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AGS RESONANT EXTRACTION WITH HIGH INTENSITY BEAMS*

L. Ahrens, K. Brown†, J. W. Glenn, T. Roser, N. Tsoupas, W. VanAsselt,
AGS Dept., BNL, Upton, NY

Abstract

The Brookhaven AGS third integer resonant extraction system allows the AGS to provide high quality, high intensity 25.5 GeV/c proton beams simultaneously to four target stations and as many as 8 experiments. With the increasing intensities (over $7x10^{13}$ protons/pulse) and associated longer spill periods (2.4 to 3 seconds long), we continue to run with low losses and high quality low modulation continuous current beams.[1] Learning to extract and transport these higher intensity beams has required a process of careful modeling and experimentation. We have had to learn how to correct for various instabilities and how to better match extraction and the transport lines to the higher emittance beams being accelerated in the AGS. Techniques employed include "RF" methods to smooth out momentum distributions and fine structure. We will present results of detailed multi-particle tracking modeling studies which enabled us to develop a clear understanding of beam loss mechanisms in the transport and extraction process. We will report on our status, experiences, and the present understanding of the intensity limitations imposed by resonant extraction and transport to fixed target stations.

1 INTRODUCTION

The Brookhaven AGS Resonant extraction system and the beam transport and switchyard systems were designed in the pre-AGS Booster era,[2, 3, 4] when the kinetic energy of the injected beam was 200 MeV. In the post-Booster era, this energy is now approximately 1.6 GeV. For these two energies the ratio of $\beta\gamma$ is approximately 3.5. Therefore the maximum possible beam emittance is over 3.5 times larger for post-Booster high intensity beams. In order to obtain high intensity beam, the transverse emittance is increased, even though the Booster acceptance is the same as the AGS acceptance.[1] Recent emittance measurements in the AGS Switchyard show that indeed, the beam is larger. The horizontal emittance is about 2 times larger and the vertical emittance is about 1.5 times larger, than they were in the pre-Booster era. [5]

In addition to the larger beams, other factors have changed significantly since the design of the AGS SEB systems. The AGS now uses fast quadrupole magnets to jump the gamma transition point during acceleration. For minimal beam losses to occur during the γ_{tr} jump the momentum spread of the beam has to be minimized. This puts constraints on how large the longitudinal emittance can be. This is due to the highly distorted dispersion function created by the fast quadrupoles, which defines the momentum aperture.[6] Among other changes, we have moved the locations of the drive sextupoles used to create the 26/3 resonance for SEB extraction. This changed the orientation of the separatrix at the electrostatic and the magnetic septums in the AGS, but only slightly. The reason for moving the locations of these sextupoles was to increase the available chromaticity correction. There are now 12 horizontal chromaticity sextupoles, plus the 4 drive sextupoles.

Another fundamental change is the harmonic number used for the AGS. Although this has no obvious impact on the SEB operation, when the system was designed the AGS only worked on an harmonic of 12. We have now operated SEB at high intensity with the AGS on harmonics of 8 and 6. When we ran at very high intensities on a harmonic of 8 it was observed that there were significant coupled bunch oscillations occurring after transition. These have the effect of increasing the longitudinal emittance and diluting the phase space. When we ran on a harmonic of 6 the coupled bunch oscillations were still there, but did not increase the emittance or dilute the phase space as well as before.

Finally, in order to further our understanding of the SEB process, and to try to understand beam loss mechanisms, we have improved and developed models of these systems. In particular is work we have done to track particles through actual field maps of the AGS magnets, to understand the dynamics of what is occurring when the beam is passing through the changing gradient of the combined function magnets. These modeling studies confirmed suspicions we had that significant tails were developing on the beams, which could not be contained in the aperture of the transport lines. The models also confirmed the location of beam losses in the beam line. This allowed us to come up with strategies for reducing and controlling these tails, allowing us to reduce the beam losses resulting from them.

2 SEB HIGH INTENSITY PERFORMANCE

Basic performance parameters are summarized in table 1.

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† Email: kbrown@bnl.gov

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Table 1: AGS SEB Performance Parameters

Parameter	**Value**	**Units**
Momentum	25.5	GeV/c
Peak Intensity	71.5	10^{12} proton/pulse
Extract. Eff.	96-98	%
Transport Eff.	90-95	%
Rep. Period	5	second
Flattop Length	3	second
Spill Length	2.8	second
Working Point	8.67/8.76	Tune (ν_x, ν_y)
Chromaticity	-2.3/0.2	Chrom. (ξ_x, ξ_y)

2.1 *Beam Loss Issues*

The primary beam loss issues have not been in the extraction process itself, but in the transport of the extracted beam to target stations. There were two primary beam loss areas. First, and what was our most pressing problem, was beam losses in the region where the two highest intensity beam lines split off from each other. External "chipmunk" monitors (tissue equivalent ionization detectors, originally developed at FNAL) located outside the beam line shielding, limited the beam intensity that we could put into this region of the beam transport, thus limiting the amount of beam we could deliver to two major experiments. The main cause of the problem was not completely clear. We had made emittance measurements, including measurements of the initial twiss parameters, which showed the beam at the entrance to the switchyard had changed from the canonical set of parameters we had used in our models. Using the new twiss parameters and emittances we developed a new set of optics, which did help significantly (we were able to meet the experimenters requirements). But there were still unexplained losses in the transport.

Explaining the new twiss parameters and emittances gets us back to the extraction process. The beam certainly is larger, as we explained above, but why would the twiss parameters change ? Interestingly enough, the vertical twiss parameters did not change significantly, and could be argued to agree with pre-Booster era measurements. The horizontal twiss parameters were significantly different, although on careful inspection we realized that the ratio of α to β was the same for both the pre- and post-Booster era measurements. In other words, the angular orientation of the beam in phase space was the same, it was just much longer and fatter. Tables 2 and 3 summarize these emittance measurements (note: β and α are referred to switchyard S_0, after AGS magnet F13).

The second beam loss area, which was not fixed by having a new optics solution, was in the region of the transport between the thick septum ejector magnet from the AGS, located at F10, and the first matching quadrupole in the switchyard, located next to the F14 AGS magnet. This beam loss did not cause any chipmunks to limit the intensity but it was nevertheless significant. To understand this beam loss we developed models of the transport and orbit of the beam in the AGS during extraction. We did single particle tracking studies using field maps of the AGS combined function magnets. These studies showed, given the large internal emittance beam, that the extracted beam could easily develop a tail, which could not be confined in the acceptance of the switchyard.

Table 2: Horizontal emittance measurements

	$\epsilon_x^{95\%,N}$	β_x *(m)*	α_x
Pre-Booster	31.9	57.61	-6.636
Post-Booster	64.37± 9.60	8.77 ± 1.4	$-0.92\pm$ 0.2

Table 3: Vertical emittance measurements

	$\epsilon_y^{95\%,N}$	β_y *(m)*	α_y
Pre-Booster	38.8	3.249	0.8708
Post-Booster	54.71± 5.0	4.18 ± 0.4	1.01 ± 0.09

Figure 1 shows the phase space of the beam at the entrance to the thin septum extraction magnet and the phase space at F13, just before entering the matching quadrupoles at the entrance of the switchyard. In this case the beam entering the switchyard has a large tail. Figure 2 shows particles from the edges of the phase space ray traced down the C line. As can be seen the tail cannot stay contained in the aperture in the matching section (at the beginning of the line) and again hits apertures in the middle of the line. Interesting enough, the latter location is where the beams split off between the B and C lines, the area of problems noted above. We can reduce, and even eliminate, the tail by moving the two septum magnets 2/10 inch further inside. This was done and it significantly reduced beam losses in both the two problem sections.

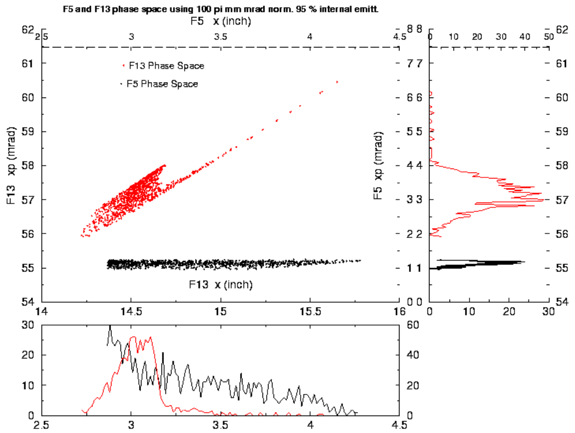

Figure 1: Tracking Simulation of extracted beam passing through AGS Main Magnets

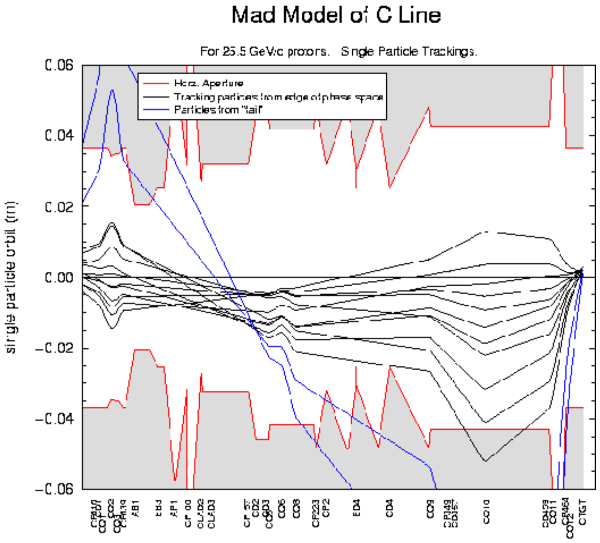

Figure 2: Single particle tracking for transport down C-Line

2.2 *Spill Structure*

In the FY98/99 SEB run we ran into a new problem; significant spill structure not associated with power supply ripple. This spill structure was analyzed and found to be random kilohertz oscillations. We found no correlations between these oscillations and power supply ripples. The power supply ripple only accounted for about 20 % of the spill structure. At high intensity the spill was 100 % modulated (intensity dependent). Recall that the spill structure is a consequence of variations in velocities in tune space:

$$S(t) = \frac{dN}{dQ} \cdot \dot{Q}_0 (1 + \frac{\dot{Q}_v}{\dot{Q}_0}) \qquad (1)$$

When there is very little power supply ripple, the remaining structure is a consequence of the rate at which the beam is moved into resonance and the distribution of the particles in tune space. The random kilohertz structure appears to be a direct reflection of the distribution of particles in tune, or more properly, momentum space. Our solution to this problem was to use the VHF cavity during extraction, placing the 93 MHz buckets between the beam and the resonance, such that the particles were forced between the RF buckets before going into non-linear resonant growth. Since we have a slight negative $\dot{B}$ during extraction the RF buckets would have only a small space between which the beam could pass, breaking up any structure that existed in the beam. This potentially puts 93 MHz structure on the spill, which was not a problem for the experimenters using the beam. Figure 1 shows the beam spill with and without the VHF cavity on during extraction.

3 CONCLUSIONS

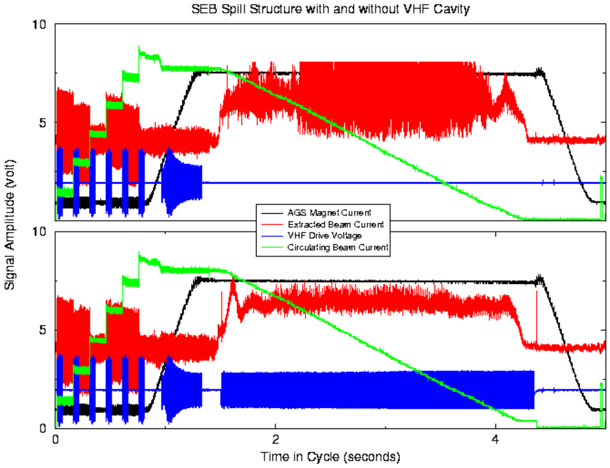

Figure 3: Extracted beam spill with and without VHF on

The AGS SEB system is able to supply high quality, high intensity proton beams for multiple simultaneous experiments. We are able to contend with instabilities that arise from the high current accelerated beams, as well as unexpected effects, such as spill structure uncorrelated with power supply ripple. For the AGS the VHF cavity has proven to be invaluable for diluting longitudinal phase space and now for smoothing spill structure.

4 REFERENCES

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