High Efficiency, High Power Ion Thrusters for Operation at Specific Impulses Greater than 7000 s

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Objective

- What design maximizes the accelerator system life for a given:
  - Specific Impulse ($I_{sp}$)
  - Plasma Density Profile

- Free Parameters
  - Screen Grid:
    - $ds$
    - $ts$
    - open area fraction (OAF)
  - Accelerator Grid:
    - $da$
    - $ta$
    - OAF
  - Grid Gap, $lg$

![Diagram](image-url)
Ion Beam Extraction

- The grid design is complicated by the radial variation in plasma density upstream of the grids

![Graph showing beam current density vs. radial position in beam (cm)]

- Point 1 (2.3 kW)
- Point 2 (2.0 kW)
- Point 3 (1.6 kW)
- Point 4 (1.3 kW)
- Point 5 (0.9 kW)
- Point 6 (0.5 kW)
New Toys

- New 2D and 3D ion optics codes have recently been developed with the following features:
  - Fast Execution on a PC
    - As little as 10 minutes in some 2D cases
  - Shape and size of beamlets
  - Energy dependent Charge Exchange (CEX) ion production
  - CEX ion tracking
  - Number, energy, and angle of CEX ions hitting the accelerator grid
  - Can model circular or square holes

![Ion Trajectories](image)

**CEX Ions – Birth Locations for Ions hitting the accel. Hole wall**
Electron-Backstreaming Variation with Accelerator Grid Hole Diameter

Graph showing the relationship between Electron-Backstreaming Voltage (mm) and Accelerator Grid Hole Diameter (mm). The graph includes data points labeled as ELT Data and a line labeled as Calculation. The x-axis ranges from 1.15 to 1.55 mm, and the y-axis ranges from -220 to -150 mm.
Accelerator Grid Aperture Enlargement is a Major Life Limiting Wear Mechanism

- Nominal 2.3 kW Operating Point
- Point 1 (2.3 kW)
- Point 2 (2.0 kW)
- Point 3 (1.6 kW)

Electron Backscattering Limit (V)

LDT Run Time (Hours)

- Grid Webbing
- Aperture Wall Erosion

NSTAR TH15 with LDT tank pressure effect

Grid Radius (cm)

Calculated Hole Wall Erosion Rate (mg/cm²)

After 9.2 hrs at TH15

Calculated Hole Diameter (mm)

With Tank Effect
LDT Pin Data

Initial Diameter
Erosion on the Downstream Side of the Accelerator Grid is Less Important at High Isp

- Scaling to High Isp – The Good News
  - Keep all ratios constant
    - $lg/ds$, $ts/ds$, $da/ds$, $ta/ds$
  - Keep electric field constant
    - $E = V_T/I_g$
    - As the total voltage, $V_T$, increases so does $I_g$
    - Increasing the grid gap, $I_g$, increases all the other grid parameters resulting in:
      - Thicker Grids
      - Larger Holes
  - The accelerator grid voltage does not increase as fast as the beam voltage and accel. grid thickness

![Graph showing backstreaming voltage limit vs. beam voltage](image)

Simulation Results

![Downstream face of accelerator grid after 8200 hours at 2.3 kW](image)
![Simulated erosion contours overlaid on measured erosion pattern](image)
Scaling to High $lsp$ – The Bad News

Operation at higher $lsp$ (greater beam voltage) increases both the energy and number of CEX ions hitting the hole walls

This effect has a major impact on the grid design for long life.

**Graph 1:**
- **Equation:** $y = 3.049E-01x$
- **$R^2$:** 9.856E-01
- **Equation:** $E = 2300 \text{ V/mm}$
- **$n_i$:** $2 \times 10^{17}$

**Graph 2:**
- **Equation:** $y = 2.608E-11x^2 + 2.964E-08x + 4.944E-04$
- **$R^2$:** 9.756E-01
- **Equation:** $E = 2300 \text{ V/mm}$
- **$n_i$:** $2 \times 10^{17}$

**Beam Voltage (V)**

**CEX Ion Energy in Hole Wall (eV)**

**Jhole/beamlet**
At sufficiently low current densities all of the CEX ions produced between the grids get focused out through the accelerator grid aperture.
The Ratio of Maximum to Minimum Plasma Densities is Independent of the Electric Field

Minimum Plasma Density
Maximum Plasma Density

$V_b = 12,370 \text{ V}$
$V_a = -1500 \text{ V}$
Accelerator Grid Hole Tailoring

Change hole diameters to follow the beamlet size

May enable operation at high propellant efficiencies and high overall thruster efficiencies
New computer simulations of the ion accelerator system will enable the development of long-life, high $Isp$ ion engines.

The energy of CEX ions hitting the accelerator grid hole walls is a function of the beam voltage. Higher $Isp$ thrusters will see much greater accelerator grid erosion even if the accelerator grid voltage doesn’t change much.

Tailoring of the accelerator grid apertures to follow the beamlet diameters will enable the development of very high efficiency ion thrusters.