Development of physical models of electron cooling in collisionless plasma thruster plumes

Mario Merino, Eduardo Ahedo, Pablo Fajardo

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- Comparison with magnetized plasma jet expansions (magnetic nozzles)
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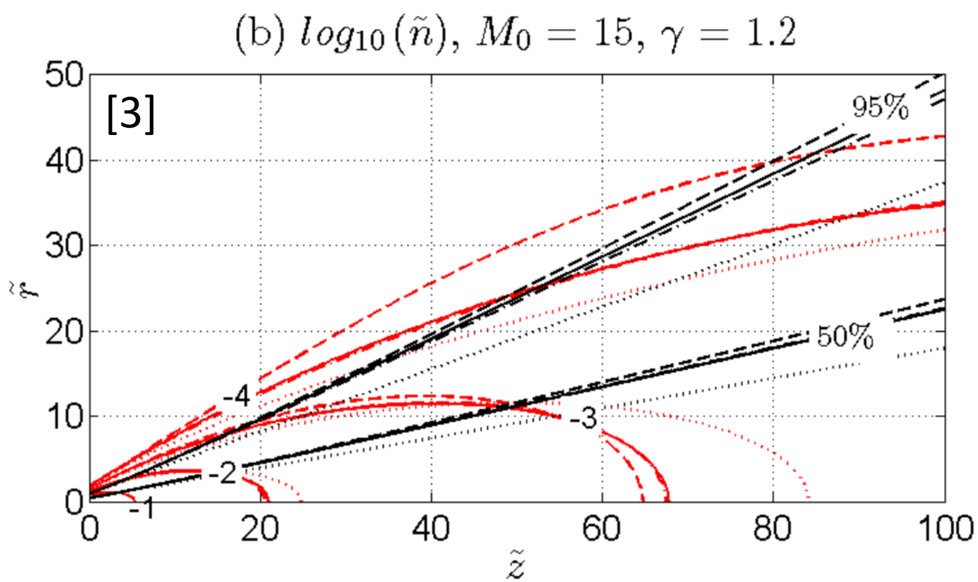
The plasma plume expansion problem

- Energetic charges are emitted by plasma thrusters (HETs, GITs) which can damage spacecraft parts upon impact
- Their expansion and acceleration ultimately depend on the electric potential in the plume region:
  - In the case of slow CEX ions, potential profile completely determines their trajectory and energy ($\sim \Delta\phi$)
  - The potential is governed essentially by the plume itself so the determination of the plasma properties and the electric potential profile are coupled
- Understanding the plasma thruster plume expansion into vacuum is of utmost importance to:
  - Accurately characterize the electric potential around the spacecraft with EP
  - Assess the erosion and contamination of satellite surfaces and objects embedded in it

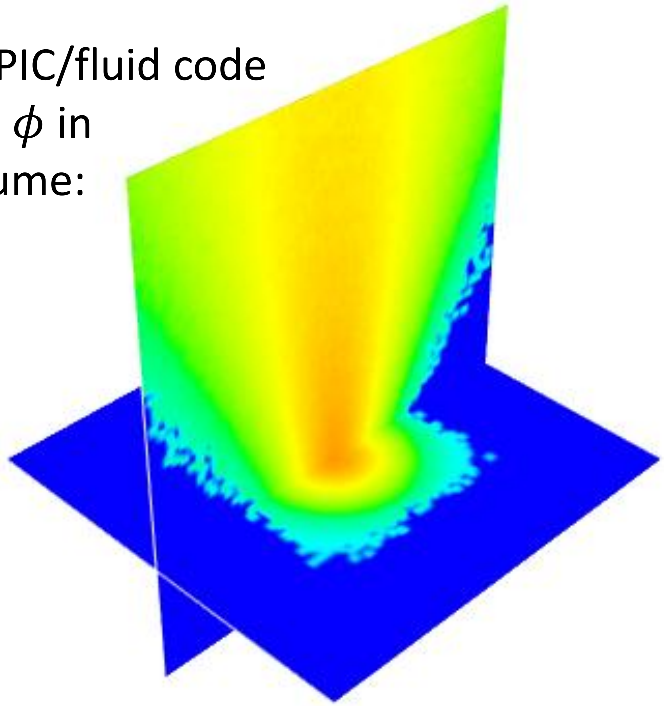
The plasma plume expansion problem

- EP2-UC3M group in Madrid has experience modeling plasma plumes with fluid models (EASYPLUME [1]) and PIC codes (EP2-PLUS [2]):

EASYPLUME density and velocity curves:



EP2-PLUS PIC/fluid code simulating ϕ in plasma plume:

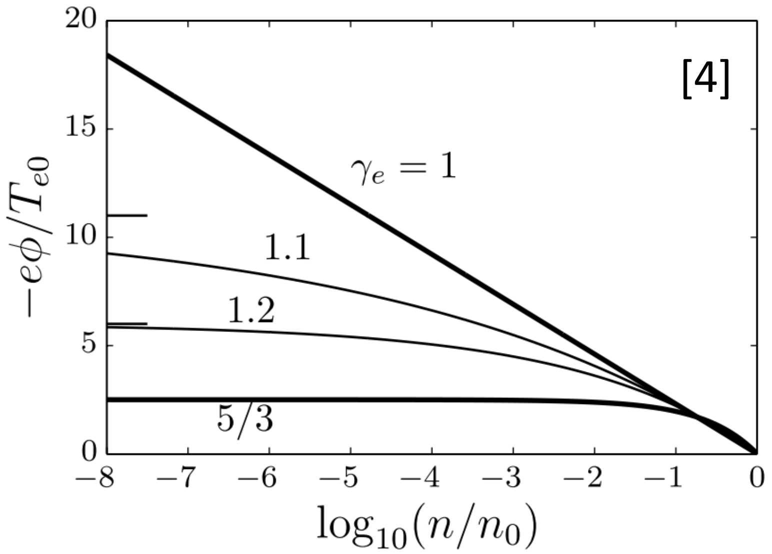


- HET and GIT plumes expanding into vacuum are near-collisionless ($\lambda_{coll} \gg L$). Thus the plasma is not in local thermodynamic equilibrium (LTE): electron response is *global*

[1] Merino, M., Cichocki, F., and Ahedo, E., "Collisionless Plasma thruster plume expansion model," Plasma Sources Sci. Tech., Vol. 24, No. 3, 2015, pp. 035006
[2] Cichocki, F., Merino, M., Ahedo, E., Hu, Y., and Wang, J., "Fluid vs PIC Modeling of a Plasma Plume Expansion," 34th IEPC, 2015
[3] Cichocki, F., Merino, M., and Ahedo, E., "Modeling and simulation of EP Plasma Plume Expansion into Vacuum," 50th AIAA/ASME/SAE/ASEE JPC, AIAA-2014-3828 (2014)

The plasma plume expansion problem

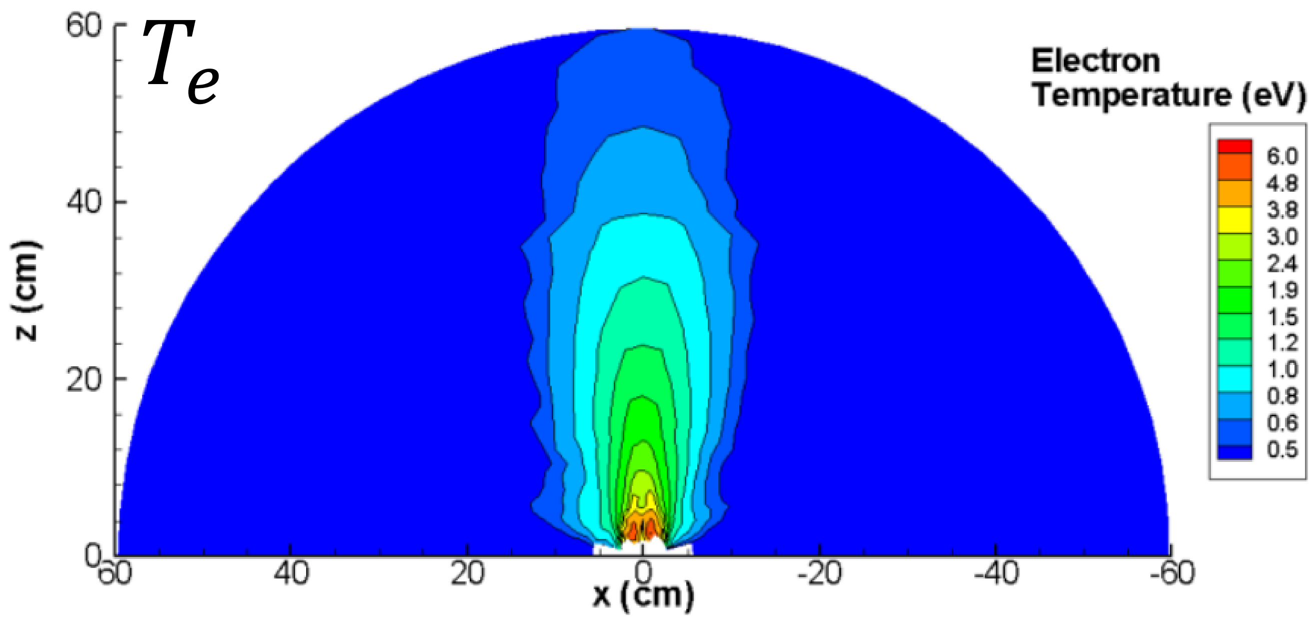
- The electric potential profile depends strongly on the electron temperature T_e in the plume ($\Delta\phi \sim T_e/e$), whose determination in a fluid model requires a closure relation of the type $T_e = T_e(n)$.
- Usually, isothermal or polytropic models are used:
  - Isothermal: $T_e = \text{const}$, and $e\phi = T_{e0}\ln(n/n_0)$ (Boltzmann)
    - Reasonably accurate in the near region; gives infinite potential fall downstream (unphysical), requires ∞ energy. Equivalent to $\gamma_e = 1$
  - Polytropic: $T_e = T_{e0}(n/n_0)^{\gamma_e - 1}$, and $e\phi = (T_e - T_{e0})\gamma_e/(\gamma_e - 1)$
    - "Adjustable" potential fall downstream with γ_e parameter; no model exists for γ_e (experimental fittings can still used). Not theoretically justified in a collisionless plasma.

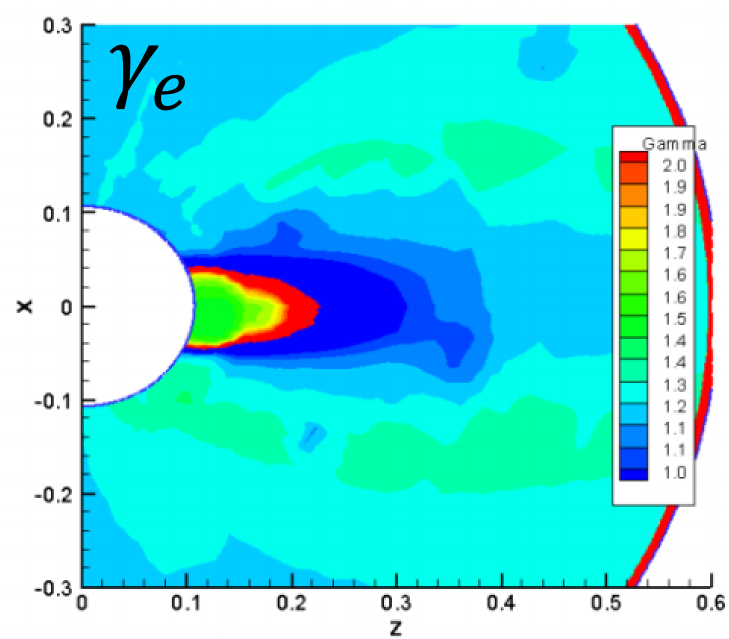


[4] Merino, M. and Ahedo, E., "Influence of Electron and Ion Thermodynamics on the Magnetic Nozzle Plasma Expansion," IEEE Trans. Plasma Sci., Vol. 43-1, pp. 244–251 (2015)

The plasma plume expansion problem

- Laboratory (and in-flight) experiments can be used to advance the understanding of the plasma plume expansion problem
  - E.g. European plasma plume database (www.electric-propulsion.eu)
- Measurements in HET plumes confirm non-trivial electron cooling with a non-constant γ_e *even downstream, where B effects are negligible* [5]:





[5] Nackles M.R., *et al.*, "Experimental and Numerical Examination of the BHT-200 Hall Thruster Plume," 43rd AIAA/ASME/SAE/ASEE JPC, AIAA 2007-5305 (2007)

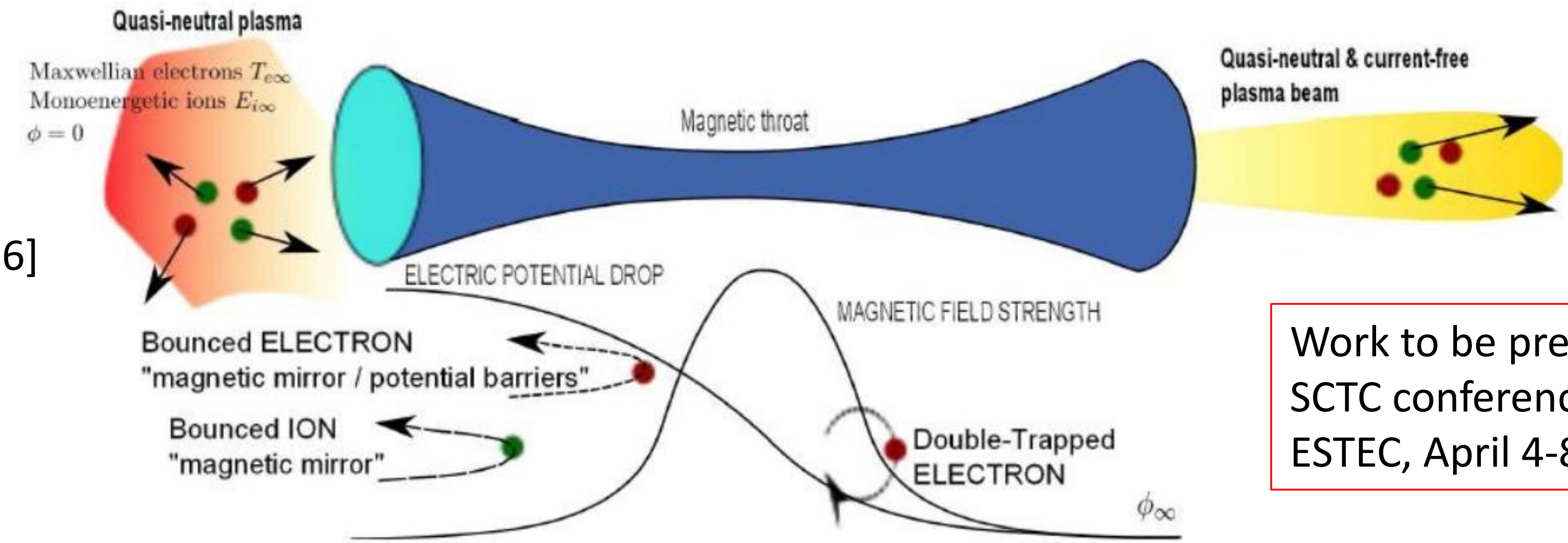
Goal of this work

- The goal of this work is to develop simple kinetic of $T_e(n)$ and ϕ along a expanding collisionless ($\lambda_{coll} \gg L$), unmagnetized ($\ell_e \gtrsim L$) plasma thruster plume
  - The cooling laws derived can then be used to inform fluid and hybrid PIC/fluid models
- This activity is part of the ESA project "Model and experimental validation of spacecraft-thruster interactions (erosion) for electric propulsion thruster plumes." Main tasks include:
  1. Detailed review of existing plume models and data by EP2-UC3M and ADS
  2. Development of the plume coolingmodel by EP2-UC3M
  3. Experimental validation to be done by ICARE-CNRS and KTH at ESA-EPL with a SPT100
  4. A simplified version of the derived $T_e\ (n)$ laws will be implemented in SPIS by ONERA

Comparison with magnetized plasma expansion

- EP2 has already modeled electron cooling of a collisionless plasma expanding in a slowly convergent-divergent magnetic field kinetically:
  - Electrons and ions are assumed fully magnetized and tied to the magnetic lines of the magnetic nozzle: distribution function has 3 dof: $f = f(z, v_{\parallel}, v_{\perp})$
  - The distribution function of each species is computed solving its Vlasov equation for a fixed electric potential axial profile
  - Imposing quasineutrality, the method is iterated until convergence in the electric potential in the steady state

[6]

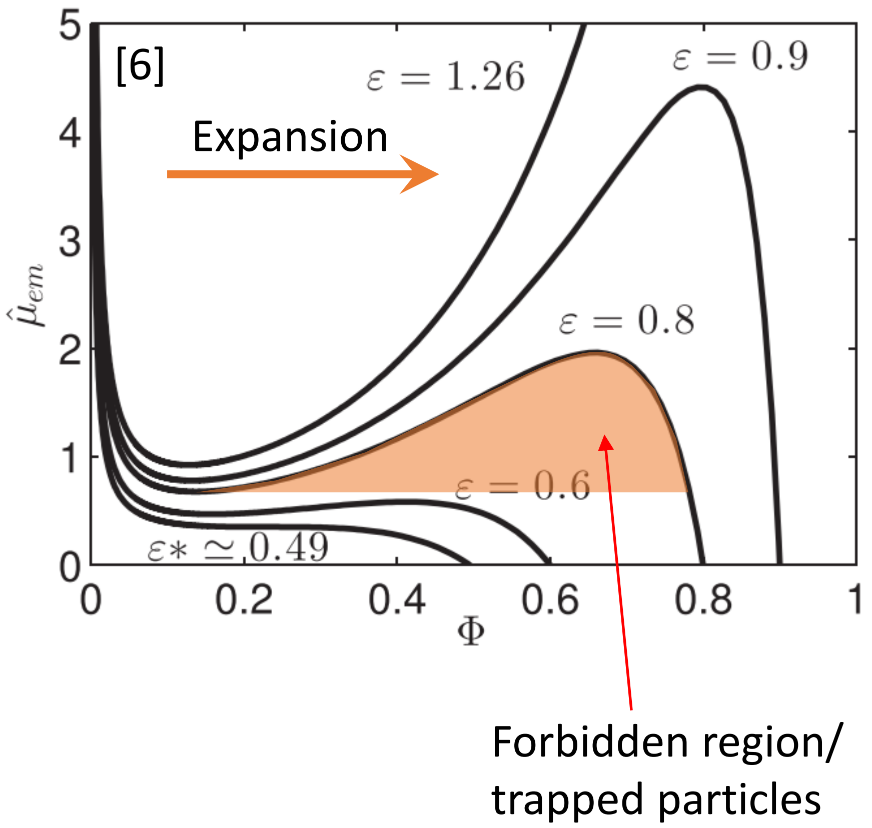


Work to be presented at SCTC conference at ESTEC, April 4-8 2016

[6] M.Martinez-Sanchez, J.Navarro,and E.Ahedo, "Electron cooling and finite potential drop in a magnetized plasma expansion," Phys. Plasmas 22, 053501 (2015)

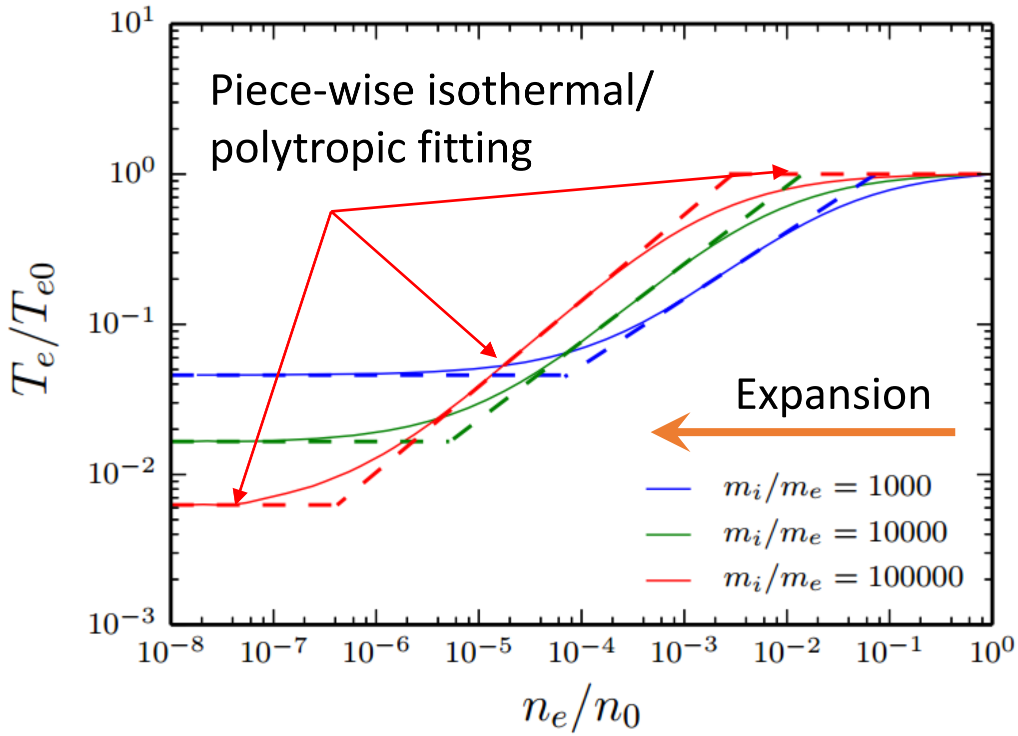
Comparison with magnetized plasma expansion

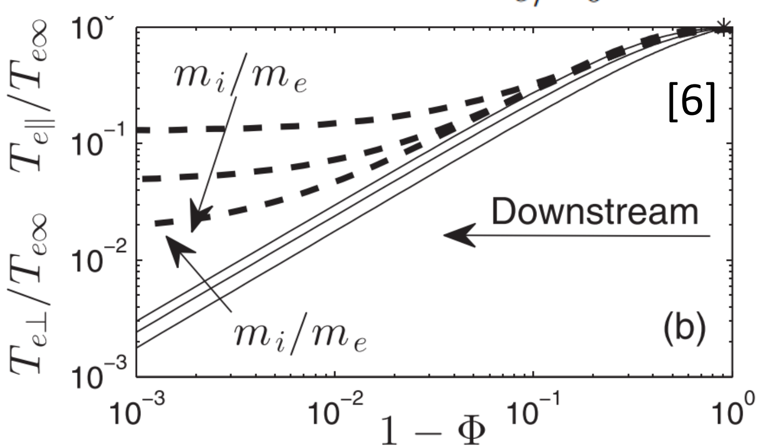
- Each particle conserves its mechanical energy ε and the magnetic moment μ (to first order)
  - Expressing the distribution function in these variables allows for fast, semi-analytical solution
- In the divergent part, the magnetic mirror effect accelerates electrons downstream and the electric potential confines electrons upstream
  - In the velocity space, there are inaccessible regions (not connected with the upstream) depending on μ and ε
  - Electron phase space is divided into
    - Free electrons (connect $-\infty$ with $+\infty$)
    - Confined electrons (connected to $-\infty$ but not with $+\infty$)
    - Empty regions (connected only with $+\infty$)
    - Doubly-trapped electrons: those that do not connect neither with $-\infty$ or $+\infty$.



Comparison with magnetized plasma expansion

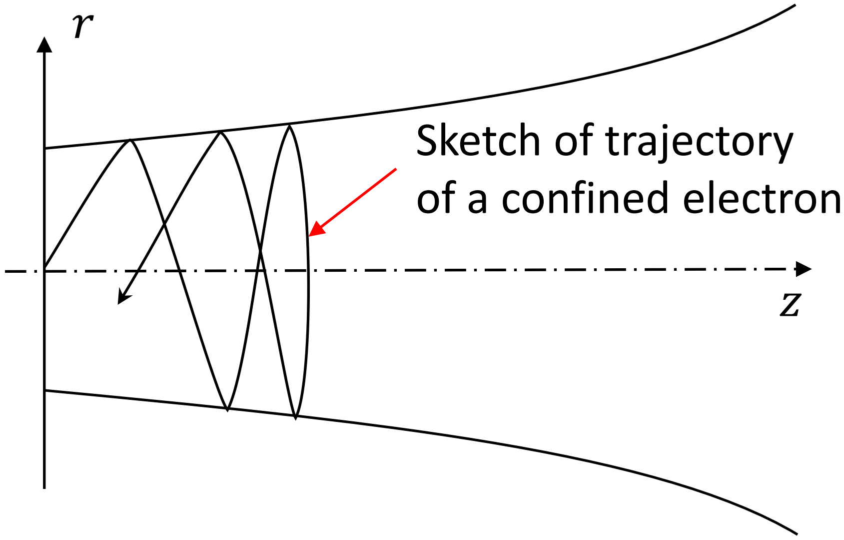
- This fragmentation gives rise to non-trivial heat-fluxes and anisotropy
- Complex cooling behavior is observed →
  - Electrons are initially quasi-isothermal
  - A region of near-constant γ_e cooling follows
  - The whole behavior depends on the m_i/m_e ratio.
- Anisotropy develops downstream too →





Intended modeling approach

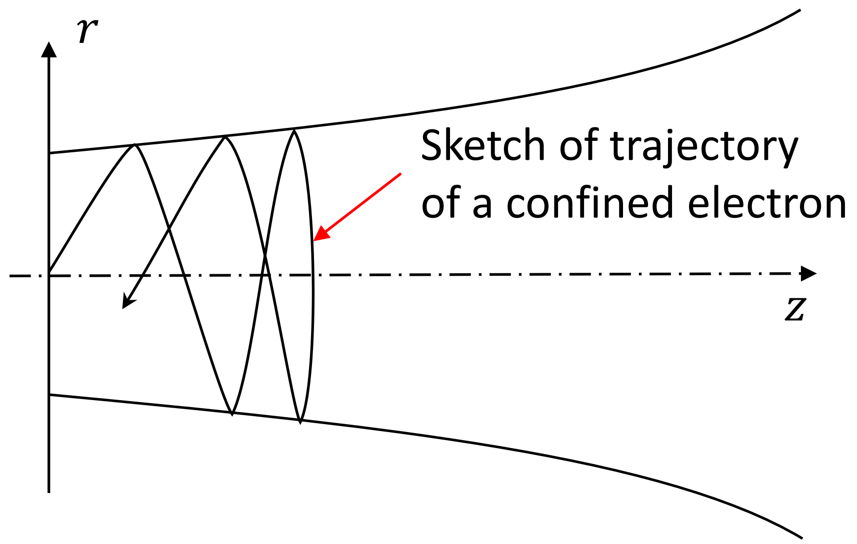
- In a collisionless, unmagnetized plasma plume we cannot study the expansion line by line, as in the magnetized case
  - The distribution functions have 5 dof: $f = f(z, r, v_z, v_r, v_\theta)$
- We similarly have the following conserved quantities at a kinetic level:
  - Particle mechanical energy, H
  - Particle angular momentum about the axis, L
  - In a slowly-diverging plume, there exist an adiabatic invariant J associated to the action integral in the r direction which is conserved to first order



- f as a function of z, r, H, L, J and averaging in the r direction gives a fast, semi-analytical solution along the expansion direction

Intended modeling approach

- The phase space after r-averaging has 1 dof more than the magnetized case, but model still tractable numerically
- From [7], for L=0 in a convergent plasma beam, it is seen that J plays an analogous role to μ in magnetized plasma plumes:
  - We expect similar behavior with confined, doubly-trapped, and free electrons in the divergent unmagnetized plume
  - Non-trivial cooling mechanisms will also be present



- EASYPLUME will be used to obtain a first iteration of the electric potential and cross-validation of the results
- Results will be fitted to approximate cooling laws as a function of a reduced number of parameters

[7] M.Martinez-Sanchez, and E.Ahedo, “Magnetic mirror effects on a collisionless plasma in a convergent geometry,” Phys. Plasmas 18, 033509 (2011)

Conclusions and comments

- Non-trivial evolution of distribution functions in a collisionless, unmagnetized plasma thruster plume warrants a kinetic approach
  - Understanding electron cooling is crucial for correct ϕ determination
- EP2-UC3M has devised a method to study the problem. A similar approach has already been successfully applied to magnetic nozzles
  - Unmagnetized case is more complex and includes extra degree of freedom, but an analog between adiabatic invariant J and magnetic moment μ exists that can be exploited after r-averaging
  - Simplified version of the model (fitting laws) to be implemented in SPIS by ONERA
- Experiments within the ESA project aim to validate model results
  - It is essential to understand that vacuum chamber and environmental effects can (will) affect the *global* electron response and modify the cooling behavior: caution must be put to limit or rule out these effects

Thank you!

mario.merino@uc3m.es
ep2.uc3m.es

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