Study of the interaction of satellite with ion thruster plume using 3D PIC simulation

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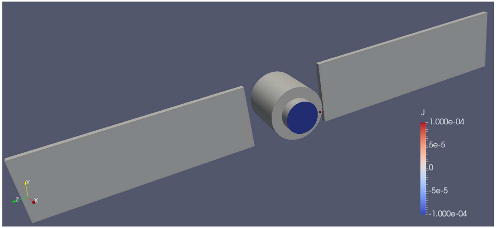
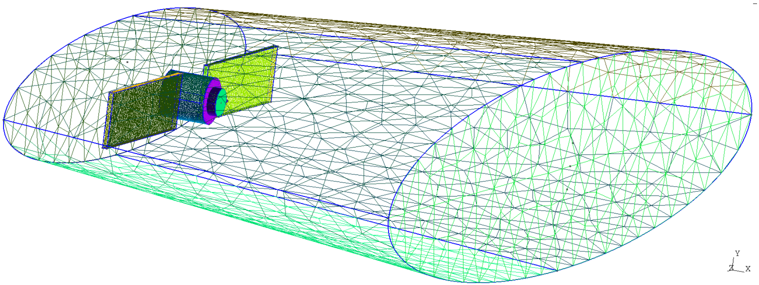
Outline

Satellite



Main radius	0.5 m
Length	1 m
Thruster radius	0.3 m
electron gun radius	2 cm
Solar panels	$4 \times 1.2 \times 0.1$ m
Thruster ions: Xe	2 A, 1.5 keV acceleration, $T_i = 300$ K
Electron gun	2 A, 10 V acceleration, $T_e = 300$ K
Thrust	~ 0.1 N

Geometry



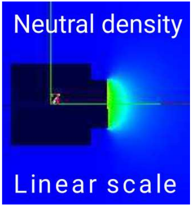
Generated with gmsh (C. Geuzaine and J.-F. Remacle)

Total volume	53.1 m^3
Length	10.2 m
Number of vertices	328384
Number of tetrahedra	1727140
Particles per cell	$\lesssim$ 100

Numerical approach - PTetra[1]

- Fully kinetic PIC with physical particle charges and masses.
- Explicit, electrostatic.
- Unstructured adaptive tetrahedral mesh.
- Arbitrary distribution function of background plasma particles.
- Fixed and 1^{st} order perturbed magnetic fields.
- Photoelectron and secondary electron emission.
- Optional biasing of selected satellite components.
- Null collision model of charge exchange collisions.
- Single-processor and multi-processor (MPI) versions.
- Extended to account for electrons or ions injection:
  - from any number of satellite components,
  - with arbitrary particle distribution functions.

[1] Marchand, IEEE Trans. Plasma Sci., Vol. 40, 2012



Neutrals and CX cross section

From Wang, et al.[1]:

$$\sigma = [k_1 \ln(v_i) + k_2]^2 \, \mathrm{m}^2,$$

where $k_1 = -0.8821$, $k_2 = 15.1262$, and v_i is the ion speed in m/s in the neutral local rest frame.

- Interpolate the neutral Xe density and temperature to calculate:
    - the probability of CX for each ion at each time step,
    - the velocity of new ions when a CX collisions occurs.

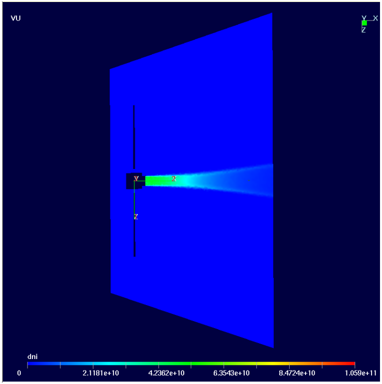
[1] J. Spacecraft and Rockets, Vol. 38, No. 3, 2001

Low flux simulations

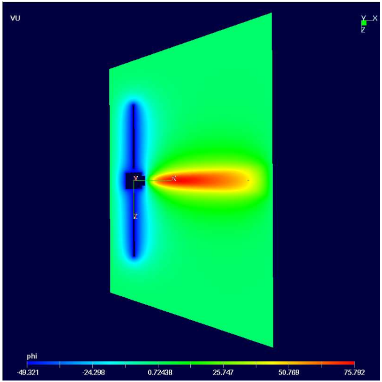
Solar wind and thruster parameters

n_e	$10^7 \mathrm{m}^{-3}$
T_e	15 eV
Ion species	100% protons
n_i	$10^7 \mathrm{m}^{-3}$
T_i	15 eV
Sola wind velocity	$(-4 \times 10^5,\ 0,\ 0)$ m/s
$\vec{B}$	$\vec{0}$
Photoelectrons	neglected
Secondary electrons	neglected
Thruster ions: Xe	$I_b = 0.2$ mA, 1.5 keV accel., $T_i = 300$ K
Electron gun	$I_e = 0.2$ mA, 10 V accel., $T_e = 300$ K

With neutralizing electron gun

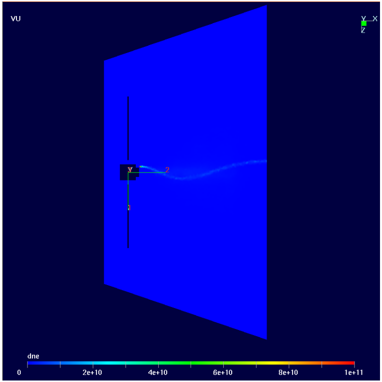


Ion density

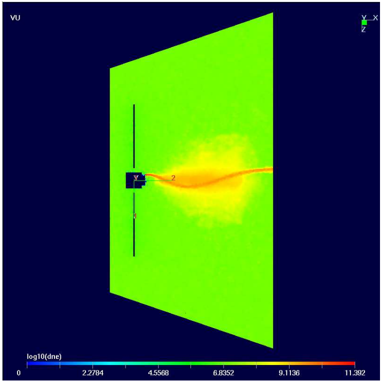


Electrostatic potential

With neutralizing electron gun

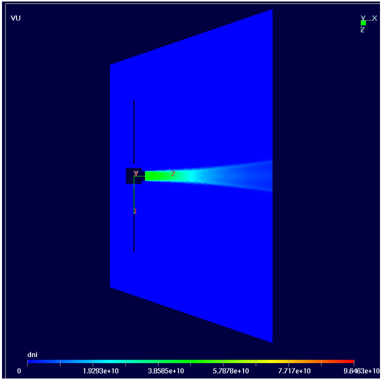


Electron density

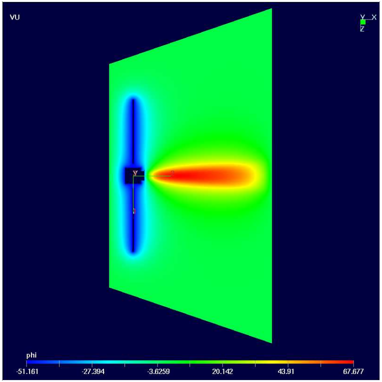


log of electron density

Co-injection

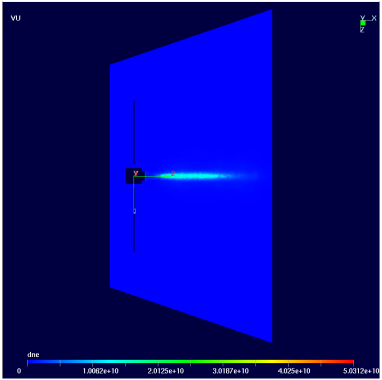


Ion density

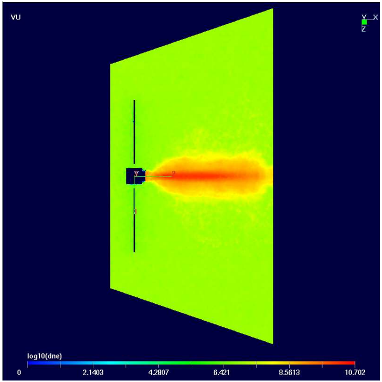


Electrostatic potential

Co-injection



log of electron density



log of electron density

Higher flux and CX

Thruster ions: Xe	$I_b = 2$ A, 1.5 keV accel., $T_i = 300$ K
Electron gun	$I_e = 2$ A, 10 V accel., $T_e = 300$ K

At exit, the ion beam density is

$$n_b = \frac{I_b}{\pi a^2 e v_b} \simeq 9.4 \times 10^{14} \mathrm{m}^{-3}.$$

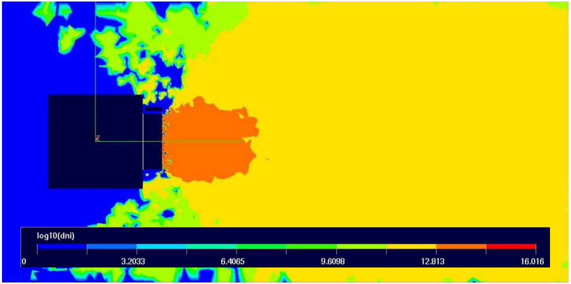
$$\Delta V \sim \frac{n_b e a^2}{4\epsilon_0} \sim 400 \mathrm{kV}.$$

$\rightarrow$ Relativistic electrons.

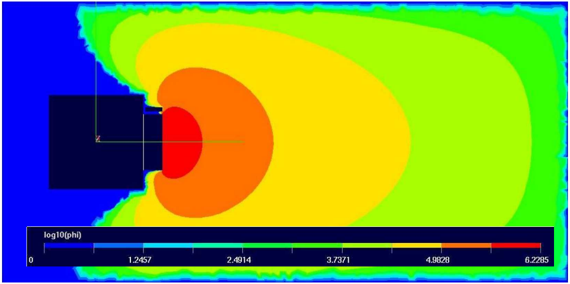
Simulation conditions

- The background solar wind plasma is neglected.
- The electric field is artificially suppressed near the thruster and the electron gun in order to prevent reflection of particles due to the high space charge electric field.
- The simulation domain is also smaller in order to facilitate a higher spatial resolution of the mesh.

Beam density and potential

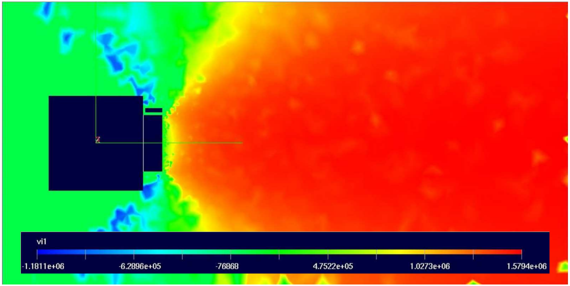


n_i

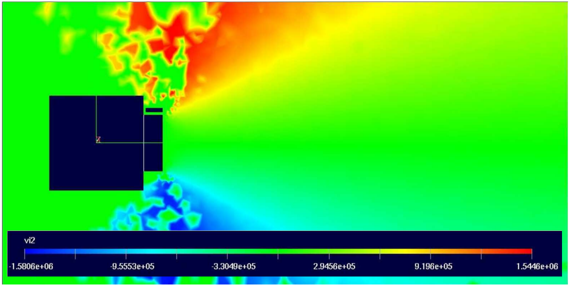


ϕ

Ion velocities



v_x



v_y

Summary

- In our simulations the ion beam remains largely un-neutralized.
- Neutralization by background or electron gun electrons requires large volumes.
- Close to the spacecraft, the ion beam is dense and its potential is large.
  $\Rightarrow$ Electrons entering the beam become relativistic if it is not neutralized.
- Simulations with high density ion beams in a "small" computational domain lead to unrealistically high spacecraft potentials of order of hundreds of kV.