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ABSTRACT

Three cloverleaf cyclotrons employing three dees excited by three-phase rf were built. The phase generator that was used to produce the three-phase rf, the servomechanisms and phase control equipment that were used to maintain the dees in tune, and the relationship of the electrical characteristics of the resonator to the control problem, are discussed.

The rf systems were built in 3-kw and 37-kw sizes and could be extended to produce many megawatts of power, if necessary, by employing larger vacuum tubes. Cloverleaf cyclotrons appear to be capable of producing megawatts of beam power with an rf efficiency greater than 70%.

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INTRODUCTION

Conventional fixed-frequency cyclotrons are limited to low energies because of the inability to simultaneously provide the necessary focusing conditions and maintain the phase relations between the particles and rf voltage that are necessary for energy gain. The frequency-modulated cyclotron reconciles these requirements but is subject to a duty-cycle limitation, which prevents it from delivering large currents.

In 1938 L. H. Thomas[1] showed theoretically that a fixed-frequency machine with suitable azimuthal periodicity in the magnetic field meets all the requirements for acceleration of particles to relativistic energies. Accelerators of this latter type were studied by the theoretical[2] and experimental[3, 4, 5] groups at Berkeley, and two electron models were built. A third machine,[6, 7] a 20-inch proton cyclotron without azimuthal variation of the magnetic field, was built in order to study rf and ion-source problems.

The second electron model was an eighth-scale model of a proposed 300-Mev deuteron machine, and was complete in every essential detail. The radial and axial focusing of the magnetic field were sufficiently strong to prevent any beam from being lost to the poles or accelerating electrodes at large radii, even for electrons that did not start on the median plane. This property and the low-threshold dee voltage indicate that the full-scale machine would convert a large fraction of the rf power into beam power. This figure probably would exceed 70% for beam currents above 10 milliamperes.

Figure 1 shows the cloverleaf-like shape of one of the pole pieces of the second electron model. The geometry of the magnetic poles suggests the use of three dees, placed in the valleys out of the way of the beam and excited by three-phase rf (see Fig. 2). This construction does not require the minimum magnetic gap to be any greater than the dee gap, and greatly reduces the number of ampere turns required by the magnet.

In the beginning of the rf development program an attempt was made to develop a self-excited three-phase rf system. Although three-phase oscillators[8] are not new, there is comparatively little in the literature about them. Two successful three-phase oscillators were built, but were abandoned in favor of a driven rf system, which seemed to lend itself better to the study of cyclotron beam dynamics.

The first rf system that was actually applied to a machine derived the three phases by means of delay lines each differing in length from the next by 120 electrical degrees. The delay lines were excited by a crystal oscillator and the voltages appearing across the line terminations were amplified and applied to the dees. Three servo systems were employed, two of which maintained the desired phase relations between the dee voltages while the third maintained the final amplifiers at maximum efficiency. Later the delay lines were replaced by a phase generator, which permitted adjustment of the phase angles without changing the magnitude of the output voltages.

Only the three servos that control the resonator are absolutely essential; the phase drift in the rf amplifiers can be made negligible by suitable design of the tuned circuits. There are advantages in controlling the phase of the grid voltages of the final amplifiers for very high-powered machines. Such control permits the use of tuned circuits with higher Q and lower surge impedance, which facilitates the amplifier design. Grid servos were employed on the 20-inch proton machine which delivered 37 kw but were not used on the electron machines. Figure 3 is the block diagram of the complete three-phase rf system.

Experience gained from the machines indicates the following servo parameters are suitable: (1) The loop gain should be such that one degree of phase error will apply full power to the servo motor. (2) The speed of response should be such that the trimmer will shift the resonant frequency of the dee 1% in one minute. (3) The dee trimmer should have sufficient range to shift the resonant frequency 2%. These parameters are not minimum requirements; they are values that provide essentially perfect performance, and are easily achieved.

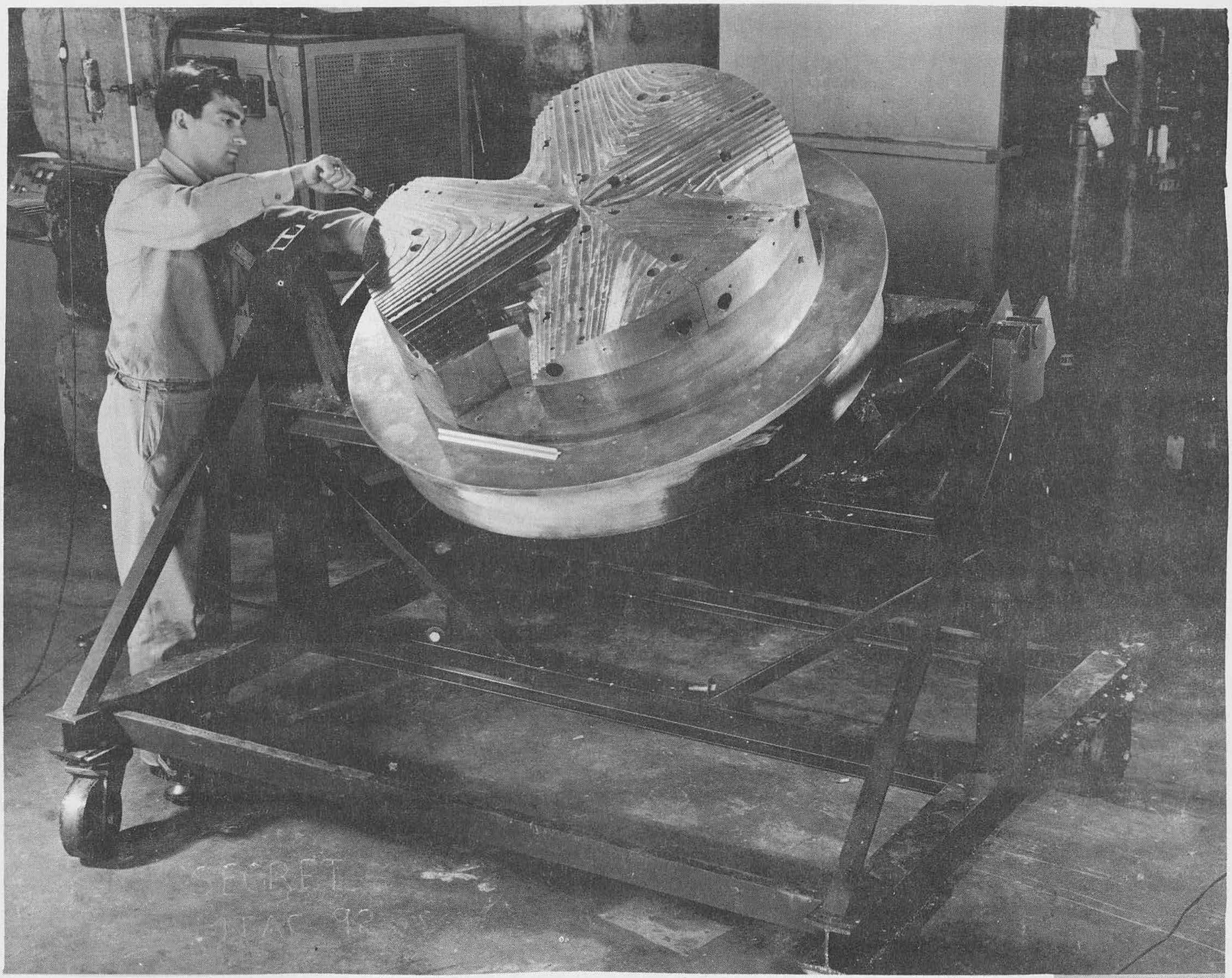

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Fig. 1. One of the magnet pole tips of the second electron model. Note the cloverlike shape from which the machine derives its name.

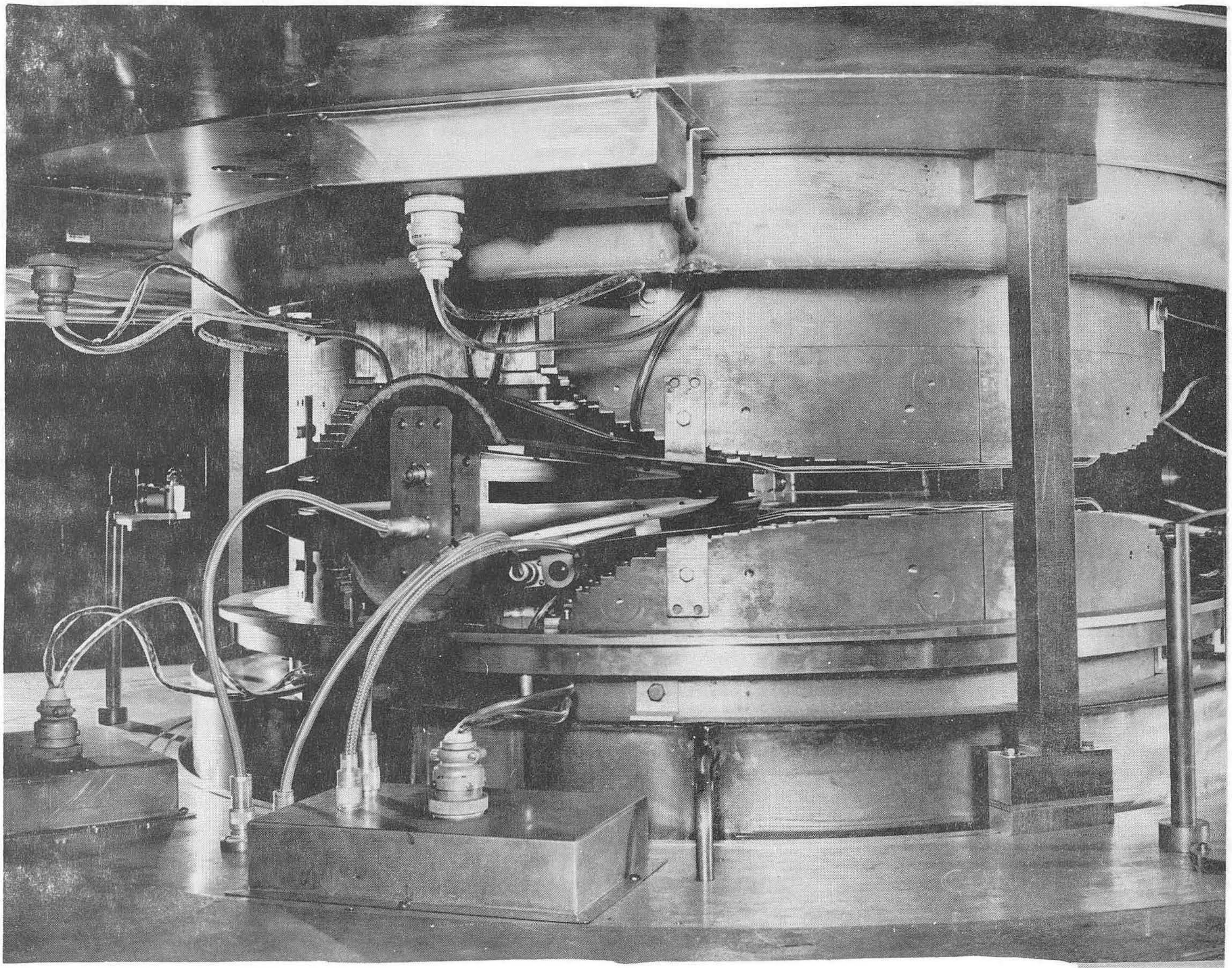

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Fig. 2. The geometry of the magnetic poles suggests the use of three dees, placed in the valleys out of the way of the beam. This construction permits the minimum magnetic gap to be no greater than the dee gap, and greatly reduces the number of ampere turns required by the magnet.

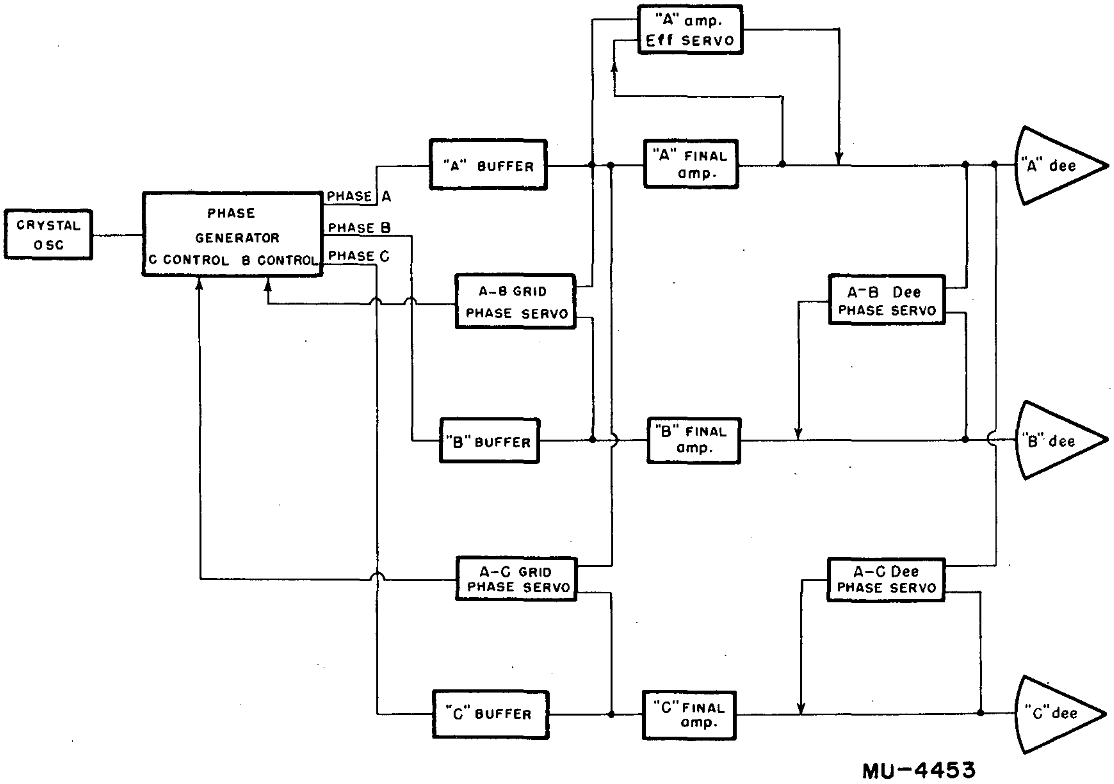

Fig. 3. Block diagram of three-phase rf system.

THE PHASE GENERATOR

The circuit of the phase generator is shown in Fig. 4. It derives its input signal from a crystal oscillator and produces three output signals, nominally spaced in phase by 120°. Two of the output signals may be adjusted through a range of approximately 160° without any change in magnitude. This device is based upon the rather interesting property of a 45° transmission line that the magnitude of the input impedance is independent of the terminating load resistance. Specifically, the input impedance of a 45° line is

$$Z_i = Z_o e^{j\theta}, \quad \text{where } \theta = \tan^{-1} \frac{1}{2} \quad \frac{Z_o}{R_L} - \frac{R_L}{Z_o} .$$

Hence, if the line is excited from a constant current source the magnitude of the voltage appearing across the input of the line is constant but the phase of the voltage depends upon the load resistance. In channel B of Fig. 4 the line is excited by a constant current which leads the input voltage by 60°. As a result of the 180° phase shift through the vacuum tube, phase B appears to lag phase A by 120°, if $R_L = Z_o$, and of course may be adjusted either side of this value. Phase C is produced in the same way except that the line in this case is excited by a constant current that lags the input voltage by 60°.

For the 20-inch cyclotron, which operated at 11.2 Mc, the 45° transmission line consisted of a little over seven feet of RG 58/U cable. R_L was a 250-ohm 2-watt carbon potentiometer driven by a servo motor.

THE SERVO SYSTEMS

The phase signals were obtained from pickup loops placed in the inductive portions of the dee resonators. The signals were transmitted to the electronic equipment by means of unterminated coaxial cables (RG 8/U) cut to even multiples of a half wave length.

The first stage of the control equipment consisted of a diode-type frequency converter[7] that was developed specifically for the purpose. It has three important properties. First, phase is preserved, i.e., a 1° difference in phase between the rf signals shows up as a 1° difference between the intermediate frequencies. Second, the amplitude of the

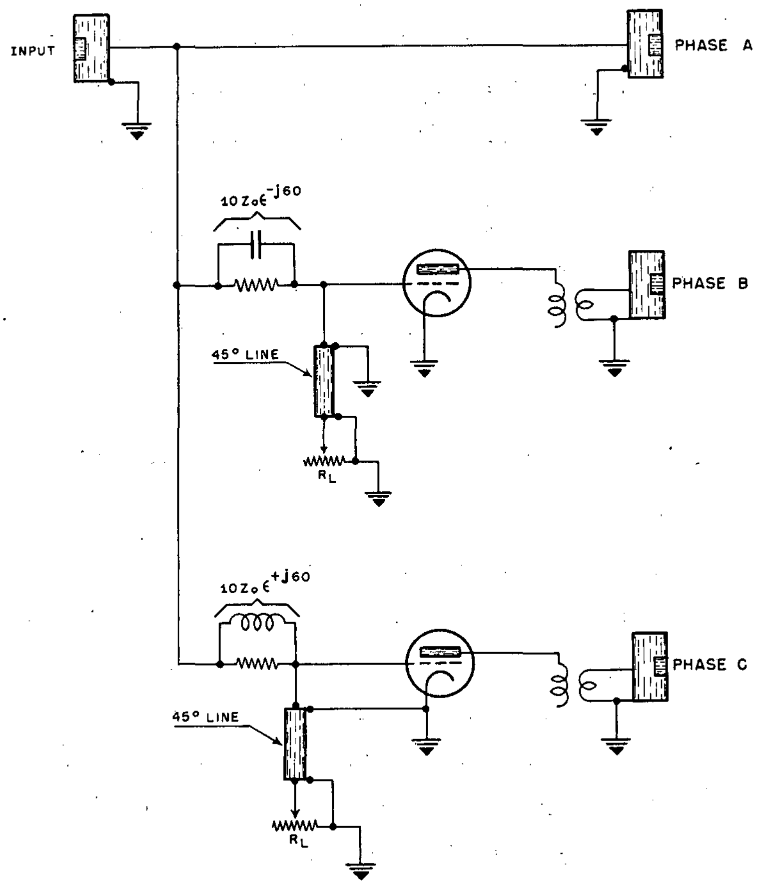

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Fig. 4. The Basic Circuit of the Phase Generator.

A 45° transmission line has the property that the magnitude but not the phase angle of the input impedance is independent of the terminating resistance. Hence, phase B or C may be shifted either side of the nominal 120° position without change in the voltage amplitude.

intermediate frequency is exactly equal to the magnitude of the local oscillator signal and entirely independent of the magnitude of the phase signals. Thus, the loop gain of the control system is independent of cyclotron operation. Third, there is an antinoise circuit which extracts the desired signal from the rf noise produced by the arc source and dee vibration.

The intermediate frequencies were amplified and applied to the phase detector,[7] which--like the frequency converter--was especially developed for this application. It adds the two voltage vectors and compares magnitudes in such a way that a null occurs for a phase angle of 120°. The output voltage is positive for angles less than 120° and negative for angles greater than 120°. The phase detector is quite sensitive and produces an output signal of 0.76 volt for a phase error of 1°. This signal drives a standard servo amplifier which controls the dee trimmer.

THE CHARACTERISTICS OF THE RESONATOR

The dee stems are foreshortened, shorted transmission lines loaded by the dee-to-ground and dee-to-dee capacitances. Over the narrow frequency range that the machine tunes, one may without serious error consider the stem as a lumped inductance and the dees as capacitances. In addition, of course, the skin losses and beam power may be represented by resistances. Assuming the validity of these assumptions we have the equivalent circuit of the resonator as shown in Fig. 5.

Physically, the dee-to-dee capacitances are concentrated near the tips of the dees. Since the source is placed between two of the dee tips the capacitance between these is appreciably lower than the capacitances between the others. This has serious consequences, as one can see from the vector diagram of Fig. 5.

Consider the currents flowing from "A" stem through the dee-to-dee capacitances. Each current leads the voltage across the respective capacitance by 90°. If the currents are not of equal magnitudes their sum has a component inphase with the voltage of "A" stem and therefore represents a power flow from "A" stem. While the dee-to-dee currents are small compared with those from dee to ground, the inphase component can be very large compared with the inphase components of dee-to-ground currents because of the high resonator Q.

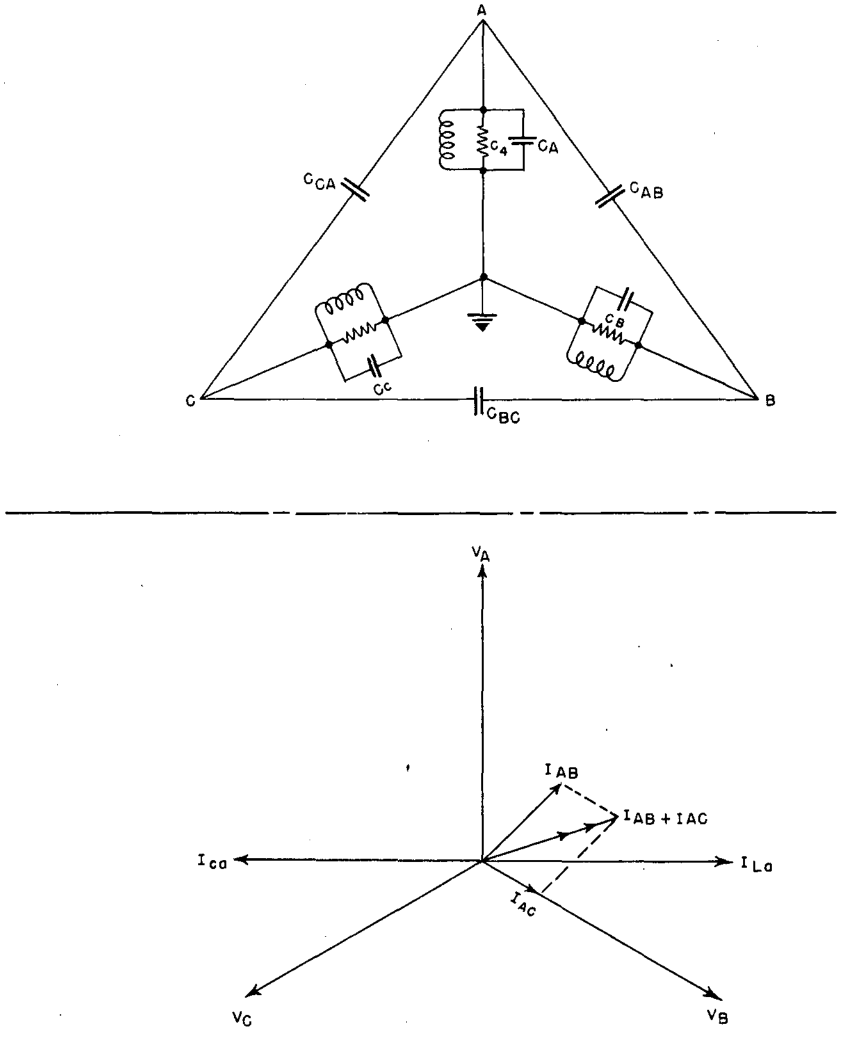

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Fig. 5. The currents flowing from "A" stem through the dee-to-dee capacitance lead their respective voltages by 90°. If they are not of equal magnitude their sum has a component inphase with the voltage of "A" stem and represents a power flow to one of the other dees. This condition, which may be intolerable, can be avoided through the use of neutralizing lines.

Physically, this means that if the dee-to-dee capacitances are not balanced, power will flow from one dee to the other. It is entirely possible for amplifier "A" to deliver more power to one of the other dees than to its own. Such a condition, of course, would be most uneconomical, but if this were the only objection it would be a simple matter to connect trimming capacitors from dee to dee in order to provide balance. The most serious objection to the dee-to-dee capacitance is the coupling between servo systems which it provides. The problem of servo stability becomes insuperable. Fortunately, the dee-to-dee capacitances can be neutralized, and this is the key to three-phase rf.

THE THEORY OF NEUTRALIZATION

The simplest way to provide neutralization is to connect inductances across the dee-to-dee capacitances, making the circuits antiresonant. Then there can be no power flow from dee to dee, and the machine is neutralized. This was done in the case of the 36-inch electron model and it worked very satisfactorily. However, in large machines the Q's of the resonators are very high and it is difficult to build inductances with sufficient Q to prevent power transfer. Probably the problem of holding voltage across such an inductance would be prohibitive also.

The method that was used on the 20-inch machine and that would be used on any high-voltage machine makes use of neutralizing transmission lines connected from dee stem to dee stem. This is not equivalent to connecting inductances from dee to dee, since it changes the resonant frequency of the resonator whereas the inductance method does not. Another difference is that almost perfect neutralization is possible with ordinary transmission-line losses, whereas it is not possible with ordinary inductance losses.

In practice, it is convenient to couple the neutralizing lines to the dee stems by means of adjustable loops. For the purpose of analysis it is more convenient to assume a direct connection; the two methods are equivalent.

In using loops it is necessary to keep the sense the same at both ends of the neutralizing line. Also, two lines and hence two loops are coupled to each dee stem. Care must be taken to keep the leakage flux to a minimum and to prevent leakage flux from coupling the two adjacent neutralizing lines together. This is accomplished by placing the neutralizing loops close to and preferably on opposite sides of the center conductor.

The three-phase resonator can be built by the superposition of three single-phase resonators. Thus, if the conditions necessary to neutralize the dee-to-dee capacitance between two dees can be determined, the neutralized three-phase resonator can be obtained by superposition.

Consider the circuit of Fig. 6, which represents two dee stems and the dee-to-dee capacitance. Suppose that only one of the two stems is excited as indicated by V_a. We seek that value of V_n which will cause V_B to be zero, i. e., we wish the excitation of "A" to produce no voltage on the other dee.

If V_B is zero then the current through the dee-to-dee capacitance is simply $jV_a \omega C_{DD}$. Applying the transmission-line equations to "B" stem reveals that

$$V_n = V_a \omega C_{DD} Z_o \sin\beta\ell_1 ,$$

$$I_n = \frac{-jV_n}{Z_o} \left(\cot \beta\ell_1 + \cot \beta\ell_2 \right).$$

These values of voltage and current are the load conditions for the neutralizing line. The length of the neutralizing line is chosen to fit the geometry of the machine. Then, the input voltage and current required for the neutralizing line are computed by means of the transmission-line equations, using the above load conditions. As the required input voltage for the neutralizing line is proportional to V_a, it is obtained by tapping to the proper point on A stem.

The three neutralizing lines of the 20-inch cyclotron were identical, and enough range of coupling was allowed to take care of the different dee-to-dee capacitances.

The performance of the neutralizing lines is indicated by the neutralizing coefficients, which are defined as

$$N_{ij} = e_j/e_i,$$

where e_j is the voltage appearing on "j" dee when only "i" dee is excited to a voltage of e_i. It is assumed that e_j is tuned to a maximum at the time

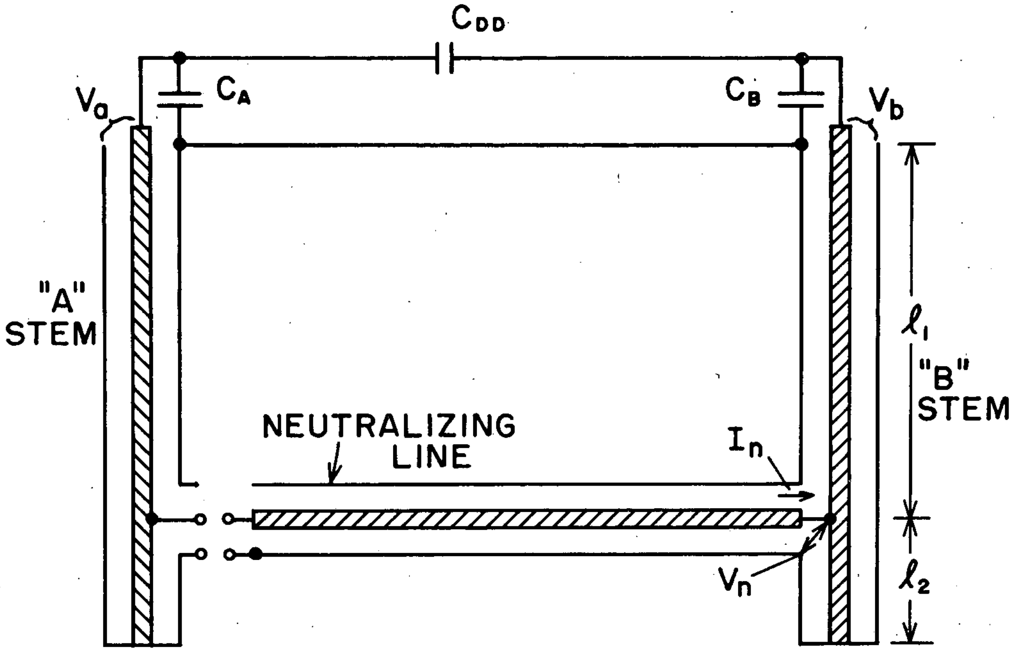

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Fig. 6. Equivalent circuit of two resonators, the dee-to-dee capacitance, and the neutralizing line.

of the measurement. The coefficients for the 20-inch cyclotron were below 3%.

In order to adjust the coupling loops of the neutralizing lines the dee stems were excited one at a time and the loops were adjusted for minimum neutralizing coefficient. It was necessary to do this while the machine was down to air, in order to avoid multipactoring.

CONCLUSION

The problem of producing three-phase rf on the dees of a cyclotron is merely one of electronic control. Two rf systems, producing 3 and 37 kw respectively, were built, and each operated reliably. Once the three dees are isolated electrically by adjusting the neutralizing loops the machine behaves like three separate single-phase systems. In high-power installations, where adequate safety factors are difficult to achieve, the reduction of the rf equipment into three small independent units is indeed a convenience. There does not appear to be any reason why it should not be possible to produce many megawatts of power.

The rf system described in this paper was developed from a basic design of Dr. K. R. MacKenzie.

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Information Division
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