The Upgrade Project for the RF System for the Brookhaven AGS*

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I. INTRODUCTION

The AGS operates a varied program of proton, heavy ion, and polarized proton acceleration for fixed-target experiments and will soon serve as the injector of these beams into the Relativistic Heavy Ion Collider, RHIC[1]. The new Booster synchrotron[2] extends the range of intensities and masses that can be accelerated. The 1.5 GeV injection energy increases the space charge limit by a factor of four to more than 6 x 10^{13} protons per pulse. To accommodate the increased beam current the rf system will be upgraded to provide more power and lower impedance to the beam. The flexibility of the rf system will also be enhanced by virtue of a new rf beam control system[3] and installation of individual tuning servos for the ten rf cavities.

The fundamental necessity for upgrading the rf system is to deliver more power to the accelerating beam. At 6 x 10^{13} ppp the power demand will peak at 740 kW. The present ten power amplifiers can produce 40 kW each. Moreover, stability of the beam and the rf system in this heavily beam-loaded regime demand that the effective impedance of the cavities be reduced. The intrinsic impedance of the cavities (given mostly by losses in the ferrites) is about 16 kΩ which implies a generator current at 20 kV (midrange) of 1.25 A. At full intensity with short bunches the beam current will reach 7.2 A, giving a beam loading parameter[4] of Y=5.8. An impedance reduction of at least a factor of three is called for in order to avoid multi-loop instabilities[5]. An additional requirement also applies. Since the AGS is batch-filled by four injections from the Booster it must operate with a partially filled ring and transient beam loading effects are important[6]. Transient beam loading is a broadband phenomenon and therefore determined not by the impedance of the cavity but by its R/Q.

Three key ingredients of the upgrade project address these requirements; 1. new power amplifiers provide the necessary power, and are closely coupled to the cavities, 2. wideband rf feedback reduces the effective impedance by a factor of 10, 3. the capacitors loading the acceleration gaps (four per cavity) are increased from 275 pF to 600 pF. Including 130 pF of intrinsic capacitance the stored energy is increased and the R/Q decreased by a factor of 1.8. This is the practical limit of additional loading capacitance because of Q-loss phenomena in the ferrites at high bias fields.

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II. POWER AMPLIFIER

The Upgrade Power Amplifier uses the Thomson-CSF TH573 300kW power tetrode in a single-ended grounded cathode configuration. The choice of tube was based on many factors of which the current and power handling capabilities required at phase transition were the most important. Other factors in the choice included conservative rating for long life and a low plate resistance.

At phase transition the load is reactive and the operating line for the tube is elliptical. Because of this, plate dissipation at phase transition will be typically 200kW with a peak plate current of 125 amperes. During the acceleration cycle, at maximum beam intensity, the average plate current will range from 24 to 33 amperes. At maximum acceleration the anticipated plate dissipation will be 100kW and the peak plate current will be nominally 80 amperes. Combined power output, cavity losses plus beam loading, will be as high 200kW. The power tube is biased so that it operates in an AB1 mode. The operating parameters are as follows:

Plate voltage..................12kVdc
Screen voltage ....1500 Vdc
Grid bias......................-370 Vdc
Quiescent cathode current......5.0 amperes
RF plate voltage(maximum)......10kV peak

The cavity impedance is lowered by the low dynamic plate resistance (unusual for a tetrode, about 500 Ω at full drive) which is coupled to the gap by a 1:1 balun.

The required drive for full output is less than 300 Volts peak rf, thus the control grid never is driven into the positive region. The power amplifier is packaged in an all aluminum enclosure and located at the cavity for close coupling. All controls and associated power equipment and circuitry are located outside the tunnel.

III. RF FEEDBACK

The proximity of the power amplifier to the cavity allows the implementation of wideband rf feedback. Although the feedback does not change the demands made on the power amplifier, it does change profoundly the beam loading interaction. In essence, the voltage induced by the beam (within the bandwidth of the feedback) and therefore the effective beam loading parameter are reduced by the open-loop feedback gain. The gain, however, is limited by time delay around the loop which reduces the phase margin. Low phase margin causes the closed-loop impedance to increase with respect the open-loop value away from the cavity resonance. This effect can reduce the threshold for multi-bunch instabilities[7]. This system achieves 20 dB gain with a time delay of 80 ns and less than 3 dB of impedance increase. Figure 1 shows a block diagram of the system. $G_3(s)$ represents the cavity, G_2 the power amplifier, H is a broadband voltage divider measuring the gap voltage, and $G_1(s)$ is the feedback amplifier. The magnitudes of the gains at resonance are indicated.

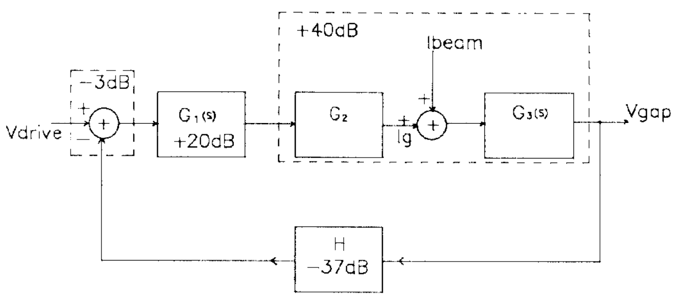

Figure 1. Block diagram of rf feedback servo system.

The feedback amplifier, $G_1(s)$, is also a closed-loop system. It must drive the power tube control grid (950 pF) to 300 Volts peak with a minimum of phase shift. A tunable inductance in parallel with the grid makes the grid impedance real. The inductor is tuned via an open-loop program based on a measurement of the rf drive frequency, which may vary from 1.7 to 4.5 MHz. The Q of this tuned circuit should not be high because then the accuracy of the tuning program would have to be high. The Q is set to <5 by a 200 Ω power attenuator connected to the grid. This attenuator (-20dB) serves as the feedback element for the local loop. Using a 200 Ω load proved superior to transformer matching a 50 Ω load because the transformer led to spurious resonances at high frequency. The inductor is an autotransformer of eight turns wound on two 125 mm o.d. toroids of 4M2 ferrite with 54 x 31 mm cross section. The open loop gain to the 200 Ω load is 46 dB, achieved with two stages of four EIMAC 4CX350 tetrodes in parallel. Radiation hardness precluded solid state devices. Figure 2 shows the feedback amplifier circuit.

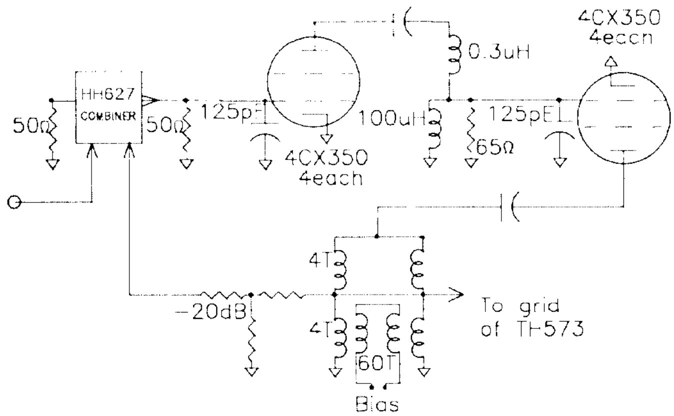

Figure 2. Feedback amplifier and tuned transformer

The interstage network is optimized for minimum open loop group delay since the local feedback has wide bandwidth. Commercial hybrid transformers, ANZAC HH627, are used for the summing junction to close the feedback loop with 23 dB loop gain. Figure 3 shows the open and closed loop frequency response and group delay of the feedback amplifier. At the resonance frequency of the transformer the closed loop group delay is 50 ns.

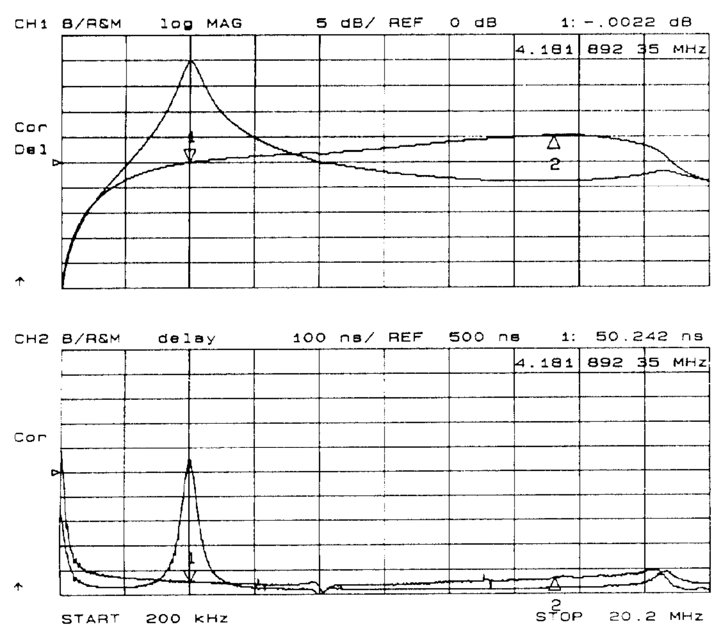

Figure 3. Feedback amp., freq. response and group delay

The loop around the cavity is closed by sensing the voltage at one of the gaps with a capacitor voltage divider of -37 dB and summing with the cavity drive signal via another sum and difference hybrid (developed and produced in-house for this application). The gain from the grid of the power tube to the acceleration gap is 40 dB so that the loop gain around the cavity is 20 dB and 200 W of drive power is required for 10kV per gap, ie: 400 kV per turn. Figure 4 is a measurement of the open and closed loop frequency response of the cavity loop.

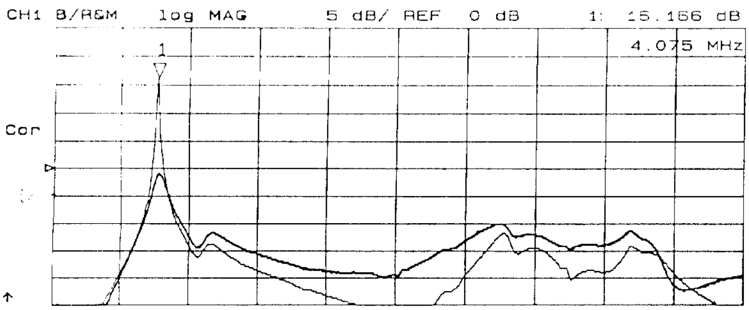

Figure 4. The open and closed response of the cavity loop. The frequency axis is linear, 1 to 21 MHz.

IV. HIGHER MODES IN THE CAVITY

Although the feedback system is intended to have gain only within $\pm$ 0.5 MHz of the cavity resonance, higher order responses of the cavity were seen to cause four spurious peaks in the loop gain between 12 and 25 MHz, all potentially unstable. See Figure 5. The responses are caused by spurious inductances of the cavity assembly. The cavity comprises four cells of ferrite loaded push-pull resonators connected in parallel by three pair of heavy copper bus bars, which also carry the ferrite bias current (1200 A). The gaps of the resonators are loaded with 600 pF capacitors. Since the combined length of the bus bars is 2.5 m, they and the capacitors form standing wave resonances in this band. The coupling line between the power amplifier and the cavity is of comparable length, forming a system of four coupled modes.

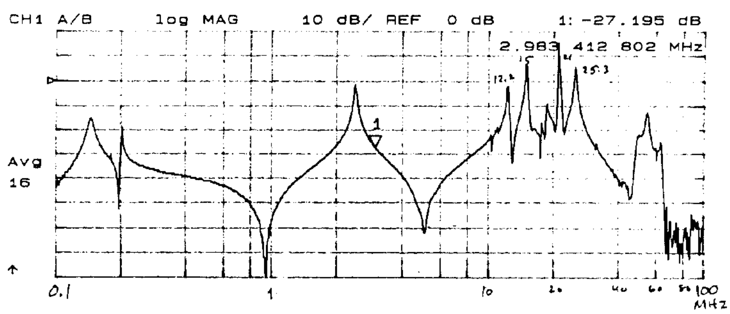

Figure 5. Higher order modes due to cavity bus bars.

It was possible to effectively damp the higher order modes by modifications to the bus bar arrangement. Fortunately the cavities were built with four leadout connections per gap, an inside and outside lead both upstream and downstream. By adding bus bars to the inside, as well as the outside leads, the inductances were cut in half. Furthermore, the 600 pF of loading capacitance was installed symmetrically inside and outside the gaps, increasing the frequencies of the bus bar modes. The then higher frequency modes could be damped by installing 40 Ω, 25 mm diameter by 600 mm power resistors in parallel with the bus bars. The mode due to the line between the power tube and the cavity remained. The effect of this mode on the rf feedback was greatly reduced by taking the feedback from the gap itself, as apposed to the anode of the power tube.

V. BEAM TEST

A prototype of the power amplifier and the rf feedback was tested in the AGS ring. A single, low longitudinal emittance, bunch was accelerated to 1.2 GeV in the Booster and injected into the AGS ring with the rf on. The bunch executed quadrupled oscillations in the miss-matched bucket and attained a minimum length of 28 ns. This bunch served as an impulse stimulus to the test cavity. The response of the cavity was observed with the feedback on and off and is shown in Figure 6. One can see that the free oscillation is damped within two rf cycles with feedback on. The FFT of these responses are also shown in the figure. Since the Fourier transform of the impulse response is the impedance of a system, these plots show the impedance reduction due to the rf feedback, a factor of 12.

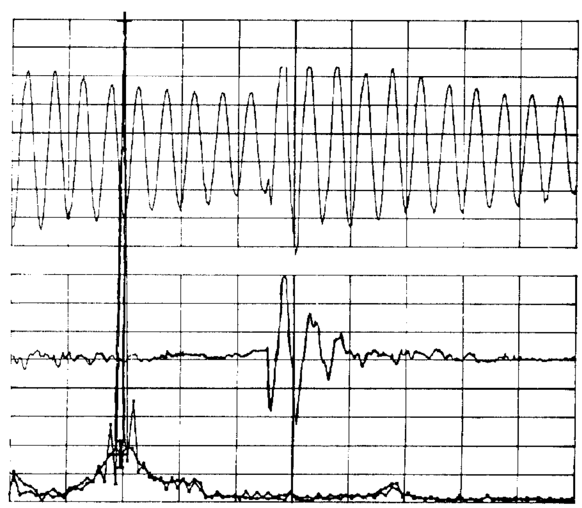

Figure 6. Cavity response to an "impulse". Top, feedback off. Middle, feedback on. Bottom, FFTs of above, linear axes, abscissa is zero to 20 MHz.

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