Initial Performance of the 184-Inch Cyclotron of the University of California

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THE successful application of the *principle of phase stability*[1,2] to a cyclotron has been reported from this Laboratory.[3] The satisfactory results of these experiments, performed on the 37-inch cyclotron, led to the decision to complete the 184-inch cyclotron then under construction as a frequency modulated machine. It is the purpose of this note to describe briefly the equipment and experiments by which deuteron and alpha-particle beams of approximately 200 and 400 Mev, respectively, have been produced.

The angular velocity of such ions in a magnetic field decreases by 11 percent because of the relativistic increase in mass during acceleration. In addition, a radial decrease of magnetic field, essentially linear from the center of a value of 95.4 percent of the central field at a radius of 80 inches, is provided to focus the ion beam properly. This field shape is produced by shims inside the vacuum chamber with contours empirically determined through measurements on a scale model. Thus a total minimum frequency variation of 16 percent is required; in practice it is desirable to provide a substantially greater frequency variation to insure that a satisfactory shape of the frequency *vs.* time curve is obtainable and to make adjustments less critical.

The frequency modulation is produced by a rotating mechanical vacuum capacitor similar in principle to that previously used.[4] Modulation frequencies up to 2000 c.p.s. are obtainable. The single dee and the capacitor are mounted at either end of a shielded line forming a resonant system, whose frequency varies between 12.6 and 9.0 megacycles. The system is excited by means of a grounded grid self-excited oscillator inductively coupled to the resonant circuit.[5] A power input of 18 kilowatts to the plate circuit produces a dee voltage of 15 kilovolts (peak voltage averaged over a frequency-modulation cycle). The magnetic field has a value of 15,000 oersteds at the center; the useful magnetic gap is 19 inches; the height available for the ion beam is 5 inches.

In line with our previous experience, it is necessary to apply a d.c. bias voltage to the dee system to serve as a clearing field; in the absence of such a bias, residual ionization at low dee voltages so loads the oscillator as to prevent the build-up of dee voltage. Similarly it has been found desirable to enclose the dee with grounded shields to reduce the volume available for glow discharges.

A low voltage arc discharge of the type commonly used in cyclotrons serves as ion source. Provision is made for the application of the arc voltage for a time variable between 1 and 110 microseconds at the appropriate point in the frequency-modulation cycle. Our present experience indicates that greater output is obtained from such a pulsed arc than from one operating continuously. For cloud-chamber and similar experiments, a single pulse may be produced at a time controlled by the equipment in question.

All our present experiments are being performed with an internal probe target. It is not planned to attempt to deflect the beam out of the magnetic field in the immediate future.

Under these conditions a deuteron beam is observed at a dee voltage as low as 8 kilovolts and a corresponding optimum capacitor speed of 120 r.p.m. (equivalent to 48 c.p.s.). In accordance with theory, the latter is not critical. At present, normal operating conditions include a dee voltage of 15 kilovolts and a frequency-modulation rate of 120 c.p.s.; with an average energy gain per revolution of one-half the pos-

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[1] E. M. McMillan, Phys. Rev. 68, 143 (1945).
[2] V. Veksler, J. Phys. U.S.S.R. 9, 153 (1945).
[3] J. R. Richardson, K. R. MacKenzie, E. J. Lofgren, and B. T. Wright, Phys. Rev. 69, 669 (1946).
[4] F. H. Schmidt, Rev. Sci. Inst. 17, 301 (1946).
[5] K. R. MacKenzie and V. Waithman, to be published when patent release can be obtained.

sible maximum, this involves a total number of turns of the order of 10^4, and a time of flight from the ion source to a target at 80 inches radius of approximately 1000 microseconds. The time-average current to a probe at 20 inches radius approximates 0.6 microampere; this current remains constant as the radius is increased to 40 inches corresponding to 52 Mev. At this point the measured current to the target decreases rapidly and is barely measurable ($\sim 2\times 10^{-10}$ amp.) at a radius of 81 inches, and is zero beyond 82 inches. During this decrease the direct neutron radiation from the target increases steadily and falls abruptly to zero in the neighborhood of 82 inches radius. This decrease in current between 40 and 81 inches can be explained by the penetration of the beam through the leading edge of the tapered probe target, and the energy at which it occurs agrees with the calculated range of the deuterons. We do not believe that a substantial fraction of the current is lost between 40 and 81 inches. Measurements of the radiation (which is highly directional) and the induced radioactivity of dee and probe indicate that beyond 82 inches the ion beam is lost to the dee through vertical spreading. In general it may be said that the detailed performance, as far as it has been investigated to date, is in accord with the theory.[6] In view of the fact that this output is more than adequate for our present experimental program, and that the cyclotron is as yet imperfectly shielded, no attempt has been made to increase the current beyond the values obtained initially.

Replacement of the deuterium gas with helium leads (after thorough flushing of the system) to an alpha-particle beam of twice the deuteron energy resulting from the acceleration of doubly charged ions. Radiation yields from such a beam are comparable to those obtained with deuterons, but few experiments using these ions have as yet been carried out.

[6] D. Bohm and L. Foldy, to be published.

No direct measurement of the deuteron or alpha-particle energies has as yet been made. From geometrical considerations, the expected energies at 81 inches radius are 195 Mev for deuterons, and 390 Mev for alpha-particles. Since the conical shape of the magnetic field centers the ion beam quite strongly, we do not believe that the actual energy is substantially lower. It may be noted in this connection that careful measurements of the range of protons accelerated to 15 Mev on the 37-inch f-m cyclotron show excellent agreement with that predicted from the geometry.

Measurement of the directional properties of the neutron radiation emitted from a target, both by means of ionization chambers and the use of radioactive detectors activated by fast neutrons, show that a large fraction of the radiation is emitted in the forward direction in a cone of angle 11 degrees at half-intensity. Disintegrations resulting in the emission of many particles from both deuteron and neutron bombardment are observed from radio-chemical investigations, and from the observation of numerous "stars" in cloud chambers and photographic emulsions. Preliminary estimates of the neutron-energy distribution through proton recoils observed in a cloud chamber using a 10,000 oersted field indicate a distribution extending to the neighborhood of 100 Mev. These and other experiments will be reported in detail by the workers involved when the experiments are completed.

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