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100-MHZ POWER AMPLIFIER DESIGN AND CONTROL FOR A HEAVY-ION ACCELERATOR

by
J. S. Lunsford, J. P. Shipley, and J. Sutton

ABSTRACT

The proposed heavy-ion accelerator at Los Alamos Scientific Laboratory (LASL) contains ~80 spiral resonating cavities, each with its own power amplifier and associated control systems. This report describes the design details of a typical power amplifier and its control systems, and also gives operational procedures and some experimental results.

One design problem for a large power amplifier generating 20 kW of 100-MHz rf power is stray reactance. Proper choice of impedance transformations, resonating elements, and neutralization can help, but a better initial design is a more effective solution.

Plate circuit design is important for maximum efficiency and stability. The original movable-short, fixed-tap design used for our experiments was not optimal, and several improvements are described.

Perturbation controllers are required for the cavity rf phase, amplitude, and resonant frequency. The amplitude control is particularly interesting because it is done by varying the power amplifier screen-grid voltage. Typical power amplifier output is 20 kW at 33% plate efficiency and 19-dB gain.

I. INTRODUCTION

Recent increasing interest in heavy-ion physics prompted Los Alamos Scientific Laboratory (LASL) to design a new heavy-ion accelerator with improved characteristics. This accelerator is a continuous-field machine with ~80 spiral resonating cavities, all tuned to the same master reference frequency. These resonators are independently phased, the phase of each being adjusted to be optimum for the velocity of the ion to be accelerated. Hence, although a single power amplifier could drive several cavities, each cavity requires its own phase control. Furthermore, the desired cavity operating power levels are constant in time, but the load each cavity presents to the power amplifier may vary widely because of temperature shifts and other perturbations. Each cavity, therefore, must have its own amplitude control, and thus a power amplifier can drive only one cavity. This report covers the design and operation of such a power amplifier/cavity combination and its associated instrumentation and controls that was built and tested at LASL.

II. THE POWER AMPLIFIER DESIGN

A. Basic Requirements and Constraints

The power amplifier design was dictated by the accelerating cavity design and the test program. We estimated that 25 kW of cw rf power would be needed to obtain the desired field levels in the cavity. At this power level, a possible resonant frequency shift of ±500 kHz could be expected, because of the cavity mechanical design, thus requiring a 1-MHz amplifier bandwidth. This allows the control systems to maintain the desired power level, whatever the cavity frequency drift. None of the cavities we tested was tunable, and it is difficult to construct them with the precisely correct resonant frequency. Therefore, the amplifier must be tunable over a ±10-MHz range about a nominal 100-MHz frequency. Radio-frequency drive available from the two ENI Model 3100L wide-band amplifiers on hand is ~250 W, requiring an amplifier gain of ~20 dB.

Two Eimac 4CW 50 000E water-cooled power tetrode tubes were available from a previous rf system. They were used because Eimac had shown that this tube will deliver rated power at 108 MHz. The Eimac 4CW 50 000E tube has a 50-kW plate dissipation rating at a maximum 110-MHz operating frequency. Interelectrode capacitances in a grounded cathode configuration are specified at input 310 pF, output 53 pF, and feedback 0.7 pF. Maximum dissipations are 50 kW in the plate, 1500 W in the screen grid, and 400 W in the control grid. The filament is rated at 12.0 ± 0.6 V at 220 A. The Eimac SK-2050 water jacket and the socket are needed with this tube.

Previously, we found the standard socket to be inadequate at 100 MHz; however, Eimac designed a new socket with better electrical characteristics for use at 100 MHz. The first generation of this new socket was made poorly; it had to be repaired several times and finally rebuilt.

The socket and the tube must be cooled during operation. A water flow of 0.83 ℓ/s (for 50-kW plate dissipation) is required for the plate, and an air flow of 123 ℓ/s is needed for the socket and the tube base. Both coolant flows are required during filament operation because filament power is ~2700 W. Therefore, the air flow and water flow are interlocked to the filament power to protect the tube. Other interlocks to protect the tube are: (1) a control-grid bias interlock to prevent plate or screen-grid voltage application without bias; (2) a plate supply/screen-grid supply interlock to prevent applying screen-grid voltage without plate voltage; and (3) a 5-min time delay to heat the filament to operating temperature before other voltages are applied.

Another aspect of protection is personnel safety. All high-voltage (hv) supplies and the amplifier cabinet are equipped with door interlocks to prevent access during operation. Movable grounding hooks provide a positive ground for all hv points while work is being done on the amplifier system. Whenever the tube filaments are on, a rotating warning beacon indicates that the system is operating. Because it is not known at what level 100-MHz rf radiation becomes a health hazard, access to the room containing the amplifier system is limited when the rf field strength is >10 mW/cm^2, a level one-tenth of that prescribed for microwave systems.

B. Power Supplies

Power supply connections and associated decoupling components are shown in Fig. 1. Nearly 2700 W is supplied to the filament by an Opad Electronic Company Model 2316 dc welding supply, rated at 0-32 V and 300 A. In operation the filament current is usually kept <200A to prolong tube life; increased filament current does not seem to increase the amplifier efficiency. The dc supply was modified to permit remote operation and interlock installation. Another requirement for tube protection is to prevent occurrence of current surges >300 A during filament turn-on. The dc supply was modified so that at turn-on only 8V is applied to the filament briefly, until the filament current stabilizes.

A Dresser-Barnes Model 32-101 dc voltage supply, rated at 300 V and 2 mA, provides control-grid bias. It is automatically turned on at the same time as the filament supply.

The screen-grid supply, built at LASL for another project, was modified for this rf system It consists of

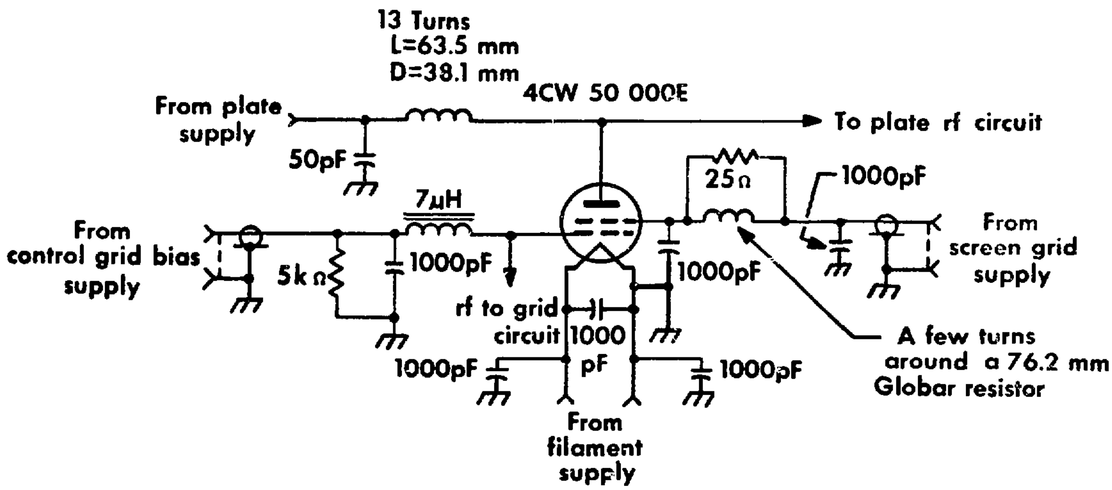

Fig. 1.
Power supply connections to the Eimac 4CW 50 000E power tetrode tube.

a 3-phase, full-wave rectified source of ~1500 V followed by a shunt regulator (Fig. 2). The regulator tube is an Eimac 290 with a maximum plate current rating of 2 A; its control grid is supplied by the circuit described in Sec. III. B. The maximum requirements of the screen grid are ~1500 V at 0.5 A.

The plate voltage and current requirements, set at 0-12 kV and 10 A, are provided by a Megavolt, Inc., Model 12-10 000 power supply. This is an unregulated supply, operating from the 480-V, 3-phase line. Output voltage is controlled by varying the input voltage with a Variac, which consists of three stacks of six Powerstat Model 1256D Variacs and provides each phase with a rating of 47 kVA. To isolate the plate supply output from the cooling water supply, coils of rubber hose are used between the water inlet and tube plate and between the water outlet and tube plate.

C. Grid Circuit Design

Figure 3 shows the circuit components and parasitic elements, L_1, L_2, C_{gp}, C_{gs}, and C_{gk}, associated with the grid circuit. The capacitors C_1 and C_2 and the 75-Ω cable are used to obtain voltage gain between the driving source and the grid-to-cathode nodes, while matching the 50-Ω impedance of the driving source. The values of these elements are determined with the tube under zero gain conditions, but with filament power on. The dynamic effects of the cathode inductance L_2 and Miller capacitance C_{gp} are neutralized under normal operating conditions. The simplified circuit in Fig. 4 is used to determine the values of grid-matching components. Capacitor C_1 is chosen to provide sufficient voltage from cathode to grid with enough bandwidth that retuning the grid circuit is not necessary to drive a cavity at various power levels. Capacitor C_2 and resistor R are adjusted to obtain an input impedance Z of $100\angle\ 0^0\ \Omega$. This impedance is transformed to 50 Ω with a quarter-wavelength (1/4-λ), 75-Ω cable.

The maximum drive available for the grid circuit is ~360 W. With the circuit values given in Fig. 4, 260-W input provides ~160 V rms from cathode to grid, as is verified by adjusting the dc bias until grid current begins flowing. Figure 5 shows the mechanical details of capacitors C_1 and C_2.

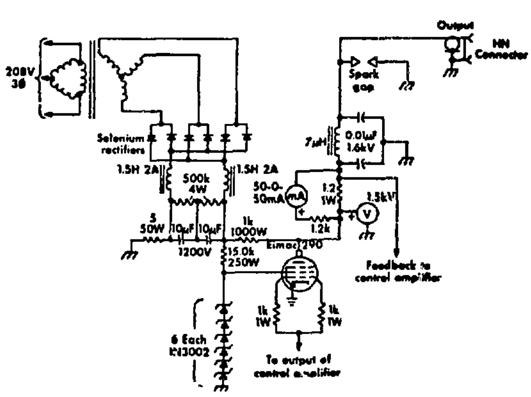

Fig. 2.
Basic screen supply and regulator.

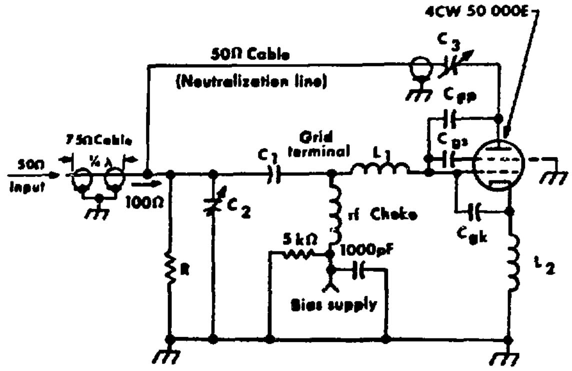

Fig. 3.
Equivalent grid circuit.

D. Neutralization

Neutralization compensates for the plate-to-grid capacitance and the cathode inductance. Figure 3 shows the neutralization line connections. At the grid end the neutralization line is properly terminated in 50 Ω because the grid circuit is tuned to 100 Ω, and the driving source impedance is

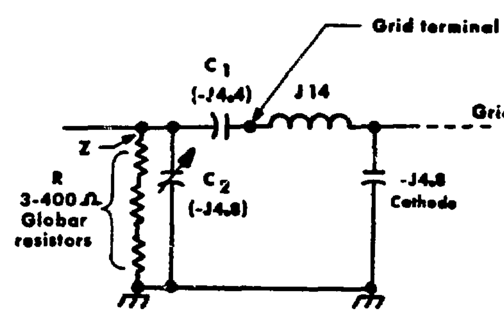

Fig. 4.
Simplified circuit to determine values of matching components.

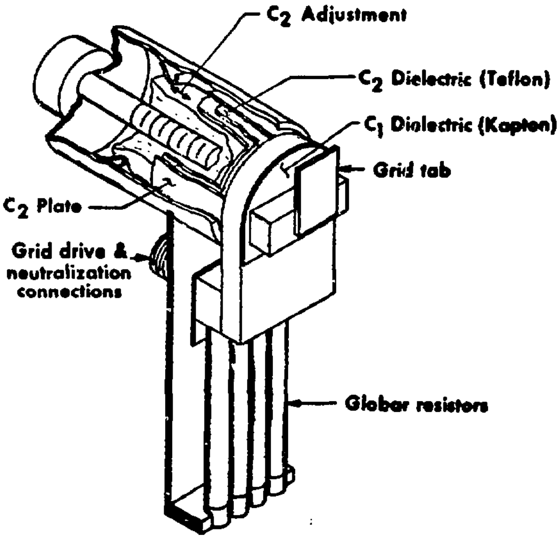

Fig. 5.
Construction of capacitors C1 and C2.

transformed to 100 Ω with the 1/4-λ, 75-Ω cable. The line length required for correct phase of the neutralization signal is nλ, where n = 0, 1, 2,... . The line length used was 1 λ. Under normal operating conditions, the voltages and currents in the neutralization cable are large enough to overheat polyethylene cable; therefore, fiber glass- and Teflon- insulated cable RG-225U is necessary. The amount of neutralization is adjusted with the variable capacitor C_3. The construction of C_3 is shown in Fig. 6.

The following procedure is used to adjust the neutralization. With the tube in the zero gain condition, the grid circuit impedance is tuned to $50 \angle 0^0$ Ω. Then, capacitor C_3 is adjusted to give minimum input mismatch over the desired output range.

This method of neutralization gives good results with fairly high gains and no instability, even when driving a cavity. The neutralization does change with frequency because electrical lengths and impedances change. This proved to be somewhat of a problem when driving a cavity at various power levels because the cavity resonant frequency varies with power input. During a typical run, if the power into the cavity was varied from 0 to 10 kW, the resonant frequency varied from 94.9 to 94.75 MHz, and the reflected power from the grid varied from 0 to 10% of the input power. This performance of the grid circuit is satisfactory.

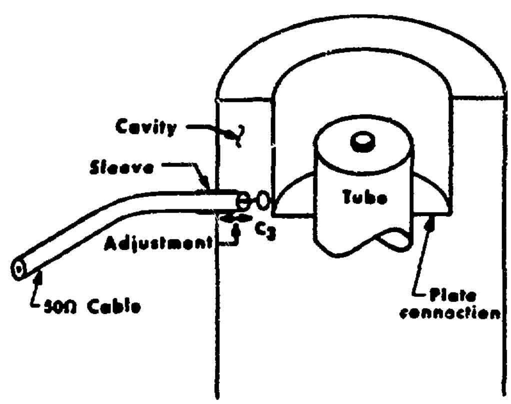

Fig. 6.
Neutralization adjustment capacitor C_3.

E. Plate Circuit

The plate circuit, as originally designed, is shown in Fig. 7. The circuit is a shorted transmission line with a 50-Ω load tapped at the proper point to present optimum load to the plate. The shorted line is of proper length to resonate with the tube's plate capacitance. This design has the disadvantage that

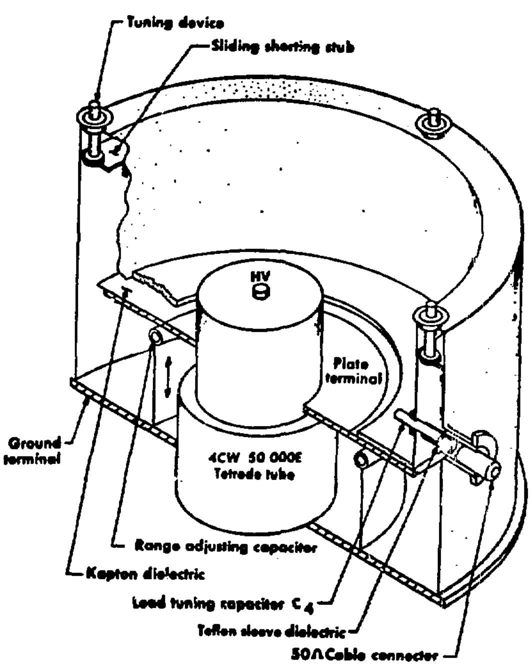

Fig. 7.
Plate circuit configuration.

the plate loading is not adjustable, whereas the loading changes as the cavity is tuned over the desired frequency range. To correct this the plate circuit was modified as shown in Fig. 8. With this configuration tuning the plate circuit does not appreciably affect the plate loading, and loading can be varied by a small amount. The load tuning capacitor C_4 shown in Fig. 7 was used to series-resonate with the coupling inductance. Difficulties were experienced with this capacitor burning out because of the high currents and voltages in high-power operation. We found that replacing C_4 with a solid piece of copper, as shown in Fig. 8, had negligible effect on the power obtainable but did change the plate tuning slightly.

The plate circuit of Fig. 8 was simulated on NET-2 (Ref. 1) with lumped elements, and the results agreed well with our experiments. Time was too short to use the computer as a design tool, but NET-2 should be very effective for designing similar circuits, especially after the transmission line model is added to the program.

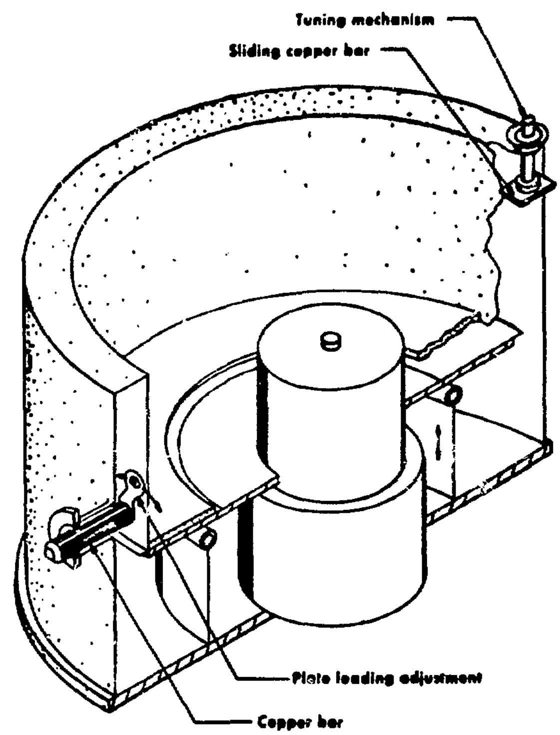

Fig. 8.
Modified plate circuit configuration.

F. Loads

Two loads can be used with the rf amplifier. One is a 25-kW, water-cooled, 50-Ω dummy load (Bird Model 8752). Required water cooling is a minimum 0.48-ℓ/s flow. We used this load primarily during testing and design of the power amplifier. The other load, the particle accelerating cavity to be tested, is a spiral-loaded resonator for accelerating the low-velocity ions in a linear heavy-ion accelerator. It operates at room temperature and has nominal accelerating field phase velocities ranging from β = 0.02 to 0.10 (β = v/c). Electrically, the resonator resembles a 1/4-λ transmission line, shorted at one end and open at the other. Several variations of this structure were tested, but the basic construction is shown in Figs. 9 and 10.

The nominal cavity input impedance at resonance is 50 Ω. However, because the cavity is a resonant device, the impedance is a function of frequency, and the zero-power resonant frequency varies from one cavity to the next. The resonant frequencies of the cavities range from 94.8 to 102.5 MHz. Frequency shifts with power vary from −5 to 50 kHz/kW. The quality factor of the cavities is usually between 2000 and 3000.

Coupling between the amplifier and the loads is made by a 41.3-mm-diam, 1/2-λ, 50-Ω coaxial cable. Coupling into the accelerating cavity is made by connecting to the spiral a short distance from the shorted end through a ceramic vacuum seal. The connector's inductance is resonated out with a Jennings vacuum capacitor. The connection point to the spiral is selected to make the resultant resonant input impedance 50 Ω resistive. This construction is shown in Fig. 10.

G. Instrumentation

All important parameters are metered at a remote location. These parameters are plate voltage, plate current, plate-supply Variac position, and screen voltage. Other quantities metered at the power amplifier are control-grid bias, control-grid current, filament voltage, filament current, and screen current.

The rf power levels are also monitored remotely. Incident and reflected power amplifier output powers are measured by a Bird Thruline power meter, Model PN2150-043. Radio-frequency drive powers, incident and reflected, are also monitored with small Bird Model 301 power meters. All the power-level indications are available at the remote location.

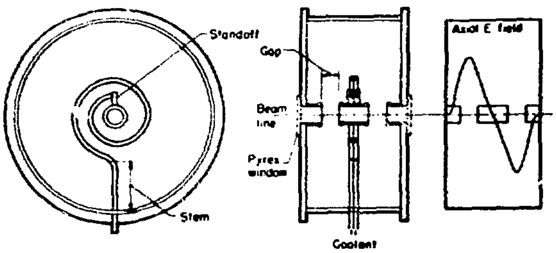

Fig. 9.
A 100-MHz single-spiral resonator.

III. CONTROL SYSTEMS

The power amplifier system is designed to provide the nominal required operating characteristics. Because of various disturbances (temperature effects of rf heating, component aging, etc.), the operating point of the system is not stable enough. Therefore, perturbation controllers on the important variables are necessary.

Fig. 10.
Spiral resonator with end plates removed.

A. Basic Requirements

The three most important variables are the rf amplitude in the resonant cavity, the rf phase in the cavity relative to some reference, and the resonant frequency of the cavity relative to the rf frequency. The allowable rf amplitude variation is ±0.5% of its nominal value, and the allowable phase variation is ±0.5°. There is no primary specification on the cavity resonant frequency because it is driven by a master oscillator of the correct frequency. However, if the cavity resonant frequency and the master oscillator frequency differ greatly, it generally will be impossible to control the rf amplitude and phase adequately. Therefore, a controller is provided either for the cavity resonant frequencies when using multiple cavities, or for the master oscillator frequency when only one cavity is used.

The bandwidths of the controllers are important. The cavity rf phase is most critical in a long accelerator, so small phase shifts are corrected with the highest possible bandwidth, preferably > 10 kHz. The amplitude control must be able to damp out mechanical vibrations of 10-400 Hz in the cavity. The amplitude controller bandwidth therefore is at least 400 Hz. Because gross shifts in the cavity resonant frequency are normally slow (<10-Hz bandwidth), the frequency controller bandwidth can be small. We have found that a 10-Hz bandwidth is sufficient for most cases.

B. Amplitude Control

The power amplifier has a variable voltage screen supply controlled by a shunt regulator; consequently, the regulator is a convenient place to inject the amplitude control signal. Furthermore, screen voltage changes have little effect on the rf phase, so the amplitude and phase control loops can be decoupled.

A block diagram of the power amplifier and control systems for driving one cavity is provided in Fig. 11. The amplitude feedback control signal is obtained by extracting a small signal from the resonant cavity, detecting its amplitude, amplifying and subtracting from a reference dc level, and using the resulting signal to control the screen voltage through a shunt regulator.

Figure 12 is a schematic diagram of the amplitude control circuits. Amplitude detection is accomplished conventionally, using a hot carrier diode with a field effect transistor (FET) source follower for impedance transformation. The reference signal is processed in exactly the same manner (except for a

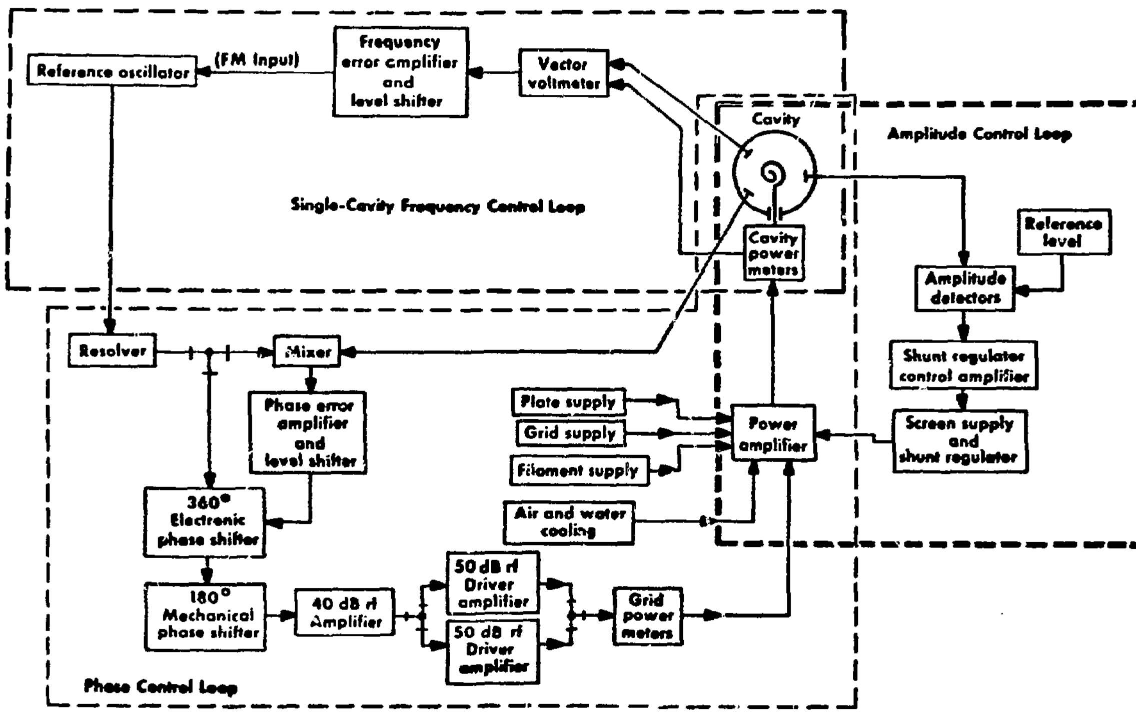

Fig. 11.
Power amplifier, cavity, and control systems.

sign inversion) to minimize tracking errors. This approach also allows the reference signal to be either dc or an rf signal of the same frequency as the cavity rf. Variable resistors control the gains of the reference signal and the amplitude-detected cavity signal, and the difference between these signals (the amplitude error) is injected into the summing junction of the shunt regulator control amplifier, as shown in Fig. 12.

When measuring the small signal transfer function from shunt regulator control amplifier input to power amplifier output rf level, we found that it had an upper cutoff frequency of ~1 kHz owing to the screen supply decoupling elements. Therefore, the control system can handle cavity disturbances with bandwidths up to ~1 kHz. One of the major sources of cavity disturbance is the mechanical vibration of the spiral resonating structure, which has a bandwidth <400 Hz for the cavities we have been using. The control system easily damps out these mechanical vibrations; in fact, the cavities would be nearly inoperable, particularly at higher power levels, if this capability were missing.

The measured amplitude stability of the cavity rf is better than 1% from dc to 10 kHz with the amplitude control system working. The stability is worse at dc because of temperature drifts in the amplitude detector. This problem could be helped by better detector design or by adding a pole at the origin in the forward transfer function. However, these alternatives were not pursued because the stability is adequate.

One disadvantage of screen-voltage amplitude stabilization is that the screen-voltage dynamic range must be larger than it is without stabilization. If the nominal screen voltage is set at its maximum value, the control system must still be able to vary the screen voltage about that value to retain control. When first attempting to put power in a cavity, the screen voltage should be raised above its lower limit by ~150 V (from 400 to 550 V) to give the control system some range in which to work.

C. Phase Control

Control of the rf phase in the cavity is accomplished as shown in Fig. 11. First, the desired phase with respect to the master oscillator is set with the mechanical resolver. Then this reference phase is

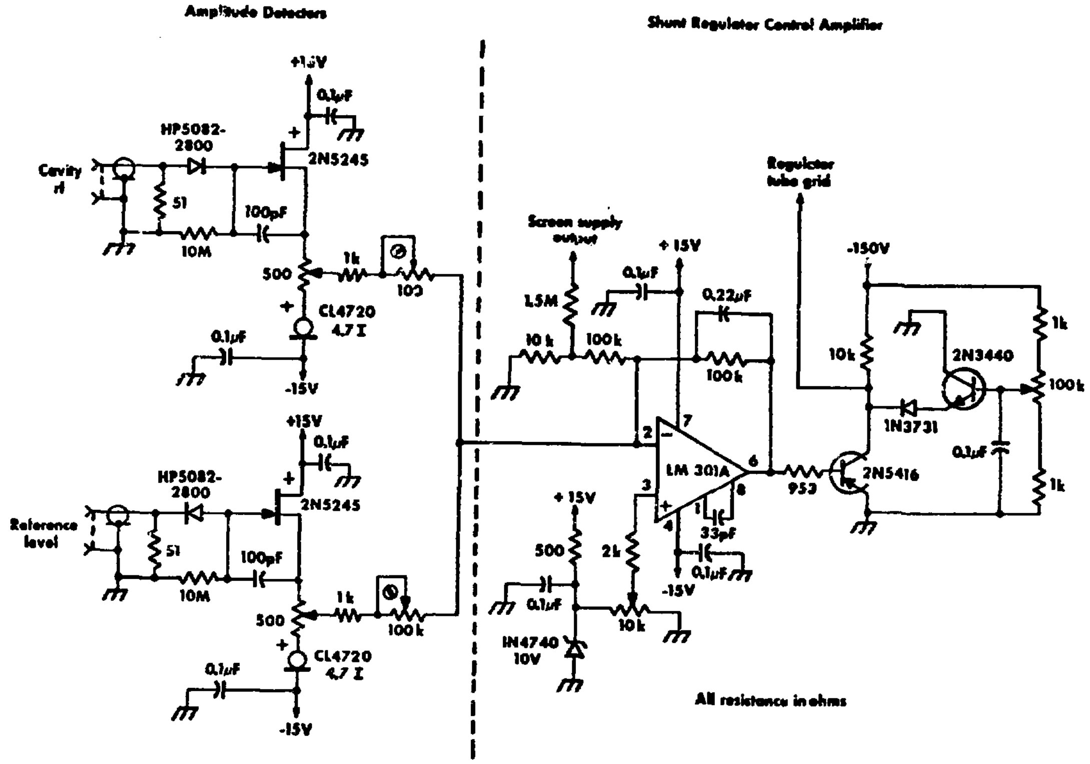

Fig. 12.
Ampiitude control loop circuitry.

compared to the cavity phase in a double-balanced mixer, and the resulting error is amplified and applied to a 360° electronically-controlled phase shifter in the master oscillator signal paths to the power amplifier driver. The mechanical phase shifter inside the control loop is an offset adjusting device to ensure that the mixer operates in its best region with nearly equal phase inputs.

Figure 13 shows a schematic of the phase control circuitry. The cavity phase information is obtained from a probe in the cavity similar to the probe for obtaining the amplitude signal. The double-balanced mixer has an output voltage given by

$$E_o = K\, E_r\, E_p \sin(\sigma + \phi),$$

where

K is a gain constant,
E_r is the reference signal,
E_p is the probe signal,
σ is the phase angle between E_r and E_p, and
ϕ is a constant phase offset.

The mixer's output voltage E_o is amplified in the phase error amplifier (PEA), a high-gain, wideband, dc-coupled amplifier, and then level-shifted to be compatible with the zero point of the electronic phase shifter.

The bandwidth of the phase control loop is determined entirely by the PEA bandwidth for our choice of components. The Zeltex Model 148C operational

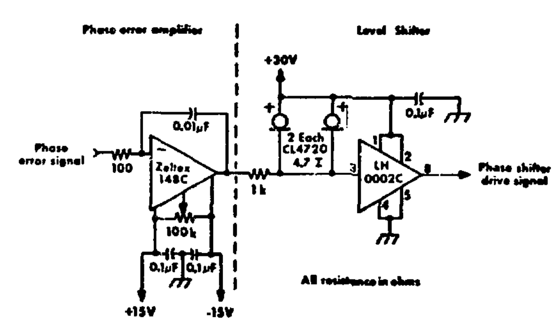

Fig. 13.
Phase error amplifier (PEA) and level shifter.

amplifier has a gain of 100 at 15 kHz, so that the reduction in sensitivity to phase errors introduced in the driver, power amplifier, and cavity is at least a factor of 100 for phase-error frequencies below 15 kHz. Because the PEA is operated as a low-pass filter, the sensitivity reduction is much greater at lower frequencies.

Because phase shifts in the resolver, the probe signal cable, and the mixer are not reduced with this control scheme, these must be good, stable components. The fact that the mixer output depends on the amplitudes of the reference and probe signals introduces two other effects. First, the loop gain changes with signal level. This is not much of a problem because the loop gain is already high. Second, a phase error occurs if the mixer and phase shifter are not operating at their zero points. These problems were not attacked because the original intent was to operate the power amplifiers at some constant power level.

We measured the small signal loop bandwidth by observing the mixer output while perturbing the phase with another electronic phase shifter inserted after the 360° electronic phase shifter. The bandwidth observed was ~12 kHz. A dc phase disturbance of ±100° resulted in a phase error of ~±0.1°, which is well within the specifications. An amplitude change of 20 dB in either the reference signal or the probe signal (but not both) caused a phase error of ~±1°.

D. Single-Cavity Frequency Control

In an actual accelerator with many resonant cavities, each cavity must be tuned to the reference oscillator frequency. However, for the single-cavity experiments we have done, it is easier and cheaper to tune the reference oscillator frequency to the cavity's resonant frequency. The reference oscillator we use, a Hewlett Packard Model 608, has an FM input with sufficient bandwidth and range.

Figure 11 is a block diagram of the single-cavity frequency control loop. The difference between the reference oscillator frequency and the cavity resonant frequency is sensed by measuring the phase shift between the rf input to the cavity and an rf signal obtained from a probe in the cavity using a vector voltmeter. When the frequency difference is zero, this phase shift has some constant and known value depending on the placement of the cavity probe. Then the phase output of the vector voltmeter is amplified and level-shifted for compatibility with the reference oscillator and applied to the FM input of the reference oscillator. Figure 14 shows a schematic diagram of the amplifier and level shifter.

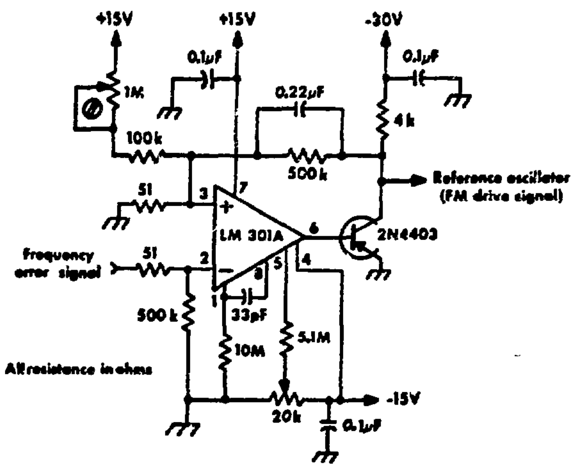

Fig. 14.
Frequency error amplifier and level shifter.

The frequency control loop has a small bandwidth (~10 Hz), entirely because of the bandwidth of the vector voltmeter. This is sufficient to damp out all frequency perturbations at constant or slowly changing cavity power levels. Power level changes must be made slowly enough so that the frequency control loop can maintain a small frequency difference; otherwise, the cavity resonant frequency will move rapidly away from the reference oscillator frequency. Consequently, the cavity must be allowed to stabilize at several intermediate power levels when bringing the system up to full power.

IV. OPERATION AND RESULTS

A. Operation

System start-up begins by turning on the main power breakers, oscillator, preamplifier, driver amplifier, control systems, and cooling water. The rest of the start-up procedure is handled from the remote control room. The control panel is arranged so that each succeeding operation cannot be made until the previous steps or conditions are satisfied, as follows.

1. Control power - turns on control panel power;
2. Cooling - turns on cooling air;
3. Power amplifier air - cooling air interlock;
4. Power amplifier water - cooling water interlock;
5. Filament power - turns on power amplifier and grid-bias supply;
6. Filament time delay - 5 min warm-up;

7. Bias interlock - indicates bias is on, if closed;
8. Amplifier ready.

With the amplifier ready to operate, rf drive is supplied from the oscillator, applying rf to the power amplifier. All control systems except the amplitude control are disabled. The plate supply is turned on and raised to ~4 kV. Then the screen grid supply is turned on and the screen-grid voltage raised until plate current is indicated. The oscillator frequency is tuned until the accelerating cavity begins to absorb power. The frequency control system is zeroed and enabled next. The plate voltage is raised to a voltage appropriate for the desired power out, and then the screen-grid voltage control becomes the power output adjust; increasing the screen voltage now increases power out. At this point, with the amplitude and frequency control systems on, constant power is delivered into the load.

Shutdown is accomplished by reducing screen voltage to its minimum and turning it off and by reducing plate voltage to zero and turning it off. Reversing the start-up procedure completes the shutdown.

The above procedure assumes the power amplifier is tuned to the load. Otherwise, the initial resonance of the accelerating cavity is determined by using a vector impedance meter at the input to the cavity. Then, using the vector impedance meter set at the resonant frequency of the accelerating cavity, the grid circuit is tuned so the power amplifier input impedance is 50 Ω. Plate tuning is done with the power amplifier in operation by tuning for maximum power out. Neutralization is then adjusted to minimize the reflected rf drive power. The preamplifier and drivers are wide-band amplifiers requiring no tuning.

Several aspects of the power amplifier could complicate its operation. The amplitude control system controls the rf output level by adjusting the screen-grid voltage. If rf drive were turned off, the screen-grid voltage would be driven to its maximum value, an undesirable operating condition. Another complication is that the "catching" of the resonance of the accelerating cavity in the turn-on procedure is no easy matter. There is a necessary conditioning period for the cavity after each time it is brought back to atmospheric pressure. During this period, there apparently is much out-gassing from heating in the accelerating cavity; at this time, the resonance cannot be found or "caught." This period is quite long for some resonators, perhaps as much as an hour.

B. Results

The highest power output achieved from the rf amplifying system was 24 kW. However, this was not maintained for very long because of a failure in the output coupling capacitor. Powers of 20 kW were recorded many times for long periods. The best gain obtained was 19.3 dB at 20 kW with a plate efficiency of 32.7%. The highest efficiency recorded was 48.1% with a gain of 15.8 dB. Two sets of typical power amplifier operating conditions are given below.

E plate	9 kV	8.7 kV
I plate	6.9 A	6.95 A
E screen	1140 V	1350 V
I screen	100 mA	115 mA
E grid	−200 V	−195 V
I filament	190 A	195 A
P drive	240 W	245 W
P output	20.3 kW	20.1 kW
P output (reflected)	260 W	0 W
Frequency	94.62 MHz	98.49 MHz
Efficiency	32.7%	33.1%
Gain	19.3 dB	19 dB

The first set was taken while driving an accelerating cavity; the second was taken while driving the dummy load. The frequencies at which the power amplifier was actually operated ranged from 94.6 to 102.5 MHz.

The above results were taken from typical tests conducted during development of the amplifier system. Actual experimental results obtained by accelerating alpha particles in a single cavity are provided in Ref. 2.

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