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Baseline investigation of grid erosion and internal material transport in ion optics using SEM–EDX and micro-CT diagnostics

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Abstract

The lifetime of gridded ion engines is primarily limited by erosion of the ion optics system. Despite extensive research, the availability of quantitative, spatially resolved erosion data under long-duration operation remains limited, particularly for internal erosion features such as aperture barrel erosion. This work presents a quantitative characterisation of erosion in a three-grid ion optics system using a combination of scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM–EDX) and micro-computed tomography (micro-CT). The micro-CT approach, previously explored in preparatory studies within the same programme frame, is here applied to enable non-destructive, volumetric assessment of eroded ion optics after long-duration operation. A dedicated experimental design incorporating three distinct aperture regions within a single ion optics system allows direct comparison of erosion behaviour under identical plasma and facility conditions during a 1000 h endurance test with xenon propellant. Erosion characterisation was performed at multiple time points (0, 100, 500, and 1000 h), combining surface and volumetric diagnostics to resolve both edge and barrel erosion processes. The results show consistent trends in erosion behaviour across different aperture regions, indicating a systematic dependence on local geometry. Quantitative analysis reveals distinct erosion modes, including significant barrel erosion and configuration-dependent edge evolution. SEM–EDX analysis confirms inter-grid material transfer, while no redeposition of facility materials was detected above the sensitivity limits of the method. The combined diagnostic approach is validated by the consistency between SEM and micro-CT observations, demonstrating its capability for non-destructive, quantitative assessment of ion-optics erosion. The presented results establish a high-fidelity baseline dataset and provide experimental insight into erosion mechanisms and material transport within the extraction region under realistic operating conditions.

Keywords Grid erosion, Lifetime test, Radiofrequency ion engine, Gridded ion engine

Introduction

Despite extensive research on ion-optics erosion [1–4], the availability of quantitative spatially resolved erosion data during long-duration operation remains limited. Most existing diagnostics rely either on surface inspection techniques, such as SEM, profilometry, laser triangulation, and telemicroscopy, for surface feature identification [5–8], Coordinate Measurements Machines with precise pins for surface and, in some cases, barrel erosion [6, 7, 9], or on indirect measurements, neither of which provides a complete three-dimensional description of erosion processes [10–12].

In particular, non-destructive volumetric diagnostics capable of resolving internal erosion features, such as barrel erosion within apertures, have seen limited application. Within the framework of the present research programme, micro-computed tomography (micro-CT) was previously investigated with a focus on reconstruction methodology and artefact mitigation [13]. However, reliable quantitative reconstruction of eroded grid geometries under realistic operating conditions remained unresolved.

The present work demonstrates, for the first time, that with appropriate selection of acquisition parameters and reconstruction strategy, micro-CT enables quantitative, non-destructive characterisation of ion-optics erosion, including internal barrel erosion, after long-duration operation and delivers insights into erosion and re-deposition progression throughout the endurance sequence.

In parallel, systematic experimental comparisons of different ion-optics geometries are often complicated by variations in plasma conditions, facility effects, and thruster-to-thruster differences [14]. As a result, isolating the influence of geometric parameters on erosion behaviour remains challenging.

To address these limitations, the present work employs a dedicated experimental approach in which multiple ion-optics configurations are integrated into a single thruster and operated under identical plasma and facility conditions during a long-duration endurance test. This enables a direct comparison of erosion behaviour across different aperture geometries without the confounding effects typically associated with separate experiments. The study combines scanning electron microscopy (SEM-EDX) with micro-computed tomography to provide both surface and volumetric characterisation of erosion. The micro-CT approach is further developed and validated against SEM measurements, enabling non-destructive, quantitative assessment of erosion and the evolution of internal geometry in the ion optics.

The present paper reports the first 1000 h of operation with xenon propellant, establishing a baseline dataset for erosion behaviour and demonstrating the capabilities of the combined diagnostic approach. The present work is not intended as a complete lifetime-qualification report or as a validation dataset for numerical erosion modelling. Instead, the study focuses on the experimental methodology, comparative erosion behaviour under identical operating conditions, and the application of complementary SEM-EDX and micro-CT diagnostics for non-destructive erosion assessment. This baseline forms the foundation for subsequent investigations, including studies on propellant modification strategies to reduce erosion.

Experimental setup

The experimental campaign was conducted in the R2D2 vacuum facility at Universität der Bundeswehr München (UniBwM) using a Mini Radiofrequency Ion Thruster (RIT3.5) equipped with a specially designed ion optics set. The facility provides high-vacuum conditions suitable for extended endurance testing, while the modified ion optics enable detailed studies of erosion processes under controlled plasma conditions. A combination of surface and volumetric diagnostics was employed, including scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDX), micro-computed tomography (micro-CT), quartz crystal microbalance (QCM) sensors, and residual gas analysis (RGA). The following subsections describe the facility, thruster configuration, and diagnostic methods in detail.

R2D2 vacuum facility

The R2D2 vacuum facility, located at the REL laboratory on the UniBwM campus in Munich, is shown in Fig. 1. The facility consists of a main chamber and a hatch, separated by a high-vacuum gate valve, with a total volume of about 4.5 m^3 . The main chamber is approximately 1.9 m in diameter and 4 m in length, while the hatch provides an additional cylindrical volume with a diameter of 0.75 m.

The pumping system combines turbomolecular and cryogenic stages, providing a total pumping speed of about 24,000 l/s and achieving base pressures as low as 1×10^{-8} mbar without propellant flow. Special care was taken to keep the partial pressure of nitrogen below 5×10^{-8} , which is reported to have a crucial influence on the extraction process [15]. During thruster operation with standard flow rates, chamber pressures of $1 - 5 \times 10^{-6}$ mbar were maintained, which are representative of typical ion thruster test conditions. The thruster under test was mounted in the hatch and operated downstream into the main chamber toward a carbon beam target located at the chamber end. The target surface was positioned at 45° relative to the thruster axis to reduce back-sputter towards the ion optics while maintaining realistic scattering conditions. Chamber



Fig. 1 R2D2 test facility

conditions were monitored with six vacuum gauges and a set of calibrated temperature sensors on the cryopanel and target. Further technical information on R2D2 can be found in the facility description provided by UniBwM [16].

μ RIT3.5 and experimental grid set

The thruster used in this campaign was the engineering model of the miniaturised radio-frequency ion thruster μ RIT3.5 (EM), originally developed and qualified by TransMIT GmbH to TRL 5 within the frame of ESA project 4000104822/11/NL/CP “Miniaturised Gridded Ion Engine Breadboarding And Testing For Future Earth Observation Missions” [17–19] and is currently being industrialised and further qualified by MarsSpace Ltd [20–22]. The thruster employs an electrodeless inductive discharge for plasma generation, based on the standard configuration of an inductively coupled plasma source. A schematic of the thruster is shown in Fig. 2.

The μ RIT3.5 EM consists of four main sub-assemblies:

- *Ioniser*: ceramic discharge chamber with an RF coil for inductive plasma generation.
- *Gas inlet*: feedline with gas isolator to electrically decouple the floating discharge chamber from the spacecraft ground.
- *Grid system*: three-grid extraction optics.
- *Thruster housing and interface*: structural support and back plate with interfaces for RF, HV, and propellant connections.

A photograph of the μ RIT3.5 EM is shown in Fig. 3.

For the erosion campaign, a dedicated grid set was manufactured. The geometry of the extraction apertures followed the initially qualified μ RIT3.5 design dimensions (diameter, thickness, spacing), without modification. A three-grid system was selected to ensure suitable potential distribution. The experimental grid set was fabricated from materials not otherwise present inside the facility to allow clear discrimination of sputtering sources. The screen grid was made of molybdenum, the acceleration grid of titanium, and the deceleration grid of copper.

The selected material combination (Mo–Ti–Cu) differs from typical flight ion optics, which are often based on molybdenum, titanium, or carbon-based materials. However, both molybdenum [1] and titanium [23] are widely used and well-characterised in ion thruster applications, whereas copper has been extensively studied in early ion-optics development, and its sputtering behaviour is well documented [24].

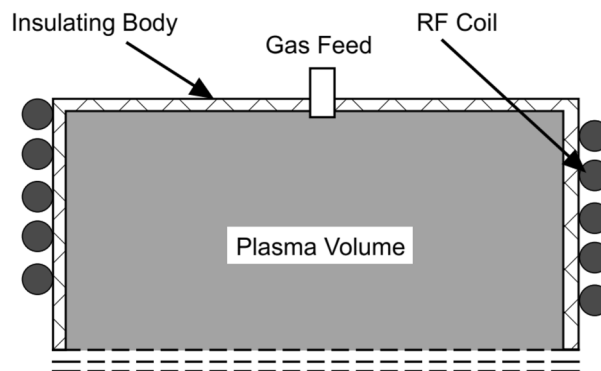


Fig. 2 Schematic of an RF ion thruster showing induction coil, insulating body, gas feed and three-grid accelerator structure [1]

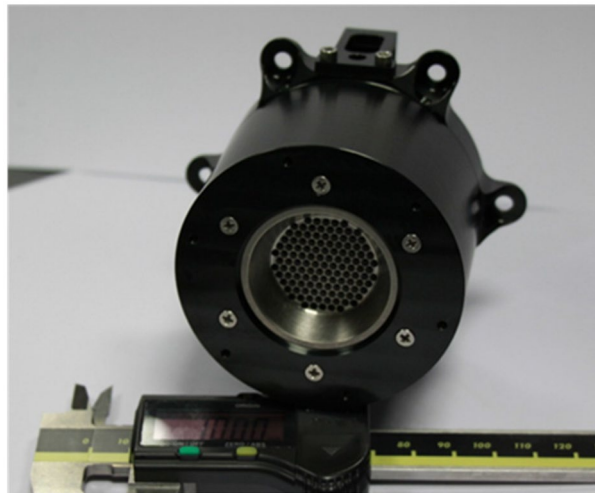


Fig. 3 Engineering model of the μ RIT3.5 thruster

Although these materials exhibit different sputter yields and secondary electron emission properties under xenon-ion bombardment, the underlying erosion and material-transport mechanisms are well understood. This enables interpretation of the observed erosion behaviour in a broader physical context.

The use of dissimilar materials was intentionally chosen to enable unambiguous identification of sputtering sources via SEM–EDX analysis, which would not be possible in a single-material grid system.

While the normalised aperture evolution reported in this study is therefore not directly transferable to a specific flight configuration, the observed trends in erosion behaviour, including the influence of aperture spacing, the distinction between edge and barrel erosion, and the dominance of internal material transport mechanisms, are expected to remain qualitatively representative for conventional ion optics systems.

Six extraction areas were distributed at equal radii from the thruster axis:

- Three single apertures, to provide statistics on isolated erosion profiles.
- Three multiple-aperture arrays of seven holes each, with centre-to-centre spacing of $1.15 \times d_s$, $1.3 \times d_s$ and $1.45 \times d_s$ (d_s stands for diameter of screen grid aperture per design) corresponding to effective screen-grid transparencies of approximately 68.6%, 53.7%, and 43.1%, respectively. These configurations were selected to assess differences between pit-and-groove erosion behaviour and barrel erosion under varying local extraction-area transparency conditions.

In total, 24 apertures were prepared for extraction. These regions were operated simultaneously under identical plasma and facility conditions, enabling direct comparison of erosion behaviour without the variability associated with separate thruster or experiment configurations. This approach ensures that observed differences in erosion behaviour arise from local geometric variations rather than differences in operating conditions or facility effects. The acceleration and deceleration grids included four additional alignment apertures. These features, together with fiducial marks on the screen grid, allowed verification of ion optics coaxiality using a telecentric imaging system after each disassembly and reassembly. Figure 4 illustrates the baseline design of the experimental grid

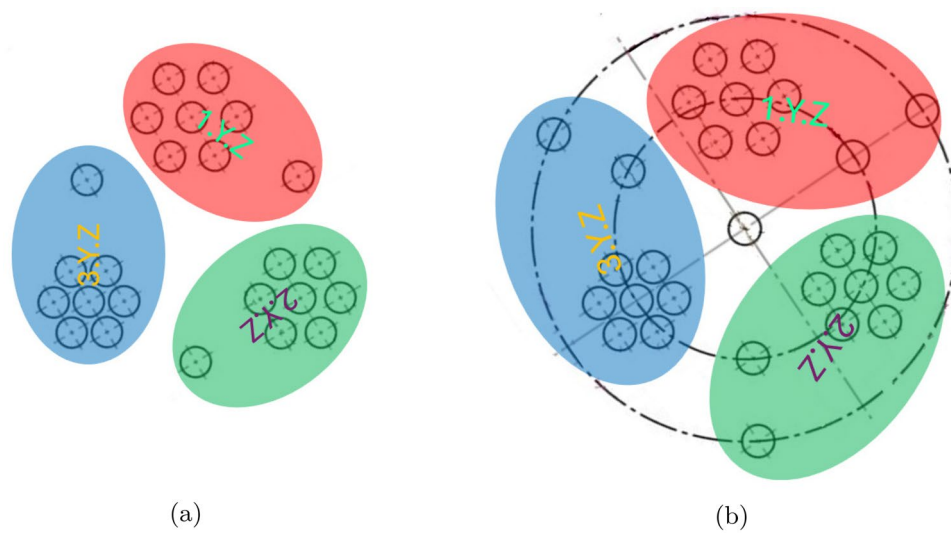


Fig. 4 The scheme of extraction and alignment apertures on the screen grid **(a)** and on the acceleration and deceleration grids **(b)**

set, showing the distribution of apertures on the first grid (Fig. 4a) and on the second and third grids (Fig. 4b).

The ion optics employed a reduced-transparency configuration with an overall transparency of approximately 20%, significantly lower than that of standard RIT3.5 configurations. Absolute geometric parameters (e.g. aperture diameter and grid spacing) are not disclosed due to the commercial nature of the system.

To facilitate analysis, a dedicated hole-numbering scheme was introduced. Each grid was observed from the plasma-facing side. The central aperture was defined as position 0.0.0. Around this, three extraction segments were distinguished:

- (1) **Segment 1 (red)**: A 7-hole group with $1.45 \times d_s$ spacing, plus two adjacent single apertures in the clockwise direction.
- (2) **Segment 2 (green)**: A 7-hole group with $1.3 \times d_s$ spacing, plus two adjacent single apertures in the clockwise direction.
- (3) **Segment 3 (blue)**: A 7-hole group with $1.15 \times d_s$ spacing, plus two adjacent single apertures in the clockwise direction.

Within each 7-hole group, the central aperture is indexed as $Y=0, Z=0$, with surrounding apertures numbered $Z=1-6$ in clockwise order. Single apertures are indexed with $Y=1$, with $Z=0$ for apertures on the smaller extraction diameter and $Z=1$ for apertures on the larger, alignment-monitoring diameter.

This systematic scheme allowed consistent comparison of the diameter changes between the different aperture types and locations.

Test arrangement

The μ RIT3.5 thruster with its experimental grid set was installed in the hatch of the R2D2 facility and operated downstream into the main chamber. The thruster was aligned toward a carbon beam target located at the opposite end of the chamber. During the endurance test, erosion monitoring and facility diagnostics were arranged as follows (see Fig. 5 for a schematic view):

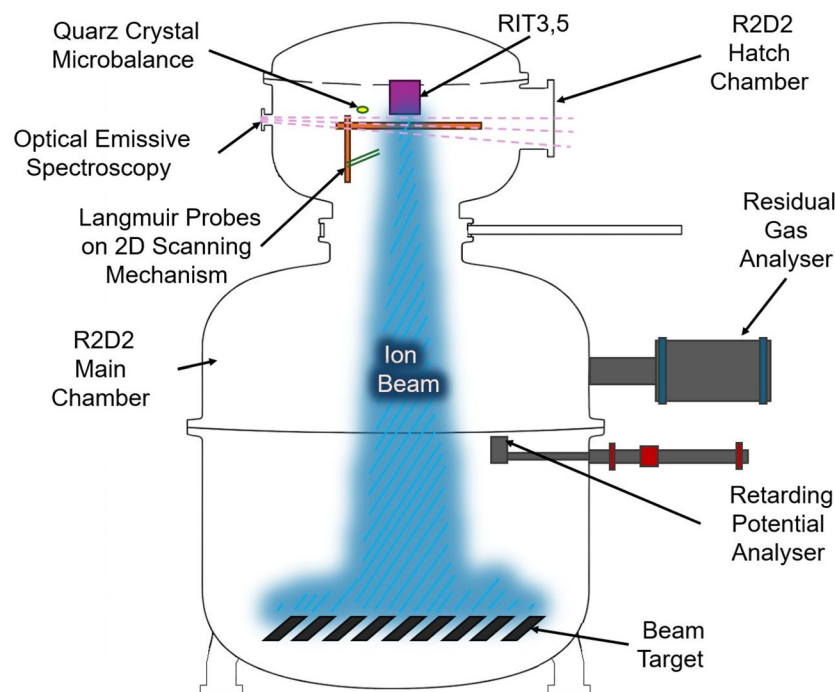


Fig. 5 Schematic view of the test arrangement

- Quartz Crystal Microbalance (QCM): positioned next to the thruster, in the direction of the beam, at a distance sufficient to ensure proper operation while still monitoring deposition from sputtered material. Additional probes were placed near the bottom of the chamber to assess redeposition in other locations.
- Residual Gas Analyser (RGA): connected to the main chamber to monitor gas composition and detect any contamination during long-duration operation.
- Optical access: allowed for optical emission spectroscopy (OES), which, together with probe diagnostics, was used to confirm nominal thruster operation after each reassembly and to monitor changes in the thruster characteristics over time.
- Langmuir Probes: An array of Langmuir probes was installed in the hatch on a two-dimensional moving arm, allowing scans across the thruster diameter and at different downstream distances. The Langmuir probe array was performing scans only in between endurance sequences and was removed from the beam during long-duration tests.
- Retarding Potential Analyser (RPA): mounted on a moving arm in the main chamber compartment, enabling measurements of the ion energy distribution function (IEDF). At full extension, the RPA could be positioned in the beam centre, while during endurance operation, it was retracted to avoid influencing sputtering.
- Thermal monitoring: PT100 sensors recorded cryopanel and target temperatures, with data collected via a Keithley DAQ system.

The RF generator used to ignite and sustain the discharge was an APCON RFG-40 EM, a unit designed for RIT operation, mounted on a water-cooled plate inside the vacuum chamber next to the thruster. The high-voltage power supplies and mass flow boards were installed externally, adjacent to the hatch. Plasma diagnostics (Langmuir probes,

retarding potential analyser, and optical emission spectroscopy) were applied intermittently between endurance sequences to verify stable and repeatable thruster operation and to confirm that plasma conditions evolved consistently with changes in operating parameters. These measurements were used for operational validation and are not reported here, as they are not central to the scope of the present erosion study.

Thruster operating parameters (mass flow rates, voltages, currents, RF power and frequency) as well as facility conditions (vacuum pressure, cryopanel and target temperatures, and laboratory environment parameters) were continuously monitored and recorded throughout the campaign to ensure stable and controlled test characteristics.

Erosion assessment diagnostic

Grid erosion was characterised with a combination of scanning electron microscopy (SEM) and micro-computed tomography (micro-CT). No cleaning or surface treatment was performed between endurance sequences to preserve the as-operated surface condition of the grids.

A tabletop SEM (Hitachi TM 3030 Plus) was used for surface inspection of the ion optics. By scanning the sample with a focused electron beam and detecting secondary and backscattered electrons, the instrument provides high-resolution images with a large depth of field, enabling detailed analysis of pit-and-groove erosion patterns. Energy-dispersive X-ray spectroscopy (EDX) integrated into the SEM allowed elemental composition analysis, which was applied to verify the presence or absence of redeposited species on the ion optics.

For volumetric and non-destructive assessment, a Bruker SkyScan 1173 micro-CT scanner was employed. The scanner uses an X-ray source and flat-panel detector to reconstruct three-dimensional datasets of the ion optics, with a detail detectability of about $4\text{--}5\mu\text{m}$. This technique enabled a complete inspection of the grid system without disassembly, reducing the risk of information losses (e.g. deposited or loose materials known to be located within grid gaps) or misalignment during reassembly and providing quantitative erosion data for the entire grid set. CT reconstructions were further processed using the manufacturer's software suite and compared against reference CAD models to extract erosion depths and profiles. Building on previous exploratory investigations of micro-computed tomography for ion-optics inspection, the present work demonstrates that, with appropriate acquisition parameters and reconstruction strategy, micro-CT enables quantitative, non-destructive characterisation of erosion in multi-aperture ion thruster grids, including internal features such as barrel erosion under long-duration operating conditions.

Together, SEM/EDX and micro-CT provide complementary diagnostics: SEM yields detailed local surface morphology and chemical analysis, while CT offers global three-dimensional erosion mapping. This combination enabled both qualitative and quantitative evaluation of the ion optics during the endurance test campaign.

Results

Thruster operating parameters

The thruster has been operated for up to 1000h on xenon propellant with inspections at 0h, 100h, 500h, and 1000h. Parameters such as discharge power, grid currents, and propellant flows were continuously monitored. The results are presented normalised to

the initial values at the beginning of the test (Fig. 6). The selection of particular operating conditions corresponds to a high-thrust regime of a miniaturised RF ion thruster, with beam currents and voltages within the range commonly reported for systems of similar class.

Due to the commercial nature of the thruster system (RIT3.5, MarsSpace Ltd.), detailed design parameters cannot be fully disclosed. However, representative operating conditions are provided to enable interpretation of the results. The thruster was operated at a nominal operating point corresponding to ≈ 2 mN thrust. The total input power was in the range of ≈ 35 – 50 W, with a screen grid voltage of 1500 V. The propellant mass flow rate was in the range of 0.1–0.2 sccm, scaled to account for the reduced grid transparency of the experimental optics. The beam current was maintained at a constant level of ≈ 7 mA throughout the endurance test [21].

During the endurance campaign, the operating point was actively controlled to maintain constant beam current and grid voltages, thereby preserving a representative high-thrust operating regime. This was achieved through coordinated adjustment of the RF power and propellant mass flow as erosion progressed.

From 0 to approximately 500 h, both the RF power and the propellant mass flow were gradually increased (Fig. 6). The increase in aperture diameter due to erosion leads to higher neutral losses from the discharge chamber; therefore, additional propellant flow was required to maintain the discharge conditions. The RF power was increased simultaneously to sustain ionisation efficiency while limiting the magnitude of mass-flow adjustments.

Beyond approximately 500 h, a deviation from this trend was observed. During this phase, RF power was progressively reduced while propellant mass flow was increased more strongly. This change in control strategy was associated with operational constraints of the RF generator and a temporary variation in acceleration grid current behaviour. As a result, the second half of the endurance test is characterised by increased neutral density in the discharge and extraction regions compared to the initial phase.

These operational adjustments reflect the need to maintain stable beam extraction under evolving ion-optics conditions and should be considered when interpreting long-duration erosion trends. However, all aperture configurations were operated simultaneously under identical and continuously varying conditions, ensuring that the observed differences in erosion behaviour between configurations remain physically meaningful.

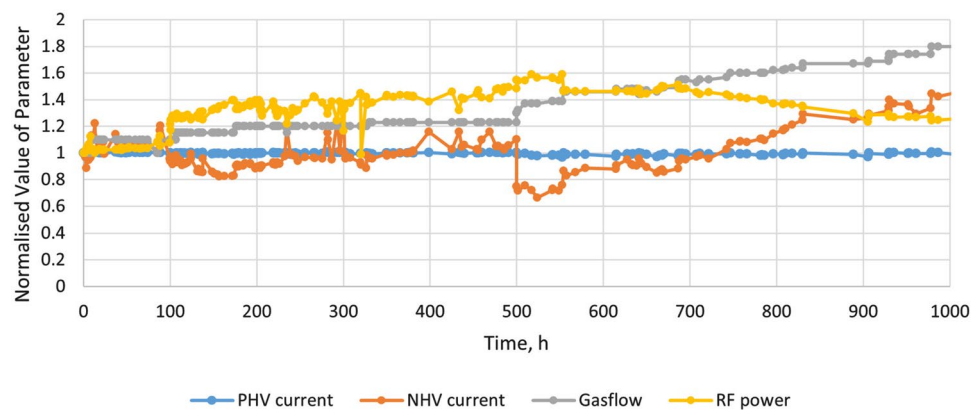


Fig. 6 Normalised thruster operating parameters vs. time, 0–1000 h

SEM observations

SEM imaging was used to monitor the evolution of the aperture edge diameters during the endurance test. The diameter of each aperture was estimated by approximation of two orthogonal measurements to reduce directional bias. While no measurable pit-and-groove erosion was observed up to 1000h, measurable changes in aperture diameters were recorded. These changes are presented in normalised form relative to the initial diameters (Figs. 7, 8, 9).

To provide a quantitative reference, characteristic erosion rates were estimated from the measured evolution of the diameter over time. For the screen grid, erosion rates ranged from approximately $-0.1\%/1000\text{h}$ to $+2.1\%/1000\text{h}$ depending on the configuration and time interval, with evidence of partial redeposition in some cases. The accel grid exhibited substantially larger relative aperture growth, ranging from approximately 7.6 to $12.0\%/1000\text{h}$.

Absolute erosion-rate values are intentionally not reported at this stage of the campaign. During the initial operational phase of gridded ion thrusters, erosion behaviour is typically characterised by transient beginning-of-life effects, including aperture-edge

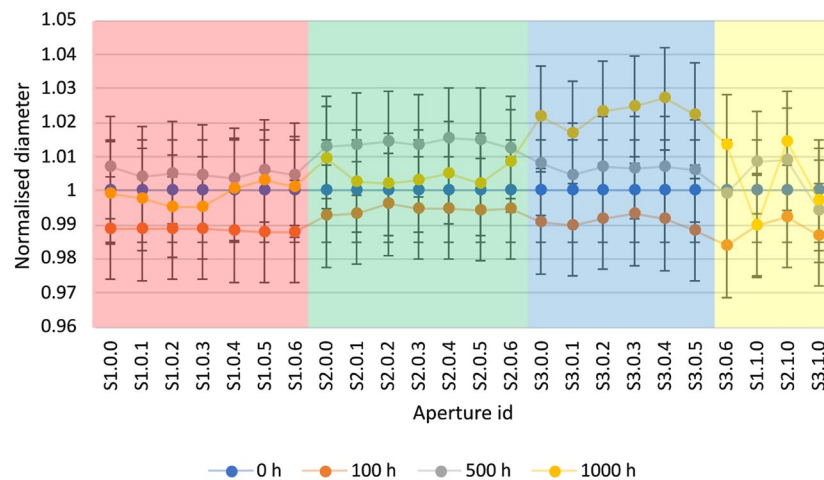


Fig. 7 Normalised aperture diameter evolution for screen grid at 0–1000 h

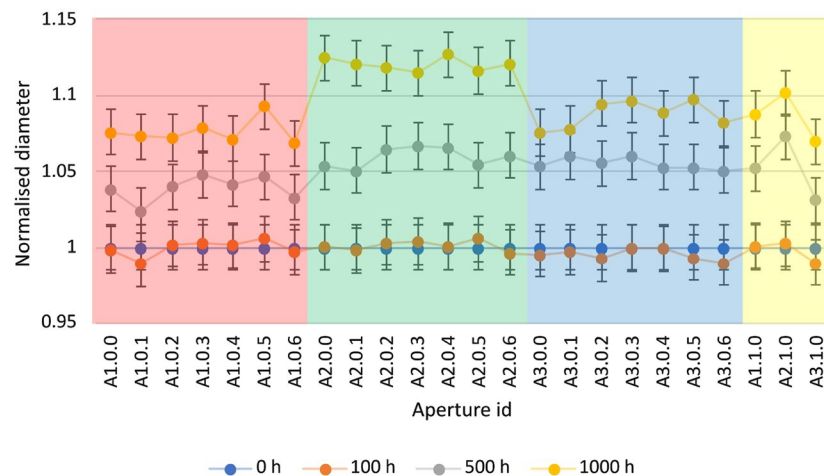


Fig. 8 Normalised aperture diameter evolution for the accel grid at 0–1000 h

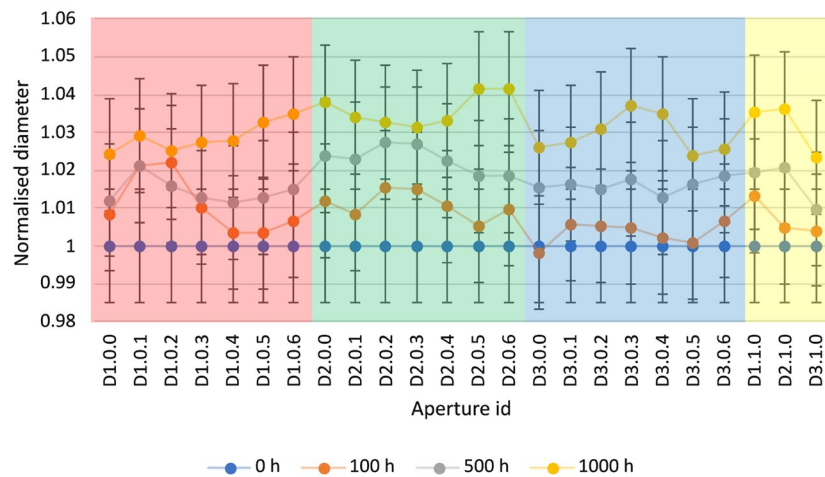


Fig. 9 Normalised aperture diameter evolution for the decel grid at 0–1000 h

conditioning, local redeposition, and geometry adaptation processes, resulting in a non-linear temporal evolution of the aperture geometry. Under such conditions, a single steady-state erosion-rate value would not be representative of the observed physical processes. The present study, therefore, focuses on comparative normalised aperture evolution between different ion-optics configurations operated under identical conditions, rather than on deriving long-term absolute wear-rate metrics.

While these values allow comparison of characteristic erosion magnitudes, the relative ranking of configurations is not unambiguous, as different erosion modes (edge vs barrel, screen vs accelerator grid) exhibit different trends. The results, therefore, indicate a trade-off between erosion mechanisms rather than a single optimal configuration.

During preparation of the extended journal manuscript, the aperture metrology procedure was further refined to improve consistency between inspection datasets and reduce sensitivity to local image-scaling variations. In the preliminary conference contribution, the pixel-to-micrometre conversion factor was derived from a limited set of secondary geometrical references. In the present work, the calibration was expanded using multiple centre-to-centre distances between apertures within each segment. Since erosion modifies the aperture rims but does not shift the aperture centres, these distances provide a geometrically invariant reference for scaling. The measured inter-aperture distances were compared with the nominal CAD geometry, and the resulting averaged correction coefficient was applied consistently across all datasets.

The uncertainty associated with SEM-based aperture-diameter measurements was estimated primarily from image discretisation and the repeatability of manual edge identification. Since aperture-edge determination was performed manually on SEM images with partially rounded and redeposition-affected boundaries, a conservative edge-localisation uncertainty of approximately ± 4 pixels per edge was assumed. Relative image resolution averaged to approximately 0.117% of the aperture diameter per pixel across the investigated datasets.

Based on these assumptions, the uncertainty of the individual aperture-diameter measurements was conservatively estimated to remain within approximately $\pm 1.05\%$ for all investigated aperture groups. Since the reported quantities correspond to normalised diameter ratios between different inspection intervals, uncertainty propagation increases

the uncertainty of the normalised values to approximately $\pm 1.5\%$. The reported uncertainty should therefore be interpreted as a conservative practical measurement uncertainty for comparative aperture-evolution analysis rather than as a formal metrological certification in accordance with the ISO GUM methodology.

The dominant uncertainty contribution originates from manual edge identification rather than from SEM magnification stability or geometrical scaling calibration. Since the present work focuses on comparative normalised aperture evolution across different aperture configurations operated under identical conditions, the obtained uncertainty level was considered sufficient to resolve the observed comparative erosion trends. Furthermore, consistent trends are observed across different apertures and grid segments, indicating a systematic evolution of the aperture geometry. These trends are further supported by independent micro-computed tomography measurements, when applicable, which show qualitatively consistent geometric changes.

SEM-EDX analysis of the grid surfaces in the apertures proximity (see typical area of interest, as discussed in section "Discussion" 4, Fig. 13) confirmed the presence of sputtered grid material but showed no measurable redeposition from the target and chamber wall materials within the sensitivity limits of the method (Fig. 10). It should be noted that very thin redeposited layers below the detection threshold of SEM-EDX cannot be excluded. This indicates that the observed surface composition is primarily determined by internal thruster processes and material transfer within the extraction region and the near-field ion beam, rather than contamination from the facility, including target back-sputtering.

In addition to grid surface analysis, SEM-EDX was performed on the quartz crystal microbalance (QCM) probe located adjacent to the thruster in the near-field region. The analysed surface composition consisted primarily of Au (57.3 wt%), Oxygen (21.4 wt%) and Si (10.9 wt%), corresponding to the QCM crystal and electrode materials, with minor contributions of Fe (7.7 wt%) and Cr (2.8 wt%) attributable to stainless steel from the vacuum chamber. No measurable traces of molybdenum, titanium, or copper were detected on the QCM surface within the detection limits of EDX.

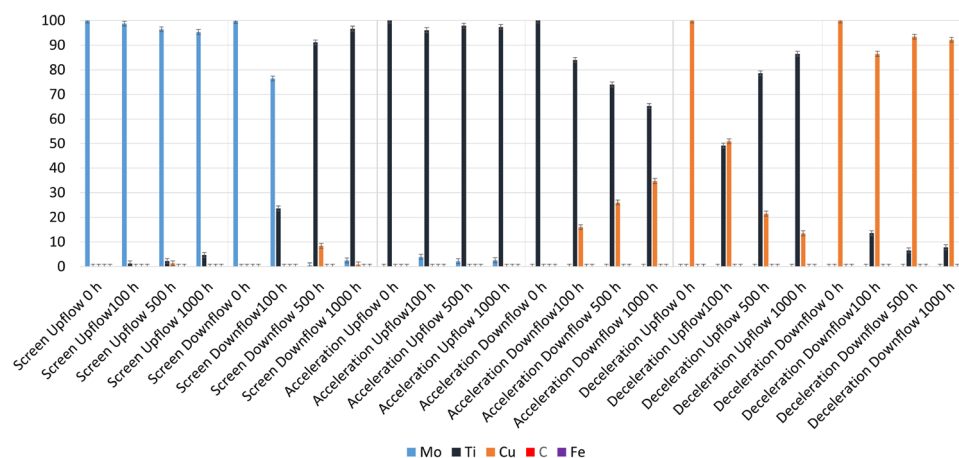


Fig. 10 Grid surface material composition from SEM-EDX analysis

The absence of detectable grid material signatures on the QCM indicates that sputtered grid material is largely confined to the extraction region and does not significantly redeposit at the QCM location under the present conditions. While carbon redeposition from the graphite target cannot be conclusively assessed due to spectral overlap between the carbon line and the first gold peak, no distinct evidence of substantial carbon accumulation was observed.

CT reconstructions

Micro-CT scanning was used to obtain three-dimensional reconstructions of the ion optics. The results confirmed the aperture diameter changes measured by SEM and additionally showed barrel erosion along the aperture walls. This effect is most relevant for the accel grid, where ion–surface collisions gradually increase the internal diameter. Although scans were performed for all the grids, for clarity, only the accel grid data are presented here, due to its most pronounced barrel erosion. The values are normalised to the initial geometry and shown as maximum internal diameter for the 7-hole array segments at 0 h and 1000 h (Fig. 11). The CT results support the SEM findings and add information that cannot be obtained by surface inspection. Because the test campaign is ongoing and data processing is time-intensive, only the 0 h and 1000 h results are included at this stage.

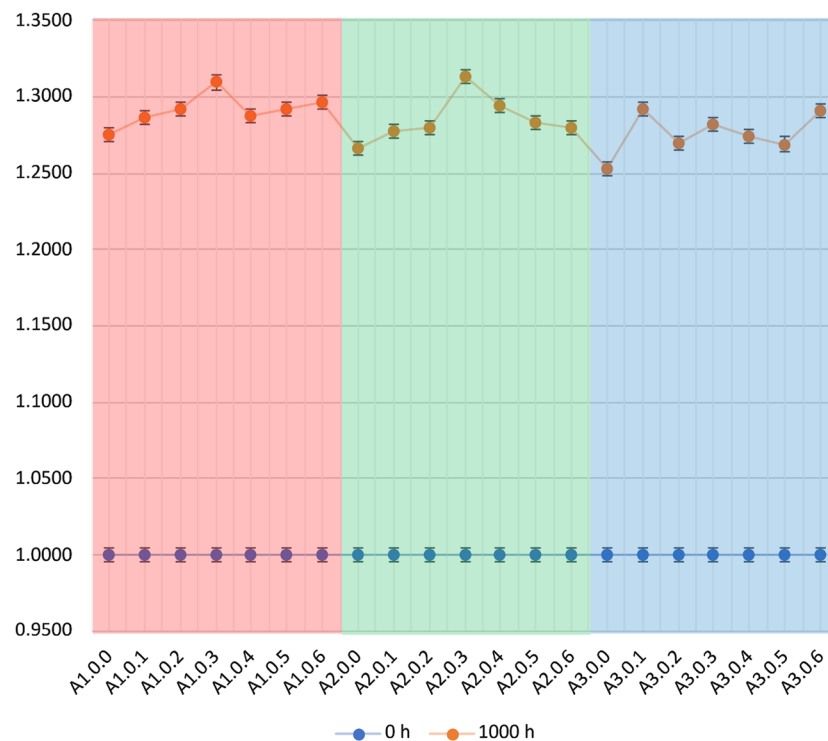


Fig. 11 Normalised barrel erosion of accel grid apertures from CT reconstructions at 0 h and 1000 h

Discussion

The endurance test was conducted at constant thrust and beam voltage conditions, requiring progressive adjustments of the RF power and propellant mass flow. During the first 500 h, thrust stability was maintained mainly by increasing RF power, with small adjustments of mass flow. After 500 h, the RF generator reached its maximum output, and further adjustments relied on higher propellant flow, introducing a systematic change in the neutral density and charge-exchange currents. The magnitude of this propellant flow increase corresponds well with the quadratic aperture diameter change measured by SEM and CT, confirming that erosion of the grid apertures directly affects changes in the thruster performance.

Refined aperture metrology revealed a small ($\leq 1\%$) reduction of the screen grid aperture edge diameter during the first 100 h of operation across multiple segments. Although subtle, this trend is systematic and persists after calibration refinement, although its magnitude is comparable to the conservative measurement uncertainty. Such non-monotonic early-time behaviour suggests the presence of a transient conditioning regime preceding steady-state erosion. Several mechanisms may contribute to this effect. SEM-EDX analysis demonstrated material transfer between grids, in particular, titanium originating from the accel grid, which was deposited on the downstream surfaces of the molybdenum screen grid. Early-stage sputtering of the accel grid may therefore lead to partial redeposition at the screen aperture rims, effectively reducing the measured edge diameter. An additional contribution may arise from thermo-mechanical relaxation of residual manufacturing stresses during initial thermal cycling. Since both mechanisms would be most pronounced during the first operational period, the disappearance of the shrinkage trend after 100 h is consistent with the transition to a quasi-steady erosion regime.

Beyond the initial 100 h transient, the accel and decel grids exhibit monotonic aperture widening, with the accel grid showing the strongest growth due to progressive barrel erosion confirmed by CT reconstructions. This behaviour is consistent with sustained ion-surface interaction driven primarily by charge-exchange ions. In contrast, the screen grid does not follow a purely monotonic trend. After partial recovery from the initial shrinkage at 500 h, segments 1 and 2 exhibit a slight reduction in edge diameter between 500 h and 1000 h, whereas segment 3 shows continued widening, reaching 1.022 times its initial value. The magnitude of these variations remains within approximately 1–2% of the initial diameter but is systematic across repeated measurements.

This non-uniform evolution suggests that the screen grid is subject to competing processes: direct sputter erosion and redeposition of material originating from the accel grid. SEM-EDX analysis confirmed titanium transfer from the accel grid to the screen grid surfaces, supporting the presence of internal material transport within the extraction region. The balance between sputter erosion and redeposition appears to depend on aperture spacing, which modifies local ion current density and angular distribution within the extraction region. The densest array ($1.15 \times d_s$, segment 3) shows the strongest net widening, which may indicate enhanced local ion flux and reduced relative impact of redeposition. In contrast, the more widely spaced configurations exhibit

smaller net growth and slight late-time narrowing, consistent with a stronger relative contribution of material deposition.

An additional factor influencing the non-monotonic evolution of the screen grid may be the change in operating regime after 500 h. During the first half of the endurance test, mass flow was approximately constant while RF power was progressively increased to compensate for changing grid transmittance and maintain constant beam current. After 500 h, the RF power was reduced and the mass flow increased in order to maintain the same extracted current. This operational shift likely altered the neutral-to-ion ratio within the discharge and extraction region. An increase in neutral density enhances charge-exchange ion formation and modifies gas-phase scattering of sputtered species. Consequently, the balance between direct sputter erosion and redeposition at aperture rims may shift. The late-time narrowing observed in the more widely spaced screen grid arrays may therefore reflect an increased relative contribution of redeposition under higher neutral density conditions, whereas the densest configuration remains dominated by direct ion-driven erosion. Due to the small magnitude of these effects and the coexistence of multiple mechanisms, quantitative separation of sputter erosion and redeposition contributions is not possible within the present dataset. Representative SEM images of apertures from all three grids are shown in Fig. 12. Localised irregular features visible

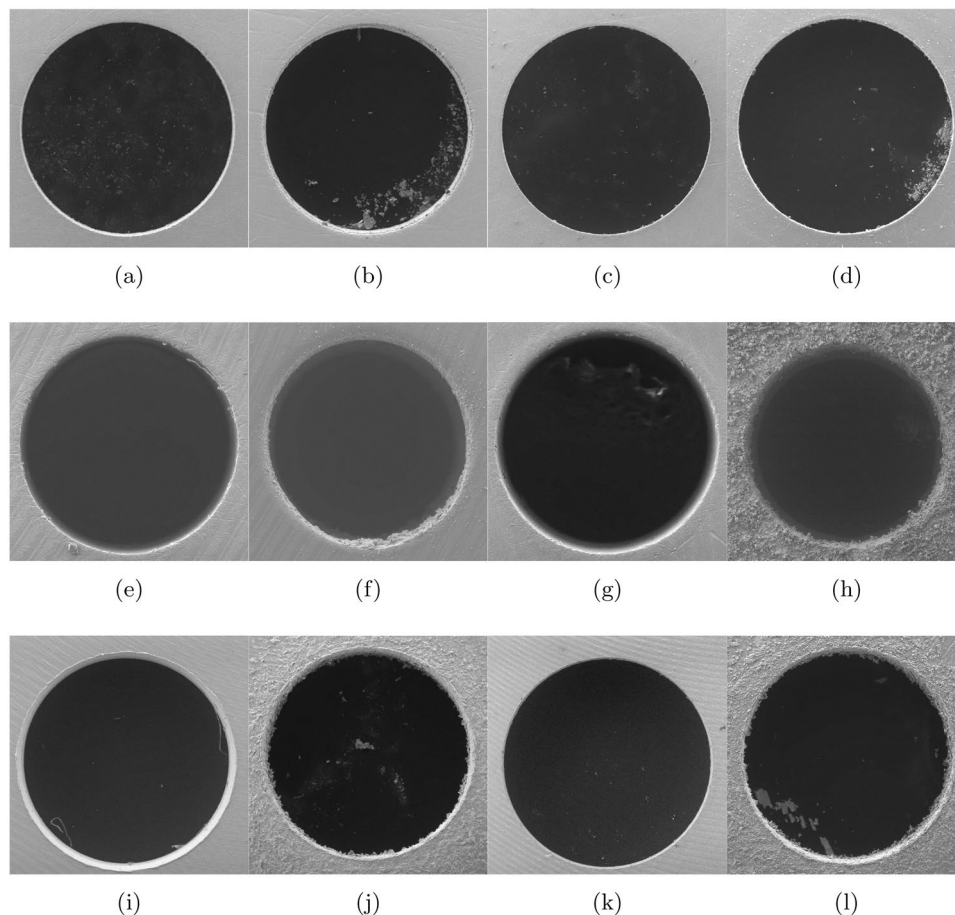


Fig. 12 SEM images comparing grid apertures before (0h) and after 1000 h of operation. Rows display the screen grid (a–d), accel grid (e–h), and decel grid (i–l). The first two columns show upstream (plasma-facing) surfaces, while the last two show downstream (beam-facing) surfaces. Within each pair, the pre-test image is on the left and the 1000h image is on the right

within several apertures in Fig. 12 are attributed to weakly adhered redeposited material and/or surface fragments remaining after disassembly and handling during intermediate inspections. The grids were intentionally not cleaned between inspection stages in order to preserve the surface condition and avoid altering the ongoing erosion and redeposition processes. While all handling procedures were performed with care, partial detachment of loosely adhered deposits during manipulation cannot be fully excluded. SEM images are provided to qualitatively illustrate surface morphology, redeposition structures, and aperture-edge evolution. Absolute dimensional scaling is intentionally omitted due to confidentiality restrictions associated with proprietary ion-optics geometry.

SEM-EDX analysis of grid surfaces confirmed inter-grid material transfer, while analysis of the QCM probe positioned adjacent to the thruster detected no measurable accumulation of molybdenum, titanium, or copper above the EDX detection threshold. The QCM surface composition was dominated by intrinsic sensor materials (Au, Si, O) with minor Fe and Cr contributions attributed to stainless steel background (Figs. 10, 13). These observations suggest that, under the present experimental conditions, material transport within the ion optics system and near-field plume dominate the detectable surface composition, while contributions from vacuum chamber materials remain below the detection threshold of the employed diagnostics. Although sub-threshold deposition cannot be excluded, the results indicate that such contributions are not dominant compared to material transport originating from the ion optics. This finding challenges the common assumption that vacuum chamber materials inevitably dominate surface contamination during long-duration ground testing.

CT reconstructions confirmed SEM-based edge diameter measurements and uniquely enabled quantification of barrel erosion without destructive sectioning. For the accel grid, the CT data showed that within each 7-hole group, the central aperture (X.0.0) consistently eroded least, while peripheral apertures exhibited stronger barrel widening (Figs. 11, 14. The reconstruction is presented for qualitative visualisation of internal erosion morphology; quantitative analysis is derived from the processed geometric data rather than from the visual representation itself.). Interestingly, the $1.45 \times d_s$ array, which showed the slowest surface erosion in SEM, exhibited the highest barrel erosion, while the $1.3 \times d_s$ and $1.15 \times d_s$ arrays showed comparable results.

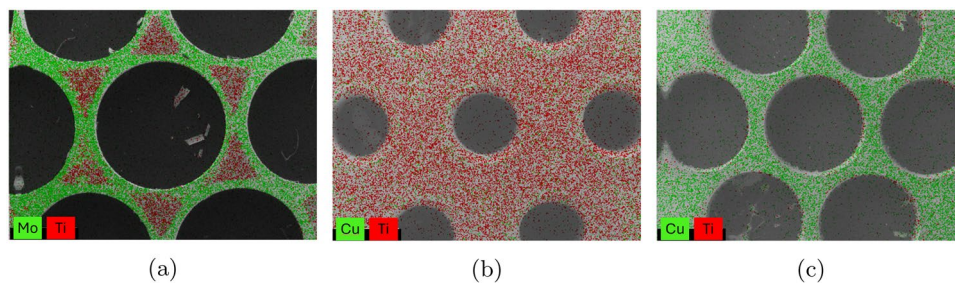


Fig. 13 Examples of obtained with SEM-EDX elemental composition of downflow surfaces: screen grid, 100 h (a); accel grid 500 h (b); decel grid 500 h (c)

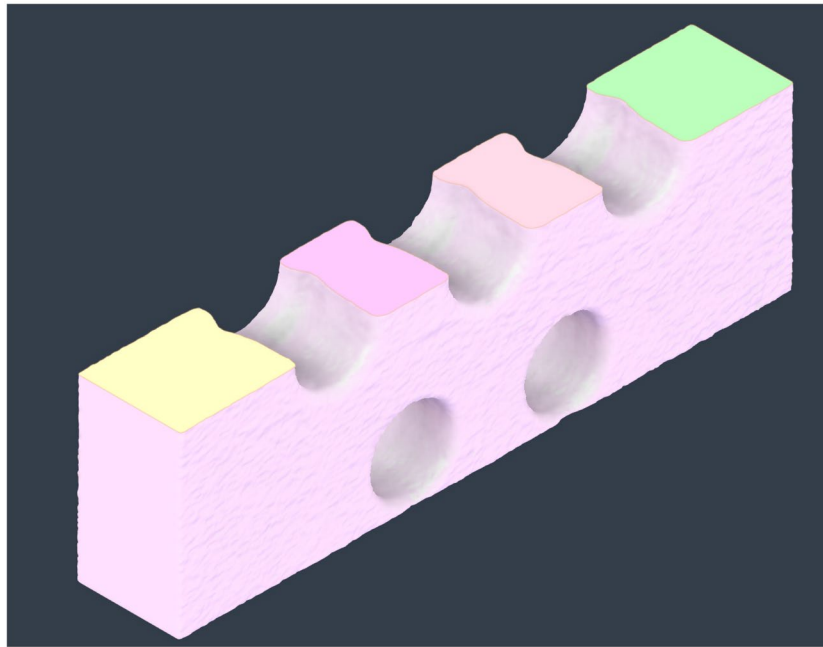


Fig. 14 Example of CT reconstruction of accel grid apertures showing barrel erosion profiles at 1000h, viewed from the downstream (ion beam-facing) side. Colours correspond to surfaces generated during sectioning of the reconstructed mesh and do not represent material composition or quantitative values. They are used solely to enhance the visual distinction of internal geometry

Conclusions

The present study investigated the evolution of ion-optics aperture geometry during long-duration operation, with a particular focus on the influence of aperture spacing on erosion behaviour. A dedicated experimental approach was employed in which a single ion optics system incorporated multiple aperture configurations, enabling direct comparison under identical plasma and facility conditions. The combination of SEM–EDX and micro-computed tomography provided complementary surface and volumetric diagnostics for characterising erosion processes.

SEM measurements showed that aperture spacing affects the erosion rate, with distinct trends observed in single- and multi-aperture configurations. The screen grid erosion appears non-monotonic, consistent with transient redeposition effects during early operation, although the absolute changes are within the margin of SEM measurement uncertainty. In contrast, SEM measurements indicate progressive widening of the accel grid aperture edge, while Micro-CT reconstructions confirm substantial internal barrel erosion.

Complementary compositional analysis by SEM-EDX confirmed internal material transfer between the grids, while no measurable contribution from redeposited vacuum-chamber materials was detected within the method's sensitivity limits. Analysis of the QCM probe detected Fe and Cr, consistent with stainless steel originating from the vacuum chamber, while no measurable amounts of molybdenum, titanium, or copper were observed above the EDX detection threshold. Within these detection limits, the results indicate that the aperture erosion behaviour during the present endurance campaign is predominantly governed by internal thruster processes.

Volumetric analysis via micro-CT validated SEM-based aperture metrology and uniquely enabled non-destructive quantification of internal barrel erosion. The

combined diagnostic approach shows that aperture-edge evolution and internal-barrel widening are not necessarily proportional, suggesting distinct ion populations and trajectories contribute to material removal.

The present study reports the first 1000 h of xenon operation within an ongoing endurance campaign. An additional 1000 h of xenon operation, followed by testing with additive-enriched propellant, is planned as part of the ongoing experimental campaign to assess potential lifetime-extension strategies. The diagnostic methodology established here provides a robust framework for the quantitative evaluation of erosion processes in future test phases.

Abbreviations

μ RIT3.5	Miniaturised Radiofrequency Ion Thruster, 3.5 cm beam diameter (engineering model)
RIT	Radiofrequency Ion Thruster
IOS	Ion Optics System (grid assembly)
IEDF	Ion Energy Distribution Function
SEM	Scanning Electron Microscope
EDX	Energy-Dispersive X-ray Spectroscopy (X-ray mass spectrometry mode of SEM)
CT	Computed Tomography (X-ray-based non-destructive 3D imaging)
QCM	Quartz Crystal Microbalance
RPA	Retarding Potential Analyser
RFG	Radiofrequency Generator
NHV	Negative High Voltage
PHV	Positive High Voltage
TRL	Technology Readiness Level
UniBwM	Universität der Bundeswehr München
d_s	Diameter of screen grid aperture per design

Author contributions

P.S. performed lifetime tests, processed data, carried out microscopy, and prepared figures. M.S. conceptualised the research, proposed the methodology, and provided equipment. A.M. managed the project and assisted in methodology development. R.K. performed plasma diagnostics of the ion beam. C.H. conducted computer tomography scans of the grids. A.M.C. processed CT scans, maintained the vacuum chamber, and assisted in lifetime tests. J.S. provided scientific supervision. N.W. provided ESA-side supervision. F.G. provided MarsSpace-side supervision. P.S. and M.S. wrote the main manuscript text. All authors reviewed and edited the manuscript.

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Data availability

The data supporting the findings of this study are available within the article. Additional raw datasets generated during the current study are not publicly available due to confidentiality agreements with industrial partners, but may be made available from the corresponding author on reasonable request and subject to approval by the involved parties.

Materials availability

Not applicable. The research utilised commercially available products from MarsSpace under a confidentiality agreement.

Code availability

Not applicable.

Declarations

Ethics approval and consent to participate

Not applicable. The research involved testing of rocket propulsion systems.

Consent for publication

All authors consent to the publication of this article.

Competing interests

The authors declare no competing interests.

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