HIGH INTENSITY PROTON ACCELERATION AT THE BROOKHAVEN AGS - AN UPDATE

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Abstract

The AGS accelerator complex is into its third year of 60+ x10^{12} (teraproton = Tp) per cycle operation. The hardware making up the complex as configured in 1997 is briefly mentioned. The present level of accelerator performance is discussed. This includes beam transfer efficiencies at each step in the acceleration process, i.e. losses; which are a serious issue at this intensity level. Progress made in understanding beam behavior at the Linac-to-Booster (LtB) injection, at the Booster-to-AGS (BtA) transfer as well as across the 450 ms AGS accumulation porch is presented. The state of transition crossing, with the gamma-tr jump is described. Coherent effects including those driven by space charge are important at all of these steps.

1 INTRODUCTION

The Brookhaven National Laboratory's Alternating Gradient Synchrotron (AGS) complex delivers slowly extracted protons at 24 GeV simultaneous into four beam lines with a spill length of 2 seconds in a total cycle time of 3.6 seconds. Over the last several years the available intensity in this mode has increased, from 25 Tp in '93, to 40 Tp in '94, then to just over the design goal of 60 Tp in '95 [1],[2]. During 1996 the total number of protons delivered per hour of running continued to increase, though the peak intensity achieved was unchanged.

Experience from each yearly running period suggests modifications both to the accelerator hardware and to acceleration strategies. Available resources including the time between runs, together with the flexibility of the complex and its control system allow some of these modifications to be implemented. This report summarizes the changes of this sort made prior to the 1997 high intensity proton run and operational experience during this ongoing run as these changes have been implemented.

2 THE RECENT PAST - THE 1996 RUN

Losses during acceleration and at extraction have grown as the intensity has increased but not so fast as to be a constraint on operations until the '96 run. Probably as a result of successful efforts to reduce losses experienced just at AGS extraction in '95, losses further down the extraction lines naturally increased somewhat. This creates a more serious problem to the operation of the machine simply because these losses occur closer to areas where ongoing work must be carried out. As a result efforts to reduce the chronic radiation levels associated with the extracted beam were the primary focus of activity during the 1996 run. These transport losses are dependent on beam handling throughout the acceleration cycle, and in particular with the setup of the four transfer accumulation on the AGS front porch, the passage through transition, and the machine quadrupole and sextupole settings between transition and extraction, as well as on the slow extraction dance itself.

For losses occurring earlier during the acceleration cycle, the sensitive spots are 1) transition crossing, at about 9 GeV, 2) AGS injection, including both losses in the transfer process, and losses incurred as the four Booster batches are accumulated on a magnetic porch and 3) injection from the Linac into the Booster at .2 GeV.

The transition losses, which are potentially serious radiation sources because of the beam energy, usually remained below 4%. Keeping them at this level required continual attention since the transition jump scheme with its inherent distortion of the machine dispersion function sets the machine momentum aperture.

The losses at AGS injection amounted to about 20 Tp, 25% of the beam available in the Booster, and so merited attention because of the associated activation and simply as a potential beam source for increasing the AGS output. The '96 AGS injection beam losses were categorized, from current transformers and the loss monitor arrays which cover all the regions (a new loss monitor system was commissioned in the AGS during the '96 run). A quarter of these loss, perhaps less, occurred in the Booster and in the BtA transfer line. A quarter occurred slowly, while the beam is stored on the porch and well away from the transfers. Progress on reducing this "drool" loss had been made the previous year ('95) by

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powering some "prototype" octupoles in the AGS A modest extension to that system in ‘96 did not further reduce the drool. Sharp "coherence" losses can occur during these storage intervals, and are controlled by vertical betatron tune adjustments in conjunction with the AGS vertical damper. A third quarter of the losses could be seen on the AGS current transformer on a millisecond time scale at each of the four transfers. The remaining quarter was not explicitly accounted for either in the loss monitor or wall monitor analysis. It was most likely occurring in the AGS on a time scale of tens of turns around the machine, too fast for the usual transformer, to subtle each turn for the wall monitor, and ending in ring locations having low sensitivity in the loss monitors. These losses could be space charge driven[3].

The highest loss point, in terms of protons, was at Booster injection. The Linac delivers 35 mA beam current and is capable of maintaining this for pulse widths of 500 usec and so can totally saturate the Booster capacity. In fact the Booster is routinely delivering 22 Tp/ cycle x 4 cycles/ AGS cycle, operating 50% above its "design" intensity of 15 Tp. Space charge driven losses early in the cycle are expected, but pouring more Linac beam in is the obvious source (beside chipping away at losses later in the cycle) for higher AGS output. Losses at Booster injection vary significantly but are typically 30%.

3 CHANGES FOR THE 1997 RUN

Efforts to improve the transport efficiency of the extracted beam came first. By the end of the '96 run measurements of the emittance of the extracted beam had generated Twiss parameters credible enough to encourage a substantial rework of the optics at extraction and down the many transfer lines. The implementation of this optics under the highest intensity operation was the priority activity at the '97 startup and into the run. Instrumentation upgrades to further refine the emittance measurement and to allow quantitative measurements of the tails of the extracted beam were implemented (flags, and scanning targets) [4].

The transition situation, though satisfactory at this intensity was given additional tuning flexibility in that three of the twelve horizontal high field sextupoles in the AGS, the three most effective during the dispersion distortions of the transition jump, were equipped with additional power supplies - allowing them to function beyond their roles as chromaticity sextupoles. The objective is to reduce the expected nonlinear growth of the momentum compaction spread within the beam caused by the basic jump scheme itself [5]. The sextupole set has been powered without ill effects on the beam, and awaits higher intensity and study time.

The orbit correction system in the AGS was redone for the '97 proton run. Though this replacement was required by maintenance issues both for the hardware and controls, the replacement system addressed the fact that the injection momentum has increased four fold from the days of direct Linac injection. Each replacement dipole has 25 times the strength of a dipoles in the old system, the number of magnets is halved. This system allows significant ‘local’ aperture scanning on the AGS injection porch, yielding clean identification (plane and side) for observed losses. By combining several magnets there is sufficient strength to bump the orbit at transition, where millimeter motion at the jump quadrupoles significantly affects the jump induced orbit distortion. The system has been commissioned in these modes and has taking over the basic harmonic orbit correction from the old system.

The attack on the AGS injection porch drool loss continued with the addition of four powerful (4 inch radius, 2 KG pole tip field) octupoles to the AGS lattice. With these, and the four previously existing octupoles, the betatron tune space on the AGS injection porch has been revisited. Using a pencil beam probe, losses intentionally created by slowly sweeping the beam across the normal octupole lines passing through the point where both betatron tunes equal 8.75 were removed. The octupole currents yielding optimal survival in the study are not the currents demanded by the highest intensity machine. The addition of a large ‘zero theta” octupole component is tolerated by the high intensity machine with no immediate effect either beneficial or destructive.

In another response to losses in the AGS at injection, a simplification was introduced into the injection situation. The orbit bump which deforms the equilibrium orbit against the injection septum had always been pulsed (2 ms width) for each of the four transfers. This bump is now held on throughout the injection porch, and then ramped down before acceleration. Having the new static situation allows the residuals from this 3/2 lambda bump to be corrected in a straight forward way (using in part the controls made available by the new orbit correction system), and provides a single orbit across the porch, a single sampling of the fields of the machine for stop band correction.

In the BtA a high loss region and residually hot spot could be associated with a slightly low beam pipe, which was repositioned. The ‘96 loss at this position was sensitive to vertical steering, which was impossible to adjust without affecting AGS survival. By redistributing the available trim dipoles in the BtA transfer line, steering at the tight point and steering into the AGS ring were decoupled. (The original positions of these magnets allowed creating a dog-leg between the Booster and AGS. The shift was never needed due to an early resurvey and local repositioning of the adjacent region of the AGS ring.)

The most interesting change at transfer between Booster and AGS implemented for the '97 run was an increase of the transfer kinetic energy, from 1.54 GeV to 1.91 GeV, an 18% increase in momentum. In conjunction with this change several other variables for the acceleration strategy were also modified, and despite the pedagogical difficulties introduced, all the changes were applied simultaneously, during one four hour study period after a two hour prep session.

Each Booster acceleration cycle was lengthened by one clock tick of the super cycle, 1/60 sec. This allowed time for the Booster to rise to higher fields without forcing the Booster injection process to be fundamentally reworked. (To fit a cycle rising by 18% into the old 7.5Hz constraint, the derivative of the field at injection would have had to be higher or injection moved right to the beginning of the cycle - both interesting but risky choices given the available time). In fact the time increase is sufficient to also give systems such as the ring rf a bit more time to come to a stable starting value each cycle before beam is injected. The highest Booster extraction field occurs as the magnet is about to roll over - namely at a point of zero Bdot. Over the Booster history the extraction Bdot has been decreased from 8T/sec -(full ramp rate at the time) to 2 T/sec for the last two years, and now to zero. Along with allowing the highest momentum transfer, this also allows several other explorations in particular the reduction of the Booster rf gap volts. The Booster and AGS could be longitudinal matched were that desirable.

Of course the injection fields in the AGS had to be scaled up to accommodate the momentum increase. The actual frequency for the rf's and the "synchro" dance providing the clean bunch-to-bucket transfers required the appropriate parameter adjustments, as did the frequency sent to the dilution cavity which is active across the injection porch. The rest of the AGS cycle was unchanged as much as possible, with the exception that the cycle time lost due to the lengthening of the Booster cycles was recovered by a just slightly more enthusiastic acceleration in AGS.

Factors benefitting from the momentum increase include the 8% transverse beam size reduction simply due to the adiabatic shrinkage. The space charge tune shift in the AGS becomes lower due to the higher momentum and also to the extent that the longitudinal match strategy yields lower peak currents in the AGS bunches just after transfers before the dilution cavity can do its work[3]. Possible detrimental results include the obvious need to push the magnetic elements, and in particular the kickers at both ends of the transfer line, 18% harder. In addition, since the transverse phase space occupied by the beam in AGS tends to fill the AGS acceptance, - perhaps by the intentional space charge reducing mismatch during injection, the beam with which AGS extraction will have to cope may be larger.

The latest results from this step in the acceleration is that indeed the loss reported by the loss monitors within the BtA line is gone, and Booster extraction is relatively quiet. The overall beam lost in the transfer process is half that seen last year though the Booster late intensity is also a bit down.

In the Booster, improvements were made to the rf systems. The h = 4 second harmonic cavity system has been improved to allow the system to be active throughout the Booster cycle. A beam "feed forward" system has been introduced, again active throughout the cycle. The "orbit display" which has suffered from the high intensity runs, was brought back to life to allow orbits for the turn on.

4 STATUS AND CONCLUSIONS

The '97 high energy physics run started just six weeks ago but will end just six weeks hence. It is a physics production run; not a setup period. In addition, the sending of the AGS beam by eight fast extractions to the 'g-2' experiment (down the beam line that leads to RHIC) has occurred on a pulse stealing basis for the past three weeks. Study/setup activities typically use twelve hours each week. The changes described here, especially the many facets of the BtA momentum shift, have been applied quickly; and only by using the full capability of the accelerator control system which can keep several different machine setups available with 'pulse-to-pulse modulation'. There has not yet been much 'tuning' time for Operations to exploit the changes, which is ultimately how intensity increases come about. Nevertheless, the performance of the past has been equaled, and the protons/hour delivered this year is the highest yet. Next running period the plan is to commission a barrier bucket system in the AGS which will allow transfer of additional Booster batches into AGS [1], pushing the envelope.

5 ACKNOWLEDGMENTS

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6 REFERENCES

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