Submitted to: Space Charge Physics in High Intensity Hadron Rings
Shelter Island, NY May 4-7, 1998

BNL-65736

High Intensity Performance and Upgrades at the Brookhaven AGS*

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Recent AGS High Intensity Performance

Fig. 1 shows the present layout of the AGS-RHIC accelerator complex. The high intensity proton beam of the AGS is used both for the slow-extracted-beam (SEB) area with many target station to produce secondary beams and the fast-extracted-beam (FEB) line used for the production of muons for the g-2 experiment and for high intensity target testing for the spallation neutron sources and muon production targets for the muon collider. The same FEB line will also be used for the transfer of beam to RHIC.

The proton beam intensity in the AGS has increased steadily over the 35 year existence of the AGS, but the most dramatic increase occurred over the last couple of years with the addition of the new AGS Booster[1]. In Fig. 2 the history of the AGS intensity improvements is shown and the major upgrades are indicated. The AGS Booster has one quarter the circumference of the AGS and therefore allows four Booster beam pulses to be stacked in the AGS at an injection energy of $1.5 - 1.9\,GeV$. At this increased energy, space charge forces are much reduced and this in turn allows for the dramatic increase in the AGS beam intensity.

The 200 MeV LINAC is being used both for the injection into the Booster as well as an isotope production facility. A recent upgrade of the LINAC rf system made it possible to operated at an average H^- current of 150 μA and a maximum of 12×10^{13} H^- per 500 μs LINAC pulse for the isotope production target. Typical beam currents during the 500 μs pulse are about 80 mA at the source, 60 mA after the 750 keV RFQ, 38 mA after the first LINAC tank (10 MeV), and 37 mA at end of the LINAC at 200 MeV. The normalized beam emittance is about 2 π $mm\ mrad$ for 95 % of the beam and the beam energy spread is about ± 1.2 MeV. A magnetic fast chopper installed at 750 keV allows the shaping of the beam injected into the Booster to avoid excessive beam loss.

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

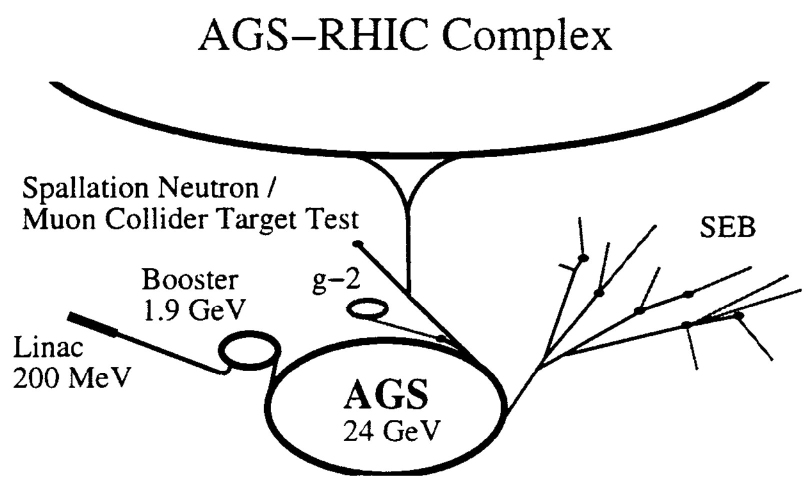

Figure 1: The AGS-RHIC accelerator complex.

The achieved beam intensity in the Booster surpassed the design goal of 1.5×10^{13} protons per pulse and reached a peak value of 2.3×10^{13} protons per pulse. This was achieved by very carefully correcting all the important nonlinear orbit resonances especially at the injection energy of 200 MeV and by using the extra set of rf cavities that were installed for heavy ion operation as a second harmonic rf system. The second harmonic rf system allows for the creation of a flattened rf bucket which gives longer bunches with lower space charge forces. The fundamental rf system operated with 90 kV and the secondary harmonic with 30 kV. The typical bunch area was about 1.5 eVs. Even with the second harmonic rf system the incoherent space charge tune shift can reach one unit right at injection (3×10^{13} protons, norm. 95 % emittance: 50 π mm $mrad$, bunching factor: 0.5). Of course, such a large tune shift is not sustainable, but the beam emittance growth and beam loss can be minimized by accelerating rapidly during and after injection. Best conditions are achieved by ramping the main field during injection with 3 T/s increasing to 9 T/s after about 10 ms. The quite large non-linear fields from eddy currents in the Iconel vacuum chamber of the Booster are passively corrected using correction windings on the vacuum chamber that are driven by backleg windings[2].

The AGS itself also had to be upgraded to be able to cope with the higher beam intensity. During beam injection from the Booster, which cycles with a repetition rate of 7.5 Hz, the AGS needs to store the already transferred beam bunches for about 0.4 seconds. During this time the beam is exposed to the strong image forces from the vacuum chamber which causes beam loss from resistive wall coupled bunch beam instabilities within as short a time as a few hundred revolutions. A very powerful feedback system was installed that senses any transverse movement

AGS Proton Intensity History

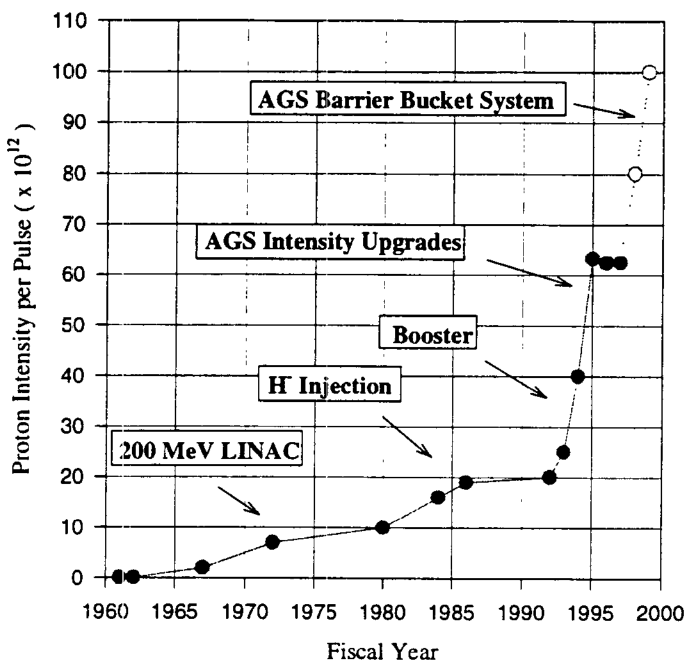

Figure 2: The history of the evolution of the proton beam intensity in the Brookhaven AGS.

of the beam and compensates with a correcting kick. This transverse damper can deliver $\pm 160\ V$ to a pair of $50\ \Omega$, one-meter-long strip-lines. A recursive digital notch filter is used in the feed-back circuit to allow for accurate determination of the average beam position and increased sensitivity to the unstable coherent beam motion. This filter design is particular important for the betatron tune setting of about 8.9 which is required to avoid non-linear octupole stopband resonance at 8.75. With an incoherent tune shift at the AGS injection energy of 0.1 to 0.2 it is still necessary, however, to correct the octupole stopband resonances to avoid excessive beam loss.

To reduce the space charge forces further the beam bunches in the AGS are lengthened by purposely mismatching the bunch-to-bucket transfer from the Booster and then smooth the bunch distribution using a high frequency 100 MHz dilution cavity. The resulting reduction of the peak current helps both with coupled bunch instabilities and stopband beam losses.

During acceleration the AGS beam has to pass through the transition energy after which the revolution time of higher energy protons becomes longer than for the lower energy protons. This potentially unstable point during the acceleration cycle was crossed very quickly with a new powerful transition energy jump system with only minimal losses even at the highest intensities. The large lattice distortions introduced by the jump system prior to the transition crossing severely limits the available aperture of the AGS in particular for momentum spread. Efforts to correct the distortions using sextupoles have been partially successful[3]. After the transition energy, a very rapid, high frequency instability developed which could only be avoided by purposely further increasing the bunch length using again the high frequency dilution cavity.

The peak beam intensity reached at the AGS extraction energy of $24\,GeV$ was 6.3×10^{13} protons per pulse also exceeding the design goal for this latest round of intensity upgrades. It also represents a world record beam intensity for a proton synchrotron. With a 1.6 second slow-extracted beam spill the average extracted beam current was about $3\,\mu A$. This level of performance was reached quite consistently over the last few years and during a typical 20 week run a total of 1×10^{20} protons are accelerated in the AGS to the extraction energy of $24\,GeV$.

At maximum beam intensity about 30 percent of the beam is lost at Booster injection (200 MeV), 25 percent during the transfer from Booster to AGS (1.5 GeV), which includes losses during the 0.4 second storage time in the AGS, and about 3 percent is lost at transition (8 GeV). Although activation levels are quite high all machines can still be manually maintained and repaired in a safe manner.

Possible Future AGS Intensity Upgrades

Currently the number of Booster beam pulses that can be accumulated in the AGS is limited to four by the fact that the circumference of the AGS is four times the circumference of the Booster. This limits the maximum beam intensity in the AGS to four times the maximum Booster intensity which itself is limited to at most 2.5×10^{13} protons per pulse by the space charge forces at Booster injection. To overcome this limitation some sort of stacking will have to be used in the AGS. The most promising scheme is stacking in the time domain. To accomplish this a cavity that produces isolated rf buckets can be used to maintain a partially debunched beam in the AGS and still leave an empty gap for filling in additional Booster beam pulses. The stacking scheme is illustrated in Fig. 3. It makes use of two isolated rf buckets to control the width of this gap. Isolated bucket cavities, also called Barrier Bucket cavities, have been used elsewhere[4]. However, for this stacking scheme, a high rf voltage will be needed to contain the large bunch area of the high intensity beam. An additional important advantage of this scheme is that while the beam is partially debunched in the AGS the beam density and therefore space charge forces are reduce by up to a factor of two. A successful test of this scheme has recently been completed[5] and two 40 kV Barrier cavities are being installed in the AGS with the aim of accumulating six Booster beam pulses in the AGS to reach an intensity of about 1×10^{14}.

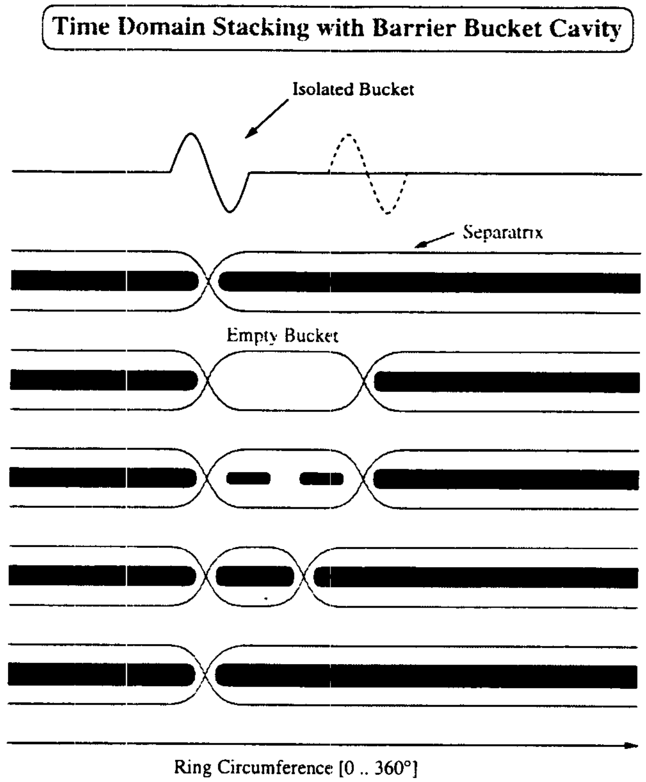

Figure 3: Time domain stacking scheme using a barrier bucket cavity. The evolution of the longitudinal beam structure during the stacking process are shown from top to bottom.

For further increases in the intensity the space charge forces at Booster injection represent the main limitation. This could be overcome by an energy upgrade of the LINAC to about 600 MeV by replacing part of the present 200 MHz cavities with higher gradient 400 MHz cavities driven by Klystrons. At 600 MeV the space charge limit at Booster injection would be 5×10^{13} protons per pulse or 2×10^{14} protons in the AGS for 4 cycles per AGS cycle.

As more Booster beam pulses are accumulated in the AGS the reduction in the overall duty cycle becomes more significant. For fast-extracted beam operation (FEB) the accumulation of four Booster pulses contributes already significantly to the overall cycle time. With the addition of a $2\,GeV$ accumulator ring in the AGS tunnel this overhead time could be completely avoided. Such a ring could be build rather inexpensively using low field magnets. The maximum repetition rate of the Linac and Booster is 10 Hz. Since the circumference of the AGS is four times that of the Booster a repetition rate of 2.5 Hz would maintain a throughput of 80 μA through the whole accelerator chain. Such an increase of the AGS repetition rate by a factor of 2.5 could be achieved by an upgrade of the AGS main magnet power supply only. The resulting beam power of 2 MW at 25 GeV corresponds to the required proton driver performance needed for a demonstration muon collider project [6]. The upgrades to the AGS complex are summarized in Fig. 4.

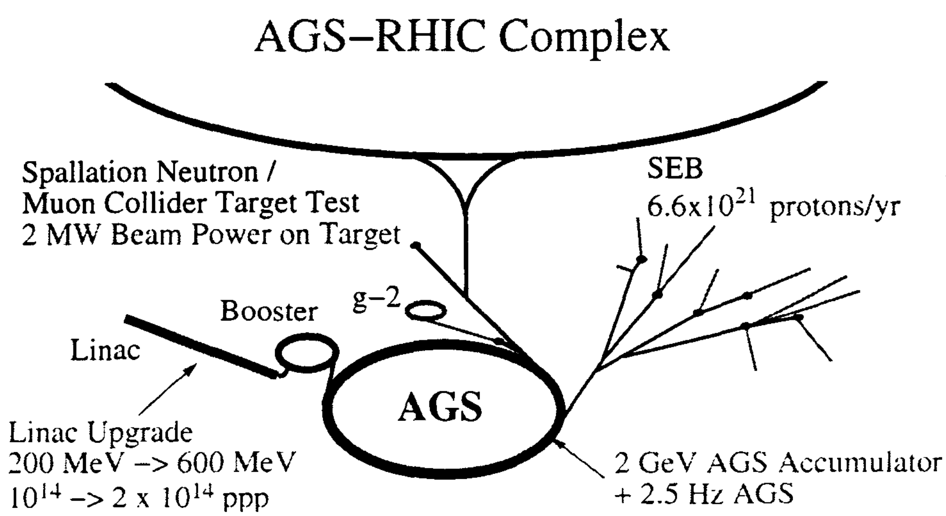

Figure 4: Summary of intensity upgrades for the AGS.

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