A VARIABLE ENERGY CYCLOTRON*

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In the past, variable energy particle accelerators have, in general, been limited to the energy range below about 4 MeV. Many fixed energy machines have been built to operate above this energy but the field of physical research made possible by a variable energy machine between 2 and 12 MeV has been largely neglected. With particles of energy above about 10 MeV some energy variation may be achieved with absorbing foils, but this technique is unsatisfactory at lower energies. In consequence it was felt that the development of a machine capable of accelerating protons in the energy range 2–12 MeV would make a useful contribution to the tools of the nuclear physicist.

Electrostatic generators are costly and difficult to construct for energies much above 3 MeV, and early in 1953 it was decided to make design studies

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of a variable energy linear accelerator and of a variable energy cyclotron. In the middle of the year the decision was taken to build the cyclotron. The choice was determined by financial considerations, by technical difficulties, and by the greater flexibility of the cyclotron. The variable energy cyclotron described here is designed to accelerate protons in the range 2–12·5 MeV, deuterons in the range 4–6·3 MeV, and α-particles in the range 8–12·5 MeV. The machine can be used not only as a flexible research instrument but also for the production of radioactive isotopes. The obligation to supply this latter facility for medical research and treatment in this country has strongly influenced some details of the design. The machine has some unusual technical features and it was thought that these are of sufficient interest to justify a brief description though the machine is not at present operational.

Technical Details

In order to make a variable energy cyclotron with the range specified, it is necessary to be able to vary both the dee voltage frequency and the magnetic field over a range of 2·7 to 1.

The Radio-frequency System.—The radio-frequency system is required to deliver 100 kV to the dee with continuously variable frequencies in the range 8·5–22 Mc/s. To cover this tuning range with a conventional quarter wave line, the dee stem would have a length of about 14 ft and a short circuit which could be moved over a distance of nearly 10 ft. With such a long stem supporting the dee, it was certain that difficulty would be experienced in keeping the dee central within the vacuum box. Accordingly a compromise solution has been adopted in which the dee stem is made some 8 ft long with the short circuit variable over a distance of about 5 ft. To obtain resonance at low frequencies a variable loading capacitor has been installed on the dee stem just back from the dee. This allows the effective dee capacitance to be increased fourfold for tuning to the lowest frequency.

If a small frequency change is to be made, the dee line is tuned from the control desk using the loading capacitor. For a large frequency change, the short circuit is moved. The short-circuit spider consists of four wide copper straps terminated by fingers which make contact with the inner and outer conductors. The fingers are pressed against the line conductors by shoes actuated by eight hydraulic cylinders operating at a pressure of 200 lb/in^2.

The radio-frequency power (up to 50 kW) is supplied by an oscillator-power amplifier system, loop coupled to the dee line. The final power amplifier is a neutralized single triode stage using an STC type 3Q/261E valve with a plate dissipation of 20 kW.

The variable radio-frequency requirement dictates the choice of a single dee machine. The 3 in. dee aperture is comparatively large to permit the acceleration of beam currents of the order of 1 mA for isotope production. The deflector is contained within the dee and is supplied with up to 80 kV D.C. provided by a voltage doubling rectifier set. Figure 1 is a line drawing of the main features of the machine.

The Design and Performance of the Magnet.—The magnet is made from cast steel, with 0·10 per cent. of carbon present and less than 0·15 per cent. of silicon and 0·15 per cent. of manganese. It weighs 45 tons and is 9 ft 4 in. long, 4 ft wide and 7 ft 3 in. high. The pole pieces are 40 in. in diameter and the

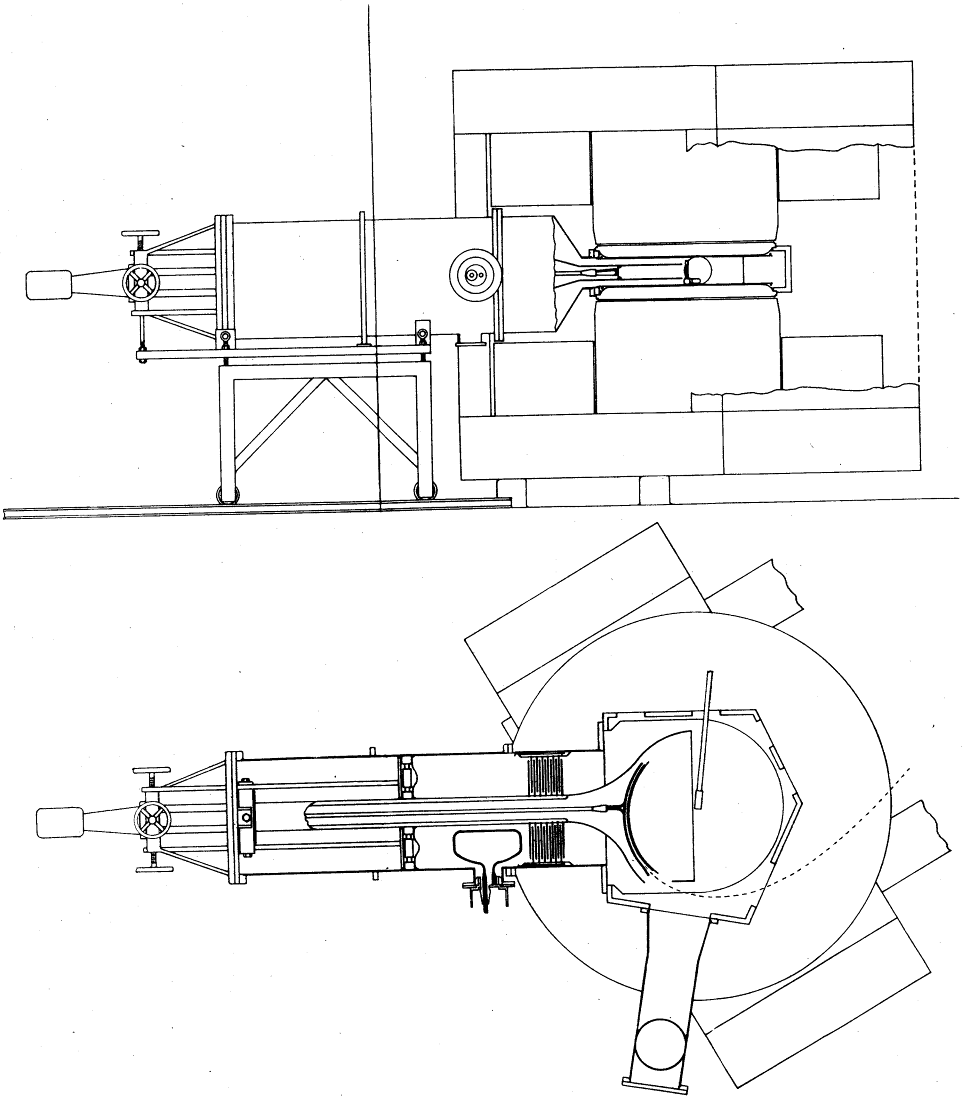

Fig. 1.—Design features of variable energy cyclotron.

magnet gap is 6 in. wide. The pole tips are 2·7 in. thick and form the lids of the vacuum box. Between the pole tips and the main pole pieces there is a $\frac{5}{16}$ in. shim gap in which iron shims may be placed to give fine adjustment to the field in the main gap. The pole tips are held in place with 2 in. steel bolts through the pole pieces.

The design of the pole tips differs from that of other cyclotrons where the final energy of the accelerated particles is held constant. In order to vary the particle energy it is necessary to change the magnetic field in the gap while keeping the field profile constant. This requires that the iron in the pole tips be kept below saturation particularly along the gap faces. For this reason the pole tips were designed with a rounded outer edge in such a way that the maximum flux density at any point of the surface of the iron was less than $1 \cdot 3$ times the flux density in the gap, thus avoiding the saturation that occurs at sharp edges. The design field profile called for a decrease in the field from the centre to the exit radius at $14 \cdot 4$ in. of $1 \cdot 8$ per cent. The maximum desired field was 14,000 G.

The machining tolerances on the magnet are critical. The two pole tips need to be accurately machined and the final gap between the pole tips was specified to $\pm 0 \cdot 002$ in. In fact with the pole tips in position the gap was found to be accurate to $\pm 0 \cdot 0015$ in. Small tolerances are required because the field should have circular symmetry about the centre of the gap with errors of the order of $0 \cdot 01$ per cent.

The field at the centre of the gap was measured as a function of excitation current using a small coil and flux meter calibrated against a nuclear resonance signal. A field of 12,500 G was obtained at 800 A at which point the excitation curve showed little signs of saturation. A current of 1200 A gave a field of 14,500 G with considerable saturation present. The field profile has been investigated using a nuclear resonance system and a pair of rotating coils. These measurements showed that the profile closely followed the design, that the profile was independent of the central field for fields up to 12,500 G, and that there was little change in the profile for fields up to 14,000 G. The pair of rotating coils was used to measure the symmetry of the field about the central axis at various radii. The results obtained showed the azimuthal variations out to the exit radius to be less than $\pm 0 \cdot 02$ per cent.

The coils for exciting the magnet are wound with 256 turns of hollow rectangular aluminium conductor. These coils are energized by a motor generator which is capable of providing 1300 A at 70 V. The field is stabilized to 1 part in 5000 by electronic stabilization of the current. The coils are cooled by passing 8 gal of water per minute through the conductor.

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