High Intensity Proton Operation at the Brookhaven AGS Accelerator Complex*

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Abstract

With the completion of the AGS rf upgrade, and the implementation of a transition "jump", all of accelerator systems were in place in 1994 to allow acceleration of the proton intensity available from the AGS Booster injector to AGS extraction energy and delivery to the high energy users. Beam commissioning results with these new systems are presented. Progress in identifying and overcoming other obstacles to higher intensity are given. These include a careful exploration of the stopband strengths present on the AGS injection magnetic porch, and implementation of the AGS single bunch transverse dampers throughout the acceleration cycle.

1. INTRODUCTION

The Brookhaven AGS complex has included the Booster in its chain of accelerators since 1992, but because of new systems added to the AGS it was not a priori obvious what intensity limits for the 1994 proton run would be. Indeed as of this writing the limit is still not clear as the peak beam intensity at extraction has passed 3.7×10^{13} protons per 3.8 second acceleration cycle and continues to creep up. The highest intensity accelerated during the '93 run was just below 2.5×10^{13}. This paper will briefly describe the Linac and Booster setup, which are not fundamentally changed from previous reviews.[1] The changes made this year in the AGS were substantial and will be described along with the performance gains associated with their introduction. Some mention will be made of future developments. The capacity of the extraction lines, targets and proton users to accept beam continues to increase. One should understand that these users - the beam is slowly extracted (a one second or longer spill) from the AGS at 24 GeV and used to produce secondary beams at 6 target stations - are only interested in intensity and time uniformity of beam on target. The 6 dimensional emittance prior to extraction is relevant only in so far as it limits efficient acceleration, extraction, and transport. Tuning tends to have a strong empirical flavor with losses and intensity the primary optimized parameters.

2. LINAC AND BOOSTER

Both the Linac and Booster increased their repetition rate from 5 Hz to 7.5 Hz for the '94 run achieving the Booster design value. The transfer momentum between Booster and AGS was increased from the '93 value of 1.41 GeV (kinetic energy) to 1.56 GeV, which is slightly above the design value. These changes required the Booster Main Magnet Power Supply to run at full voltage. Most of the "dwell" interval between Booster cycles had to be eliminated but cycle-to-cycle injection field reproducibility remained excellent with adjustment of the gain of the "slow" current loop and the addition of a "feed forward" compensation for the first beam cycle. (The Booster runs with a preconditioning "dummy" magnet cycle.) The higher repetition rate reduces the time the beam must survive on the AGS front porch by 200 ms and of course also increases the output per second from the complex. The transfer momentum increase reduces the importance of space charge effects during the 400 ms spent on the AGS accumulation porch but also pushes the fast kicker magnets involved in the transfer between machines to their limits. The field ramp rate at Booster injection was held at the 1993 value (3T/sec). The Linac current has been a very healthy 27 ma. A survey of the Booster magnets just prior to the '94 run indicated that the main dipoles and quadrupoles had developed systematic tilts which were removed. As a result of this work the uncorrected closed orbit excursions were reduced from the rather anomalous 15 mm of '93 to 5 mm.

A further change was a reduction in the harmonic number in Booster from 3 to 2 (and in AGS from 12 to 8). This change gives a more stable machines both by reducing the number of potential transverse and longitudinal instabilities and by lowering demands on the acceleration hardware. The change also opens up the possibility due to existing "heavy ion" cavities in the Booster of a future addition of a 2nd harmonic accelerating potential to lengthen bunches at Booster injection.

The actual Booster setup is still well described by reference 1. The orbit and ramp rate changes required a recorrection of Booster stopbands [2]. The Booster transverse dampers have not yet been required, though at highest intensities there is occasional indication of vertical coherence late in the cycle. Average Booster extraction intensities of greater than 1.5×10^{13} protons per cycle over the four

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

cycle transfer have been achieved along with a single cycle peak of 17.5×10^{13} which is above the design value.

3. AGS

The AGS is the machine where most of the action has been this year with the accelerating rf system, the "very high frequency" (VHF) 92 MHz dilution cavity, and the Gamma-tr jump system the major players. Figure 1 gives one summary of the acceleration cycle. The horizontal axis gives time (200ms/box) during the acceleration cycle. The traces, from the top down, are the AGS intensity, showing the four transfer steps from Booster, a small loss at transition, and the beginning of the ramp down during slow extraction; the AGS magnetic field, with the injection, dilution, and extraction porches; the AGS rf accelerating voltage, with lower levels on the porches and at transition, and finally the voltage on the VHF cavity. Transfer efficiency between Booster and AGS (after the 4th transfer) approaches 90%, with the majority of this loss occurring in the AGS. The four cycle reproducibility, steering, and optics of the beam presented to AGS remain active topics. Early acceleration, transition, and late acceleration inefficiencies are typically 1 or 2 percent. Significant slow losses across the front porch have so far been avoided, perhaps because the bunches are flattened in time, reducing the peak charge.

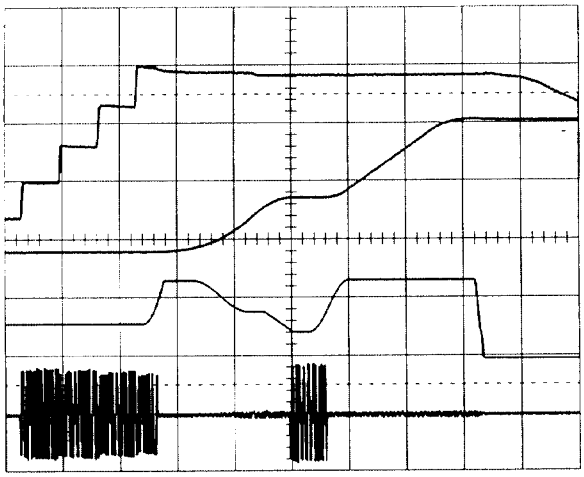

Figure 1. The AGS Acceleration Cycle

A major upgrade of the accelerating rf system has been completed. This work, which is described in these proceedings [3] moved the final power amplifiers for the 10 cavities into the ring coupling them directly with the cavities. A "fast feedback" loop was also implemented. The low level rf system (new last year) continues to evolve. A bunch-shape damper has recently been included in the system which proved essential for efficient transition crossing. It is the existence of the new rf system which has opened the door for exploration of the next intensity limitations.

A likely intensity limiting candidate is beam loss associated with crossing AGS transition energy (8 GeV). In the past transition has been coped with by increasing the longitudinal beam size using the VHF cavity along with assorted rf gymnastics. A system to speed up passage of the beam through the transition region (to "jump") can allow higher intensities. A jump to cope with at least 5×10^{13} had been designed for the AGS in the late 1980's [4] and was commissioned at the start of the '94 run [5].

The Gamma-tr jump system employs six quadrupoles with alternating polarity symmetrically spaced around the AGS lattice. By gradually increasing the currents in these quadrupoles, the AGS transition energy is slowly pushed up from its normal value, by as much as 3 units, and then by "crowbaring" the supplies the transition energy rapidly returns to normal. For each quadrupole the peak current of up to 3 KAmps is diverted to a .7 Ohm resistor by a GTO (gated turn-off) switch. The timing of this "jump" is such that the machine transition energy crosses through the beam energy during the rapid fall and the relative crossing rate for the beam center is increased by a factor of order 30. The system ramps up in about 60 ms and falls in less than one ms. The price paid for the shifting of transition in this way is a reduction in aperture due to the implied distortions in the dispersion and betatron functions. The dispersion evolves from a well behaved function with values of 1.9 +/- .3 Meters to a bipolar function with amplitudes of about 10 Meters. Figure 2 gives an example of this evolution vs time (10 ms/div) at a particular location in the ring - at the Ionization Profile Monitor. The beam horizontal profile is measured at 1 ms intervals, one measurement per acceleration cycle. The dispersion at the IPM reverses sign as the jump distortion grows causing the measured beam width to pass through a minimum (providing measures of both the transverse size and the momentum spread). Also given on the figure is the current wave form in one of the six quadrupoles - which gives the time dependence of the resulting shift in transition energy.

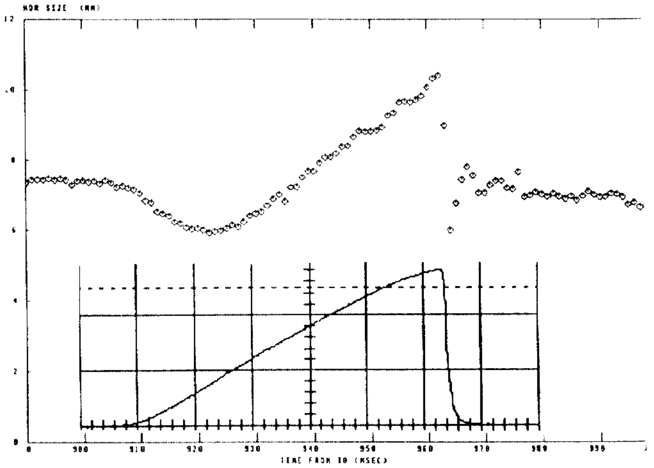

Figure 2. Beam Size Variation due to the Gamma-tr Jump

Because of the large dispersion, and to a lesser extent because the equilibrium orbit is not centered in all of the quads beam loss is very sensitive to the momentum spread and momentum deviation of the beam during this period. This translates into a sensitivity to the longitudinal dilution occurring in the cycle prior to transition, and to the setting of the radial loop reference function during the distortion period - which determines the momentum offset. The jump requires less longitudinal dilution before transition and eliminates the usual longitudinal dilution (blow-up) associated with a slow crossing and so creates a dense beam in longitudinal phase space after transition The resulting beam was not stable across the remainder of the cycle to extraction even at relatively low intensities. The solution to this situation involves the VHF cavity.

The VHF cavity was introduced into the AGS in prebooster days specifically to provide a controlled dilution of longitudinal phase space for transition.[6] The cavity is driven at a multiple of the beam revolution frequency which is then phase modulated at about twice the synchrotron frequency. Further, this frequency is varied slightly in a sawtooth fashion. During the '93 proton run, the cavity was also activated on the AGS injection porch in a fixed frequency mode. The incoming bunches from Booster were intentionally offset from the centers of the AGS buckets.The highly nonlinear interaction between the oscillating bunches and the VHF cavity produced long smooth bunches. This was again the situation in '94 when the Gamma-tr jump was first tried, with too much momentum spread at the jump and too little after. Both problems were solved at least at this intensity by moving the time of the dilution porch from before to just after transition.

A related problem as the jump was ramped up was the occurrence of beam loss at vulnerable points in the ring - in particular at the full aperture ferrite kicker used to bring the injected Booster beam on to the equilibrium orbit. Presumably this loss was associated with the clean-up of momentum tails on the beam at points targeted by the jump distortion. This loss caused equipment-protection motivated beam trips. The activation of the new bunch-shape damper around the transition jumping time removed the problem[3].

4. OTHER DEVELOPMENTS

The betatron tune space of the AGS injection porch was scanned using a low intensity beam. The AGS stopband correction system developed over the years for 200 MeV direct Linac injection remains. It can apply corrections for the two half integer quadrupole lines $2Q_x=17$ and $2Q_y=17$, and the two third order sextupole lines $3Q_x=26$ and $2Q_x+Q_y=26$. These lines were marginally correctable, with the correction dependent on the radial position and the chromaticity correction in effect. No other lines were found to cause significant loss. Further more, the high intensity performance in AGS has not yet been sensitive to the tuning of these lines. The coherent tunes at injection are presently $Q_x=8.86$ and $Q_y=8.88$.

The AGS transverse dampers [7] provide bunch by bunch center-of-mass damping in both planes. The vertical system has been powered throughout the cycle for the present run. While at the moment it is not required its damping effect enlarges the space available for tuning. The most obvious coherence signal associated with the tight passage through transition mentioned above was a vertical coherence presently held off by the late VHF cavity dilution.

The damper can generate from its "diagnostic memory" a turn by turn history of the transverse center-of-mass motion of all 8 bunches for many milliseconds of the cycle. Synchrotron as well as betatron motion for all bunches on a single cycle can be studied. A complementary diagnostic involving digitization throughout an acceleration cycle and retrieval in real time of the longitudinal evolution of a particular bunch has also been commissioned[8]. An example of output from this package can be found in ref 3.

5. CONCLUSIONS and ACKNOWLEDGMENTS

A hard limitation to intensity increase at the AGS complex has not yet been found, but we continue to search. That search involves the entire AGS department. Since the startup of the Booster, substantial blocks of dedicated time have been made available for the commissioning work. That was again true for this run with two months of beam time used, and is crucial to the progress made.

6. REFERENCES

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