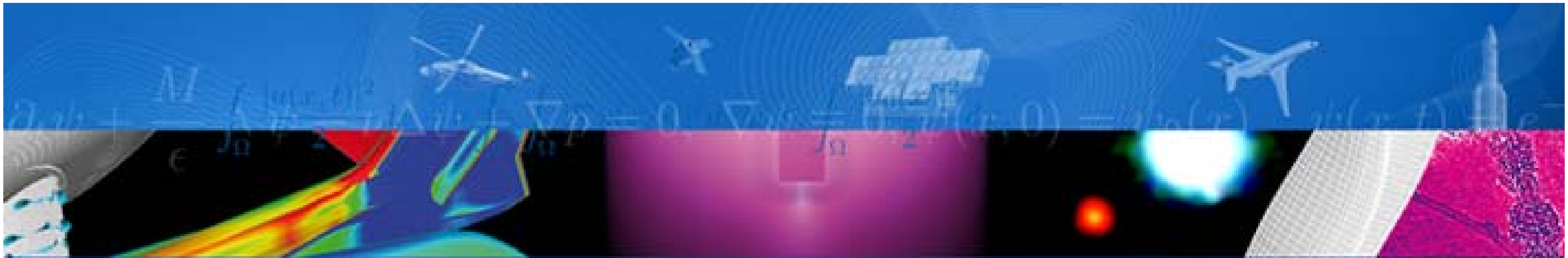

SPIS multi time scale and multi physics capabilities: development and application to GEO charging and flashover modeling

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ONERA
THE FRENCH AEROSPACE LAB

return on innovation

Outline

- Introduction
- New modelling capabilities
  - Multi time scale
  - Multi physics
- Simulation cases
  - Charging in GEO
  - Flashover expansion
- Conclusions and perspectives

SPIS context and project overview

- SPINE *(Spacecraft Plasma Interaction Network in Europe)* community setup around year 2000 (A. Hilgers, J. Forest...):
  - An idea was born: 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

    } this presentation

  SPIS releases (open souce):
  - v4.0 July 2009
  - v4.3 soon
  - Others:
    - Some community developments
    - Some CNES-funded enhancements (EP, ESD)
    - ESD triggering modelling almost completed (ESA TRP) ← next presentation (Pierre Sarrailh)
    - Next steps: EP integration (Astrium), SPIS-GEO (Artenum), SPIS-Science...

Overall status of SPIS code

- SPIS-UI:
  - Real framework: task monitor, data management, script console (jython)…
  - Interfacing with modeler/mesh-generator, postprocessing tools…
- SPIS-Num:
  - Plasma:
    - Matter models: PIC (leapfrog/exact (potential P1)), Boltzmann distribution, multi physics
    - E field solver: Poisson, non linear Poisson, singularities (wires, plates)
    - Volume interaction: CEX (MCC)
  - Spacecraft:
    - Material properties: secondary emission (under electron/proton/UV), conductivities (surface/volume, intrinsic/RIC), field effect, sputtering (recession rate, products generation and transport)
    - Equivalent circuit: coatings (RLC) + user-defined discrete components (RCV), implicit solver
    - Sources: Maxwellian, Axisymmetric, two axes
  - Specific features:
    - Time integration: control at each level (population, plasma, simulation)
    - Numerical times: integrate fast processes over a smaller duration (electrons/ions, plasma/SC…)
    - Multiscale capabilities: cell = box / 100,000
    - Modularity: OO (Java), "plug-in" classes (Java introspection)

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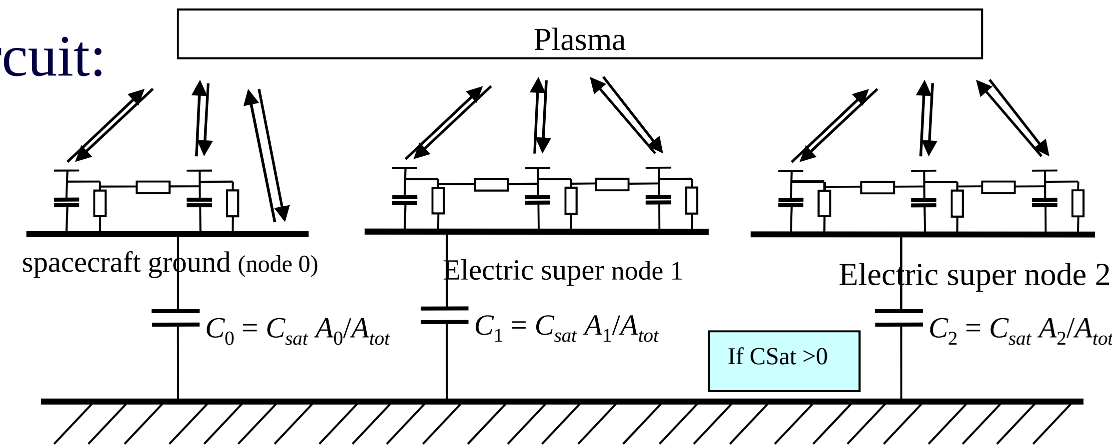
Multi time scale: requirements

- Examples of modelling requirements:
  - Charging in GEO: fast absolute charging (ms) / slow relative charging (mn)
  - ESD triggering: slow precharge (mn) / very fast electron avalanche (ns!) + steep field emission
- Surface potentials => SC circuit:

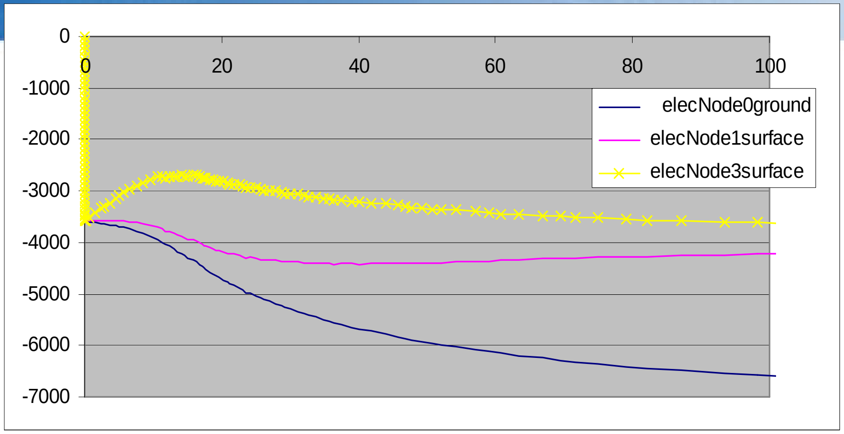


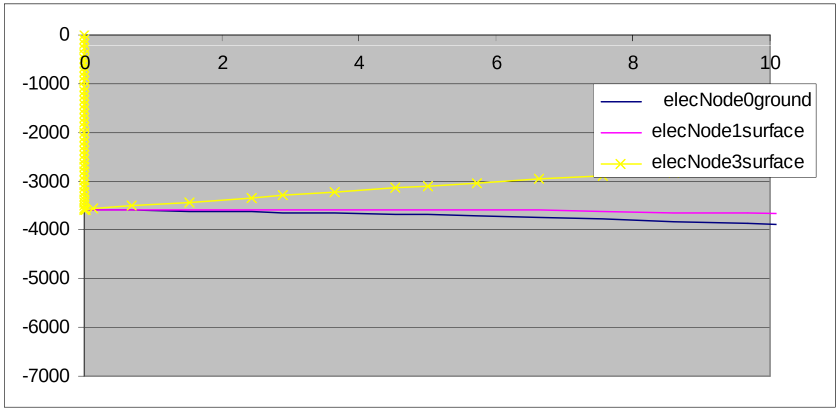
- New SW requirements:
  - Circuit:
    - Inductances
    - "Exact Csat" (charge conservation through Gauss theorem) instead of user defined Csat
  - Circuit solver:
    - Implicit
    - Variable, automatic time step

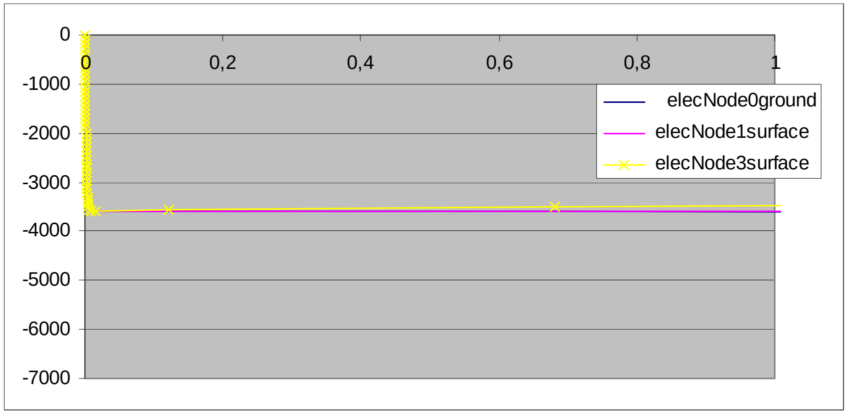
Newton type solver with:
- dI/dV predictor (a matrix) with validity control
- automatic time steps (saturating validity)

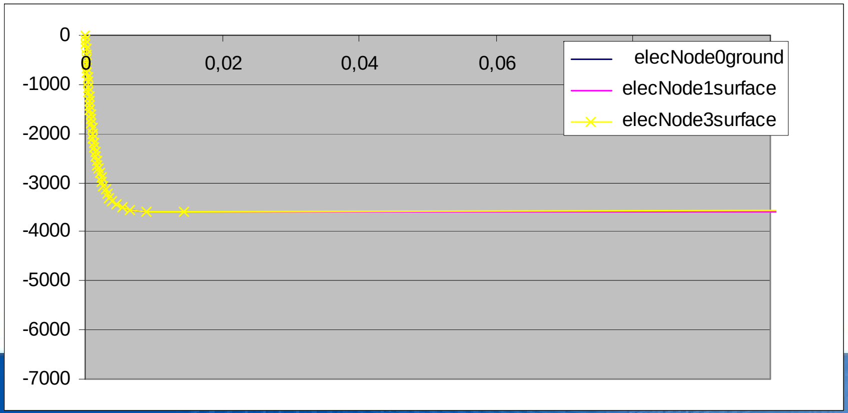
The circuit solver: a test case

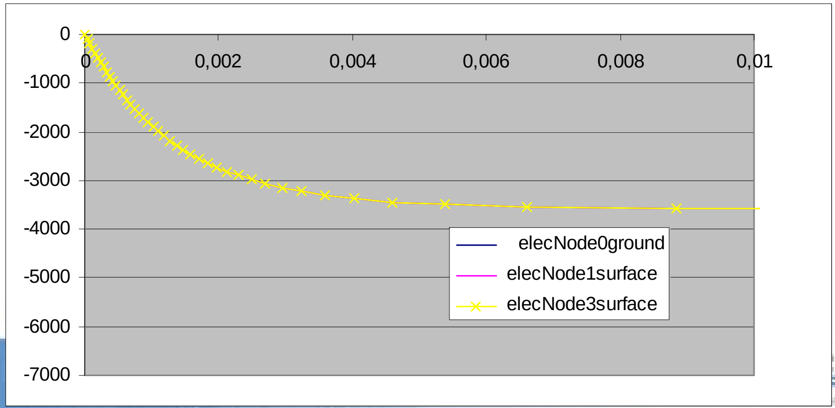
- Implicit solver / automatic time step:
  - An example (GEO charging with very large electron flux)
  - Quite large range of time scales











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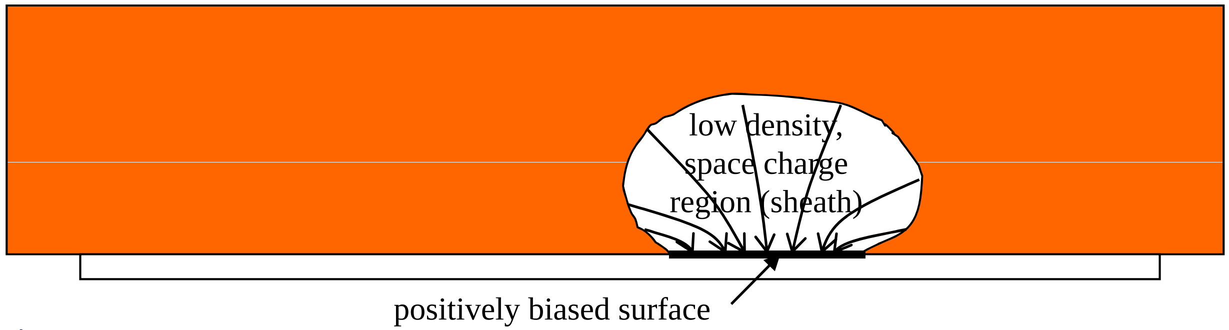
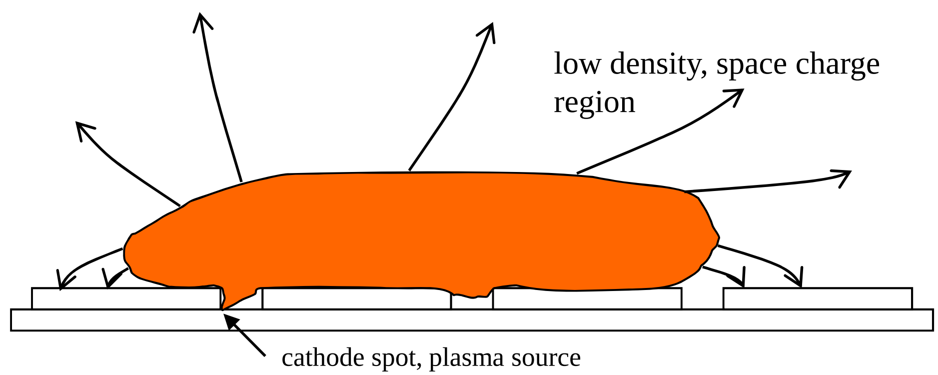
Multi physics modelling requirement

- 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…):

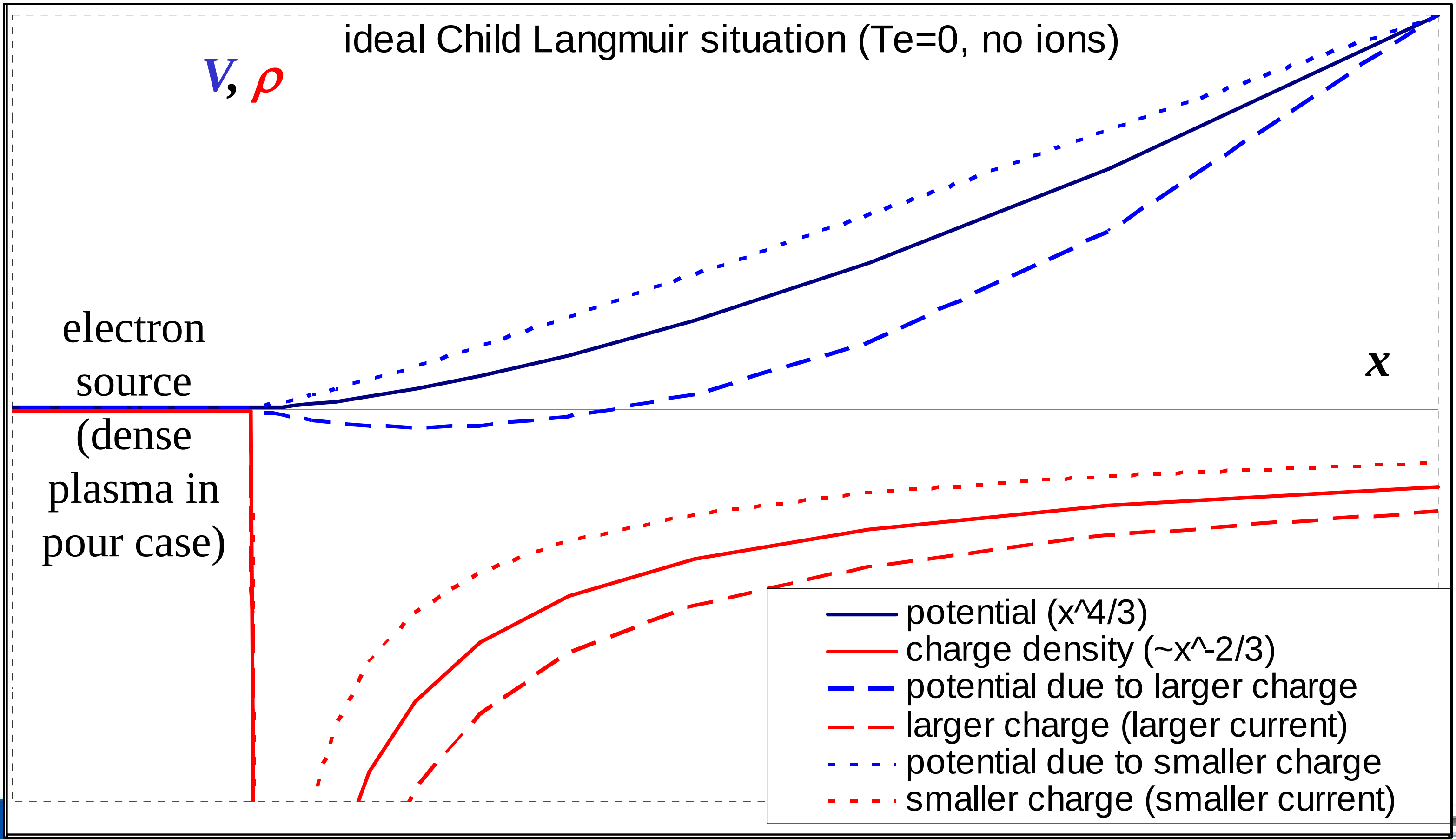


- Method:

multi-zone, interface handling at sheath edge or plasma bubble edge

The physics at the boundary

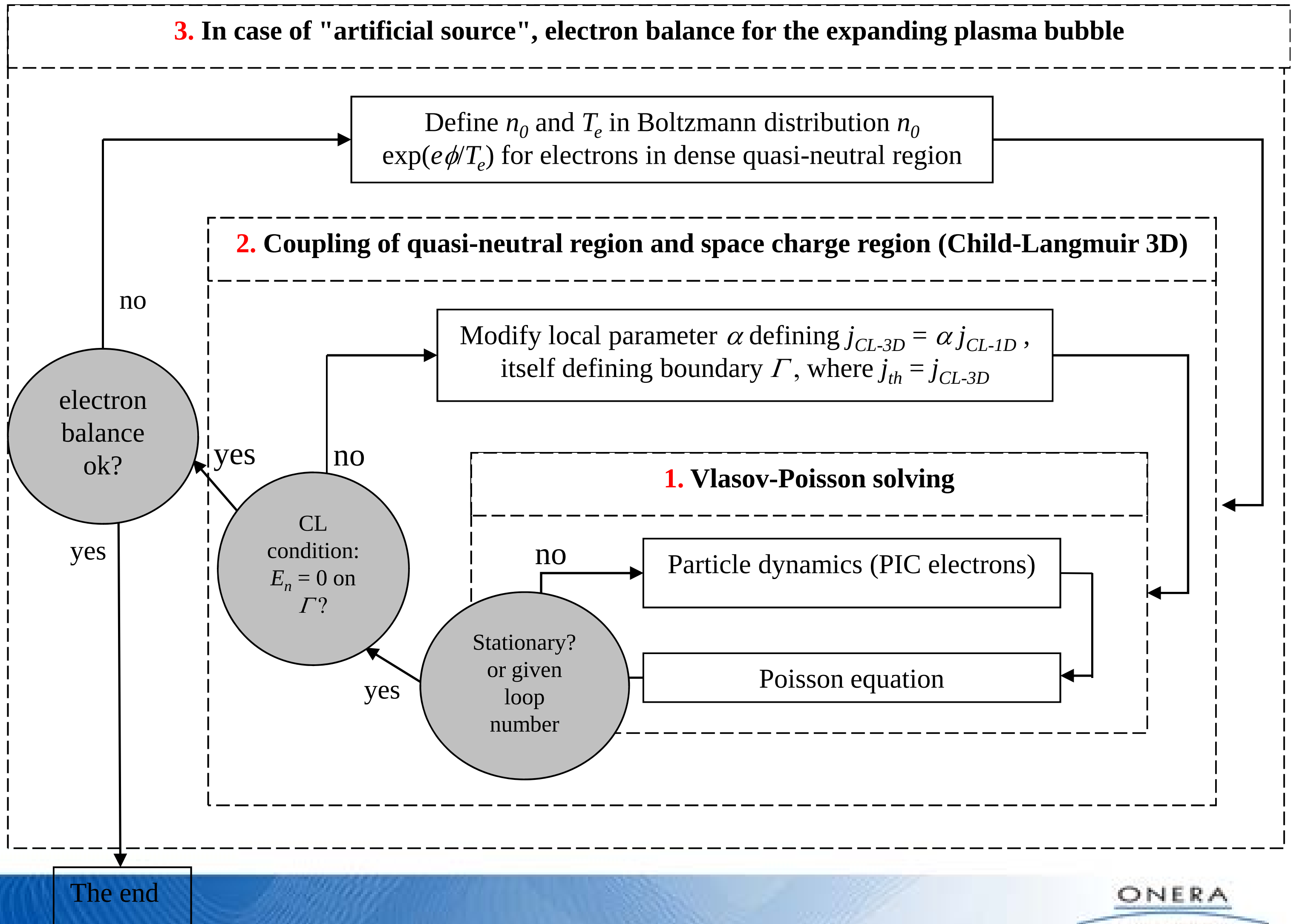
- Child-Langmuir theory:
  - The current emitted at the boundary is the maximum allowed by space charge (space charge limitation): E = 0 in the emission plane ($T_e = 0$)
  - Case 1D analytical: $j_{CL} \sim V^{3/2} / d^2$



Algorithm

- Multi-physics solver design:

- Loop 1: plasma dynamics
- Loop 2: CL condition
- Loop 3: "floating potential" of the plasma bubble (including cathode spot), still lacks stability



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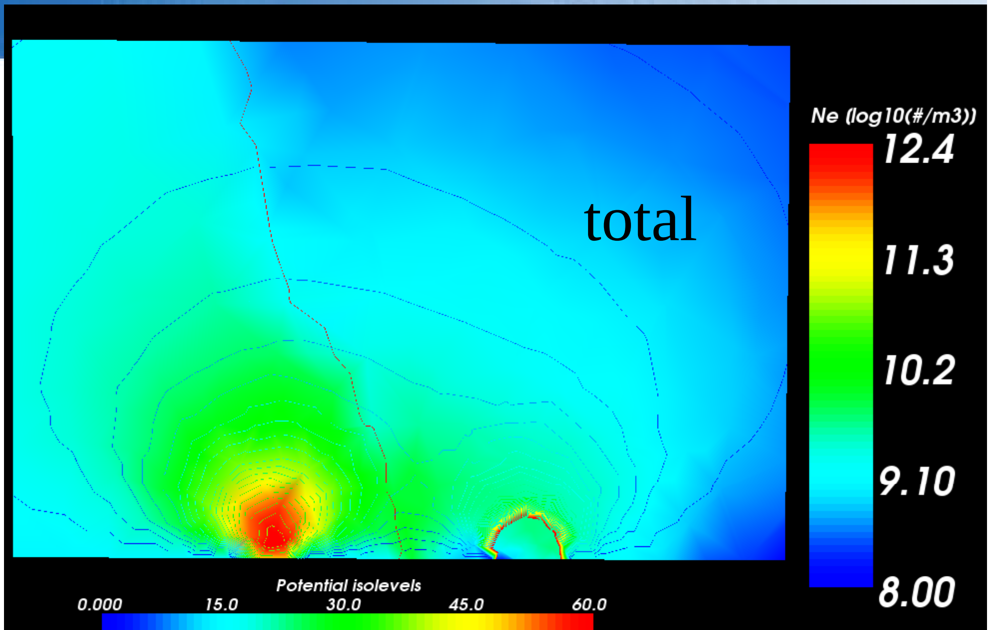
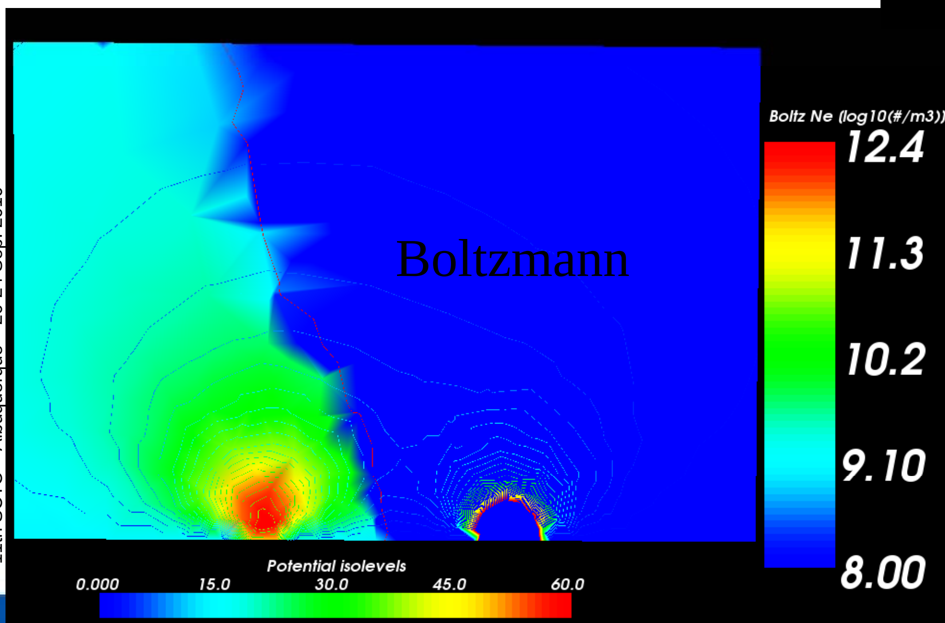
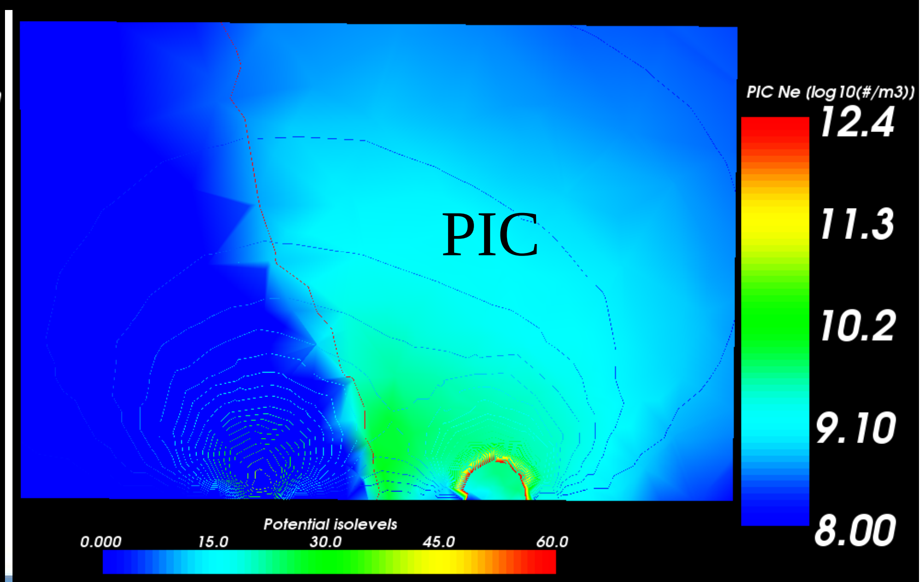
Test case 1 – bubble LD

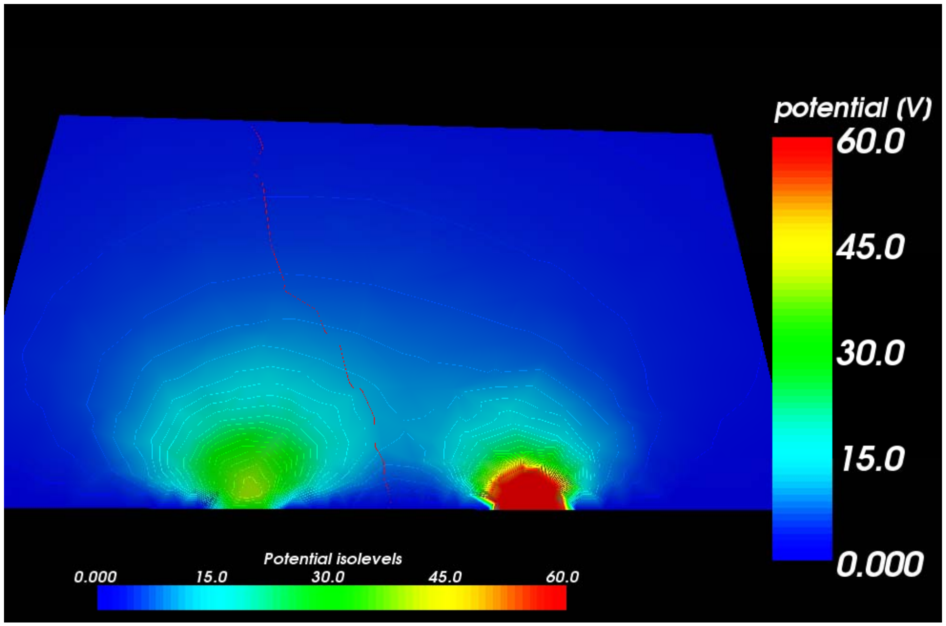
- Test case: plasma bubble expansion
- Electron density:
  - composed of Boltzmann electrons in dense ion zone (quasi neutral)
  - and PIC electrons in low density zone (non neutral)

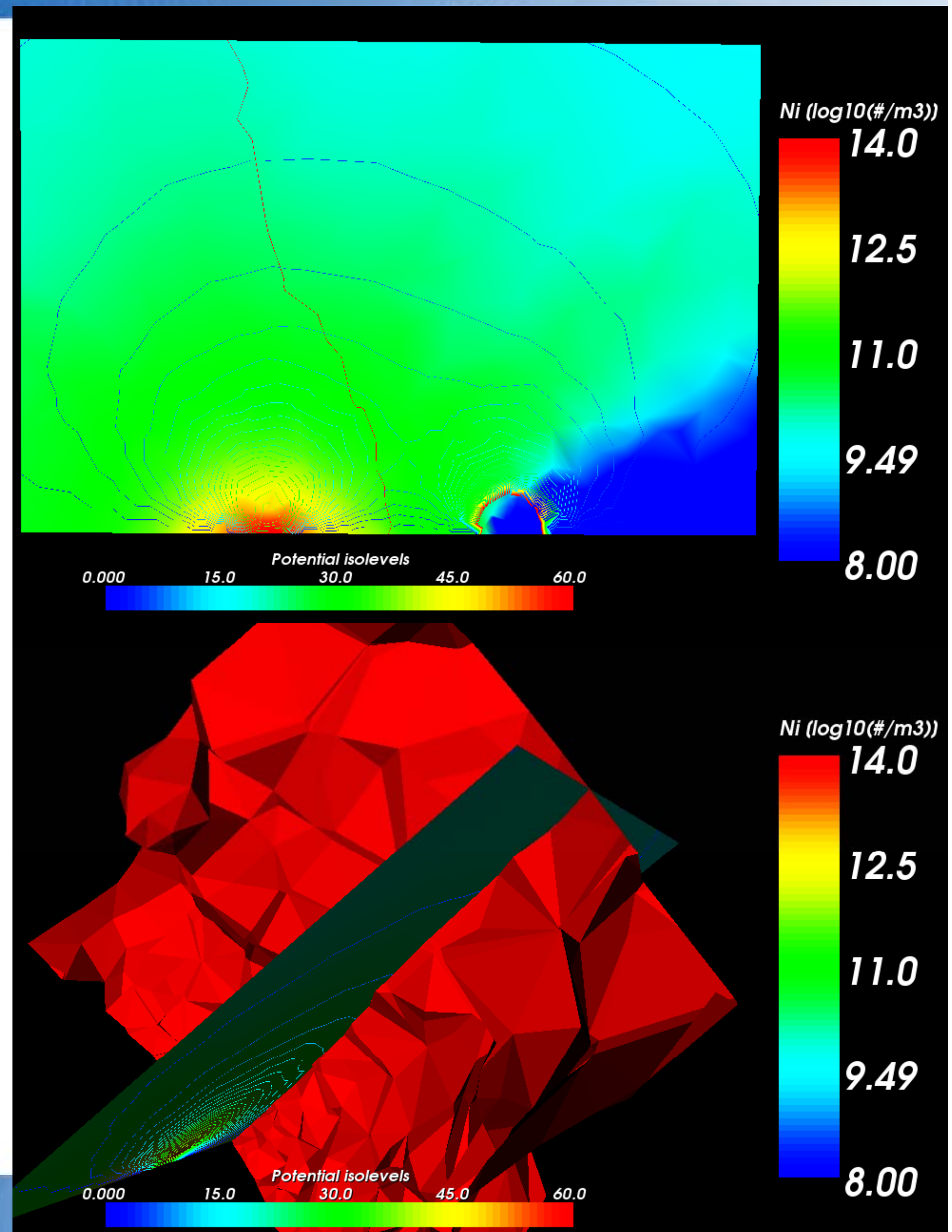






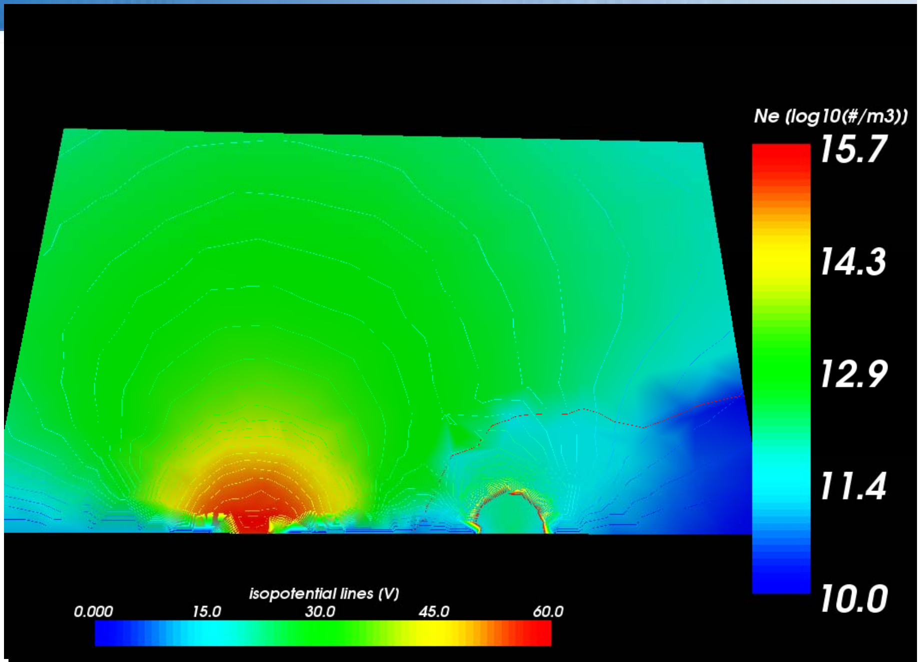
Test case 1 – bubble LD

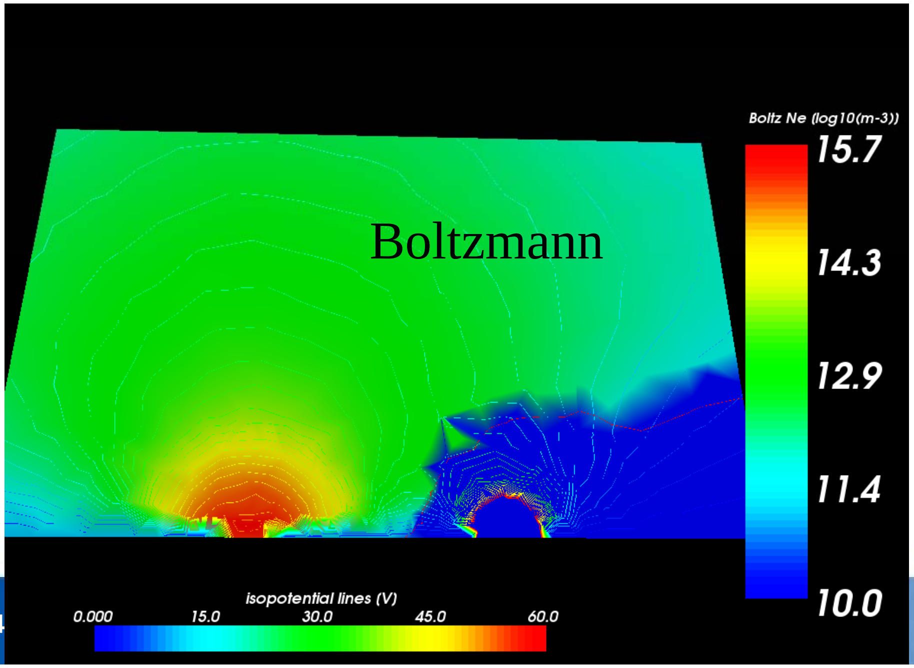


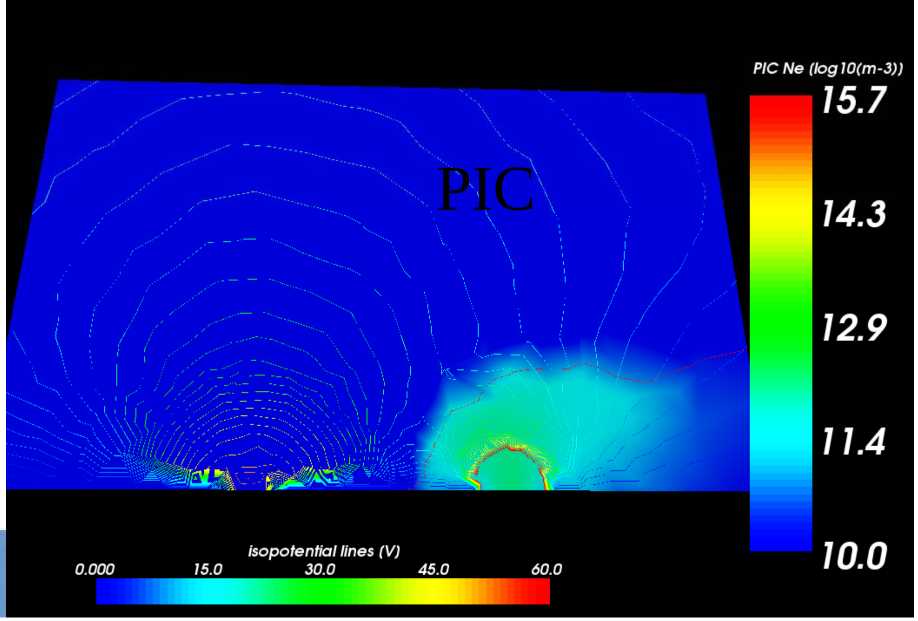


Test case 2 – bubble HD

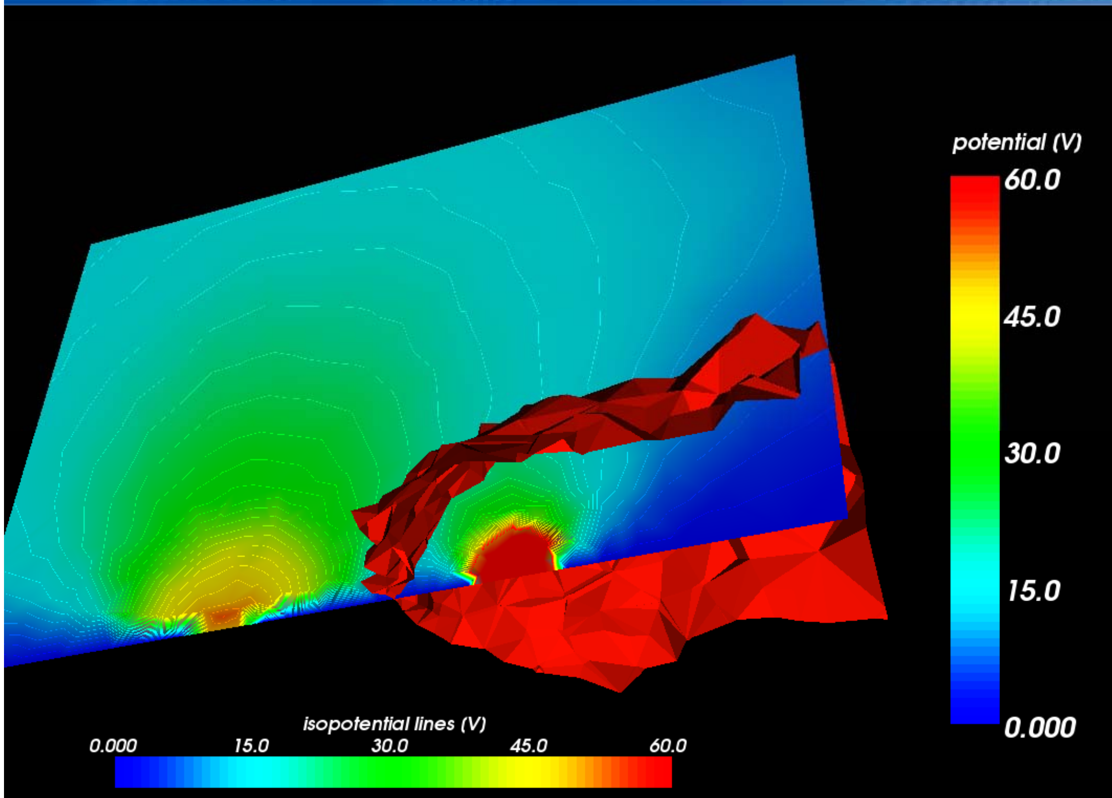
- Test case2: plasma bubble expansion
- Higher electron density (x 100)

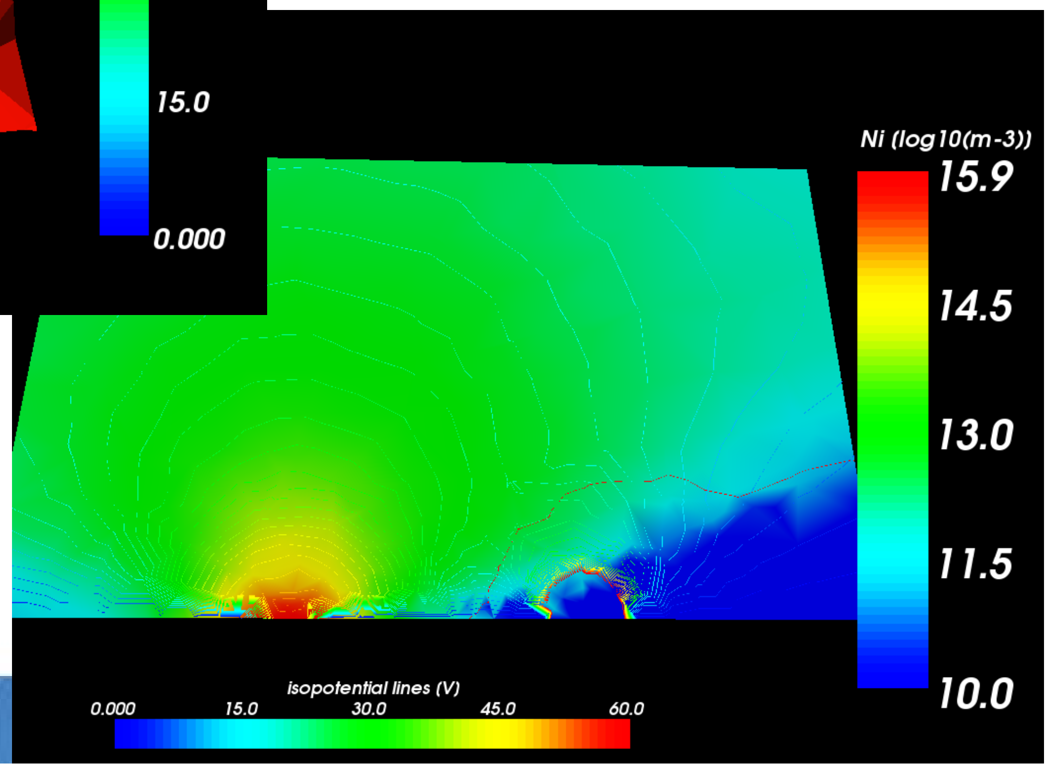






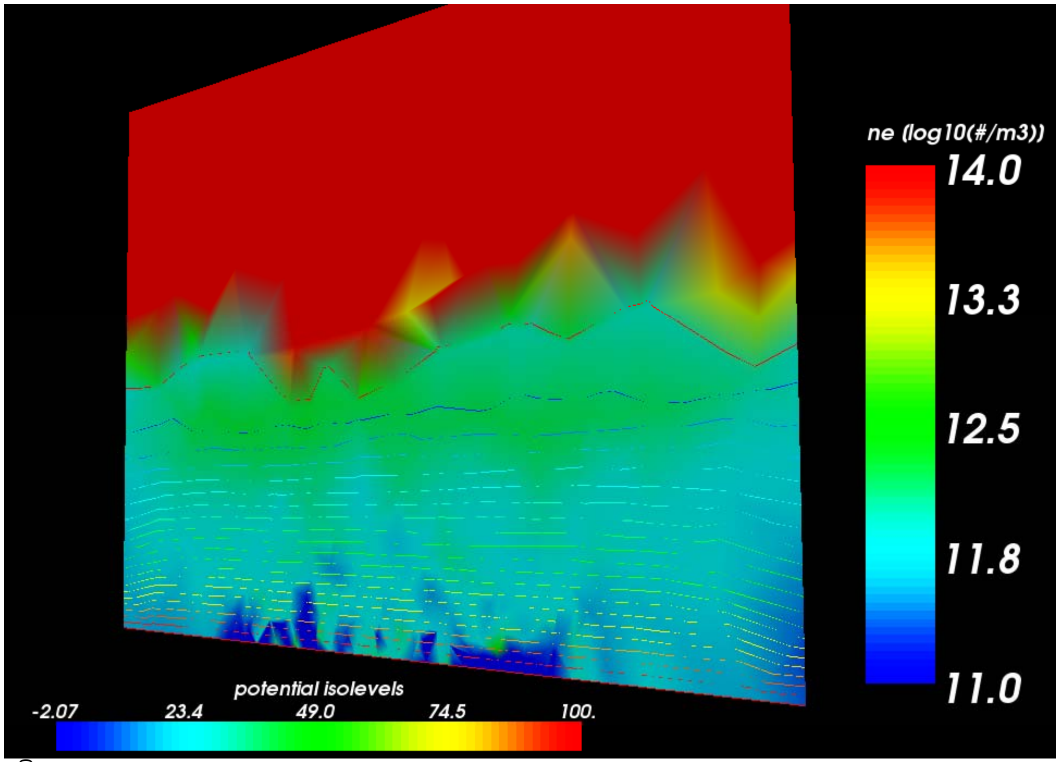
Test case 2 – bubble HD

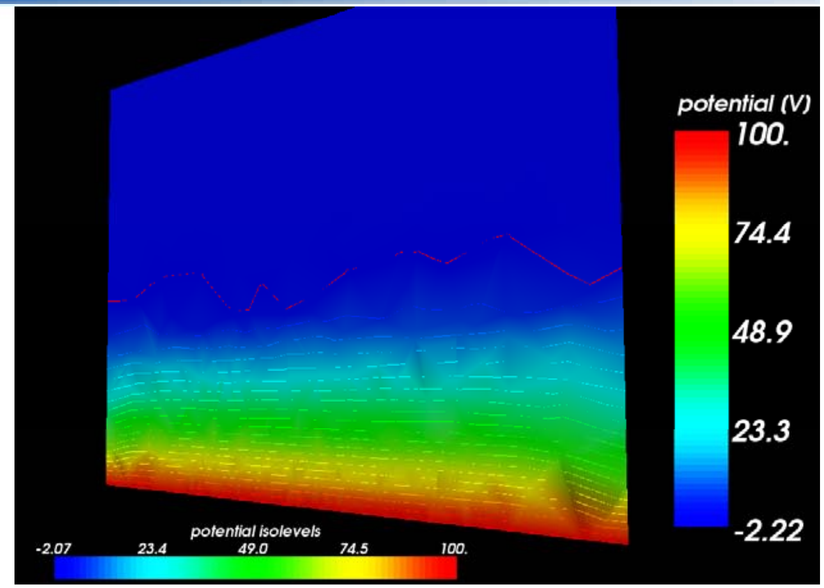


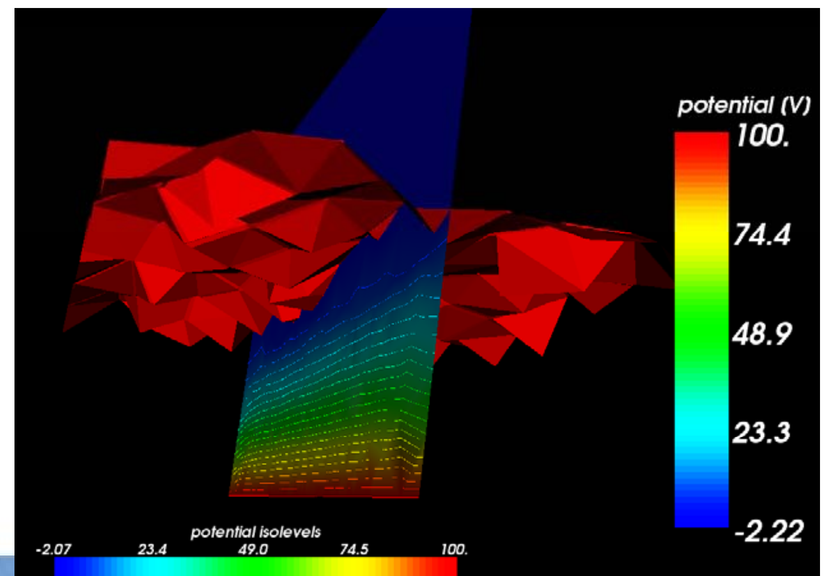


Test case 3 – Child-Langmuir test case

1D test case, close to ideal CL 1 case







SPIS current density = 0.35 A/m^2

CL theory at T_e = 0:

- jCL = 0.233 A/m^2
- fine, as much as can be checked

Specific difficulties encountered

- Some extra instabilities were discovered and had to be handled (with specific algorithms):
- CL condition feed back loop can be unstable (Bohm type instability) if too small ion gradient:
  - extracting electric field can be due to a positive space charge in the space charge zone, and increasing the electron emission is not necessarily an improvement!
  - stability condition $(l_i / d)\ (e\phi_s / kT_e) < 1$, with: l_i the typical scale of ion density variation (fixed at electron time scale), d the sheath size, ϕ_s the sheath potential drop and T_e the electron temperature
  - => need to consider a possible positive space charge in the space charge zone to improve the algorithm
- Bi-stable behaviour:
  - A region can be consistently considered as:
    - either in quasi-neutral zone (high density)
    - or in the space charge zone (smaller density)
    - (appeared when considering Ne not strictly = Ni in quasi-neutral)
  - => control of non neutrality w.r.t. cell size / Debye length ratio

…

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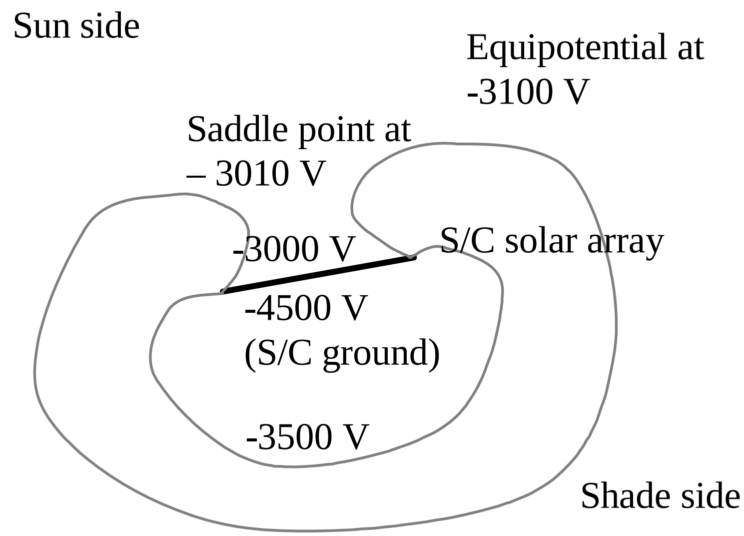
Modelling charging in GEO

- 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 detector also e.g.)



- 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
  - Similar model with SPIS (B. Andersson, SSC)
  - Comparison of potential maps and time variation

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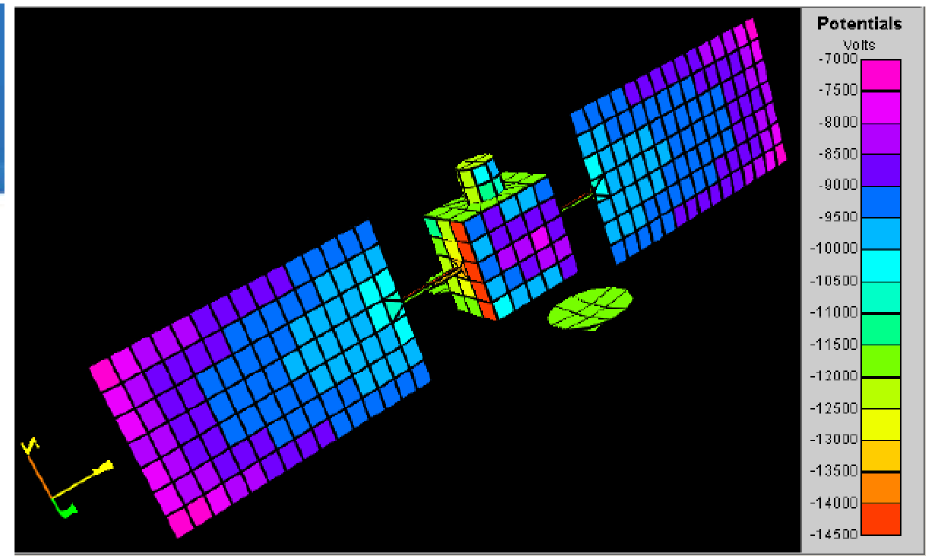
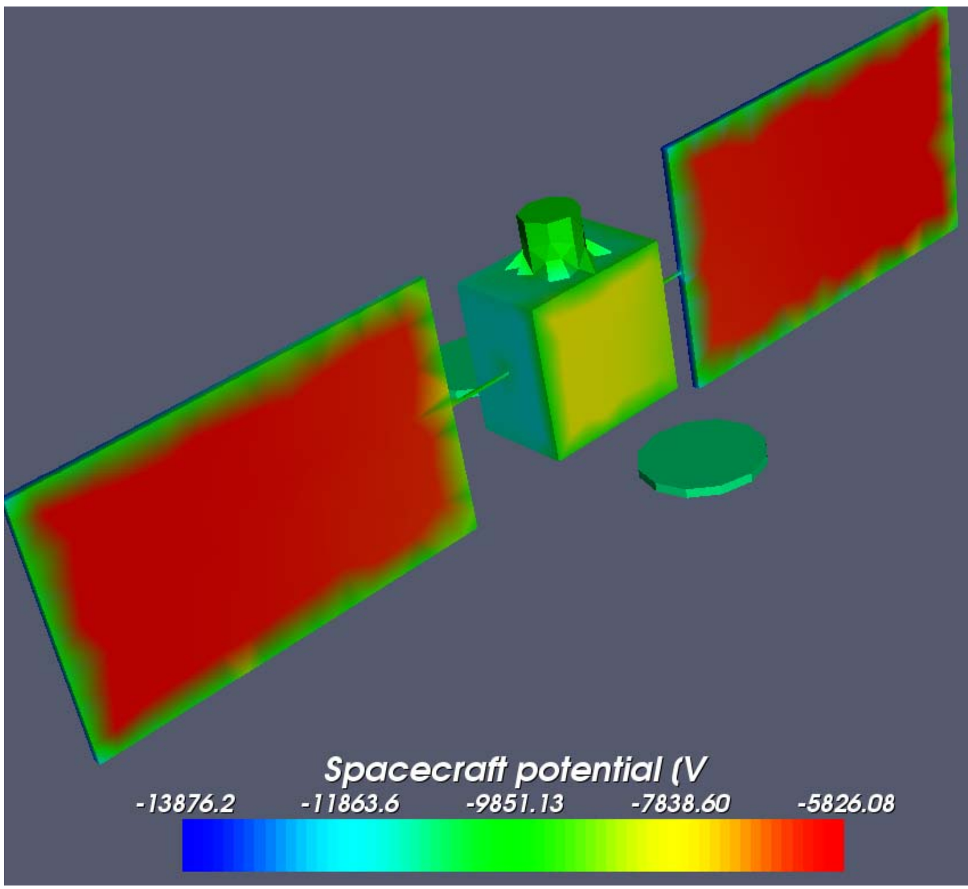
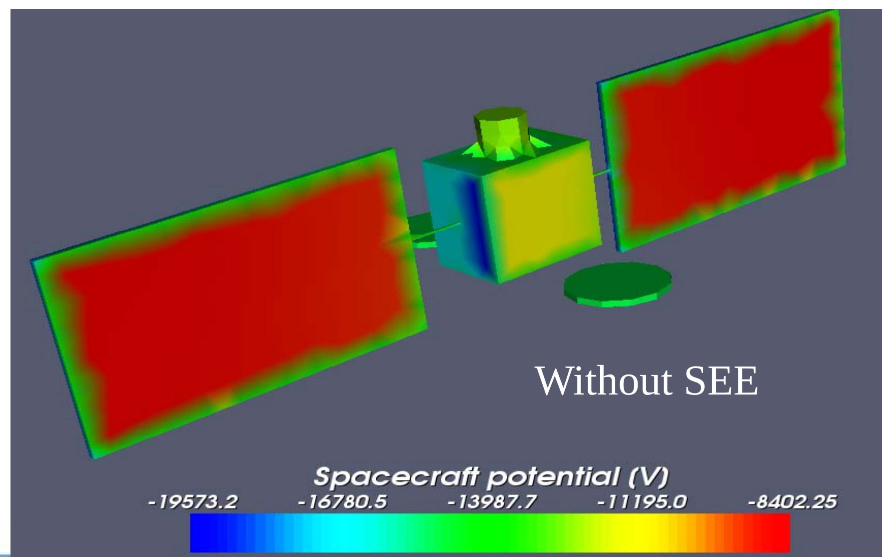
Potential maps (t=1000s)

- 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

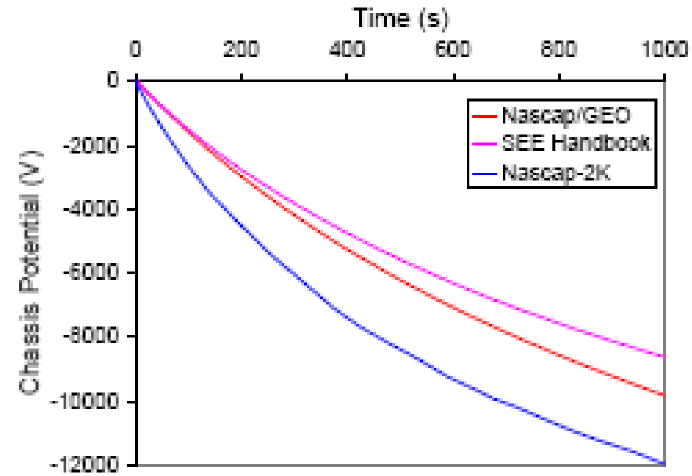
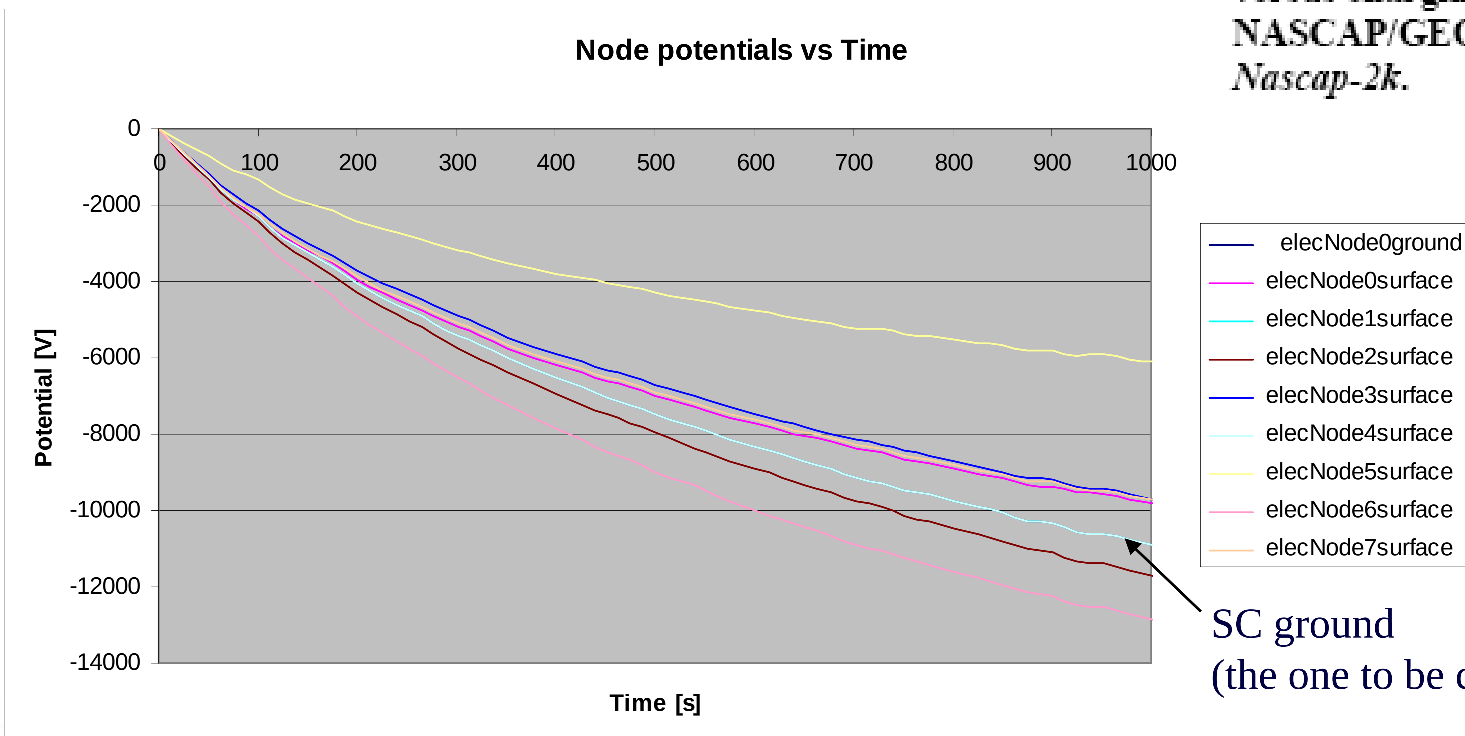


Figure 8. Comparison of chassis potential versus charging time as computed by NASCAP/GEO, SEE Handbook, and *Nascap-2k*.



SC ground
(the one to be compared)

Part of the s/c	Chassi	PVSA (shadow side)	OSR	PVSA (solar side)	Main SC structure	Top Antenna	Circular antennae
Material	Black kapton	Kapton	OSR	Solar Cells	Teflon	Non-conducting paint	Graphite
Absolute Charging (kV)							
NASCAP/GEO	-10.0	-8.2 to -13.1	-8.23 to -10.7	-5.2 to -7.68	-7.5 to -12.7	-8.3 to -10.3	N/A
SEE Handbook	-8.6	None in model	-7.3 to -9.6	-3.6 to -5.7	-6.8 to -11.3	-7.5 to -11.3	N/A
Nascap-2k	-12.0	-11.5 to -14.4	-10.0 to -13.7	-7.2 to -10.8	-7.9 to -14.0	-7.9 to -14.0	N/A
SPIS	-10.9	-12.9 (-10.9 to -13.9)	-11.7	-6.1 (-5.8 to -6.4)	-9.8 (-7.9 to -11.6)	-9.7 (-9.6 to -9.8)	-10.9
Differential charging (kV)							
NASCAP/GEO		1.8 to -3.1	1.77 to -0.7	4.8 to 2.3	2.5 to -2.7	1.7 to -0.3	N/A
SEE Handbook		None in model	1.3 to -1.0	5 to 2.9	1.8 to -2.7	1.1 to -0.3	N/A
Nascap-2k		0.5 to -2.4	2 to -1.7	4.8 to 1.2	4.1 to -2	2 to -0.2	N/A
SPIS		-2.0 (0 to -3.0)	-0.8	4.8 (5.1 to 4.5)	1.1 (3 to -0.7)	1.2 (1.1 to 1.3)	0

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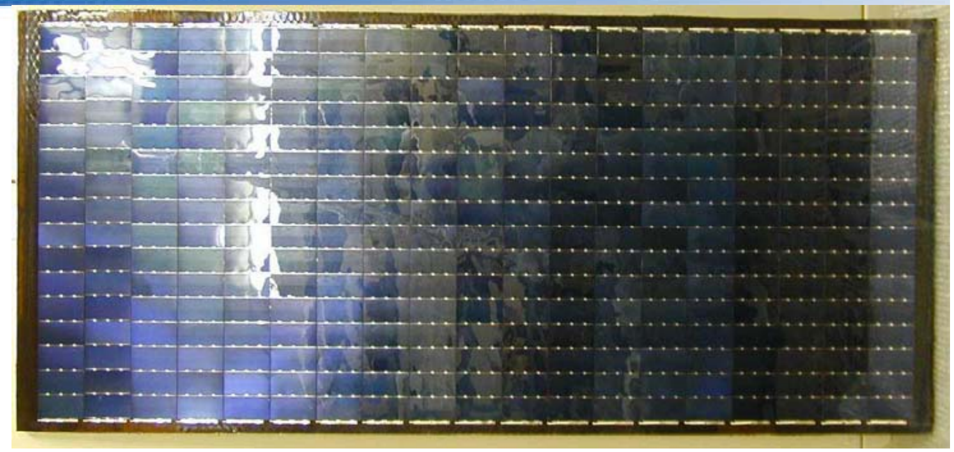
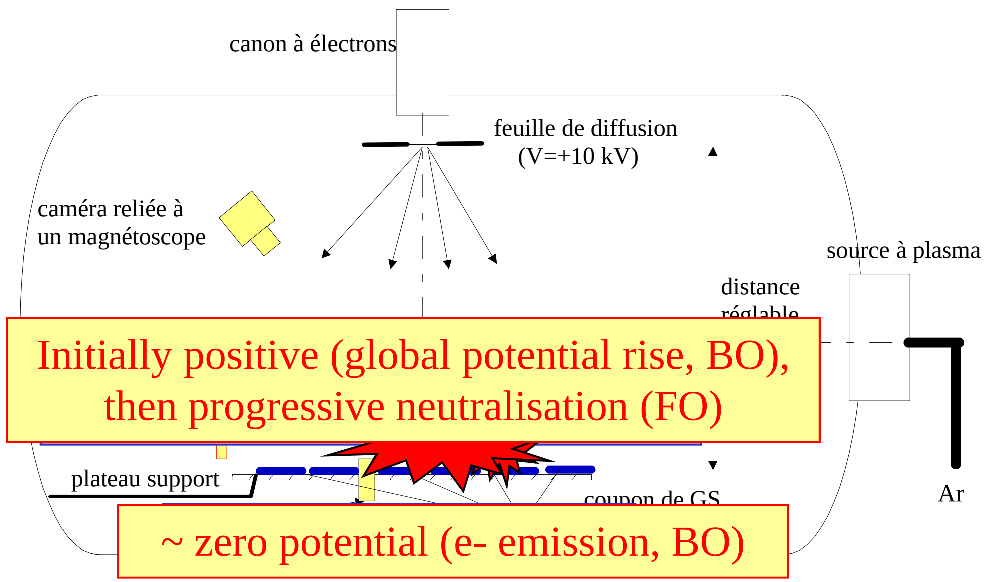
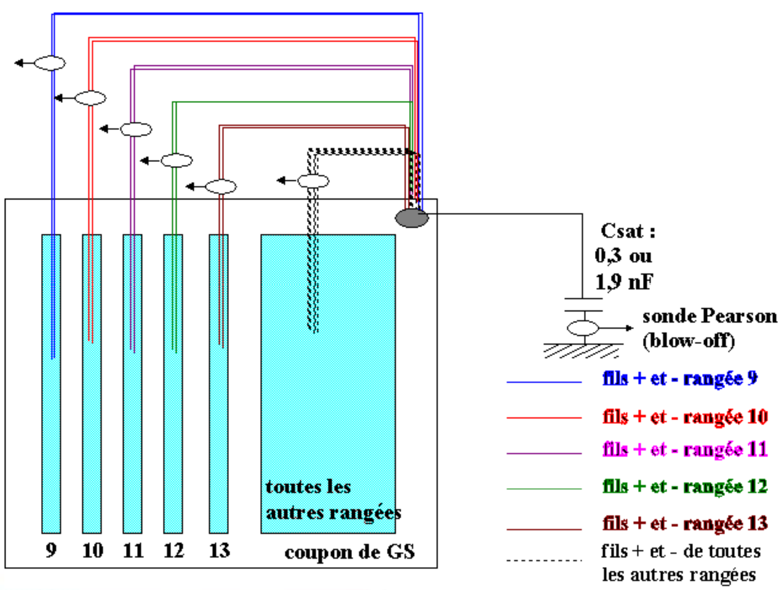
Flashover experiment: the setup

- Inverted Potential Gradient charging of a large coupon (CNES R&T)
- In JONAS plasma tank (ONERA/DESP)
- Monitoring of flashover current individually on some of the strings



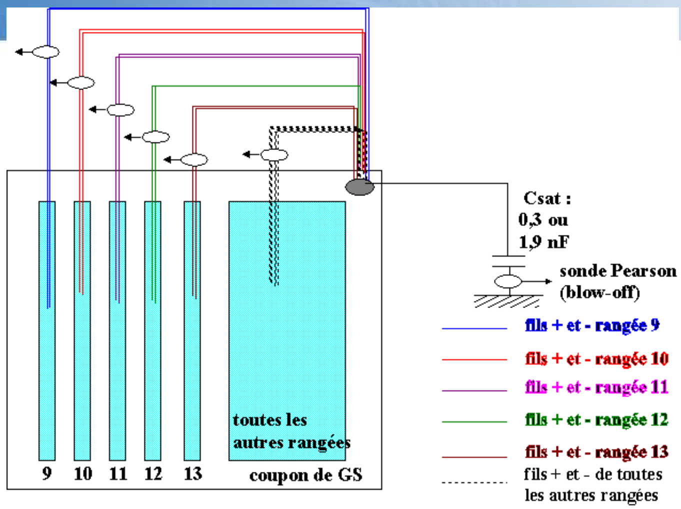
Large PVSA coupon: 1.33 x 0.6 m, 19 strings



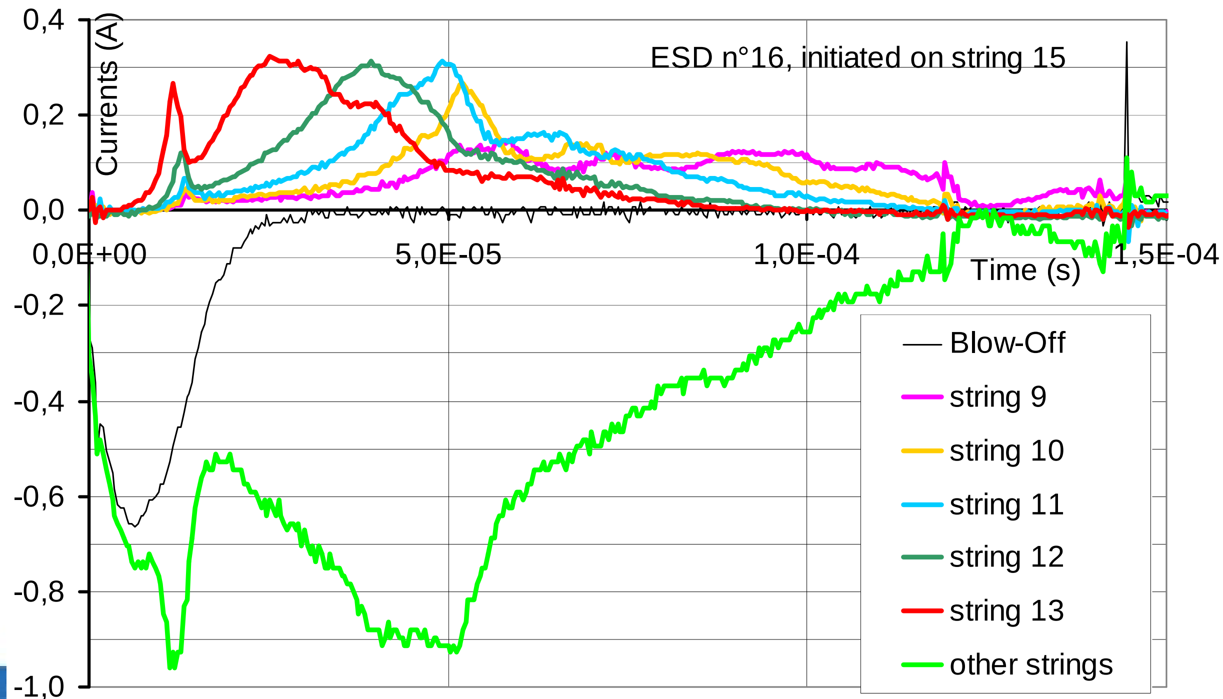


Flashover experiment: the measurements

- Individual currents on intermediate string (9 to 13) + others together
- This ESD (No 16) on string 15

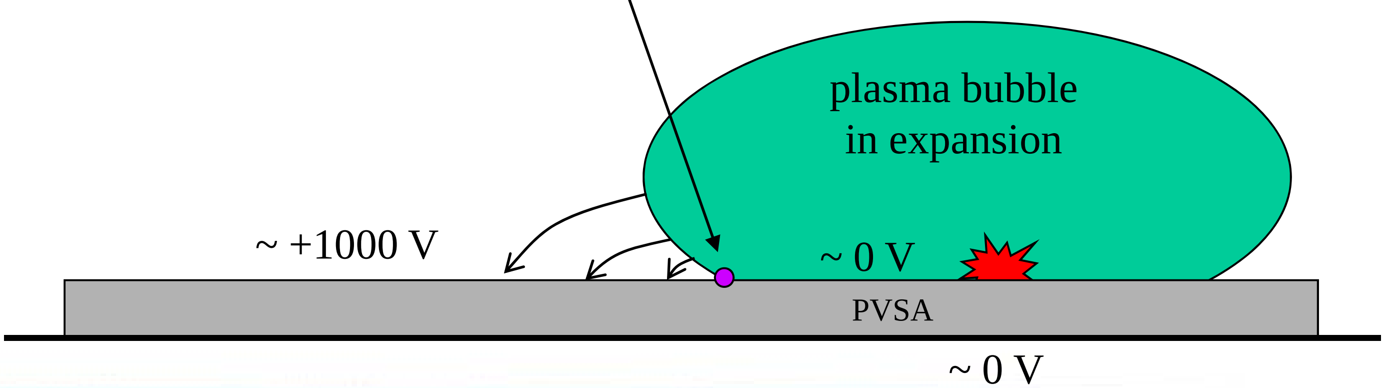


- Delay of flashover on successive strings consistent with plasma expansion at 10^4 m/s
- Ahead of the plasma front, smaller current thought to be carried by electrons only (limited by space charge)



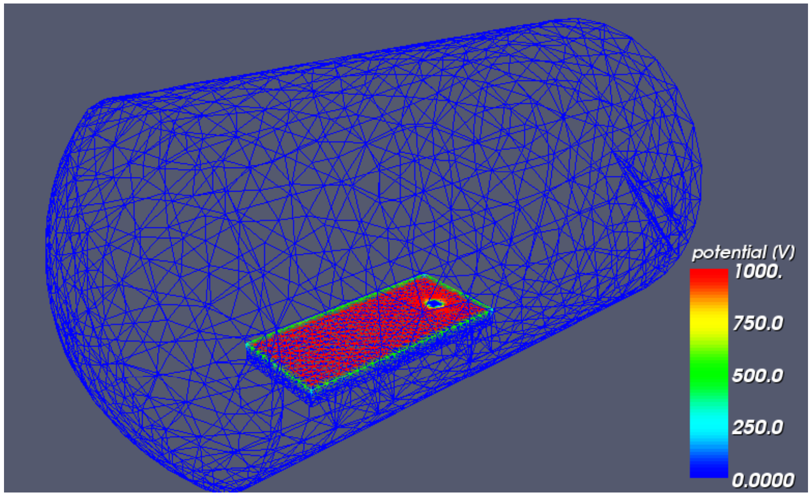
FO modelling: the challenge

- Multi physics:
  - dense zone (plasma expansion)
  - low density with positive potential
- Multi time scale
  - Large currents in dense plasma
  - Small currents out of the plasma (electrons)
- Difficult of coupling of both:
  - Propagation of the plasma edge on the PVSA
  - => brutal variation of current expected on the cells
  - Moving singular point

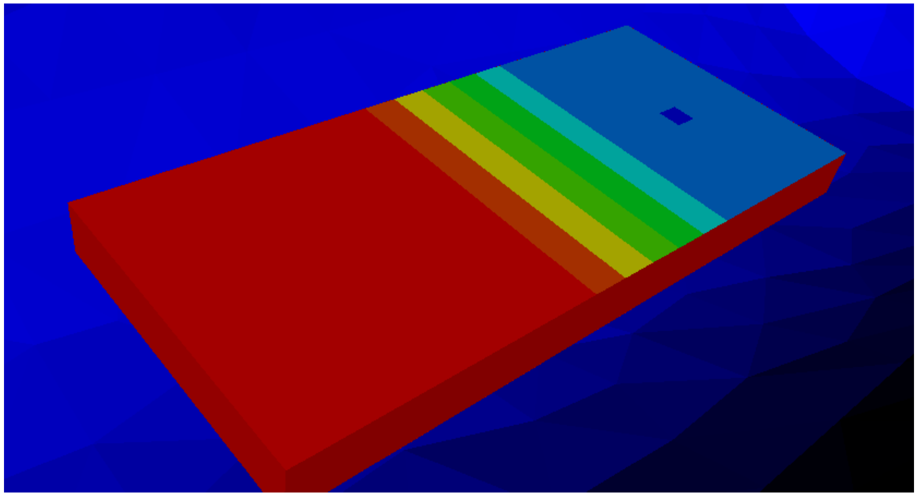


FO modelling

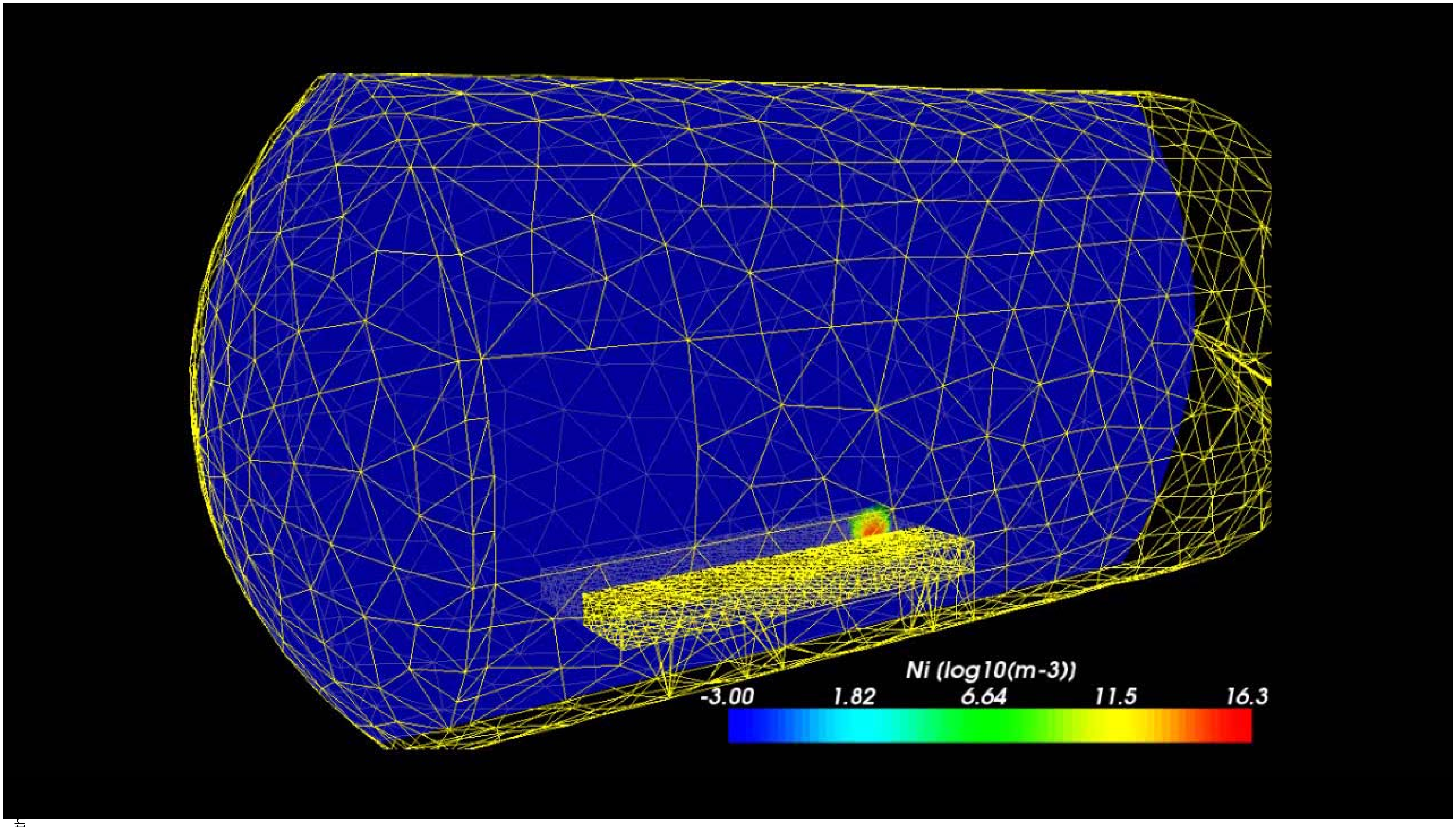
- Initial conditions
  - After the blow off
  - PVSA ground already back to ~ 0
  - Reason: loop 3 of multiphysical model is needed to model that ("floating potential of the plasma bubble)



- ESD model
  - Ion source on a 5x5 cm patch (Maxwellian, 10 mA – 1A range, 10-100 eV)
  - Electron: Boltzmann distribution (10 eV, $n_0 = 10^{16}\ m^{-3}$) in the dense zone + PIC in the space charge zone



FO modelling: plasma expansion / ion density



11th

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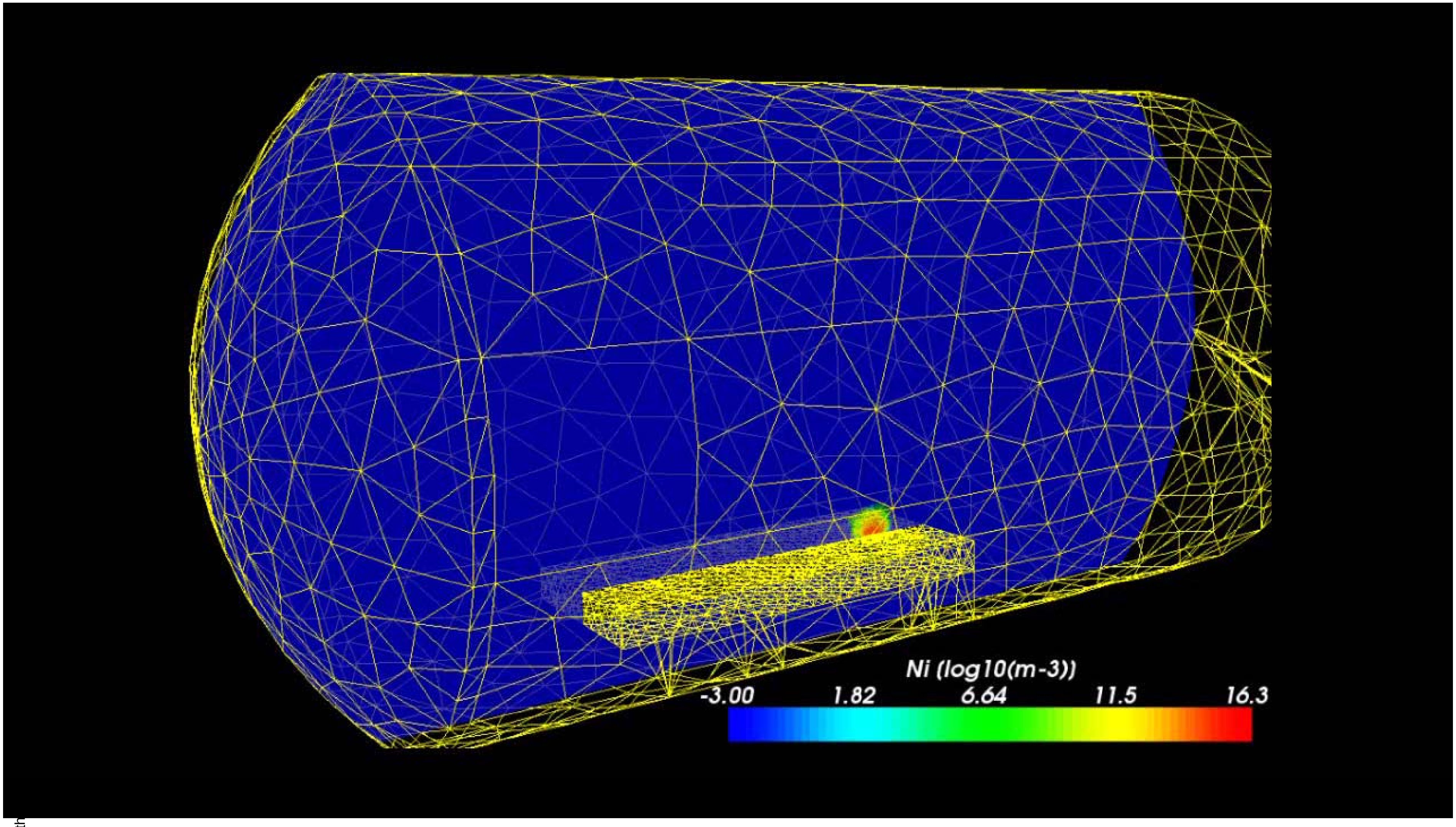
FO modelling: plasma expansion / ion density + zone boundary



11th

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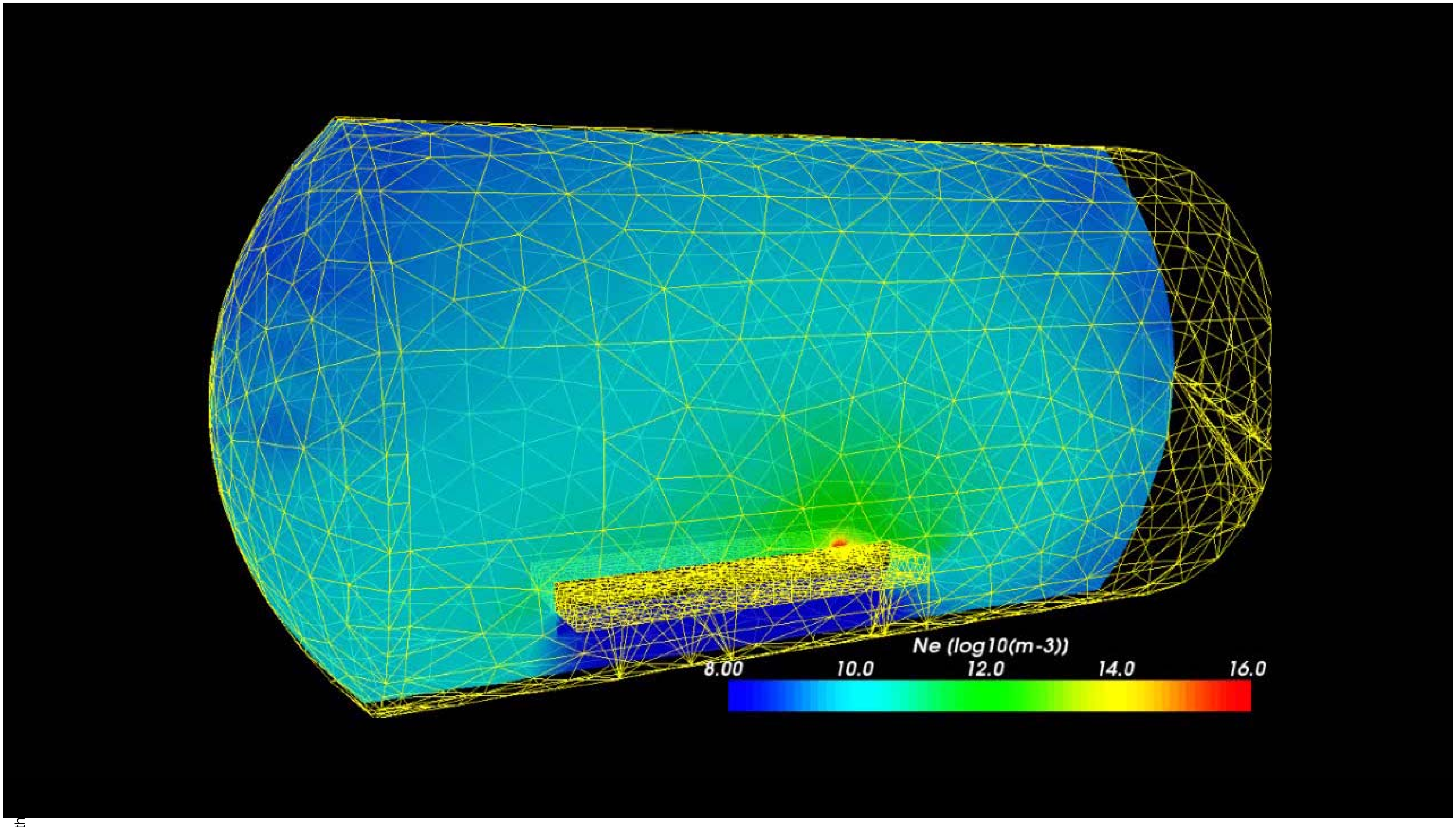
FO modelling: plasma expansion / electron density



11th

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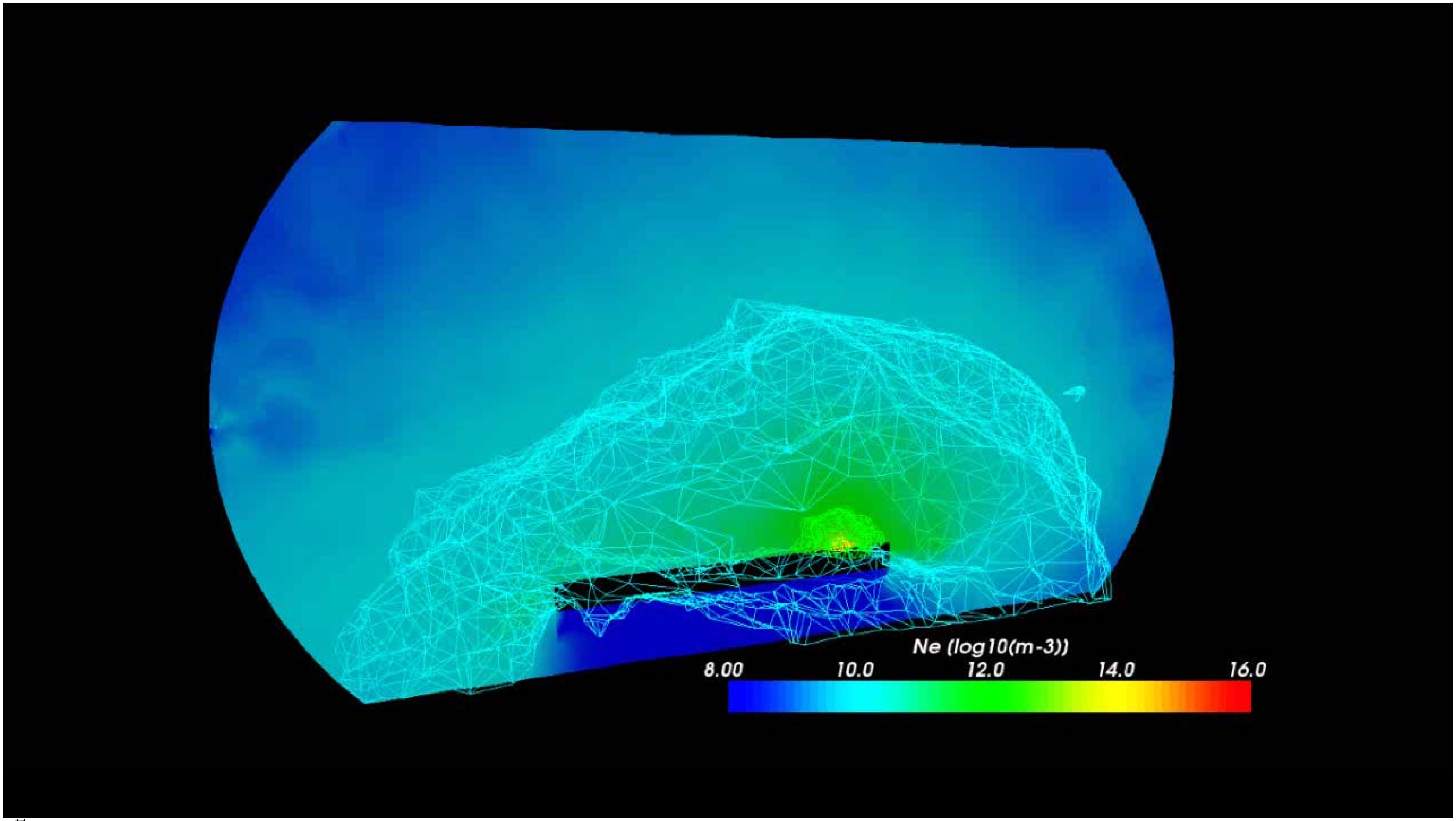
FO modelling: plasma expansion / electron density + isocontours



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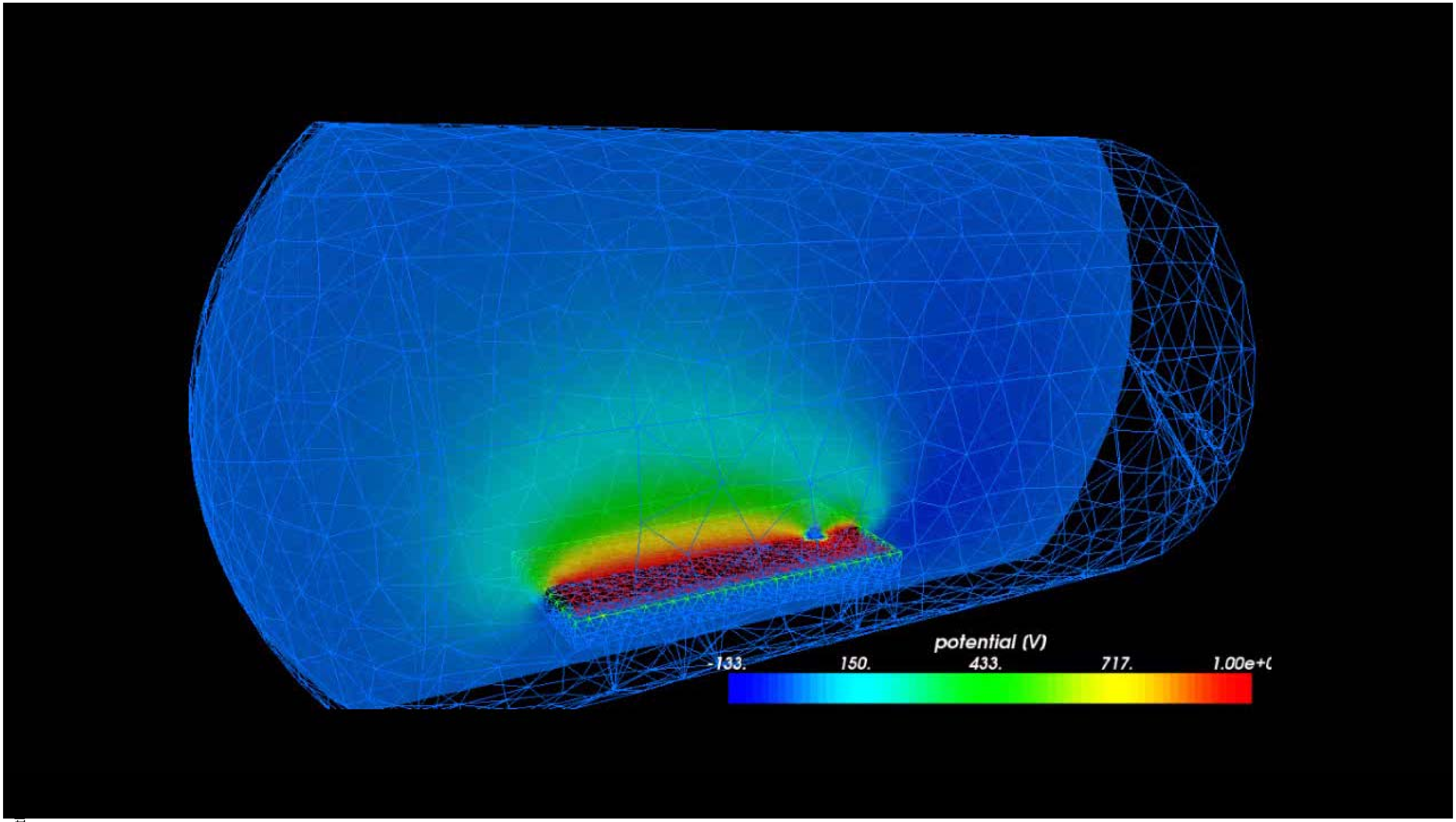
FO modelling: potential



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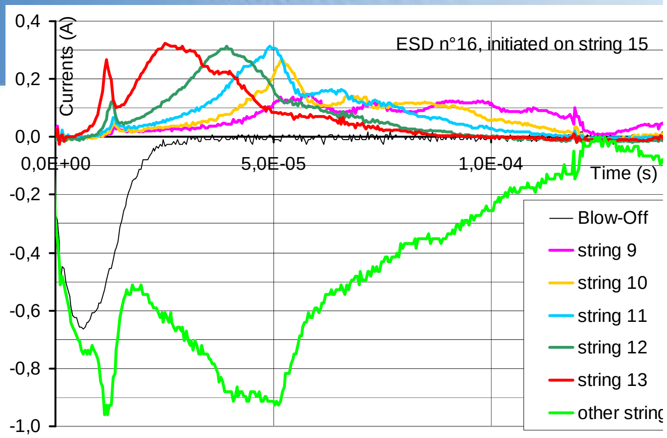
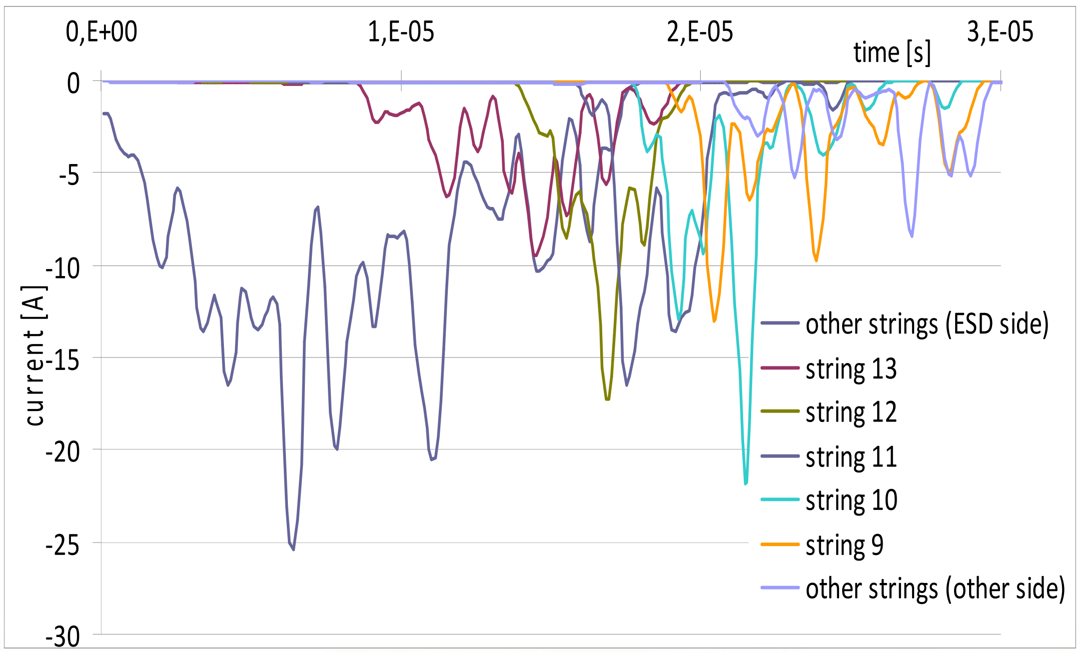
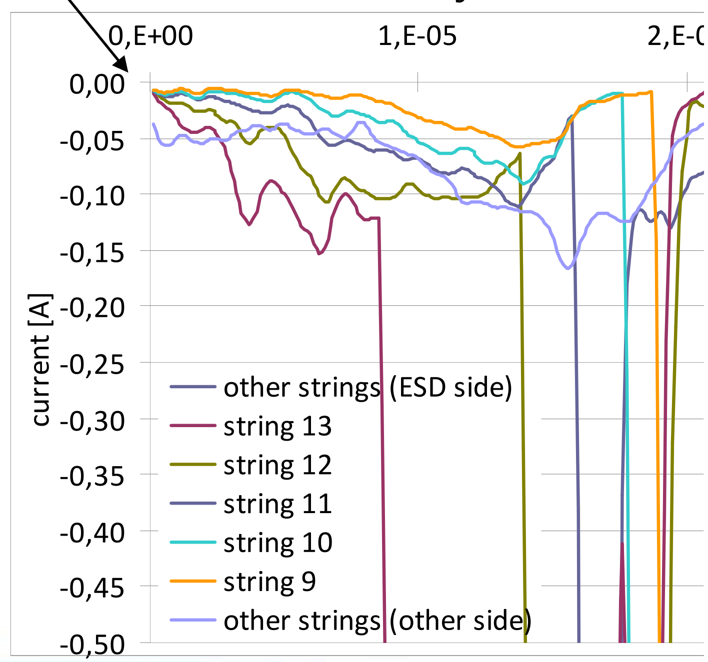
FO modelling: current collection



- Reaches all strings successively, but not the whole panel
- Expansion speed somewhat too fast
- Electron current ahead of the plasma correct
- In presence of plasma, the plotted current is too large due to faster neutralisation and potprocessing artefact (current x 3 here due to an absence of current update in the implicit solver $I \Rightarrow I + dI/dV\ \delta V$)



zoom on current y-axis



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Conclusions on FO simulation capabilities

- Plasma expansion in volume with dynamical adjustment of the zone boundary:
  - Operational
  - Robustness could be improved:
    - Several instabilities were identified (with respect to the ideal CL approach)
    - Stabilisation schemes were proposed and tested => ok, sometimes needing manual tuning (UI-accessible parameters)
    - Improved schemes could be developed:
      - Improved feed back function (non linear…)
      - Theoretically proven
- Plasma expansion on S/C surfaces: interaction of zone boundary with surfaces
  - Expansion certainly less favourable than in reality:
    - Total neutralisation of PVSA not demonstrated in SPIS, although exists in experiments
    - Stopped expansions exist in experiments, but are thought to be more related to cathode spot phenomena
  - Difficulty = presence of a singular point (line) where zone boundary crosses panel
  - No specific handling => steps/peaks in current when boundary reaches a new node
  - => detailed study of this singular region needed (in particular centring of all quantities)

Conclusions and perspectives

- Major solver improvements for SPIS: multi-physics, multi time scale
- Very ambitious
- Achievements:
  - Most features operational, not bad given the difficulties
  - Still a lack of robustness of some points
- Many applications:
  - ESD triggering (electron avalanche), cf. next presentation: mn scale (charging) to ns scale (electron avalanche)
  - Positive biasing in a dense plasma (probes on SC, connectors on PVSA…)

    …
- Perspectives
  - Revisit some of the control features:
    - to improve robustness
    - To simplify the control parameters (more sophisticated automation)
  - Complete (stabilise indeed) the external loop for multi physics ("floating potential" of the plasma bubble)