RADIO-FREQUENCY SYSTEM FOR THE MSU CYCLOTRON(*)

W.P. Johnson
Michigan State University, East Lansing

The proposed radio-frequency system for the 64 in. multi-particle cyclotron at Michigan State University consists of two dees, each a quarter-wave resonant line, and a power amplifier capacitively coupled to one dee. The general arrangement of the magnet, dees, and amplifier is shown in Fig. 1. The two 140° dees are separated by RF ground planes so that acceleration can be achieved on even as well as odd harmonics, utilizing the characteristic push-push and push-pull modes of such a system1). Acceleration on all harmonics, of course, reduces the frequency tuning range necessary for multi-energy, multi-particle acceleration, as compared with the tuning range when the even harmonics are not used. The two resonant modes of a two-dee system are easily separated, and a given mode can be excited by proper choice of the driving frequency. The power amplifier includes an anode tank circuit that prevents the final amplifier tubes from driving into a non-resonant load when the dee cavity sparks2).

A full-scale model of the dee cavity and anode tank was constructed to test design concepts. This model has been invaluable in determining the electrical properties of the cavity and in establishing a firm basis for RF techniques being employed.

Dee Cavity

The decision to reduce the frequency tuning range to 13.5 - 21.5 Mc/s by using even-harmonic acceleration has greatly decreased the size of the resonant cavity, and, in our case, gives a consequent reduction in the RF drive power. The cavity is tuned by changing its volume near the short with movable panels as is done at LRL3). Voltage and current distributions along the dee stem are shown for two frequencies in Fig. 2. The two dee stems are isolated from each other to prevent inductive coupling near the short. It was found in the model studies that this inductive coupling could resonate with the dee-to-dee capacitance and effectively isolate one dee from the other. Trimming capacitors on each dee stem provide for fine adjustment of the resonant frequency.

The power amplifier is coupled to the extreme end of one dee by a small capacitor. This coupling position offers high voltage step-up between amplifier and dee, with consequent large step-down for transients travelling toward the amplifier. The gap between dee and capacitor is greater than the dee-to-liner gap so that sparking toward the amplifier is inhibited. In addition, the coupling capacitor is in the

---

(*) Work supported by the National Science Foundation.

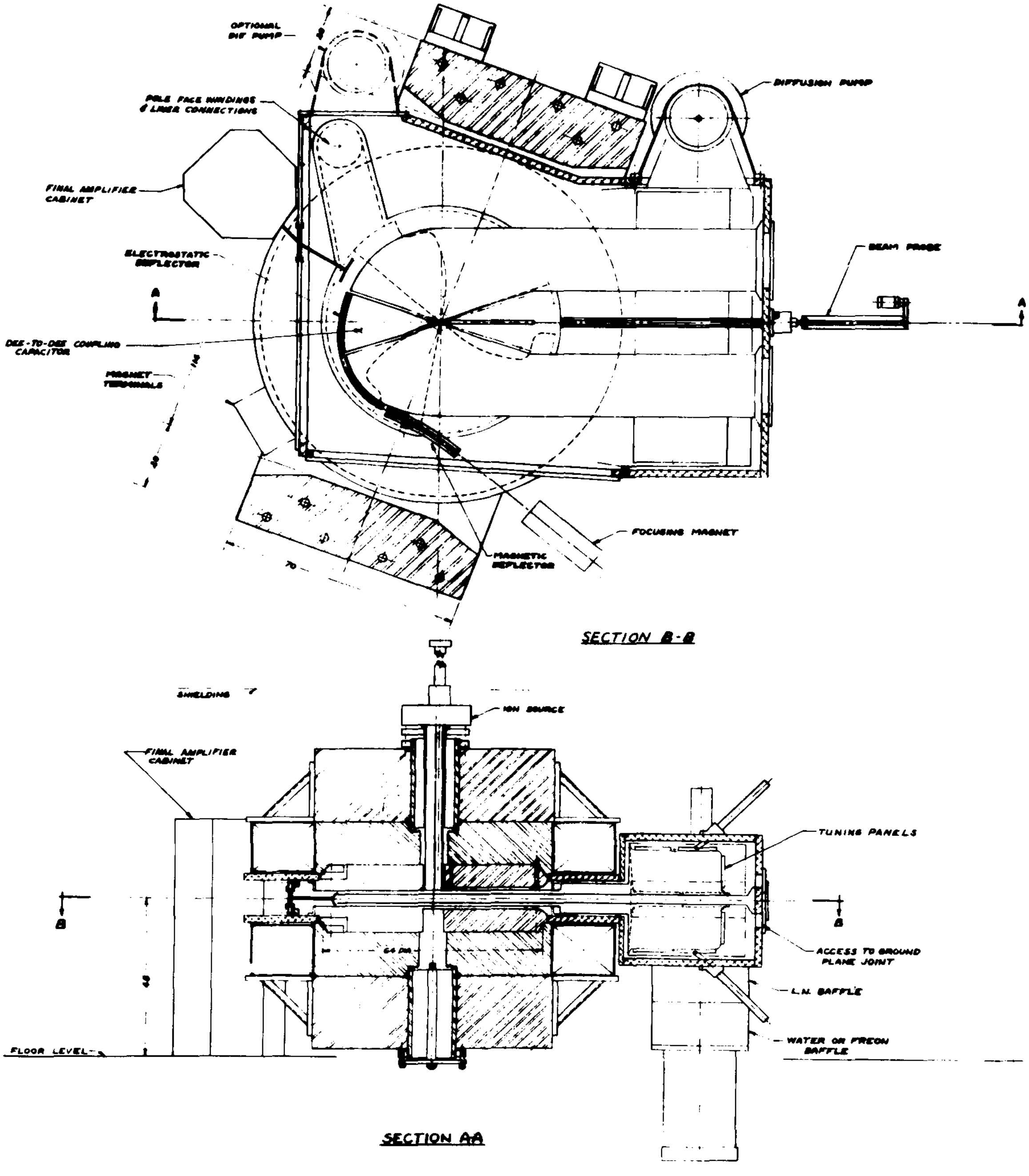

Fig. 1 Cross-section views of the RF system and magnet. The dee cavity tunes from 13.5 to 21.5 Mc/s by changing the dee stem inductance with the movable panels. The panels are shown in the high frequency position by the solid lines and in the low frequency position by the dashed lines. The dees are driven by a 240 kW amplifier capacitively coupled to one dee. Dee-to-dee coupling is accomplished by the "pieshaped" capacitor between the dees.

magnetic field, this further reduces the possibility of sparking.

Dee-to-dee coupling is accomplished by the "pie-shaped" structure between the dees, Fig. 1. This section is d.c. isolated from the liner, which results in the equivalent circuit shown in Fig. 3b. In the out-of-phase resonant mode for the two dees, point b in Fig. 3b is at nearly zero potential (if the magnitude of the voltages on the dees are equal). Thus, the full dee voltage is available for acceleration.

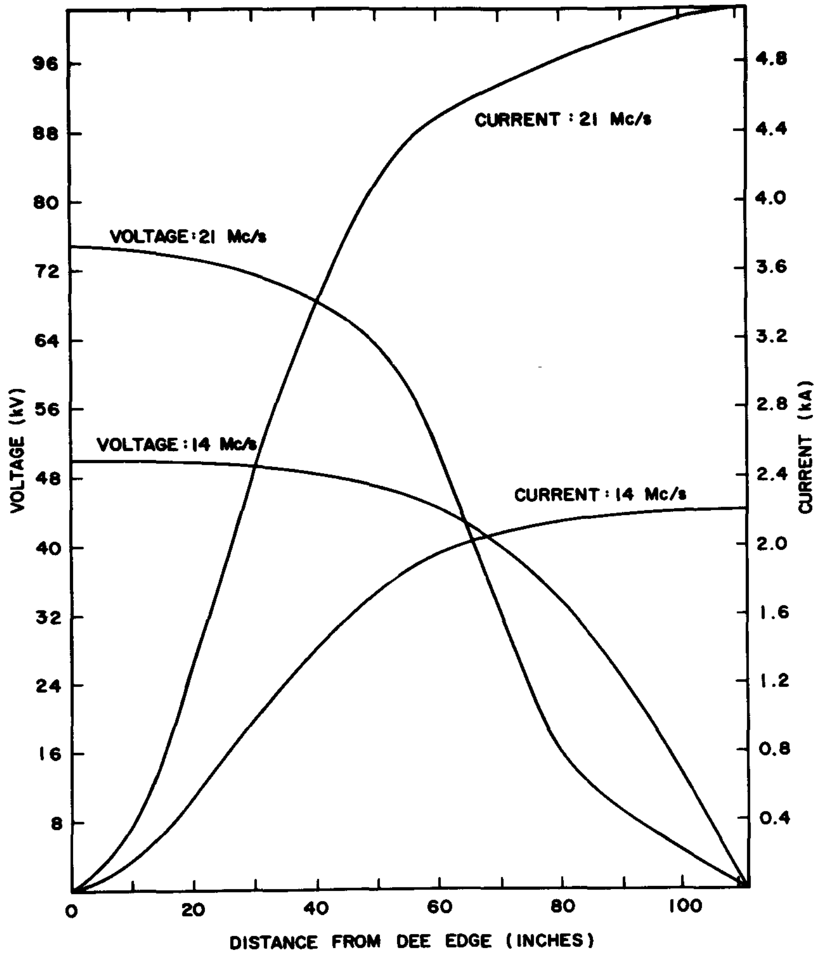

Fig. 2 Dee-cavity current and voltage distributions. The dee voltage will decrease as the frequency is lowered to maintain constant ion orbit geometry.

The resonant frequency is given by the expression

$$f_{180^\circ} = [L_1 (C_1 + C_c)]^{-1/2} \quad . \tag{1}$$

For the in-phase mode, point b is not at ground potential but is at a potential given by $2C_c/C_L$ times the dee-to-liner potential. Since circulating particles see the potential drop between dee and coupling capacitor, there is a reduction in the accelerating voltage as compared with the out-of-phase mode. The resonant frequency in this case is given by

$$f_{0^\circ} = [L_1 (C_1 + \frac{C_c C_L}{2C_c + C_L})]^{-1/2} \quad . \tag{2}$$

It can be seen that there must be a compromise between making the accelerating voltage for the in-phase mode as large as possible, and having $|f_{0^\circ} - f_{180^\circ}|$ large enough so that the two modes can be resolved in frequency. The capacitance C_c is limited by voltage breakdown between dee and capacitor, hence, leaving only C_L

as a variable. For the model studies, C_L was chosen such that $f_{0^\circ} - f_{180^\circ}$ was approximately 140 kc, giving $2C_c/C_L = 0.1$. It is expected that in the cyclotron itself this frequency difference may be made smaller, since the Q should be higher than in the model.

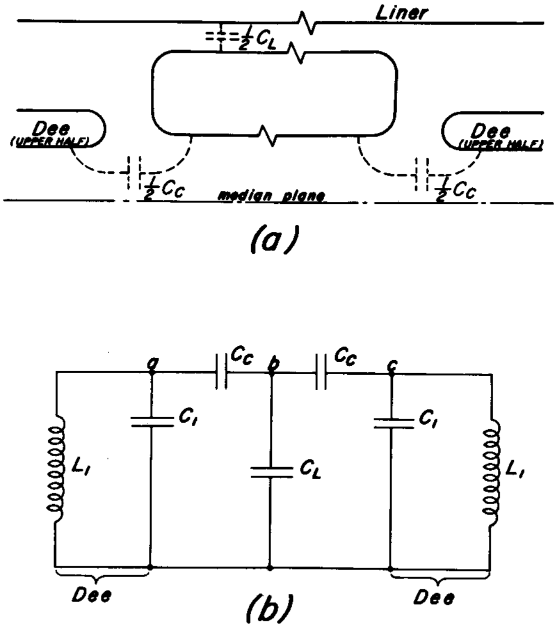

Fig. 3 a) Cross-section of the upper half of the dees and the inter-dee-coupling capacitor.
b) Equivalent circuit of the dee cavity.

The Amplifier

The RF amplifier is capable of delivering 240 kW of power to the dees, which should be sufficient to produce 70 kV of dee potential at 21 Mc/s. The amplifier is divided into three major components : final amplifier, driver amplifier, and a frequency source. A block diagram is shown in Fig. 4 and Fig. 5 shows a schematic of the final amplifier.

The final amplifier contains two Eimac 4CW50,000C tetrodes[4] operated in parallel. While these tubes are normally rated at 50 kW dissipation each, Eitel-McCullough has authorized their operation at 100 kW each with an increased flow of cooling water. They certainly can handle more than this for short periods of time. The tubes will be operated as linear amplifiers in Class AB_1 or possibly Class B_1 with an efficiency on the order of 70%. The anode tank consists of an adjustable shorted stub in parallel with a variable capacitor. The grid tank has an adjustable stub in parallel with the input capacitance of the tubes; it is swamped by a 100 ohm resistive load. The tubes are neutralized by feeding a small amount of RF voltage from anode to grid, according to the Bruene method[5].

The driver amplifier is a commercial wideband amplifier, the Marconi HS.113[6]. It is capable of delivering 1 kW of RF power to the grid tank at any frequency in the range 2 to 24 Mc/s without tuning. Since no moving parts are used in this amplifier, mechanical failure is practically eliminated. In addition, because of the multi-tube techniques employed in distributed amplifiers, failure of a tube is very unlikely to cause breakdown in service.

The Marconi operates as a linear amplifier and is driving, as indicated above, a linear final; thus, it will be possible to regulate the RF voltage on the dee by controlling the RF input to the driver. About 10 mW input is required for full output from the amplifier. At present, plans call for two feedback loops, one inside the other, Fig. 4. The inside loop is around the driver amplifier and the final. This loop takes advantage of the relatively wide bandwidth of the final tank circuits so that a large amount of feedback can be used to present a ripple-free, well regulated

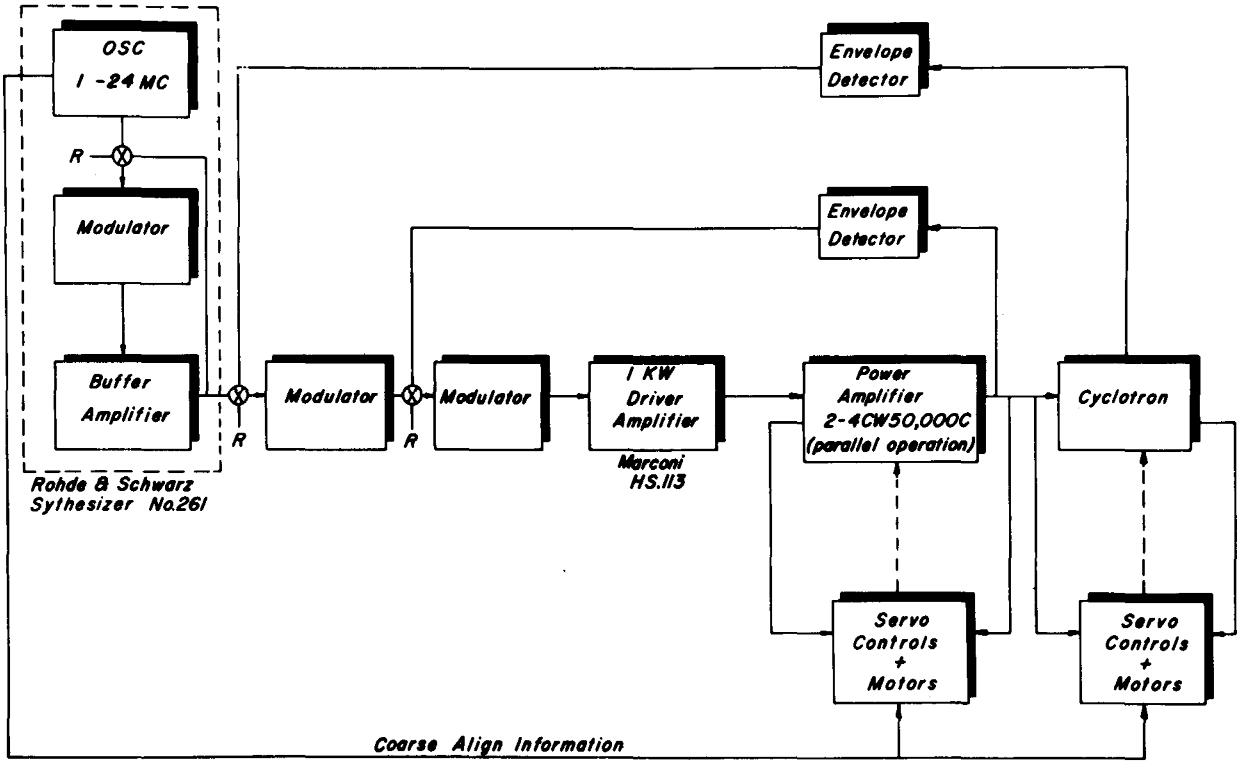

Fig. 4 Block diagram of RF amplifiers, servo and voltage regulator circuits.

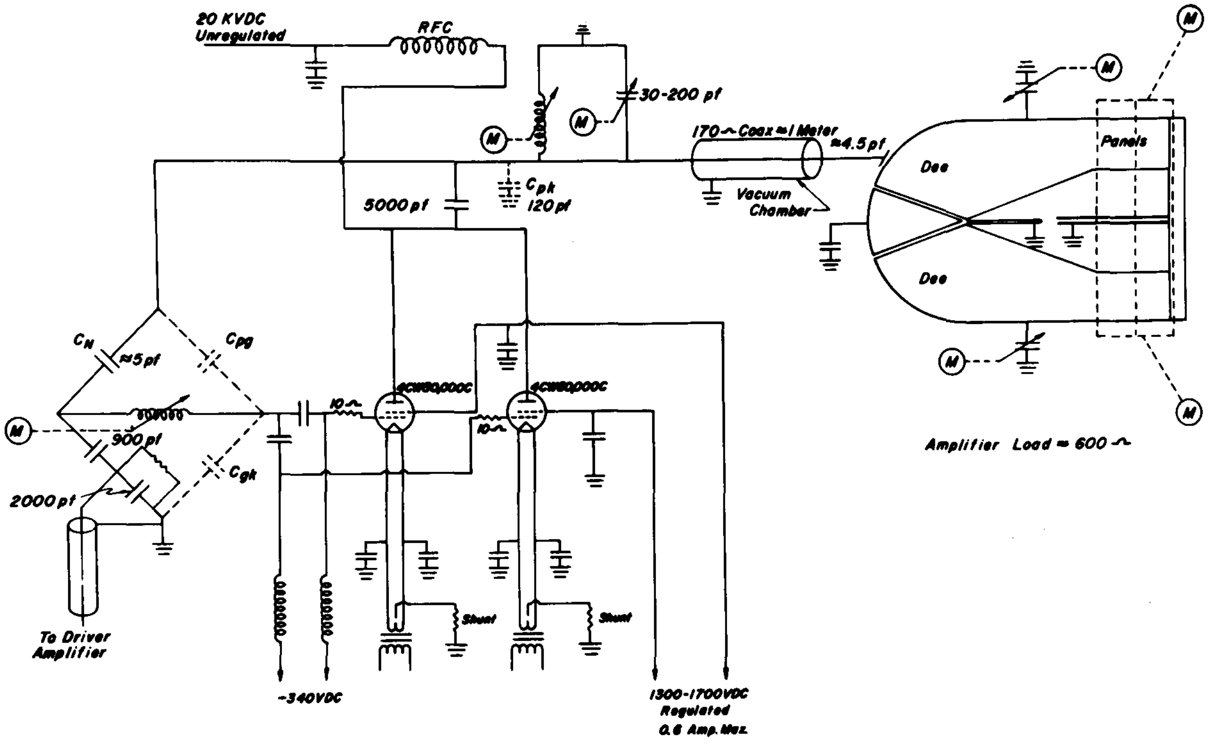

Fig. 5 Schematic diagram of the final amplifier. The anode inductor and capacitor are mechanically coupled such that resonant modes are not excited by the second and third harmonics of the operating frequency.

RF envelope to the cyclotron cavity. The outside feedback loop, around the dee cavity, final, and driver, will control fluctuations of the dee voltage caused by changes in ion loading, ripple from the ion source, small mechanical vibrations, etc. A means will be provided for opening the outside loop when the dee cavity sparks to prevent overdriving the grid of the final amplifier.

The frequency source is a Rohde and Schwarz Type No 261 decadic frequency synthesizer$^{7)}$ having a stability of 3 parts in 10^7 per day. The synthesizer has sufficient output to drive the modulator preceeding the driver amplifier. It contains a regulating feedback circuit to reduce the output ripple to a negligible amount.

The tuning servos, which are d.c. stepping motors$^{8)}$ obtain course alignment information from the synthesizer. Fine tuning is obtained by requiring 180° phase-shift between grid and anode of the final amplifier; by requiring 90° phase-shift between anode and dee; and, in conjunction with information about the relative phase difference between dees, by requiring equal voltage on the two dees. The grid tank of the final amplifier is tuned such that the servo obtains a resistive load for the driver amplifier. The servo motors are controlled by digital logic circuits that sample error signals from the phase detectors or position indicators. A motor runs at a constant stepping rate until the error signal is reduced to within a predetermined interval about zero, which causes the motor to stop within one step.

Present Status

The full-scale model is now being used to develop the dee voltage regulator and to test the logic being used in the tuning servos. In addition, as changes are made in the dee cavity, they are tried first on the model to make certain that no resonant modes are introduced that would prevent obtaining full dee voltage at all frequencies. Components on hand include the synthesizer and the driver amplifier. Orders have been placed for the anode supply and the final amplifier tubes. Design of the dee stems and vacuum chamber is in progress, as is the design of the final amplifier cabinet. It is hoped that the initial testing of the amplifier can begin in September 1963.

Acknowledgements

Two electrical engineering graduate students, T. Perfit and C. Moore, provided invaluable assistance in the detailed design of the amplifier.

References

1. John Backus, Rev. Sci. Instr. 22, 84 (1951) and F.H. Schmidt and M.J. Jakobson, Rev. Sci. Instr. 25, 136 (1954).
2. R. Smythe, University of Colorado; private communication.
3. B.H. Smith, Nucl. Instr. and Meth. 18-19, 184 (1962).
4. Eitel-McCullough, San Carlos, California, U.S.A.
5. W.B. Bruene, CQ, p 11 (August, 1950).
6. Marconi's Wireless Telegraph Company Limited, London, England.
7. Rohde and Schwarz, Munich, West Germany.
8. Slo-Syn motors manufactures by Superior Electric Co., Bristol, Connecticut, U.S.A.

DISCUSSION

MACKENZIE : Is the voltage gradient along the dee lips considered unimportant?

BLOSSER : We estimate a voltage gradient along the dee lips of around 10%. We have checked this; it has a negligible effect on the orbit. It is much smaller than the so-called gap-crossing resonance.

WATERTON : Are the feedback loops in the RF system purely for audio frequency ripple or are they also d.c. feedbacks?

JOHNSON : They are both d.c. and a.c. up to 6 kc/s.

WATERTON : What are the reasons for choosing to separate push-pull and parallel mode by means of inter-dee capacity rather than by inter-dee-stem mutual inductance?

JOHNSON : The latter provides excellent separation at low frequencies but the mutual inductance is much reduced by the movement of the panels for increasing the frequency. Therefore, the mutual inductance was minimized by an earth plane between the dee stems, and the alternative system adopted.

LAPOSTOLLE : Your two 140° dee system cover almost the whole circumference of the cyclotron. Does that not make the extraction too difficult?

JOHNSON : Actually the beam leaves the machine at one of the gaps between the two dees and passes outside the dee. There is plenty of space. We have a problem at the dee edge, but with cleanliness we can prevent sparking at this point.