A CYCLOTRON POWER-AMPLIFIER RF SYSTEM USING A 4CW50,000/8350 TETRODE

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Summary and Introduction

The radio frequency system of the University of Colorado 52" cyclotron has been described at earlier stages in its evolution.[1-4] The purpose of the present report is to describe a major change in the power amplifier and other changes in the control circuits, and to report operating experience with the system. Table 1 lists some of the parameters of the system.

The change in the power amplifier resulted in an appreciable simplification. Excluding the dee resonant circuit, there is now only one circuit in the rf system requiring remote tuning. The dee voltage control circuit incorporates current limiting protection for the power amplifier tubes to prevent damage to the system by inexperienced operators. The system is particularly easy to operate. After the operator has set the system up on the operating frequency and the dee voltage control is set to the desired value, the dee voltage is turned on and off by means of two push buttons, and requires no other attention. Changes in frequency require from one to ten minutes, depending on the distance that the short must be moved.

The Power Amplifier

The rf power amplifier has been rebuilt, using a modern ceramic and metal tetrode (8350) in place of the venerable glass triode (ML 5681) formerly used. The large reduction in feedback capacitance makes it possible to realize a much larger power gain in the final power amplifier thus reducing the required driving power. The complete system, from master oscillator through the dee resonant circuit, is illustrated in Fig. 1. The master oscillator, the frequency multipliers, and the 8321 amplifier are located on a single chassis in the control desk. The 8168 and 8350 power amplifiers are located in a cabinet mounted on the dee stem tank carriage in the cyclotron vault. The plate circuit of the 8168 and the dee resonant circuit are the only ones requiring remote tuning. All tube voltages are applied automatically in a timed sequence when the system is turned on, including the plate voltage (15 kV) for the 8350. The only exception is the power supply which provides plate voltage to the 8168 and the screen grid bias to the 8350. This voltage is used as the on-off control for dee voltage. The lower power stages operate continuously.

The power amplifier and the dee resonant circuit are shown in detail in Fig. 2. The cable carrying the signal from the control console to the grid of the 8168 is terminated in its characteristic impedance.

A bridge-type neutralization circuit couples the 8168 plate to the 8350 grid. The neutralization capacitor C_n was originally adjusted by removing the plate and screen grid voltages from the 8350, applying full drive signal to the grid, and adjusting C_n for minimum rf voltage on the 8350 plate. The adjustment was later refined by adjusting C_n for coincidence of maximum dee voltage and minimum plate current as the dee was tuned through resonance. Both adjustments were made at 16 Mc/s, and later checked at 20 Mc/s. With the loading resistor, the interstage circuit Q ranges from 10 at 7 Mc/s to 30 at 21 Mc/s, so the neutralization adjustment is not critical.

The plate of the 8350 is coupled to the dee resonant circuit by a fixed capacitance of approximately 15 pF located in the magnet gap. The capacitor (3) and the resistor (4) in Fig. 2 serve to isolate the transmission line from the dc plate voltage. If this is not done, a Phillips-Ion-Gauge-type discharge can start in the magnetic field inside the vacuum tank near the positive transmission line. The discharge electrons will migrate along the transmission line to the ceramic window where it leaves the vacuum, damaging the window. An electron trap was constructed to "dump" these electrons. However, on one occasion, probably due to poor vacuum, the trap was melted and the window was ruined. It therefore seemed prudent to remove the dc voltage from the transmission line.

Dee Voltage Control

The primary purpose of the dee voltage control circuit is to maintain the dee voltage at the value set by the operator on the 10 turn potentiometer at the control console. The circuit also stabilizes the dee voltage against power supply ripple and variation in beam loading, and it protects the power tubes from plate current excesses. Control of the dee voltage is by means of a shunt tube to ground on the 8168 screen grid. The modulation amplifier is shown in Fig. 3, along with the current-limiting amplifiers which limit the anode dissipation in the 8168 and 8350 tubes. The dee voltmeter diode and the outputs of the two current-limiting amplifiers form a logical "or" gate for the linear signals, thus allowing each of the three possible controlling signals (dee voltage, 8168 cathode current, and 8350 cathode current) to limit the output of the 8168 amplifier stage. Under normal operating circumstances, the signal controlling the modulation is derived entirely from the dee voltmeter, and the outputs from the current-limiting amplifiers are completely cut off. As a result of these circuits improper tuning cannot damage the power tubes.

The conservative power levels at which this system operates allow the use of a fixed reference voltage for the current-limiting amplifiers. In another system it might be desirable to let the reference voltage vary with the rf plate voltage so that plate dissipation would be limited to a constant value. Then the tube would be protected when the plate circuit was tuned off of resonance and yet full power would be available when the plate circuit was properly tuned.

Other signals may be applied to the "or" gate at the input of the modulation amplifier. The current-injecting circuit shown in Fig. 3 has been used to pulse the cyclotron beam for short half-life experiments. The dee voltage is depressed about 1% for each 10 μA of injected current, and because a balance is maintained at the input of the amplifier, the recovery time is limited only by the bandwidth of the dee voltage control system.

The Frequency Servo

The dee resonant circuit is equipped with a trimming capacitor, a movable grounded blade which faces one edge of the dee. As it moves, it changes the capacitance between the dee and ground. It is capable of changing the resonant frequency by approximately 1%. The trimming capacitor is driven by a Minneapolis-Honeywell servo motor and amplifier. The error signal for the servo is produced by a phase detector which compares the phase of the plate voltage of the 8350 tube with the phase of its grid voltage. The phase detector which has been developed for this purpose is independent of frequency, and is shown in Fig. 4. It consists of a pair of limiting amplifiers, which produce square waves in phase with the grid and plate voltages of the 8350, some resistor-inductor differentiating circuits which produce positive and negative voltage pulses of a few nanoseconds width at the time of the positive and negative zero-crossings of the signal voltages, and a non-saturating flip-flop of conventional design, capable of operation at a rate considerably faster than the highest rf frequency to be used. The negative pulses set and reset the flip-flop at the rf rate, with the duration of the "one" state determined by the relative phase of the grid and plate signal voltages. In the desired situation, when the plate signal is 180° out of phase with the grid signal, the flip-flop spends equal periods of time in the two possible states, while a capacitive or inductive load in the plate circuit will cause the flip-flop to spend more time in one of the states than it does in the other. The signal from one side of the flip-flop is filtered and applied to the dc servo amplifier which drives the compensating capacitor. A resistance in series with the negative supply voltage to the flip-flop is used as a fine adjustment of dee tuning.

The frequency servo is automatically disabled unless the dee voltage is 20 kV or more. Manual push buttons allow the operator to run the compensator in or out until reaching a dee voltage of 20 kV, at which time the servo takes over and completes the tuning. It is necessary to disable the servo because below a dee voltage of 15 kV, the flip-flop will remain in one state and only if the dee circuit happens to be tuned to the low frequency side of resonance will the servo run in the proper direction.

Although the phase detector is mounted six feet from the acceleration chamber on the median plane of the cyclotron, 1500 hours of operation have resulted in only slight changes in the characteristics of the transistors.

Operating Characteristics and Experience

The installation of the 8350 tetrode as the main power amplifier tube took place in May, 1964. Since that time, cyclotron operation has been largely restricted to nighttime operation due to construction of a building addition. Nevertheless, there is sufficient experience with the new tube to allow the presentation of some statistics. Rf system "down time" is defined as the time when cyclotron runs were delayed or inconvenienced by rf system malfunctions. During the first 1500 hours of system operation, the down time for the three 500 hours segments was 6.8%, 4.4%, and 0.6% respectively.

The cyclotron was initially put into operation in April, 1962. Some experiences since that time regarding reliability of components deserve comment. During the evolution of the final stage power amplifier, vacuum capacitors have been used in various ways in its plate circuit. None has been found to stand up satisfactorily. Another design problem of considerable concern was the design of the electrical contacts on the movable short. It was decided to use Eimac grid collet (which is .020" thick in contrast to their regular line of finger stock which is .010" thick) mounted on water cooled copper blocks which clamped it positively against the dee stem. The dee stem surface was silver-plated copper which was also water cooled. The shorting plane as originally installed has been in service for nearly three years and has performed flawlessly. There is no discoloration or other indication of heating of the contacts, despite routine operation to 110A/in and occasional operation to higher current densities.

References

1. W. R. Smythe, National Academy of Sciences - National Research Council Publication 656, P. 167-170 (1959)
2. D. A. Lind, J. J. Kraushaar, Rodman Smythe, and M. E. Rickey, Nuclear Instruments and Methods <u>18</u>, <u>19</u>, 62-65 (1962)
3. Rodman Smythe, Nuclear Instruments and Methods <u>18</u>, <u>19</u>, 582-583 (1962)
4. J. J. Kraushaar, D. A. Lind, M. E. Rickey, and W. R. Smythe, European Organization for Nuclear Research (Cern) Report 63-19, P. 31-38 (1963)

Table 1.

Parameters of the rf system of the University of Colorado Cyclotron.

Magnet Pole Diameter	52"
Beam Extraction Radius	23.6"
Electrode	Single 180° Dee
Maximum Operating Dee Voltage	80 kV
Frequency Range	7.5-21.3 Mc/s
Dee to Liner Spacing	1.22"
Capacitance of Dee	525 pF
Resonator Type	Coaxial Line
Resonator Tuning	Movable Short
Dee Stem Diameter	10.00"
Dee Stem Tank Diameter	40.00"
Movable Short Travel	100"
Maximum Operating Current Density at Short (21 Mc/s)	120 A/in (rms)
Coupling to Dee	Fixed Capacitance
Power Tube	Eimac 8350/4CW50,000C
Driver Tube	Eimac 8168/4CX1000A
Plate Power Supply (Unregulated)	15 kV, 10 A
Master Oscillator (1.5 to 3.0 Mc/s)	Collins 70H9

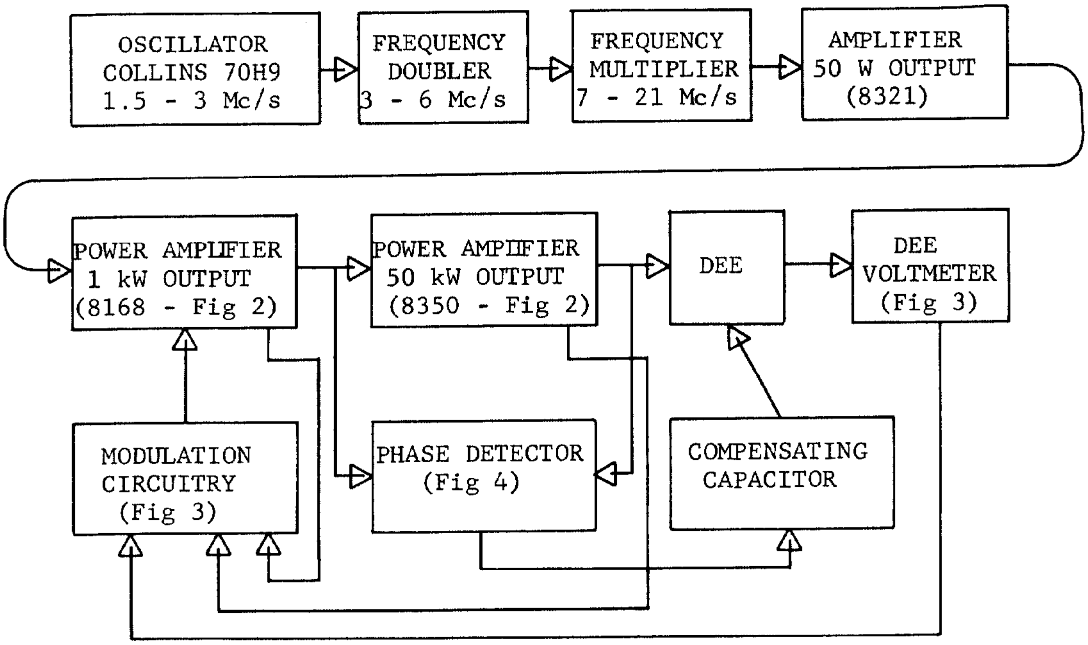

Figure 1.

The RF System.

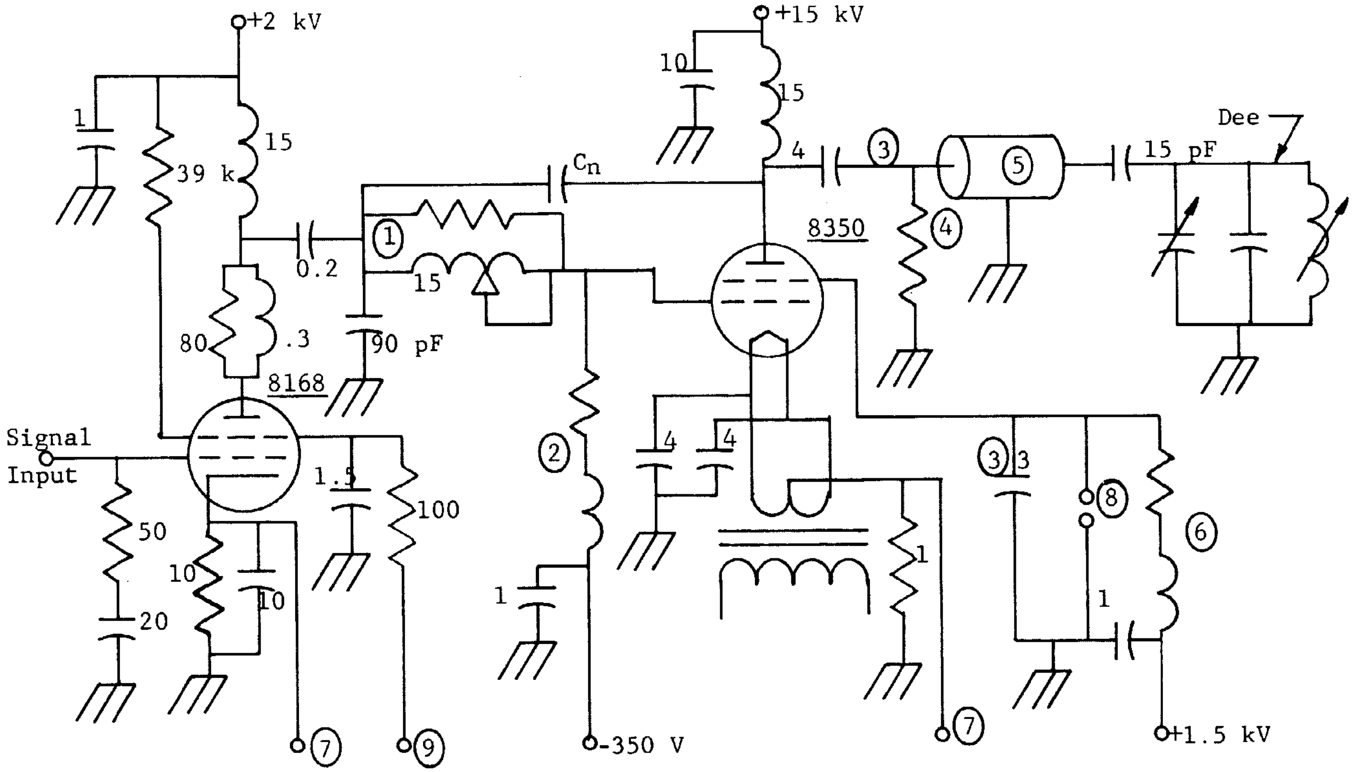

Figure 2. Power Amplifier Detail. Resistors in ohms, capacitors in nanofarads, and inductors in microhenrys unless noted.

1) 3.2 k, 1 kW, 4 ea. Corning Glass works type HL-250.
2) 1 k, 250 W, wirewound resistor, measured inductance 320 μH.
3) Paralleled Centralab type 859S-500N.
4) Water Resistor
5) Transmission Line eight inch dia. three ft. long
6) 250 ohm, 250 W wirewound resistor, measured 83 μH.
7) To cathode current meters and current limiting amplifiers (see figure 3).
8) Spark gap, 6 kV.
9) From modulation amplifier output (see figure 3).

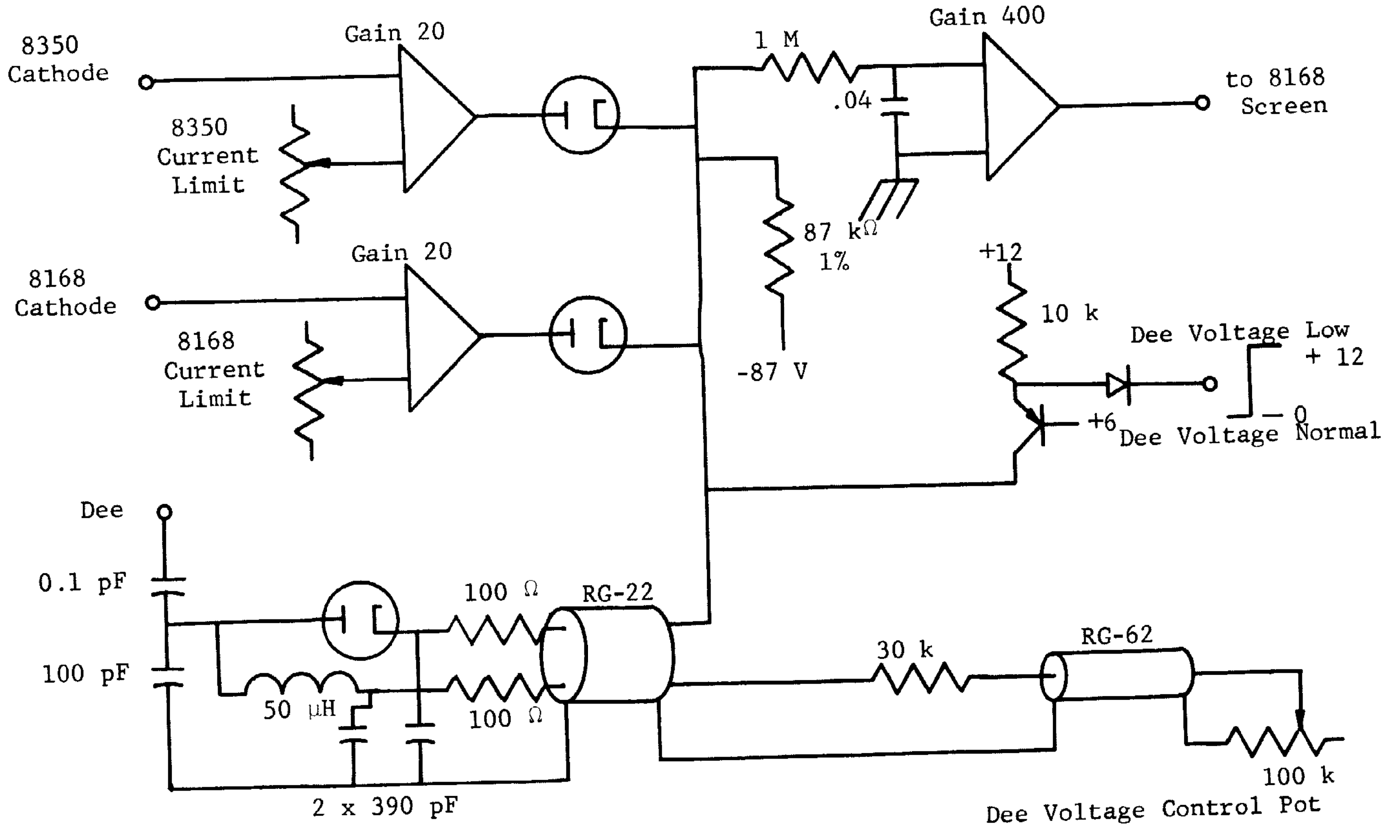

Figure 3.
Dee Voltage Control Circuitry.

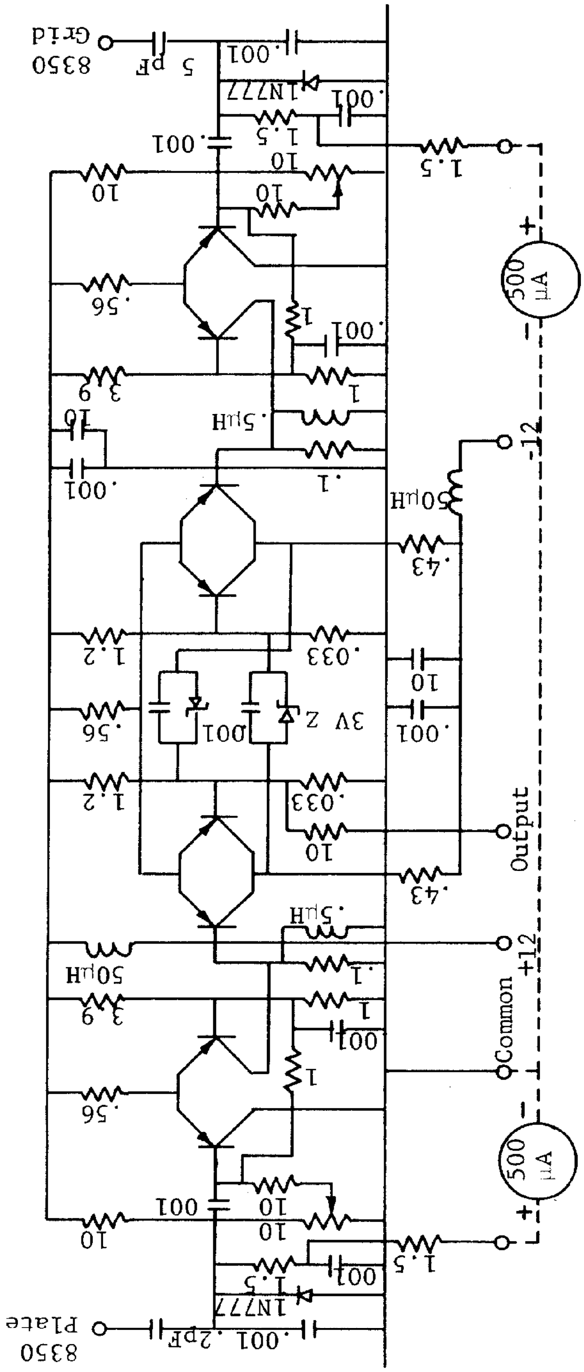

Figure 4.

The Phase Detector.

The signal pickoff capacitors are adjusted to provide 200-300 microamperes on the external meters. Transistors are 2N964; capacitors in microfarads, resistors in k ohms.