SPIS simulations in optimisation of FEEP design and contamination analysis

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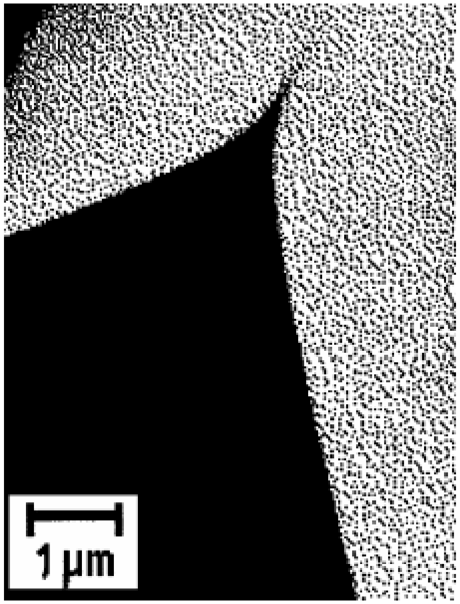
Introduction

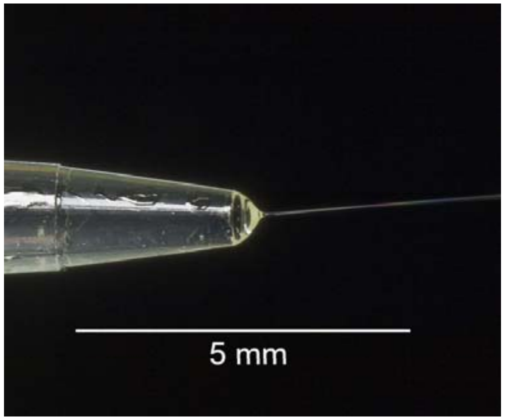
- Spacecraft exist in a plasma environment
- Electric propulsion (EP) modifies spacecraft/plasma interactions
- It introduces new particle populations from
  - the emitter itself,
  - the neutraliser (if present)
  - ions created in the plume by the charge exchange process.
- EP involves the same physics as simulation of spacecraft plasma interactions and so the same software can be used.
- SPIS (Spacecraft Plasma Interaction Simulation) has been used to
  - assess the rates and location of contamination to a spacecraft
  - assess the sensitivity of the FEEP to deviations from the nominal design

FEEP

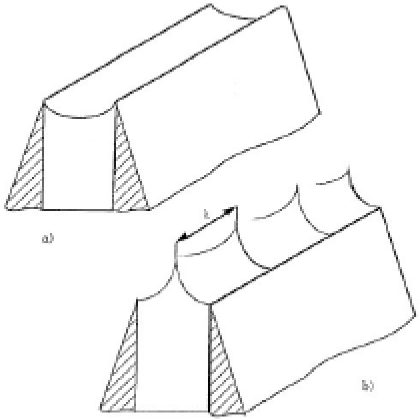
- Field-Emission Electric Propulsion (FEEP) is a technology that provides high efficiency and high precision for micro-propulsion applications in space.
- FEEPs will be flown in on Lisa Pathfinder where ultra precise control of the spacecraft velocity vector and orientation is required.
- Indium and Caesium FEEPs have been considered for Lisa PathFinder
- Ions are emitted from a needle (In) or blade (Cs) under the influence of high electric fields imposed by an accelerator plate
- Accelerated ions (~6KeV) emerge from an aperture in the accelerator plate.
- Outside of the FEEP these ions can undergo charge exchange with neutral propellant atoms and which can return to the spacecraft surface under the influence of the electric fields

Taylor Cone

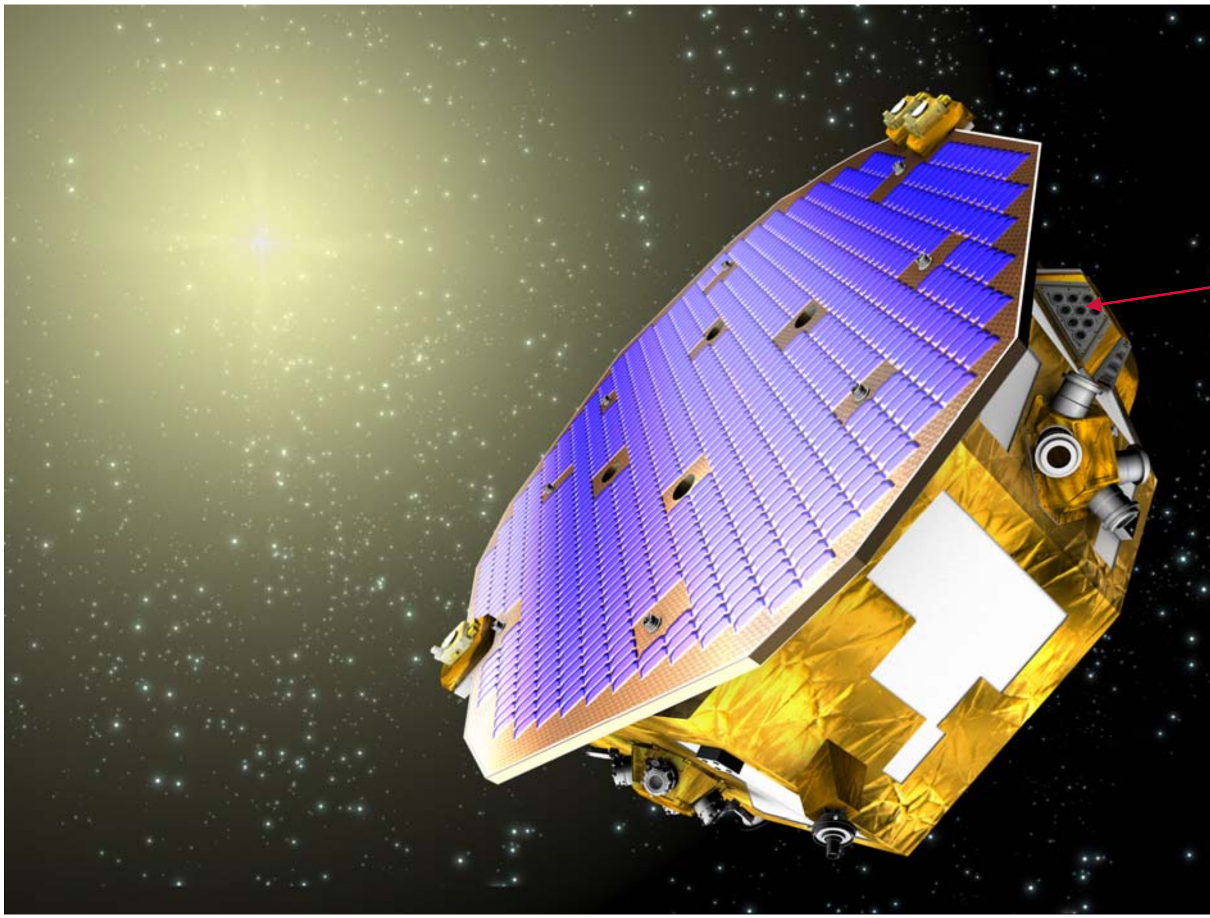




FEEP emission process involves the creation of Taylor cones (usually around a few microns in diameter)

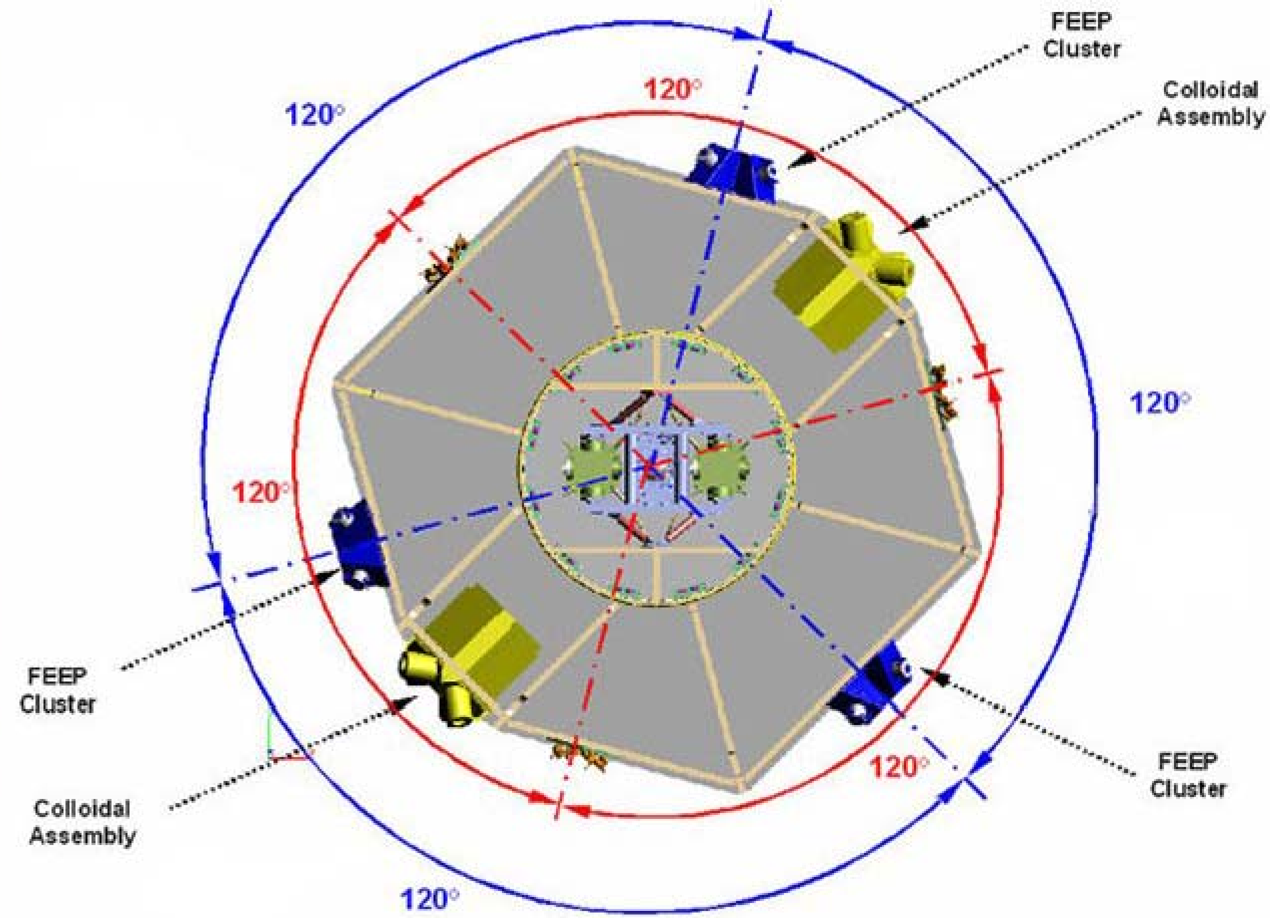


Lisa PathFinder



FEEP cluster (In FEEP shown)

FEEP thruster locations



SPIS

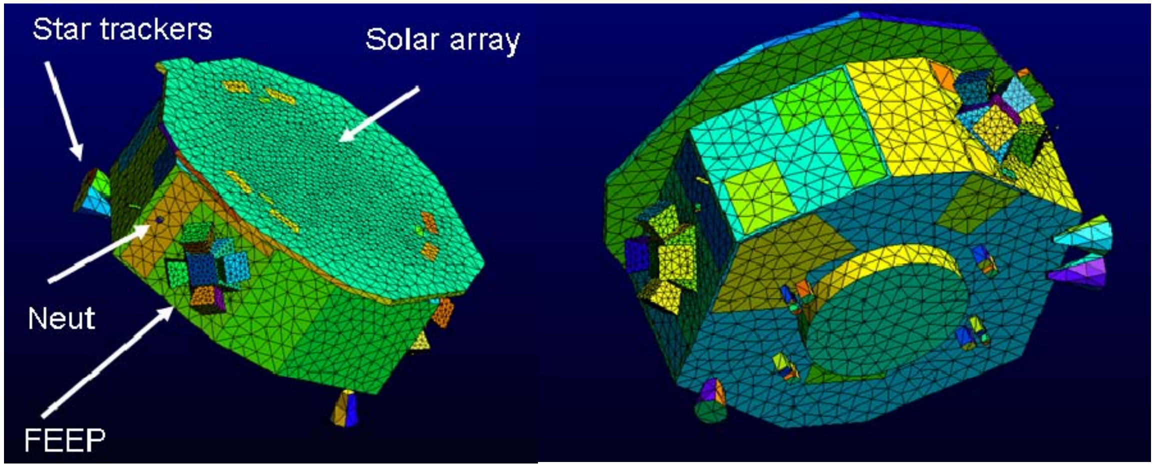
- SPIS was developed by ONERA (F) in cooperation with Artenum (F), initially under ESA Funding.
- Further ESA and CNES studies have been used to develop SPIS capabilities.
- SPIS continues to be developed
- Released under an Open Source licence
- Packaged with existing Open Source pre- and post processing tools
- http://dev.spis.org/projects/spine/home/spis

SPIS

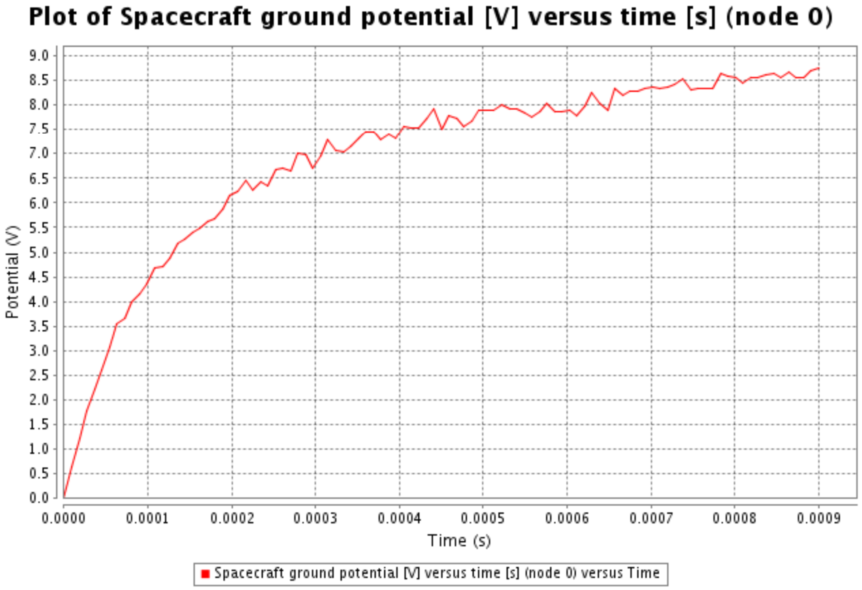
- SPIS characteristics
  - PIC/Hybrid/Reverse trajectory particle movers
  - Unstructured Mesh
    - Very wide range of mesh sizes
  - Implicit/Explicit Poisson solvers
  - Variety of boundary conditions
  - Spacecraft materials and circuit definition
  - Numerical speed-up methods

Contamination assessment

- Aim
  - Determine rate of CEX contamination due to In and Cs FEEPs

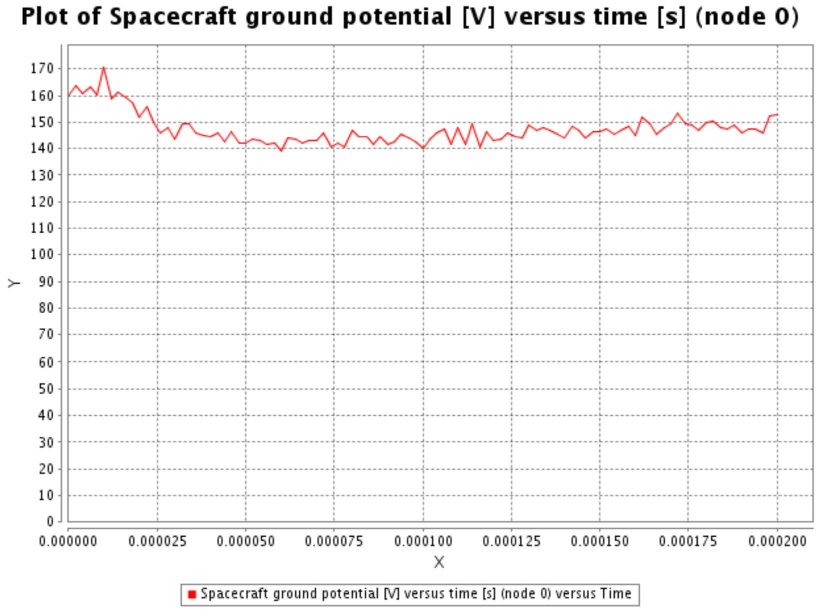


Floating potential calculation



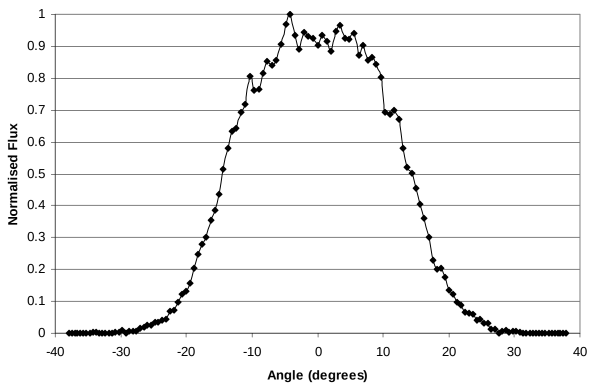
Floating potential (no EP)

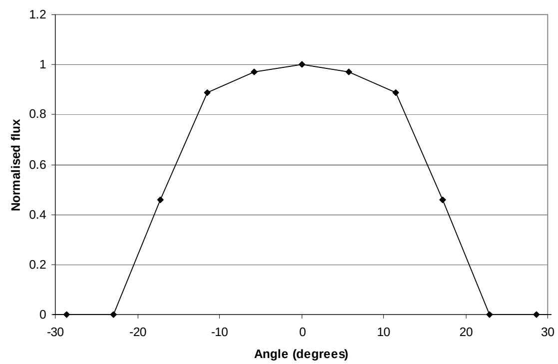
Floating potential (EP and 150eV neutralizer bias)



Simulation inputs

- Beam composition
  - Cs (84% - Cs+, 12% - Cs2+, 4% - Cs3+)
  - 70% and 99% efficiencies
  - In (98% In+, 2% In2+ - droplets ~100atoms)
- Beam profiles



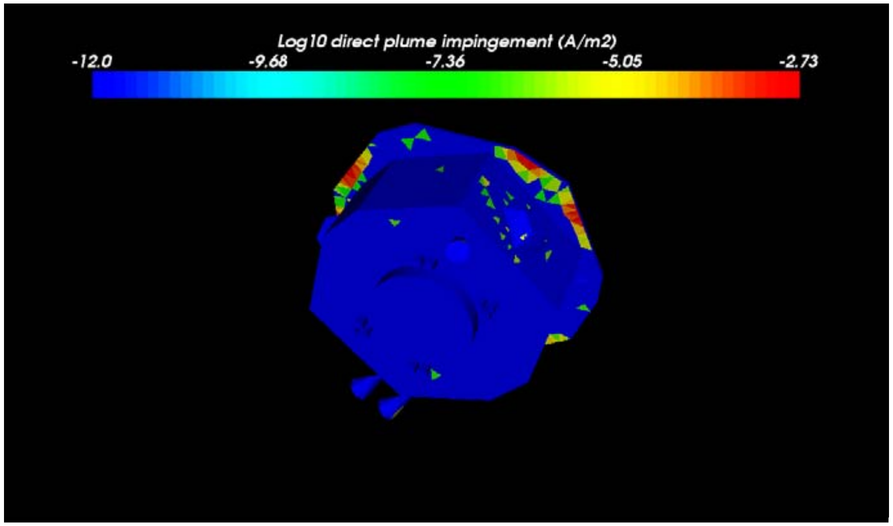


(Cs)

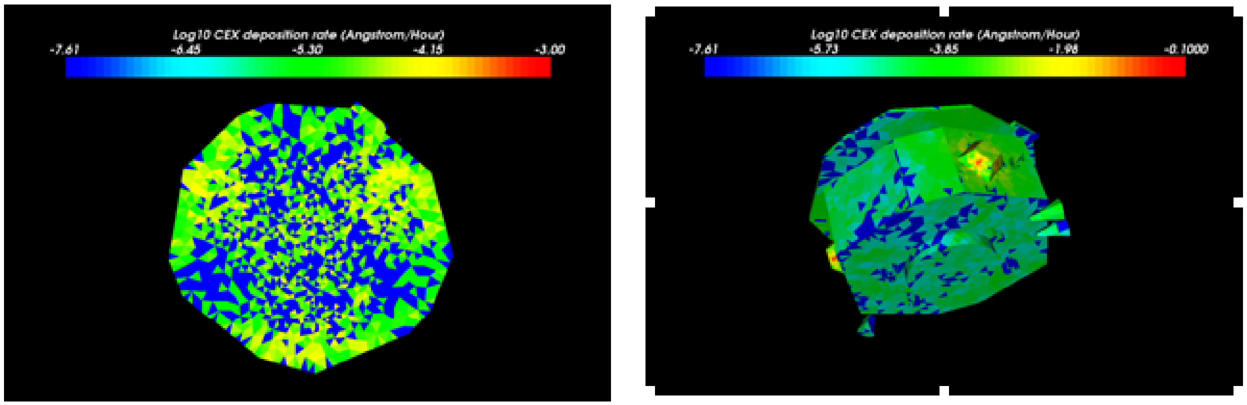
- Floating potential
  - +10V without FEEPS or neutraliser
  - +50 to +150V with FEEPS + neutraliser

Contamination results

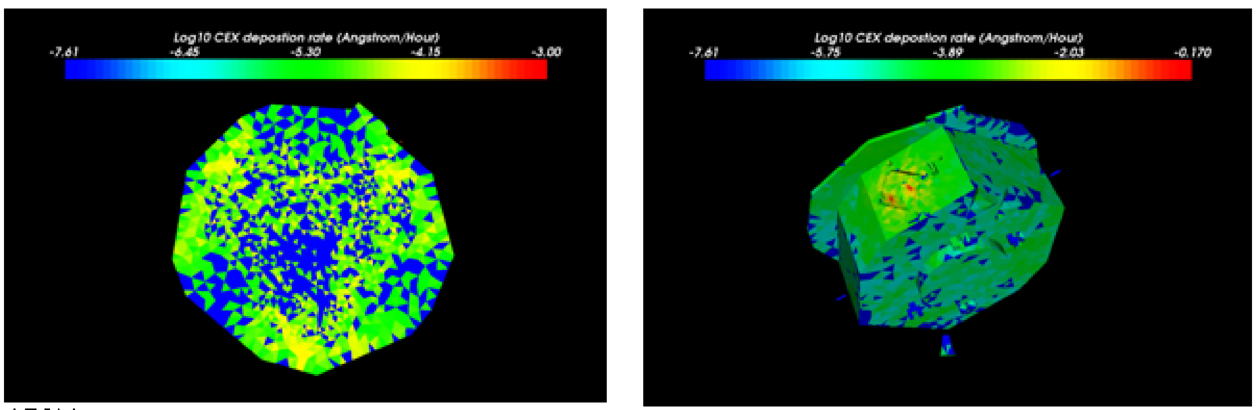
Direct impingement Cs



Contamination results



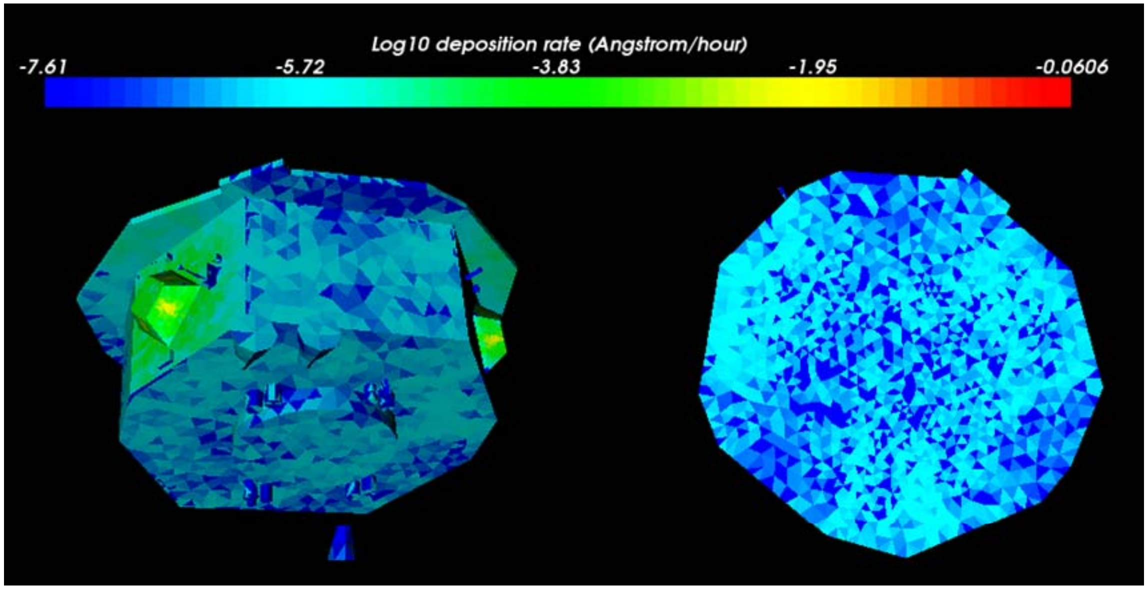
0V



150V

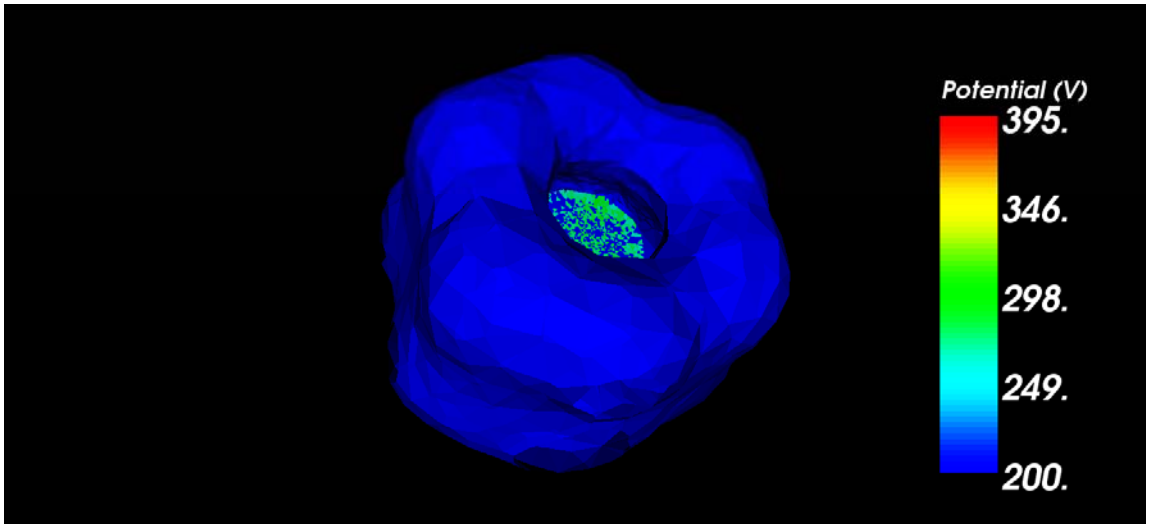
Cs contamination (0V and 150V spacecraft potential, 70% efficiency)

Contamination results



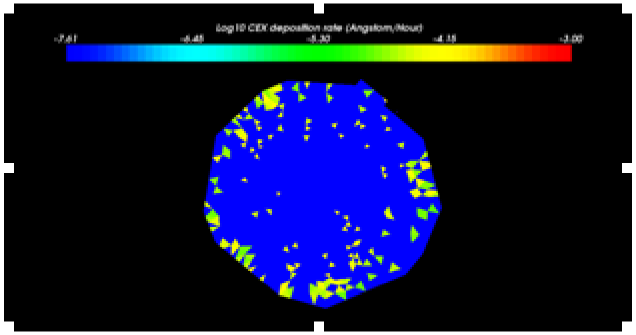
Cs contamination (0V) 99% efficiency

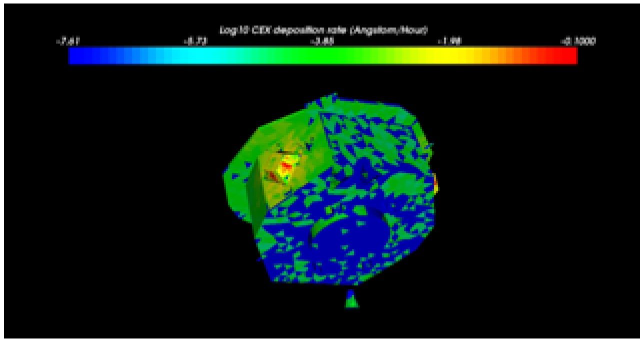
Contamination results



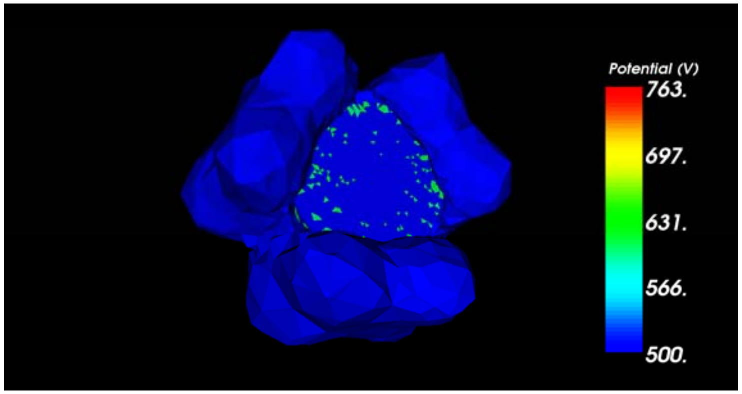
200V iso-potential contour (with 0V spacecraft potential)

Contamination results

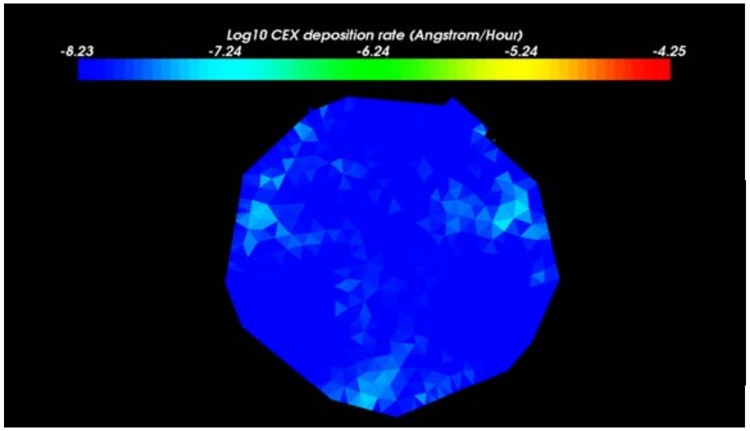




Contamination with 500V spacecraft potential



500V iso-potential contour (with 0V spacecraft potential)



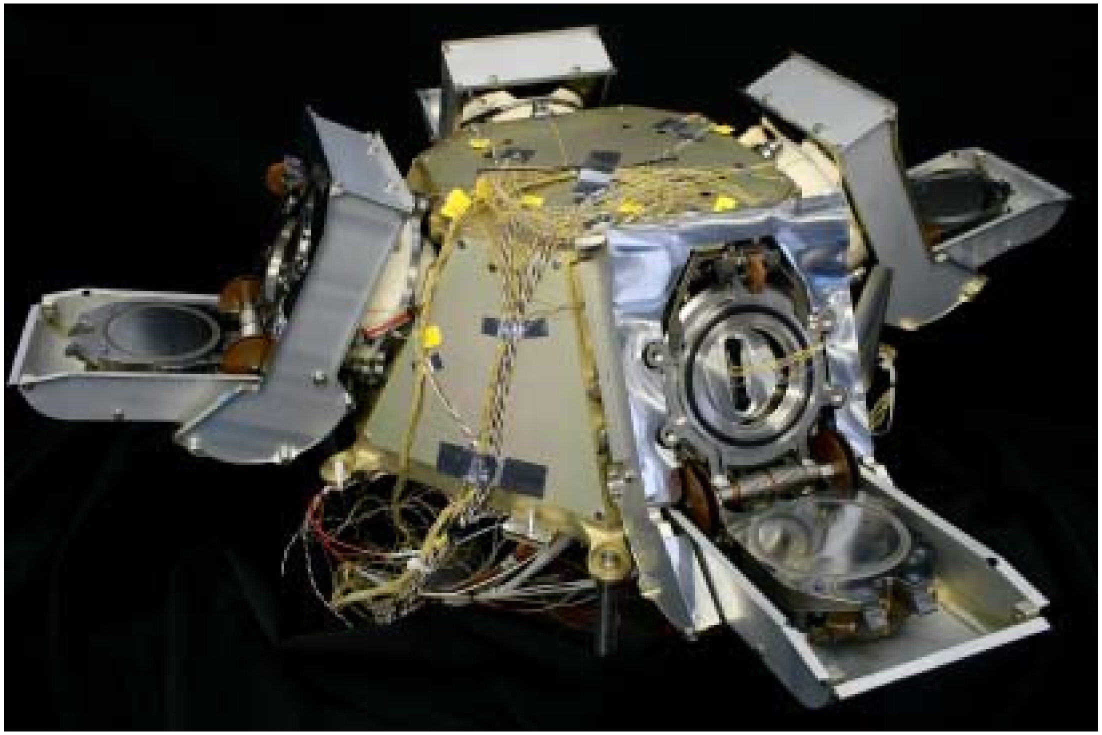
In contamination (99.94% efficiency)

Contamination results

1. Worst-case contamination rates were assessed.
2. Some contamination was observed everywhere on the spacecraft surface
3. Due to the plume potentials generated, contamination rate was independent of spacecraft potential for the range of voltages expected (0 to +150V)
4. Significant reduction of contamination was observed at 500V spacecraft potential
5. The spacecraft potential was not altered significantly by the presence of interconnects and bus bars on the solar array
6. Contamination from direct impingement of Cs+ ions was observed on the back side of the solar array
7. Results have also been calculated for the clusters of Indium needle FEEPs
8. Contamination was not a significant hazard to the spacecraft

Design optimisation

Cs FEEP



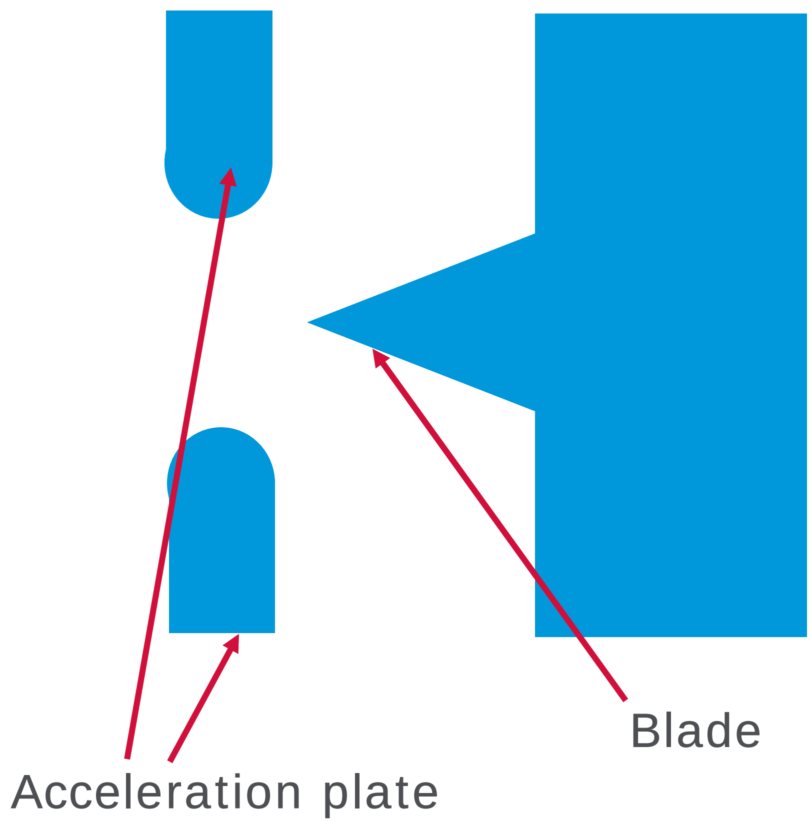
Design optimisation

Aims

- To observe whether there is direct impingement and thruster vector shift in case of
  - Displacement of FEEP blade- caused by manufacturing uncertainty
  - Asymmetric emission from blade – caused by spreading of wetted zone
- To assess two possible accelerator plate designs
  - Fat acceleration plate
  - Thin acceleration plate

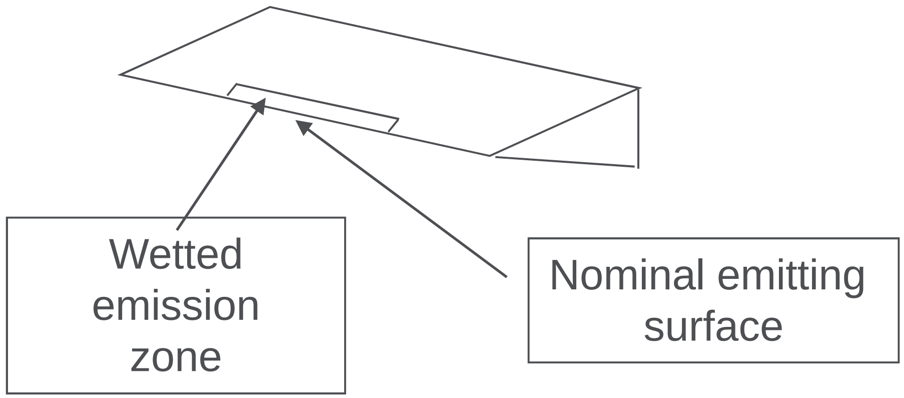
Design optimisation

Fat acceleration plate

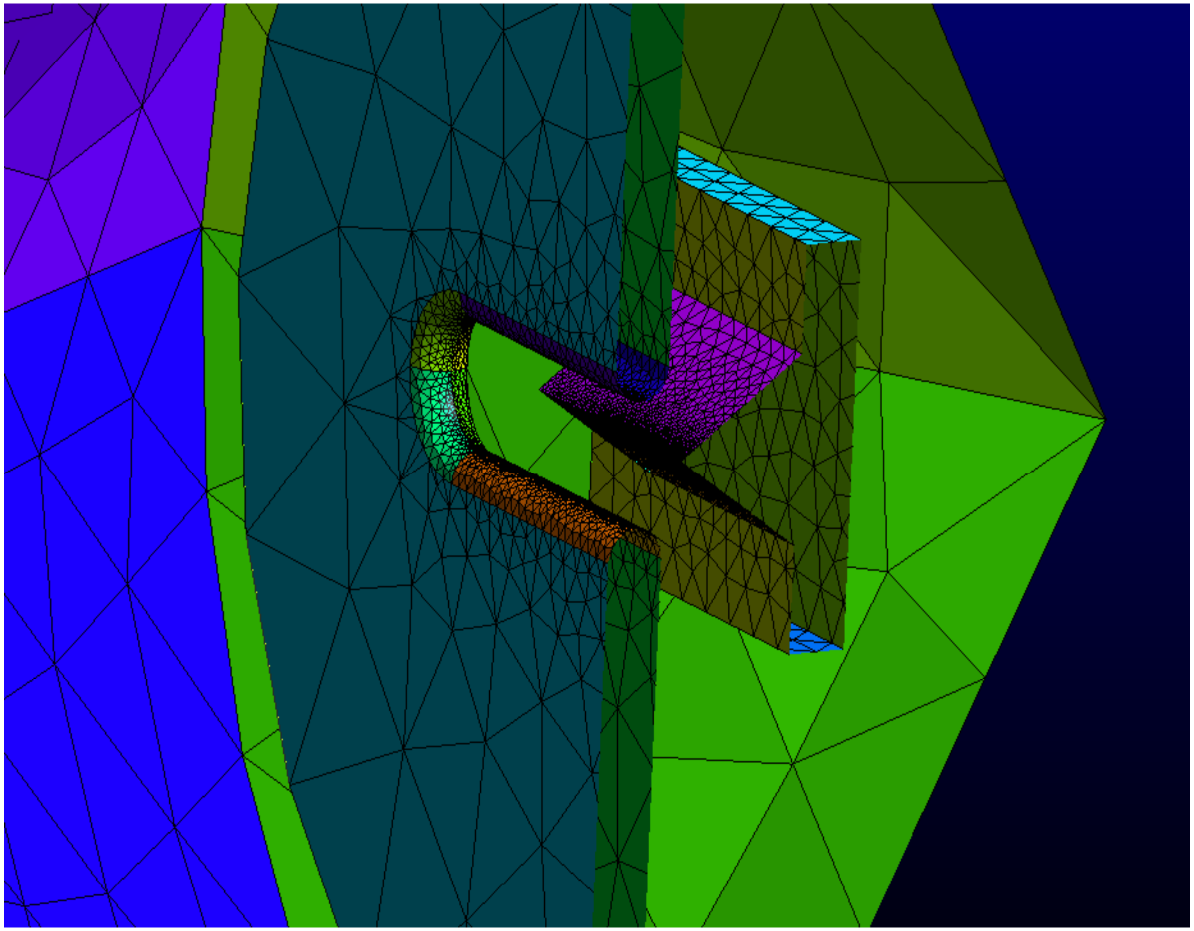


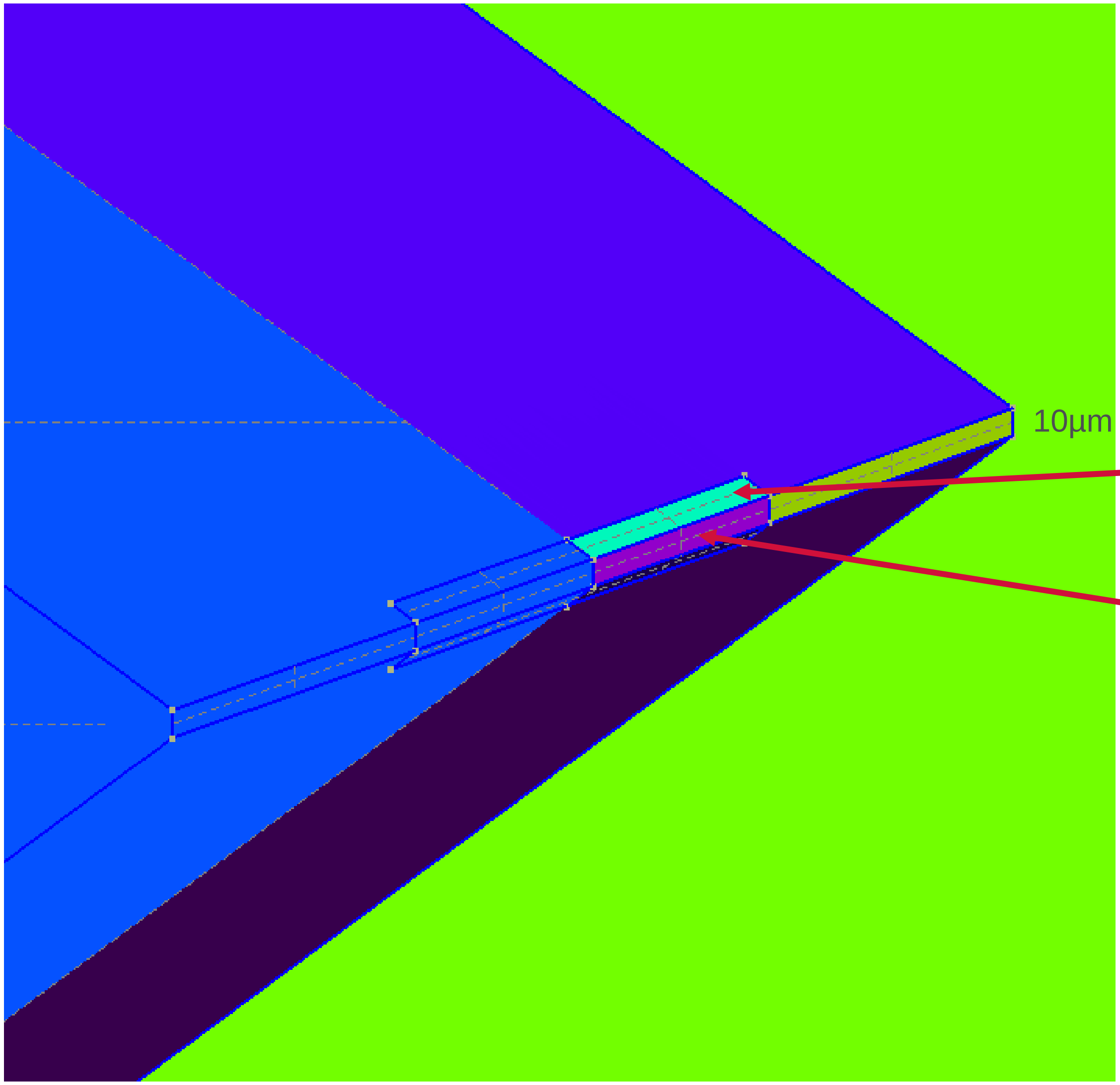
Thin acceleration plate

Design optimisation



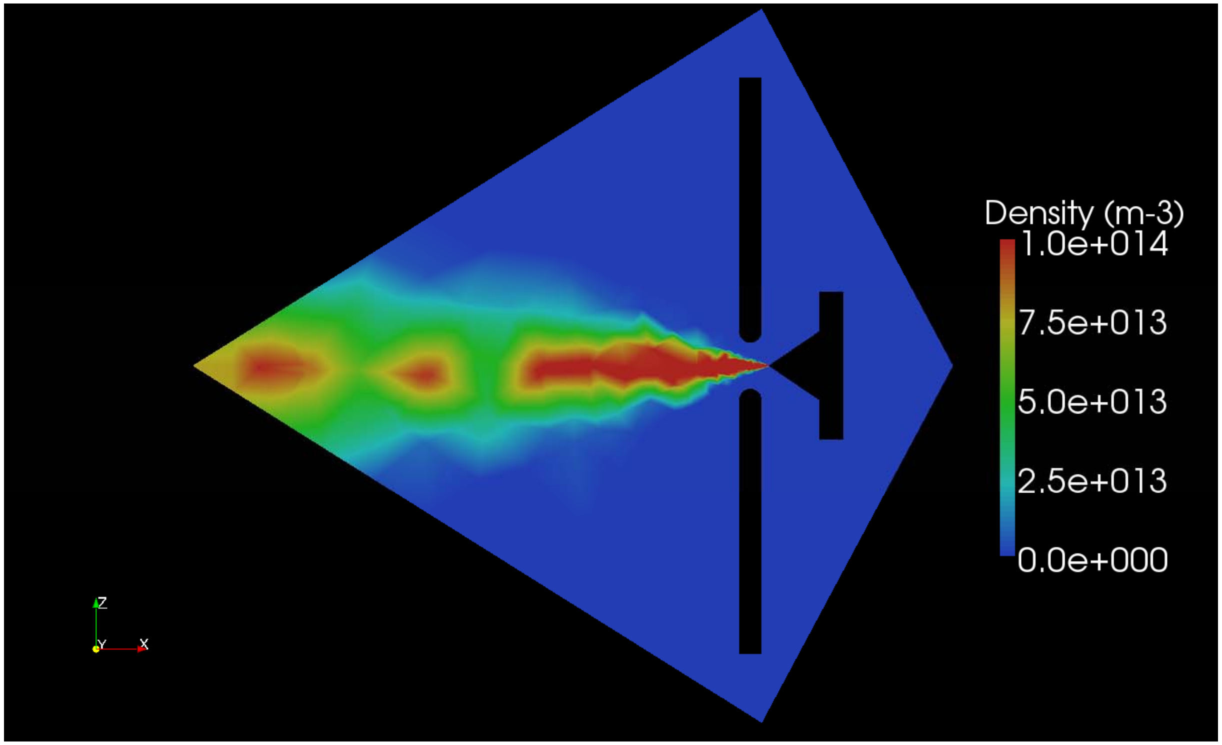
- Simplified SPIS model of the FEEP geometry
- Mesh resolution adapted to concentrate accuracy on areas of high fields and high importance



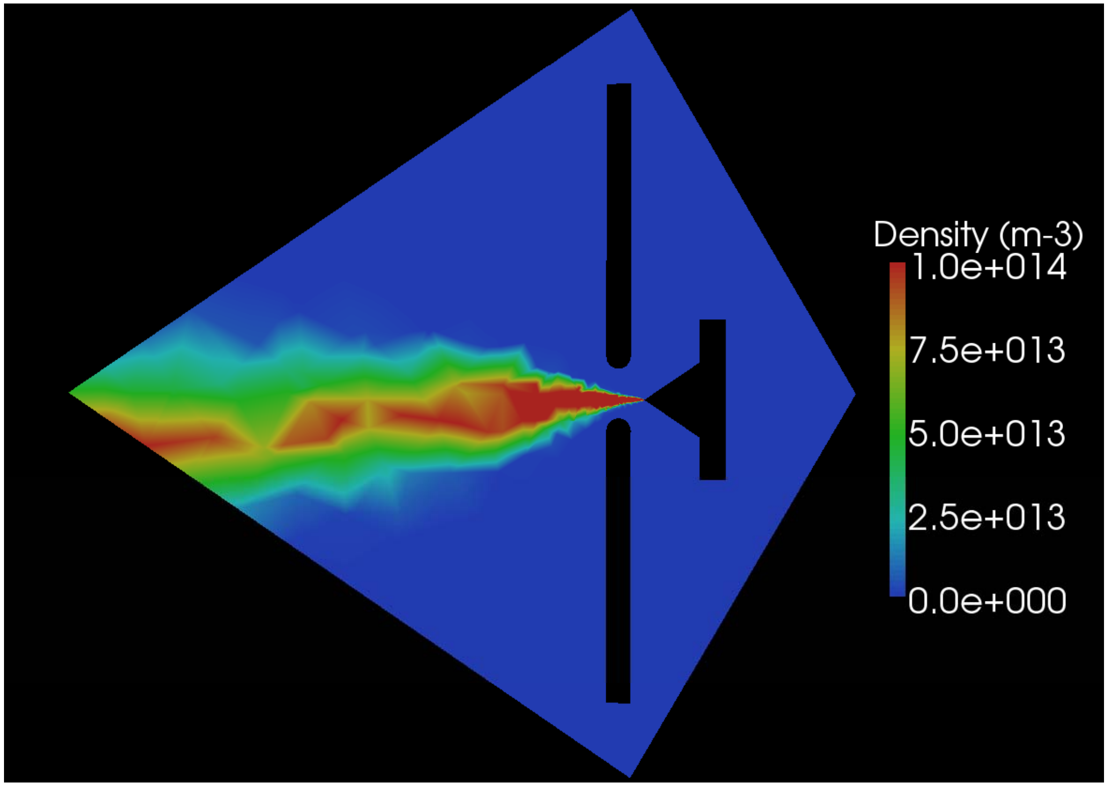


Alternative emission surface

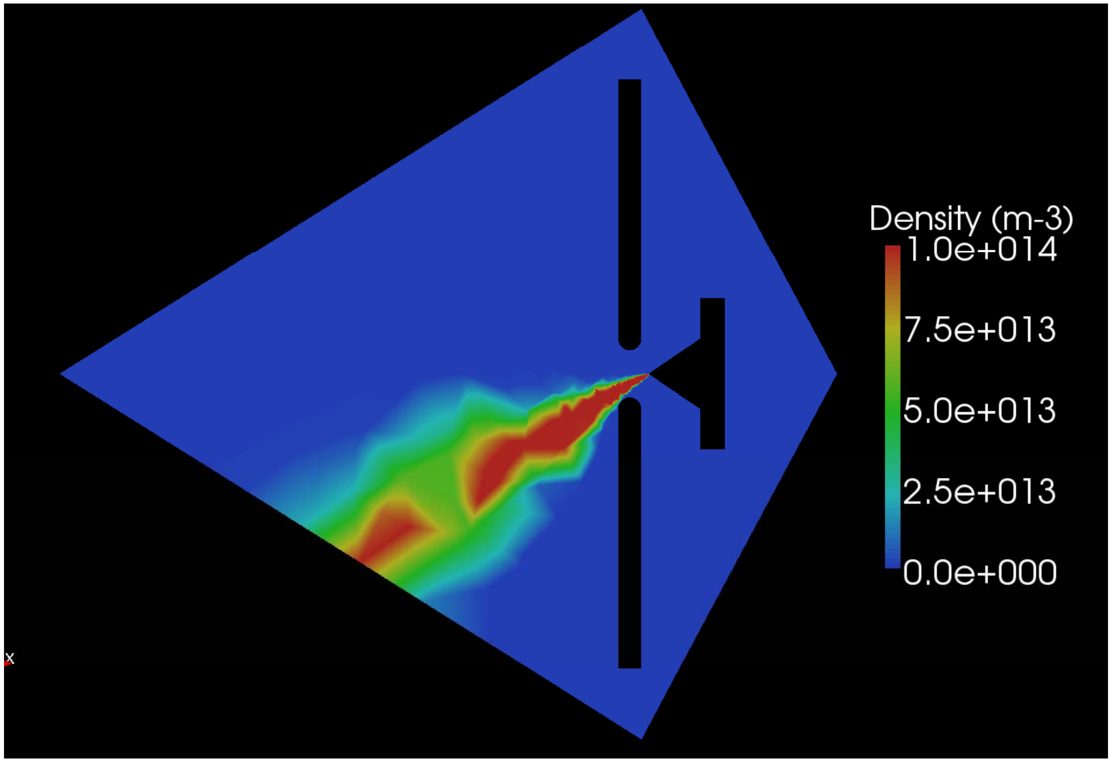
Nominal emission surface



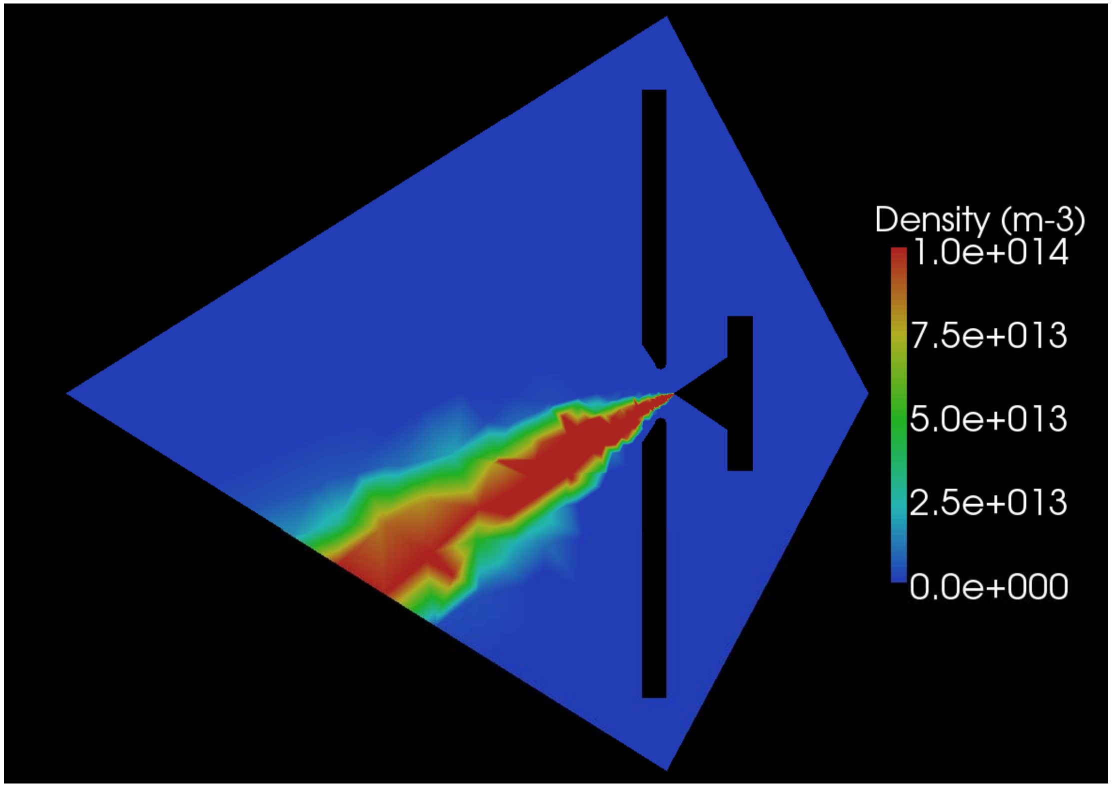
Emission with a nominal emitter



Emission with a displaced emitter (0.5mm down and 0.5mm away from accelerator)



Emission from alternative emission zone



Emission from alternative emission surface with thin acceleration plate

Results

1. Misalignment of the emitting blade would cause minor thrust vector change and no direct impingement
2. Emission of ions from the side, instead of the tip, of the blade would lead to a strong deviation of the thrust vector and direct impingement for the fat acceleration plate
3. Accelerator plate with thinner edge gave only a marginal improvement against direct impingement

Conclusion

1. Lisa PathFinder is not expected to have problems with contamination
2. Care is required in controlling the emission site on the FEEP blade
3. SPIS can be useful in assessing EP performance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Thank you for your attention
European Space Agency

Charge exchange process

Both the Caesium and Indium cross-sections follow this formula:

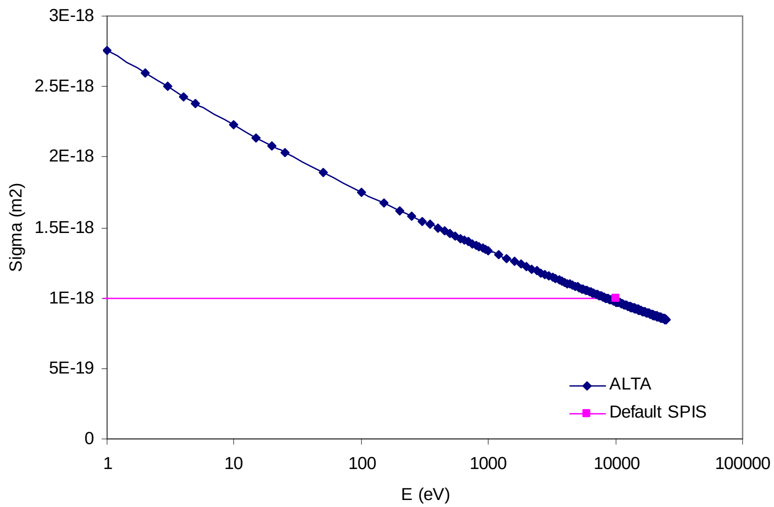
$$\sigma_{CEX} = (k1 \times \ln(v) + k2)^2$$

Where v is the interaction velocity and

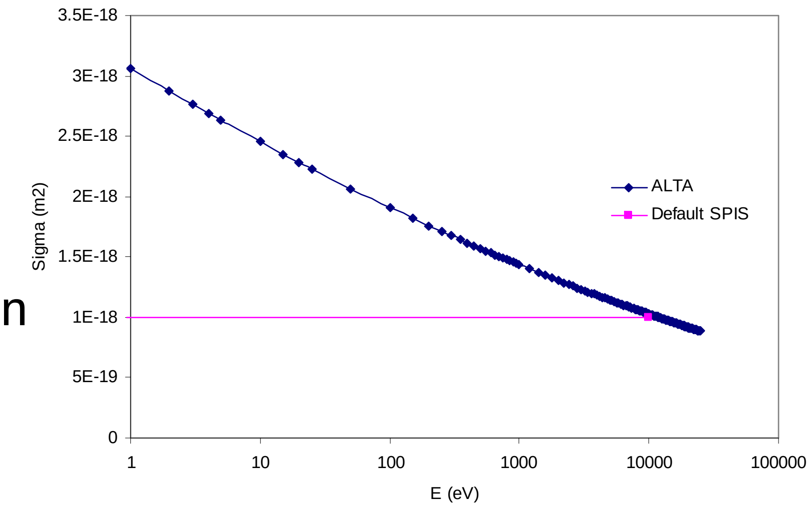
Caesium k1 = -1.4611×10^{-10} s, k2 = 2.6963×10^{-9} m

Indium k1 = -1.599×10^{-10} s, k2 = 2.884×10^{-9} m

Cs



In



Summary

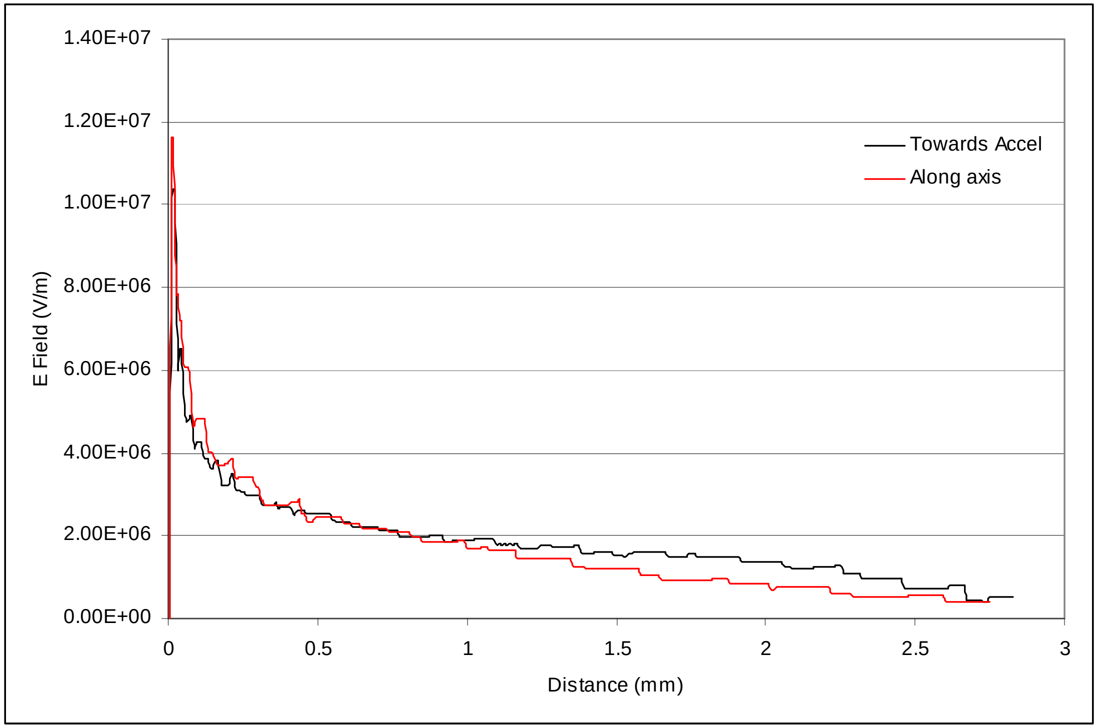
Summary

	Log10 CEX deposition rate (Angstrom/Hour)		
Pot. (Mass Eff.)	**150V (70%)**	**150V (99%)**	**Direct Imp.** [1]
Other bays	-4.88	-6.31	None
Star trackers	-5.77	-6.29	None
S/C bottom	-4.64	-6.12	None
Bay with FEEP	-3.68	-5.13	None
Immediate FEEP area	-0.06	-1.56	None
SA (back) nr FEEP	-4	-5.5	0.25-50
SA (sun) across **SA (sun) nr FEEP**	-5.1 -4.65	-6.43 -6.13	None None

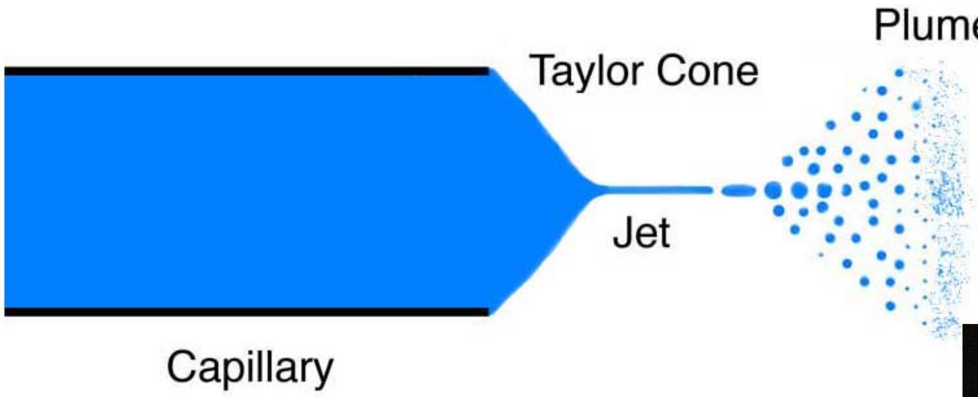
Caesium

	Low CEX		High CEX	
Pot. (Mass Eff.)	**0.06% neutrals**	**50% droplets**	**30% neutrals**	**20% droplets**
Other bays	8.11	None	-5.65	None
Star trackers	-7.83	-6.2 (sides)	-5.12	-6.4 (sides)
S/C bottom	-7.93	None	-5.24	None
Bay with FEEP	-7.05	-5.6	-4.35	-5.9
Immediate FEEP area	-4.24	None	-1.55	None
SA (back)	-7.41	-4.6	-4.73	-5
SA (sun)	-7.94 -8.07	None None	-5.33 -5.5	None None

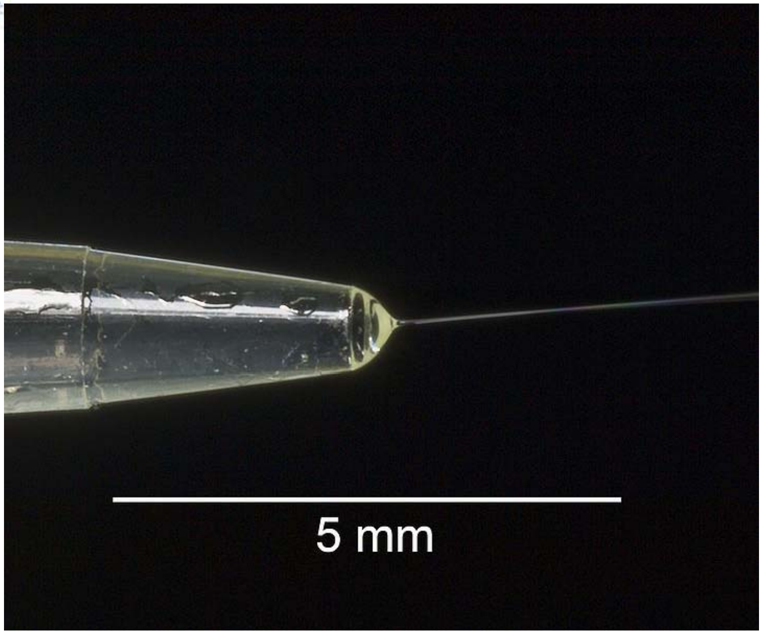
Indium



1.40E+07
1.20E+07
1.00E+07
8.00E+06
6.00E+06
4.00E+06
2.00E+06
0.00E+00
E Field (V/m)
0
0.5
1
1.5
2
2.5
3
Distance (mm)
Towards Accel
Along axis



Electrospray Taylor cone



Taylor cone producing polyvinyl thread

Abstract

1. Field-Emission Electric Propulsion (FEEP) is a technology that provides high efficiency and high precision for micro-propulsion applications in space. FEEPs will be flown in on Lisa Pathfinder where ultra precise control of the spacecraft velocity vector and orientation is required. In FEEPs, propellant ions are emitted from a needle or blade under the influence of high electric fields imposed by an accelerator plate with an aperture through which the emitted and subsequently accelerated ions pass. Outside of the FEEP these ions can undergo charge exchange with neutral propellant atoms and which can return to the spacecraft surface under the influence of the electric fields.
2. The simulation of ion flows in FEEPs and in the plume requires much the same physics as simulation of spacecraft plasma interactions and so the same software can be used. SPIS (Spacecraft Plasma Interaction Simulation) has been used assess the rates and location of contamination to the spacecraft due to charge exchange. In addition it is has helped in assessing the sensitivity of the FEEP to deviations from the nominal design.
3. For contamination assessment, the spacecraft geometry was represented in 3-d, with FEEPs as plasma sources and a realistic ambient plasma. Significant positive space charge potentials were found in the plumes and this leads to the attraction of charge exchange ions onto the spacecraft surface. Although contamination is greatest near the FEEP aperture, ions can be deposited virtually anywhere on the spacecraft surface. Simulations were used to investigate whether maintaining a positive spacecraft potential would be a means of controlling contamination. However, rates of deposition are low and deposited ions would evaporate away from most surfaces.
4. Simulations addressing ion trajectories inside the FEEP were performed to assess off centre emission, to see the possible consequence this would have on direct impingement. This involved simulation of the emitting blade down to sizes approaching the microscopic Taylor cones which form in the liquid propellant and from which ions are extracted. SPIS handled the 4 orders of magnitude range of feature sizes, including the emitting blade 10 microns thick, an acceleration slit 4mm wide and the 100cm simulation box. The simulations showed that the misalignment of the emitting blade would not easily lead to direct impingement. However, emission of ions from the side, instead of the tip, of the blade could lead to a direct impingement and a deviation in the thrust vector.