CONSTRUCTION and EARLY COMMISSIONING RESULTS of the AGS BOOSTER*

W. T. WENG, L. AHRENS, R. DAMM and A. J. McNERNEY
BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

ABSTRACT

The AGS Booster synchrotron has been designed to accelerate protons from 200 MeV to 1.5 GeV and heavy ions from several MeV per nucleon to several hundred MeV per nucleon for all the nuclei up to gold. The design requirements and measurement results of major accelerator components and systems are presented. The early commissioning results of the injection is also presented.

I. INTRODUCTION

The circumference of the Booster ring is 201.78 M, one-quarter of that of the AGS. The ring consists of 24 FODO cells and has tune of about 4.82 in both planes. Twelve straight sections are created by the missing magnet scheme resulting in 36 dipoles, each providing 10° bend.

The Booster receives a 200 MeV proton beam from the Linac through the Linac-to-Booster (LTB) transfer line, accelerates it to 1.5 GeV in 63 msec, and feeds four pulses into the AGS at 7.5 Hz rate through the Booster-to-AGS (BTA) line. It also receives heavy ion beams from the Tandem Van de Graaff through HITL-to-Booster (HTB) line, a 900 M long transfer line. The Booster accelerates the heavy ions to their final energy in about 0.5 sec and feeds one pulse to the AGS for physics research or for future injection into the RHIC ring. The layout of the Booster ring and its three beam transfer lines is shown in Figure 1.

Detailed design parameters and complete component specifications of the Booster can be found in the Booster Design Manual [1]. In reference [2], important design issues and their solutions for fast cycling high intensity proton acceleration has been reported. In Section II, the design issues and solutions for heavy ion operation will be discussed. In Section III, the test results of some of the accelerator systems and the early commissioning are presented.

II. DESIGN ISSUES for HEAVY ION ACCELERATION

A. Ultra-High Vacuum

The heavy ions coming out of the Tandem do not have high enough energy to be fully stripped. Current vacuum in the AGS ring is a few 10^8 Torr, only nuclei with mass number less than sulfur can have reasonable survival rate inside the AGS vacuum, see Figure 2. The Booster is designed to have vacuum in the range of 10^{-10} to 10^{-11} Torr
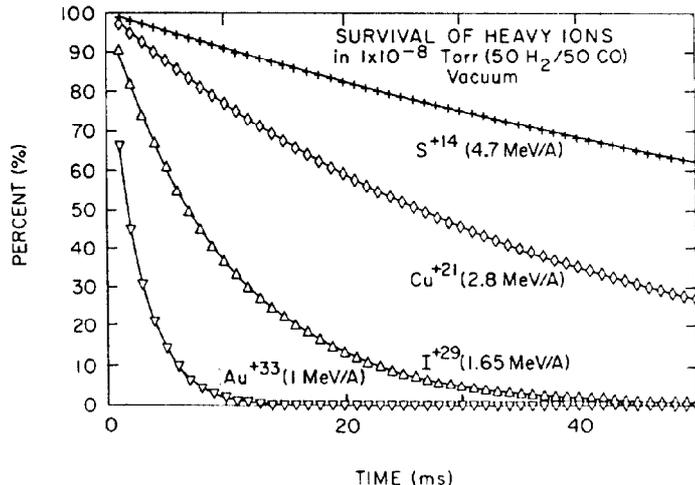
Figure 2 Heavy Ion Survival Rate

so that all ion species can be accelerated to high enough energy to be fully stripped before entering the AGS. Such a vacuum falls into the ultra-high vacuum domain. The component processing and system design has been reviewed in Ref. [3] So far two-thirds of the ring has been baked out and pumped down to 3×10^{-11} Torr pressure.

B. Wide Momentum Range

The resonant frequency of the Booster RF system, to properly accelerate all the intended ion species and protons, falls between 178 KHz to 4.2 MHz. Such a wide range of frequency variation, about a factor of 22, is impossible to achieve with the traditional tuning method of controlling the permeability of the ferrite inside the cavity. For reliable operation, three separate RF acceleration systems will be required if same harmonic number 3 is adopted for all three systems. The other possibility is to operate Band I and Band II at the same frequency, but using harmonic number 12 for low momentum acceleration and switch to harmonic number 3 for medium momentum acceleration. These two scenarios can be summarized in Table 1.

Table 1 RF Frequency (in MHz) of Two Designs

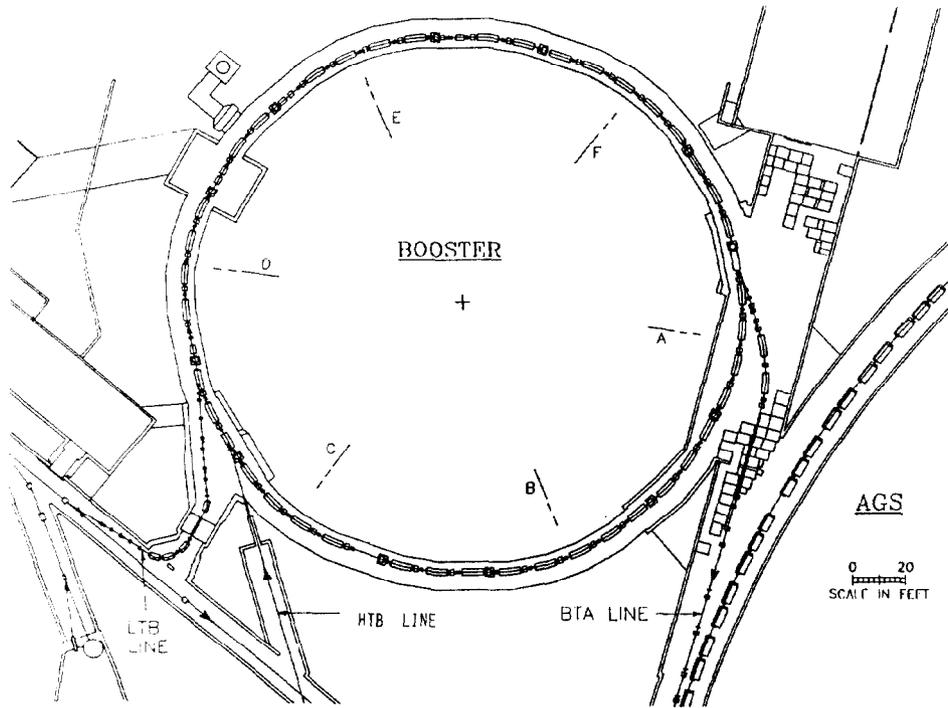|	Band I	Band II	Band III
Design 1	0.18 - 0.68	0.6 - 2.5	2.4 - 4.2
Design 2	0.72 - 2.50	0.72 - 2.50	2.4 - 4.2

Figure 1   The Booster Location and Component Layout

There are advantages of operating two RF systems in an identical way. For example, it will result in more accelerating voltages, a built-in a pair in case of emergency, running the Band I system at higher frequency helps to stay away from the intrinsic ferrite instability at low frequency.

For proton acceleration, only the Band III system is required. The design voltage of the cavity is 22.5 KV per gap resulting in 90 V for two stations. Shown in Figure 3 is the output voltage of one gap providing 22.5 KV in the upper trace and the cathode current varying from 5 to 8 amperes in the lower trace [4].
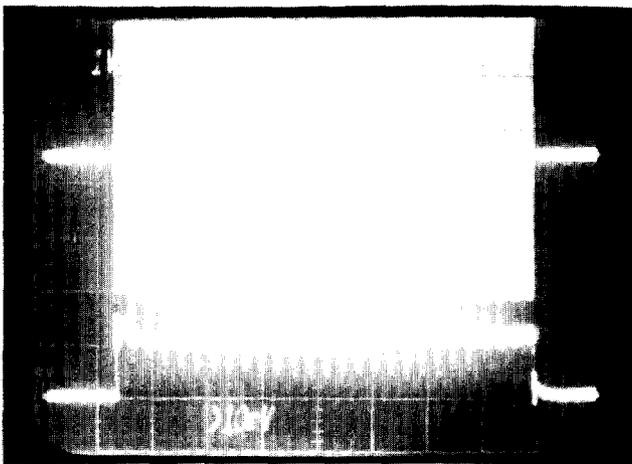

Figure 3   RF Voltage

The requirement to operate for wide momentum range is not unique for the RF system, it also applies to the beam position monitor (BPM) system. To design a BPM system

linear and stable for such a wide frequency is harder than that of a narrow frequency system. Stripline type electrodes were not chosen because of their narrow bandwidth and low signal level for heavy ion low intensity application. The chosen design is the split cylinder capacitive pick-up electrode which can be made to provide sufficient response over a wide frequency range.[6] The offset of the electrical center line of the BPM system as a function of operating frequency can be made to be a linear function for high frequency application, but it will deviate more from this linear curve in the low frequency region. This effect introduces about 0.2 mm degradation in the accuracy of the position information for heavy ions.

For proton acceleration, the desired repetition rate is 7.5 Hz, but that of heavy ion is about 1 Hz. This adjustable rep rate requirement limits the design choice of the main magnet power supply system. Among the three possibilities considered, the resonance type is ruled out for its single frequency limitation, the motor-generator set approach is too expensive, while the programmable multi-phase DC power supply controlled by SCRs has been chosen for its moderate cost and adjustable rep rate. A price to pay is the perturbation to the power distribution system of the utility company. Necessary protection measures has been discussed in reference [2].

To achieve fast cycling at 7.5 Hz, 12 rectifier modules are connected in series [5]. Each module is capable of delivering 433 V and 3000 A. During heavy ion acceleration, 4 modules are used in series, each capable of supplying 6000 amperes. All 36 dipoles and 48 quadrupoles are connected in a series with additional quadrupole trim supplies for adjusting the tunes of the accelerator. Shown in Figure 4 is the output from 2 modules of the power supply. The lower trace indicates the

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current ramped up to 1500 amps in 110 msec and the top trace shows the voltage steps.
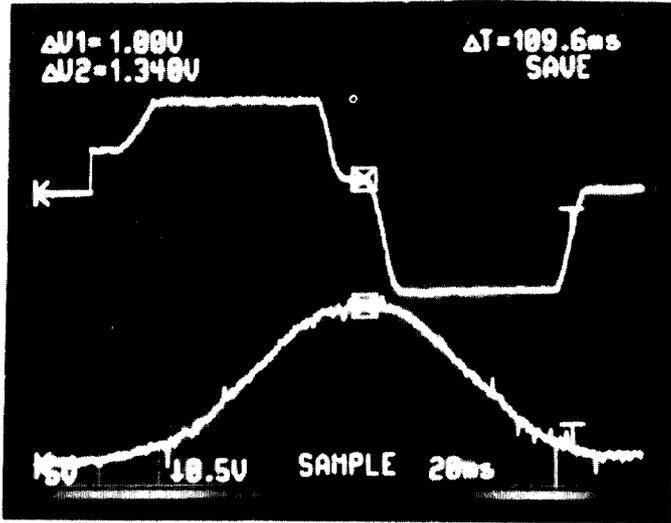

Figure 4   Power Supply Current Output

C. *Pulse-to-Pulse Modulation*

The requirements to run the Booster for different heavy ion species on a pulse-to-pulse basis is driven by the need to utilize the Booster for machine study during the long idle time between AGS pulses and the capability to collide different species in the RHIC. Two major problems could arise for such application. The first is the requirement to reset all the ring and transfer line components in one second. The second is the hysteresis of the magnetic component involved. So far, the most difficult situation is for alternate proton and heavy ion pulses. This is because the required vacuum pressure for proton is the 10^{-8} Torr range and that of the heavy ions is in the 10^{-10} Torr range. High intensity, proton acceleration tends to heat up the vacuum chamber and cause excessive out-gassing. Therefore, for the alternate proton and heavy ion application, the intensity of the proton has to be limited to allow for ultra-high vacuum condition.

Another special design consideration for accelerating different species in a pulse-to-pulse basis is the requirement on the control system. The Booster control system is Apollo based, hierarchical, distributed control system. Most of the operation is data base driven. To accommodate pulse-to-pulse acceleration, a super cycle generator structure has to be introduced such that a different set of timing and data base instruction is selected for different applications (mini cycles) encompassed within the super-cycle. The pulse-to-pulse modulation design and examples of Linac-Booster-AGS super cycles has been presented by D. Barton [7].

III. RESULTS of COMPONENT TESTS and BEAM COMMISSIONING

The Booster ring employs 36 dipoles, 48 quadrupoles and 48 sextupoles. The design parameters of all the magnets are summarized in Table 2. Very stringent magnet to magnet random errors are required for polarized proton acceleration. Higher order multipoles, both normal and skew components, up to order six of both dipoles and quadrupoles are all within the acceptable tolerances.

Table 2   Parameters of Booster Magnets

	Dipole	Quadrupole	Sextupole
Number	36	48	48
Length (m)	2.34	0.47	0.10
Aperture (cm)	8.25 (v)	8.25	8.25
Field	1.27 T	10 T/m	50 T/m^2
Random Error (Tolerance)	1.5×10^{-4}	1×10^{-3}	2×10^{-2}
Random Error (Measured)	1.7×10^{-4}	0.4×10^{-3}	3.5×10^{-3}

For the proton acceleration, the Booster has to run at 7.5 Hz rep rate. This will induce strong eddy current effects in the dipole vacuum chamber which is made of 2 mm thick inconel steel with an elliptical shape. The eddy current generates both dipole and sextupole fields. The dipole component can be corrected by adjusting the power supply. To compensate the sextupole field, a set of correction coils have been wound on a vacuum chamber giving linear current distribution in the radial direction [8]. A series resistor is chosen to cancel the sextupole field induced in the chamber. Shown in Figure 5 is the results of the testing. The lower trace of Figure 5 shows the sextupole field at several constant excitation current displaying the expected ion saturation effect at high field. The upper trace is the induced sextupole field at a ramp rate of 32.6 KA/s without the chamber correction coil connected. Figure 5B shows the same test with the chamber correction coil connected indicating that the eddy current induced sextupole field has been successfully canceled. Since this is a passive correction scheme independent of the ramp rate, the induced sextupole field is zero throughout the acceleration cycle. A detailed report on the magnetic measurement is given in Reference [9].

Another important device employed in large quantities is the beam position monitor system. The mechanical structure of the pick-up-electrode is made of copper split cylinder 20 cm long and 7.5 cm in diameter. The design goal is to give $\pm$ 0.1 mm precision within $\pm$ 30 mm range. One design challenge is the reproducibility of the performance before and after 900° vacuum firing and 200° in-situ bakeout. Repetitive tests shows that the repeatability has been achieved. Each electrode has been calibrated for its electrical center line and linearity range by fitting the expression:

$$\text{Position} = K \times \Delta/\Sigma + \text{offset}$$

The parameters "offset" and the gain coefficients "K" can be recorded in the database of the particular PUE for operation. On the other hand, the spread of those constant indicates the quality of the design and workmanship, and a total of 60 PUE measurements shows that the standard deviation of "offset" is 0.2 mm and that of "K" is 0.19 which gives an error of 0.07 mm without correction [10].
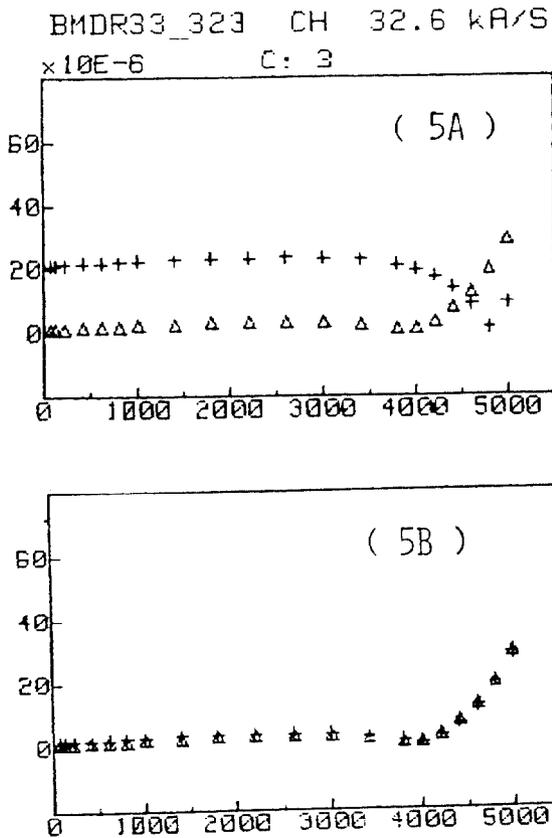

Figure 5 Eddy Current Induced Sextupole Field
With Correction Coil Off (5A) and On (5B)

The Booster ring construction was completed by the end of April. All the magnetic components has been tested and installed. The main magnet power supply system is in place and each module has been tested d.c. to 3000 amps and ramped at 5 Hz to 1500 amps. Shown in Figure 6 is the Booster ring at the proton injection area. Figure 7 shows part of the main magnet power supply gallery. In the left side is the twelve rectifier modules and in the right is the reference dipole magnet in series with the ring magnet. The precision field measurement device, the gauss clock, is installed for field detection providing timing triggers at injection, flattop and extraction.

So far, four sessions of beam commissioning have been performed [11]. The 200 MeV H⁻ beam has been successfully diverted from the end of the Linac into the LTB line, passed through the bored yoke of C5 dipole, stripped into H⁺ and propagated over one-sixth of the ring to a beam stop at D6.

As shown in Figure 1, the LTB line is 107 feet long and consists of 5 dipoles, 9 quadruples, 6 steering dipoles, 9 radiation loss monitors, 6 stripline type BPMS, 2 multiwire profile monitors, and 2 current transformers. The total angle of bend is 126° with the dipole field limited to below 9 KG to avoid H-stripping by the field.
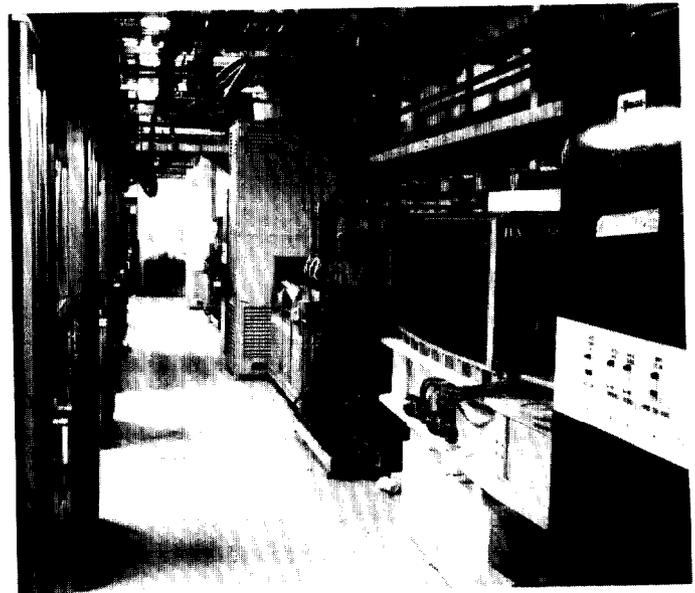

Figure 6 Booster Tunnel

Figure 7 Power Supply Gallery

The display of the BPMS in the LTB line is given in Figure 8. It shows both horizontal and vertical trajectories have been corrected to better than 2 mm except at the end for injection. In fact, the final steering was accomplished by an AUTO-STEER program which made the orbit observation, calculating the required correction and made the correction automatically.

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An AUTO-EMIT program has also been implemented to vary the Q1-Q2-Q3 quadrupole as a triplet to sweep through the waist of the beam profile at the profile monitor downstream and perform a least square fit to obtain the beam emmitance at the entrance of the first switching magnet. Shown in Figure 8 is the display of 15 profiles as function of the strength of the triplet quadrupole Q1-Q2-Q3. A waist is visible in the middle of the ramp [12]. The fitted emittance of this preliminary run is about 5 mm-mrad, smaller than past measurements in the HEBT line. More measurement will be attempted when the commissioning resumes in May.
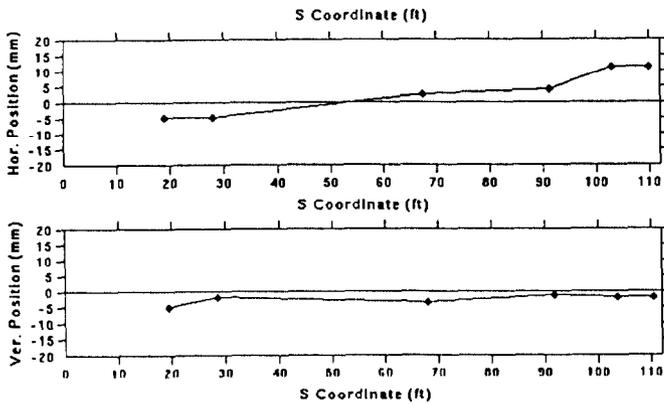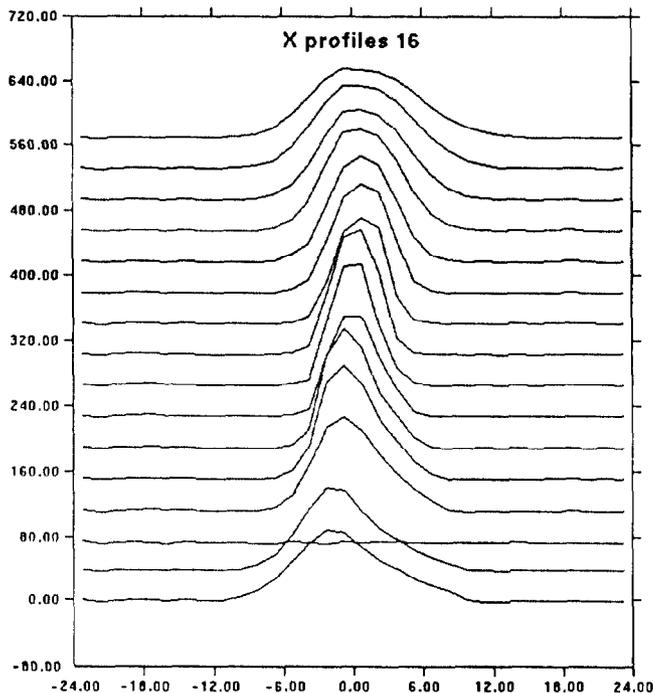
We plan to commission the Booster ring again in the third week of May. Orbit, tune, chromaticity and beam profiles in the ring will be measured. Acceleration and extraction will take place in June. Injection into the AGS and tuning for high intensity will be started after the summer shutdown. Heavy ion commissioning will be started in the spring of 1992.

To accelerate more than 2×10^{13}p per pulse in the AGS, the existing RF system and transverse damping system have to be upgraded. The new RF system will have power amplifier placed next to the cavity and a fast feedback correction scheme will be implemented to reduce beam loading and coupling impedance. A new and more powerful, bunch-to-bunch damper system will be implemented to suppress both the coupled bunch instability and injection errors from the Booster.

Figure 8 LTB Line BPM Display

Figure 9 Profile Display from AUTO-EMIT

ACKNOWLEDGEMENT

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