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STUDY OF AXIAL INJECTION FOR THE GRENOBLE CYCLOTRON

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I. Introduction

The injection of ions into a cyclotron via a hole drilled in the axis of the yoke presents many problems.

1) For an injected ion beam, of given energy eU, to be accelerated by the dees (RF Voltage V) and correctly extracted from the cyclotron, it is necessary that the centre of the first orbit coincide with a defined position.

2) The injection system must transform the vertical (i.e. axial) motion of the ions into a horizontal orbital motion centred at the correct position and in the magnetic median plane.

For the ions, the entrance into the magnetic field acts as a strong focusing lens, so that they must be injected accurately along the axis of the hole in the yoke. To eliminate magnetic field asymmetry the hole must be drilled precisely along the axis of the yoke. Thus, there is no possibility to move the injection axis.

3) After the end of the first revolution the accelerated beam is at a minimum distance from the deflector. Therefore, the increment ΔR of the orbital radius R for the first turn must be greater than half the horizontal dimension of the deflector gap plus the distance between the deflector and the dummy dee.

For the Grenoble cyclotron ΔR must be greater than 1.2 cm.

Consequently, the energy of the injected ions must be smaller than a fixed value which can be approximated as follows.

The injection radius R_o is given by

$$R_o = \frac{\sqrt{2\ U\ W}}{B\ c} \sim \sqrt{\frac{U\ (kV)}{10}}$$

for the Grenoble cyclotron.

If $eW = m_o c^2$ then

$$R_1 \text{ (after 1 turn)} \sim \sqrt{\frac{U + 4\ V \cos \emptyset}{10}}$$

for the Grenoble cyclotron $\emptyset = 50°$, V = 50 KV

$$\Delta R \sim R_1 - R_o$$

we have $U \lesssim 60$ KV for protons.

II. Planned Deflection Systems

a) We have been able to satisfy the above conditions by placing in the magnetic field an ordinary constant field electrostatic deflector. The ion path during the deflection process has the appearance of a helix, due to the action of the magnetic field (see pictures of the deflector).

The equations of motion are:

$$x = \frac{A}{2}\left[\frac{2}{1-4K^2} + \frac{\cos(2K-1)b}{2K-1} - \frac{\cos(2K+1)b}{2K+1}\right].$$

$$y = \frac{A}{2}\left[\frac{\sin\ (2K+1)b}{2K+1} - \frac{\sin\ (2K-1)b}{2K-1}\right]$$

$$z = \cdot\text{-}A \sin b$$

Where the z axis is the axis of the cyclotron, the x - y plane is the median plane.

The electric field at the deflector entrance is along the x - axis.

A is the radius of curvature of the electric field.

b is a parameter ($o \leq b \leq \frac{\pi}{2}$) such that the ion path length is given by s = AB.

R is the radius of curvature of the magnetic field.

$$K = \frac{A}{2R}$$

For a given injection energy eU, R is fixed and the only free parameter (A) does not allow the optimum positioning of the orbital centre, i.e. at the deflection exit.

b) We have therefore modified the effective magnetic field intensity along the deflector by means of an additional horizontal electric field (E) proportional to the horizontal component of the ion velocity. This produces a force on the ions proportional to and aligned with the force due to the magnetic field, and an effect equivalent to that produced by a change in the magnetic field intensity. The equations of motion thus remain the same.

To produce this electric field, we have inclined the electrodes at an angle β and slightly tapered the gap from 7 mm to 6 mm (see Fig. 1) such that the field E_V remains constant and E_H has the calculated value. The equations given above remain the same if K is replaced by K' where

$$K' = K + \frac{k}{2} \quad \text{and} \quad \tan\beta = k\sin b$$

The advantage of such a system is that the centre of curvature of the ion trajectory at the deflector exit is not the same as the centre of curvature during deflection. k provides an extra parameter which can be used to place the beam orbital centre at the optimum position (see Fig. 2).

$R_1 = \frac{A}{2K'}$ radius of curvature inside the deflector

$R_2 = \frac{A}{2K}$ radius of curvature at deflector exit

It is not possible to alter the deflector geometry, so that the beam trajectory during deflection must remain constant for all ion extraction energies. As a result U and E must vary as B^2, and for the beam to remain correctly centred, the cyclotron must be operated with constant orbital geometry. The cyclotron can be operated only in a limited energy range without changing the deflector system owing to technical limitations on the range of rf amplitude.

III. Results

a) Experimental Lay-out

In order to check the functioning of the deflection system, we have built an electron model using a vertical 1035 eV electron beam and a 42, 5 gauss constant magnetic field, these parameters allowing us to construct a full-sized working model. After deflection into the horizontal plane, the electrons were accelerated by a dee system which simulated the cyclotron. Due to considerations of the orbital centre we chose the following parameters

$$A = 6\ \text{cm} \qquad K = 1,2 \qquad K' = 1,5$$

This system simulates proton injection at 62, 5 KeV with a magnetic field of 14 500 gauss, and an rf amplitude of 50 KV, the voltage between the plates of the deflector being 18 KV.

b) Trials of the Deflection System

When used to deflect a parallel electron beam (with a circular cross-section, diameter 2. 5 mm), we obtained a transmission factor greater than 95%. At the exit the beam size was 5-6 mm (vertically) and appeared to form an image 30 mm up stream from the exit. Horizontally the roughly parallel beam had a width of 1-2 mm.

c) RF System

We have devised a rf system to accelerate the electrons which gives a rf amplitude of 900 V on the dees at a frequency of 120 MHz (see Fig. 3). We attempted before the experiment, to make an approximate calculation of the vertical focusing during acceleration, by considering the dee gaps as two slit lenses separated by a rf electric field (the computation is similar to that used in the Pitch equations for the calculation of the effect of two hole lenses separated by a constant field). The numerical calculation, for different phases, showed that the vertical beam divergence led to a loss of electrons during the first revolution. We have had to shield the deflector from the rf. The results of Fig. 5 were obtained using a probe 2. 5 mm wide.

Conclusion

This injection principle has been shown to operate with electrons. We hope that it will also work with ions. The possibility of injection of relatively high energy ($\sim$50 KeV) protons allows us to hope that the reduction in the effects of space-charge will give us a high transmission factor for the passage through the yoke.

Due to this advantage one can use lower injection energies and thus obtain a variation in the energy of the extracted proton beam. We also think that this system will improve the acceleration and the extraction efficiency.

It must be pointed out that these first experiments gave us a beam at the 6th or 7th turn which was only a few per cent of the injected beam. This fact may however be explained by the rudimentary design of the dee system, which we have not had time to improve.

It is still true that an ion-model must be built to confirm the viability of this system.

References

1) W. P. Powell, B. L. Reece, M.I. and M 32, 325.

2) W. I. B. Smith, M.I. and M 9, 49.

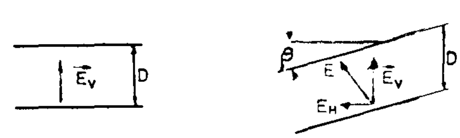

Figure 1.

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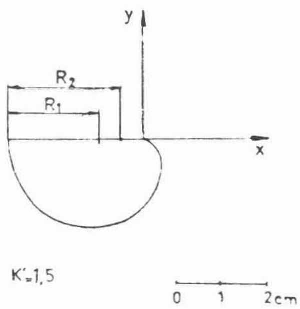


Figure 2.

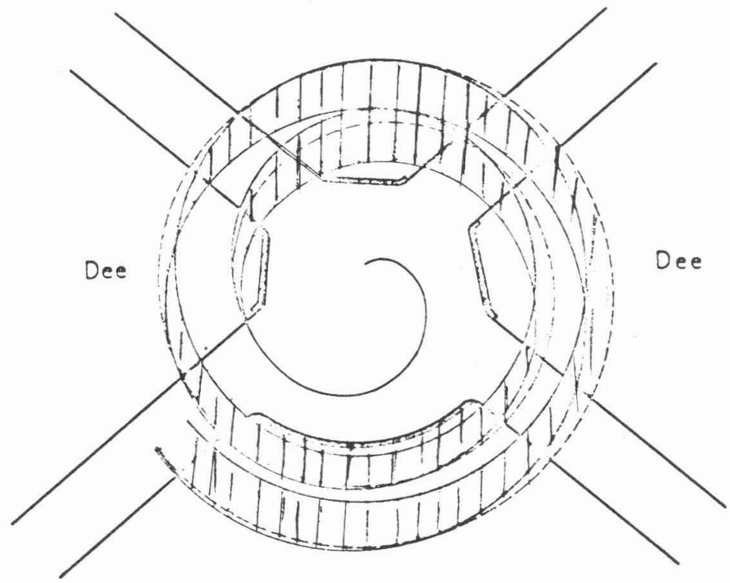


Figure 3.

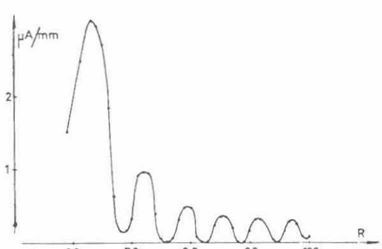
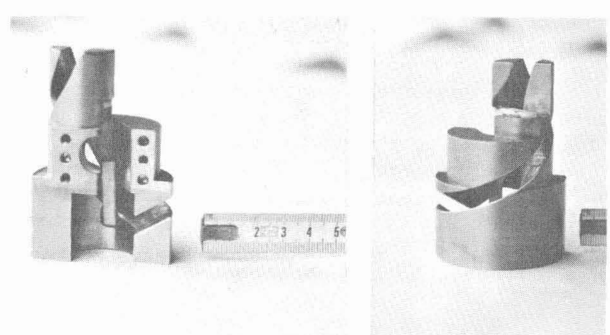


Figure 4.



The electrostatic deflector

Figure 5.