Interactions between ion thruster plumes and vessel walls

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For satellite missions, ion thrusters have to be qualified in large vacuum vessels to simulate space environment. One caveat of these experiments is the possible modification of the beam properties due to interaction of the energetic ions with the vessel walls. To study such effects, a Monte Carlo code was developed. It samples a primary distribution of ions with respect to energies, angles and species and follows these pseudo-particles interacting with the vessel walls. Hitting a wall, based on sputter rates calculated by a binary collision cascade code, the back-flow of eroded particles from vessel walls towards the ion thruster acceleration channel is calculated. The development of a strategy to reduce the back-flux towards the thruster exit needs a fundamental understanding of the basic processes. Therefore, carbon tiles inside the vessel and the problem of hydro-carbon re-deposition is discussed. A possible baffle structure to reduce the back-flux is studied.

Nomenclature

r	= distance
Y	= sputter yield
R_c	= radius of the cylinder
Z_c	= length of the cylinder
R_{sp}	= radius of the sphere
D	= diameter of the thruster nozzle
θ	= emission angle of the thruster
α	= tilting angle of the baffle
l	= baffle length
d_c	= baffle distance in the cylinder part
d_{sp}	= baffle distance in the spherical part

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I. Introduction

Ion thrusters are getting more and more important for scientific and commercial space missions. Compared to the commonly used chemical thrusters they have a 5 to 10 times higher specific impulse and their mass is reduced by some 100 to 1000kg.

For satellite missions, these thrusters have to be qualified in large vacuum vessels to simulate space environment. One caveat of these experiments is the possible modification of the beam properties due to the interaction of the energetic ions with the vessel walls. Impinging ions can produce sputtered impurities or secondary electrons from the wall. The secondary electrons modify the potential distribution as additional electron source adding to the neutraliser. This contribution discusses the effect of sputtering at the vessel walls, from which sputtered impurities can stream back into the acceleration channel of the thruster and produce co-deposited layers. Over the long operation time of thousands of hours, such layers can modify the optimized geometry and induce by this changes of the ion beam properties, e.g. broadening of the angular distribution and thrust reduction.

To study the back-flux of sputtered particles into the thruster exit, a Monte Carlo (MC) model for the interaction of ion thruster beams with vessel walls is presented. Two strategies to reduce the back-flux are shown comparing carbon and aluminium walls and introducing baffles.

II. Description of the Monte Carlo model

The Monte Carlo method is a common approach for plasma-wall problems, e.g., MC simulations of sputtering and re-deposition are well established in fusion-oriented studies[1] and magnetron sputtering[2,3]. The idea of the Monte Carlo model is to sample a primary distribution of ions with respect to energies, angles and species. These pseudo-particles are followed hitting the vessel walls and generating sputtered particles, based on sputter rates calculated by a binary collision cascade code. Their angular distribution are sampled and the back-flow of eroded particles from vessel walls towards the ion thruster acceleration channel is calculated.

In this work we assume a particle beam without divergence and without scattering within the volume. Thus, particles move along rays according to its source distribution. This means that the so-called geometrical optics assumption[4] is applied. In reality, a trajectory of ions in the plume of an ion thruster can be disturbed by both magnetic and electric fields. Magnetic fields in ion thrusters drop very fast with respect to distance r from the thruster ($\sim 1/r^3$). Therefore, their influence is negligible for distances larger than 1 m, which is a typical distance at which experimental measurements of ion current densities are performed. The self-induced magnetic field is also negligible due to the small thruster current ($\sim 1 - 50\ A$)[5]. Usually, a neutraliser is used in Hall thrusters both for providing the primary source of electrons and for neutralization of the plume to avoid a charging of the device[5]. The latter allows the plume to be considered quasi neutral. Therefore, the electric field in the plume is negligible, justifying the geometrical optics approach.

In this 3D model, the vacuum chamber is assumed to be a cylinder with two spherical caps attached to its ends[6]. The ion thruster is assumed as coaxially placed into the cylinder close to one of the ends (see Fig. 1). Its exit is represented as a circle, where the back-flux is collected on. The angular source distributions assumed to be given as they are available from measurements[7]. The sputter yield is taken from SDTrimSP[8] simulations.

During operation of the thruster, impinging ions and neutrals with energies larger than the sputter threshold create micro roughness on the thruster surfaces. Due to shadowing, this micro-roughness modifies the real angle of incidence, effectively reducing its range to values between $20°$ and $50°$. For this angular range, sputter yields vary only slightly with angle. Therefore, we assume sputter yields to depend only on the energy of the impinging ions. It is also assumed that sputtered particles obey a cosine law[9] for their angular distribution. Due to their low energies, the sputtered particles are assumed to have a sticking coefficient of 1. Therefore only particles with direction towards the thruster exit are followed.

The task of this work is to determine the angular distribution of the particles, which are scattered back from the vessel wall to the ion thruster. This distribution can be used in a next modelling step, e.g., for the simulation of the erosion and re-deposition on the thruster surfaces. A more detailed description of the model, as well as analytical calculation to validate the code can be found in[10].

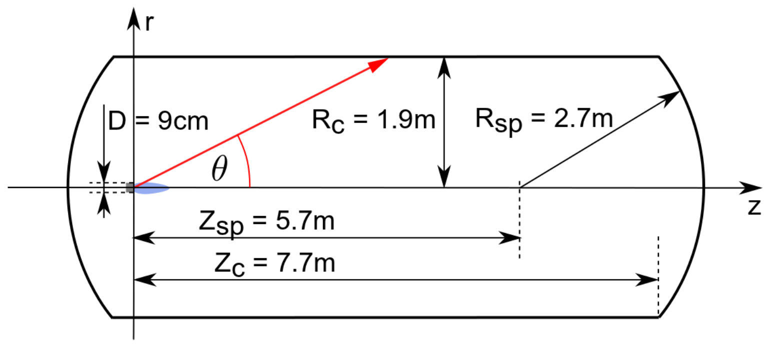

Figure 1. Sketch of the vessel model.

III. Back-flux with different wall materials

An obvious strategy to reduce back-flux from vessel walls is to reduce the number of sputtered particles by choosing a wall material with a low sputter yield. The most promising material is carbon, which has a sputter yield $Y_c(300eV, Xe^+) = 0.08$ for a $300eV$ Xenon ion bombardment. For the commonly used wall material aluminium the sputter yield is higher with $Y_{Al}(300eV, Xe^+) = 0.45$[11]. In experiments, those carbon walls are frequently realized by carbon-coated tiles.

For the simulation a vessel at Aerospazio[13] in Siena, Italy was taken as reference. It has a cylinder length of $Z_c = 7.7\ m$ and radius of $R_c = 1.9\ m$. The spherical cap at the end has a radius of $R_{sp} = 2.7\ m$. For the thruster nozzle the diameter was taken as $D = 9.0\ cm$ (see Fig. 1). The angular distributions of the mean ion energy, the current and the species fraction were generated with respect to the emission angle θ. For ion current and energy, we used distributions similar to those published for SPT-100[7]. The Xenon fraction was taken arbitrary. All used source distributions are shown in Fig. 2.

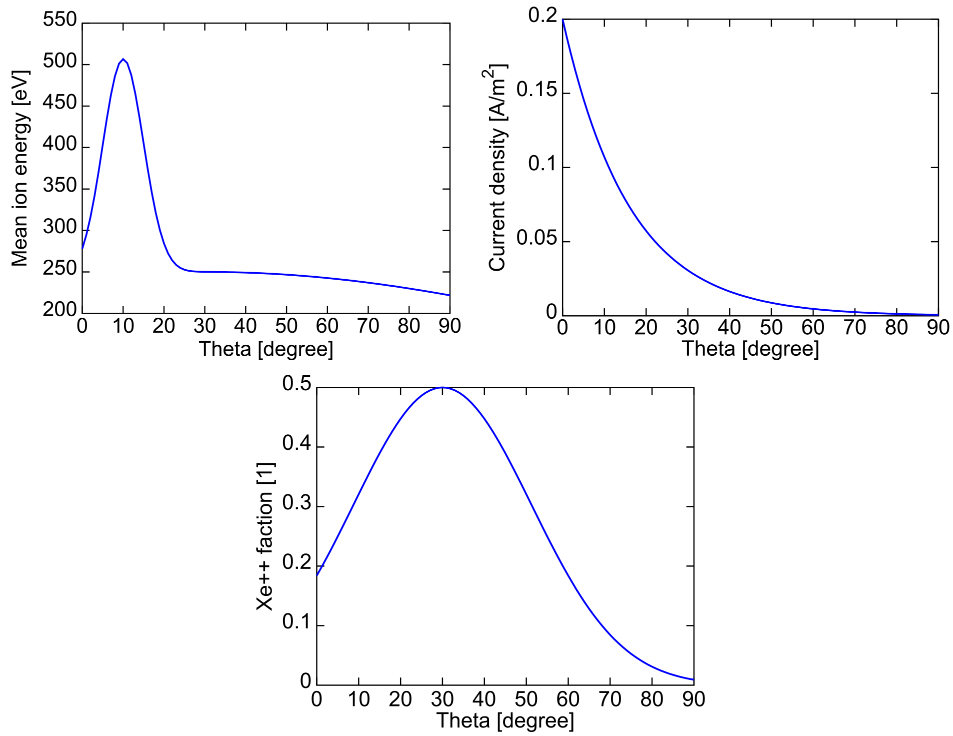

Figure 2. Distribution of mean ion energy, current density and Xe^{2+} faction of the ion thruster.

The calculated back-flux fraction towards the source is shown in Fig. 3 for carbon (left) and aluminium walls (right). It is given by the number of particles hitting the thruster exit in a certain angular range $[\theta; \theta + \Delta\theta]$, with $\Delta\theta = 1°$, divided by the total number of source particles. As expected, the back-flux is much lower for carbon walls, with an integral flux fraction of 4.75×10^{-7}, than for aluminium which has an integral flux fraction of 1.97×10^{-5}, which is about 41 times higher. As ion thrusters have to be qualified for thousands of hours of run time, this integral flux can be sufficient to influence the operational regime of such thrusters. For the chosen parameter of the vessel, the back-flux for $\theta = [0; 14°]$ originates by the spherical cap, while for $\theta = [14°; 90°]$ it comes from the cylindrical walls of the vessel. Both materials are showing

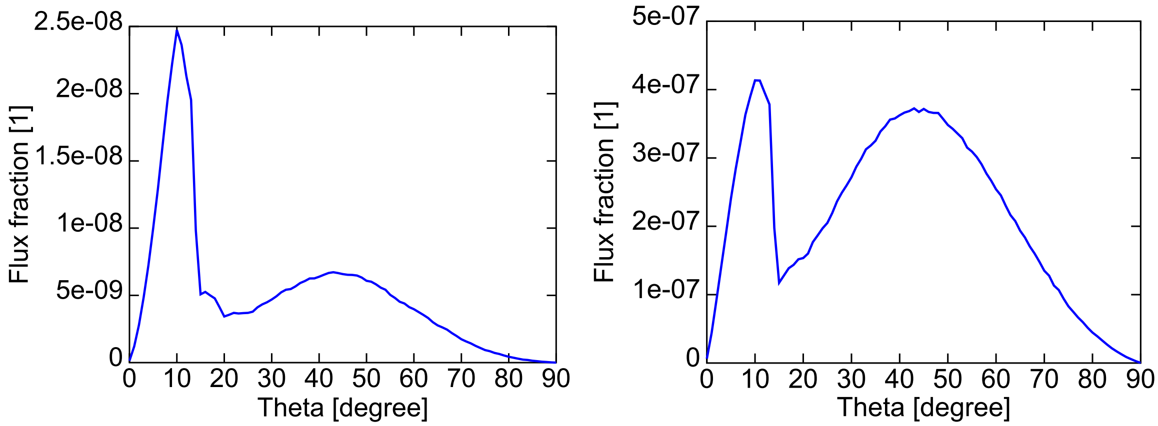

Figure 3. Calculated back-flux to the source for carbon (left) and aluminium walls (right) with the total flux fraction 4.75×10^{-7} for carbon and 1.97×10^{-5} for aluminium.

a pronounced peak around 10° and a broader one at about 45°. These structures are determined by the combination of the mean ion energy distribution of the emitted Xenon ions, the sputter yield and the cosine distribution of the sputtered particles. The first peak at 10° is dominated by the maximum of the mean ion energy which takes place at the same emitting angle. The second peak is given by the combination of decreasing mean energy with increasing θ and increasing back-flow, given by the cosine law. For carbon, this peak has an amplitude of approximately 1/4 of the first one, while for aluminium the peak has about the same hight. This different behaviour is determined by the mean ion distribution and the different threshold energies of sputtering. This is shown in Fig. 4, where the sputter yield is calculated based on the energy distributions, see Fig 2. For each angle theta the mean ion energy from the primary source distribution determines the sputter yield. This results in a dependence of sputter yield as a function of the emission angle. In Fig. 5 the number of back-flowing particles for aluminium walls from Xe^{+} and Xe^{2+} ions and in

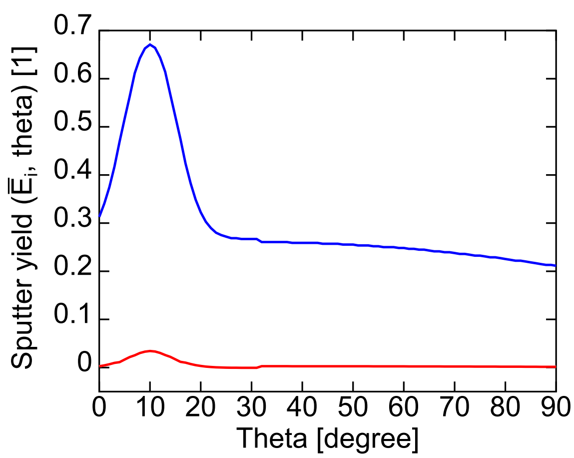

Figure 4. Sputter yield for Xenon bombardment on C (red) and Al wall materials (blue) dependent on the emission angle θ and the mean ion energy distribution.

total is shown. Since the energy is two times higher for doubly charged ions than for single charged ones, the amount of back-scattered particles from Xe^{2+} is higher and the maxima are at a different position as for the single charged Xenon ion.

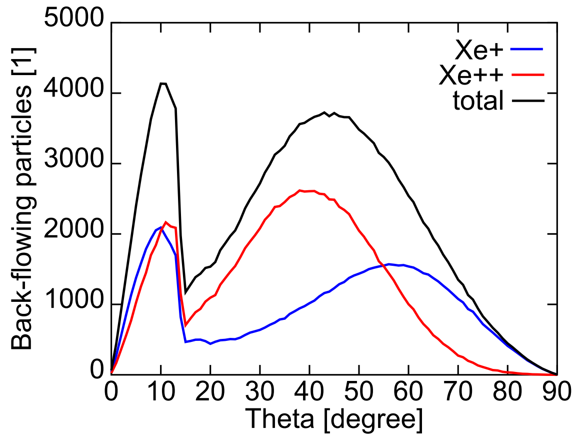

Figure 5. Number of back-flowing particles due to bombardment of aluminium walls in total (black) and for Xe^{+} (blue) and Xe^{2+} ions (red).

In the case of carbon the release of hydro carbons is a major problem linked to the sponge-like characteristics of carbon with respect to its plasma assisted interaction with hydrogen. This means that every time the vessel is opened the carbon tiles are coated by a thin water film. With the assistance of the thruster plasma, O_2 forms CO_2 at the carbon surface which reacts with the water to form hydro-carbons. Because of the porous structure of graphite, water molecules can diffuse quite deep into the bulk of such graphite tiles and produce there hydro-carbons. The ions bombarding the tiles release this large reservoir and create a hydro-carbon back-flow to the thruster[12,13,14,15,16]. Co-deposited layers of hydro-carbons are created in the acceleration channel. These layers can get conductive depending on their thickness hence changing the potentials and produce sub-sequent problems. The result is a different performance of the thruster in the vessel compared to the one in space. Using metal walls instead of carbon, the rates of physical sputtering are larger, but the evaporation at hot channel parts will prevent deposition inside the thruster.

IV. Back-flux with baffle implementation

Another strategy to reduce deposition of sputtered particles is the implementation of baffles inside the vessel. Accelerated particles from the thruster, impinge on the vessel walls and sputter its surface. As described before, due to micro roughness of the surface, the distribution function of the sputtered particles follows a cosine function, as sketched in Fig. 6a in red. Its orientation is mainly vertical to the surface, but nearly independent on the incident angle of the accelerated particles. For a tilted baffle, open towards the thruster, this cosine distribution results in a reduced amount of back-scatted particle towards the thruster channel.

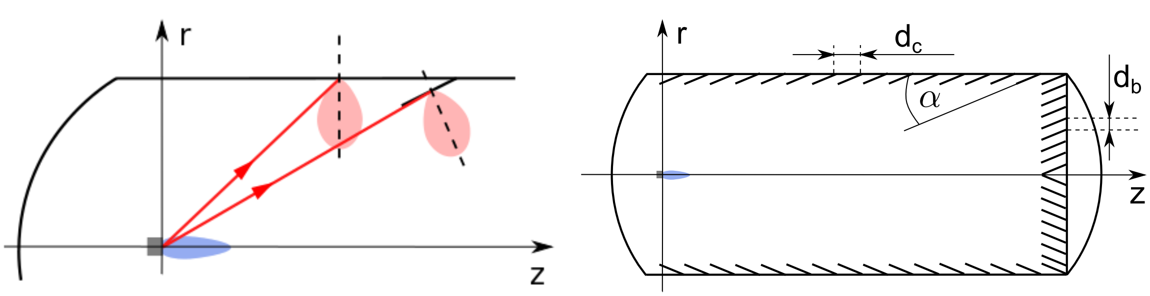

Figure 6. a: Influence of a baffle on the amount of back scattered particles towards the thruster channel. b: Implemented baffle structure.

For the Monte Carlo model the same source distribution functions of the thruster were used as in section III. The simulated vessel with implemented baffle structure is shown in Fig. 6b. Here the spherical cap is replaced by a vertical wall. Studies showed an ideal tiling angle α between 10° and 15°. In this work two angles are investigated ,$\alpha = 10°$ and $\alpha = 15°$. The baffle length is set as $l = 55cm$. For the inter-space of the baffles a constant distance is chosen, with $d_c = l \cdot \cos(\alpha)$ in the cylinder and $d_b = l \cdot \sin(\alpha)$ in the bottom region. With this set-up particles still flow back towards the thruster exit, but the main part of the produced sputtered particles are sticking at baffle tiles faced towards the point of impact.

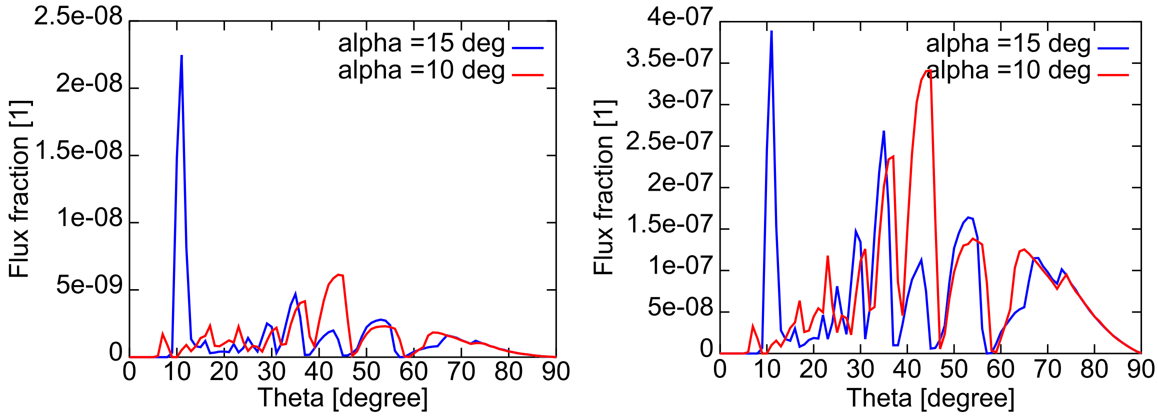

Figure 7. Back-flux for carbon (left) and aluminium walls (right) with baffle tilting angle $\alpha = 10°$ (red) and $\alpha = 15°$ (blue).

Figure 7 shows the calculated back-flux with implemented baffles for both wall materials. The total fluxes are given in Tab. 1. A reduction is clearly visible with reduction factor of 74% for carbon and 68%

	No baffles	Baffles with $\alpha = 10°$	Baffles with $\alpha = 15°$
C	4.75×10^{-7}	1.22×10^{-7} (74.3%)	1.26×10^{-7} (73.5%)
Al	1.97×10^{-5}	6.99×10^{-6} (64.5%)	5.72×10^{-6} (71.0%)

Table 1. Calculated total flux fraction. The reduction factor is given in brackets.

for aluminium. For both tilting angles the back-fluxes have a jagged structure. This is determined by the constant baffle distance d_c respectively d_b, which does not ensure total shadowing of the vessel wall. Beside the reduction of back-flux, the tilting angle influences the angle of the maximum flux towards the thruster exit. For the chosen vessel parameter the highest peak for $\alpha = 15°$ is at $\theta = 10°$, while for $\alpha = 10°$ the maximum is shifted towards $\theta = 45°$. This behaviour can be used to reduce the back-flux towards special thruster components.

V. Conclusion

The analysis of deposition of sputtered particles during terrestrial qualification tests are important due to long run times. The wall material and the vessel geometry plays an important role and can influence the result of the performance test. The accelerated ions are impinging on the vessel walls and producing sputtered impurities. These can stream back into the acceleration channel of the thruster and produce co-deposited layers. Over the long operation time of thousands of hours, such layers can modify the optimized geometry and induce by this changes of the ion beam properties, e.g. broadening of the angular distribution and thrust reduction.

In this work a Monte Carlo model calculating back-flux towards the thruster exit generated by sputtered particles at the vessel walls was introduced. In the comparison of aluminium walls and carbon coated walls the amount of sputtered back-flux of carbon walls is reduced by factor of about 41, for the chosen energy distribution and vessel size. But the hydro-carbon layers, generated by ventilation of the vessel, produce hydro-carbon back flows and re-deposited hydro-carbon layers inside the thruster channel. These can get conductive, which can lead to short circuit in the thruster. Another strategy to overcome deposited layers inside the thruster is the implementation of baffles inside the vacuum vessel. In this work an ideal tilting angle between 10° and 15° was found and the flux fraction for both angles was plotted. For both materials the back-flux was reduced by at least 64%. It was shown that the tilting angle also influences the position of the maximum peak of back-flux and can therefore be used in order to reduce the back-flux towards special thruster components.

Acknowledgements

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