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Effect of Different Physical Models on PIC Plume Calculation for Hall Effect Thrusters

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5th SPINE MEETING

SPACECRAFT PLASMA INTERACTION NETWORK IN EUROPE

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Presentation Overview

- Introduction
- PICPluS 2: code overview and modelling options
- Code validation and study of the effect of:
  - Quasi-neutrality hypothesis
  - Electron temperature model
  - Collisions model
- Preliminary results on SMART-1 test case
- Conclusions

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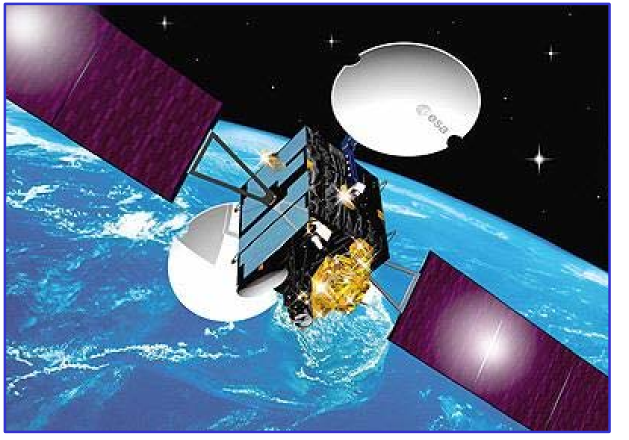
Introduction

Electric thrusters for spacecraft

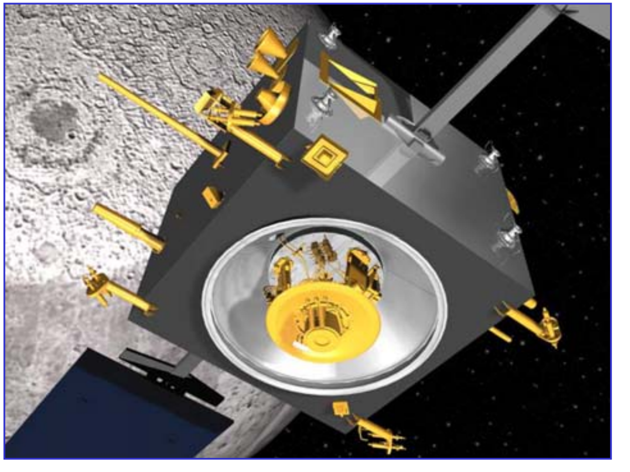


- Hall Effect Thrusters and Gridded Ion Engines are consolidating as two of the most effective new spacecraft technologies.

- Plasma thruster integration on spacecraft poses some problems that simulation can help to sort out.

- Centrospazio-CPR and Alta S.p.A. developed a 2D hybrid PIC code for plume simulation that was validated against literature data and experiments in Alta facilities.

- The PICPluS 2 code was used to preliminarily analyse SPINE WG2 test case: SMART-1.



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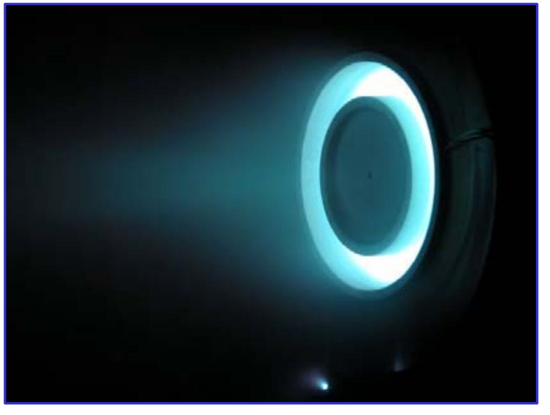
Centrospazio – Alta EP Activities (1)

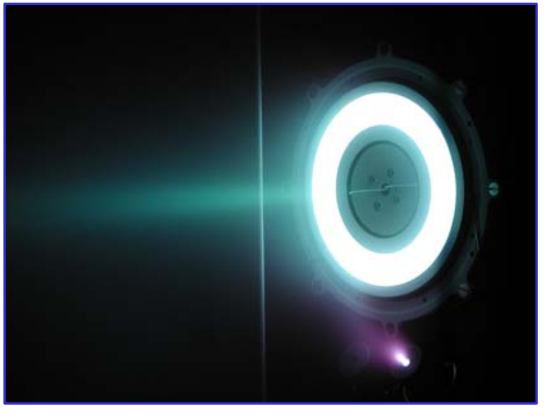
EP activity

- Presently involved in virtually all HET/GIE development efforts in Europe
- Own technology (HET, DS-HET) or in partership with SNECMA Moteurs, Astrium Ltd & Gmbh, QinetiQ, …
- Operating a set of unique EP facilities, 10 UHV test chambers with size up to 5.7 x 12 m and pumping speed up to 1,500,000 l/s [Xe]

Alta 700 W HET, lab model



Alta 5 kW HET, lab model



Alta-Astrium 2 kW HET, EQM

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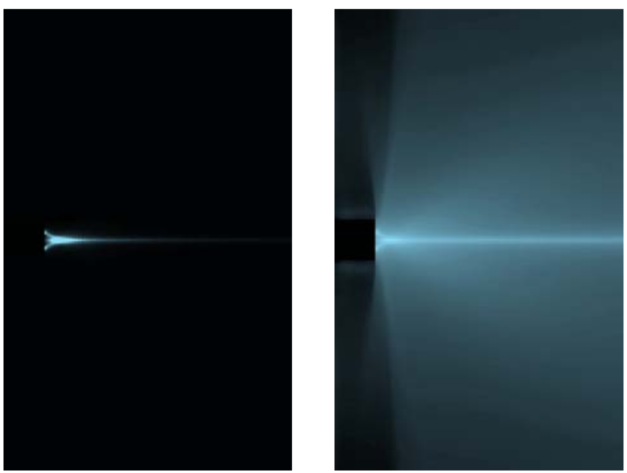
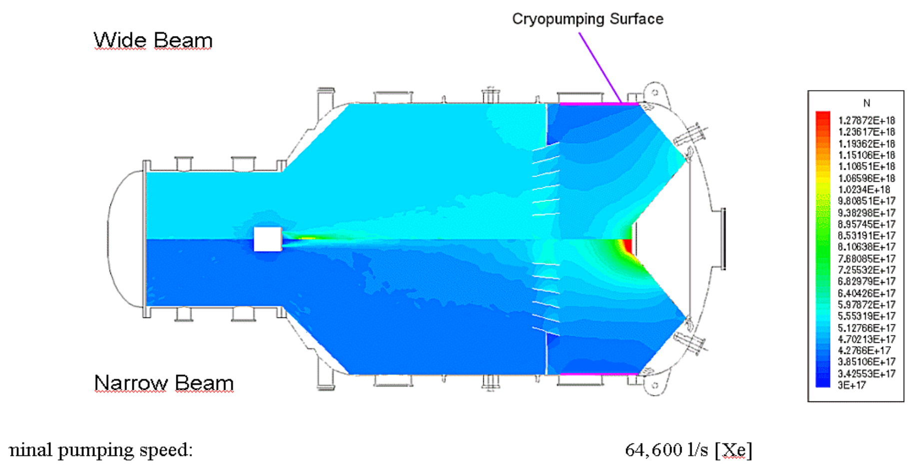
Centrospazio – Alta EP Activities (2)

Computational activities

- EP computational activity centred on plume simulation, integration with spacecraft, and complex laboratory configuration simulations
  - hybrid PIC (kinetic ions+non isothermal fluid electrons), 2D axially symmetric, non neutral (SOR Poisson solver) for accurate plume calculation and impact of backflow of vehicle surface (simple geometries)
  - charge neutral DSMC, 2D axially symmetric, for analysis of complex configurations, e.g. thruster in vacuum chamber with realistic pumping arrangement





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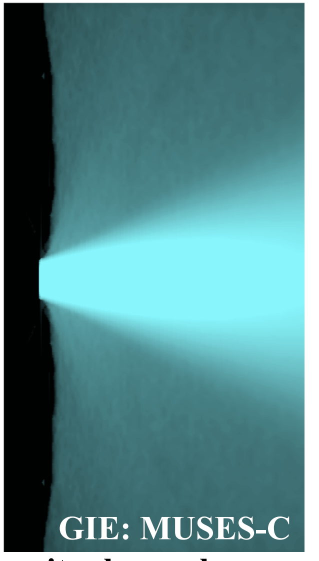
PICPluS 2 – Characteristics (1)

PICPluS features

- 2D axisym, 3 components of velocity
- Structured grid with variable cell size (scaled to local Debye length)
- Xe+, Xe++, Xe simulated particles
- Elastic, CEX collisions (3 different algorithms)
- Effect of background pressure and vacuum chamber walls
- Input from experimental distributions or from external simulations (magnetostatic FEM)
- Simulated engines: Hall Effect Thruster or Gridded Ion Engine



Ion Number Density: log scale

Particle Species	PICPluS v.2.0
Xe^{+} ions	Simulated
Xe^{+2} ions	Simulated
Xe^{+n} ions	Can be added
Xe atoms	Can be added
CEX ions	Simulated

Particle species presently simulated

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PICPluS 2 – Characteristics (2)

Algorithms

- Particle in Cell with Ruyten weighting
- Nanbu-Kitatani TPMC or two different versions of VHS MCC collisions (from Nanbu and Szabo)
- 3 models for collision cross-sections
- Potential from Poisson solver (SOR method, Chebishev acceleration, checker-board ordering) or quasi-neutrality (Boltzmann relation)
- 3 models for electron temperature (constant, adiabatic, first order Chapman-Enskog) or experimental distribution
- Full DSMC option for neutrals
- All input fields/distributions from experiments, simulations, or simplified models

$$T_e = const.$$

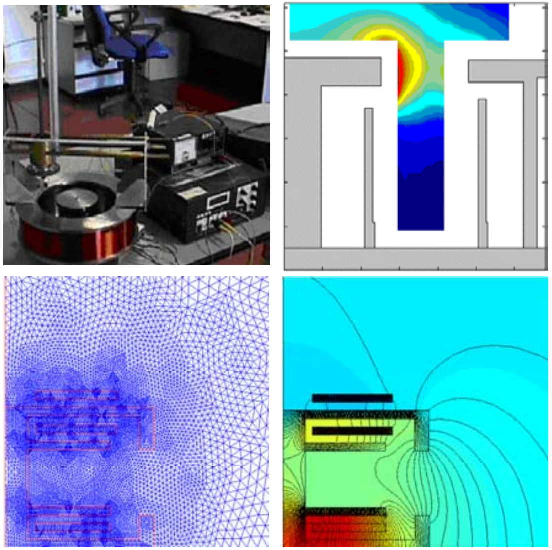
$$\nabla^2 (T_e) = 0$$

Pre-processed

$$T_e(r,z) = T_{ref} \left(\frac{n_e(r,z)}{n_{ref}} \right)^{\gamma - 1}$$

Updated step-by-step

Electron temperature models



Magnetic field: from experiments or simulations

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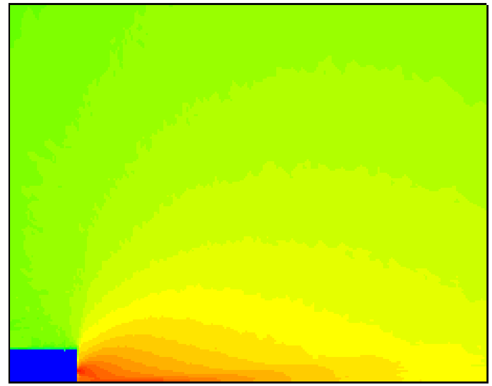
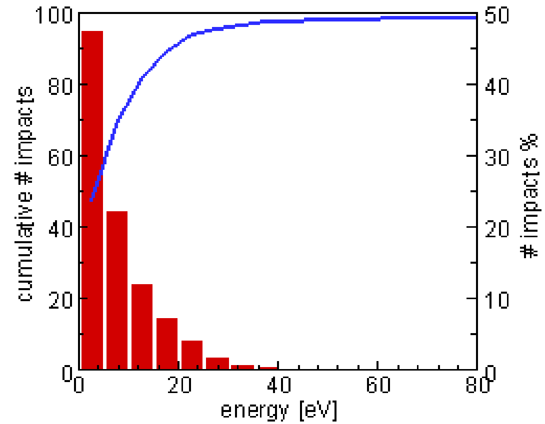
PICPluS 2 – Characteristics (3)

Outputs

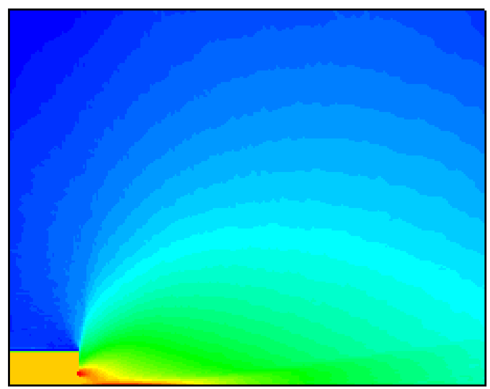
- Instantaneous and averaged fields at steady state (species by species)
- Instantaneous and averaged thrust and beam ion current
- Ion current density measured with virtual Faraday's probe rakes
- Ion beam energy distribution measured with virtual RPA probes
- Impact history on (possible) solid external surface and related statistics



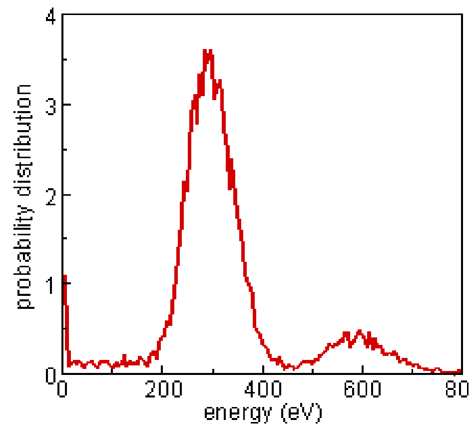
Ion number density



Back-flow impact energy



Plasma potential



Ions energy distribution function

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PICPIuS 2 Validation – Test Cases

Code results compared with similar programs and experimental data from literature and in-house tests:

- Four test cases for HET and one for GIE
- All test cases achieved stationary conditions in about 40,000 time steps
- Computed thrust and ion beam current within ±1% of measured values
- Peak on axis (GIE) and slightly low current density at high angles (HET) are usually seen

Thruster Model	SPT-100	SPT-100	SPT-100	Alta-XH5	MUSES-C
Mass Flow Rate [mg/s]	4.99	5.12	5.084	9.2	0.21
Discharge Voltage [V]	300	300	300	350	1500
Discharge Current [A]	4.5	4.5	4.5	11.16	0.14
Background Pressure [mbar]	$2.9 \cdot 10^{-6}$	$4 \cdot 10^{-5}$	$5.32 \cdot 10^{-5}$	$8.32 \cdot 10^{-5}$	$2.0 \cdot 10^{-6}$
Thrust [mN]	84.54	90.39	84.07	181.6	8.85
Ion Beam Current [A]	4.61	4.82	3.87	8.96	0.149
Domain Size [m]	1.2 x 1.5	1.2 x 1.5	1.2 x 1.5	1.0 x 1.5	1.0 x 2.5
Total Particle number	$\sim 1. \cdot 10^{6}$	$\sim 1. \cdot 10^{6}$	$\sim 1. \cdot 10^{6}$	$\sim 1.5 \cdot 10^{6}$	$\sim 0.5 \cdot 10^{6}$
Reference	Manzella *1995*	Kim *1996*	King *1998*	Biagioni *2003*	Matsushiro *2003*

Test case matrix

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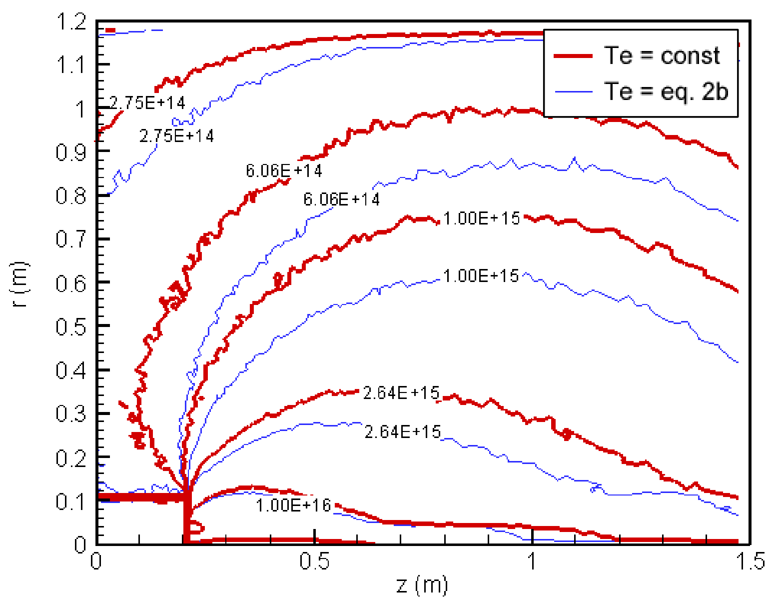
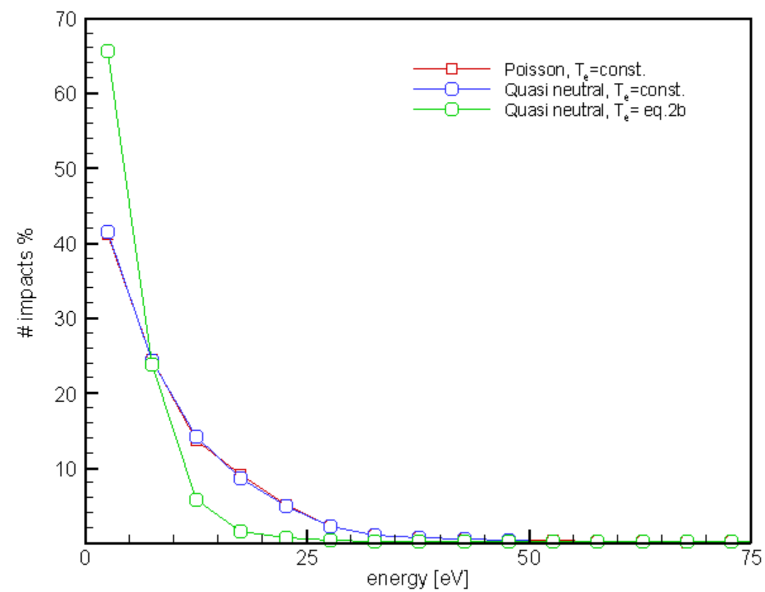
PICPluS 2 Validation: Remarks (1)

- Injection ion temperature has no big impact on results
- Electron temperature has significant effect, especially for ion distribution and impact energy of backflow CEX
- Divergence angle at inflow boundary has largest impact on current density and plasma field



Effect of T_e on ion number density



Effect of T_e on back-flow impact energy

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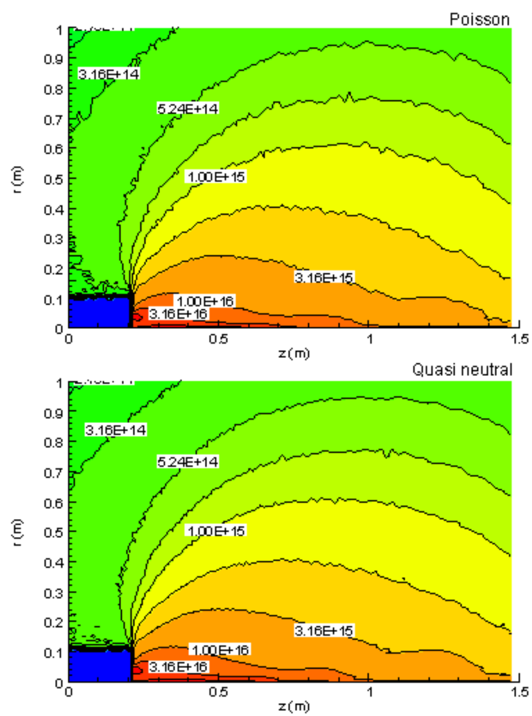
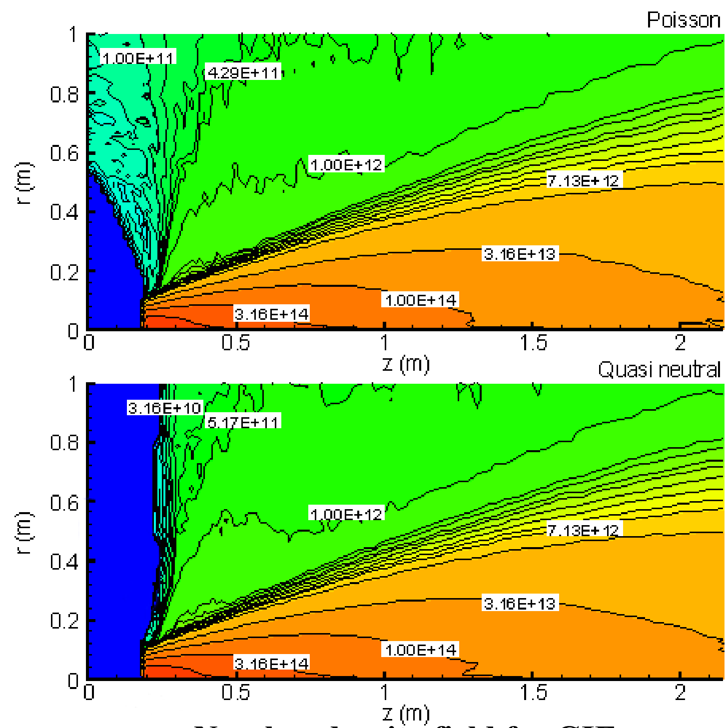
PICPluS 2 Validation: Remarks (2)

- HET: no significant difference between Poisson solver and QN approach
- GIE: differences in back-flow region, QN under-predicting ion density



Number density field for HET



Number density field for GIE

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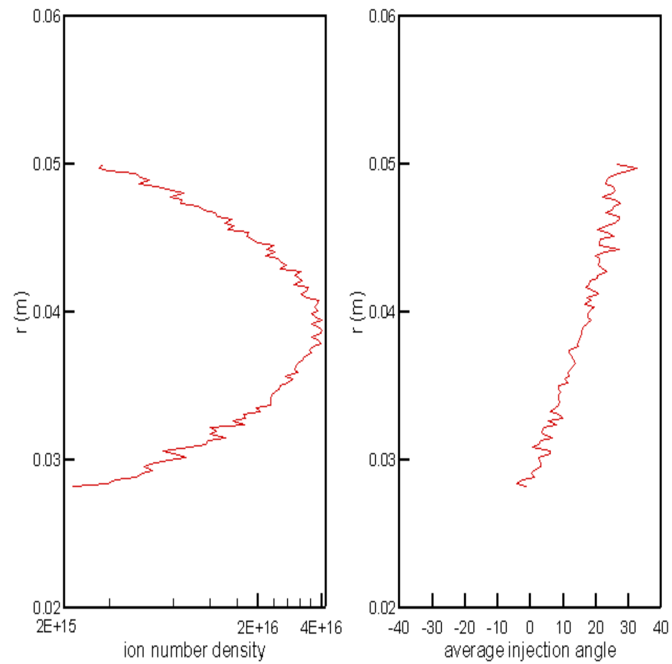
PICPluS 2 Validation: SPT-100 Model

Optimal injection distribution (inflow boundary) fitting near and medium distance measurements of current density:

- Gaussian distribution for number density
- Linear distribution (with radius) for average divergence angle
- Gaussian distribution of actual divergence angle around the average value

Good agreement for different background pressure and test conditions (in particular different fraction of double ionized propellant)



Optimal injection distribution for SPT-100

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Effect of Collision Models (1)

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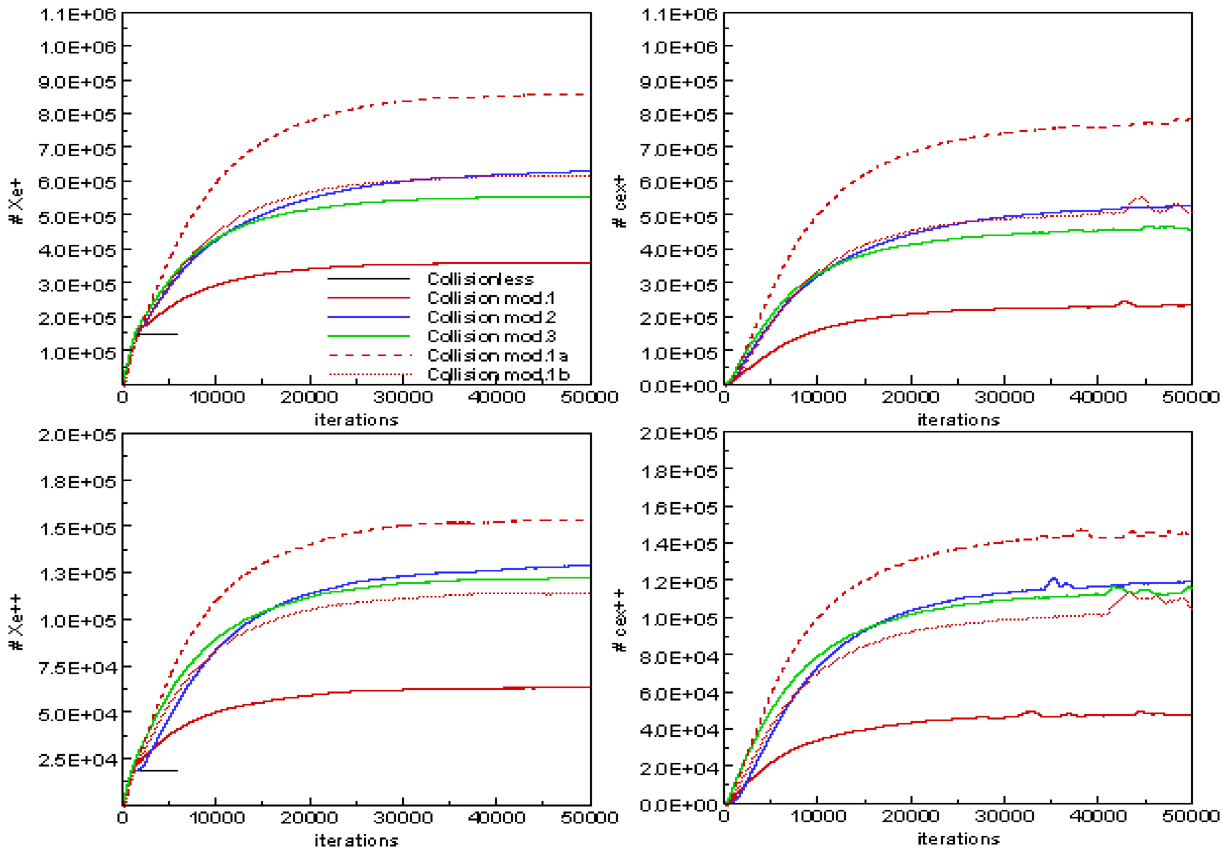
Convergence histories

- Time to steady state is approximately constant.
- Number of molecules at steady state is very similar for the two VHS models but not for Nanbu's TPMC.
- TPMC results are very similar to the other two models if a β_∞ value of 4.5 is used instead of the nominal 3.



Convergence histories obtained for a collisionless plasma, and using the three available collision models. Model 1: β_∞=3; Model 1a: β_∞=6; Model 1b: β_∞=4.5

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Effect of Collision Models (2)

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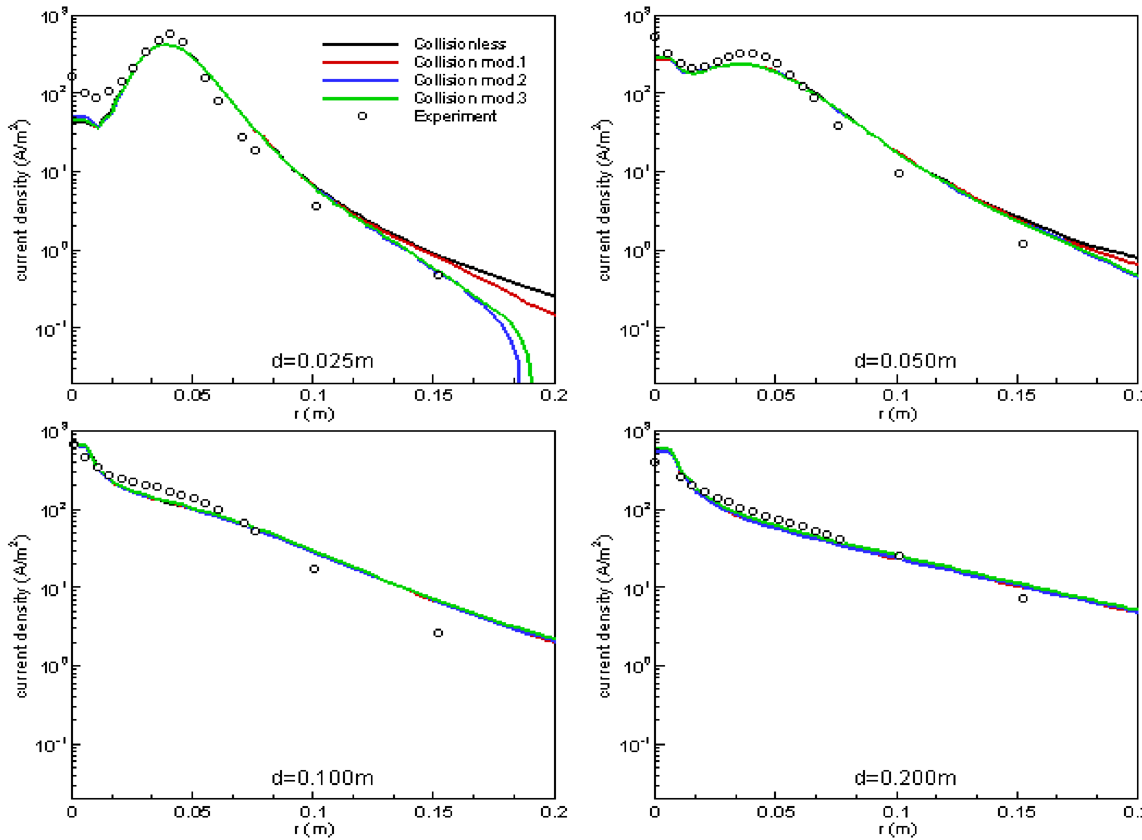
Near-field current densities

- Small influence of collision model
- At very near distances (d=0.025m) lower collision rates result in a higher beam divergence



Comparison of current densities computed with available collision models with the experimental data of Kim

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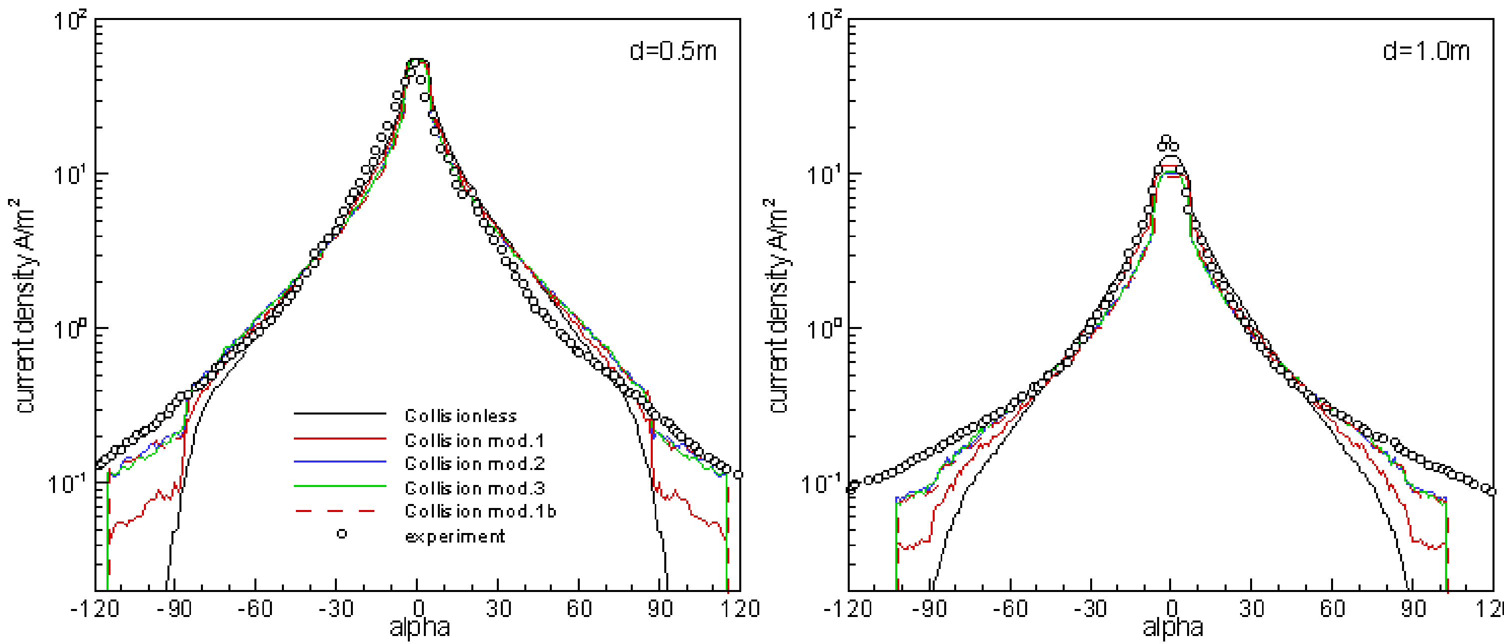
Effect of Collision Models (3)

Far-field current densities



- A correct estimate of collision rates and post collision velocities is essential to predict current densities at high angles (>45°)
- Models can be to some extent "tuned" with the aid of available experimental data set

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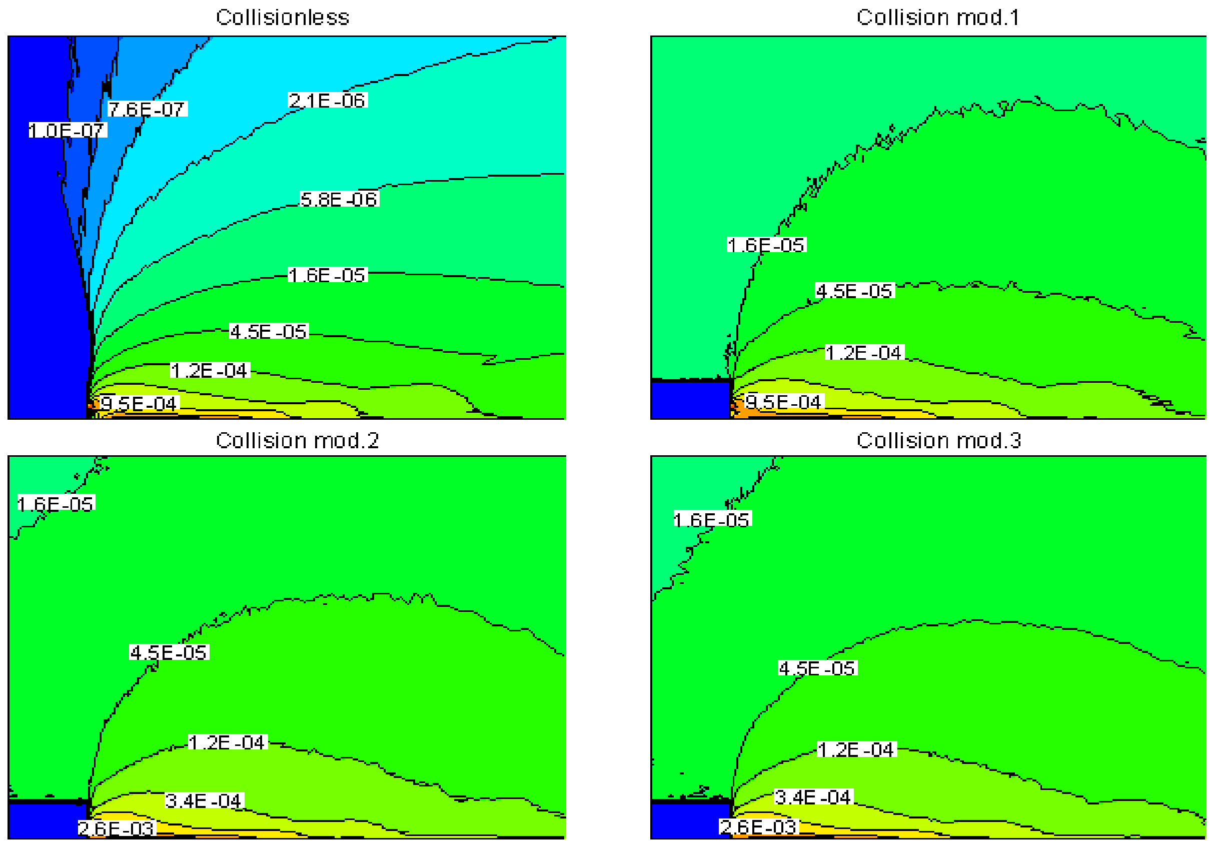
Effect of Collision Models (4)

Charge density distribution

- The collision model is important to obtain satisfactory predictions of number densities and kinetic energy in the backflow region, dominated by the presence of slow CEX ions

- This allows to obtain correct estimates of plume-satellite impingement



Contour lines of electric charge density computed for a collisionless plasma, and using the three available collision models

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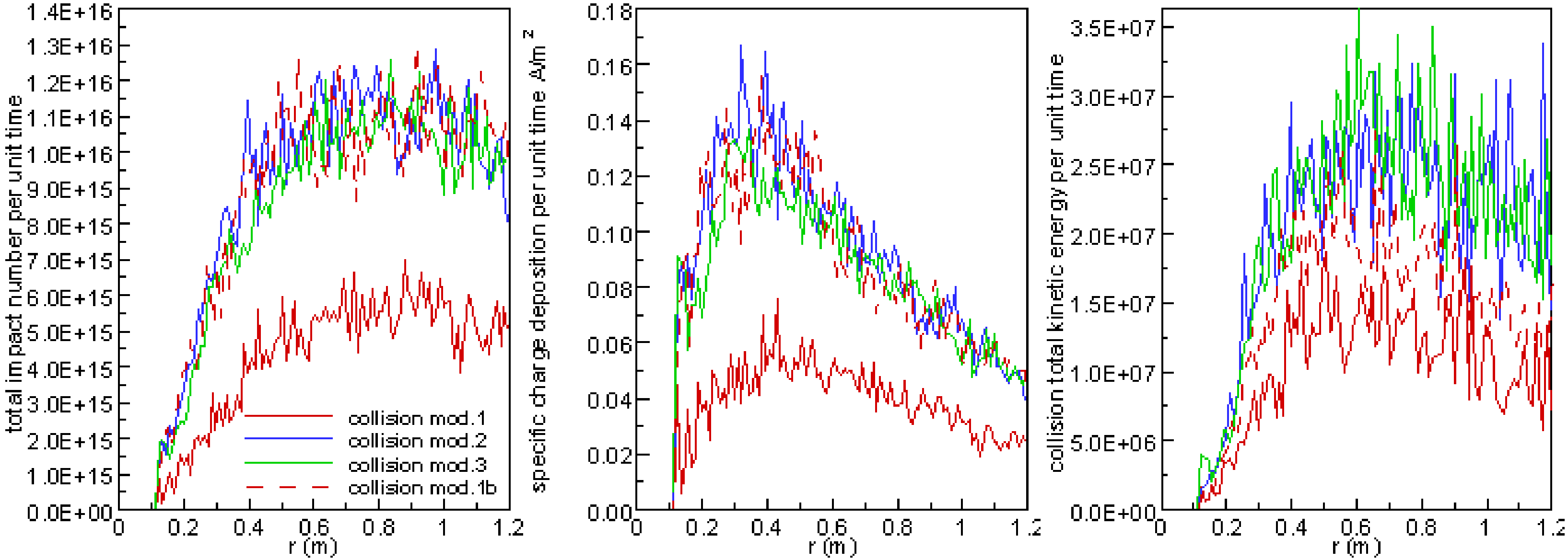
Effect of Collision Models (5)

Interaction with spacecraft surfaces

- Values of number of impacts and subsequent charge deposition, and characteristic impacts kinetic energies, are correlated with the adopted collision model.



Impacts number per unit time (left), specific charge deposition (center) and collisions kinetic energy per unit time per macro-particle (right) obtained with the three available collision models; Model 1: β_∞=3; Model 1b: β_∞=4.5

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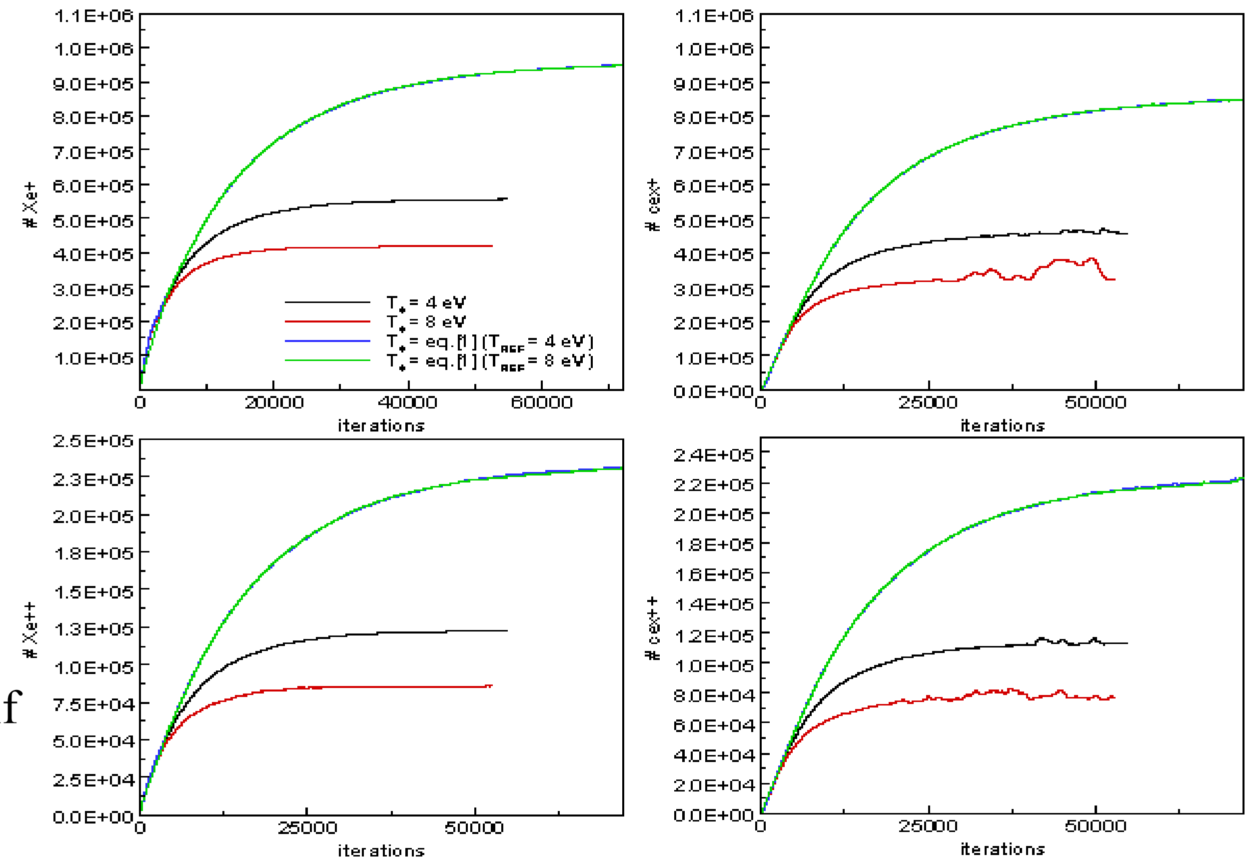
Effect of Electron Temperature Models (1)

Convergence histories

- Time to steady state increases significantly if electron temperature is not constant.

- Number of molecules at steady state increases significantly if electron temperature is not constant

- No big changes with $T_e ref$ if the adiabatic model is used.



Convergence histories obtained for constant electron temperature (T_e = 4/8 eV) and adiabatic electron temperature (T_{REF} = 4/8 eV)

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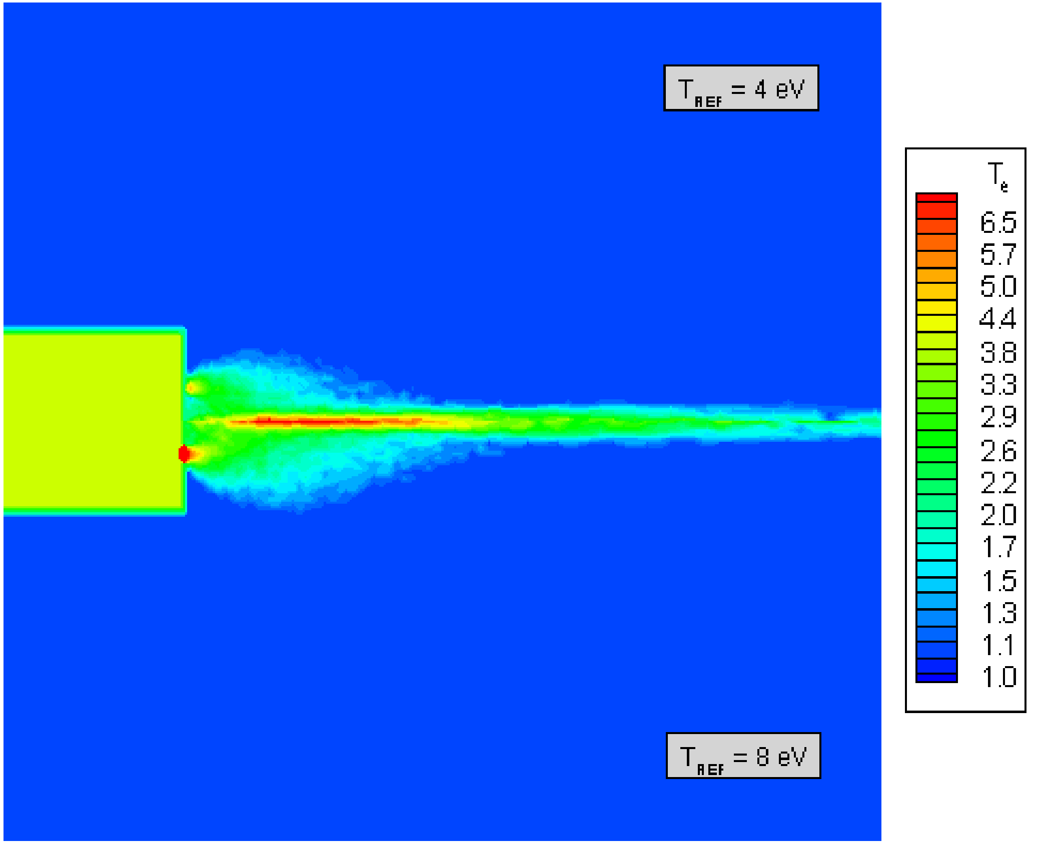
Effect of Electron Temperature Models (2)

Computed temperature fields



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Effect of Electron Temperature Models (3)

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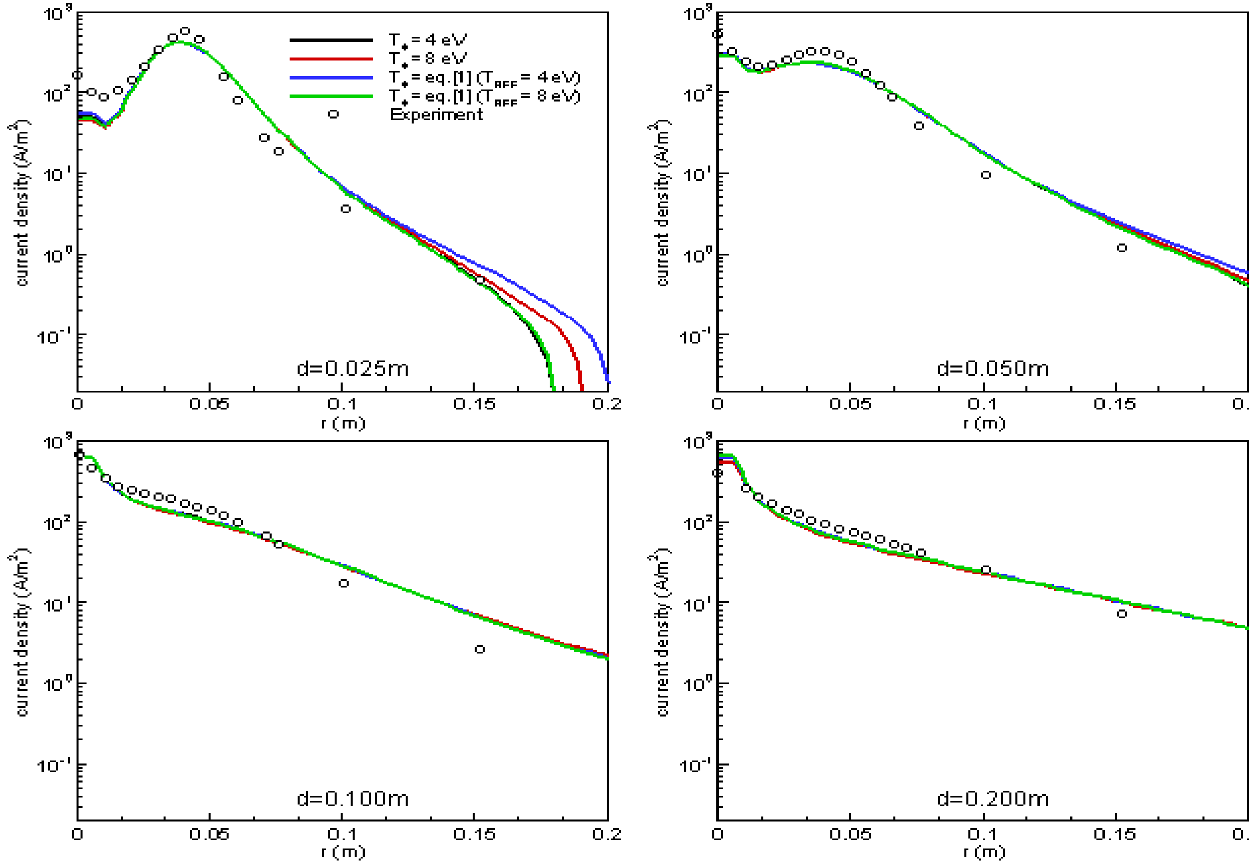
Near-field current densities

- Small influence of electron temperature model can be observed



Comparison of current densities computed with the different electron temperature models with the experimental data of Kim

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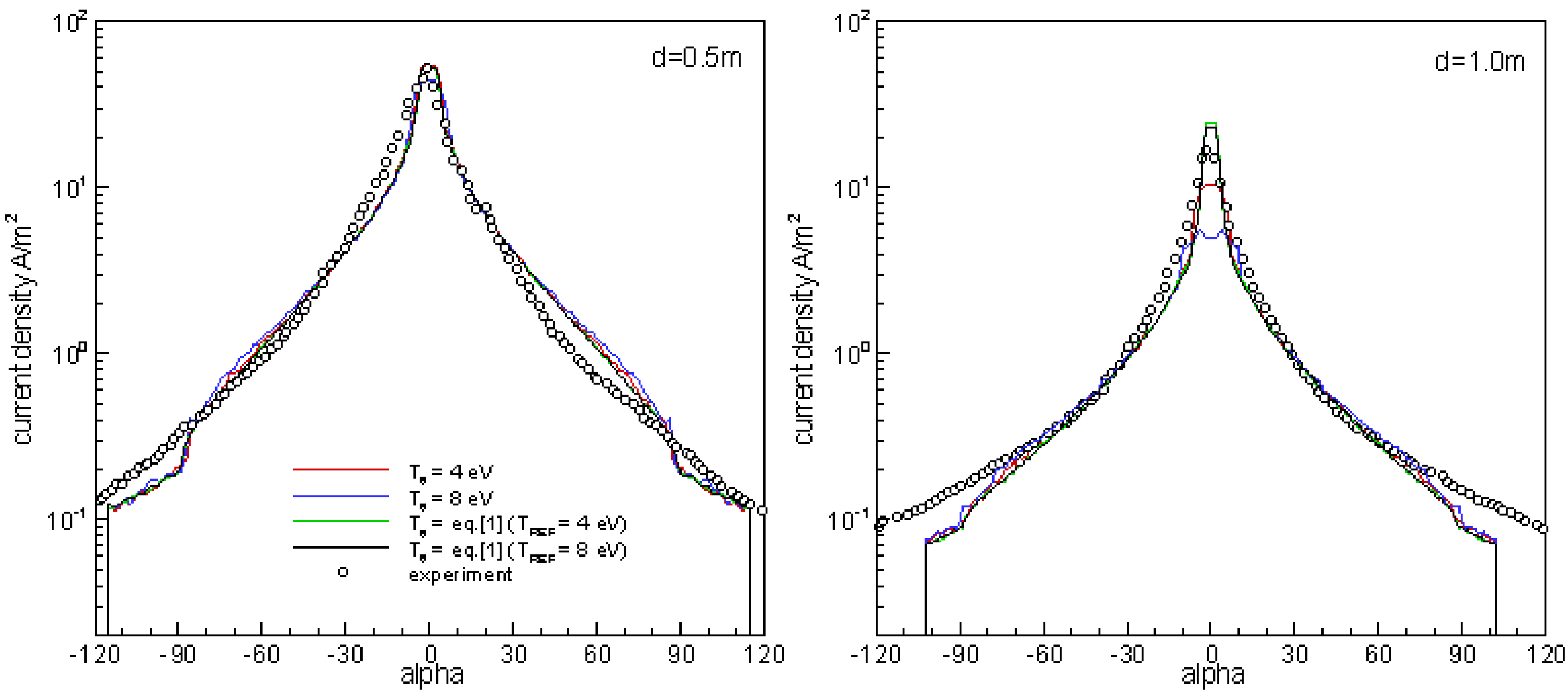
Effect of Electron Temperature Models (4)

Far-field current densities



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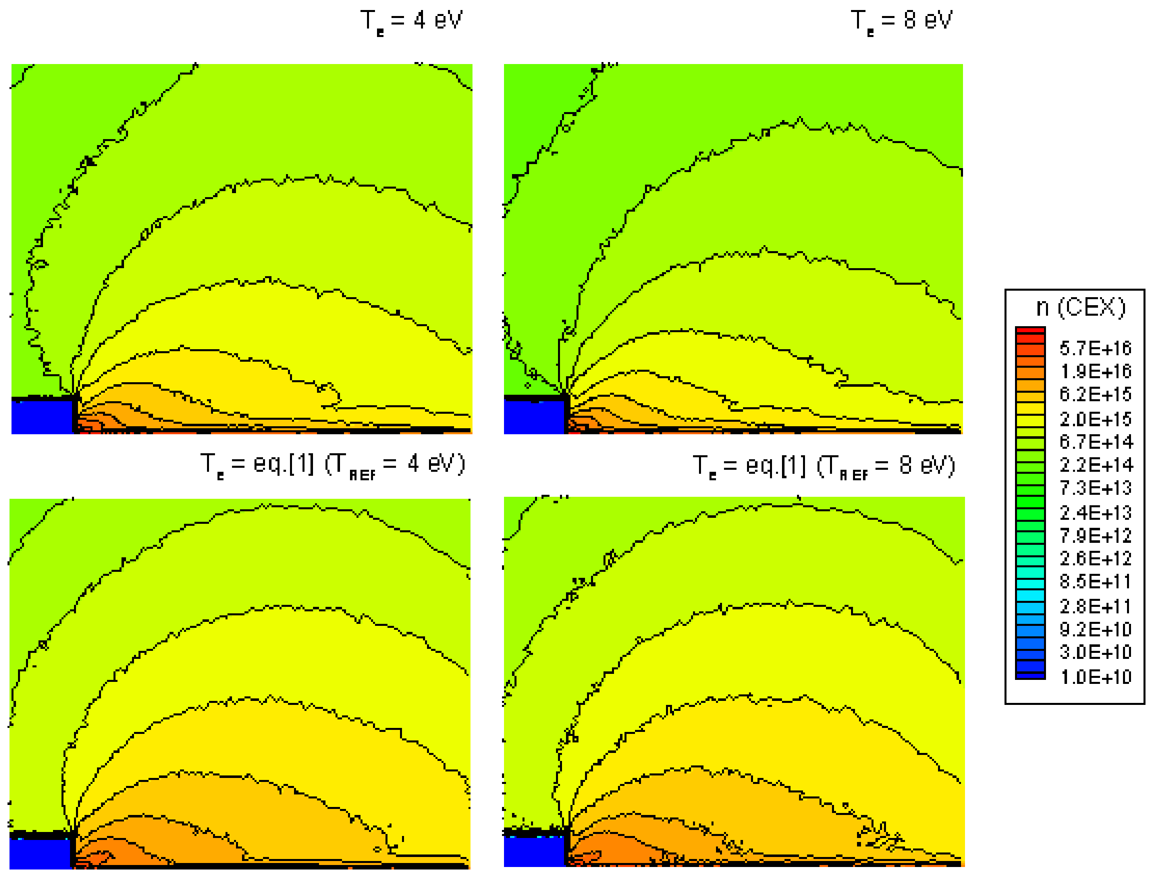
Effect of Electron Temperature Models (5)

CEX ions distribution

• Using an adiabatic equation results in higher CEX production rates

• CEX number densities are higher both inside the plume and in the backflow region

• No significative differences are observed when the reference electron temperature is changed from 4 eV to 8 eV



Contour lines of CEX number densities obtained for constant electron temperature (T_e = 4/8 eV) and adiabatic electron temperature (T_{REF} = 4/8 eV)

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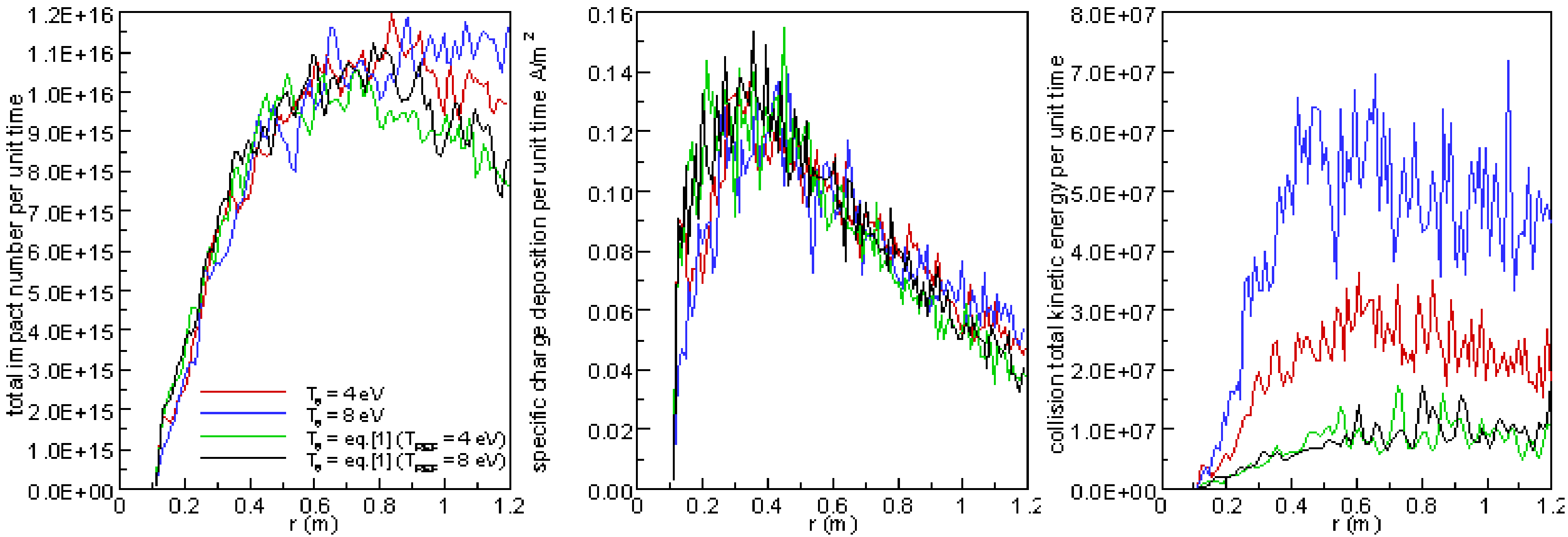
Effect of Electron Temperature Models (6)

Charge deposition and collisions energy spatial distributions

• Number of impacts and subsequent charge deposition are similar using constant or variable electron temperature models

• In the latter case, lower current densities can be observed at higher distances from thruster axis, and the impacts kinetic energies are lower, being directly related with the local electron temperature



Impacts number per unit time (left), specific charge deposition (center) and collisions kinetic energy per unit time per macro-particle (right) obtained with the different electron temperature models

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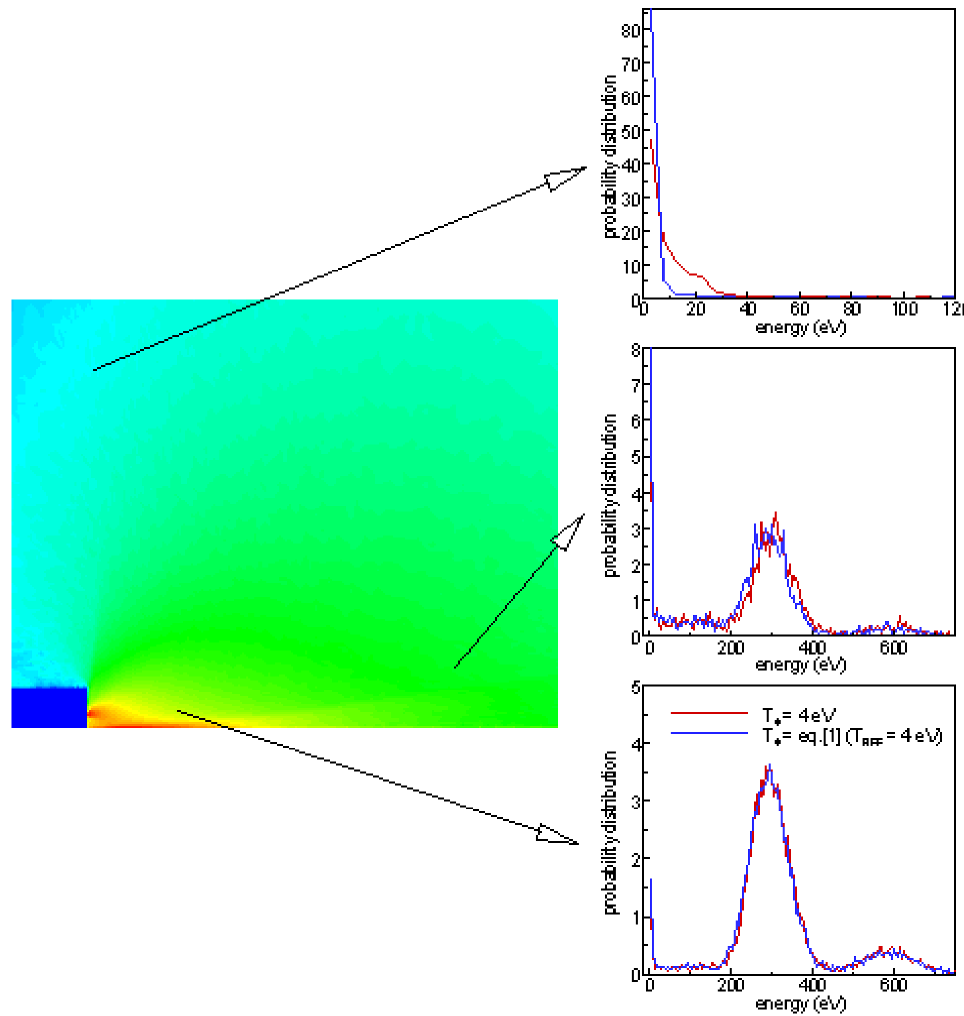
Effect of Electron Temperature Models (7)

Beam ion population: energy distribution function

- The second peak due to double charged ions can easily be recognized in the near-plume region

- Again, it can be seen how the adiabatic temperature model results in less energetic CEX ions in the backflow region



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SMART-1: Preliminary Results (1)

Thruster working conditions

Mass flow rate = 4.21 10^{-6} kg/s (from anode)

Discharge voltage = 350 V

Discharge current = 3.47 A

Thrust = 72.1 mN

Background pressure = 0 (case 1)

10^{-2} Pa (case 2)

Input parameters and modeling options

Ionization efficiency = 90%

Double charged ions = 25%

Electron temperature = eq.[1] (T_{REF} = 4 eV, n_{REF} = 1.8 10^{16})

Potential field: quasi-neutrality hypotesis

Collision model: 3 (Szabo VHS)

Plume neutrals distribution pre-computed using DSMC approach

Injection conditions as used for SPT-100

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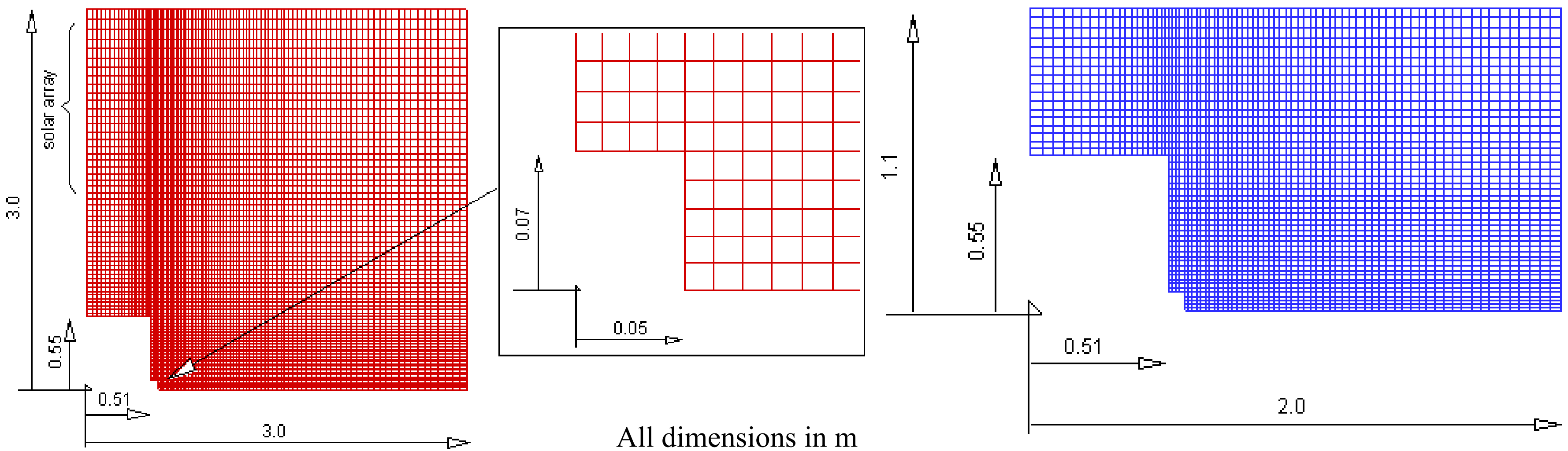
SMART-1: Preliminary Results (2)

2D axysim geometry models

• Configuration with deployed solar panels

• Configuration with folded solar panels within vacuum chamber



All dimensions in m

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SMART-1: Preliminary Results (3)

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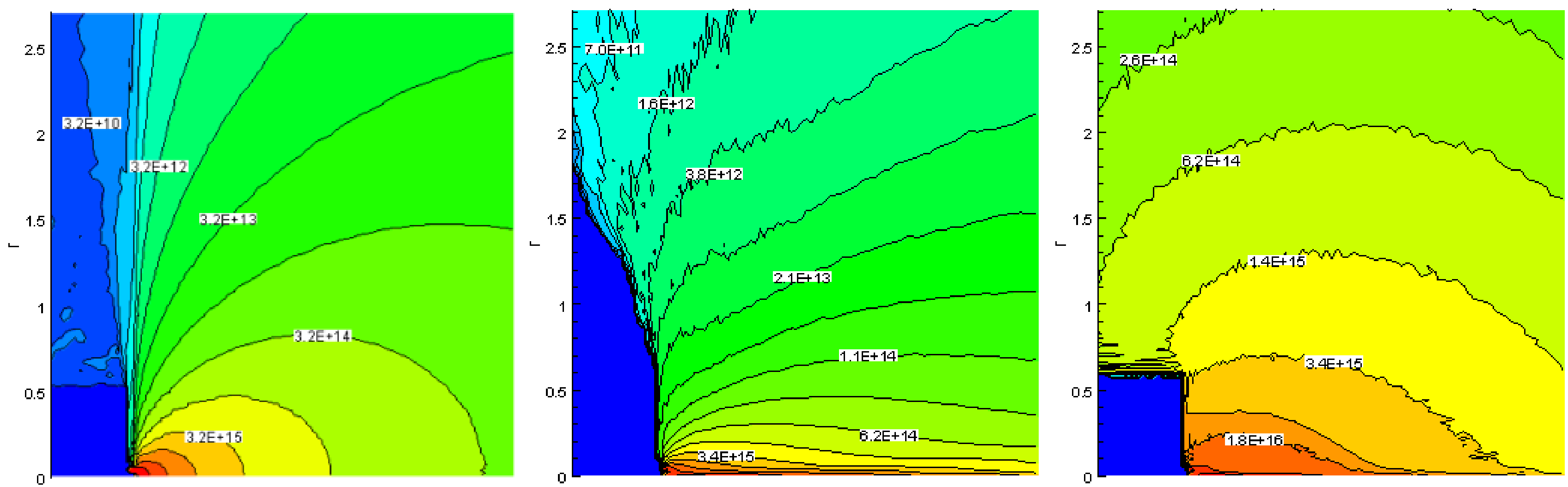
Ion density

- The plume of neutrals exiting the thruster was pre-computed using the full DSMC option
- Drastic changes in plume shape with background pressure
- Ion impingment on back surface overlap very close to solar panel surface



DSMC computed plume neutrals   Ion density: Low Pressure   Ion density: high pressure

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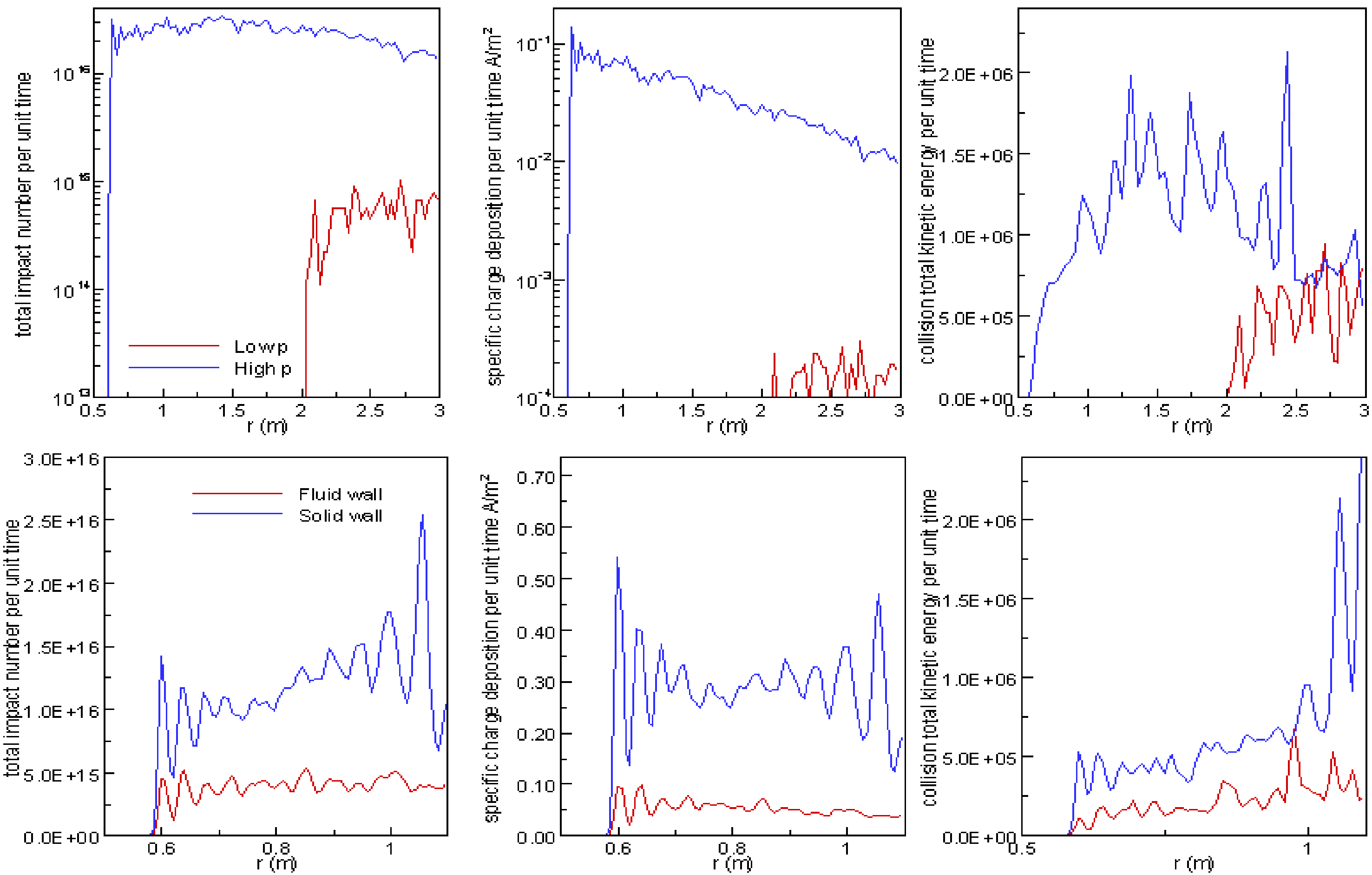
SMART-1: Preliminary Results (4)

Charge deposition and impact energy spatial distributions



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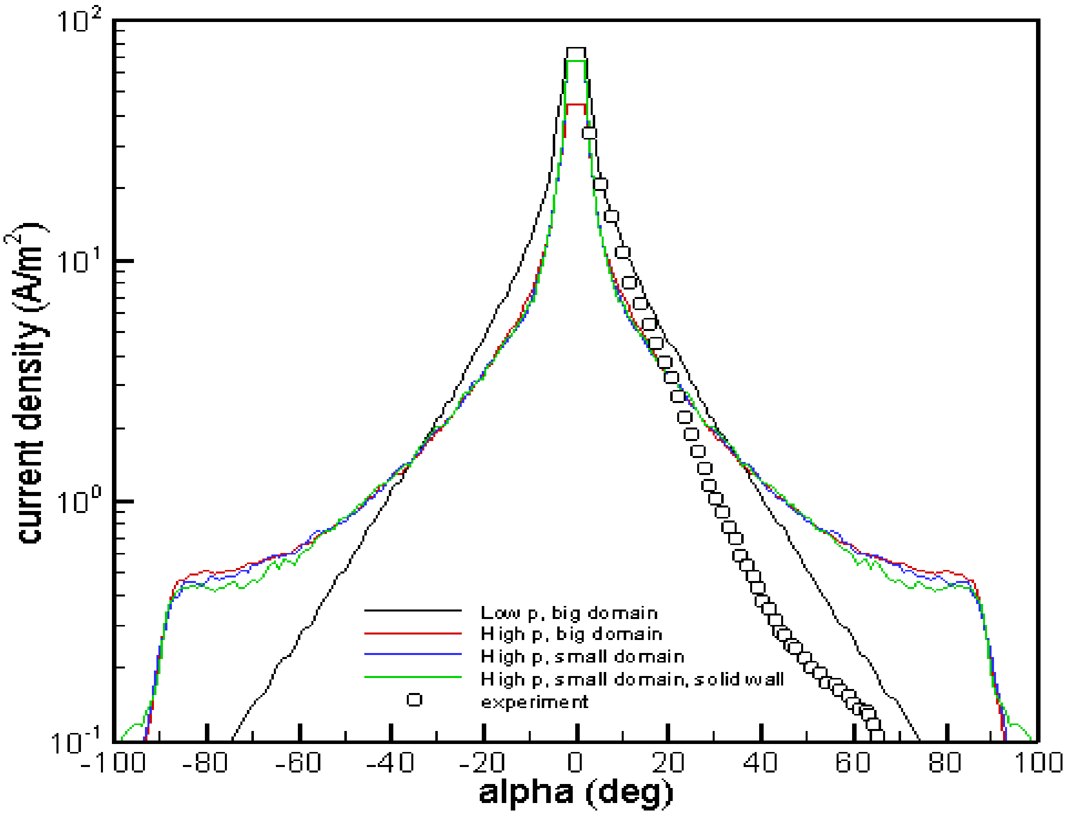
SMART-1: Preliminary Results (5)

Current density (d=0.65 m)



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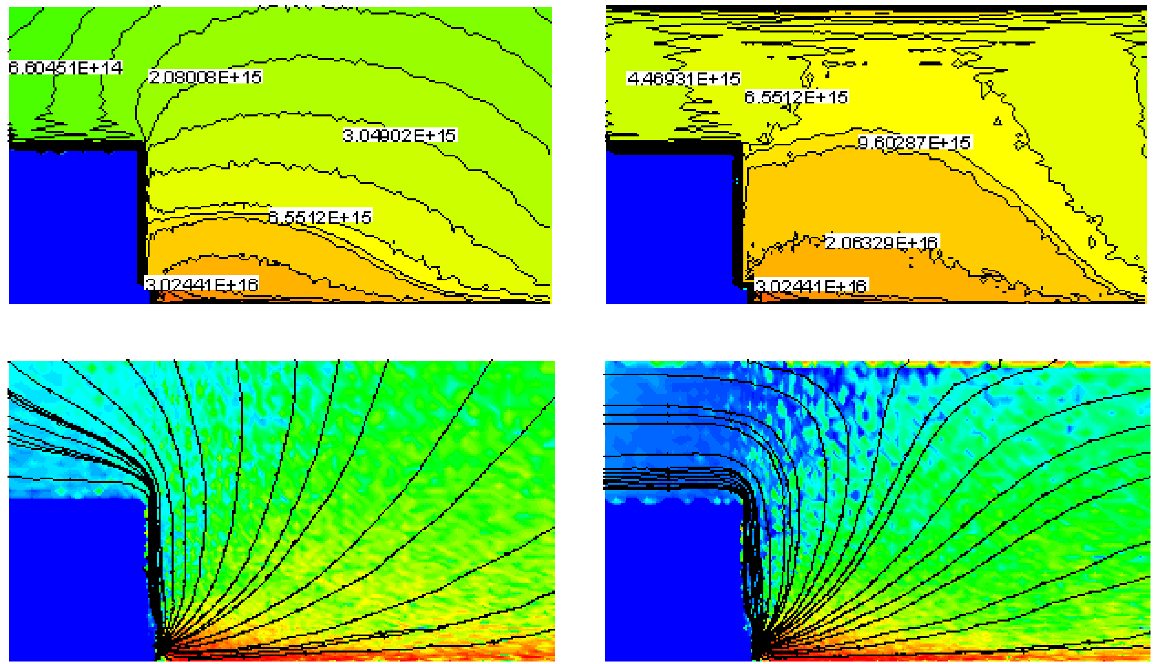
SMART-1: Preliminary Results (6)

Solid walls

- Plume shape is heavily influenced not only by background pressure but also by vacuum chamber solid walls.
- Ion trajectories and energy vary greatly in the two cases.
- Ion current density does not change much, though, due to the fact that the vast majority of ions are very slow CEX.



Ion number density (up) for the high pressure case without and with vacuum chamber solid walls; Ion stream lines plotted on ion energy in the two cases (down)

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PICPluS – Future Developments

Code Developments

- Upgrade to 3D configurations (3D version presently under alpha testing)
- Routines for plasma-wall interaction
- Routines for re-deposition of sputtered particles (DSMC method)
- Extension to HET inner channel (ionization, acceleration, …, presently under alpha testing)

New Test Cases

- Double Stage HETs (collaboration with SNECMA Moteurs)
- HET Beam steering (3D, collaboration with SNECMA Moteurs)
- HET cluster on realistic geometry (3D)
- SMART-1 (3D, SPINE WG2)

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Conclusions (1)

- Centrospazio-CPR and Alta have developed and validated a two-dimensional hybrid PIC code for plasma thruster plume simulations. The code allows to use several different physical models and algorithms, therefore enabling the user to understand their influence on results.

- Particular care was devoted to understand effect of QN approach, electron temperature and collision models.

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Conclusions (2)

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• Preliminary calculations of the SMART-1 configuration were carried out, showing interesting results related to the effect of background pressure and vacuum chamber environment. Current density is not particularly well predicted, probably due to the fact that literature SPT-100 data were used instead of actual measurements of PPS-1350 performances.

• Further investigations will be devoted to the identification of a “best” configuration for injection parameters in order to reproduce available experimental measurements (starting from 2D configurations and ending on 3D models). The calculated plume and injection distribution could be made available for the building of the SPIS model of the PPS-1350 thruster.

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