Beam Divergence and Ion Current
in Multiaperture Ion Sources

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IPP 4/252   March 1992

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Abstract

Two different measurements of the divergence of high-current ion beams formed in a multiaperture ion source have been made. The current dependence of both measurements shows characteristic differences which are explained as a result of an inhomogeneity of the current density across the emission area.

The model of Coupland et al. with a spherical beam geometry in the acceleration gap is reexamined. It is shown that a rigorous application of this model gives a beamlet defocusing in the decel electrode which is stronger by a factor of 1.35 than assumed hitherto. The implications on offset steering are discussed.

I. Introduction

Usually multiaperture multiamp ion sources as used for neutral injection show a beam divergence which is much higher than it may be expected from theoretical considerations. The ion sources used for W7AS injection for example show a minimum (1/e)-divergence of about 1° for Helium beams and of about 1.3° for hydrogen beams. Expected transverse ion temperatures of $\sim$ 1 eV for helium and of $\sim$ 3.5 eV for hydrogen would give a beam divergence of $\sim$ 0.25° and $\sim$ 0.5° for helium and hydrogen, respectively. It may be supposed, that a major cause for this large average divergence is the inhomogeneity of the ion current density delivered from the source to the extraction grid. A major argument in favour of this interpretation is the dependence of the divergence on the total extraction current measured with two independent methods with the same beam: beam calorimetry, measuring the whole beam, and Doppler spectroscopy, measuring only along a line of sight. Both methods give about the same minimum divergence, but the optimum perveance determined spectroscopically is smaller than the one determined calorimetrically. This may easily be interpreted as a difference between an area average and a line average of the divergence which varies across the extraction surface. It should be mentioned that the term *divergence* used here is defined as the 1/e-half-width of the beam angular distribution.

II. Beamlet divergence and current density

The usual idea of the ion optics of a three-electrode system is the following:

1. The electric field between the decel and the earth electrode is small compared with the accelerating electric field. The decel field is therefore neglected, and the problem is reduced to a two-electrode system.

2. The accelerating field penetrates through the hole in the decel electrode. Its shape causes a defocusing of the beam.

3. The beam has to be focused in the accelerating gap in such a manner that together with the defocusing a parallel beam is obtained.
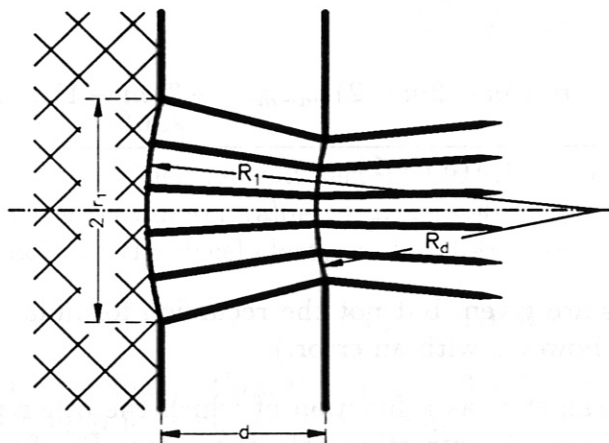
Figure 1:
Model of an extraction gap

The focal length for the beam defocusing in the decel electrode is given by Davisson and

Calbick [1]:

$$f_d = \frac{4\,U_0}{E_d}$$

with the acceleration voltage U_0 and the electric field in front of the decel electrode E_d. Following the ideas of Coupland et al. [2], the acceleration gap is taken as the sector of a spherical diode which was treated mathematically already by Langmuir and Blodgett [3]. 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 with the current of the whole diode I by

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

Langmuir and Blodgett [3] obtained the following connection of voltage and current in a spherical diode

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

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

$a_1 = 1$

$a_2 = -0.3$

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

for $n > 2$.

(In [3] only the first six coefficients are given, but not the recursion formula. Brewer [4] takes over the coefficients of [3], a_4 however with an error.)

The radius R_1 is the important parameter, as a function of which the other parameters can be calculated: 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, and, finally, the maximum angle ω_s of the beamlet in the acceleration gap and ω after passing

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the decel electrode:

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

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

$$\omega_s = -\frac{r_1}{R_1}$$

$$E_d = \left(\frac{dU}{d\alpha}\frac{d\alpha}{d\gamma}\frac{d\gamma}{dr}\right)\Bigg|_d$$

with $\quad \dfrac{dU}{d\alpha}\Big|_d = \dfrac{4}{3}\dfrac{U}{\alpha_d}, \quad \dfrac{d\alpha}{d\gamma}\Big|_d = \displaystyle\sum_{n=1}^{\infty} n\,a_n\,\gamma_d^{n-1}, \quad$ and $\quad \dfrac{d\gamma}{dr}\Big|_d = \dfrac{1}{R_d}$

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

$$\omega = -\frac{r_1}{R_1} + \frac{r_1}{f_d}\frac{R_d}{R_1}$$

$$= \frac{r_1}{d}\frac{d}{R_1}\left(-1 + \left|\frac{(d\alpha/d\gamma)|_d}{3\,\alpha_d}\right|\right)$$

Introducing P_0 as the **perveance** of a plane diode with gap d and radius r_1

$$P_0 = \frac{I}{U^{3/2}} = \frac{p}{4}\left(\frac{r_1}{d}\right)^2,$$

the perveance of a single extraction hole becomes

$$P_s = \left(\frac{d}{R_1}\right)^2\frac{1}{\alpha^2}\,P_0.$$

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 $R_{1,opt}/d = 3.227$. The **electrical field strength** at the decel electrode for these parameters is

$$E_{d,opt} = 1.796\,(U/d),$$

a value distinctly higher than the value $4/3 \times U/d$ which is estimated for a plane diode. The **focal length** for defocusing the beam at the decel electrode becomes

$$f = \frac{4\,U}{E_{d,opt}} = 2.227\,d$$

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compared with the value usually taken $f = 3\,d$. The smaller value for f means that the deflection of a beamlet in case of an offset between the axes of the extraction holes is stronger than assumed hitherto. And in the special case of the Periplasmatrons with spherical extraction grids (radius R_g) but extraction holes lying not concentric but on axis-parallel lines, the focal length for the beam as a whole $f_b = R_g/(1 + d/f)$ is not $0.75\,R_g$ but $0.69\,R_g$. The optimum perveance becomes $P_{s,opt} = 0.545\,P_0$.

This may remind the reader to the surprisingly strong offset focusing which was observed with the JET neutral injection ion sources (Green et al. [5], Duesing et al. [6]). The accelerator was a four-grid system, and the offset was done with the third grid (decel grid) only. The fourth grid (on ground potential) was not offset. It is not immediately clear, which acceleration gap should be taken four this system to calculate the offset focal length. The additional offset between third and fourth grid may also have had an effect. However this may be interpreted — the real beamlet offset was found to be twice as large as originally expected from simple considerations. It agreed with the results of three-dimensional orbit computations which were made later on.

IV. Comparison with Coupland et al. [2]

In ref. [2] not the whole series development for α is used. Only a first order term of d/R_1 is included to calculate the perveance of the extraction sector. Their result therefore is different from the results obtained here. The maximum angle in a beamlet according to equation (A II.6) of [2] is

$$\omega = \frac{4}{15}\frac{r_1}{d}\left(1 - \frac{9}{4}\frac{P}{P_0}\right).$$

The comparison of both results is shown in Fig. 2. The optimum perveance as well as the dependence of the maximum angle on a deviation from the optimum are different. The "exact" curve may be represented by straight lines which have slightly different gradients below and above the optimum. Their representation is (ω in radians, different from Fig. 2)

$$\omega = \gamma_\omega \frac{r_1}{d}\left|1 - 1.835\frac{P}{P_0}\right|, \quad \gamma_\omega = \begin{cases} 0.425 & \text{if } P > P_0 \\ 0.482 & \text{if } P < P_0. \end{cases}$$

An experimental test of the two different dependencies is difficult because of the ambiguity in interpreting a real extraction geometry in terms of only two lengths, compare next section.

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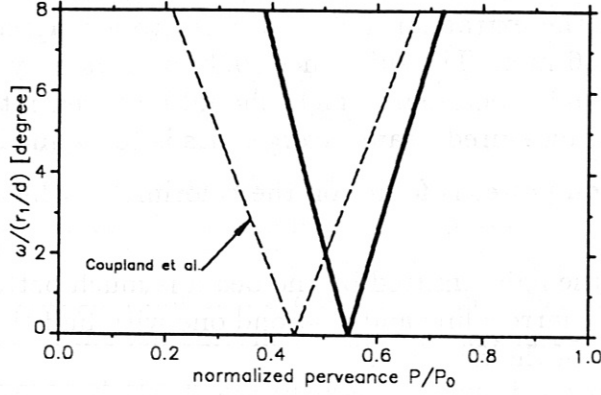
Figure 2:
Maximum beam angle versus normalized perveance P_0, P_0 = plane diode perveance

V. Application to W 7-AS beams

The translation of a real extraction geometry into the parameters radius r_1 and gap d is nontrivial, because real electrodes are not infinitely thin. The extraction geometry applied in the W 7-AS-Periplasmatrons is shown in Fig. 3. As a first trial, the data for r_1 and d are taken as shown in this figure. This means $r_1 = 3.45$ mm, $d = 9.3$ mm.
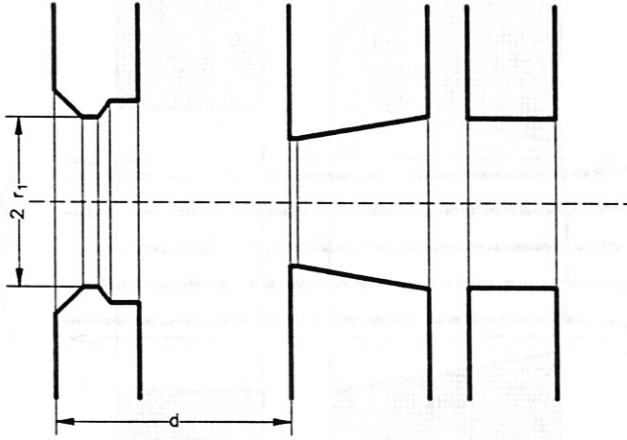
Figure 3:
Gap geometry of the W7-AS extraction grids

The species ratio of the accelerated ions is measured to be about $H_1^+ : H_2^+ : H_3^+ = s_1 : s_2 : s_3 = 0.5 : 0.3 : 0.2$. This gives an average mass of $1/\sqrt{M_i} = s_1/\sqrt{1} + s_2/\sqrt{2} + s_3/\sqrt{3}$ or $M_i = 1.46$, and a parameter $p/4 = 1.340 \times 10^{-7}$ A/V$^{3/2}$. With a number $N = 313$ of extraction holes and a voltage of $U = 45$ kV, the extraction current for the whole periplasmatron is

$$I_{Peri} = N \frac{p}{4} \left(\frac{r_1}{d}\right)^2 \frac{(d/R_1)^2}{\alpha^2} U^{3/2}$$

$$= 5.34 \times 10^{-5} \, \text{A} \times \frac{(U/\text{V})^{3/2}}{\sqrt{M_i}} \left(\frac{r_1}{d}\right)^2 \left(\frac{d}{R_1}\right)^2 \frac{1}{\alpha^2},$$

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giving an optimum of 31.7 A for a hydrogen beam of 45 kV and 22.4 A for a helium beam of 50 kV. The actual optimum lies at a much lower value, around 25 A for hydrogen and 18 A for helium. This is interpreted as a screening of the edge of the extraction hole due to the non-Pierce shape of the extraction hole. In order to get agreement, the radius has to be reduced to $r_1 = 3.06$ mm. The difference (0.39 mm) is only a tenth of the electrode thickness. Two additional experimental facts should be taken into account, when a comparison of calculated and measured beam divergencies is to be made:

- only about 75 % of the extraction power is found on the calorimeter when the beam is optimally focused,

- a Gaussian fit to the spectra of the light emitted by the beam is much better, if not a single line is used but a sum of a narrow line and a second one with half the intensity and a width 2.5 times the width of the first one.

Both facts show, that there is a beam halo. Its origin is supposed to be the edge region of the extraction hole, where ions are extracted but the plasma boundary is not yet spherical. In order to calculate the divergence of the beam core, the radius taken is further reduced by $\sqrt{2/3}$ to 2.50 mm. This reduction of the useful extraction cross section is illustrated in Fig. 4.
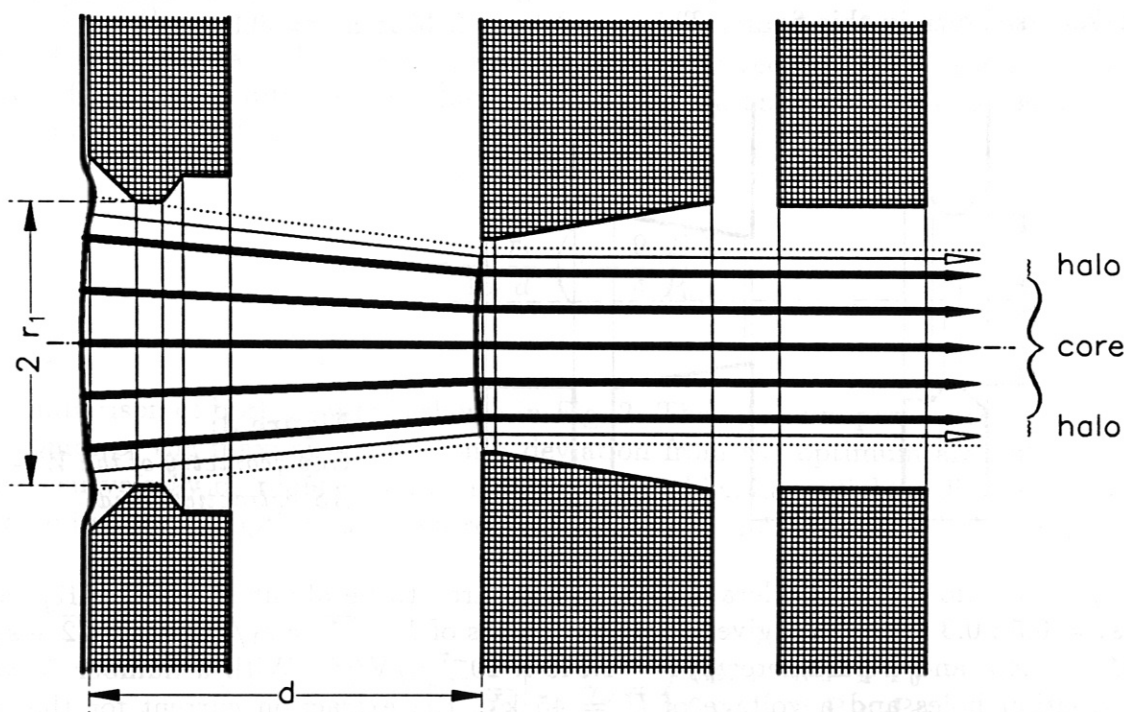
Figure 4:
*Beam core, halo and dark edge as a model for observations*

Experimentally, it is convenient to measure the $(1/e)$-*divergence* of the beam, whereas in the derivation in section II the *maximum angle* of the beamlet was taken. The angular

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distribution of a beamlet as treated above is elliptical, giving a (1/e) divergence angle $0.930\times$ the maximum angle.

The core divergence, as introduced here, should show a dependence on the beam perveance similar to Fig. 2. The minimum, although not zero, should be explainable by effects of a transverse ion temperature. This temperature, in case of hydrogen beams, is determined by the kinetic energy of the atoms obtained in a dissociation process. The average dissociation energy was determined by A.Valance [7] to be about 5 eV, giving a transverse temperature of $T_d \sim 3.3$ eV and a minimum beam divergence of $\sqrt{T_d/E_0} \sim 0.5°$. The actual minimum for hydrogen beams was about 1.3°. In helium beams no spreading due to Franck-Condon-effects should occur. The minimum divergence for helium was in fact lower than for hydrogen, but still around 1°. Two other effects may deteriorate the divergence: oscillations of the ion current density in the source and a source inhomogeneity.

Measurements of the beam divergence have been done with two independent methods. Firstly, the temperature distribution on a beam calorimeter was fitted by a Gaussian distribution, taken into account the finite focal length of the beam. This method gives an average of the beam as a whole (*area average*). Secondly, the Doppler-shifted light emitted from the beam in the neutralizer was spectroscopically analyzed. The diameter of the analyzed cylinder was 1/7 of the beam diameter and thus delivered a *line average* through a beam cross-section. The results are the dots shown in Figs. 5-9. The curves in these figures are hyperbolic least-square fits to the measured points.
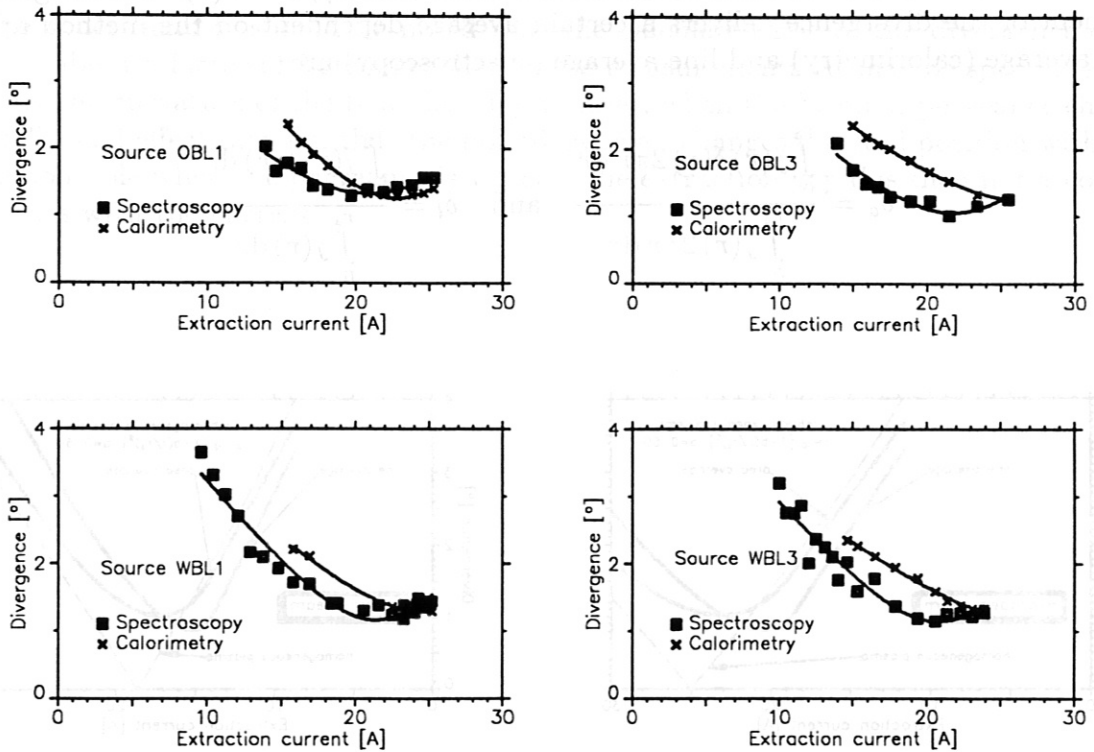
Figure 5-8:
Divergence versus extraction current for all four sources, hydrogen beams with 45 kV

A common feature of all these measurements is that the two divergences are not identical but deviate in a systematic way from each other. The spectroscopic minimum is usually smaller than the calorimetric minimum, and the two curves are shifted against each other. Both, the different height of the minima and the shift may be explained by the assumption that the source is radially inhomogeneous.
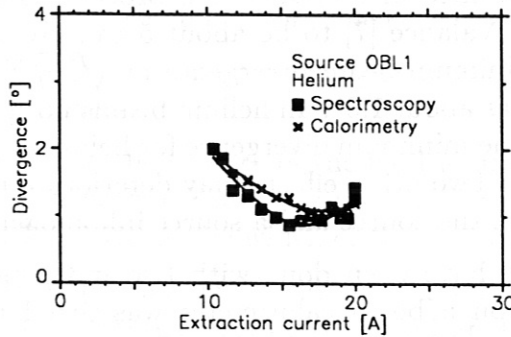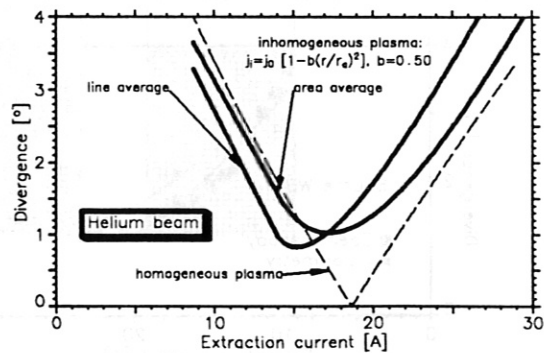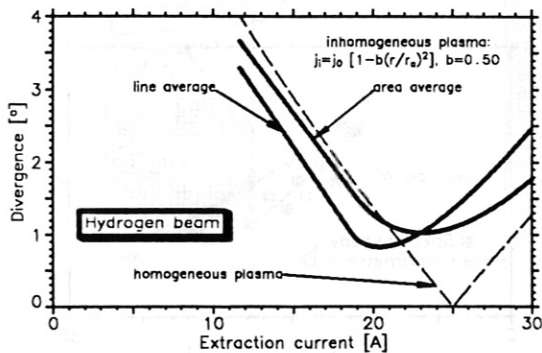

Figure 9:
Divergence versus extraction current, source OBL1, helium beam with 50 kV

VI. Beam divergence with an inhomogeneous source plasma

In an inhomogeneous source, the beamlet divergence will vary across the extraction grid in accordance with the variation of the local current density, $\delta = \delta(r)$. An integral measurement of the divergence delivers a certain average dependent on the method applied. Area average (calorimetry) and line average (spectroscopy) are

$$\delta_a = \frac{\int_0^{r_a} j(r)\,\delta(r)\,2\pi r\,\mathrm{d}r}{\int_0^{r_a} j(r)\,2\pi r\,\mathrm{d}r} \quad \text{and} \quad \delta_l = \frac{\int_0^{r_a} j(r)\,\delta(r)\,\mathrm{d}r}{\int_0^{r_a} j(r)\,\mathrm{d}r}.$$

Figure 10-11
Calculated divergences for homogeneous and inhomogeneous plasma for hydrogen with 45 kV and helium with 50 kV

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Figures 10 and 11 show the calculated average divergence for the beam core (neglecting the halo) with an inhomogeneous ion source. The simplest inhomogeneity is taken in the calculation: a parabolic radial dependence

$$j_i = j_{i0} \left[1 - b \left(\frac{r}{r_a} \right)^2 \right]$$

with the edge radius r_a and the inhomogeneity parameter b. In both figures this parameter is set to $b = 0.5$. Any ion temperature effects are neglected. According to Bonnal [8], a decrease of the ion current density at the edge to half the maximum value is reasonable, although the radial dependence is more complicated and, furthermore, varies with the source operation conditions.

VII. Discussion

The shift between the line-averaged and the area-averaged devergences is strikingly common to calculated and measured data. This shift supports the assumption that a major cause for the size of the minimum is radial inhomogeneity. Ion temperature effects give a smaller contribution (see section **V**). Oscillations cannot be excluded as a possible cause for an enhancement of the divergence. They would, however, deteriorate line-average and area-average in the same way. They are therefore thought of having a minor influence.

On the other hand it should be noted that the calculated rise of the divergence on the flanks is about a factor of 2 stronger than in the measurements. It may be speculated that not only the curvature of the boundary layer varies, when the beamlet perveance changes. An additional effect may be, that the boundary layer changes its axial position within the extraction hole when the perveance is varied. The extraction gap d is then not a constant but varies with the current.

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