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BNL UPGRADE PLANS*

Horst W.J. Foelsche
Brookhaven National Laboratory
Upton, NY 11973

Abstract

Brookhaven National Laboratory is proposing two major upgrade projects for a future experimental program with protons and heavy ions. The first is the construction of a Relativistic Heavy Ion Collider (RHIC) which will use the AGS complex as an injector. The second initiative is an upgrade of the AGS proton intensity and duty cycle. Both objectives require a Booster for the AGS which has recently been approved as a construction project. With the completion of the booster, and with certain modifications of the AGS, the facility will ultimately become capable of supporting average proton currents on the order of 25-50 microamperes. The RHIC will provide center-of-mass collision energies of 2x100-125 GeV/amu for ions up to the heaviest masses, and 2x250 GeV for protons.

Introduction

The 30 GeV AGS has evolved into a multifaceted facility supporting a vigorous experimental program with average proton currents of about 1-2 microamperes, with polarized proton beams of lower intensity, and most recently with heavy ions (up to the mass of sulfur). There is a fast single turn spill for neutrino physics at a cycle period of 1.2 - 1.4 sec (2 microampere average current) or a slowly extracted beam with nominally 40% duty cycle (1 microampere average current) and a repetition period of 2.5 - 3 sec. A start is being made to upgrade the proton beam current by an order of magnitude or more, to increase the slow spill duty cycle, to increase the polarized proton yield to a level more nearly like the unpolarized beam intensity, and to add the capability to accelerate the heaviest ions in the AGS. Finally the proposal to construct a Relativistic Heavy Ion Collider (RHIC) has been submitted.

The BNL upgrade plans derive from a reassessment of the physics opportunities, which occurred in 1983 after the high energy physics community abandoned the CBA and decided to pursue the SSC (Superconducting Super Collider) as a first priority objective. On the one hand, an AGS user task force[1] pointed out extraordinary opportunities for frontier research in the areas of rare kaon decays, which would provide fundamental tests of the standard model predictions, and also in the areas of neutrino interactions and oscillations, and muon physics. Intense hadron and polarized proton beams for the detailed study of QCD, as well as unique intermediate energy kaon beams to explore the structure of exotic atoms,

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dibaryons and hypernuclei were envisioned. These are the motivations for kaon factory proposals which have been made by several laboratories around the world. At the same time the nuclear physics community supported the development of an entirely new area of experimental physics, high energy heavy ion interactions to explore new states of nuclear matter at extremely high densities and temperature, and new initiatives were taken in this area both at CERN[2] and at BNL.[3,4,5] At BNL this program would be based at first on the AGS as a fixed target facility for heavy ion beams,[3] and ultimately on the proposed new relativistic heavy ion collider,[5] which would provide 200-250 GeV/amu collision energy in the center-of-mass. It was realized at the time that an evolutionary approach, driven at each step by the demands of the experimental proposals would be feasible and appropriate. The construction as well as the commissioning of the necessary new facilities to support these new objectives was to proceed off-line, without major interruptions of the ongoing physics program.

The BNL upgrade plans envision a unified response to these opportunities. Immediately, the BNL Tandem accelerators were prepared as injectors of pulsed ion beams for the AGS, and were connected to the AGS by means of a heavy ion beam transfer line.[3] Direct injection of beams from the Tandems into the AGS is feasible for lower mass ions (up to sulfur), and this program is getting underway. For heavier ions a booster[4] is needed to achieve full stripping prior to injection into the AGS. The AGS proton current has improved over time to the point where the very large incoherent space charge tune spread at the injection energy of 200 MeV has become a barrier to further progress. A booster is needed to raise the injection energy of the AGS and thus to increase the space charge limit. The anticipated intensity improvement with the booster can ultimately be more than an order of magnitude, provided the necessary improvements of major AGS systems such as the rf, magnetic corrections, extraction hardware, vacuum systems, etc. are undertaken in due course. The booster will assume a third function as an accumulator of low intensity polarized proton pulses from the fast pulsing linac during the duration of the slower AGS cycle. Together with a major development program on high intensity polarized proton sources this will ultimately result in polarized proton intensities comparable to what is available for unpolarized beams now. A 30 GeV stretcher ring is envisioned later to increase the slow spill duty cycle to nearly 100% and to increase the average current by another factor of two. The booster construction has been approved and is being funded. The stretcher is proposed to be added at a later time.

The highest priority new facility proposal at BNL is the construction of the RHIC.[5] Technically this proposal makes full use of already existing resources, such as the nearly completed machine enclosure, and the complete refrigeration plant originally constructed for the abandoned CBA project. Although a discussion of this facility does not fit within the technical scope of this workshop, a summary of its main features is presented below, so that the full scope of the BNL upgrade plans can be seen in the proper context.

A layout of the BNL site with the present and future facilities is shown in Fig. 1.

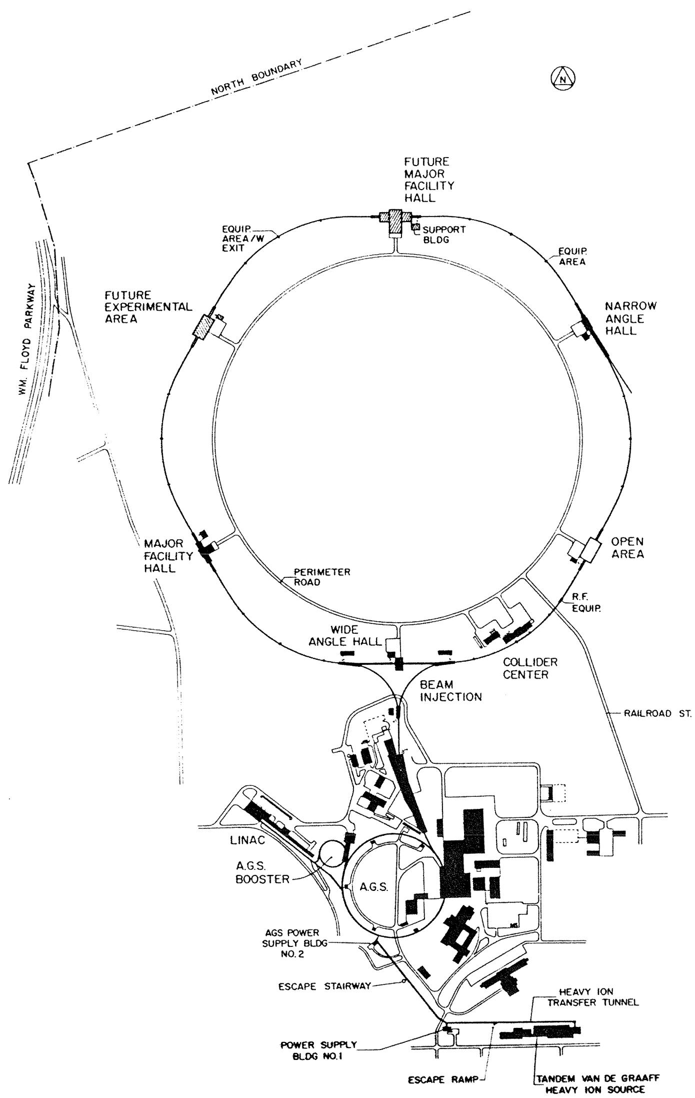

Fig. 1. BNL site plan showing Tandem van deGraaff, heavy ion transfer line, proton linac, booster (approved), and relativistic heavy ion collider-RHIC (proposed).

AGS Booster

The AGS Booster[4] is designed to serve three objectives:

a) to increase the AGS proton current by raising the space charge limit of the AGS at injection,
b) to accelerate the heaviest ions in the AGS, and
c) to increase the polarized proton current by acting as an accumulator for the rapidly cycling linac.

The layout of the booster between the 200 MeV Linac and the AGS is shown in Fig. 2. While the booster is under construction, the capabilities of the AGS subsystems are to be improved as well to match the new requirements.

A summary of the parameters of the booster is given in Table I. The lattice parameters, and in particular, the betatron tunes are chosen to facilitate the injection of very high proton beam currents at 200 MeV with an incoherent space charge tune shift not exceeding what is prevailing in the AGS at present. The maximum field, on the other hand, is chosen so that the heaviest ions, in the least favorable ionization state, can be preaccelerated to an energy high enough to permit full stripping before injection into the AGS. The maximum energy for proton injection into the AGS is therefore very high, making it possible, in principle, to achieve a very large improvement in the proton current without an increase in the incoherent space charge tune shift. The combination of the proton and heavy ion requirements results in a design with a very

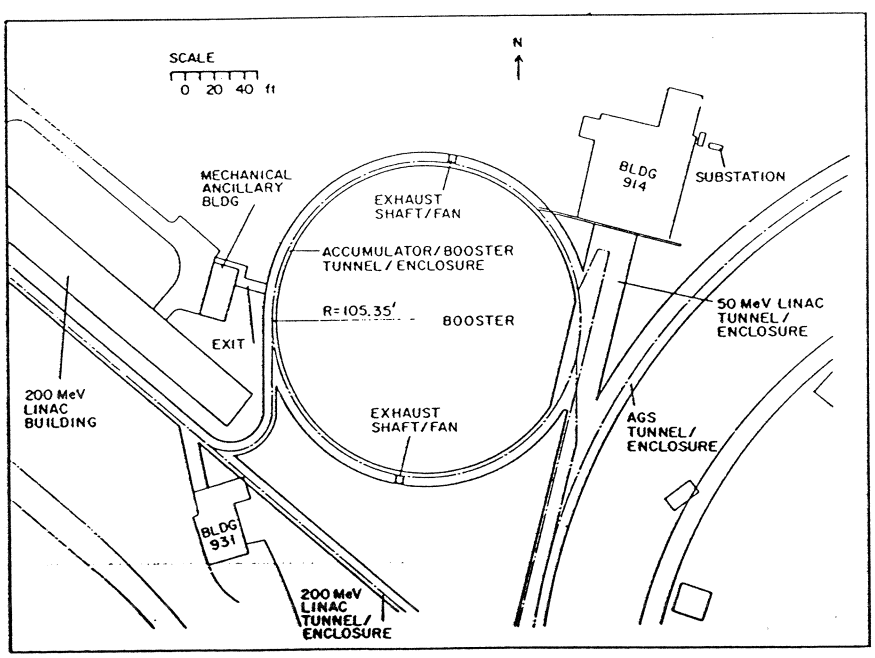

Fig. 2. Layout of booster between the 200 MeV linac and the AGS.

high inherent potential for intensity improvement in the AGS.

The booster will be a rapidly cycling synchrotron with a circumference of 201.78 m, one quarter that of the AGS. The maximum magnetic rigidity of the lattice is $B\rho$ = 17.5 Tm. Its injectors will be the rapidly cycling 200 MeV linac for protons, and the Tandem van deGraaff for heavy ions. For protons the booster will cycle at a 7.5 Hz rate and four booster loads will be inserted into the AGS in box-car fashion at the start of the AGS cycle. Initially the main power supply will be configured in such a way that the maximum energy with rapid this cycle will be limited to 1.5 GeV ($B\rho$ = 7.5 Tm), with the possibility of an extension to 2.5 GeV or higher and the injection of up to 12 booster loads into the AGS later in the life of the machine. For heavy ions, on the other hand, a slower cycle to the maximum rigidity of 17.5 Tm is provided (e.g. 350 MeV/amu kinetic energy for a gold ion in the charge state 33^+), and the AGS is loaded with a single pulse. For polarized protons, where space charge limitations are not likely to be approached, the machine will simply accumulate about 20 lower intensity pulses from the rapidly cycling linac while waiting for the start of the next AGS cycle. The AGS booster supercycles for protons and heavy ions are illustrated in Fig. 3.

Table I. General Parameters of Booster

Type of machine	synchrotron for protons and heavy ions, polarized proton accumulator
Maximum $B\cdot\rho$	17.5 T·m
Circumference (1/4 AGS)	201.78 m
No. of particles/pulse (protons)	$1\text{-}3\times10^{13}$
" (polarized protons)	$\sim 10^{12}\text{-}10^{13}$
Transverse emittance, inj., (90% area/π)	50 mm-mrad
Longitudinal emittance, inj.-ejec. (rms area/π) protons bunched to	17.5 eV-s
heavy ions bunched to	0.05 eV-s/nucleon
Lattice, total 24 cells, FODO	8.4075 m
Betatron tune, x,y	4.82, 4.83
$\beta_x$max, min	13.865/3.5754 m
$\beta_y$max,min	13.644/3.7033 m
Horizontal dispersion, max, min	2.951/0.540 m
Magnetic field, dipole, ejec., protons	0.546 T
heavy ions (max)	1.2743 T
Magnetic radius of curvature	13.75099 m
Magnetic gradient, quad, ejec. GF: protons	1.20 T/m
Heavy ions	2.8 T/m
Gd: protons	1.24 T/m
Heavy ions	2.9 T/m

Table I -- continued

Dipole length (magnetic/ physical) excl. coils	2.4/2.34 m
Quad length (magnetic/ physical) excl. coils	0.50375/0.472 m
No. of dipole magnets	36
No. of quadrupoles magnets	48
Dipole excitation current, max	
protons	2220 A
heavy ions	5200 A
Quad excitation current, max	
protons	2220
heavy ions	5200
Vacuum chamber dim.,	
dipoles	70 x 152 mm
quadrupoles (circular)	152.4 mm
rf harmonic number	3
rf frequency	0.2 - 0.69 MHz
	0.69 - 2.5 MHz
	2.5 - 4.5 MHz
Acceleration period	
protons	62 ms
heavy ions (max)	500 ms

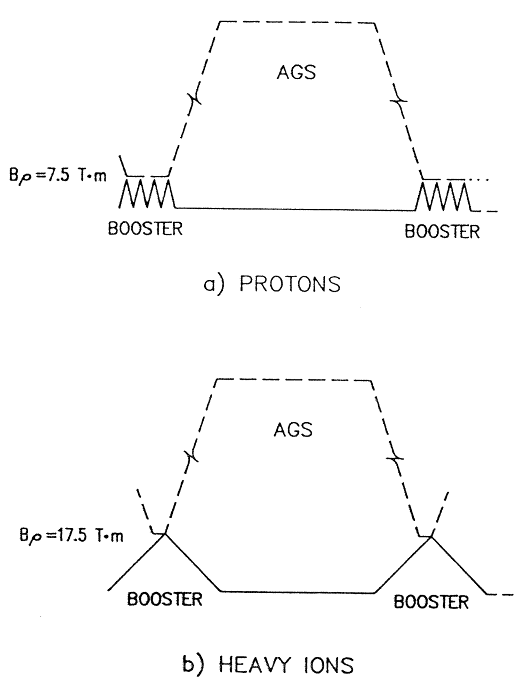

Fig. 3. AGS-Booster cycles for: a) protons; b) heavy ions.

The booster will have a separated function lattice with six identical superperiods. In each superperiod some of the bending magnets are omitted to create space for rf acceleration, injection, extraction, and abort systems without otherwise interrupting the basic periodicity. The betatron tunes are $\nu = 4.82$, and $\nu = 4.83$. The admittance of the vacuum chamber is about 1.5 times that of the AGS in each plane, and the incoherent space charge tune spread for protons at injection is about half that of the AGS. With about 25 mA of H^- current available from the linac, one can fill the booster to an intensity at least as high, or probably twice as high as that of the AGS, before approaching the space charge limit. Four such pulses can be accepted by the AGS, and at the injection energy of 1.5 GeV, the tune spread in the AGS will then be only about 30-60% of what it is at present, at 4 - 8 times higher intensity. This level of current will mark the first phase of the intensity improvement program of the AGS. If the booster energy were later raised to 2.5 GeV or higher (the maximum magnetic rigidity would permit 4.4 GeV), another factor of three would be accepted by the AGS while the space charge tune spread could become less than 45-90% of what it is at present. The new AGS booster configuration alone is intrinsically capable of providing average currents of 4 - 8 microamperes initially, 12 - 24 microamperes if the proton cycle is eventually raised to 2.5 GeV energy. A stretcher would double these currents again while also providing 100% spill duty factor. The full realization of this potential can be approached, at best, in stages, subject to the priorities of the heavy ion program. It will require extensive modifications of the AGS subsystems and of the experimental areas to make full and efficient use of these intensities.

Heavy ions are supplied to the booster by the Tandem van deGraaff accelerators, which are equipped with a pulsed Middleton ion source for this purpose.[6] This ion source has provided a large variety of ion species covering much of the periodic table. While lighter ions arrive fully stripped, ions heavier than sulfur will be in a partially stripped charge state. Table II gives a summary of the injection and extraction parameters for several typical ion species.

Table II. Booster Injection and Extraction Parameters

	Z	Q	A	v/c (inj)	E_{in} MeV/A	B_{in} kG	v/c (ext)	E_{ex} GeV/A	B_{ex} kG
p	1	+ 1	1	0.566	200.0	1.563	0.923	1.500	5.459
d	2	+ 1	2	0.177	15.0	0.817	0.870	0.964	8.024
C	6	+ 6	12	0.126	7.5	0.575	0.871	0.967	8.024
S	16	+14	32	0.100	4.69	0.519	0.872	0.967	9.170
Cu	29	+21	63	0.0782	2.86	0.531	0.853	0.854	11.08
I	53	+29	127	0.0595	1.65	0.590	0.790	0.588	12.74
Au	79	+33	197	0.0478	1.07	0.645	0.687	0.350	12.74

The maximum excitation of the booster magnet is needed for the heaviest ions, which will arrive from the Tandem in the partially ionized state. The vacuum in the booster chamber needs to be lower than 3×10^{-10} Torr to minimize the loss of ions from stripping on the residual gas during the acceleration process. After having been accelerated to the maximum rigidity the heavy ions will be extracted from the booster and will be stripped of all electrons with good efficiency, before being injected into the AGS.

The booster will be provided with several rf accelerating systems, which will cover the large frequency swing in proper sequence (0.2 - 4.5 MHz), initially always accelerating on the third harmonic of the revolution frequency. The lower frequency range for heavy ions will be subdivided into two systems, one operating from 0.200 to 0.690 MHz, and the other covering the band from 0.69 to 2.5 MHz. The third and final acceleration stage for heavy ions, as well as the acceleration of protons from their injection energy of 200 MeV, are handled by the proton rf system, which will operate in the frequency range from 2.5 to 4.5 MHz. This is the configuration which will be available at the beginning, and it will optimally serve the requirements of the fixed target program at the AGS, and the first phase of the AGS proton intensity improvement (factor 4 - 8). Four rapid proton cycles with three bunches each will be accumulated in the twelve AGS rf buckets for acceleration to full energy. Later in the course of further developments, to optimize the performance of the RHIC, a very low frequency cavity will be added to be able to initiate acceleration of heavy ions on the first harmonic, thus providing a single bunch rather than three for synchronous bucket-to-bucket accumulation in the AGS and in RHIC.

The booster will use negative ion injection in the case of both unpolarized and polarized protons, as is done at the AGS at present. Upon reaching the injection orbit of the machine, the H^- ions pass through a thin stripping foil, and a great many turns are accumulated in this manner with a rather flexible distribution in phase space. Heavy ions on the other hand arrive in a partially stripped positive charge state, and they are injected by a standard multiturn technique, using a collapsing orbit bump, accumulating about eight turns. Beam transfer to the AGS is initiated by single turn extraction of the bunched beam, and the booster bunches are deposited in the waiting rf buckets of the AGS.

AGS Upgrade

In the AGS numerous modifications will be made in due course to prepare the machine for the potential performance made possible by the booster. The vacuum system is being upgraded to achieve pressures in the 10^{-9} Torr range to obtain the highest possible degree of reliability. At the same time the vacuum envelope of the machine will be smoothed out and the pick-up electrodes and other beam diagnostic systems will be redesigned with the objective of reaching the lowest feasible coupling impedances with respect to the beam. The low field correction magnet systems of the AGS will be strengthened for the higher injection energy, and the high field multipole systems will be upgraded with modern programmable power supplies to permit a very flexible control of the working line during the acceleration cycle. The main magnet power supply (Siemens Motor Generator Set) will be brought under precise computer control with the ultimate aim of mixing several excitation modes in a very flexible supercycle (pulse-to-pulse modulation). The AGS rf system will be rebuilt to make allowance for an order of magnitude increase in the beam current. A transition gamma jump system and a very high frequency rf system for longitudinal phase space dilution are being designed to minimize beam losses at the transition energy. The maximum proton beam from the booster will have an invariant emittance more than 50% larger than at the present time. Thus the apertures of the extraction systems of the AGS will be modified where necessary. A beam abort system will be built which will dump the beam outside the AGS under all circumstances of emergency or routine beam disposal.

At the 200 MeV proton linac the two 750 kV Cockcroft Walton preinjectors are scheduled to be replaced by an RFQ accelerator, and the development of a properly matched H^- ion source for this system is underway as well. The polarized proton program is already using an RFQ. A new generation of polarized H^- ion sources is under development at BNL which will employ cold atomic beams and a D^- ring magnetron charge exchange system to obtain an improvement of the current into the milliampere range. This development and the future use of the booster as an accumulator of multiple linac pulses will improve the polarized beam currents to values approaching what is available for unpolarized beams at present. In collaboration with other interested laboratories a study is underway to find a replacement for the linac power amplifier tubes (7835) which will be more reliably supported by industry in the long range future. Other linac improvements include the upgrade of the outdated computer control systems.

In the experimental areas the configuration of the secondary beams is expected to change gradually. The AGS beam switchyards in the SEB (Slowly Extracted Beam) area split the beam into four principal primary beam lines. It is expected that the increased intensity of the primary beam will be exploited to obtain high intensity separated particle beams of very high beam purity, for a future generation of very high sensitivity rare kaon decay experiments. The target stations to support such new facilities will be rebuilt to include new concepts of target design and radiation hardening which are being discussed at this workshop.

These and other changes are to be undertaken gradually in the course of the ongoing accelerator improvement projects. The first phase which envisions an intensity improvement of a factor 4 - 8 is scheduled to be accomplished by the time the initial booster configuration has been commissioned.

Relativistic Heavy Ion Collider (RHIC)

The Relativistic Heavy Ion Collider proposal[5] is a response to the major scientific questions facing the field of nuclear physics, and it will become the highest priority new facility initiative in this field in the United States. It is the central element, and also the largest project in the BNL upgrade plan. Here we summarize its parameters and its main technical features. It has already been discussed above how the requirements of the heavy ion program have shaped the design of the booster, and how enormously this has expanded the ultimate intensity potential of the AGS as a proton facility. It is necessary to note here, however, that the high priority to be given to the construction of RHIC will delay the schedule for the full realization of that potential.

The collider will provide two counter-rotating heavy ion beams, at an energy up to 100-125 GeV/amu each, colliding in six experimental interaction regions, with up to 200-250 GeV/amu total energy in the center-of-mass of the reaction. The rings are to be installed in the existing CBA tunnel, and they will employ superconducting magnets which will make use of the already installed CBA refrigeration systems. Injected beams will be provided by the Tandem-Booster-AGS complex through a beam transfer line for which a tunnel and some magnet equipment already exist as well. The major parameters of the Collider rings are given in Table III. A detailed description of the facility is given in a conceptual design proposal.[5]

At the lower end of its operating range, the Collider is designed to cover collision energies down to 2 x 30 GeV/amu with beam lifetimes of the order of half a day, and even lower energies with somewhat shorter lifetimes. Moreover a fixed gas jet target in the collider would provide coverage at the lowest collision energies to join smoothly onto the fixed target program covered by the AGS itself.

The two rings have 4.75 times the AGS circumference, and they are filled in box-car fashion by direct bucket-to-bucket transfer of the beam bunches from the AGS. Since there are 12 bunches in the AGS, there will be 57 bunches in the Collider. The harmonic chosen for the RHIC acceleration rf system is $h = 6 \times 57$, and it provides an adequate match to the AGS parameters at a peak voltage of 1.2 MV. The bunch separation is 67 m, or about 220 nanoseconds in time. The beams which are injected at the maximum AGS energy (in the range 11 - 14.6 GeV/amu) are accelerated to the final

Table III. General Parameters for the Collider

Energy range (each beam)	
Au	7-100 GeV/nucleon
Protons	28.5-250 GeV
Average luminosity: Au-Au, 100 GeV/nucleon, 10 h	4.4×10^{26} $cm^{-2} sec^{-1}$
Diamond length @ 100 GeV/nucleon	± 27 cm rms
Circumference (4-3/4 C_{AGS})	3833.87 m
Number of crossing points	6
Free space at Crossing point	± 9 m
Beta @ crossing,	
horizontal/vertical	6 m
low-beta insertion	3 m
Betatron tune,	
horizontal/vertical	28.82
Transition energy, γ_T	25.0
Filling mode	Box-car
No. of bunches/ring	57
No. of Au-ions/bunch	1.1×10^9
Filling time (each ring)	~ 1 min
Magnetic rigidity, $B\rho$:	
@ injection	96.5 T•m
@ top energy	839.5 T•m
Beam separation in arcs	90 cm
rf frequency	26.7 MHz
rf voltage	1.2 MV
Acceleration time	1 min

energy and are brought into collision in the experimental equipment for a time of the order of half a day. The rf system will stay on during this time in order to maintain the bunch structure, thus assuring ample luminosity for the experimenter.

The lifetime of the beam and many design parameters are strongly affected by intrabeam scattering, the exchange of longitudinal and transverse momenta between particles in the same bunch by Coulomb scattering. This process can usually be ignored in proton machines, but it causes substantial beam growth in the case of fully charged heavy ions. Its ramifications are strongest for the heaviest ions at the lowest energies. The aperture of the superconducting magnets must provide sufficient room for beam growth during acceleration and during the storage period. This aperture has been chosen so that a gold beam with an energy of 30 GeV/amu will be contained for about ten hours. Beams will therefore be replaced about twice a day, and the replacement is expected to consume much less than an hour.

The Collider lattice is made up of six arcs, with the two rings in a common horizontal plane. The arcs are joined by the intersecting regions, where the beams collide as they cross from the inner to outer arc or back. The beam optics parameters of the intersection regions are designed to be adjustable without affecting the overall tune of the rings. The crossing angle of the beams is variable from 0 to 2 mrad. There is about 9 m of free space on each side of each intersection point for the experimental apparatus. The maximum energy is 100 GeV/amu for the heaviest ions, 125 MeV/amu for the low mass ions with a larger charge/mass ratio, and 250 GeV for protons. This energy requires a maximum field of 3.45 T in the bending magnets.

A cross-sectional drawing of the dipole magnet is shown in Fig. 4. Several prototype magnets have been built and have reached the design fields without training quenches and with about 25% safety margin.

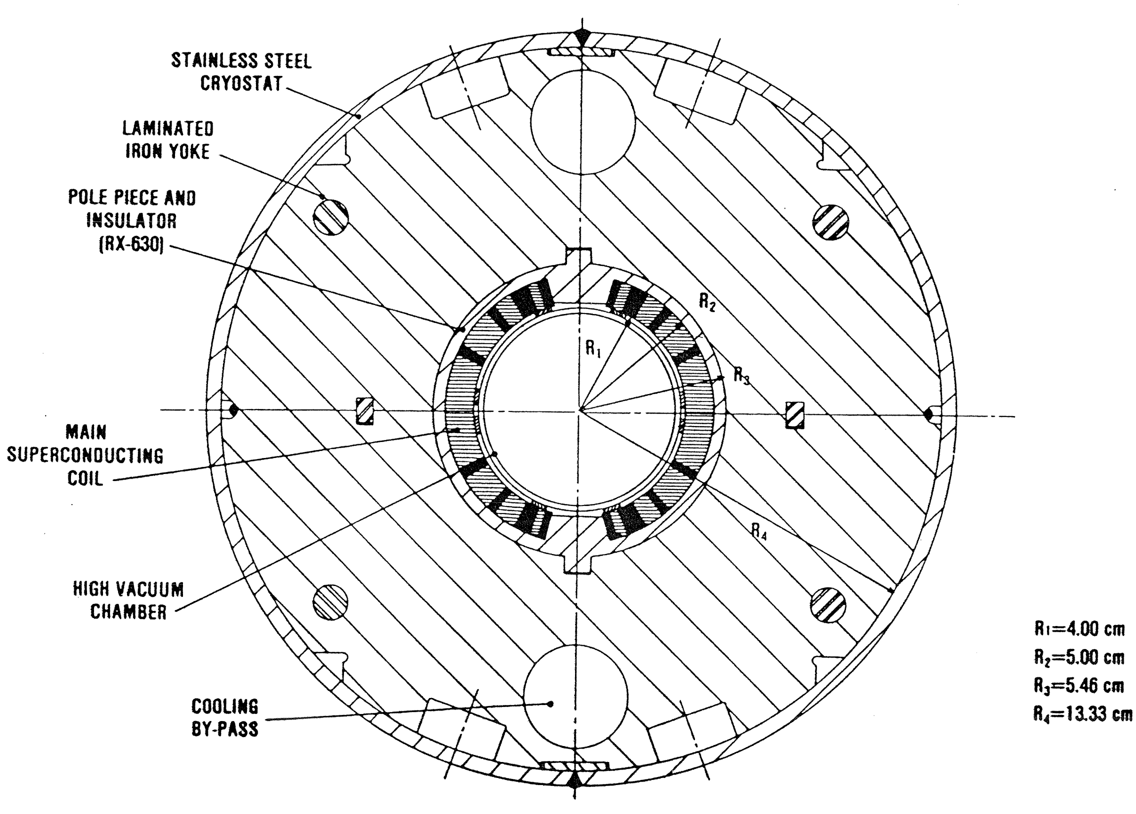

Fig. 4. RHIC dipole magnet cross section.

The initial specifications call for design luminosities in the range from $10^{26}/cm^2sec$ for gold up to $5 \times 10^{30}/cm^2sec$ for protons, averaged over the cycle. These luminosities can be readily supplied by the Tandem-Booster-AGS injector complex. It is expected that in the long term future, beam intensities can be improved by nearly an order of magnitude by a combination of an electron beam ion source (EBIS), an RFQ and a low beta linac as an injector system for the booster.

Stretcher

The stretcher is to be a 30 GeV storage ring which will accept beam from the AGS at the maximum available cycle rate, and will provide a uniform slowly extracted beam to the experimental areas with nearly 100% duty cycle. Since the AGS can cycle more than twice as fast without a slow spill flattop of its own, the average current delivered to the experimenters will be more than doubled as well.

The design of the stretcher is, at this time, developed only in rough outline. Two options are under study. One option, which is not favored, envisions a normal ring in the existing AGS tunnel. The second option, which will cause less disruption of the ongoing experimental program at the AGS would include a separate tunnel. The beam would be extracted to the general area of the existing switchyards and experimental facilities.

Because the priority will be given to the construction of the booster and RHIC, the construction of the stretcher would follow later.

Summary

The overall thrust of the BNL upgrade plans is to open up new areas of physics experimentation with both high intensity proton beams and high energy heavy ion beams and colliders. The AGS booster whose construction is getting underway, will serve both objectives. The proton facility has the ultimate potential of becoming a very powerful kaon factory similar in capacity to other such proposed facilities, although the aproach to that final state must necessarily be gradual. The Relativistic Heavy Ion Collider will create states of matter at densities and temperatures which have hitherto not been observed in the laboratory.

When discussing the prospective schedule for the full realization of a high current hadron (proton) facility at BNL, or elsewhere in the US, it is necessary to keep the RHIC proposal in view. If the RHIC were approved for construction start in 1989 as proposed its completion by 1993 would claim first priority. In the meantime the booster will be completed with an initial maximum proton energy of 1.5 GeV, and an interim improvement of the proton current to 4 - 8 microamperes is expected by about 1992. As the RHIC construction winds down the construction of a stretcher ring could be started with completion perhaps in 1995, increasing the proton current and the duty cycle by another factor of two. The booster lattice is designed such that the maximum proton energy can eventually be raised from 1.5 to more than 2.5 GeV, raising the space charge limit of the AGS by another factor of three. The upgraded AGS hadron facility can therefore ultimately achieve a proton current as high as 24 - 48 microamperes. The rate of development of this potential will be driven by the imperatives of the physics program, tempered by funding constraints.

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