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PERFORMANCE and MEASUREMENTS OF THE AGS and BOOSTER BEAMS*

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Abstract. In May 1995, the AGS reached its upgrade intensity goal of 6×10^{13} ppp, the highest world intensity record for a proton synchrotron on a single pulse basis. At the same time, the Booster reached 2.2×10^{13} ppp surpassing the design goal of 1.5×10^{13} ppp due to the introduction of second harmonic cavity during injection. The critical accelerator manipulations, such as resonance stopband corrections, second harmonics cavity, direct rf feedback, gamma-transition jump, longitudinal phase space dilution, and transverse instability damping, will be described as well as some beam measurements. Possible future intensity and brightness upgrades will also be reported.

INTRODUCTION

The achievable intensity in a proton synchrotron is limited by many accelerator physics reasons. Most notable and widely discussed is the incoherent space charge tune shift during injection (1,2). Due to the strong energy dependence of the amount of tune shift caused by the space charge force, raising injection energy can alleviate this limiting effect. Empirically, it has been shown both at the AGS Booster and the CERN PS Booster(3,4) that resonance stopband correction is effective in limiting the growth of betatron oscillations and hence retaining more particles inside the synchrotron under large space charge tune shifts. However, there are many possible mechanisms also playing a very important role in limiting the achievable intensity of a proton synchrotron. First, is the available horizontal aperture to accommodate the beam for its maximum momentum spread, usually occurring during injection or gamma-transition. Secondly, the beam loading effect from the beam on the accelerating cavity. If the current is such that the resultant accelerating bucket is insufficient to contain the beam, feedforward or feedback corrections have to be applied to raise the intensity. Thirdly, the transverse coupled bunch instability due to the resistive wall effect tends to occur on the order of a few 10^{12} ppp for proton synchrotrons in the few GeV range. Once an effective damping system is in place, this limitation can be easily eliminated. Fourthly, the loss introduced by the transition energy crossing, which can cause particle loss by a large momentum spread, large

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dispersion function or exciting coherent instabilities. The fifth category includes the single bunch instabilities, such as microwave, head-tail, or mode-coupling instabilities.

There is no telling, a priori, that which of the above-mentioned limiting factors will come first to limit the achievable intensity of a given accelerator. Only careful calculations and machine studies can reveal the relative importance of each mechanism. In the following, we will use the AGS as a prototypical example to show specific effects of some of the factors mentioned above and methods introduced to combat them.

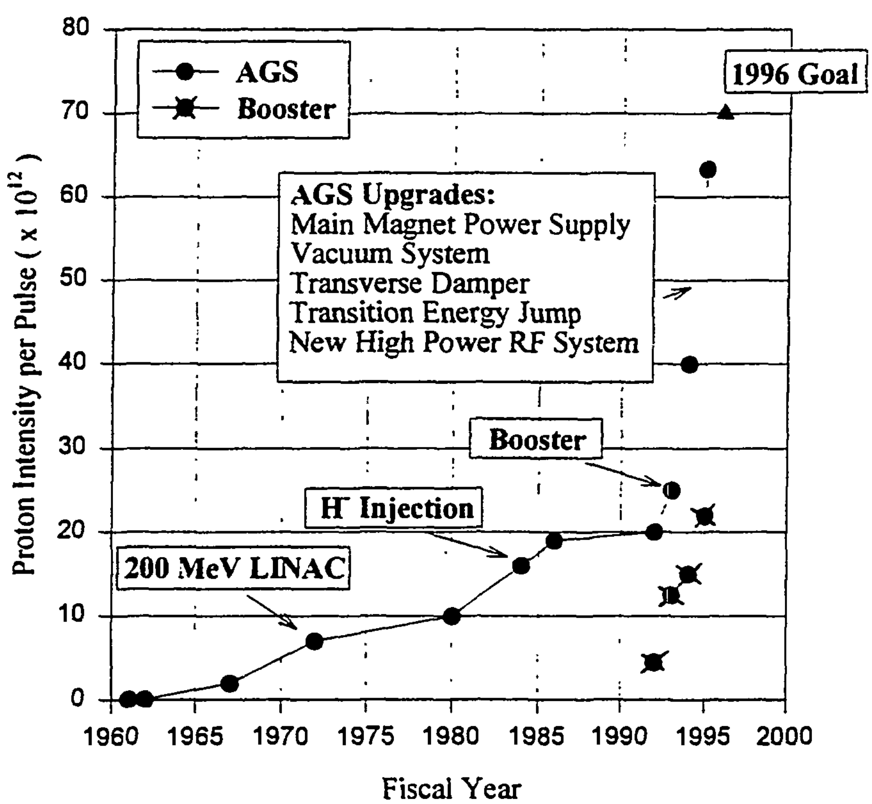


Figure 1. The evolution of the AGS proton intensity.

Shown in Figure 1 is the intensity evolution of the AGS since its completion in 1961. The accelerator was originally proposed with an intensity of a few 10^9 ppp in mind and it eventually reached 6.3×10^{13} ppp in 1995. Major improvements in the intensity record are summarized briefly in the following chronology.

Year	Parameters or Improvements	Intensity
1970	50 MeV Linac injector Space charge limited at Injection ($\Delta\nu_y \approx 0.3$)	3×10^{12}
1976	200 MeV Linac injector Resonance stopband correctors Transverse damper	10^{13}
1990	H^- injection Rf feedforward compensation $\Delta\nu_y \approx 0.7$	1.6×10^{13}
1995	1.5 GeV Booster injection Resonance stopband correctors Direct rf feedback γ-transition jump $\Delta\nu_y \approx 0.35$	6.3×10^{13}

It is clear that raising the injection energy is the most effective way to increase the achievable intensity for a space-charge limited low energy proton synchrotron. It is also clear that many accelerator physics manipulations have to come into play to keep all those particles inside the synchrotron. In the following we will describe some of those processes introduced in the AGS and Booster. A brief description of how the Booster and AGS are linked together in both proton and heavy ion operations, can be found in Reference 5. To assist the readers and facilitate the discussion, some of the relevant accelerator parameters are summarized below.

	Booster	AGS
Circumference, m	201.78	807.12
Injection energy, GeV	0.2	1.5
Extraction energy, GeV	1.5	28.0
ν_x / ν_y	4.82/4.83	8.7/8.8
x_p, m	2.9	2.2
γ_{tr}	4.5	8.5
Harmonic number, h	3(2)	12(8)
RF voltage, kV	90	400
Intensity, 10^{13} ppp	2.2	6.3
Estimated tune shift, $\Delta\nu_y$	0.35	0.25

CRITICAL PHYSICS PROCESSES

A. Resonance Stopband Corrections

The Booster working points are chosen to be about $\nu_x = 4.85$ and $\nu_y = 4.90$ at injection and the estimated space charge tune shift at full intensity is about $\Delta\nu_x = 0.25$ and $\Delta\nu_y = 0.35$. At high intensity, the tune of some of the particles can cross $2\nu_x = 9$, $2\nu_y = 9$, $\nu_x - \nu_y = 0$, $\nu_x + \nu_y = 9$, $3\nu_x = 14$, $3\nu_y = 14$, $\nu_x + 2\nu_y = 14$, $2\nu_x + \nu_y = 14$ lines. Examples of particle losses due to some resonance lines and the survival of beam after correction are shown in Figure 2 (3).

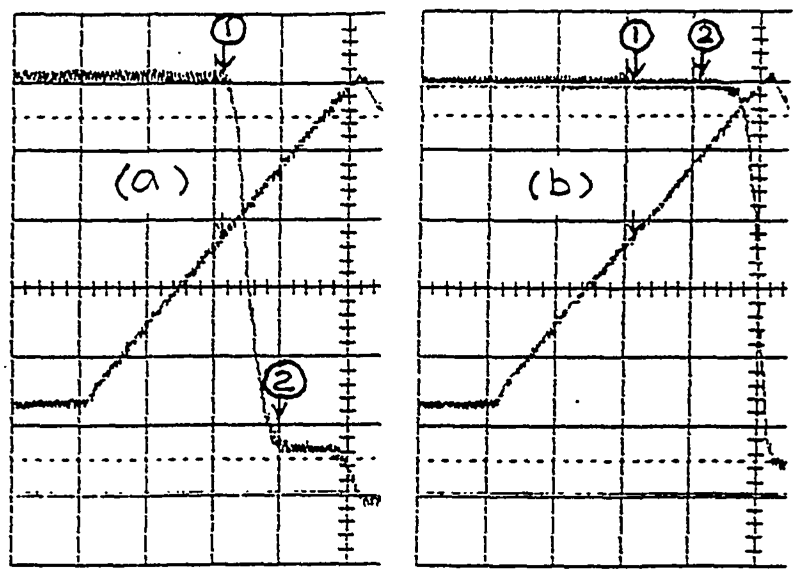


Figure 2. Stopband correction: (a) without correction and (b) with correction, (1) $2\nu_x = 0$ and (2) $\nu_x + \nu_y = 9$.

The left trace shows the beam intensity decrease when it encounters the first resonance of $2\nu_x = 9$ and further decreases when it encounters the second resonance $\nu_x + \nu_y = 9$. The right trace shows that the total beam intensity is almost constant in crossing those two resonances after the correction system is turned on. The same process is repeated for all the resonances listed above. Such a correction study is carried out at flattop by varying the tune. During acceleration, with or without correction, this can make a 5-10% difference for weak resonances and a 30-50% difference for strong resonances. Shown in Figure 3 is the comparison with and without stopband correction of the full beam intensity over the acceleration cycle. During 1995 running, it was discovered that octupole correction was needed for the AGS during injection. The effect of the octupole correction is shown in Figure 4.

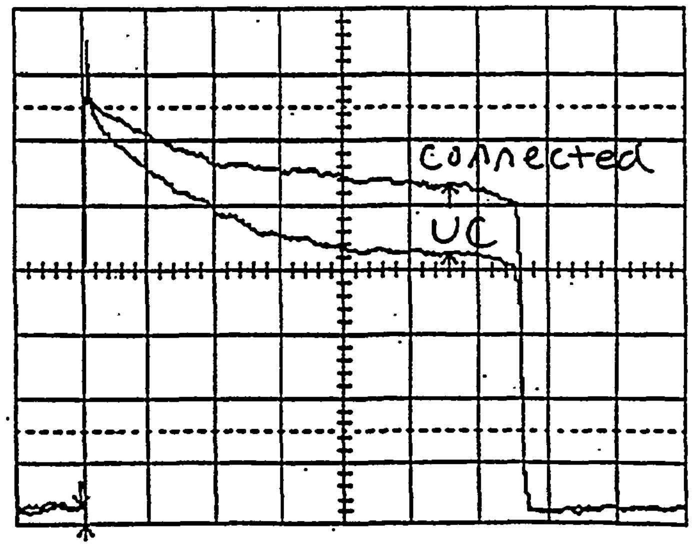


Figure 3. Booster intensity in one cycle with or without stopband corrections.

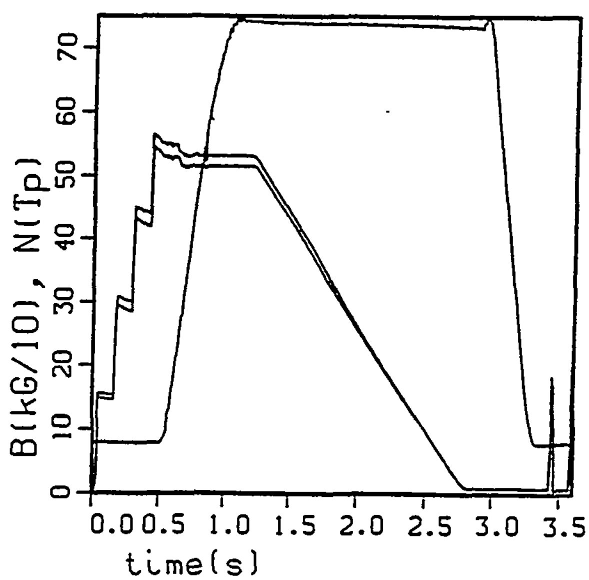


Figure 4. AGS intensity with and without octupole corrections.

B. Second Harmonic Cavity

If the accelerating rf system has only one and the same frequency, the resultant rf bucket usually assumes a parabolic shape with the maximum around the synchronous phase angle. The final charge distribution tends to have a sharp maximum in the middle and hence a larger space charge force.

Along with the main rf system, an additional second harmonic cavity can also be added, so that the voltage can be described as

$$V = \frac{e}{2\pi h} V_o[Sin\phi + rSin2(\phi - \delta)],$$

where V_0 is the first amplitude, r = r(t) is a second amplitude (as a fraction of V_0), $\delta = \delta(t)$ is a phase shift of the second harmonic with respect to the first harmonic.

The reason for the large space charge tune shift at capture is due to the charge inhomogeneity resulting from the single rf system. By judiciously choosing ϕ_s, r, and δ the charge distribution in the vicinity of ϕs can be made to be uniform, hence, reducing the bunching factor and space charge force. Thus, the relative deviation in the capture efficiency for the double system compared to the single system will be within the strip between the two curves $\delta\ell$ and δA in Figure 5. In other words, the capture efficiency of the double rf system should be better than that of the single rf system by about 20-30% (6).

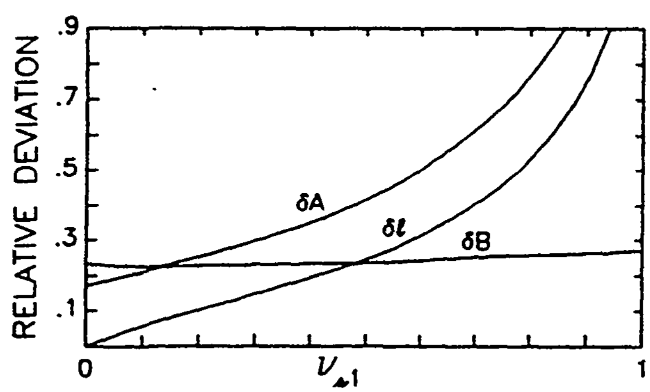


Figure 5. Relative deviations in bucket length, area and bunching factor.

The actual double voltage shape and resultant charge distribution in the AGS Booster is shown in Figure 6 (7), where the lower trace represents the rf waveform and the upper trace represents the beam current. It is clear that with a double rf system, the resultant current distribution is smoother in the middle. Such a second harmonic cavity raised the final intensity in the Booster from 1.5 x 10^{13} ppp in 1994 to 2.2 x 10^{13} ppp in 1995.

(a)

(b)

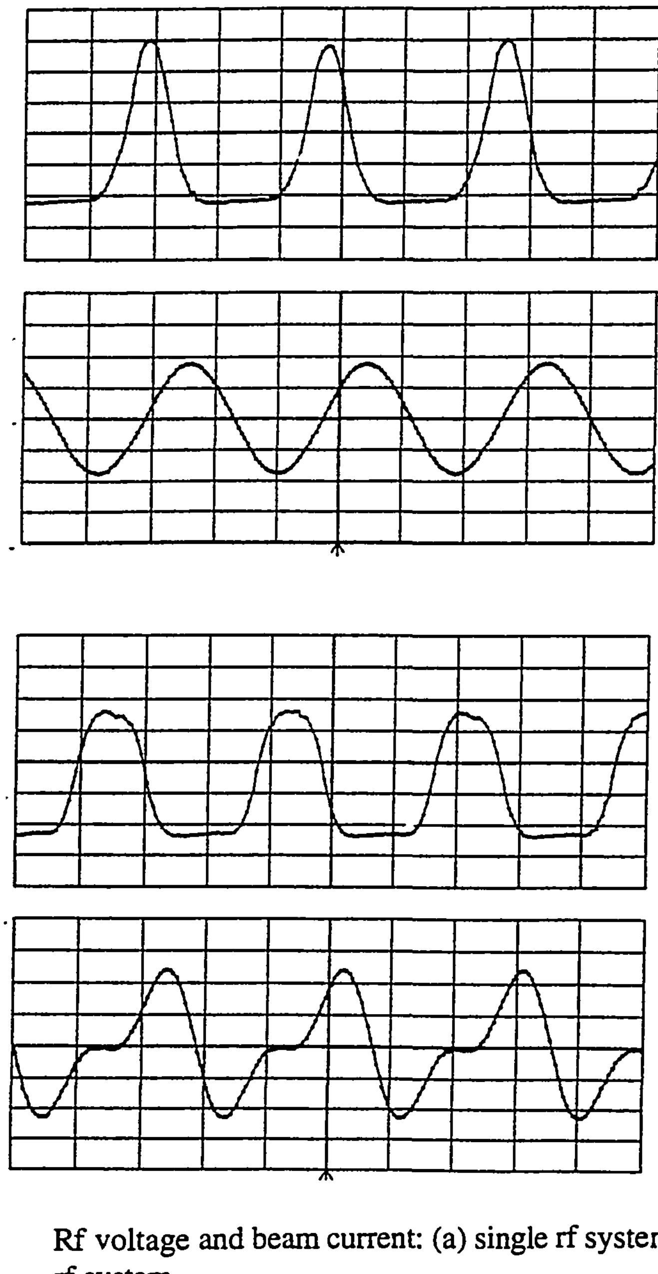
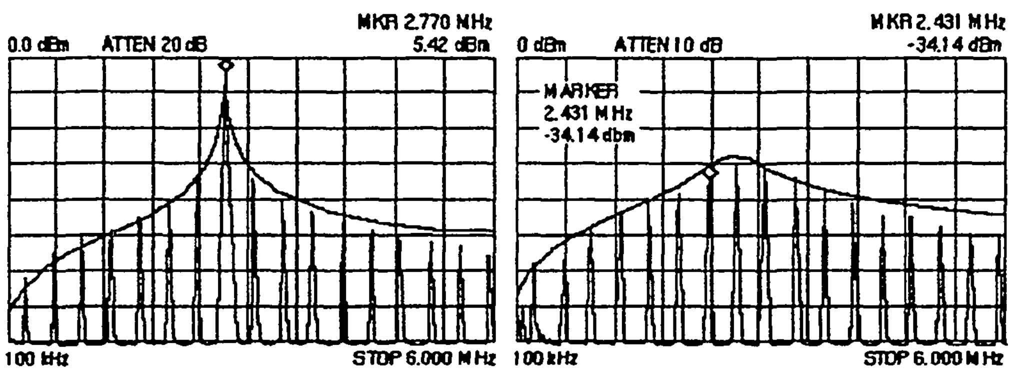


Figure 6. Rf voltage and beam current: (a) single rf system, (b) double rf system.

C. Direct RF Feedback

At injection into the AGS, the cavities are operated at 1.5 kV/gap, which requires 0.5 A of current from the power amplifier, (I_o). At 6 x 10^{13} ppp the rf beam current, (I_B), is 6.0 A, implying a beam loading parameter, I_B/I_o, of 12. It has been shown (8, 9) that when the beam loading parameter becomes greater than 2, the beam control loops, tuning, AVC, and phase, are cross-coupled and become unstable. RF feedback is needed to reduce the effective beam loading parameter. Feedback reduces the perturbations of the gap voltage by the value of the loop gain, and the beam current, seen from the control loops, is effectively reduced. Loop gains of 17 dB and greater (depending on the operating point of the tetrode) are used to reduce the beam loading parameter to less than 1.7 (10).

RF feedback does not reduce the impedance of the cavity but it does reduce the impedance that the beam "sees". It also reduces the beam intensity that the beam loops "see". To measure the effectiveness of the feedback the cavity was stimulated with beam of wide spectral content by using a single bunch, kept short by the other cavities. The short bunch makes spectral lines of almost constant amplitude over the first 17 revolution harmonics. The cavity is tuned to the eighth harmonic with the power amplifier off and shows a characteristic resonance response with a Q of 50 in Figure 7a. In Figure 7b, the power amplifier and the rf feedback have reduced the Q to 5, which is consistent with the feedback loop gain. These results agree well with low-level network analyzer measurements, but are more rigorous in that they stimulate the cavity directly at the gap with beam and are done at high level. At 25 MHZ, the beam signal is down by 20 dB, but is still useful in showing that the higher order modes on the busbars have been effectively damped (10).



(a) (b)

Figure 7. Cavity impedance measurements: (a) cavity voltage with amplifier off and (b) cavity voltage with amplifier and rf feedback on.

Without such a direct feedback system, the beam loading effect will limit the achievable AGS intensity to about 2.5 x 10^{13} ppp.

D. Longitudinal Phase Space Dilution

Right after injection, the proton beam suffers longitudinal coupled bunch instabilities when the intensity exceeds 2 x 10^{13} in the AGS. The growth rate and mode of excitation depend strongly on the intensity and the initial injection errors from the Booster. The way we elect to combat the instabilities is to use the existing VHF cavity, operating at 93 to 100 MHZ, to create a controlled blowup of the longitudinal emittance of the beam. Once the space charge density is reduced, the beam stays stable during the 600 msec period of injection. Since those bunches injected earlier experience a longer time of dilution, the emittance will be larger than later bunches. The mountain range display of bunches inside the AGS from injection time to top energy is shown in Figure 8.

Another time the bunch dilution system is used is right after transition. At this time, the bunch length is the shortest, and the space charge effect is most severe. A strong transverse single bunch instability develops right after transition. Again, the VHF cavity is activated to blow up the longitudinal emittance to reduce the space charge effect and hence alleviate the violent beam blowup as shown in Figure 8.

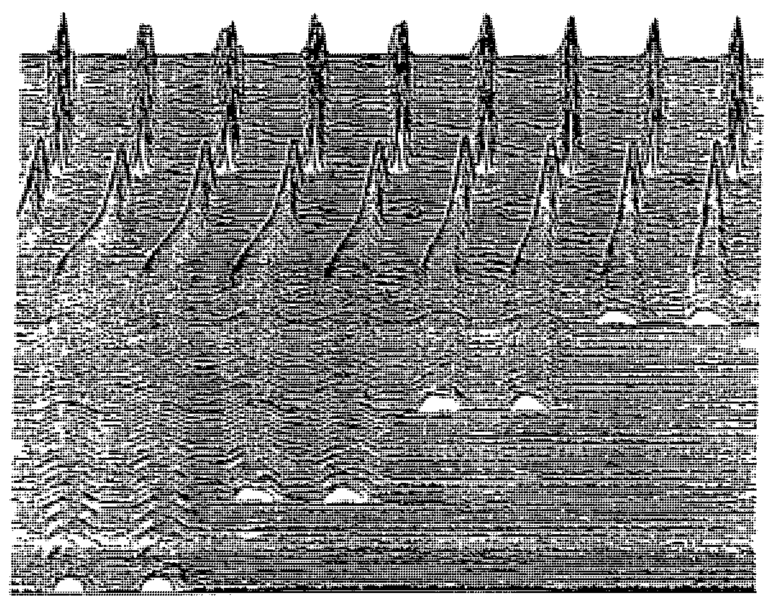


Figure 8. AGS bunch dilution from injection to beyond transition.

E. Gamma-Transition Jump

At an intensity of approximately 1.5 x 10^{13} protons per pulse, AGS beam losses at transition are less than 5%. However, as improvement plans are implemented and the intensity is increased to 6 x 10^{13} protons per pulse, new mechanisms will become important and the losses will increase. A gamma-transition jump system has been built, minimizing these losses by speeding up passage through transition. It follows the work of Werner Hardt (11) at CERN.

Part of the work involves minimizing losses at transition caused by the negative mass instability. Pulsed quadrupole doublets are used to speed up passage through transition. Existing magnets separated by 3/2 betatron wavelength appear adequate for the purpose. Computer modeling has been carried out to determine the rise time and strength of the quadrupoles.

Hardt's idea, which has been implemented at the CERN PS, was based on the observation that quadrupole pairs separated by ½ betatron wavelength and configured as doublets can alter γ_t of a synchrotron without affecting its tune. By arranging to cross transition while γ_t is rapidly decreasing, the bunch area blowup caused by the negative mass instability can be substantially reduced. The criterion for no blowup due to negative mass instability is shown in Figure 9 (12). Here the attainable AGS intensity is plotted as a function of bunch area for several crossing speed enhancement factors, f'.

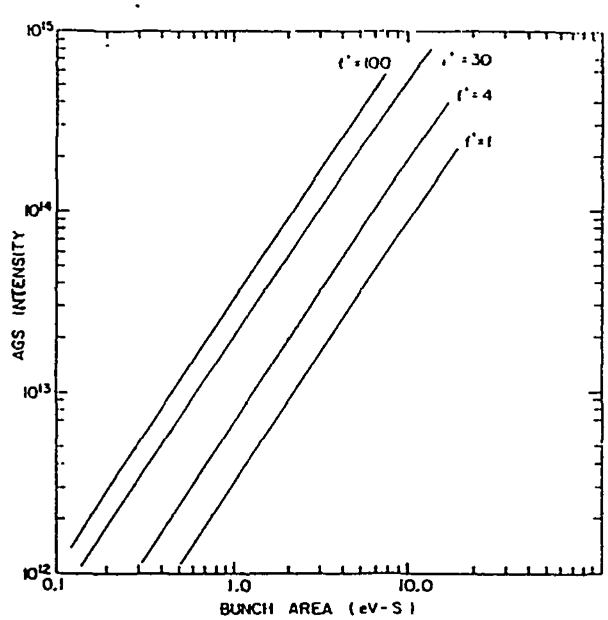
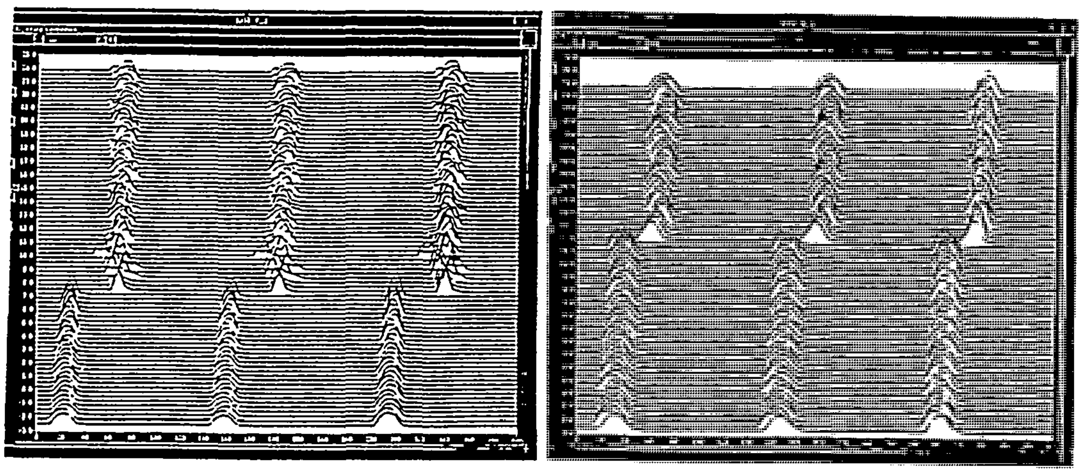


Figure 9. AGS intensity for lossless transition as a function of bunch area and crossing speed enhancement factor, f'.

As can be seen from Figure 9, to pass through transition at 6 x 10^{13} ppp without appreciable loss requires $f' \approx 30$ with bunch area about 2.0 eV-sec, which is conveniently satisfied by the VHF cavity after injection. The effect on AGS bunches with or without γ_{tr}-jump can be seen in Figure 10 (13).



(a) (b)

Figure 10. Bunch shape before and after phase transition: (a) without gamma-transition jump and (b) with gamma-transition jump.

Currently, the AGS still suffers beam losses at transition crossing. This is partially due to the fact that the present gamma-transition jump system does not preserve the dispersion function. In fact, it even increases the dispersion function from 2 m to about 6 m. During transition crossing, the momentum spread is much larger and hence the horizontal beam size due to the dispersion function. An improved system with acceptable dispersion function increase is under investigation for future operations. Another reason for the beam loss during transition in the past is the shrinkage of the rf bucket due to severe beam loading, which has been improved with direct rf feedback.

F. Transverse Coupled-Bunch Instability and Its Damping

It has been estimated that the threshold for transverse coupled bunch instability excited by the resistive wall is at about 4-5 10^{12} ppp. A damper system has been constructed to damp such an instability when it occurs. In Figure 11, the upper trace is the position signal of the vertical orbit and the lower trace is the current of the beam. When the instability occurs, about 60% of the beam is lost. The suppression of coherent motion had been tried successfully by the transverse damper system. The actual threshold of vertical instability has been found to be about 7 x 10^{12} ppp, when $\upsilon_x = 4.94$ and $\xi_x = -0.25$, which can be avoided by adjusting the tune and chromaticity of the machine. Active damping is necessary when the beam intensity is larger than 10^{13} ppp (14). By supplying a constant amplitude of damping, instead of proportional to the oscillation, the power requirement of the damping system can be reduced by a factor of four. The effectiveness of the constant amplitude method has also been tested in the Tevatron.

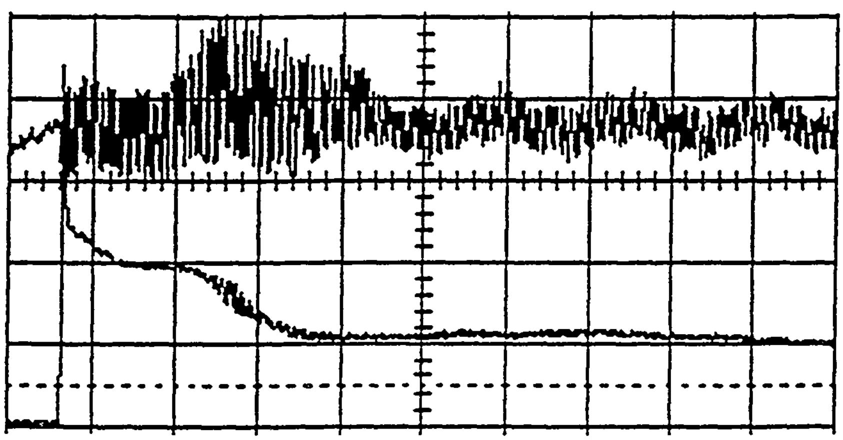


Figure 11. Signal of transverse instability and intensity.

FUTURE IMPROVEMENTS

A. Stopband Corrections

During 1995 operations, it was found that octupole corrections were needed during the injection process in the AGS. At that time, only two octupoles were available. A more complete correction system with 8 octupoles will be installed for future operations. Out of the 16 sextupoles used for stopband corrections in the past, some were found to develop shorts in the coil winding. These will be repaired and put back in service.

B. New Gamma-Transition Jump Configuration

As mentioned above, the present gamma-transition jump system induces a dispersion increase which in turn limits the horizontal aperture available. A new configuration without undue dispersion increase will be implemented for further intensity increases.

C. Barrier Cavity

During the 1994 and 1995 proton runs, a slow loss observed on the AGS injection porch severely limited the number of protons that could in principle be accelerated. This loss was drastically reduced when the rf was turned off and, to a lesser extent, when the bunch length was increased. A barrier cavity system in the AGS might increase the intensity by avoiding bunched beam operation during injection. This method is discussed in more detail in this Workshop by M. Blaskiewicz (15).

D. AGS Accumulator Ring

To further increase the intensity in the AGS to beyond 10^{14} ppp, an accumulator ring inside the AGS tunnel is needed. Currently, the AGS accepts only 4 pulses from the Booster, which can be operated at 7.5 Hz. If an accumulator can be employed to accept beam continuously without interruption during 1.2-2.5 sec of the AGS cycle times, 2-3 times more beam can be accumulated and delivered into the AGS ring every cycle.

E. Emittance Preservation and Particle Loss Control

So far we have only focused on the attainment of high intensity in the AGS with little regard to the preservation of emittance or particle losses. A better understanding of the critical physics processes can lead to improvement of those two problems. Particle loss is important for current high intensity synchrotrons, such as: AGS, ISIS, and PSR. These accelerators run at a few percent loss during one cycle, which is barely tolerable from the personnel safety and component protection point of view. In all discussions of the next generation pulsed neutron source, a few parts in 10^4 efficiency is required to keep the total particle losses comparable to today's practice.

Preservation of emittance is important for injection into colliders, such as: RHIC, LHC, and the Tevatron. More theoretical exploration, computer simulation, and machine studies are required to improve the understanding of the fundamental physics processes involving space charge effects and achieve design goals for these colliders.

ACKNOWLEDGMENTS

The work discussed in this report has been performed collectively by the accelerator staff in the AGS Department over the past several years.

REFERENCES

1. L.J. Laslett, On Intensity Limitations Imposed by Transverse Space-charge Effects in Circular Particle Accelerators, Proc. 1963 Summer Study on Storage Rings, Accelerators and Experimentation at Super-high Energies, BNL Report 7534, 324-67.

2. W.T. Weng, Space Charge Effects--Tune Shifts and Resonances, in Physics of Particle Accelerators, Ed. M. Mont, AIP Conf. Proc. 154 (AIP, New York, 1987).

3. C. Gardner, et al., Observation of Correction of Resonance Stopbands in the AGS Booster, Proc. 1993 PAC, p. 3633.

4. J. Gareyte, et al., Beam Dynamics Experiments in the PS Booster, Proc. 1975 PAC, p. 1855.

5. W.T. Weng, Operation of the Brookhaven AGS with the Booster, Proc. 1993 PAC, p. 3726.

6. J.M. Kats and W.T. Weng, Effects of the Second Harmonic Cavity on RF Capture and Transition Crossing, Proc. XVth Int. Conf. on High Energy Accelerators, Hamburg, Germany, July 20-24, 1992, p. 1052.

7. J.M. Brennan, private communication, BNL, 1995.

8. F. Pedersen, Beam Loading Effects in the CERN PS Booster, IEEE Trans. Nucl. Sci., NS-22, 1975, p. 1906.

9. D. Boussard, Design of a Ring RF System, Proc. CERN School on RF Engineering, p. 474, Oxford, England, April 1991.

10. J.M. Brennan, The Upgraded RF system for the AGS and High Intensity Proton Beams, Proc. 1995 PAC.

11. W. Hardt, Gamma Transition-jump Scheme of the CPS, Proc. Ninth Intl. Conf. on High Energy Part. Accel., p. 434, Stanford, 1974.

12. P. Yamin, et al., A Fast Transition Jump Scheme at the Brookhaven AGS, Proc. 1987 IEEE PAC, p. 1216.

13. W.K. van Asselt, et al., The Transition Jump System for the AGS, Proc. 1995 PAC.

14. D. Russo, M. Brennan, M. Meth, T. Roser, Results from the AGS Booster Transverse Damper, Proc. 1993 PAC, p. 2286.

15. M. Blaskiewicz, Barrier Cavity Longitudinal Dynamics, these proceedings.