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On the left of this photograph, between the tapered pole-pieces of the electromagnet, is the vacuum chamber of the 37-inch cyclotron at Berkeley. Two of the four wheels, which are to facilitate the removal of the vacuum chamber, can be seen. In the background are water tanks which serve as a protection against the effects of neutrons.

THE CYCLOTRON

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with a foreword by
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FOREWORD

IT has been a great pleasure reading the manuscript of this interesting monograph on the cyclotron. As the author has so well indicated, the technique of the cyclotron is steadily advancing, and I am glad of the opportunity to add a brief word on a matter of especial interest at the present time. It is the question of the practical upper limit to the energy of ions producible by the cyclotron, for certainly the next great experimental problem is the production of atomic projectiles in the energy range above one hundred million volts.

Bethe has pointed out that the relativity increase of mass imposes a difficulty in reaching very high energies with the cyclotron. Indeed, it has been said that the difficulty is in the nature of a strict practical limitation and that it is useless to build cyclotrons larger than those already in operation. As is frequently the case in experimental physics, however, it is possible to get around this apparent practical limitation in several ways. In the first place, a defocusing action of a radially increasing magnetic field required by the relativity condition can be overcome by a suitable provision of electrostatic focusing, and Thomas has shown how an azimuthal adjustment of the magnetic field will accomplish the same purpose. Perhaps the simplest solution of the experimental problem is merely to increase the accelerating voltage. In this direction the 60-inch cyclotron in Berkeley now operates with about a quarter of a million volts on the dees, so that in accelerating doubly charged helium ions to 32 million volts, the ions

Alvarez[63] when he succeeded in accelerating a beam of completely stripped C^{12} ions having energies of about 120 Mev. With such beams Miller, Hamilton, Purnam, Haymond and Rossi,[62] and Ghiorso, Thompson, Street and Seaborg[69] have effected a number of nuclear transformations involving an increase in atomic number up to and equal to six units as, for example:

$$Al^{27}_{13} + C^{12}_{6} \rightarrow Cl^{34}_{17} + He^{4}_{2} + n^{1}_{0}$$

$$Au^{197}_{79} + C^{12}_{6} \rightarrow At^{205}_{85} + 4n^{1}_{0}$$ [62]

$$U^{238}_{92} + C^{12}_{6} \rightarrow Cf^{244}_{98} + 6n^{1}_{0}$$

It was also hoped in 1941, as Professor Lawrence says in the foreword to this monograph, that, by extending what had been done successfully with the 60-inch cyclotron and by applying an r.f. potential of one or two million to the dees, it would be possible to obtain helium ions with energies of 100-to 200-million electron volts and work on the 184-inch cyclotron was started at Berkeley with the intention of utilizing this expedient. Before this cyclotron could be completed along these lines, however, the war intervened and the potentialities of the 184-inch magnet were temporarily diverted to comply with the harsh necessities of that period. But prior to and immediately following this period of conscription an idea had been mooted independently in different parts of the world, which, upon resumption of work on the Berkeley magnet as a cyclotron, completely revolutionized its design.

It is now quite certain that the first paper really to focus attention on this idea, embodying the principles of frequency modulation and phase stability, was, chronologically, the last, namely that of McMillan in 1945.[64] Very detailed papers had previously been published by Veksler in 1944[65] and 1945[66, 67] in which the principles had been quite clearly enunciated. These papers were later quoted

by Veksler in 1946 in a letter to the Physical Review[68] subsequent to McMillan's publication and it is fairly reasonable to suppose that but for the unfortunate cleavage of the world of physics into two semi-independent entities the work of Veksler would have received much earlier recognition in the cyclotron laboratories of the world; it was as McMillan pointed out in reply[69] another case of independent ideas occuring, when the time was ripe, in different parts of the world simultaneously. Prior even to this, however, Oliphant[70] had suggested the principle of frequency modulation without the concept of phase stability while in 1934 Szilard[71] had suggested both. It is certain, however, that neither of the two post-war sponsors of the principle of phase stability, Veksler and McMillan, had cognizance of this early proposal by Szilard which for some reason unknown remained in the complete obscurity of a British Provisional Patent Application for at least fifteen years; longer than the normal life of a fully-fledged patent.

To understand the concept of phase stability let us consider the phase of the circulating ions in relationship to the variation of the voltage applied to the dees. The time variation of the latter is shown in Fig. 32. As has been pointed out at the beginning of Chapter V ions crossing the gap between t_1 and t_2 and between t_3 and t_4 will experience a net focusing action and will be retained in the beam while those crossing between t_0 and t_1 and between t_2 and t_3 will experience a net defocusing action due to the electric field and will, in general, be lost. This focusing, or defocusing, action occurs, however, only at low energies where the time of transit between the dees is still relatively long. But the final result is that the ions, which are accelerated to higher energies and which are circulating at the larger radii of curvature, cross the gap between the dees in bunches between times t_{n+1} and t_{n+2}, t_{n+3} and t_{n+4}, and so on, corresponding to the shaded field, the equilibrium orbit will follow along with the movement of the point of zero electric intensity, for decreasing applied voltage, along the time axis and the ions will gain in energy and the equilibrium orbit in radius until the ions reach the periphery of the vacuum chamber with energies well above the limit previously set by the relativity effect. At the same time a decreasing magnetic field can still be used to focus the ions into the median plane.

After the war the 184-inch cyclotron at Berkeley was accordingly modified to incorporate frequency modulation after, however, the principle had first been tested on the 37-inch cyclotron. The 37-inch cyclotron was not large enough to give orbits in which the final velocity of the ions was a sufficiently large fraction of the velocity of light and so the relativistic effect was simulated by means of introducing a sufficiently large radial decrease in the magnetic field[72] to give a corresponding decrease in the angular velocity ω.

In this investigation Richardson, MacKenzie, Lofgren and Wright calculated the amount by which the field in the 37-inch cyclotron should be decreased by considering the change in frequency which would be required to obtain deuterons of energy equal to 200 Mev in the 184-inch cyclotron. Thus if W is the energy of the ion in units of Mc^2, the frequency of revolution n of the ion in a magnetic field H is given by

$$n = \frac{n_0}{1+W}\,\frac{H}{H_0}$$

where n_0 is the frequency the ion would have at low energy in the magnetic field H_0. Thus the effect deriving from an increase in W may instead be simulated with relatively low-energy ions by decreasing H at larger radii from H_0 at the centre of the magnetic field. The value of W for 200-Mev deuterons is 0·107, the rest mass of the

deuteron being 1876 Mev, so that $1+W$ becomes 1·107 and the frequency change necessary to draw out the phase-stable orbits will be 10·7 per cent. Using a radial decrease in magnetic field of 13 per cent on the 37-inch cyclotron, Richardson, MacKenzie, Lofgren and Wright were able to simulate this 10·7 per cent decrease in frequency which would be required to draw out the orbits in the 184-inch cyclotron and also allowed for a 2·3 per cent radial focusing decrease in field of the 184-inch magnet. With this radial decrease in magnetic field and with a peak dee voltage of only 3 kv they accelerated deuterons to an energy corresponding to 7 Mev using a frequency modulation of 600 cycles per second which corresponded to an acceleration time for any given deuteron of 500 microseconds and a total path of about 5000 turns. Without such frequency modulation the maximum energy which could be obtained with this dee voltage was 0·5 Mev. Only one dee was used in these experiments with the 37-inch cyclotron the vacuum chamber at ground potential acting effectively as the other dee. With such an arrangement, which is made possible by the lower dee voltages required in a frequency-modulated cyclotron, the single dee is mounted on a resonant line with the diametral plane of the dee opening perpendicular to the axis of the resonant line. Frequency modulation was achieved by means of a rotating condenser at the other end of the line. This condenser was constructed with a disc-shaped rotor having 36 teeth arranged on a circle of 2-feet diameter moving between two stators having 36 teeth apiece so that at 1,000 r.p.m. a modulation of 600 cycles per second was obtained. Under these conditions the resonant line had a voltage node near the centre and this node moved back and forth as the resonant frequency was changed by means of the rotating condenser, and a 20 per cent change in frequency was obtained. It is interesting to note that Szilard in his 1932 British Patent Application proposed using such a condenser with two oppositely rotating discs with teeth to achieve the necessary change in frequency. In this case however it was necessary to have an increase followed by a decrease in frequency since he proposed using a magnet in which the pole pieces were composed of a number of segments to give a radial increase in magnetic field. It was also found in the Berkeley experiments that the output was increased by a factor of ten if the dee and resonant line system were allowed to float at a positive d.c. potential of about 1,500 volts and the authors believe that this effect was bound up with starting conditions for the ions with such low single dee voltages. Pickavance, Adams and

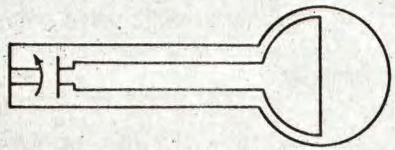

FIG. 33

Snowden, in their description[73] of the Harwell cyclotron, recommend that a positive d.c. bias voltage of 500 volts be applied to the dee and to the associated resonant line system for the purpose of collecting stray electrons which would otherwise be liable to initiate discharges in the r.f. field and thus cause unnecessarily heavy loading of the oscillator.

The method of coupling the rotating condenser to the resonant line support of the dee is illustrated diagrammatically in Fig. 33. The rotating condenser used in the experiments with the 37-inch cyclotron, which was initially constructed to operate in air but was later designed to operate in a vacuum, has been described by Schmidt.[74] In the case of the 184-inch cyclotron it was necessary to use a bigger rotating condenser and, although initially one similar to that described by Schmidt having seven discs

each with 24 teeth was used, the final version consisted of a drum-shaped rotor with six rows of 72 teeth in each row, in order to achieve the much greater change in capacity required, from about 1,000 $\mu\mu$f to 2,000 $\mu\mu$f. In the experiments with the 37-inch cyclotron the capacity varied from about 300 to 800 $\mu\mu$f for a corresponding decrease in frequency from about 11·9 to 9·5 megacycles. Although this change in frequency was greater than the 13 per cent required the rate of change is so slow compared with the frequency of the r.f. voltage applied to the dee (i.e. 600 in the initial experiments[72] compared with 10^7 cycles per second) that the drawing out of the phase-stable orbits will be effectively adiabatic and the ions will appear in bursts over that range of frequency to which their mass is instantaneously accommodated. There would, however, be little point in general in having the change in frequency much greater than that which is required by the relativistic change in mass, and radial decrease in magnetic field, since any frequencies, beyond the range of frequencies in which the ions are resonant, would represent wasted time in which acceleration cannot be achieved.

In later and more detailed experiments on the 37-inch cyclotron, Richardson, Wright, Lofgren and Peters[75] varied the modulation frequency from zero to 2,400 cycles per second and found a maximum value of the deuteron current around 1,200 cycles per second which was in good accord with theoretical prediction.

The principle of phase stability has, as was pointed out by Veksler and McMillan, many possible applications both to the acceleration of light and heavy particles. In his first letter on the subject[64] McMillan points out that the 'equation of motion' which he derives for the oscillations of the orbits around the equilibrium phase-stable orbit is analogous to the equation of motion of a pendulum of unrestricted amplitude subjected to both a constant

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