THE MAGNETIC FIELD OF A TWO-PARTICLE FIXED-ENERGY AVF CYCLOTRON WITHOUT TRIMMING COILS

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We have made a study of a fixed-energy AVF machine. This machine accelerates protons to an energy of about 27 MeV. The pole diameter is 1.40 m, the mean gap 24 cm and the magnetic induction at the cyclotron centre 13300 gauss.

As the magnetic field is fixed we need not take into account the influence of saturation effects in the pole. Thus it is not necessary to bevel the edges of the segments as has been done for the Philips variable-energy AVF Cyclotron[1]. The magnetic field is of the spiral-ridge three sector type. There are no circular or harmonic coils to adjust the field shape. The pole segments must be shimmed so that sufficient isochronism and vertical focusing is reached over the whole acceleration region.

We have measured the magnetic field for this cyclotron in a model magnet. Measurements at several excitations show a variation of the field shape due to saturation effects in the iron. For a magnetic induction of 14900 gauss at the centre the increase with radius of the mean magnetic induction is diminished such that the field shape is suitable for the acceleration of deuterons (and alpha-particles) to an energy of 16 MeV (32 MeV).

The Magnetic Field

The main conditions for the magnetic field are: 1) isochronism for protons and for deuterons (alpha-particles), and 2) sufficient vertical focusing.

We start with the vertical focusing condition. The magnetic field has a three-fold symmetry. The amplitude of the third harmonic A_3 is about 0.25. The spiral angle γ of the segments is chosen so that enough vertical focusing is acquired. The relation $\tan\gamma = r d\varphi/dr$ defines the spiral angle (r = the radius, φ = the phase of the third harmonic). At a radius of 55 cm, $\gamma = 48^0$, and $\nu_z^2 = \frac{1}{2}A_3^2\ (1 + 2\tan^2\gamma) - k \approx 0.05$, where the field index $k \approx 0.06$ is determined by the condition for isochronism for 27 MeV protons. This formula gives a rough idea about the focusing properties. For better estimations we used the analytical formula given in Ref. 2.

If the focusing for protons is sufficient, then this is also the case for deuterons (alpha-particles), since for these the value of k is less. Due to saturation effects the amplitude A_3 decreases somewhat with increasing magnetic induction, but this is not serious.

In the central region the vertical focusing, originating from the magnetic field tends to zero. However, if the particles start at a phase of -20^0 with respect to

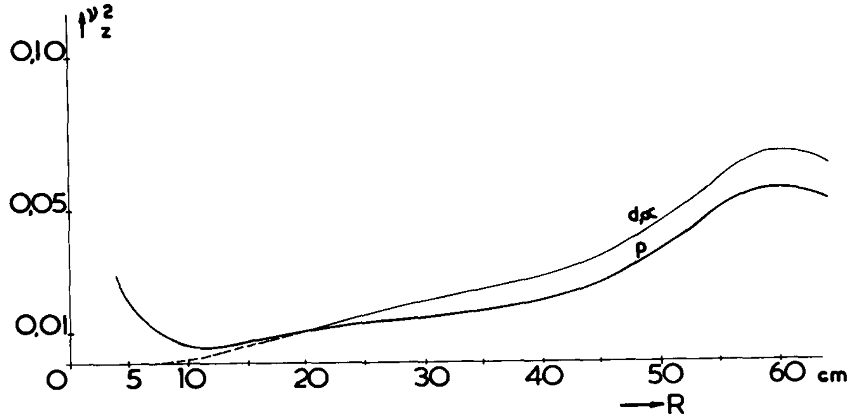

Fig. 1 The vertical focusing versus radius for deuterons and protons. The dotted curve in the central region represents the contribution from the magnetic field, the other part arises from the electric focusing.

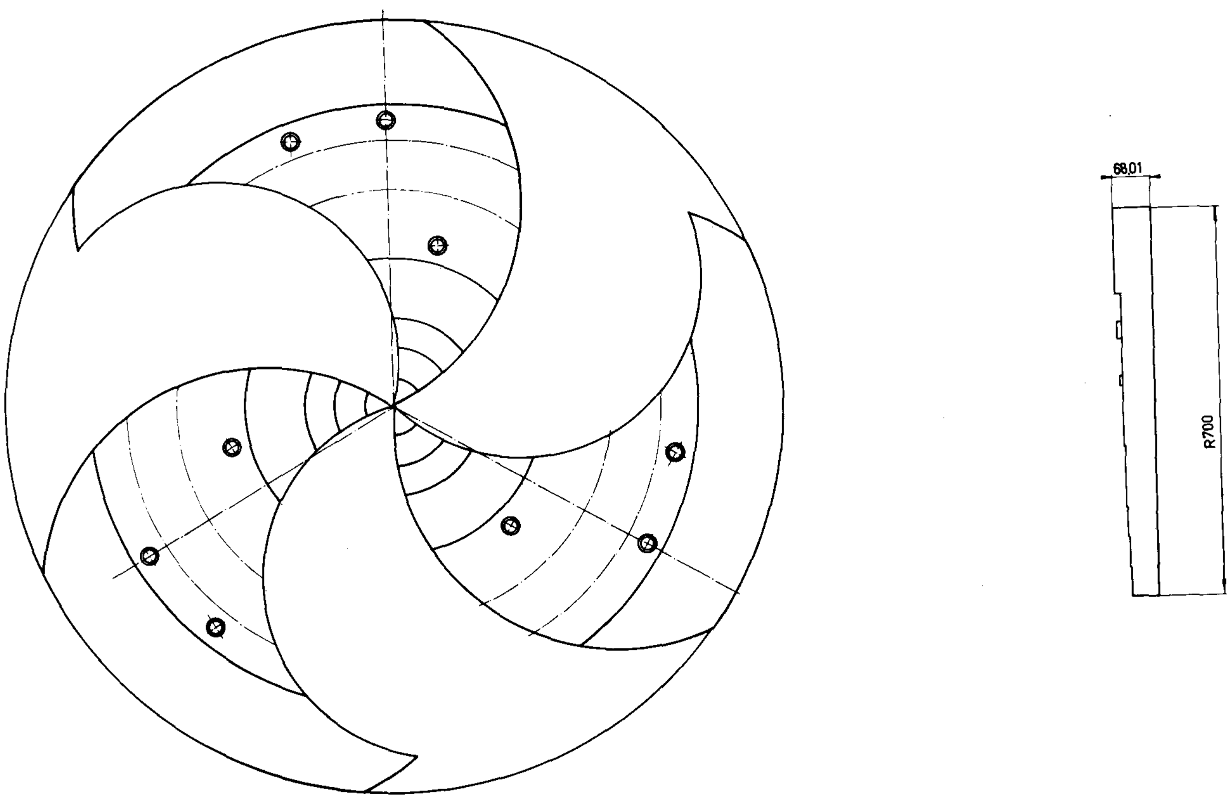

Fig. 2 The shape of the pole segments.

the phase of the RF, there will be sufficient electric focusing. In Fig. 1 ν_z^2 is given versus radius for both p and d(α). One sees the contributions from the magnetic field and the electric field between dee and dummy dee at the centre.

The condition for isochronism is prescribed by Eq. (5, 6) of Ref. 2. As was checked by computer results, this formula is sufficiently accurate (Fig. 3 of Ref. 2). We have made pole segments which by a first estimation should give a reasonable isochronous field for protons. After this the magnetic field and the influence of

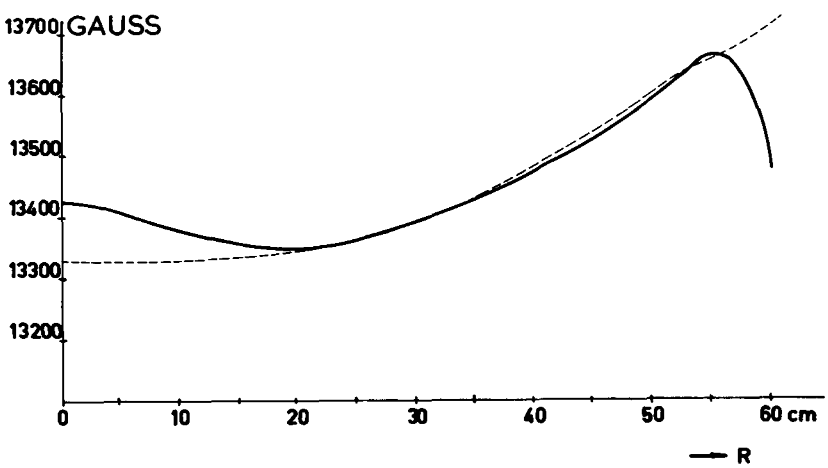

Fig. 3 The isochronous field for protons.

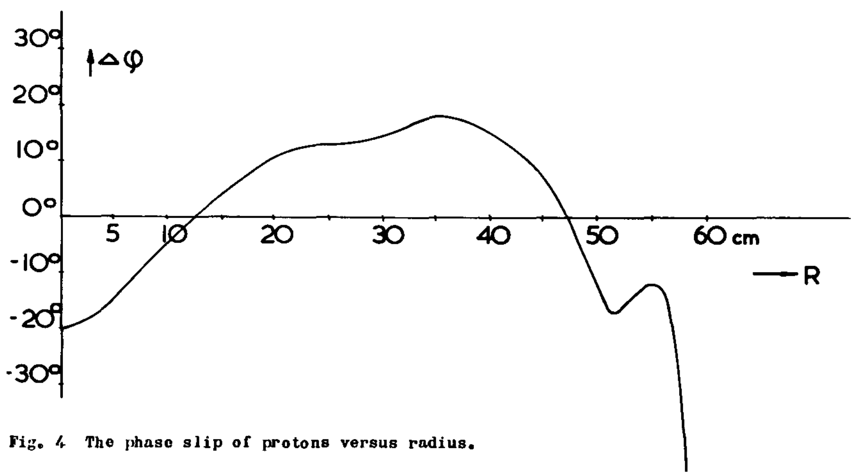

Fig. 4 The phase slip of protons versus radius.

shims and trenches have been measured. With all this information a second estimation was made for the top surface of the segments. After a few steps we arrived at a pole segment which should give isochronism for protons (Fig. 2).

The mean magnetic induction as a function of radius is given in Fig. 3. Here the dotted curve is the isochronous field prescribed by the theory, and the full line represents the realized field.

The phase lag at different radii is shown in Fig. 4. We see that due to the higher field in the centre the phase oscillates about 0°. For the calculation of the phase slip we have assumed a dee voltage of 50 kV, so the energy gain is 100 keV/turn. The frequency of the RF oscillator is 20.4 Mc/s for protons in a magnetic field of 13300 gauss.

As mentioned in the introduction the shape of the magnetic field varies with different excitations. At a field level of 14900 gauss we find a shape which is rather well adapted for the acceleration of deuterons (alpha-particles). We have assumed also here a dee voltage of 50 kV. The RF frequency is 11.6 Mc/s. In Fig. 5 the

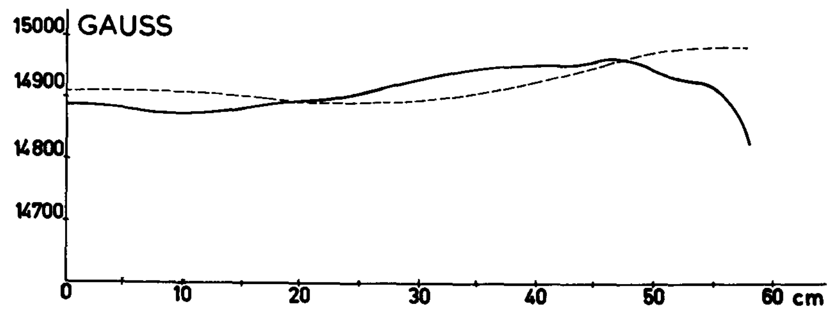

Fig. 5 The isochronous field for deuterons (alpha-particles).

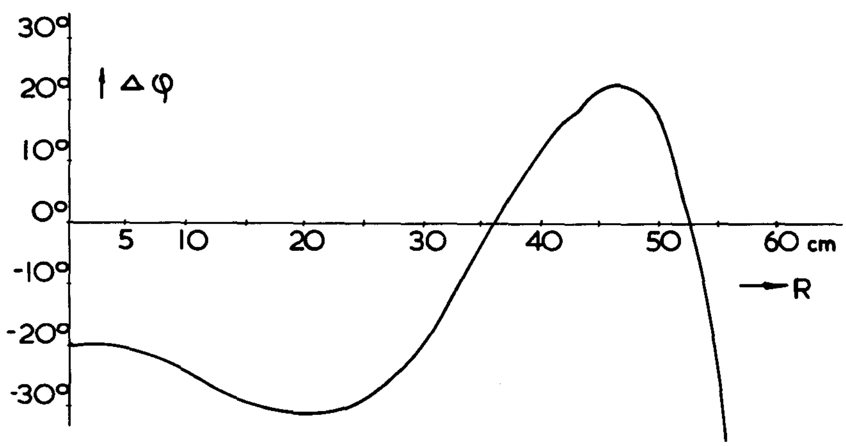

Fig. 6 The phase slip of deuterons (alpha-particles) versus radius.

isochronous and actual field shape for deuterons are represented by the dotted and the full line respectively. The phase slip of the deuterons as a function of radius is shown in Fig. 6. Here also the phase oscillates about 0^{o}. The phase of -20^{o} in the centre for both protons and deuterons is advantageous for the vertical focusing. Although in the case of deuterons the phase lag increases somewhat in the centre it is never too large during the whole acceleration. The final radius is about 56 cm. The energy of the deuterons (alpha-particles) at that radius is 16 MeV (32 MeV).

In the model we did not take special precautions to shape the magnetic field such that it became suitable for acceleration of both protons and deuterons. With small effort, however, additional saturation can be provided for in the pole segments to improve the field properties.

References

1. N.F. Verster et al., Nucl. Instr. and Meth. 18-19, 88-92 (1962).
2. H.L. Hagedoorn and N.F. Verster, Nucl. Instr. and Meth. 18-19, 2 1-208 (1962).

DISCUSSION

REISER : The phase during the early turns is always negative in the deuteron case. Did you check whether your electric focusing is sufficient?

HAGEDOORN : For electric focusing a negative phase is favourable. Thus this negative phase in the central region is not harmful for the beam. The only disadvantage is the loss of isochronism; but this is not too serious either as still 80 to 90% of the dee voltage will be available for the acceleration.