FP7-BETs: Simulation of the current collection by a cylindrical tether positively biased in a flowing plasma

18th SPINE Meeting

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outline

- Context and motivation of current collection modeling
- Numerical simulations using SPIS:
  - Simulation domain definition
  - Injection of particles
  - Time resolution strategy
- Results of simulations:
  - With drifting ions only
  - With drifting and charge exchange ions
- Conclusion and perspectives

De-orbitting with tether

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De-orbiting with tether

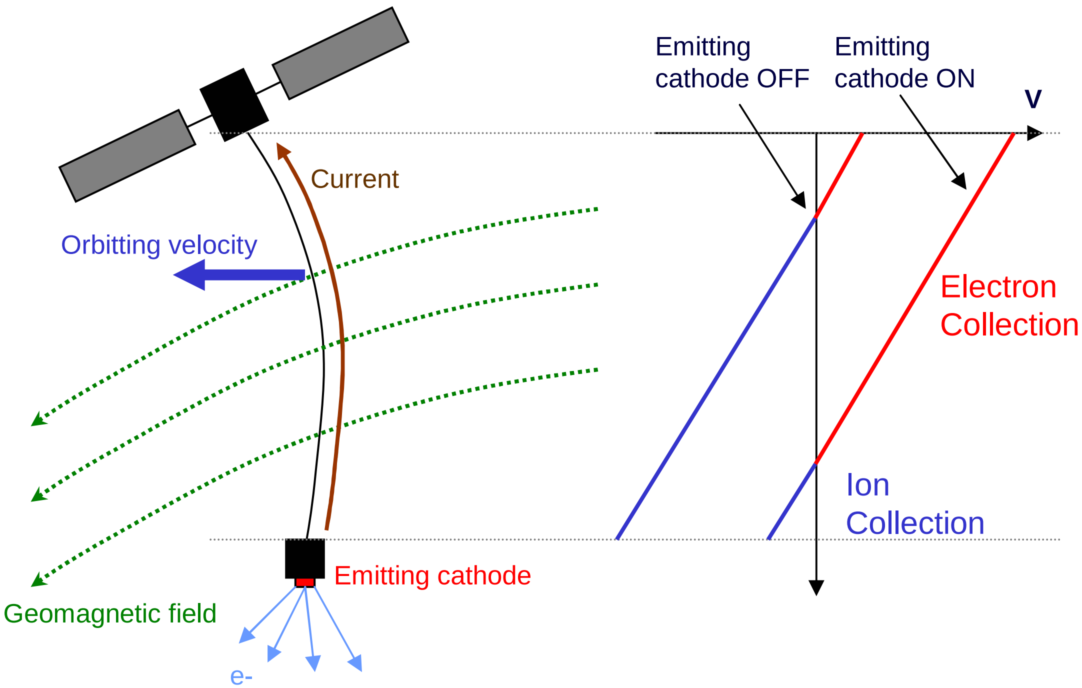
- BETs project:
  - UE-FP7 project
  - European consortium led by J.R. Sanmartin (UPM)

- Electrodynamics tethers with active emitter:
  - Electromotive force due to the orbitting velocity:

$$F_{emv} = \int_0^L \left(\vec{\mathrm{v}}_{\mathrm{orb}} \times \vec{B}\right) d\vec{l}$$

  - Current collection from plasma
  - Emitting cathode: close the current loop with plasma
  - Drag force create by the current in the tether (Lorentz force):

$$F_D = \int_0^L I(l)\, d\vec{l} \times \vec{B}$$



Current collection

- Two regimes of current collection:
  - Positively biased part: collecting electrons
  - Negatively biased part: collecting ions

- OML theory for current collection at the first order, based on several asumptions:
  - Maxwellian environment
  - Cylindrical symmetry
  - Static phenomena
  - No magnetic fields
  - No electron collisions

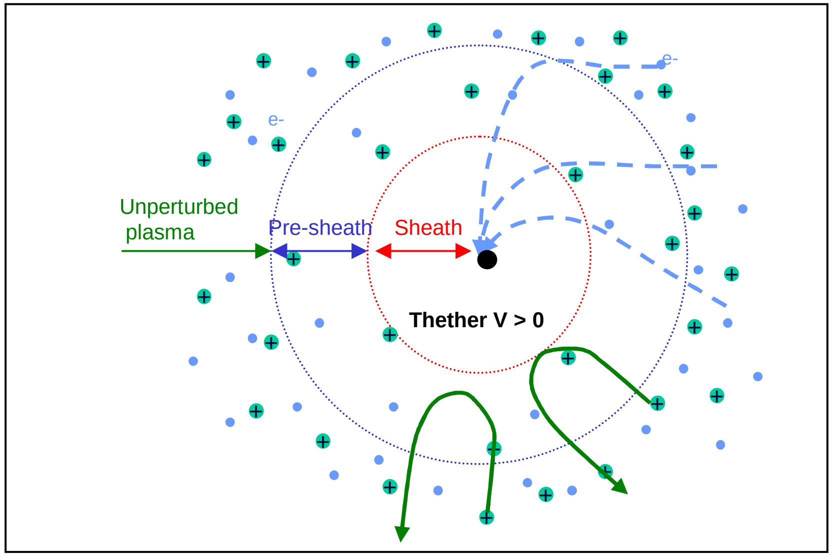
$$I_{OML} = \frac{2}{\sqrt{\pi}} \times n_0 \sqrt{\frac{eT}{2\pi m}} \times \left[\sqrt{\chi} + \frac{\sqrt{\pi}}{2} \exp(\chi) \operatorname{erfc}\left(\sqrt{\chi}\right) \right]$$

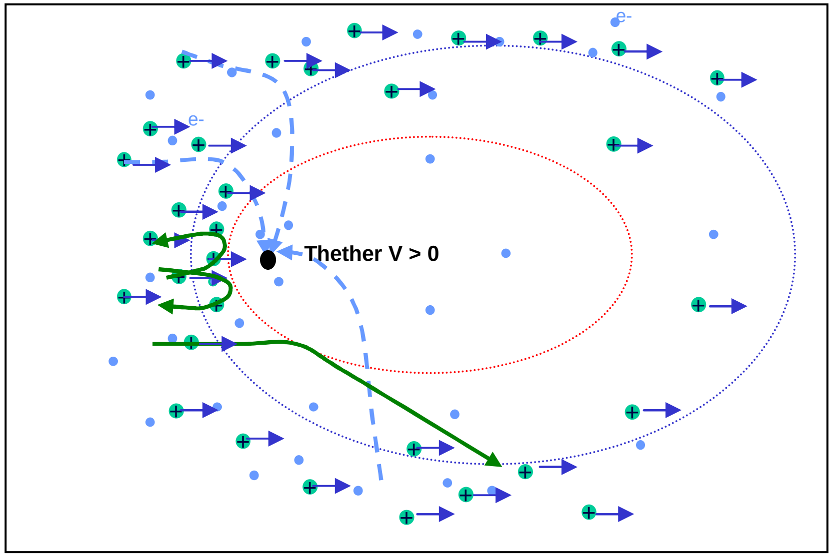
$$I_{OML} \approx \frac{2}{\sqrt{\pi}} \times n_0 \sqrt{\frac{eT}{2\pi m}} \times \sqrt{1+\chi}$$

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

- Cylindrical symmetry not valid due to the orbitting velocity of S/C
- Consider drifting ions population:

→ OML Law still valid ?





Bibliography and some figures

- LEO environment:
  - Plasma density: $n_e = n_i = 10^{11}$ m^{-3}
  - Plasma temperature: $T_e = T_i = 0.1$ eV
  - Composition: O^+/e^-
  - Orbitting velocity: 8000 m/s

  (equivalent to a ion drifting energy of 20 eV)

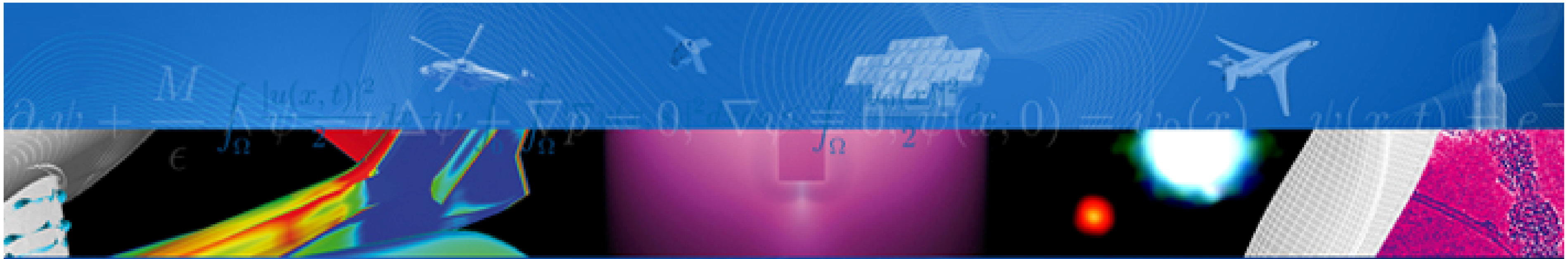
- Tether caracteristics:
  - potential: as high as 1000 V
  - Radius: about 1 λ_D

- Plasma parameters:
  - Debye length: 7.44 mm
  - Plasma frequency: 2.84×10^6 s^{-1}
  - Sheath length: $r_s = 155.5\ \lambda_D$ for $V = 5120\ T_e$

  $r_s = 1.17$ m for V = 512 V (Choinière et al.)
  - Time transit:
    - Ions: about 10^{-4} s
    - Electrons: about 10^{-7} s

- In the litterature: discrepancies with the OML theory → Current collection higher in a drifting plasma
  - Experiments: Gilchrist (2001), Choinière (2005) and Kashihara (2008)
    - End effect
    - Background pressure effect
    - Magnetic filed effect
    - Charge exchange ions effect
  - Simulation: Onishi (2001) and Deux (2005)
    - Injection of particles at the boundary
    - Stability of the simulation
    - Numerical trapping of particles or adiabatic traping ?

→ Many questions !



Simulations using SPIS

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Simulation domain

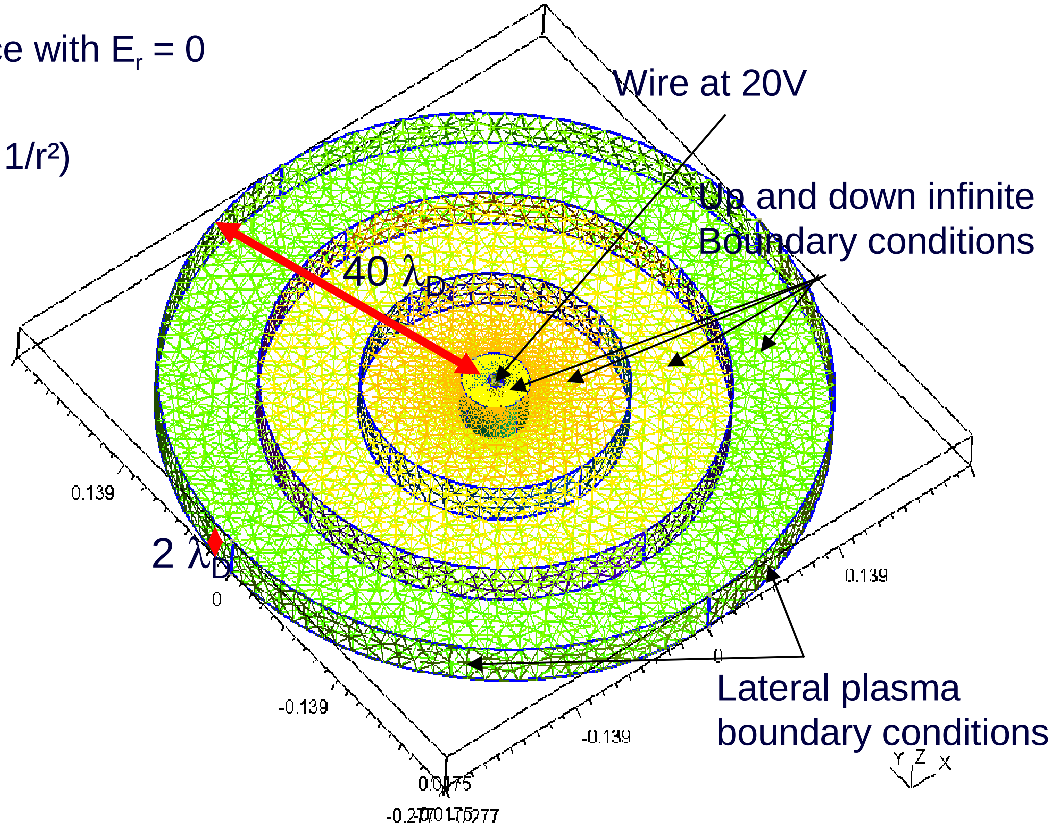
- Tether current collection: 2D geometry with positive wire
  - Temporal resolution with PIC/PIC approach
  - Infinite wire:
    - Dirichlet BC for the wire at +20V
    - Neumman BC up and down surface with $E_r = 0$
  - Environment:
    - Robin BC mimic a pre-sheath ($v \sim 1/r^2$)

- Meshing:
  - Wire meshed at 0.1 Debye length

  Refinement "box" surrounding the wire
  - Volume from 0.5 to 1 Debye length

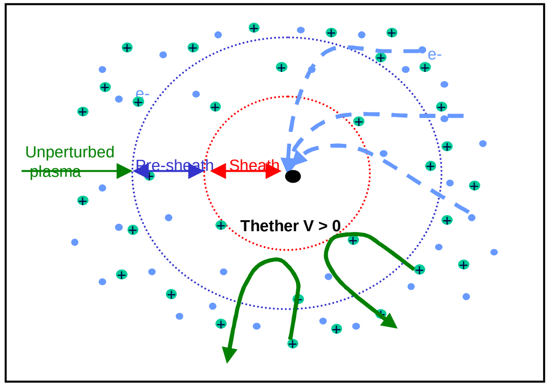
  Controled with two refinement zones

  → 80 000 tetrahedra



Injection of particles from environment

- For the potential:
  - Rodin (or Fourrier) boundary conditions
  - Mimic a pre-sheath (V ~ 1/r²)
  - → non-zero potential at the boundary



- For the electron injection, OML theory:
  - Current injected at the boundary
  - Distribution function
  - The Liouville's theorem can be applied:
    - the distribution function is constant allong a prarticle trajectory
    - Hypothesys:
      - Cylindrical symmetry of the potential
      - No time dependant evolution
      - Maxwellian distribution

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

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

$$f_{e,0}(\mathrm{v}_r, \theta, \mathrm{v}_z).d\mathrm{v} = n_0 \left(\frac{m}{2\pi eT}\right)^{3/2} \mathrm{v}_r \times \exp\left(-\frac{m\left(\mathrm{v}_r^{\,2} + \mathrm{v}_z^{\,2}\right)}{2eT}\right) d\mathrm{v}_r\, d\theta\, d\mathrm{v}_z$$

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

- For the ions:
  - Drifting ions: 1D deceleration
  - Negligible effect

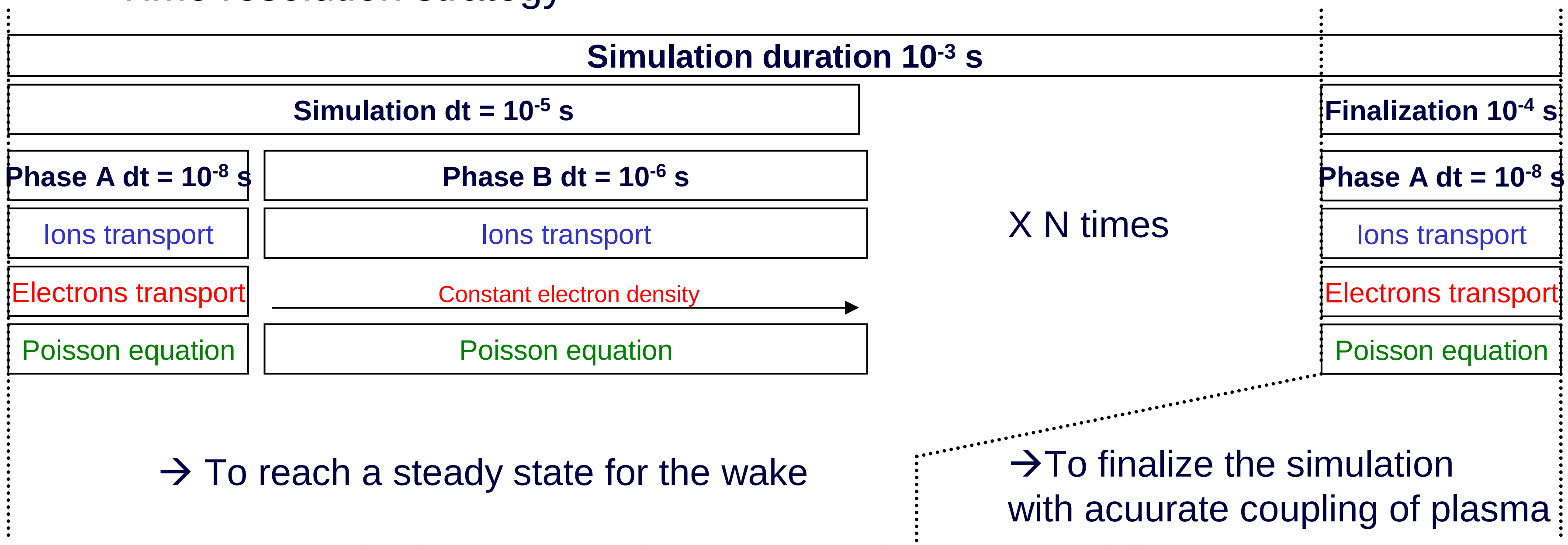
$$f_{i,0}(\mathrm{v}_x, \mathrm{v}_y, \mathrm{v}_z).d\mathrm{v} = n_0 \left(\frac{m}{2\pi eT}\right)^{3/2} \exp\left(-\frac{m\left((\mathrm{v}_x - \mathrm{v}_{orb})^2 + \mathrm{v}_y^{\,2} + \mathrm{v}_z^{\,2}\right)}{2eT}\right) d\mathrm{v}_x\, d\mathrm{v}_y\, d\mathrm{v}_z$$

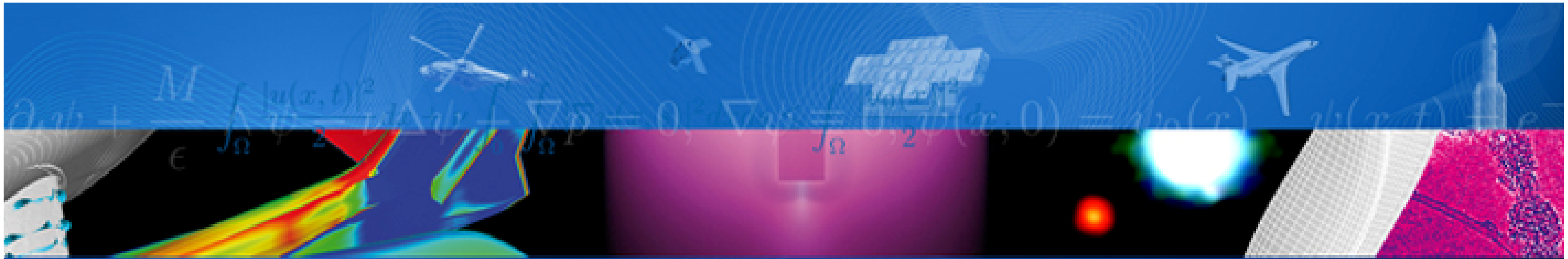
$$f_{i,i}(\mathrm{v}_x, \mathrm{v}_y, \mathrm{v}_z).d\mathrm{v} = n_0 \times \left[\frac{\mathrm{v}_{orb}}{\mathrm{v}_{orb} - \sqrt{\frac{2eV}{m}}}\right] \times \left(\frac{m}{2\pi eT}\right)^{3/2} \exp\left(-\frac{m\left((\mathrm{v}_x - \mathrm{v}_{orb})^2 + \mathrm{v}_y^{\,2} + \mathrm{v}_z^{\,2}\right)}{2eT}\right) d\mathrm{v}_x\, d\mathrm{v}_y\, d\mathrm{v}_z$$

Simulation parameters

- Time characteristics:
  - Plasma frequency: 2.84×106 s-1
  - Time transit:
    - Ions: about 10^{-4} s
    - Electrons: about 10^{-7} s
  - Several order of magnitude between the time characteristic → but not possible to use the speedup due to a strong coupling between ions and electrons

- Time resolution strategy





Results with drifting ions only

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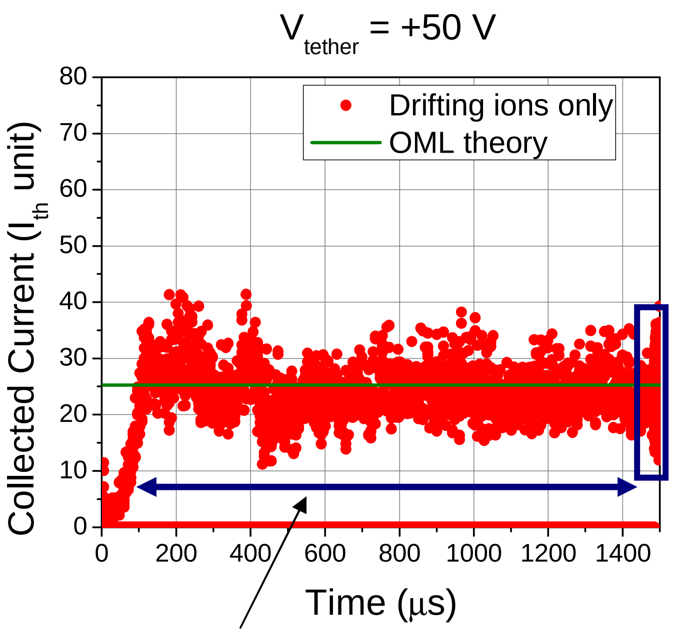
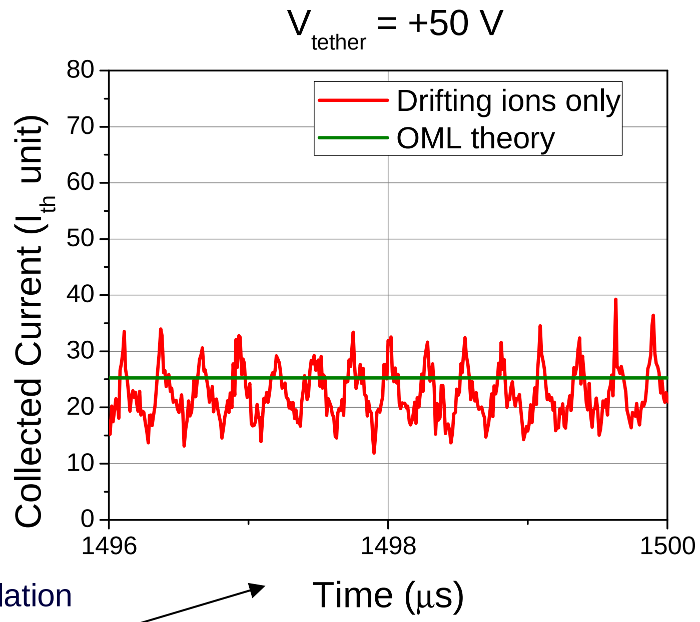
Current collection at +50 V

- Simulation conditions:
  - $N_e = 10^{11}\ m^{-3}$
  - $N_i = 10^{11}\ m^{-3}$ with $v_i = 8000$ m/s (Argons ions at 14 eV)
  - Debye length $\lambda_D = 0.007$ m.



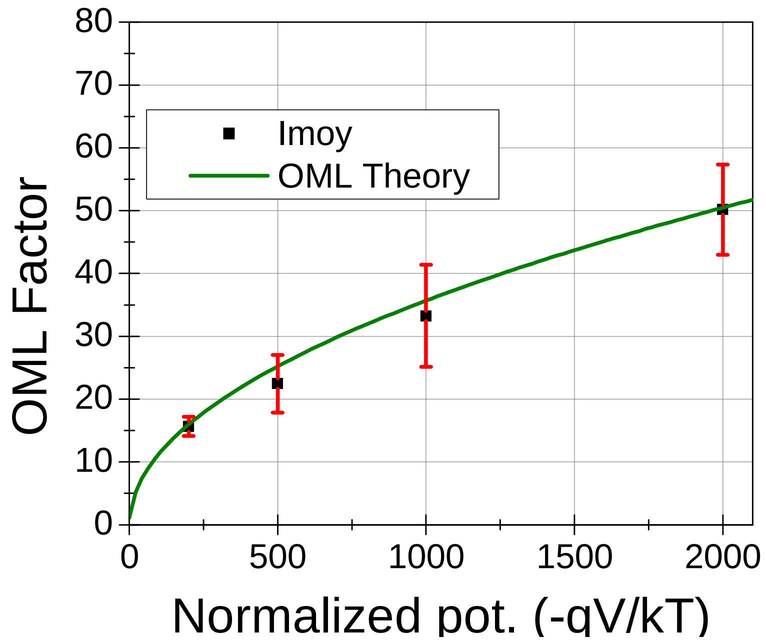


Synchronous calculation of ions and electrons

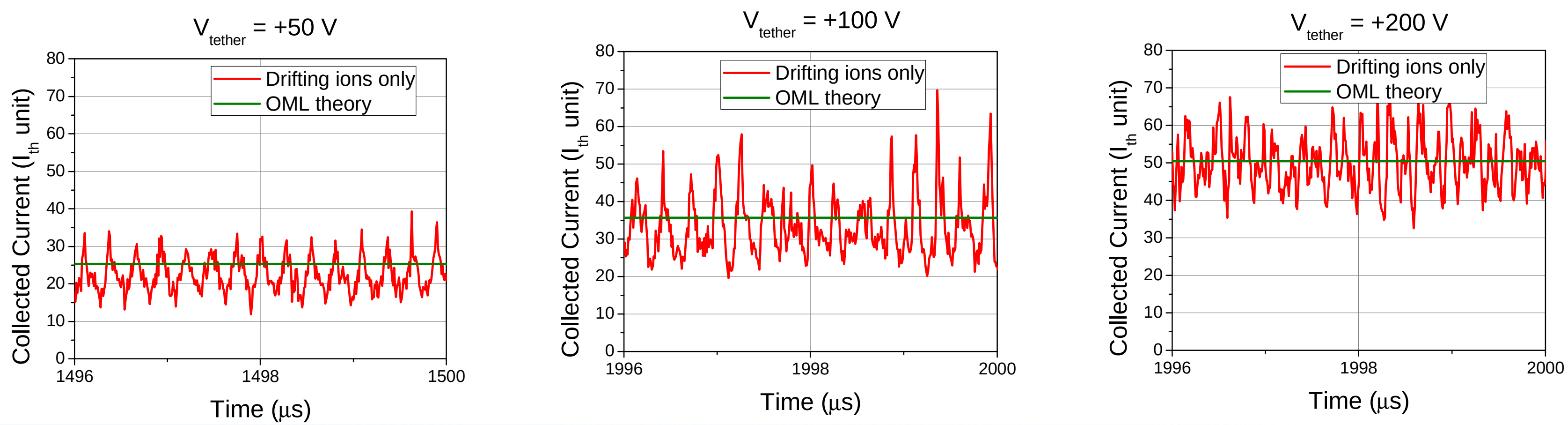
Convergence of ions popolation with a time acceleration of electrons strategy

- Result analysis:
  - Good agreement of the mean value of the current collected with the OML theory
  - Oscillations at the plasma frequency (1.3 w_{pe} - physical or statistical ?)
  - Possibliy numerical oscillations due to the finite number of part/cell

Comparison to OML

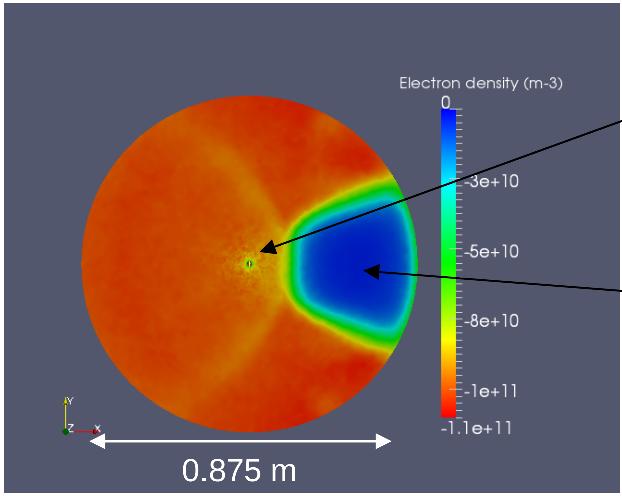


- Results analysis:
  - No deviation from the OML theory from the mean value
  - But the oscillations amplitudes increase with potential (at a pulsation corresponding to 1.3 w_{pe})
  - Possibly numerical oscillations due to the finite number of part/cell

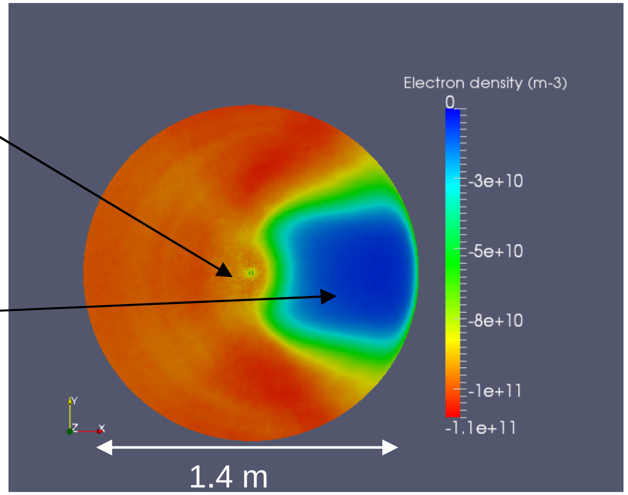


Electron and ion density

$V_{tether} = + 20\ V$

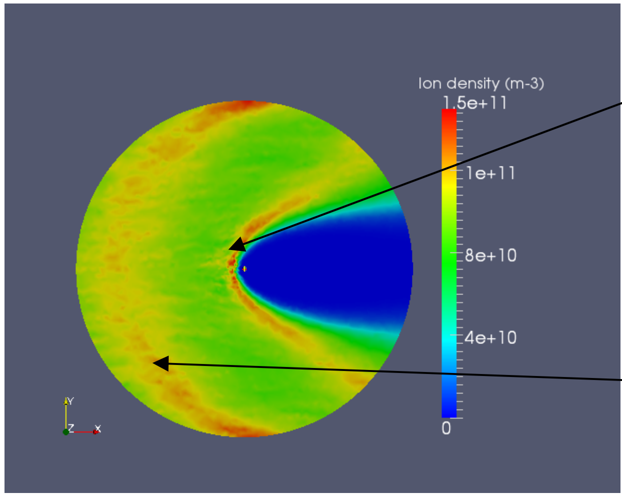


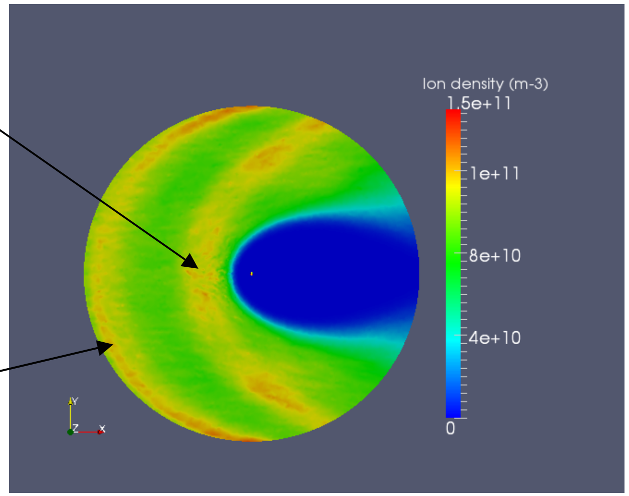
$V_{tether} = + 50\ V$



Focalization zone of electrons

Depletion zone: Wake





Compression zone: Stopping point of ions

Wave form potential evolution or artifact due to ion injection ?

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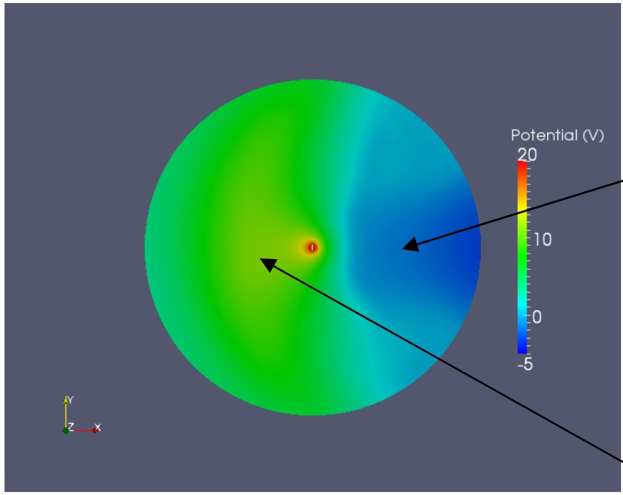
Potential map

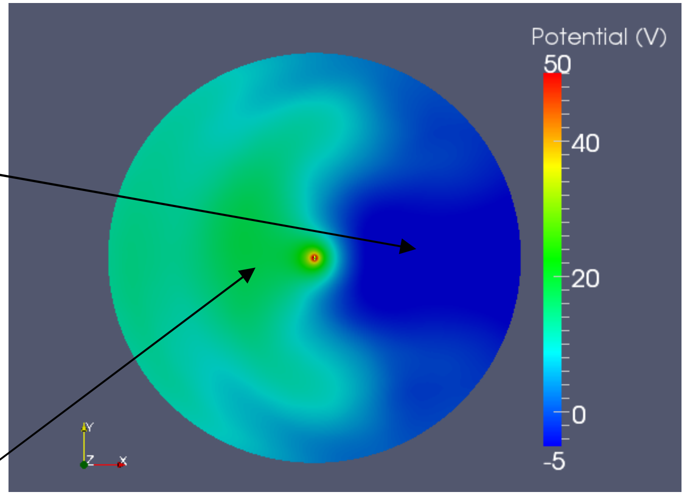
V_{tether} = + 20 V



Negative potential in the wake

Positive potential in the ion compression zone

V_{tether} = + 50 V



- Result analysis:
  - Due to the wake formation:
    - the space charge around the tether is no longer axis-symmetric
    - Negative potential in the wake due to ino depletion
  - Ion stopping pzone:
    - Potitive space chage: the electron density cannot neutralize the ions
    - Positive potentials front of the wire

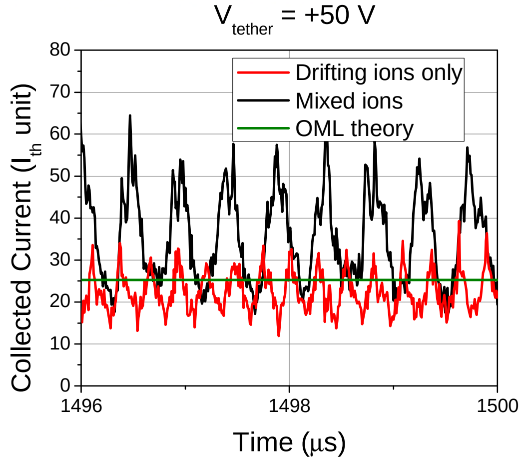
→ high potentials (compared to Te) at the boundary conditions (validity of the asumptions done for the injection ?)

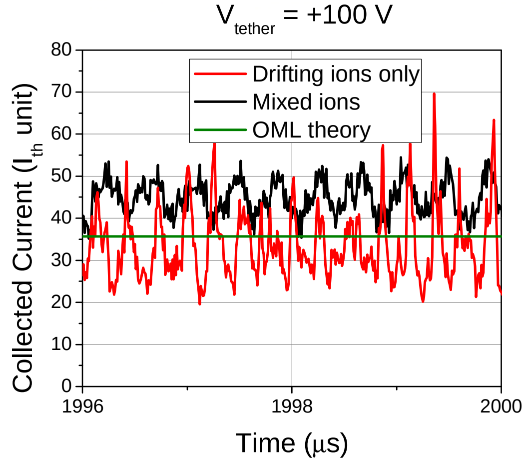
Results with a charge exchange polulation

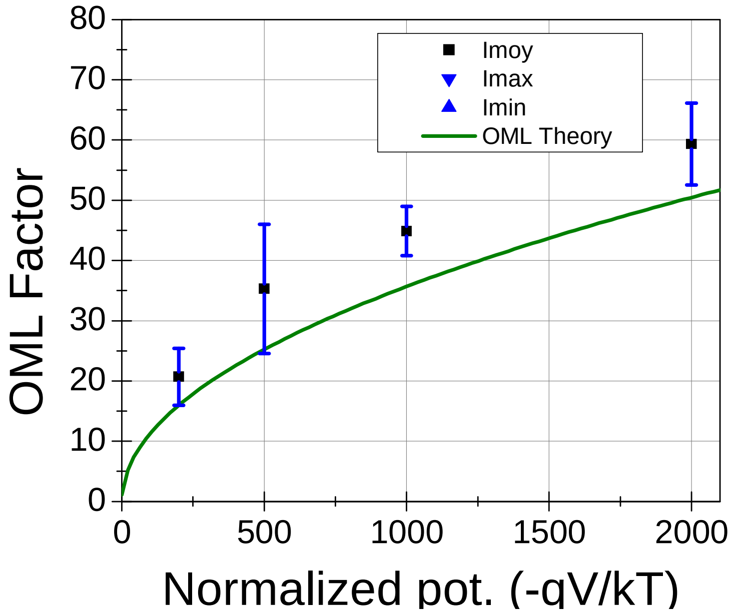
High tether potential with a thermal ion population

- Simulation conditions:
  - $N_e = 10^{11}\ m^{-3}$
  - $N_{i1} = 5x10^{10}\ m^{-3}$ with $v_i = 8000$ m/s
  - $N_{i2} = 5x10^{10}\ m^{-3}$ with $v_i = 0$ m/s

- Charge exchange ions always present in groung experiments





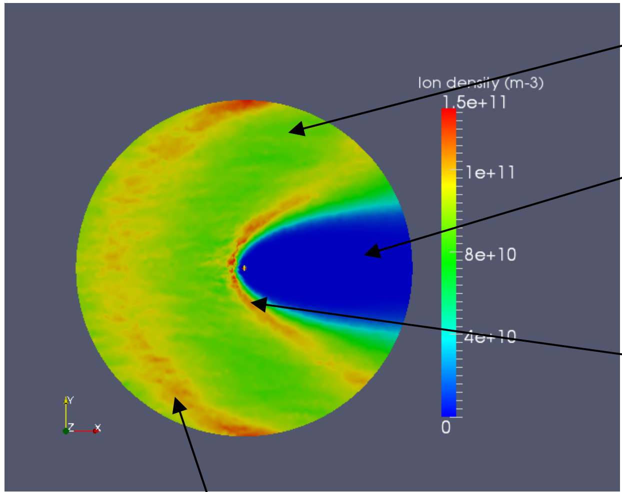


- Results analysis:
  - Higher current compared to OML for the mean value
  - Oscillations in the simulations with a period of 0.44 μs
  - Lower than the plasma frequency (0.8 w_{pe} - trapping possible)
  - Amplitudes dependant on the tether potential (seem to decrease with potential)

Ion densities

Drifting only V_{tether} = + 20 V

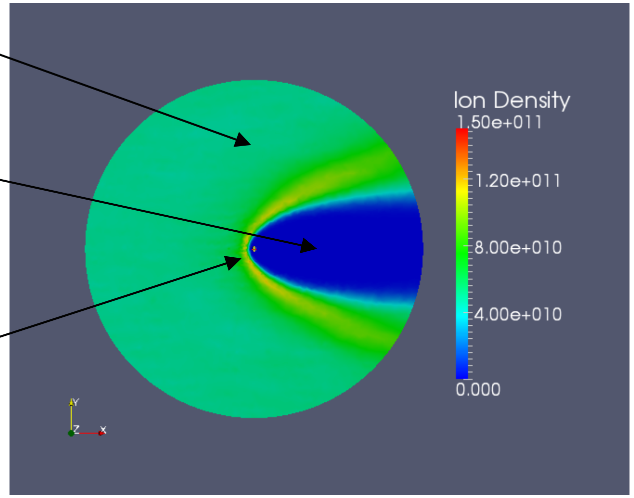
Two populations V_{tether} = + 20 V



Drifting ions

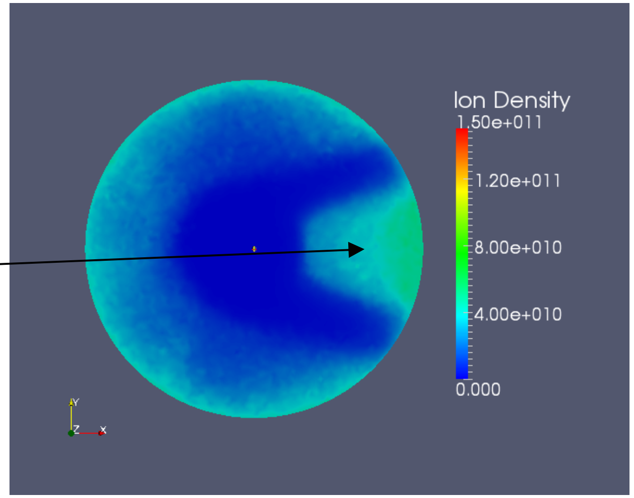
Depletion zone: Wake

Compression zone: Stopping point of ions



No second compression zone with CX ions

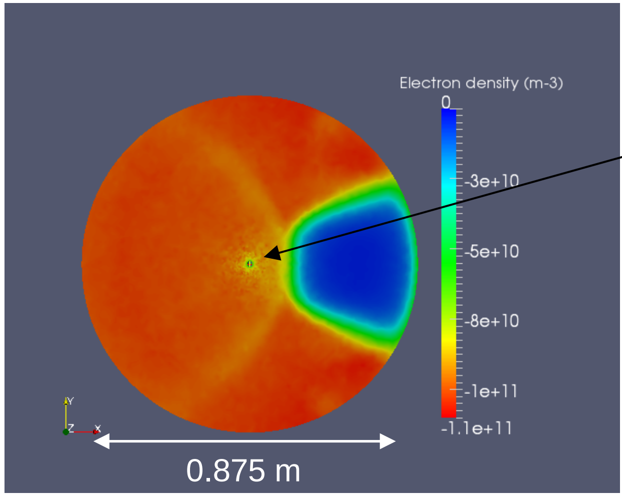
Ions attracted by the negative potentials in the wake

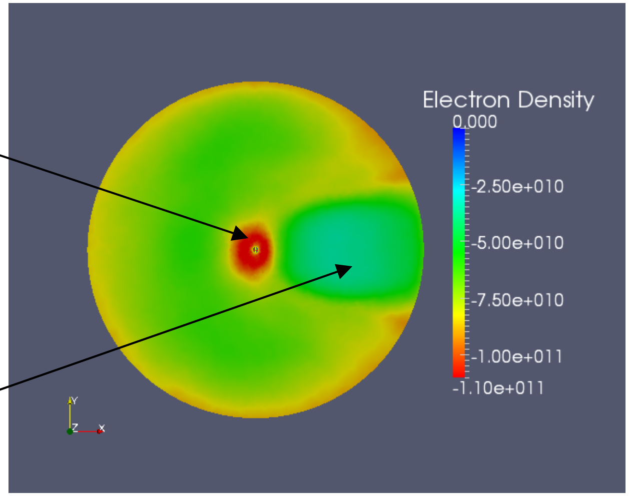


Electron density and potential map

Drifting only V_{tether} = + 20 V

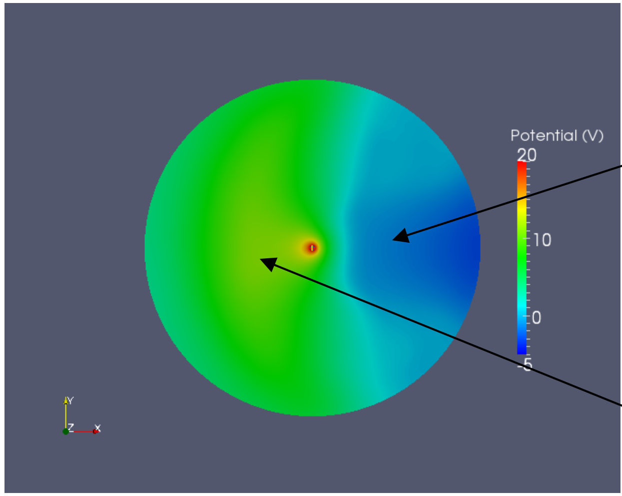
Two populations V_{tether} = + 20 V

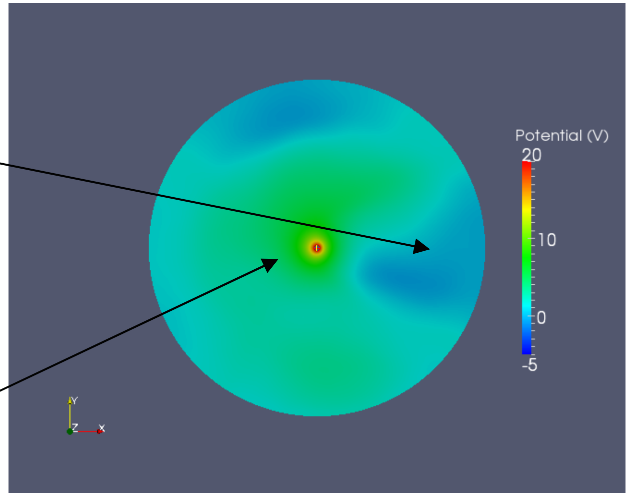




Focalization zone of electrons

Wake less visible due to the thermal ions presence





Negative potential in the wake

Positive potential in the ion compression zone

Conclusion

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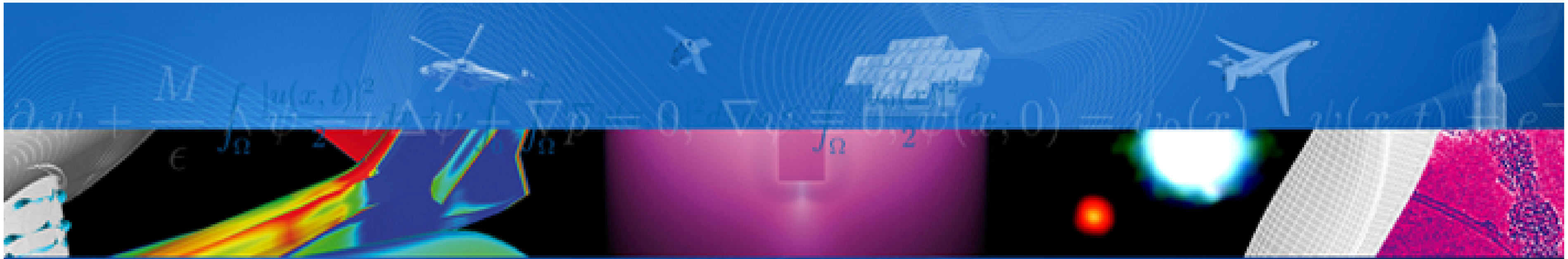
Conclusion

- No strong deviations from OML theory:
  - With drifting ions only: oscillations of the current collected but mean current in accordance with OML theory
  - With charge exchange ions: slower oscillations and mean current a bit greater than the OML theory (adiabatic traping possible)

- Oscillation obtained in the both cases (physical or numerical ?) → difficult to increases the simulation box to avoid boundary conditions effects

- Future work:
  - Detailled analysis of the simulation:
    - Verify the oscillations are not numerical
    - Determine the origin of these oscillations
  - Collisionnal electrons



Questions ?

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