Modelling of Electrostatic Environment of Ion Emitting Spacecraft

ESA ITT AO/1-8620/16/NL/LF

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version 1 of Oct. 23rd, 2017

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SPIS Status

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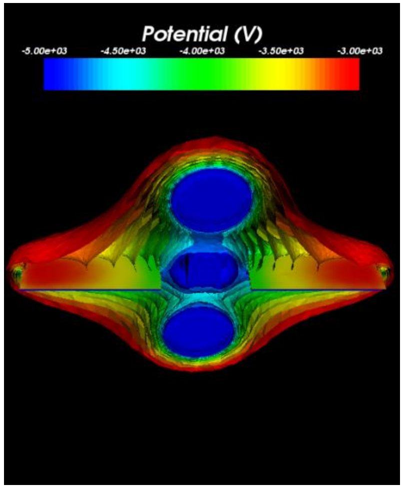
What is SPIS ?

- Spacecraft Plasma Interaction Software includes physics
  - 3D and dynamical modelling of the surrounding plasma sheath;
  - Particles and current collections;
  - Surface effects and secondary emissions;
  - Internal electrical balance;
  - Active sources.

- SPIS architecture is
  - Based on a numerical kernel, SPIS-NUM, an electrostatic 3D unstructured electrostatic Particle-In-Cell plasma model ;
  - Fully developed on a Java-based highly modular Object Oriented library
  - Include a complete Integrated Modelling Environment (IME), SPIS-UI:
    - Pre-processing (CAD, meshing, IBCs settings, simulation settings…)
    - Simulation control and monitoring;
    - Data-mining and post-processing.

- SPIS software → open-source project

SPIS quick overview

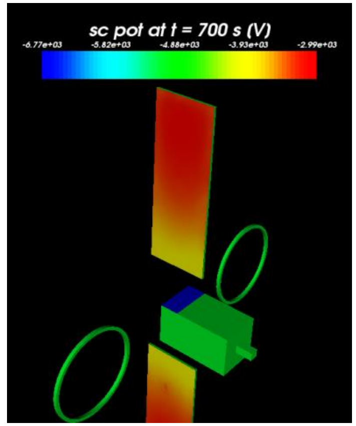


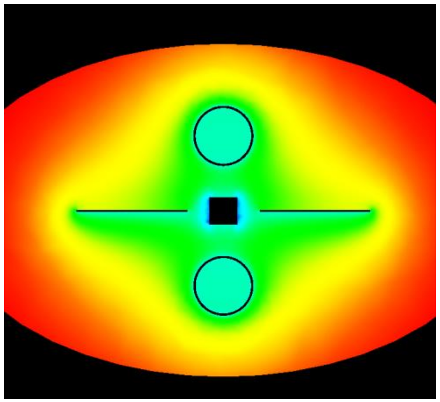
①

Electric field from:
-Particle densities
-Boundary conditions

④

Potential on S/C:
-Current balance
-RLC circuit between S/C elements



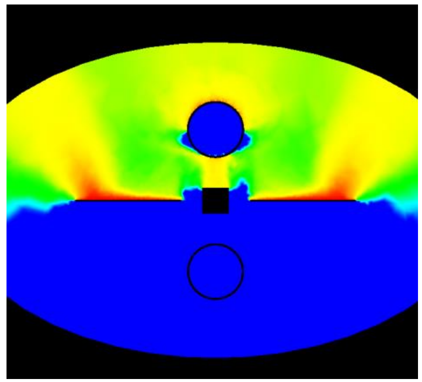


②

Particle Transport:
-Space environment
-Secondaries or Sources from S/C

③

Interaction with S/C:
-SEE by electrons
-SEE by protons
-Photo-emission
-Sources
- Erosion

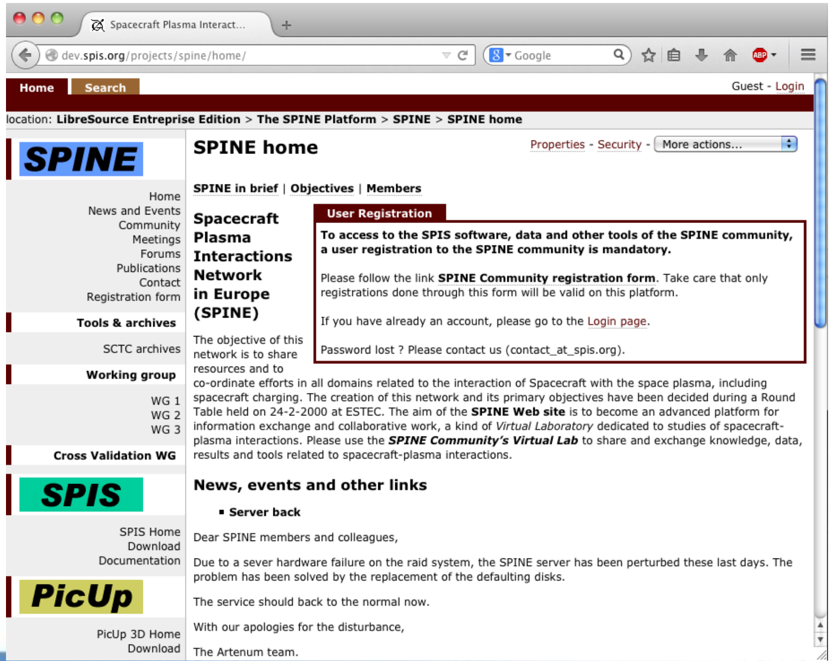


Historical context

- **SPIS**
- Initiated in 2001 by ESA, with support of several national agencies (CNES)
- About 10 major releases since 2003
- More than 8 500 downloads (all versions/branches included)
- More than 1 300 downloads for SPIS 5.1.9
- Open to various fields: ESD, instrument calibration, propulsion, dusty plasmas, internal charging.
- Various contributions:
  - SPIS-GEO
  - SPIS-Science
  - AISEPS
  - SPIS-Dust
  - SPIS-IC (To be released)
- Components mutualised with other scientific communities

SPINE, an active community

- http://dev.spis.org
- More than 900 registered members (and around 2 new registrations a week)
- About 20 active contributors (including SMEs, major industrial actors and academics)
- Regular SPINE meetings
- Numerous publications (10+ at next SCTC



Last community version

- SPIS 5.2
  - Major contribution from ESTEC contract on Dusty plasma (F. Cipriani)
  - Of course, totally different physics is included : dust grain charging, surface contamination, lunar environments
  - Improved solvers : robust particle pusher, stabilized circuit solver (even though still improvable)
  - New UI capabilities
  - Experimental validation by PhD student A. Champlain started in 2013
  - 2 publications in scientific journals

For users that are not interested by dusts:

The new capabilities **do not complicate the use of SPIS**

if you do not need it, you probably will not even see it

The **efficiency of SPIS for non-dusty simulations is not impacted**

memory usage is smaller and execution speed increased by ~10%

- SPIS 5.2 available on SPIS website

What SPIS is good at

- SC charging in GEO
  - From ESTEC/ESA contract finished in 2013 (D. Rodgers) and from initial contracts (ESA/CNES)
  - Simplified use for industry → SPIS 5 version
  - 10+ publications in scientific journals : comparison with NASCAP, LANL spacecraft data, electron emitter assessment, …

- Scientific missions dealing with low energy plasma measurements
  - From ESTEC/ESA contract finished in 2014 (A. Hilgers)
  - Lots of scientific tools → SPIS 5.1.8 version (last available)
  - 5+ publications in scientific journals: LEO Cubesat charging, Solar orbiter, Juice, …

- Ground plasma tank
  - Detailed characteristics of plasma chambers and particles sources (ion and electron guns) and instruments (LP, RPA, KP)
  - 5+ publications in scientific journals: electrodynamic tether, secondary electron emission yield, surface potential …

What SPIS can be quite good at

- Plasma thrusters interaction with spacecraft (charging, efficiency, erosion, contamination)
  - From ESTEC contract finished in 2012 (E. Gengembre) lead by Airbus DS
  - Database of thrusters available on demand at ESA
  - Updated model for electron cooling, Charge exchange reaction
  - Included in SPIS 5 but miss important physics however → SPIS-EP project
  - A few papers in scientific journals

- Thin elements
  - SPIS includes models for thin wires and thin panels (electric field and particle collection)
  - Assume long Debye length regime to obtain analytical fits

- Quick overview of capabilities is now difficult to do → look at the html user guide

Candidate contributions for the next official distribution

- Electric propulsion related projects

- ESA funded activities (started in 2016)

  1. Electron Cooling model (ESA TO K. Dannemayer)
     - Airbus DS, ONERA, UC3M, ICARE, KTH
     - Advanced hybrid models & plume measurements

  2. SPIS-EP (ESA TO F. Cipriani)
     - ONERA, Artenum, Airbus DS, TAS
     - UR gathered from ESA and from the 22nd SPINE community (March 23-24, 2016)
     - Aspects covered: cathode current, multiple thrusters, distributions of ions, plasma interaction with the power units, interconnects, chemistry, erosion, contamination, dedicated outputs, …

  3. High Power High Voltage (ESA TO G. D'accolti)
     - Airbus DS, ONERA
     - Plasma current collection on high voltage solar arrays

Possible future contributions (not mature)

- Ongoing work from PhD at Onera:
  - Patch method (A. Brunet – Onera/CNES PhD – started 2014):
    - Advanced multi-domain method allowing to refine the mesh on particular locations (“patch”).
    - Small-scale systems simulation: SC interconnectors, sensors
    - Large-scale simulations: thruster plume, wake. . .
  - Hybrid method (O. Jorba-Ferro – Onera/CNES PhD / LATMOS – started 2015):
    - Coupled fluid and perturbative-PIC method allowing the simulation of dense plasma flows
    - First targets are the MYRIADE spacecraft (TARANIS)

Project presentation

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Overview

- Project:
  - ESA ITT AO/1-8620/16/NL/LF “Modelling of Electrostatic Environment of Ion Emitting Spacecraft”
  - ESA/ESTEC TO: Fabrice Cipriani
  - Consortium: Onera, Artenum, LPP (+ IRF)

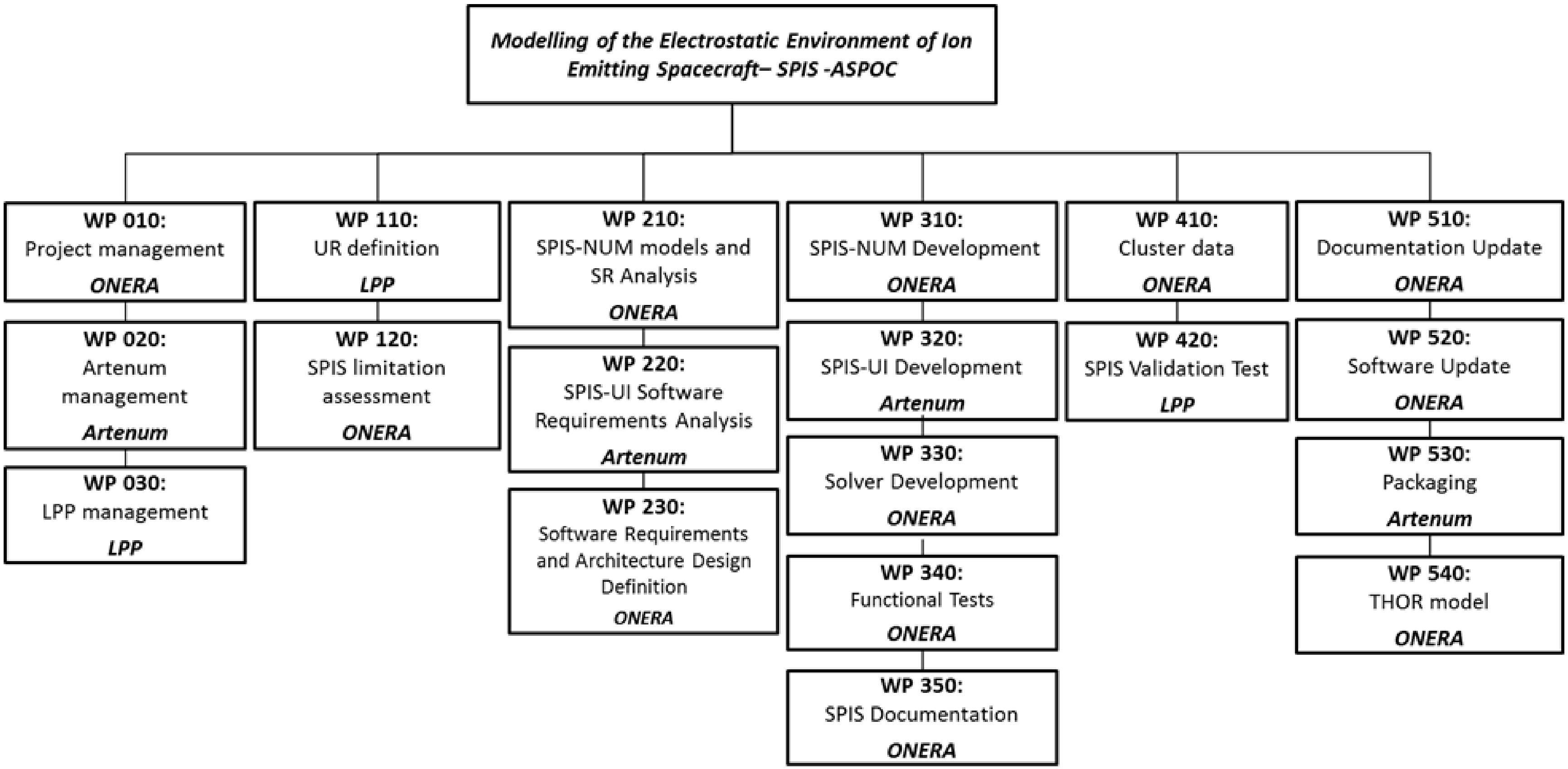
- Scope
  - ASPOC systems used to control and stabilize the spacecraft surface potential in interplanetary plasma:
    - Improvement of the electrostatic cleanliness of the SC to be able to particle and field measurement
    - But introduce others plasma perturbation due to the ion beam
  - SPIS mainly able to model the electrostatic cleanliness of the SC without ion emitter (essentially an outcome of the SPIS-SCIENCE project)
  - Effect of the ion emitter(s) on the low energy particle detector and electric field measurement difficult or partially reachable with the present version of SPIS

Overview

- Objectives
  - Better describe in SPIS the space charge effects of the ion beam on the space environment plasma and on the onboard instruments for the low energy plasma measurements
  - Improvement of the physical model and the numerical methods used in SPIS and make it available to the scientific community
  - Validate the developed model in relevant cases for THOR mission

- Method
  - **Define the modeling requirements wrt ion beam effect to the low energy plasma measurements**
  - Assess the current SPIS limitation and define development requirements
  - Develop a new version of SPIS
  - Validate the new software wrt Cluster data
  - Create a SPIS model of THOR spacecraft

Study logic



Modelling of the Electrostatic Environment of Ion Emitting Spacecraft– SPIS -ASPOC
WP 010: Project management ONERA
WP 020: Artenum management Artenum
WP 030: LPP management LPP
WP 110: UR definition LPP
WP 120: SPIS limitation assessment ONERA
WP 210: SPIS-NUM models and SR Analysis ONERA
WP 220: SPIS-UI Software Requirements Analysis Artenum
WP 230: Software Requirements and Architecture Design Definition ONERA
WP 310: SPIS-NUM Development ONERA
WP 320: SPIS-UI Development Artenum
WP 330: Solver Development ONERA
WP 340: Functional Tests ONERA
WP 350: SPIS Documentation ONERA
WP 410: Cluster data ONERA
WP 420: SPIS Validation Test LPP
WP 510: Documentation Update ONERA
WP 520: Software Update ONERA
WP 530: Packaging Artenum
WP 540: THOR model ONERA

WP 100 : *Analysis of current limitations and User Requirements Definition*

- **Overall objectives :**
  - Define the ion beam effect on low energy plasma modelling requirements
  - Assess the limitation of the current SPIS version wrt the modelling requirements

- **Overall approach for each sub-task**
  - Sub-task 110 : User Requirements definition
    - Define User requirements for the developments of SPIS
    - Survey targeting the SPIS user community
  - Sub-task 120 : SPIS limitations assessment
    - Assess the limitations of SPIS for the accurate physical representation of the electrostatic environment of an ion emitting spacecraft
    - Define performance needs for typical targets of the new SPIS functionalities

WP 200 : *Review of models and Numerical methods, Definition of Software Requirements and Architecture Design*

- **Overall objectives :**
  - Review the existing physical and numerical models improvement to perform
  - Establish the corresponding Software Requirements and a software Architecture Design
  - Define new algorithms to describe the physical processes to implement in SPIS

- **Overall approach for each sub-task**
  - Sub-task 210 : SPIS NUM model definition and SR analysis
    - Define new models for SPIS that meet the needs defined in TN1 and URD
    - Determine the software requirements for the numerical core of SPIS
  - Sub-task 220 : SPIS UI SR analysis
    - Determine the software requirements for the user interface of SPIS
  - Sub-task 230 : Software Requirement and Architecture Definition
    - Define the software requirements for SPIS
    - Define the architecture of SPIS

WP 300 : *Coding of algorithms, new models implementation and verification*

- **Overall objectives :**
  - Perform the developments, update the user manual and perform verification tests

- **Overall approach for each sub-task**
  - Sub-task 310 : SPIS NUM developments
    - Perform the development of the numerical core of SPIS, except the electromagnetic field solver
  - Sub-task 320 : SPIS UI developments
    - Perform the development of the user interface of SPIS
  - Sub-task 330 : EM solver developments
    - Perform the development of the electromagnetic field solver
  - Sub-task 340 : SPIS functional test
    - Perform the software functional test and verification
  - Sub-task 350 : SPIS documentation
    - Update the SPIS user manual

WP 400 : *End to End Validation of the ion emitting spacecraft model and related effects*

- **Overall objectives :**
  - Validated the ion beam effect model by using a wide range of environments parameters, beam currents and photoemission currents
  - Compare beam potential to experimental / flight data

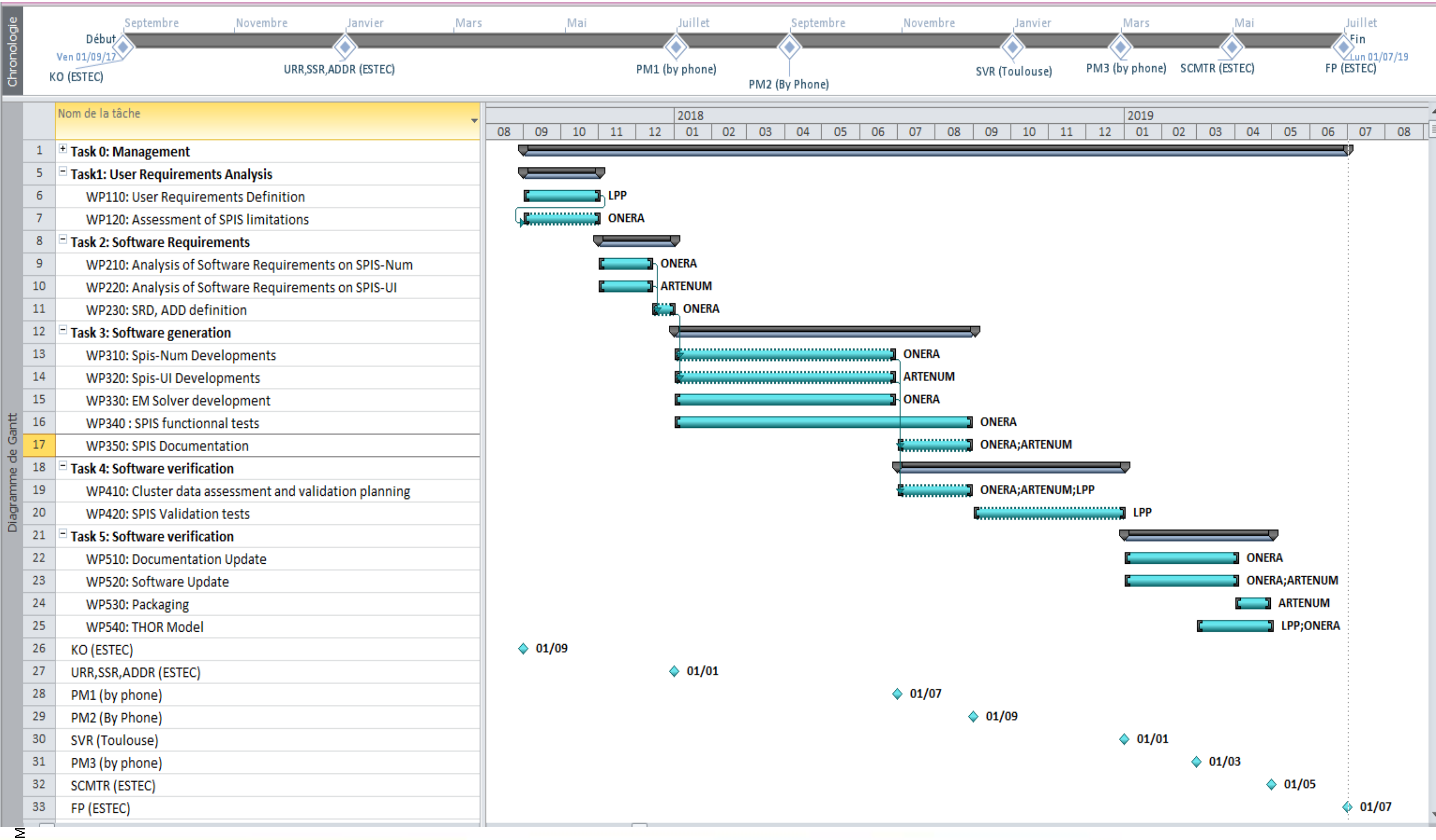
- **Overall approach for each sub-task**
  - Sub-task 410 : Cluster data assessment and validation planning
    - Provide expertise on Cluster data to help define the most interesting cases for the validation
    - Participate to the validation plan definition
    - Provide a hands-on formation to SPIS to the validation team
    - Build a mock-up simulation of Cluster to serve as a basis for the validation simulations
  - Sub-task 420 : Validation tests
    - Definition of the draft validation test plan approved at the PM2.
    - End-to-end validation testing performed according to the updated validation test plan approved by the Agency.
    - Validation test projects and the specified outputs shall be delivered

WP 500 : *Software consolidation and (THOR model) delivery*

- **Overall objectives :**
  - Consolidate the developed SPIS software based on the outcomes from the validation phase.

- **Overall approach for each sub-task**
  - Sub-task 510 : Documentation update
    - Update the SPIS documentation after validation phase
  - Sub-task 520 : SPIS update
    - Update of the SPIS software following the results of the validation phase
  - Sub-task 530 : SPIS packaging
    - Perform packaging of SPIS
  - Sub-task 440 : THOR modelling
    - Provide instrument geometry
    - Provide a THOR mock-up simulation, including configurable geometry

Schedule


Chronologie
Septembre
Novembre
Janvier
Mars
Mai
Juillet
Septembre
Novembre
Janvier
Mars
Mai
Juillet
Début
Ven 01/09/17
KO (ESTEC)
URR,SSR,ADDR (ESTEC)
PM1 (by phone)
PM2 (By Phone)
SVR (Toulouse)
PM3 (by phone)
SCMTR (ESTEC)
Fin
Lun 01/07/19
FP (ESTEC)
Diagramme de Gantt
Nom de la tâche
2018
2019
08 09 10 11 12 01 02 03 04 05 06 07 08 09 10 11 12 01 02 03 04 05 06 07 08
1 Task 0: Management
5 Task1: User Requirements Analysis
6 WP110: User Requirements Definition
LPP
7 WP120: Assessment of SPIS limitations
ONERA
8 Task 2: Software Requirements
9 WP210: Analysis of Software Requirements on SPIS-Num
ONERA
10 WP220: Analysis of Software Requirements on SPIS-UI
ARTENUM
11 WP230: SRD, ADD definition
ONERA
12 Task 3: Software generation
13 WP310: Spis-Num Developments
ONERA
14 WP320: Spis-UI Developments
ARTENUM
15 WP330: EM Solver development
ONERA
16 WP340 : SPIS functionnal tests
ONERA
17 WP350: SPIS Documentation
ONERA;ARTENUM
18 Task 4: Software verification
19 WP410: Cluster data assessment and validation planning
ONERA;ARTENUM;LPP
20 WP420: SPIS Validation tests
LPP
21 Task 5: Software verification
22 WP510: Documentation Update
ONERA
23 WP520: Software Update
ONERA;ARTENUM
24 WP530: Packaging
ARTENUM
25 WP540: THOR Model
LPP;ONERA
26 KO (ESTEC)
01/09
27 URR,SSR,ADDR (ESTEC)
01/01
28 PM1 (by phone)
01/07
29 PM2 (By Phone)
01/09
30 SVR (Toulouse)
01/01
31 PM3 (by phone)
01/03
32 SCMTR (ESTEC)
01/05
33 FP (ESTEC)
01/07

Modelling proposal

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Modelling requirements (preliminary)

SR #	Title	Description
SR-DL-01	ASPOC definition	It shall be possible to define a surface group as an ASPOC and to define its characteristics
SR-DL-02	ASPOC species definition	It shall be possible to associate species to the ASPOC and to define their types and distributions.
SR-DL-03	Instrument definition	It shall be possible to define a surface group as an instrument site and to define the instrument characteristics
SR-DL-04	Instrument geometry definition	It shall be possible to define the geometry of the instrument with the precision required for an accurate measurement simulation. The mesh refinement around the instrument shall be handled automatically by the software.
SR-DL-05	Near field description	It shall be possible to use the automated mesh refinement to model the near field region at the exit of the ASPOC.

Modelling requirements (preliminary)

SR #	Title	Description
SR-SL-01	ASPOC particle emission	The emission of particles from the ASPOC shall be simulated in accordance with the parameters defined in SR-DL-02.
SR-SL-02	Motion in magnetic field	The accuracy and performance of the particle pusher including the magnetic field shall allow for accurate simulations of the spacecraft interaction with the environment and ASPOC plume in reasonable simulation durations.
SR-SL-03	Low statistical noise	The environment and emitted populations shall be described using a low statistical noise algorithm, still preserving the accuracy of the distribution modelling.
SR-SL-04	Thin wire approximation in targeted environments	It shall be possible to simulate thin wires using the thin wire approximation in all the environments that the THOR mission may encounter.
SR-SL-05	Thin wire ends	The potential at the end of thin wires shall be accurately modelled to allow the simulation of measurements made by probes at the end of the wires.
SR-SL-06	Coupling with waves	The stability and behaviour of SPIS shall allow to simulate transient phenomena, in particular the coupling with waves
SR-SL-07	Plasma waves in magnetized environment	The plasma waves arising from the plasma coupling with the electromagnetic field shall be modelled.
SR-SL-08	Spinning spacecraft	The moderately high spin rate of the spacecraft shall be taken into account, not only by rotating the boundary conditions (as already exists in SPIS), but also the background magnetic field and the particles in the simulation domain.
SR-SL-09	Refined mesh	The numerical core of SPIS shall handle the presence of refined meshes that will be used for improving the accuracy of the instrument outputs and near field trajectories only (no self consistent calculation over the refined mesh).

Modelling requirements (preliminary)

SR #	Title	Description
SR-OL-01	CDF outputs	The relevant instrument outputs shall be exportable in the CDF format to ease comparison with observational data.
SR-OL-02	Dynamic spectra	Field measurements shall be presented as dynamic spectra.
SR-OL-03	Visualization of quantities along the thin wires	The quantities that are computed by SPIS (datafields) shall be viewable as plots in the data mining section.

SPIS-EP Status

- SPIS-EP software version dedicated to plume interaction with spacecraft:
  - Current on the spacecraft that induced charging effects
  - Current collection on solar arrays that produces power losses
  - High energy ions (> 20 eV) that produces erosion
  - Contamination by the erosion products
  - Differential charging that produces ESD
  - Coupling of the plasma plume with the plasma environment
  - Coupling between plume in case of multiple thrusters
  - Cathode/neutralizer behavior
  - Electric coupling of the thrusters with respect to the spacecraft (differential potential – CRP)

- Validation is on-going

- Final version beginning of 2018

Plume modelling

- Plasma models:
  - PIC for ions: source (Xe+ and Xe++), CEX ions and environment ions (H+ or O+)
  - Fluid/analytical electron distribution
    - Maxwell-Boltzmann for ambient plasma (LEO / MEO)
    - Polytropic or adiabatic or isothermal law for electrons from thruster/cathode block
  - Electron populations implicitly solved in Poisson equation
  - Charge exchange collisions in volume
- Surface interactions model:
  - Current collection → Implicit circuit solver (linear predictors of plasma current)
  - High voltage solar arrays interconnects (reduced analytical laws)
  - Erosion and contamination
- Thruster system block model:
  - Cathode floating potential model
  - Electric coupling with SC → floating, grounded or decoupling resistor
  - Current balance with environment plasma

Models of plume / ion sources

Legacy Maxwellian Thruster

Defines a thruster with a Maxwellian distribution using already existing surface distribution (Axisymetric tabulated and AISEPS also possible)

Maxwellian Thruster

Defines a thruster with a Maxwellian distribution using the generic thruster distribution

Maxwellian Thruster 1D

Defines a thruster with a Maxwellian distribution using a 1D energy distribution

Generic Thruster

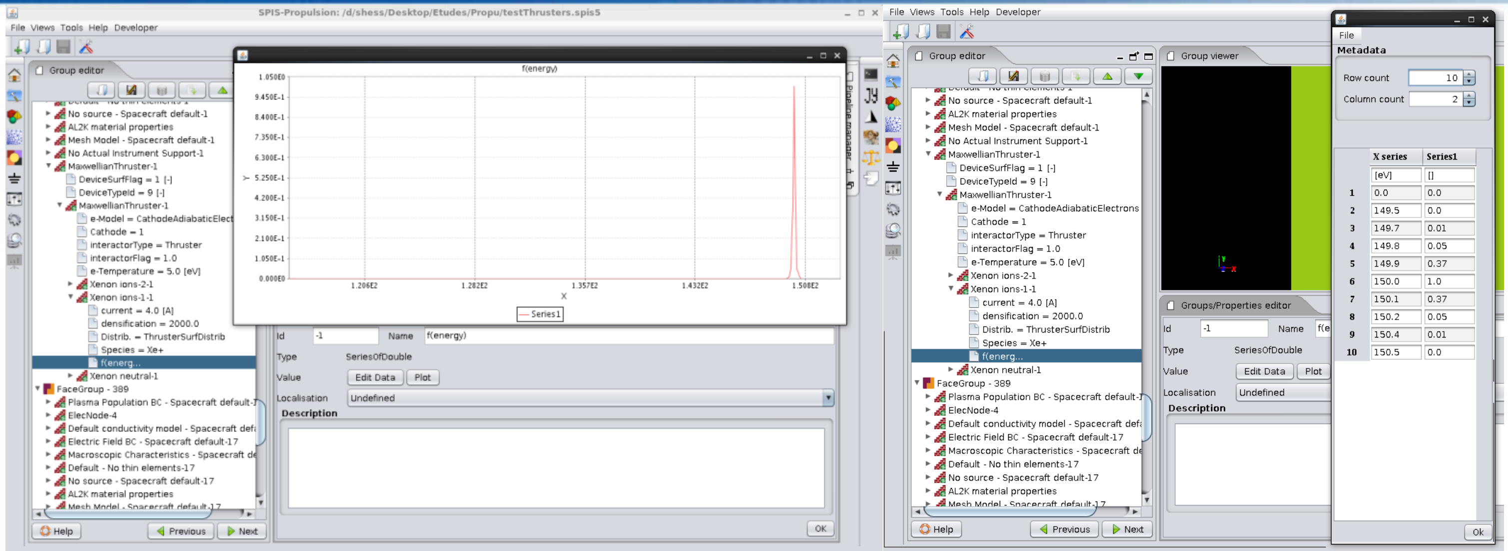
Defines a thruster with a Maxwellian distribution using a 1D energy distribution and a 2D energy-angle distribution

SPT100

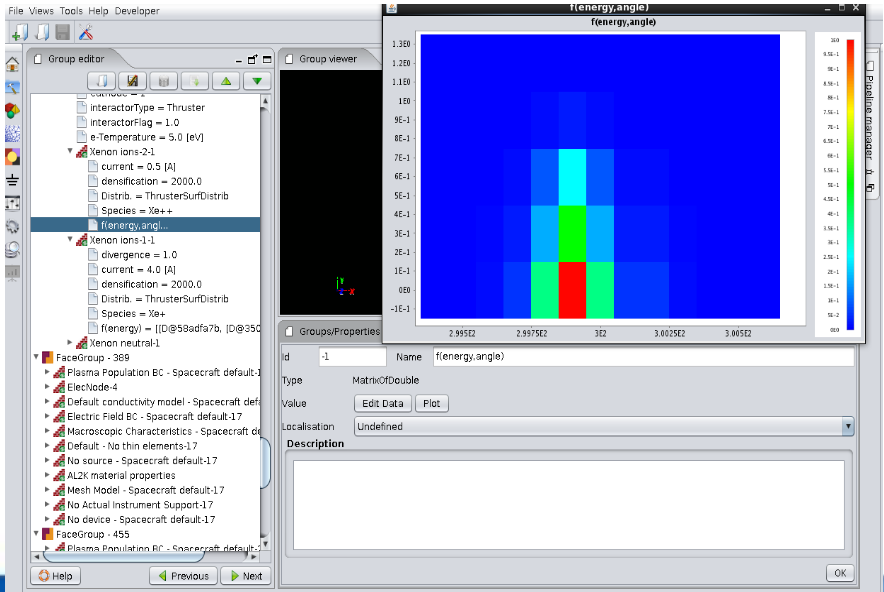
Defines a SPT100 thruster

Models of plume / ion sources

1D:



2D:



Electron cooling model implementation: Quasi – neutral approximation at global scale

- In the quasi neutral approximation
- $n_e = n_i$

- As there is no net charge the electric potential only exists to balance the thermal pressure forces
- $n_e \, grad \, V = grad \, n_e T_e$

- This is a major drawback of the method as not all potential are possible in this model. In particular highly negative potentials due to polarized conductors would lead to negative temperature and cannot be modelled.

- Usually, the electron temperature is set as a function of the electron density, but because of neutrality, it can also be expressed as a function f of the ion density. This temperature is assumed to have a smooth spatial variation:
- $T_e = f_{smoothed}(n_i)$
- The function f must be monotonic and continuous so we can compute the quasi-neutral electron density as:
- $n_{e,qn} = f^{-1}(T_e) \sim n_i$

Electron cooling model implementation: Isothermal Poisson-Boltzmann approximation at local scale

- The electron density may not be equal to the ion density locally:
- $n_e = n_{e,qn} + \delta n_e$

- Solving Poisson equation:
- $e(n_e - n_{e,qn})/\varepsilon_0 = \Delta V \sim (V - V_{qn})/\lambda_D^2$
- $n_e/n_{e,qn} = 1 + (n_e/n_{e,qn})e(V-V_{qn})/kT_e$

- $n_e = n_{e,qn} \exp[\, e(V-V_{qn})/kT_e \,]$

- In this model, $n_{e,qn}$, V_{qn} and T_e are function of the ion density, not of the local electron density, so that the mathematical form of the above equation is exactly the same as that of the usual Maxwell-Boltzmann distribution, except is local and not global.

- Contrary to the quasi-neutral case, the Poisson equation is solved explicitly (even if the electron density contribution to the Poisson equation can be implicited). It is possible to simulate non-neutral sheaths close to polarized surfaces.

Cathode modelling

SPIS models electrons like a neutralizing background with an electrostatic perturbation:

$n \sim n_0 \exp(-q(V-V_{ref})/kT)$

No kinetic effects, impossible to differentiate electron population on their origin

SPIS – EP assumes quasi-neutrality between the cathode electrons and the ions of the plume they neutralize (incl. CEX) with an electrostatic perturbation:

$n \sim n_i \exp(-q(V-V_{quasi\text{-}neutral}-V_{cathode})/kT)$

Kinetic effect taken into account via the ion density. Possible to differentiate electron population from different origins.

Possible to model cathode imbalance by exchanging parts of the plume to neutralize between cathodes.

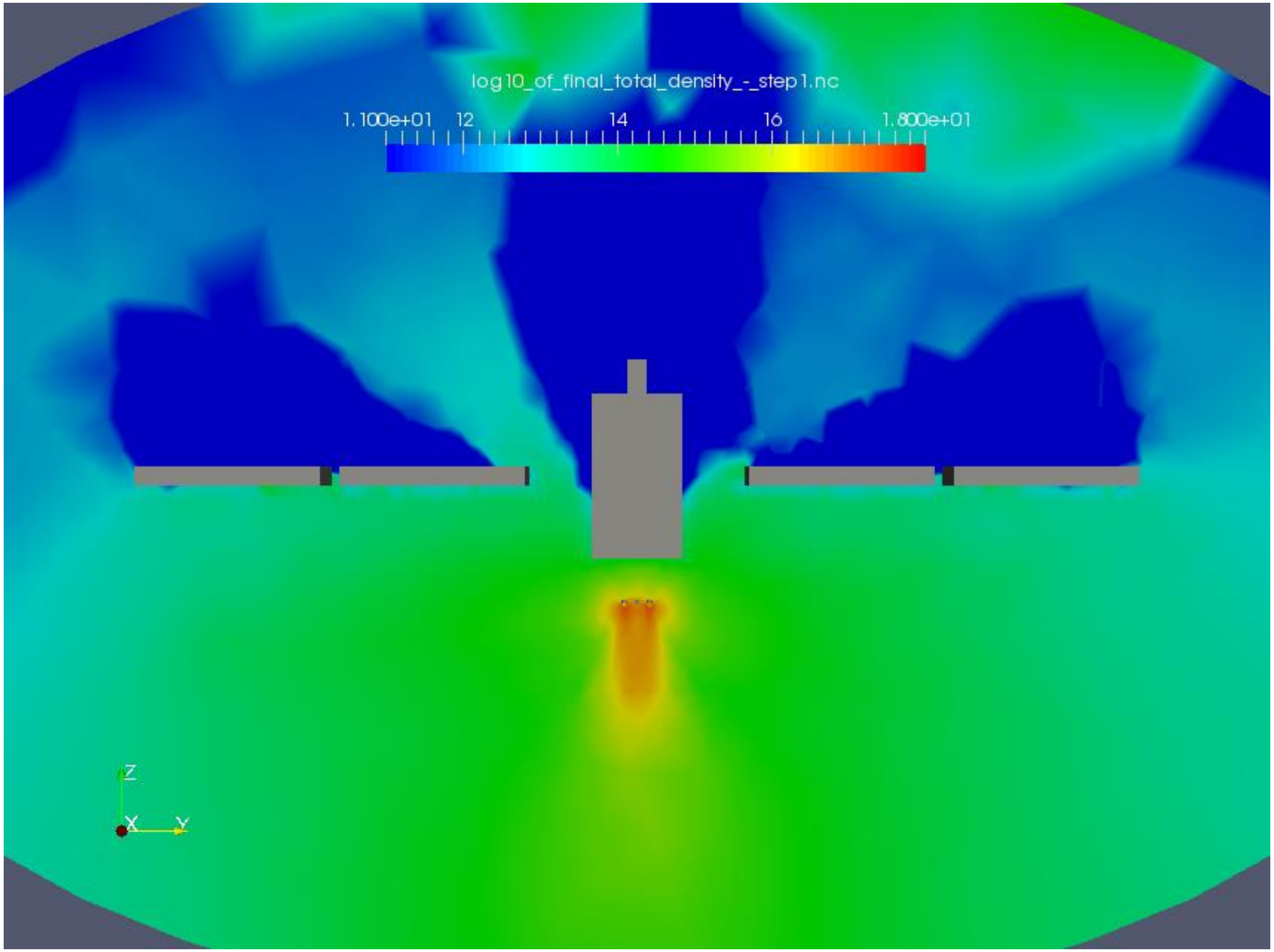
The electrons are isothermal for small densities.

$$J_\infty = J_{boundary}\sqrt{1-\frac{min(q\tilde{V},0)}{T_{boundary}}}\,exp\left(-\frac{\max(q\tilde{V},0)}{T_{boundary}}\right)$$

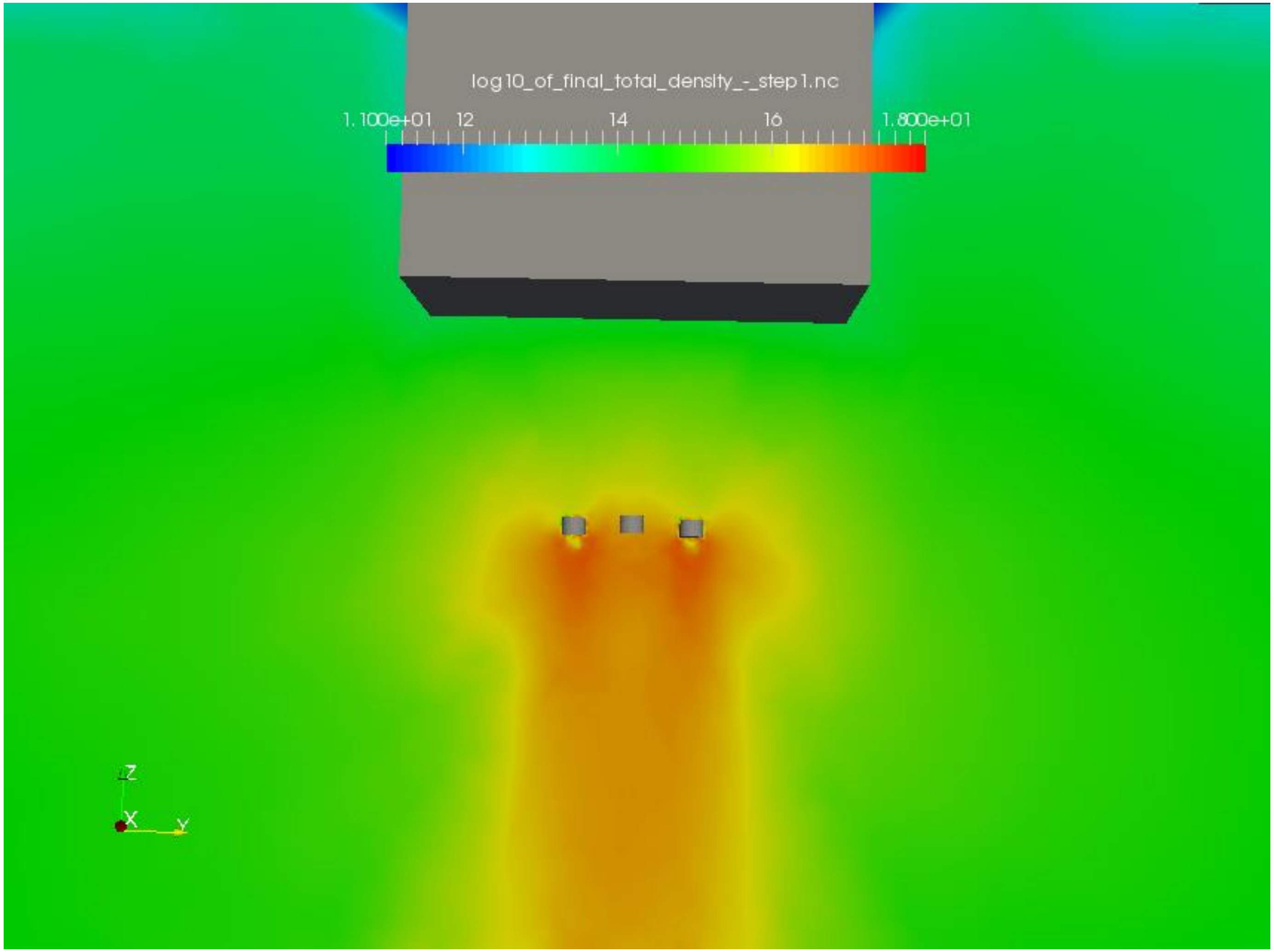
$$\tilde{V} = V_{boundary} - V_{qn;boundary} + V_{qn;\infty}$$

Simulation of a floating SC in a cold plasma environment now possible

Simulation results



Simulation results



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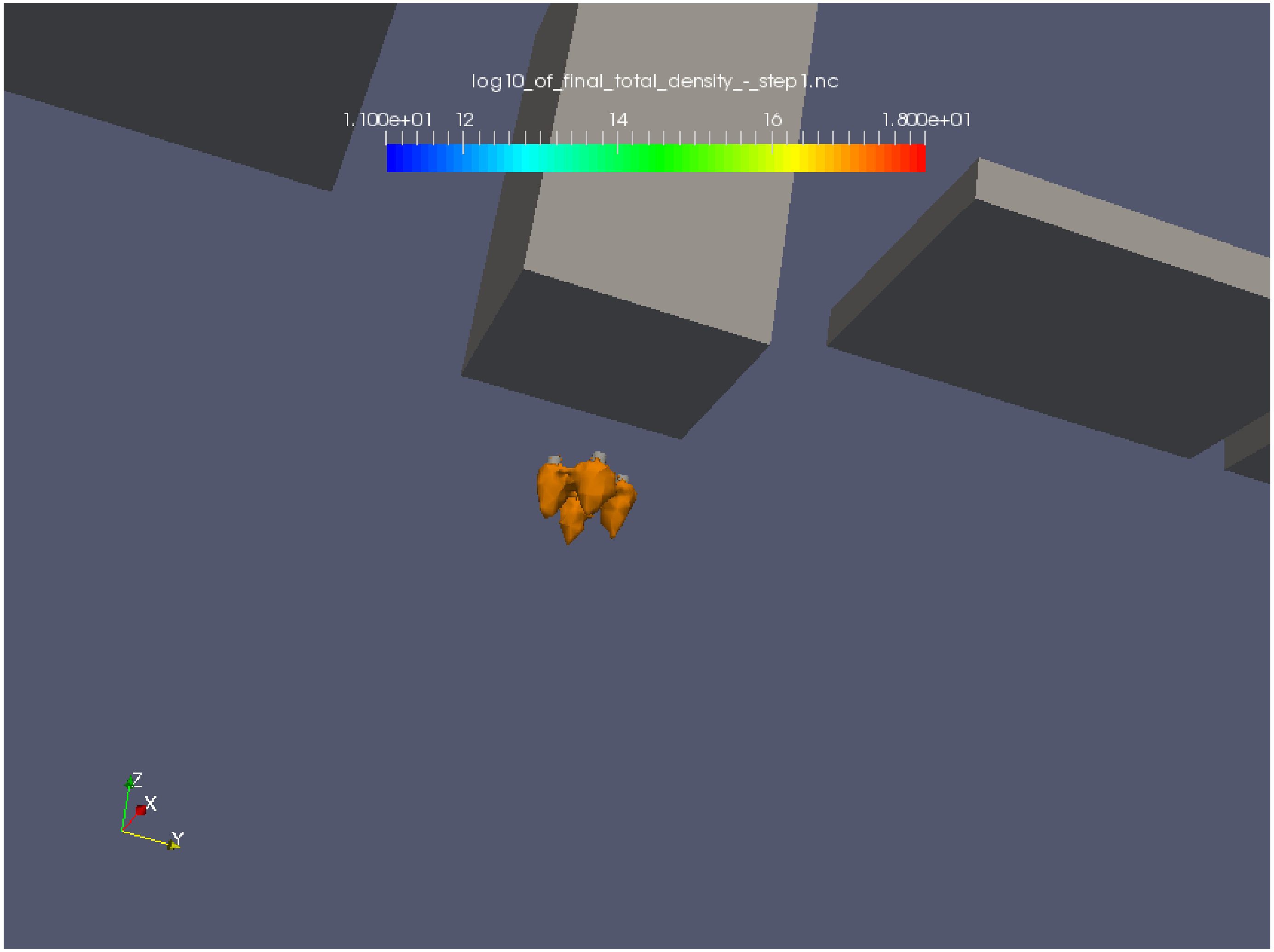

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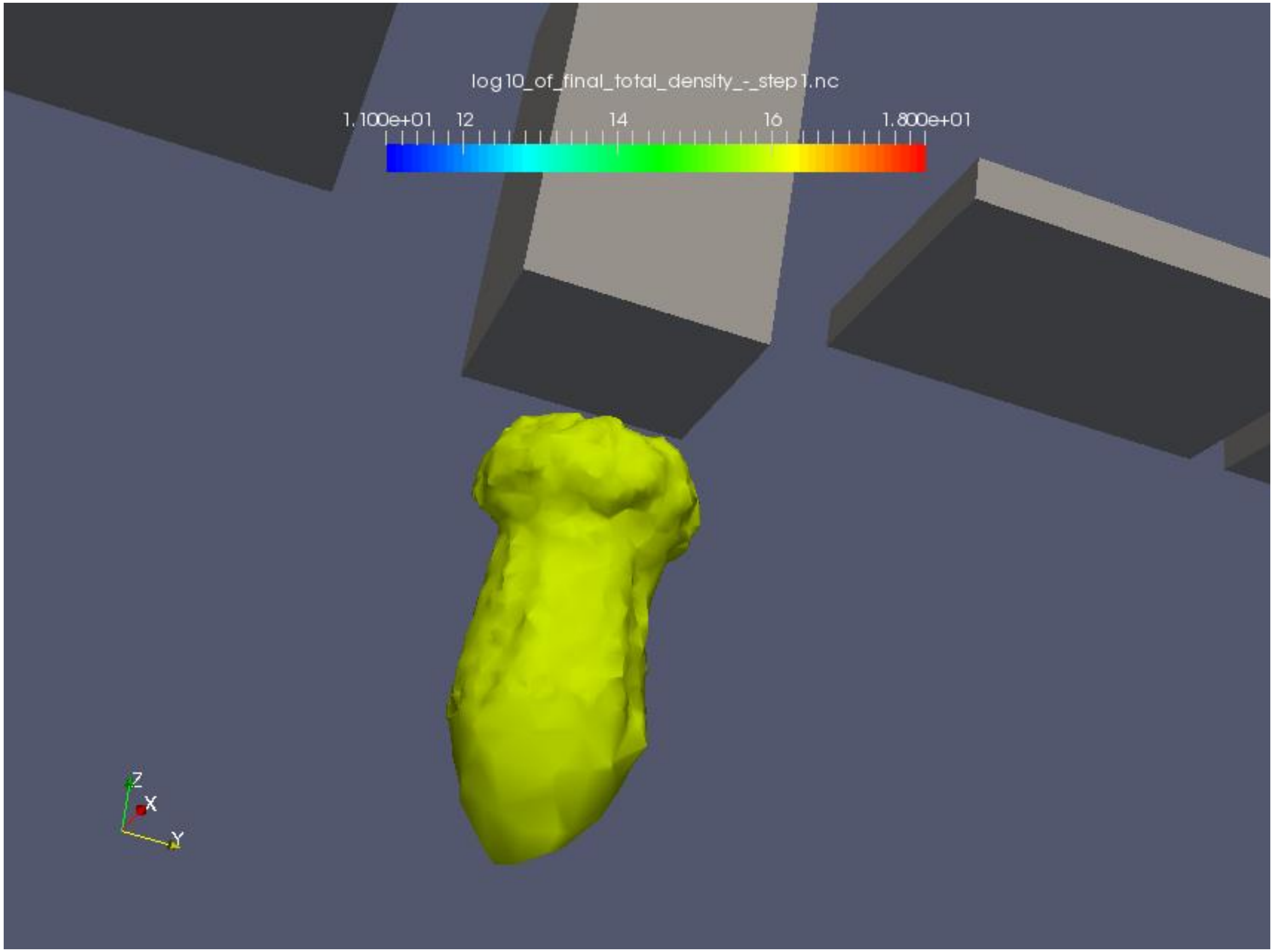

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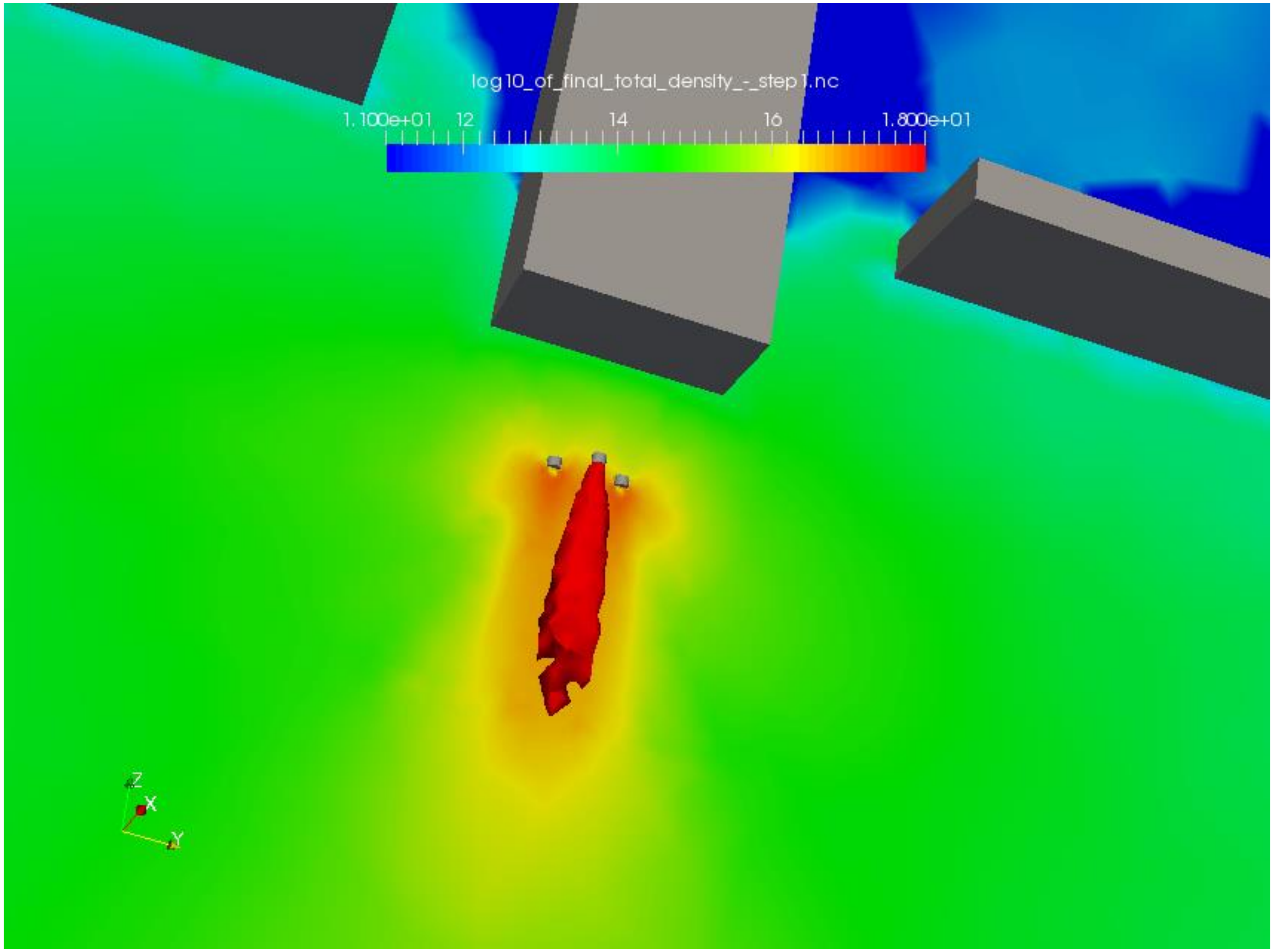

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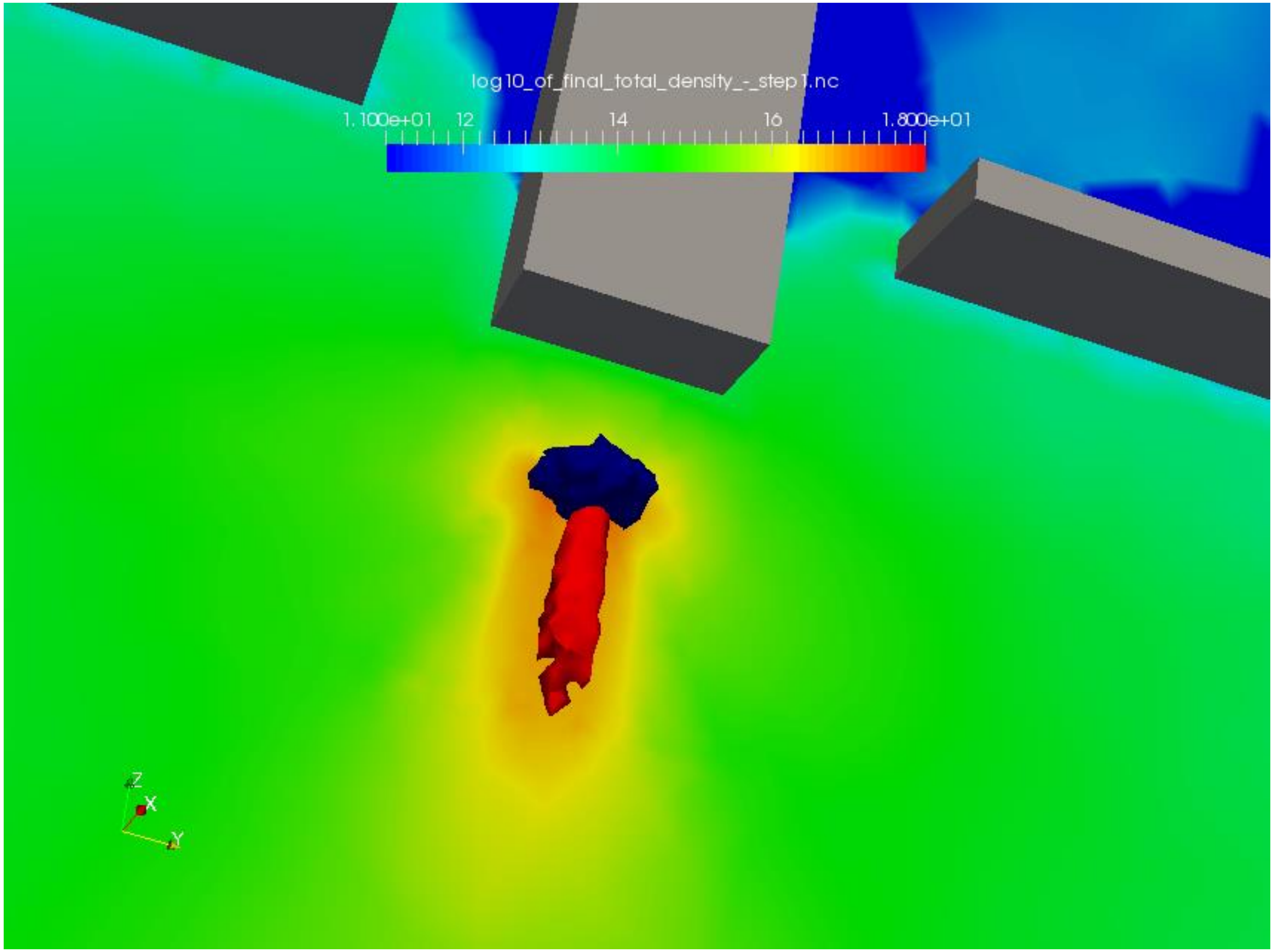
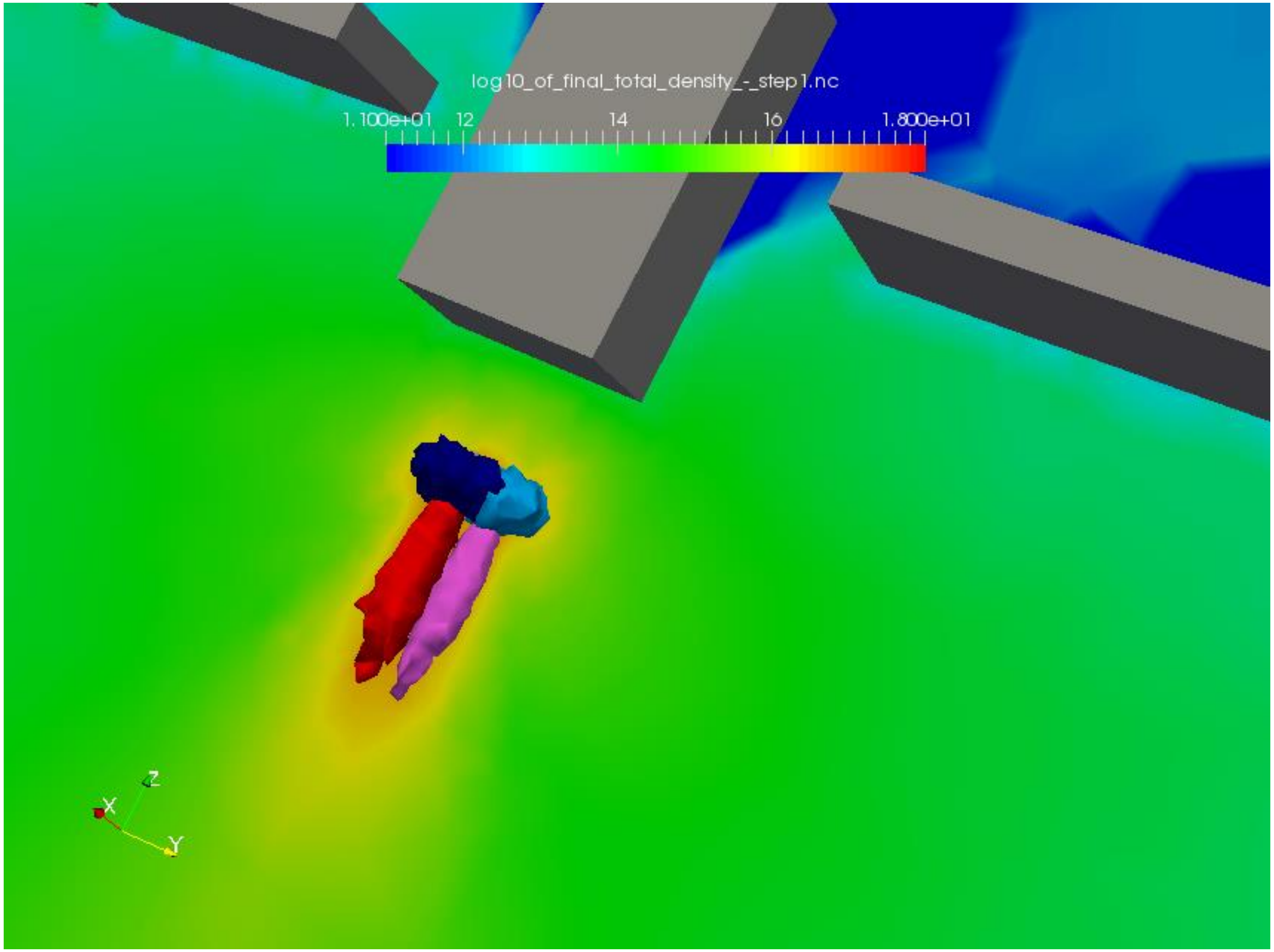


Simulation results



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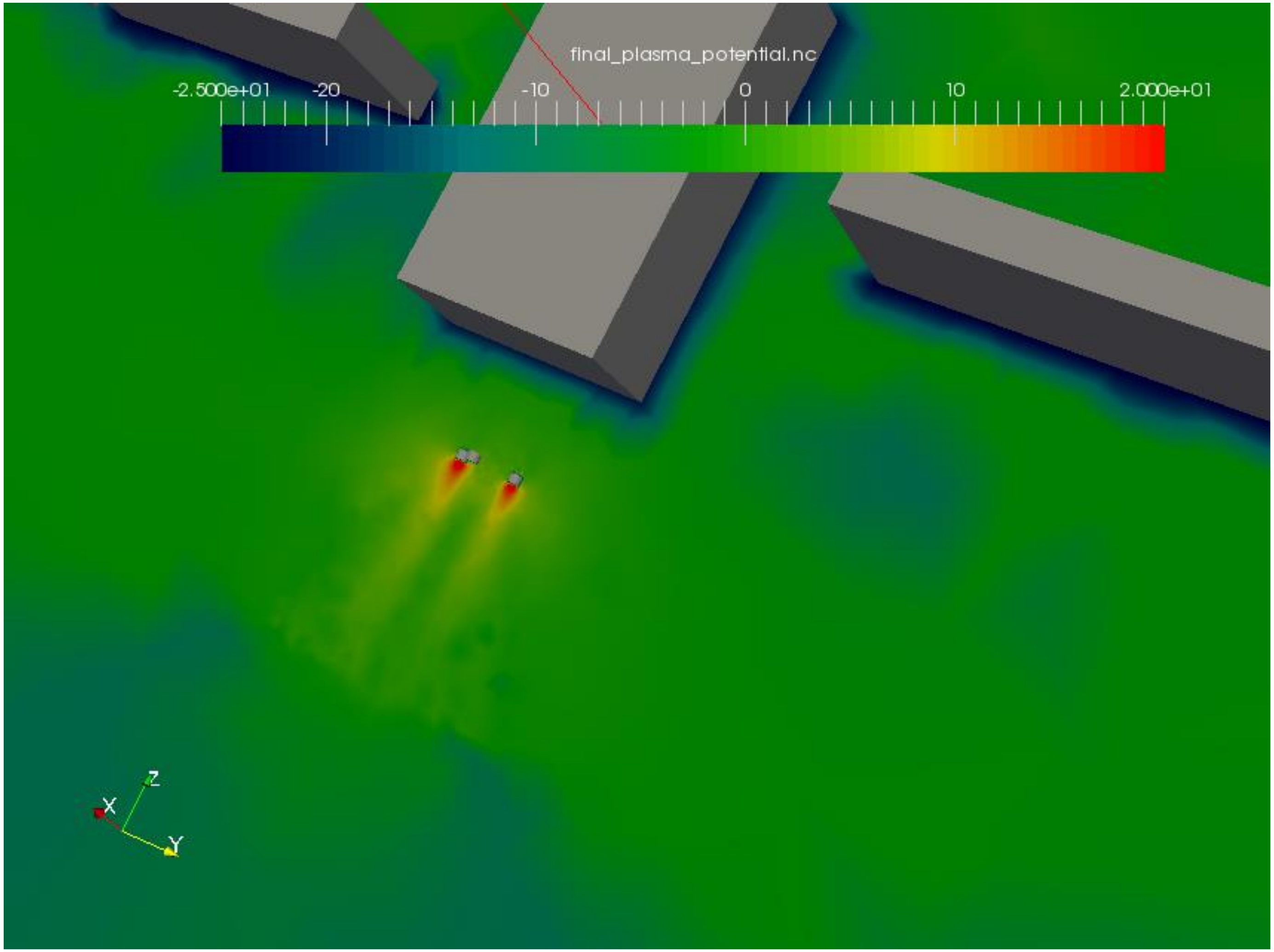

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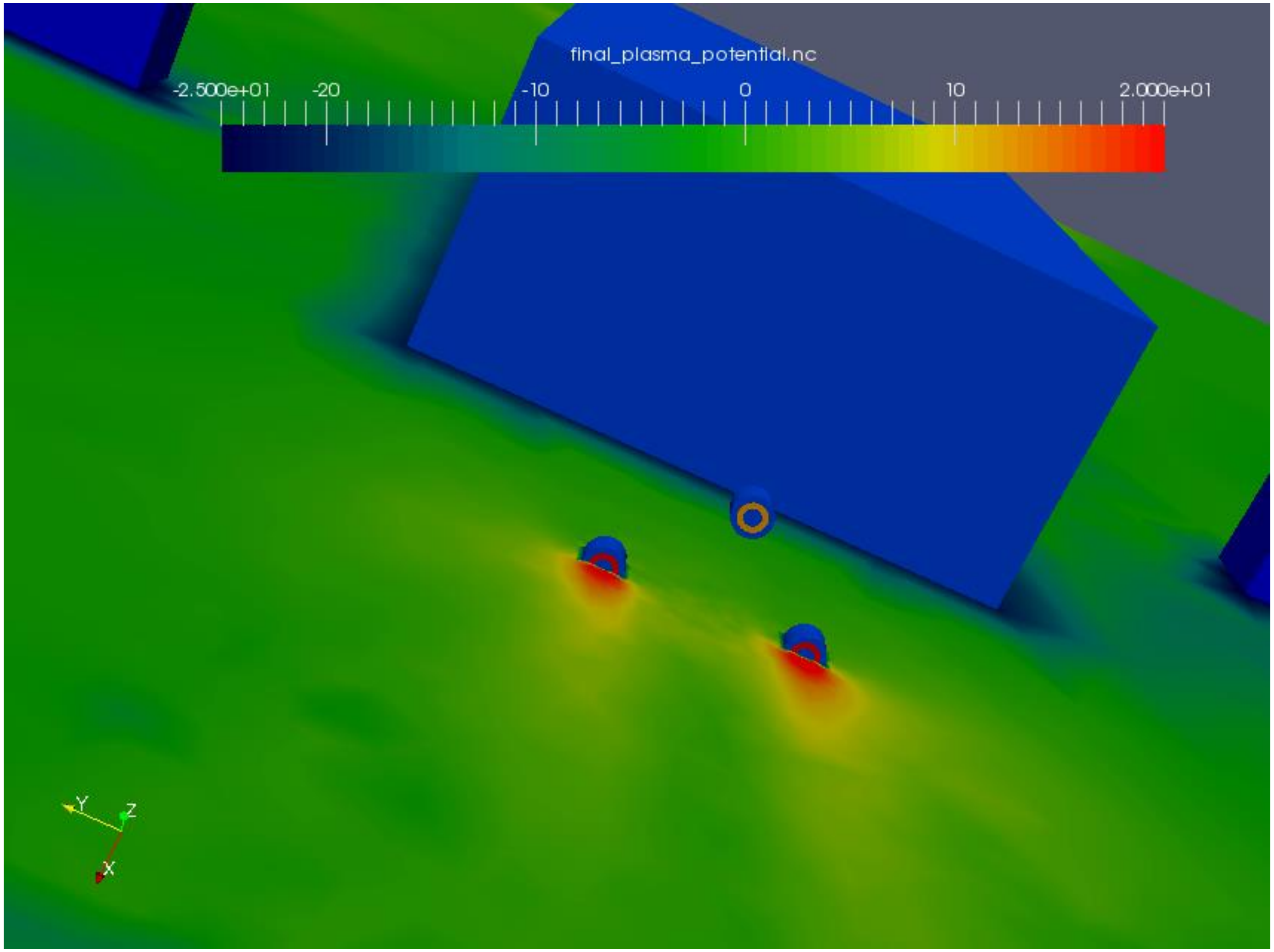

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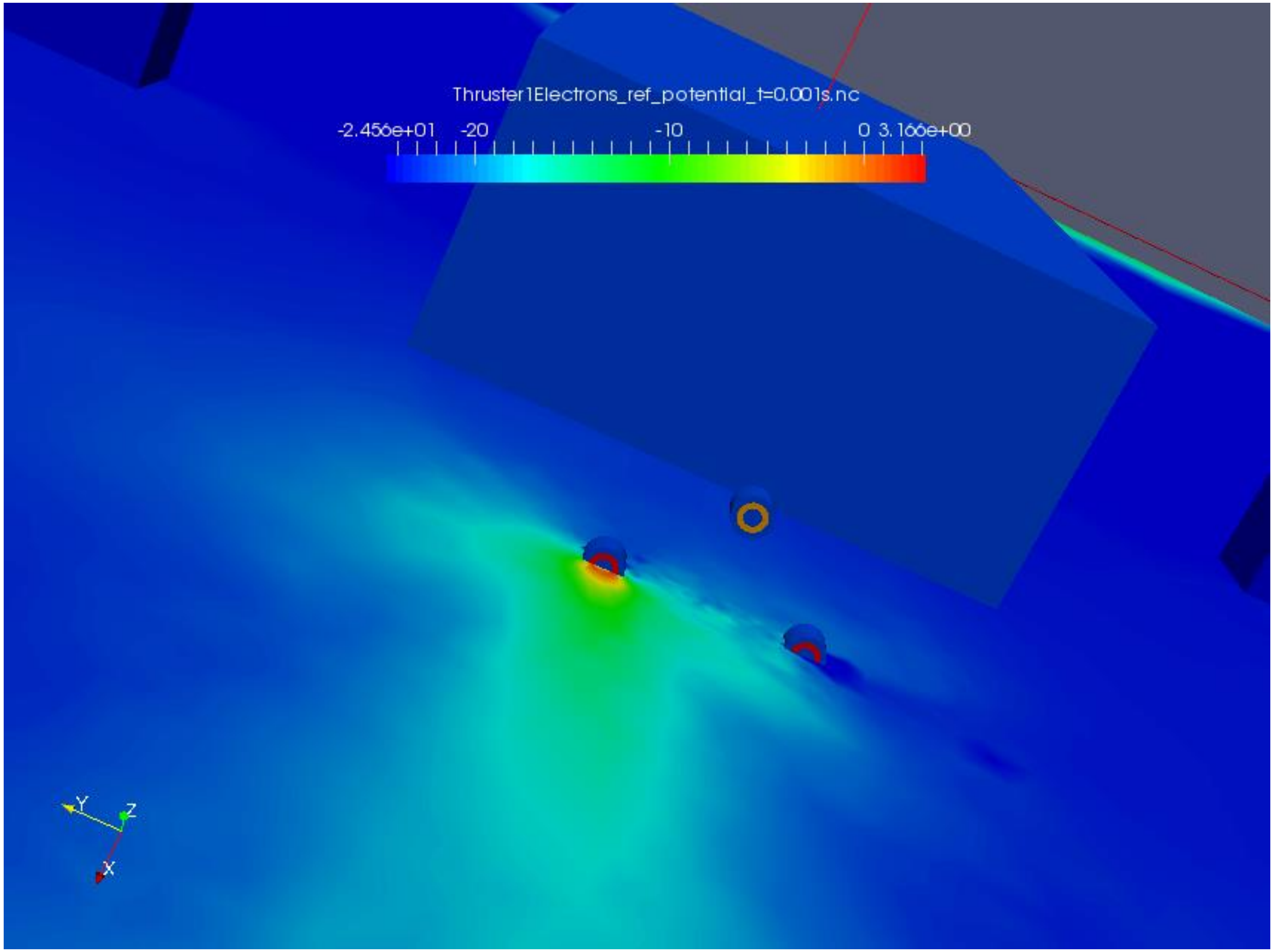

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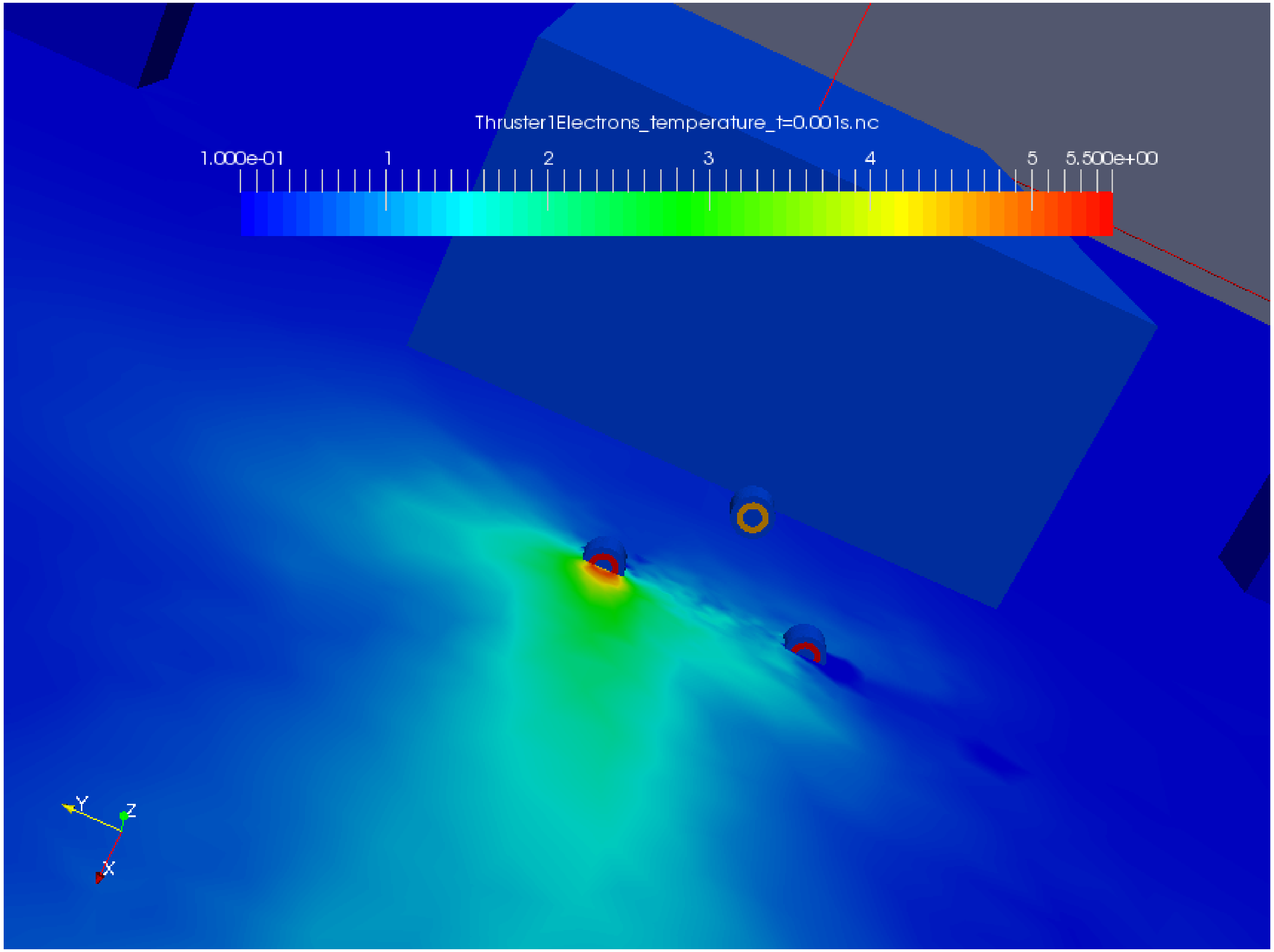


Availability: contractual terms

Because it exist no official way to contribute to the community version directly:

SPIS-EP will be made public but not delivered as an official version

Any SPIS-CORE development must be reversed automatically to the public version

All specific developments will be gathered in a SPIS-NUM plugin that will be public

Context

SPIS shall be developed to better handle scientific probes dedicated to precise plasma measurements that use active Spacecraft Potential Control (ASPOC) systems.

New difficulties, new capabilities:

- precise scientific measurements. Require low noise ($d\varphi \ll kT$) simulations

- magnetized natural plasma perturbed by dense plasma jets + waves. Magnetic field perturbation shall be modeled.

- new kind of data to compare with observations, that must be handled by existing softwares.

- spinning spacecraft.

Context

SPIS shall be developed to better handle scientific probes dedicated to precise plasma measurements that use active Spacecraft Potential Control (ASPOC) systems.

New difficulties, new capabilities:

- precise scientific measurements. Require low noise ($d\varphi \ll kT$) simulations
  - $\Rightarrow$ Use the LEO package
- magnetized natural plasma perturbed by dense plasma jets + waves. Magnetic field perturbation shall be modeled.
  - $\Rightarrow$ Develop a generalized Ohm law algorithm
- new kind of data to compare with observations, that must be handled by existing softwares.
  - $\Rightarrow$ Make ISTP/IACG compliant cdf outputs for instruments
- spinning spacecraft.
  - $\Rightarrow$ Rotate boundaries + droplets + B and vxB fields

LEO package

Developed by Oriol Jorba-Ferro for the TARANIS mission

ONERA-CNES PhD under the supervision of E. Seran (LATMOS, ISPL/CNRS)

Suite of methods that implement new fluid and PIC-perturbative methods in SPIS
Gathered in a SPIS-EP extension module.

$$f(t) = f_0(t).\int_0^V \frac{\partial f_0}{\partial V} dV + \sum_{PIC=0}^{N} w_i(t) S(x - x_i(t))$$

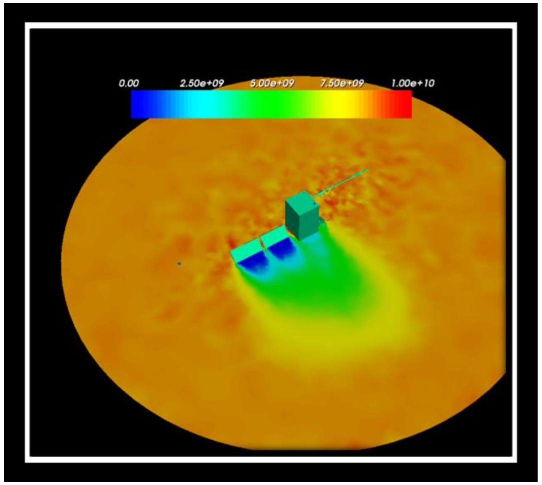
f_0 being any fluid distribution: (Drifting)Maxwell-Boltmann,…
Depending on the distribution, f_0 may be updated from PIC.

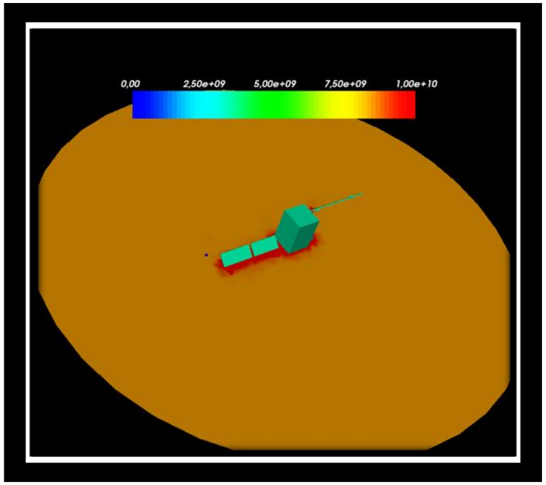
Allow to reach very low noise levels with reasonable numerical costs

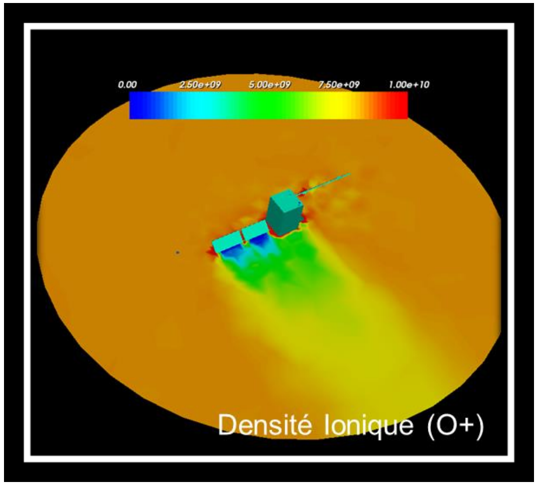
Needed to model the ASPOC impact as only particles with energy ≤ few kT impacted

LEO package

PIC	Poisson-Boltzmann	Drifting Boltzmann







Running time:18h mins.

3 mins.

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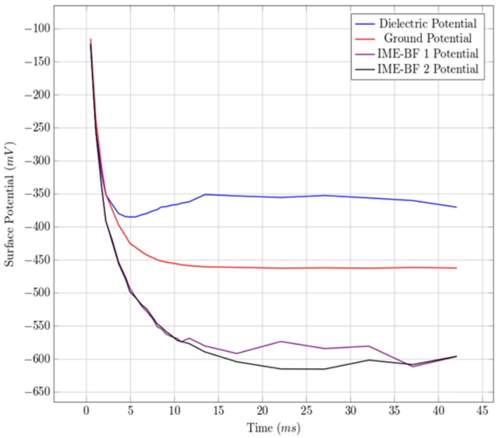
LEO package

PIC



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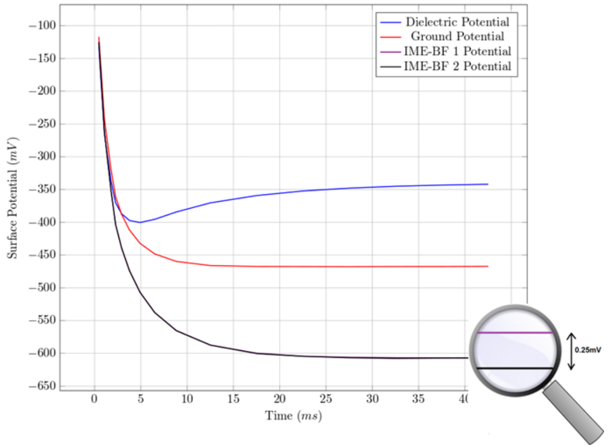
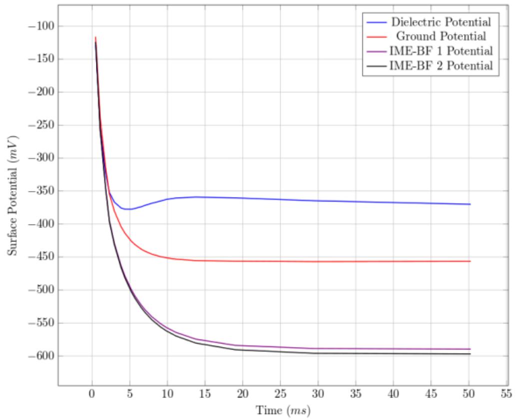
Poisson-Boltzmann



3 mins.

Drifting Boltzmann



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Generalized Ohm law

Natural plasma: drifting/spacecraft and magnetized, requires noisy PIC modelling

But ASPOC: relatively dense plasma source, need fluid electrons

If fluid electrons, Maxwell equations more complicated.
Use of Generalized Ohm Law for low frequency EM term:

$$d_t m v_e = -\nabla P \qquad - eE \qquad - e v_e \times B$$

~~Inertia~~ Pressure Electric Lorentz

$$E_{em} = \frac{J \times B}{e n_i} - \frac{J_i \times B}{e n_i} - \frac{\nabla P}{e n_i} = \frac{(\nabla \times B) \times B}{e n_i} - \frac{J_i \times B}{e n_i} - \frac{\nabla \rho_i k T_e}{e n_i}$$

implicit electron current and no high frequency EM waves ($d_t E \sim 0$)

$$E = E_{em} + E_{es} = \frac{(\nabla \times B) \times B}{e n_i} - \frac{J_i \times B}{e n_i} - \frac{\nabla \rho_i k T_e}{e n_i} - \nabla \varphi$$

reintroduce inertia for electrostatic purpose via charge separation

$$d_t B = -\nabla \times E$$

Known to be efficient and stable for structured cartesian meshes, to be developed for unstructured tetrahedral meshes

Plasma-spacecraft-wave coupling

Use of hybrid modelling prevents from capturing all the physics.
Depending on the electron modelling scheme waves that can be modeled are

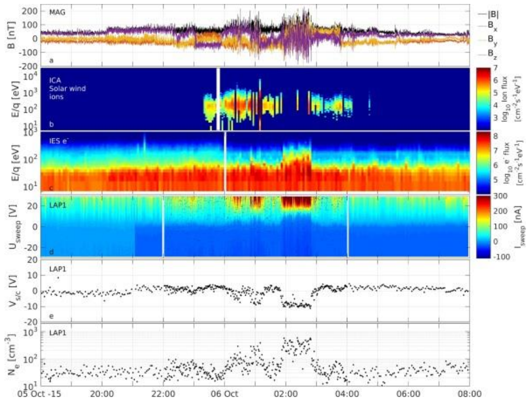
Mode name	Full PIC	Fluid e-	δf e-
Light	X	X	X
Electrostatic electron waves	√	X	?
Electromagnetic electron waves	X	X	X
Electromagnetic Ion waves	√	√	√
Electrostatic ion waves	√	√	√

Scientific instrument outputs

Formats of scientific instrument outputs have been standardized for a long time (need for long term archiving and efficient databases)

Generally, in the space physics field recommendation is to use CDF format following the ISTP/IACG recommendations for archiving and PDS or SPASE metadata format for databases (may describe observational data as well as simulated data)

Several high level tools have been developed to handle these data.

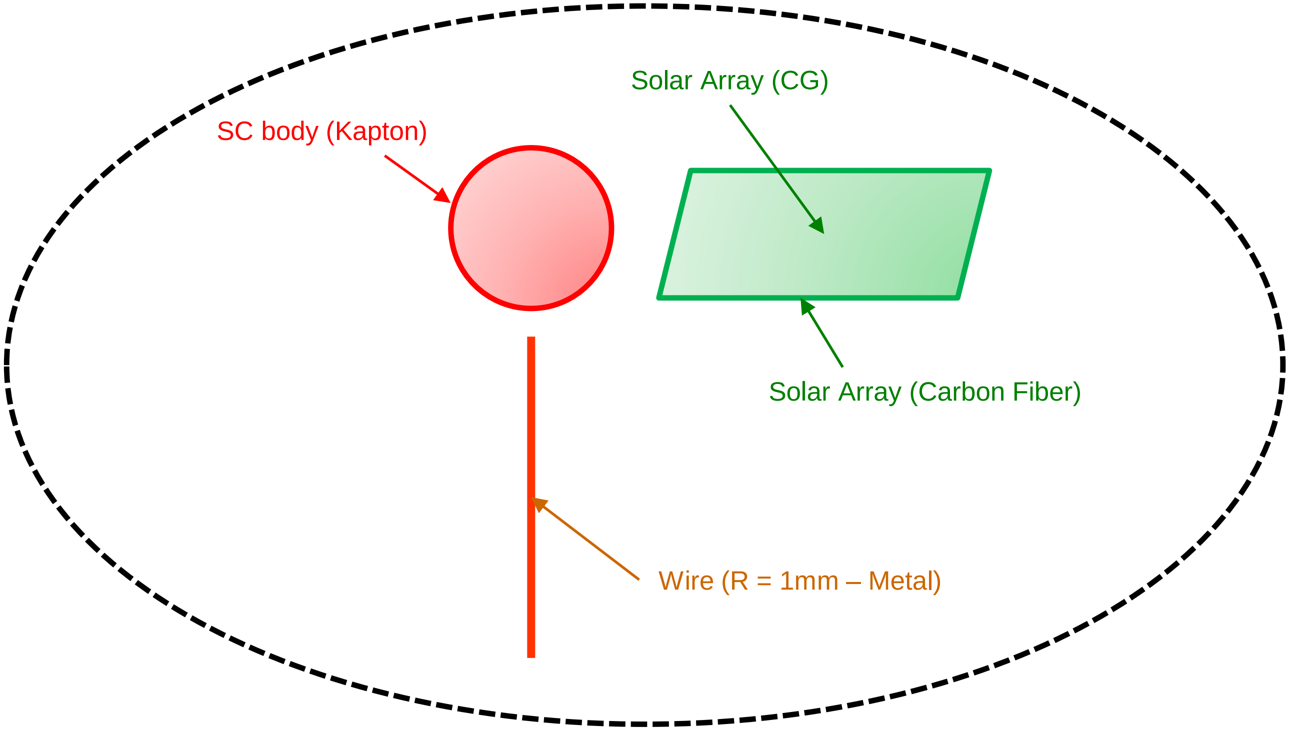


In order to ease comparison between simulations and “real” data, we propose that numerical instruments that simulate the scientific payload save their outputs in the CDF – ISTP/IACG format.

BTW: THOR team will use tools compliant with this format.

Unmeshed elements – Thin wires/Thin Panels

- Thin elements in SPIS:
  - 1D → thin wires (booms, antena, …)
    when r << Δx
  - 2D → thin panels (solar panels, …)
    when h << Δx
- One or two dimensions <u>not meshed</u> (repectively radius and thickness)
- but take into account:
  - Potential calculation (wire singularity or panel edges singularuty)
  - Current collection (wire radius)
  - Curent emission (surface area, impiging angle for SEE, …)



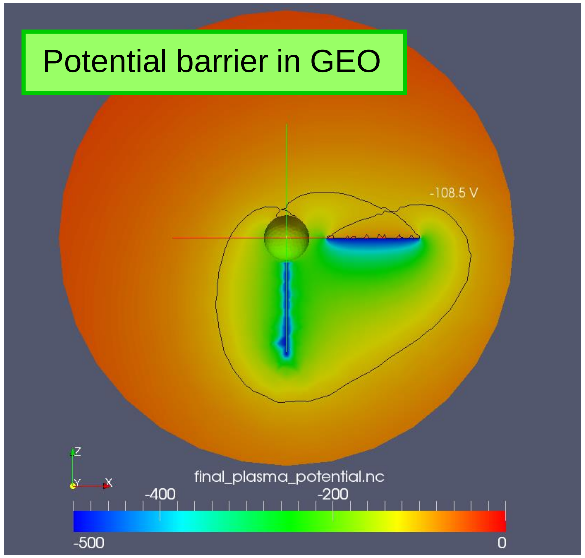
Solar Array 4m x 2m:
- Mesh size Δx = 0.2 m
- SA thickness h = 0.05 m

Too costly to mesh h → without 2D thin elements Δx < h/2 !!!

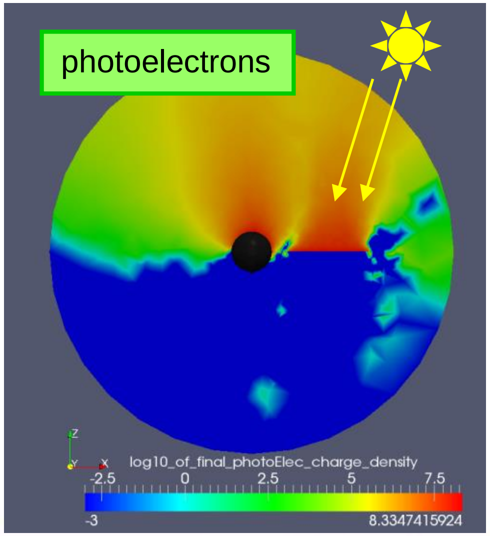
Wire 4m:
- Mesh size Δ x = 0.2 m
- Radius R = 1 mm

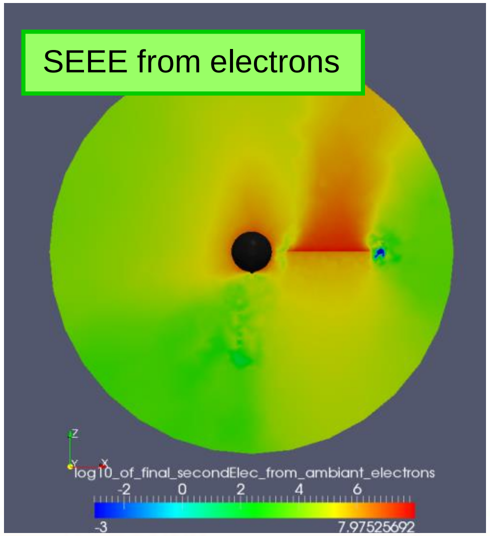
Too costly to mesh r → without 1D thin elements Δx < r/2 !!!

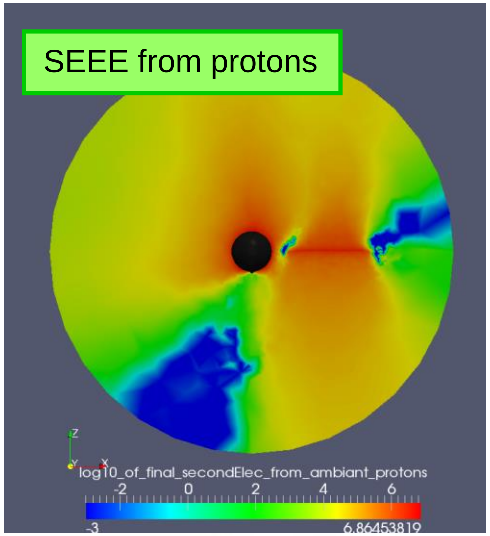
Unmeshed elements – Thin wires/Thin Panels



- Potential map:
  - Smooth potential jump → good description of the potential barrier
  - Potential effect of the wire
- Emission and collection:
  - On the wire → small effect because small radius
  - On the thin panel → standard surface (face A dielectric and face B conductor)
- Shading effect of the SC on the wire
- Wire → intensivelly used in the validation cases







Instrument/wire mesh refinement

- In the optic of improving the instrument modelling, it is proposed to automatically generate a thinner mesh around instruments and wires. The potential is computed on this mesh by solving Poisson equation, but using coarse's mesh densities for PIC populations (thus no problem of statistics). Then, thin-wire's field would be meshed for PIC motion purposes and the end of boom problem would be solved. It would also allow to solve the wire connection to surface problem (both arose from the previously employed method).