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THEORETICAL ANALYSIS OF A GRID-TRANSLATION BEAM DEFLECTION SYSTEM FOR A 30-CM DIAMETER KAUFMAN THRUSTER

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SUMMARY

A theoretical analysis has been performed on a grid translation beam deflection scheme for use with a 30-cm diameter Kaufman thruster. An analysis which included variations in beam current and grid spacing was made using a single hole model. The beam deflection angle was found to be relatively invariant with beam current. However, grid translation distance prior to direct ion impingement decreased markedly as beam current increased. Larger deflection angles were obtained for closer grid spacing. Effects caused by "dishing" the grids convex to the discharge chamber were analyzed. No serious problems were uncovered which would preclude dishing. It has been shown that this scheme can provide at least 10 degrees of beam deflection.

INTRODUCTION

A number of operational advantages can be realized if the beam from an ion thruster can be deflected about the nominal thrust axis. For example, the deflected beam of a station keeping thruster would provide attitude control for the satellite. For primary propulsion, corrections would be possible for the thrust deflection caused by mechanical misalinements or for the shutdown of one module of a thruster array. Mission analysis indicates that a 10-degree beam deflection capability would be desirable.

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One method which may be used for ion beam deflection is the translational misalinement of the screen and accelerator on a two-grid accelerator system. This system was suggested as a possible deflection technique in reference 1, which analyzed the effects of grid misalinement for the SERT II thruster (ref. 2). Additional analysis and experimental results of this type system are described in references 3 and 4.

The results of an analysis for a 30-cm diameter thruster, which includes the additional complication caused by the use of dished grids are presented in this report. Dished grids are desirable on larger thrusters for mechanical stability under thermal loading. The computer techniques described in reference 1 were used in the present analysis for determining the ion trajectories.

Also included in this report for comparison with the theoretical analysis are the results from an experimental test of a 5-cm thrust deflecting system using a grid translation technique. These results, which were published in reference 5, support the theoretical analysis of both reference 1 and the present work.

MODEL AND GENERAL APPROACH

The Model

The model chosen for the base case of this analysis was a set of dished 30-cm grids fabricated and tested at Lewis Research Center. The model is shown in figure 1. Figure 1(a) shows the overall dimensions of the system and figure 1(b) shows the cross section through a single hole set and the detailed dimensions. This accelerator system produced a total ion current of 2.0 A through a grid system consisting of 11,980 holes of the size shown in figure 1(b). The average current per hole is thus about 0.17 mA. However, the plasma density is not uniform across the discharge chamber. It has been estimated that the current through the holes in the central region of the grid may be 1.5 to 2 times the average value, while a hole near the edge of the grid may pass about half of the average value. Therefore, to cover the range of currents expected, solutions were obtained for three values of current per hole (0.09, 0.17, and 0.30 mA). In addition, cases were run with a grid spacing equal to half that of the base case.

The location of the plasma sheath and the ion trajectories can be determined by an iterative technique using the Lewis digital computer program (ref. 6). First, an arbitrary sheath shape and location are assumed and numerical values of the current density as a function of radial position are obtained from the digital solution. Then the sheath shape and location are readjusted in an attempt to obtain uniform current density across the sheath. A second criteria for convergence is to match the resulting total current with a previously specified value.

The General Approach

When the two grids are misalined, axial symmetry of the holes is destroyed and the resulting configuration is not directly solvable using presently known techniques. However, as proven in reference 1, perturbations of the electrodes of a two-dimensional case with planar symmetry can be solved numerically, and the solutions approximate the perturbed axially symmetric solutions. Referring to figure 1(b), the centerline represents the line of axial symmetry for the circular holes. One plane of symmetry for the unperturbed two-dimensional case passes through this line and is perpendicular to the page. Any plane parallel to the plane of the page is also a plane of symmetry.

The general procedure was as follows: Initially, the plasma sheath shape and location were determined for the axially symmetric case. The resulting sheath shape was a "dish" concave to the interelectrode region and appears as a curve in cross section (fig. 1(b)). Next, the shape and location of this curve were held fixed, and a space-charge-limited solution was obtained for a two-dimensional configuration. For this case the sheath can be viewed as a section of a cylinder. All misalinements were then analyzed as two-dimensional cases and compared with the results for the unperturbed, two-dimensional analysis.

The results of this analysis are presented in three sections. First, the effects on the ion trajectories for various degrees of misalinement and various beam current values for a single hole are presented. Then the total ion beam and the special effects of grid dishing are considered. Finally, a discussion of the results as they apply to deflecting the beam of a 30-cm thruster is presented.

RESULTS AND DISCUSSION

Single Hole Misalinement Effects

Axially symmetric solutions were obtained for grid spacings of 0.96 and 0.48 mm and single hole currents of 0.09, 0.17, and 0.30 mA. Two-dimensional solutions were then obtained by the procedure outlined above. Next, solutions were obtained for grid translation distances (δ) of 0.1, 0.2, 0.3, 0.4, and 0.5 mm. (All symbols are defined in the appendix.) Not all combinations of these parameters were analyzed. Results for those values selected for analysis are shown in table I, which gives the amount of beam deflection attainable for each condition.

For each of these cases, the ion beam deflection angle α was obtained as follows: Either 18 or 20 trajectories were initiated equally spaced at the plasma sheath. For a given trajectory j, the deflection angle α_j is defined by

$$\alpha_j = \arctan\left(m_{j_f} - m_{j_o}\right)$$

where m_{j_o} is the slope of the trajectory at the neutralization plane for $\delta = 0$ and m_{j_f} is the slope for the perturbed case. The total deflection angle is then given by

$$\alpha = \frac{\sum_{j=1}^{n} \alpha_j}{n}$$

where n is the number of trajectories.

Using the data from table I, the variation of beam deflection angle was plotted as a function of the grid translation fraction, defined as the ratio of grid translation distance to the accelerator hole diameter (fig. 2). Results from references 1 and 5 are included in figure 2 for comparison. Reference 1 was a theoretical study while reference 5 shows results of experimental tests. The geometries and operating conditions for these cases were quite different as shown in table II. However, the amount of deflection for a given value of grid translation fraction is nearly the same for all cases as evidenced by the relatively similar slopes of the curves on figure 2.

Previous work (ref. 4) had suggested that a correction must be made to the results of a two-dimensional analysis to obtain a realistic beam deflection angle for the axisymmetric case. The technique suggested indicates that a reduction of about 35 percent in the deflection angle could be expected. However, as reported in reference 3, an experimental value of 8 degrees was obtained for a system for which an 8.4 degree uncorrected deflection angle had been predicted. Based on this experimental evidence, no corrections were made to the results of the present study.

Results shown in figure 2 support the conclusion of reference 1 that the beam current level has only a very small effect on the deflection sensitivity. For the case with 0.96 mm grid separation a variation of the beam current by a factor of 3.3 yielded less than half a degree difference in deflection angle up to about 15 degrees. The primary difference occurs at the upper end of the curves where the sensitivity decreases as the beam gets very near to the accelerator. The lower current case exhibited a much smaller initial beam diameter and therefore allowed a higher degree of deflection before impingement. This result was expected since it is known that a higher density beam more nearly fills the accelerator aperture.

The upper limit for the allowable misalinement was defined to be at the onset of direct ion impingement on the accelerator grid. The distance of closest approach of the ion beam to the accelerator grid Δr is compared with the grid translation fraction δ/d_a in figure 3 for each case studied. It can be seen from this figure that the limiting case is the higher current configuration (0.30 mA) for the 0.96 mm grid separation. This high current case represents the center hole of the grid system and impingement can be expected at $\delta/d_a = 0.11$. Impingement will occur at $\delta/d_a = 0.22$ for the intermediate current case (0.17 mA). At the edge of the grid, represented by the low current case (0.09 mA) a value of $\delta/d_a = 0.30$ is expected before impingement.

An alternate case with grid separation of 0.48 mm was also analyzed for two current per hole values (0.17 mA and 0.32 mA, see fig. 2) and resulted in a marked increase in deflection sensitivity. This was expected because the closer accelerator separation has a stronger effect on the potential distribution at the screen aperture due to the increased field strength, and perturbations would be expected to have a correspondingly stronger effect. In addition, the sheath takes a more concave shape for the closer spacing at constant voltages and constant current. Thus, the more highly focused beam will allow more deflection before impingement. For the closer spacing (y = 0.48 mm), impingement would be expected at $\delta/d_a = 0.27$ for a current per hole, J_h of 0.17 mA, and at $\delta/d_a = 0.16$ for $J_h = 0.32$ mA.

Effects of Grid Dishing

Several special effects were anticipated as a result of dishing the grid system convex to the thruster discharge chamber. These will be discussed prior to discussion of the overall application of the deflection results to the 30-cm thruster.

Variable perpendicular spacing. - Because both the screen and the accelerator were dished to the same radius of curvature, it was expected that the perpendicular spacing at the edge of the grid would be slightly smaller than at a point on the thruster axis. However, the calculated change in spacing was very small (of the order of 3 percent for a 67-cm radius of curvature) and by extrapolating between curves for the two spacings shown in figure 2, it may be observed that a negligible sensitivity change will occur.

Initial misalinement. - Because the screen and accelerator grids were match-drilled prior to dishing, some of the screen accelerator hole pairs will no longer be alined after dishing. Figure 4 shows a typical misalined hole pair from a grid set dished to a radius of curvature R. At any angle θ off the thruster axis as measured from the center of curvature, the centers of the screen and accelerator apertures will be misalined by the same angle θ. At all points on the grid, the axial separation S will be constant. The initial perpendicular spacing y' will vary as the cosine of θ. (All primed symbols represent initial perturbations, i.e., with no grid translation.) The initial misalinement δ' will vary as the sine of θ. Figure 5 is a plot of δ' and $\Delta y' = S - y'$ as functions of the angle θ. The basic system used for this study had a radius of curvature of 67 cm which resulted in a maximum angle at the edge of the active area, of $\theta = 12.6^{\circ}$. The initial misalinement, which was also a maximum at the edge, was 0.21 mm. This misalinement corresponds to a beam deflection angle of $\alpha = 10$ degrees for the 0.96 mm separation distance. The above effects are reduced for the closer grid spacing.

The initial misalinement does not represent a net change in the direction of the thrust vector because of the axial symmetry of the grid. The beam deflection will in all cases be radially inward, adding to the beam focusing effect for the dished grid system and, consequently, will result in a net reduction in axial thrust. One way to counteract this effect would be to compress the accelerator grid hole pattern to eliminate the initial misalinement δ' (fig. 4).

Variable spacing due to translation. - When the grids are translated in a plane perpendicular to the thruster axis, the separation distance is decreased on one side of the grid system and increased on the other. This effect is maximum at the edge holes. The change in spacing is given by $\Delta y = \delta(\sin\ \theta)$. For a grid set dished to a radius of curvature of 67 cm and with a grid spacing of 0.96 mm, the maximum Δy would be 0.041 mm for a grid translation fraction of 0.10. Another effect of translating the grid is a decrease in the effective translation distance δ which is given by

$$\delta_{eff} = \delta(\cos\ \theta)$$

The departure from δ is maximum at the edge holes and for the same case as above $\delta_{eff} = 0.18$ mm which is 5 percent smaller than δ. This effect, unlike the previous ones, is the same on both sides of the grid. That is, the δ_{eff} is always smaller than δ.

Thrust Deflection System Design

The limiting factor to the deflection capability of a grid translation system is the interception of primary beam ions by the accelerator hole walls. The limiting values of the deflection angle as a function of current per hole for the two-grid spacings studied were determined from figures 2 and 3 and are plotted in figure 6. The current per hole values analyzed cover the range of current density variation typically measured from an ion thruster. A typical current density profile generated during experimental tests of a 30-cm thruster is illustrated in the inset of figure 6. From this profile it was determined that the holes near the center of the grid were operating at approximately 1.4 times the average current per hole, $\bar{J}_h$(0.24 mA/hole) and holes near the edge of the grid were operating at about 0.35 $\bar{J}_h$(0.06 mA/hole). These extremes are illustrated in figure 6 by the vertical broken lines. Only a short extrapolation of the data at the low current end was necessary to cover this range of currents.

The allowable deflection angle for a current of 0.35 $\bar{J}_h$ is 23.5 degrees (see fig. 6) compared to 12.5 degrees at 1.4 $\bar{J}_h$. Even though, as shown in the previous section, the edge holes are initially misalined and a deflection angle of 10 degrees results, a margin of 13.5 degrees is still present for the edge holes. For this reason the center hole becomes the limiting case for the overall vectoring capability of the system with 0.96 mm grid separation. For the closer grid spacing (0.48 mm) the limit is 21 degrees at the center and 23 degrees at the edge after a 6 degree correction because of initial misalinement.

The above results indicate that translating grid beam deflection systems should have a deflection capability greater than 10 degrees, and should therefore be useful for operational systems.

CONCLUDING REMARKS

A theoretical analysis has been performed on a grid translation thrust deflection mechanism for use on a 30-cm diameter Kaufman thruster. Special effects brought about by "dishing" the grids convex to the discharge chamber were analyzed. No serious problems were uncovered which would preclude the use of this type of system. The use of the same hole spacing for both grids results in a net reduction in axial thrust. A more compressed hole pattern for the accelerator grid could be used to counteract this effect. Additional analysis may be necessary to optimize the deflection capability and experimental tests should be conducted to correlate the theoretical results. In conclusion, it has been shown that this type of thrust deflection system can meet the requirements for 10 degrees deflection without appreciable interception of the beam by the accelerator electrode.

APPENDIX - SYMBOLS

d_a	accelerator hole diameter
d_s	screen hole diameter
J_h	current per hole
m_j	slope of j^{th} trajectory
n	number of trajectories
R	radius of curvature of grid
S	axial separation distance of screen and accelerator
t_a	accelerator thickness
t_s	screen thickness
w_a	accelerator webbing thickness
w_s	screen webbing thickness
y	perpendicular screen-to-accelerator spacing
α	ion beam deflection angle
δ	grid translation distance
Δ	incremental value
θ	grid dish half angle

Subscripts:

eff	effective
f	final value
o	initial value

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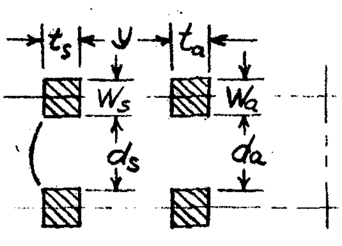
TABLE I. - CALCULATED VALUES OF BEAM DEFLECTION ANGLE α FOR VARIOUS GRID SPACINGS y AND TOTAL CURRENT PER HOLE J_h IN MILLIAMPERES

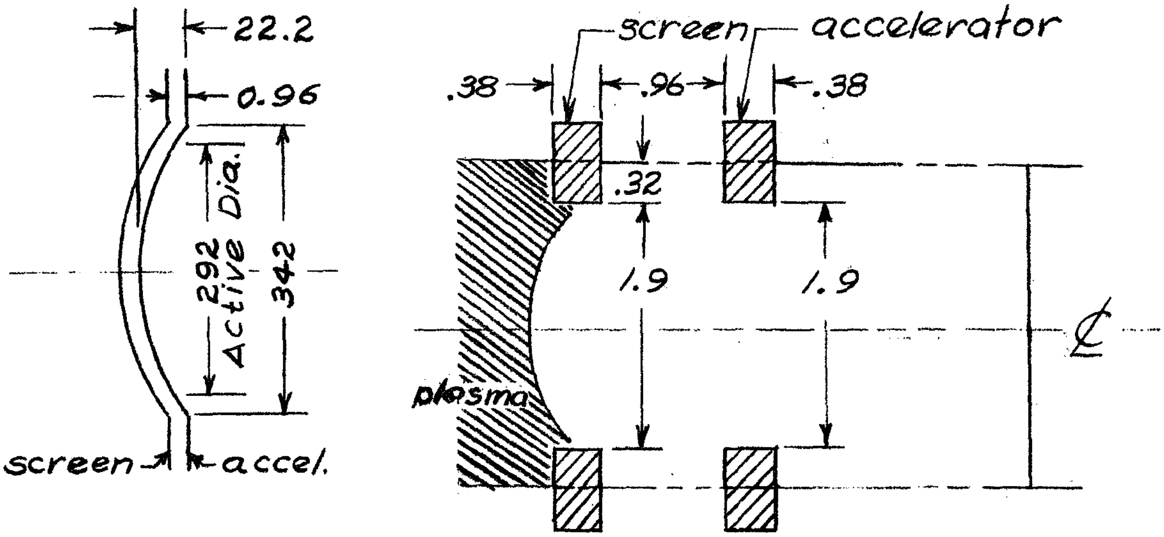
[Left columns show grid translation δ in physical distance (mm) and as a fraction of accelerator hole diameter δ/d_a]

δ, mm	$\frac{\delta}{d_a}$	Beam deflection angle α deg				
		y = 0.96 mm			y = 0.48 mm	
		J_h = 0.09	J_h = 0.17	J_h = 0.30	J_h = 0.17	J_h = 0.32
0.1	0.053	4.67	4.78	5.01	6.14	5.86
.2	.105	----	9.47	8.59	----	11.76
.3	.158	13.55	13.92	----	17.06	----
.4	.211	17.21	17.12	----	21.63	----
.5	.263	20.81	-----	----	-----	----

TABLE II. - SINGLE HOLE CONFIGURATIONS OF

REFERENCES 1, 5, AND THE PRESENT STUDY

	Reference 1 (SERT II)	Reference 5	Present study
Geometry, mm			
d_s	4.04	2.40	1.90
t_s	0.76	.63	.38
W_s	.46	.50	.64
y	2.50	1.15	0.96 and 0.48
d_a	3.26	2.40	1.90
t_a	1.52	1.27	.38
W_a	1.24	.50	.64
Potentials, V			
Screen	3000	1000	1360
Accelerator	-2000	-1000	-460
Average beam current			
Per hole J_h, mA	0.30	0.11	0.17



(a) Grid system (not to scale).

(b) Single-hole model.

Figure 1. - Cross sections of the 30-centimeter dished accelerator system and the single-hole model (all dimensions in mm).

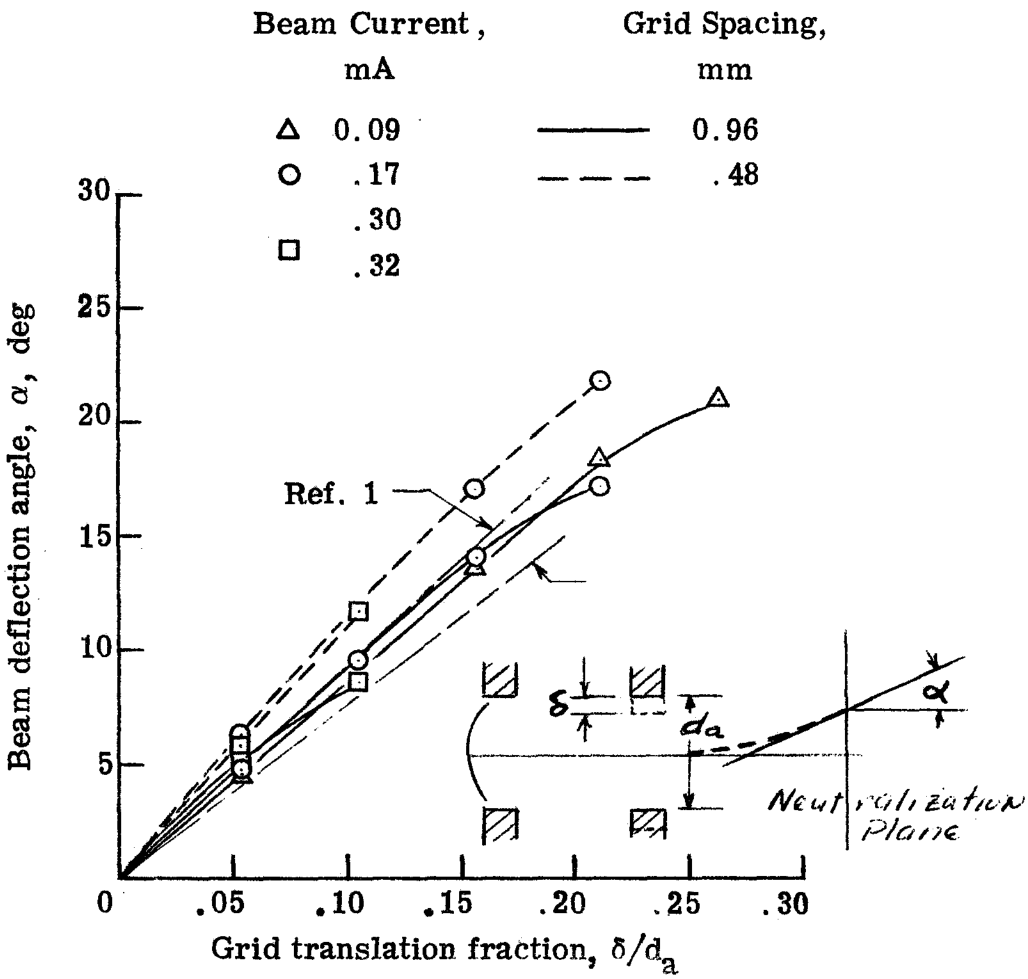


Figure 2. - Ion beam deflection angle α as a function of grid translation fraction δ/d_a (grid displacement/hole diameter).

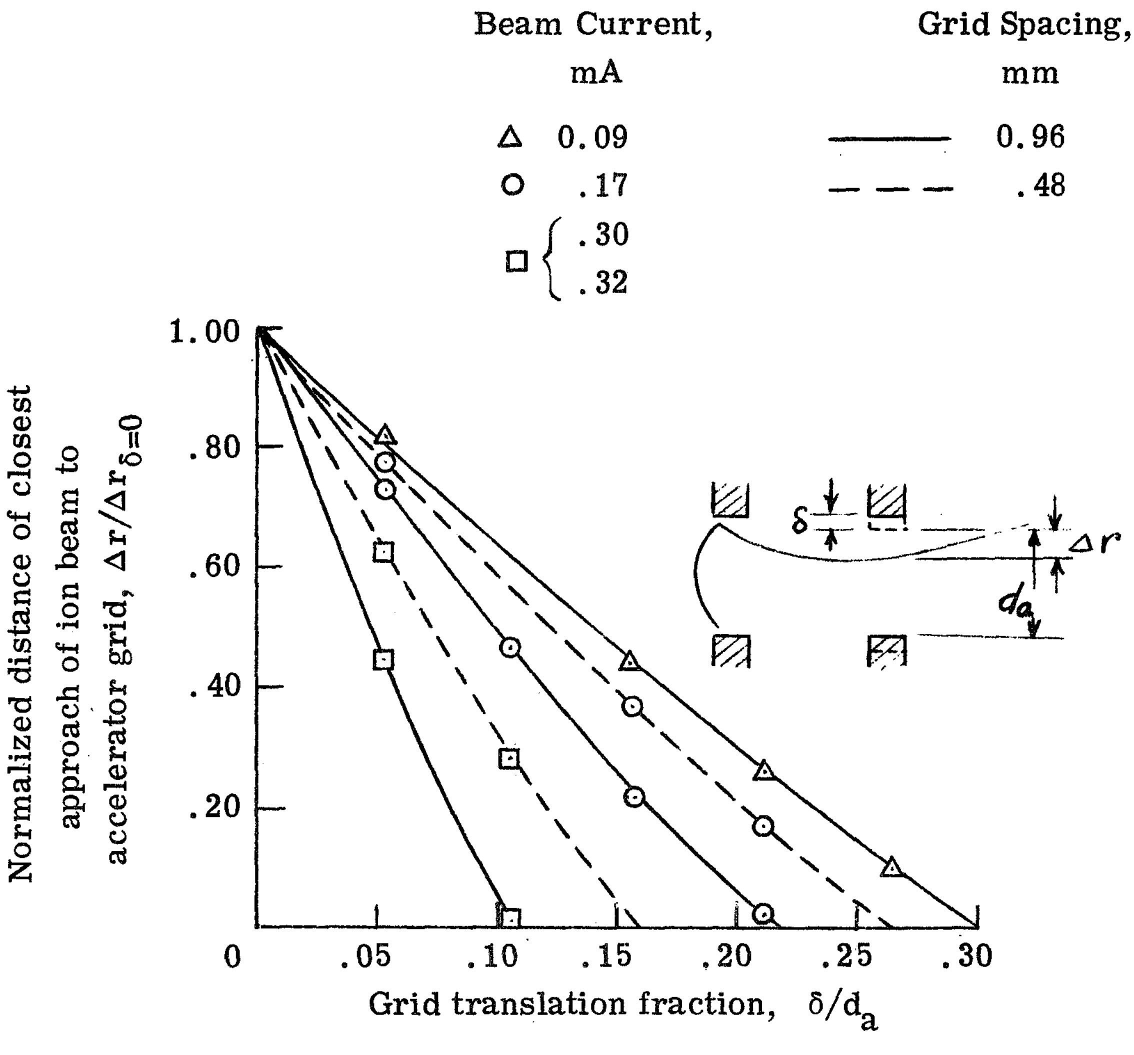


Figure 3. - Normalized distance of closest approach of beam to accelerator grid $\Delta r/\Delta r_{\delta=0}$ as a function of grid translation fraction δ/d_a.

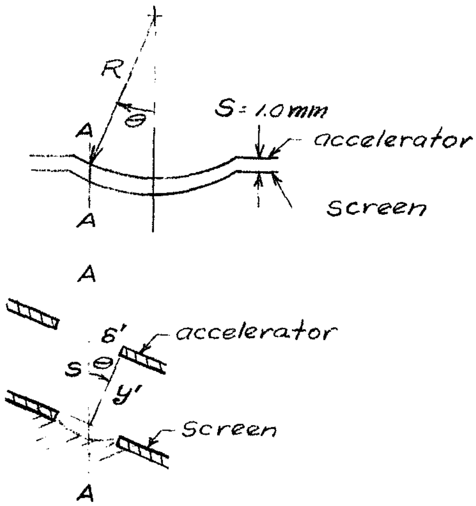


Figure 4. - Typical misalined hole pair from dished accelerator grid system.

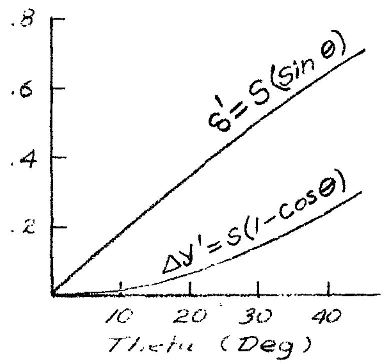


Figure 5. - Nondimensionalized plots of the initial misalinement δ' and the decrease in grid spacing Δy as functions of dishing angle θ.

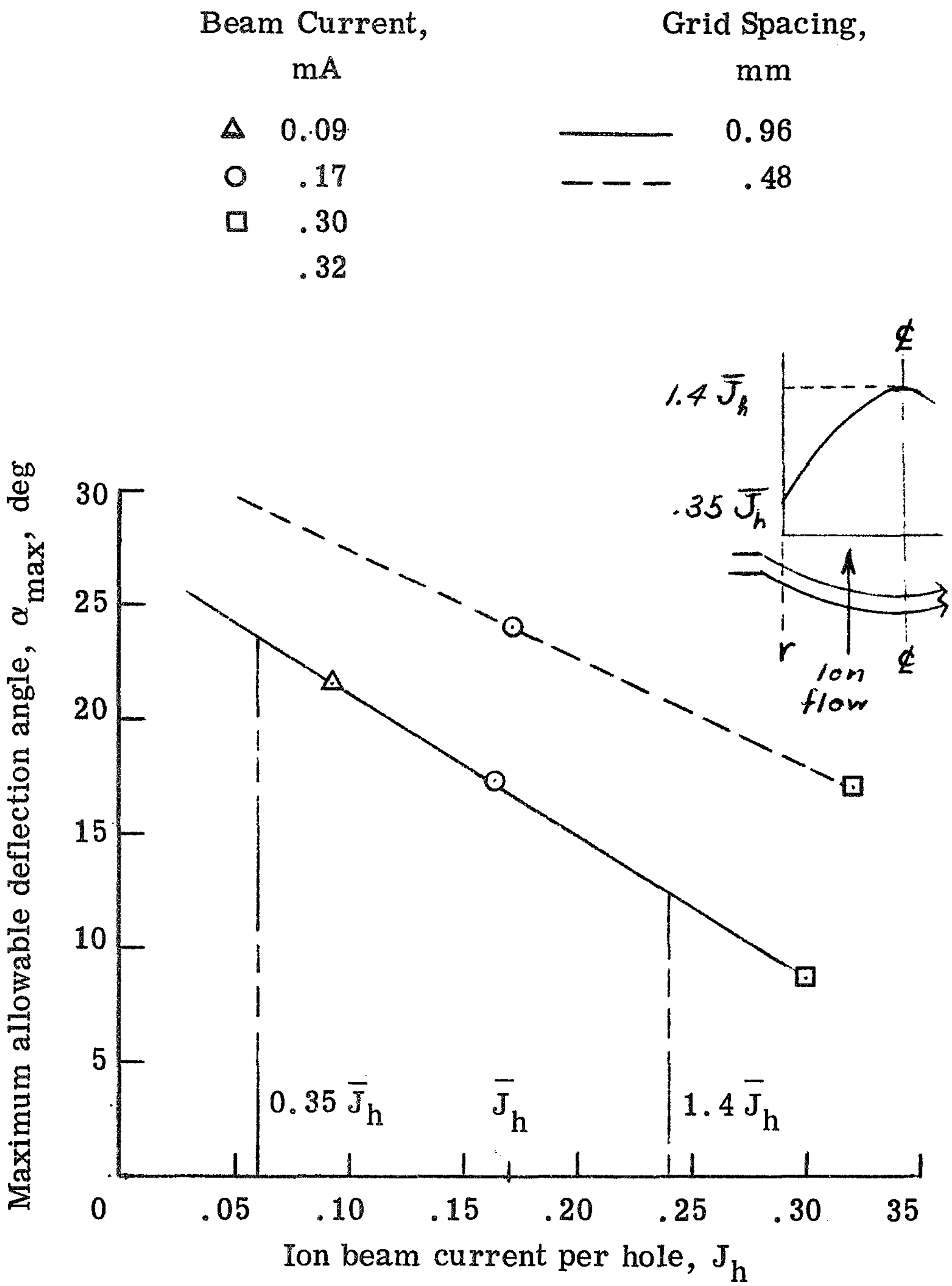


Figure 6. - Maximum allowable deflection angle α_{max} as a function of current per hole J_h for two grid spacings.