IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

MEDIAN PLANE EFFECTS IN THE EINDHOVEN AVF CYCLOTRON

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Summary

The median plane of the main magnetic field of the Eindhoven AVF Cyclotron does not coincide with the midplane of the cyclotron magnet at small radii. This tends to decrease the axial acceptance of the cyclotron for the injected beam.

The effect of an asymmetric excitation of inner circular correction coils is described. With this it is possible to alter the position of the magnetic median plane and thereby change the area of the axial acceptance of the cyclotron.

A deflection voltage on axial deflection plates in the centre of the cyclotron can shift the axial cyclotron acceptance, so as to properly match the ion source emittance. In combination with the asymmetric excitation of inner circular correction coils this parameter provides a good means to optimize the beam current in the centre of the cyclotron.

Finally, numerical calculations show that there is only a small effect on the ion beam of an accelerating gap which has an inclined dee with respect to the dummy dee.

1. Introduction

In many experiments on the beam behaviour in the centre of the Eindhoven AVF Cyclotron it turned out that the ion beam does not move in the plane of symmetry of the cyclotron magnet. The difference in vertical position of the orbit on two successive revolutions can amount to several millimeters.

Examinations to explane these deviations and to possibly correct for them, were undertaken. They are based on the magnetic field data [1] and on three dimensional electric field maps of the electrode system in the central region [2,3]. The magnetic and electric field data are used in a numerical particle trajectory program that is especially suited for the calculation of the horizontal and vertical particle motion in the central region of the cyclotron.

The Eindhoven cyclotron is the prototype Philips AVF cyclotron [4]. It is a constant orbit, variable energy machine that can accelerate light ions, with proton energies up to 30 MeV. The cyclotron has a one-dee system and a conventional (Livingston type) ion source. The ion source can be reproducibly positioned with respect to the puller by remote control in axial and radial direction, and along the dee gap. The cyclotron has ten pairs of circular correction coils, B_1 to B_{10}. Of these the inner two pairs (with diameter of 10 cm and 15 cm respectively) can be excited asymmetrically. The vertical distance of these coils is about 13 cm.

Floating wire experiments performed in the Eindhoven cyclotron have shown that the median plane of the main magnetic field differs from the midplane of the cyclotron magnet at small radii. In figure 1 this deviation above the midplane is plotted versus radius. Asymmetrical excitation of correction coils changes the vertical position of the magnetic median plane. For equal excitation of upper and lower coils the coil symmetry plane coincides with the midplane in between the poles; for excitation of only the upper coils such a symmetry plane coincides with the lower pole face. We define the magnetic median plane as that plane with horizontal magnetic field strength equal to zero. An estimation of the vertical position z of the magnetic median plane of asymmetrically excited coils with respect to the midplane of the cyclotron can now be given :

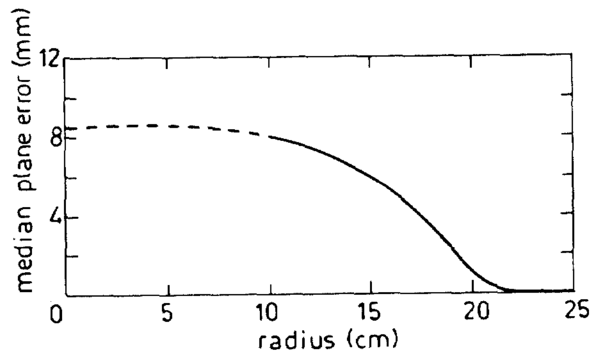

Fig. 1 Deviation of the main magnetic field median plane from the midplane of the cyclotron magnet. The dashed part represents an extrapolation towards the centre.

$$z = -\tfrac{1}{2}h \frac{I_a/4I_s}{1 + I_a/4I_s} \tag{1}$$

In this formula I_s represents the current through the lower coil, whereas I_a+I_s represents the current through the upper coil. The quantity h is the distance between upper and lower coils. Typical values for the inner circular correction coils of our cyclotron are : I_a = 40 Amp, I_s = 50 Amp. With these currents the median plane of coils B_1 can be approximately lowered by 10 mm.

2. The effective median plane

In ideal magnetic and electric fields in the cyclotron the axial particle motion is described by the differential equation :

$$\ddot{z} + \nu^2_{z,el}\, z + \nu^2_{z,magn}\, z = 0 \tag{2}$$

where the differentiation is with respect to the azimuth and where $\nu^2_{z,el}$ and $\nu^2_{z,magn}$ represent the electric focussing of the dee gap and of the magnetic field respectively. The values of $\nu^2_{z,el}$ are strongly phase dependent. However, we present in the following only calculations carried out for particles with a central position phase of −30 deg. under the puller after the first dee gap crossing [5].

In the presence of a median plane error $z_o(r)$ of the main magnetic field (figure 1) an inhomogeneous differential equation results for the axial motion :

$$\ddot{z} = \nu^2_{z,el}\, z + \nu^2_{z,magn}\, (z-z_o(r)) = 0 \tag{3}$$

When the inner circular correction coils B_1 and B_2 are excited an extra axial focussing term must be added. The focussing strengths calculated from the cyclotron field data [1] are given in figure 2, together with ν^2_z for the main magnetic field.

The differential equation for the vertical motion in the cyclotron in the presence of asymmetric excitation of coils B_1 and B_2 has the form :

$$\ddot{z}+\nu^2_{z,total}\, z=\nu^2_{z,magn}\, z_o+\nu^2_{z,B_1}\, z_{B_1}+\nu^2_{z,B_2}\, z_{B_2} \tag{4}$$

Asymmetric currents are supplied to coils B_1 and B_2 such that their median planes lie at height z_{B_1} and z_{B_2} respectively.
In this equation ν^2_{z,B_1} and ν^2_{z,B_2} are the focussing

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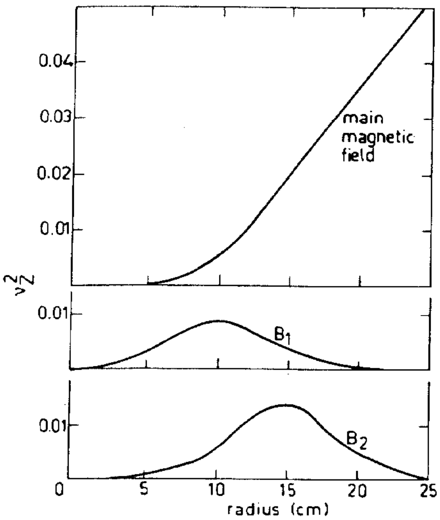

Fig. 2 ν_z^2 *versus radius for the main magnetic field, for* B_1 *and for* B_2

strengths of coil B_1 and B_2, and $\nu^2_{z,total}$ is the sum of the seperate focusing strengths :

$$\nu^2_{z,total} = \nu^2_{z,el} + \nu^2_{z,magn} + \nu^2_{z,B_1} + \nu^2_{z,B_2} \qquad (5)$$

The effective median plane error is now given by

$$\Delta z = \frac{\nu^2_{z,magn}}{\nu^2_{z,total}} z_o + \frac{\nu^2_{z,B1}}{\nu^2_{z,total}} z_{B_1} + \frac{\nu^2_{z,B2}}{\nu^2_{z,total}} z_{B_2} \qquad (6)$$

The several terms in this equation are given in figure 3a and 3b. By a proper asymmetric excitation of B_1 and B_2 the median plane heights z_{B1} and z_{B2} can be chosen such that Δz is as small as possible. In figure 3c this situation is given, for z_{B1} = 6 mm and z_{B2} = 5 mm. One must remark that the effective median plane is phase dependent because the electric focusing is phase dependent.

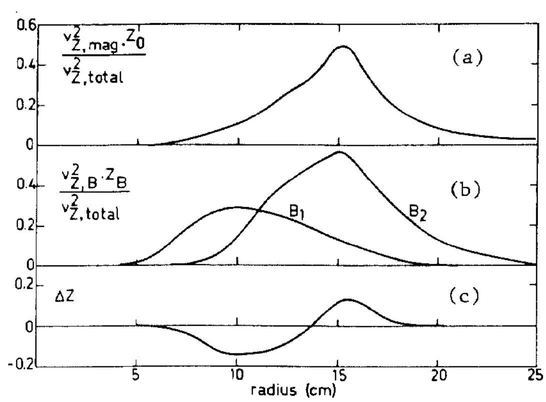

Fig. 3 *The effective median plane error. In (b) the value of* z_B *belongs to maximum values of* I_a *and* I_s.

3. Axial acceptance

The axial particle motion is taken linear in ω. Therefore the transformation of an axial phase space point from one aximuthal position to another one is given by a 2 x 2 matrix. Physical boundaries by which the beam is intercepted (for instance the dee aperture) are transformed back to a position under the puller at azimuth 90 deg. after the first dee gap crossing, and yield the axial cyclotron acceptance.

We will show two cases :

a. the axial cyclotron acceptance using the conventional ion source. For this case the vertical opening of the cyclotron is 20 mm.
b. The axial acceptance of the cyclotron using the trochoidal injector system [6]. This system is used at the Eindhoven cyclotron for injection of polarised protons of 5 keV initial energy. In this case the vertical opening of the cyclotron is 8 mm.

For the above mentioned cases the oscillation amplitudes may not be larger than 10 mm and 4 mm respectively. When median plane errors are present, they have to be even smaller.

In figure 4 and figure 5 the axial cyclotron acceptances are drawn. They are given for the case with no median plane error, for the case with a median plane error present due to the main magnetic field, and in the case after correction by asymmetric excitation of coils B_1 and B_2. It is seen that the axial acceptance diminishes substantially, or even vanishes for the situation of 8 mm vertical opening, due to the deviation of the main magnetic field median plane with the cyclotron magnet midplane. A proper asymmetrical excitation of correction coils B_1 and B_2 can largely restore the axial acceptance.

4. Axial deflection

Electric fields, especially between ion source and puller, can have a certain angle with respect to the symmetry plane of the cyclotron magnet due to a small inclination of the chimney or due to a wrong axial position of the ion source. Because of these fields axial oscillations can be induced. In the Eindhoven cyclotron electric deflection plates are positioned at the second turn. For a proton beam of 50 keV (final energy 7 MeV) a voltage of approximately 300 V has to be applied to get maximum internal beam current (and maximum extraction efficiency).

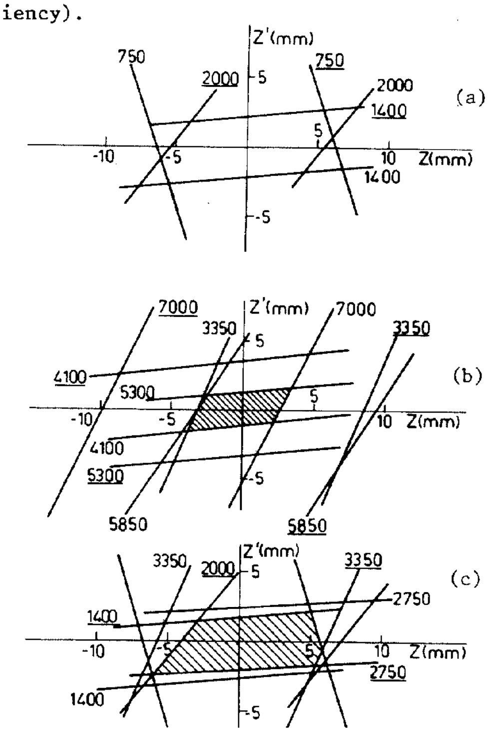

Fig. 4 *Axial acceptance for a verticle opening of 20 mm, without a median plane error (a), with a median plane error of the main magnetic field (b) and for correction by asymmetric excitation of* B_1 *and* B_2 *(c). Only those lines limiting the axial acceptance are drawn.*

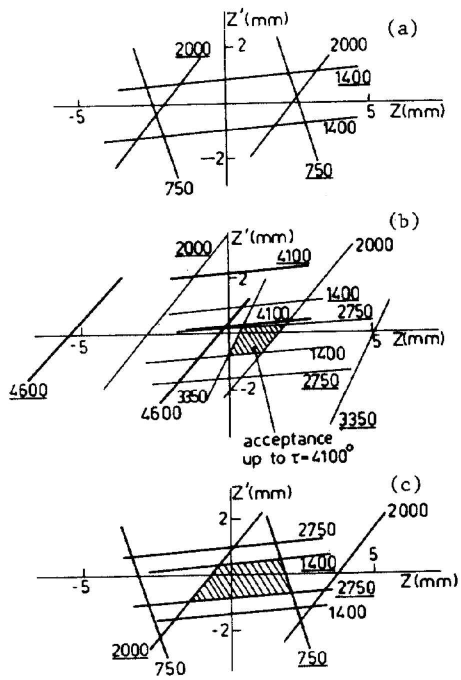

Fig. 5 Same as figure 4, except for a vertical opening of 8 mm, which occurs in case of use of the trochoidal median plane injector.

The effect of a deflection voltage at a certain azimuthal position is a shift of the ion beam emittance along the $\dot{z}$-axis in the axial phase space at that azimuth, or conversely a shift of the cyclotron acceptance in the opposite direction. The magnitude of the shift can easily be calculated in terms of the particle energy, deflection voltage and azimuthal extent of the deflection plates. The shift of the cyclotron acceptance has been transformed back to the azimuth of 90 deg. under the puller (cf. figure 6). At this azimuth we have also indicated the shift of the ion source emittance when the vertical position is lowered, and when the chimney is inclined with respect to the magnetic field lines. An inclination of the chimney of several mrad can easily occur. The figure shows that such an inclination can be corrected for by the deflecting voltage.

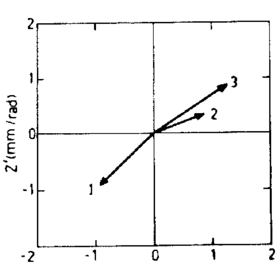

Fig. 6
Shift of axial acceptance at a deflection voltage of 400 V (1) and shift of ion beam emittance for axial mispositioning of 0.5 mm (2) and for vertical inclination of 40 mrad (3) of the ion source

Experimental data of the internal beam current versus deflection voltage, and versus asymmetric excitation of B_1 are given in figure 7. In this situation we have placed an axial slit with an opening of 3 mm and a radial extent of 8 cm in the centre of the cyclotron, to make the median plane effects more pronounced. It shows that both the deflection voltage and the asymmetric excitation have to be present to get any beam current.

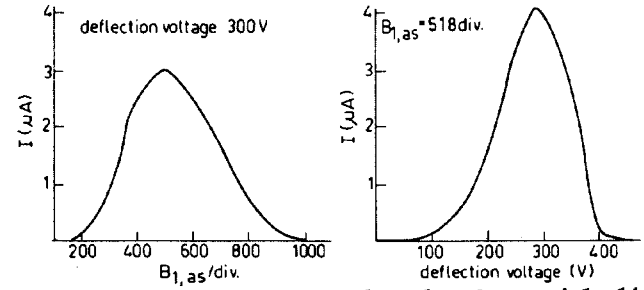

Fig. 7 Internal beam current through a 3 mm axial slit, radial extent 8 cm, as a function of deflection voltage and of asymmetric excitation of coil B_1.

5. A tilt of the accelerating field outside the first dee crossing

Exact positioning of the dee with respect to the dummy dee is a tedious task. Misalignments of a few millimeter can easily occur. A vertical misalignment of the dee with respect to the dummy dee at a particular dee gap crossing can be described by a rotation of the electric field around the centre point in the dee gap at that crossing. Then to the weak vertical electric field components a portion is added of the strong accelerating field components.

An overall vertical displacement of the dee with respect to the dummy dee seems to yield a negligable effect since the vertical displacement of the dee on the one crossing is roughly compensated at the next crossing. However, for a vertical inclination of the dee along the dee gap with respect to the dummy dee the vertical displacements at the successive turns are additive.

We have investigated these effects numerically by applying a position dependent rotation to the electric fields encountered by the particles. As said the numerical trajectory calculation program uses a three dimensional electric field map measured for the cyclotron centre. The results of these numerical evaluations will be mentioned briefly :

- an overall vertical displacement of the dee with respect to the dummy dee gives a negligable vertical displacement of the trajectories. A vertical beam displacement of about 0.2 mm was calculated for an overall dee displacement of 2 mm.
- vertical height displacements of the particles of the order of 1.5 mm per turn in the cyclotron centre could only be reached for a large dee inclination of 40 mrad with respect to the dummy dee.

6. Conclusion

Asymmetric excitation of the inner correction coils increases the axial acceptance of the cyclotron if the main magnetic median plane does not coincide with the midplane of the cyclotron magnet.

A deflection voltage in the centre of the cyclotron can shift the axial acceptance, so as to properly match a wrong position of the ion source emittance in phase space.

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