RF POWER SYSTEM FOR THE SEPARATED-ORBIT CYCLOTRON EXPERIMENT*

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Summary

The SOCE is designed with 11 radio frequency cavities (injector - 3, buncher - 2, SOC - 6), each requiring up to 15 kW of rf drive power under full beam loading. A separate three-stage power amplifier unit using an Eimac 4CW25,000A tetrode as the final amplifier is provided for each cavity. Each unit is provided with automatic servo tuning, and with precise phase and amplitude regulation. A master signal generator supplies a common 50-MHz drive signal, which also serves as the phase reference. Although requirements vary from one cavity to another, all power amplifier units are identical and connected to a single set of dc power supplies and controls. The components were designed conservatively so that the rf system could be operated at greatly increased power levels for high intensity beam studies, with only the addition of an auxiliary dc plate power supply. Most of the design features in the SOCE's multiple-amplifier radio frequency system will be directly applicable to later SOC-type accelerators, even for a much higher total rf power requirement.

Introduction

The various SOC design studies[1, 2, 3, 4] of the past few years considered machines with many rf cavities, each cavity requiring a large amount of drive power and precision control of rf voltage amplitude and phase. These requirements are conveniently satisfied in a system that provides an individual power amplifier for each cavity, thereby permitting rf phase and amplitude controls to operate on low level rf signals. The SOCE cavities will operate at comparatively low power levels with respect to other SOC's, nevertheless precision phase and amplitude controls are essential.

Separate dc power supplies for each PA would be preferable for most SOC designs to provide maximum rf isolation and to permit continued operation of the remaining PA's while one or more units are temporarily disabled by transient conditions. Relaxed reliability requirements and lowered power levels permit the use of a single set of dc power supplies for all of the SOCE PA's. The latter arrangement is considerably less expensive than the use of multiple power supplies, both in regard to power supply cost and because some large dc power supplies are already on hand.

A 15-kW cw rf power amplifier was designed for use with each of the cavities. A prototype unit was fabricated; it is being tested at reduced power.

Design Parameters

The design requirements for the SOCE power amplifiers are given in Table I.[5, 6]

TABLE I

Frequency	49.18 MHz
Cavity rf voltage amplitude stability	±0.5%
Cavity rf voltage phase stability	±1°
SOC cavity excitation power (with 10-mA ion beam)	15 kW - cw
Linac cavity excitation power (with 10-mA ion beam)	8 kW
Buncher cavity excitation power (with 10-mA ion beam)	8 kW
RF excitation signal	1 V rms into 50 Ω

The Power Amplifier

A simplified schematic diagram of a typical SOCE PA is shown in Fig. 1. The master signal generator consists of a type 0-91A/FRT-5 variable frequency (2.0 to 4.5 MHz) oscillator (taken from a surplus AN/FRT-6 radio transmitter), a frequency multiplier, and a low impedance output amplifier. The servo-tuned frequency stabilization capacitor in the oscillator was replaced by a varactor network.

Each PA unit is connected to the MSG output circuit via a terminated 50-ohm transmission line. The line lengths can be adjusted for proper rf voltage phasing between respective cavities and the MSG. The PA input rf voltage is about 1 volt rms.

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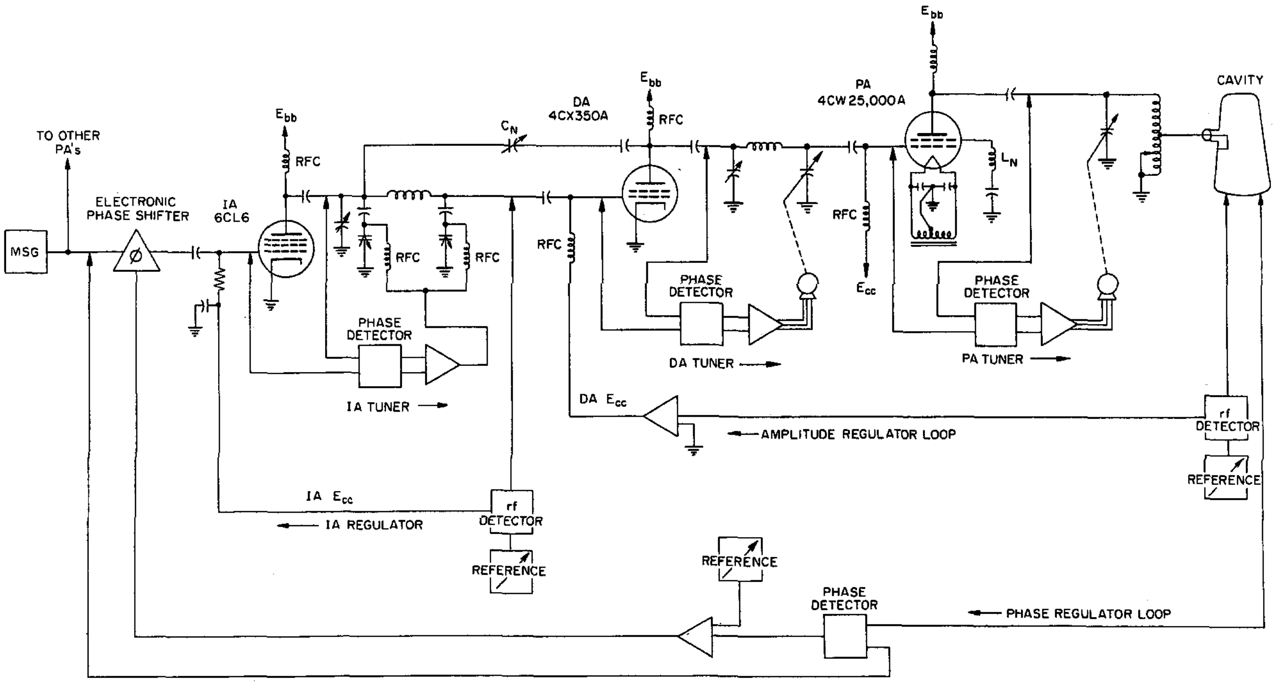

Fig. 1 Simplified schematic diagram of a typical SOCE 15-kW power amplifier unit.

The first amplifier stage or intermediate amplifier (IA) is a 6CL6 pentode with a grounded cathode and a pi network plate circuit. The main tuning capacitor is manually adjusted for coarse tuning. The varactors (for fine tuning) are coupled to an automatic tuner which can cover a frequency range of approximately f_o ±0.8 MHz (f_o is normally 49.18 MHz). Grid bias for the IA is derived from the difference between the output of an rf detector in the plate circuit and a dc reference voltage, thereby stabilizing the output voltage within about ±5% of the required 30-volt peak rf level.

The second stage or driver amplifier (DA) is an Eimac 4CX350A tetrode in a grounded-cathode circuit. A variable capacitor between the DA plate and the IA plate provides rf feedback for neutralization. The DA is a high gain class AB_1 stage capable of about 300 watts of output rf power. The grid bias is controlled by the cavity rf voltage amplitude regulator. A bias range of -60 V to -30 V swings the DA output from 0 to 300 watts.

The DA plate tank circuit is a stripline pi network with a DA plate/PA grid voltage ratio of 3/1. The tuning capacitor on the DA side of the network is manually controlled for coarse tuning. The tuning capacitor on the PA side is servo-controlled for fine tuning. The pi-network Q is intended to be around 20 to 25, with about 1/3 of the circuit losses in the copper stripline and 2/3 in the PA grid. In the event that the PA grid is more efficient than expected, aluminum will be substituted in the stripline.

The final stage (PA) is an Eimac 4CW25,000A tetrode in a grounded cathode configuration with screen neutralization. The 25-kW plate dissipation rating makes this tube somewhat oversized for a 15-kW amplifier, but with the water cooled plate it is more compact than most air cooled tubes in the 10 to 15 kW size range, such as the 4CX15,000A and the 4CX10,000A. The 4CW25,000A is only slightly more expensive than the latter two types.

The PA plate circuit is a quarter wave stripline with both a movable shorting plane and a variable shunt capacitor for tuning. The capacitor is servo-tuned. The shorting plane is manually tuned, but may be modified for automatic tuning. The cavity drive loop will eventually be connected to a fixed low impedance tap on the stripline. The output impedance can be varied by adjusting the shorting plane and retuning the PA plate with the shunt capacitor.

The prototype PA unit is shown under construction in Fig. 2 and with its covers in place in Fig. 3. The enclosure is 44 in. long, 38 in. high and 13 in. deep. Each unit will be mounted on the side of its corresponding rf cavity, with only a few inches of line between the drive loop and the PA plate tank. Controls, power supplies, and metering will be remotely located. The L-shaped top compartment contains the PA plate circuitry. The 4CW25,000A is on the right with the plate blocking capacitor concentrically mounted. The stripline is on the left, and the plate rf choke and water columns are in the screened area on the upper right. The

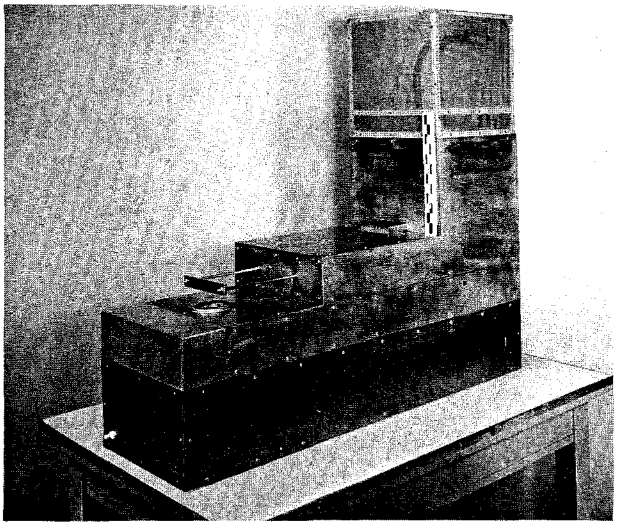

Fig. 2 The prototype 15-kW rf power amplifier.

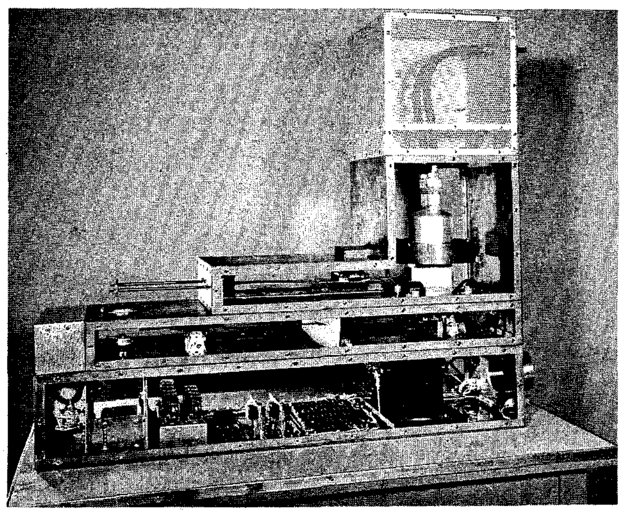

Fig. 3 The prototype 15-kW rf power amplifier, with covers removed.

middle horizontal compartment contains the DA plate-PA grid pi network. The polyethylene panel standing perpendicular to the stripline (halfway between the PA and DA) is an air flow barrier. The lower horizontal compartment contains the IA on the left, interlock relays and servo amplifiers in the center, and power terminals and the PA filament transformer on the right. Coolant air enters the lower compartment on the left and exhausts through screened openings above the DA tube and above the PA tube.

Tuning Servos

Automatic tuning devices are required throughout an SOC rf system due both to the rf cavity phase stability requirements and to the large number of components requiring tuning. Within each PA unit, tuning servos minimize phase errors across each amplifier stage, while phase regulator loops control the accumulative phase errors between the MSG and each rf cavity.

In each tuning servo the phase detector is a 75-ohm four-arm coaxial hybrid with an rf detector on each of the two output legs (see Fig. 4). For the IA tuner, the two input legs are connected via equal length 75-ohm lines and voltage dividers to the grid and plate respectively. The detectors' summing point swings negative for negative phase error or positive for positive phase error; it nulls when 180° phase shift is obtained across the amplifier. The detector swings about 5 mV/degree of phase error for normal input signals of 1 volt peak rf on each leg.

In the IA tuner, the error signal from the phase detector is amplified in a Fairchild ADO-13 operational amplifier, with a booster stage on the output providing bias voltage for the varactors in the IA plate-DA grid pi network. The loop gain (~60 db) maintains phase stability within ±5° for an rf tuning range of 49.18 ±0.8 MHz. For a plate circuit Q of about 20, the improvement factor (ratio of phase shift without tuner to phase shift with tuner) is about 5.

The amplified phase error signal in the DA tuning servo drives a complimentary pair of Schmitt triggers. One trigger has a +2 volt threshold while the other has a -2 volt threshold. The trigger levels correspond to phase errors of ±4°. The triggers operate relays K1 and K2 (Fig. 4(b)) which control the Bodine hysteresis motor which drives a tuning capacitor. DC motor braking is employed for damping purposes. The PA tuning servo is identical to the DA tuning servo.

Both the IA tuner and DA tuner have been operated on the prototype PA unit and appear to be quite stable. It will probably be possible to increase the loop gain on these tuners with further reduction in maximum amplifier phase error. An increase in the rf voltage input to the phase detectors causes proportional increases in error signals, thereby reducing the phase error.

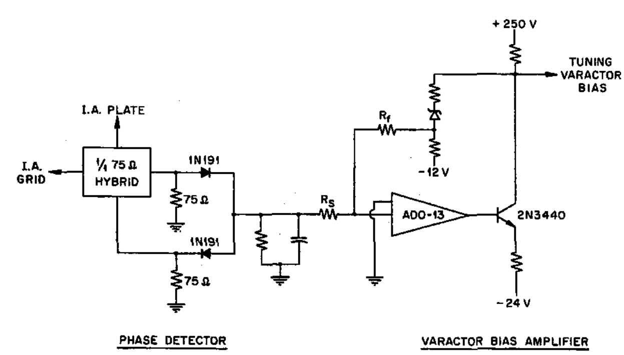

Fig. 4(a) Simplified IA tuner.

Cavity Phase Control

The accumulative phase error between the MSG and the cavity drive loop will be held to less than ±15° by the tuning servos associated with each amplifier stage. Cavity tuning information is not yet available but it is expected that the phase error with respect to the drive loop will be less than ±10°. To hold the cavity voltage within a phase error of ±1° with respect to the MSG, an additional correction device will be inserted between the MSG and the IA grid as shown in Fig. 1.

The cavity phase regulator is shown in greater detail in Fig. 4(c). The phase control element is a Merrimac PSE-3-50 electronic phase shifter which is capable of covering a range of ±60° with a dc-bias swing of 1.5 V to 13.5 V. The bias is obtained from a phase detector and amplifier arrangement similar to that used in the IA tuning servo. A loop gain of ~60 db is required with phase detector input signals of 1 V peak rf.

Amplitude Control

The cavity voltage regulator loop is shown in Fig. 1 with an rf detector on the cavity feeding an error signal to an operational amplifier that provides grid bias for the DA. The dc reference voltage for the detector will be obtained from a master source so that the rf voltage on all cavities will be simultaneously variable. An addition vernier control for each PA unit will permit adjustments for individual cavities.

Provisions will be made for coupling error signals from ion beam position probes to the voltage amplitude regulator loops so that the ion beam will be centered in its proper orbits. Transient protection devices, which reduce rf drive during cavity sparking or amplifier overload conditions, will also be incorporated in the loop. The amplitude control circuitry for each PA will be similar to that previously described for the ORIC rf system.[7]

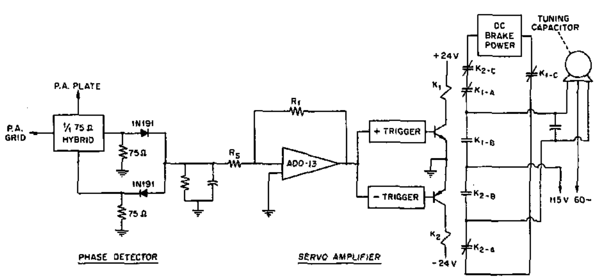

Fig. 4(b) Simplified tuning servo for PA and DA.

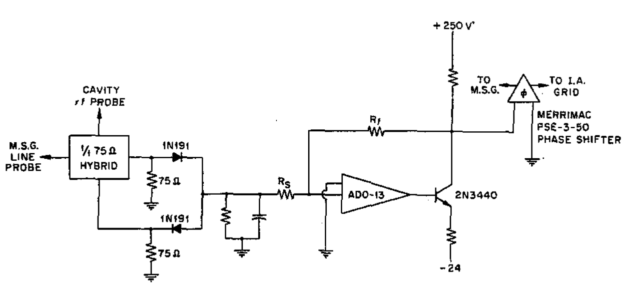

Fig. 4(c) Simplified cavity phase regulator.

Conclusion

The IA and DA stages of the prototype power amplifier unit have been tested at full power with their tuner loops and the IA regulator loop in operation. The PA stage will be tested at full power driving a dummy load in the near future. At that time the phase and amplitude regulator loops will be closed. Tests with an rf cavity await completion of the first of the SOCE cavities several months from now. As soon as the PA has been successfully operated at full power, fabrication of the remaining ten units will begin.

The planned PA rf output capability will be sufficient to obtain a 10-mA ion beam in the SOCE. If experiments with higher beam currents are desired, a threefold increase in beam power will be possible with the addition of an extra plate power supply for the final amplifier stages.

Although the 15-kW PA has been designed specifically for the SOCE, it will also make an excellent driver stage for the 500-kW 6949 power amplifiers which have been planned for the 50 MeV SOC. The various automatic tuning and phase control techniques developed for the SOCE will be directly applicable to the other SOC-type accelerators which have been under study.

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