HIGH INTENSITY PERFORMANCE OF THE BROOKHAVEN AGS*,

L.A. Ahrens, J. Alessi, M. Blaskiewicz, J.M. Brennan#, K. Brown,
C. Gardner, J.W. Glenn, T. Roser, K. S. Smith, W. VanAsselt, S.Y. Zhang, BNL, Upton, NY

Abstract

The Brookhaven AGS provides 24 GeV protons for a multi-user program of fixed-target high energy physics experiments, such as the study of extremely rare Kaon decays. Up to 7×10^{13} protons are slowly extracted over 2.2 seconds each 5.1 seconds. The muon storage ring of the g-2 experiment is supplied with bunches of 7×10^{12} protons. Since the completion of the a 1.9 GeV Booster synchrotron and installation of a new high-power rf system and transition jump system in the AGS various modes of operation have been explored to overcome space charge limits and beam instabilities at these extreme beam intensities. Experiments have been done using barrier cavities to enable accumulation of de-bunched beam in the AGS as a potential path to significantly higher intensities. We report on the present understanding of intensity limitations and prospects for overcoming them.

Run Year	Harmonic Numbers		Booster Cycles	Intensity $\times 10^{12}$
	Booster	AGS		
94	3	12	4	40
95,96, 97	2 & 4	8	4	63
98 SEB	1 & 2	6	6	71
98 g-2	1 & 2	$6 \rightarrow 12$	6	58

Table 1. Development of harmonic number and intensity for the last five runs. SEB is slowly extracted beam to the fixed targets. g-2 is fast bunch extraction to the muon storage ring.

1. INTRODUCTION

Very high intensity operation of the AGS began in 1994 after the completion of an extensive upgrade program. The AGS injection energy was increased from 200 to 1900 MeV by the 7.5 Hz Booster which is ¼ of its circumference.[1] As series of harmonic numbers have been used in attempt improve peak intensity and efficiency. The trend to fewer and longer bunches makes more stable beam with less tune spread. Bunches are made longer by; emittance dilution[2], double harmonic rf, and controlled bunch shape oscillations. Emittance dilution is limited by a constriction in the momentum aperture when the transition jump system operates. A low impedance rf system allows low voltage at high beam current during accumulation in the AGS.

With one bunch in the Booster six loads are put into the AGS, thus removing the need for the highest intensities in the Booster. Table 1 summarizes the configurations of several runs.

2. BOOSTER INJECTION

Experience shows that Booster injection is pivotal for good performance throughout the cycle. Up to 33 mA of 200 MeV H^- is injected for 300 turns as the dipole field rises corresponding to 8.7 GeV/s. A fast chopper after the 750 keV RFQ cuts the beam to phase bites of about 180° of the rf bucket. The chopper can also skip turns to make 10:1 intensity changes without changing the linac macro pulse length. This is useful for studying intensity-driven effects without changing transverse phase painting parameters that determine beam emittance and distribution. Making long smooth bunches is essential for achieving high intensity. Somewhat smoother bunches are produced by ramping the linac energy by 1% to match the Booster field ramp. Attempts to flatten the bunches by chopping two pulses into one bucket thus making a smoke-ring distribution in longitudinal phase space were unsuccessful. At 1.5×10^{13} protons the Lasslett tune shift reaches $\Delta v = 0.5$ and up to 15% beam loss occurs within the first 10 ms.
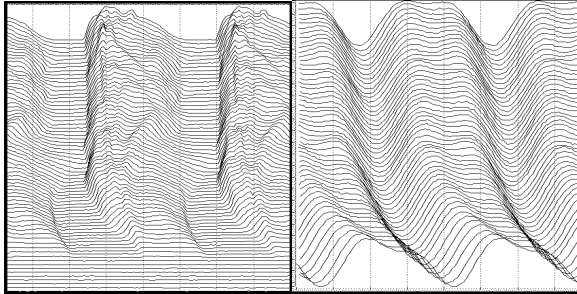
Figure 1 Mountain range view of the first millisecond of injection. The 300 injected bunches are 180 degrees long. The vector sum of the h=1 and h=2 rf cavities is shown on right. By careful choice of the phase and pulse width of the rf chopper smooth bunches can be obtained.

3. BOOSTER ACCELERATION

The Booster accelerates to 1.9 GeV in 75 ms. The rf voltage is a composite of the first and second harmonics at up to 60% amplitude of the fundamental. Two adjustable functions of time control the relative amplitude (by counter phasing) and phase of the harmonics. These functions are empirically tuned for best intensity and efficiency. The bunches are made longer at extraction by pumping the longitudinal quadrupole bunch-shape oscillation by modulating the rf voltage at $\pm 10\%$ at twice the synchrotron frequency, figure 2. The phase of the h=2 voltage is adjusted to linearize the bucket for this operation. Feedforward beam loading compensation on these cavities is necessary.
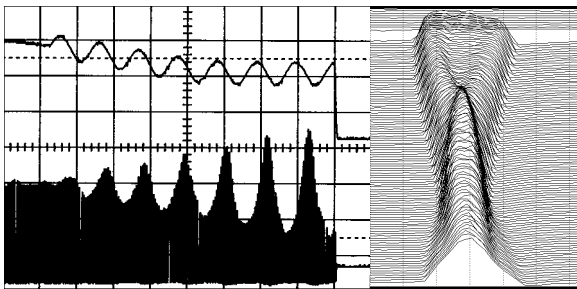

Figure 2 Pumping the coherent quadrupole mode in the Booster to make the bunches longer (x2) before transfer to the AGS. Left, envelope of pick up and rf voltage, 1ms/division. Right, mountain range view of last oscillation cycle.

4. AGS INJECTION

Most of the beam loss in the AGS (up to 20%) occurs during the injection and accumulation process which lasts for 750 ms. Here the Lasslett tune shift is significant $\Delta \nu = 0.3$) and tune is set just below the integer, $\nu_x = 8.9$. The

Booster output energy was increased from 1.5 to 1.9 GeV kinetic to reduce the tune spread of the accumulating beam.
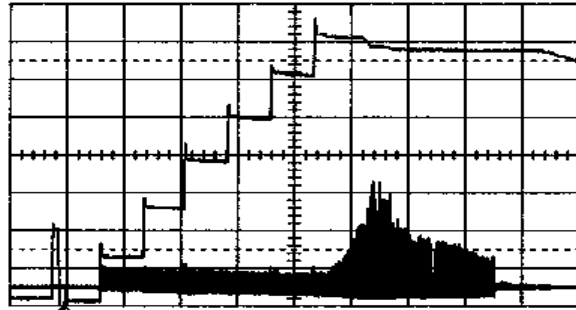

Figure 3 Current transformer and longitudinal pick-up (wall current monitor) in AGS. Fast loss is seen at each injection pulse. A 5% loss at transition can also be seen .

Significant beam loss occurs in the first 1 ms, figure 3. A plausible conjecture for the mechanism of loss is halo (which scrapes vertically) formed by the space charge coupling of coherent center of mass motion to particles at the fringe of the phase space distribution. The coherent motion arises from injection dipole and quadrupole mismatch. Intensity dependent tune along the bunch creates de-phasing, making wiggles in bunch centeroid that develop more rapidly as intensity increases, figure 4. Synchrotron motion and chromaticity mixes particles with different tunes and dissipates the coherent motion, thereby stopping halo pumping and loss. The benefit from high synchrotron frequency (500 Hz) during accumulation outweighs the penalty at transition for longitudinal emittance growth due to exceeding the matching voltage for the long Booster bunches.

Figure 4 Coherent within-the-bunch vertical motion at AGS injection. Each trace is a new turn. Different parts of the bunch oscillate at different frequencies because of different local coherent tune shift. (because the intensity varies along the bunch) Left is low intensity, 3×10^{12}. Right is high intensity, 10^{13} per bunch.

Figure 5 shows a single bunch when the first bunch is stored. The wakefield must be of order the bunch length since no coupling between bunches is seen. The head of the bunch is undisturbed. The oscillation of the center of the bunch grows until beam loss reduces the intensity and the instability self-limits.
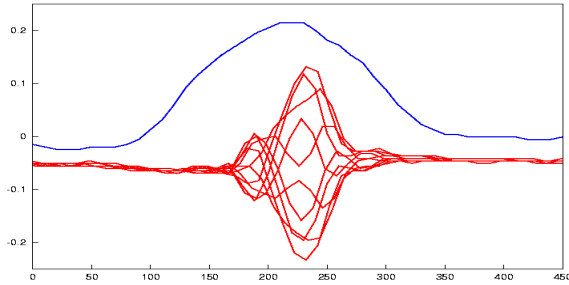
Figure 5. Single bunch vertical instability in the AGS, 10^{13} protons per bunch, 1.9 GeV kinetic. Top trace is sum of up & down pickups, bottom are difference.

5. AGS ACCELERATION

The only significant beam loss (<5%) during acceleration occurs at transition crossing. [3] The high power (>2 MW) rf system is stabilized by rf feedback against beam loading instabilities. [4] At intensities above 5×10^{13} beam image currents that escape the vacuum chamber are a serious noise problem. It was necessary to short chambers together in groups of five to minimize the quantity of rf bypasses between chambers.

6. SLOW SPILL

A smooth 2.2 second spill is achieved by ramping the dipole field by –1% by a time varying reference function augmented with feedback on the extraction rate. [5] Controlled de-bunching spreads and flattens the momentum distribution. Maintaining homogeneity of the longitudinal phase space distribution is difficult at high intensity. A high harmonic (h=270) cavity operates continuously after transition to drive emittance blow up. The cavity is also used during the spill to reduce fast (>100 Hz) rate fluctuations (x10 improvement) by quickly accelerating beam micro-bunches into the 3rd order extraction resonance.[5, 6]

7. G-2 EXPERIMENT

The AGS fills the muon storage ring of the g-2 experiment [7] by single-bunch extraction. The accelerator repetition period is 2.5 seconds. Both 6 and 12 bunches per cycle were provided. To extract 12 bunches the 6 injected bunches were split in two at injection energy and accelerated on h=12, figure 6. The splitting technique was recently developed at CERN [8].
Bunches were shortened by a factor of two in a similar way to Booster extraction. The key difference being the sustained (200 ms) bunch shape oscillations without emittance growth which was accomplished by the adiabatic nature of the rf voltage modulation.[9]

8. BARRIER BUCKET INJECTION

A novel type of beam accumulation was tested using barrier bucket rf cavities in a collaboration experiment with KEK. The barrier cavities allowed accumulation of de-bunched beam.[10] One of the two cavities, developed by KEK, [11] employed a new magnetic material, FINEMET, which surpasses ferrite in peak rf magnetic field achievable. The experiments showed that de-bunched beam can be accumulated, rebunched and accelerated and that details of the barrier waveform are important.
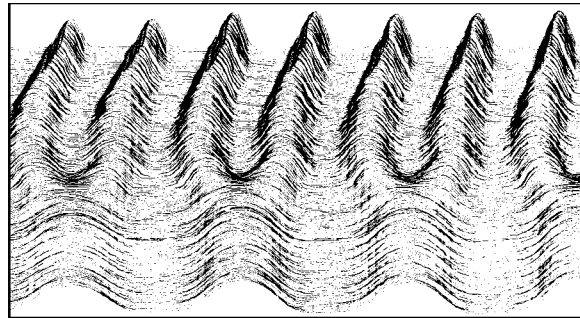
Figure 6. Splitting (h: 6→12) of 10^{13} bunches at 1.9 GeV with little emittance growth. Horizontal scale 1.5 μs. Vertical scale is 50 ms.

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