Electrostatic charging

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- 1. Introduction
- 2. Contamination by charged particles
- 3. Surface charge effects
- 4. Space charge effects
- 5. Quantitative assessments
- 6. Conclusions

1. Introduction

The good side of the spacecraft

- Provide mobility, power, pointing capabilities, etc…

The downside:

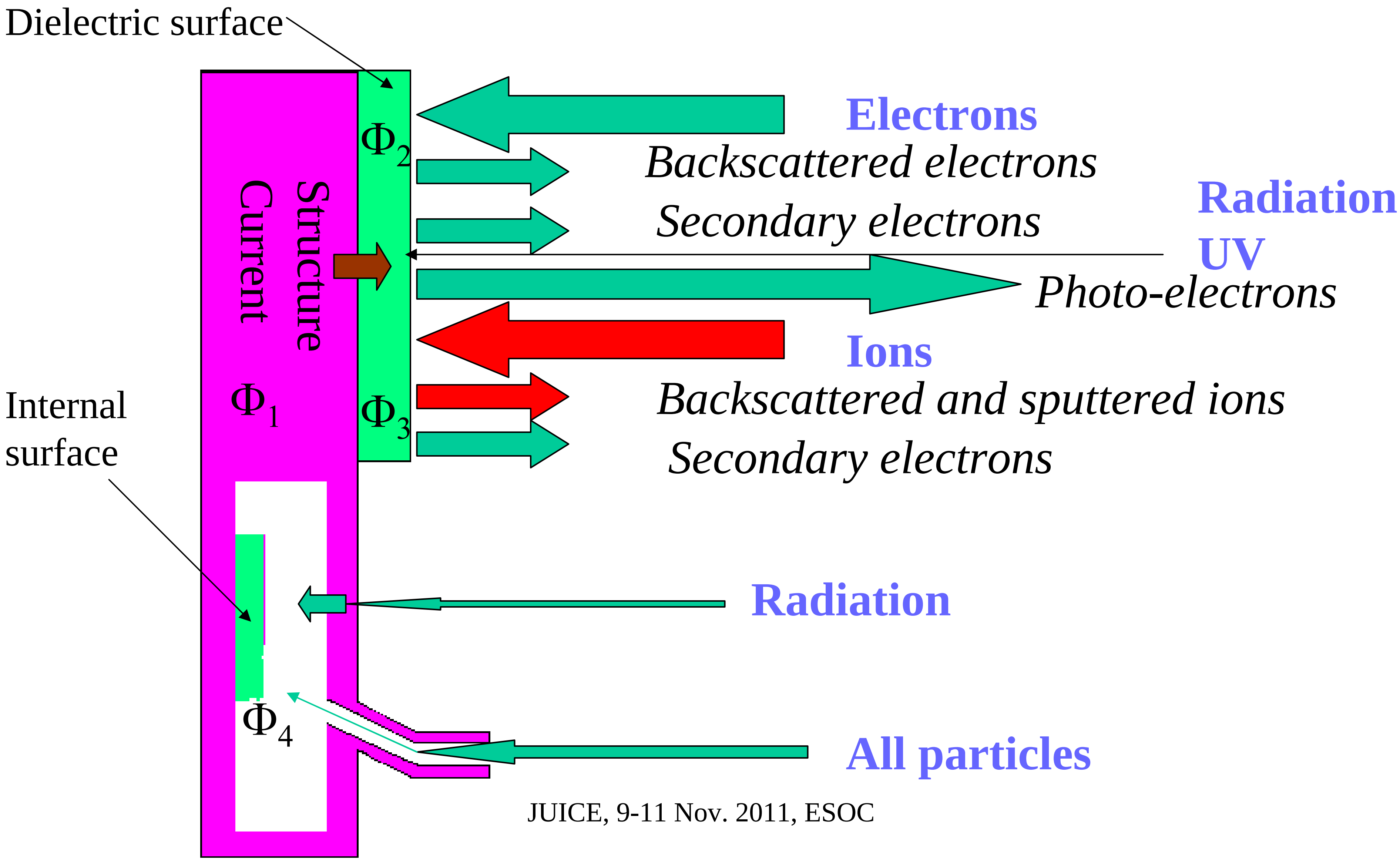
Spacecraft effects on plasma and field measurements:

- FOV obstruction, thermal, high energy radiation, etc…
    - Affect performance, electronic, materials and structure
- Micro-particle impact induced transient environment
- Magnetic and EMC
- Contaminants from passive and active sources of electrical charges
    - Create background, interferences and degradation
- Surface and space charge induced E-field
    - Affect particle trajectories
    - Other disturbances

Scope of this presentation

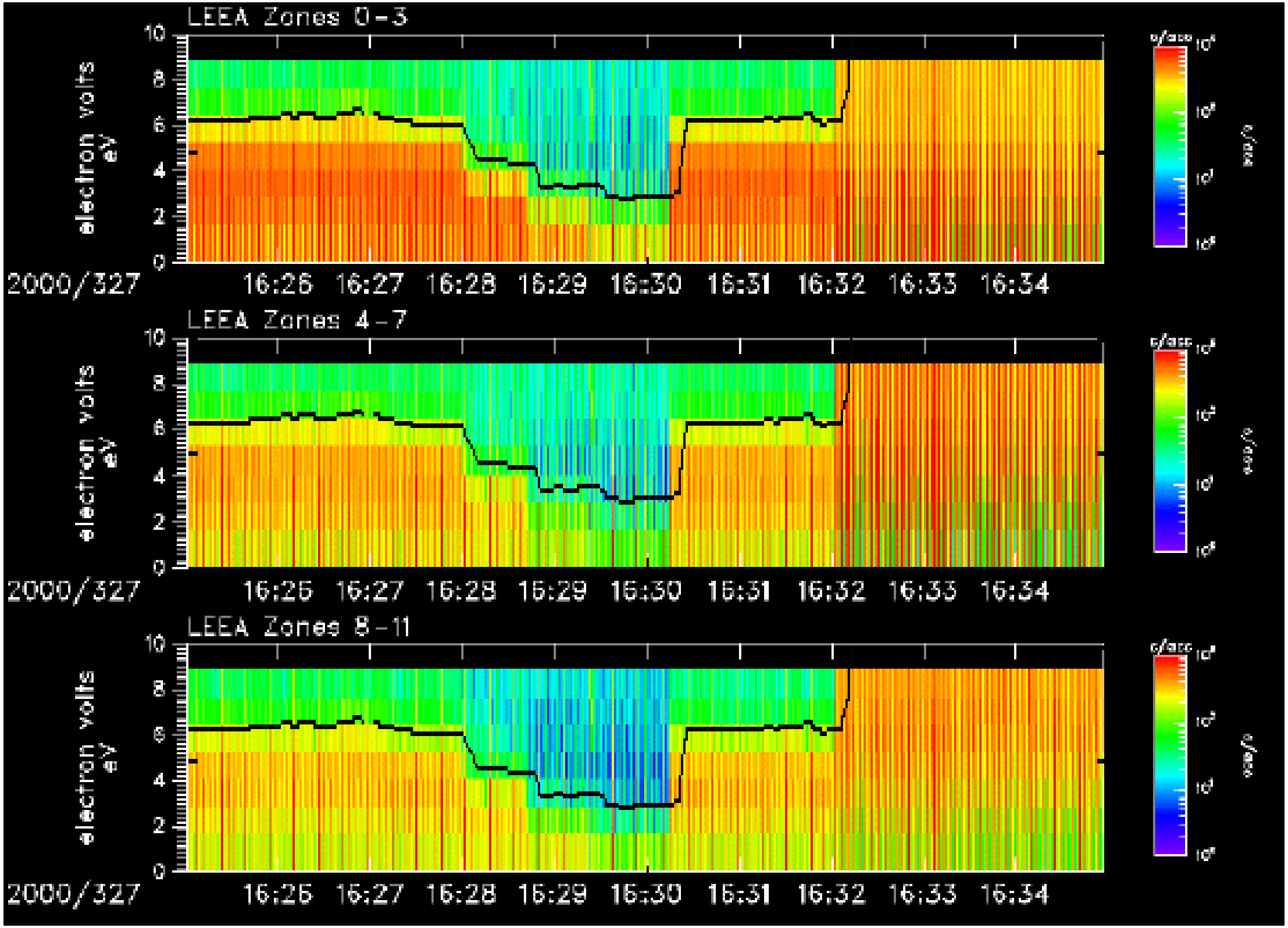
- The following effects on plasma particle detectors are addressed:
  - Contamination by secondary and injected particles
  - Surface charge effects
  - Space charge effects
- Specific requirements for scientific instruments (particle detectors, Langmuir probes):
  - small magnitude effects matter

Key features and glossary

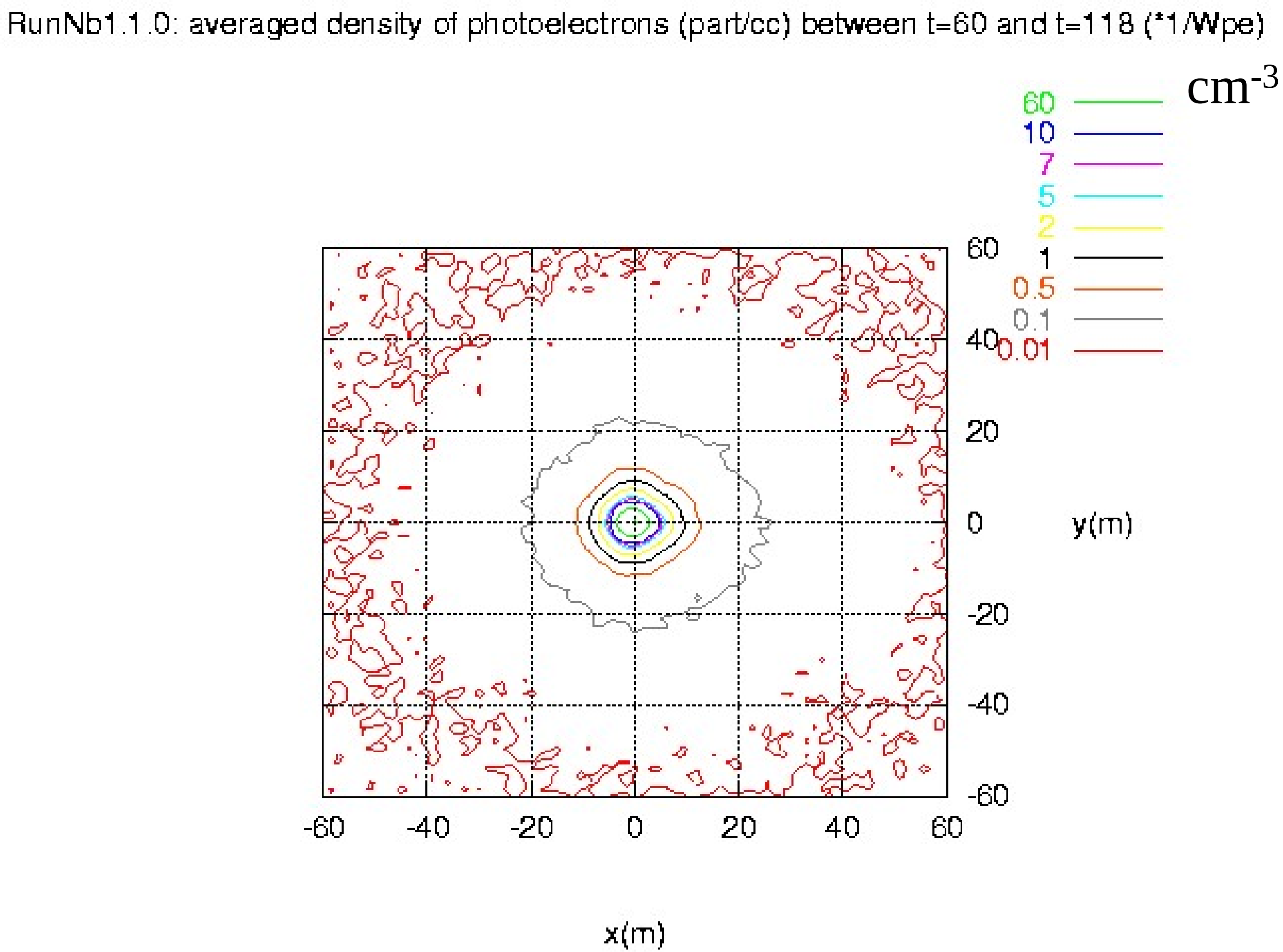


2. Contamination by induced or injected particles

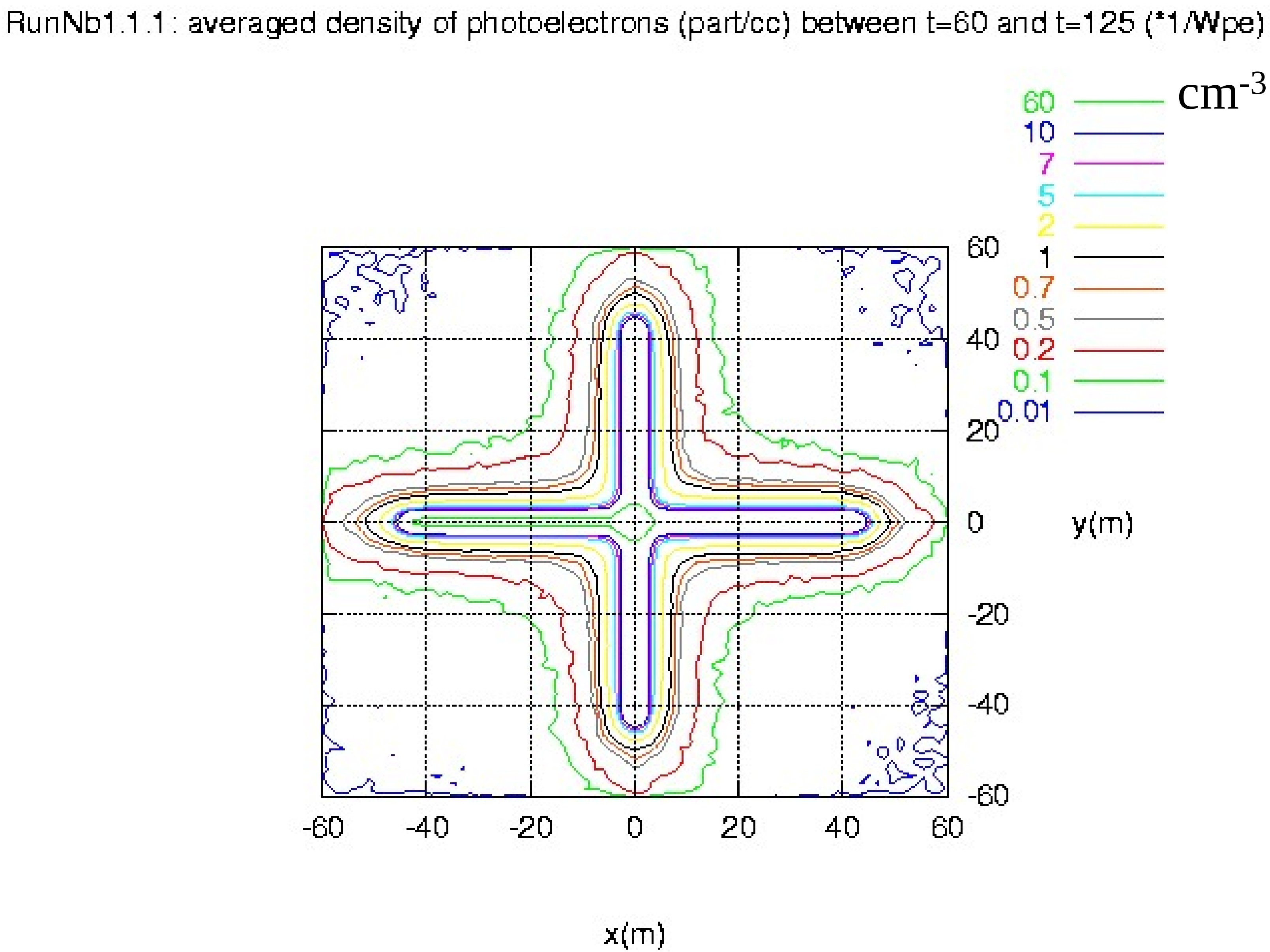
- Secondary particles and photo-electron generated on surface
- Particles from active sources
  - Primary ions or charge-exchange ions from E-thruster
  - Secondary ions created by charge-exchange, CIV, or photo-ionisation of neutrals.



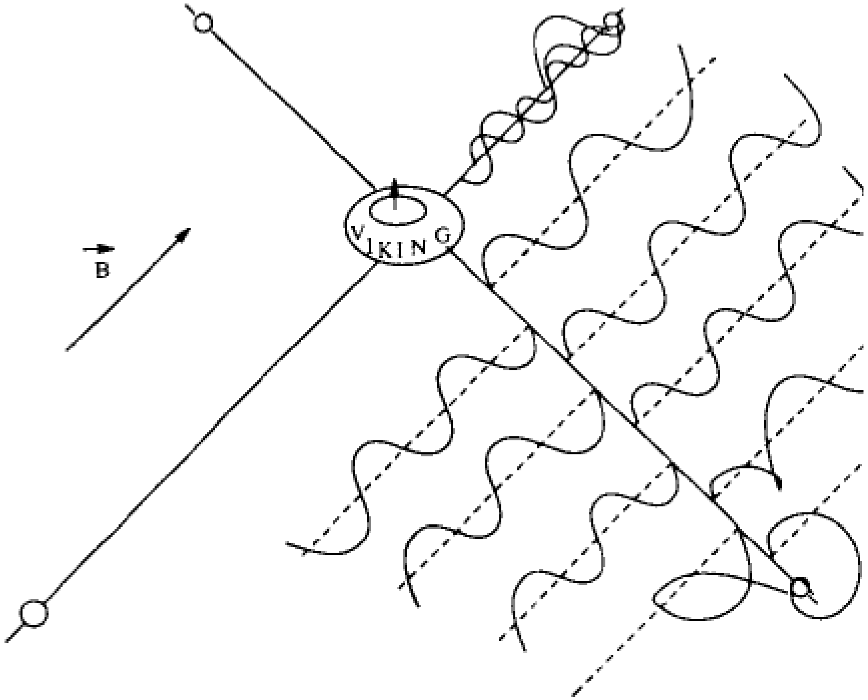
Cluster/PEACE spectrograms (from Torkar et al. 2001)

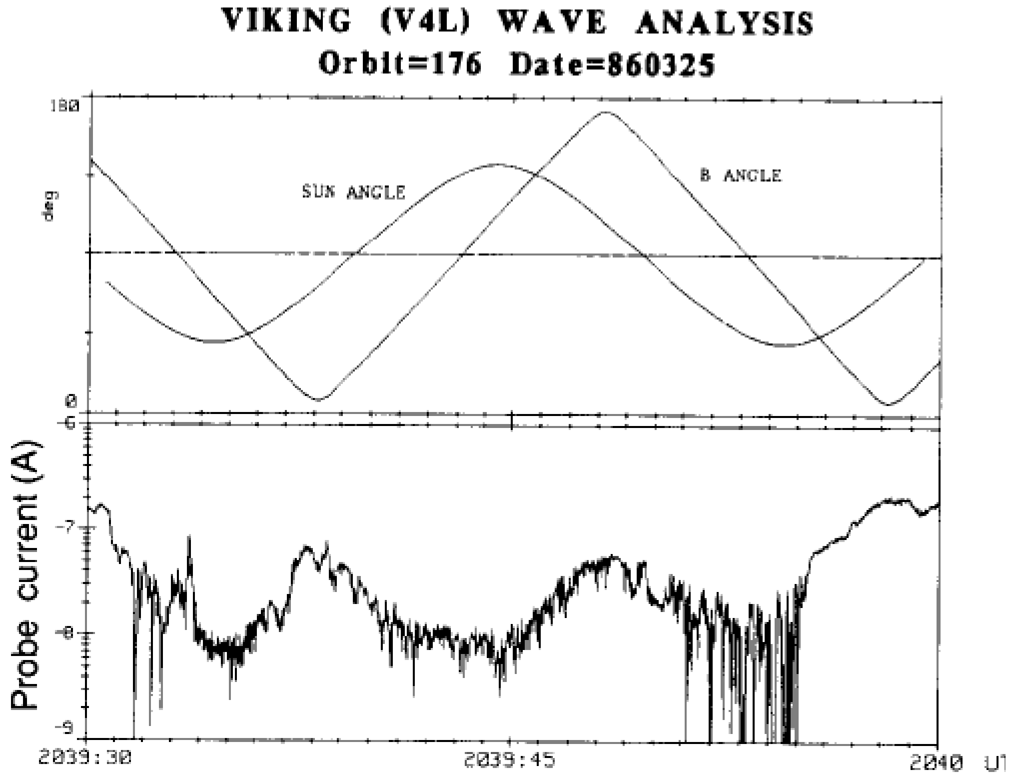


PIC simulation of half-emitting spacecraft (Thiébault et al., 2005)



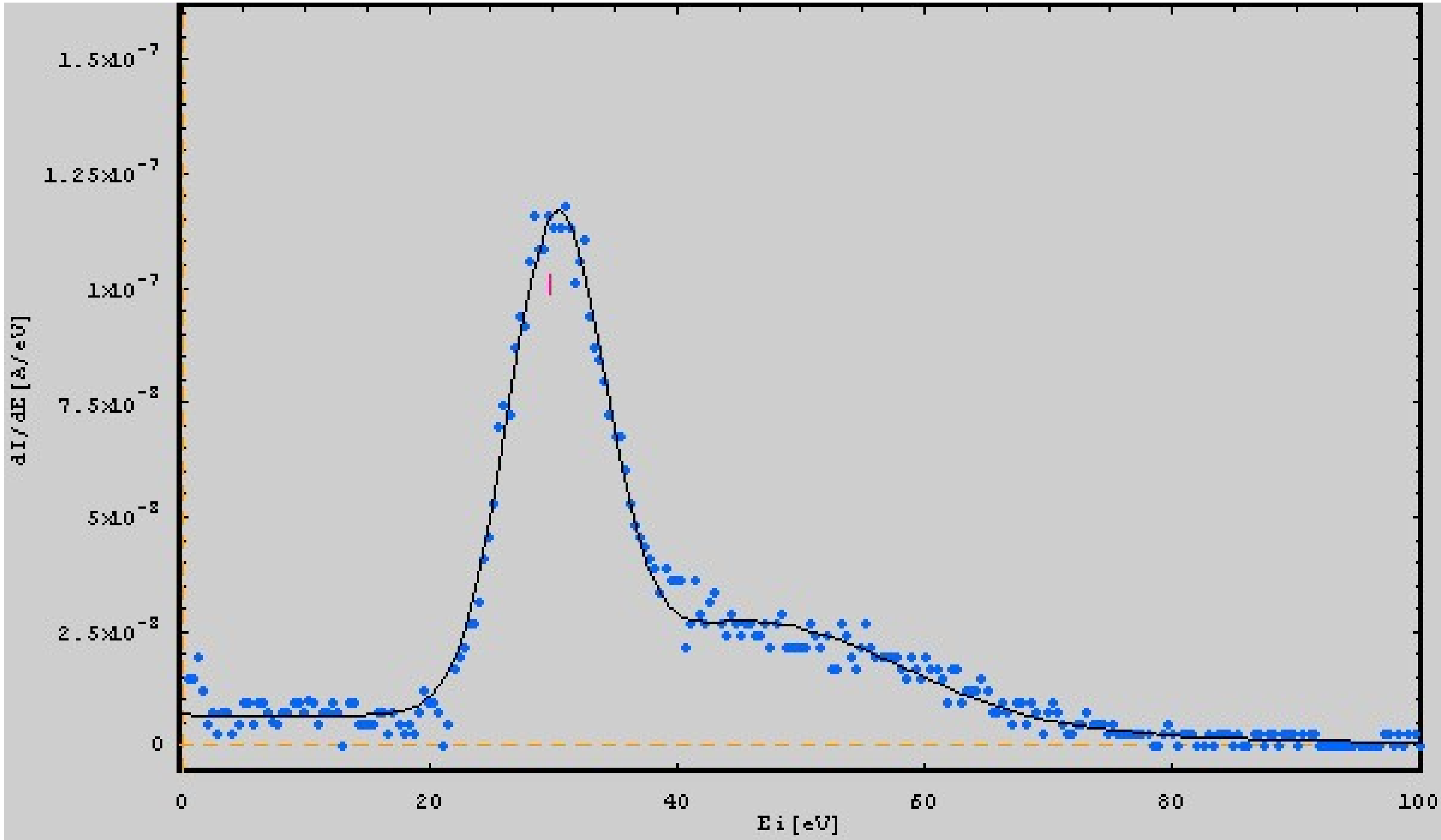
PIC simulation of photo-e along booms (Thiébault et al., 2003)





Effect of magnetic field on photo-electron transport (Hilgers et al., 1992)

Detection of E-thruster ions



RPA analyser on SMART-1 (Capacci et al., 2003)

Specificity of JUICE environment

- Photo-emitted electron fluxes expected to be an order of magnitude lower than on Earth orbit (typically ~10^{-5} Am^{-2} on Earth)
- Secondary electron fluxes may be signicative (typically ~10^{-5} Am^{-2} for Jovian env)
- Ion ram fluxes (speed up to ~100 kms^{-1})

Mitigation techniques for charged particle contamination

- Choice of material depending on emissivity
- Choice of location of detector
- Use of electrostatic potential barriers
- May require accurate modelling

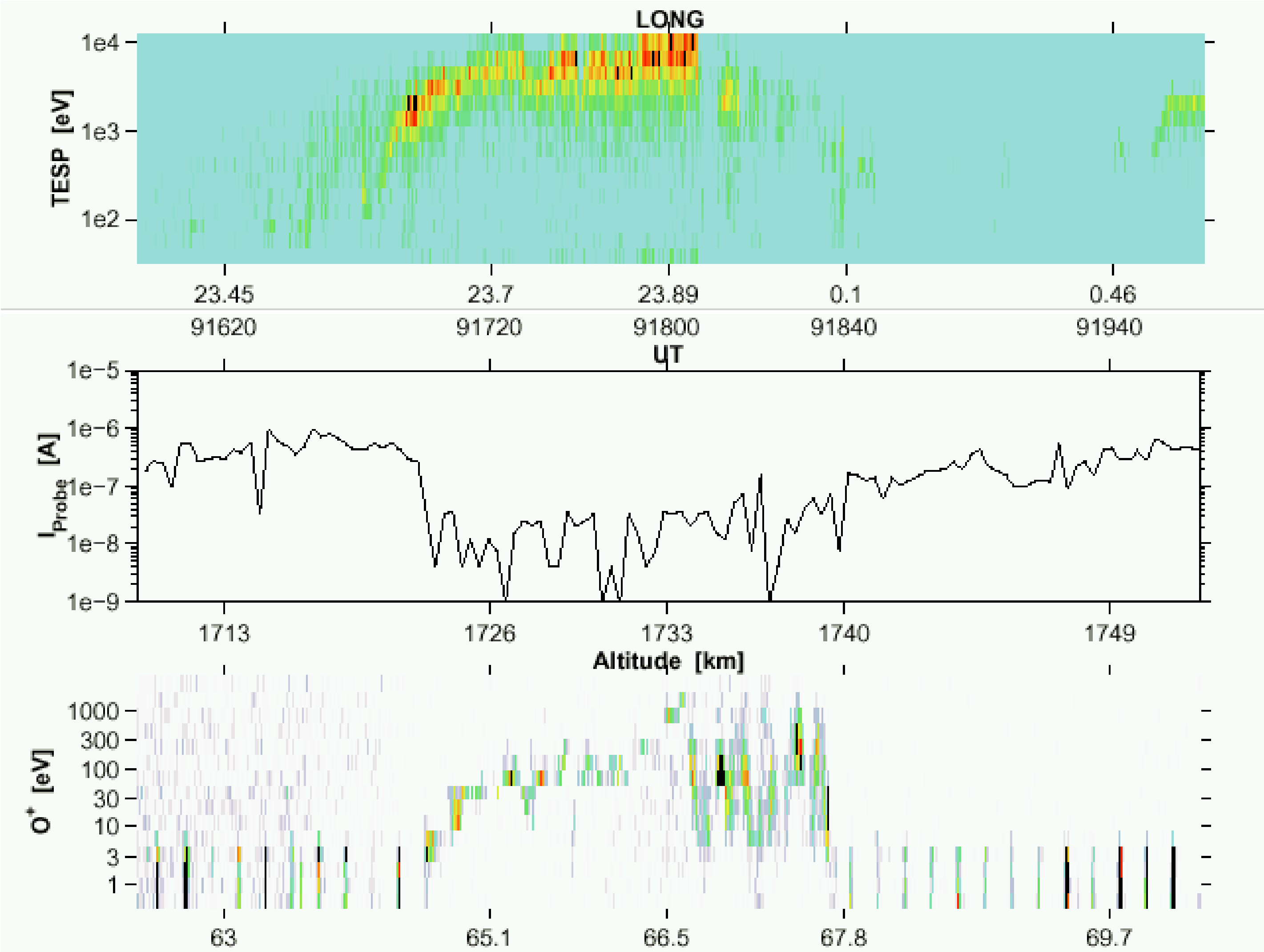
3. Surface charge effects

- Negative charging
  - Example: Freja (Wahlund, Eriksson, Hilgers), DMSP (Many AFRL papers), ISEE-1 in sun light (Olsen and Whipple, 1988)
- Positive charging
  - Example: Interball-2 (Hamelin et al.), Rosetta (cf Berthelier), Ulysses (Scime et al.)
- Active voltage source
  - Example solar array

Negative surface charging

- Often slightly negative in dense ionospheric plasma but also a few tens of volts, sometimes up to several kilovolts, in magnetospheric plasma:
  - in eclipse
  - under irradiation by > 1keV electrons fluxes
  - in low density regions (typically less than 100 cm^{-3})
- Few example of high level charging in daylight explained by potential barriers due to negative parts of the spacecraft (on the non-sunlit side) or negative space charge.

Kilo-Volt Negative Charging



Blind sensor
ESD risk
Contamination
…

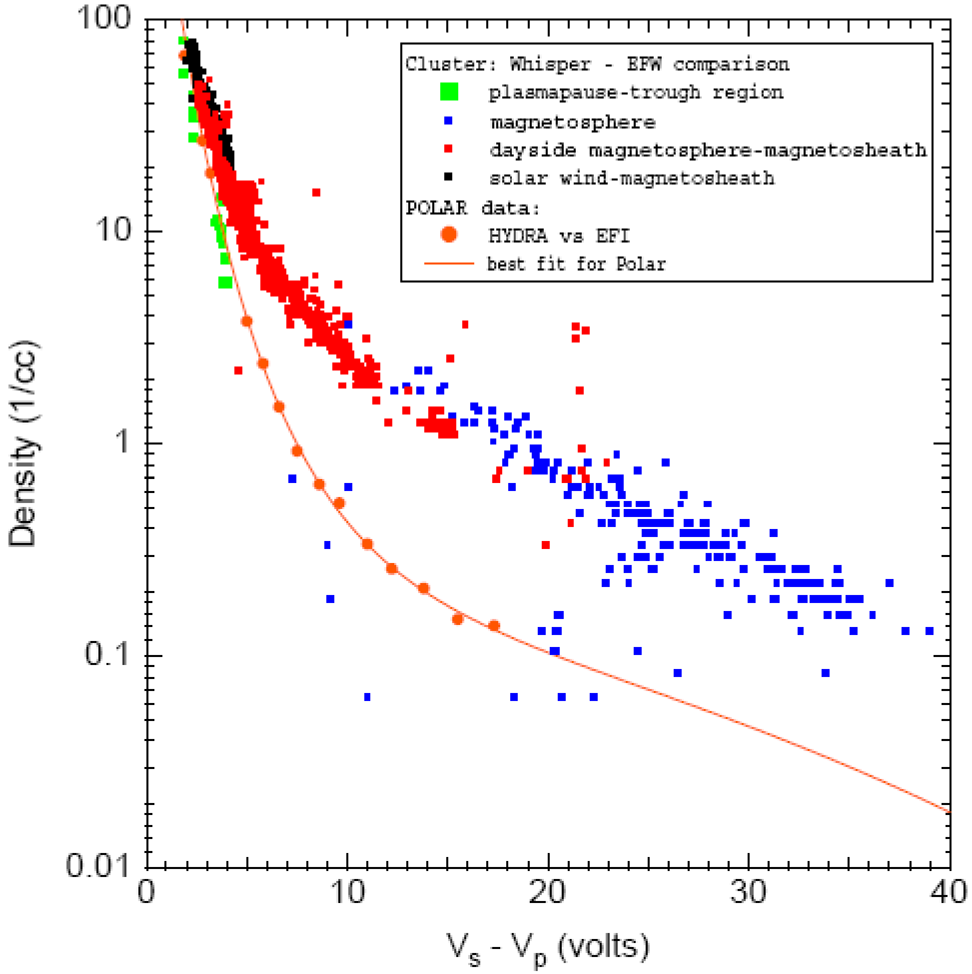
1-10 keV
electrons is
A concern

(e.g, Sasot et al.)

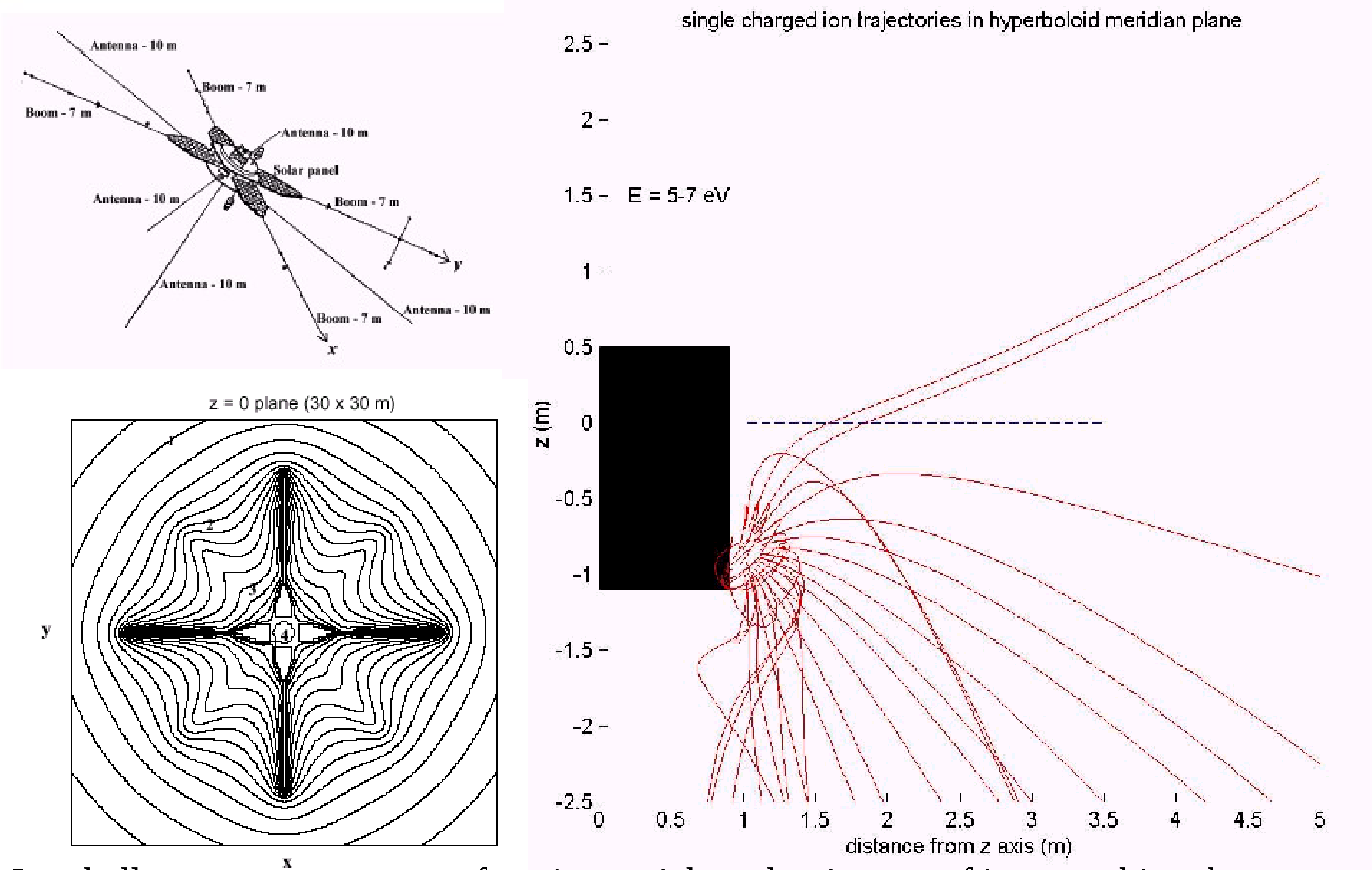
Positive charging

- Often a few volts positive driven by photo-electron emission in the low density magnetosphere, sometimes a few tens of volts in depleted regions, e.g., lobes, auroral acceleration regions.

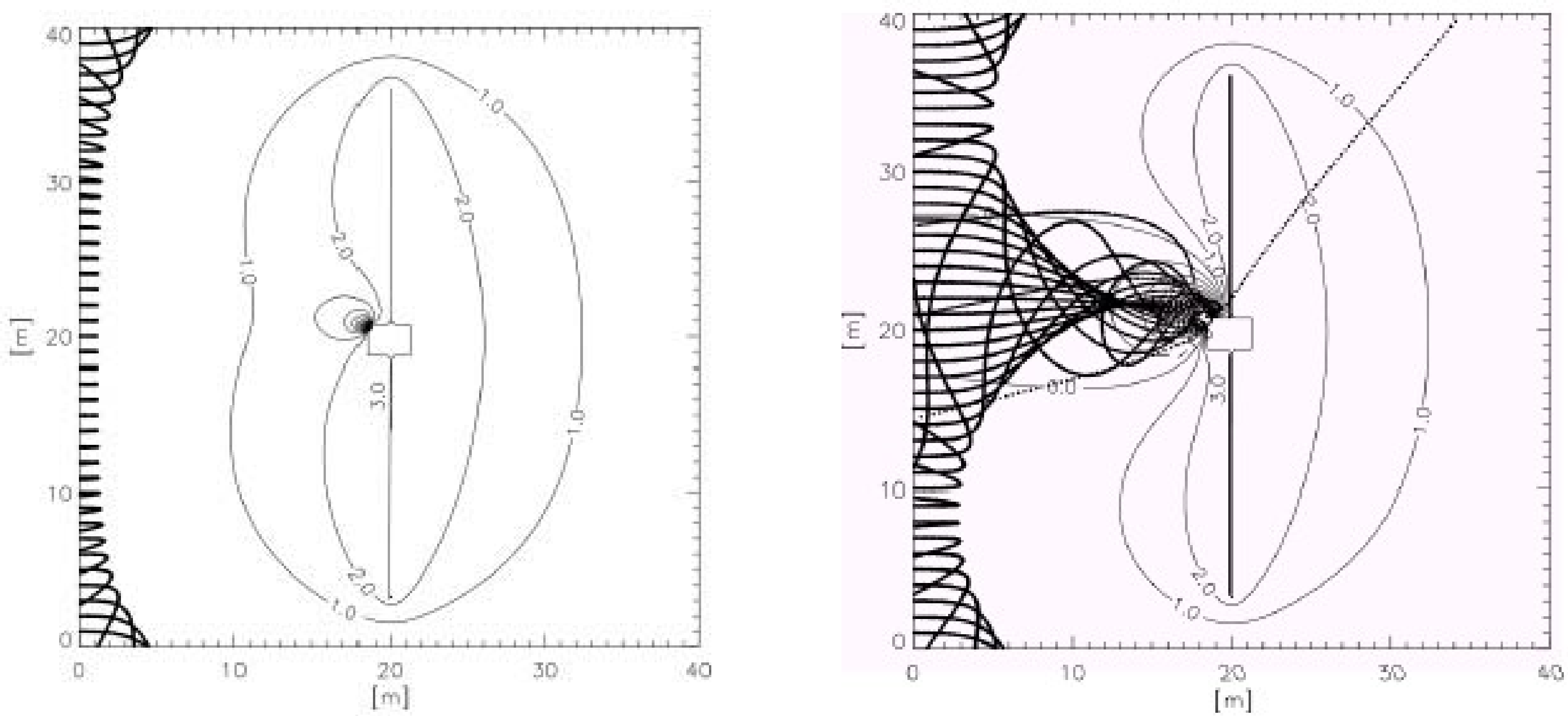
Spacecraft Potential in the magnetosphere



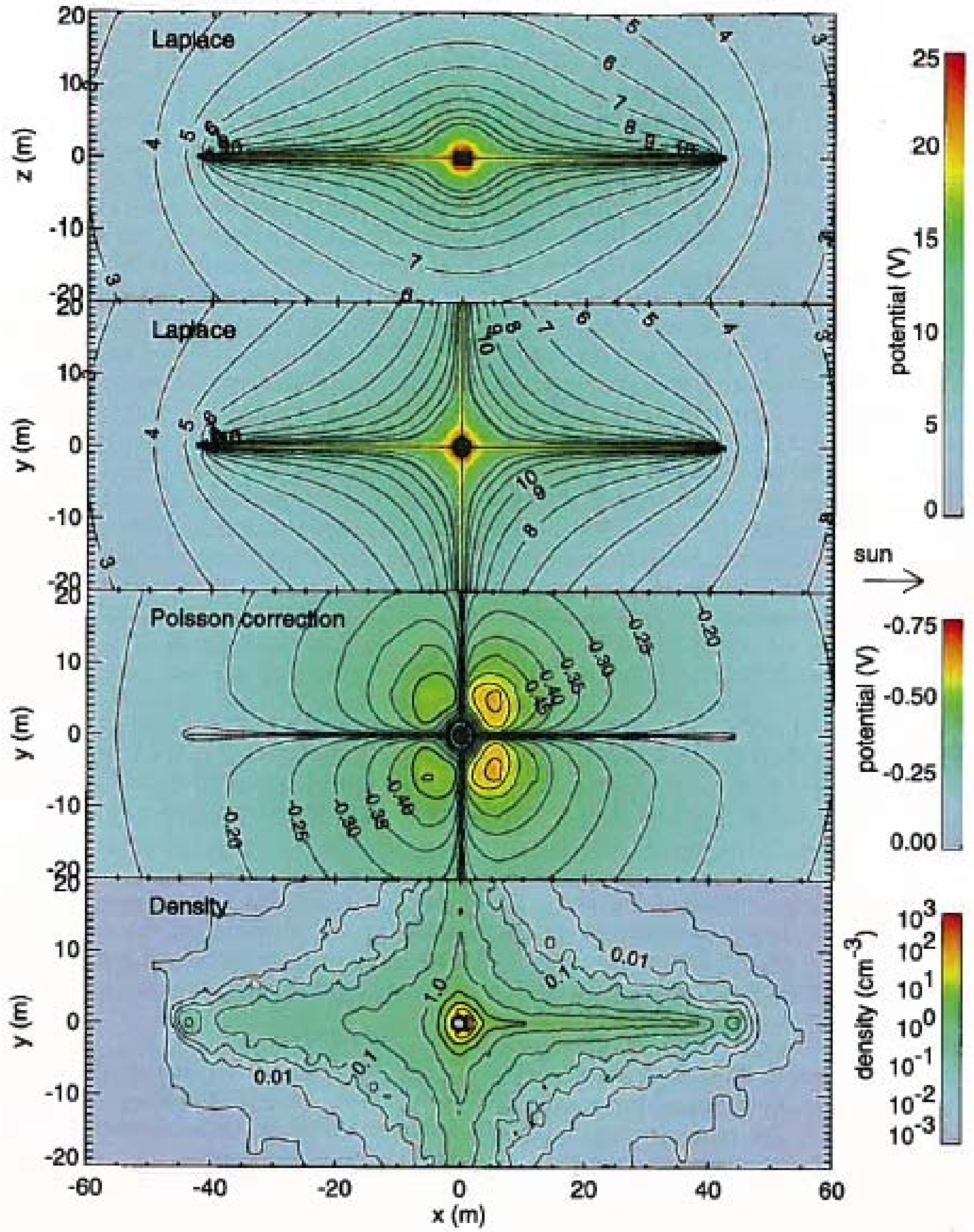
spacecraft potential vs density (Pedersen et al., 2001)



Interball geometry, contours of equipotentials and trajectory of ions reaching the HYPERBOLOID particle detector (from Hamelin et al., 2001).



Simulation of cometary ion collection by a detector on Rosetta at +3V with a grid at 0V (left) and a grid a –50 V (right) (from Nyffenegger et al., 2001).



boom potential effect (Cully et al., 2007)

Specificity of JUICE environment

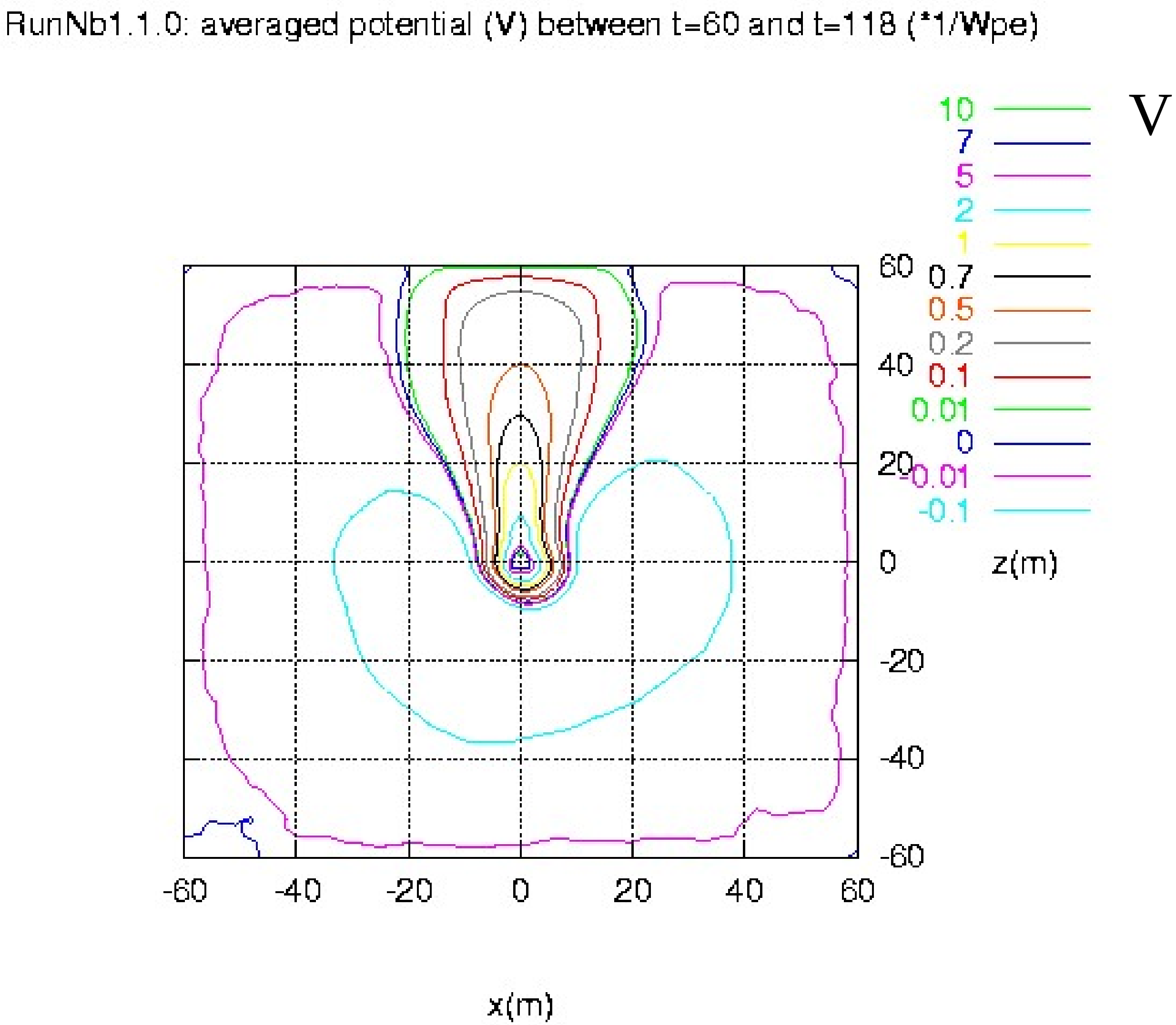
- Surfaces rather negative because of the low photo-emission but not systematically.
- Ram-wake differences

Mitigation techniques for surface charging

- Choice of material with high secondary electron emission and good conductivity.
- Reduce potential via active particle emission.
- Adapt entrance potential of detector.
- Location of detector (possibly on boom).
- Inverse method to retrieve plasma parameters (e.g., Genot et al., Geach. et al.)

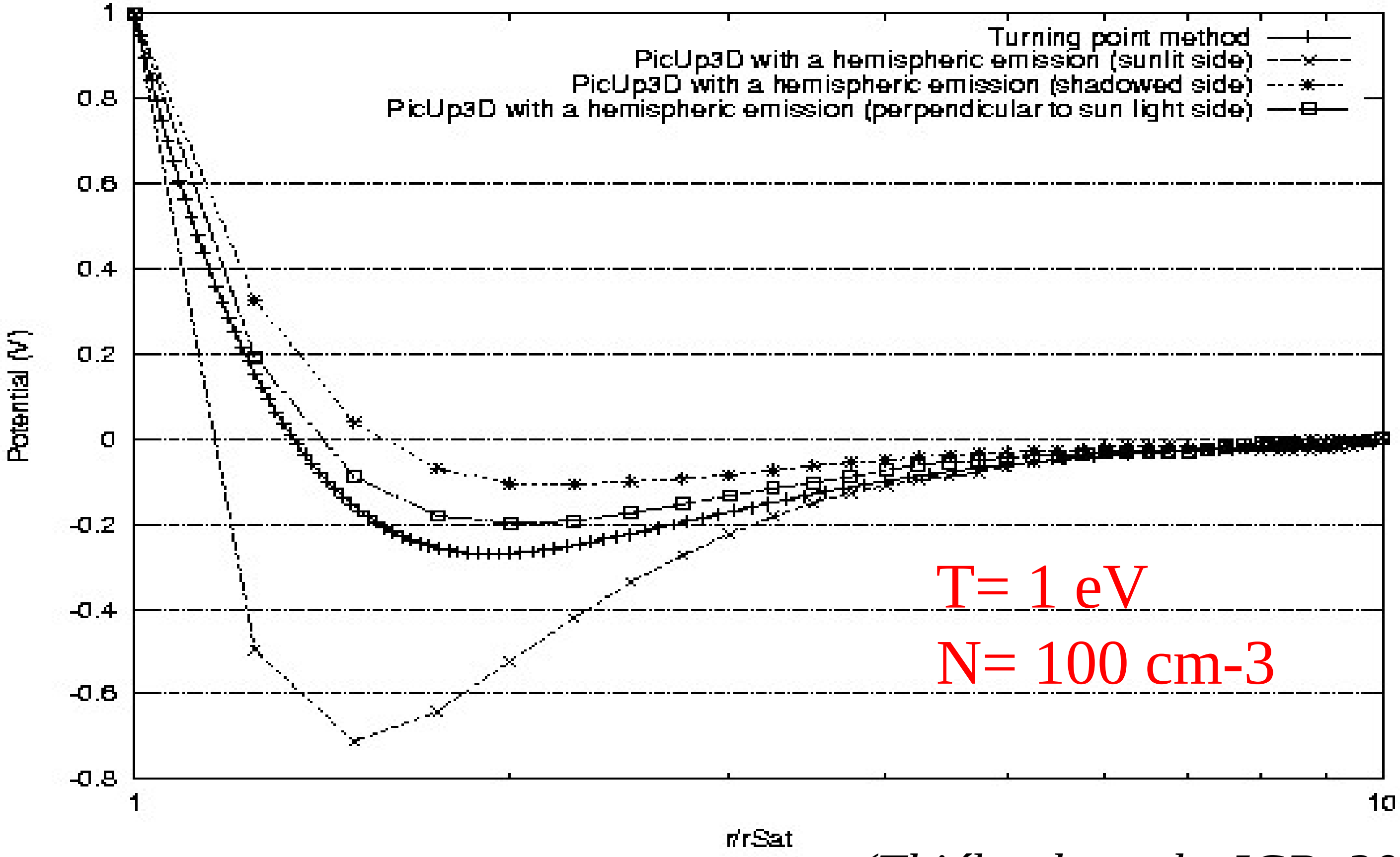
4. Space charge effects

- Active source environment
  - Example: Polar (Singh et al., 2001), Cluster (ESA unpublished), SMART-1
- Secondary electron induced potential barriers
  - Example: ATS-6 (Whipple), Cluster(Zhao, ESA), Rosetta (Roussel et al.)
- Wake
  - Examples: (Cooke, Samir, …), ISEE-1 (A. Pedersen, 1984), Cluster (Engwal et al. , Anderson et al.)



Preliminary results of potential distribution around an ASPOC like ion plume on a cylindrical spacecraft (Thiébault et al., 2003).

Negative potential barrier

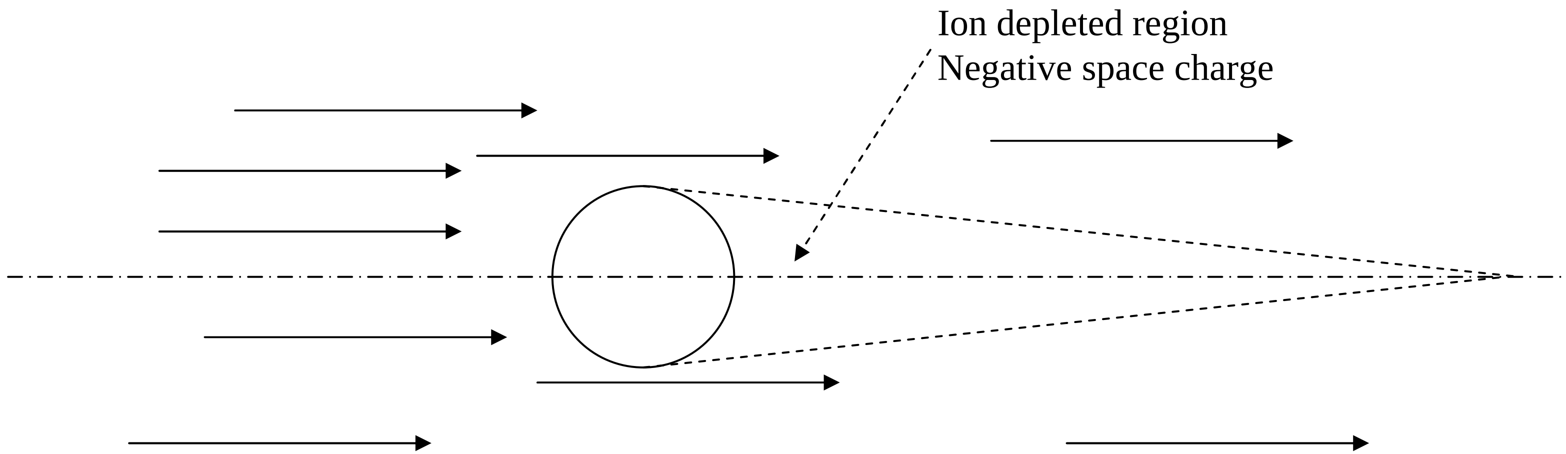


(Thiébault et al., JGR, 2004)

Wake

Effect of wake in meso-sonic regime

- Ion depletion
- Space charge



Mitigation techniques

- Reduce number of secondary particles.
- Use of modelling and inverse methods.
- Choice of location of detectors.

Specificity of JUICE environment

- Possibility of negative barrier due to secondary electron emission
- Wake space charge expected

5. Quantitative estimates

- Estimate of current <= hypothesis on distribution of particles and potential
- Estimate of potential <= requires computation of current and solving current balance equation
- Time scales <= requires capacitance estimate

Typical current density (Earth)

Region	Particle density (SI)	Bulk velocity (SI)	Temperature (eV)	Debye length (SI)	Electron current density (SI)	Ram ion current density (SI)
Ionosphere (min)	1.E+09	7.E+03	1.E-01	7.E-02	2.E-05	1.E-06
Ionosphere (max)	1.E+12	7.E+03	1.E-01	2.E-03	2.E-02	1.E-03
Plasmasphere	1.E+07	7.E+03	1.E+00	2.E+00	5.E-07	1.E-08
Auroral arcs	1.E+06		1.E+04	7.E+02	5.E-06	
Plasmasheet	1.E+06	7.E+03	1.E+04	7.E+02	5.E-06	1.E-09
Lobe	1.E+05		1.E+02	2.E+02	5.E-08	
Magnetosheath	1.E+06		1.E+02	7.E+01	5.E-07	
Solar wind	1.E+06	3.E+05	1.E+00	7.E+00	5.E-08	5.E-08
Photo-emission	1.E+09		1.E+00	2.E-01	-5.E-05	

Current density typically $< 10^{-5}$ A m^{-2} (1 nA cm^{-2})

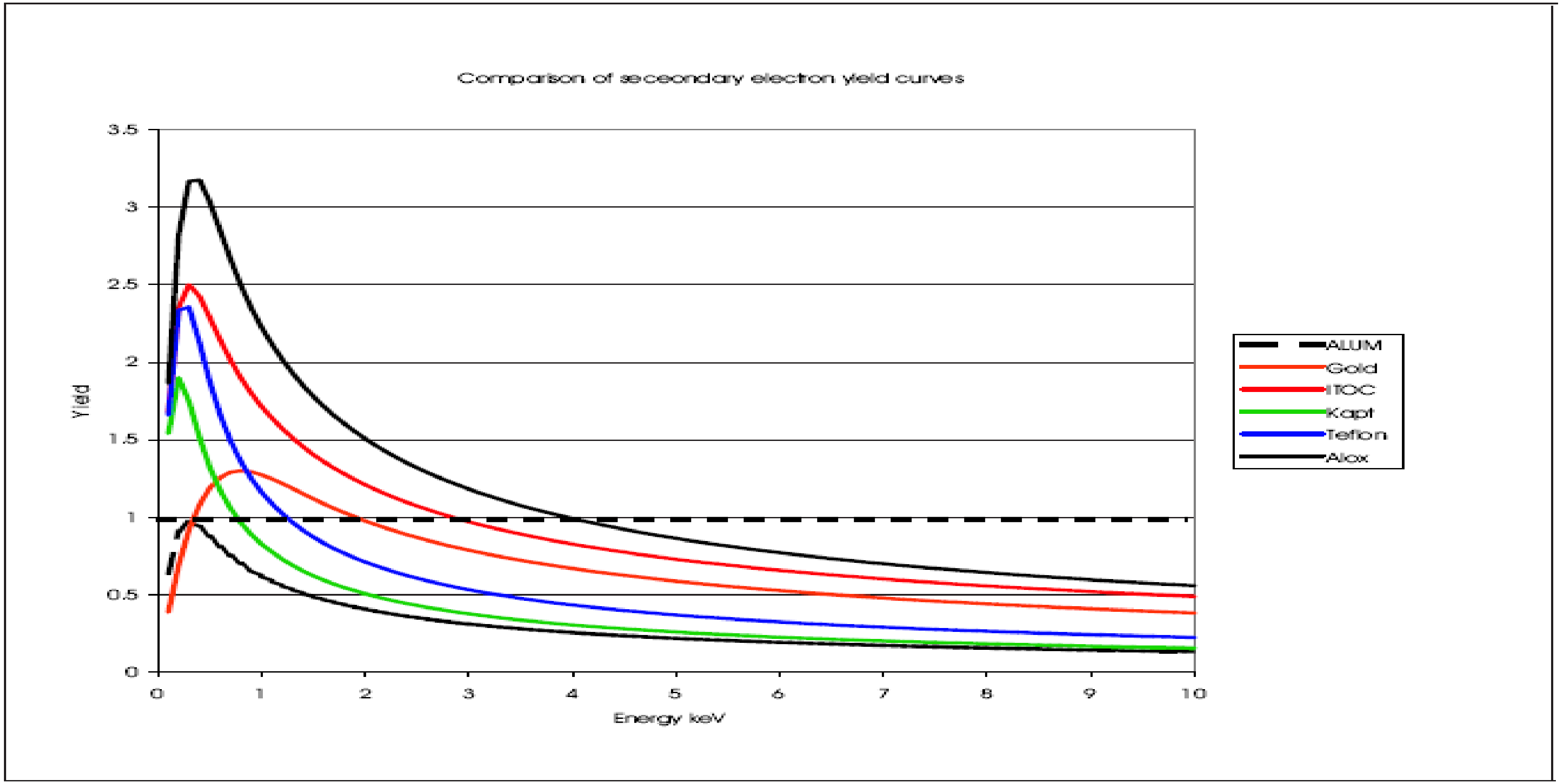
Sunlit surfaces tend to charge positively except in high density regions.

Typical current density (Jupiter)

Region	Density (SI)	Drift velocity (SI)	Temperature (eV)	Debye length (SI)	Electron density current (SI)	Drift ion current (SI)
Cold Torus (3.5 RJ)	5.E+07	4.E+04	5.E-01	7.E-01	2.E-06	4.E-07
Warm Torus (5.5 RJ)	1.E+09	7.E+04	1.E+00	2.E-01	5.E-05	1.E-05
Hot Torus (7 RJ)	1.E+09	8.E+04	1.E+01	7.E-01	2.E-04	1.E-05
Plasmasheet (8 RJ)	1.E+07	1.E+05	1.E+03	7.E+01	2.E-05	
Outer mag (20 RJ)	1.E+06	2.E+05	1.E+03	2.E+02	2.E-06	3.E-08
Photo-emission	4.E+07		1.E+00	1.E+00	-2.E-06	

Based on Garrett and Hoffmann (2000)

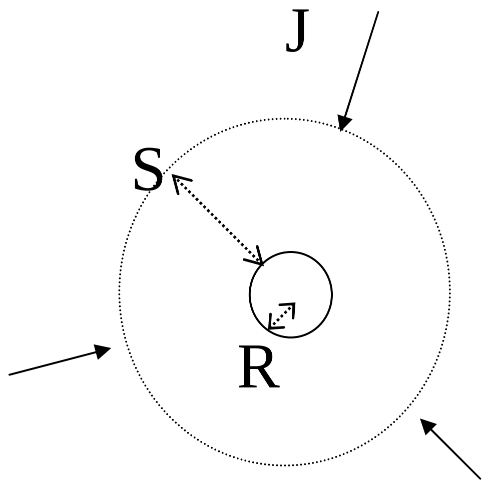
Secondary electron emission yield



Critically depending on surface material properties.
Contaminants should be taken into account.

Sheath

Volume around the object where space charge is significant (i.e., $\phi > kT/e$)

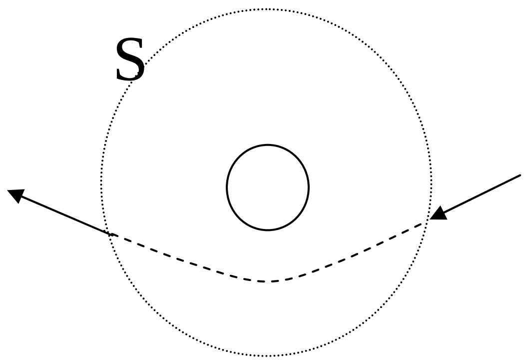


Crude approximation of current, for a sheath of size S,

attracted species: $I_a = 4\pi S^2 J_a$

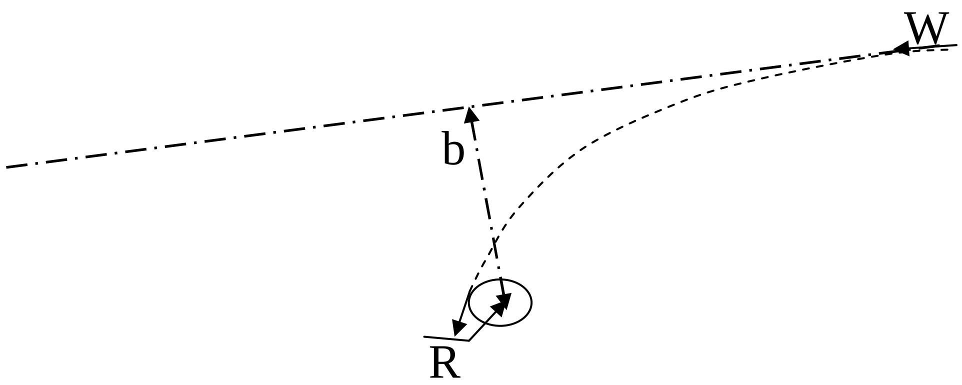
repelled species: $I_r = 4\pi R^2 \exp\left(-\frac{q_r \phi}{kT_r}\right) J_r$

However this neglects potential barriers and orbital motion effects:



Orbital motion limitation in vacuum

(cf Mott-Smith and Langmuir, 1926)



Conservation of energy

$$mW_R^{\ 2} + 2q\varphi = mW^2$$

and angular momentum: $RW_R = bW$

=> $\quad b < R\left(1 - \frac{2q\varphi}{mW^2}\right)^{\frac{1}{2}}$ to reach R

This constitutes an effective interaction length.

Attracted species: $\quad I_a = 4\pi\, R^2\left(1 - \frac{q_a\varphi}{kT}\right)J_a$

Repelled species: $\quad I_r = 4\pi\, R^2 \exp\left(-\frac{q_r\varphi}{kT}\right)J_r$

Magnetic field limitation

Minimum distance at infinity to reach R, [Parker and Murphy, 1967].

$$R_p = R\left(1+\sqrt{\frac{8 q_a \phi}{m \omega_a^2 R^2}}\right)^{1/2}$$

Crude approximation of current, for a sheath of size S,

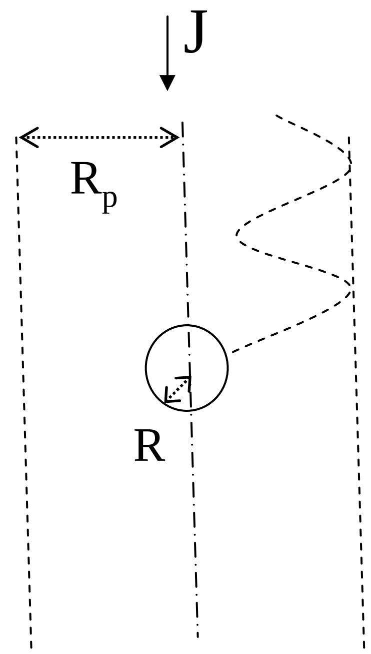
attracted species:

$$I_a = 4\pi R_p^2 J_a$$

repelled species:

$$I_r = 4\pi R^2 \exp\left(-\frac{q_r \phi}{k T_r}\right) J_r$$

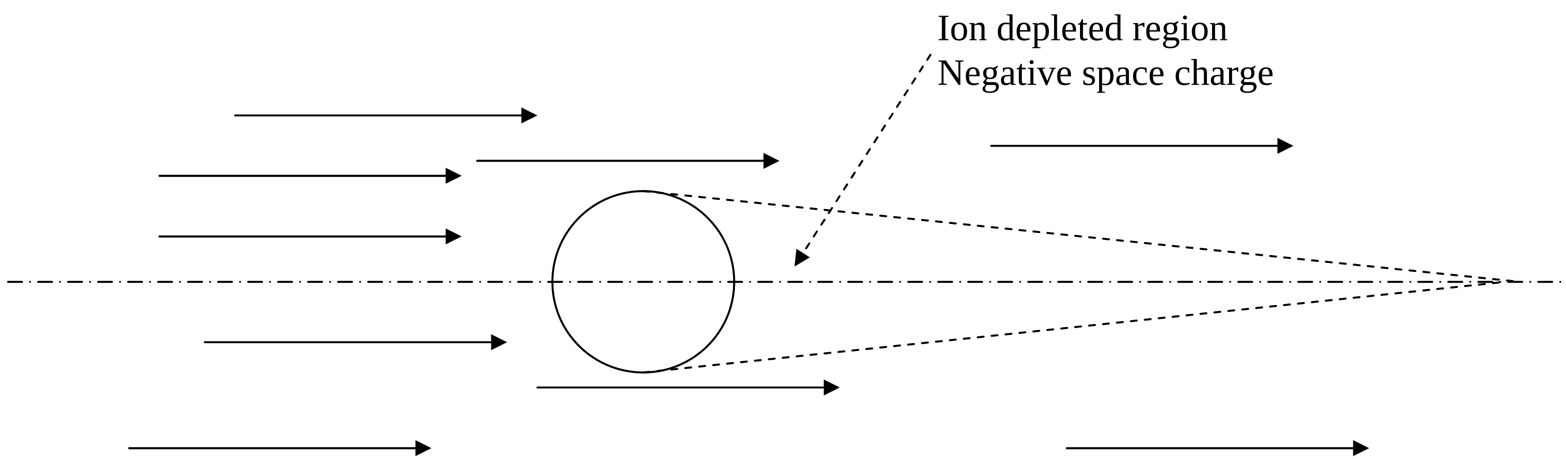
There is an improved formula to take into account temperature [Lafranboise]



Wake

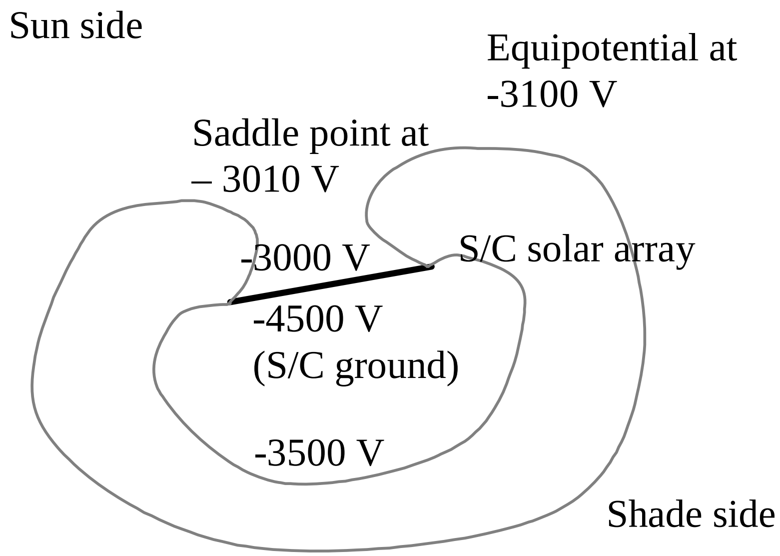
Effect of wake in meso-sonic regime

- Ion depletion
- Space charge



Differential charging

- Potential barrier blocks secondary (photo-emitted) electron emission on one side.



5.2 Computational methods

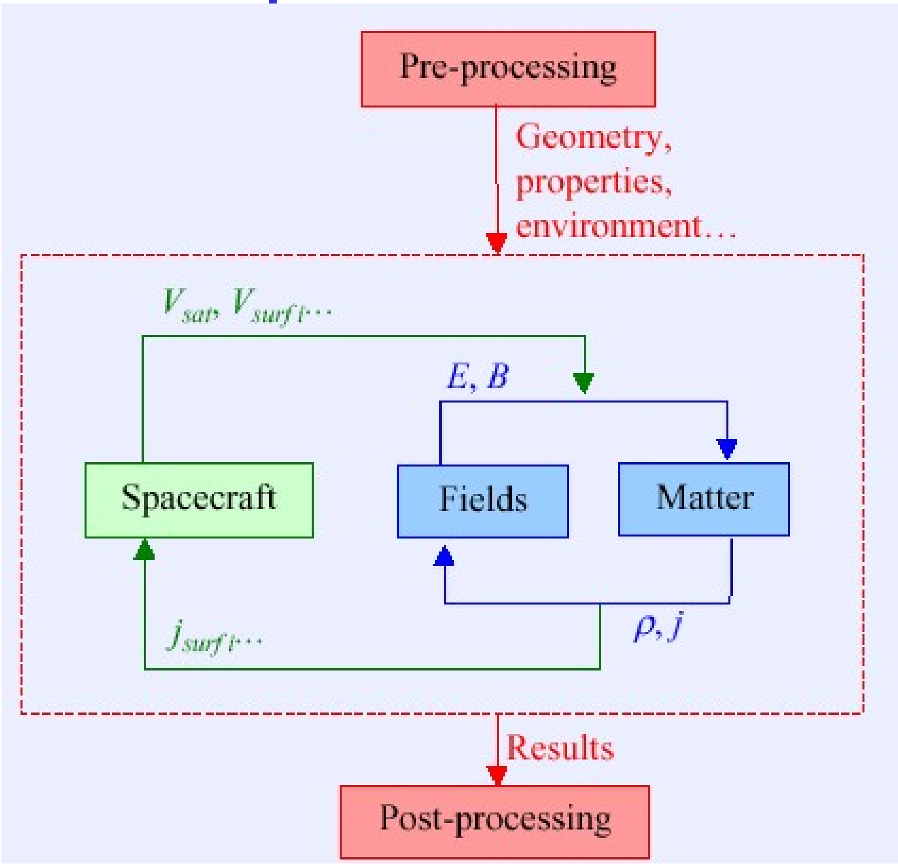
- Analytical methods (when allowed by simplifying hypotheses, consideration of symmetry, time scale).
  - Cf: Laframboise, Parker, Parrot, Sanmartin, etc…
- For general case (complexe geometry, multi-sources, time dependency): simulation of a statistically representative set of particles.

SPIS Code (collaboration: ESA, CNES, Onera, Artenum)

- Unstructured surface and volume mesh.
- Includes various modules (e.g., sources, 1D, 2D elements) and databases (e.g., for material properties).
- Spacecraft equivalent electric circuit solver.
- PIC/Boltzmann distributions
- Poisson solver (FEM with conjugate gradient, linear/ non-linear)
- OO and Java based.
- Supported by SPINE, ESA, CNES.
- Open source and freely available on www.spis.org.

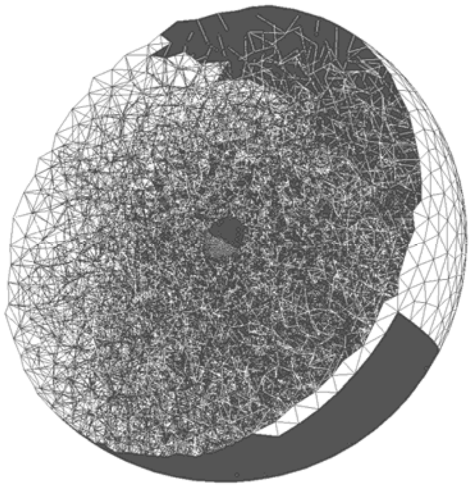
SPIS-NUM
Simulation loop

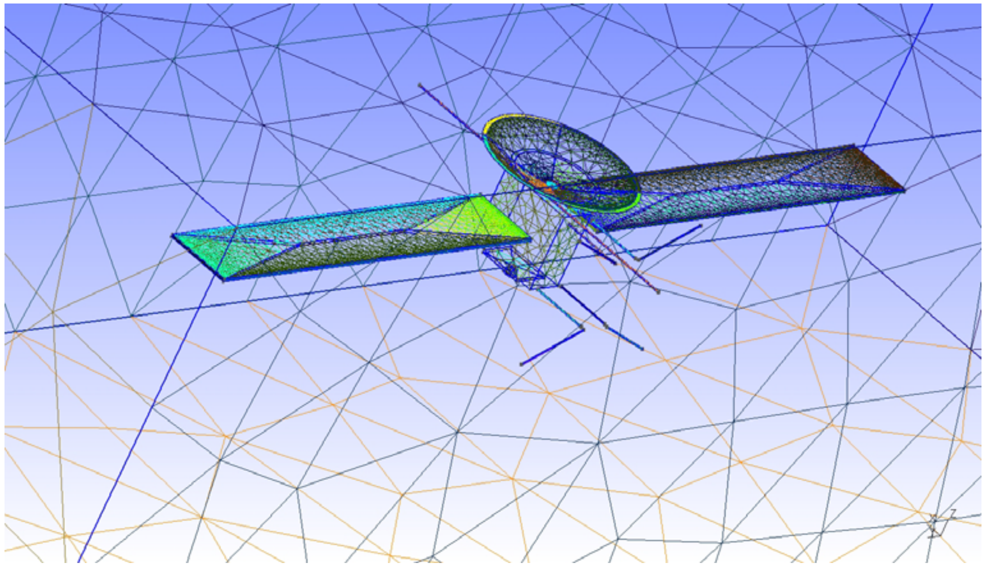
- Definition of all properties (geometry, environment, material, etc…)
- Plasma dynamics loop
- Spacecraft circuit loop
- Post-processing and visualization of computation results



Geometry/meshing

Sophisticated geometries
Gmsh modeler/mesher
Possibility to mesh up-to 1E6 cells mesh (unstructured).
Mesh size ratio largest to smallest element up to 1e5
Strong improvement of meshing algorithms in Gmsh 2.4 and higher





Plasma model

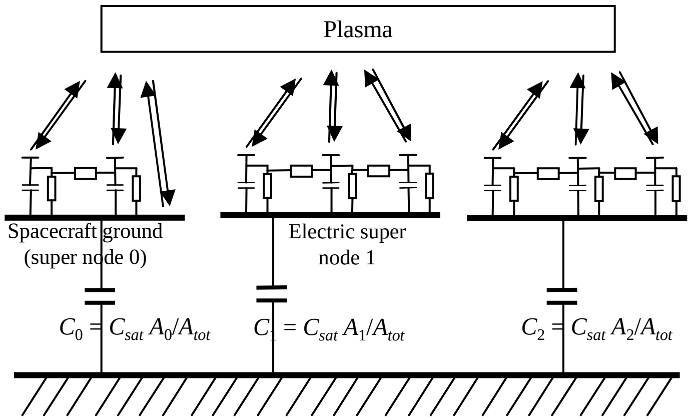
- Particle-In-Cell Model
- Bi-maxwellian environment (2 electron populations and 2 ion/neutral populations)
    - Maxwell injection at external boundaries + initial volume filling
    - Injection distributed over the time step
- Analytical model
    - Boltzmann distribution (unlimited, linear for positive potentials)
    - User-defined reference density for null voltage
    - <u>Generally correct for negative potentials (for electrons)</u>
- Exact trajectory integration in case of uniform E in each cell (and no B)
    - Because the potential is considered as step-wise linear
    - Exact analytical parabolic trajectory
- Else
    - (If presence of a magnetic field,
    - Or special shape of potential (non linear) in the vicinity of thin wires (1D) or thin plates (2D))
    - Iterative method : Runge-Kutta Cash-Karp iterative and adaptive method (4th and 5th order to determine and control the error)
- Backtracking for current collection on the spacecraft (only for ambient particles)

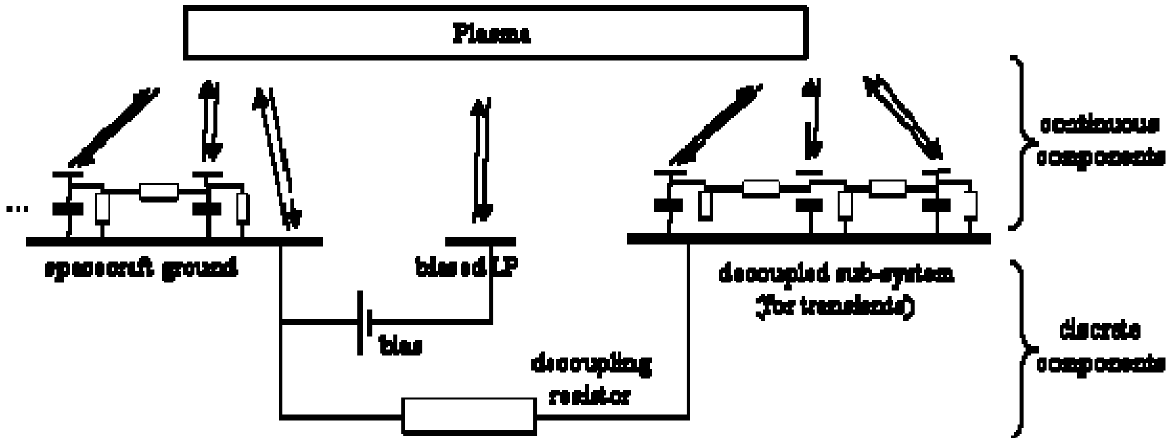
Poisson solver model

- Finite elements method
- Linear solver
  - Iterative solver
  - Conjugate gradient method with pre-conditionner
  - Based on java Lapack library
- Non linear solver
  - The non-linear Poisson equation includes 1 (or 2) Boltzmann distributions of electrons
  - Implicit scheme (Newton type) : major advantage to be stable even for cells larger than Debye length
    - Validity (user responsability): negative potentials and no potential barrier (particles with no inerty)
  - Extendable to other analytical laws
- Poisson boundary conditions on potential are
  - On the spacecraft
    - Always Dirichlet (fixed potential)
    - Initial potential : user-defined (globally or locally)
  - On the external boundary
    - Dirichlet
    - Fourier (mixed Dirichlet-Neumann) with parameters defined so as to give an asymptotic behaviour in r^{-n}
      - $1/r$ ~ vacuum
      - $1/r^2$ ~ pre-sheath

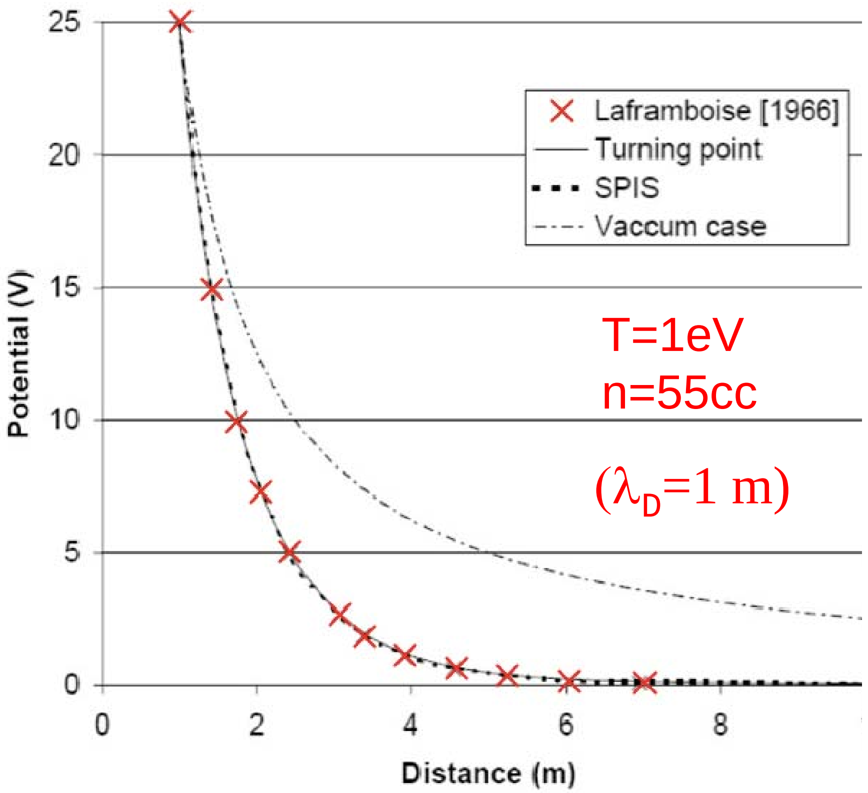
Spacecraft electrical circuit

– Current collection (as e.g. from the ambient plasma) and emission (as e.g. SEEE)
– Covering dielectric = R-L-C models
– Spacecraft capacitance : user-defined or exact calculation (through Gauss theorem)
– Possibility to have user-defined discrete components (R-C-V)

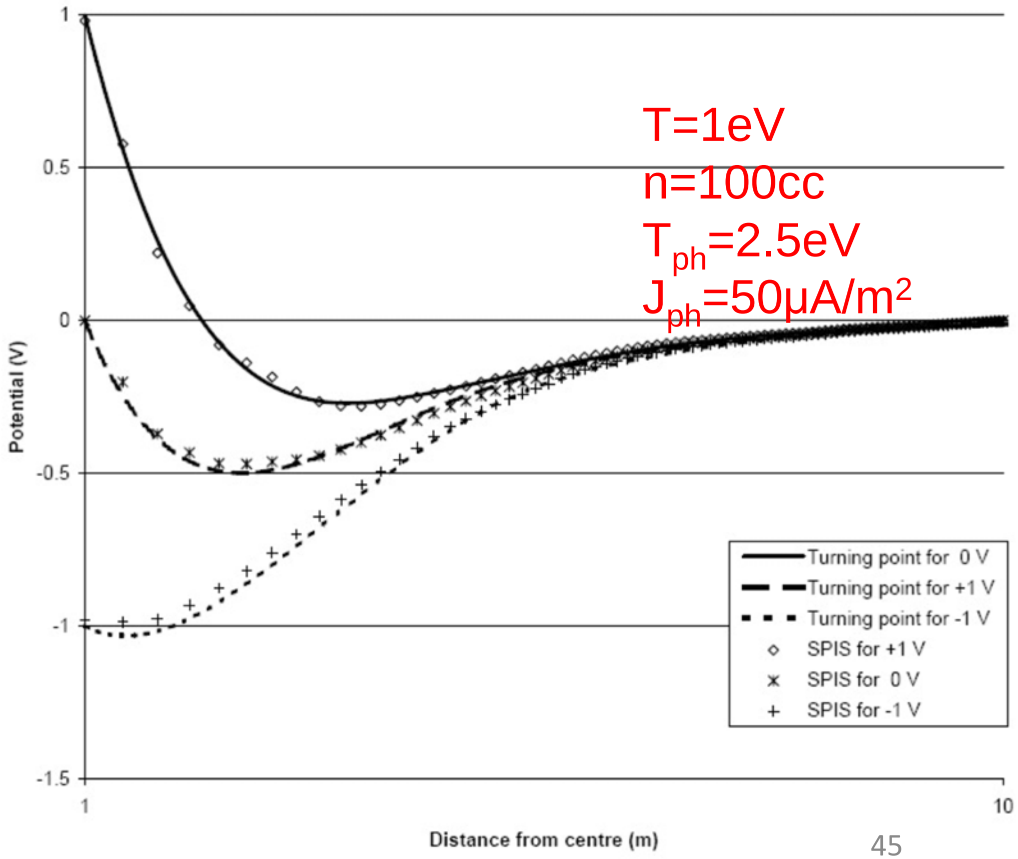




Examples of Validations

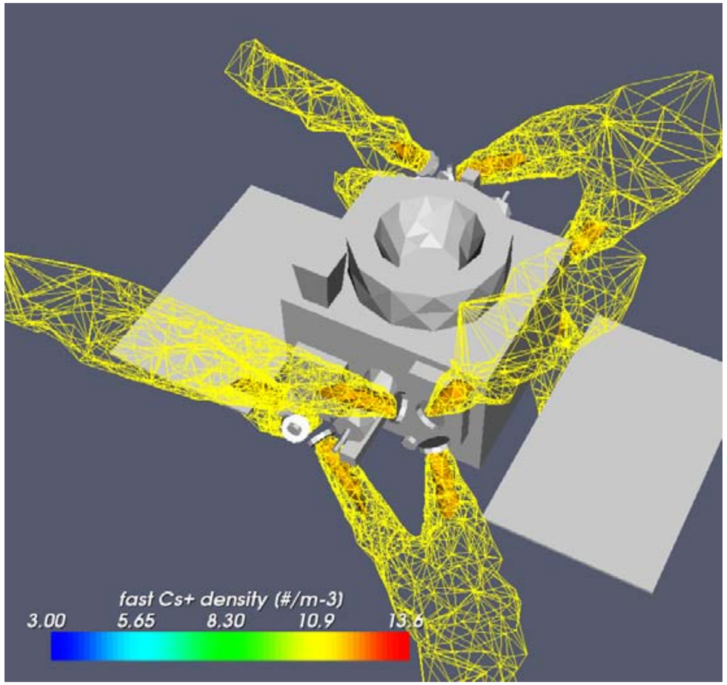


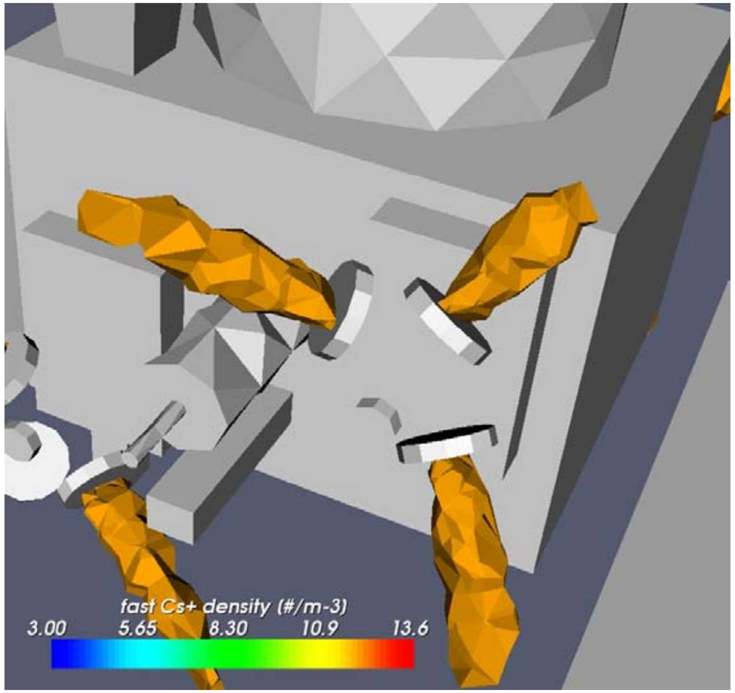
Potential versus radial distance without photoemission



Potential versus radial distance with photoemission

Application: Microscope FEEP plume plasma expansion



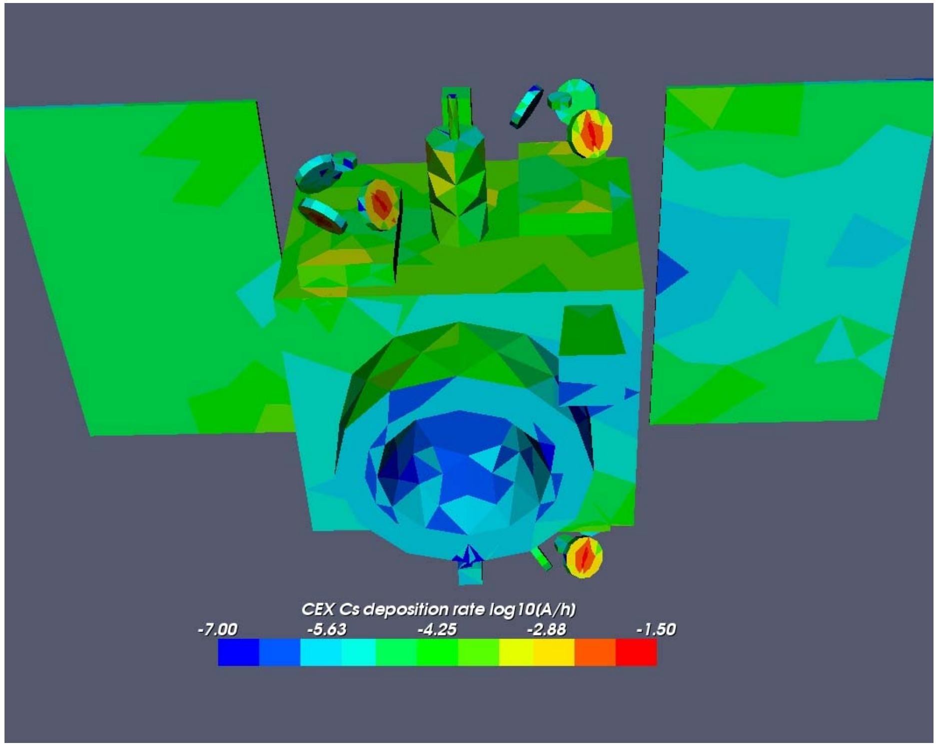


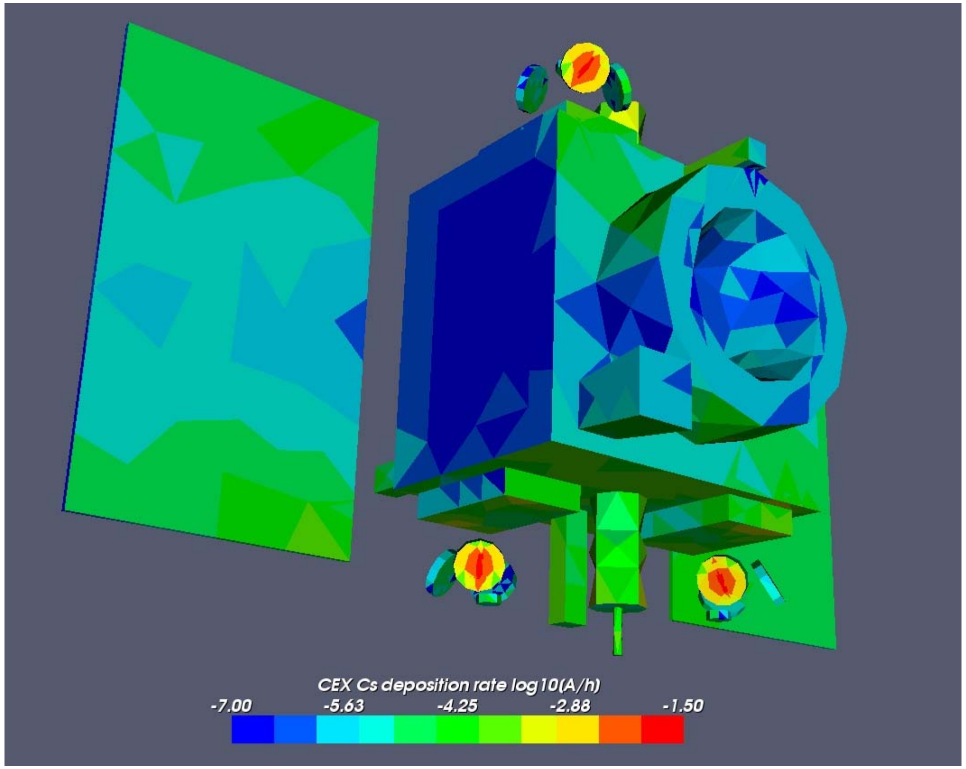
Ref.: Roussel et al., IEEE Trans. Plasma Sc., 36, 5, 2008.

iso-contour surfaces, n = 10^{11} m^{-3} (yellow) and 10^{12} m^{-3} (orange)

NB: mesh refined locally close to FEEP nozzles

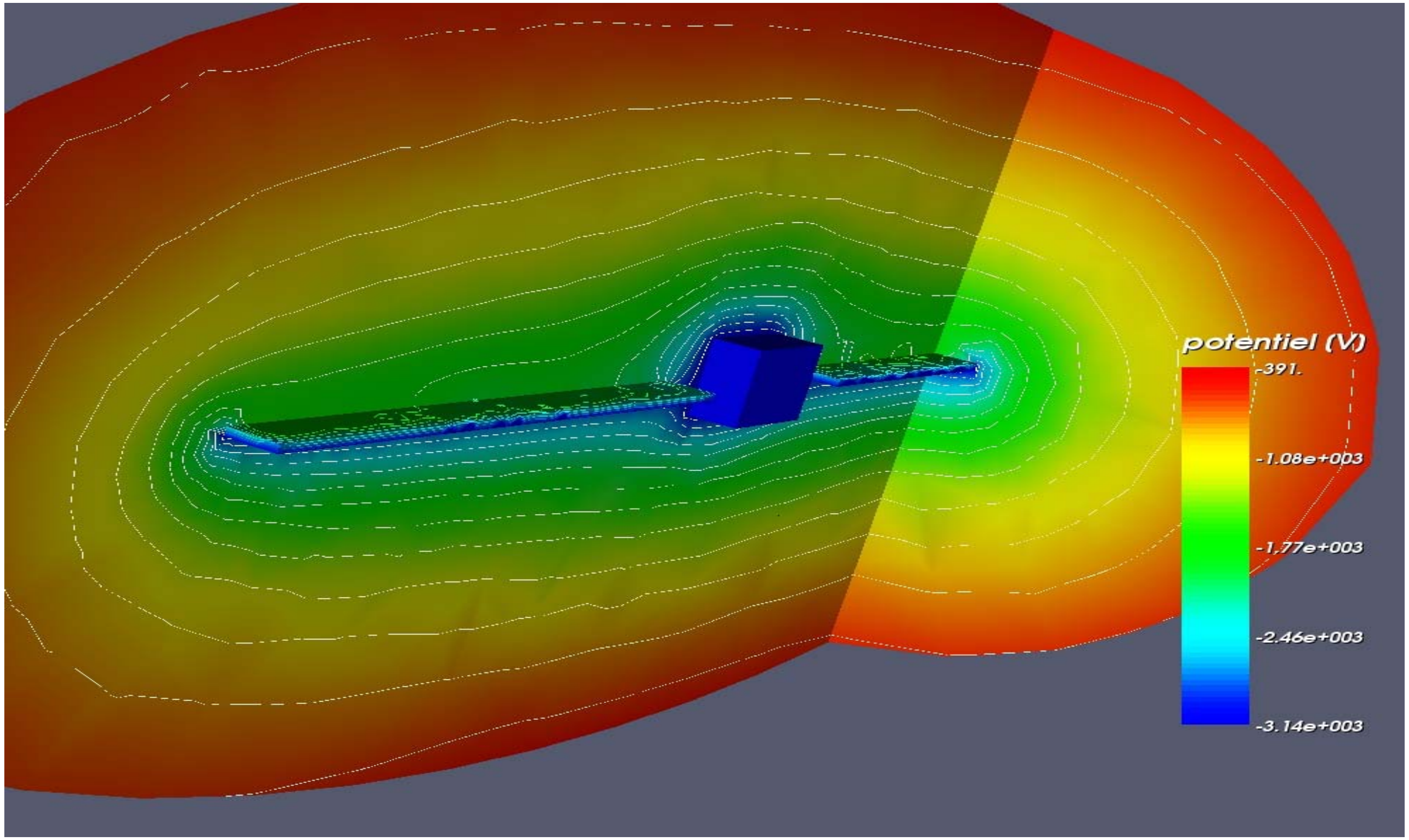
Contamination by secondary ions





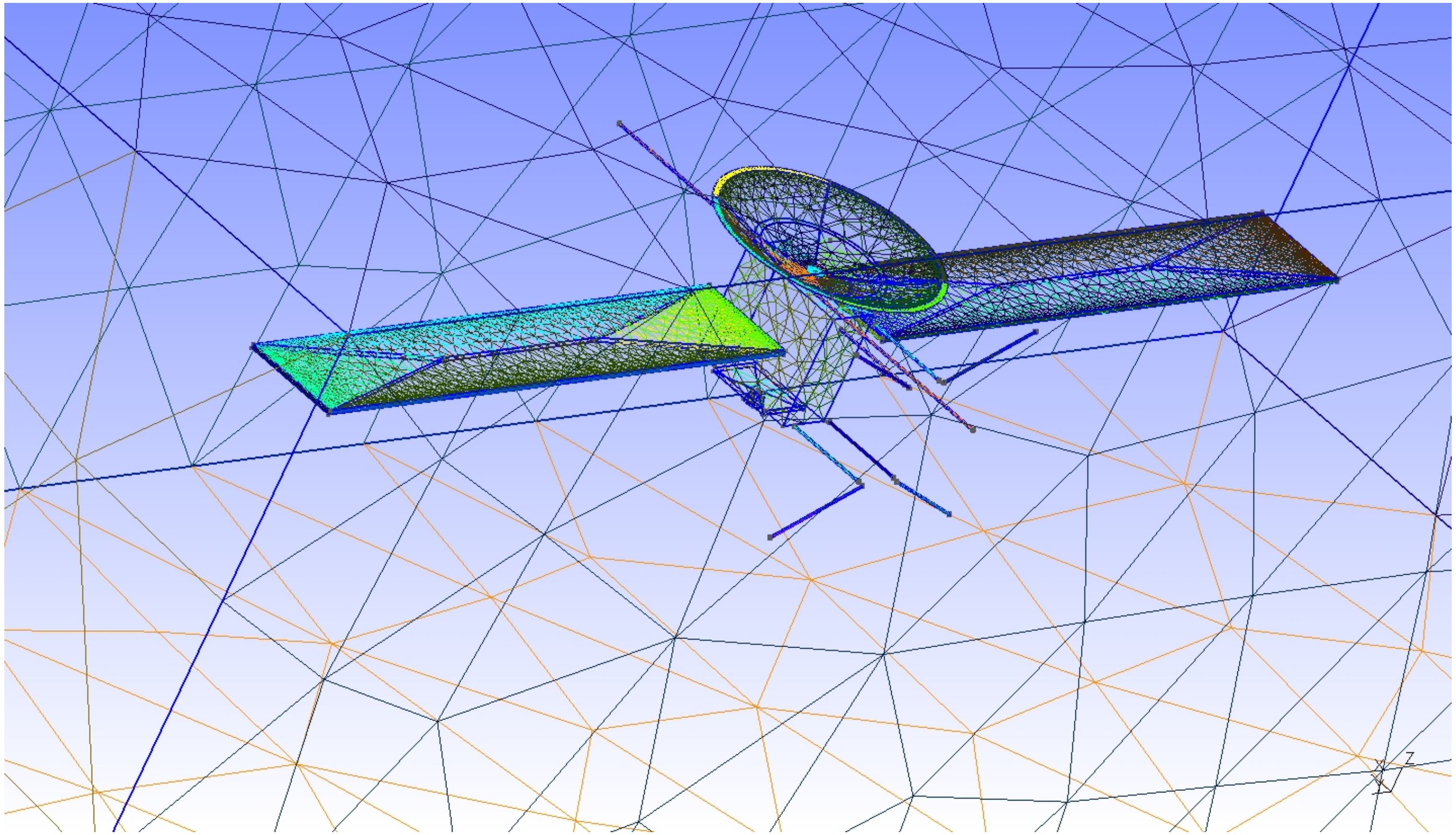
No direct impingement from thrusters but deposition of slow ions from CEX reaction

Application: kV charging in GEO



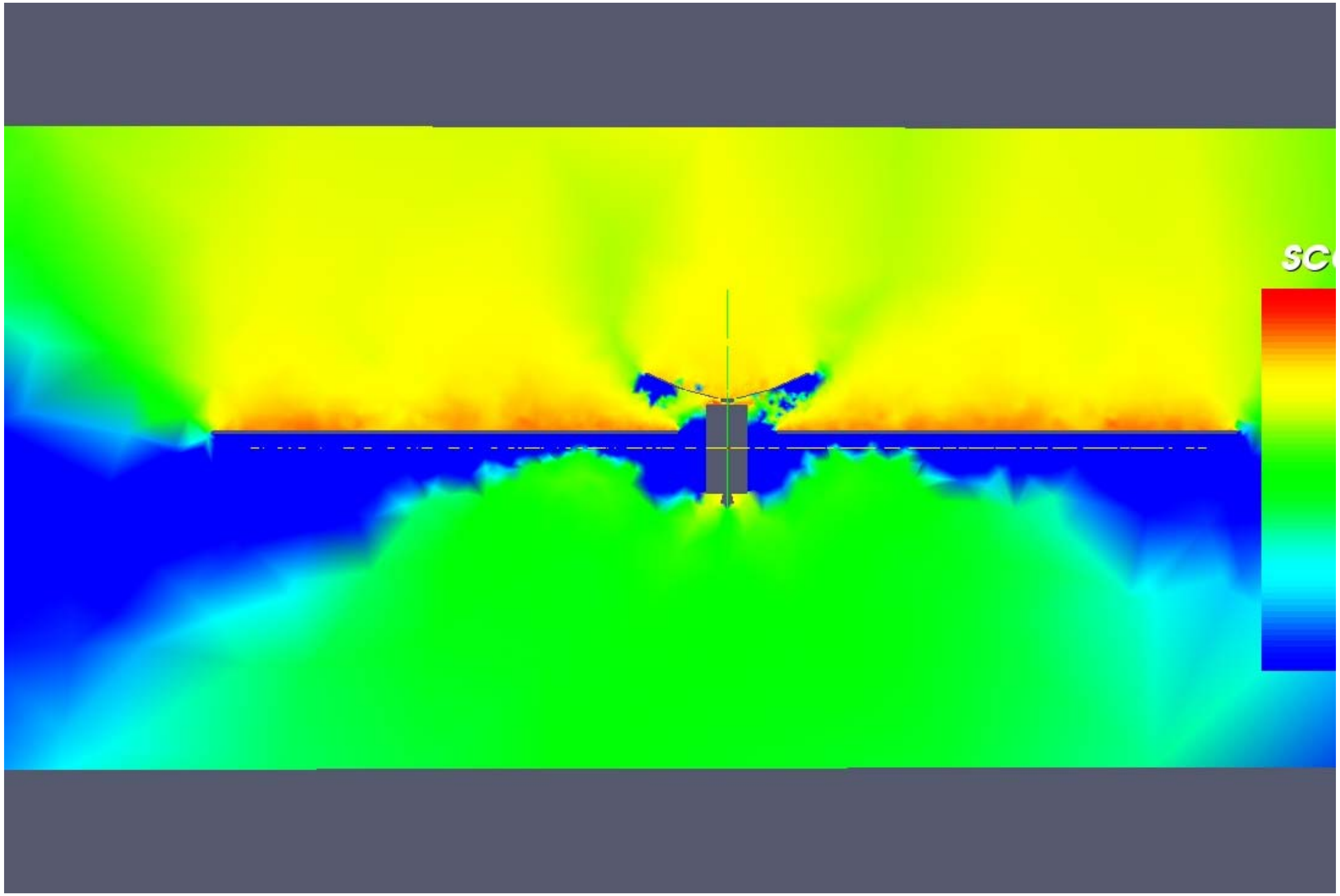
Roussel et al. ONERA study, IEEE.

Application to EJSM



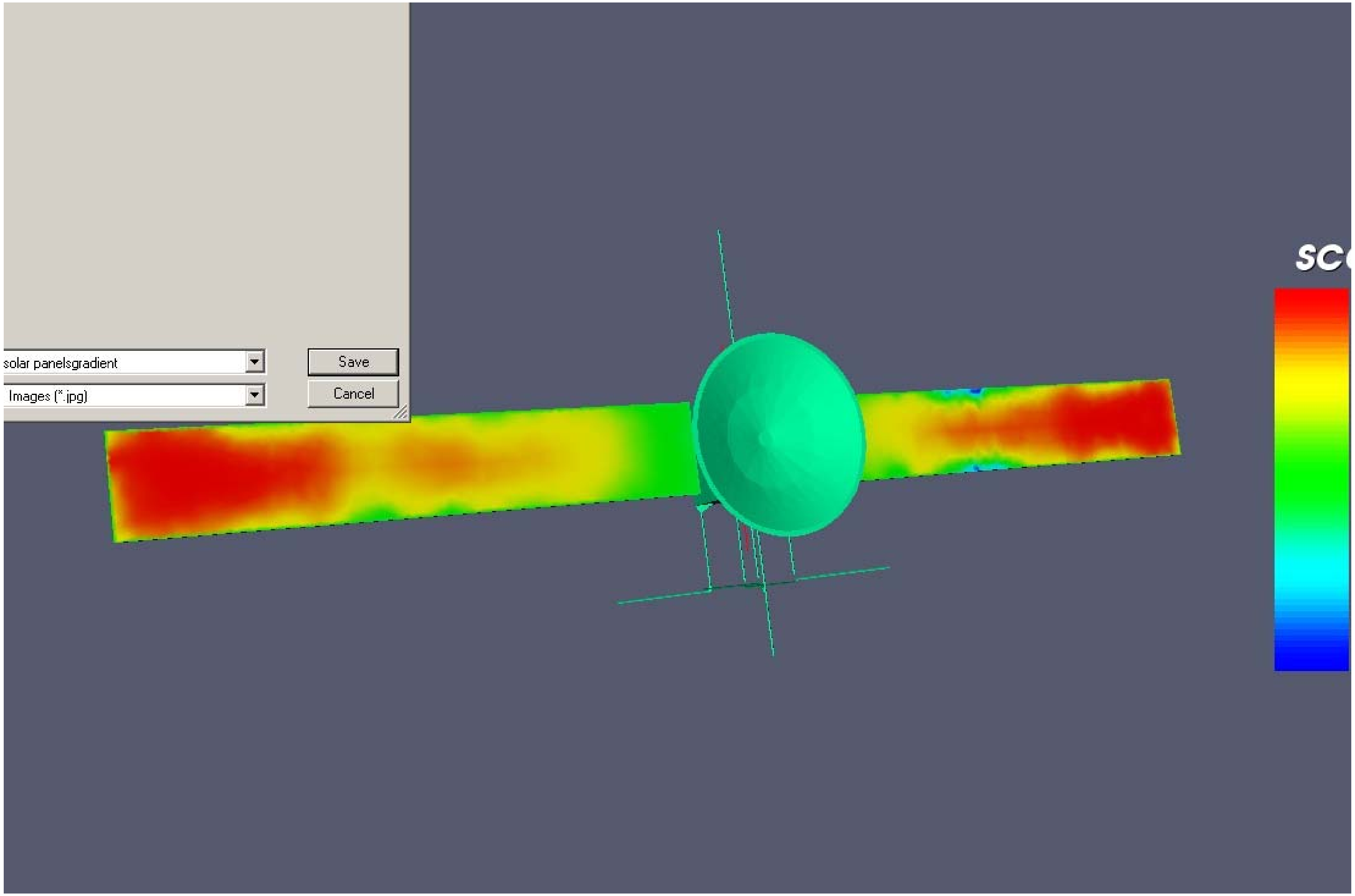
wrk in progress ESA, F. Cipriani.

Photoelectrons densities



wrk in progress ESA, F. Cipriani.

Potential gradient along the panels



wrk in progress ESA, F. Cipriani.

Computational tools for electrostatic cleanliness and payload accommodation analysis TRP study

- Objectives:
  - Upgrade current ESA and industry plasma modelling capabilities to address issues related to plasma measurements payload accommodation.
  - Current capabilities appropriate for large magnitude effects on system (e.g., kV charging, contamination by electric propulsion ion backflow).
  - Target capabilities (perturbations of the order of 1 V, contamination by charged exchange ions from outgassing)

- Status
  - Started: October 2010 and will end in April 2012.

- Output:
  - Improved accuracy
  - Improved diagnosis to perform accuracy test
  - Possibility to simulate instruments
  - CAD model of 5 ‘COSMIC vision missions’ (including EJSM)
  - Validation test cases

Validation test cases

- Cluster E-field
- Cluster electron measurements
- Solar orbiter E-field and wake
- Solar orbiter electron measurements
- Cassini electron measurements

SPIS accessibility

- SPIS made available **to all for free under LGPL license** on internet by Artenum
  - http://dev.spis.org/projects/spine/home/spis (start at www.spis.org)
- Registration
  - http://dev.spis.org/projects/spine/home/captcha
- Download of the sources and executable
  - http://dev.spis.org/projects/spine/home/spis/software/download
  - SPIS is a Java based application called through a Jython script. SPIS can be run on almost all platforms with a JVM previously installed
- Documentation
  - in the repertory \SPISROOT\DOC\
  - For the numerical core (models, solvers, parameters setting, etc…)
    - \Doc\DocSpisNum\HowTo\
- Spine community
  - Annual workshops (last workshop in Uppsala, Sweden, Jan 17-19, 2011)
  - Forum: http://dev.spis.org/projects/spine/home/community/forumsPages

Conclusions

- There are several spacecraft effects which may limit significantly the scientific return of plasma instruments including:
  - Contamination by charged particles
  - Surface voltages and effects (incl. ESD, EMC, degraded measurement performance, interferences)
  - Disturbance of electrostatic voltage in volume and effects
- The implications for the project include:
  - a careful assessment is needed of possible voltage achieved by the instrument exposed surface and possible impact on spacecraft voltage.
  - some instruments need awareness of electrostatic potential distribution around the spacecraft
  - some instruments may require use of boom or of active systems with exposed voltage or particle emitters
  - some trade-off between instrument requirements and shared time mode may be required.
- Significant modelling effort is required for optimising the set-up and/or retrieving a ‘clean’ signal.
- Beyond first order assessment of surface effects, 3D plasma simulations may be very useful.
- Current major source of uncertainty in the modelling comes from the relatively crude knowledge of relevant material properties (especially conductivity, secondary and photo-electric emission yields).
- Actions are taken in ESA TR&D plan and world-wide to improve accuracy of such models.
- European free and ESA supported tool available from www.spis.org and www.spenvis.oma.be.

Remaining issues

- Environment not so well known (regions, dynamics, kappa distribution etc…).
- Spectrum of secondary and photo-emitted particles not well known.
- Related surface properties not well characterised for all materials in use.
- Sheath modelling difficult
- Modelling of wire antennas challenging due to small transverse side.
- Many sources of uncertainties - error estimates complicate
- Trade-off with other instruments requirements.