SPIS-SCIENCE

Computational tools for spacecraft electrostatic cleanliness and payload accommodation analysis

Final Presentation

ESA Co 4000102091/10/NL/AS
ESTEC, Noordwijk, NL, 20th of March 2013

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(2) ARTENUM, PARIS Science & Groupware

ONERA(1) THE FRENCH AEROSPACE LAB

IRF (3)

IRAP (4)

return on innovation

Context

- ESA/ESTEC contract 4000102091/10/NL/AS
  - Technical Officer: Alain Hilgers
  - Partners: ONERA, ARTENUM, IRAP, IRFU
- Long-term scientific program of ESA has planned missions dealing with plasma measurements
  - Solar Orbiter, Juice
  - Relatively low energy (few eV) plasma measurements
  - Electrostatic cleanliness becomes very important

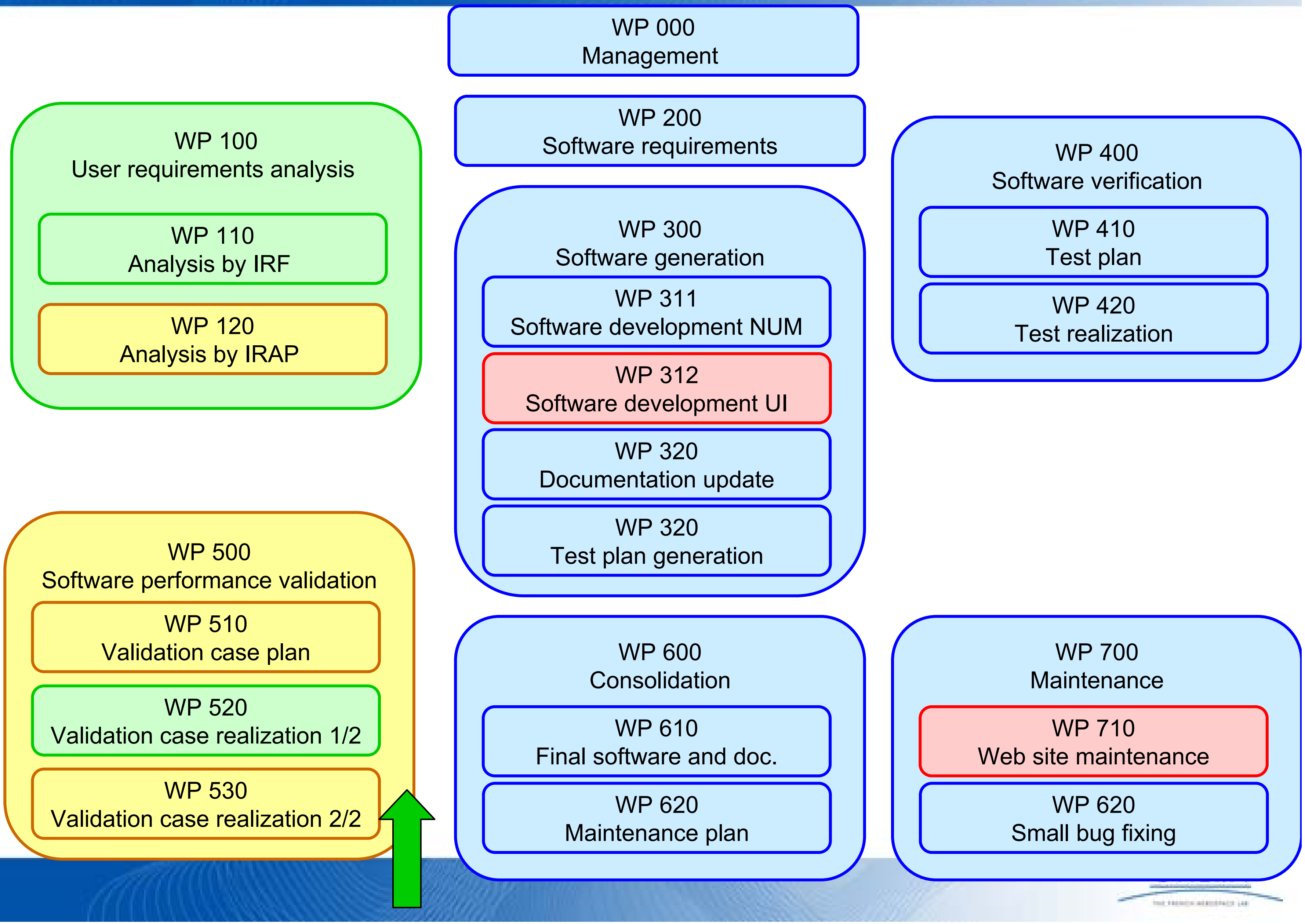
- Objectives
  - Provide a computational tool able to predict quantitatively
    - The charging of a S/C
    - The space charge in its environment
    - Their consequences in low energy plasma measurements
  - Outputs for the user (= scientific community)
    - New version of SPIS software
    - Validation test cases related to the scientific mission conditions
    - One year maintenance

Outline

- Team and work breakdown structure
- User requirements
- SPIS-SCI evolution
  - Precision
  - Performance
  - User-defined ambient plasma and spacecraft interactions
  - Pre-defined transient phases
  - Instruments
    - How to mimic scientific particle detectors, Langmuir probes, electric field analyzers
    - Illustrative example of application to Solar Orbiter
  - Unmeshed elements
- Validation campaign
  - Solar Orbiter
  - Cassini
  - Cluster
- Conclusion and perspectives

Team and work breakdown structure

ONERA
ARTENUM
IRF
IRAP



WP 000
Management

WP 100
User requirements analysis

WP 110
Analysis by IRF

WP 120
Analysis by IRAP

WP 200
Software requirements

WP 300
Software generation

WP 311
Software development NUM

WP 312
Software development UI

WP 320
Documentation update

WP 320
Test plan generation

WP 400
Software verification

WP 410
Test plan

WP 420
Test realization

WP 500
Software performance validation

WP 510
Validation case plan

WP 520
Validation case realization 1/2

WP 530
Validation case realization 2/2

WP 600
Consolidation

WP 610
Final software and doc.

WP 620
Maintenance plan

WP 700
Maintenance

WP 710
Web site maintenance

WP 620
Small bug fixing

Deliverables 1/2

Ref	Description	Status
D1-URD	User requirements document	100%
D2-SRD	Software requirements document	100%
D3-ADD	Architectural design document	100%
D4-SDD	Software design document	100%
D5-SUM	Software user manual	75%
D6-VeTP	Verification test plan	100%
D7-VeTR	Verification test report	100%
D8-VTP	Validation test plan	100%
D9-VTR	Validation test report	80%
D11-MP	Maintenance plan	
D12-TDP	Technical data packages	
D13-ES	Executive summary	
D14-FP	Final presentation in PowerPoint	
D16-FR	Final report	
D17-ESR	Executive summary report	

Deliverables 2/2

Ref	**Description**	**Status**
SW1	Set of newly developed SPIS modules	99%
SW2	Set of modified SPIS modules	100%
SW3	New version of SPIS with newly produced and modified modules integrated	99%
SW4	SPIS computer models of Solar Orbiter and JUICE (2 configurations)	33 %
SW5	Final version of the software items	99%
SW6	Updated version of the software items	After Maintenance

User requirements - Methodology

- User requirements were gathered from various sources
  - ESA Statement of work
  - ESA extended requirements
  - Propositions based on the consortium background experience
  - Organisation of 17th SPINE meeting (Uppsala 2011)
    - Computational tools for electrostatic cleanliness and space instrument accommodation analysis
    - 20 presentations / around 50 attendees
    - inputs for validation plan too
- Outputs
  - List of effects expected on science missions instruments and associated causes (40)
  - Detailed requirements on physical models
  - Complete and not limited user requirements list
  - Priority level given to each UR by scientists of IRF and IRAP
    - 53 UR
    - 31 High priority
    - 22 Medium/Low priority

Software requirements

- ALL 53 UR transformed into 75 SRs
- Selection of the highest priority SRs
  - in agreement with ESA TO as a trade-off between SoW and collected URs
  - 45 SR finally developed

- Other UR/SR are gathered in a list for future development plan

- Blocks of SRs
  - Instruments: Particle detectors and Electric fields sensors
  - Plasma sensors
  - Semi-transparent grids
  - Environment and space charge effect
  - Particles from spacecraft
  - Fields generated by spacecraft
  - Software processing
  - Performance

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Precision

Reason of development	UR	SR	Methods developed
SPINE community required better accuracy.	ESC-001 ESC-003	ESC-002 ESC-003	Boundary conditions for particle injection and electric field
Statistical noise close to small elements	DOC-002 PE-001 PE-002	PE-002	Dynamic optimisation of injected particles
Lack of monitoring for simulation evolution	DOC-002 PE-001 PE-002	VPS-001 to 004	Live monitoring of plasma and spacecraft properties

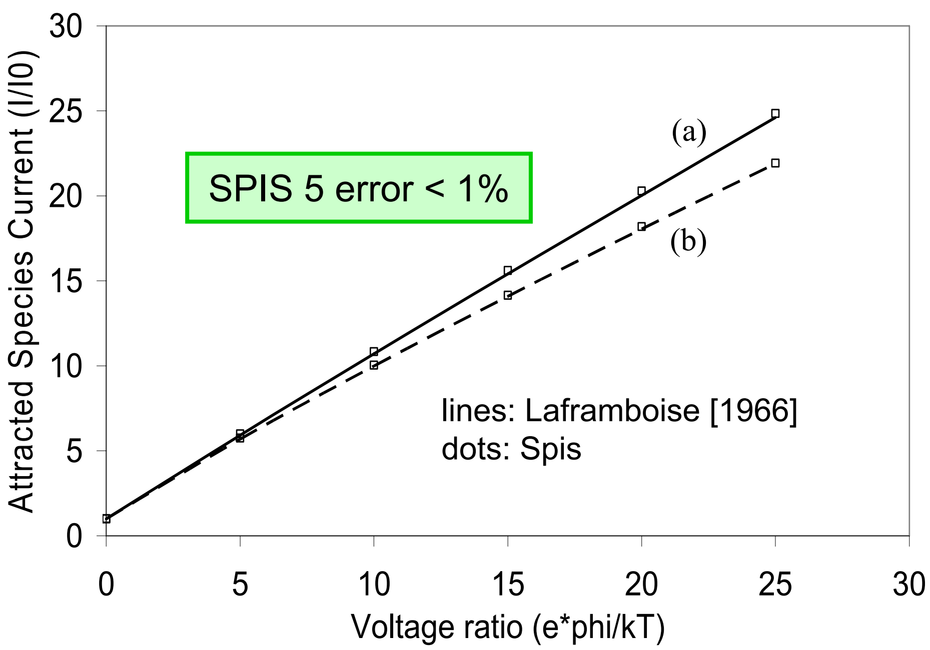
Precision

Characteristics of a spherical probe immersed in maxwellian plasma

Quantity	**Value (a)**	**Value (b)**
Temperature	0.5 eV	0.2 eV
Electron/ion density	6.91×10^{8} m^{-3}	2.763×10^{10} m^{-3}
Debye length	0.2 m	0.02 m
Potential	[0 to 12.5 V]	[0 to 5 V]
Sphere radius	0.1 m	0.02 m
Particle model	full-PIC	full-PIC
Number of tetrahedrons	127,759	56,726
Simulation box diameter	1.3 m	0.2 m
Number of macro-particles	430,000 to 1,500,000	193,000 to 650,000

SPIS 4 error ~3-5 %

SPIS 5 error < 1%

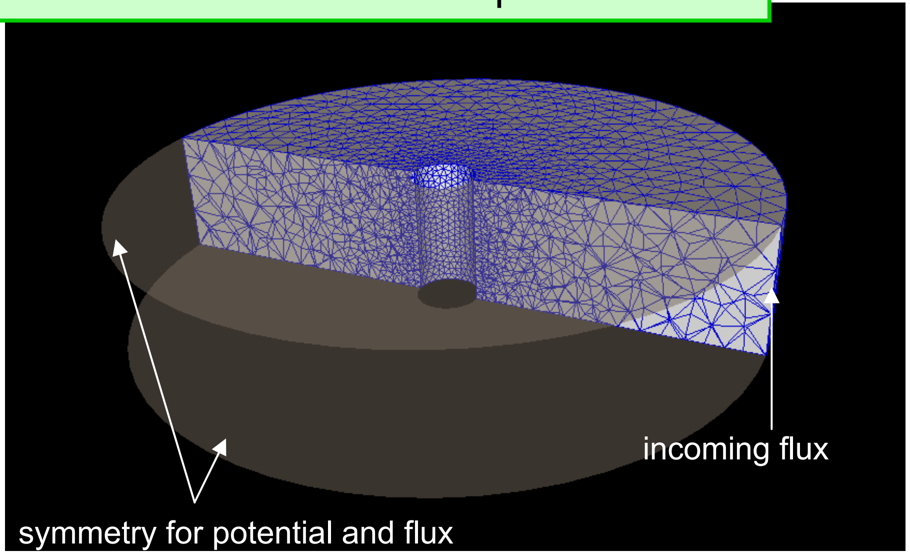


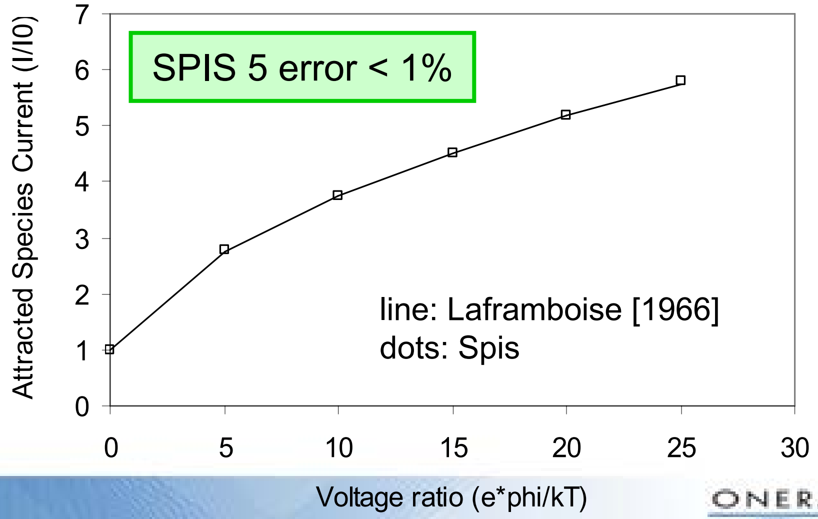
Precision

Characteristics of a cylindrical probe immersed in maxwellian plasma

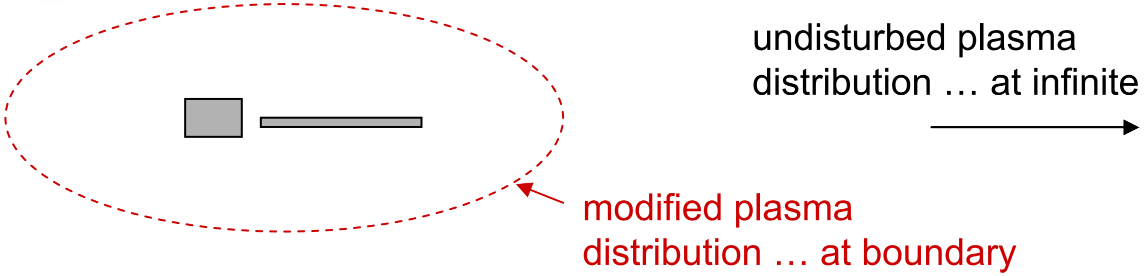
SPIS 4 error > 10 %

Quantity	Value
Temperature	0.2 eV
Electron/ion density	2.76×10^{10} m^{-3}
Debye length	0.02 m
Potential	[0-5 V]
Cylinder radius	0.02 m
Cylinder length	0.08 m
Number of tetrahedrons	45,000
Simulation box diameter	0.4 m
Number of macro-particles	460,000





Precision



undisturbed plasma
distribution … at infinite

modified plasma
distribution … at boundary

Upgrade of
Matter Boundary Conditions using
Liouville's theorem

Flux of a repulsed
maxwellian distribution

$$F_{repulsed} = n_0 \sqrt{\frac{eT}{2\pi m}} \times \exp(\chi)$$

$$\text{with } \chi = -\frac{q}{e}\frac{V}{T}$$

Flux and distribution of an attracted
maxwellian distribution in 2D

$$F_{OML,2D} = \frac{2}{\sqrt{\pi}} \times n_0 \sqrt{\frac{eT}{2\pi m}} \times \left[\sqrt{\chi} + \frac{\sqrt{\pi}}{2} \exp(\chi)\, \mathrm{erfc}\left(\sqrt{\chi}\right) \right]$$

$$f(\mathrm{v}_r, \theta, \mathrm{v}_z).dv_T = \begin{cases} \frac{m\mathrm{v}_r^{\,2}}{2eT} > \chi, & n_0 \exp(\chi) \times \left(\frac{m}{2\pi eT}\right)^{3/2} \mathrm{v}_r \\ & \times \exp\left(-\frac{m\left(\mathrm{v}_r^{\,2} + \mathrm{v}_z^{\,2}\right)}{2eT}\right) d\mathrm{v}_r\, d\theta\, d\mathrm{v}_z \\ \frac{m\mathrm{v}_r^{\,2}}{2eT} < \chi, & 0 \end{cases}$$

Flux and distribution of an attracted
maxwellian distribution in 3D

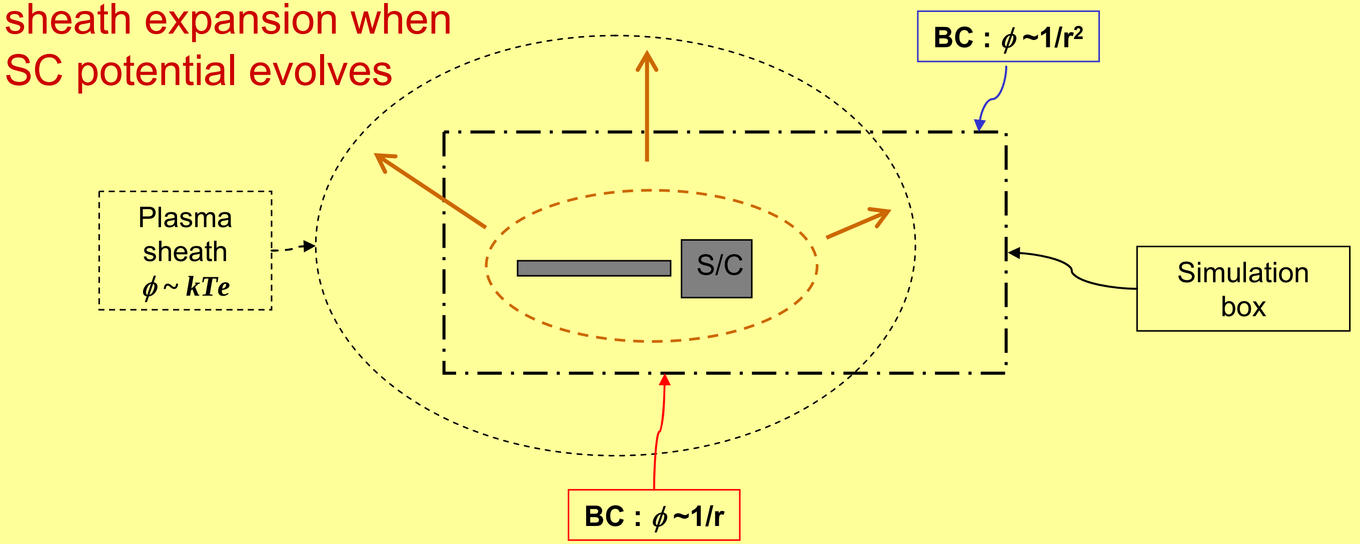
$$F_{OML,3D} = n_0 \sqrt{\frac{eT}{2\pi m}} \times [1 + \chi]$$

$$f(\mathrm{v}).dv_T = \begin{cases} \frac{m\mathrm{v}^2}{2eT} > \chi, & n_0 \times 4\pi \exp(\chi) \times \left(\frac{m}{2\pi eT}\right)^{3/2} \mathrm{v}^2 \\ & \times \exp\left(-\frac{m\left(\mathrm{v}^2\right)}{2eT}\right) d\mathrm{v} \\ \frac{m\mathrm{v}^2}{2eT} < \chi, & 0 \end{cases}$$

Precision

Methods developed – Electric Field Boundary Conditions

Automatic change of BC during plasma sheath extension



sheath expansion when
SC potential evolves

Plasma
sheath
$\phi \sim kTe$

S/C

BC : ϕ~1/r²

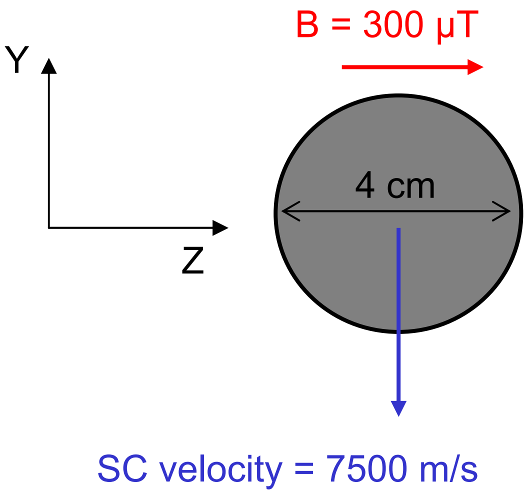
Simulation
box

BC : ϕ~1/r

Precision

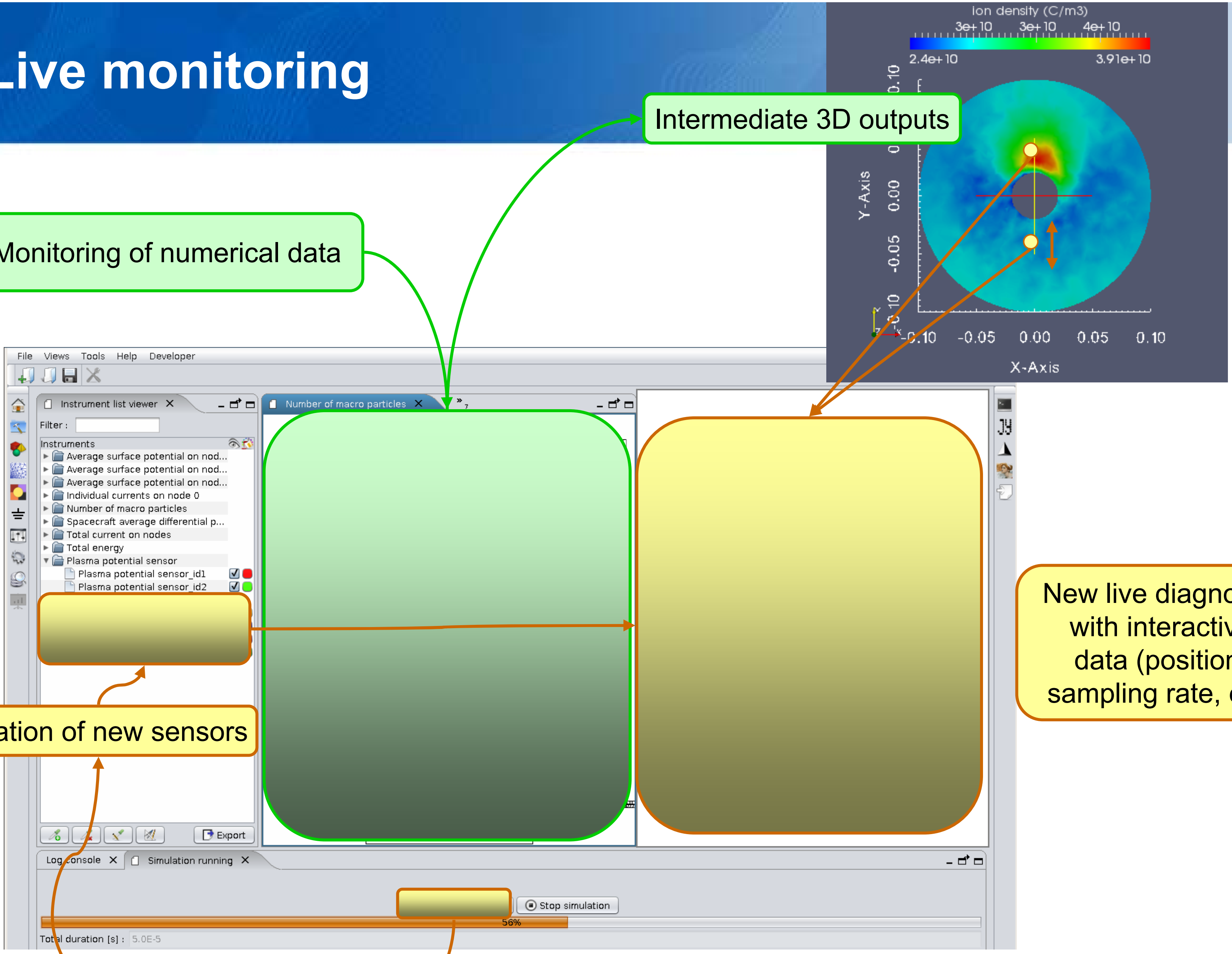
- Illustrative example = **Motional Sphere in magnetized plasma**

Reason of development	UR	SR	Methods developed
Motional electric field (Vcross B) can produce 10s of volts	FGS-004	FGS-003	Apply a new boundary condition Modify particle pusher



Quantity	Value
Temperature	0.2 eV
Electron/ion density	2,8×10^{10} #/m^3
Debye length	0.02 m
Sphere radius R	0.02 m
Number of tetrahedrons	~40,000
Simulation box diameter	0.20 m
Number of macro-particles	~500,000
Bz	3×10^{-4} T
Electron Gyro Radius / R	0.18
Ion Gyro Radius / R	7.6
Spacecraft velocity Vy	- 7500 m/s

Live monitoring



Intermediate 3D outputs

Live Monitoring of numerical data

New live diagnostic with interactive data (position, sampling rate, etc)

Creation of new sensors

Pause simulation
(SR-SP-014)

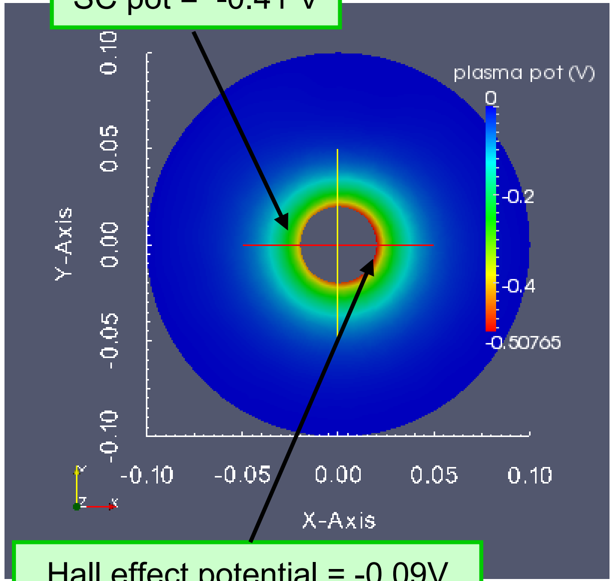
Results accuracy level estimation

Default Live Monitoring

Interactive live monitoring

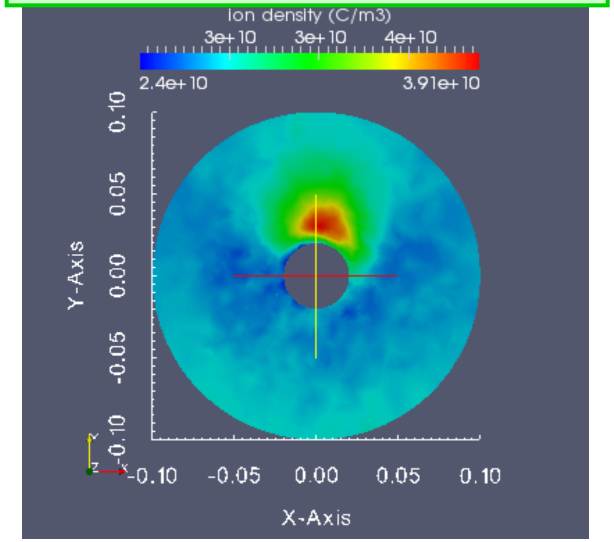
Results

SC pot = -0.41 V

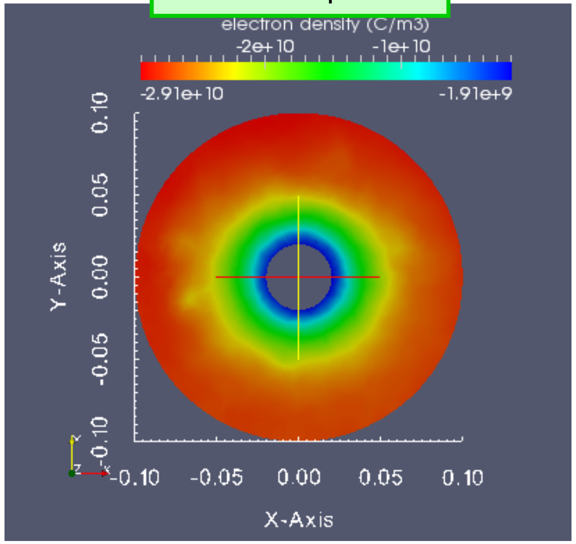


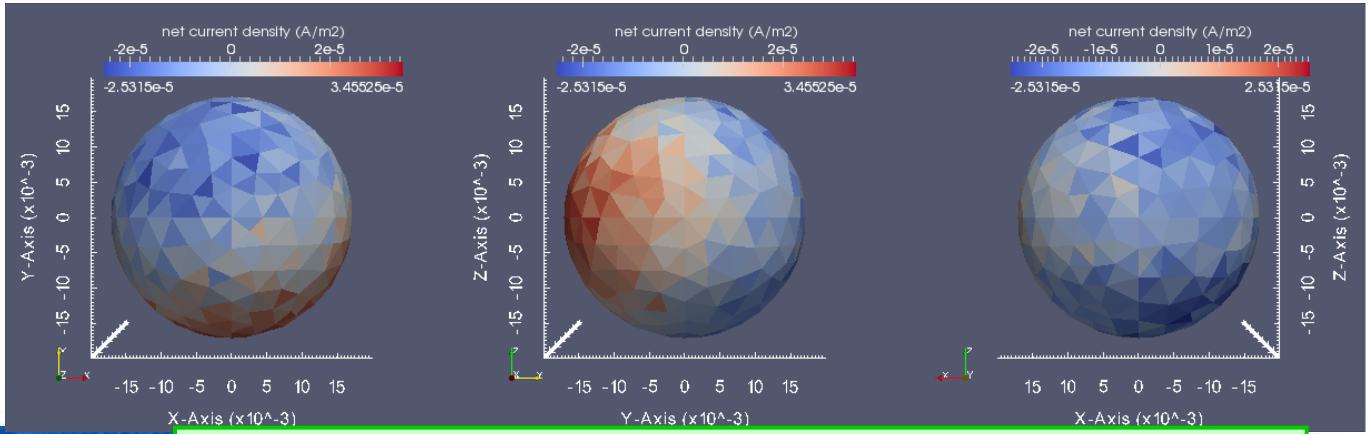
Hall effect potential = -0.09V
→ Min = -0.5 V in +X direction

Asymmetrical ion deflection by VcrossB



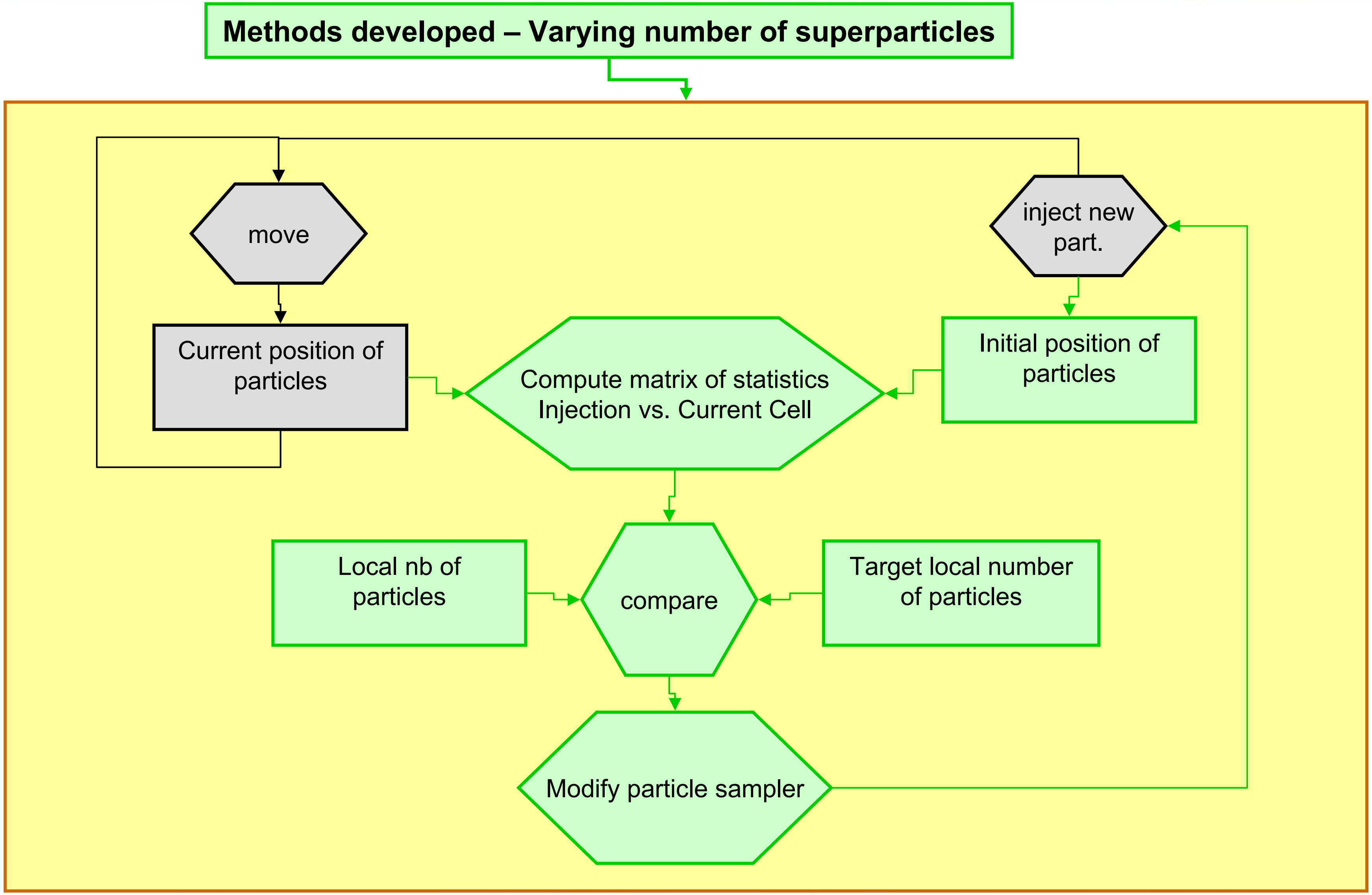
Electron repulsion





Complex net current in agreement with previous publication (Marchand 2012)

Precision


Methods developed – Varying number of superparticles

move

inject new part.

Current position of particles

Compute matrix of statistics Injection vs. Current Cell

Initial position of particles

Local nb of particles

compare

Target local number of particles

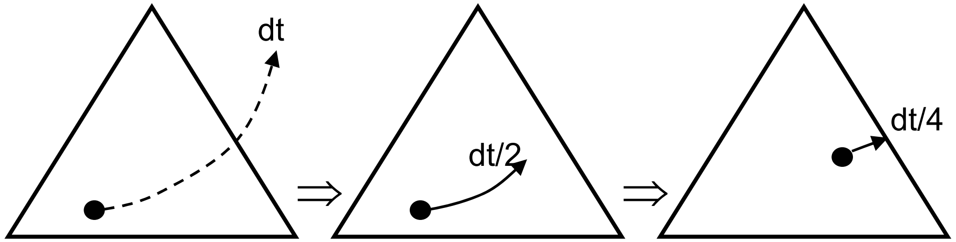
Modify particle sampler

Performance

Reason of development	UR	SR	Methods developed
Fast run speed for large number of particles	DOC-002 PE-001 PE-002	PE-004	Multi-threading of particle pusher
Fast run speed for large number of spacecraft dielectric surfaces	none	none	Iterative circuit solver
Large computation time when using magnetic field	ESC-002 ESC-003	ESC-004	Iterative dichotomy method for particle pusher

Dichotomy-like method for pusher

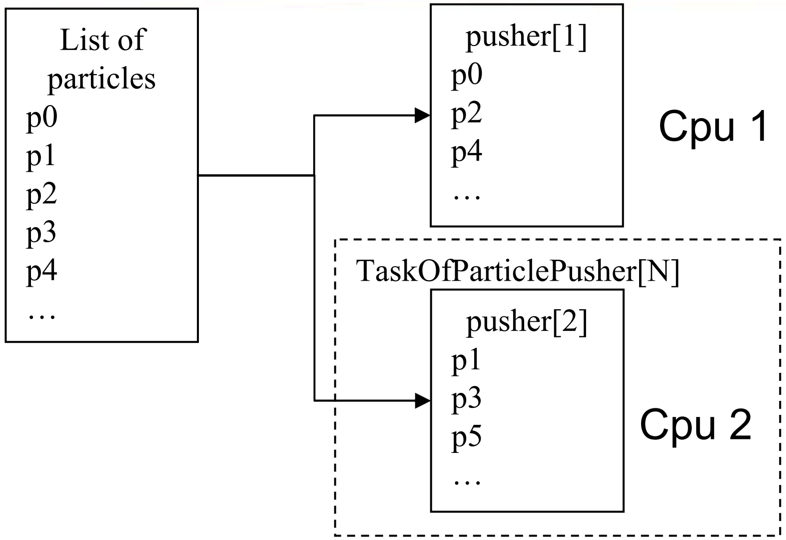
- Previous version of SPIS used the Runge-Kutta Cash-Karpe fifth order scheme to solve particle dynalmics in magnetic field
- The new method permits gains up to 10 or 100 pending on the cases tested so far
  - Analytical trajectory when uniform E-field
  - But : interception with surface not analytical
  - Dichotomy-method:
    - initial dt = Min(CFL / gyrofrequency / Efield acceleration)
    - Move particle
    - If out of the cell and far outside → go back and reduce dt
    - Exit = outside and very close to surface



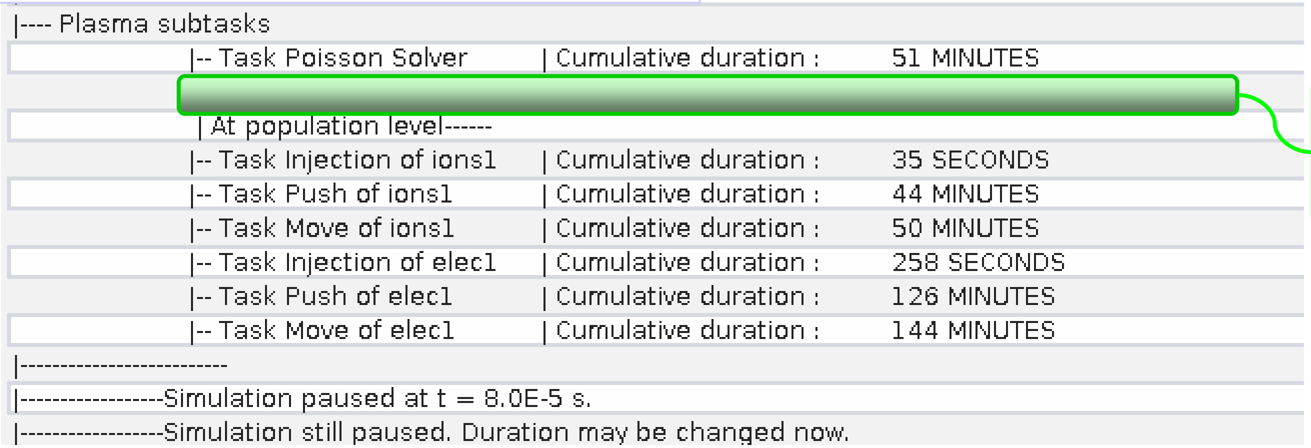
    - Tolerance level is 1 to 3 order of magnitude less constraining than previous solver
    - Also developed for collection by thin wires

Multi-threading

- Particle pusher is often very costly
- Multi-threading of java is used



Precise monitoring computational times



```
|---- Plasma subtasks
            |-- Task Poisson Solver     | Cumulative duration :    51 MINUTES

             | At population level------
            |-- Task Injection of ions1 | Cumulative duration :    35 SECONDS
            |-- Task Push of ions1      | Cumulative duration :    44 MINUTES
            |-- Task Move of ions1      | Cumulative duration :    50 MINUTES
            |-- Task Injection of elec1 | Cumulative duration :    258 SECONDS
            |-- Task Push of elec1      | Cumulative duration :    126 MINUTES
            |-- Task Move of elec1      | Cumulative duration :    144 MINUTES
|-------------------------
|------------------Simulation paused at t = 8.0E-5 s.
|------------------Simulation still paused. Duration may be changed now.
```

VcrossB case
~ 3 hours on 8 threads
8 millions of particles
Bfield
duration = 80 µs / dt = 50 ns

User-defined distributions and SC interactions

Reason of development	UR	SR	Methods developed
Detailed characteristics of charged particle environment	ESC-001		User defined distributions for ambient
Energy spectrum of secondaries (including photons)	PS-001 PS-002 PS-013	PS-001 PS-002 PS-008	Double maxwellian distribution (photoelectron) Isotropic (non-maxwellian) distributions User-defined distributions
SEEE yield model is not always adapted to ground measurements	PS-010 PS-011 PS-012	PS-10	User-defined yield as a function of energy and incidence angle

User-defined distributions

SPIS 4 : double maxwellian for ambient ions and electrons

→ TabulatedDistributionFunction (mode 1)

```
# X tab (table of X values)
-200000.0
-100000.0
0.0
200000.0
400000.0
# Y tab (table of Y values)
-5.0e+4
-2.5e+4
-1.0e+4
0.0
1.0e+4
1.5e+5
3.0e+5
# Z tab (table of Z values)
-8e+4
-4e+4
0.0
1.0e+5
1.5e+5
# X = -2000.0
0.0          0.0          0.0          0.0          0.0
0.0          0.0          0.0          0.0          0.0
0.0          0.0          0.0          0.0          0.0
0.0          0.0          0.0          0.0          0.0
0.0          0.0          0.0          0.0          0.0
0.0          0.0          0.0          0.0          0.0
0.0          0.0          0.0          0.0          0.0
# X = -1000.0
0.0          0.0          0.0          0.0          0.0
0.0          0.9          0.9          0.9          0.0
0.0          0.9          0.9          0.9          0.0
0.0          0.9          0.9          0.9          0.0
0.0          0.9          0.9          0.9          0.0
0.0          0.9          0.9          0.9          0.0
0.0          0.0          0.0          0.0          0.0
# X = 0.0
…
```

ASCII file type 1 (structured)

SPIS 5
=
SPIS 4
+
Unlimited number of ambient populations with distributions functions defined by user with own reference basis

→ TabulatedDistributionFunction (mode 2)

```
# vx        vy          vy          f           dvx         dvy         dvz         df/dvx      df/dvy

-100.0      -10.0       -10.0       1.0         90.0        10.0        10.0        0.0         0.0         0.0
-100.0      -10.0       10.0        1.0         90.0        10.0        -10.0       0.0         0.0         0.0
-100.0      10.0        -10.0       1.0         90.0        -10.0       10.0        0.0         0.0         0.0
-100.0      10.0        10.0        1.0         90.0        -10.0       -10.0       0.0         0.0         0.0
-10.0       -10.0       -10.0       1.0         10.0        10.0        10.0        0.0         0.0         0.0
-10.0       -10.0       10.0        1.0         10.0        10.0        -10.0       0.0         0.0         0.0
-10.0       10.0        -10.0       1.0         10.0        -10.0       10.0        0.0         0.0         0.0
-10.0       10.0        10.0        1.0         10.0        -10.0       -10.0       0.0         0.0         0.0
0.0         -10.0       -10.0       1.0         2.0         10.0        10.0        0.0         0.0         0.0
0.0         -10.0       10.0        1.0         2.0         10.0        -10.0       0.0         0.0         0.0
0.0         10.0        -10.0       1.0         2.0         -10.0       10.0        0.0         0.0         0.0
0.0         10.0        10.0        1.0         2.0         -10.0       -10.0       0.0         0.0         0.0
2.0         -10.0       -10.0       1.0         10.0                                            0.0         0.0
2.0         -10.0       10.0        1.0         10.0                                            0.0         0.0
2.0         10.0        -10.0       1.0         10.0                                            0.0         0.0
2.0         10.0        10.0        1.0         10.0                                            0.0         0.0
…
```

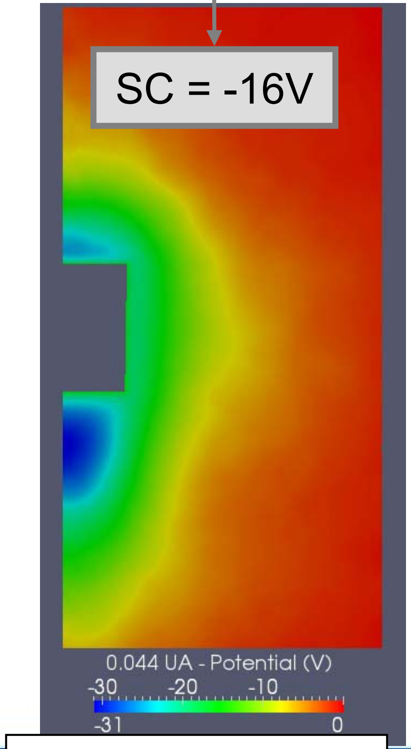
ASCII file type 2 (unstructured)

Also in SPIS 5:

Isotropic tabulated distributions for ambient and secondaries
+
Kappa and Maxwellian distribution
+
Add of a drift

User-defined distributions

Cylindrical SC @ 0.044 AU from the Sun
Plasma maxwellian 7e9 m-3 / 80 eV / 300 km/s
Photoelectron DF: Maxwellian at 2 eV

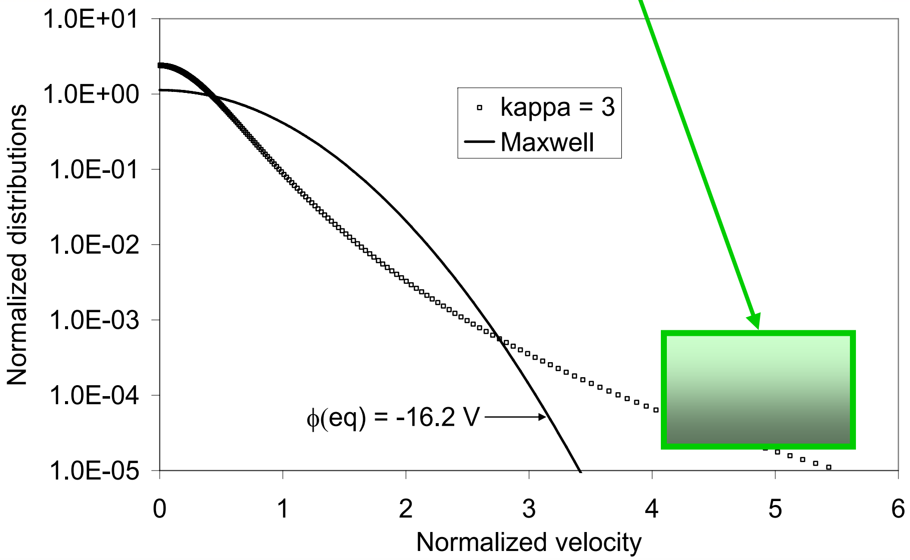


S. Guillemant [2012]

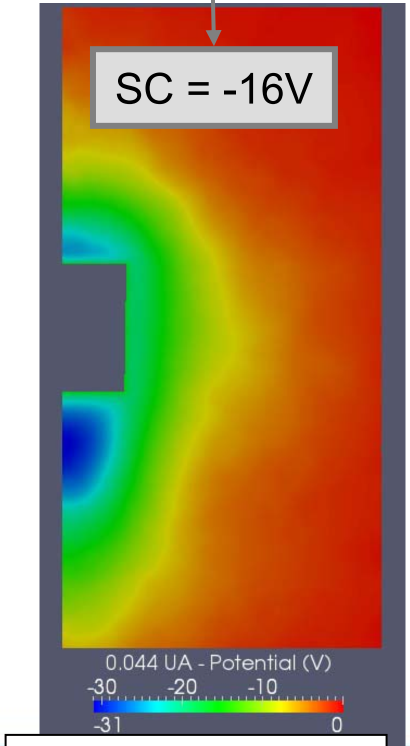
User-defined distri

Kappa distribution used in validation campaign on Solar Orbiter case

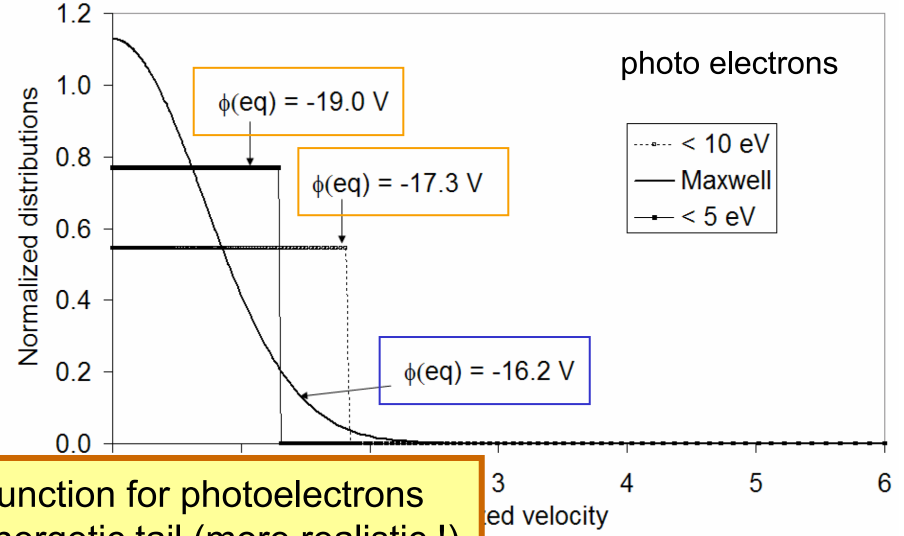
Kappa DF for ambient electrons
- k = 3: energetic tail
- SC more negative



Cylindrical SC @ 0.044 AU from the Sun
Maxwellian plasma 7e9 m-3 / 80 eV / 300 km/s
Photoelectron DF: Maxwellian at 2 eV



SC = -16V



ϕ(eq) = -19.0 V

ϕ(eq) = -17.3 V

ϕ(eq) = -16.2 V

Heavyside function for photoelectrons
- no energetic tail (more realistic !)
- SC more negative

S. Guillemant [2012]

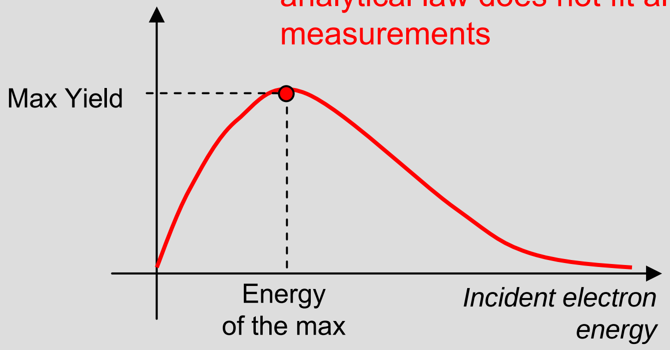
User-defined SEEE yield

SPIS 4 model of Secondary electron emission under electron impact

Distributions functions

True secondaries: Maxwellian
Backscattered : 2/3 of initial energy

true SEEE yield



analytical law does not fit all measurements

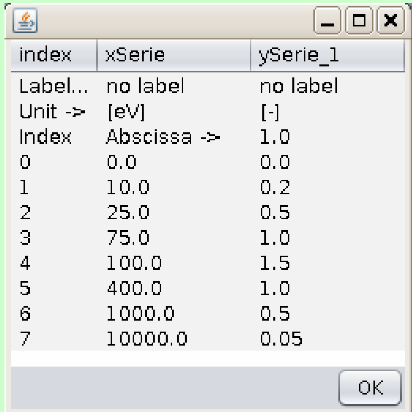
+ cos(θ) law not adapted to grazing incidence

User-defined SEEE yield

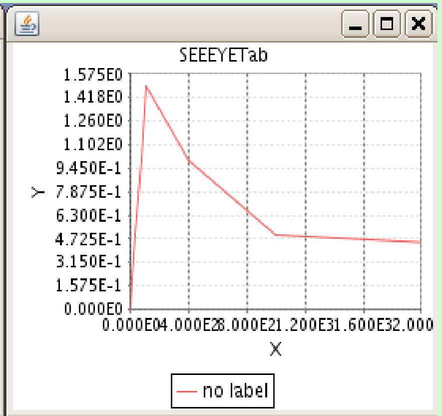
SPIS 5

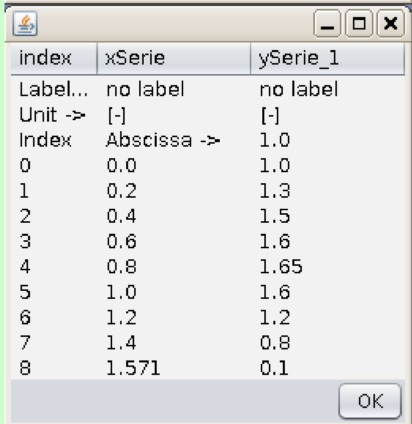
Isotropic distributions
defined by user
for true secondaries (ASCII tables or analytical)

Tabulated material property
→ true and backscattered
→ yield = yield (E)
→ relYield = relYield(theta)

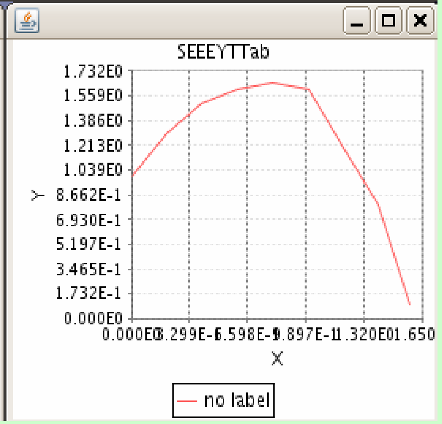


index	xSerie	ySerie_1
Label...	no label	no label
Unit ->	[eV]	[-]
Index	Abscissa ->	1.0
0	0.0	0.0
1	10.0	0.2
2	25.0	0.5
3	75.0	1.0
4	100.0	1.5
5	400.0	1.0
6	1000.0	0.5
7	10000.0	0.05





index	xSerie	ySerie_1
Label...	no label	no label
Unit ->	[-]	[-]
Index	Abscissa ->	1.0
0	0.0	1.0
1	0.2	1.3
2	0.4	1.5
3	0.6	1.6
4	0.8	1.65
5	1.0	1.6
6	1.2	1.2
7	1.4	0.8
8	1.571	0.1



Transitions

Reason of development	UR	SR	Methods developed
Transient effects due to : • spinning spacecraft • artificial sources activation • IV sweeps	SP-003 PS-018 PPD-004 PPD-005	SP-003-006 SP-008-011	Dynamic change of • sun flux, population distribution basis, magnetic field, VcrossB field • source flux • bias potentials

Transitions

Spinning spacecraft

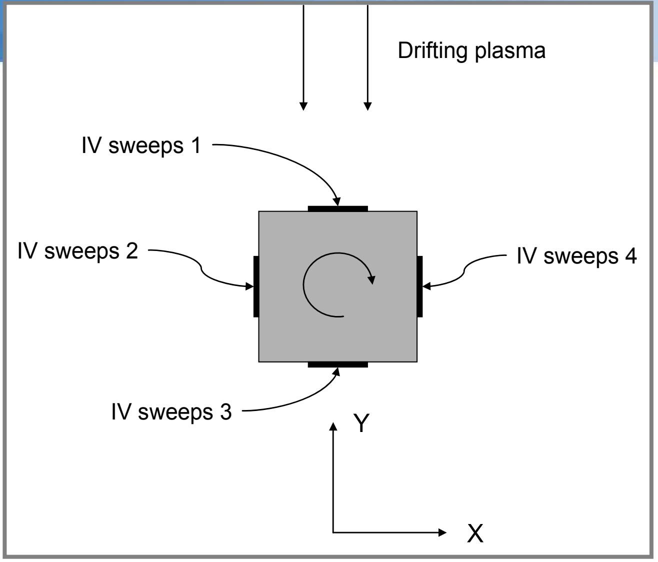
Transition class	Action	Updater classes used	ASCII file name	ASCII file column 1
SpinningSpacecraft	Rotates progressively the ambient particle injection basis, sun flux, B and V cross B field	*SunFluxUpdater* *VcrossBfieldUpdater*	SpinningSpacecraft.txt	X-coord of spin axis Y-coord of spin axis Z-coord of spin axis SC Ang. vel. (rad/s) Check time period (s)

Voltage sweep

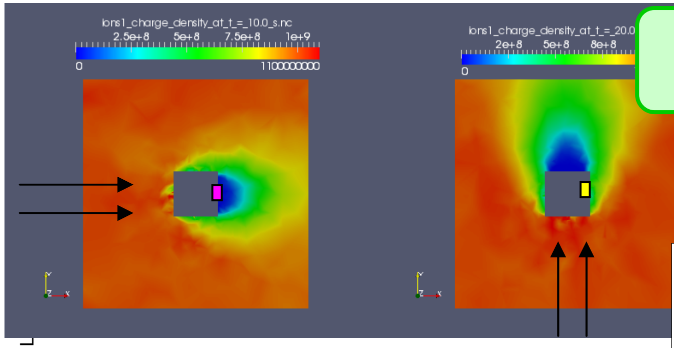
Transition class	Action	Instrument
LangmuirProbeTransition	Perform potential sweep	LangmuirProbe

Very precise algorithm
See particle detectors

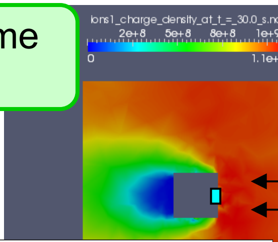
Illustration of spinning spacecraft with LP

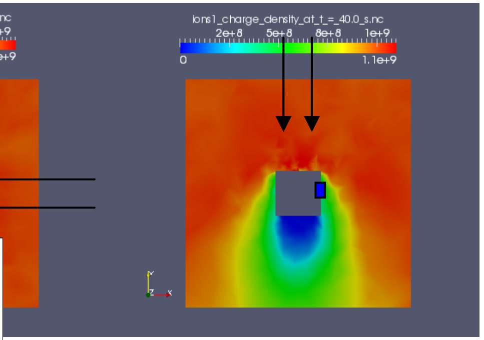


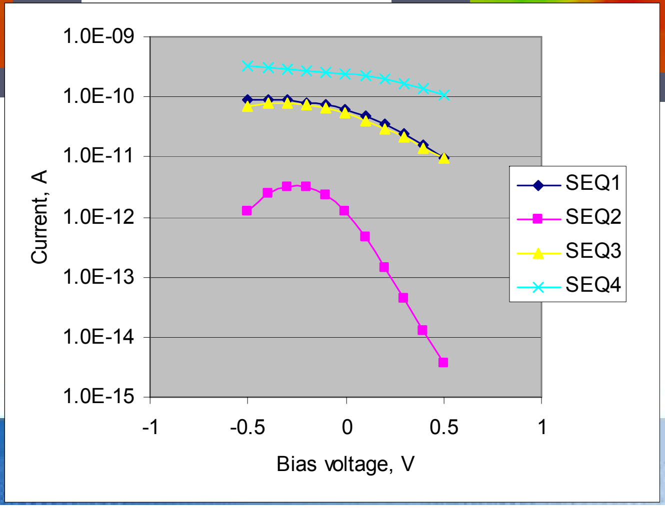
Cubic SC at 0 Volt
Spin of ¼ rotation each 10 seconds around Z
Maxwellian plasma 1e9 m-3 / 0.1 eV / 7 km/s
4 Langmuir probes (20 steps, -0.5 / + 0.5 V, 10 s)



Immobil spacecraft frame
→ rotating ion







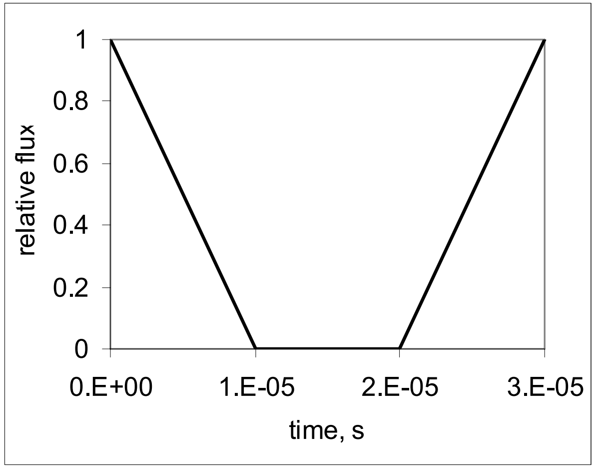
Particle instruments algorithm
→ 5 orders of magnitudes
→ very precise: low noise !

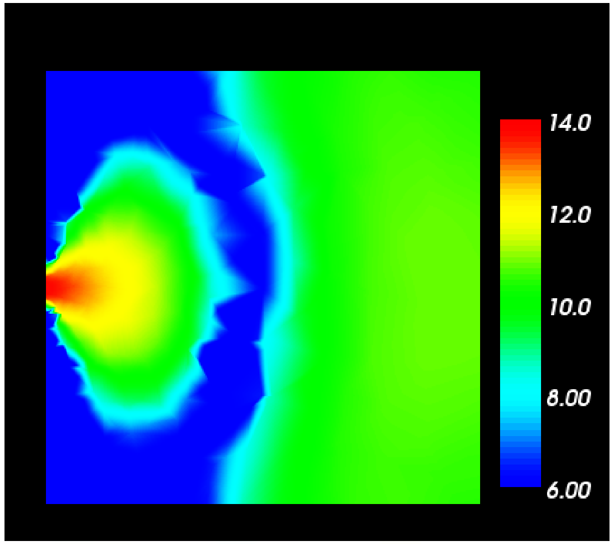
LP used in Validation campaign on Cassini and Cluster cases

Transient sources

- Useful to simulate
  - Thruster activation / deactivation
  - Plasma generation by dust impact / ESD …

Transition class	Action	ASCII file name	ASCII file column 1	ASCII file column 2
TransientArtificialSources	modifies the flux of a source	TransientArtificialSourceX.txt where X is the Id of source	time (Unit: [s])	relative source flux wrt to initial definition [-]





Outline

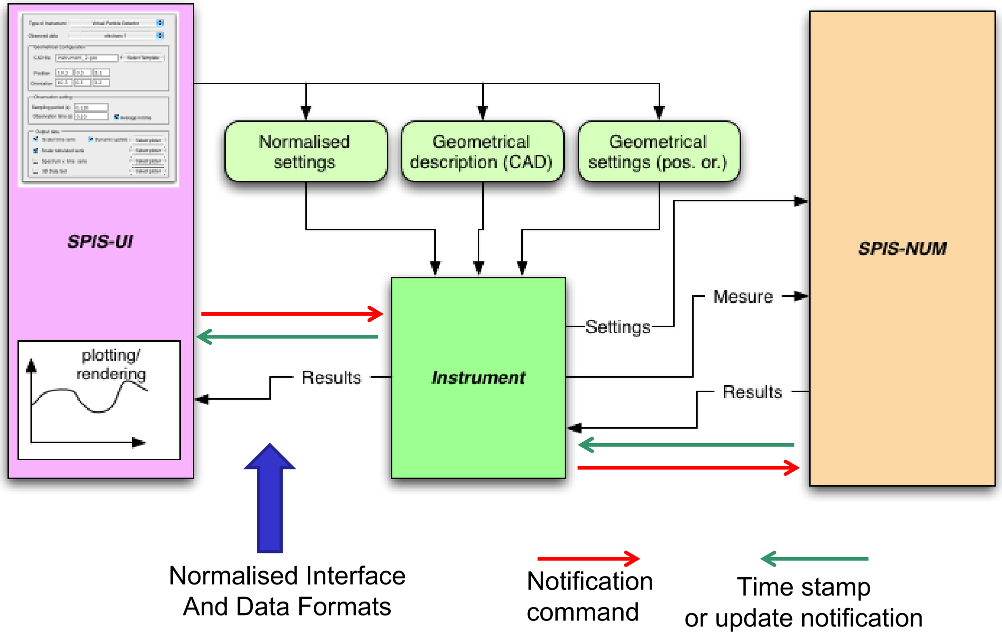
- Team and work breakdown structure
- User requirements
- SPIS-SCI evolution
  - Precision
  - Performance
  - User-defined ambient plasma and spacecraft interactions
  - Pre-defined transient phases
  - Instruments
    - How to mimic scientific particle detectors, Langmuir probes, electric field analyzers
    - Illustrative example of application to Solar Orbiter
  - Unmeshed elements
- Validation campaign
  - Solar Orbiter
  - Cassini
  - Cluster
- Conclusion and perspectives

Instrument Interface

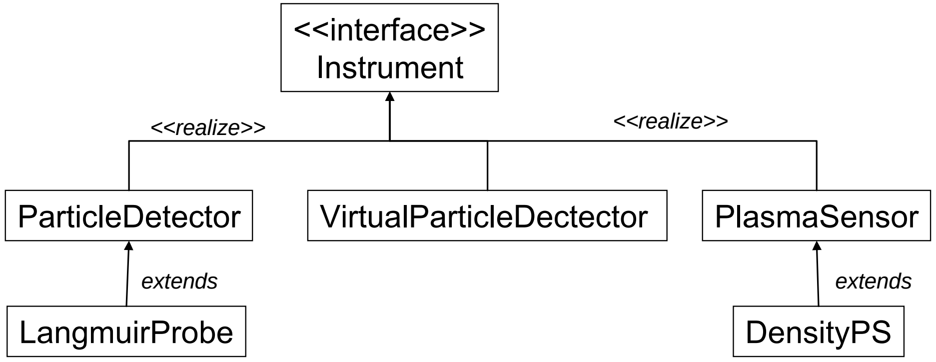
Reason of development	UR	SR	Methods developed
User-Friendly GUI for instruments mimicking real or virtual instruments	PPD-001 PPD-002	PD-001 PPS-001	Common interface for all the instruments, automatic adaptation of mandatory parameters
Performant and securized collaboration between UI and NUM	PPD-001 PPD-002	PD-001 PPS-001	Observer/Observable patern for the instrument interface
Visualize and update the results at the user demand	PPD-001 PPD-002	PD-001 PD-011 PD-012 PD-013 PD-014 PPS-001 PPS-003	Dedicated GUI panels automatically adapted to the intrument outputs (time series, spectrum, Data Fileds, …)

Instrument Interface – Global architecture

- Observer/Observable pattern
  - Observable is the simulation
  - Observers are the instruments attached to the simulation
- Instanciated by SPIS-UI (mandatory parameteds, instrument support virtual or on SC)
- Two modes of execution:
  - On user demand, from the modeling framework, for a punctual and specific observation
  - On the basis of regular observations using a sample frequency defined at the framework level
- Specific outputs depending of the instrument type
- Instrument objects are shared by UI and NUM

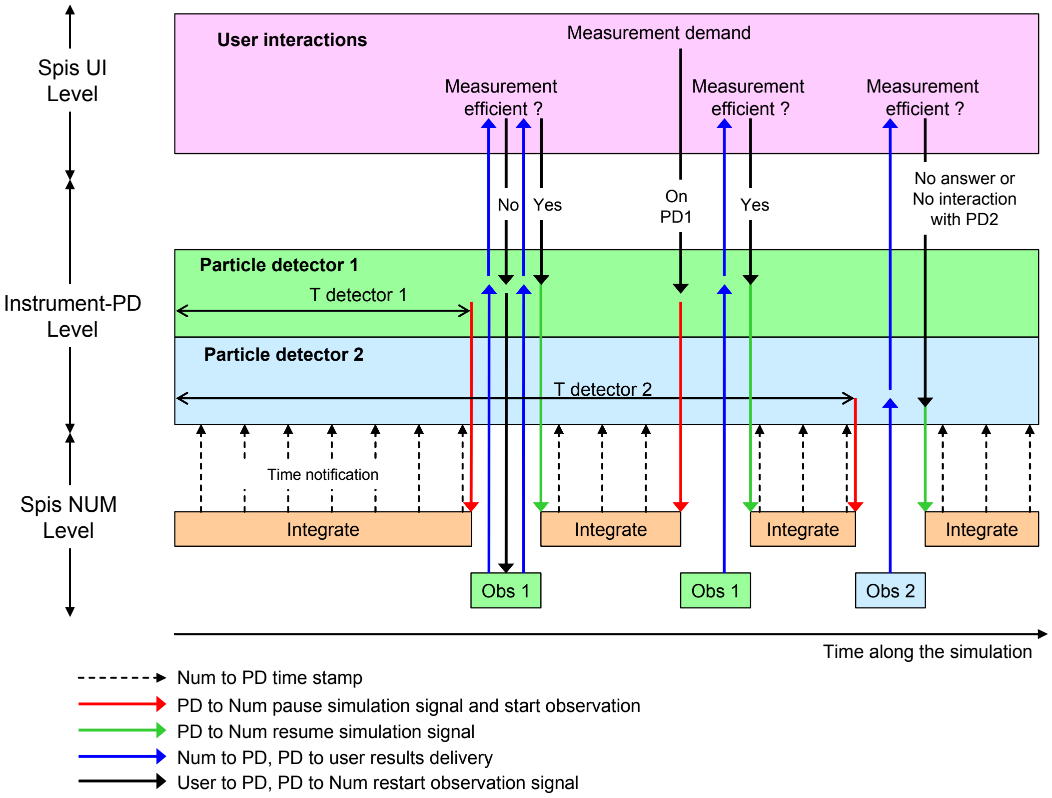


- Java OO common interface for all the instruments
  - Implements the <<Instrument>> interface
  - Instrument factory →list of instrument available
- Instrument categories:
  - Particle detector: ParticleDetector and LangmuirProbe
  - Virtual instrument: VirtualParticleDetector
  - Plasma sensor: SCMonitors, PointPS (DensityPS, PotentialPS, etc…), LinePS (PotentialLPS) and SphericalPS (EnergyDistFunctionPS, etc…)

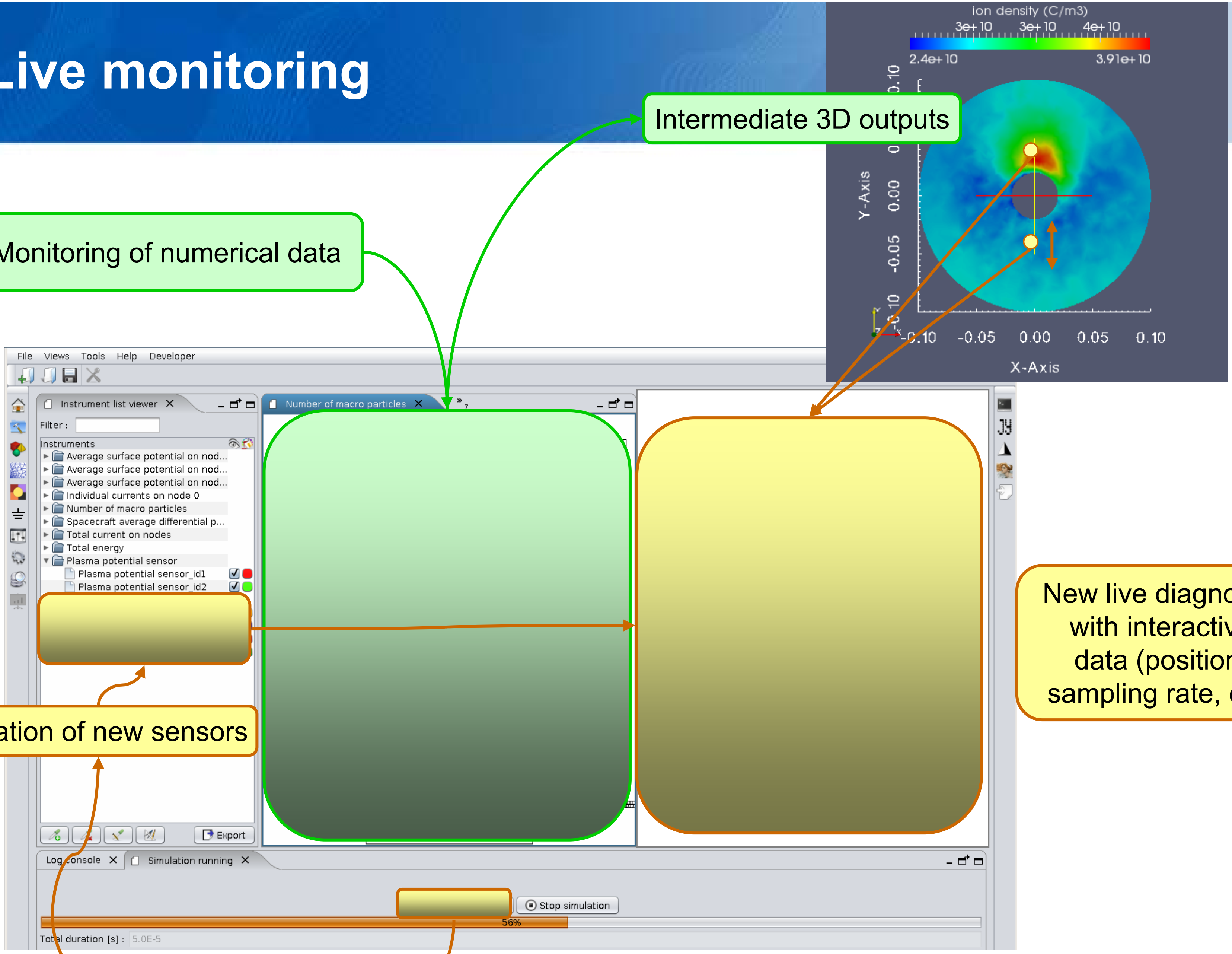


Instrument Interface – UI/NUM collaboration

SPIS-UI →	- builds the simulation (as usual) - convert the simulation from UI to NUM - instantiate instruments using the minimal constructor
SPIS-NUM →	- informs UI of the possibilities offered in term of instrument input parameters
SPIS-UI →	- invites the user to set the mandatory parameters - call the initialize method at NUM level using the data from the user at GUI level
SPIS-NUM →	- initialize the instrument - informs UI of possible invalid instrument parameter (InvalidInstrumentException is thrown)
SPIS-UI →	- asks the user to change parameters if necessary - adds the instruments to the numerical simulation core - start the numerical integration
SPIS-NUM →	- run the simulation including, - perform the pre-defined or user requested prompt measurements
SPIS-UI →	- monitors the results in different panels - gets user notifications of instrument modification (performMeasure) - updates the characteristics of the instrument



Live monitoring



Intermediate 3D outputs

Live Monitoring of numerical data

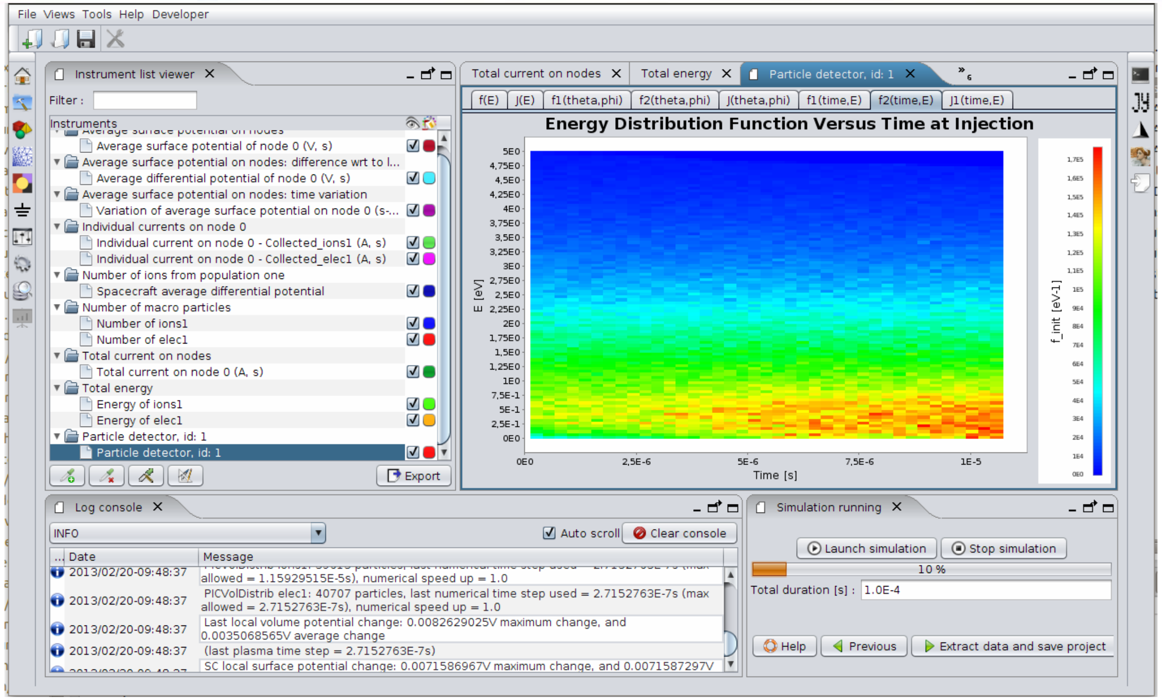
New live diagnostic with interactive data (position, sampling rate, etc)

Creation of new sensors

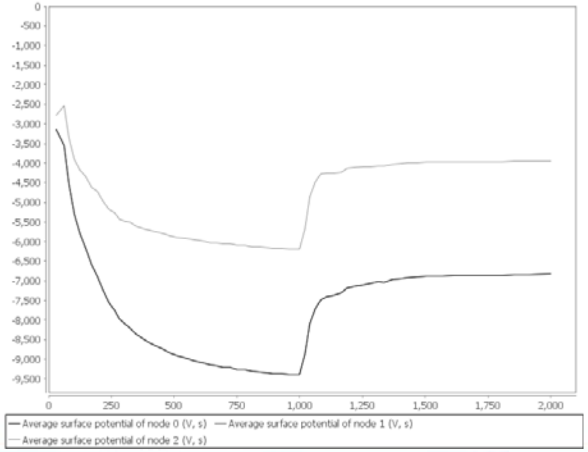
Pause simulation
(SR-SP-014)

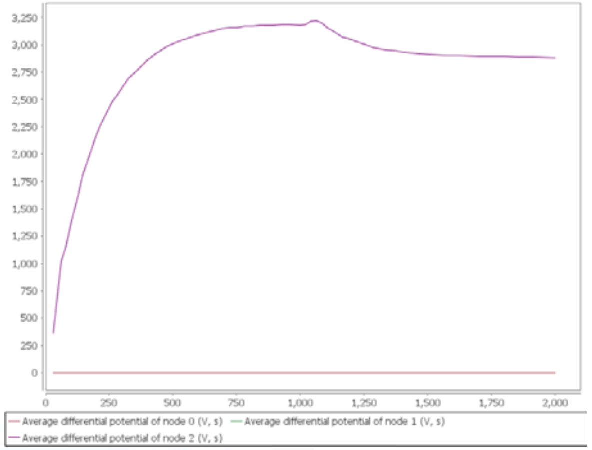
Instrument Interface – Specific outputs

- Results are specific to the instrument class
- Time series (potential, density, number of particles, etc … as a function of time)
- 2D plots (distribution function for one energy as a function of azimut and elevation, etc…)
- Spectrometer (distribution function in energy evolution as a function of time)
- ASCII files
- Datafields (current collection on PD or origin of current collected)



```
2013/02/20-09:48:37  PICVolDistrib ions1: ... particles, last numerical time step used = 2.7152763E-7s (max
                     allowed = 1.15929515E-5s), numerical speed up = 1.0
2013/02/20-09:48:37  PICVolDistrib elec1: 40707 particles, last numerical time step used = 2.7152763E-7s (max
                     allowed = 2.7152763E-7s), numerical speed up = 1.0
2013/02/20-09:48:37  Last local volume potential change: 0.0082629025V maximum change, and
                     0.0035068565V average change
2013/02/20-09:48:37  (last plasma time step = 2.7152763E-7s)
                     SC local surface potential change: 0.0071586967V maximum change, and 0.0071587297V
```





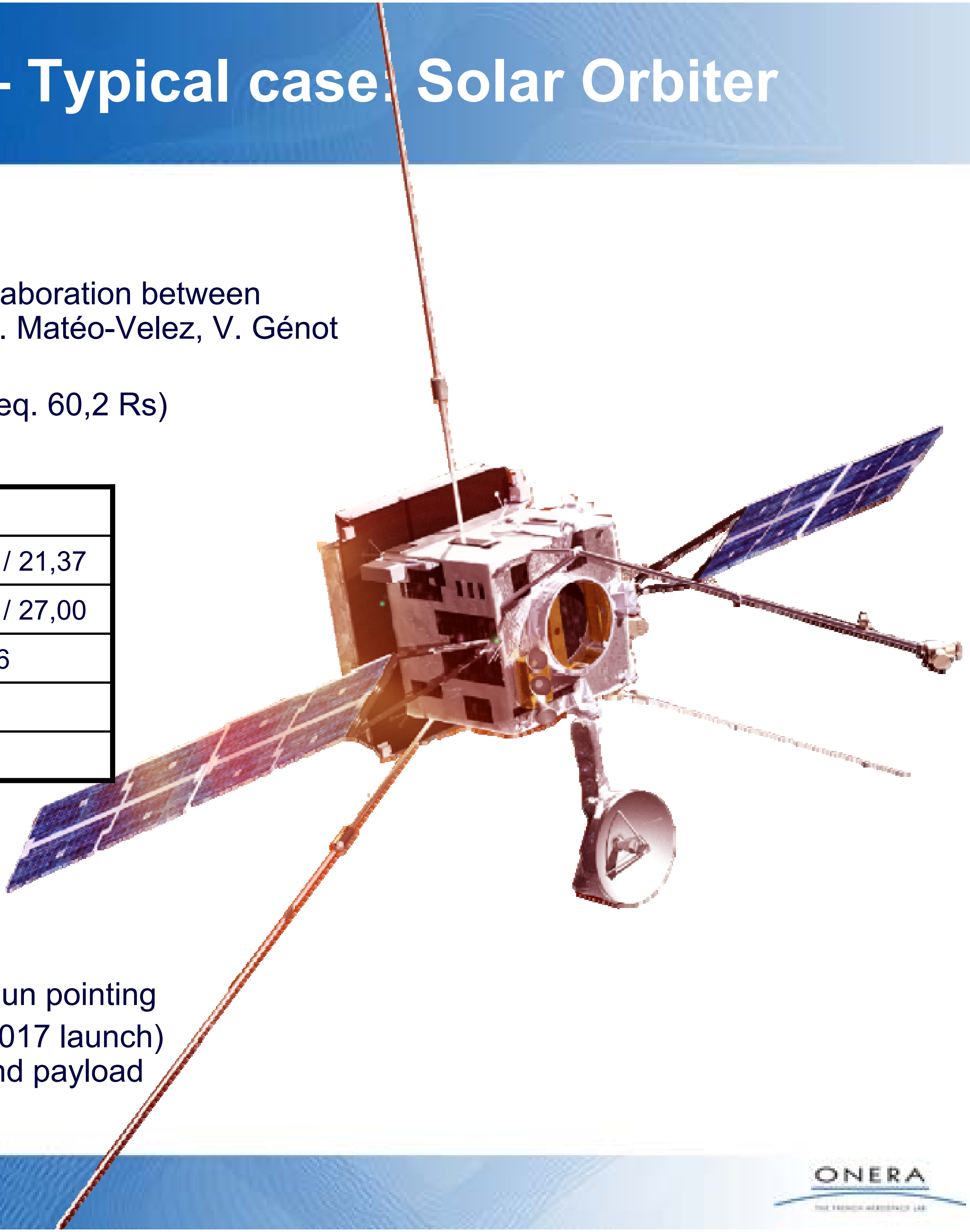
Particle Detectors

Reason of development	UR	SR	Methods developed
Simulate a particle detector measurement in SPIS	PPD-001 PPD-002	PD-002 PD-011 PD-012 PD-013 PD-014	GUI for intrument with all the input parameters and the outputs vizualization
Control the statistical noise of PD results such as current or 3V distribution function	PPD-001 PPD-002	PD-010	Test particle in backtracking using an OcTree algorithm for adapting the 3V DF refinement
Change PD detector parameters during simulation	PPD-001 PPD-002	PD-001	User interactive modes available for PD

Particle Detectors – Typical case: Solar Orbiter

- Validation case:
  - SPIS simulations performed in collaboration between ONERA/IRAP (S. Guillemant, J.-C. Matéo-Velez, V. Génot and P. Sarrailh)
  - Solar wind conditions at 0.28 AU (eq. 60,2 Rs)

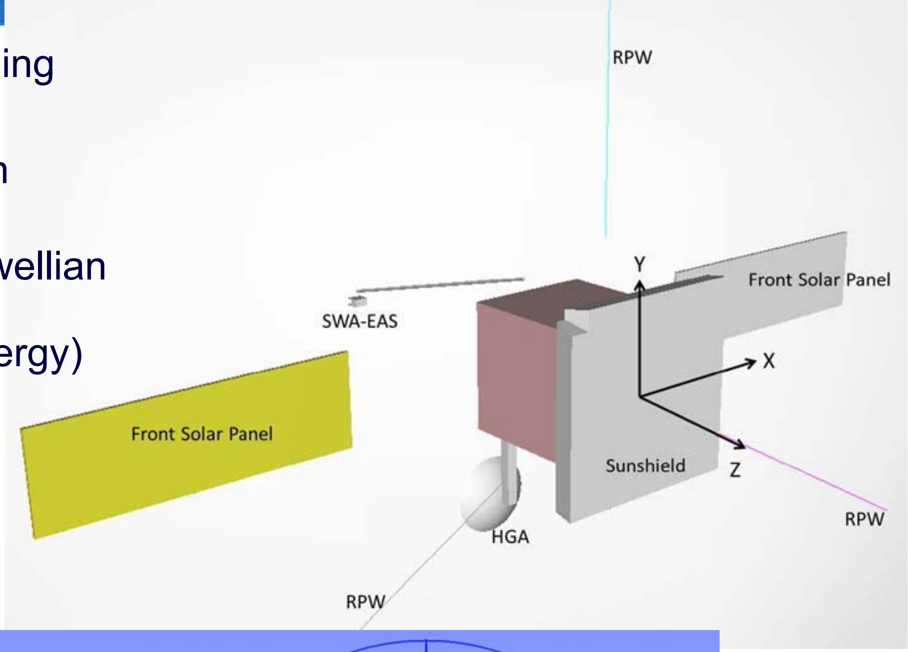
Sun Flux (#1AU)	12,76
Electrons Ne (m-3) / Te (eV)	$1,04 \times 10^8$ / 21,37
Ions H+ Ni (m-3) / Ti (eV)	$1,04 \times 10^8$ / 27,00
Vz ram H+ (km/s) / Mach Number	400 / 7,86
Debye length (m)	3,38
Debye length photoelec (m)	0,27

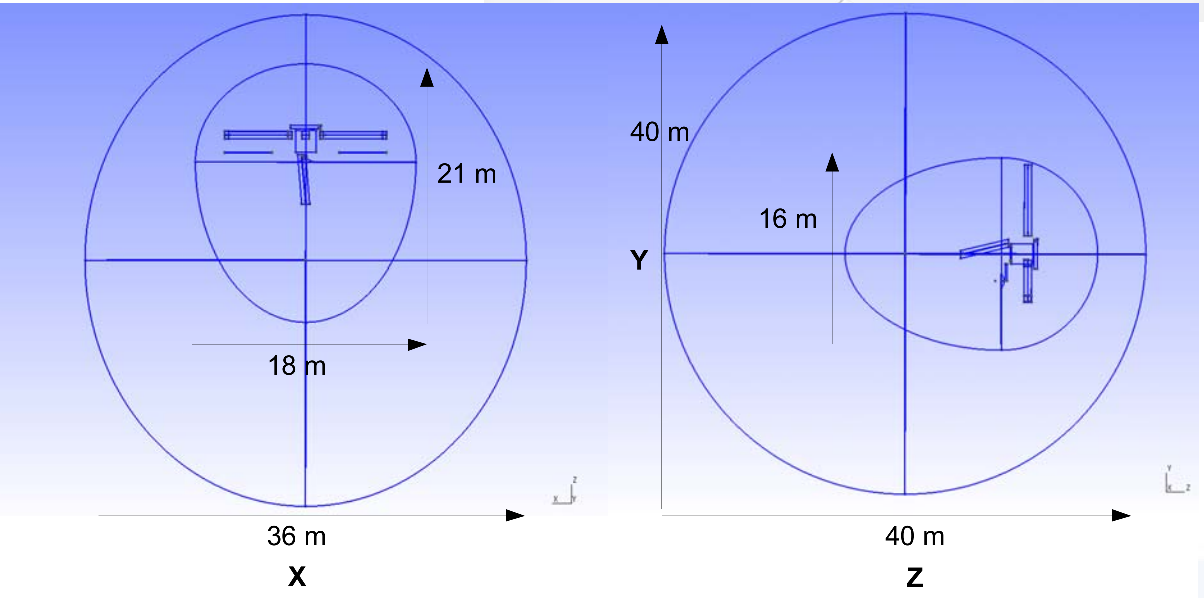


- SO basics:
  - source ESA
  - Three-axis stabilized spacecraft, Sun pointing
  - Closest Sun encounter 0.28 AU (2017 launch)
  - Heatshield to protect spacecraft and payload

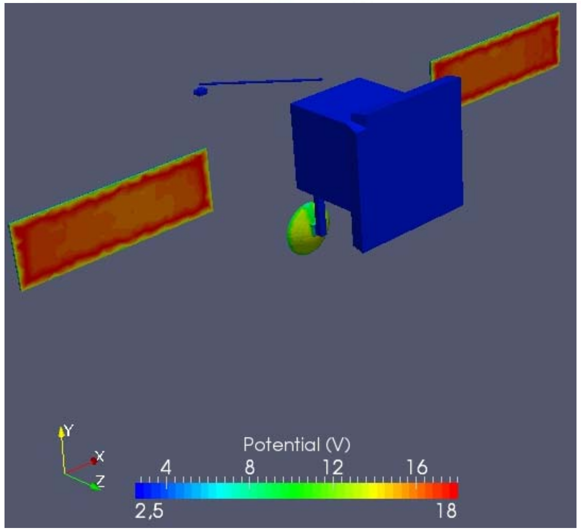
Particle Detectors – Geometry model of Solar Orbiter

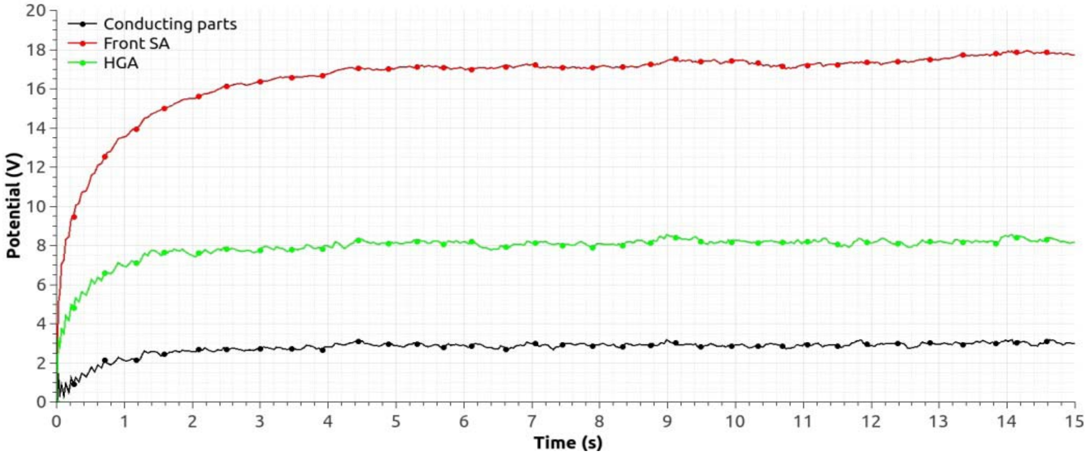
- Electrons : e- with Particle in Cell (PIC) modeling
- Ions : H+ with Particle in Cell (PIC) modeling
- Photoelectrons: PIC modeling of a Maxwellian distribution, Temperature = 3 eV
- Secondary electrons: PIC modeling of a Maxwellian distribution, Temperature 2 eV, backscattered electrons simulated (with 2/3 of their initial energy)
- External boundary conditions : Fourier, $1/R^2$ decrease of potential
- No magnetic field considered





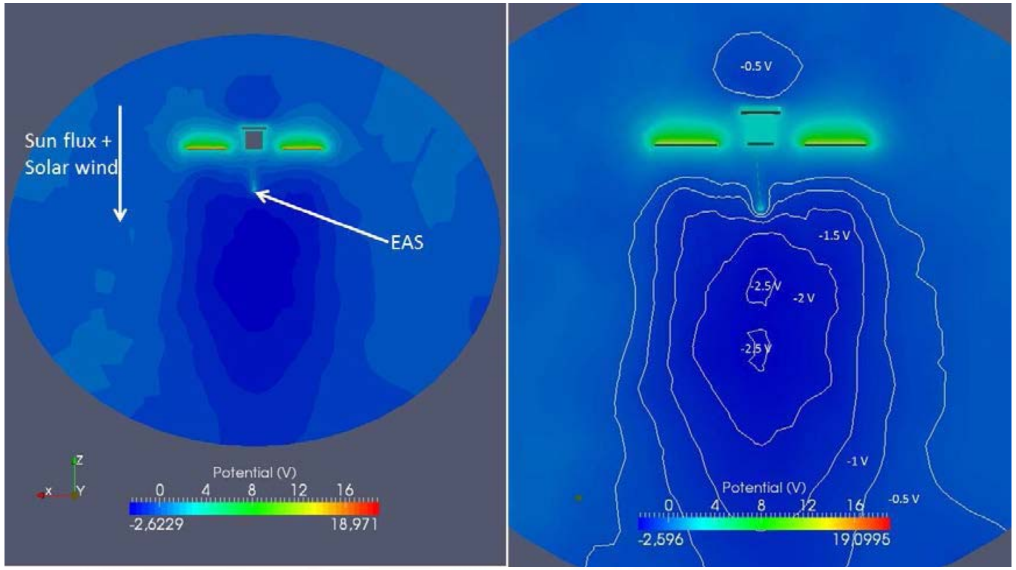
Particle Detectors – Electrostatic cleanliness





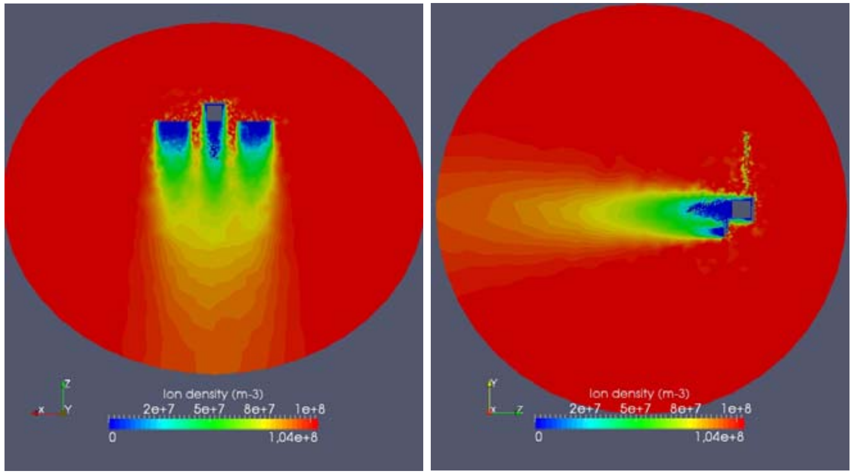
- Globally positive SC:
  - Solar panels at +17 V
  - SC body at +2,5 V

- In volume:
  - Potential map affected by the positive potential of the SC
  - Potential barrier for electrons (<0) in the ram and in the wake
  - In ram: due to the photoemission
  - In wake: due to the ion depletion



Particle Detectors – Plasma densities

Ions from environment



- Wake effect due to ion drifting:
  - Depletion of the ion density
  - Ion collection on the ram side
- Secondary emission from electron impact:
  - All around the SC
  - Density as high as electron from environment
- Photo-emission:
  - In the sunlight direction
  - Denser than environment
  - Space charge effect

Secondaries from electron impact

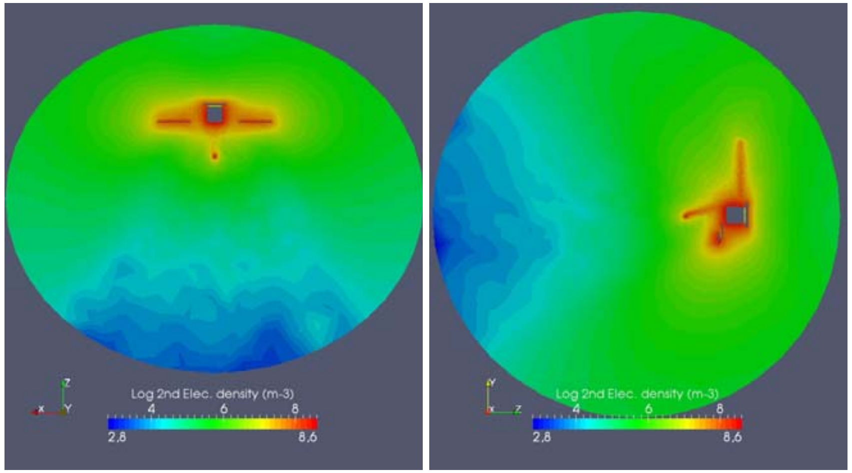
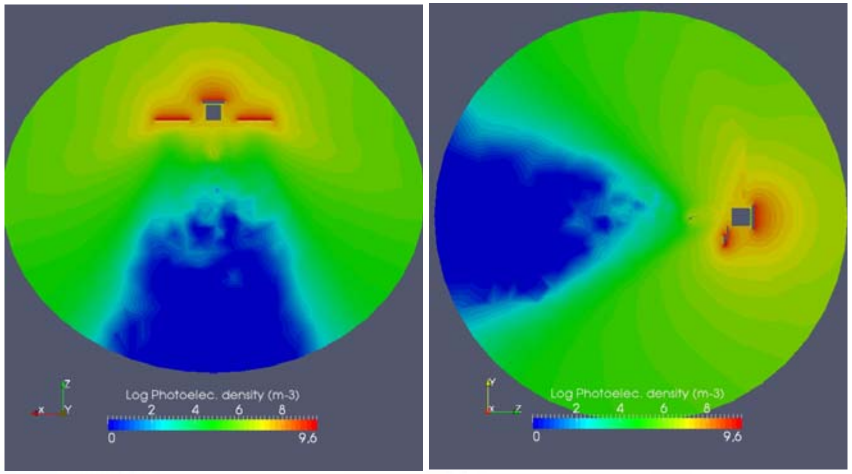
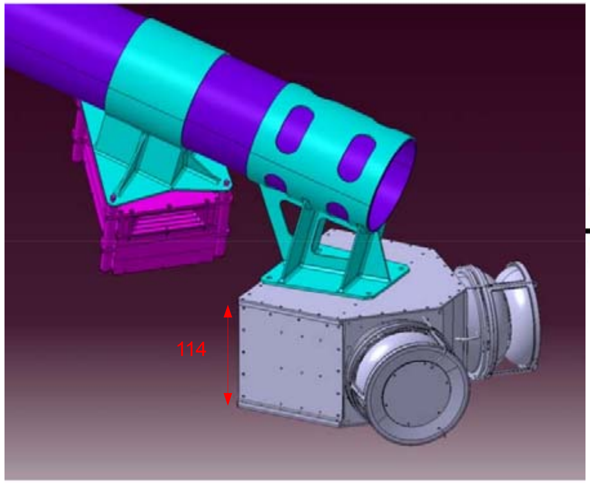


Photo-electrons

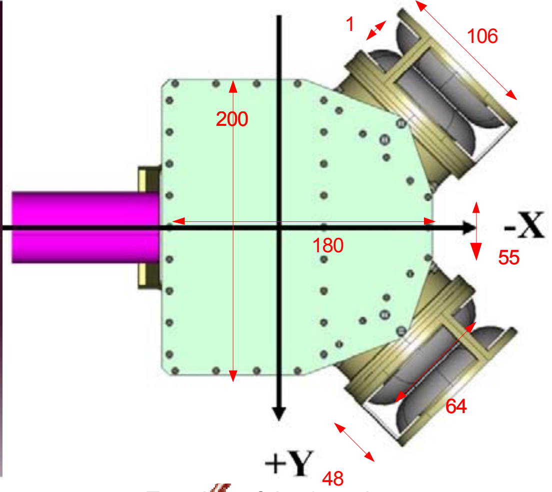


Particle Detectors – EAS detector on Solar Orbiter

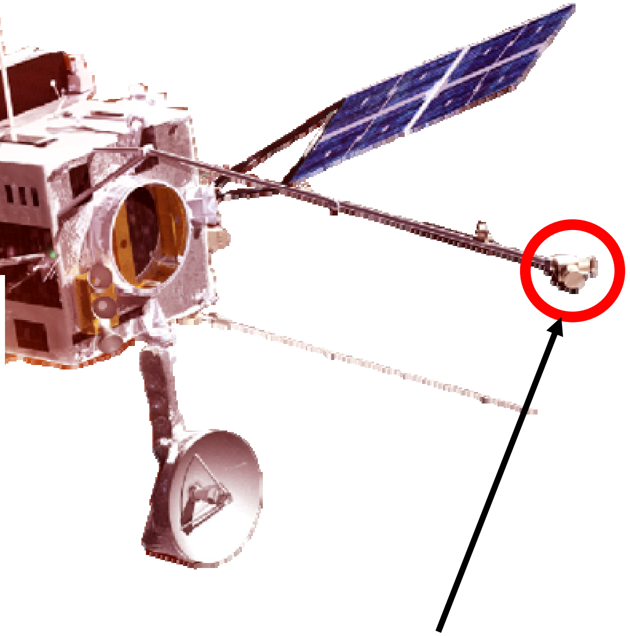
- Objectives
  - Compute the 3V distribution function of detected particle by EAS
  - Environment electrons influenced by the potential (repelled in the wake due to <0 potential and attracted by the SC due to >0 potential)
  - Measurement of secondaries electrons from the S/C
  - Multi-Scale in space: Detector aperture 1 mm << S/C length ~ 10 m
  - Statistical problem using PIC method



EAS mounted on its support, at the end of the boom



Top view of the 2 analysers



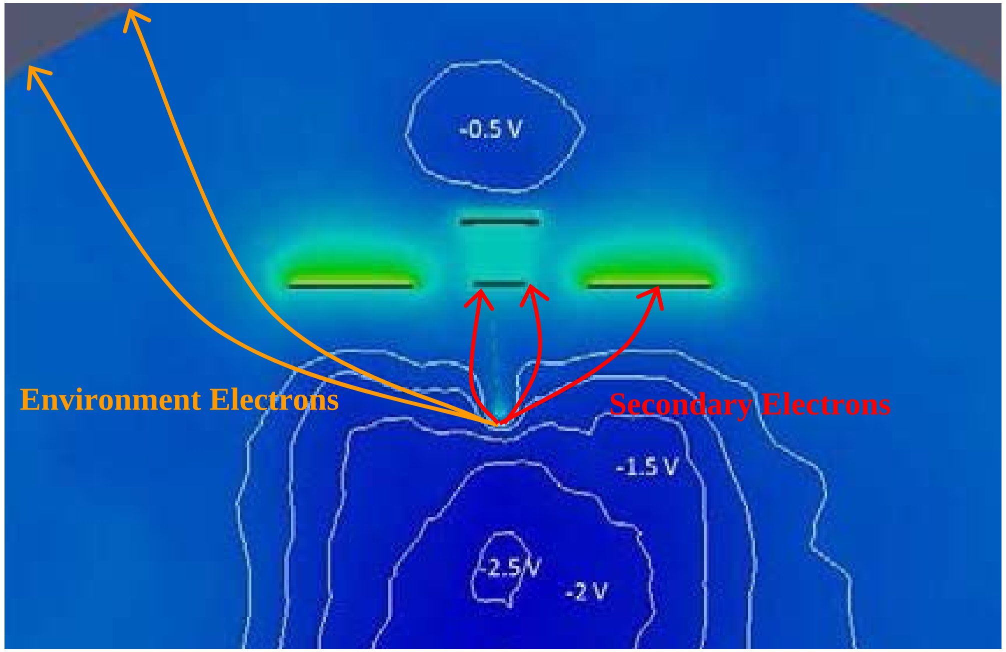
Particle Detectors – "Backtracking" priciple

- Objectives
  - Compute the 3V distribution function of a population on an arbitrary surface of the computation domain
  - Control the statistics of the detection

- Algorithm details
  - Based on the Liouville theorem:
    - Conservation of the DF value along a particle trajectory
    - DF known on the Boundary Limits
    - E and B fields stationnary in comparison to the particle transport

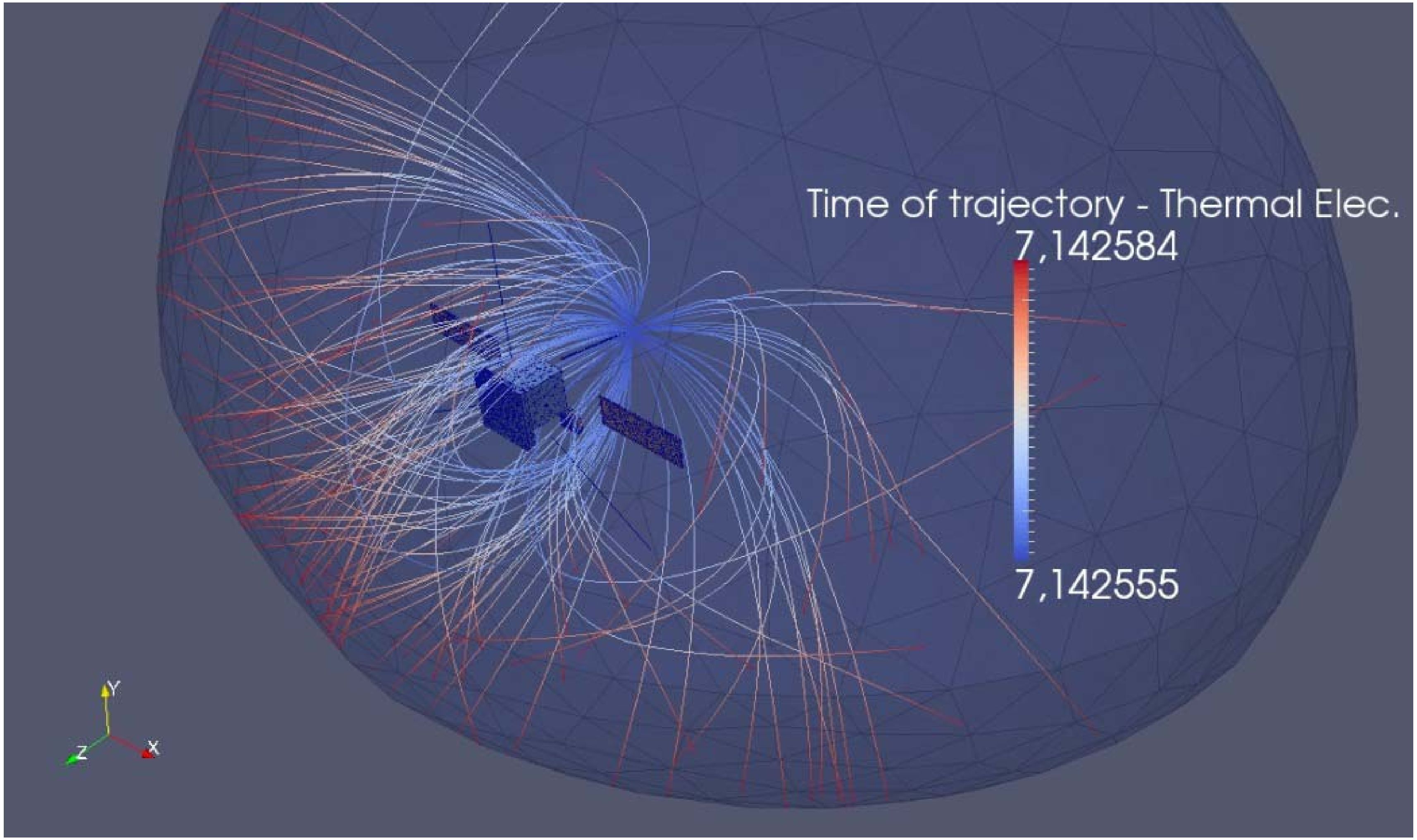
$$(\vec{x}_B, \vec{v}_B) \xrightarrow{Traj} (\vec{x}_D, \vec{v}_D)$$

$$f_D(\vec{x}_D, \vec{v}_D, t) = f_B(\vec{x}_B, \vec{v}_B, t)$$

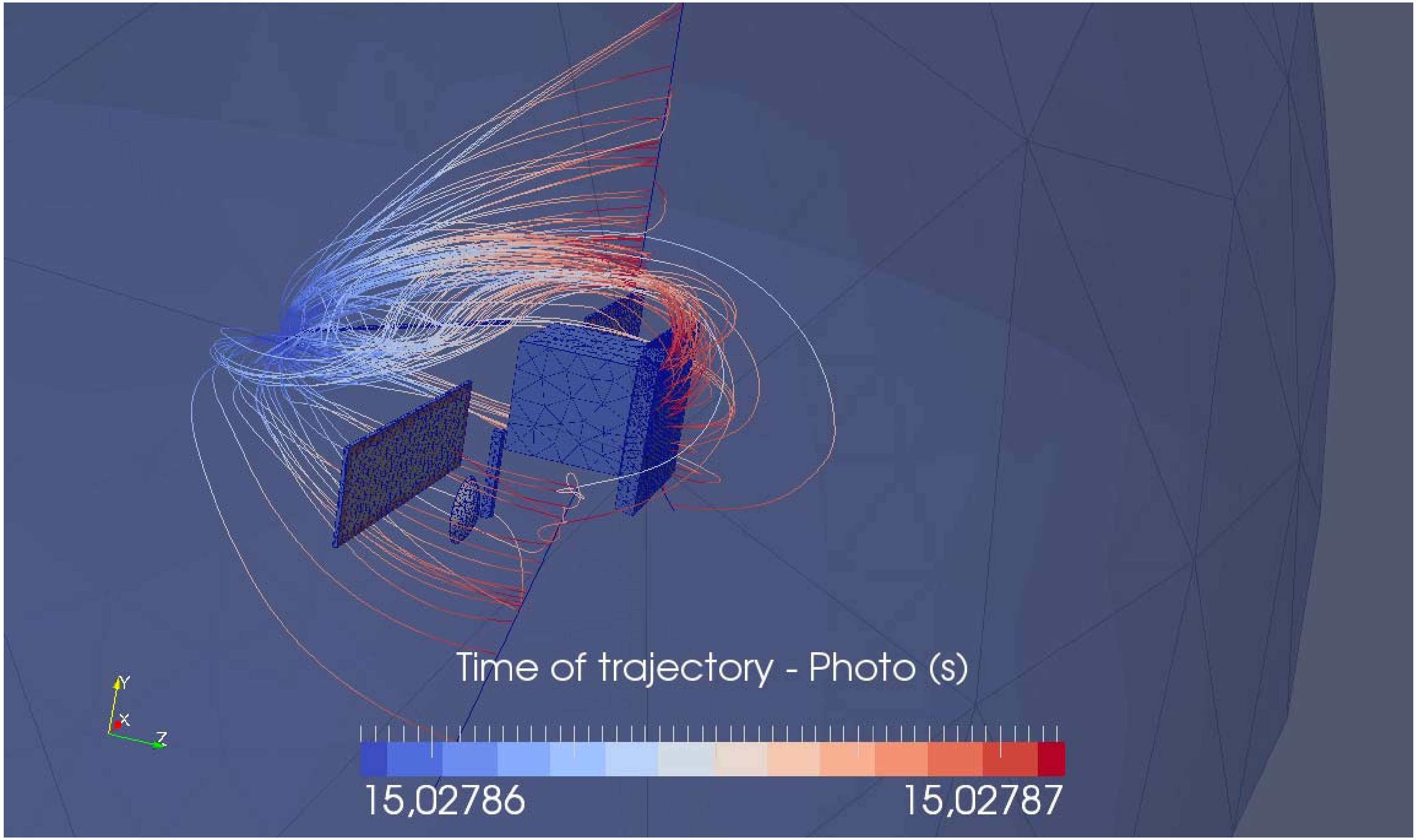


- Key point: discretization of the DF in the phase space
  - Use of an OcTree based algorithm → adaptative refinement of the phase space mesh throw an euristic of optimization
  - Use of the PIC foward solution

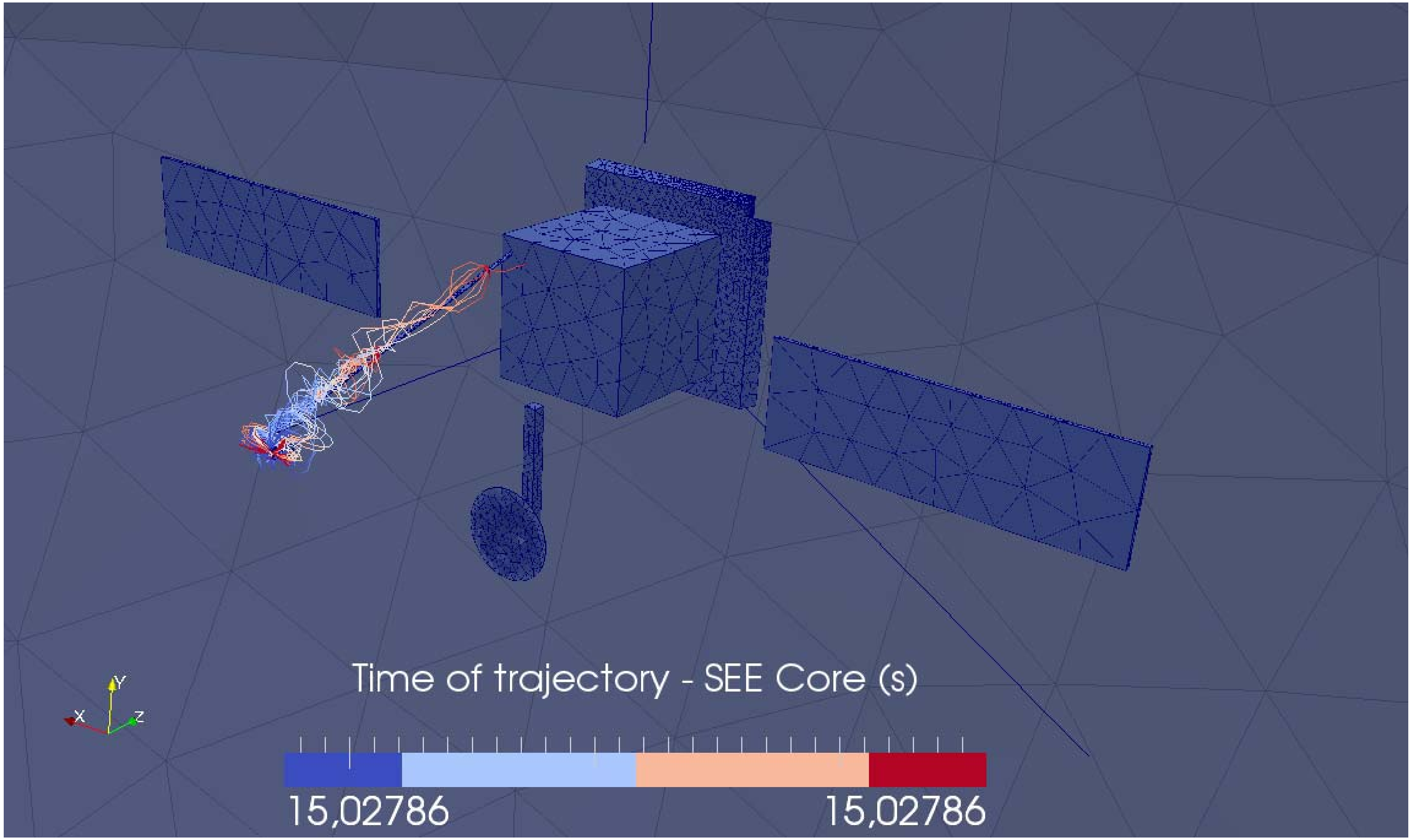
Particle Detectors – Environment electrons



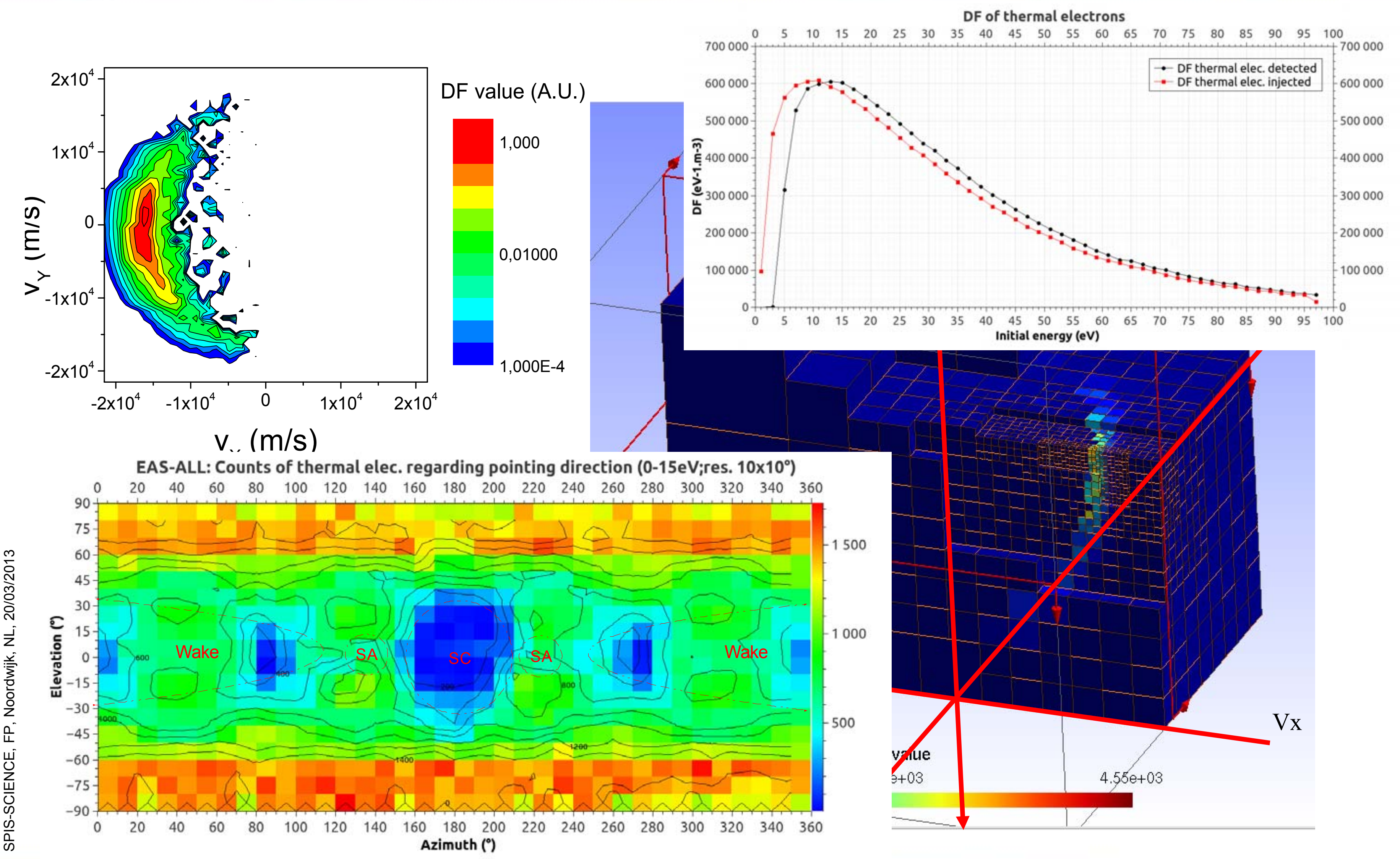
Particle Detectors – Photoemission electrons



Particle Detectors – Secondary emission electrons from electron impact



Particle Detectors – Example of DF results



Unmeshed elements

Reason of development	UR	SR	Methods developed
Thin wire modeling with a very small radius in comparison to the mesh size (booms, antena, RPW instrument,…)	FGS-005	FGS-004	1D thin elements in SPIS taking into account the effect of the singularity on the potential map, the current collection and emission, and the monitoring
Thin panels modeling with a very small thickness in comparison to the mesh size (solar array for example)	FGS-002 FGS-003	FGS-001	2D thin elements in SPIS taking into account the effect of the edge singularity on the potential map, the current collection and emission, and the monitoring
SA interconnectors modeling with a very small size in comparison to the mesh size	FGS-002 FGS-003	FGS-002	Collection law on the solar array tacking into account the interconnector potential
Virtual instrument not interacting with the simulation	PPD-002	PD-003	User define instrument shape (2D) and measurement done as a Particle Detector
Semi-Transparent Grid (STG) without meshing the aperture	PPD-003	STG-001 STG-002 STG-003 STG-004 STG-005	Specific surface delimiting two computation volume with a transparency

Unmeshed elements – Thin wires/Thin Panels

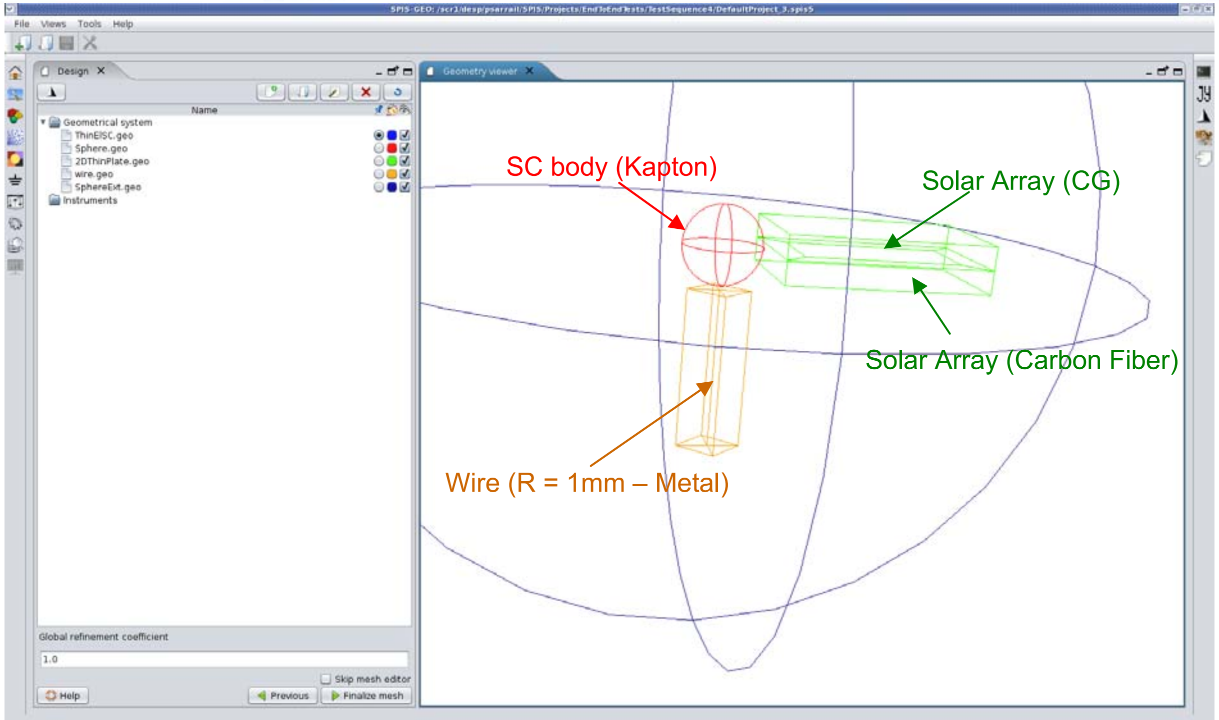
- 2 sorts of thin elements in SPIS:
  - 1D → thin wires (booms, antena, …)

    when r << Δx
  - 2D → thin panels (solar panels, …)

    when h << Δx

- One or two dimensions not meshed (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

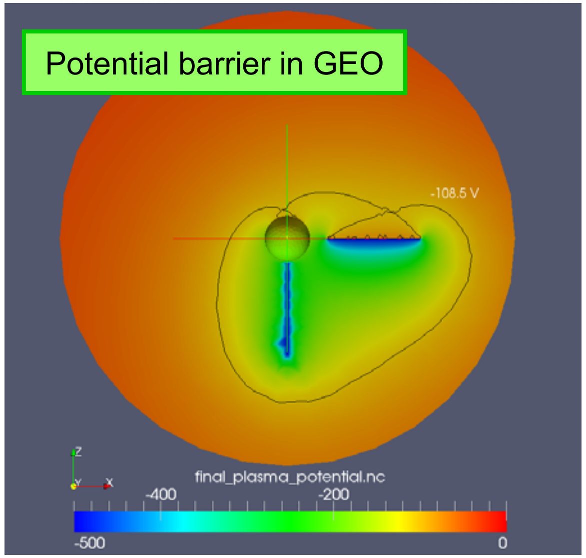
Too costly to mesh h → without 2D thin elements Δx < h/2 !!!

Wire 4m:

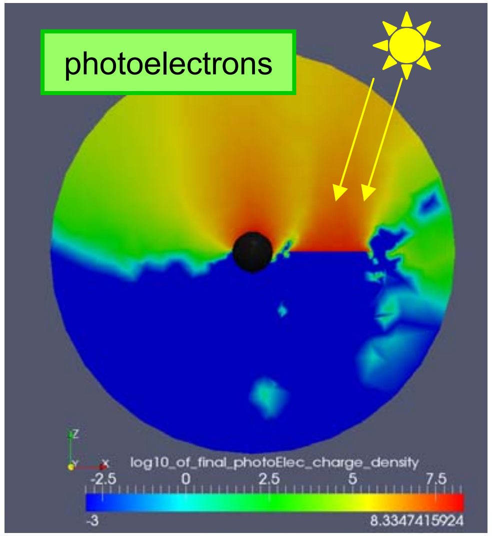
- Mesh size Δ x = 0.2 m
- Radius R = 1 mm

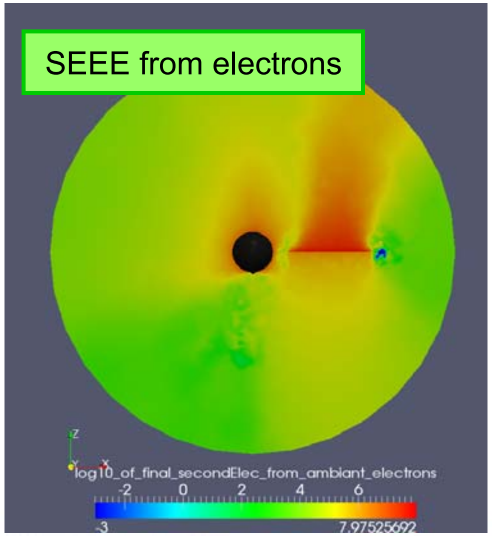
Too costly to mesh r → without 1D thin elements Δx < r/2 !!!

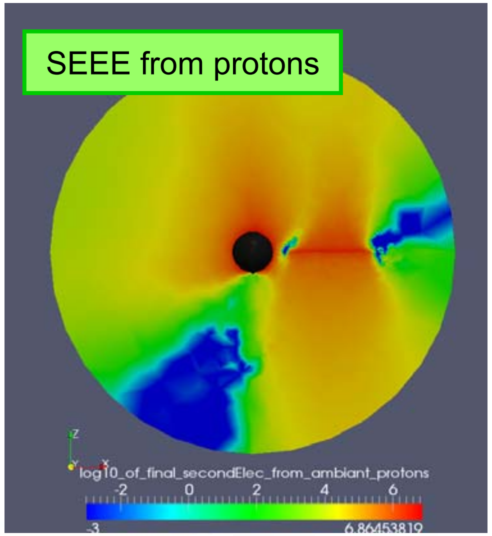
Unmeshed elements – Thin wires/Thin Panels



- 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

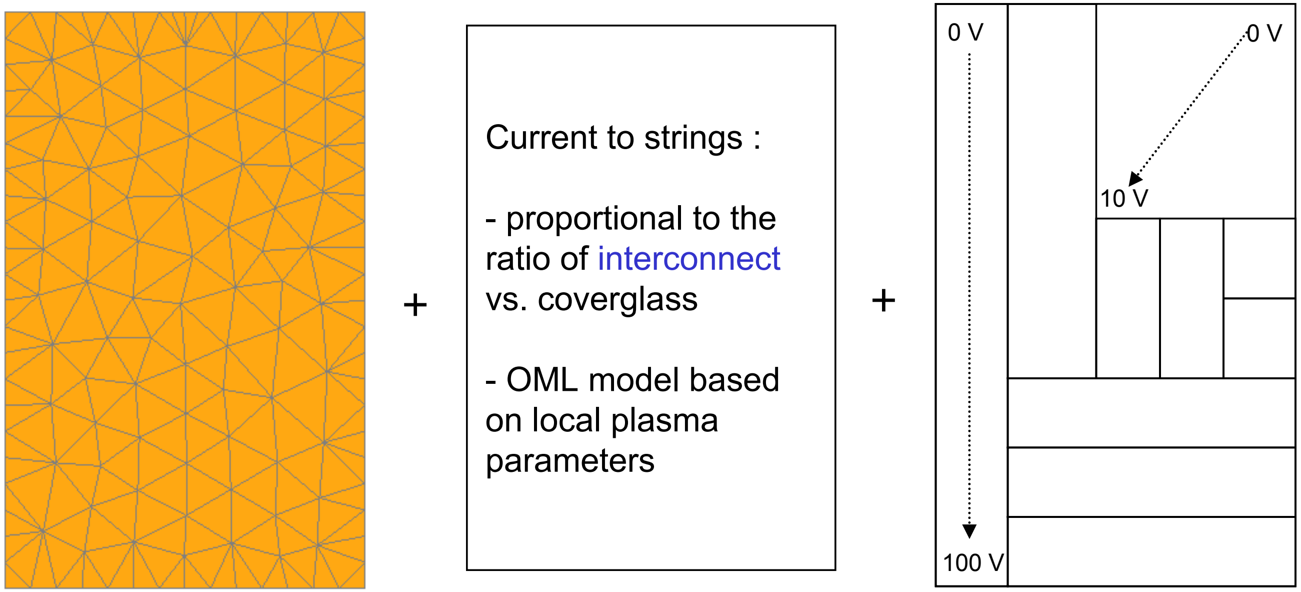






Unmeshed elements – Interconnectors

- Interconnector modelling:
  - Interconnect not meshed
  - Globally the plasma is not affected by the interconnect
  - Locally current distributed between the cover-glasses and the interconnects
  - Current distribution affected by the potential of the interconnect behind the cover-glasses



Current to strings :

- proportional to the ratio of interconnect vs. coverglass

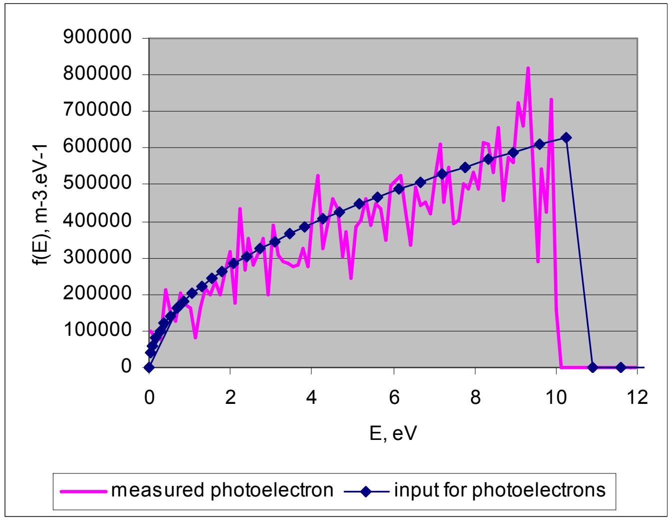
- OML model based on local plasma parameters

- Illustration in AISEPS FP (ASTRIUM)

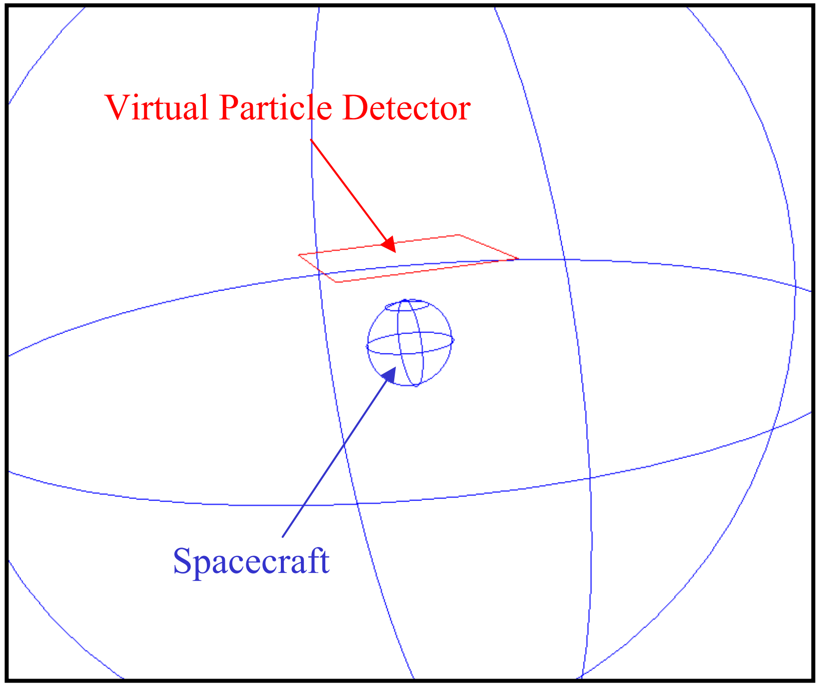
Unmeshed elements – Virtual instruments

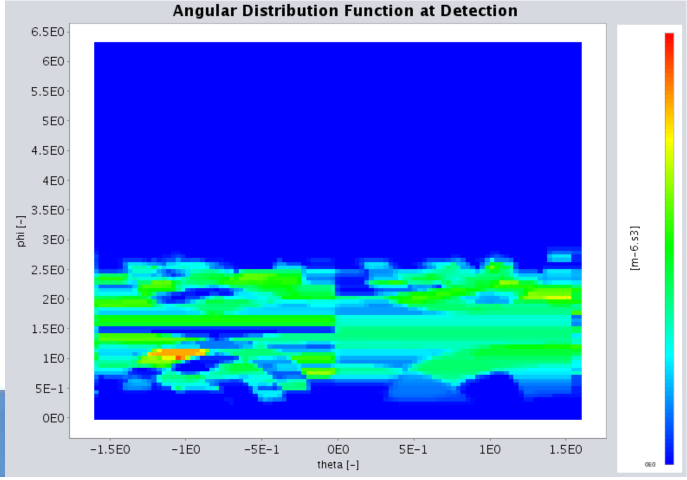
- Same as a Particle Detector but the instrument suport is defined on an additionnal mesh (surface) not linked to the computationnal volume

- Responsibility of the user to set this mesh in the computational volume



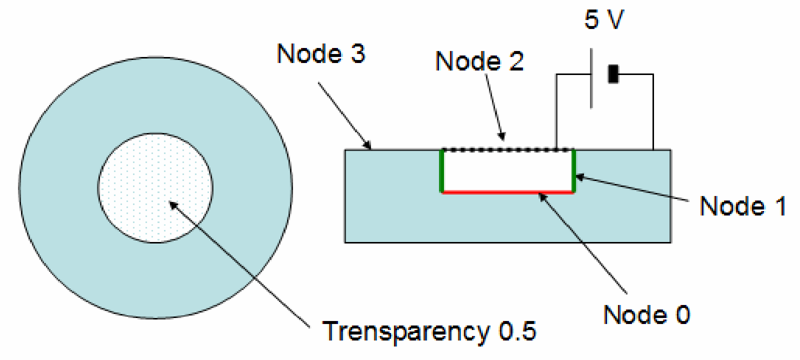
- Functionnal test sequence #1



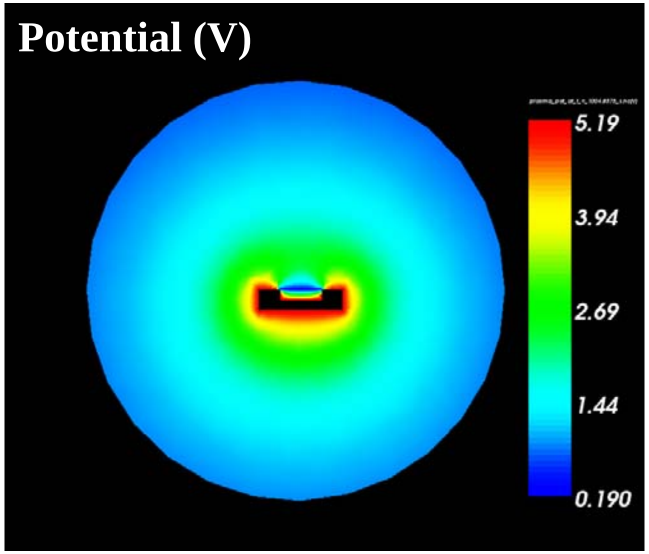


Unmeshed elements – Semi-Transparent Grids (STG)

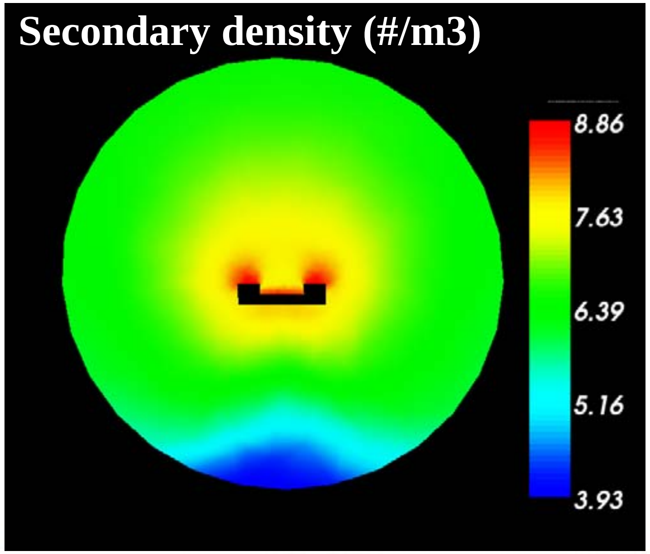
- Aperture not meshed → transparency coefficient
- Functionnal test sequence #2 (simplified RPA)



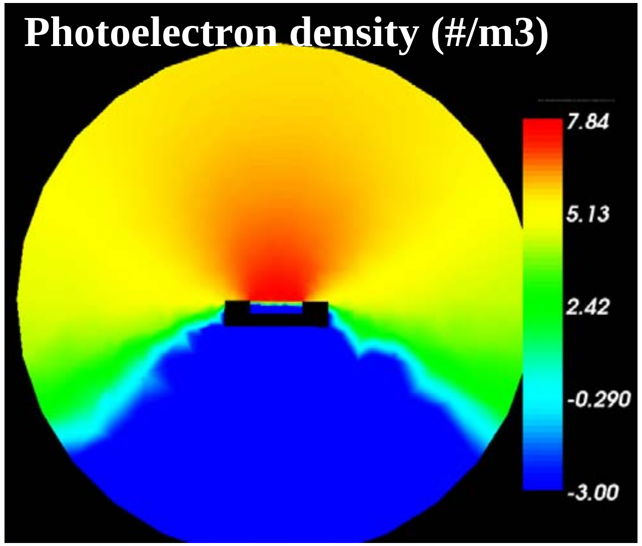
Potential (V)



Secondary density (#/m3)



Photoelectron density (#/m3)



Outline

- Team and work breakdown structure
- User requirements
- SPIS-SCI evolution
  - Precision
  - Performance
  - User-defined ambient plasma and spacecraft interactions
  - Pre-defined transient phases
  - Instruments
    - How to mimic scientific particle detectors, Langmuir probes, electric field analyzers
    - Illustrative example of application to Solar Orbiter
  - Unmeshed elements
- Validation campaign
  - Solar Orbiter
  - Cassini
  - Cluster
- Conclusion and perspectives

VC-5 : Solar Orbiter validation cases
Electron measurement

Objectives:

- Evaluate the evolution of SC/plasma interactions with the varying environments at several heliocentric distances:

  → *what are the final potentials ? are there potential barriers ?*

- Evaluate the impacts of SC/plasma interactions on EAS low energy electron measurements:

  → *are the electron measurements reliable ? to what extent ?*

Input parameters:

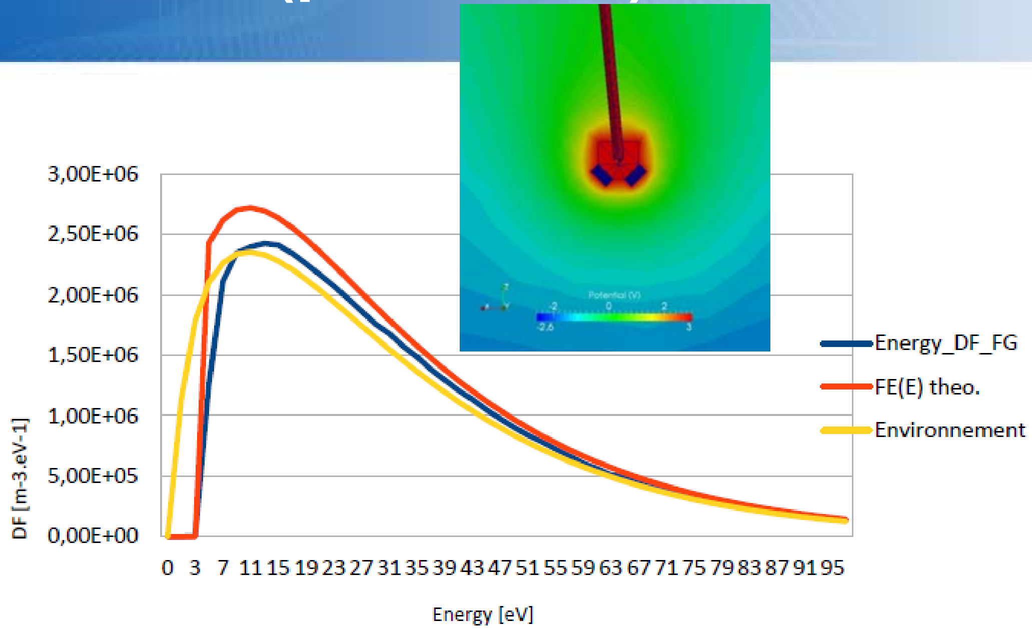
Simulation ID	**SO1**	**SO3**	**SO5**	**SO5-Kappa**
Distance (AU)	1	0,72	0,28	0,28
Distance (Rs)	215	154,8	60,2	60,2
Sun Flux (#1AU)	1,00	1,93	12,76	12,76
Thermal elec. Model	PIC - Maxwell velocity distribution	PIC - Maxwell velocity distribution	PIC - Maxwell velocity distribution	PIC - specific velocity distribution
Ne_Core (cm-3)	**6,93**	**13,5**	**104**	**82,8**
Te_Core (eV)	**8,14**	**10,41**	**21,37**	**19,82**
Ne_Halo (cm-3)				**0.8**
Te_Halo (eV)				**99,95**
Ne_Strahl (cm-3)				**5,80**
Te_Strahl (eV)				**30,16**
Vz_Drift_Strahl (km/s)				**5300**
Kappa parameter				**5**
Ni (cm-3)	6,93	13,5	104	89,4
Ti (eV)	8,00	11,21	27,00	27,00
Vz ram protons (km/s)	430,00	429,50	400,00	400,00
Mach number	15,53	13,11	7,86	7,86
Debye length (m)	**8,06**	**6,52**	**3,38**	**3,38**
Debye length photoelec (m)	**0,98**	**0,71**	**0,27**	**0,27**

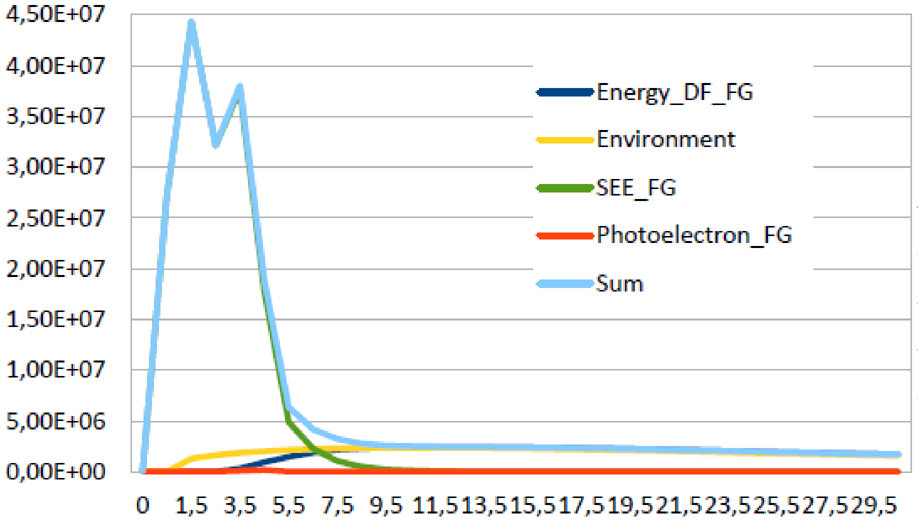
Far from the Sun → **Close to the Sun**

N, T, SunFlux ↑ and λ, V ↓

SO5 – Solar Orbiter @ 0.28 AU (perihelion)

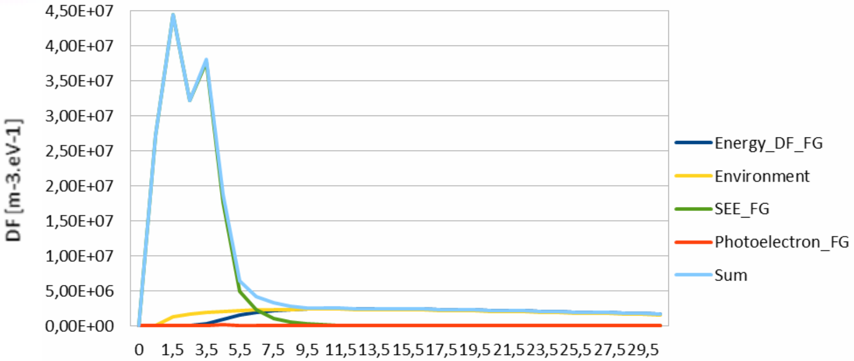
- Discrepancy less than 5% between
  - SPIS measurement of environment electrons on the EAS surface (blue)
  - Theoretical calculation considering only the acceleration of the environment electrons (red)
- Effect of the EAS potential is not simply a shift of the DF in energy

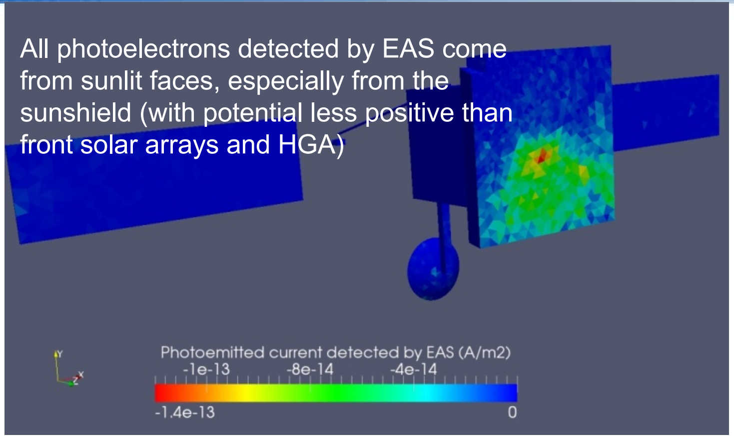




- High disturbance of the environment spectrum measured by EAS:
  - 157% difference in density
  - Spectrum dominated by the secondaries behind 10eV
- Disturbance due to the SEE by electron impact on the instrument itself and the boom

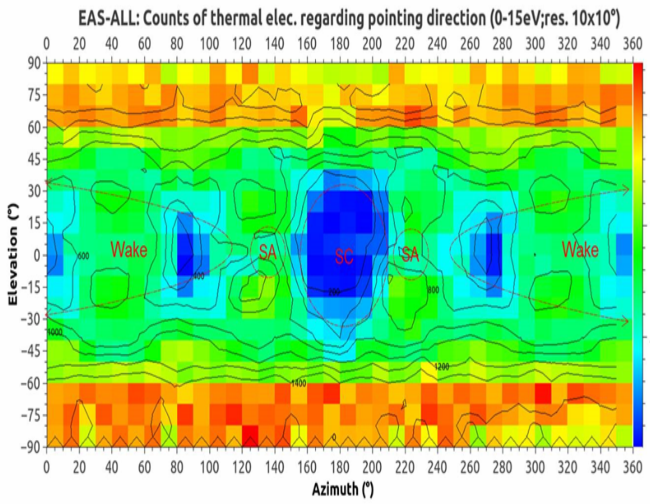
SO5 – Solar Orbiter @ 0.28 AU (perihelion)

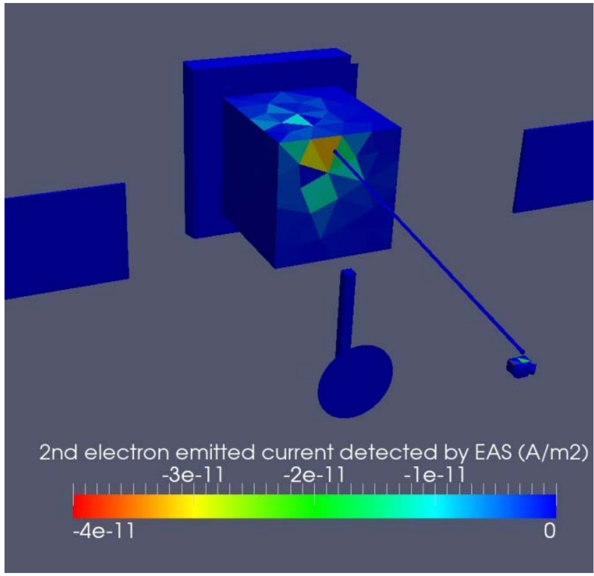




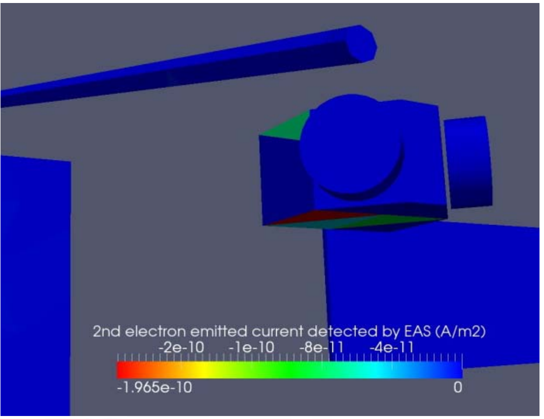
All photoelectrons detected by EAS come from sunlit faces, especially from the sunshield (with potential less positive than front solar arrays and HGA)

Large disturbances on EAS-measured differential flux :
- Density overestimation (Δn/n=157%)
- Preponderance of secondaries below 7 eV



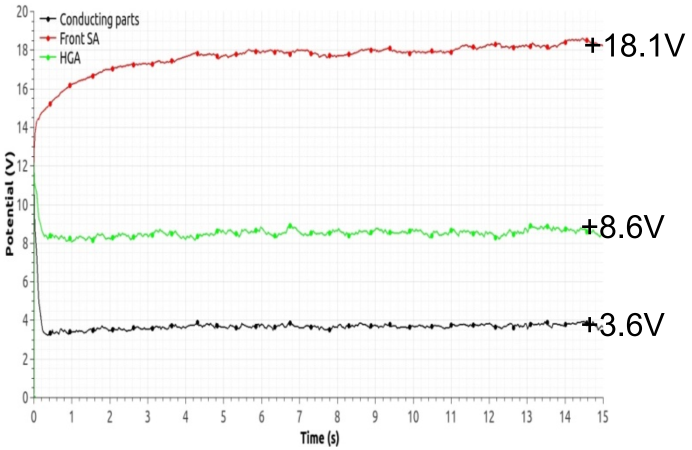


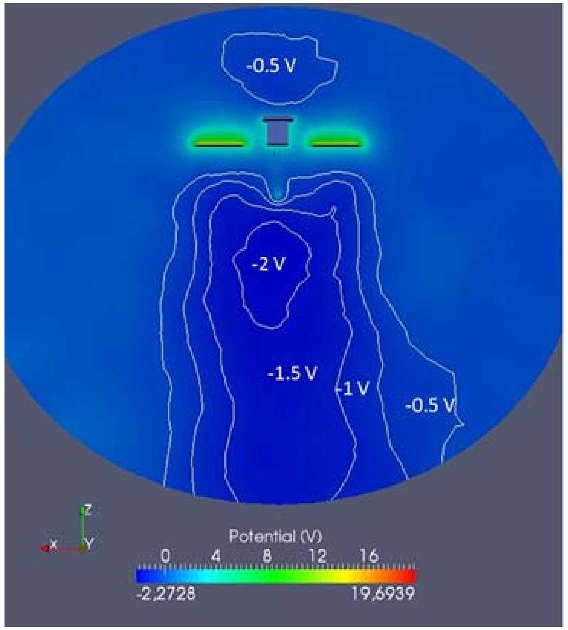
All SEE detected by EAS come from the rear side of SC main body, around the boom, and from EAS box itself

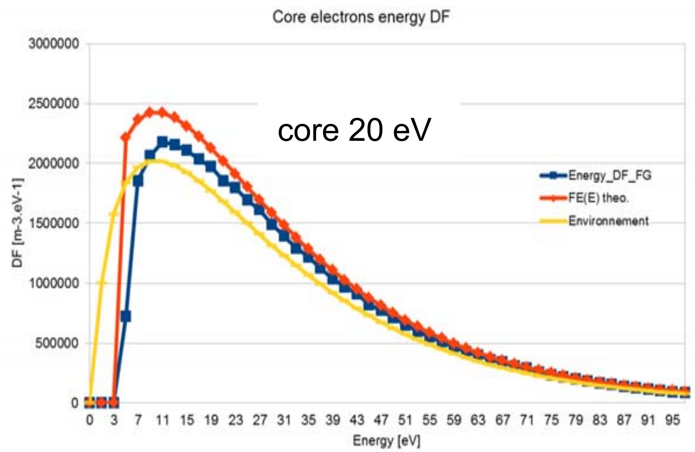


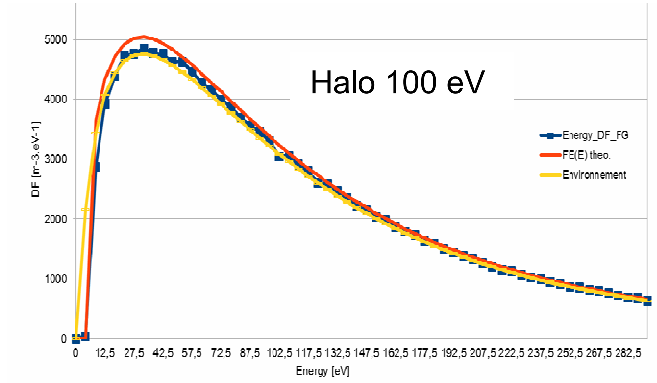
Regarding EAS pointing direction, we identify obstacles to thermal electron detection: electrostatic blockage (wake) or physical blockage (SC structure)

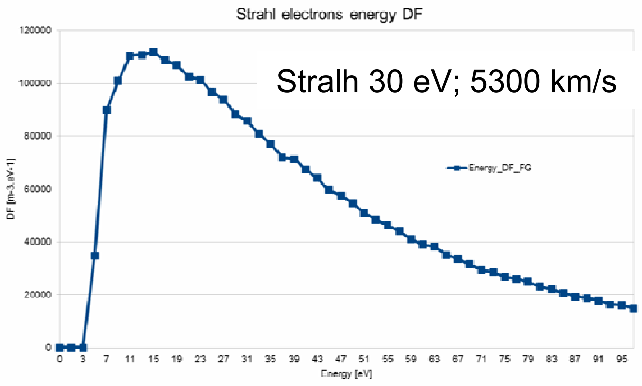
SO5-Kappa – Solar Orbiter @ 0.28 AU – Non Maxwellian



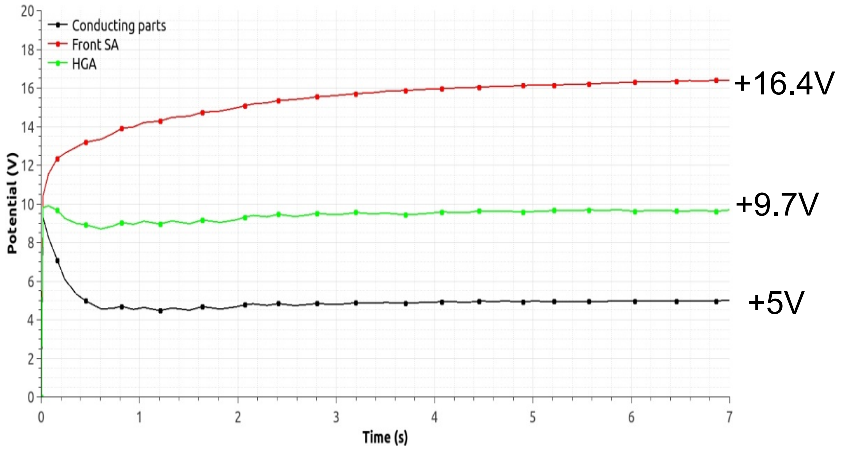


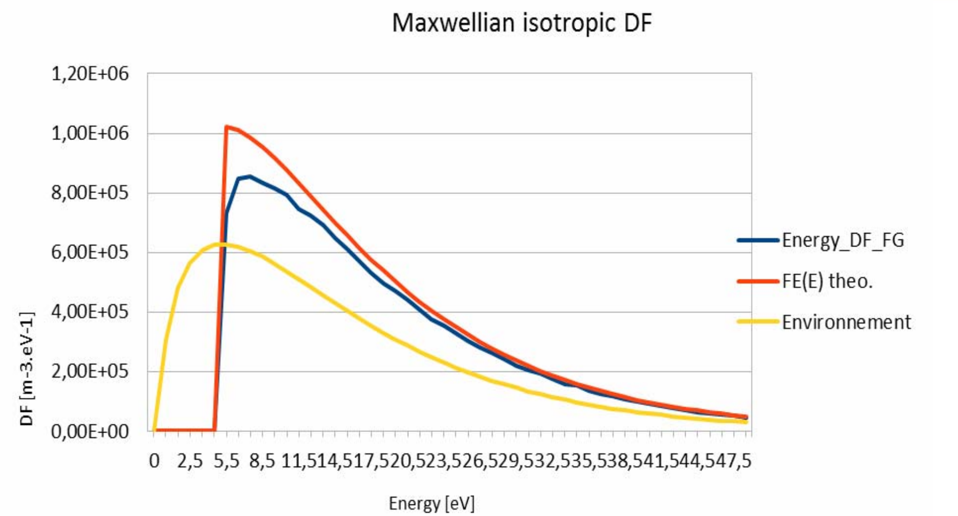




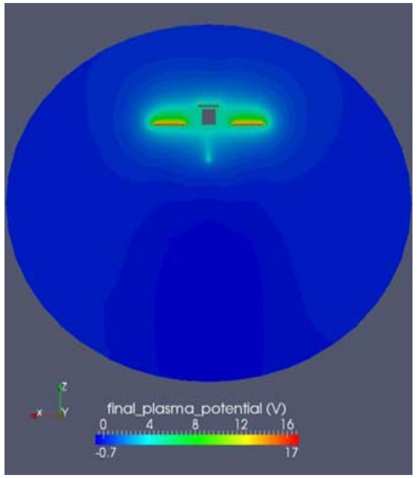


SO3 – Solar Orbiter @ 0.72 AU from the Sun

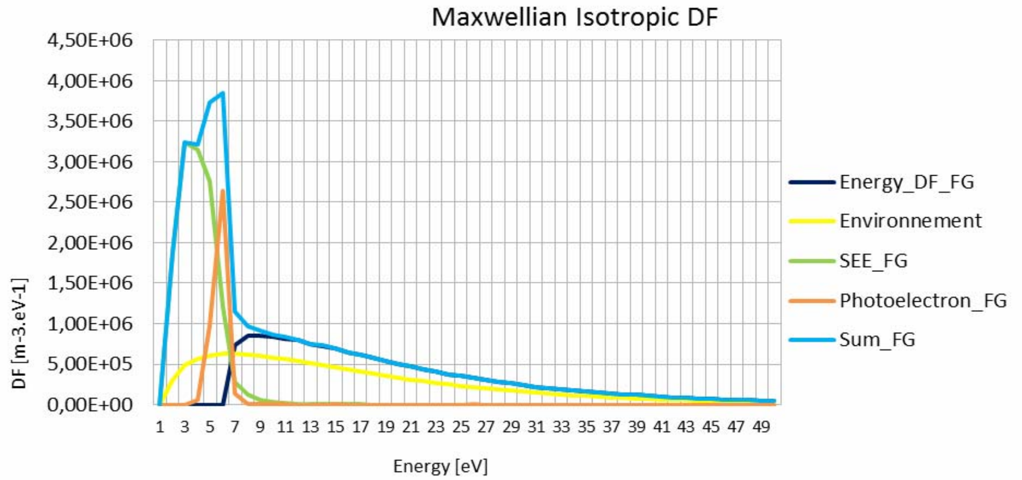




15% overestimation between SPIS measured thermal electron and true environment

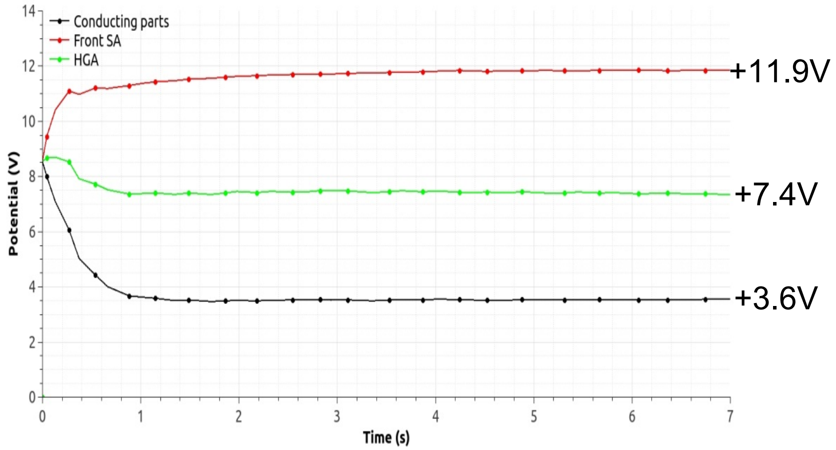


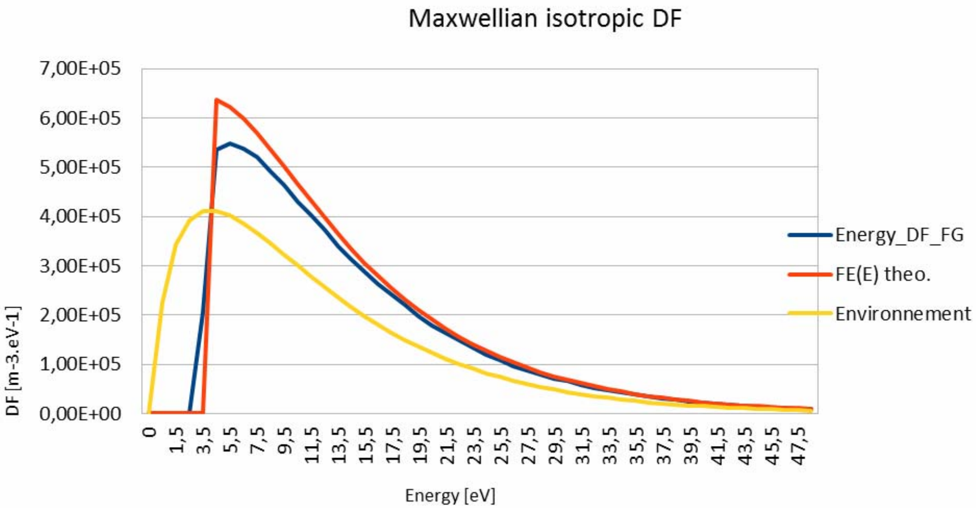
At 0.72 AU there are **no potential barrier** for 2nd-e nor v-e within the plasma (compared with SO5 at 0.28 AU) → monotonic decrease of potential from SC surfaces to infinity.



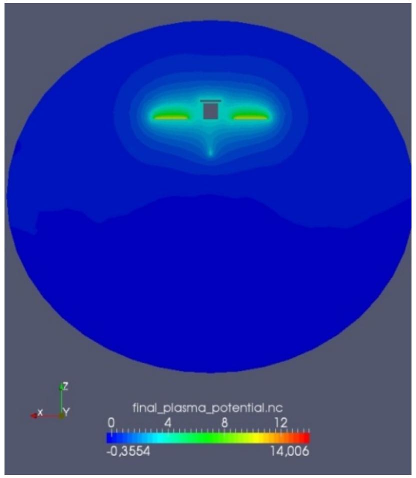
Large disturbances on EAS-measured differential flux :
- Density overestimation (Δn/n=138%)
- Preponderance of secondaries below 7 eV

SO1 – Solar Orbiter @ 1 AU from the Sun

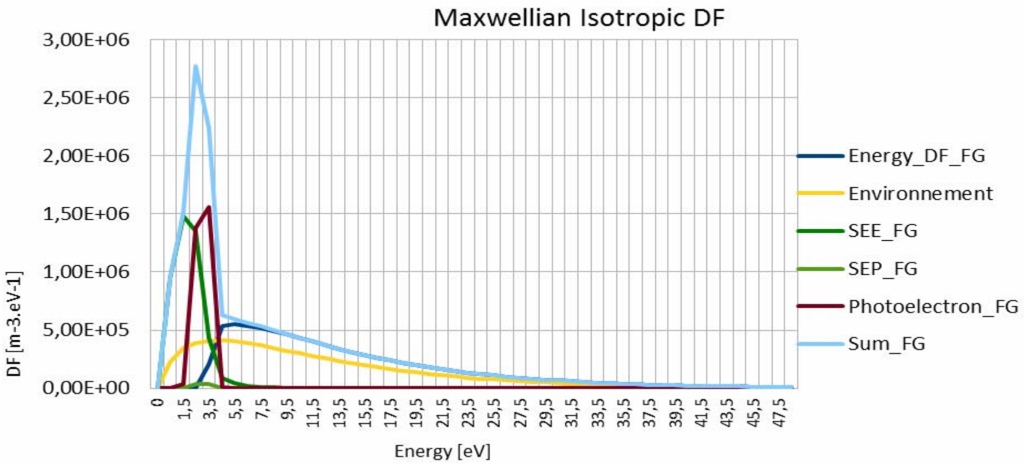




17% overestimation between SPIS measured thermal electron and true environment



At 1 AU there are **no potential barrier** for 2nd-e nor v-e within the plasma (compared with SO5 at 0.28 AU) → monotonic decrease of potential from SC surfaces to infinity.



Large disturbances on EAS-measured differential flux :
- Density overestimation (Δn/n=125%)
- Preponderance of secondaries below 5 eV

Summary of VC-5 on Solar Orbiter electron measurements

- Validation of SPIS capabilities to simulate a complex particle detector

- Moderate potential barriers (a few V) exist in the perihelion case

- SC potentials vary in the 3-5 V range

- Discrimination between effects of
    - Positive detector potential
    - Geometrical perturbations

- Could be responsible for large overestimation (~X2) of total electron density measured by real particle instrument at all heliospheric distances

- Large contamination by secondary electrons below 10 eV

- EAS position in the wake strongly limits the measured photoelectron flux (even if non-negligible impact of the 3 RPW long antenna)

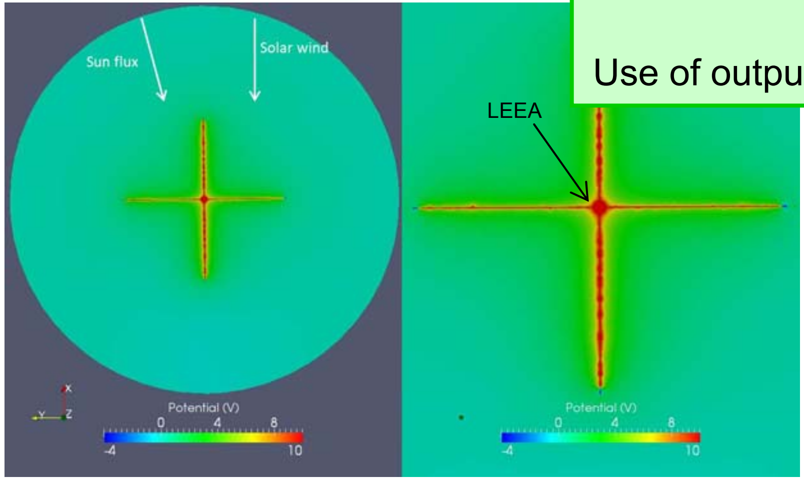
Electric field measurements

- PPt by IRFu

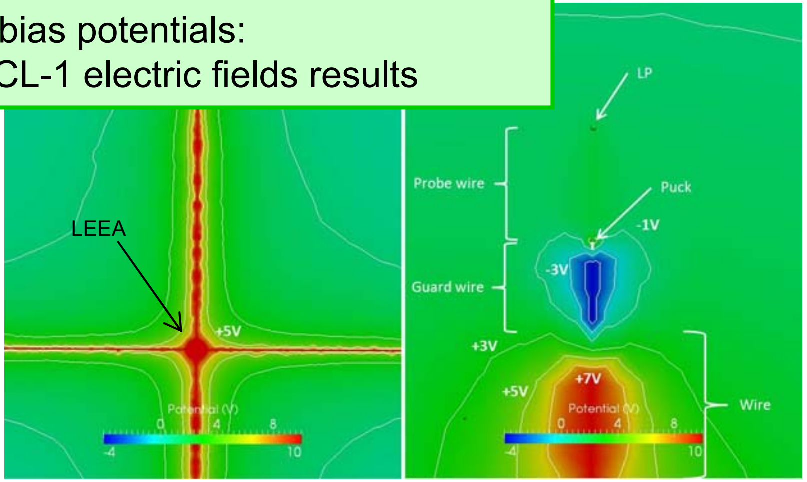
Cluster: CL1- Electron measurements (IRAP)

Conditions = Cluster 2, 2009-02-01 03:00 tenuous solar wind

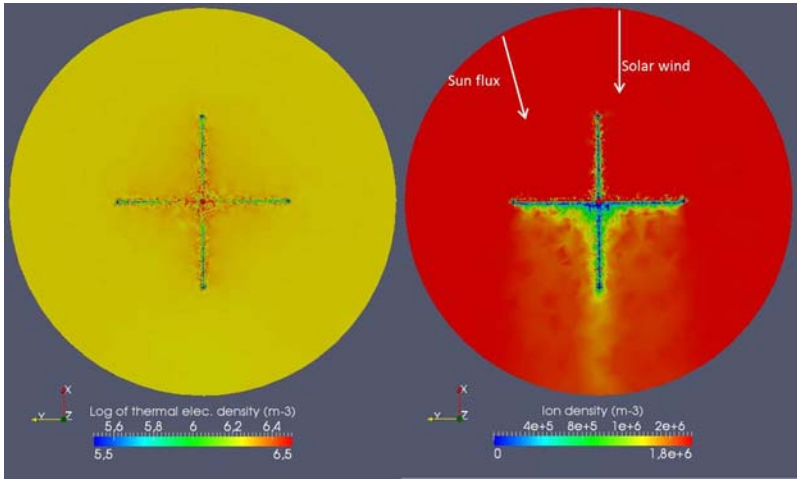
LP bias potentials:
Use of outputs from CL-1 electric fields results



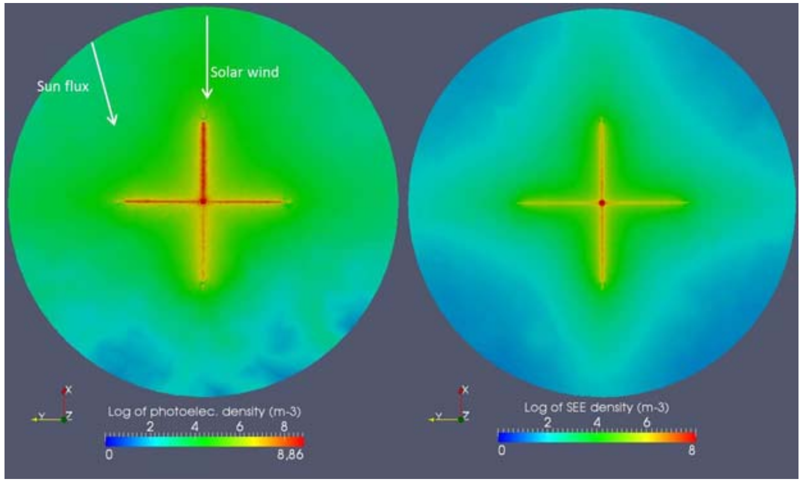
Potential around Cluster in the XY plane (left) and zoom on Cluster in the same plane (right)



Potential around Cluster in the XY plane (zoom)

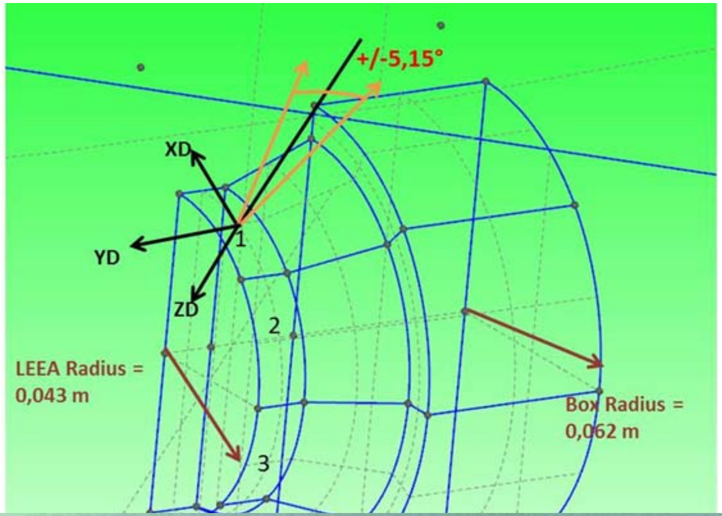


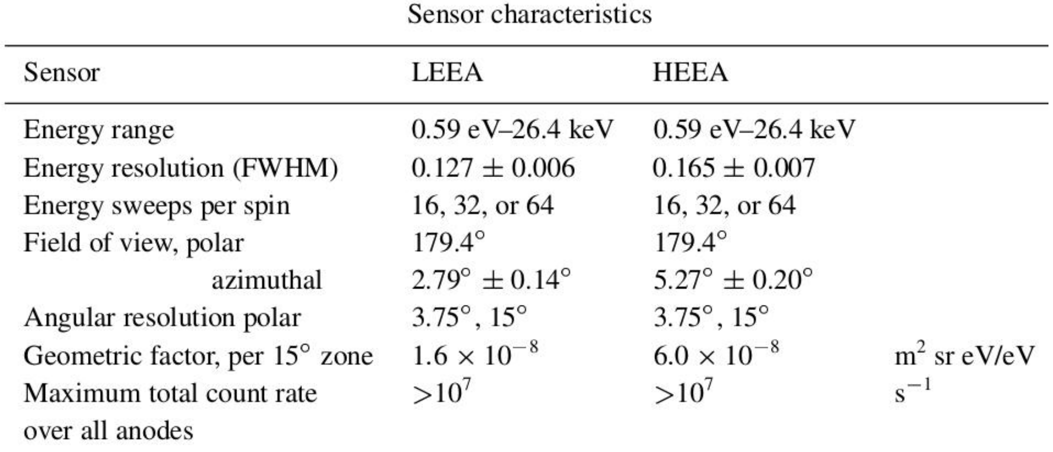
Thermal electron density around Cluster (left) and ion density in the XY plane (right)



Photoelectron density around Cluster (left) and SEE density in the XY plane (right)

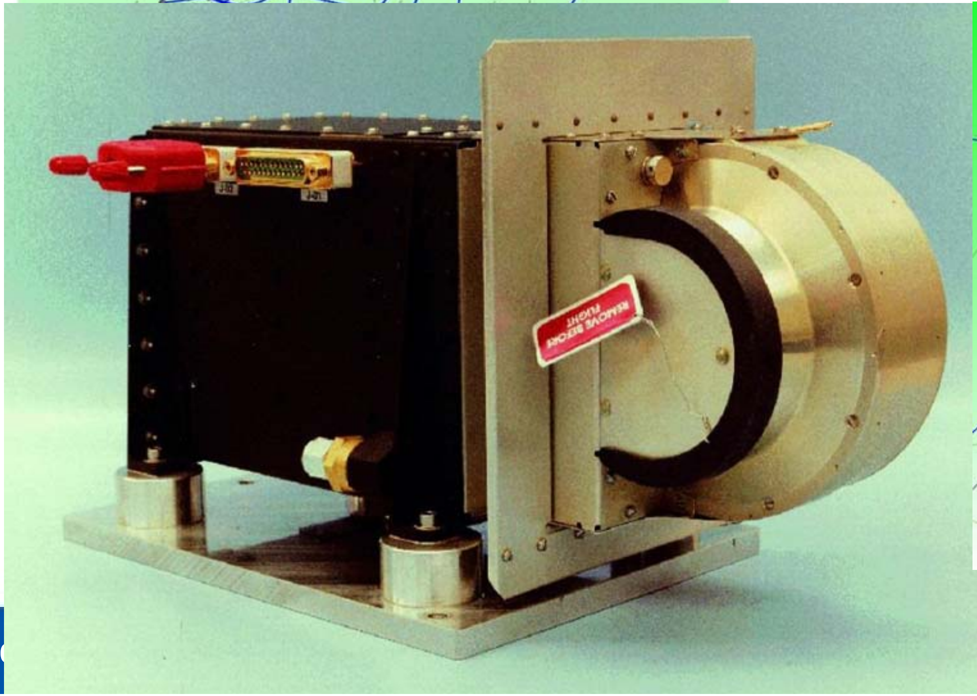
Cluster 1 – LEEA Data

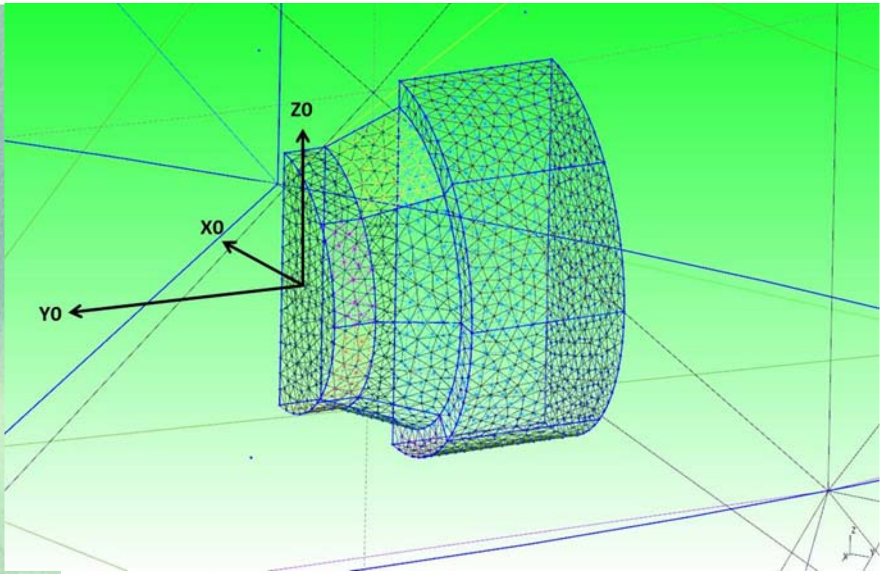




Sensor characteristics

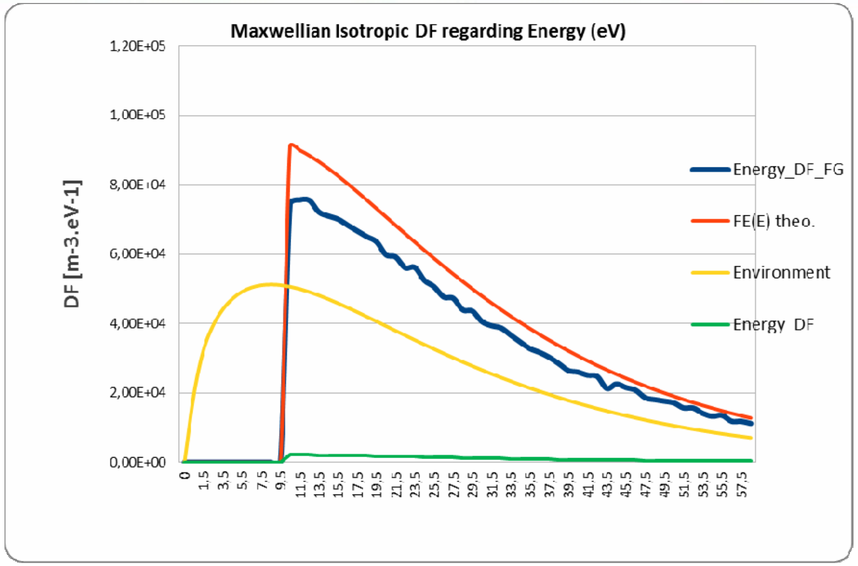
Sensor	LEEA	HEEA	
Energy range	0.59 eV–26.4 keV	0.59 eV–26.4 keV	
Energy resolution (FWHM)	0.127 ± 0.006	0.165 ± 0.007	
Energy sweeps per spin	16, 32, or 64	16, 32, or 64	
Field of view, polar	179.4°	179.4°	
azimuthal	2.79° ± 0.14°	5.27° ± 0.20°	
Angular resolution polar	3.75°, 15°	3.75°, 15°	
Geometric factor, per 15° zone	1.6×10^{-8}	6.0×10^{-8}	m^2 sr eV/eV
Maximum total count rate over all anodes	$>10^7$	$>10^7$	s^{-1}

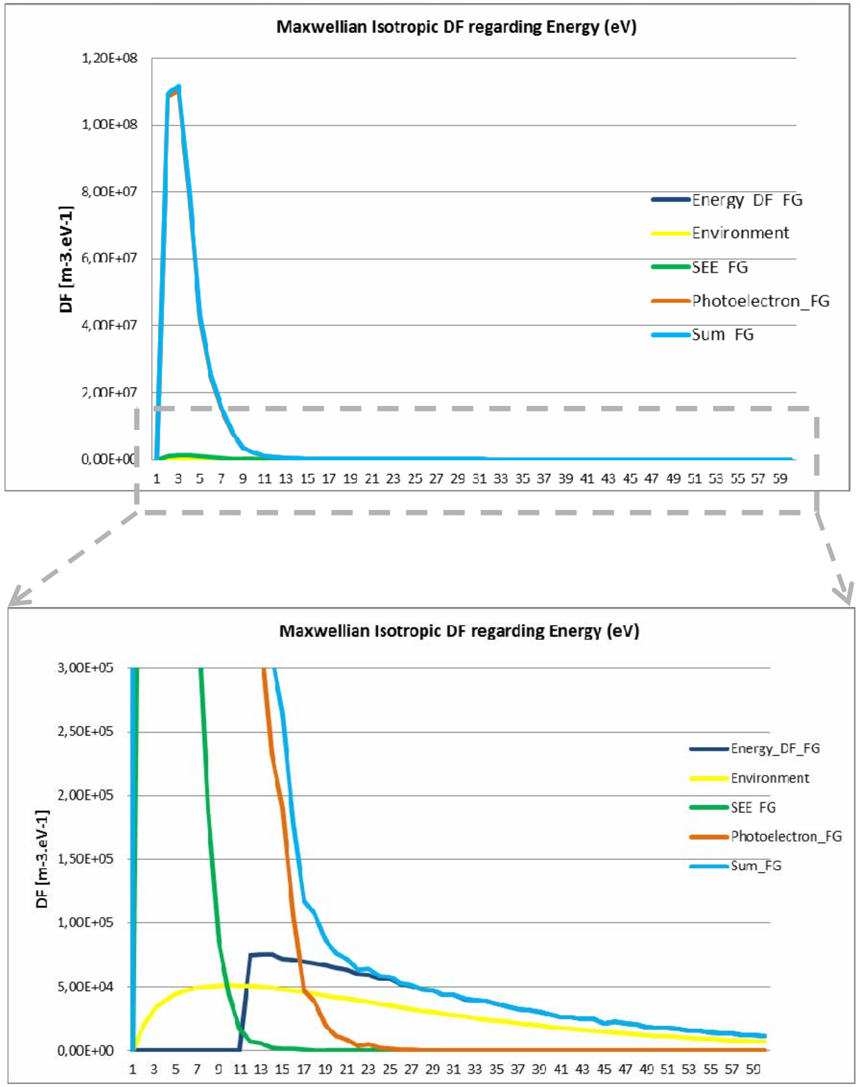




Cluster: CL1

Cluster 2, 2009-02-01 03:00 tenuous solar wind

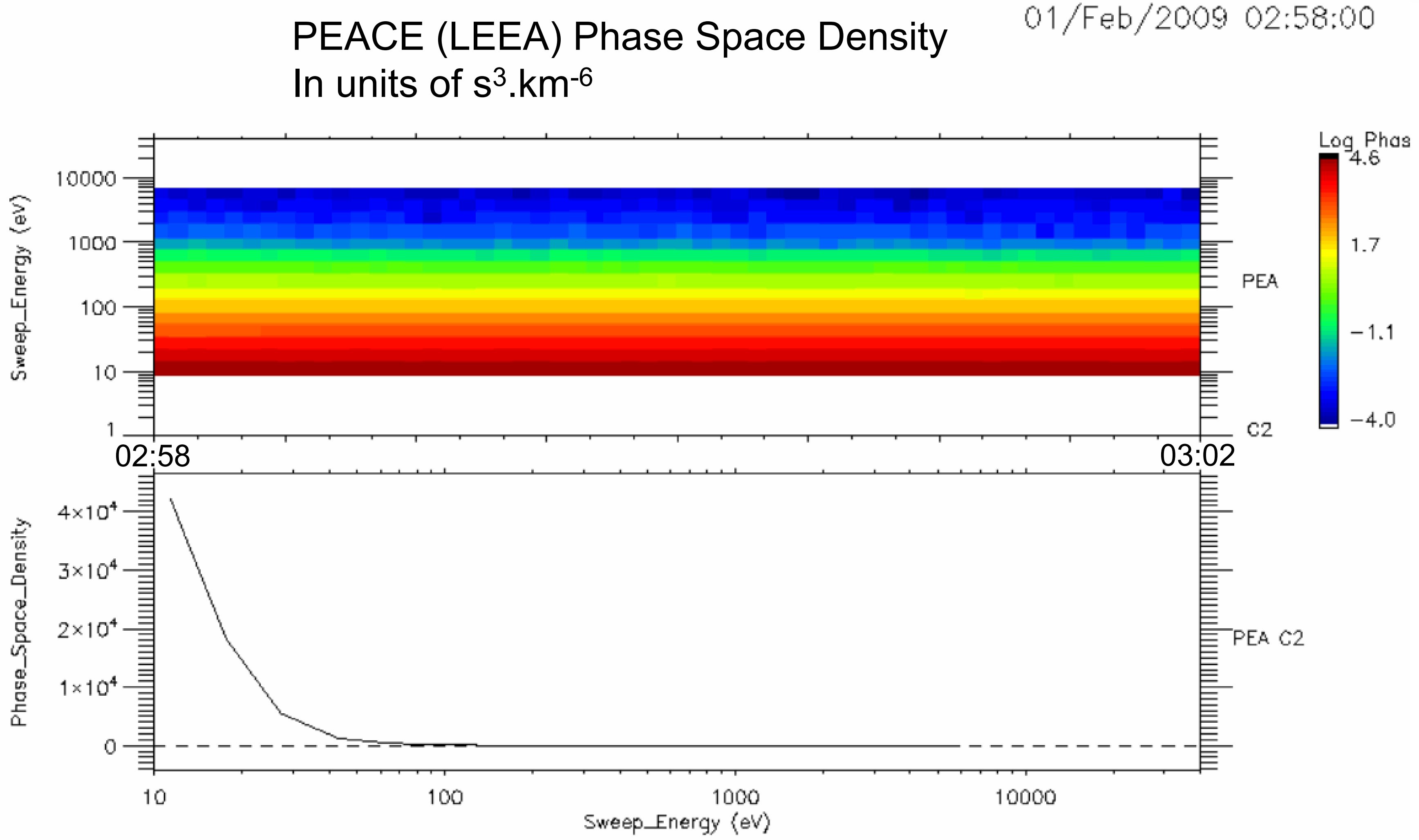




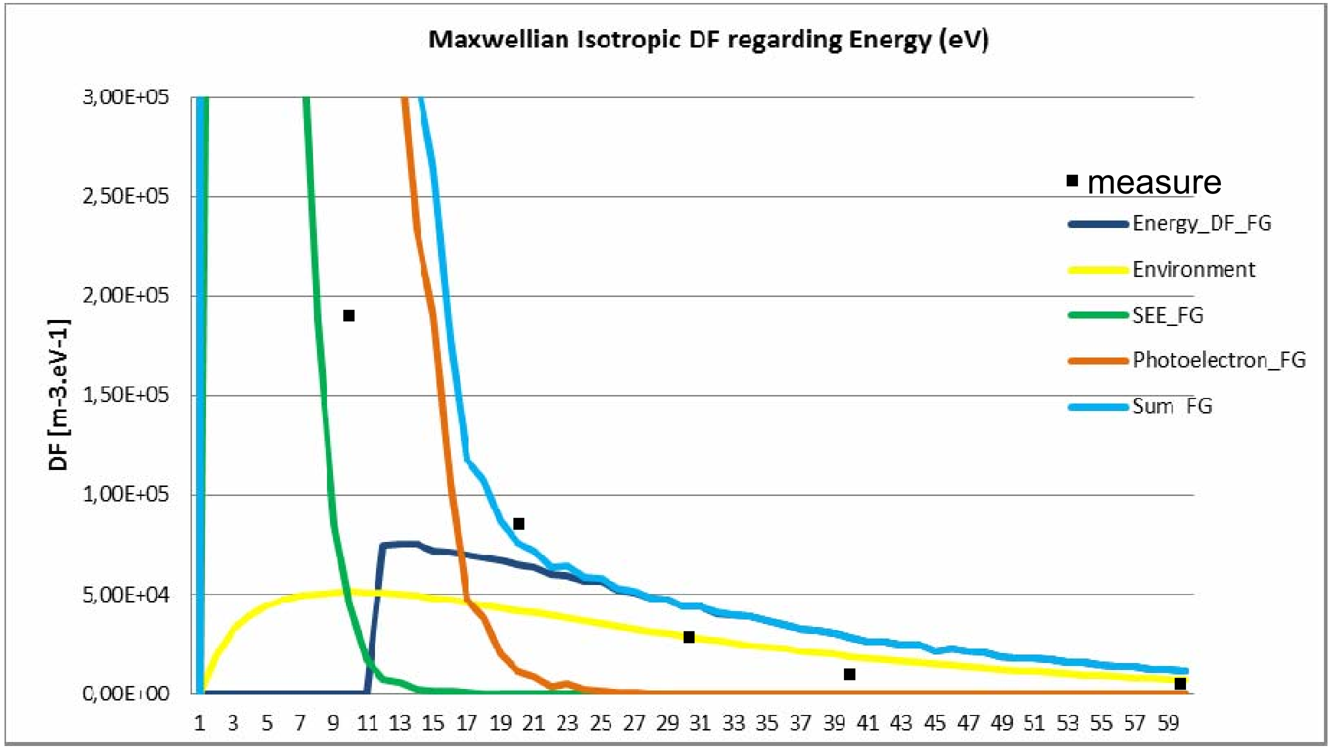
The simulated corrected measurements of pure thermal electrons give a good accuracy with less than 15% of difference with the true injected environment.
The total density (including secondaries) is however estimated.

Cluster CL1: Comparison with real data

PEACE (LEEA) Phase Space Density
In units of s^3.km^{-6}



Cluster CL1: Comparison with real data



Order of magnitude of DF is well reproduced:
Looks like as if part of photoelectrons were considered as ambient by instrument in -flight
Important information to discriminate origin of electrons

Outline

- Team and work breakdown structure
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    - Precision
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    - Pre-defined transient phases
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        - How to mimic scientific particle detectors, Langmuir probes, electric field analyzers
        - Illustrative example of application to Solar Orbiter
    - Unmeshed elements
- Validation campaign
    - Solar Orbiter
    - Cassini
    - Cluster
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Summary 1/2

- SPIS-SCI provides scientists with powerful tools permitting to assess spacecraft cleanliness for low energy plasma measurements
- Evolutions concern a large scope : precision and performance, instrumentation and diagnostics, ambient and secondary particles models, unmeshed elements…
- SPIS-SCIENCE is used to model three scientific missions with various environments and showed capacity to predict SC impact on plasma and instruments behavior
- User interface made more user-friendly in conjunction with SPIS-GEO
- Important Remark : SPIS-GEO, SCIENCE, PROPULSION (AISEPS) have the same code trunk (no fork) thanks to a coordinated activity (progressive merging) between contractors (ARTENUM, ONERA, EADS-ASTRIUM) and ESA teams

Summary 2/2

- Work pending
  - Finish reporting and update documentation
  - SPIS tool with SCIENCE update will be soon delivered to ESA and to the SPINE community
  - Start the one year maintenance

Perspectives

- The exhaustive list of user requirements gathered in this activity may be used to reinforce the code with new models

- Increase the domain of validation by simulating other missions
  - BEPI Columbo
  - JUICE
  - CHAMP/Swarm
  - Demeter
  - Stereo
  - …

- Or other situations
  - Environment parameters
  - Ground plasma chambers
  - Inside detectors
  - …

Publications

Title	Authors	Date	Journal./ Conf
SPIS SCIENCE: modelling spacecraft cleanliness for low-energy plasma measurement	JC Matéo-Vélez et al.	May 2012	Proc. 12th SCTC, May, KittaKyushu, Japan
Scientific spacecraft cleanliness: influence of heliocentric distance	S. Guillemant et al.	May 2012	Proc. 12th SCTC, May, KittaKyushu, Japan to be published next IEEE, sp. issue on Spacecraft Charg..
Electrostatic Cleanliness on Solar Orbiter and its Effect on Plasma Measurements	C. Cully et al.	May 2012	in proceedings of ESA Workshop on Aeropace EMC, Venice, Italy.

SPIS-SCIENCE

Computational tools for spacecraft electrostatic cleanliness and payload accommodation analysis

Final Presentation

ESA Co 4000102091/10/NL/AS
ESTEC, Noordwijk, NL, 20th of March 2013

J.-C. Mateo-Velez[1], P. Sarrailh[1], J. Forest[2], B. Thiébault[2], B. Jeanty-Ruard[2],

A. Eriksson[3], V. Genot[4], S. Guillemant[4], Th. Nilsson[3]

(2) ARTENUM, PARIS
Science & Groupware

ONERA(1)
THE FRENCH AEROSPACE LAB

IRF (3)

IRAP (4)

return on innovation

ESTEC, Noordwijk, NL, 20th of March 2013

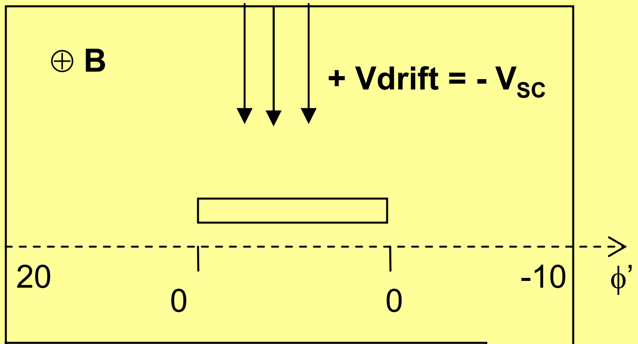
Backup slides

V cross B field

Particle dynamics in R' of spacecraft

$$\dot{x}' = v'$$

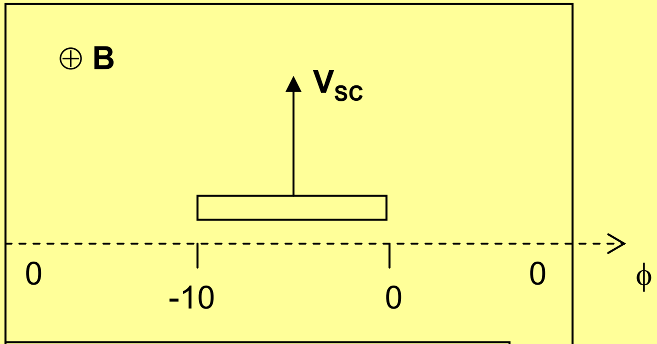
$$\dot{v}' = \frac{q}{m}\left(E + v' \otimes B + V_{SC} \otimes B\right)$$



R' of SC :
- electric field in plasma is modified according to change of referential
- conductive elements are isopotential

Poisson equation in R of plasma
→ BC on spacecraft due to Hall effect

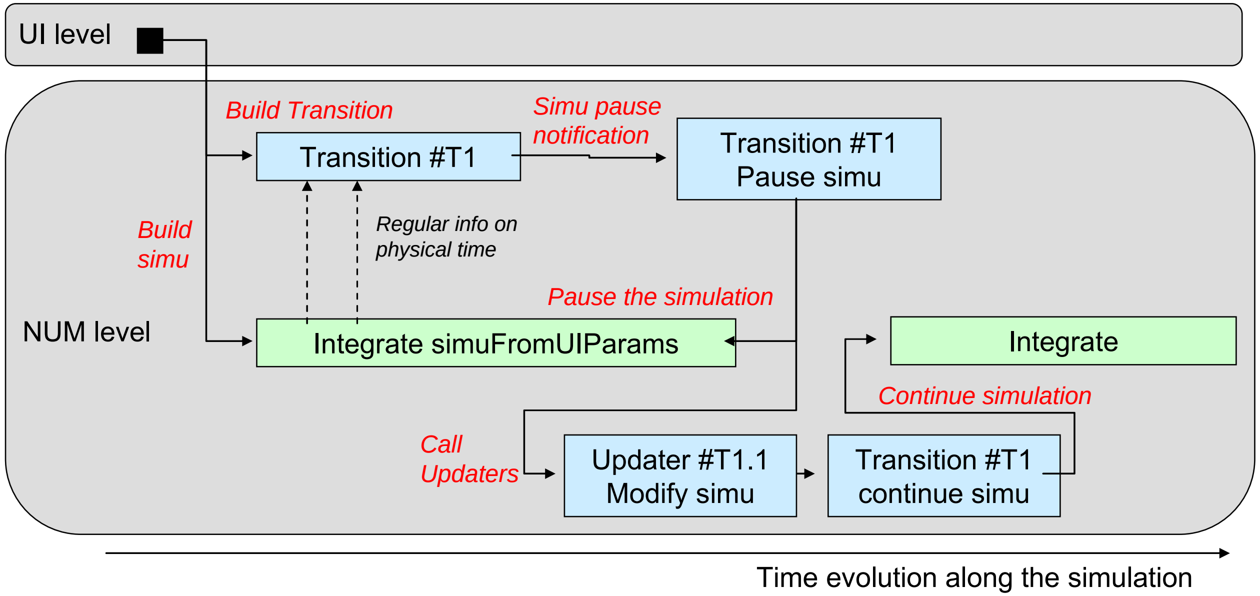
$$\phi_{SC} = \phi_{SC}' + \left(\mathbf{V}_{SC} \otimes \mathbf{B}\right) \cdot x_{SC}$$



R of plasma :
- undisturbed electric field is null
- potential gradient in SC conductors due to Hall effect
- Boltzman equilibrium df is defined in this referential

Transition overview

- Generic classes Transition instantiated and added to the simulation *at the beginning*
- Notification mechanism between *simulation* and *transitions*
- Pre-defined check point times for updating simulation parameters



UI level

Build Transition

Simu pause notification

Transition #T1

Transition #T1
Pause simu

Build simu

Regular info on physical time

Pause the simulation

NUM level

Integrate simuFromUIParams

Integrate

Continue simulation

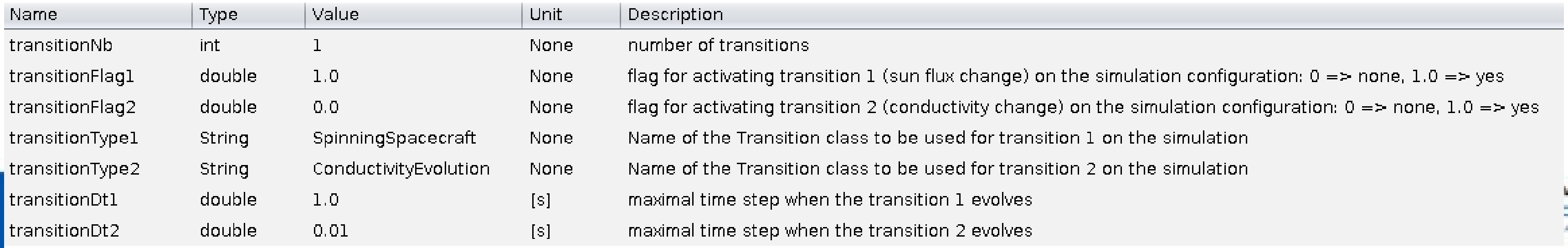
Call Updaters

Updater #T1.1
Modify simu

Transition #T1
continue simu

Time evolution along the simulation

- Use of global parameters : activate, control time steps (important for smooth changes !)



Name	Type	Value	Unit	Description
transitionNb	int	1	None	number of transitions
transitionFlag1	double	1.0	None	flag for activating transition 1 (sun flux change) on the simulation configuration: 0 => none, 1.0 => yes
transitionFlag2	double	0.0	None	flag for activating transition 2 (conductivity change) on the simulation configuration: 0 => none, 1.0 => yes
transitionType1	String	SpinningSpacecraft	None	Name of the Transition class to be used for transition 1 on the simulation
transitionType2	String	ConductivityEvolution	None	Name of the Transition class to be used for transition 2 on the simulation
transitionDt1	double	1.0	[s]	maximal time step when the transition 1 evolves
transitionDt2	double	0.01	[s]	maximal time step when the transition 2 evolves