Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

BEAM PROPERTIES OF PHILIPS' A.V.F. CYCLOTRONS.

A.A. van Kranenburg **, H.L. Hagedoorn *, P. Kramer *, D. Wierts **

* Philips' Research Laboratories, Eindhoven Netherlands.

** Philips' Cyclotron Development Group, Eindhoven Netherlands.

Abstract

Some Parameters determining the beam-quality and energy resolution, will be discussed.
Experiments have been performed, and results will be shown.

1) Introduction

The motion of the particles in the cyclotroncentre is important for the quality of the beam.
Misalignments in this region easily can disturb the beam properties. Many articles have been published about the cyclotroncentre (1,2,3). We only will discuss here the influence of some parameters on the particle orbits. Many measurements on the dimensions of the beam have been performed. We have found that 80% of the external beam intensity has a radial quality of 10 mmmrad and an axial quality of 20 mmmrad for protons of 25 MeV. The full width half peak value of the energy spectrum is 1/3 %. The compensation of first harmonic perturbations by harmonic correction coils is important. First harmonic perturbations caused by the Dee gap crossing resonance are in general very small and not dangerous.

2) The influence of radial oscillations on beam quality

The extraction efficiency and the quality of the external beam depend strongly on the radial oscillations of the internal beam during the whole acceleration period.
So it is important to eliminate all perturbations causing radial oscillations of the beam. Instead of studying the radial oscillations one also can investigate the precession of the orbit centre. This will sometimes simplify the representation of the radial motion (4).

An offcentered beam is excited by a misaligned ionsource, a too low or too large Dee voltage as well as a first harmonic component in the magnetic field. Especially in the cyclotroncentre during the first 10 or 20 revolutions, the radial frequency is so close to unity that oscillations can easily be excited.
Cohaerent oscillations in this region can in principle be eliminated by a first harmonic field component.
Both calculations and experiments indicate that cohaerent radial oscillations, caused by a misalignment of the source of 3 mm, can be corrected in this way. Larger deviations cannot be fully compensated. One finds a worse beam quality due to non-linear effects (ref5).
Cohaerent oscillations can be observed after many revolutions. However, due to the H.F. phase-width of the beam, ions with the same energy can have a different number of revolutions. Therefore these ions will have different radial oscillationphases. After a large number of revolutions cohaerent oscillations become inobservable, resulting in a ring-shaped phase figure giving a very bad quality. This H.F. effect on cohaerent oscillations always will enlarge the phasefigure of particles with the same energy. For the best beam quality - the smallest phasefigure - it is important therefore to avoid cohaerent oscillations. It appears, that cohaerent oscillations excited in the cyclotroncentre never can be compensated fully by first harmonic field components in the extraction region. The best beamquality is achieved if all perturbations during the whole acceleration are eliminated. The beam quality then depends on the phasefigure representing the ions leaving the ion source and will be inversely proportional to the square root of the energy (ref6). One effect which we did not mention here is the gap crossing resonance (ref7).
We will show in section 4 that this effect is very small in our cyclotrons. Radial oscillations in the extraction region are excited to get better extraction efficiency. More will be said about this in ref11).

3) Axial oscillations

If the ion source, the magnetic median plane, the Dee and the dummy Dee all coincide with or are symmetric with respect to the geometrical median plane only incohaerent axial oscillations will be observed. The beam will be symmetric around the median plane and it will have its largest height at the place of least axial focusing. At this place which lies 10 to 20 revolutions away from the centre the Dee will behave as a diaphragm. During the rest of the acceleration the height of the beam is smaller than $g\left(\frac{\nu_z(R)}{\nu_{z0}}\right)^{-\frac{1}{2}}$

 Reprinted from IEEE Transactions on Nuclear Science NS-13 (4), Aug 1966

(where g represents the Dee aperture and ν_{Z0}, $\nu_Z(R)$ are the minimal axial frequency and the axial frequency at radius R respectively).

The main part of the axial focusing in the cyclotroncentre arises from the electric field between Dee and dummy Dee (ref[2,9]). The magnetic focusing becomes more important after a radius which is equal to half the mean magnet gap. At this radius the magnetic focusing takes over the role of the electric focusing and the total axial focusing is minimal. Perturbations in the median plane at this place easily arise and disturb the axial motion. In fig.1 is given the axial focusing in a cyclotron with three and fourfold symmetry. One can observe that the beam in a fourfold symmetric cyclotron seems to be smaller theorethically than in a three fold symmetric cyclotron. However the difference lies only in the fact, that in the fourfold symmetry case, a larger part of the axial phasefigure is cut off, thus giving less maximum beam current (this effect can be acquired in a three fold symmetric cyclotron by decreasing the Dee aperture). The influence on the axial motion of perturbations in the weak focusing region of the fourfold symmetric cyclotron will be larger than in the case of threefold symmetry.

In practice there will be misalignments of source position, Dee and Dummy Dee and magnetic median plane. Axial coherent oscillations will be excited already during the first revolutions (ref[10]). Due to the H.F. influence and the value of $\nu_Z \approx 0{,}2$ these cohaerent oscillations will rapidly give ringshaped phasefigures, decreasing the axial beam quality.

Axial oscillations are easier excited (low value of ν_Z) and more difficult to avoid than radial oscillations.

Much care must be taken for the vertical alignment of all parts in the cyclotroncentre.

At the extraction region the beam passes the $\nu_R = 2\nu_Z$ coupling resonance. By a correct adjustment of the harmonic coils at the extraction region, to get maximum extraction efficiency, the beam is easily accelerated through this resonance without much increase of its height (ref[8]).

4) The gap crossing resonance

The theory of the gapcrossing resonance in A.V.F. cyclotrons has been given by M. Gordon some years ago at the Los Angelos conference (7). This resonance gives a first harmonic effect in a threefoldsymmetric cyclotron with two or four acceleration gaps due to interference effects.

Following the theory of Gordon we find an acquivalent first harmonic component, expressed in field quantities:

$$\bar{C}_1 \cos(\vartheta-\vartheta_1) = \frac{1}{4\pi n}\left[\left(\frac{11}{60}B_3' + \frac{9}{20}B_3\right)\cos\vartheta - \left(\frac{3}{20}A_3' + \frac{11}{20}A_3\right)\sin\vartheta\right] =$$

$$\frac{1}{4\pi n}\left[\tilde{A}_1 \cos\vartheta - \tilde{B}_1 \sin\vartheta\right]$$

(where $\tilde{A}_1$ and $\tilde{B}_1$ are the components of the first harmonic. The magnetic field is represented as:

$$B = B_0\left(1 + \mu' x + \ldots + \sum_{k=1}^{\infty}(A_{3k} + xA'_{3k} + \ldots)\cos\vartheta + (B_{3k} + xB'_{3k} + \ldots)\sin\vartheta\right)$$

(n is the number of revolutions). In fig. 3 we have given the quantities $\tilde{A}_1$ and $\tilde{B}_1$, the components of the first harmonic as a function of radius in a Philips AVF cyclotron. The effect is largest at the central region and quite small at the extraction region. In practice even in the center region, this small first harmonic effect of the Dee gap crossing resonance is automatically compensated by adjustment of the harmonic corrections coils, for optimal performance of the cyclotrons.

The high quality of the external beam (see section 6) does not indicate a harmfull influence of this resonance on the particle motion.

5) Depolarisation of a polarised proton beam

With help of the theorethical derivations of Khoe and Teng 12) it is found that depolarisation of a polarised proton beam in our threefold symmetric cyclotron is negligibly small.

(In the notation of Khoe and Teng $P_2 < 10^{-4}$).

6) Experimental results

Radial oscillations can be measured in several ways. In a cyclotron where the beam is accelerated beyond the $\nu_R = 1$ resonance one target is sufficient to observe the presence of radial oscillations.

These oscillations can cause a loss of beam intensity in the resonant region (ref[8,11]).

However, for a more general investigation shadow methods with two or three targets are convenient (ref[10]). One example of such a method is shown in fig.3.

We have found incohaerent radial oscillations with amplitudes smaller than 2 mm, considering the extraction efficiency we even arrive at values smaller than 3/2 mm. The cohaerent oscillations of the beam in the region before $\nu_R = 1$ are always kept small in order to get a good quality of the external beam (fig.4).

Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

The axial height of the beam has been measured with a radiogram and a threefinger target. The results are shown in fig. 5 and 6. For 20 MeV protons the beam has a height of 3 mm and for 10 MeV protons 4 mm.

From these figures one finds a radial and axial beam quality of the internal beam.

$$Q_{rad} = \pi X_o X_o' \leqslant 14 \text{ mmmrad}$$

$$Q_{axial} = \pi Z_o Z_o' \leqslant 7 \text{ mmmrad}$$

These numbers can be compared with the quality of the external beam, which has been measured by radiograms and by a vibrating target.

The quality of the external beam was determined by two radiograms at places 1,35 m separated from each other. The following results have been found (see fig.7):

for protons

	E	Q_r	Q_z
a.	10 MeV	16 mmmrad	28 mmmrad
b. *	12,9 MeV	15 mmmrad	15 mmmrad
c.	15 MeV	38 mmmrad	24 mmmrad
d.	25 MeV	10 mmmrad	20 mmmrad
e.	20 MeV	22 mmmrad	10 mmmrad

	machine	method
a.	prototype	radiogram
b.	Free Univ.of Amsterdam	"
c.	prototype	vibrating target
d.	prototype	radiogram
e.	prototype	vibrating target

* Measured by J.Rethmeyer, Free University of Amsterdam.

(The quality Q is defined as the phasefigure, in which 80% of the beam lies). Measurements with a vibrating target are less accurate.

It has been found quite clearly that the radial beam quality becomes worse for the lower energies. This is not only observed by means of these radiograms but is also concluded from a decreasing extraction efficiency which is for 10-25 MeV more than 70%, but for energies of 3-5 MeV less than 60%. The radial quality of a 3 MeV beam is about 30 mmmrad.

The axial quality of the external beam is different from the quality of the internal beam. This must be ascribed to perturbations during the last revolutions and during the path through the fringing field. It is possible to improve the axial beam quality by a good adjustment of the magnetic median plane and by good focusing properties of the external beam path through the fringing field. In the machine of the Free University of Amsterdam this resulted in a better axial beamquality. External beam currents of 100 µA have been obtained. For this a copper cooled septum is used. As mentioned already above the extraction efficiency depends slightly on the energy. At the low energy side this must be ascribed to a decreasing beam quality At the high energy side the influence of saturation effects in the pole on the particle orbits becomes important.Both effects diminish the extraction efficiency.For protons of 27-28 MeV we have a maximum efficiency of 80%

Extraction efficiencies of 95% have been found for a 0,1 mm thin tungsten septum. However a septum of this type can easily be destroyed for external currents above 10 µA.

For a large range the mechanical position of the extraction system does not need to be changed. The direction and the position of the beam leaving the cyclotron can be made independent of the energy by adjusting the voltage on the extraction electrode, and the fringing field.

The energyspectrum of the external beam has been measured by an analysing magnet and by solid state counters. Both methods give

$\frac{\Delta E}{E} \approx 1/3\,\%$ full width half peak value.

Numerical calculations give the same result (see ref[11]).

The central region and the extraction region of the 30 MeV cyclotron is used as a model for larger cyclotrons. Therefore at least the same experimental results for the beam in machines with higher energies will be attained.

References

1) International Conference on sector focused cyclotrons, CERN 63 - 19 , 1963 , 193 -222

2) Smith, W.I.B., Nucl.Instr. (Methods 9,49, 1960).

3) Los Angelos Conference on sector focused cyclotrons 1962, Vol.18,19 347 - 387 , 336 - 338.

4) Hagedoorn, H.L. and Verster, N.F. Orbits in AVF cyclotrons, Los Angelos Conference 1962, Nucl.Instr.Methods, Vol.18 - 19, 1962, 201 - 228.

5) Hagedoorn, H.L. and Verster, N.F. Analogue Computerstudies, Los Angelos Conference 1962, Nucl.Instr.Methods, Vol.18 - 19, 1962, 336 - 338.
Gordon, M.M. and Blosser, H.G., Acceleration of particles into stable orbits in an Isochronous three sector cyclotron, Los Angelos Conference 1962, Nucl.Instr.Methods, Vol.18, 19, 1962, 378 - 386.

6) Livingston R.S.
Survey of operating sector focused cyclotrons, CERN conference on sector focused cyclotron 1963, CERN 63 - 19 , 1 - 8.

7) Gordon, M.M.
The electric gap-crossing resonance on a three sector cyclotron, Los Angelos Conference 1962, Nucl.Instr.Methods, Vol. 18, 19, 1962, 268 - 280.

 Reprinted from IEEE Transactions on Nuclear Science NS-13 (4), Aug 1966 © IEEE 1966

Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

8) Hagedoorn, H.L. and Verster, N.F. The extraction of the beam of the Philips AVF cyclotron, CERN Conference 1963, CERN 63 - 19 , 228 - 236.

9) Kramer, P et al. The central region of the Philips AVF cyclotron, CERN conference 1963, CERN 63 - 19 , 214 - 222.

10) Kelly, E.L. General description and operating characteristics of the Berkeley 88-inch cyclotron, Los Angelos Conference 1962, Nucl. Instr.Methods, Vol. 18 - 19 , 1962 , 33 - 41.

11) Hagedoorn, H.L. and Kramer, P. Extractionstudies on an AVF cyclotron. This Conference.

12) Khoe, T.K. and Teng, L.C. Depolarization process in sector focusing cyclotrons, CERN Conference 1963, CERN 63 - 19, 118 - 127.

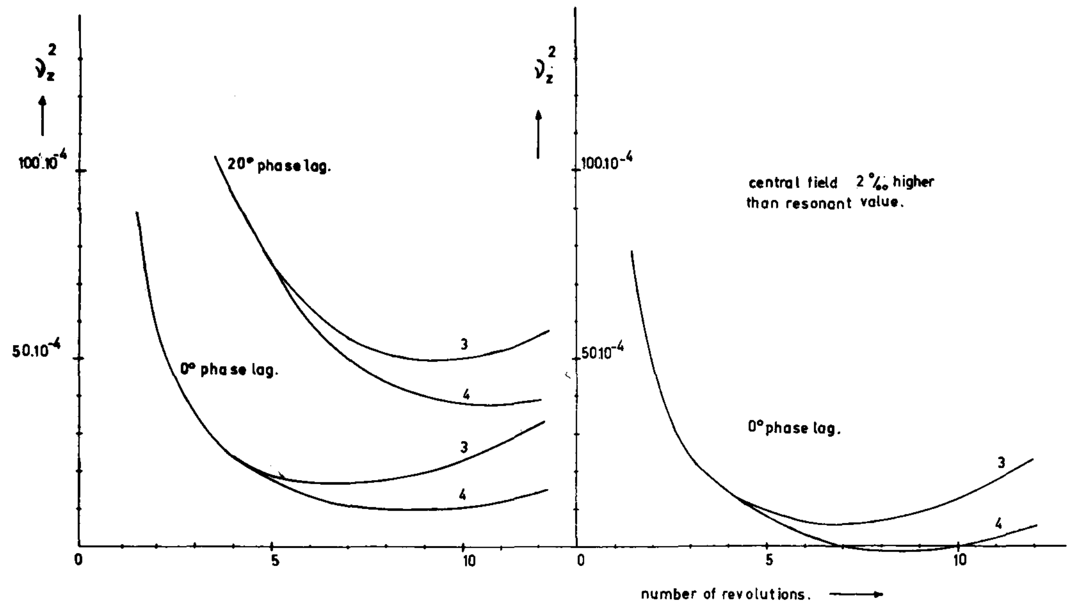

Fig.1. The axial focusing is given as a function of revolution number in the central region of the cyclotron for three and four fold symmetric magnetic fields.
(Curves marked 3 belong to 3-fold symmetry, marked 4 belong to 4-fold symmetry).
We have given three cases:
1) the phase of the particles with respect to the H.F.phase is 0°
2) the phase of the particles with respect to the H.F.phase is -20°, resulting in a better axial focusing
3) mean magnetic field in the centre 2 o/oo higher than the resonant value, resulting in a worse axial focusing.

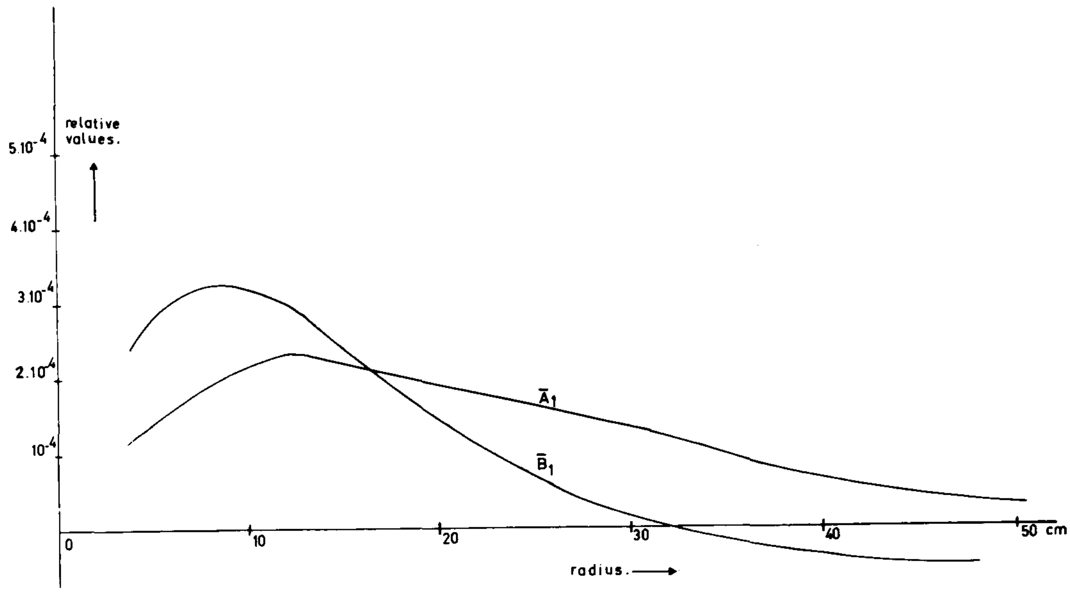

Fig.2. The influence of the gap crossing resonance represented as a first harmonic field perturbation in a 30 MeV Philips AVF cyclotron.

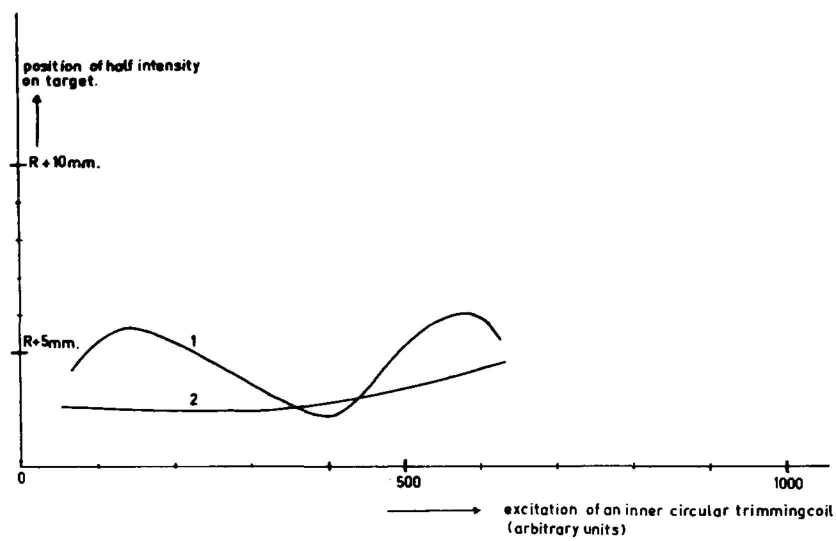

Fig.3. An example of a shadow method with two targets to determine the cohaerent radial oscillation amplitude. One target has a fixed radial position. The radial position of the other target is changed to achieve an equal distribution of beam current on both targets.

The phase of the radial oscillation is changed by a slight detuning of the magnetic field - i.e. by variation of the number of revolutions. Therefore the radial position of the second target for equal intensity distribution is a function of the mean magnetic field.

For a complete revolution in phase space of the radial oscillation one can expect for the movable target position a sinusoidal dependence on the magnetic field. In this figure curve 1 represents a cohaerent radial oscillation and Curve 2 represents a case where the cohaerent oscillations have been made small by a correct adjustment of the ion source position and the centre harmonic coils.

To change the number of revolutions, the excitation of a circular correction coil was varied.

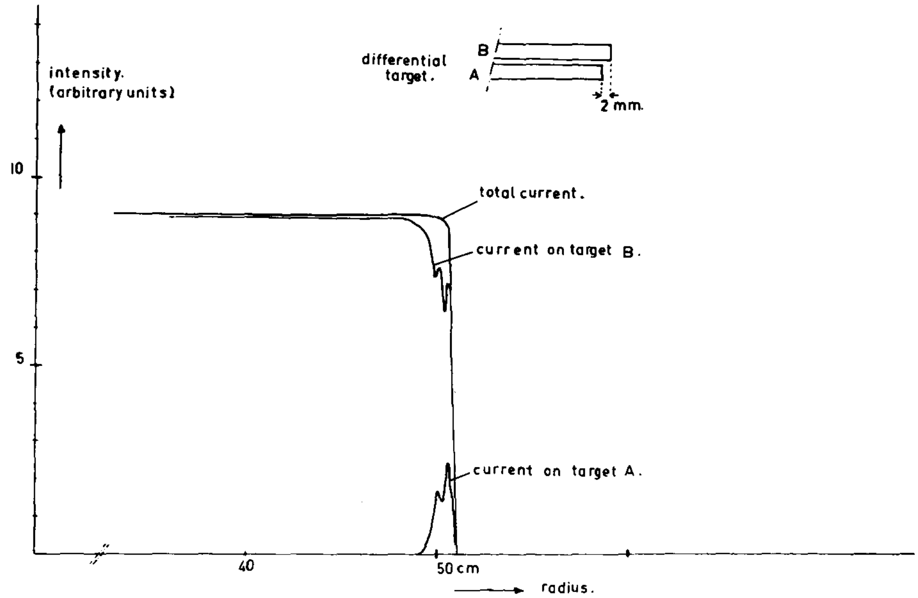

Fig.4. The beam intensity on a differential target as a function of radius.

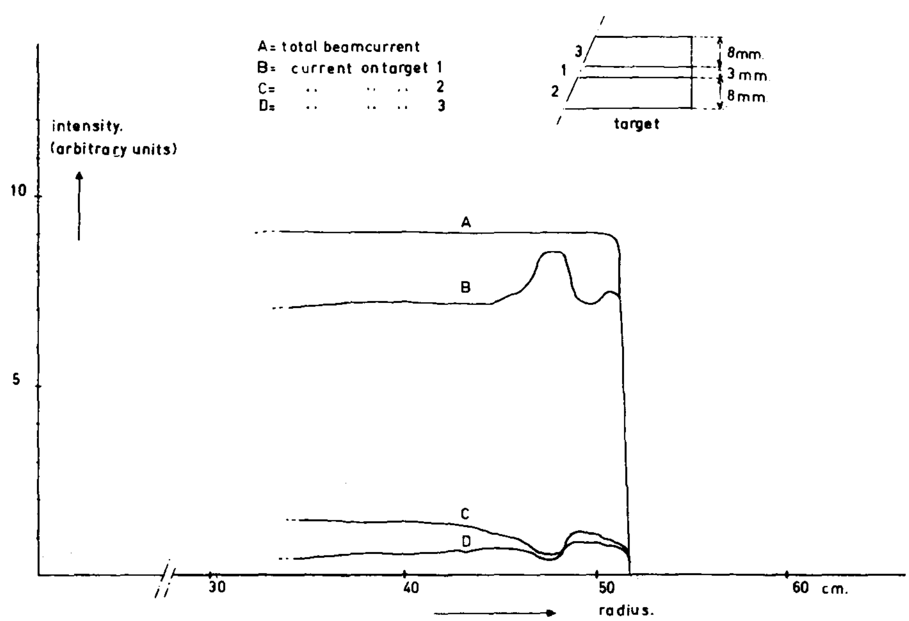

Fig.5. The axial intensity distribution of the beam measured with a three finger-target as a function of the radius. A very small increase in height is observed at the $\nu_R = 2\nu_Z$ resonance.

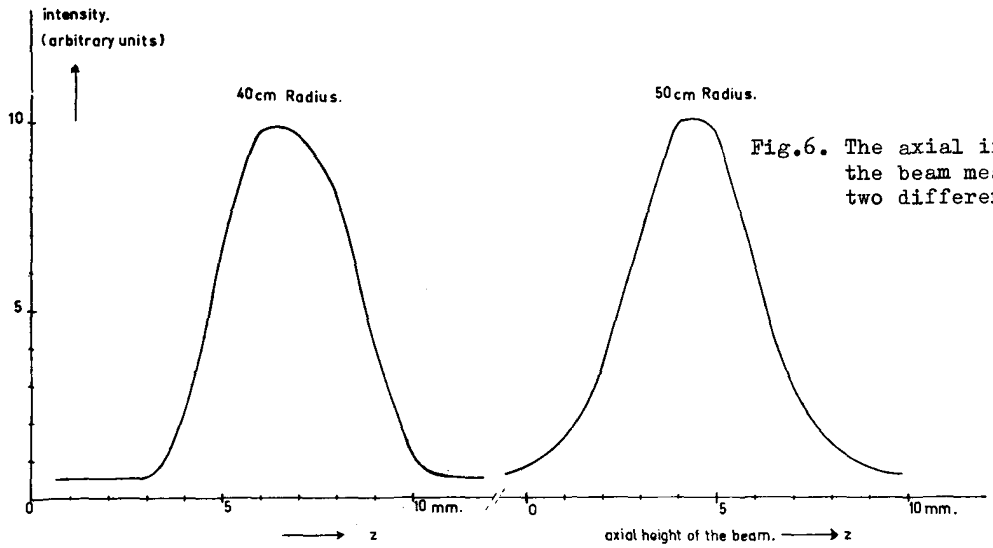

Fig.6. The axial intensity distribution of the beam measured with a radiogram at two different radii.

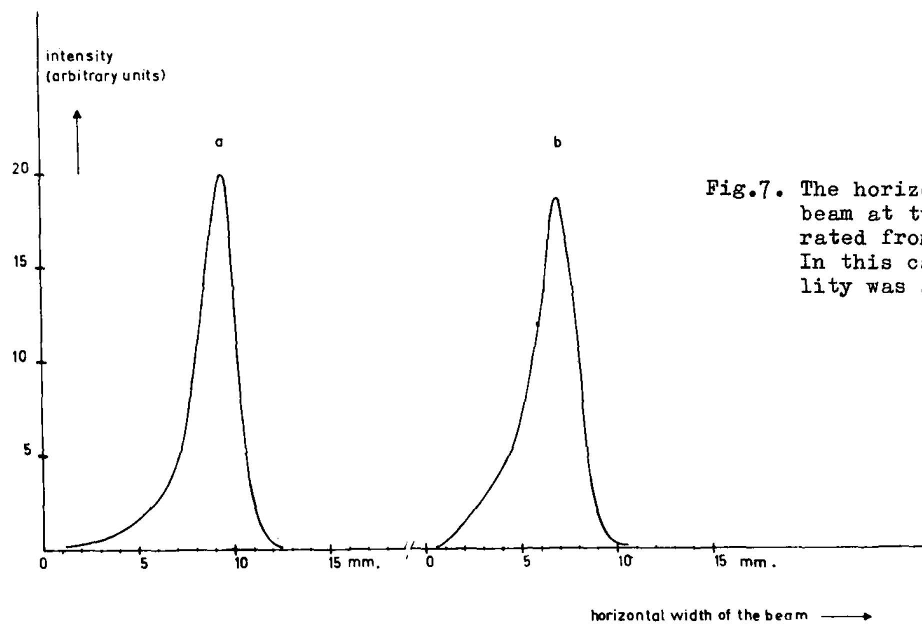

Fig.7. The horizontal width of the external beam at two places, 1,35 meter separated from each other.
In this case the measured radial quality was about 10 mmmrad.

DISCUSSION

LIVINGSTON: You mentioned something about the gap-crossing resonance, and your conclusions with respect to it. Would you repeat?

HAGEDOORN: The first-harmonic component in the central region due to this effect is about 3 to 4 gauss; at the extraction region it is about one-third gauss.

LIVINGSTON: Could I ask Mr. Blosser to comment on this same point? He has pointed out that the gap-crossing resonance is perhaps a serious problem in 3-sector machines.

BLOSSER: The gap-crossing resonance is a sizeable nuisance rather than a serious problem. I am sure Dr. Hagedoorn recognizes that it contributes an amplitude, and in any given situation one can calculate just how much it contributes. The slide I showed with ΔX and ΔP_x was an example of the effect of the gap-crossing resonance; it contributed something like 5 millimeters. Five millimeters, it is quite correct, is not going to wreck the performance of the beam. On the other hand, it seems to me, it is an effect which, now that you know about it, you would do better to design away from, rather than into. The phenomenon gets much worse if you slide the rf phase, or if you use cut-back dees, or when you use harmonic acceleration. In the worst situation the beam can be driven out of the stable region and lost. So the effects of the resonance vary greatly, depending on the particular situation.