THE AGS BOOSTER HIGH FREQUENCY RF SYSTEM*

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Abstract

A high level RF system, including a power amplifier and cavity, has been designed and built for the AGS Booster. It covers a frequency range of 2.4 to 4.2 MHz and will be used to accelerate high intensity protons, low intensity polarized protons and heavy ions, to the 1.5 GeV level. A total accelerating voltage of up to 90 kV will be provided by two cavities, each having two gaps. The internally cross-coupled, pushpull cavities are driven by an adjacently located power amplifier. In order to accommodate beam intensities up to 0.75 x 10^{13} protons per bunch, a low plate resistance power tetrode is used. The tube anode is magnetically coupled to one of the cavity's two parallel cells. The amplifier is a grounded cathode configuration driven by a remotely located solid-state amplifier. It has been tested in the laboratory at full gap voltage with satisfactory results.

Introduction

The AGS Booster has two RF systems covering a frequency range from 600 kHz to 4.2MHz. The range of the low frequency system is 600 kHz to 2.4 MHz, and will be used for heavy ions. The range of the high frequency system is 2.4 to 4.2 MHz, and will be used to accelerate heavy ions, polarized and nonpolarized protons.

The high frequency system will be required to function with widely different gap voltage ranges, and from essentially no beam loading to proton beam intensities as high as 0.5 x 10^{13} protons per bunch. However it has been conservatively designed for beam intensities as high as 0.75 x 10^{13} protons per bunch.

This paper will describe the high frequency system, also known as the Band III system. The low frequency system is discussed in a separate paper, also included in these proceedings.

RF System Configuration and Parameters

The system requirements for high intensity proton beams determine, for the most part, the system configuration and parameters. Table I is a tabulation of requirements for protons, and also two extremes from a light ion to a heavy ion, sulphur to gold respectively.

Table I

	p	S^{+14}	Au^{+33}
RF Amplitude			
injection	45 kV		
ejection	53 kV	< 17 kV	< 17 kV
at max. accel.	90 kV	≤ 17 kV	≤ 17 kV
Harmonic Number	3	3	3
RF Frequency			
injection	2.5 MHz		
ejection	4.11 MHz	3.89 MHz	3.06 MHz
Phase Space Area/A	1.5 eV-s	0.0707 eV-s	0.0707 eV-s
Intensity (per bunch)	0.5×10^{13}	5×10^{9}	1.1×10^{9}
Total Gap Impedance ($f_{rf} = 4.1$ MHz)	< 24 kΩ	—	—
Acceleration Time	62 ms	≤ 0.7 s	≤ 0.7 s
Peak Beam Power Delivered to Beam	184 kW	1.0 kW	0.4 kW
Maximum $\dot{B}$	9.5 T/s	< 3.5 T/s	< 3.5 T/s
$\dot{B}_{inj}$	1.5 T/s	< 0.15 T/s	< 0.15 T/s

To achieve the above requirements, a practical set of parameters were developed. These parameters take into consideration such aspects as beam loading, realizable high voltage designs, limited selection of commercially available electron tubes and high power components, and the limited space available in the Booster tunnel. Furthermore, the shunt impedance will satisfy the Robinson Criterion for open loop operation.[1]

The system parameters are tabulated in Table II.

Table II

Number of RF Cavities	2
Number of Accelerating Gaps	4
Peak RF Voltage per Gap	22.5 kV
Peak RF Power per Cavity (180 kW rms nominal)	264 kW peak
Frequency Range	2.4 to 4.2MHz
Duty Cycle	50% Maximum
Output Impedance	6000 Ohms
Number of Power Amplifiers	2

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Cavity

The accelerating cavity is pushpull, two gap, and ferrite loaded. It is driven single-ended but is cross coupled to provide for pushpull operation. It is bias tuned to change frequency. It is physically located above and directly coupled to the RF power amplifier. See Figure 1.

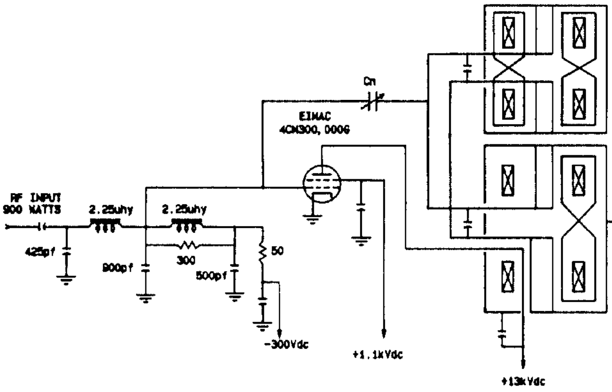

Fig. 1. Schematic Diagram of Band III Power Amplifier and Cavity.

To keep the gap voltage at a reasonable level, and keep the RF flux density, and in turn, ferrite losses manageable, the Band III cavity was designed to have two pushpull cells. The maximum RF voltage per gap is 22.5 kV peak. These cells are connected in parallel. The cavity is coupled to the power amplifier in a single-ended fashion to just one cell. The two ferrite stacks in each cell are cross coupled internally with figure-of-eight windings, essentially causing the cavity to operate as a balanced 1:2 step-up transformer.[2]

The design of the cavity is ultimately determined by the choice of ferrite. The material found best suited to the application is be Philips 4M2. The study of ferrite samples included measurements of permeability, dissipation, instabilities, and other possible anomalies.[5]

The cavity design requires 56 rings total or 14 per stack. Each ring measures 50 cm O.D. by 25 cm I.D. by 2.72 cm thick. With a gap capacitance of 350 pf per gap (chosen for a desired transient response and tuning servo bandwidth), the permeability ranges from 118 with a dc bias of 100 amperes at 2.4 MHz, down to 38.7 with a dc bias of 900 amperes at 4.2 MHz.

The ferrite dissipation is manageable with water cooling provided by copper cooling plates between each ferrite ring. Across the passband the peak dissipation varies from about 0.2 watt/cm^3 statically to 0.325 watt/cm^3 dynamically(ferrite losses are sweep rate dependent), corresponding to total peak power levels of 40 kW to 73 kW, respectively.

The Booster ring will be operated at ultrahigh vacuum and will require that the vacuum chambers, including the cavity, be baked at 200° C. The cavity beam pipes have built-in electric heating elements and thermocouples.

The ferrite stacks are dc biased from a single turn winding. The outer can, beam pipe, and gap connecting busswork form the bias winding. Because the two cavity cells are effectively in series with the dc bias, but in parallel for the RF drive, there is cancellation of RF on the dc bias leads to the cavity. Additional filtering is provided by a bifilar choke inserted into the external bias leads at the cavity.

A Band III power amplifier and cavity is shown installed in the Booster in Figure 2.

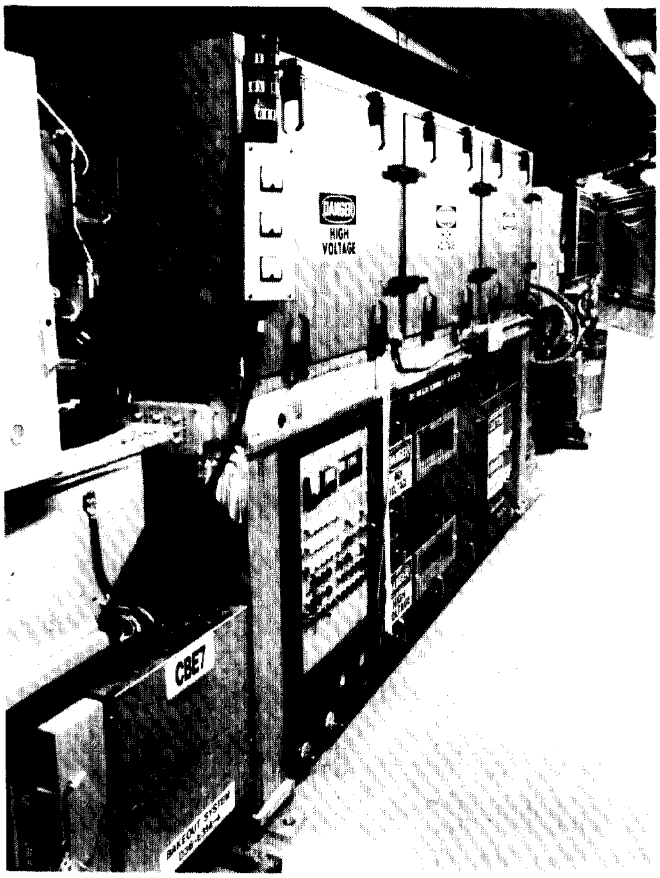

Fig. 2. Band III Power Amplifier and Cavity.

Power Amplifier

The Band III power amplifier design was bounded by a number of constraints. Some of the more important of these include power output requirements, Robinson Stability Criterion, and physical size.[3]

At maximum acceleration, 90 kV peak total accelerating voltage, the total output power required is about 180 kW rms. The amplifier was designed to deliver over 200 kW rms.

Power tube selection and amplifier configuration require careful consideration. Since the shunt impedance is low, the likely tube choice would be triodes. However, it was found that a large power tetrode (the EIMAC 4CM300,000G), could provide an average plate resistance of less than 500 ohms, providing a margin of safety. A grounded cathode tetrode also simplifies the circuit and is able to meet the physical space limitations.

The power tube operates class AB_1. Because of the 1:2 step-up at the cavity, it is necessary for the anode to swing only 11.25 kV. The dc anode voltage is 14.5 kV with a peak plate current of 65 amperes and a short-term average of 24 amperes. The screen voltage is 1.1 kVdc with an average current of about 0.5 amperes. The control grid bias voltage is -300 Vdc and the RF drive voltage is about 280 V peak.

The output circuit of the stage is simplified by bringing the anode voltage lead through the cavity for decoupling as well as RF coupling to the cavity. The need for blocking capacitors and a broadband RF choke are eliminated.

A broadband low pass filter terminated in 50 ohms is used to accommodate a high input capacitance as well as provide a standard impedance for the driver stage. A small amount of neutralization is required and is provided by a neutralizing capacitor coupled from the control grid to the 180° out-of-phase half of the cavity.

The driver stage is a pair of ENI 500 watt solid-state broadband linear amplifiers summed with a high power combiner. These amplifiers are remotely located from the Booster ring to avoid of possible radiation damage.

Cavity Tuning System

Tuning is accomplished by varying the cavity ferrite saturating bias current in response to two signals. The first of these is generated by an open loop program obtained from a function generator which is driven by a frequency-to-voltage converter. The second is the output of a phase detector which compares the phases of the output stage grid and plate voltages. Together they regulate the cavity tuning to within +/-10 degrees of resonance at all gap voltages up to 22.5 kV peak.

The coarse tuning open loop program is used to generate a function that will closely follow the cavity's static tuning curve. Added to this function is a function that is rate sensitive, and roughly corrects for the anomalous response of the ferrite to df/dt.

As the RF drive is swept across the passband from 2.4 to 4.2 MHz, a transistor bank adjusts the bias current from 100 amperes to 900 amperes without beam loading. With beam loading at rated Booster beam intensities, the detuning effect of the quadrature component of the beam current is small. The estimated increase of tuning current at injection is about 22 amperes, and 33 amperes at extraction. The system can deliver up to 1200 amperes.[4]

An important consideration in the servo design is the response to beam induced transients and detuning. Tuning servo frequency response is sensitive to the tuning bias current level. At injection the closed loop bandwidth is estimate to be about 15 kHz. For tuning currents up to 750 amperes the bandwidth is estimated to be 10 kHz. At 900 amperes it is approximately 7 kHz.

Status

The commissioning of two completely tested systems with a proton beam is scheduled for late spring 1991.

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References

1. K. W. Robinson, CEA, Report No. CEAL-1010, 1964.
2. M. Meth, A. Ratti, Push-pull Operation of the Cavity, Booster Tech. Note 84, July 1987.
3. M. Meth, A. Ratti, Specifications and Design of the RF Power Amplifier for the Proton Cavity, Booster Tech. Note 92, September 1987.
4. M. Meth, A. Ratti, Beam Loading Analysis of the Booster RF System, Booster Tech. Note 191, April 1991.
5. M.A. Goldman, et al., Proc. IEEE particle Accelerator Conf., Vol. 1, pp.165-167, Chicago, Ill. March 20-23, 1989. Rev.4-22-91.