Thrust-vector tilting caused by grid misalignment*

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Geometrical perturbations of the axial-symmetric extraction channels by off-axis shifts of the accelerator grid holes give rise to an ion beamlet tilt which under certain conditions is dependent on the beamlet current. In this study, the characteristics of the beamlet deflection are presented which were obtained by a 3D trajectory simulation. The thrust-vector migration in RIT10 ion thruster test for the GOCE mission may be traced back to a slight grid misalignment.

Introduction

Broad-beam ion sources have found widespread use in numerous applications, including terrestrial techniques in material processing and surface modification [1] as well as propulsion of space vehicles [2]. For all these applications, multi-aperture two-grid or three-grid extraction systems are commonly employed to generate low-energy (<2 keV) intense broad ion beams. A great deal of effort is continuously invested towards designing and optimising extraction grid systems of the ion source for the demands of the particular application. A modelling strategy can efficiently assist in this task, significantly reducing the experimental effort. Furthermore, such an approach can give an efficient assistance in analyzing obscure experimental results.
It is well known, that the off-axis shift of extraction grid apertures may cause a remarkable tilting of the ion beamlet [3] which may be exploited to produce a focused ion beam using flat grids. However, grid displacement may also occur unintentionally as a consequence of a misalignment or thermal grid deformation, considerably deteriorating pertinent ion beam technological and space propulsion applications. So far, hole-shift effects were studied experimentally in the context of beam injectors at higher acceleration voltages (>10 keV) [4]. Moreover, in multi-beamlet negative-ion sources the beamlet steering technique has also been used to compensate the beam deflection caused by electron-retaining magnetic fields [5]. The linear optics consideration of beamlet steering in triode extraction systems by Whealton [6] yielded the ion beamlet deflection proportional to the respective electrode shift.
In order to investigate the effect of a grid hole displacement in a low-energy range (<2 keV) in the outlined wide context, we carried out 3D trajectory calculations, using the KOBRA3 code [7]. The characteristics of the deflected beamlets will be discussed. It will be demonstrated that just a slight grid misalignment produces a thrust-vector tilt which may be not tolerable for spacecraft propulsion applications. Thus, in the investigation of the RIT10 ion thruster (Astrium GmbH) as it was tested for the GOCE mission, the thrust vector was found to vary with the thrust level in a systematic, reproducible way [8] which now can be traced back conclusively to a slight grid misalignment. The characteristics as obtained in this study enable the definition of critical tolerances of the grid mounting.

Modelling of beamlet deflection

Under common operational conditions, the single extraction channels are considered to work independently from each other. Moreover, the extracted beamlet is

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Table 1: Geometrical parameters of the grid sets used in this study.

	GS 1	RIT10 Evo
screen grid hole diameter	1.9 mm	1.9 mm
screen grid thickness	0.3 mm	0.3 mm
accel grid hole diameter	1.2 mm	1.2 mm
accel grid thickness	0.5 mm	1.0 mm
decel grid hole diameter	1.9 mm	1.9 mm
decel grid thickness	0.3 mm	0.5 mm
screen-accel grid distance	1.0 mm	0.7 mm
accel-decel grid distance	0.5 mm	0.5 mm
screen grid voltage U_{beam}	800 V	900 V*
accelerator grid voltage U_{acc}	-700 V	-180 V*
decelerator grid voltage U_{dec}	0 V	0 V

* 1200V / -400V at higher thrust levels

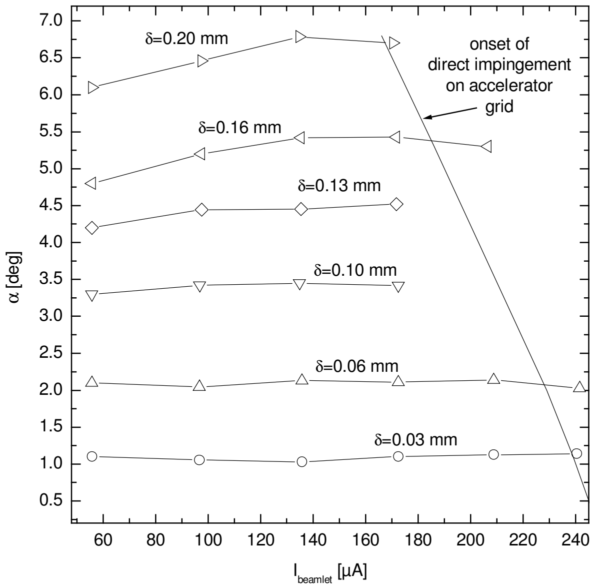

Figure 2: Deflection angle α in dependence on extracted beamlet current and aperture shift δ (grid configuration GS 1, see table 1)

considered to be axial symmetric and can be simulated in two dimensions, thus reducing the computational effort.

Obviously, an off-axis shift of one of the extraction grids breaks the axial symmetry, therefore a real three-dimensional approach is necessary. In this study, the KOBRA3 code [7] is employed which simulates the ion extraction from a plasma and the formation of the beamlet without any symmetrical restriction.

Characteristics of the accelerator grid shift

In order to study the basic characteristics of a accelerator grid hole shift, a three-grid system (GS 1, with the parameters given in table 1) was used as reference case. At an electron temperature of 3 eV the plasma density was varied between 15 A/m² and 100 A/m² yielding xenon beamlet currents of 50 μA to 250 μA covering the average beamlet currents in the experiments.

The trajectory plots of an upward off-axis aperture shift of the accelerator grid in figure 1 reveals an opposing downward beamlet deflection. Due to the aperture shift the lower beamlet envelope approaches to the hole edge of the accelerator grid, therefore more strongly experiencing the potential distortions of the electrode which are known for their diverging effect [9]. The upper beamlet envelope removes from the edge of the accelerator electrode and crosses the aperture plane near the axis at a lower diverging electric field. Consequently, all extraction parameters should be taken into consideration which can change the beamlet diameter and, hence, the distance between aperture edge and trajectories.

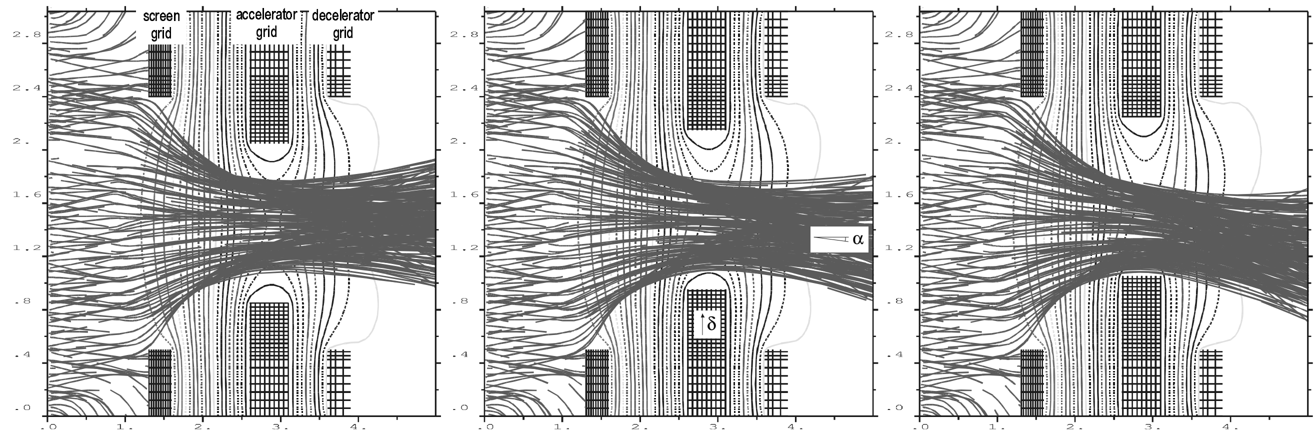

Figure 1: Trajectory plots of deflected beamlets (from left: δ=0mm, 0.1mm, 0.2mm, $I_{beamlet}$=134μA, GS 1 in table 1)

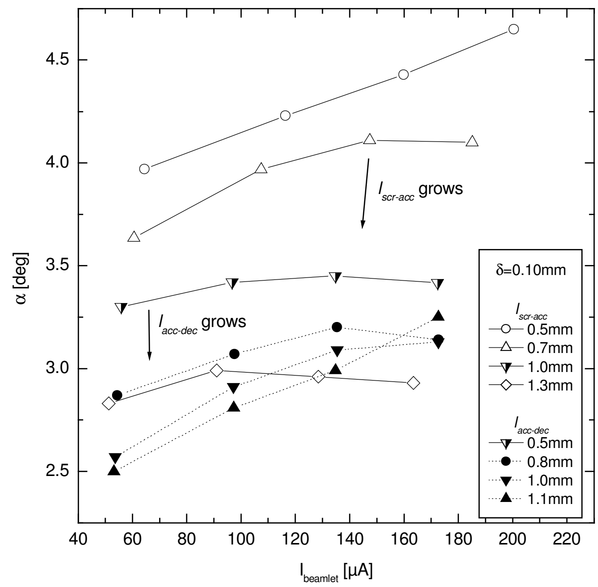

Figure 3: Deflection angle α in dependence on distances between screen and accelerator $l_{scr-acc}$ and accelerator-decelerator grids $l_{acc-dec}$

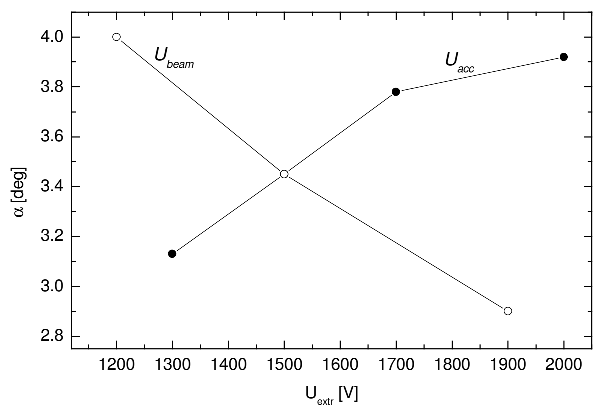

Figure 4: Effect of extraction voltage on beamlet deflection (all other parameters as in table 1)

At first sight, the beamlet deflection angle (α in figure 2) reveals a proportionality to the off-axis accelerator aperture shift δ, stressing the effect of the integral potential alterations. At small beamlet currents and large δ shifts, the interaction between perturbed potential and adjacent trajectories clearly imposes a dependence of the beamlet deflection on the beamlet current which is in contrast to earlier studies at higher energies (e. g. see [4]). The extracted beamlet current proves largely independent on the aperture shift δ. At large extracted beamlet currents and aperture shifts, a small amount of beamlet ions may impinge directly on the accelerator grid. Since only a small section of the aperture is involved in the direct impingement, the grid current grows slower with the beamlet current than in the unshifted configuration. Furthermore, in this case the deflection angle is presumably reduced.

As suggested by a basic geometrical consideration, in long extraction channels (i.e. large screen-accelerator and/or accelerator-decelerator grid distances $l_{scr-acc}$ and $l_{acc-dec}$, respectively) an accelerator-hole shift brings on weaker beamlet deflection than in compact configurations (figure 3). This effect is more pronounced for the screen-accelerator grid distance.

The electrical extraction conditions, represented by the extraction voltage $U_{extr}=U_{beam}-U_{acc}$, strongly determine the efficiency of an accelerator aperture shift in deflecting the beamlet (figure 4). An increase of the screen grid voltage U_{beam} leads to a beamlet narrowing and the potential distortion less efficiently deflects the ion trajectories. An increase of the extraction voltage by reducing the accelerator grid voltage U_{acc} also brings on a reduction of the deflection in the screen-accelerator region caused by the stronger beamlet focusing but, in contrast to the former case, this trend is dominated now by the stronger deflecting effect of the accelerator-decelerator grid region.

The results obtained so far clearly prove the significant role which also the region between accelerator and decelerator grid plays in deflecting the beamlet. As suggested by geometrical considerations and subsequently verified by simulation, an off-axis shift of both the accelerator-grid hole and decelerator-grid hole brings on smaller beamlet deflection.

Thrust-vector tilting

In experimental tests of the RIT10 ion thruster for the GOCE mission a reproducible systematic variation of the thrust vector with the thrust level was found ([8], see figure 5). By increasing the thrust from 1 mN to 11 mN, i. e. average beamlet currents from 14 μA to 150 μA, the tilt of the thrust vector increases by 0.5°. Because of the good reproducibility no thermal effects can be accounted for. Instead, this behaviour can be traced back to a slight off-axis shift of the accelerator grid.

The reference grid configuration GS 1 reveals only a slight dependence of beamlet deflection by off-axis aperture shifts on the ion beamlet current. However, the variation of grid parameters shows that there are configurations in which the beamlet current efficiently affects the deflection angle. The RIT10 configuration (see table 1) proved to show such a behaviour, which is depicted in figure 6 for two grid voltage combinations with the higher extraction voltages being necessary for

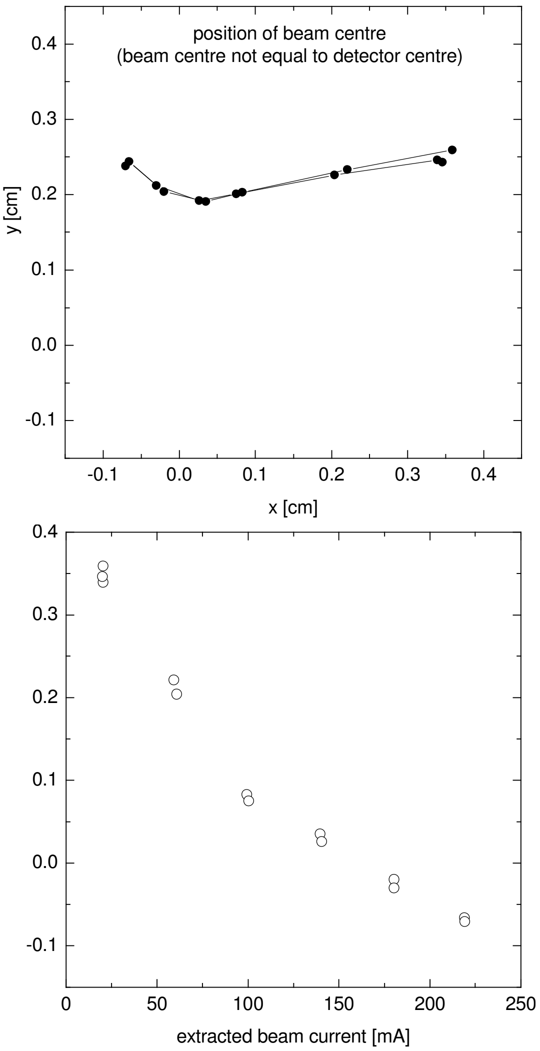

Figure 5: Migration of the thrust vector for thrust levels 1..12 mN

higher thrust levels. In order to achieve the observed increasing of the thrust-vector tilt a displacement of the accelerator grid by 0.03 mm is sufficient resulting in a total thrust-vector tilt of 1° at 11 mN and 0.5° at 1 mN at the low-voltage combination.

According to the counteracting effects of the beam and accelerator grid voltages on the deflection which has been discussed in the previous chapter (see figure 4), the higher voltages (bottom plot in figure 6) will slightly reduce the deflection angle. Therefore, at higher thrust levels and, hence, higher voltages the deflection will not increase in the same extent (for example, going from 11 mN at the lower voltages to 25 mN at the higher voltages increases the deflection angle from 1.0° to 1.2°).

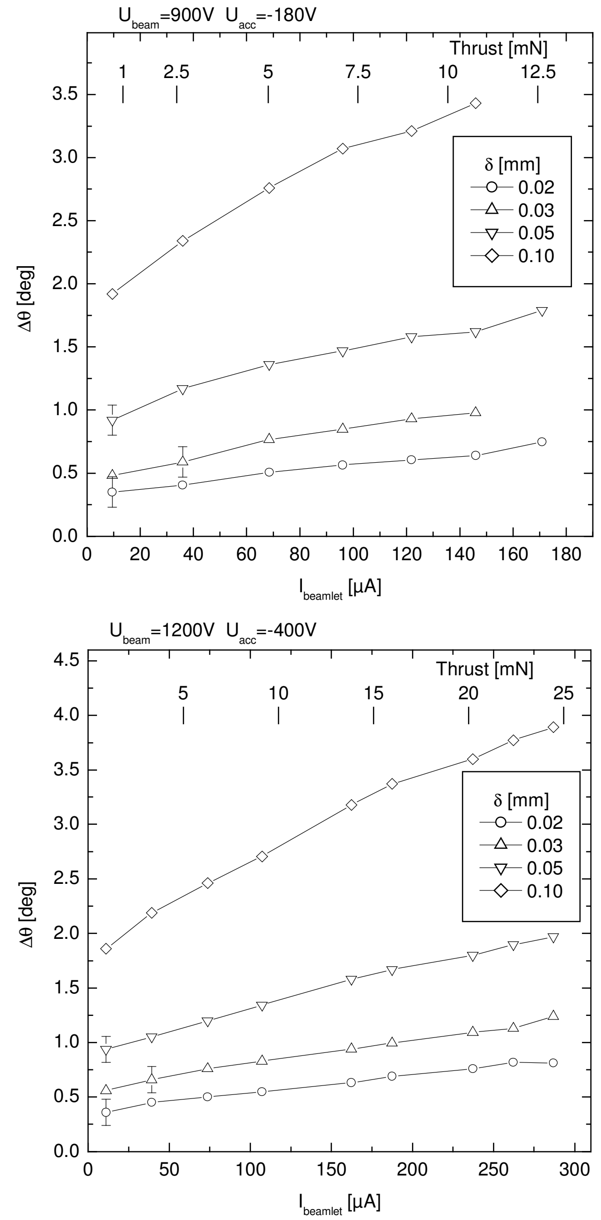

Figure 6: Deflection angle α in dependence on extracted beamlet current and aperture shift δ. (grid configuration RIT10 Evo, see table 1)

Direct impingement does not occur at this small grid shifts.

Due to the inhomogeneous plasma density distribution a shift of the accelerator grid leads to different deflection angles of central and edge beamlets which results in a slightly deformed beam current density profile. Such a modification of the profile, however, could not be reliably observed in this experiments.

Conclusions

Owing to their potential for steering and focusing purposes, discussing the geometrical perturbations of ion extraction systems proves to be of great relevance particularly in the low-energy region (<2 keV). As these distortions break the axial symmetry, the pertinent investigations must be inevitably based on an explicit 3D treatment. The beamlet deflection resulting from a shift of the accelerator grid was found to be mainly proportional to the aperture shift. In contrast to literature, a dependence was found of the deflection on the extracted beamlet current. On the basis of the present results, mainly a slight displacement of the accelerator grid could be determined as the source of the observed thrust-vector migration in the RIT10 ion thruster tests for GOCE.

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