OPERATION OF THE BROOKHAVEN AGS WITH THE BOOSTER*

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Abstract

The Brookhaven Alternating Gradient Synchrotron (AGS) received protons directly from a Linac and heavy ions directly from a Tandem Van de Graaff before 1992. The newly constructed Booster has been brought on line to serve as an injector for the AGS. The operational status of the acceleration of proton and heavy ions through the Booster and the AGS is reviewed. Accelerator improvement programs to increase proton intensity for physics research and to prepare heavy ion beams for RHIC injection are discussed.

I. INTRODUCTION

The Booster construction was completed in April of 1991, followed by a short commissioning period in May and June to accelerate 200 MeV beam to a top energy of 1.2 GeV and to successfully extract the beam out of the machine. The Booster was brought on line to serve the high energy physics program using proton beam from February to April, and nuclear physics research from May to June, 1992. In 1993, eight weeks of dedicated machine studies was performed from March to May. This paper will summarize the performance of the Booster and the AGS up to May of 1993.

In Section II, the results of the measurement of basic machine functions of the Booster are presented. In Section III, the status of proton acceleration and intensity performance are reviewed. In Section IV, the status of heavy ion acceleration will be presented. Finally, in Section V, plans for future AGS upgrades for high intensity proton acceleration and preparation for heavy ion beams for RHIC injection will be discussed.

II. MACHINE FUNCTIONS OF THE BOOSTER

A schematic layout of the AGS complex is shown in Figure 1 [1, 2]. Working MAD-based computer models now exist for the LTB, Booster, and BTA. The models correctly predict the transfer matrixes and beta functions of all three areas. In the following, selected measurements will be discussed.

A. Booster Orbits

The Booster bare orbits indicate RMS horizontal errors of about 5 mm and RMS vertical error of about 3 mm, which can be corrected to about 0.5 mm and 0.2 mm, respectively[3]. The relatively large errors of uncorrected orbit are not consistent with the alignment reading of 0.2 mm RMS misalignment of quadrupoles and the amplification factor of 15. A total re-survey, including survey monuments, will be carried out in the summer of 1993.

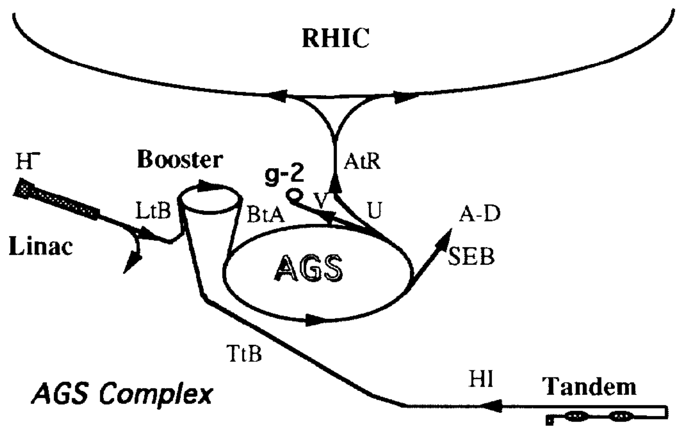

Figure 1. AGS Complex.

B. Tunes and Chromaticities of the Booster

Using the time function of the orbit signal obtained at one BPM, an automatic tune display is provided through a Fast Fourier Transform (FFT) analyzer. The orbit signal and the tune display are shown in Figure 2. The measured uncorrected tunes of $\nu_x = 4.56$ and $\nu_y = 4.60$ are very close to the prediction of the MAD program using the measured quadrupole strength. Trim power supplies have been provided to adjust the tunes within one unit for proton acceleration and 0.5 unit for heavy ion acceleration.

The natural chromaticities of the accelerator are $\xi_x = -5.1$ and $\xi_y = -5.5$. Both are measured and confirmed by measuring the tunes of various energy beams in the Booster. During acceleration, the eddy current correction coil has to be provided to compensate the sextupole field produced by the vacuum chambers. Again, trim supplies have been provided to control the chromaticity within $\pm$ 5 units. For stable operation, the chromaticity is set at a small negative value.

C. X-Y Coupling

One application of the tune measurement device is to detect the existence of the X-Y coupling and to confirm its minimization by coupling correction skew quadrupoles. If there is little coupling, a sizable orbit oscillation in the horizontal plane cannot excite the oscillation in the vertical

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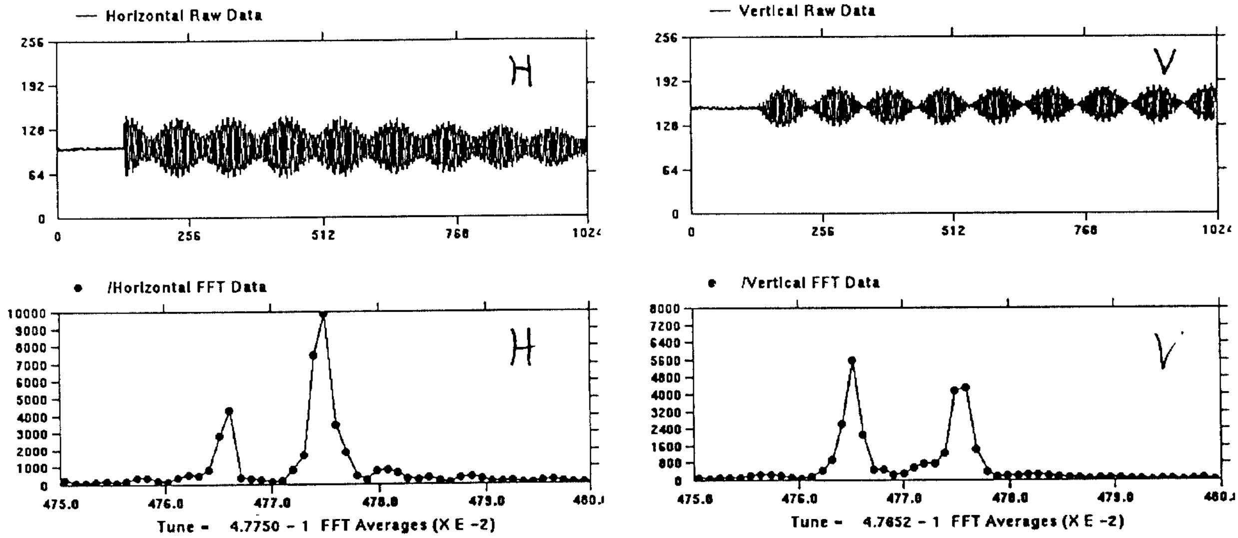

Figure 2. Horizontal and vertical orbit signals and tune display.

plane, and the horizontal and vertical tunes assume their well defined values with a single peak in the FFT display. When there is coupling between the horizontal and vertical planes, a sizable oscillation in the horizontal plane will excite visible oscillations in the vertical plane, as shown in of Figure 2. At this time, both horizontal and vertical tunes display double peaks indicating he existence of the normal modes and the separation between two peaks is a measure of the strength of the coupling. Such X-Y coupling can be minimized by powering the skew quadrupole correction system to eliminate the oscillation in the vertical plane.

D. *Emittance Growth by the Foil*

The RMS horizontal beam emittance of the Linac beam is about 1.2 π mm-mrad. After proper steering, matching of beta-function and dispersion function, the minimum beam emittance achievable inside the Booster is about 2.3 π. Such a factor of two increase in beam emittance can be explained by the multipole Coulomb scattering of the proton beam through the H^- striping foil. The way we inject into the Booster, the proton beam passes through the foil about 30 to 50 turns. According to a six-dimensional tracking simulation [4], such a multipole transverse of the foil will increase the beam emittance by a factor of two. After the initial fast growth, the emittance will grow at a much reduced rate. At the foil location, the vertical beta function is close to minimum; hence, the perturbation in divergence caused by the foil is comparatively smaller in the vertical plane. To minimize emittance growth in the stacked horizontal plane, it may be a better choice to place the foil at the horizontal beta minimum. With such a pencil beam, the Booster horizontal aperture has been confirmed to be about $\pm$ 4 cm instead of $\pm$ 5 cm as required. Further correction of the orbit and avoidance of obstructions are needed to restore the available aperture to $\pm$ 5 cm. Furthermore, the aperture of the extraction channel is found to be about $\pm$ 2.2 cm, corresponding to a normalized emittance of 52 π.

III. PERFORMANCE WITH PROTON BEAM

Once the linear machine properties are determined, the acceleration of proton beam requires injection and acceleration of over 200 turns of Linac beam. To accomplish such a task, understanding of rf capture, space charge tune spread, stopband correction, and coherent instabilities play an important role. Some of the experiences will be discussed in this section.

A. *Beam Size and Emittance Tracking*

The ionization profile monitor (IPM) [5] is used to measure the beam size and emittance over the acceleration cycle. Shown in Figure 3 is the horizontal and vertical profiles taken from the IPM.

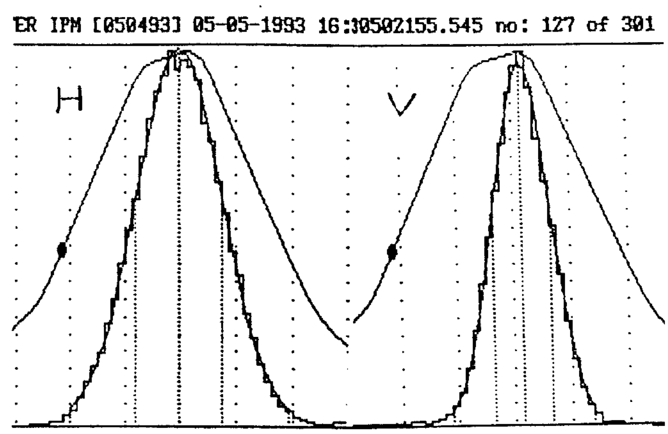

Figure 3. Beam profiles from the IPM.

The traces show the beam profiles taken at the dotted moment in the acceleration cycle. The evolution of the beam emittances over one cycle, including deceleration, are recorded.

Horizontal emittance tends to grow more both by the foil transverse and the non-linear resonance, which will be explained below. Many machine operation modes were devised to minimize the emittance growth gathered from such a display. Absolute beam size calibration will be accomplished by comparison with external SEM readings.

B. Working Point, Space Charge Tune Shift and Stopband Correction

The Booster working points are chosen to be about $\nu_x = 4.85$ and $\nu_y = 4.90$ at injection and the estimated space charge tune shift at full intensity is $\Delta\nu_x = 0.25$ and $\Delta\nu_y = 0.35$. At high intensity, the tune of some of the particles can cross $2\nu_x = 9$, $2\nu_y = 9$, $\nu_x - \nu_y = 0$, $\nu_x + \nu_y = 9$, $3\nu_x = 14$, $3\nu_y = 14$, $\nu_x + 2\nu_y = 14$, $2\nu_x + \nu_y = 14$ lines. Examples of particle losses due to some resonance lines and the survival of beam after correction are shown in Figure 4 [6].

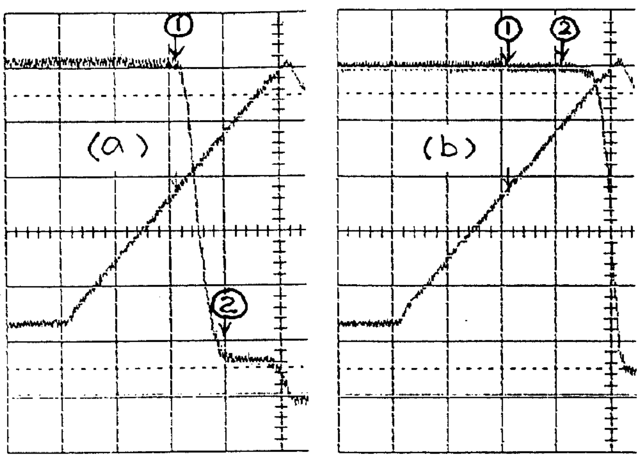

Figure 4. Stopband Correction; (a) without correction and (b) with correction, (1) $2\nu_x = 9$ and (2) $\nu_x + \nu_y = 9$.

The left trace shows the beam intensity decrease when it encounters the first resonance of $2\nu_x = 9$ and further decreases when it encounters the second resonance $\nu_x + \nu_y = 9$. The right trace shows that the total beam intensity is almost constant in crossing those two resonances after the correction system is turned on. The same process is repeated for all the resonances listed above. Such a correction study is carried out at flattop by varying the tune. During acceleration, with or without correction, this can make a 5-10% difference for weak resonances and a 30-50% difference for strong resonances[6].

C. Transverse Coupled-Bunch Instability

It has been estimated that the threshold for transverse coupled bunch instability excited by the resistive wall is at about 4-5 x 10^{12} ppp. A damper system has been constructed to damp such an instability when it occurs. Shown in Figure 5 is the signal of the instability. The suppression of coherent motion had been tried successfully with a prototype system. The new system will be available in June. The actual threshold of vertical instability has been found to be about 7 x 10^{12} ppp, when $\nu_x = 4.94$ and $\xi_x = -0.25$, which can be avoided by adjusting the tune and chromaticity of the machine. Active damping is necessary when the beam intensity is larger than 10^{13} ppp [7]. By supplying a constant amplitude of damping, instead of proportional to the oscillation, the power requirement of the damping system can be reduced by a factor of four. The effectiveness of the constant amplitude method has been tested in the Tevatron [8].

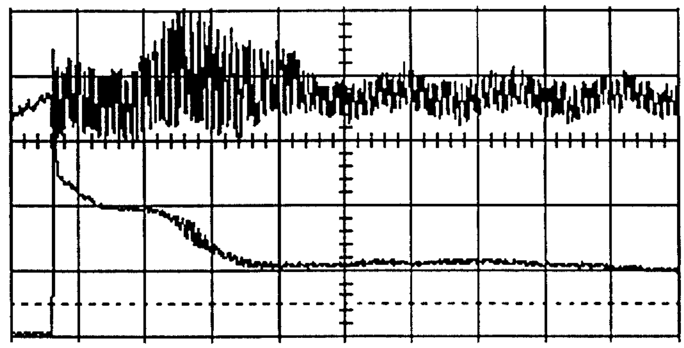

Figure 5. Signal of transverse instability and intensity.

D. Summary of Performance

After acceleration to the top energy of 1.5 GeV, the Booster beam is extracted and transported to the AGS. Four batches are needed to fill up the whole AGS ring as shown in Figure 6. At this time, the performance record of the four-batch Booster intensity and AGS intensity are summarized in Table I. In 1993, the AGS is limited by the capabilities of the old rf system. An accelerator improvement plan is in progress to replace the power amplifier system and low level system, which will be described in Section V.A. This new system will be installed in the summer of 1993.

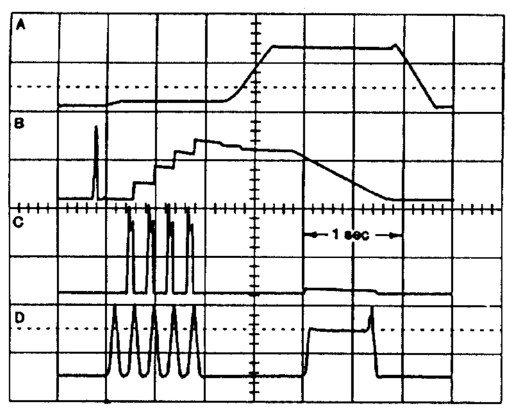

Figure 6. Proton acceleration with a study cycle: (A) AGS and (D) Booster magnetic field cycles, and (B) AGS and (C) Booster beam intensities.

TABLE I Booster and AGS Intensities (x 10^{13} ppp)				
	Design	May 1993	1994	1995
Booster	7	4.0	6	7
AGS Injected	6.5	2.4	4	6
AGS Acceleration	6	1.5	3.5	5

IV. PERFORMANCE WITH HEAVY ION BEAM

The AGS vacuum is about 10^{-8} Torr. The heavy ion beam from the Tandem Van de Graaff with masses higher than sulfur cannot survive due to their partially stripped state. The Booster vacuum is designed to be in the 10^{-11} Torr range [10] where any heavy ion beam can survive without loss from charge exchange or the electron stripping process. In the past, the fully stripped Si^{14+} beam has been injected into the AGS directly. At the end about 10^8 nucleons were extracted from the AGS. Now the Booster can accept Si^{8+} from the Tandem and accelerate it to 2 GeV/nucleon, extracted, stripped to Si^{14+} and injected into the AGS. The final intensity achieved is 2 x 10^9 nucleons, a factor of 20 better than direct injection into the AGS. This gain is due to the much better efficiency of stripping into Si^{8+}, instead of Si^{14+}, after the Tandem.

Another price to pay in accelerating Si^{8+} is that its injection energy is much lower than Si^{14+} and hence the rf frequency at injection is about 500 kHz instead of 2 MHz. The solution to this problem is to run the rf cavity at a harmonic number of 12 instead of 3 at injection and switch to a harmonic number of 6 one-third of the way through acceleration and to 3 two-thirds of the way through acceleration. During the switch from the higher harmonic to the lower one, two rf bunches have to be properly controlled and coalesced into one[9]. The bunch coalesce from two into one is shown in Figure 7.

After successful acceleration of Si^{8+}, the gold beam Au^{33+} was injected into the Booster and accelerated to the to energy of about 350 MeV/nucleon and extracted, stripped, and injected into the AGS. At the running time, no reliable knowledge was available for the proper foil thickness to optimize for either Au^{79+} or Au^{78+}. After stripping, the profile monitor showed two equal peaks, each with about 40% efficiency [10]. In the next running period, several foils will be provided to find the optimal stripping efficiency for Au^{79+} and Au^{78+}. In accelerating Au^{33+} in the Booster, five harmonic switches have been performed and the overall efficiency is about 70%. There certainly is room for improvement in future running. The final gold beam of 11 GeV/nucleon is the first ever achieved in the laboratory. About 3 x 10^7 npp has been accelerated and used for heavy ion research.

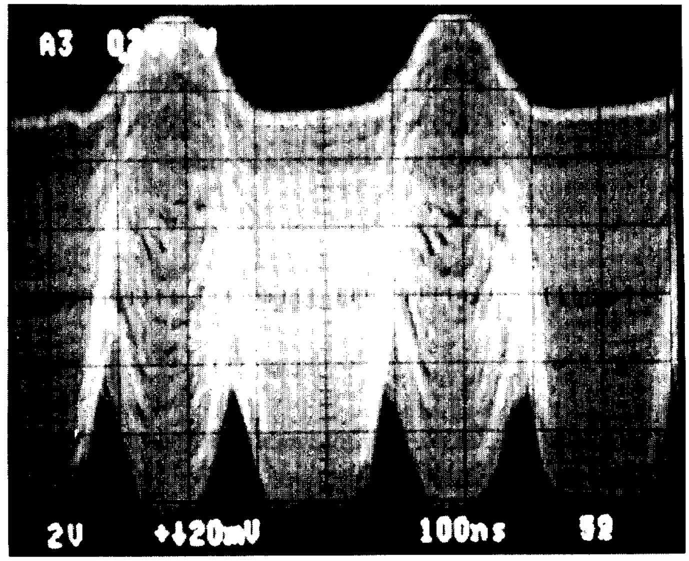

Figure 7. Bunch coalesce.

For RHIC injection, 3 x 10^9 npp from the AGS is needed. The current performance and future plan for gold intensity in the AGS is shown in Table II.

TABLE II Gold Intensity from the AGS				
	1992	1993	1994	1995
Tandem Beam	Au^{33+}	Au^{33+}	Au^{14+}	Au^{14+}
Intensity	$3x10^7$	10^8	$5x10^8$	10^9

V. AGS UPGRADE PROGRAMS

A. AGS RF System

The current AGS rf system was designed and installed in 1970. The original design was to accelerate 10^{13} ppp with a power amplifier system capable of delivering 60 kW. With the Booster as the injector, the expected beam intensity will be more than 6 x 10^{13} ppp, which requires a system capable of delivering 200 kW to drive the rf cavities. Therefore, the plan is to replace the existing 10 Philips 8752 tubes with the new Thomson 573 tubes, which also presents much less impedance to the beam [11].

In the existing AGS, the high level power amplifier system and the low level beam control system are integrated into one system for all ten acceleration stations, sharing the same frequency tuning loop, the AGC and phase loop. Therefore, there is no freedom for tuning each station individually and often times, the output voltage varies from station to station. In the new arrangement, both the high level and the low level system will be independently adjusted. Such a capability is crucial for beam loading compensation, which would include transient, periodic, and steady state cases. An rf feedback system with loop delay of less than 200 nsec will be provided for each driver to counteract the strong beam loading effect created in the injection process from the Booster. A factor of 15 reduction in the induced voltage has been achieved by the rf feedback method on a prototype cavity. All ten stations will be replaced in the summer of 1993. This is the reason that the final AGS intensity can go beyond 2 x 10^{13} ppp after 1993.

B. Gamma-Transition Jump

With high intensity beam, during the transition crossing in the AGS, the non-linear space charge force can blow up the beam emittance when the bunch length reduces beyond a certain critical length. One way to combat such an effect is to modify the gamma-transition parameter of the synchrotron in such a way that the beam energy crosses the gamma-transition as fast as possible. The figure of merit of this fastness of crossing can be increased by a factor of twenty by quickly pulsing special quadrupoles provided for such a purpose. Calculations have been done to show that with an initial longitudinal emittance of 1 eV-sec, such a gamma-transition jump system can reduce the emittance growth from 5 eV-sec to 3 eV-sec. If the initial emittance is increased to 2 eV-sec, such a system can reduce the emittance growth to less than 15% even at an intensity of 10^{14} ppp [12]. A 96 MHz VHF system has been built to control the beam emittance before transition crossing and the gamma-transition jump system will be installed in the summer of 1993.

C. Heavy Ion Intensity and Emittance

Using Au beam as an example, the RHIC collider requires an Au^{79+} beam of 3 x 10^9 npp with a transverse emittance of 10 πmm-mrad and a longitudinal emittance of 0.3 eV-sec. During the 1992 running period, the AGS produced 3 x 10^7 npp Au^{79+} with a transverse emittance of 25 π and a longitudinal emittance of 1 eV-sec. One way to increase the Au intensity is to inject Au^{14+} into the Booster instead of Au^{33+}. This will increase the Au^{14+} intensity by a factor of 5 inside the Booster. Another factor of 5 can be gained by minimizing the number of harmonic switches in the Booster by using lower frequency rf systems and by increasing the Tandem current and lengthening its pulse. A final factor of 4 can be gained by improving the acceleration and extraction efficiencies in the AGS. Further possible gains can be obtained by running Au^{77+}, instead of Au^{79+}, in the AGS which will be tried in 1994.

The Au^{79+} suffered a factor of three emittance growth in the AGS during transition crossing. Careful machine studies are needed to minimize such a growth. The charge density of Au^{79+} inside 0.3 eV-sec longitudinal phase space is high enough to suffer space charge blow up during transition crossing. The newly provided gamma-transition jump system will be used to minimize the emittance growth both in the transverse and longitudinal planes.

D. SEB Spill Servo

In the AGS, sextupole excitation is used to generate third-integer resonance and extract the large amplitude beam from the ring to the experimental area over a 1 second flattop. The performance so far is satisfactory in terms of efficiency and beam emittance delivered. The only drawback is in the uniformity of the spill over the 1 second period. The intensity fluctuation can be as large as 50%, which is undesirable from the experimental point of view. Sources of such a fluctuation include power supply ripples, non-uniform energy distribution and space charge tune spread. A system is under design to sense the extracted beam intensity and feedback on the strength of the sextupole field to control the spill uniformity to better than 10%.

Other ongoing AGS upgrade projects, not covered here, include longitudinal damping system, Linac power transmission system, new beam position monitor system, and polarized proton acceleration system. If the space charge tune shift becomes excessive, a second harmonic cavity can be employed in the Booster.

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