of the heavy ions.

Table 1
AGS Parameters for Low-Mass
Heavy Ion Acceleration

Energy Range	6-200 MeV/ nucleon	0.2-14.5 GeV/ nucleon
RF Frequency	0.5-2.5 MHz	2.5-4.5 MHz
Harmonic Number	12	12
Energy Gain/Turn	4.0 keV/ nucleon	70 keV/ nucleon
Magnetic Field Rise Rate	0.1 T/sec	2.0 T/sec

Fig. 2. The BNL accelerator site showing Tandem Van de Graaff, AGS, Booster (op. 1989) and Relativistic Heavy Ion Collider (proposed).

beam at 7 MeV/nucleon, a pulsed negative ion beam is accelerated to the positive high voltage terminal of the MP-7 Tandem which normally operates at 14 to 15 MV. Stripping in a thin foil at the terminal produces several positive charge states, of which the $O(7^+)$ state is selected in the first stage of the beam line to the AGS, whereupon it is stripped of its remaining electron.

For the production of beams of silicon or sulfur, the ion source is located at the terminal of a second, lower voltage Tandem, MP-6, operating at negative high voltage. The negative ions are accelerated to ground potential and to the terminal of MP-7, where a stripping foil is again located. After two further strippings at intermediate and full energies, the ions are transported to the AGS.

The fractional energy spread of these Tandem beams is approximately 2×10^{-4}. The measured 90% emittance (normalized) of a 70 μA oxygen beam at 7 MeV/nucleon is about 0.25 π-mm-mr and of a 18 μA silicon beam at 6.7 MeV/nucleon is about 0.50 π-mm-mr.

AGS Injection and Acceleration

Direct injection of the Tandem heavy ion beam into the AGS is accomplished using standard multiturn injection into horizontal phase space of the accelerator using a pulsed orbit bump and a dc electrostatic septum. Nominal injection comprises about 10

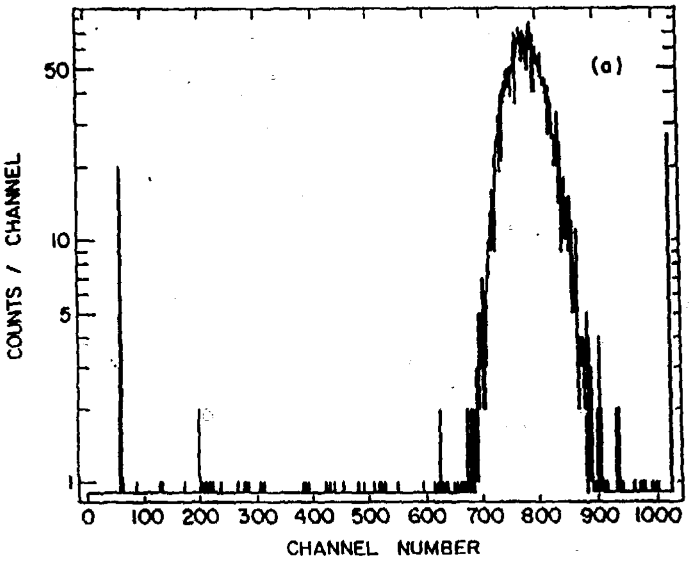
Harmonic Number	12	12
Energy Gain/Turn	4.0 keV/ nucleon	70 keV/ nucleon
Magnetic Field Rise Rate	0.1 T/sec	2.0 T/sec
Acceleration Time	0.45 sec	0.60 sec
Experimental Beams Spill Duration	~ 1.0 sec	
Total Cycle Time	~ 3.2 sec	

Initial Performance

During commissioning and the first physics run in Oct.-Nov. 1986, the Tandem delivered to the AGS a beam of oxygen at a peak current of about 90 μA. More typical operating conditions comprised the injection of up to about 12 turns of a 50 to 60 μA beam into the AGS with an average multiturn injection efficiency of about 50%. Capture and early acceleration efficiency was low (~10%) during this run, leading to a beam at full energy of about 5×10^8 ions/pulse. This intensity is significantly more than the level required for the direct fixed target program. The operational lower limit on intensity in the AGS will be set by the level required to maintain beam control in the bootstrap low-level rf system, which is approximately 1×10^9 electronic charges. It is expected that the new low-level rf system will eventually be used to control the full acceleration cycle and reduce the intensity threshold for acceleration of the heavier ions up to sulfur. For these ions, Tandem yields are lower and losses in the AGS due to electron pick-up in the residual gas are more severe with an expected fractional loss for sulfur injected at 6.8 MeV/nucleon of about 40-50%.

The passage of the hand-over between the two rf systems was very smooth with only a few percent loss of beam. The limits to performance in the acceleration of directly injected heavy ions occur in the early portion of the cycle.

The 14.5 GeV/nucleon oxygen beam was extracted from the AGS using standard resonant extraction. The beam was delivered to three beam lines in which nine experiments collected data. The typical intensity useful to these experimenters ranged from 5 x 10^3 to 10^5 ions per spill, so substantial collimation of the extracted intensity of 5 x 10^8 ions per spill was required. Contamination of the beam by fragments generated by ion collisions in beam extraction and delivery septums and collimators was a concern before this run; however, the observed purity of the beam was found to be excellent. Fig. 3 shows the result of a measurement of beam purity made after dilution and collimation of the beam by a factor of 10^5 [10]. The normalized emittance of this typical beam delivered to an experiment was ~ 0.75 πmm-mr.



heavier species. The Tandem beam will be transported from a point near the end of the new transport line, inside the AGS tunnel to the booster, located near the old 50 MeV linac injection line. The booster repetition rate for heavy ion operation will be <1Hz with a peak dipole field of about 1.3 T, while for proton operation, the rate will be 7.5 Hz with a maximum field of 0.55 T. The maximum magnetic rigidity of the heavy ions after acceleration is 17.5 T-m, which is sufficient for an efficiency of >50% for fully stripping Au(33+) before injection into the AGS. Table 2 lists representative parameters for operation of the booster with heavy ions and protons. The booster rf accelerating system, like the present AGS system, will comprise a heavy ion pre-acceleration system, with a lower frequency of 200 kHz for the heaviest ions, and a system which will accelerate protons and heavy ions above 2.4 MHz.

Table 2

AGS Booster Parameters for Heavy Ions

	p	S	Au
Injection:			
Net charge	1	14	33
Mass Number,A	1	32	197
T	200 MeV	4.7 MeV/ nucleon	1.1 MeV/ nucleon
Bρ	2.15 T•m	0.71 T•m	0.89 T•m
RF frequency	2.5 MHz	446 kHz	206 kHz
Extraction:			
T	1.5 GeV	0.97 GeV/ nucleon	0.35 GeV/ nucleon
Bρ	7.51 T•m	12.6 T•m	17.5 T•m
RF frequency	4.11 MHz	4.13 MHz	3.06 MHz
No. particles per pulse	1-3x10^{13}	1.5x10^{10}	3.2x10^9

Fig. 3. Pulse height spectrum from 1 mm scintillator in 14.5 GeV/nucleon oxygen beam. Pedestal and oxygen peaks are prominent features, with less than 1% contamination by nuclear fragments.

During the first running period only oxygen ions were accelerated in the AGS. A silicon beam was produced at the Tandem and its properties were studied in the transfer line. The April 1987 run, for which set-up is in progress, will utilize primarily silicon. The task of accelerating sulfur, which will entail low intensities from the Tandem and poor survival in the AGS vacuum, has not been attempted yet, and may be possible only if open-loop operation of the rf system can be established.

AGS Pre-acceleration Booster

The second phase of the BNL program for heavy ions will begin with the completion of the AGS Booster project, which is scheduled for the end of 1989. This machine, one-fourth the circumference of the AGS, was proposed to upgrade the intensities achievable in the AGS proton program by a factor of 3-4 and, operating as an accumulator, by a factor of 10-20 for polarized protons. In addition, the booster will be able, because of its excellent vacuum ($\sim 10^{-11}$ Torr), to pre-accelerate beams of partially stripped ions over the full mass range.

In this phase of the operation, one Tandem Van de Graaff will provide fully stripped ions of low mass, and partially stripped ions of sulfur and

The booster project construction has been modestly funded since FY 1986 and is approaching the task with a highly refined design. Recent work has focused on the fabrication and measurement of prototype magnets, tracking studies of the effects of vacuum chamber eddy-currents, rf ferrite measurements and system design, and ring power supply design.

Relativistic Heavy Ion Collider

The proposed RHIC facility has been designed to accept beams of heavy ions and/or protons from the AGS and to accelerate and provide collisions at energies up to 100 GeV/nucleon for gold and 250 GeV for protons. The two rings of superconducting magnets will occupy the existing CBA tunnel and utilize the existing cryogenic plant and experimental halls from that project. The physics of relativistic heavy ions puts rather different demands on the machine design, than are common in high energy hadron-hadron colliders. The luminosities required are modest because of the large cross sections of ion-ion interactions. The machine must be able to provide reasonable luminosities over its full energy range, and allow the collisions of unlike ion species as well as like species.

Collider Design and Performance

The lattice of the accelerator consists of two separate rings with six intersections arranged to permit collisions at a crossing angle which may be varied from 0 to 2 mr.[11] Table 3 summarizes some general parameters of the collider.

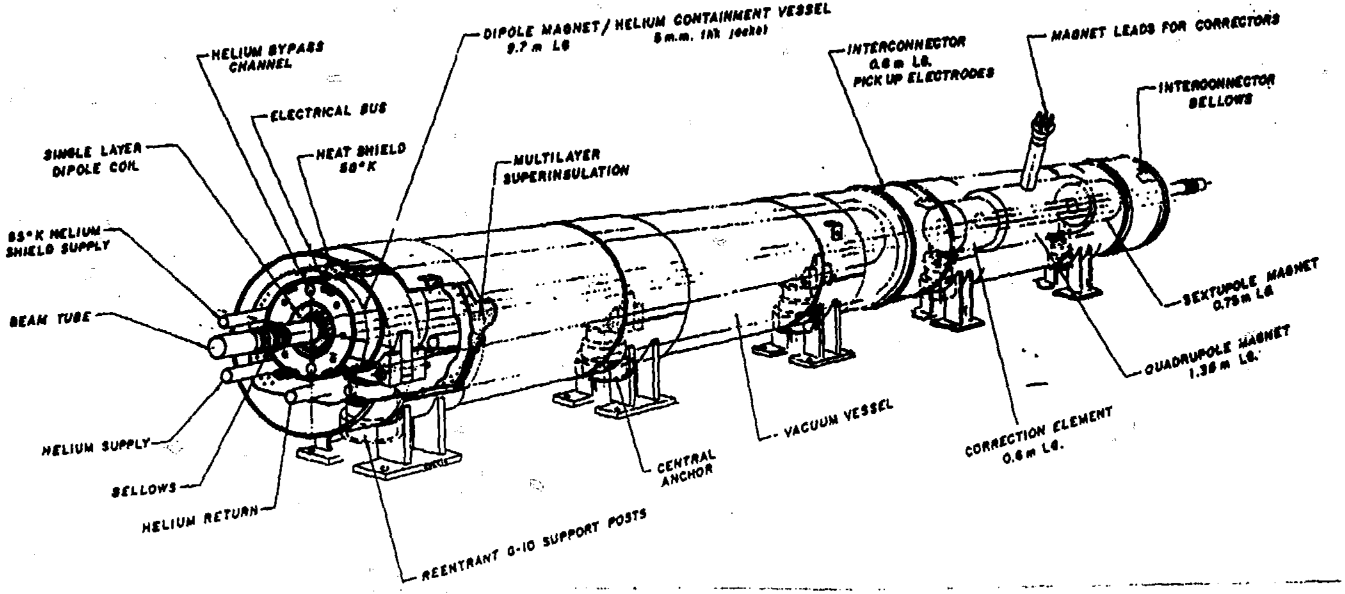
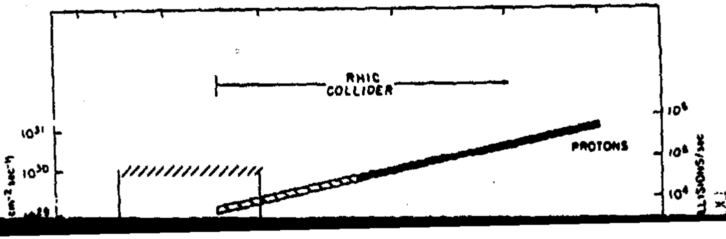


Fig. 4. Isometric drawing of RHIC half-cell with dipole, corrector, quadrupole, sextupole magnets and interconnections.

Table 3
General Parameters for RHIC

Energy range (each beam),	
Au	7-100 GeV/nucleon
protons	28.5-250 GeV
Average luminosity (10 hr),	
Au-Au, 100 GeV/nucleon	4.4×10^{26} cm^{-2} sec^{-1}
Diamond length @ 100 GeV/nucleon	35 cm rms
Circumference (4-3/4 C_{AGS})	3833.87 m
Beam separation in arcs	90 cm
Number of crossing points	6

luminosity lifetimes at lower energies to less than the nominal 10 hours expected above 30x30 GeV/nucleon.



Circumference (4-3/4 C_{AGS})	3833.87 m
Beam separation in arcs	90 cm
Number of crossing points	6
Free space at crossing point	9 m
Beta @ crossing point,	
horizontal/vertical	6 m
low-beta insertion	3 m
Betatron tune,	
horizontal/vertical	28.82
Gamma transition	25.0
Filling mode	Box-car
Number of bunches/ring	57
Number of Au ions/bunch	1.1×10^9
Filling time (each ring)	1 min
Magnetic rigidity, Bρ:	
@ injection	96.5 T·m
@ top energy	839.5 T·m
RF frequency	26.7 MHz
RF voltage	1.2 MV
Acceleration time	1 min

The dipole magnets in the main arcs will be 9.5 m long, with a magnetic field of 3.5 T. Fig. 4 shows a drawing of an arc half-cell assembly. Both dipole and quadrupole magnets [12] are single-layer magnets wound using superconducting cable developed for the SSC. Maximum flexibility of operation is maintained by providing separate vacuum vessels for each ring. The cold-bore aperture of 73 mm has been specified to satisfy the performance requirements taking into account intrabeam scattering [13].

Figure 5 shows the expected average luminosity for head-on collisions of several representative ion species over the full range of energies. The performance for fixed target operation of the AGS and RHIC are also indicated. Intrabeam scattering limits

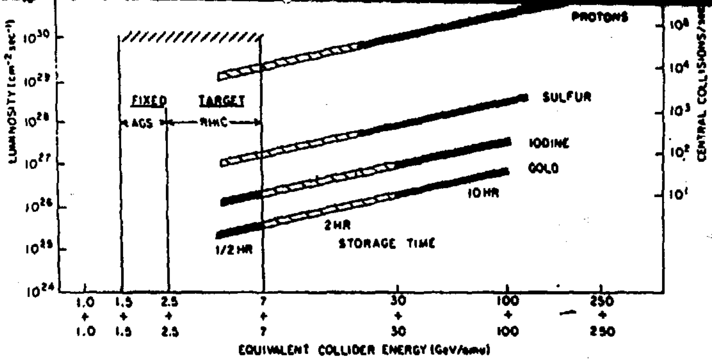


Fig. 5. Luminosity vs. center-of-mass energy for AGS and RHIC programs. Right-hand scale refers to collisions at impact parameters less than 1 Fermi.

Status and Outlook

Over the past two years, magnet system R&D has produced magnet models which have comfortably met the performance specifications for the RHIC facility. Recently, four full-length dipole magnets have been in fabrication using HERA tooling under an agreement with the DESY Laboratory in Hamburg. The coils have been wound at BNL and one magnet has been assembled at BNL. The other three are being built by Brown, Boveri et Cie (BBC). The BNL magnet has just undergone preliminary tests, in which it ran immediately to a field above the nominal operating point for full RHIC energy. Fig. 6 shows the training history of this 9.4 m magnet. The first of the three BBC magnets has arrived at BNL and is being prepared for tests, with the others due in the next two months.

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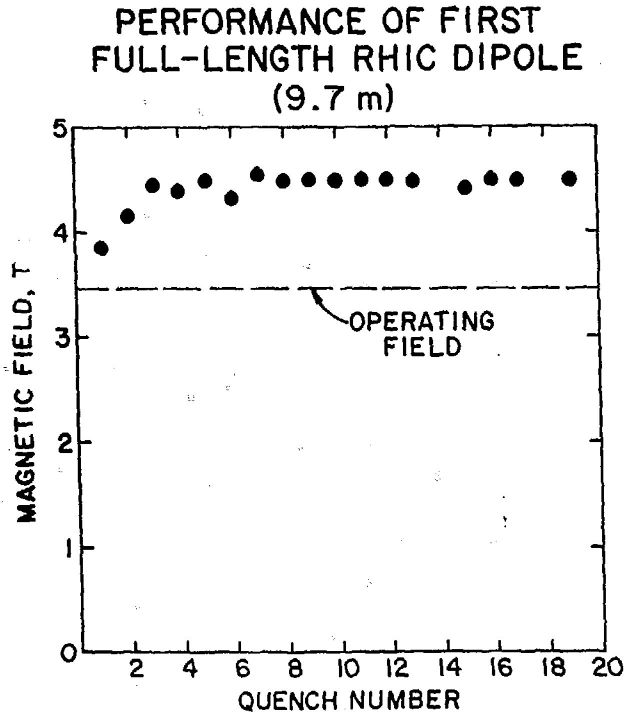

Fig. 6. Training history of full-length prototype RHIC dipole magnet (4.3 K).

In addition to magnet R&D, extensive work has been done on lattice refinements and tracking studies of dynamic aperture limitations due to magnet imperfections [14]. Some milestones from the BNL plan for further R&D on magnets and accelerator systems [15] are given in Table 4.

Table 4

RHIC R&D Milestones

References

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4. H. Foelsche, D.S. Barton and P. Thieberger, "Light Ion Program at BNL", Proc. 13th International Conference on High Energy Accelerators Novosibirsk, USSR (August, 1986).
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12. E.H. Willen, "Magnets for RHIC", Proc. of ICFA Workshop on Superconducting Magnets, P. Dahl (ed.), BNL-52006 (May, 1986).

[15] are given in Table 4.

Table 4
RHIC R&D Milestones

Magnet Full Cell Test	1988
Mag. Error & Corr. Coil Sys. Studies	1988
Magnet Full String Test	1989
RF Cavity and Amplifier Model	1989
Injection Kicker Model	1989
Internal Target Concepts	1989

The RHIC proposal has recieved an initial validation from the Department of Energy at an estimated cost to completion of approximately $200M (FY88 $). It is estimated that an additional $70M will be required for detectors for the initial experiments. A construction schedule of five years with a project start in FY 1989 is now being discussed . A strong constituency already exists for this facility in the international nuclear and high-energy physics communities. A second major workshop on experiments and detectors for RHIC will take place at LBL in May, 1987, and BNL anticipates a possible call for letters-of-intent early in 1988.

12. E.H. Willen, "Magnets for RHIC", Proc. of ICFA Workshop on Superconducting Magnets, P. Dahl (ed.), BNL-52006 (May, 1986).
13. G. Parzen, "Strong Intrabeam Scattering in Proton and Heavy Ion Beams", IEEE NS-32, 5, 2326 (1985).
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15. R&D Plan for a Relativistic Heavy Ion Collider, BNL-36818 (May, 1986). Present milestone estimates are one year later than those in Ref. 15 and in Ref. 6.