SPIS current capabilities for cosmic vision missions

SPINE Workshop, January 17-19, 2011

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Outline

- Introduction
- Current SPIS capabilities (architecture, modules, models)
  - SPIS-UI
  - SPIS-NUM
- Simulation cases

Introduction - SPIS context

- SPINE (Spacecraft Plasma Interaction Network in Europe) community setup around year 2000 (A. Hilgers, J. Forest, JF Roussel, …):
  - Gather European efforts for SC-plasma interactions
  - Exchange: knowledge, data, codes, results...
  - Boost the development of a common simulation toolkit: ESA ITT in 2002 => SPIS
- SPIS Development (Spacecraft Plasma Interaction Software) :
  - Initial development: 2002 – 2005
    - ONERA-Artenum consortium
    - ESA/ESTEC TRP contract
  - Major solver enhancement: 2006 – 2009
    - Mostly ONERA
    - ESTEC ARTES contract, French funding
  - ESD triggering modelling : 2010
    - ONERA-Artenum consortium
    - ESA/ESTEC TRP contract
  - Others:
    - Some community developments
    - Some CNES-funded enhancements (EP, ESD)
    - Next steps: EP integration (EADS Astrium), SPIS-GEO (Artenum), SPIS-Science (ONERA), SPIS-Deep charging (TAS/TRAD/INTA/DHConsultancy/G4AI/ONERA/ARTENUM)

SPIS releases (open source):
- v4.0 July 2009
- v4.3 since November 2010

- SPIS ESD 1.0 in January 2011

Introduction - SPIS installation

- SPIS made available on internet by Artenum
  - http://dev.spis.org/projects/spine/home/spis
- 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 (this workshop in Uppsala, Sweden, Jan 17-19, 2011)
  - Forum: http://dev.spis.org/projects/spine/home/community/forumsPages

SPIS 4.3.1

- New release available, including bug fixes outlined in the 4.3.0
- Additional features at SPIS-UI level, like Wizard, issued from SPIS-ESD
- See, http://dev.spis.org/projects/spine/home/spis/software/download

- Strong efforts done to support the various flavors of Linux:
  - 32/63bits
  - Various versions of glibc (2.5 and higher then 2.7)
- Improved Ant based packaging and validation process
- Extended documentation and tests/validation/example projects
- Should reduce the difficulties of deployment observed on some old Linux systems.
- Please check the compatibility table to download the most adapted package.

SPIS current capabilities

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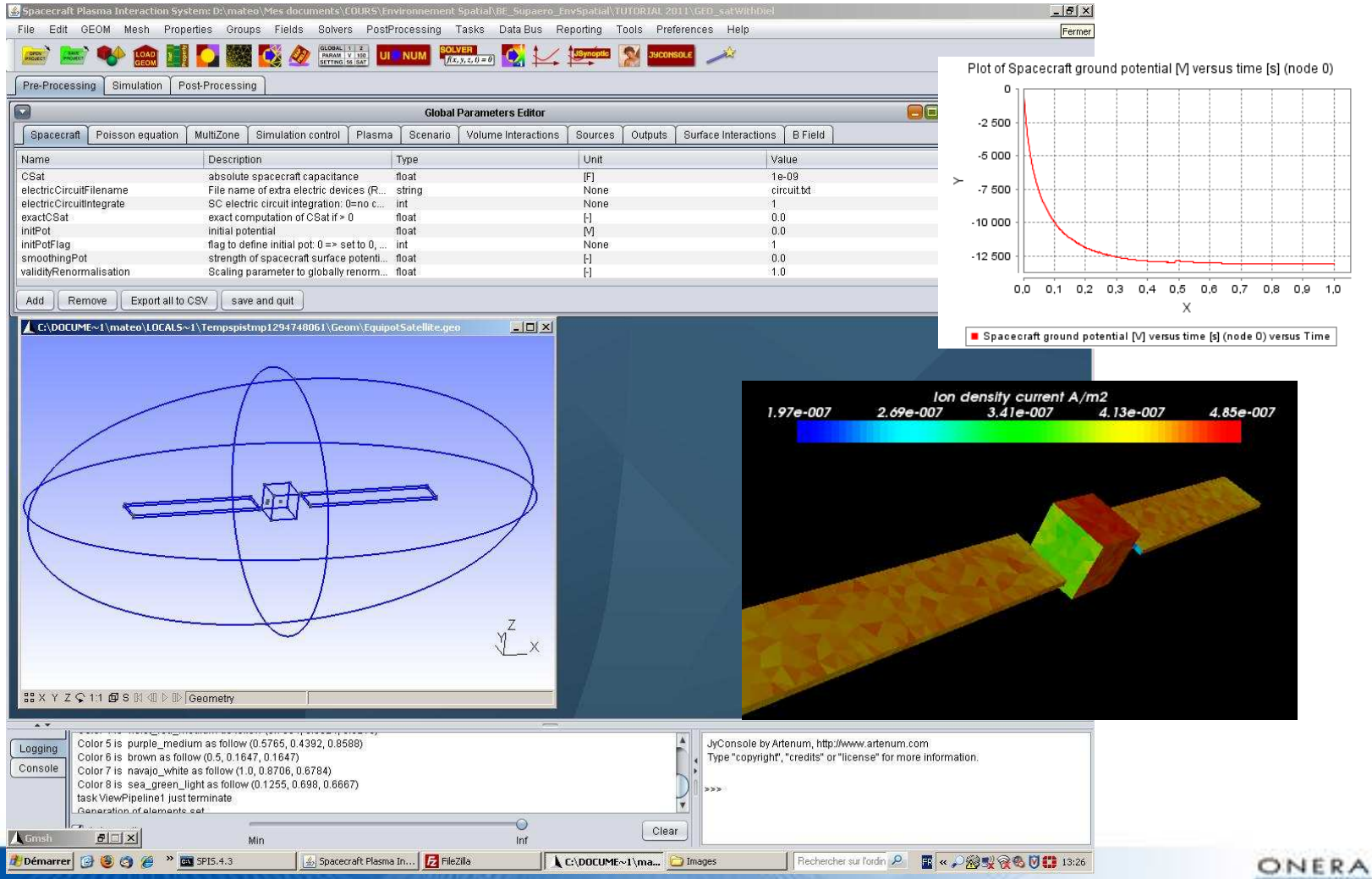
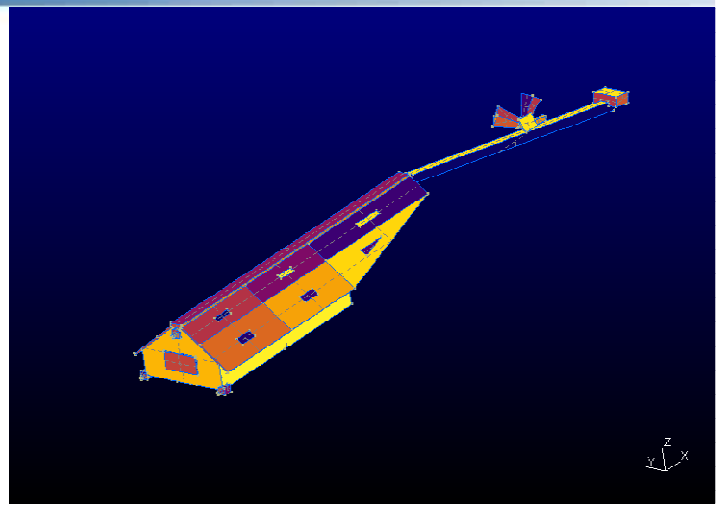
Current SPIS-UI capabilities

- Real framework: task monitor, data management, script console (jython)…
- Interfacing with modeler/mesh-generator, postprocessing tools…



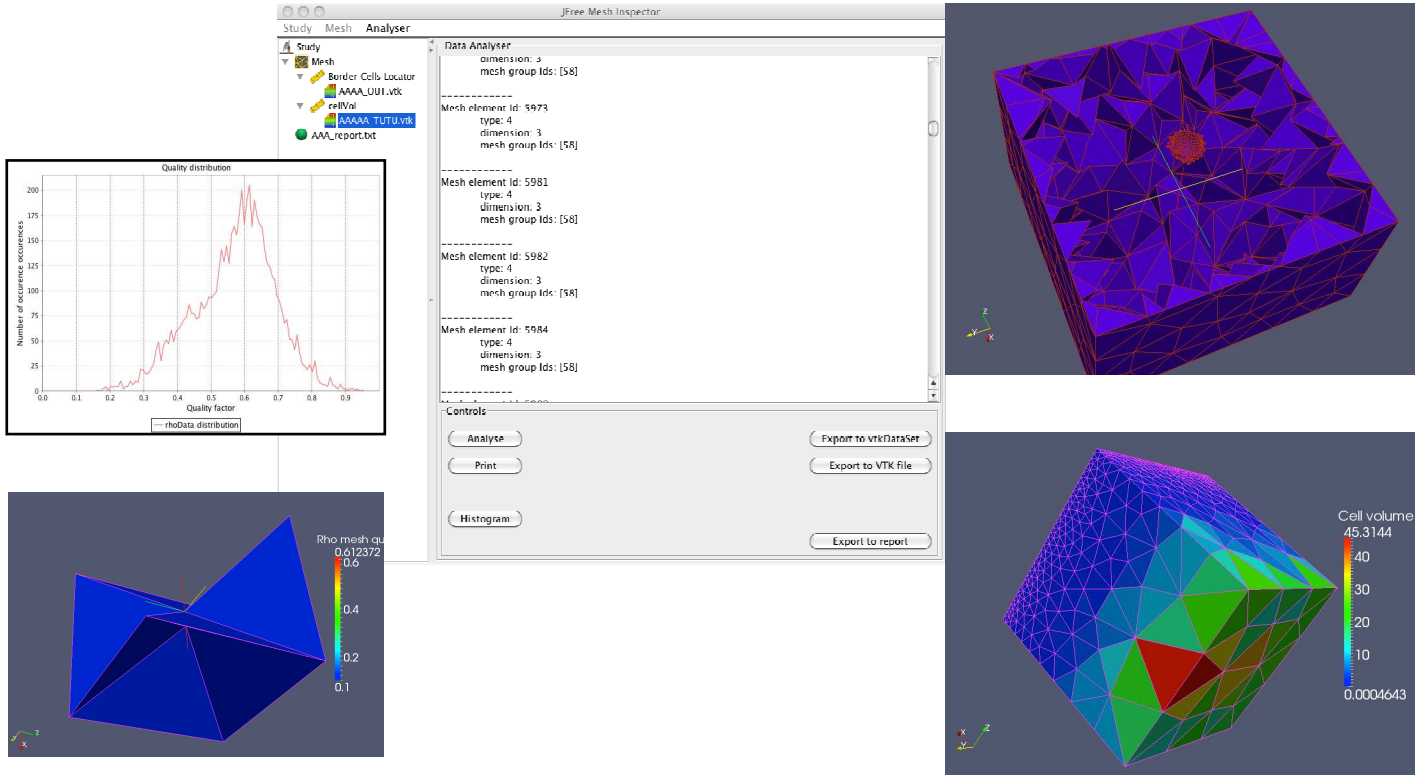
Current SPIS-UI capabilities



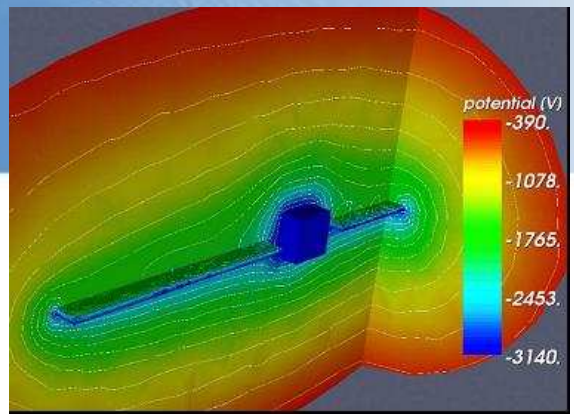
- Geometry/meshing
  - Rich and complex geometries
  - Gmsh modeler/mesher
  - Possibility to mesh up-to 1E6 cells mesh
  - Mesh size factor of 1e5 between the largest and the smallest mesh elements
  - Refinements control by increasing boxes
  - Strong improvement of meshing algorithms in Gmsh 2.4 and higher
- 2 modes for SPIS launching
  - Interactive mode with the GUI layer
    - Preparation of model and simulation
    - Data extraction and analysis in post-processing
    - Generation of spis-tracks and scenarios (NUM) to define and control automatised processes
  - Batch mode, using spis-tracks
    - Possibility to performs simulations on remote HPC
    - Reduce the memory foot-print
    - Easier for long and intensive simulations
    - Allows to perform systematic and parametric studies

Current SPIS-UI capabilities

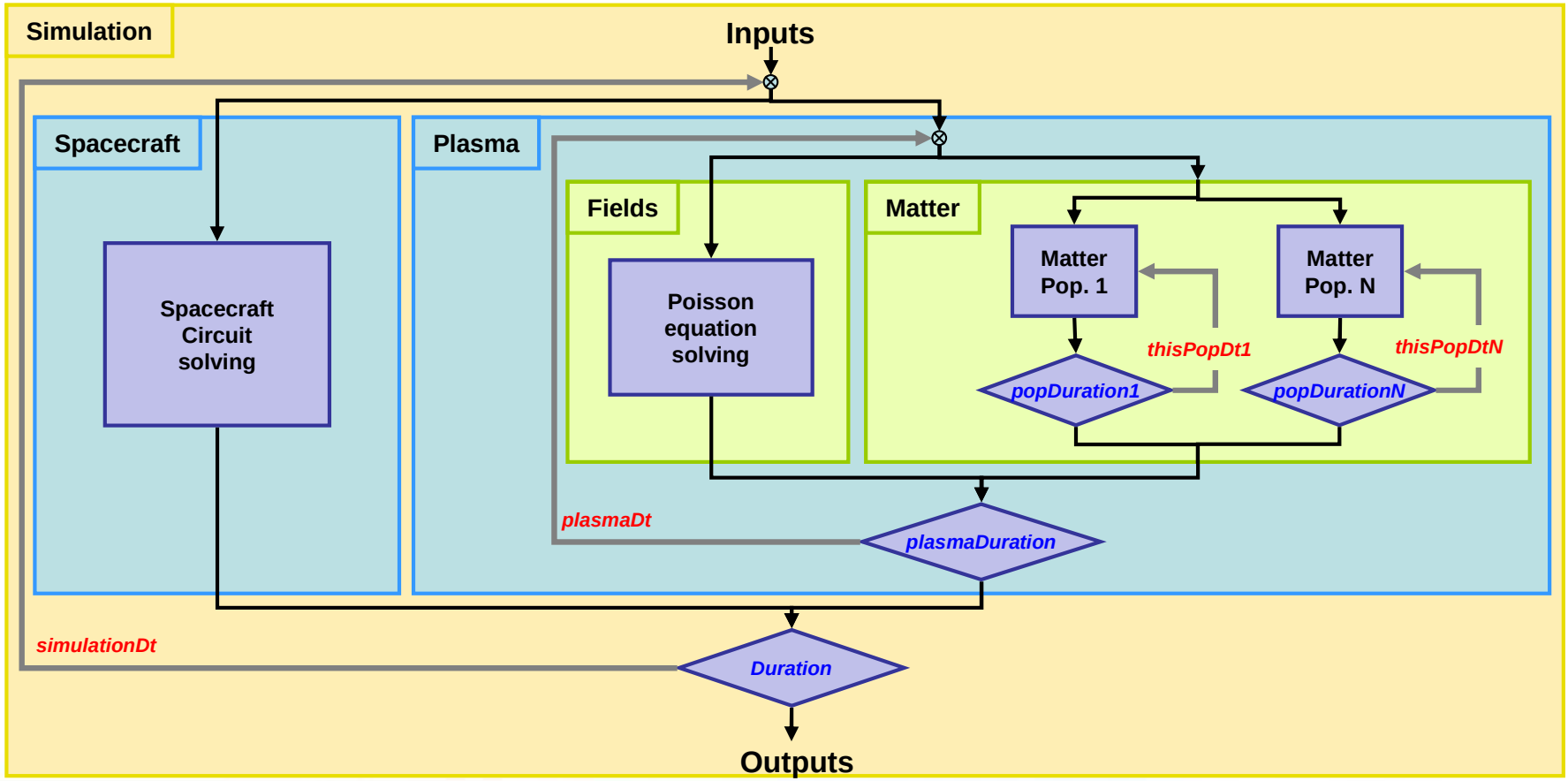
- SPIS UI
  - Error treatment with improved stack trace, explicit message, JFreeMesh inspector



Current SPIS-NUM capabilities



- Plasma/Spacecraft Interaction imbricate loops

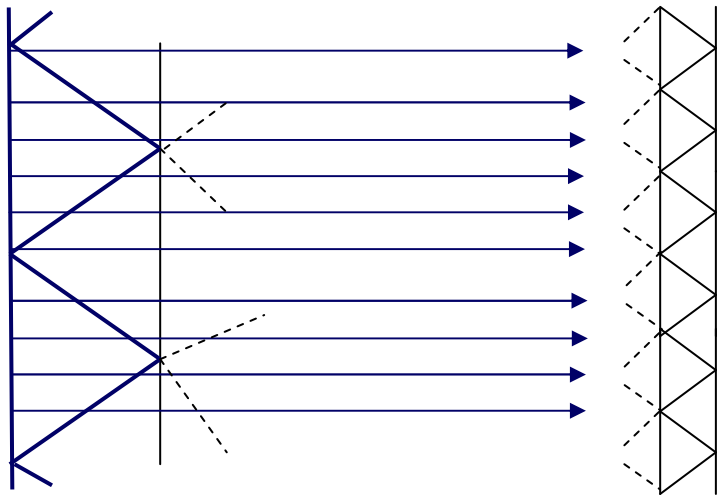


1.1 Plasma – Matter models

- Bi-maxwellian environment (2 electron populations and 2 ion/neutral populations)
- Analytical model
  - Boltzmann distribution (unlimited, linear for positive potentials)
  - User-defined reference density for null voltage
  - Generally correct for negative potentials (for electrons)

1.1 Plasma – Matter models

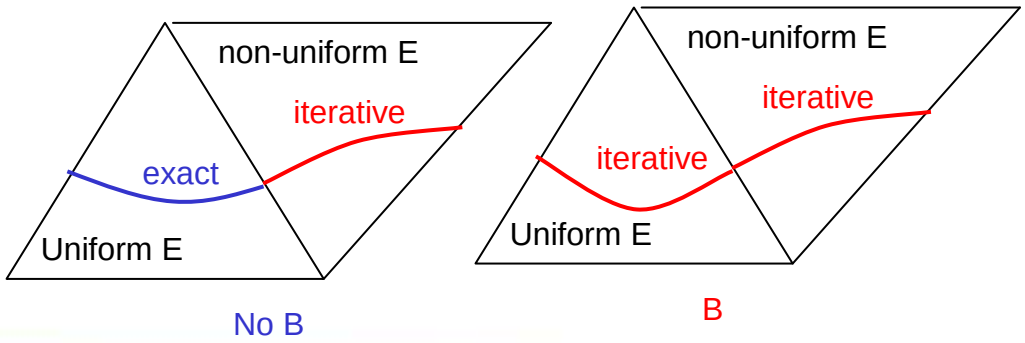
- Particle-In-Cell (PIC) Model
  - Charge injection
    - Maxwell injection at external boundaries + initial volume filling
    - Injection distributed over the time step
    - Calculated to have an average of "X particles/cell" on plasma boundary (X is user-defined)
    - Good while cell volume and particle velocity are constant



  - Charge deposit helps increase the statistics however
    - Charge density is computed from the sampled particle distribution (Monte Carlo) following PIC scheme
    - Each particle deposits its density along the whole trajectory → increases the statistics
    - Each node (on which Poisson equation is calculated) receives charge deposit from the surrounding cells (6 cells in average) → also increases the statistics (by a facor of 6)

1.1 Plasma – Matter models

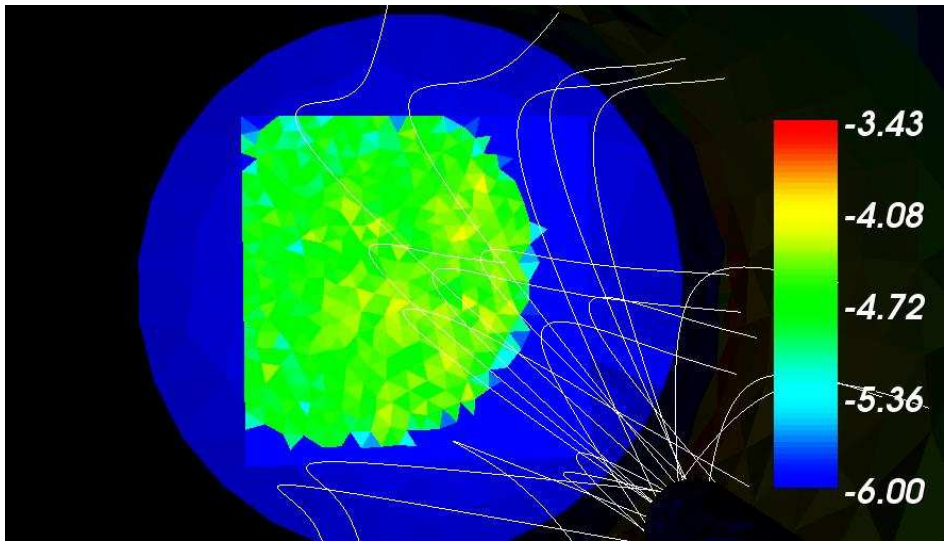
- Particle-In-Cell Model
  - Exact trajectory integration in case of uniform E in each cell (and no B)
    - Because the potential is considered as step-wise linear
    - Exact analytical parabolic trajectory
  - Else
    - (If presence of a magnetic field,
    - Or special shape of potential (non linear) in the vicinity of thin wires (1D) or thin plates (2D))
    - Trajectories are still analytical (accelerated screw), only the intersections with the tetrahedra planes are not
    - Iterative method : Runge-Kutta Cash-Karp iterative and adaptive method (4th and 5th order to determine and control the error)
  - Local switch between the exact integration method and the iterative method
  - Possible amelioration = quasi exact
    - Exact trajectory
    - B or non-uniform E: interception of trajectory with tetrahedra surface by dichotomy-like method

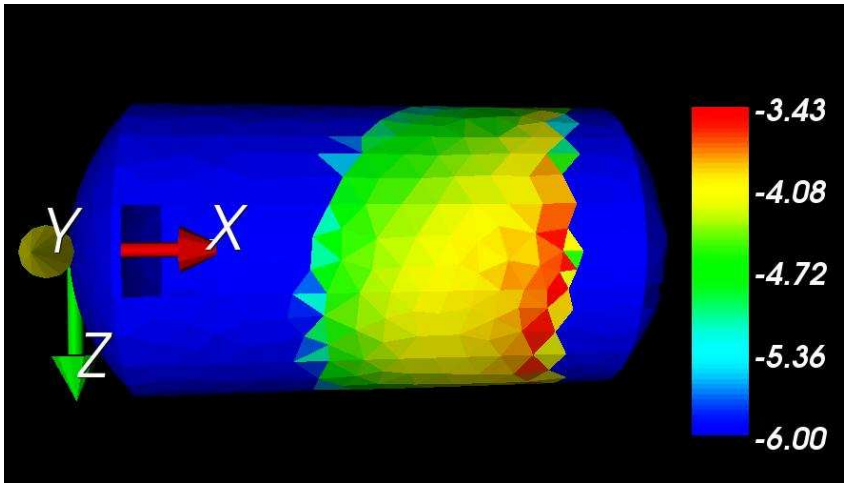


1.1 Plasma – Matter models

- Trajectories are possible to monitor
  - Useful to check the simulation

- Illustration in the case of a B field and (tetrahedron)-uniform E field
  - Electron gun (X-direction emission) in ONERA/JONAS plasma chamber
  - Deviation by the magnetic field (if no compensation)

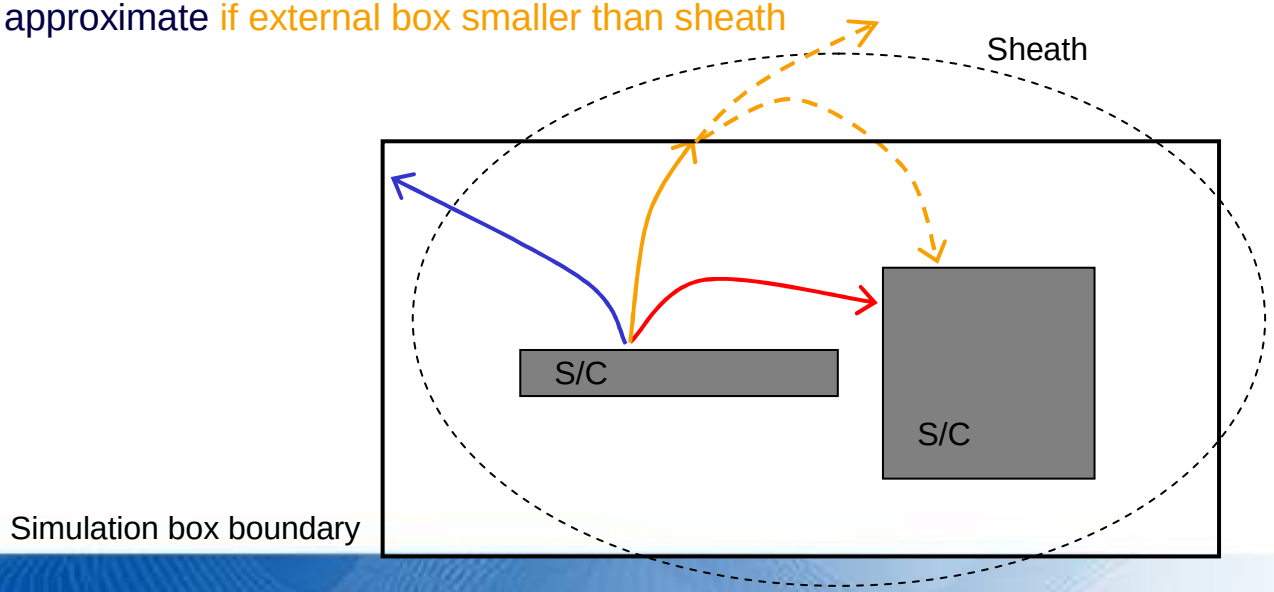




5.5 keV Electron trajectories and log10 of current collection (A/m2)

1.1 Plasma – Matter models

- Composite PIC model:
  - Forward Boltzmann/PIC model for charge density deposit in the volume
  - Backtracking for current collection on the spacecraft (only for ambient particles)
    - Very useful to increase the statistics on current collection
    - Virtual emission of particle from the spacecraft with equivalent local voltage drop energy wrt plasma
      - Case 1: the trajectory reach the plasma boundary (filled trajectory) : Liouville theorem states the distribution function is conserved along the trajectory in phase space → current contribution from infinite
      - Case 2: if not, trajectory not filled (only for ambient particles) → no current contribution
    - Limited to non-drifting species
    - Only approximate if external box smaller than sheath



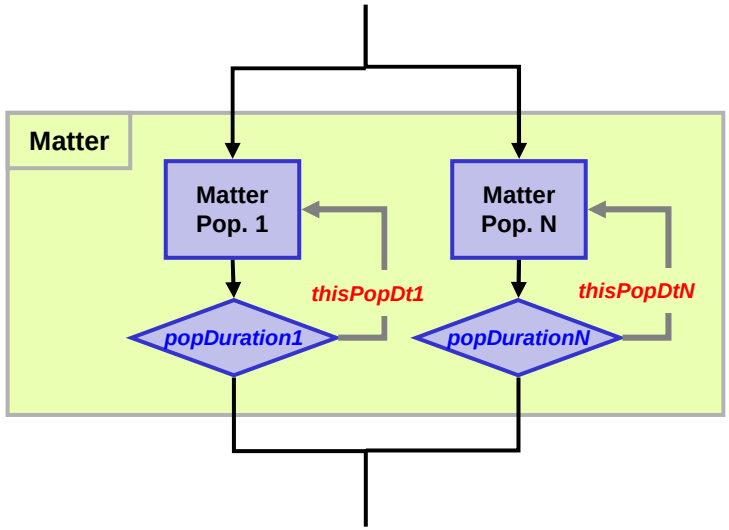
1.1 Plasma – Matter models

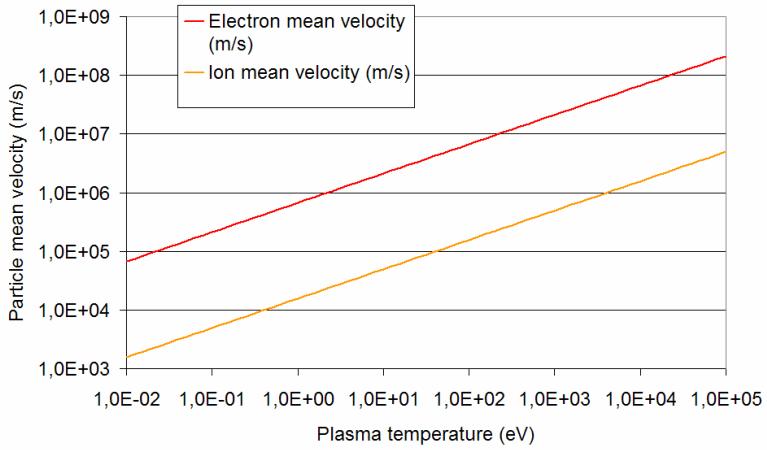
- PIC model
  - Time steps and integration duration associated with particle dynamics
    - Automatic
    - User-defined
    - Mix of user-defined and full-automatic
  - Guideline for particle dynamics duration
    - Several times the transport duration over simulation box
    - May be very different from a specie to another
    - Permit to save calculation CPU time
  - Guideline for the particle time step
    - Linear charge deposit

    → no CFL-like time step restriction

    → save CPU time
  - To be adapted in each case

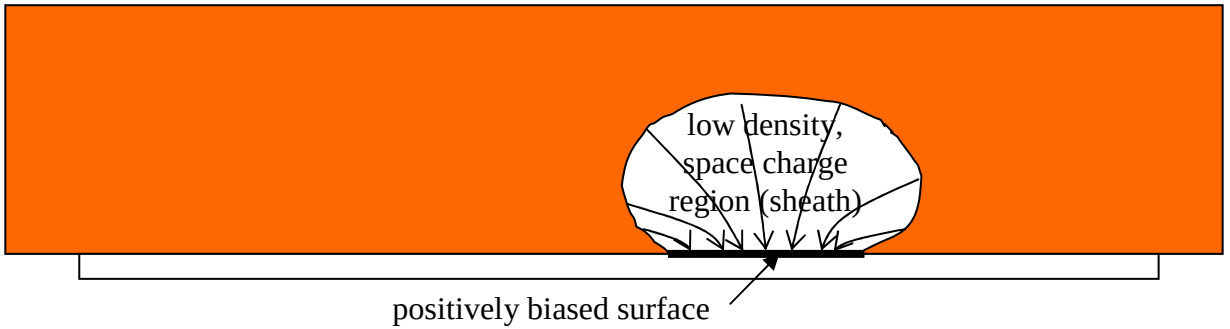
    (at least considering also Poisson equation and spacecraft circuit…)



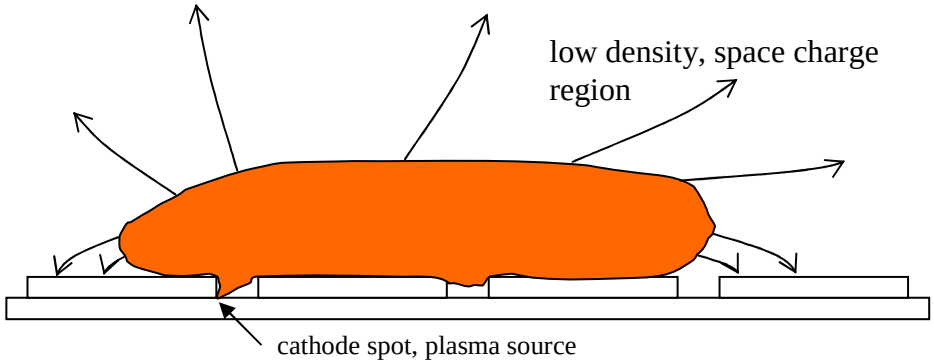


1.1 Plasma – Matter models

- Multi domain / Multi physics :
  - Typically simulate in a single simulation:
    - Dense quasi-neutral regions
    - Low density, space charge regions
  - Examples:
    - Ambient plasma at rest / sheath:



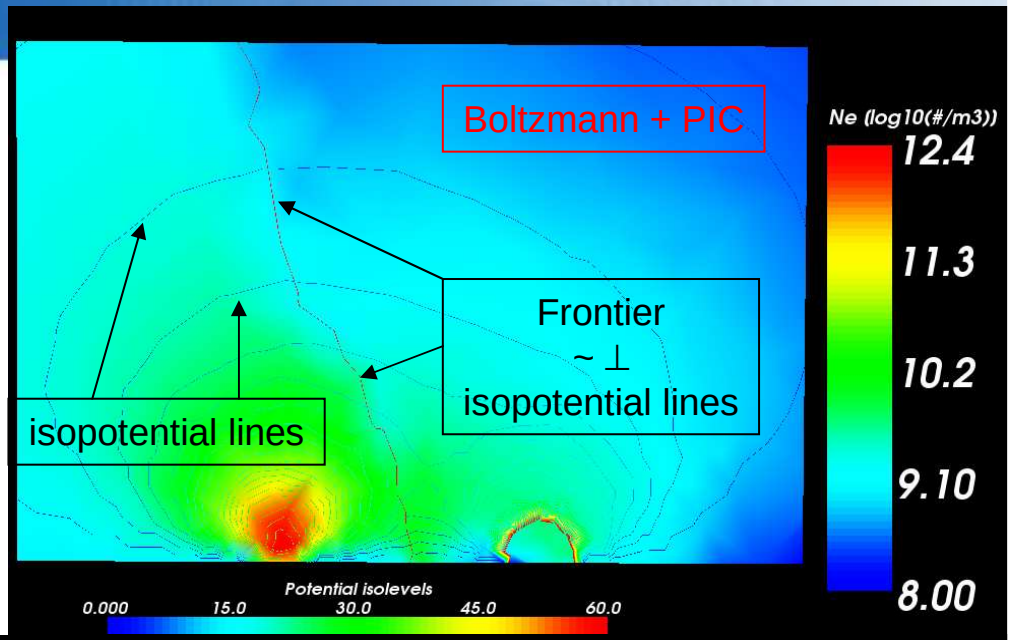
    - Expanding plasma / fast electrons ahead of the plasma front (ESD, EP ignition…)

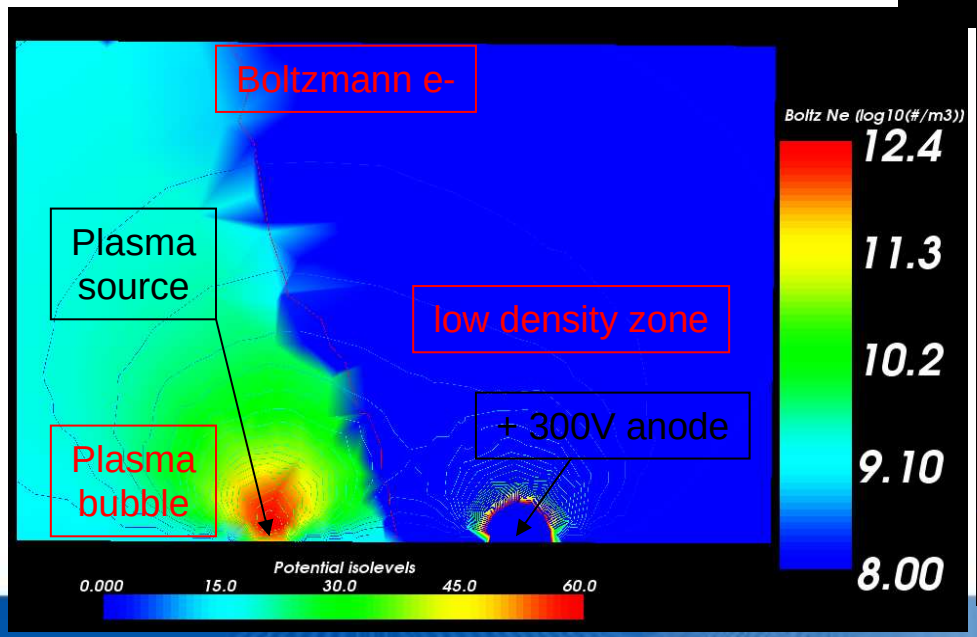


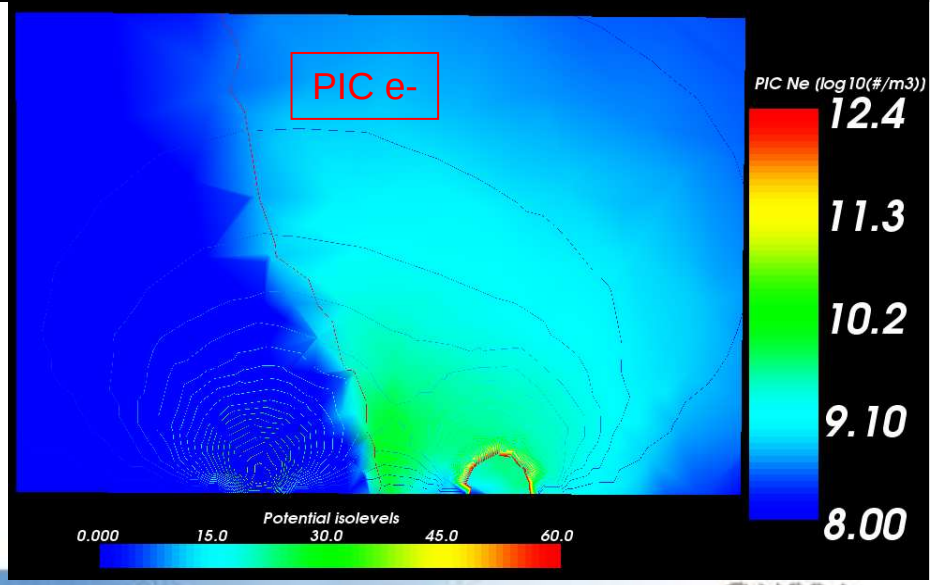
    - Method
      - Multi-zone
      - Interface handling at sheath edge or plasma bubble edge : tricky point of the method

1.1 Plasma – Matter models

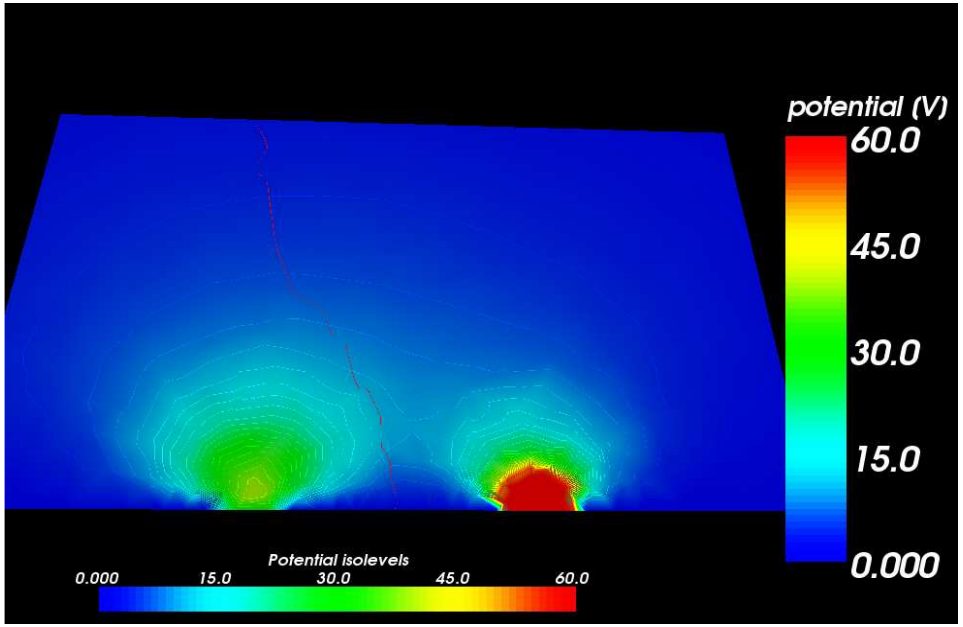
- Test case : plasma bubble expansion
- Electron density:
  - composed of Boltzmann electrons in dense ion zone (quasi neutral)
  - and PIC electrons in low density zone (non neutral)

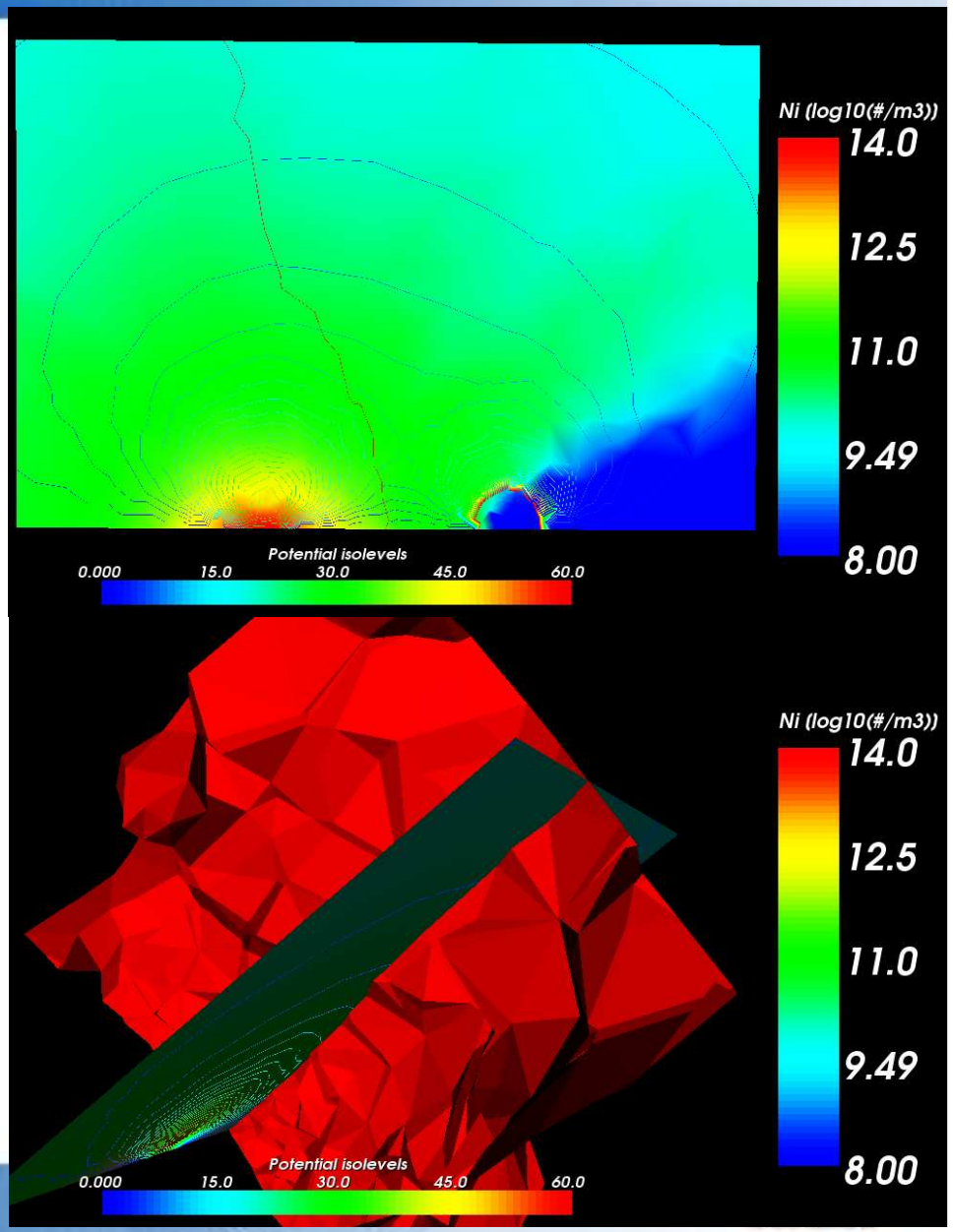






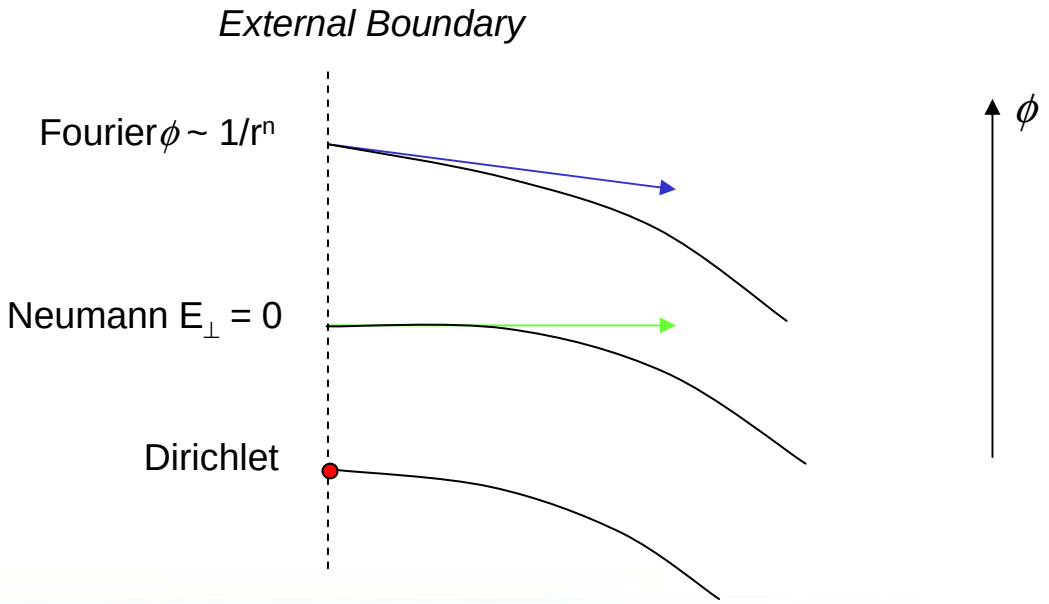
ONERA


potential (V)
60.0
45.0
30.0
15.0
0.000
Potential isolevels
0.000
15.0
30.0
45.0
60.0


Ni (log10(#/m3))
14.0
12.5
11.0
9.49
8.00
Potential isolevels
0.000
15.0
30.0
45.0
60.0
Ni (log10(#/m3))
14.0
12.5
11.0
9.49
8.00
Potential isolevels
0.000
15.0
30.0
45.0
60.0

1.2 Plasma – Electric field model

- 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



1.2 Plasma – Electric field model

- Poisson solver
  - 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 one (or two) Boltzmann distributions of electrons from environment

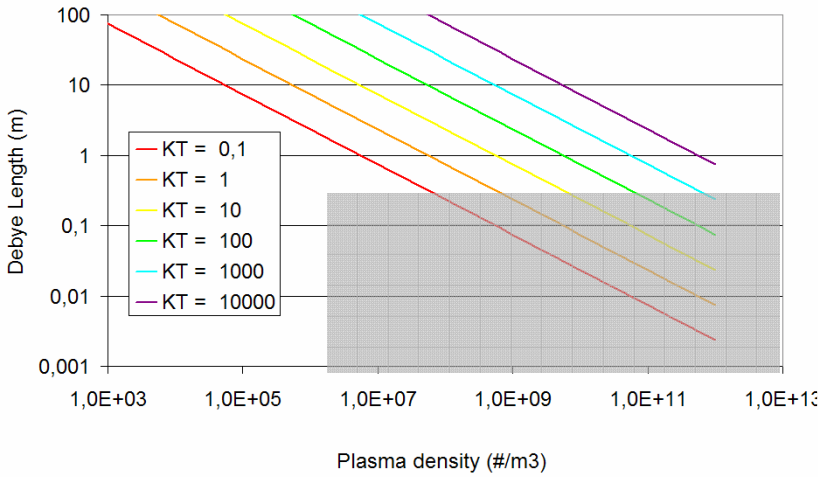
$$\Delta\phi = \frac{\underbrace{q_i n_i} - en_{e1}\exp\left(e\phi/kT_{e1}\right) - en_{e2}\exp\left(e\phi/kT_{e2}\right)}{\varepsilon_0}$$

    - n_i = the total charge density of other particles (usually PIC-modelled ions, but possibly also other PIC-modelled electrons)
    - n_{ex} is the electrons density of the x-th electron distribution (a scalar, contrarily to n_i which is a field) and T_{ex} its temperature.
    - 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

1.2 Plasma – Electric field model

- Guidelines to reduce the mesh size (and save CPU time cost)
  - If possible : Use of the Boltzmann electron model + Non-linear Poisson solver
  - else if (positive potentials or potential barrier significant w.r.t. to electron temperature)

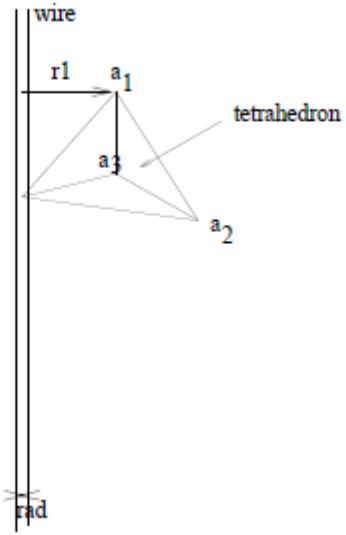
    - Solution 1
      - Full PIC modelling
      - Quasi-neutral plasma regions to be meshed below the Debye length (0.5)
      - Risk: small Debye length w.r.t. simulation dimension



    - Solution 2
      - Use of multi-zone model
      - only PIC-electron in the positive region
      - Capability was tested on plasma bubble expansion and collection by a positive electrode
      - Robustness to be validated on case per case basis

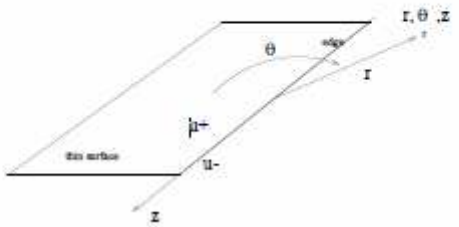
1.2 Plasma – Electric field model

- Thin elements
  - Thin wire
    - Regular part
    - Singular part
      - *log(r/rad)* law
      - Function of wire radius



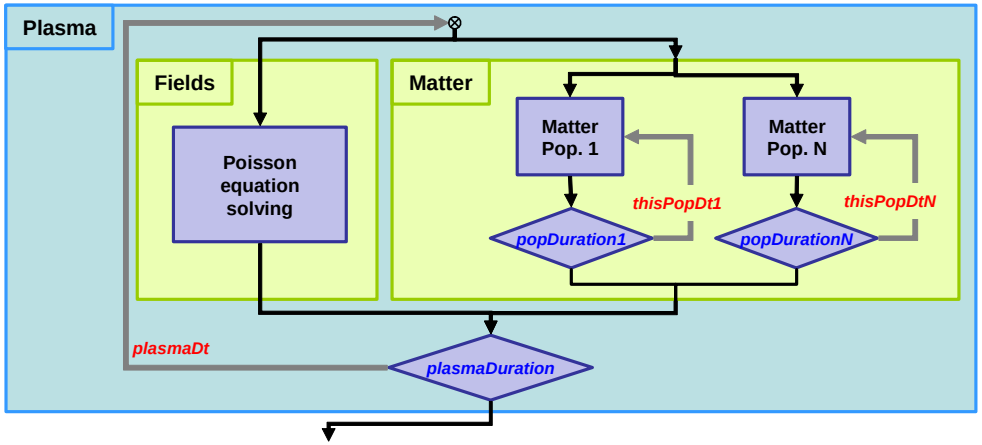
  - Edge of thin panels
    - Regular part
    - Singular part
      - function of front and rear side potentials

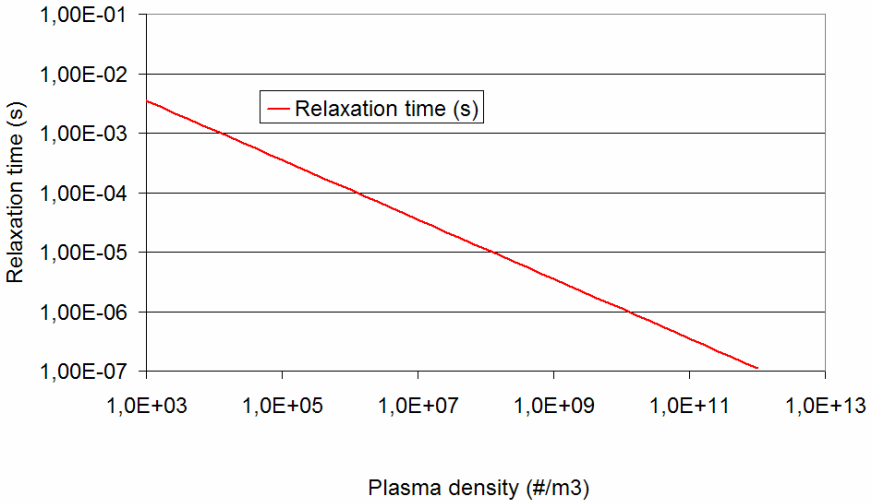
$$u_{sing} \approx (u_- - u_+)\frac{\theta}{2\pi} + u_+$$



1.3 Plasma – Matter / Field coupling

- Matter – field coupling
  - Time steps and integration duration associated with plasma dynamics
    - Automatic
    - User-defined
    - Mix of user-defined and full-automatic
  - Guideline for plasma time step
    - Less than the relaxation time *T* (plasma pulsation)
    - Quantitatively 0.2*T
  - Guideline for the plasma integration
    - several plasma time steps
    - several particle integration duration
  - To be adapted in each case

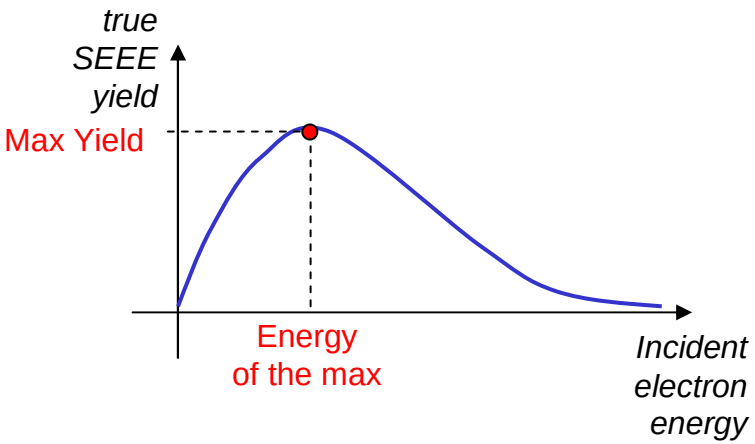




2.1 / Spacecraft – Material properties

- Secondary electron emissions under electron/proton/UV impact
  - PIC modelling for secondaries
  - Maxwell distribution injection: user-defined temperature

  - Under electron impact (SEEE, true and backscattered)
    - from ambiant electron
    - or from SC sources
    - maximum yield at zero-incidence angle (in material data base, user-defined)
    - user-defined energy of the max yield
    - NASCAP analytical law for the yield = f(max yield, incidence angle, energy)
    - secondaries from secondaries: hoping

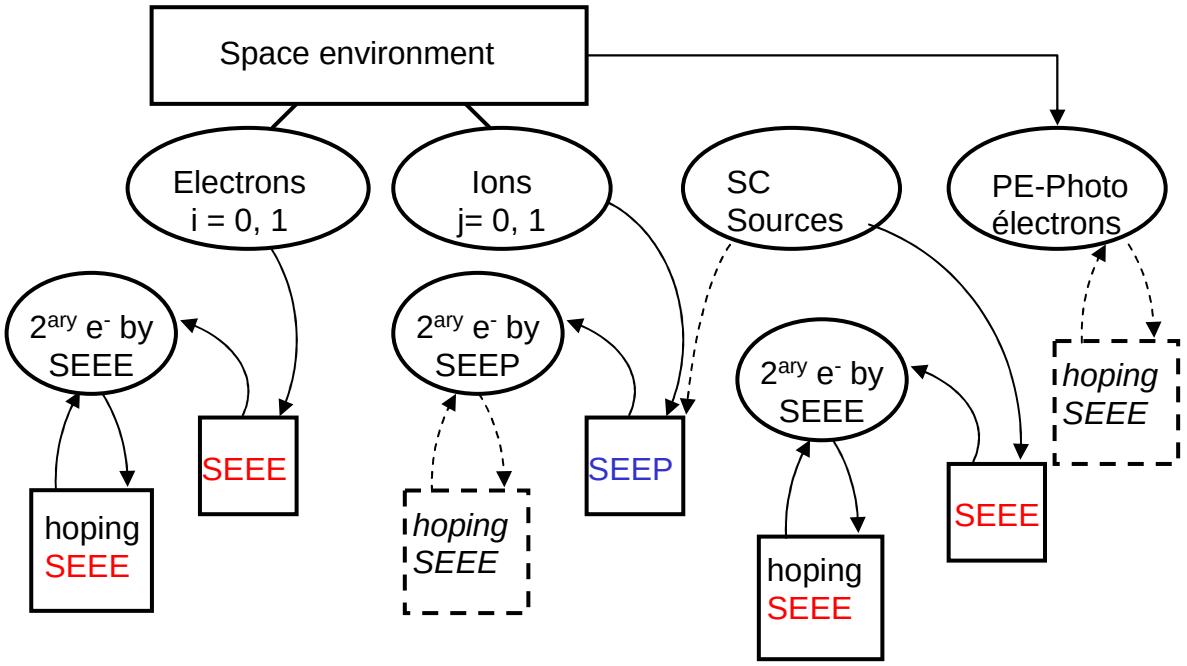


2.1 / Spacecraft – Material properties

- Secondary electron emission
  - Under UV illumination (PE)
    - User-defined current density at zero-incidence angle → material base
    - Dependence on the incidence angle
    - Shadowing but no self-shadowing
    - secondaries from photo electrons : not from UI by now
  - Under proton impact (SEEP)
    - From ambient ion
    - No snapover (secondaries from secondaries)

2.1 / Spacecraft – Material properties

- Secondary electron emission
  - Summary
  - Possible to implement easily: snapover, SEEE from photo electrons, SEEP from SC ion sources



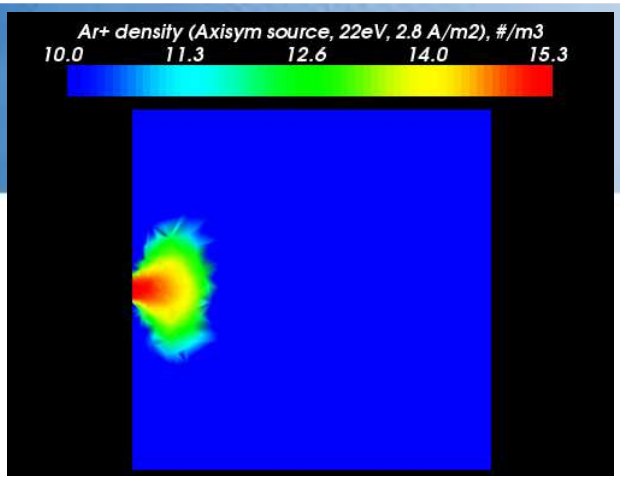
2.1 / Spacecraft – Material properties

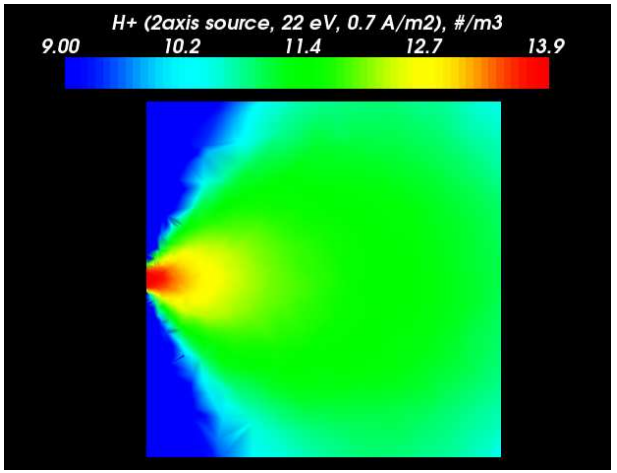
- Conductivities
  - Surface/volume, intrinsic/RIC
  - Default or User-defined scalar parameters : through the .xml material properties list

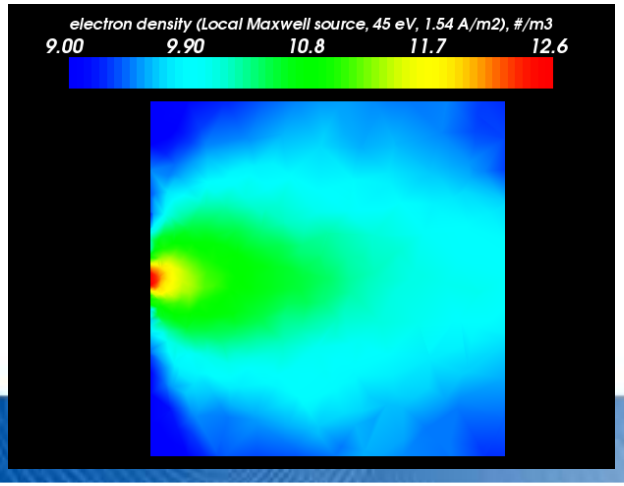
- Sputtering under ion impact
  - recession rate
  - products generation and transport
  - beyond the scope of this activity

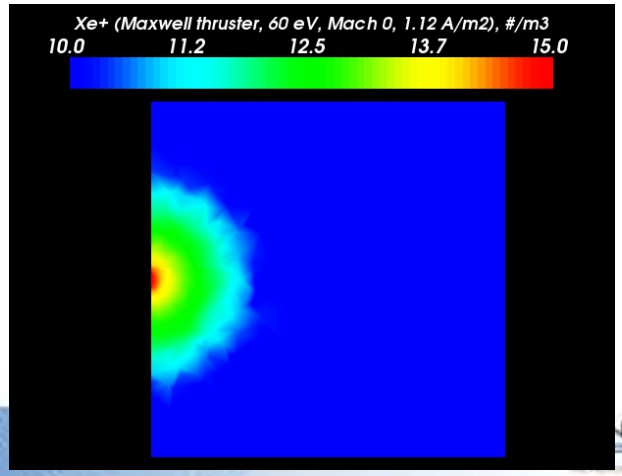
2.2 / Spacecraft – Sources

- Several types of particle sources are available
  - Single sources
    - Maxwellian, Maxwellian thruster, Axisymmetric, Two axes
    - Extension in progress by Astrium in the frame of another ESA contract
    - PIC modelling (densification factor of super particle number)
  - Multiple sources on a single emitter
    - Emission of several species with different models of source
    - Example with 4 sources



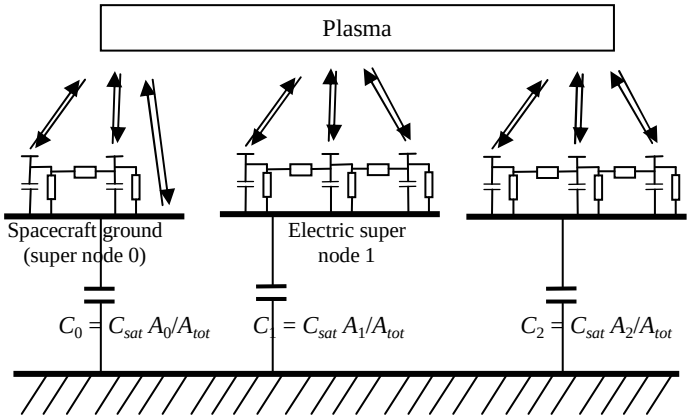


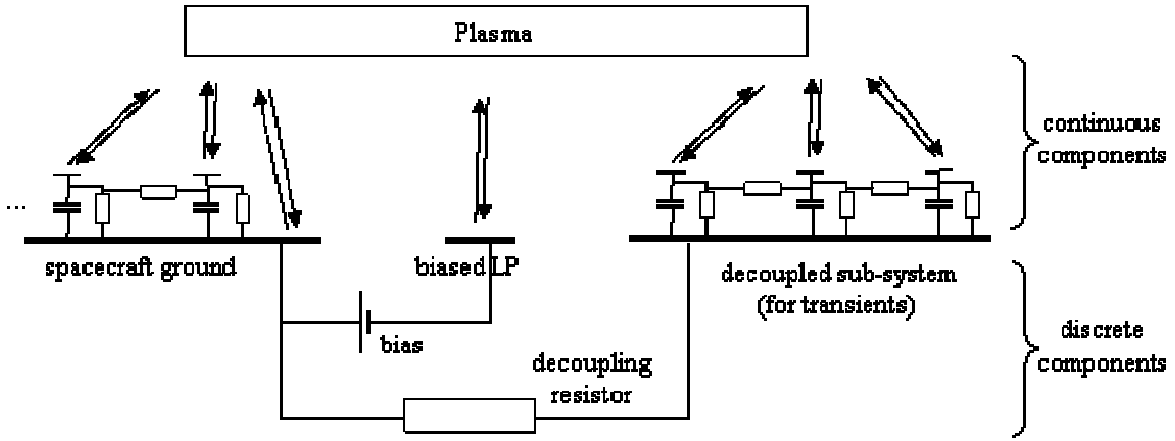




2.3 / Spacecraft – Surface potential

- Multi-time scale modelling of spacecraft surface potential
  - 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)





2.3 / Spacecraft – Surface potential

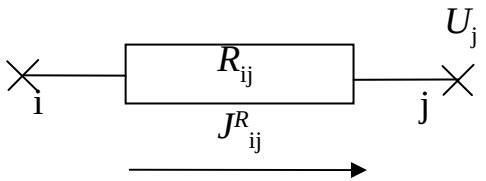
- Circuit solver
  - Circuit equation

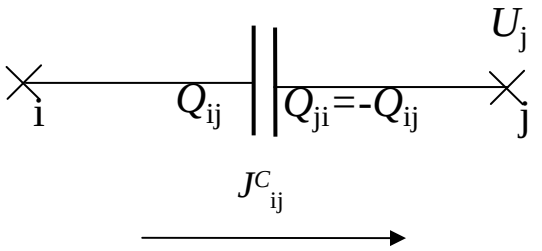
$$-\underline{\underline{C}}.\dot{\underline{U}} + \underline{\underline{G}}.\underline{U} + \underline{\underline{P}}\,\underline{J^L} + \underline{I^I} = 0$$

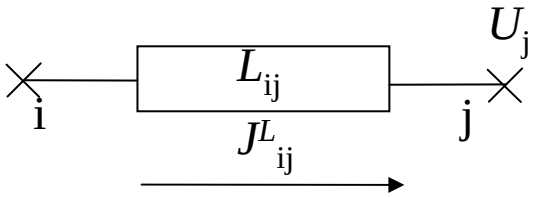
$$\underline{\dot{J}^L} = \underline{\underline{H}}.\underline{U}$$

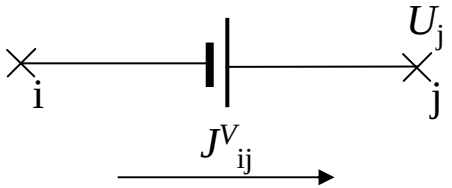
$$\text{or :} \quad \begin{bmatrix} \dot{\underline{U}} \\ \underline{\dot{J}^L} \end{bmatrix} = \begin{bmatrix} \underline{\underline{C^{-1}}}.\underline{\underline{G}} & \underline{\underline{C^{-1}}}.\underline{\underline{P}} \\ \underline{\underline{H}} & 0 \end{bmatrix}.\begin{bmatrix} \underline{U} \\ \underline{J^L} \end{bmatrix} + \begin{bmatrix} \underline{\underline{C^{-1}}}.\underline{I^I} \\ 0 \end{bmatrix}$$

  - Solver
    - Implicit
    - Variable, automatic time step
    - Need to anticipate on I variation with V
      - Linear (in the matrix equation)
      - Or non linear on the source term $I^I(V)$: plasma collection
    - => each physical process to supply *dI/dV* and validity
    - Time step maximised to saturate validity



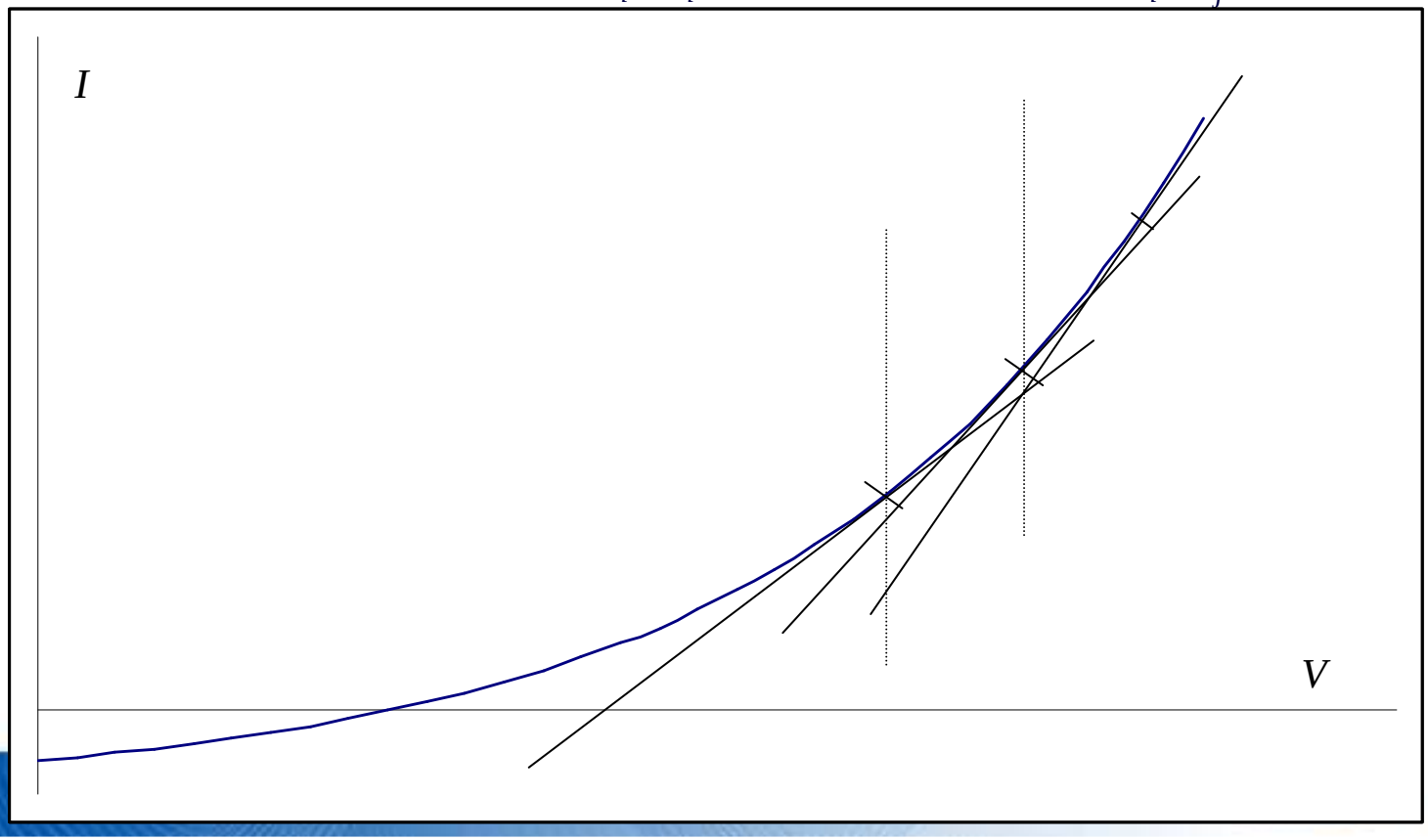






2.3 / Spacecraft – Surface potential

- Principle of the implicit solver (Newton type)
  - Compute plasma currents to/from SC for given potentials (and time)
  - Supply an estimator from analytical assumptions of the plasma current changes when potential changes = dI/dV + a validity range of this estimator
  - Apply Newton method: locally on each node (dI_i/dV_i), or not (non diagonal dI_i/dV_j matrix):



2.3 / Spacecraft – Surface potential

- Current scalers depend on the physical phenomena and on the geometry

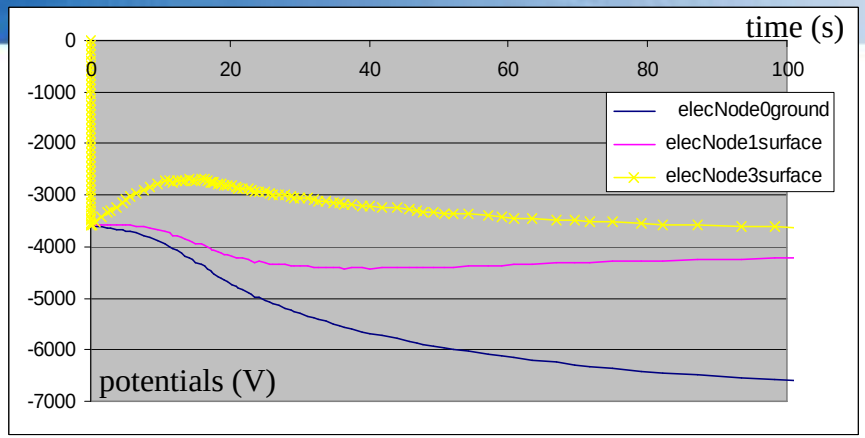
- Available current scalers
  - Automatic selection depending on the population model
    - Constant current scaler
    - Maxwell Boltzmann current scaler
    - Fowler-Nordheim
  - User choice
    - GEO potential barrier for secondary electrons

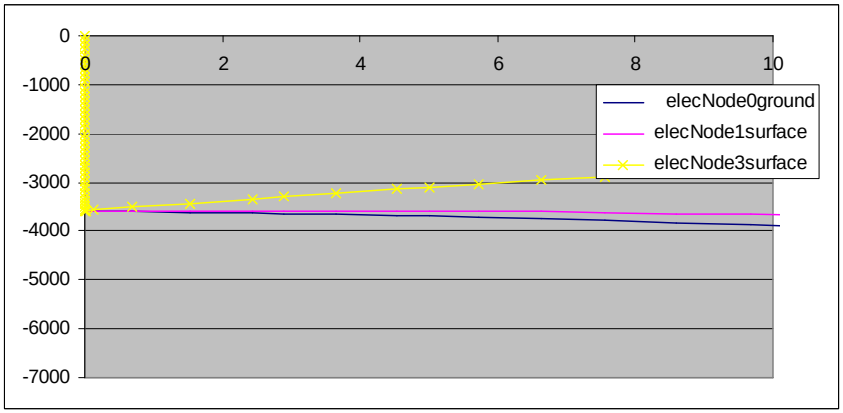
2.3 / Spacecraft – Surface potential

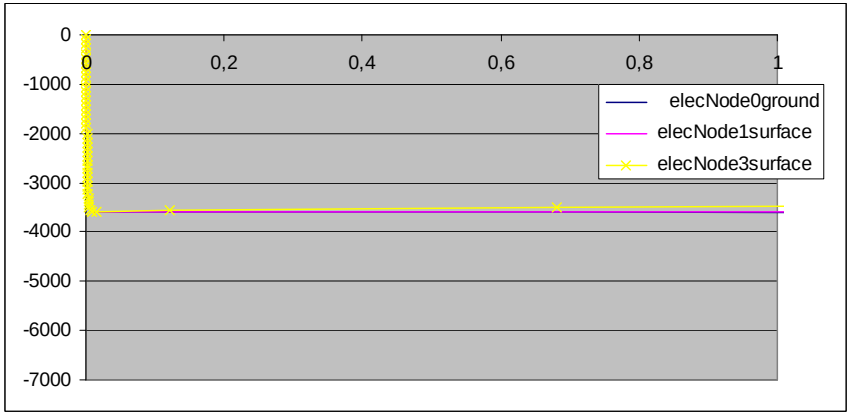
- Thin elements
  - Thin wires : no collection nor emission implemented
  - Thin panels :
    - collection and emission
    - temporarily not supported by SPIS-UI

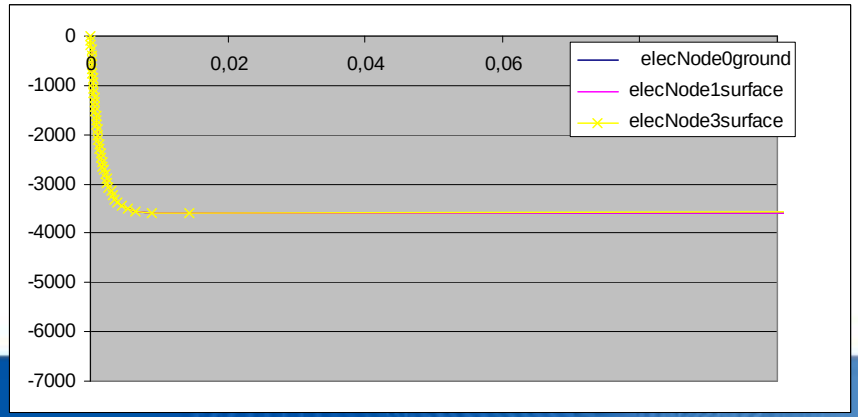
2.3 / Spacecraft – Example

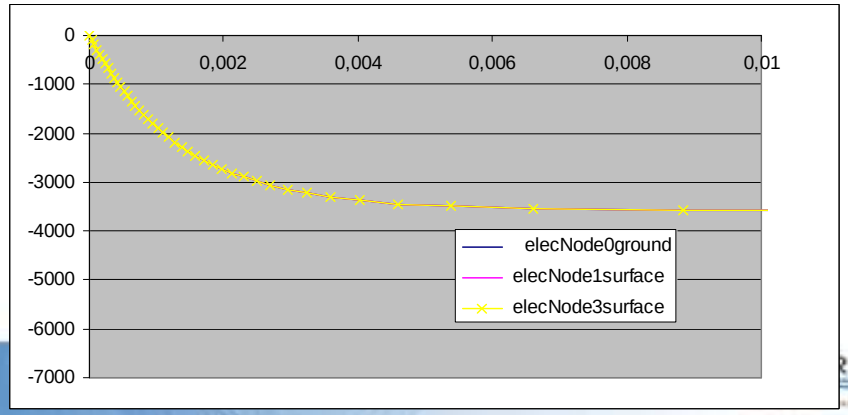
- Test case of the implicit solver / automatic time step:
  - An example (GEO charging with very large electron flux)
  - Quite large range of time scales











SPIS simulation test cases

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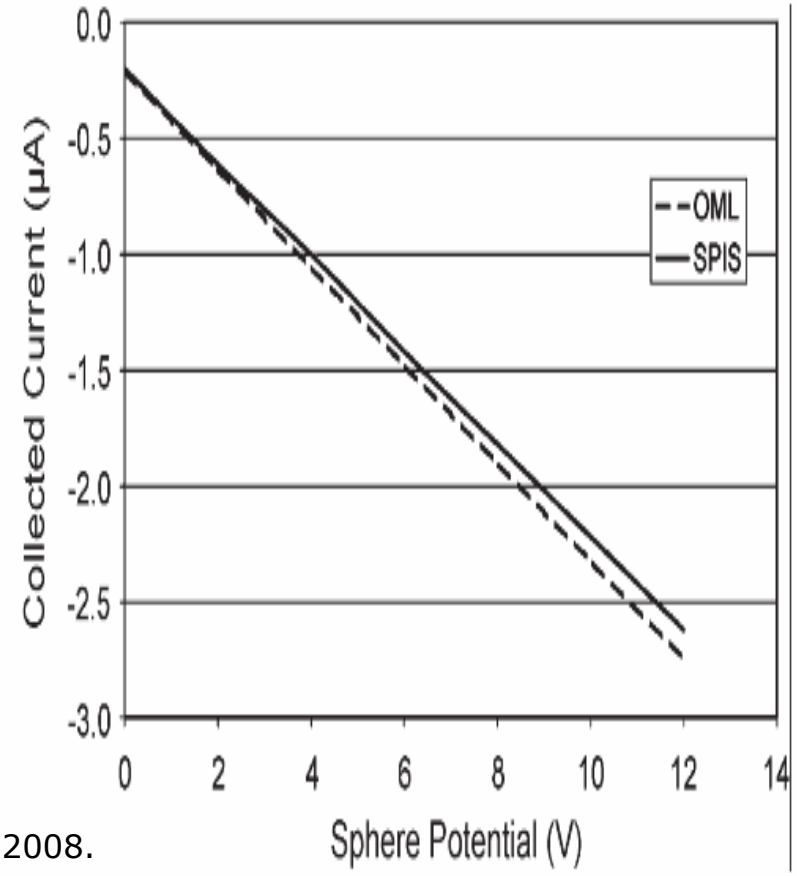
Validation test 1 – full PIC model

Sphere in large Debye length regime:
- difference of 5% found.
- no found explanation

Quantity	Symbol	Value	
Temperature	T	1.0	eV
Electron density	n	10^7	m^{-3}
Debye length	λ	~2.35	m
Potential	ϕ	[0,12]	V
Sphere radius	ρ	0.25	m
Number of tetrahedrons		~30,000	
Simulation box diameter		20	m
Number of macro-particles		~300,000	



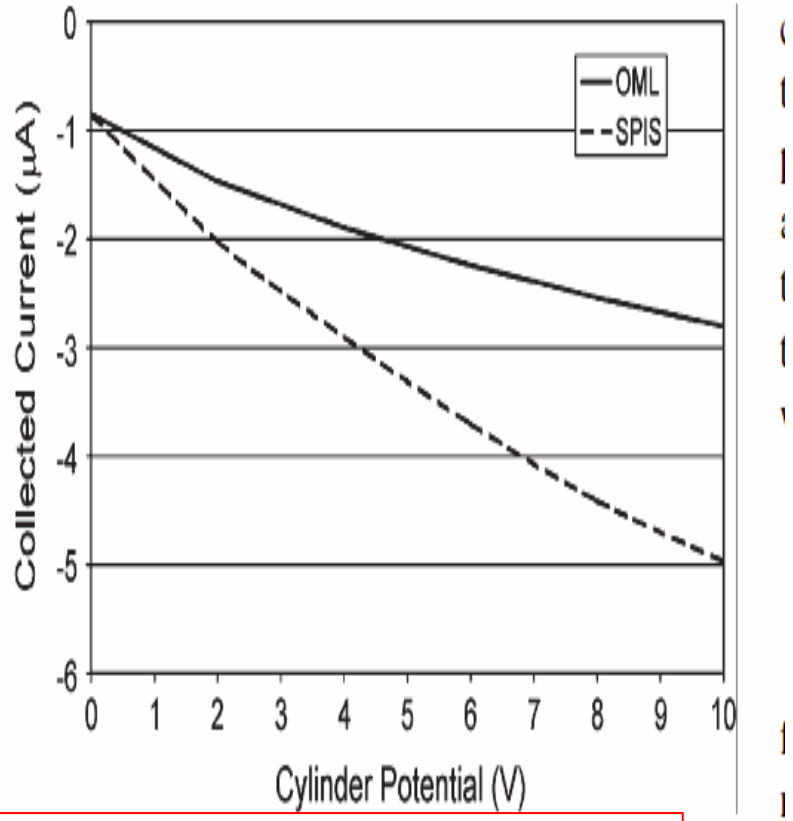
Ref.: Hilgers et al., IEEE Trans. Plasma Sc., 36, 5, 2008.

Validation test 2

Cylinder in large Debye length regime:
- Very large difference is found.
- Finite length effect was suspected

Quantity	Symbol	Value	
Temperature	T	1.0	eV
Electron density	n	10^7	m^{-3}
Debye length	λ	~2.35	m
Potential	ϕ	[0,12]	V
Cylinder radius	r	0.26	m
Cylinder length		16	m
Central node length		2.0	m
Number of tetrahedrons		~60,000	
Simulation box diameter		20	m
Number of macro-particles		~300,000	

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



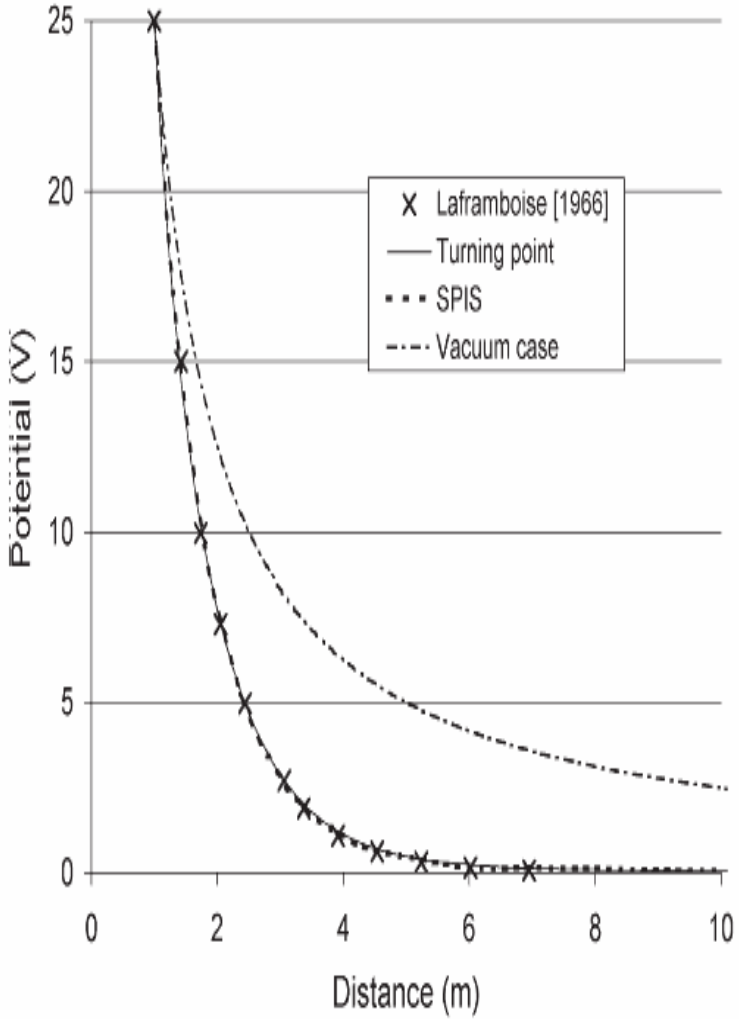
SPIS 4.3 = possible to use Symmetry Boundary Conditions for particles injection

Validation test 3

Sphere in medium Debye length regime:
• good agreement with other analytical models .

Quantity	Symbol	Value	
Temperature	T	1.0	eV
Electron density	n	$5.5\ 10^{7}$	m^{-3}
Debye length	λ	1.0	m
Potential	ϕ	25	V
Sphere radius	ρ	1.0	m
Number of tetrahedrons		~10,000	
Simulation box diameter		40	m
Number of macro-particles		~300,000	

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

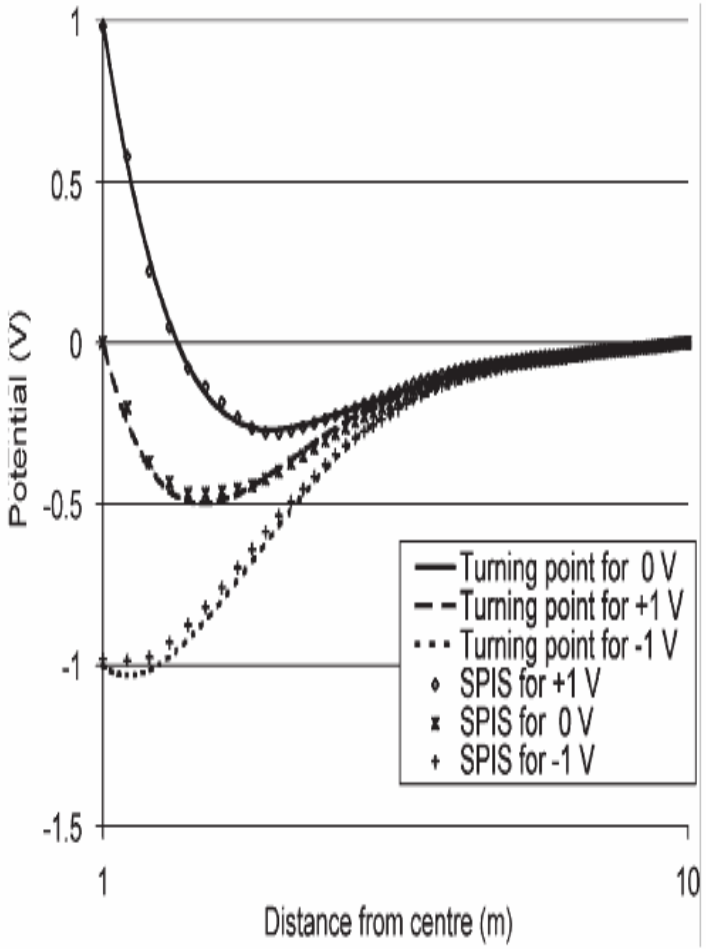


Validation test 4

Photo-emitting sphere:
• good agreement with another analytical model.

Quantity	Symbol	Value	
Temperature	T	1.0	eV
Emitted electron temperature		2.5	eV
Maximum emitted electron current density		50	μAm^{-2}
Electron density	n	10^8	m^{-3}
Debye length	λ	0.74	m
Potential	ϕ	-1,0,1	V
Sphere radius	ρ	1.0	m
Number of tetrahedrons		~50,000	
Simulation box diameter		40	m
Number of macro-particles		~300,000	

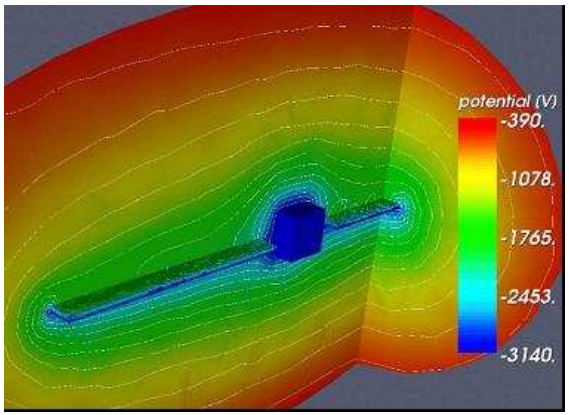
Ref.: Hilgers et al., IEEE Trans. Plasma Sc., 36, 5, 2008.

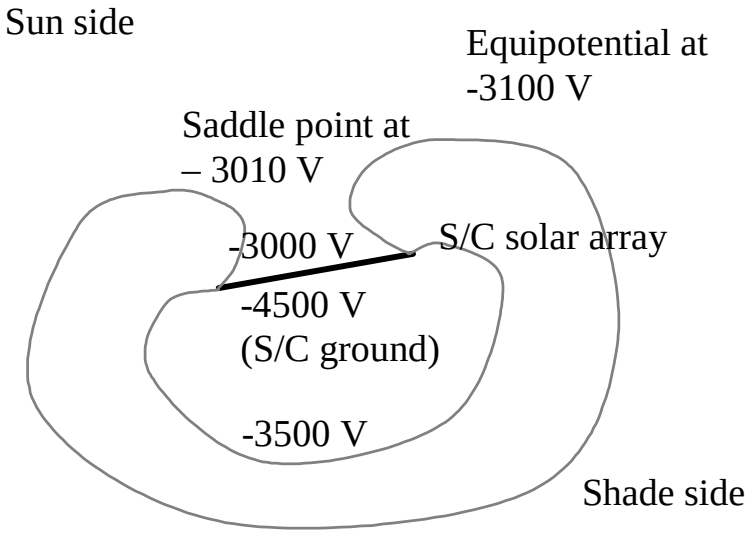


Charging in GEO

- Plasma dynamics :
  - Blocking of photo/secondary emission by the barrier (small barrier height compared to potentials involved)
  - Accuracy of (collected) currents: small object in a large computation box (noisy) => backtracking needed (can be useful for detectors)

- Multi-time scale modelling
  - Implicit SC circuit solver



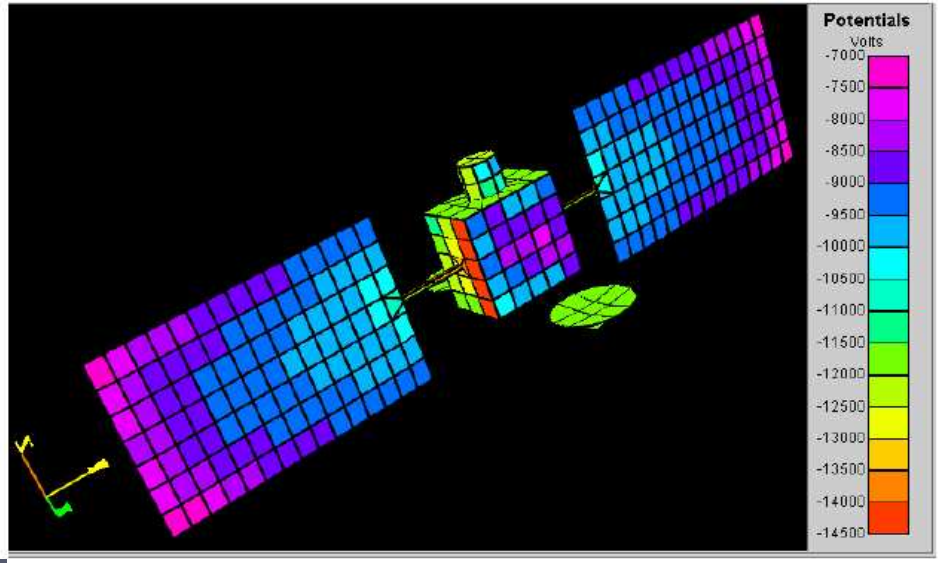


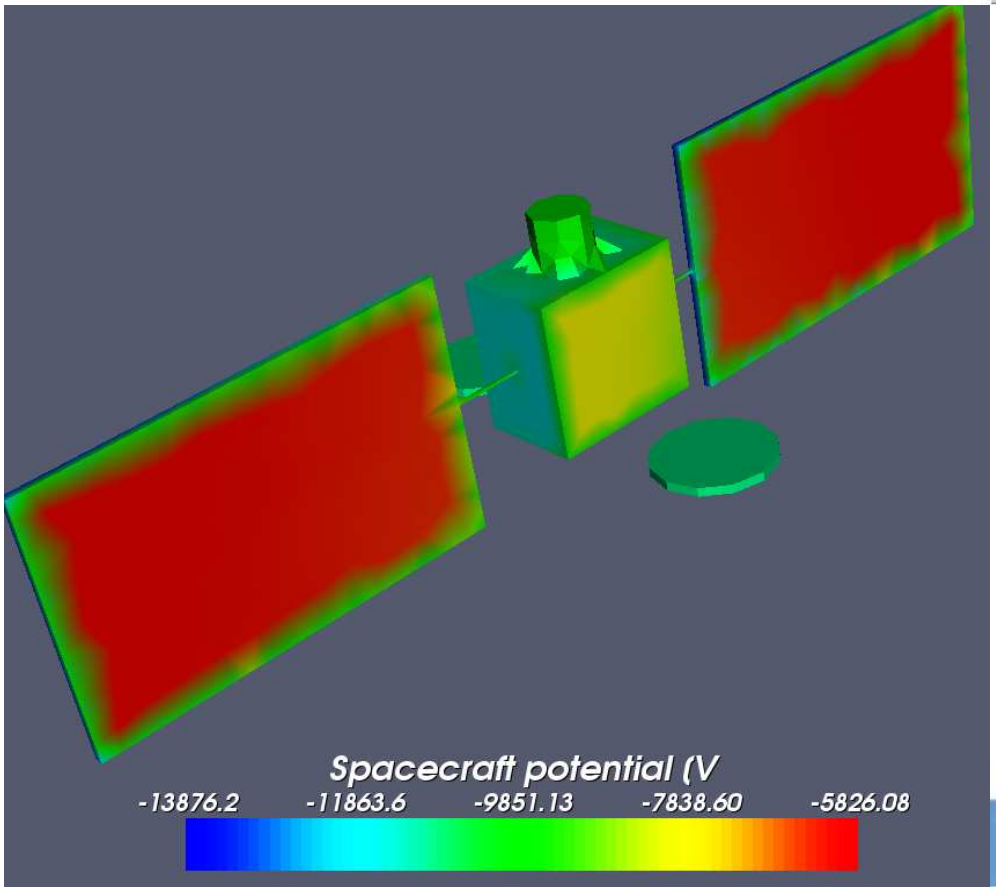
Comparison with NASCAP modelling

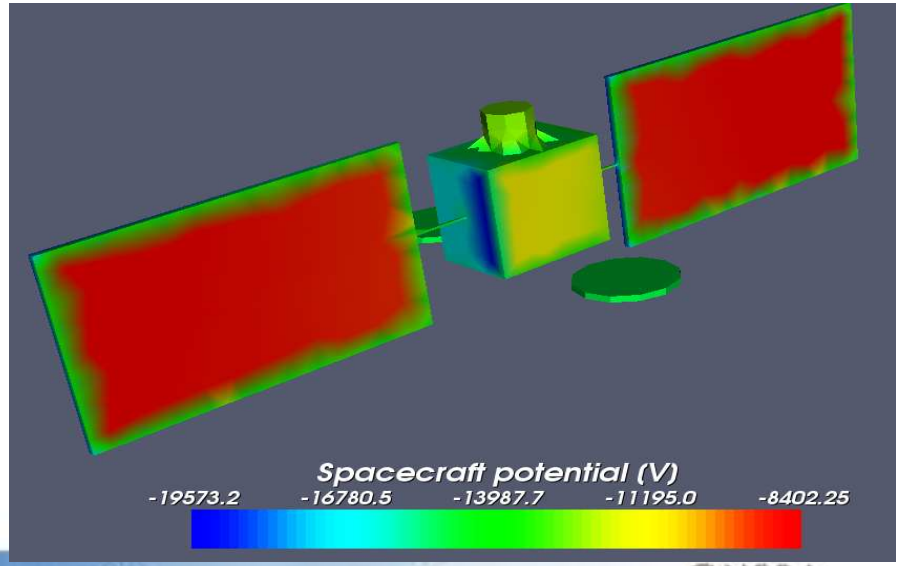
- Published model (Davis et al)
  - "Validation of NASCAP-2K spacecraft-environment interactions calculations", V. A. Davis, M. J. Mandell, B. M. Gardner, I. G. Mikellides, L. F. Neergaard, D. L. Cooke and J. Minor, 8th Spacecraft Charging Technology Conference, Huntsville, Alabama, USA, 20-24 oct. 2003
- Published SPIS comparison
  - JF Roussel et al., " SPIS multi time scale and multi physics capabilities: development and application to GEO charging and flashover modeling " , 11th Spacecraft Charging Technology Conference, Albuquerque, NM, USA, 20-24 sept. 2010.
  - Similar model with SPIS (B. Andersson, SSC)
  - Comparison of potential maps and time variation

Potential maps (t=1000s)

- Comparison with NASCAP
  - Globally good agreement
  - Small local differences (OSR e.g.)
  - Often smaller gradient







Time evolution

- Comparison with NASCAP:
  - falls within NASCAP-series code results

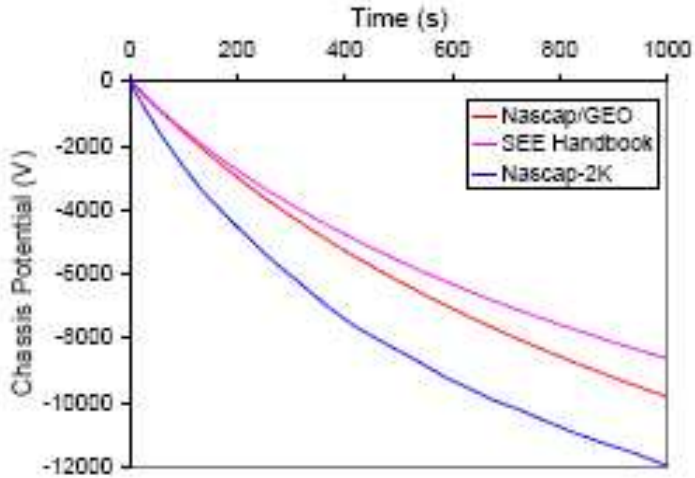
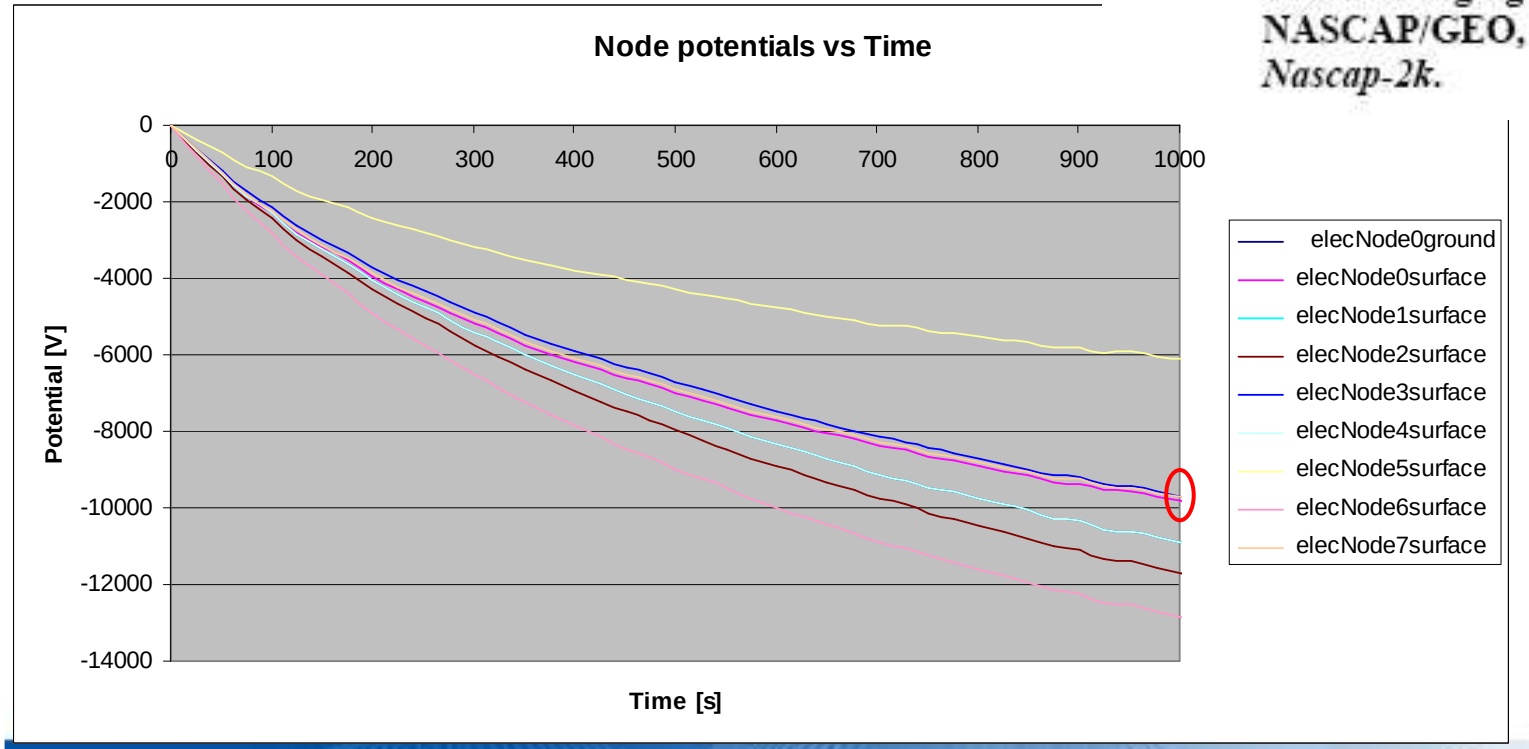
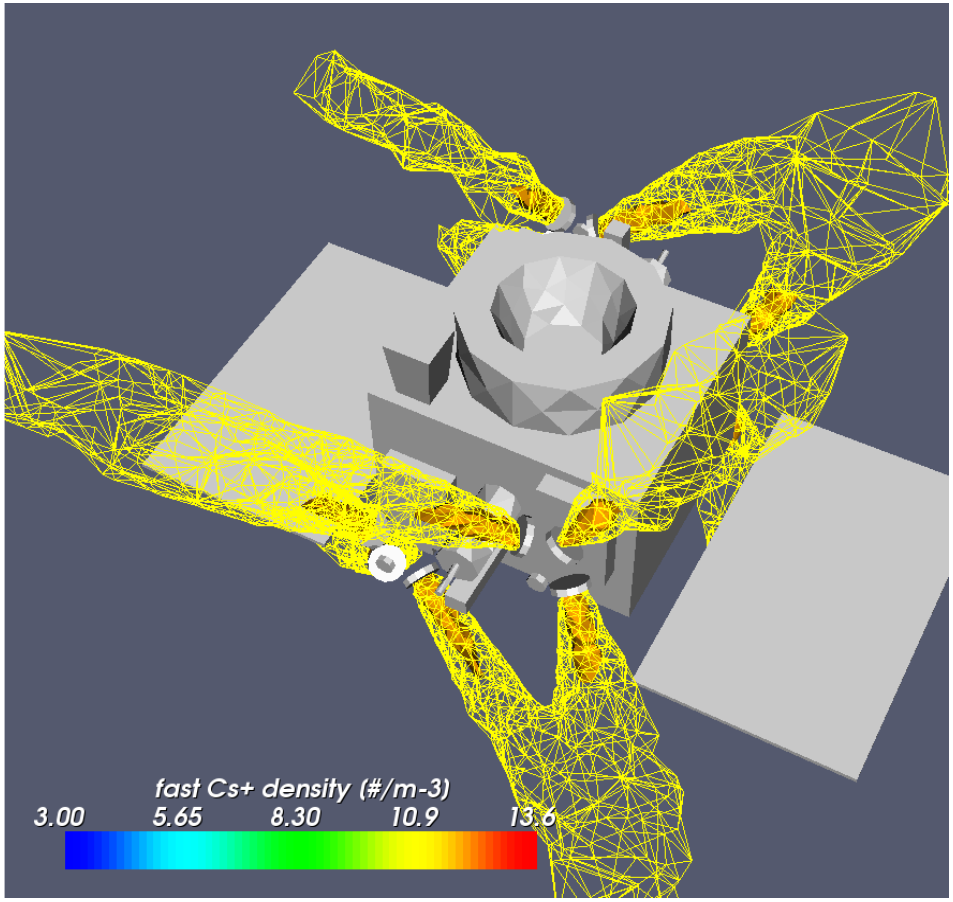


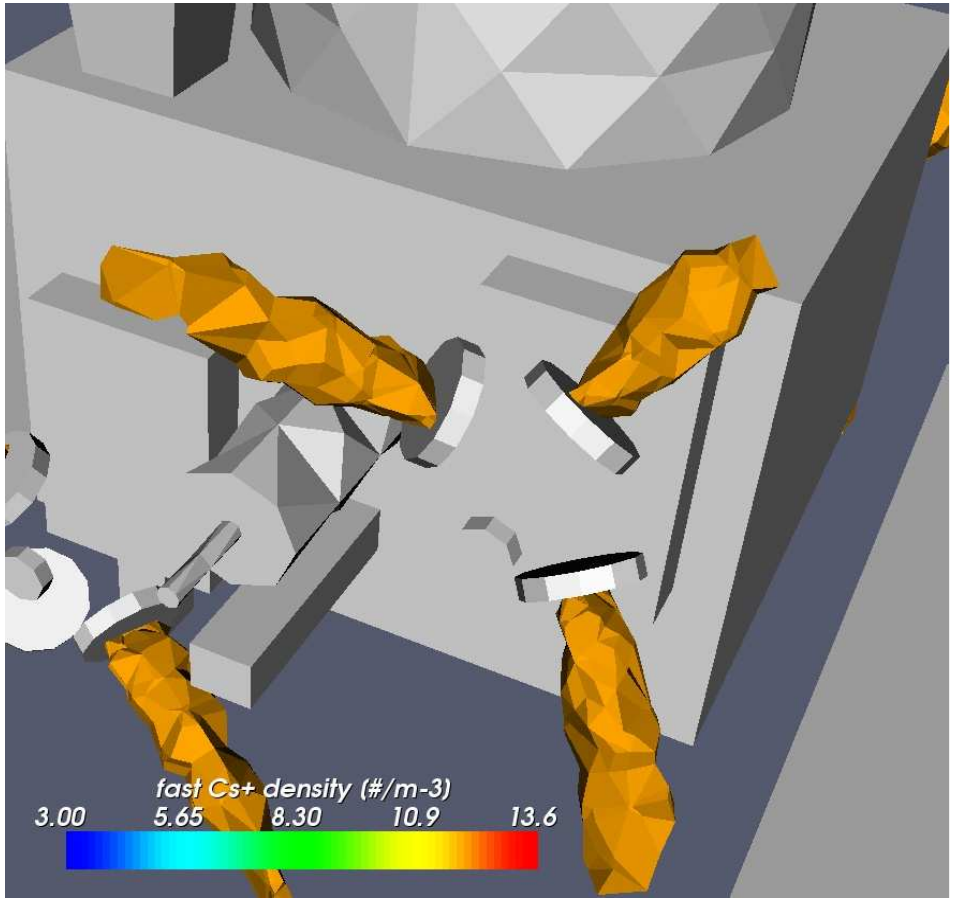
Figure 8. Comparison of chassis potential versus charging time as computed by NASCAP/GEO, SEE Handbook, and *Nascap-2k*.



Electric Propulsion on MICROSCOPE (LEO)

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

Multi length scale capability with imbricate box

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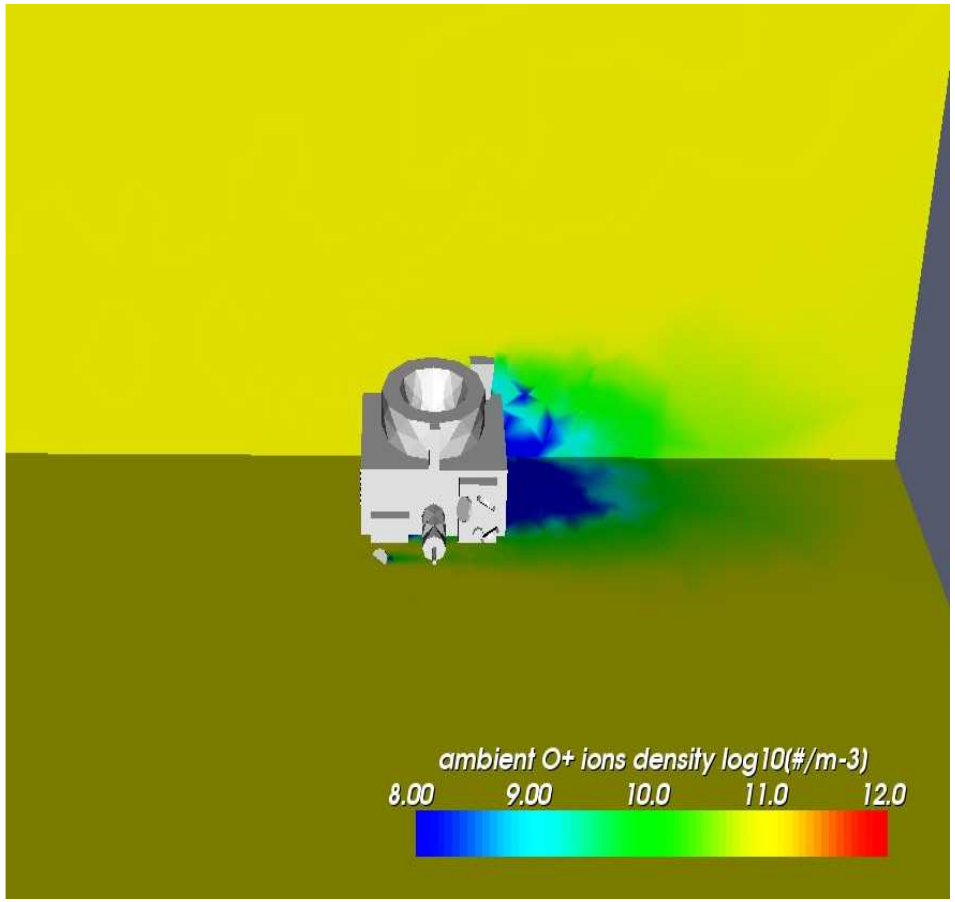
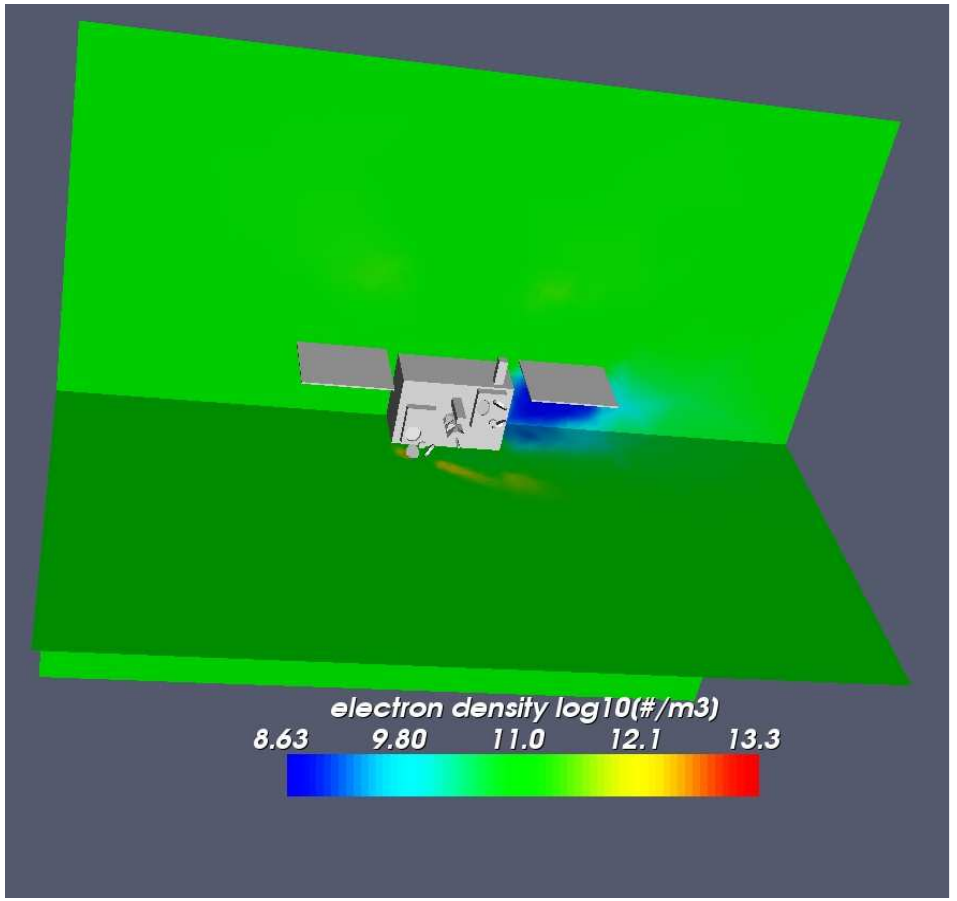
Ambient densities



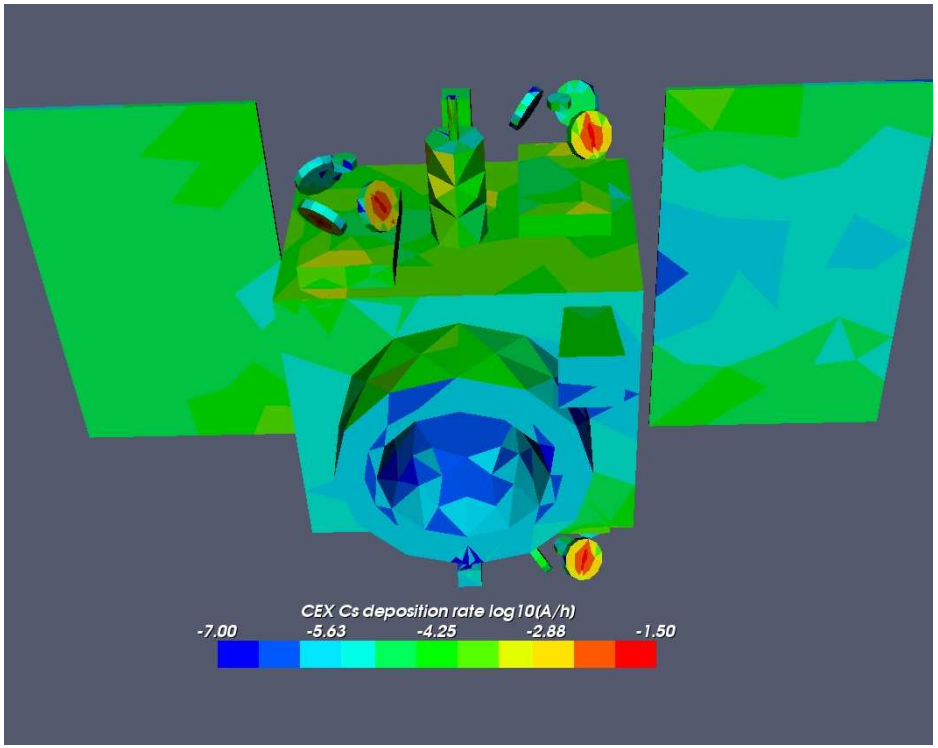
O^+ ions: wake depletion

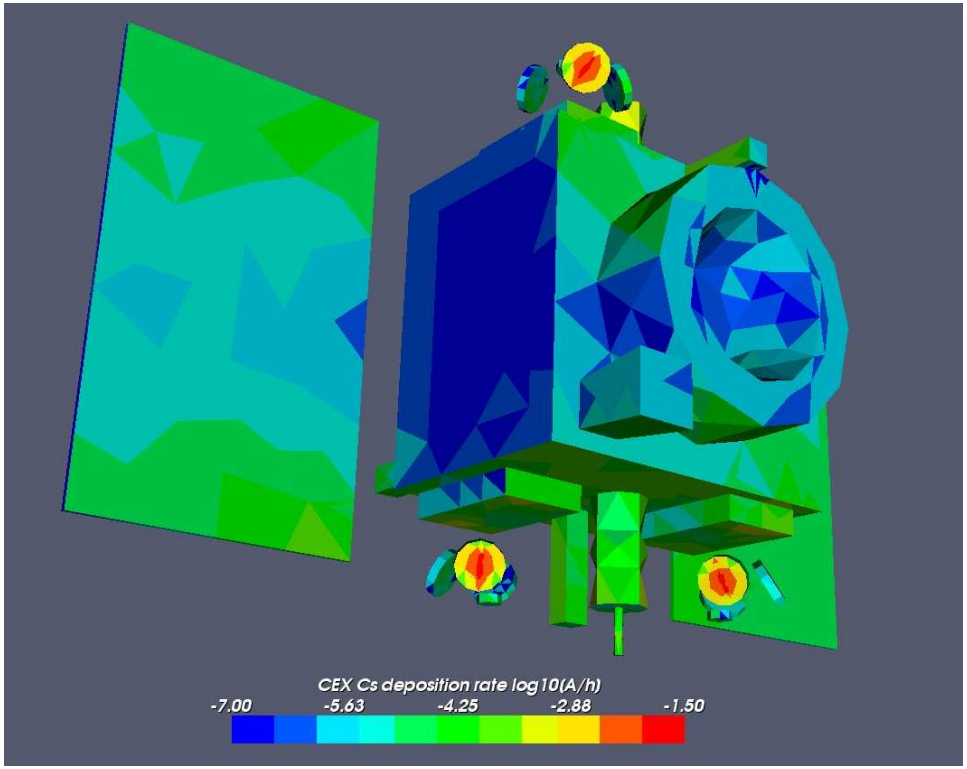


Boltzmann electrons: wake depletion + neutralisation of Cs^+ in plumes

CEX ion deposition rate

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

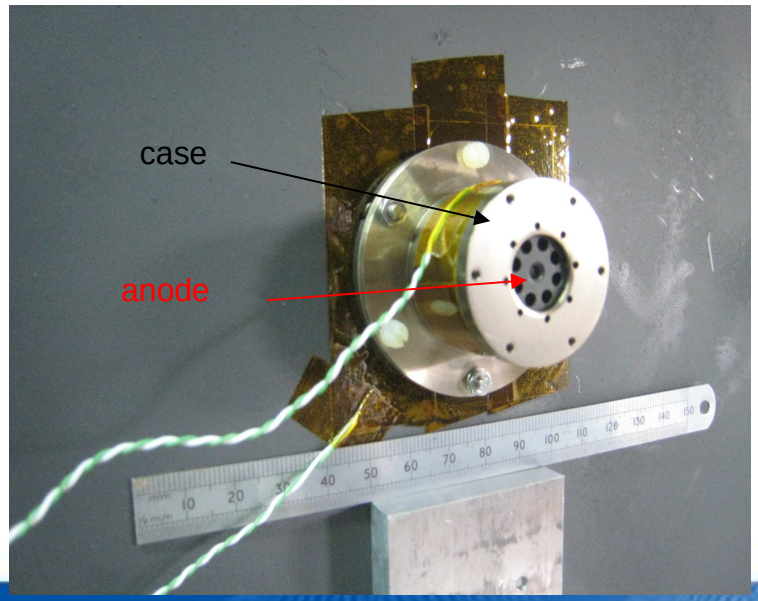


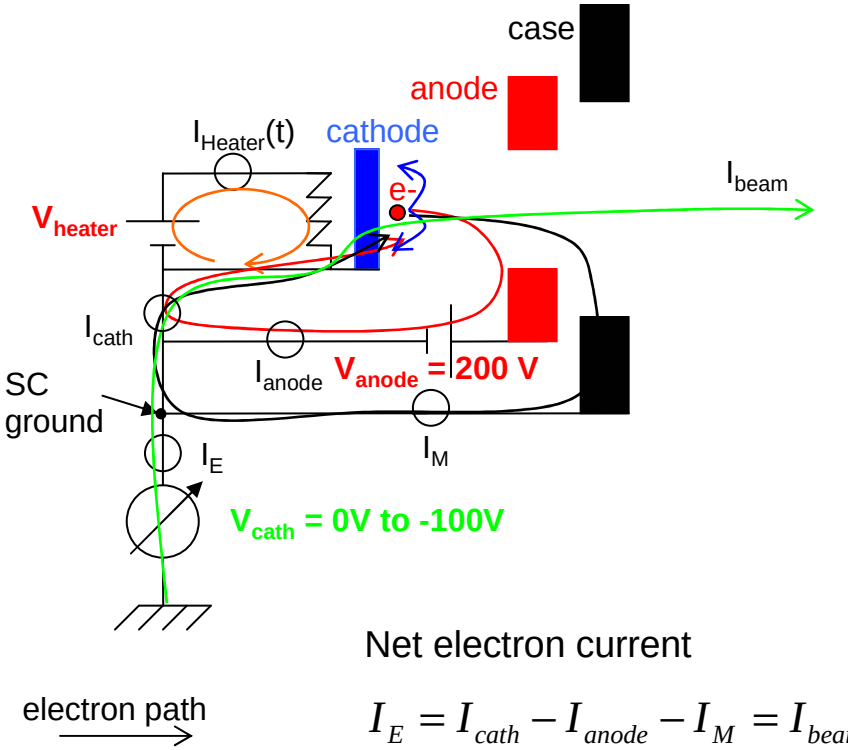


Simulation of an electron emitter

- Ref: J. Mateo-Velez et al., "Neutralization for Micro Propulsion - Experiments and SPIS Simulations", 44th AIAA Joint Propulsion Conference & Exhibit, 21–23 July 2008, Hartford, CT, USA

- TAS neutralizer
  - Heated impregnated cathode
  - Extractor electrode (anode)

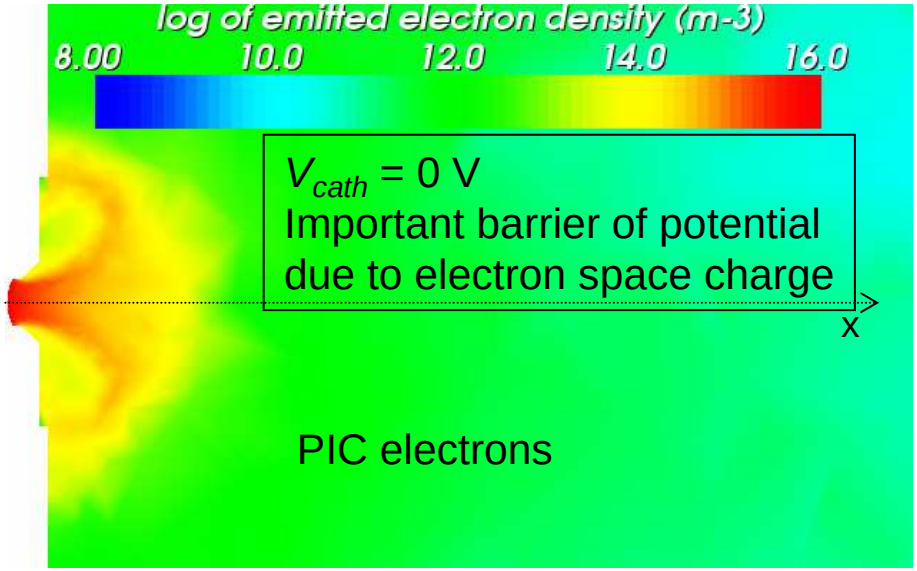


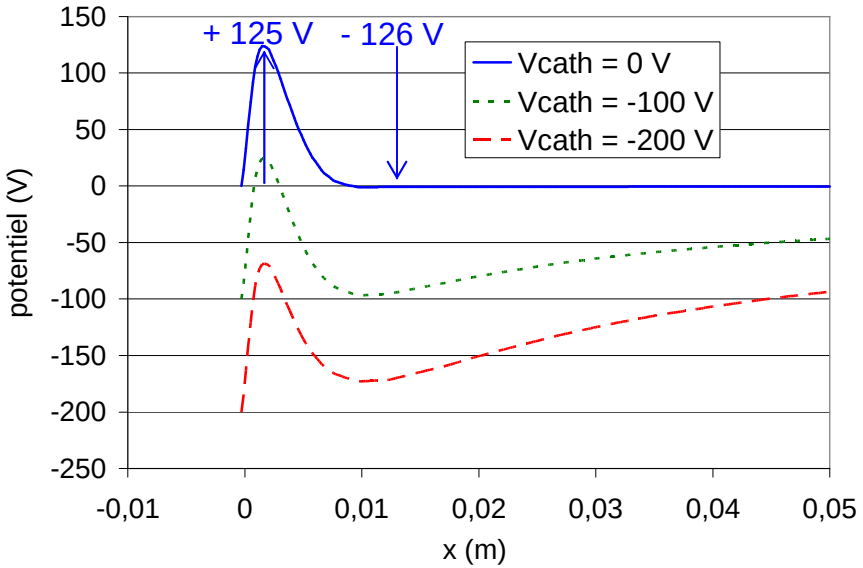


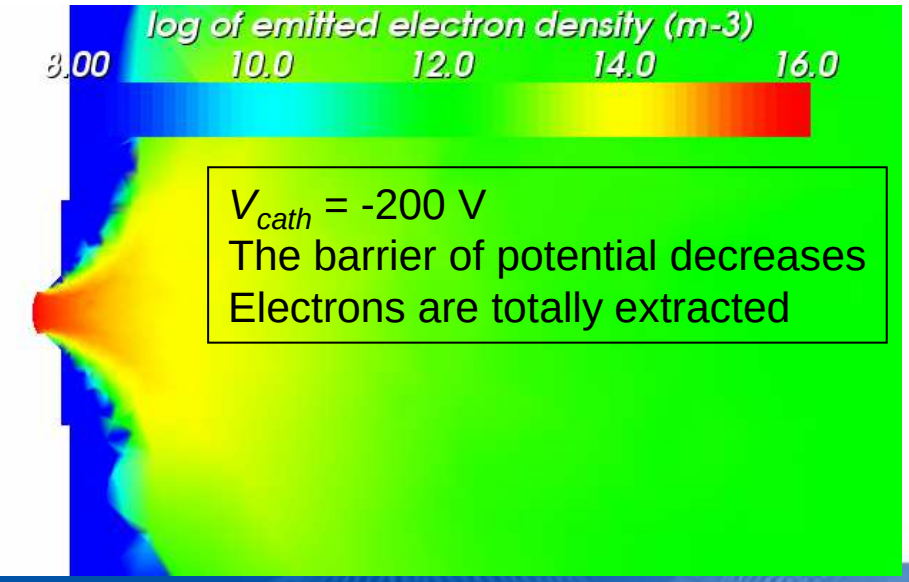
Net electron current

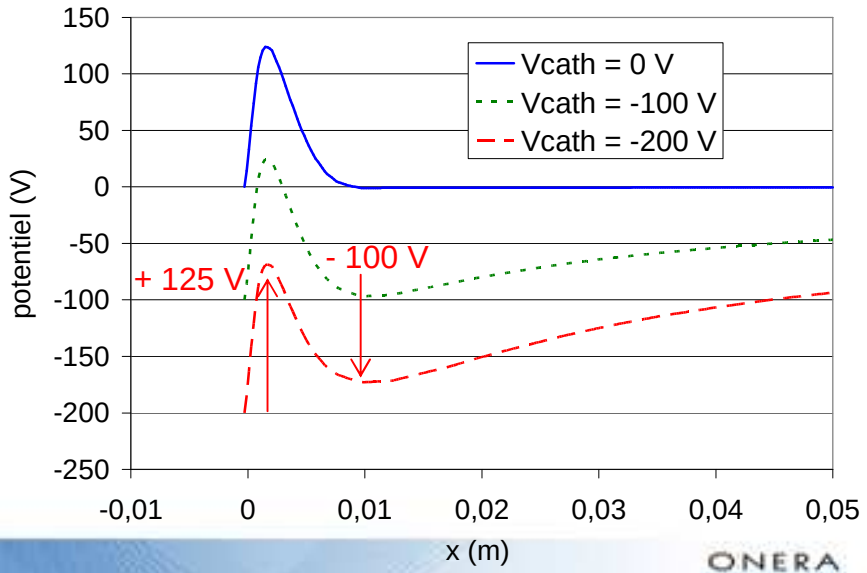
$$I_E = I_{cath} - I_{anode} - I_M = I_{beam}$$

Simulation of an electron emitter









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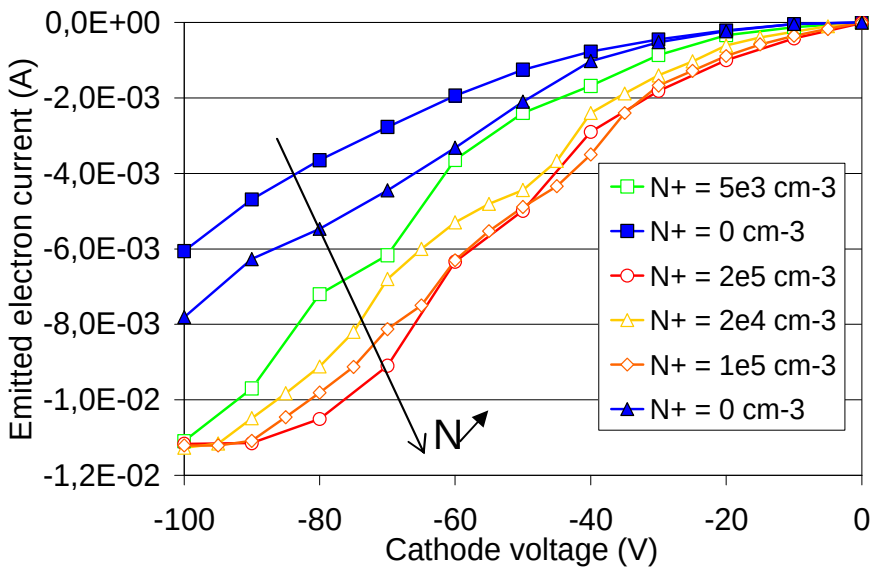
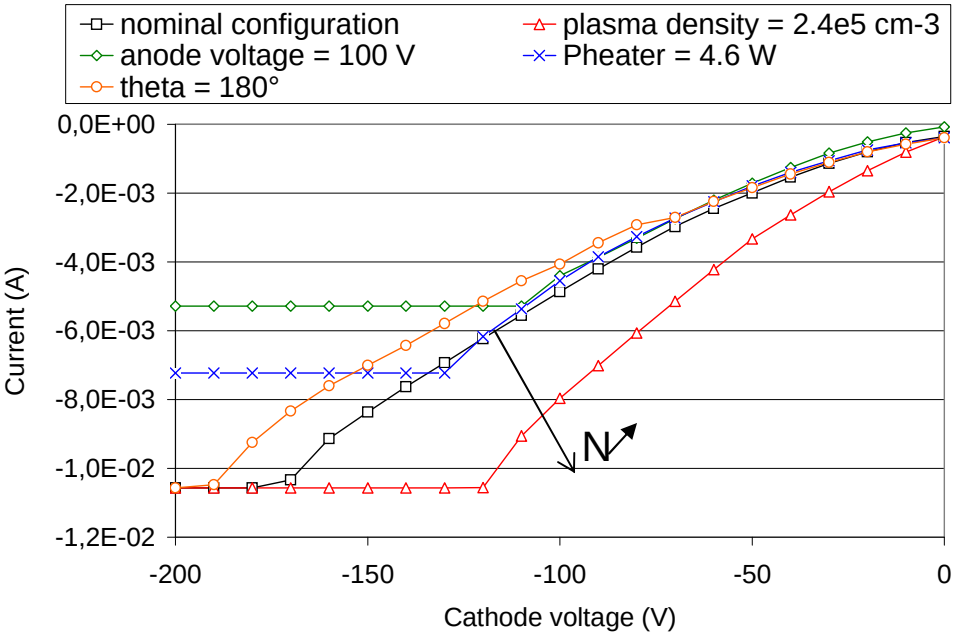
Simulation of an electron emitter

- Good tendencies wrt to experiments
  - increase in the ambient plasma density → increase in the electron current extraction
  - because of the limitation of the potential barrier



Experiments



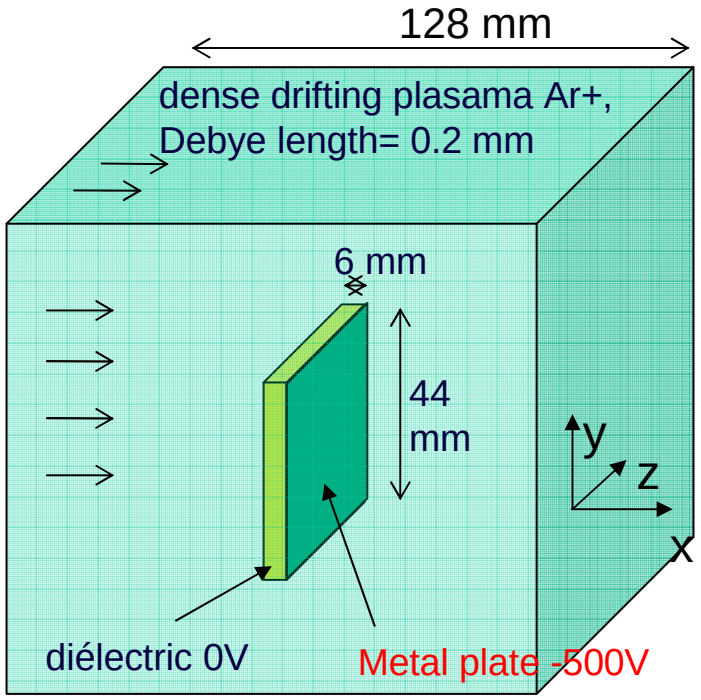
Simulations

SPIS MUSCAT cross comparison

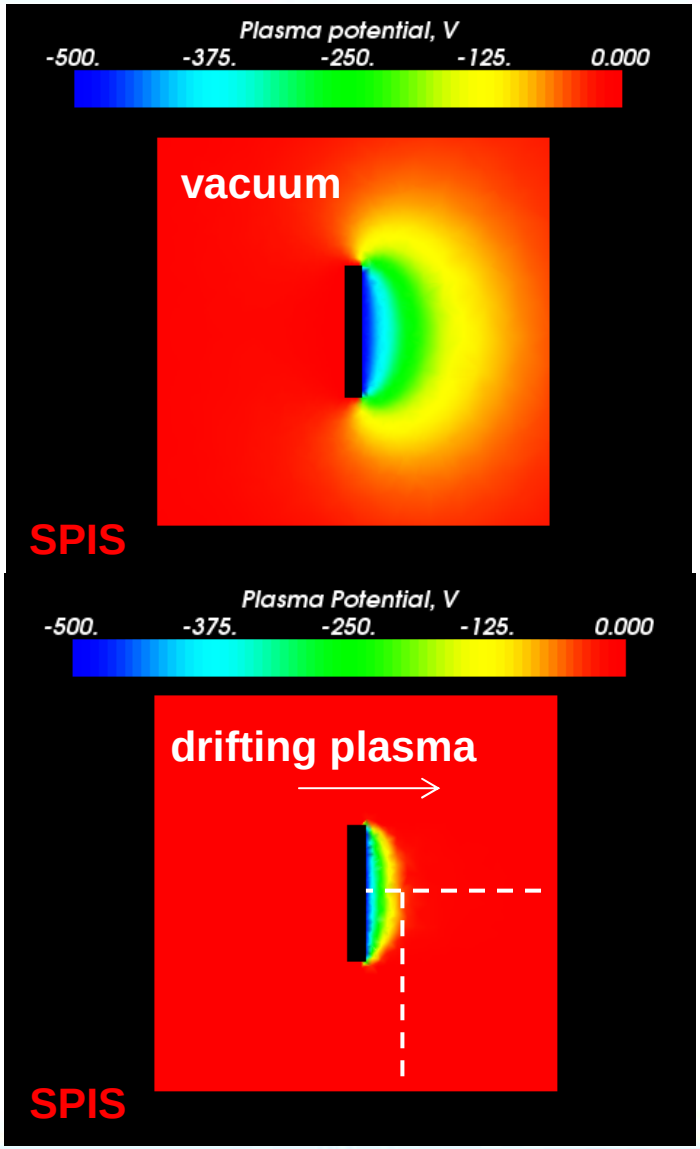
- Ref: JC Mateo-Velez, " SPIS MUSCAT comparison on LEO-like environment " , 11th Spacecraft Charging Technology Conference, Albuquerque, NM, USA, 20-24 sept. 2010.

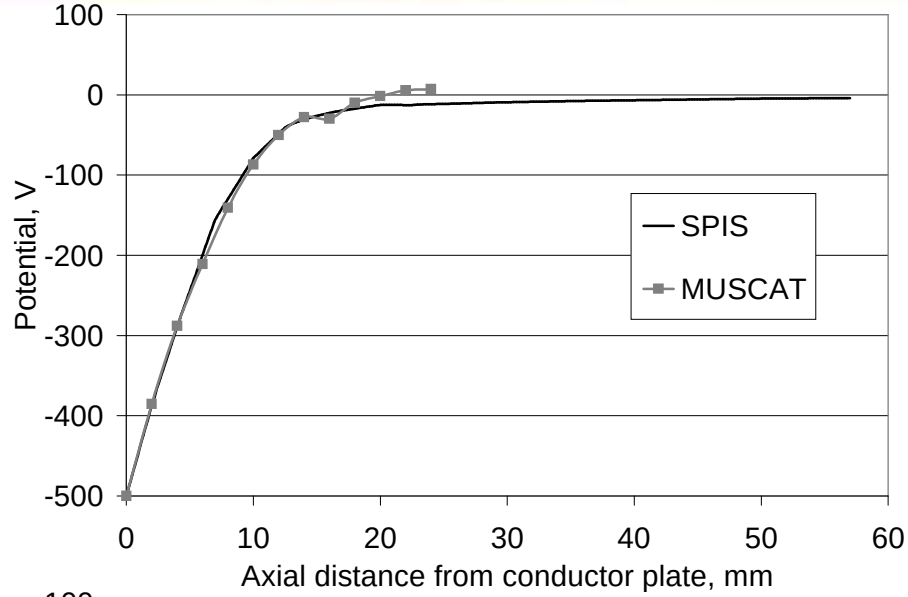
- Physics
  - Drifting plasma / sheath
  - High negative potential on the rear side
  - Deflexion and collection of ions

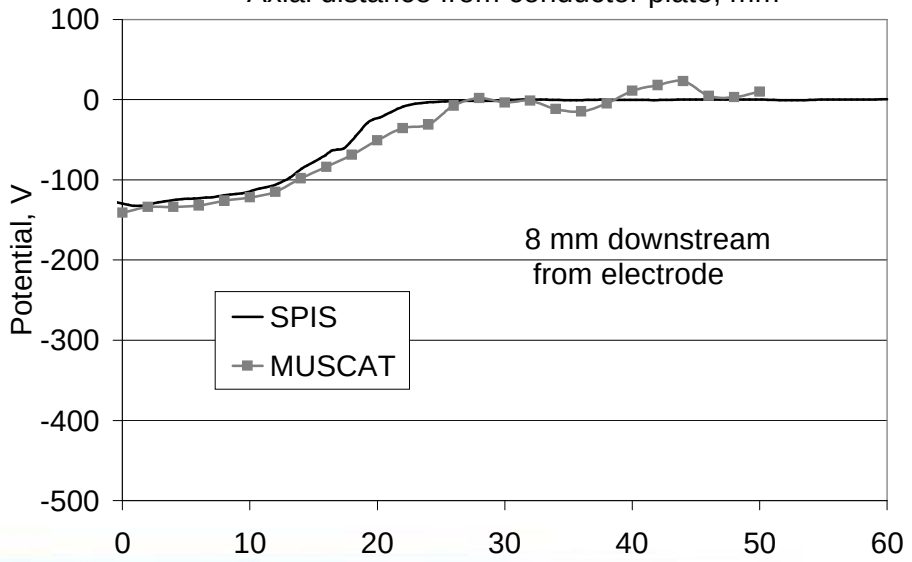
- Modèle
  - Boltzmann distr. for electrons



Results

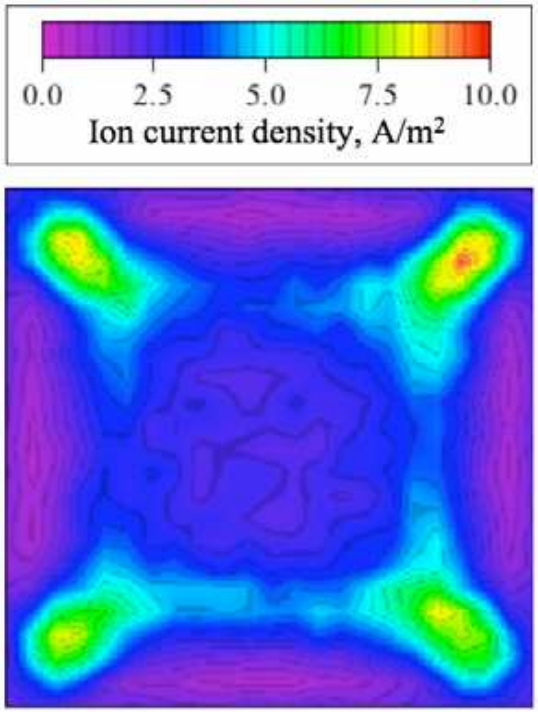

Plasma potential, V
-500.
-375.
-250.
-125.
0.000
vacuum
SPIS
Plasma Potential, V
-500.
-375.
-250.
-125.
0.000
drifting plasma
SPIS


100
0
-100
-200
-300
-400
-500
Potential, V
0
10
20
30
40
50
60
Axial distance from conductor plate, mm
SPIS
MUSCAT

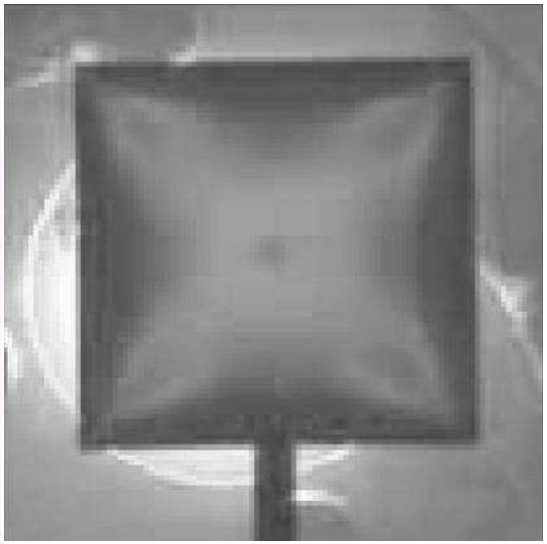

100
0
-100
-200
-300
-400
-500
Potential, V
0
10
20
30
40
50
60
Radial distance from centerline, mm
8 mm downstream
from electrode
SPIS
MUSCAT

Results – Ion Collection on the rear side

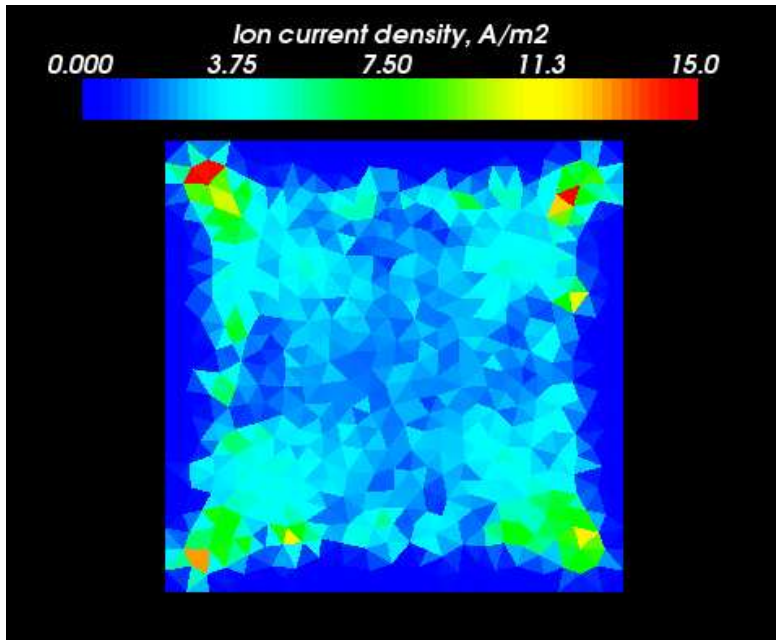
It was necessary to increase the ion statistics



MUSCAT



KIT exp.



SPIS

Hosoda et al., "Laboratory Experiments for Code Validation of Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT)", IEEE Trans. Plasma Sci., Oct 2008.

Total collected current 6.4 mA pour MUSCAT
5.0 mA pour SPIS

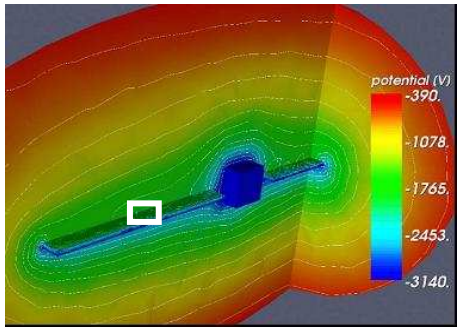
Good agreements between the 2 codes and experiments

SPIS-ESD

- New SPIS-ESD release since January 2011
- Simulation of the Electrostatic Discharge onset on solar cells in GEO
  - Slow precharge (mn) / very fast electron avalanche (ns!) + steep field emission
- Ref: P Sarrailh et al., “Comparison of numerical and experimental investigations on the ESD onset in the Inverted Potential Gradient situation in GEO”, 11th Spacecraft Charging Technology Conference, Albuquerque, NM, USA, 20-24 sept. 2010.

General overview of SPIS-ESD

Macroscopic scale



Global S/C potential (input for the ESD Risk tool)

SC voltage

Simulation at mesoscopic scale

barrier of potential

photon, electron

dielectrics

capacitive and conductive coupling

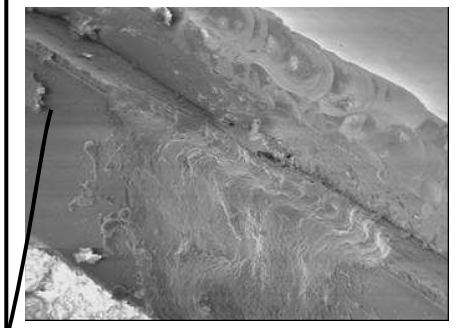
dielectrics

metal

Fowler-Nordheim electron emission + recollection

Secondary electron emission by electron impact + recollection

Microscopic scale model



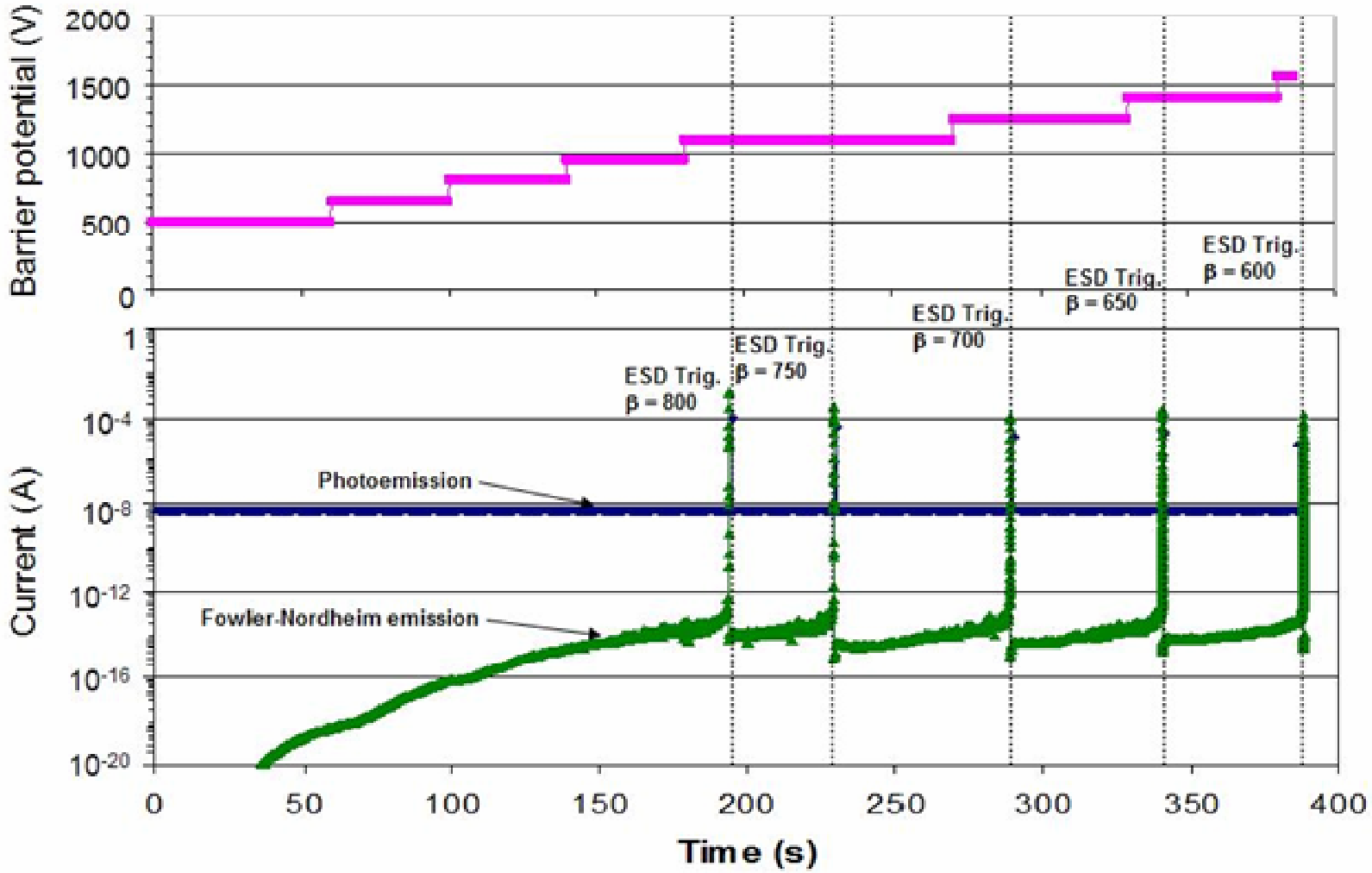
Microscopic scale
- *β electric field amplification*

tip melting and neutral ionization

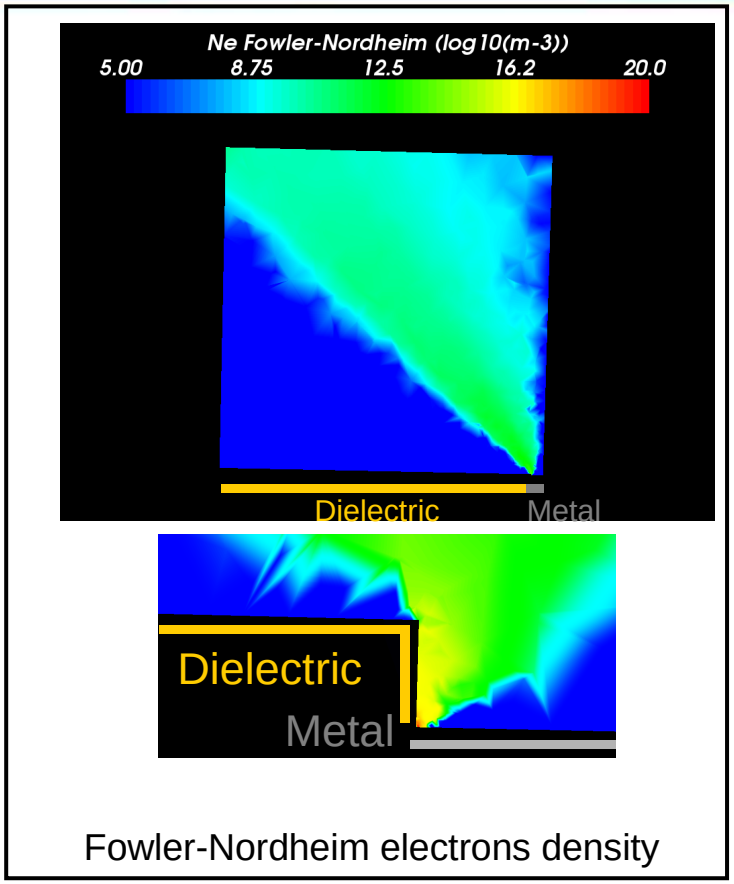
SPIS ESD results

SPIS-ESD is able to simulate the charging phase (min) and the electron avalanche (ns)

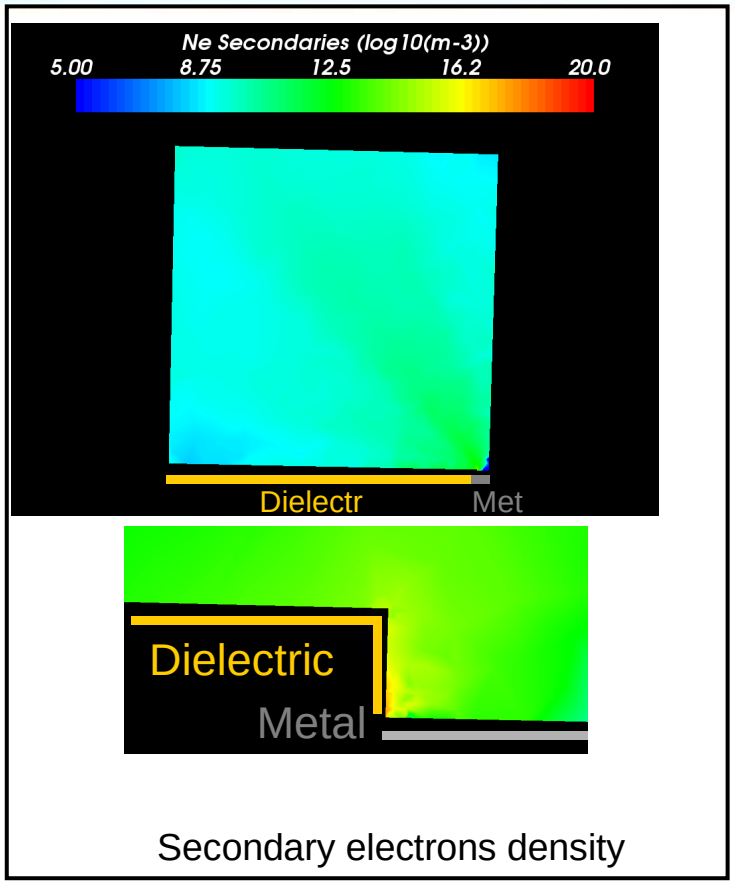
+ Good agreement with experiments !



SPIS ESD Results



Fowler-Nordheim electrons density



Secondary electrons density

- F-N primary electrons:
  - directed toward the barrier potential
  - Max density can reach 10^{20} m^{-3} (Space charge effect)
- Secondary electrons are present on the top side of the dielectric due to hoping