The external injection system for the Groningen cyclotron

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ABSTRACT

The injector is described as it will be used in the cyclotron. Calculations on orbits are done mainly with an analog computer. The complete system will be tested in a small magnet and the ions will be accelerated a few turns by an rf field. Details of the beam guiding system consisting of a series of cylindrical magnetic lenses made of permanent magnet ring cores arranged around a vacuum tube, are discussed.

1. THE INJECTION SYSTEM

The A.V.F.-Cyclotron in Groningen has a central axial hole for the purpose of vertical ion beam injection. Seen from the median plane this hole has three sections: 330 mm with a useful diam. of 28 mm, 710 mm with diam. 90 mm, 1120 mm with diameter up to 200 mm. The cyclotron will work as a constant orbit cyclotron over the entire energy range. This is a favourable condition for vertical injection, but it also means that the injection energy must be variable over at least a factor of ten. We have chosen the range of 4–40 keV for protons. The ion source will be placed in a room on top of the cyclotron vault, so the minimum distance from the source to the median plane is ~9 m.

For the experiments on vertical injection we use a small magnet with a pole diam. of 80 cm, a gap of 10 cm and a homogeneous field. The axial hole consists of two sections: 170 mm with a diam. of 30 mm, 800 mm with a diam. of 90 mm. The ion source for protons and deuterons is an rf source followed by a unipotential lens, an acceleration lens, a 15° bending magnet and a quadrupole triplet to match the ion beam to the beam transport system.

The reflector is a gridded plane mirror, located exactly at the centre of the cyclotron. After the mirror a circular 120° deflection channel, consisting of two parallel electrodes, will bring the ions to the region where they are accepted by the cyclotron. In front of the reflector a strong but short electrostatic quadrupole will be used to match the beam to the cyclotron.

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2. THE LOW ENERGY BEAM GUIDE SYSTEM

Since the low energy ions must be transported over a long distance we have to pay attention to the beam transport system. The system best suited for this purpose is a so called 'periodic focussing structure', consisting of short lenses placed close together. In comparison with systems consisting of stronger lenses placed at distances of 30 cm or more it maintains a smaller beam diameter, it is less sensitive to the influence of stray fields, and it is not very critical with respect to alignment.

A very simple system could be realised with cylindrical magnetic lenses, made of rings of permanent magnetic material. The system now in use is the one of Fig. 1(A). One lens element consists of four axially magnetised rings of the anisotropic Ferroxdure Fxd 300 R completed on each side with one half of the radially magnetised rings of the isotropic Ferroxdure Fxd 100. The maximum field strength on the axis is 1600 G. The first order paraxial ray equation turns out to be a Mathieu equation, with which the stability for protons and heavier particles was easily established. Matrix calculations are more flexible and yield for the orbit to a first approximation:

$$r_n = r_o \cos(kln + \Phi) \qquad \ldots (1)$$

with k^2 = strength of the lens, l = length of one element, n = element number. Considering each lens as a homogeneous field lens one finds for protons of V = 10 keV and B_m = 2 kG

$$k^2 = \frac{1}{8}\frac{q}{A}\frac{B^2}{V} \simeq 40$$

If the beam width is not more than half the lens diameter, to keep aberrations small enough, the acceptance turns out to be about 1500 mm mrad. The acceptance is inversely proportional to $\sqrt{V}$, so when the system is designed for the lowest energy of protons it is also adapted for the higher energies using the same source. In a constant orbit cyclotron the acceptance will be the same for all ions.

At the end of the beam transport system a strong but short quadrupole doublet will adapt the beam to the last section of the axial hole.

On the basis of rough calculations we determined the optimum distance between the 300 R packets to obtain maximum field, and the demagnetisation of the 300 R cores. Using standard spherical aberration formulas we calculated the aberrations. The system of Fig. 1(A) has some demagnetisation but the field did not change over one year.

Due to aberrations the phase space area r, r' will expand by ~10% per metre.

The best result would give the system of Fig. 1(C), using axially magnetised cores of the material 360 R, but this is not yet commercially available in the required size, so 330 K will be used in our case.

The beam transport system described has the advantage of being very inexpensive and the construction is like stringing beads around a stainless steel tube. The centring of the cores seems to be not very critical.

During experiments with a beam of 10 keV protons having a phase space area of more than 300 mm mrad, which was not well centred either, more than 90%

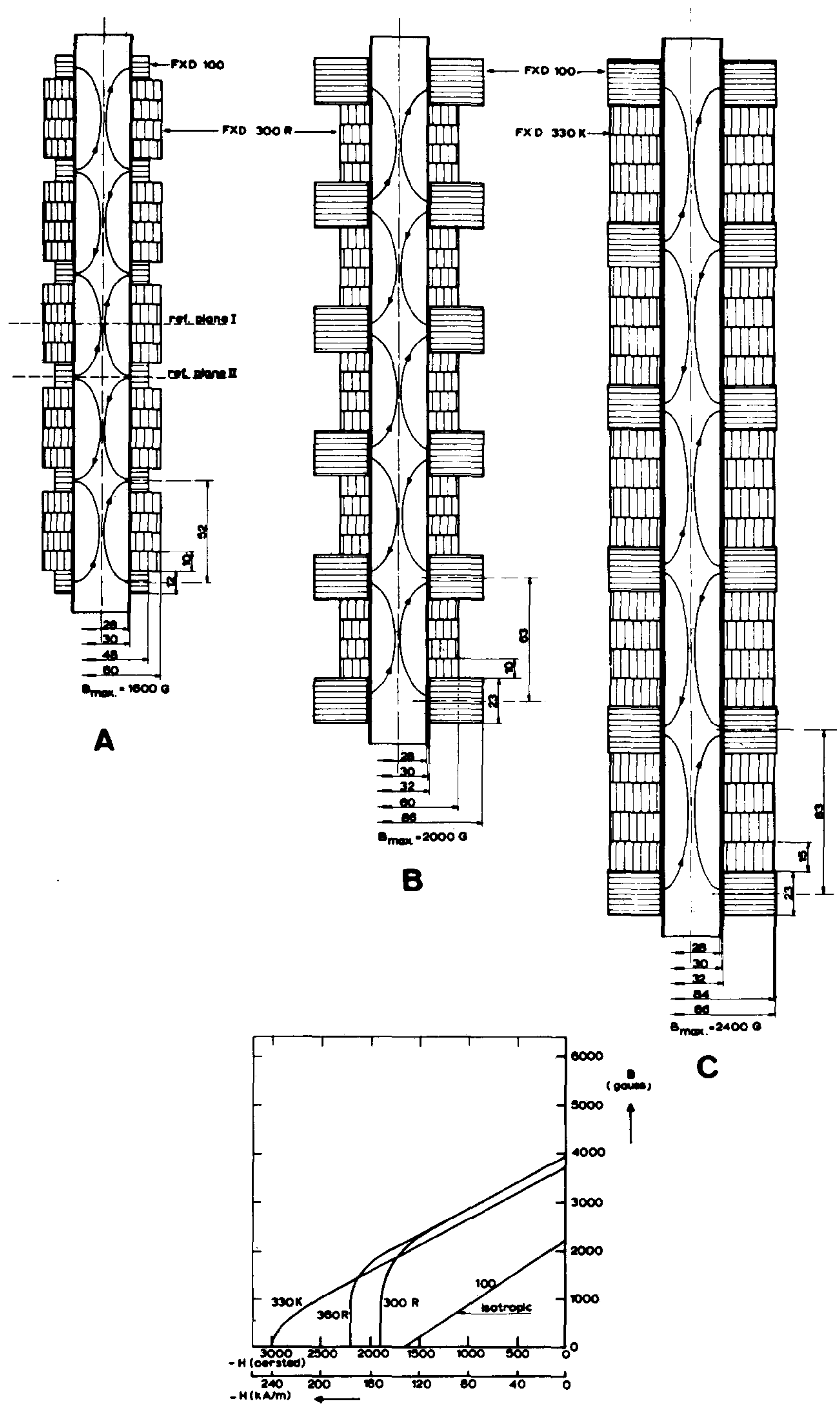
FXD 100
FXD 300 R
ref. plane I
ref. plane II
Bmax. = 1600 G
A
FXD 330 K
Bmax. = 2000 G
B
Bmax. = 2400 G
C
B (gauss)
330K
360R
300 R
100
isotropic
-H (oersted)
-H (kA/m)

Fig. 1.

arrived as a fine and homogeneous spot of 2 mm diam. at the centre of the small cyclotron. The beam current was measured with a probe of special construction which could be moved along the axis of the hole.

3. CALCULATIONS ON LENS ELEMENTS WITH LESS ABERRATION

Calculations are in progress to find the field distribution in the lens elements for which the aberrations are minimum. For this purpose one needs higher derivatives of the field along the axis and it is not possible to deduce second and third derivatives of a measured field with a good accuracy. We use a model which calculates the field from the potential integral

$$V = \int \frac{\tau}{r} \mathrm{d}S \qquad \ldots (2)$$

On the closed surface S in Eqn (2) the charge density τ has to be specified which produces the measured field on the axis as closely as possible. Then the model is used to calculate the higher derivatives and to vary the field distribution to find one which will give minimum aberration. To perform the field calculation the integrand in Eqn (2) is developed in a series of Legendre functions with the intersection of the z axis and reference plane I or II as points of symmetry [see Fig. 1 (A)]. The two field curves of B_z as a function of z growing from reference plane I in one direction and from reference plane II in the opposite direction are connected together. In this way only four Legendre functions are needed: P_3, P_5, P_7, P_9 around reference plane I and P_2, P_4, P_6, P_8 around reference plane II.

To see what possibility there is of minimising aberrations one may use the original form of the Liouville theorem. This states that if one has a system of n first order differential equations, $\dot{R} = F(R, t)$, where $r_1 \ldots r_n$ are the phase space co-ordinates, the following equation holds

$$\frac{\mathrm{d}W}{\mathrm{d}t} = \int \nabla . F \frac{D(R)}{D(R_o)} \mathrm{d}r_{10} \ldots \mathrm{d}r_{no} \qquad \ldots (3)$$

In Eqn (3) W is volume in the phase space,

$$\nabla . F = \frac{\partial f_1}{\partial r_1} + \frac{\partial f_2}{\partial r_2} + \ldots \frac{\partial f_n}{\partial r_n},$$

and $D(R)/D(R_o)$ is the Jacobian of the transformation of co-ordinates from $t = 0$ to $t = t$.

When we use canonical co-ordinates then $\nabla . F = 0$ and $\mathrm{d}V/\mathrm{d}t = 0$ in which form Liouville's theorem is normally used.

When studying aberrations we are not interested in canonical co-ordinates but in the radial position of particles and their impulses as a function of z. From the Hamilton equation of motion and a series development of the magnetic vector potential the following equations are easily deduced, using cylindrical co-ordinates:

$$A_\theta(r, z) = \frac{1}{2} B(z) r - \frac{1}{8} B^{(2)}(z) r^3 + \frac{1}{96} B^{(4)}(z) r^5$$

$$\frac{\mathrm{d}r}{\mathrm{d}z} = \frac{P_r}{P_z}$$

$$-\frac{\mathrm{d}P_r}{\mathrm{d}z} = \frac{q^2}{P_z} A_\theta \frac{\partial}{\partial r} A_\theta$$

$$-\frac{\mathrm{d}P_z}{\mathrm{d}z} = \frac{q^2}{P_z} A_\theta \frac{\partial}{\partial z} A_\theta$$

$$\nabla . F = + \frac{1}{4} \frac{q^2}{P_z{}^2} B(z) r^2 \left[\frac{\partial B(z)}{\partial z} - \frac{1}{8} B^{(3)}(z) r^2 \right] \qquad \ldots (4)$$

In principle it is possible to make $\nabla . F$ small in a region where normally aberrations become serious. In our case it is possible to get a more convenient field by making a small air gap between the two ring cores at reference plane 1.

From Eqn (4) it is also easy to see that the strong lens which the particles will see when they come out of the axial hole into the air gap of the cyclotron magnet will suffer from serious aberrations. So it is wise to use not more than half the diameter of the hole for the beam width at this place.

In our case this means that the acceptance of the last part of the hole, 28 mm diam. and 330 mm long, will not be more than 300 mm mrad, when we do not use lenses in this part.

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