Plasma Simulations at ESA for Spacecraft Plasma Interactions

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- Problems to solve.
- PicUp3D
- SPIS
- Examples of applications

Problems to solve

Terms to compute:

- Charged particle current
  - ion, electron
  - photo-electron
  - secondary electron emission
  - active emission
- self-consistent potential distribution
  - In material for deep dielectric charging.
  - Outside material for surface interactions.
- Multi-physics problems
- Very small community in Europe (~5 man*Y/Y)

Simulation Methods

Essential features of tools available from www.spis.org:

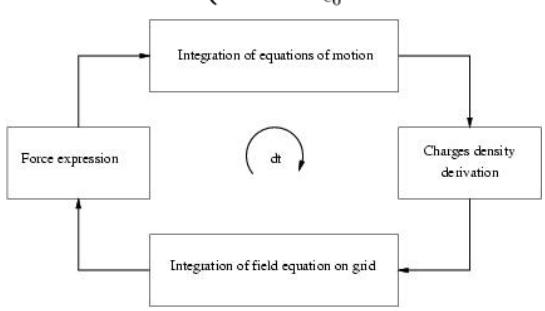
- 3D Kinetic model of all particle species transport for 'large' λ_D (Boltzmann equilibrium of electrons otherwise).
- PIC method for particle transport and density calculation.
- Poisson solver , e.g., finite difference (PicUp3D) or FEM (SPIS).
- Spacecraft Equivalent electric circuit solver (SPIS).
- Surface physics modules (SPIS).

Plasma modelling with PicUp3D

- Vlasov-Poisson system :

$$\begin{cases} \dfrac{\partial f(t,x,v)}{\partial t} + v\dfrac{\partial f(t,x,v)}{\partial x} + F\dfrac{\partial f(t,x,v)}{\partial v} = 0 \\ F = q(\mathbf{E} + v \wedge \mathbf{B}) \\ \nabla \cdot \mathbf{E} = \dfrac{\rho}{\epsilon_0} \\ \Delta\phi = -\dfrac{\rho_{tot}}{\epsilon_0} \end{cases}$$

Particle-In-Cell code loop:



PicUp3D Simulation techniques

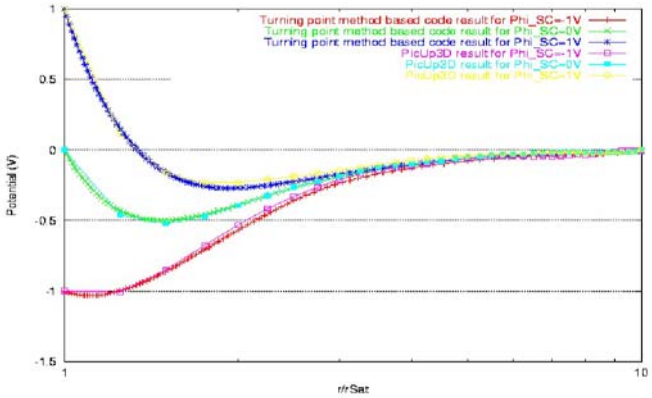
- PIC method for particle transport and density calculation.
- Poisson solver with finite difference on regular rectangular grid.
- Object defined with triangular surface mesh technique.
- BC on nearest object grid point.

Software Features

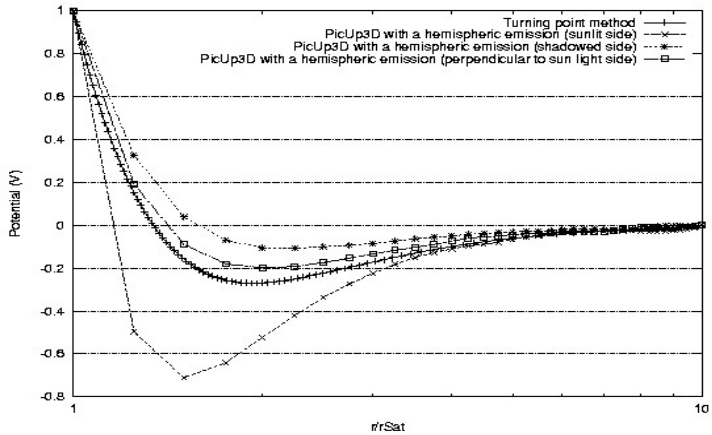
- Open source and freely available from: www.spis.org
- OO and Java based.
- Supported by SPINE, ESA, IRF, CNES.
- In use since 2001 at ESA.
- ESA investment (r&d +dev): ~90 kEuro + ~1 man*year.

Validation of PicUp3D with uniform photo-emission

- Comparison TP-PicUp3D (100 cc, 1 eV)



Example of non-uniform photo-emission effect *(Thiébault et al., JGR, 2004)*



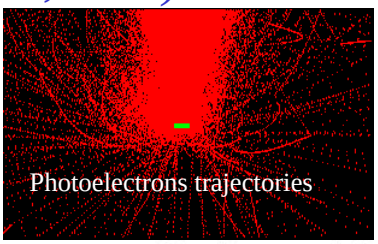
T= 1 eV
N= 100 cm-3

Example: Cluster Electrostatic Sheath in large λ_D regime

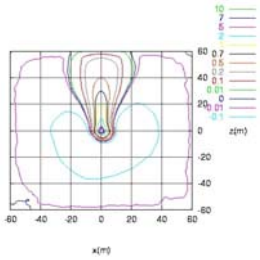
(Thiébault et al., sctc, 2003)

Sheath and photoelectron cloud structure and effects

- Ion plume neutralised and potential shielded in the near sheath region by photo-electrons
- Far sheath dominated by photo-electrons
- Possible effects on the electric field measurements (requires higher resolution)



Potential map of Cluster sheath



PicUp3D current limitations

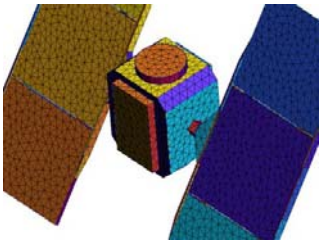
- Mesh/box limit to ~100 on rectangular grid.
- Nearest Grid Point approximation.
- Needs optimisation of numerical solvers (in progress).
- No surface physics.

New Generation: SPIS

- 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 (Conjugate gradient, linear/ non-linear)

SPIS software feature

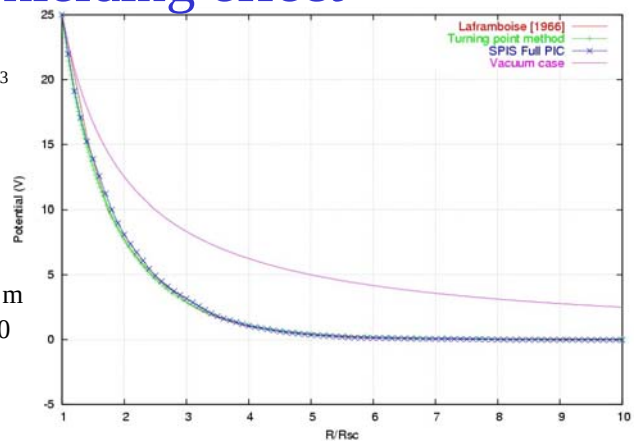
- OO and Java based.
- Advanced framework for pre- and postprocessing and numerical schemes definition.
- Supported by SPINE (Onera, artenum, GolP), ESA, CNES.
- Open source and freely available on www.spis.org.
- ESA investment (r&d +dev): 600 kEuro+1 man*year.



Passive Sphere with plasma shielding effect

- Temperature: 1.0 eV
- Number density: 55 cm^{-3}
- Debye length: 1.0 m
- Sphere potential: -25 V

- Sphere radius: 1.0 m
- Tetrahedrons: ~50 000
- Simulation box size: 40 m
- Macro particles: 300,000



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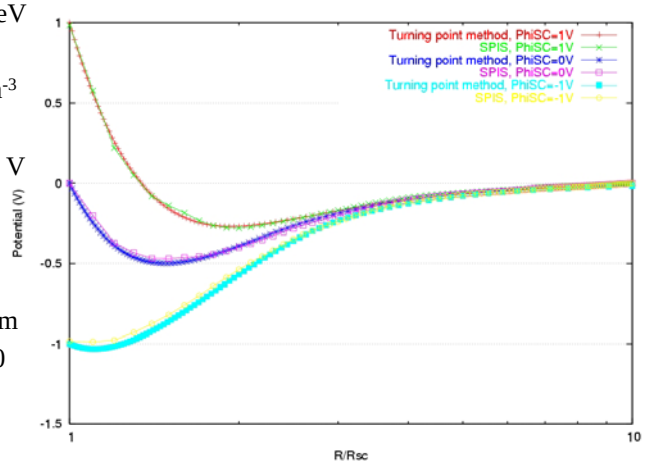
Emitting Sphere

- Ambient e- Temp.: 1.0 eV
- Photo e- Temp.: 2.5 eV
- Number density: 100 cm^{-3}
- Debye length: 0.74 m
- Sphere potential: [-1, 1] V

- Sphere radius: 1 m
- Tetrahedra: ~50 000
- Simulation box size: 40 m
- Macro particles: 300,000



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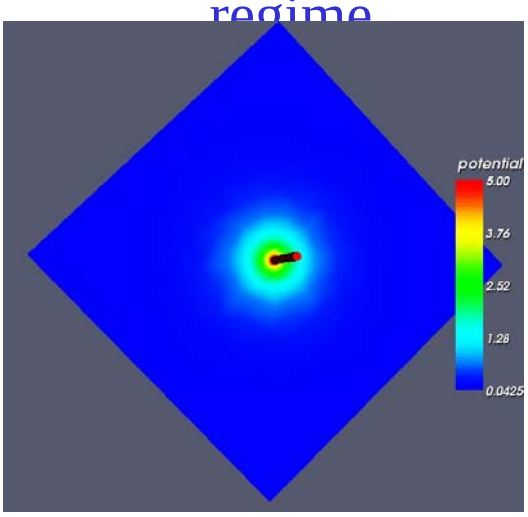
Testing Thin Cylinder in OML regime



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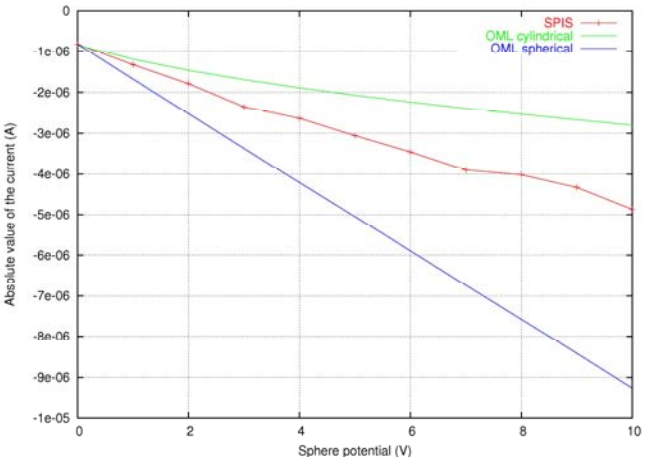
Testing Thin Cylinder OML regime

- Temperature: 1.0 eV
- Number density: 10 cm^{-3}
- Debye length: 2.4 m
- Potential: [0,12] V

- Cylinder radius: 0.25 m
- Length: 16 meter
- Central node0: 2 m
- Outer node1: 7+7 m
- Tetrahedrons: ~60,000
- Simulation box size: 20 m
- Macro particles: 300,000



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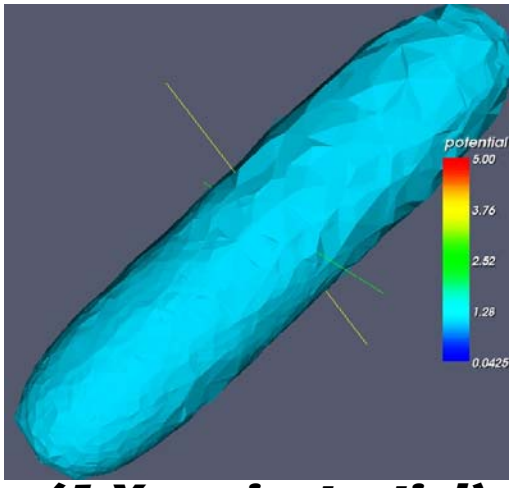
Testing Thin Cylinder in OML regime



(1 V equipotential)

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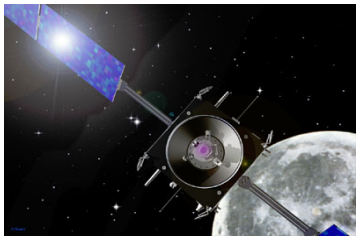
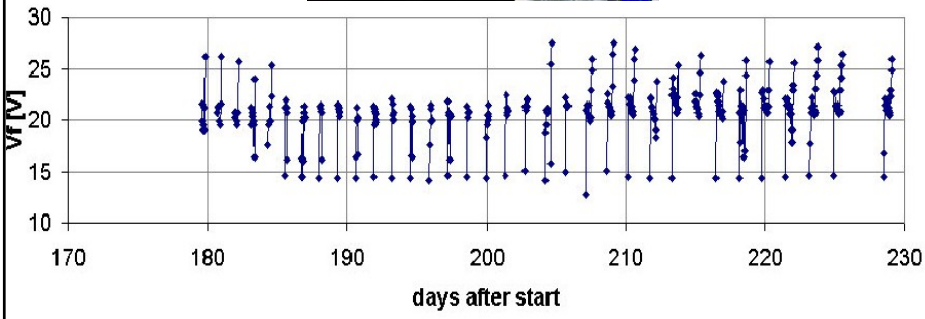
Application: SMART-1 Floating Potential





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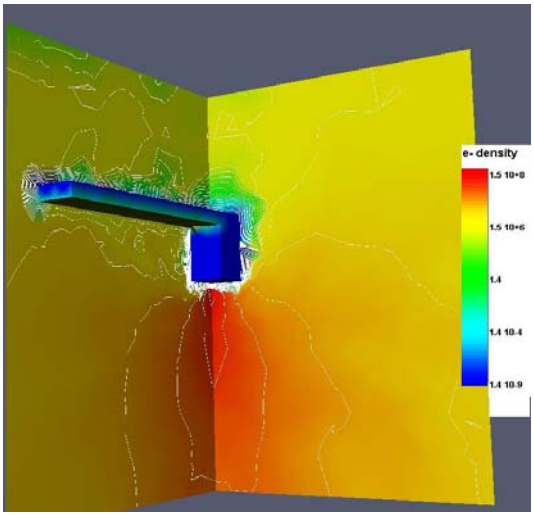
SPIS simulation of SMART-1

- Array facing:
  - ~16 V
  - ~10^7 cm^{-3}



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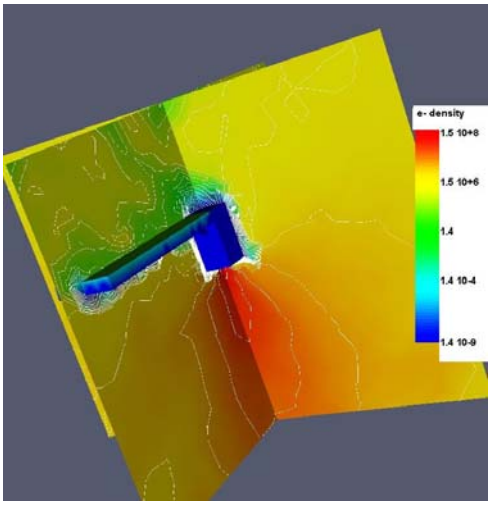
SPIS simulation of SMART-1

- Array in wake:
  - ~7 V
  - ~10^3 cm^{-3}



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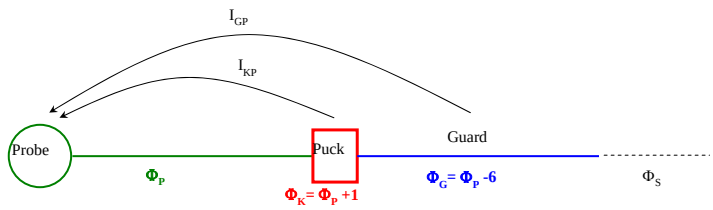
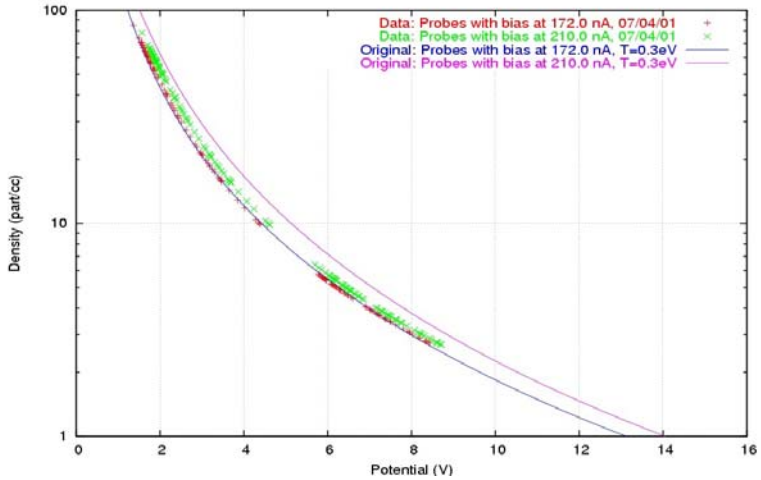
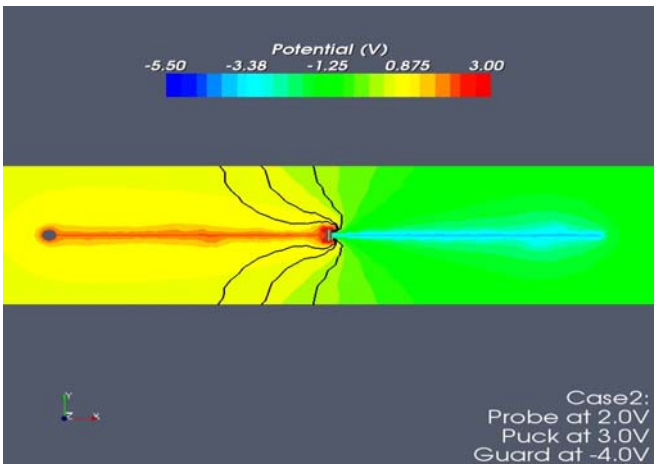
Application: Cluster Probe



Cluster Probe



Cluster Probe



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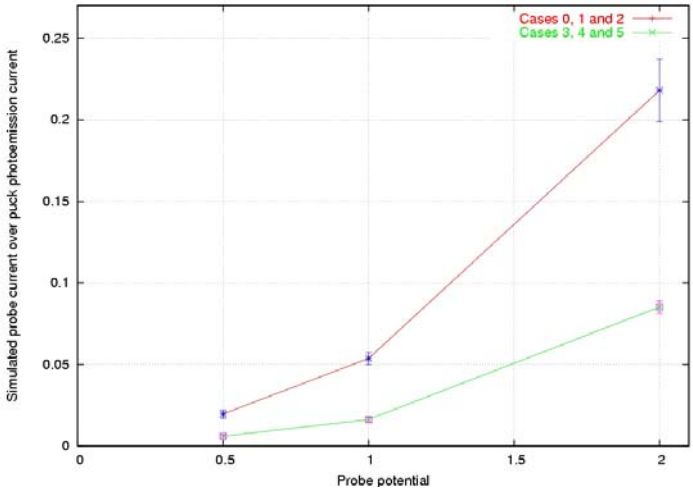
Current Coupling on Cluster Probe



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SPIS current limitations

- Need validation (including experimental) and improvement of multi-time scale phenomenas for s/c charging application in industry.
- Detailed particle trajectories near surfaces should be optimised.
- Critical mass – Link with other communities?

Conclusion

- Spacecraft-plasma interactions have to be considered for spacecraft design, some instrument calibration, electric propulsion systems, power systems, etc….
- Usually order of magnitude estimates can be made with simple formulas for basic charging state.
- Plasma simulation and detailed space-based observation for validation are necessary for refined estimates.
- PicUp3D and SPIS are open and free for these use.
- SPIS already operational after less than 2 Y development.
- www.spis.org

Back-up slides

Further reading

- Proceedings of the 7th Spacecraft Charging Technology Conference, pp.515-520, ESA/SP-476, ISBN 92-9092-745-3, ESTEC, Noordwijk, The Netherlands, 23-27 April 2001.
- Proceedings of the 8th Spacecraft Charging Technology Conference, Huntsville, AL, USA, October 20-24, 2003, NASA/CP-2004-213091.
- Proceedings of the 9th Spacecraft Charging Technology Conference, Tsukuba, Japan, April, 2005.
- Future Proceedings of the 10th Spacecraft charging technology conference, Toulouse, France, 2007.
- Info and free software: www.spis.org.