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Beam Focusing by Aperture Displacement in Multiampere Ion Sources

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L. D. Stewart, J. Kim, and S. Matsuda[‡]

ABSTRACT

Results are given of an experimental study of beam focusing by aperture displacement (Δx) in duoPIGatron ion sources. Measurements with a single aperture, accel-decel electrode geometry show that the beam deflection angle is linear with $\Delta x/z$ for the round aperture and with $\Delta x/z^{*2}$ for the slit aperture where z and z^* are respectively the extraction gap distance and the effective gap distance. Applying the result of the single aperture study to the multiaperture, duoPIGatron sources, it was possible to increase the neutral beam injection power to the ORMAK plasma by ≈ 40%. Also presented are discussion and comparison of other work on the effect of aperture displacement on beam deflection.

INTRODUCTION

Neutral beam injection into a controlled thermonuclear research (CTR) device requires high power beams to travel a few meters. The efficiency of these systems improves as the ion optics improves. Most neutral beam injectors employ a multiaperture electrode system to extract a large beam current of a few tens of amperes from a large surface of discharge plasma. The multi-beamlets form a combined beam having a resulting divergence which is primarily attributable to the beamlets on the outside of the total beam. It is therefore desired to be able to steer these beamlets towards a common point.

One means of controlling the ion optics is to deliberately misalign the apertures in the extraction gap. Overall deflection of a beamlet may result from the perturbed radial electric field due to the misaligned apertures as in Fig. 1. By employing a programmed displacement to oppose

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beam divergence we have increased the neutral beam power delivered to the ORMAK (Oak Ridge Tokamak)[1] plasma by ≈ 40%. A similar improvement in beam convergence by the programmed displacement method was reported by the Berkeley group.[2]

It should be noted that this kind of focusing has advantages over magnetic focusing. There is no ion mass dependence, no increase in beam line length due to the length of the magnet and the length of the pumping region required to keep the pressure low in the magnet, and no stray magnetic field to compensate in the source.

Beam deflection by means of aperture displacement has been studied and utilized for ion thrustor systems.[3-6] Most ion thrustors have only two multiaperture grids compared to the accel-decel electrode system used in most present CTR neutral beam injectors. Computer simulation[3,4] and experimental study[5] have all indicated that beam deflection of more than 10 degrees can be obtained with no appreciable increase in direct interception. The deflection angle was shown to vary linearly with the displacement or the ratio of the displacement to the extractor aperture diameter, $\Delta x/d$. In most ion thrustors the aspect ratio, d/z, is larger than one, where z is the distance between the grids.

In this paper we present an experimental study of the effect of aperture displacement on the beam deflection for the duoPIGatron-type ion source,[7] where $d/z \lesssim 1$. Investigation was made with a single beamlet for both circular hole and slit geometry. A strong dependence of the beam deflection angle on the displacement and the extraction gap distance was observed. Results of measurements and comparison with other work are given along with a theoretical discussion. Application of the focusing method to ORMAK neutral beam injectors will be discussed.

RESULT OF SINGLE APERTURE MEASUREMENTS

The angular deflection (θ) of a beamlet was measured for both slit and round aperture systems by scanning the extracted beamlet with a Faraday cup and then noting the position of the profile peak. The distance from the extraction plane to the cup entrance was 70 cm. The entrance hole diameter of the cup was 1.27 cm. Angular deflections then were determined from the shift of the peak position relative to the peak position with no aperture displacement. The same angular deflections were obtained when we improved the resolution by decreasing the diameter of the cup entrance by a factor of four.

The aperture sizes were fixed throughout the measurements. The circular aperture diameter was 3.8 mm and the slit width was 3.0 mm. The extraction gap was varied from 3 mm to 8 mm for several values of Δx, the relative displacement between the plasma grid and the extraction grid. In Fig. 2 all the measured deflection angles for the circular apertures are plotted as a function of $\Delta x/z$. We arrived at $\theta \propto \Delta x/z$ as the best fit after having tried other functional forms such as $\Delta x/(z + d/2)$, $\Delta x/(z + d/2)$, $\Delta x/(z + d/2)^2$, and $\Delta x/z^2$. The functional form of the fitted line in Fig. 2 is

$$\theta = 18.4\ \Delta x/z \qquad [1]$$

where θ is in degrees.

For the slit geometry, beamlet angular deflections were again found to be linear with the slit displacement at fixed z and d, where d is the width of the extraction slit. The z dependence is again pronounced, however, we concluded that the best fit is z^{*-2} rather than z^{-1} where $z^* = z + d/2 + t_{pg}$ and t_{pg} is the thickness of the plasma grid. Data points are shown in Fig. 3 and the fitted curve is given as

$$\theta = 555 \cdot \frac{\Delta x}{(z+d/2+t_{pg})^2} \qquad [2]$$

where all the lengths are in mm, and θ is in degrees.

The result of our measurements can be summed up as follows: We found that the angular deflections are linear with the aperture displacement, independent of extraction voltage in the range of 10 to 20 kV, and also independent of extracted current in the range of half to one times the optimum space charge limited current. The z-dependence of θ turns out to be different depending upon whether the aperture is a round or a slit geometry. The empirical relations given by Eqs. [1] and [2] fit our data very well. Further discussion of our results along with other work will be presented in the next section.

DISCUSSION AND ANALYSIS

In Table 1 the electrode geometry for systems used in the displacement studies are compared along with the resulting values of $\theta/\Delta x$. It is noted that the aspect ratio, d/z, is larger than one for the thrustor sources and is less than one for CTR ion sources. The thrustor work emphasized the linear dependence of θ on $\Delta x/d$, the coefficient of linearity being in the range of 8 to 10 degrees per 10% displacement. Our result shows that θ varies 1 to 3 degrees per 10% displacement of d depending upon the gap distance within the range given in Table 1. We have already stated the linear dependence of θ on $\Delta x/z$, the coefficient of linearity being 1.84 degrees per 10% displacement of z. A possible correlation between the thrustor work and our result is attempted in Fig. 4, where $\theta/\Delta x$ is plotted against $(dz)^{-1}$.

Our slit results are fairly well represented by Eq. [2], and also the Berkeley result falls very close to the empirical relation. From Table 1 the coefficient of linearity, $\theta z^{*2}/\Delta x$, is found to be 560 degree-mm for the Berkeley result as compared to 555 degree-mm for our result. The effective gap distance, z^*, includes not only the half slit width but also the thickness of the plasma grid aperture. It is not clear why θ should vary with z^{*-2} rather than z^{*-1} or z^{-1}. A simple analysis given below predicts z^{-1}-dependency for the slit geometry as well.

From qualitative models we can deduce that $\theta/\Delta x$ is approximately proportional to d^{-1} or z^{-1} separately. Figure 4 may suggest a possible combined dependence of $(dz)^{-1}$. If we assume that the beam-plasma interface is affected very little by the displacement and that the beam deflection occurs near the extraction grid primarily due to the distorted, unbalanced field in the direction normal to the axis, a simplified model to estimate the radial electric field can be generated. The first order dependence is $\Delta x/d$. Computer simulation shows also that the beam deflection angle is nearly fixed by $\Delta x/d$ for a large variety of beam currents and electrode shapes. One computer simulation data point does not fit in this analysis and is shown in Fig. 4.

The z^{-1}-dependence has been derived by Green[7] in another simple model as follows: An aperture with a different potential gradient on each side acts as a lens with a focal length,[9] $f = 4V/(E_2 - E_1)$ where E_1 and E_2 are respectively the potential gradient on accel and decel side of the extraction grid. Taking space charge into account, $E_1 \approx -4/3 \cdot V/z$ in the plane parallel plate approximation.[10] Neglecting E_2 compared to E_1 and setting $\omega \approx \frac{\Delta x}{f}$ one obtains

$$\omega \approx 19.1 \frac{\Delta x}{z} \text{ (in degrees)} \qquad [3]$$

Agreement between Eqs. [3] and [1] is rather surprising since the d-dependence is totally neglected in deriving Eq. [3], while Eq. [1] includes the effect of d in it as a fixed value.

APPLICATIONS TO ORMAK NEUTRAL BEAM INJECTORS

In applying the beam deflection by aperture displacement effect to electrode design, the strong z-dependence is important. For example, in the duoPIGatron, a slightly curved (or dished), multi-aperture electrode system is used for thermal stability and to match the plasma density gradient. The plasma grid and the extraction grid are dished towards each other with about the same radius of curvature. The gap is thus given as a function of the grid radius,

$$z(r) = z(o) + [z(r_0) - z(o)] \frac{r^2}{r_0^2} \qquad [4]$$

where z(r) is the gap distance at the radial distance r from the center of the grid and r_0 is the radial distance to the outermost apertures. In order to achieve a common focal point, the desired convergence angle must vary linearly with radius:

$$\omega = \omega_0 \frac{r}{r_0} \qquad [5]$$

where $\omega_0 = r_0/f$, the convergence angle required of the outermost beamlets at $r = r_0$ to yield the desired focal length f.

Combining Eqs. [1], [4], and [5], we obtain the radially inward displacement required of each aperture of the plasma grid as a function of the radial position,

$$\Delta x(r) = 3.11 \frac{r_c}{f} [z(o) \frac{r}{r_o} + (z(r_o) - z(o)) (\frac{r}{r_o})^2] \qquad [6]$$

This equation was used to determine the displacement of the extraction system apertures of an ORMAK injector. In this case, r_o = 7 cm, $z(o)$ = 4.7 mm, $z(r_o)$ = 6.4 mm, f = 1 m, and there were 209 apertures, each displaced according to Eq. [6].

Beam power density profiles shown in Fig. 5 illustrate the focusing effect of the aperture displacement programmed according to Eq. [6]. Fitting a Gaussian to the profiles, $j = j_o \exp[-1/2(r/a)^2]$, where j is the current density and a is the Gaussian half-width, we obtain a = 2.05 cm and j_o = 0.22 A/cm^2 for the programmed system, and a = 3.24 cm and j_o = 0.1 A/cm^2 for the non-programmed system. The Gaussian half-width angle of the programmed profile in Fig. 5 is ~ 1.1°, which is believed due to the combined effect of the single aperture lens, the finite ion temperature, and the imperfect summation of all beamlets. With the programmed aperture system we observed a spot of about 2.5 cm diameter in the center of the target which showed blistering and cracking. The power density profile shown in Fig. 5 confirms the size of the hot spot.

In Fig. 6 the beam power delivered to a beam stop in the ORMAK beam line is shown for the aligned aperture system and the aperture system with displacement programmed according to Eq. [6], both as a function of the total extracted current. The improvement in performance is certainly significant, the increase in power being about 40% on the average. We have employed this aperture displacement technique to improve the beam focusing in all four injectors in ORMAK, resulting in a combined neutral beam injection power of ~ 500 kW.

In conclusion, beam focusing by aperture displacement in multiampere, multiaperture ion sources has been very effective. The results of a basic study were applied to ORMAK neutral injection systems and a 40% increase in neutral beam heating power was obtained. Future MW neutral beam heating systems for plasma confinement devices, because of long beam line lengths and limited entrance apertures, will require displaced

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FIGURE CAPTIONS

Fig. 1. Illustration of aperture displacement and beam deflection.

Fig. 2. Measured deflection angles for the round aperture plotted against $\Delta x/z$. Data are for three different gap distances and varied extraction voltages (10 to 20 kV).

Fig. 3. Measured deflection angles for the slit aperture plotted against $\Delta x/z^{*2}$.

Fig. 4. The present measurement along with some data from the ion thrustor study plotted as function of $(zd)^{-1}$.

Fig. 5. Beam power density profiles for an ORMAK injector.

Fig. 6. Equivalent ion beam currents and beam powers delivered to ORMAK target for different aperture systems.

Table I

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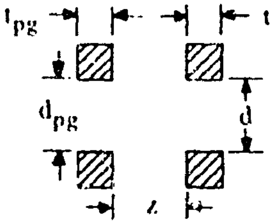
Comparison of Systems Used in Aperture Displacement Study



	NASA(4)	HRL(5)	Berkeley(2)	Present Work	
Aperture	Round	Round	Slit	Round	Slit
Theory (T) or Experiment (Expt)	T	Expt	Expt	Expt	Expt
Electrodes Extraction Voltage	Dual Grid 1.8 kV	Dual Grid 2 kV	Accel-Decel 10~20 kV	Accel-Decel 10~20 kV	Accel-Decel 10~20 kV
Dimension (mm)					
t_{pg}	0.38	0.63	0.75	1.6	1.5
t	0.38	1.27	1.87	1.6	1.5
d_{pg}	1.9	2.4	2.0	3.8	3.0
d	1.9	2.4	2.0	3.8	3.0
z	0.96, 0.48	1.15	2.25	4.65, 6.68	4.0, 6.0, 8.0
$\theta/\Delta x$(deg/mm)	46, 57	33	35	4, 2.3	11.5, 6.4, 4.7

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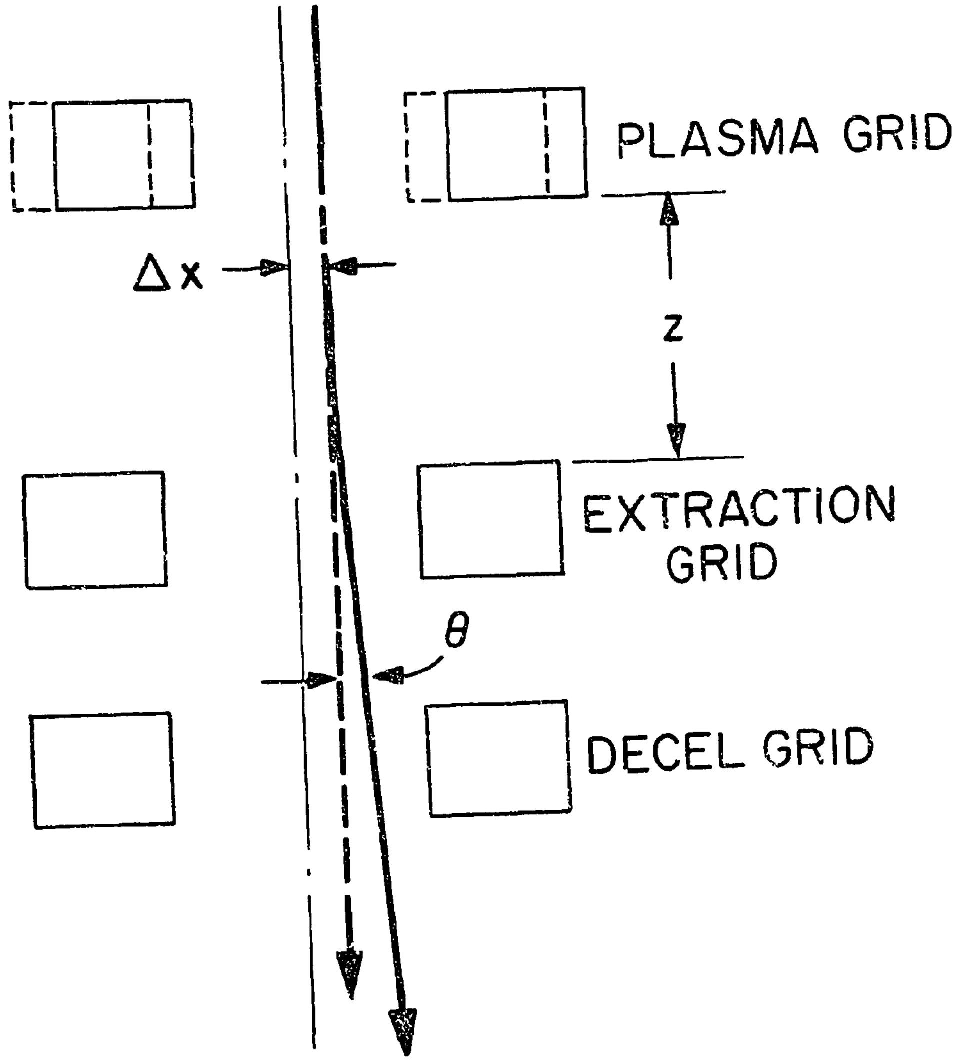

Fig. 1. Illustration of aperture displacement and beam deflection.

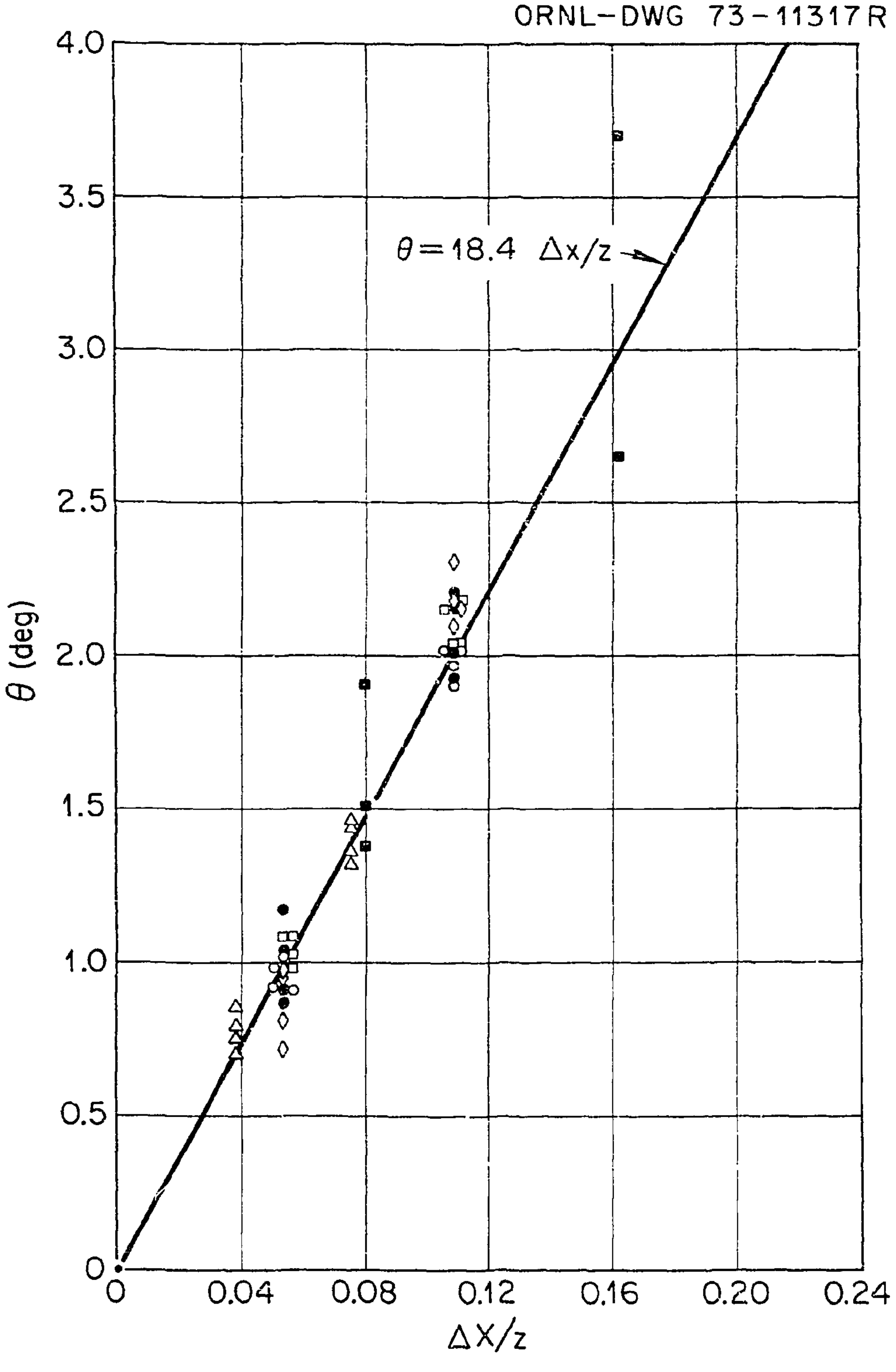

Fig. 2. Measured deflection angles for the round aperture plotted against Δx/z. Data are for three different gap distances and varied extraction voltages (10 to 20 kV).

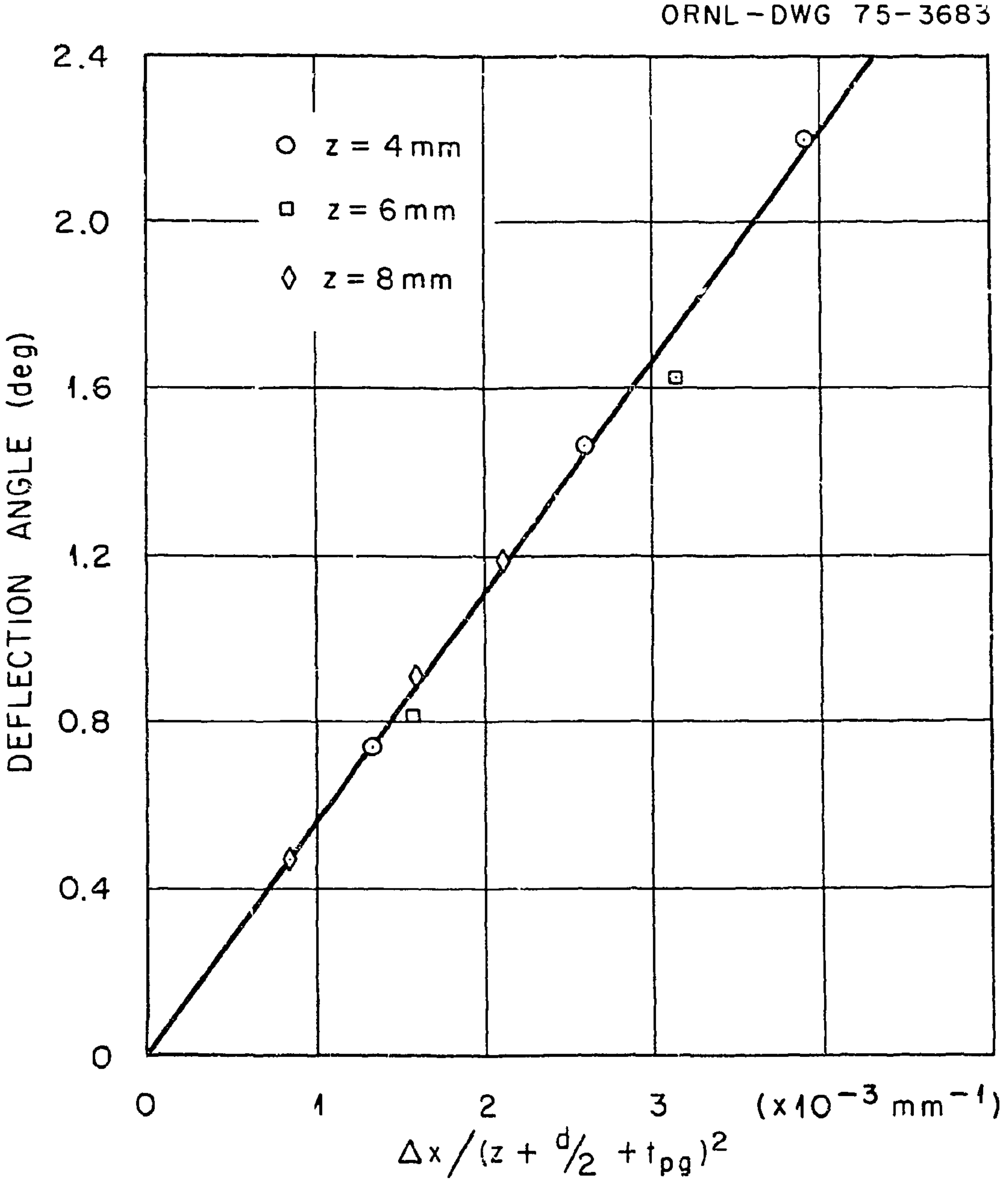

Fig. 3. Measured deflection angles for the slit aperture plotted against $\Delta x/z^{*2}$.

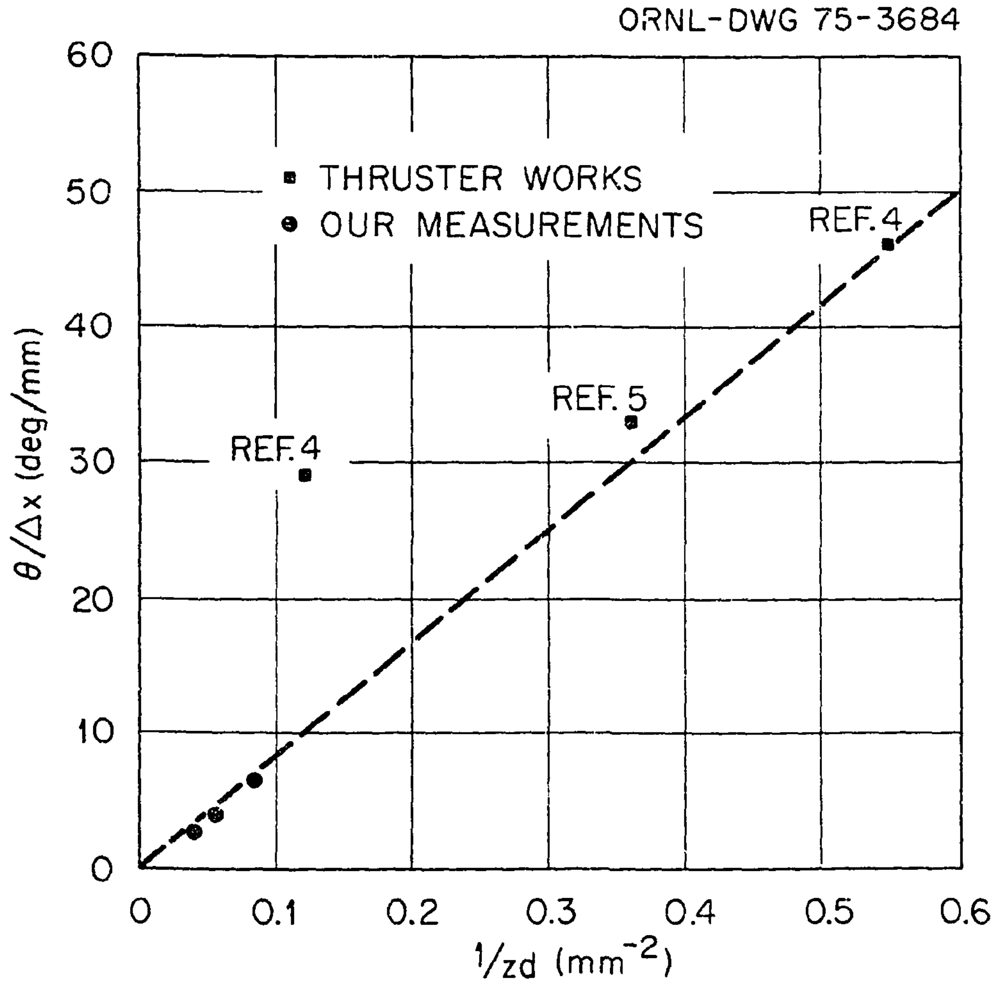

Fig. 4. The present measurement along with some data from the ion thrustor study plotted as function of $(zd)^{-1}$.

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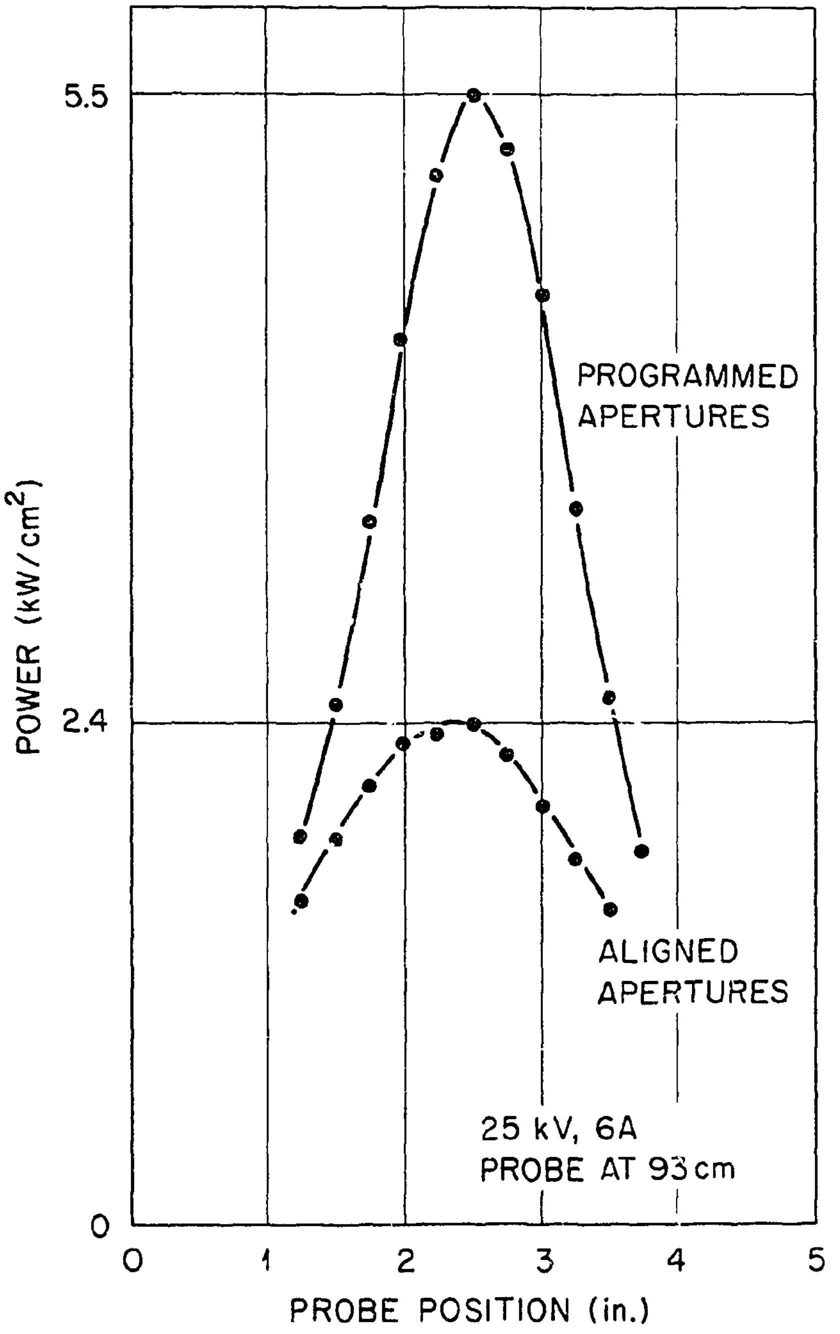

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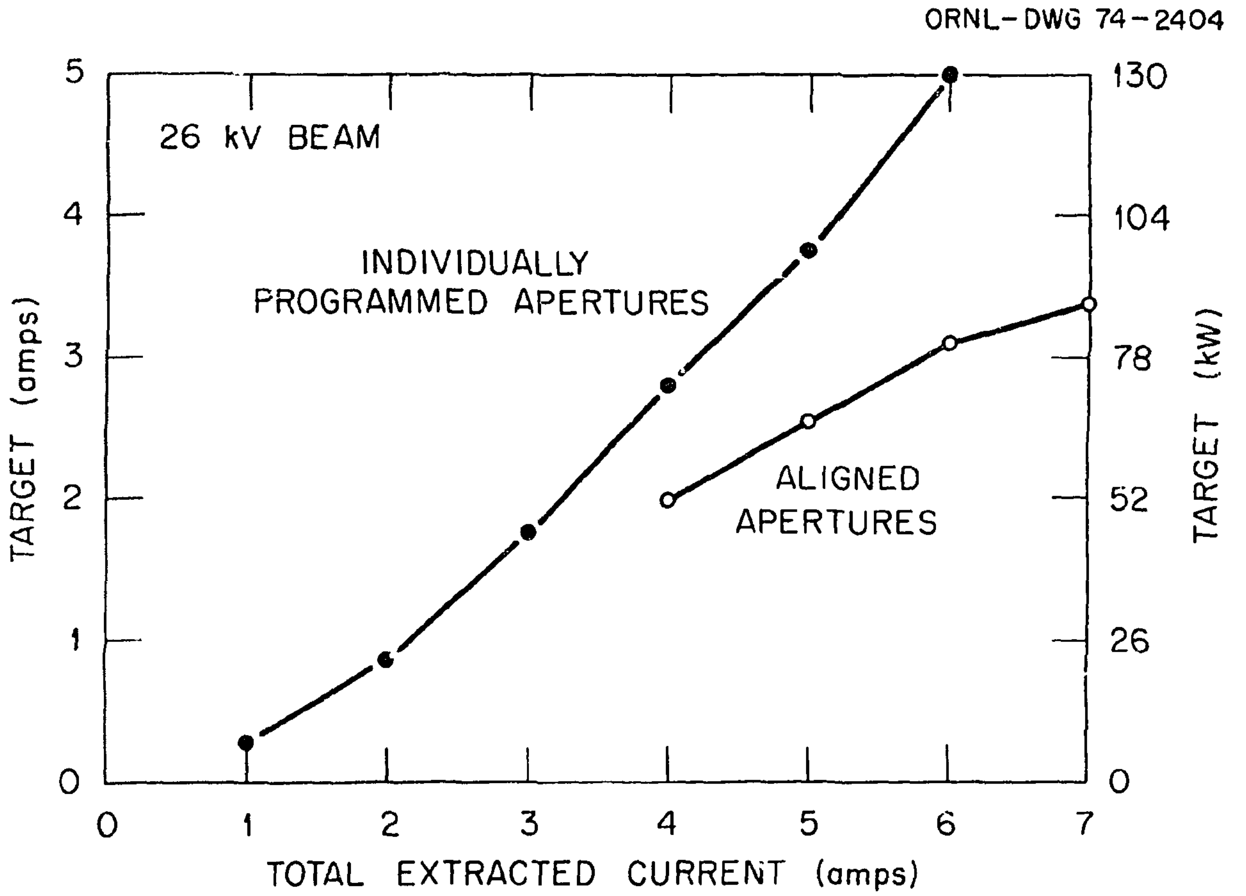

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