STUDY OF EXTRACTION GRID EROSION IN A LONG-TIME ION THRUSTER OPERATIONAL TEST

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Abstract

Lifetime evaluation of gridded ion thrusters based on the erosion parameters in the begin-of-life (BOL) state yields an underestimation. Simulations enable for a study of the evolution of the grid erosion with the operation time. However, there is a lack of corresponding experimental data covering the range between BOL and EOL states.
We performed a long-time operational test of an ion thruster where periodical breaks allowed for a detailed inspection of the extraction grids.

Introduction

In addition to materials and surface technology, broad-beam multi-aperture ion sources increasingly find application in electric spacecraft propulsion. Particularly in the latter field stable ion beam properties and long operational lifetime form stringent specific requirements. In the last decade a great deal of effort was invested towards studying the lifetime-limiting processes of ion thrusters. Grid-eroding impacts of fast primary and secondary (charge-exchange) ions were found to play the major role in destructing the extraction grids.
Therefore, lifetime estimates are of a high practical importance and, at first sight, they could be readily derived from the erosion pattern as produced in a short-time operational test over a few hours. However, corresponding simulations and lifetime experiments [1] disclosed a pronounced non-uniform progression of grid erosion and, in particular, estimation of the thruster lifetime on the basis of such beginning-of-life (BOL) data yields a too small value. Costly lifetime tests may certify the performance of the particular ion thruster for the mission duration. However, they yield a block of end-of-life (EOL) data which is not representative for a comprehensive assessment of the grid-eroding processes occurring between BOL and EOL states.
In order to come to a quasi-continuous study of the grid erosion, a long-time operational test was carried out with inspection of the grids at periodical breaks. The experiment was performed at a low cost level, i.e. operating a small ion source within a rather small vacuum chamber. Admittedly, the test conditions do not completely represent ion thruster operation, nevertheless they are well-defined and enable for a comparison with the simulation and a corresponding extrapolation to thruster operation conditions.

We employed the 4 cm rf ion source ISQ 40 RF (developed at IOM) equipped with a three-grid self-aligning extraction system. Operation conditions were applied, with contracting the erosion time scale in a well-defined way by just increasing the xenon mass flow. So far, more than 3.000 h operation time were accumulated in which every 200 – 500 h the extraction grid erosion was characterised by mass loss measurements and microscopic means.

The grid erosion process

Due to incomplete plasma ionisation, neutrals escape from the plasma chamber, forming a neutral density within the grid system. Additionally, neutrals from the residual gas in the vacuum chamber may add to this particular density. In a charge-exchange process, a primary ion collides with a neutral, converting the ion into a neutral and the former neutral into an slow ion. If this ion is born within the grid system or in its vicinity, it may be accelerated towards one of the grids. Because of the gained energy, the ion impact will sputter some material from the grid. A detailed investigation showed that most of the charge-exchange ions impinge on the inside of the accelerator grid holes, widening the holes during the operation [2].
In studying the grid erosion in dependence on the accelerator grid hole diameter, one finds the erosion to decelerate with growing hole diameter. At first a decreasing mass loss is observed, and the material is removed from a growing hole interior surface. Furthermore, the position of the maximum erosion rate moves from an upstream position towards the downstream region.
With growing accelerator hole diameter the mass flow resistance decreases. Therefore, the mass flow has to be adapted during the long operation time of the thruster which, in its turn, also affects the erosive activity. This clearly furnishes evidence of a time-dependent erosion rate. In order to predict a more reliable grid lifetime the erosion process has to be studied iteratively taking into account the operation time and the variation of the extraction conditions.
The experiment which is reported in this paper yields a broad block of data on time evolution of the grid erosion, which is available for a verification of the grid erosion simulation.

Experimental setup

The experiment was performed in a stainless steel UHV chamber (figure 1) which is evacuated by turbo pumps (2000 l/s) to a base pressure of better than 10^{-8} mbar. Due to the xenon gas flow through the ion source in operation the pressure raised up to $4 \cdot 10^{-5}$ mbar. Because of the sputter-enhancing effect of oxy-

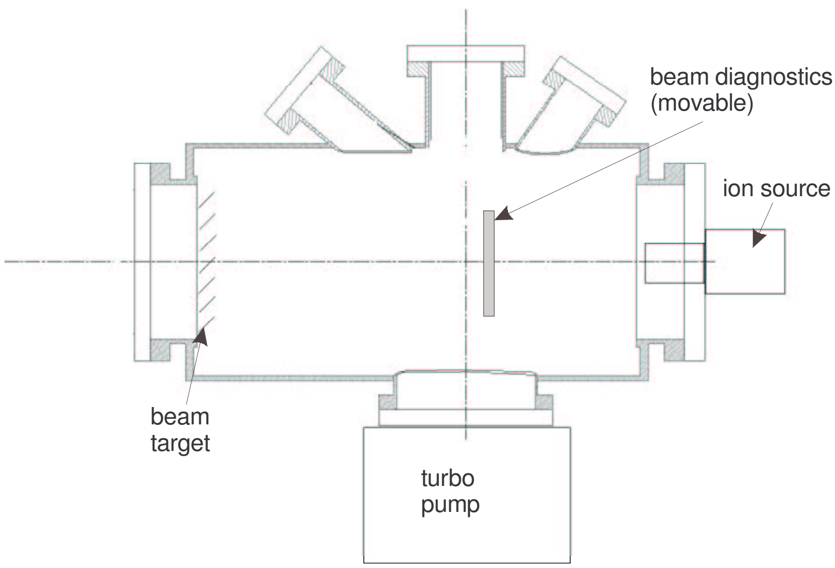

Figure 1: UHV-chamber (length: 75 cm, diameter 40 cm).

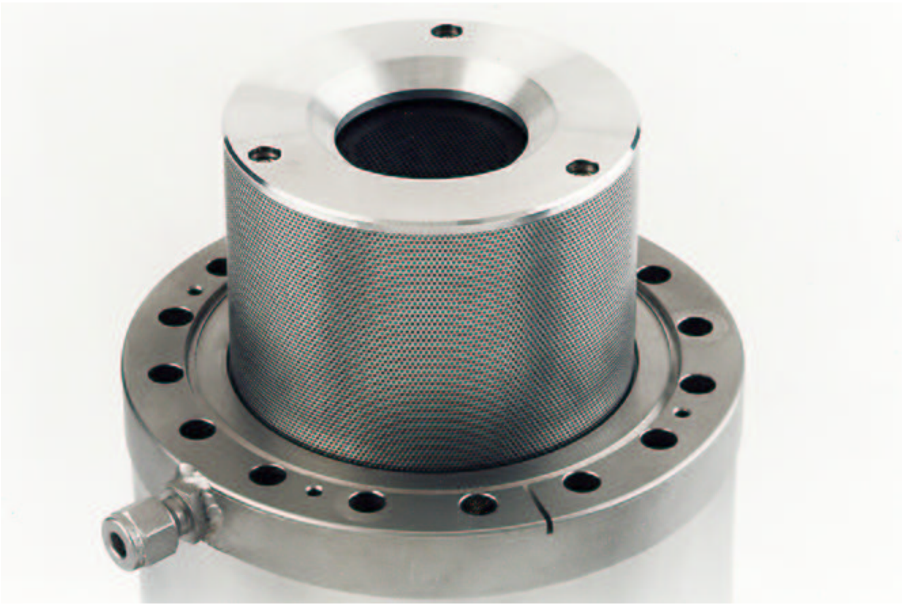

Figure 2: The 4 cm rf ion source ISQ 40 RF.

gen particularly for graphite, the residual gas composition was permanently controlled. The oxygen partial pressure was about 7 orders of magnitude lower than that of working gas xenon, so additional chemical etching is practically precluded.

We employed the 4 cm radiofrequency ion source ISQ 40 RF (figure 2), developed at IOM. The ion source is mounted on a UHV flange (CF 100) which contains all electrical and gas feedthroughs as well as the rf-matching. The source is shielded by a cylindrical stainless steel mesh which encompasses the coil-like magnetic field produced by 6 ALNICO permanent magnets and two pole pieces, the coupling coil, the three-grid system and the end plate with springs for fixing all parts of the source on the flange. The liner is an alumina tube with 40 mm both in diameter and length. The coupling coil has 4 water cooled turns and is rf fed by the generator (13.56 MHz) via a matching system.

The xenon ion beam is extracted and formed by a self-aligned three-grid system with the dimensions given in table 1. The grids are made from high-density pure graphite. The grid configuration is quite similar to the RIT-Evo assembly (Astrium GmbH). Due to manufacturing constraints, the thickness of the screen grid could not be reduced to 0.3 mm, therefore the screen grid was 0.4 mm thick and the distance between screen and accelerator grid shortened to 0.6 mm. The initial beam diameter is 3 cm. Two grid sets were manufactured, one for initial test to determine the operational parameters of the ion source and the plasma profile, and the second one for the actual life test.

The operational ion source parameters (table 2) and the grid potentials (1200V, -400V and 0V at screen, accelerator and decelerator grids, respectively) correspond to the RIT-10 ion thruster. An ion beam cur-

Table 1: Grid configuration.

Screen grid	thickness	0.4 mm
	hole diameter	1.9 mm
	distance to next grid	0.6 mm
Accelerator grid	thickness	1.0 mm
	hole diameter	1.2 mm
	distance to nexet grid	0.5 mm
Decelerator grid	thickness	0.5 mm
	hole diameter	1.9 mm

Table 2: Operational parameter ISQ 40 RF

rf-power	90 W
xenon mass flow	1.2 sccm
chamber pressure	$4{\cdot}10^{-5}$ mbar

rent of 40 mA was extracted. As compared to the RIT the initial mass flow had to be increased up to 1.2 sccm resulting in a mass utilisation of 55%. This will increase the erosion rate and contract the required operational time by a factor of about 2.5.

The envisaged experiment requires the same alignment of the grids after each assembling. This is granted by a self-aligning grid mounting. The isolation between the grids is ensured by aluminium oxide balls which are located at dedicated holes at the mounting ring of each grid. The diameter of the holes and of the balls define the distances between the grids, thereby fixing the position of one grid with respect to the others. The balls were manufactured with a precision of better 10 µm, the holes are drilled in the same step as the extraction holes on a computer controlled drilling machine. The grid package is gently fixed by springs. The grid package can be easily dismounted and mounted, it is ensured that after assembling the alignment of the grids is reconstructed within the accuracy of the balls and the holes. During the experiment, i.e. after each dismounting, the diameter and shape of the alignment holes was carefully checked.

The gas flow is determined by a mass flow controller (*MKS*) with a full scale of 10 sccm for Nitrogen.

When using a rather small vacuum facility, one is faced with the deposition of sputtered material. In order to minimise this effect, a beam target was mounted at the rear of the chamber. It consists of graphite stripes inclined to the beam by 45°. The emission of material during sputtering will be directed towards the neighbouring stripe, which prevents the dispersal of sputtered material. However, a deposition of such material on the grids and other components cannot be completely precluded. In order to estimate the remaining deposition rate, a deposition ring (aluminium) was mounted at the front plate of the source. From ring mass measurements the deposition rate is estimated.

Between the breaks the source was operated continuously, controlled and monitored by a computer. In order to check the plasma state of the ion source, the broad-beam profile and grid-current characteristics were measured periodically.

Grid inspection was done at periodical breaks (every 150 h, later on every 400 h). In each of these inspections the mass change of both the grids and the deposition ring was determined by a high-precision balance *Sartorius M210* (accuracy 10 µg). By means of a light-optical microscopy a row of holes (i.e. 13 holes) was inspected on both sides of each grid (figure 3), yielding the hole diameters and information about the shapes of the hole edges. Additional information about the grid surface and the potential grid curvature was obtained by *NanoFocus µscan®* laser-optical profilometer (scanning with steps of 2 nm along and 50 nm perpendicular to the row of holes, maximum height difference 1.5 mm).

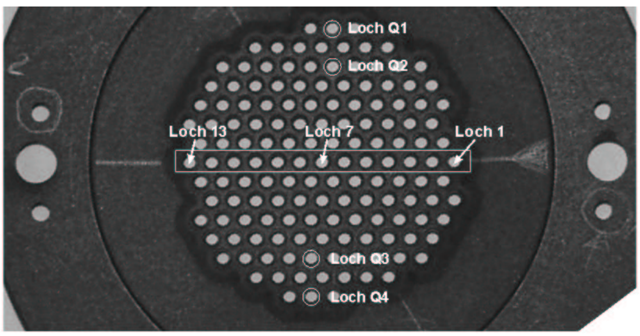

Figure 3: Row of holes inspected with µscan® profilometer.

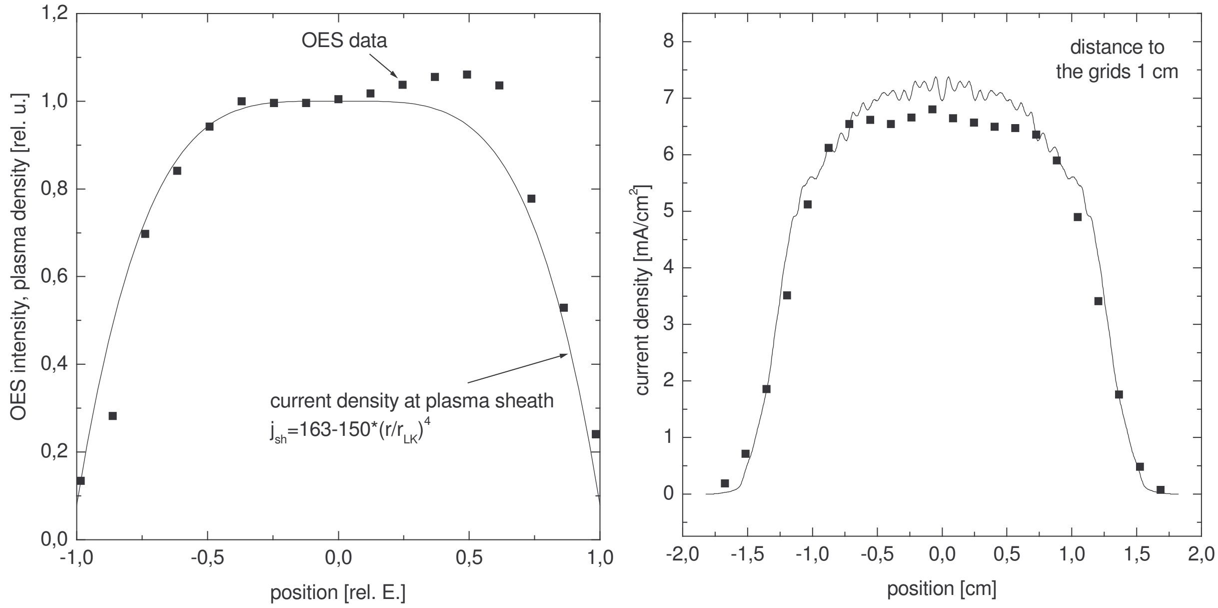

Figure 4: left: OES profile and adapted plasma density profile. right: current density profile (ISQ 40 RF, conditions of long-time test in table 2)

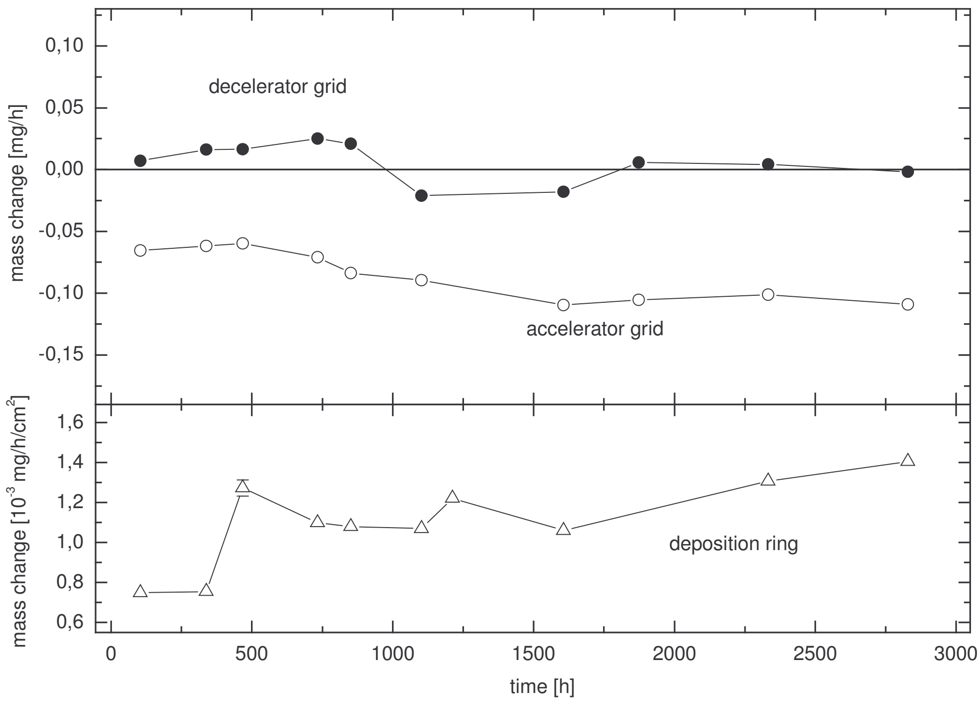

Figure 5: Mass change of the grids (respective error bars are smaller than the symbols).

Results

Plasma characterisation

The employed plasma excitation mode, applied magnetic fields, losses at the discharge chamber walls as well as ambipolar diffusion of charge carriers may produce an inhomogeneous plasma density distribution which to some extent also occurs at the plasma sheath. Therefore, the beamlet start conditions vary with the grid radius, thus affecting both the maximum extractable ion current and the ion current density distribution of the extracted beam. Obviously, knowledge of the plasma inhomogeneity is indispensable.

The plasma density profile of the ion source was characterised according to the approach described in [3]. The results from optical spectroscopy, broad-beam profile measurements at small distances from the grids and current-voltage-characteristics suggest a plasma density profile at the sheath with a pronounced plateau and a 4^{th} order polynomial was adapted (figure 4 left).

Operation of the ion source

During the first hours after each assembly, slight variations of the chamber pressure occurred which is due to the remaining outgassing of the arrangement and is significant in small vacuum chambers. The pressure variations translate into altered ion beam parameters. However, as compared to the operation time of the measuring periods (i.e. some 100 h) the variations in the run-in periods are negligible.

After the run-in period the extracted ion current was 40 mA, the currents to the accelerator and decelerator grids were 0.6 mA and 0.05 mA, respectively.

In the course of 3000 h of operation the grids were inspected 11 times. Unfortunately, due to an accidental mechanical damage of the grid the experiment could not be continued up to the envisaged EOL state of the grids.

Mass change of the grids

Figure 5 shows the mass change of the grids in dependence on the operation time. At the accelerator grid a mass reduction was observed with the rate starting at 0.07 mg/h and increasing up to 0.11 mg/h after 1500 h, which then remained constant. The mass change of the decelerator grid scatter around zero. This grid is most affected by deposition of material, hence deposition and erosion balance each other.

The mass change of the deposition ring yields a deposition rate of 1.1 $\mu g/h \cdot cm^2$ which results in an estimated mass growth rate at the decelerator grid of 0.017 mg/h which agrees with the small mass alterations of the grid. The greatest part of accelerator grid is geometrically shielded by the decelerator grid, therefore the estimated deposition rate is lower than 0.004 mg/h which amounts less than 5% of the measured mass change.

Change of hole diameters

Figures 6 and 7 show the evolution of the hole diameters at the accelerator grid as measured on both sides by light-optical microscopy. On the upstream side (facing the screen grid) the erosion starts homogeneously, further progressing slower in the beam centre than at the beam edge. On the downstream side of the accelerator grid (facing the decelerator grid) a erosion profile is found with the maximum in the beam centre which is also known from other lifetime experiments [1]. The accelerator grid erosion on the downstream side prevails that on the upstream side.

Apart from the beam centre, the accelerator hole diameter increases nearly linearly with time (figure 8). Since the erosion profiles evolve different on both grid sides the central hole becomes more conical. The average erosion rate was 61 nm/h. The laser-optical profilometer investigation is in accordance with these results.

As compared with the measuring error, the decelerator grid holes show negligible diameter changes (figure 9). The low measured grid current indicates a soft impact of charge-exchange ions, causing inconsiderable erosion. Furthermore, it is comparable with the deposition rate as discussed above.

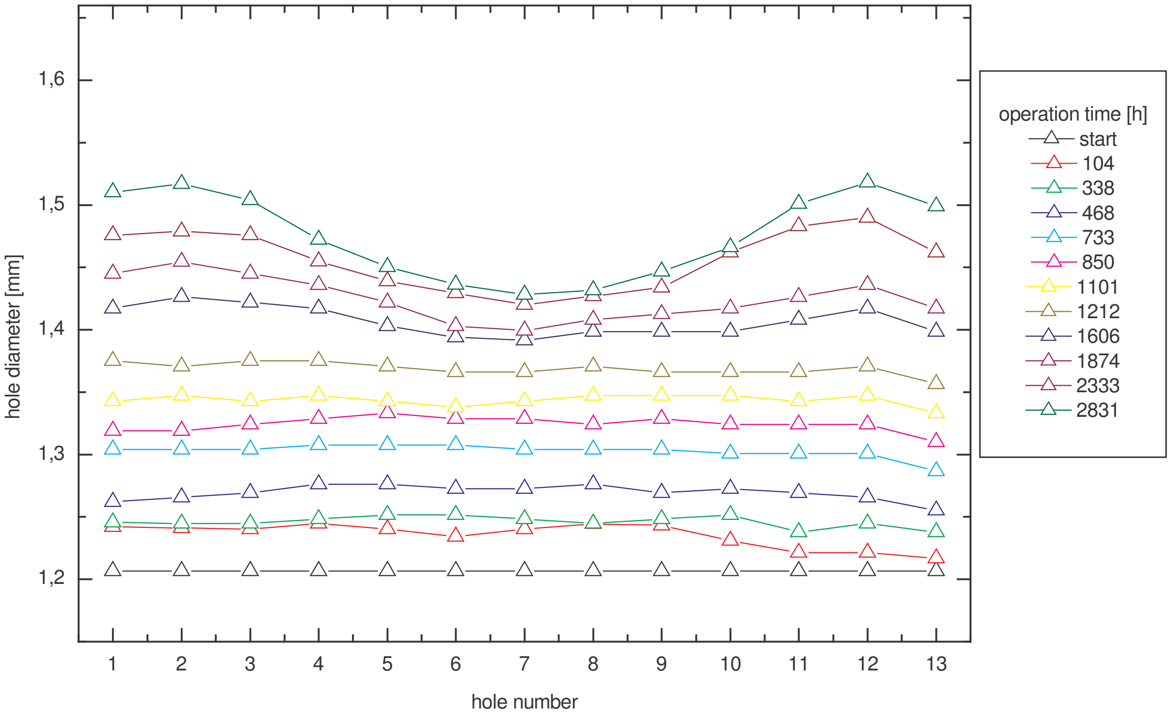

Figure 6: Hole diameter at accelerator grid, upstream side.

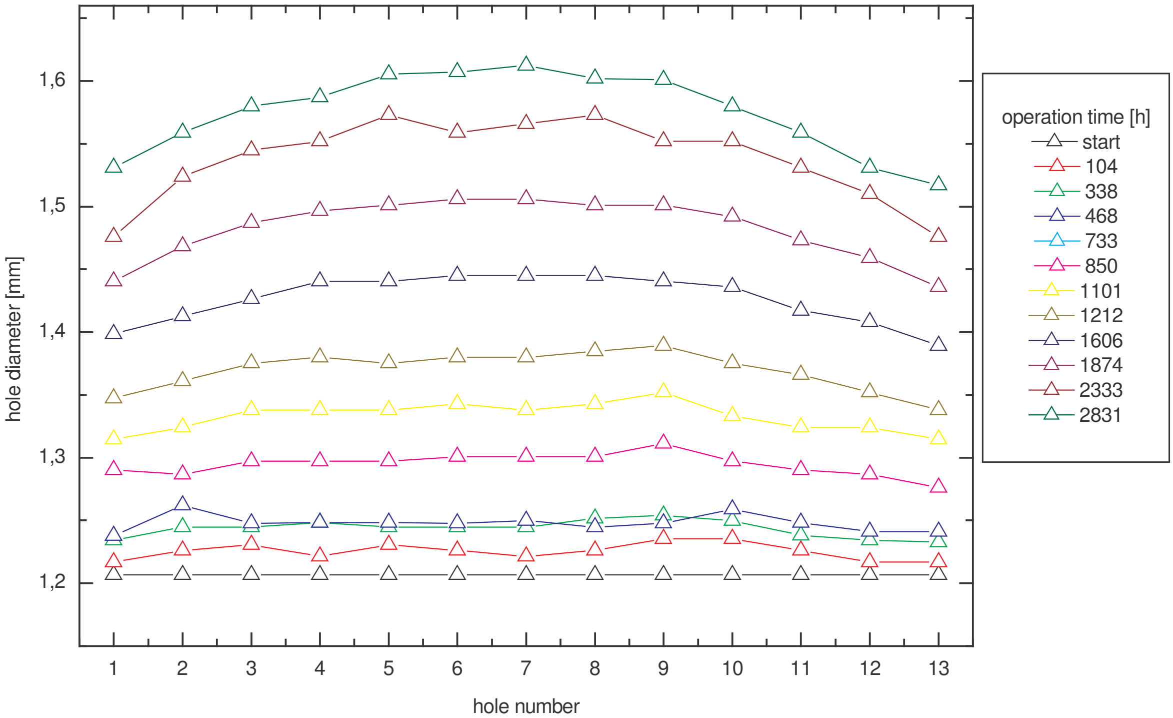

Figure 7: Hole diameter at accelerator grid, downstream side.

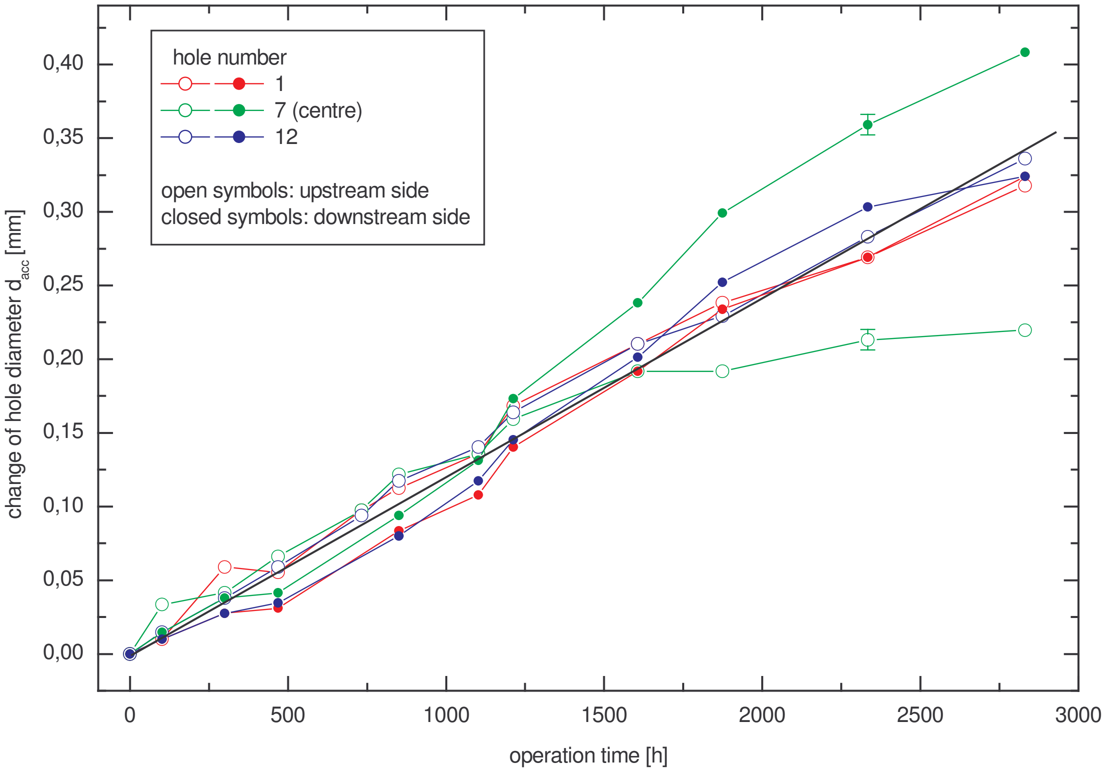

Figure 8: Evolution of the accelerator grid hole diameter. (the black line to guide the eye)

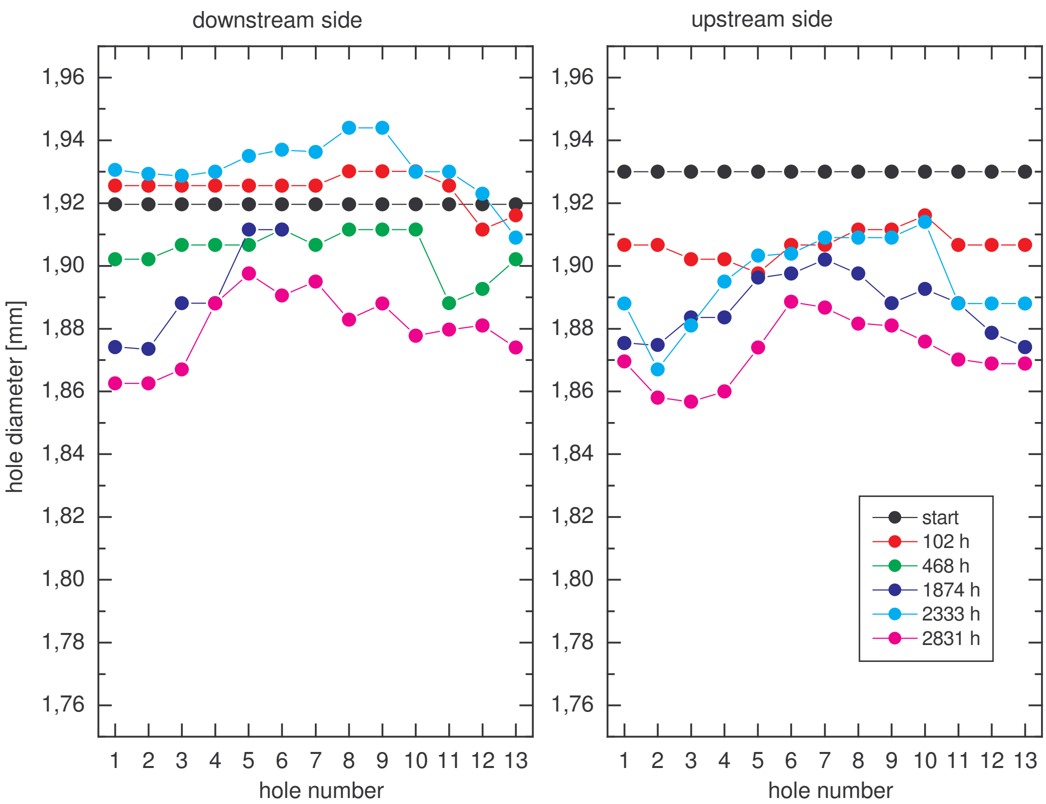

Figure 9: Evolution of the decelerator grid hole diameter.

Comparison with simulation

The initial erosion parameters were calculated using the grid erosion simulation code developed at IOM [4]. A rather good agreement with measured data was obtained (table 3). On the assumption of steady-ongoing erosion, the EOL state is reached after 8000 h. It should be noted, that under common thruster operation conditions (e.g. mass utilisation 80% instead of 55% here) the actual lifetime will be longer by a factor of about 2.5.
Currently, effort is invested into the simulation in order to establish a "real-life simulation". The experimental data should be used for a validation. Finally, it will support the investigation of the erosion profiles.

Table 3: Comparison between measured and simulated erosion parameter

	measured	simulated
I_{acc}	0.6 mA	0.78 mA
I_{decel}	0.05 mA	0.05 mA
mass loss accelerator grid	0.11 mg/h	0.09 mg/h (151 holes)
average erosion rate accelerator grid	61 nm/h	70 nm/h

Conclusions

A quasi-continuous long-time ion source operation was carried out to simulate the grid eroding processes occurring in an actual ion thruster The employed set-up was kept small, nevertheless allowing for an extrapolation to the actual thruster case. The respective erosion data from such an experiment may cover the range in between BOL and EOL states. These data prove relevant for following up the actual grid erosion by secondary processes and enable a validation of an erosion simulation methodology.
The experimental initial erosion parameters have been reproduced by the simulation in a rather good agreement. Currently, effort is invested towards this methodology to adapt it further to the erosion progression so that the time-dependent erosion process can be studied.

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