Offset steering in multiamp ion sources — revisited

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Werner Ott

Max-Planck-Institut für Plasmaphysik

Euratom Association, W-8046 Garching bei München

Abstract

Steering of the individual beamlets in multiamp ion beams by offsetting the axes of circular extraction holes in three-electrode acceleration systems is revisited. A consistent application of the Langmuir-Blodgett theory of a spherical diode gives a stronger deflection per unit offset than assumed hitherto.

I. Introduction

The enhancement of ion beam currents by collecting many single beamlets into one beam is a well-established technique in controlled fusion research and electrostatic propulsion units for spacecraft (see, for example, refs. [1] and [2]). Hundreds of individual beamlets are focused as required either by shaping the extraction electrodes or by offsetting the extraction holes against each other or by combining the two methods. Offsetting the holes bends the beamlets because the potential distribution at the beam exit forms a defocusing lens of focal length f_d. An offset δ of the extraction hole gives a deflection of $-\delta/f_d$ in the direction opposite to the offset δ.

A number of papers have dealt with offset focusing; see, for example, Coupland and Green [3]. In refs. [4], [5] and [6] a simple model of the optics of a beamlet is described. The focal length is approximated by the Davisson-Calbick formula [7],

$$f_d = 4\,V/E, \tag{1}$$

with the acceleration potential V and the electric field strength E on the high field side of the decel electrode (on the other side the electric field strength is assumed to approach zero).

In order to counteract defocusing, the beamlet must be focused in the accel gap. In this region, the beamlet may then be described as a sector of a spherical diode which was treated by Langmuir and Blodgett [8]. This model of the beamlet optics is illustrated in figure 1.

Coupland et al. use the Langmuir-Blodgett theory, but not in a consistent way. To calculate the field strength, they use the plane diode approximation, which gives a space charge enhancement factor of 4/3.

In this paper the full Langmuir-Blodgett series development is used to calculate the electric field strength at the decel electrode E_d and hence the focal length f_d.

II. Beamlet optics using Langmuir-Blodgett theory

In accordance with the ideas of Coupland et al. [5] and [6], the accel gap is taken as the sector of a spherical diode. If r_1 is the radius of an extraction hole and R_1 the radius of the extraction sphere (see Fig. 1), the current of a single extraction hole I_s is related to the current of the whole diode I by

$$I = \frac{4\,R_1^2}{r_1^2}\,I_s. \tag{2}$$

Langmuir and Blodgett [8] obtained the following connection between voltage and current in a spherical diode:

$$U = \left(\frac{I}{p}\right)^{2/3} \alpha^{4/3} \tag{3}$$

with

$$p = \frac{4}{9}\,4\pi\epsilon_0 \sqrt{\frac{2e}{m_i}} = 6.83 \times 10^{-7}\,M_i^{-1/2}\,\mathrm{A\,V^{-3/2}}, \quad \alpha = \sum_{n=1}^{\infty} a_n \gamma^n \quad \text{and} \quad \gamma = \ln\frac{r}{R_1}$$

(m_i = average ion mass, M_i = average ion mass in atomic units) and the coefficients

$$a_1 = 1,$$

$$a_2 = -0.3,$$

$$a_n = -\frac{3\,a_{n-1} + \sum_{m=1}^{n-2} a_{m+1}\left[(n-m)(3n-2m-2)\,a_{n-m} + 3\,(m+1)\,a_{n-m-1}\right]}{n\,(3n-1)}$$

for $n > 2$.

(In [8] only the first six coefficients are given, but not the recursion formula. Brewer [9] takes over the coefficients of [8], but a_4 with an error.)

The radius R_1 is the important parameter, it being possible to calculate the other parameters as a function of it:

- the current I_s of a single extraction hole,
- the radius R_d of the "target" sphere in the decel electrode,
- the electric field strength E_d at the decel electrode,

- the focal length f_d of the defocusing lens in the decel electrode,
- the maximum angle ω_s of the beamlet in the accel gap, and, finally,
- the edge angle of the beamlet ω after passing the decel electrode:

$$I_s = \frac{r_1^2}{4\,R_1^2}\,\frac{p\,U^{3/2}}{\alpha_d^2} \tag{4}$$

$$\text{with} \quad \alpha_d = \sum_{n=1}^{\infty} a_n\,\gamma_d^n, \quad \gamma_d = \ln\frac{R_d}{R_1}, \quad \text{and} \quad \frac{R_d}{R_1} = 1 - \frac{\dfrac{d}{R_1}}{\sqrt{1-\left(\dfrac{r_1}{d}\dfrac{d}{R_1}\right)^2}},$$

$$E_d = \left(\frac{\mathrm{d}U}{\mathrm{d}\alpha}\,\frac{\mathrm{d}\alpha}{\mathrm{d}\gamma}\,\frac{\mathrm{d}\gamma}{\mathrm{d}r}\right)\bigg|_d \tag{5}$$

$$\text{with} \quad \frac{\mathrm{d}U}{\mathrm{d}\alpha}\bigg|_d = \frac{4}{3}\,\frac{U}{\alpha_d}, \quad \frac{\mathrm{d}\alpha}{\mathrm{d}\gamma}\bigg|_d = \sum_{n=1}^{\infty} n\,a_n\,\gamma_d^{n-1}, \quad \text{and} \quad \frac{\mathrm{d}\gamma}{\mathrm{d}r}\bigg|_d = \frac{1}{R_d},$$

$$f_d = \frac{3\,\alpha_d\,R_d}{(\mathrm{d}\alpha/\mathrm{d}\gamma)|_d}, \tag{6}$$

$$\omega_s = -\frac{r_1}{R_1}, \tag{7}$$

$$\begin{aligned} \omega &= -\frac{r_1}{R_1} + \frac{r_1}{f_d}\,\frac{R_d}{R_1} \\ &= \frac{r_1}{d}\,\frac{d}{R_1}\left(-1 + \left|\frac{(\mathrm{d}\alpha/\mathrm{d}\gamma)|_d}{3\,\alpha_d}\right|\right). \end{aligned} \tag{8}$$

III. Optimum values

The optimum is defined as that sector field which gives a zero divergence beam. This is achieved for the parameter values $\alpha_{opt} = (-)0.4196$ and $(R_d/R_1)_{opt} = 0.6883$. The optimum values of the electric field strength E_d at the decel electrode and the focal length f_d for defocusing the beam at the decel electrode depend slightly on the aspect ratio r_1/d of the extraction holes. Two limiting values of the aspect ratio are therefore chosen and the optima for E_d and f_d are shown in Tab. 1, compared with the plane diode values.

r_1/d	0.	0.5	plane diode
$E_d/(U/d)$	1.81	1.79	1.33
f_d/d	2.21	2.24	3

Tab. 1
Optimum values of E_d and f_d
for two limiting values of the aspect ratio r_1/d
and comparison with plane diode values

IV. Offset steering

With the focal length f_d of the defocusing lens in the decel electrode, a displacement δ of the decel hole gives a beamlet deflection in the opposite direction of $-\delta/f_d$.

The smaller values for $f_{d,opt}$ (section III) mean that the deflection of a beamlet in the case of an offset between the axes of the extraction holes is a factor of ~1.35 stronger than hitherto assumed. And in the special case of periplasmatron ion sources with spherical extraction grids (radius R_g) and extraction holes lying not concentric but on axis-parallel lines, the focal length for the beam as a whole, $f_b = R_g/(1 + d/f_d)$, is not $0.75\,R_g$ but $0.69\,R_g$.

It should be repeated, however, that the beamlet convergence and hence the focal length f_d depend on the beamlet perveance as shown in Fig. 2. Thus also the deflection per unit offset depends on the perveance. When the dependence of the deflection angle on the offset is measured, it is necessary to have a clearly defined beamlet perveance. If not, any comparison with theory ([3], [4] and [10]) is questionable.

V. Discussion

If this theory is compared with experiments, the question arises what gap width is to be taken in a real extraction geometry where plasma and decel grids have a finite thickness. A "*physical gap width*" d_{phys} is used in this paper which extends from the plasma boundary to the surface of the decel electrode nearest to the source, see Fig. 3. Other authors use the metal-to-metal gap, which may be called the "*technical gap width*" d_{tech}, and which is smaller than the physical gap width because the plasma boundary may lie anywhere within the hole in the plasma grid. If the hole in the plasma grid is shaped and has a sharp edge, the plasma boundary is supposedly fixed by this edge. If the hole is unshaped (cylindrical), the situation is less clearly defined, and the position of the plasma boundary may, furthermore, depend on the beamlet perveance:

$$d_{tech} \leq d_{phys} \leq d_{tech} + D$$

with the electrode thickness D. Unfortunately, all the deflection measurements in triodes known to the author were done with unshaped apertures [4, 10, 11]. For the geometry given in ref. [4], the deflection should lie between 5.7 and 8.6 degrees/mm if the optimum value $f_d = 2.22\,d$ is taken and the gap includes or excludes the thickness of the plasma grid, respectively. The measured value was 5.4 degrees/mm. For these measurements, the sum of metal-to-metal gap and plasma electrode thickness $d_{phys} = d_{tech} + D$ would be the most appropriate. References [10] and [11] claim, however, that the metal-to-metal gap d_{tech} together with a factor of 3 gives a correct description of their measurements. In these two references it is also said explicitly that no perveance dependence was found. This would be in contradiction to the results of section IV and Fig. 2. This does not count, however, in view of the uncertainty concerning the position of the plasma boundary in a cylindrical extraction hole. Instead, a repetition of such measurements with properly shaped apertures is necessary.

This discussion may remind the reader of the difficulties which were encountered during the development of the JET neutral beam sources (Duesing et al. [12]). Beamlet deflection by offset steering was found to be a factor of 1.5 stronger than expected and led to an undesired beam profile. A comparison between the calculations presented here and the JET extractors is difficult because JET uses a two-stage accelerator. The measured deflection per unit offset was 36 mrad/mm, in agreement with a three-dimensional code applied later on but in contrast to a two-dimensional code [13] used at the beginning.

For comparison of the JET results with the simple theory presented here, the accel gap must be defined (see above). The holes in the plasma grids were shaped, and it would seem reasonable to take the gap between the edge of the first grid and the source side of the third grid, leaving aside the thickness of the second grid (see Figure 13 of ref. [12]). This gives a gap of $d = 12.7\,\mathrm{mm}$ and, for optimum parameters (section III), a deflection per unit offset of

$$1/f_d = 35.2 \ldots 35.7\,\mathrm{mrad/mm}$$

in good agreement with the measurements and the three-dimensional theory.

The two-dimensional theory [13] of beam steering in tetrode extraction systems is probably in error. It uses a linear approximation for the electric field strength E_{11} ("first lens, first gap") using a parameter k which is a measure of the curvature of the boundary. k is, however, erroneously used with a factor of 0.2 instead of 0.8.

A matter of principle may be the question, whether the Davisson-Calbick formula [7] is applicable at all. It is derived for a beam passing through a hole in case the space charge is negligeable. This condition is certainly not fulfilled. Beam space charge on the upstream side is, however, included in the calculation of the electric field in front of the decel electrode. On the downstream side, the space charge may be neglected because it is neutralized by the neutralizer plasma. It seems to be correct, therefore, to do the calculations in the way as done in sections II, III and IV.

Acknowledgment

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Figure 1: Model of an extraction gap

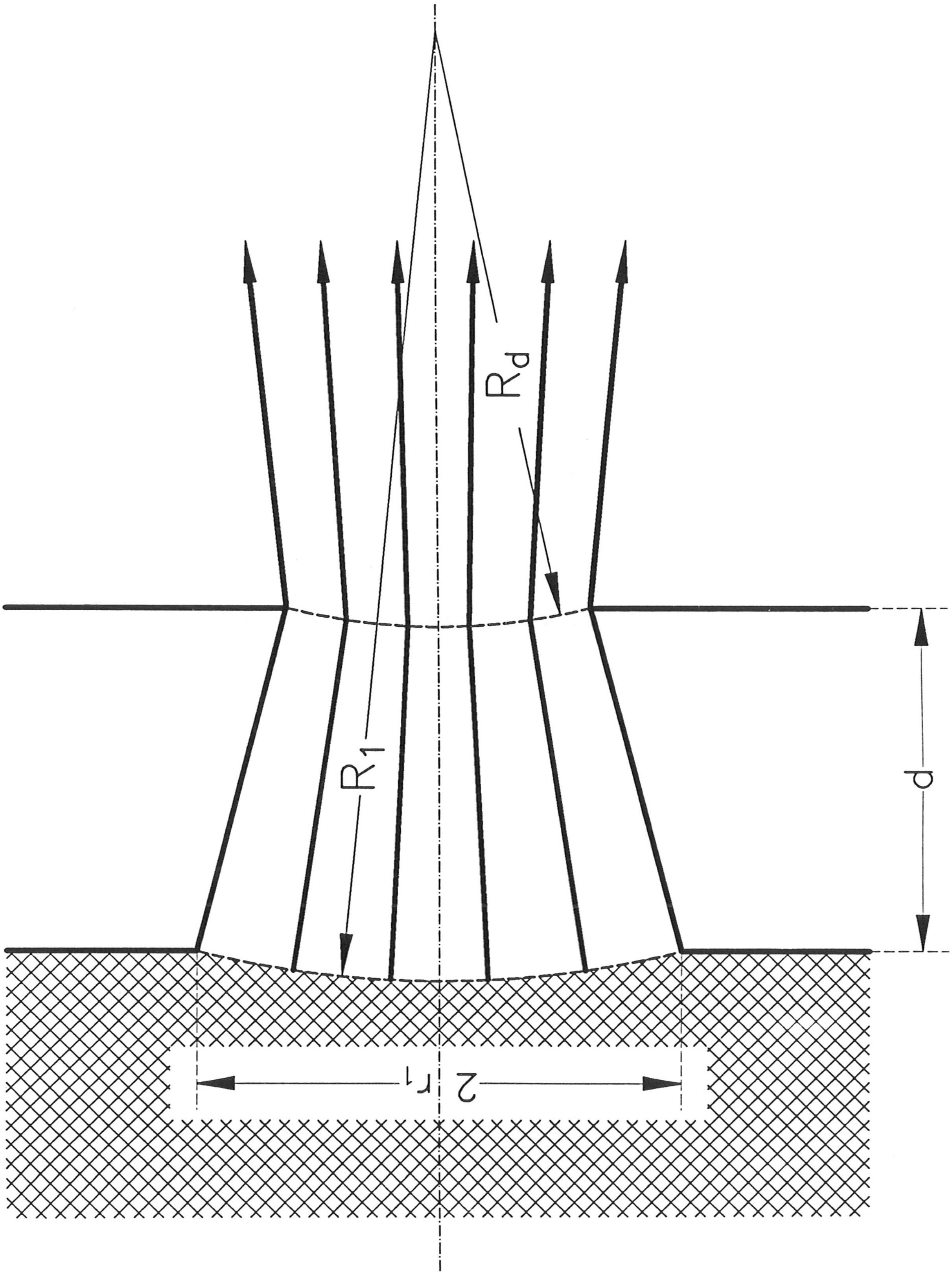

Figure 2: Focal length f_d at the decel electrode determining the deflection per unit offset versus beamlet perveance P. f_d is normalized to the extraction gap d, P is normalized to the plane diode perveance P_0.

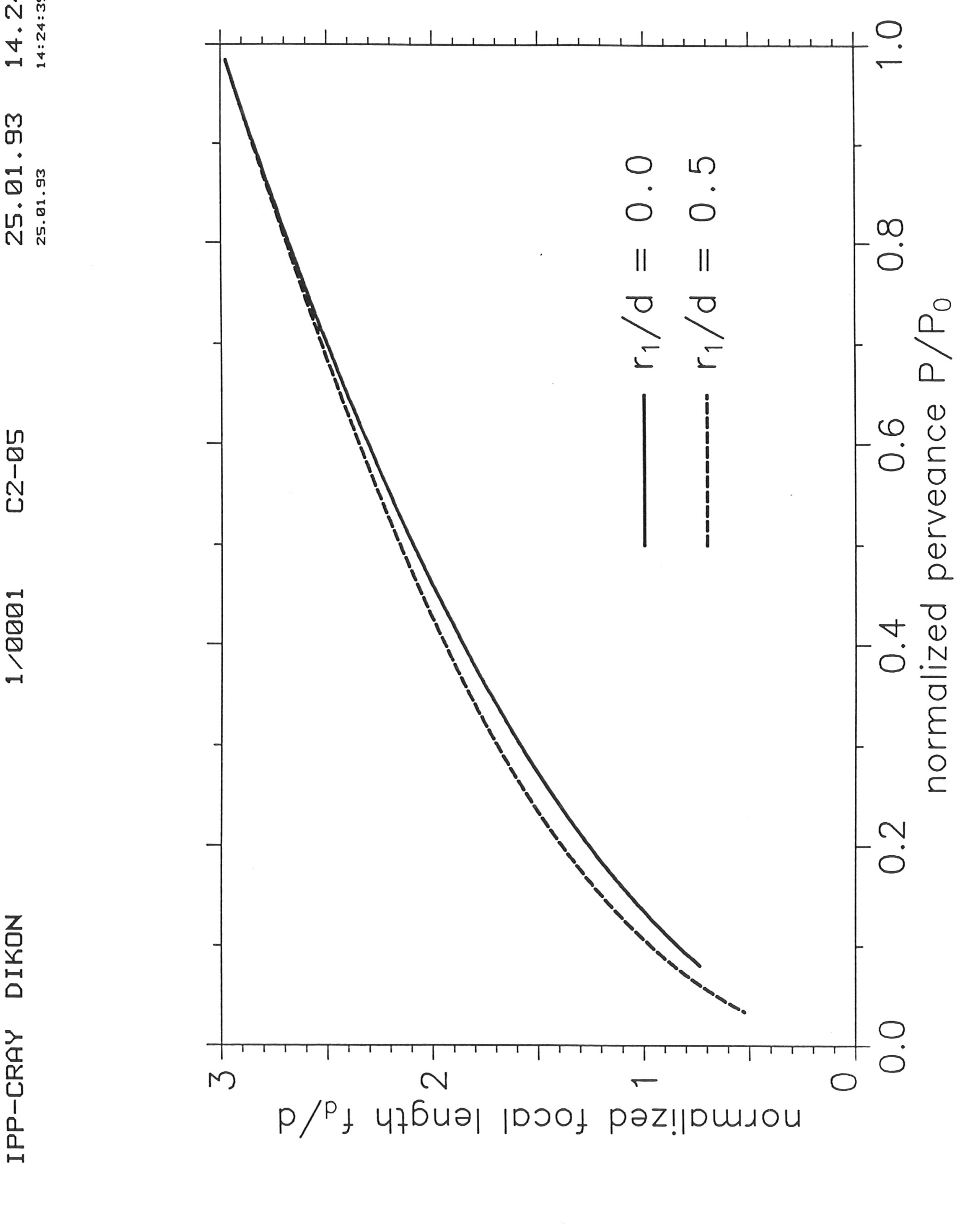

Figure 3: "Physical" and "technical" gap widths in case of unshaped apertures