HIGH INTENSITY PROTON OPERATIONS AT BROOKHAVEN *

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Abstract

In 1995 the AGS upgrade met its design goal of 60 TP (1 TP = 10^{12} protons) per pulse, made possible by significant improvements in the AGS Booster and AGS. We summarize these improvements and outline strategies for future upgrades.

I. INTRODUCTION

A schematic diagram of the proton accleration complex at Brookhaven is shown in Figure 1. The 200 MeV LINAC produces an average, chopped H^- current of 20 mA which is charge exchange injected for $\sim$ 300 turns into the AGS Booster. The Booster accelerates the protons to a kinetic energy of 1.6 GeV. They are then injected into the AGS via bunch to bucket transfer. This process is repeated four times, filling the AGS ring. The AGS accelerates the protons to a kinetic energy of 24 GeV and they are extracted via the $3Q_H = 26$ sextupole resonance as slowly extracted beam (SEB). While this general scenario has been followed since the Booster began operating in 1992, steady improvements in accelerator technology have resulted in a continual increase in performance [1], [2], [3].

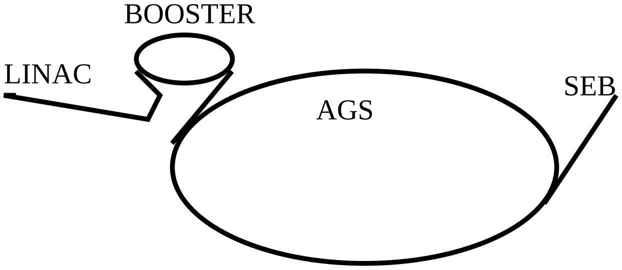

Figure. 1. Schematic of the BNL Proton Acceleration Complex.

II. AGS BOOSTER

In 1994, the AGS Booster repetition rate increased from 5 Hz to 7.5 Hz and the extraction kinetic energy increased from 1.41 GeV to 1.56 GeV. Also, the number of protons per Booster cycle increased from 12 TP to 17 TP which was in excess of the design goal of 15 TP [3]. In 1995 the peak intensity at Booster extraction was 21 TP per cycle. The main magnet current and beam intensity over the four Booster cycles for 1995 operation are shown in Figure 2. This state of affairs was the result of several efforts.

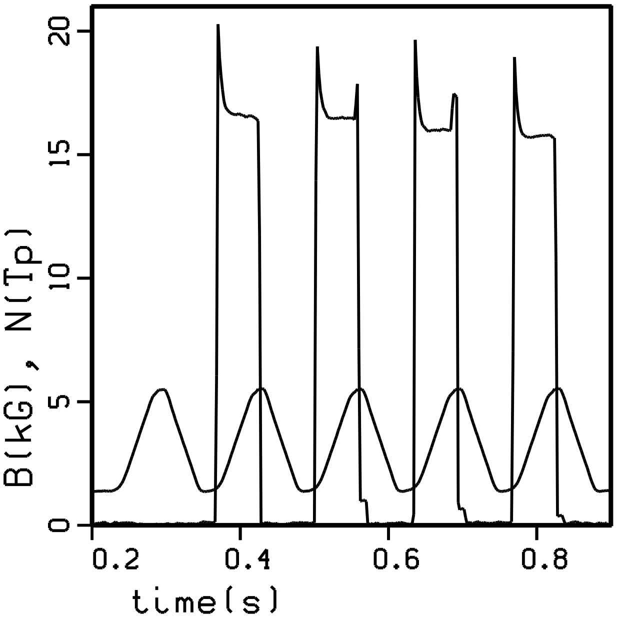

Figure. 2. Booster main magnet field and beam intensity over the four Booster cycles for 1995 operation, the current spikes at the end of the middle cycles are due to a calibration pulse.

In 1994 the harmonic number of the Booster was switched from $h = 3$ to $h = 2$ [4]. This reduced the possibility of coupled bunch longitudinal instabilities along with increasing the total bucket size. In 1995 the reduced frequency allowed the cavities normally used during heavy ion operation to operate at $h = 4$ early in the cycle as a second harmonic component.

In 1995 the magnetic field ramp rate at extraction was reduced from $\dot{B} = 8.7$ T/s to $\dot{B} = 2$ T/s. This allowed more freedom in optimizing longitudinal parameters between Booster and AGS. Stopband corrections appropriate to the new cycle were obtained via a previously derived scaling law [5] and worked well without fine tuning. At injection the vertical tune is just below 5, necessitating careful correction of the 5th harmonic of the vertical closed orbit. The horizontal closed orbit requires careful tuning as well. As the beam is accelerated the orbit corrections are scaled appropriately. In particular the “dump bump”, which moves the horizontal orbit away from the beam dump, is optimized throughout the cycle so that the horizontal aperture is maximized while keeping the majority of the beam loss at the dump. This is particularly important for high intensity operation when about 15% of the beam is lost during acceleration.

After reaching extraction energy the beam is kicked out of the Booster and through the Booster to AGS (BTA) transport line. The line is quite short with only one major bend, which makes it difficult to match the dispersion and its derivative into AGS. When fully matched, the beam size in certain portions of the line becomes unacceptably large. The large beam size is further aggravated by steering fluctuations in the extracted beam from the Booster. Such considerations, and the losses they imply, have required a transfer line with optical parameters that

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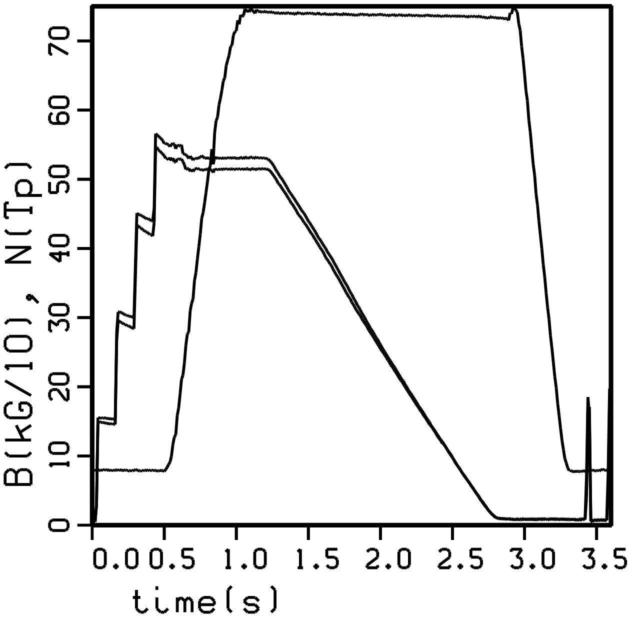

Figure. 3. AGS field and intensity with octupoles on and off.

are mismatched to the AGS. At present the mismatch is not too serious. In fact, the resulting dilution is further enhanced by intentional misteering of the beam at injection to reduce space charge tune spread.

III. AGS

In 1994 the number of protons per cycle surviving to extraction energy increased from 25 TP to a peak of 40 TP. The peak intensity increased to 60 TP in 1995 with intensities of 55 TP typical for normal operations. Figure 3 shows the beam intensity and the main magnet field in AGS for typical 1995 conditions. Several accelerator improvements contributed to this result.

A. AGS Injection Porch

A significant amount of effort has gone toward improving transfer and early survival in the AGS. There are three broad catagories of loss associated with the injection porch: fast losses due to beam oscillations and beam halo scraping in both the transfer line and AGS which occur over the first few turns, intermediate losses that occur over a few milliseconds which are associated with the rise and fall of the injection bump, and slow losses which occur over several tens of milliseconds and are attributed to stopbands. During normal 1995 operations roughly 10% of the beam at extraction energy in the Booster failed to survive for $\gtrsim$10 turns. Intermediate losses, most of which occur after the fourth transfer, are probably due to the imperfect tail-bite on the kicker. Slow losses have been the most insideous in the past and their reduction has been the focus of considerable effort.

To reduce slow stopband losses the beam is longitudinally mismatched between the Booster and AGS and the $h = 8$ rf system is augmented by a higher harmonic dilution cavity ($h \approx 270$) which aids filamentation [3] and increases the emittance. The net result is a bunching factor of $I_{\text{avg}}/I_{\text{peak}} \approx 0.4$ after 20 ms in the AGS [4] though differences in longitudinal emittance among the bunches persist throughout the cycle. We point out that not only a large bunching factor but also adequate momentum spread appear to be necessary for beam survival on the injection porch and that the dilution cavity creates both. Without it the coherent synchrotron tune shift is well beyond the Landau damping threshold and the bunch simply oscillates without filamenting.

The transverse beam size is aperture limited to $\sigma \approx 9$ mm. For 60 TP in the AGS the resulting space charge tune depression is ~ 0.2 on the injection porch. During the 1994 run there was a significant slow loss on the injection porch which was a major intensity limitation. The slow loss was greatly reduced in 1995 due to a combination of factors.

The ten fast ferrite quads used for tune manipulation during polarized proton operations were removed, locally opening the vertical aperture. Along with opening the aperture, replacing the ceramic chambers with metal ones greatly reduced the beam induced signal outside the vacuum pipe and resulted in a quieter electrical environment. Upgrading and repairing the high pass networks between the main magnet vacuum chambers, which allow image currents to pass while reducing eddy currents, helped as well. The broadband impedance of the AGS undoubtedly decreased.

A vertical survey of the AGS during the summer shutdown of 1994 led to repositioning several combined function magnets. The rms orbit excursions decreased significantly in both planes (*e.g.,* due to skew quadrupole) confining the beam to the clean spectral region in the center of the aperture. The resulting orbit was quite good, but losses were then distributed all around the ring, in particular at the ferrite injection kicker. This led to another magnet move after the 1995 startup which created a horizontal orbit distortion so that losses would go into the "catcher", a 6" thick, 7' long water cooled shield around the beam pipe designed to absorb stray beam.

Two normal octupoles were added to the AGS lattice. While these devices were added to allow study of the normal octupole resonances $4Q_H = 35, 4Q_V = 35$ and $2Q_H + 2Q_V = 35$, it was found that empirically optimized settings significantly reduced the slow losses on the AGS injection porch (see Fig 3.) and allowed smaller betatron tunes at injection without increasing losses. Perhaps the optimal settings represent a compromise among the various octupole corrections. However, it has been found that losses on the decapole lines going through $Q_H = Q_V = 8.8$ can be largely corrected by the octupoles, ostensibly due to stabilization coefficients [6]. In any case, the high intensity coherent tunes at injection are $Q_H = 8.85$ and $Q_V = 8.80$, down by ≈ 0.05 from 1994. The lower tunes are favorable for the transverse damper, resulting in more beam surviving to be accelerated than previously achieved. Additionally, the damper algorithm has been modified to employ autoregressive closed orbit subtraction which has resulted in higher gain. However, as the push for intensity with small loss continues it is likely that transverse instabilities will continue to be a prominent issue.

The final improvement, relevant to early survival in the AGS, was a modification of the setpoint function for the main magnet current. The modification was to add a small correction to the setpoint function which tends to cancel residual oscillations associated with the previous cycle. This resulted in a main magnet field which fluctuated by $\lesssim$0.1 G over the injection porch. The net result of these changes led to a peak of 65 TP surviving to be accelerated.

B. Acceleration, Transition and Extraction

Steady improvement in the acceleration phase of the AGS cycle continued. In 1995 the 10 AGS rf power amplifier individual power supplies were available, which reduced beam loading problems and allowed for more rf power [4]. The magnetic ramp rate at transition increased from 1.8 to 2.2 T/s. Fine tuning of the transition jump system which was commisioned in 1994 [7] continued. After the 1995 startup it was found that the closed orbit was not centered through the transition jump quadrupoles, most notably the one closest to the catcher. When the jump was powered the closed orbit distortions led to signficant beam loss. By moving the offending quadrupole the beam was centered through it, allowing a larger emittance and momentum spread through transition than had been achieved before. Even with the transition jump optimized, the beam size increase associated with deforming the dispersion is a major bottleneck in the cycle. The tradeoff between early beam survival and small momentum spread at transition appears to be a fundamental limit.

After transition an upgrade in the dilution cavity power amplifier allows for bunch dilution as the revolution frequency increases. This additional dilution is required to keep the peak current adequately small for the remainder of the cycle and to smooth out “ripples” in the bunches that are probably caused by longitudinal, chromatic nonlinearities [8]. Removing the previously required dilution porch after transition, reduced the time required for acceleration by ~ 0.1 s increasing the average current to the users.

Acceleration to top energy results in a smoothly bunched beam at 24 GeV. The beam is debunched using rf phaseback where the beam is moved to the unstable fixed point of the rf bucket. This results in a faster debunch than when the rf is simply turned off. For debunching, the rf cavities are counterphased at high voltage. Counterphasing, as opposed to cavity voltage reduction, allows better control over the net voltage per turn by keeping the cavities matched to the power amplifiers [4]. Improvements in beam extraction have also taken place. The peak to peak ripple in the extracted beam was reduced by a factor of four due to three efforts. Voltage dividers on the main magnet power supply were improved and their leads were rerouted to reduce noise pickup. A transformer coupled servo supply was added to sense main magnet voltage ripple and reduce it toward zero. Finally a fast, discrete frequency, spill servo was added which fed spill error signals in narrow band harmonics of 60 Hz to the horizontal tune quadrupole supply during the spill.

IV. FUTURE UPGRADES

Several near term upgrades for the AGS are planned. To reduce transverse emittance and slow losses on the injection porch a set of normal octupole correction magnets is planned. When coupled with the normal and skew sextupole corrections currently available, a significant increase (even 50%?) in beam intensity is imaginable. Without an intensity increase it may be possible to reduce the bunching factor and momentum spread early in the cycle which will lead to fewer problems with the beam size increase due to the perturbed dispersion at transition. Additionally, improved optics in the BTA line and a better understanding of AGS apertures will hopefully reduce losses. Given the possibilities of higher intensity and smaller longitudinal emittance, a damper for coupled bunch longitudinal instabilities will be installed.

Over the long term the possibility of employing barrier buckets in the AGS or even building an accumulator ring are being considered. It is likely that the push toward high intensity with low losses will continue until the experimenters are satisfied. With any luck, human nature will not allow that to occur.

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