Commissioning the New High Power RF System for the AGS with High Intensity Beam*

J.M. Brennan, D.J. Ciardullo, D-P Deng, T. Hayes,
E. Onillon, A. Otis, R.T. Sanders, A. Zaltsman

AGS Department, Brookhaven National Laboratory
Upton, New York 11973-5000 USA

Abstract

A new high power rf system has been installed in the AGS in order to raise the beam loading limit to beyond 6 x 10^{13} protons per pulse. The old system was limited to 2.2 x 10^{13} ppp by: available real power, multi-loop instability, and transient beam loading during batch filling from the Booster. The key components of the new system are: new power amplifiers in the tunnel using the Thomson-CSF TH573 300kW tetrode, rf feedback around the power stage, and reduction of the 10 cavities' R/Q by 1.8 by additional gap capacitors. Commissioning of the new rf system with high intensity beam is described. The intensity goal for the 1994 running period is 4 x 10^{13} ppp. To date, 3.7 x 10^{13} ppp has been achieved.

1. INTRODUCTION

The High Energy Physics program at the AGS demands the highest possible beam intensities. The recent completion of the 1.5 GeV Booster has raised the space charge limit by a factor of four. To accelerate high intensity, a new rf system has been built[1]. It includes new power amplifiers and a new beam control system. The 10 rf cavities have been refurbished to couple tightly to the new amplifiers, to have lower R/Q, and to suppress higher order mode resonances.

This report describes the hardware of the new rf system and some of the challenges of its commissioning. First operation with high intensity beam is also described. Two basic types of problems need to be overcome at high intensity. One type is the stability of the rf system itself, which is determined by its beam impedance. This has been measured directly with beam induced signals. The other type problem is the stability of the beam at high intensity. The rf system is operated in such a way to minimize the peak charge density in the beam (long bunches) which mitigates the de-stabilizing self-forces of the beam. Strategies for making long bunches are described.

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2. NEW HARDWARE

Power Amplifier

The high power tetrode was chosen because it provides the real power necessary for acceleration (75 kW), the reactive current (60 A peak) needed for the non-compensated cavity transient at transition, and a relatively low plate resistance to load the cavity. Each tetrode drives one of 10 cavity stations which comprise four ferrite-loaded cells connected in parallel and dynamically tuned from 1.6 to 4.5 MHz. The tube is coupled to the cavity by a line that links one of the ferrite (4L2) stacks and crosses a gap. This implements a 1:1 balun function and converts the single-ended anode voltage to the push-pull voltage on the acceleration gap with no change of impedance. Referred to a single gap, the plate resistance of the tube is multiplied by four.

Each power amplifier has its own 12 kV, 30 A dc power supply. The ac power line transformers which feed these rectifiers failed in the first few weeks of operation. They were all returned to the manufacturer for re-design. Fortunately, the dc supply for the original rf system was still available. This is a single 8.8 kV 400 A unit. It was reconfigured to supply the new power amplifiers by isolating each tetrode via 40 Ω series resistors, thereby enabling the crowbar circuits of the rectifiers to function. The commissioning and physics program proceeded, but with reduced rf accelerating voltage (7 kV/gap instead of 10 kV/gap).

R/Q

Transient beam loading is important in the AGS because it is batch-filled and operates with a partially filled ring at high beam current. The R/Q governs the transient beam loading behavior. A low R/Q implies a large stored energy for a given voltage and a relatively smaller perturbation by the bunch charge. Lowering R/Q for this type of lumped-element cavity is straightforward: increase the capacitor at the gap. Two difficulties arose here. One, the larger capacitors lowered the frequencies of the higher order modes, which then had to be damped (see ref. 1). Two, these are high current and voltage vacuum capacitors and although rated at 20 kV, about 20% have failed at 7 kV.

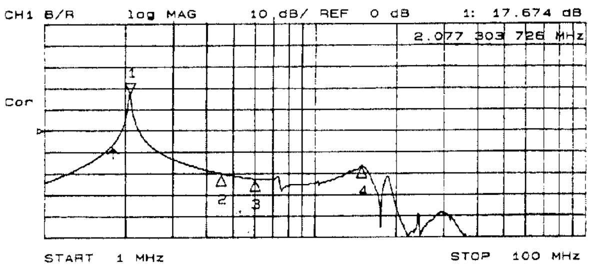

Fig. 1. Open loop frequency response, rf feedback system.

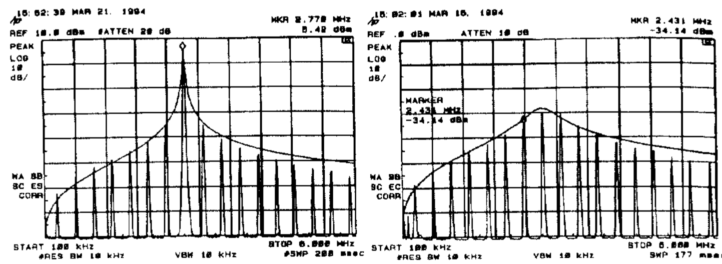
Fig. 3. Spectra of beam induced voltage on: bare cavity (left), cavity with power amplifier with rf feedback (right). Curves are calculated impedance for Q = 120, and 5.

RF feedback

RF feedback lowers the effective impedance of the cavities by the loop gain.[2] Without it, these cavities would reach a beam loading parameter (ratio of beam current to generator current) of one at 2 x 10^{13} ppp. Beyond this, multiloop instabilities could occur.[3] The maximum loop gain for stability is limited by delay around the loop. A much lower limit applies if one requires that the rf feedback does not increase the cavity impedance at adjacent revolution harmonics. For this system there is no increase (peaking) of the impedance for gains below 19 dB. Figure 1 shows that loop stability alone would allow more than 30 dB. The gain has been set conservatively at 17 dB.

Three fast protection devices prevent runaway output power in the event of voltage breakdown in the cavity or failure of the feedback pick-up or summing junction: 1. over-voltage on the control grid of the tetrode, 2. a window comparator about the reference signal for the AVC loop, 3. a fast crowbar circuit in the anode power supply.

3. MEASUREMENTS WITH BEAM

The transient response of the cavity reveals its R/Q. Figure 2 shows the response of the first bunch passage for cavities with and without feedback. While the long-term responses are quite different, since they depend on the R and Q separately, the transient portions are the same because R/Q is the same. By modeling the bunch profile as a half sinewave, one finds R/Q = 81 Ω gives the measured response. This value is consistent with 600 pF loading capacitors and 110 pF structure capacitance in the cavities.

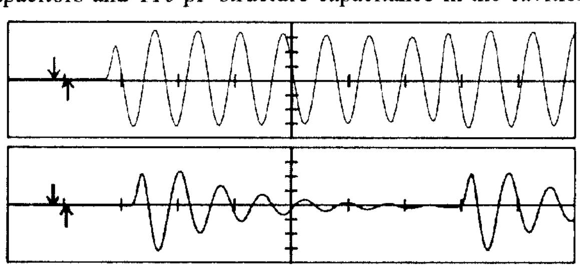
Fig. 2. Induced voltage on two cavities by first passage of a single bunch, without (top) and with (bottom) feedback.

The beam impedance was measured by stimulating a cavity with a single short bunch of 2 x 10^{12} protons and recording the induced voltage at the acceleration gap. The single bunch provided a wide frequency spectrum of drive current. The bunch was kept short by nine of the cavities while the one undriven cavity was measured. Two spectrum analyzers were triggered simultaneously to measure the beam and cavity signals. A 120 ns bunch gave a beam current spectrum of discrete lines spaced at 344 kHz. The amplitude of the beam current was down by only 3 dB at twice the rf frequency. The cavity tuning servo was locked to the phase between a filtered beam pick-up and the gap voltage. Figure 3 shows spectra of the cavity voltage under two conditions: power amplifier off, and amplifier and rf feedback system operating. Table 1 lists the impedances found for various values of the quiescent anode current in the tetrode with rf feedback off and with feedback on at 5 A. From the change of impedance with anode current, one finds the dynamic anode resistance as a function of quiescent current, which agrees well with estimates from the tubes constant-current characteristics.

Table 1

Anode Current, A	Impedance kΩ	Tetrode Output Resistance, kΩ
0.0	8.8	--
2.5	3.7	1.6
5.0	3.4	1.4
7.0	3.1	1.3
10.0	2.9	1.0
5.0	0.4	feedback on

From these values of impedance, one obtains the beam loading vector diagram of figure 4 for the situation at transition at 3 x 10^{13} ppp and 4 kV/gap (conventions follow ref. 3). The diagram predicts a transient in the loading angle of 53°, which settles to zero in about 2 ms as the tuning servo compensates the cavity. Figure 4 also shows measured transients in loading angle, with a 48° step, and the tuning current, equivalent to a 120° change in impedance angle.

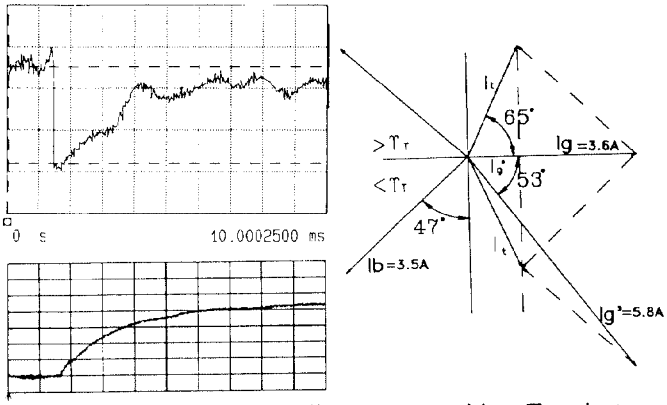

Fig. 4. Beam loading vector diagram at transition. Transients in loading angle (top, 20°/div), and tuning current (bottom, 10 A/div = 30°/div impedance angle), 10 ms full scale.

4. STRATEGIES FOR HIGH INTENSITY

The key to beam stability is long bunches. We have made the bunches as long as possible by: a. reducing the harmonic number from 12 to 8, b. mismatching the bunch to the Booster buckets before transfer, c. increasing the longitudinal emittance via controlled blow-up with a high-harmonic cavity, d. a fast transition gamma jump system which was commissioned in this run[4].

The Booster fills the AGS in four batches. The first batch of two bunches is stored for 400 ms before acceleration starts. To reduce the space charge tune shift the bunches are made long in two steps. First in the Booster, just before transfer, the coherent quadrupole mode is driven by a square wave amplitude modulation of the rf voltage. With about 20% modulation the mode grows very fast and after three synchrotron periods (1 ms) the bunch length has increased by 30 to 50%, depending on the longitudinal emittance. The bunches are transferred when they are longest. This technique enables bunch shape manipulation in the moving bucket ($\varphi_s=20°$) at high rf voltage.

By injecting the bunches off-center into the AGS buckets they are made longer again. With the phase loop open, a coherent dipole synchrotron oscillation is begun. Cappi et al[5] have shown that if such a dipole oscillation occurs in the presence of a much higher (x30) harmonic voltage then the resulting filamentation process leads to a smooth and flattopped bunch profile. The 92 MHz cavity used for emittance blow up is now also used to provide 20 kV for this flattopping operation. The main difficulty in using this technique is to treat all four batches equally. The phase loop is closed after the dipole signal damps by decoherence. When the second batch arrives, the phase loop would force the average dipole error to zero, and, thereby, imposes a new dipole oscillation on the first batch. The result would be each batch having a different emittance. The problem is solved by a bunch-by-bunch gate of the phase detector for the phase loop. The new batch is not included in the phase measurement until the coherent dipole signal damps. At high intensity, the decoherence can take a long time. In fact, without the 92 MHz cavity the dipole signal does not damp at all. This is the reason for making the bunches long in the Booster before injection. Figure 5 shows the evolution of the bunches throughout the injection process. No longitudinal coupled bunch instabilities have been observed.

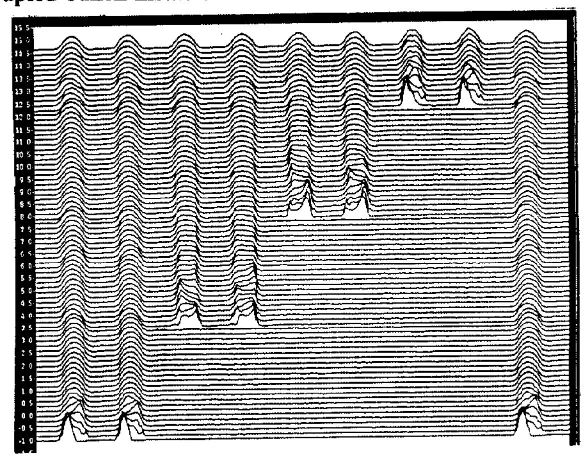

Fig. 5. Mountain range display of bunch flattopping at injection, 8 ms per trace, 3.4 μs full scale horizontal.

The new gamma jump facility is essential for lossless transition crossing at high intensity. With it the bunches do not get shorter than 60 ns, compared to 30 ns without it. Using the jump puts some constraint on the maximum longitudinal emittance, however. Because the jump process increases the machine dispersion by a factor of five, the momentum aperture can be exceeded if the full bucket area is used. In fact, the rf voltage is reduced to 50% when the gamma jump operates in order to reduce the momentum spread. The vector diagram of figure 4 applies to the reduced voltage situation. Furthermore, it is important to prevent longitudinal emittance growth before transition. To this end, it is necessary to damp a coherent (n=0) quadrupole oscillation that occurs when twice the synchrotron frequency crosses the main magnet power supply ripple frequency at 720 Hz.

5. CONCLUSION

The new rf system has enabled the AGS to achieve record intensities and after the repair of the dc power supplies will be ready for the goal of 6 x 10^{13} ppp.

6. REFERENCES

[1] J. M. Brennan, et al. Proc. of the 1993 IEEE Particle Accelerator Conference, Vol 2,p. 1241, Washington DC
[2] F.Pedersen, IEEE Trans. Nuc. Sci. NS-32, 1985, p2138.
[3] D. Boussard, Proc. CERN School on RF Engineering, Oxford, England, April 1991.
[4] L.A. Ahrens, et al. these proceedings
[5] R. Cappi, et al. Proc. of the 1993 IEEE Particle Conference, Vol 5, p. 3570, Washington DC