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A HIGH-CURRENT CLOVERLEAF CYCLOTRON FOR THE PRODUCTION OF RADIOISOTOPES*

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In 1938, Llewellyn H. Thomas proposed a modification of the cyclotron designed to alleviate the well-known limitation arising from the relativistic mass increase. Thomas showed that it was possible to design a field having an azimuthal as well as a radial dependence, which would simultaneously permit a constant period of revolution of the ion (taking its mass increase into account) as well as the necessary axial and radial stability. Leonard Schiff proposed a minor modification of this field involving a threefold periodicity in the field instead of the fourfold periodicity proposed by Thomas. The latter suggestion involves a field as a function of r and θ of the form

$$B(r,\theta) = B_o \left[1 + A\left(\frac{\omega r}{c}\right)\cos 3\theta + B\left(\frac{\omega r}{c}\right)^2 + \text{higher terms}\right].$$

A is a constant which essentially determines the magnitude of the vertical focusing forces, and $B = 1/2 - A^2/8$. The appearance of pole faces machined to produce a field of this type has led to the designation of this device as a "cloverleaf"

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cyclotron in this laboratory. Edwin M. McMillan, in this laboratory, has also suggested field configurations that can produce similar effects, and more recently, Keith R. Symon and others of the Midwestern Universities Research Association group have extensively investigated other possible arrangements.

An experimental evaluation of a machine of the Thomas type, in the Schiff modification, has been made in this laboratory with electron models to simulate the acceleration of deuterons to an energy of 300 Mev. Higher-order approximations than those used by Thomas were used in the field calculations and were found to have significant influence at these energies. These successful model tests demonstrated the basic soundness of Thomas's ideas that the desired field shape could in practice be adequately achieved and that essentially the entire circulating beam could be extracted in a usable form. This pole configuration lends itself naturally to the use of three accelerating electrodes located in the "valleys" on the pole faces, thus leaving the full magnetic gap available for the circulating ions. The practicality of a three-phase radiofrequency accelerating system using such a configuration has also been successfully demonstrated.

It thus is certain that a cyclotron of this type can be readily built to accelerate deuterons to energies of the order of 100 Mev, or other particles to a similar ratio of velocity to that of light. In view of the lack of a threshold energy gain per turn (except that arising from imperfections in the magnetic field), beam currents of the order of one ma should be achievable without undue difficulty. Such a machine would apparently have considerable utility for the large-scale production of radioisotopes not readily available from reactors, as a high-intensity neutron source for time-of-flight spectroscopy, and other similar uses.

Although there are no immediate plans to construct a cyclotron of this type, some preliminary engineering studies have been made on a cyclotron to produce large currents of protons at about 30 Mev energy. The magnetic field would have a value at the pole center of 8,800 oersteds, the final particle radius would be 36 inches. The magnetic field, defined by the equation given earlier, would have maximum and minimum values of 13,000 and 5,300 oersteds, and the corresponding pole separations would be 12 and 47 inches, with a central value of 19 inches. The magnet power would approximate 150 kw and the steel and copper would be about 700 and 30 tons, respectively. A three-phase accelerating system using three electrodes 60° wide located in the pole "valleys"

would require about 30 kw of radiofrequency power to excite to a voltage of 100 kv peak at 13.5 megacycles/sec. To this, of course, would have to be added the power in the ion beam. This construction permits a clear beam height of more than 10 inches, which compares very favorably with the minimum magnet gap of 12 inches.