THE AGS CONVERSION RADIO FREQUENCY POWER AMPLIFIER*

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Summary

To double the rate of particle energy gain per unit time, to offset heavier beam loading and to remove the electronic components to a radiation-free area, the AGS radio frequency acceleration system must be redesigned and rebuilt. The new system will be capable of delivering a total of 1440 kW RF power into 12 pairs of 50-ohm coaxial transmission lines 1100 feet long, terminating at 12 accelerating stations. Voltage amplitude and phase responses are closely controlled over a working frequency range of 1.4 - 4.5 MHz. The AGS conversion radio frequency power amplifier is composed of twelve final power amplifier stages, driven in groups of six by two paralleled drivers. These latter units are in turn driven by a cascade of lower level predriver stages. The final and driver stages are identical push-pull wideband ferrite transformer coupled grounded grid triode circuits housed in separate enclosures, each with its necessary control and safety system. The predriver is a four stage push-pull amplifier cascade with grounded grid triodes and grounded cathode tetrodes and pentodes, initially excited by a fractional voltage input signal of the proper frequency and phase. The anticipated successful performance of the system is attributable to the stable push-pull grounded grid amplifier configuration, to the carefully selected power tube complement and to the specially designed ferrite core interstage and output transformers and their associated networks.

Introduction

The objective of the AGS conversion program is to increase the usefulness of this great machine as a high energy research tool by more than doubling its pulse repetition rate and substantially increasing its proton beam intensity. To avoid radiation damage and personnel hazards, all active electronic components must be removed from the orbit tunnel. Accordingly, each accelerating cavity will be energized through a 1100 ft pair of 50-ohm foam polyethylene high power coaxial cables from a remote transmitter room. Since the time rate of energy gain must be doubled, the cavity voltage gradient and power must be increased, the additional beam loading must be compensated for and the cable losses must be taken into account, as shown in Fig. 1.

It will be noted that the maximum demand for RF accelerating power occurs toward the upper end of the frequency band, where more than 80% of the accelerating forward cycle (≧ 0.4 seconds, each second) are spent, leading to a total CW RF power output requirement of 1440 kW. This is a six-fold increase over the present AGS power amplifier, with an added requirement that all stages, including the finals, must be wideband.

Figure 2 is a block diagram of the AGS conversion RF power amplifier system. Its cost, performance and maintainability are dominating design factors. It is essentially an extension and further development of the design of the existing AGS 80 kW driver amplifier[1], where grounded grid wideband push-pull ferrite coupled triode high level stages are excited from tetrodes and pentodes of lower power.

Final and Driver Stages

Basic to the successful design and construction of moderate-cost high-performance final and driver amplifier stages at the 120 kW CW power output level in 1.4 - 4.5 MHz wideband operation are push-pull grounded grid circuits, coaxial power triodes and ferrite toroidal or equivalent closed-core RF power transformers of special designs. Fortunately for the progress of this amplifier system, there are commercially available high power coaxial triodes (e.g., Type 6696) and locally manufactured ferrite toroids of appropriate size and parameters for prototyping a typical final and/or driver amplifier stage enclosure. A modern network design approach is being undertaken to maximize the performance of the entire amplifier system.

Push-pull Grounded Grid Circuits and Enclosures

These circuits with coaxial power triodes and antiresonant Lecher lines for low-to-medium power in the VHF region were first reported by Jamieson and Whinnery,[2] and for wideband service up to 30 W and 30 MHz with ferrite coupled broadbanding networks by O'Meara.[3] At power levels of several tens of kilowatts from 1.4 - 4.5 MHz with large ferrite toroidal wideband interstage and output transformers, they were first employed in the AGS driver amplifier.[1] This basic circuit approach lends itself to a simple mechanical construction for a typical final and/or driver amplifier enclosure, reminiscent of a high power radio transmitter. It is a two-compartment unit of welded aluminum construction 6½ ft high, 5 ft wide and 2 ft deep. The left compartment houses the grid bias supplies and control equipment, while the other contains the RF components. The enclosure is RF-tight throughout. All connections are made with quick-disconnect devices from the underside to minimize servicing downtimes.

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Coaxial Power Triodes

A pair of Type 6696 general purpose water cooled coaxial power triodes, push-pull ferrite coupled, installed in a grounded grid midplane, in each of the final and driver stage enclosures, offers the most attractive tube complement with respect to cost, availability, ruggedness and high power handling capability. Their all-coaxial terminal construction minimizes lead inductances and leakage capacitance, maximizing stability and simplicity of circuits and enclosures when used with such isolating midplanes.

The somewhat conservative grounded grid stage power gains, approximately six to one, are more than offset by the fact that most of the stage input driving power reappears at the output terminals, giving high system conversion efficiency. Swamping resistors for broadbanding are eliminated since the input resistance becomes low. Also, the tube input capacitance is diminished by the inverse Miller effect.

Table 1 is a projection of the typical final stage tube operating parameters:

Table 1

Typical Operation
Class AB_2 Push-pull Grounded Grid Wideband RF Amplifier (6696 Triodes)
(Values are for two tubes)

dc Plate Voltage	7,000 V
dc Grid Voltage	- 245 V
Peak RF Grid-to-Grid Voltage	1,750 V
Peak RF Plate-to-Plate Voltage	12,250 V
Zero-Signal dc Plate Current	5.2 A
Maximum-Signal dc Plate Current	25 A
Maximum-Signal dc Grid Current	2.5 A
Effective Load Resistance, Plate-to-Plate	625 Ω
Maximum-Signal Driving Power, approx.	19 kW
Maximum-Signal Power Output, approx.	120 kW
Frequency Passband, 0.3 dB Ripple	1.4-4.5 MHz

Figure 3 is the final stage schematic diagram.

Ferrite Transformers and Modern Network Considerations

A wideband transformer may be regarded as a cascade of three networks: a high-pass filter whose cut-off frequency determines the lower passband edge, a low-pass filter whose cut-off frequency determines the upper passband edge, and an "ideal" transformer.[4] The high-pass filter is the shunt primary inductance and its distributed plus other parallel capacitances. For practical purposes, it usually suffices to make the primary inductance large enough (without appreciably augmenting those capacitances) so that its antiresonant frequency occurs more than an octave below the minimum working passband frequency, thereby fixing the position of the lower cut-off frequency.

The low-pass filter is the leakage inductance and its associated capacitances. It is the more difficult design problem, and quite largely determines the desired working passband and phase responses, as well as the upper cut-off frequency. Whatever practical transformer is designed and constructed must have its network model parameters measured, then related, along with the power tube and load resistances and capacitances, to appropriately scaled component magnitudes and network configurations derived from normalized low-pass filter prototype tables for Butterworth, Tchebycheff, or elliptic-function passband ripple and phase linearity responses of the desired character. Only in this manner can the tube operating parameters of Table 1 and a linear phase shift of predicted magnitude be achieved over the specified bandwidth.

Using commercially available nickel-zinc toroids in a double stack shell-core winding configuration, it is feasible in this manner to design and build a wideband RF output transformer for 3/10 dB passband ripple and essentially linear phase shift from 1.4 - 4.5 MHz with minimal copper and core losses and without insulation breakdown in air up to the maximum RF power output requirement. The magnitude of the combined tube and transformer capacitances leads to the adoption of 5-element low-pass filter network configurations, with these toroids. Their parameters are listed in Table 2.

Table 2
Parameters of Commercial Nickel-Zinc Ferrite Toroids

Thickness, t	1.588 cm
Outer Radius, r_2	7.375 cm
Inner Radius, r_1	3.175 cm
Initial Permeability @ 1 MHz, μ_o	125
Loss Factor, $\frac{1}{\mu_o Q}$	
@ 1.0 MHz	0.00002
@10.0 MHz	0.00016
Curie Point	350°C
Volume Resistivity	high

Enough ferrite cross section appears to be needed in the toroid stacks for the high power RF transformers in the frequency range 1.4 - 4.5 MHz to avoid noticeable core heating to limit the peak

RF flux density to $B_{max} \leq 50$ G.

Predriver Stages

The predriver is a four-stage push-pull ferrite coupled amplifier cascade which is capable of exciting the pair of driver stages in parallel with up to 40 kW CW RF power. The output stage is a pair of grounded grid triodes, preceded in the next two lower stages with pairs of modern coaxial tetrodes having high figures of merit and perveances. Small beam pentodes with remote cut-off characteristics and high figures of merit are employed for the first stage in order to facilitate the use of low-level balanced grid modulation for AGC purposes. A commercial low-level wideband (0.1 - 30 MHz between 3-dB points) ferrite unbalanced-to-balanced transformer is used to excite the control grids RF-wise at the one volt peak level from a single-ended initial input signal of a fraction of a volt, of the proper frequency and phase.

Control Circuits

The power tube filament and bias voltages are applied by an automatically timed sequence at start-up. Plate voltages are then applied manually by the AGS operator. The controls include overload protection circuits, safety interlocking and instrumentation as in standard high power radio transmitter practice.

High Voltage Power Supplies

The final and driver amplifier stages, as well as the output stage of the predriver amplifier, receive their dc plate voltage and current from four separate 700 kW power supplies, as shown in Fig. 2. Each power supply provides 7 kVdc plate voltage at full rated power, with 5% upward regulation at quiescent load. The high voltage rectifier transformers and primary switchgear are located in a transformer yard directly outside the RF amplifier building. The silicon rectifier stacks and ripple filters are installed within the building. The supplies are energized at 13.8 kV from the site power distribution system.

Concluding Remarks

The AGS conversion radio frequency power amplifier of Fig. 2 is believed to be the optimum system arrangement for cost, performance and maintainability at the present state of development of electron power tubes, RF magnetic materials and network design procedures. A prototype final and/or driver stage is being designed and built for testing up to full CW RF power output into a 250 ft pair of 50-ohm foam polyethylene high power coaxial cables terminated with a dummy load and afterward with a spare accelerating cavity, at relatively low cost.

After procurement of fourteen interchangeable amplifier stage enclosures and spares modeled after the successful prototype, the whole amplifier system could be set up and tested simultaneously into twelve dummy loads, if desired, to simulate "on-line" conditions. In actual service, there will be the important advantages for machine operation of redundancy and interchangeability: i.e., one or more final amplifier stages may fail and may be quickly replaced without halting the AGS.

To have designed this amplifier system with one super-powerful final stage employing a pair of the largest manufactured electron tubes would have involved greater costs, more AGS downtime for repairs and less ready availability of replacement tubes. A way of designing a 1.44 MW CW RF wideband output network for such a low load resistance, and a means for prototype verification, would offer severe design problems.

Acknowledgments

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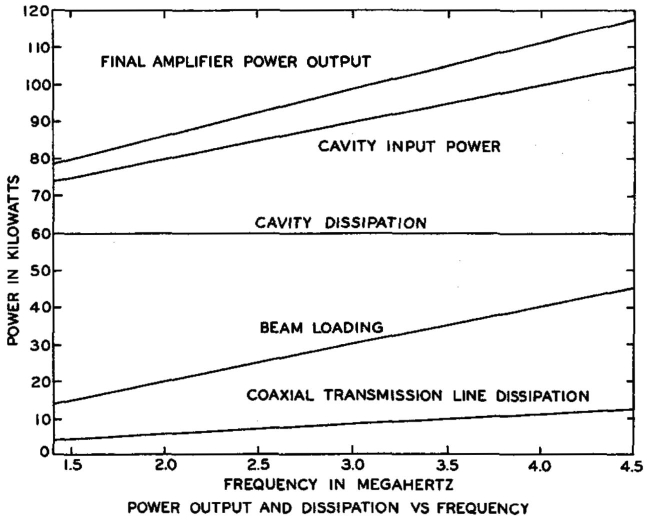

Fig. 1. Power output and dissipation vs. frequency.

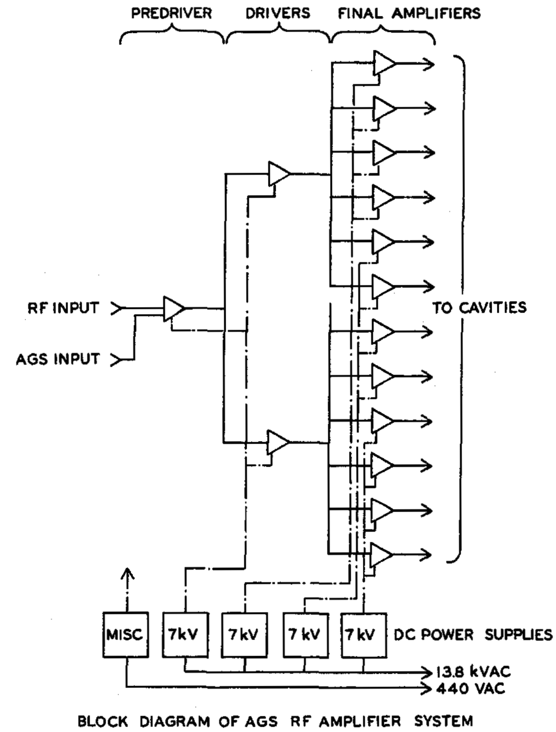

Fig. 2. Block diagram of AGS RF amplifier system.

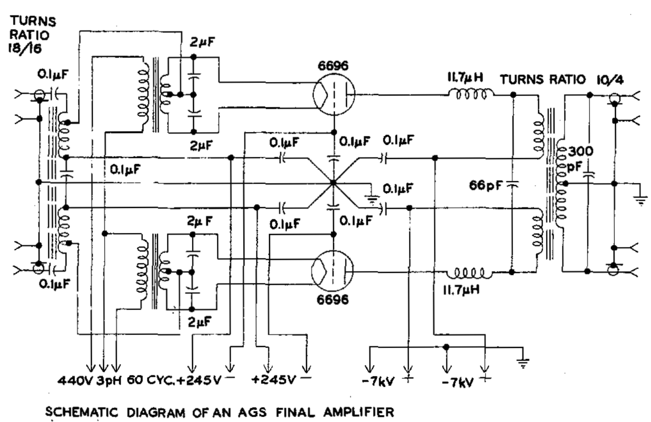

Fig. 3. Schematic diagram of an AGS final amplifier.