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HIGH INTENSITY PERFORMANCE OF THE BROOKHAVEN AGS*

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Abstract

Experiences and results from recent high intensity proton running periods of the Brookhaven AGS, during which a record intensity for a proton synchrotron of 6.3×10^{13} protons/pulse was reached, is presented. This high beam intensity allowed for the simultaneous operation of three high precision rare kaon decay experiments. The record beam intensities were achieved after the 1.5 GeV Booster was commissioned and a transition jump system, a powerful transverse damper, and an rf upgrade in the AGS were completed. Recently even higher intensity proton synchrotrons are studied for neutron spallation sources or proton driver for a muon collider. Implications of the experiences from the AGS to these proposals and also possible future upgrades for the AGS are discussed.

1 RECENT AGS HIGH INTENSITY PERFORMANCE

The proton beam intensity in the AGS has increased steadily over the 35 year existence of the AGS, but the most dramatic increase occurred over the last couple of years with the addition of the new AGS Booster[1]. In Fig. 1 the history of the AGS intensity improvements is shown and the major upgrades are indicated. The AGS Booster has one quarter the circumference of the AGS and therefore allows four Booster beam pulses to be stacked in the AGS at an injection energy of 1.5 GeV. At this increased energy, space charge forces are much reduced and this in turn allows for the dramatic increase in the AGS beam intensity.

The beam intensity in the Booster surpassed the design goal of 1.5×10^{13} protons per pulse already to reach a peak value of 2.3×10^{13} protons per pulse. This was achieved by very carefully correcting all the important nonlinear orbit resonances especially at the injection energy of 200 MeV, where the space charge tune shift reaches about 0.3, and also by using the extra set of rf cavities that were installed for heavy ion operation as a second harmonic rf system. A second harmonic system allows for the creation of a flattened rf bucket which gives longer bunches with lower space charge forces.

The AGS itself also had to be upgraded to be able to cope with the higher beam intensity. During beam injection from the Booster, which cycles with a repetition rate of 7.5 Hz, the AGS needs to store the already transferred beam bunches for about 0.4 seconds. During this time the beam is exposed to the strong image forces from the vacuum chamber which causes beam loss from coupled bunch beam instabilities within as short a time as a few hundred revolutions. A very powerful feedback system was installed that senses any transverse movement of the beam and compensates with a correcting kick. This transverse damper can deliver ±160 V to a pair of 50 Ω, one-meter-long strip-lines.

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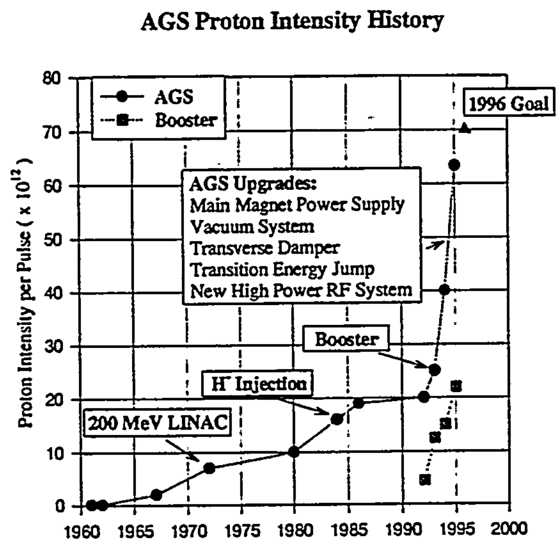

Figure 1: The history of the evolution of the proton beam intensity in the Brookhaven AGS.

The incoherent tune shift at the AGS injection energy is about 0.1 and this makes it necessary to correct in particular the octupole stopband resonances to avoid excessive beam loss. To reduce the space charge forces further the beam bunches in the AGS are lengthened by purposely mismatching the bunch-to-bucket transfer from the Booster and then smooth the bunch distribution using a high frequency 100 MHz dilution cavity. The resulting reduction of the peak current helps both with coupled bunch instabilities and stopband beam losses.

New more powerful rf power amplifiers were build and installed immediately next to the ten rf cavities. This was needed to deliver to the beam the necessary 400 kW power during acceleration and also to counteract the very large beam loading effects in the rf cavities from the high intensity beam.

During acceleration the AGS beam has to pass through the transition energy after which the revolution time of higher energy protons becomes longer than for the lower energy protons. This potentially unstable point during the acceleration cycle was crossed very quickly with a new powerful transition energy jump system with only minimal losses even at the highest intensities. However at energies higher than transition, a very rapid, high frequency instability developed which could only be avoided by purposely further increasing the bunch length using again the high frequency dilution cavity.

The peak beam intensity reached at the AGS extraction energy of $24\,GeV$ was 6.3×10^{13} protons per pulse also exceeding the design goal for this latest round of intensity upgrades. It also represents a world record beam intensity for a proton synchrotron. The bunch area is about 4 eVs each for the eight bunches which represents a very high longitudinal brightness of $2 \times 10^{12}\ protons/eVs$. The corresponding number for the Booster, before all the dilution in the AGS, is about $1 \times 10^{13}\ protons/eVs$. With a 1.6 second slow-extracted beam spill the average extracted beam current was about $3\,\mu A$. This level of performance was reached quite consistently during the last year's and the present AGS experimental runs of a total of 36 weeks during which a total of 1.7×10^{20} protons were accelerated in the AGS to the extraction energy of $24\,GeV$.

At maximum beam intensity about 30 percent of the beam is lost at Booster injection (200 MeV), 25 percent during the transfer from Booster to AGS (1.5 GeV), which includes losses during the 0.4 second storage time in the AGS, and about 2 percent is lost at transition (8 GeV). Although activation levels are quite high all machines can still be manually maintained and repaired in a safe manner.

2 POSSIBLE FUTURE AGS INTENSITY UPGRADES

The present transition jump system, although very effective, requires large distortions of the dispersion functions which increases the maximum dispersion value five times over the regular value of 2.2 m[2]. This large value severely reduces the available momentum aperture and is a dominant limitation to further intensity increases. If locations with zero dispersion are available a jump in transition energy can be accomplished more easily since it is then possible to change the dispersion only locally and compensate the resulting betatron tune shift at the zero dispersion location[3]. This scheme works well in new lattices and is planned for RHIC and the Fermilab Main Injector. The same scheme could also be used in the AGS if a zero dispersion location is created prior to transition crossing with a one-wave-length dispersion distortion. The maximum dispersion value is then only about doubled possibly allowing to reduce beam losses and further increase the beam intensity.

Currently the number of Booster beam pulses that can be accumulated in the AGS is limited to four by the fact that the circumference of the AGS is four times the circumference of the Booster. This limits the maximum beam intensity in the AGS to four times the maximum Booster intensity which itself is limited to about 2.5×10^{13} protons per pulse by the space charge forces at Booster injection. To overcome this limitation some sort of stacking would have to be used in the AGS. The most promising scheme is stacking in the time domain. To accomplish this a cavity that produces isolated rf buckets can be used to maintain a partially debunched beam in the AGS and still leave an empty gap for filling in additional Booster beam pulses. The stacking scheme is illustrated in Fig. 2. It makes use of two isolated rf buckets to control the width of this gap. Isolated bucket cavities, also called Barrier Bucket cavities, have been used elsewhere[4]. However, for this stacking scheme, a much higher rf voltage would be needed. An additional important advantage of this scheme is that while the beam is partially debunched in the AGS the beam density and therefore space charge forces are reduce by up to a factor of two. A successful test of this scheme has recently been completed[5].

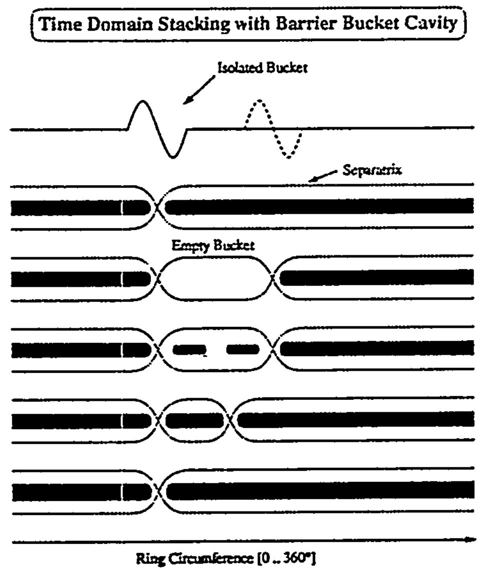

Figure 2: Time domain stacking scheme using a barrier bucket cavity. The evolution of the longitudinal beam structure during the stacking process are shown from top to bottom.

As more Booster beam pulses are accumulated in the AGS the reduction in the overall duty cycle becomes more significant. For fast-extracted beam operation (FEB) the accumulation of four Booster pulses contributes already significantly to the overall cycle time. With the addition of a 1.5 GeV accumulator ring in the AGS tunnel, shown in Fig. 3, this overhead time could be completely avoided. Such a ring could be build rather inexpensively using low field magnets. Fig. 3 shows the possible running scenarios with an accumulator and a barrier cavity.

The maximum repetition rate of the Linac and Booster is 10 Hz. Since the circumference of the AGS is four times that of the Booster a repetition rate of 2.5 Hz would maintain a throughput of 40 μA through the whole accelerator chain. Such an increase of the AGS repetition rate by a factor of 2.5 could be achieved by an upgrade of the AGS main magnet power supply only. The resulting beam power of 1 MW at 25 GeV corresponds to the required proton driver performance needed for a demonstration muon collider project[6].

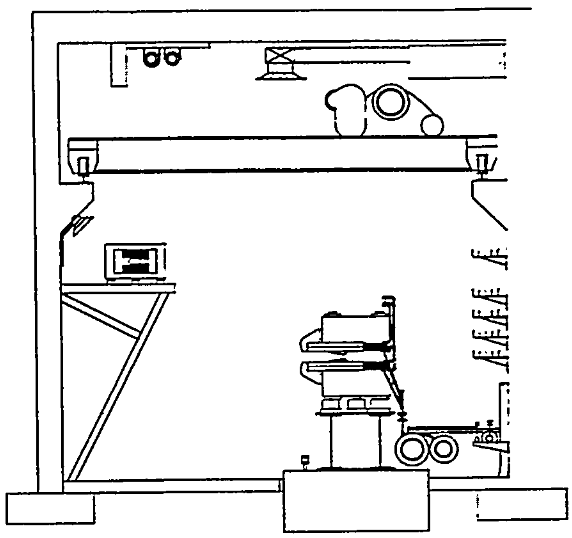

Figure 3: The location of the 1.5 GeV accumulator in the AGS tunnel is shown. The low field combined function magnets are shown on the left side of the tunnel cross section vertically displaced with respect to the AGS.

Table 1: Expected beam intensity parameters for the various AGS upgrade options discussed in the text for slow-extracted beam (SEB) and fast-extracted beam (FEB) operation.

	Protons per AGS pulse	Average extracted beam current / power SEB(1 s spill)	FEB
Present Performance	6.3×10^{13}	3 μA/ 75 kW	6 μA/150 kW
AGS + Barrier Bucket	15×10^{13}	7 μA/175 kW	11 μA/275 kW
AGS +Bar. Bucket + Accumulator	15×10^{13}	12 μA/300 kW	24 μA/600 kW
2.5 Hz AGS + Accumulator	10×10^{13}		40 μA/1 MW

3 CONCLUSIONS

With the era of the Relativistic Heavy Ion Collider (RHIC) approaching at Brookhaven the AGS will need to serve as an injector for RHIC delivering high brightness Gold and polarized proton beams. However, due to the 10 hour beam storage time in RHIC the AGS is available for about 80 % of the time for multi-GeV slow and fast extracted beams. With modest upgrades of the AGS its current high intensity performance could be greatly improved and would open up the possibility for a next round of high precision experiments and applications such as target testing for future high power spallation neutron sources and a proton driver for a demonstration muon collider.

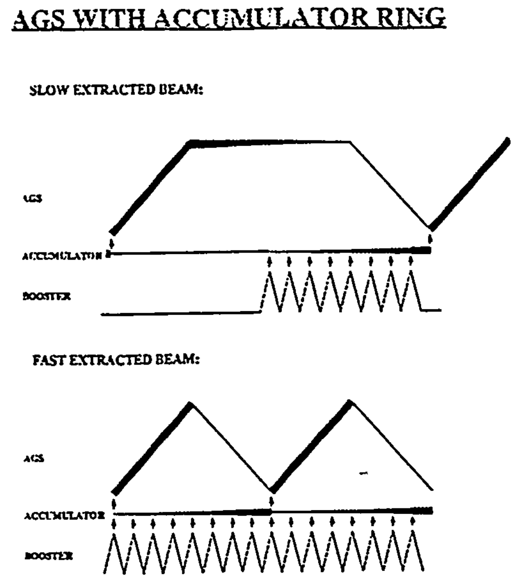

Figure 4: A 1.5 GeV accumulator in the AGS tunnel can be used for both slow-extracted beam (SEB) and fast-extracted beam (FEB) to improve the machine duty cycle. Operation scenarios for these two modes are shown with the thickness of the line indicating the beam intensity.

4 AKNOWLEDGEMENT

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