Modeling the physics of plasma thruster plumes in electric propulsion

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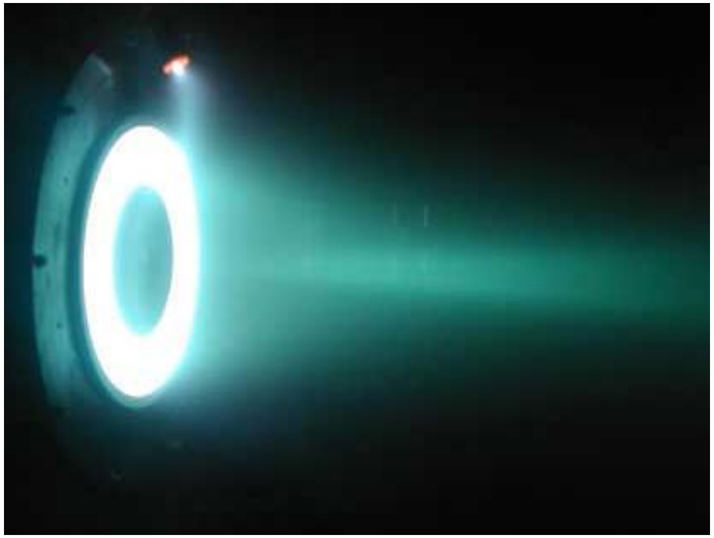
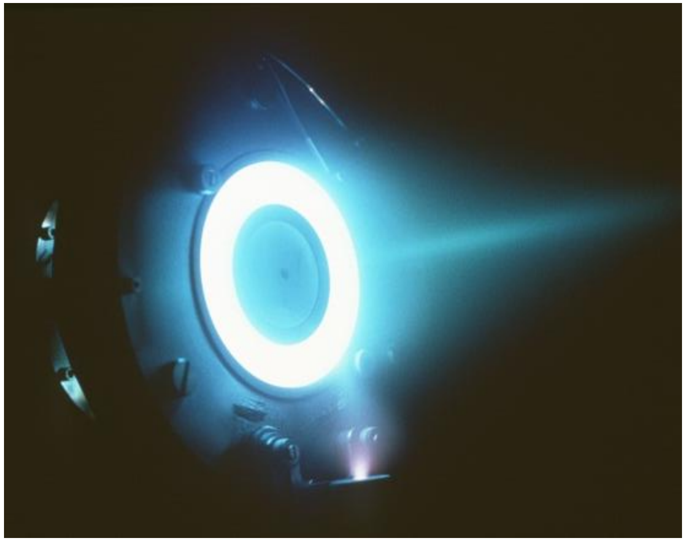
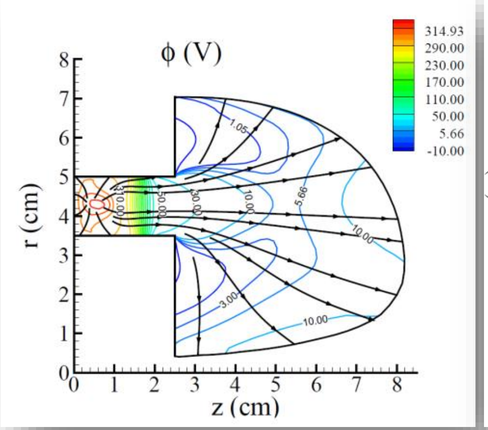


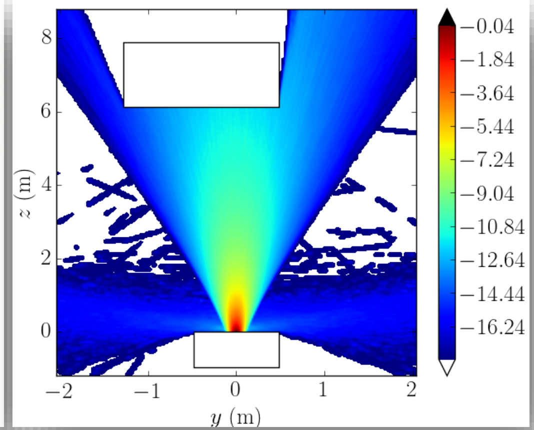


EP2 research group

Equipo de Propulsión Espacial y Plasmas (EP2) was created in 2000 at UPM. EP2 moved to UC3M in September 2013, where it is undergoing a large expansion.

- **Core strength**: modeling and simulation of plasma physics in electric propulsion systems
- **Expertise**: fluid codes, PIC codes, kinetic codes
- **Areas of work:**
  - Hall-effect thrusters
  - Magnetic nozzles
  - Electrodeless RF plasma thrusters (e.g. helicon thrusters)
  - Plasma plume expansion and S/C interaction
  - Electrodynamic tethers
  - Interdisciplinary phenomena (plasma-material interaction, instabilities, turbulent transport, active debris removal).

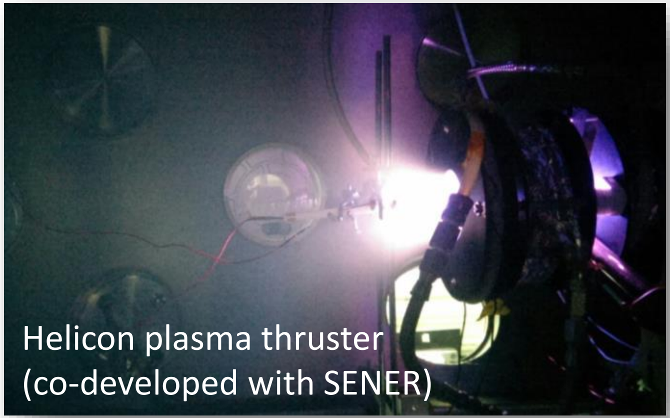




EP2 research group

- **New capabilities: plasma space propulsion laboratory**
  - Large vacuum chamber (built 2015)
    - 1.5 m inner diameter, 3.5 m long
    - Oil free, 35000+ l/s Ar and Xe (turbopumps+cryopanels)
    - Multiple probe diagnostics with 3D robot system

- **EP2 members:**
  - 1 senior researcher
  - 4 junior researchers
  - 3 part-time collaborators
  - 10 PhD students

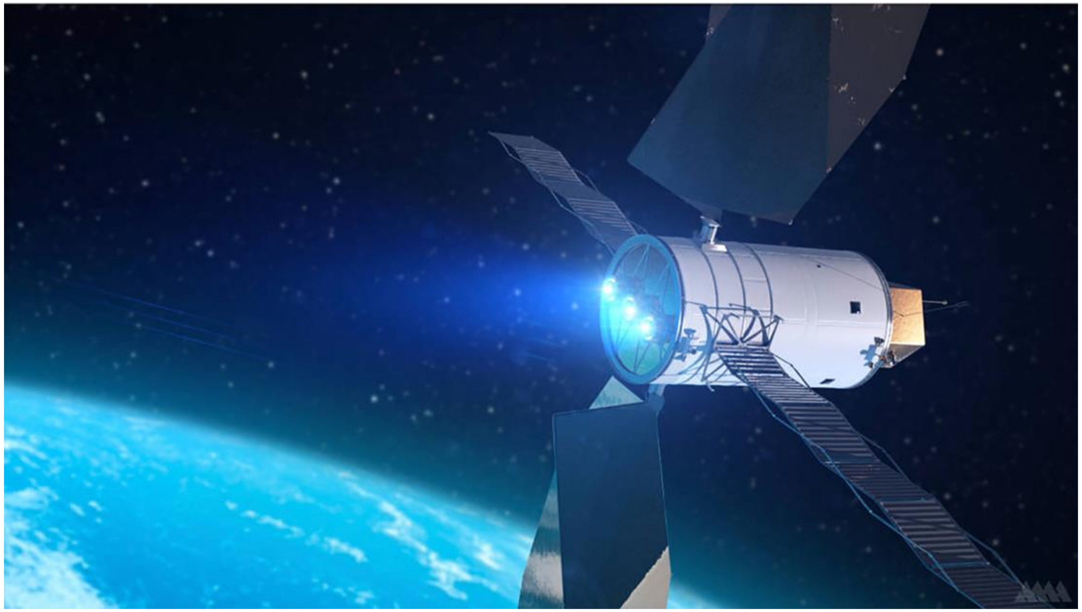


Helicon plasma thruster (co-developed with SENER)

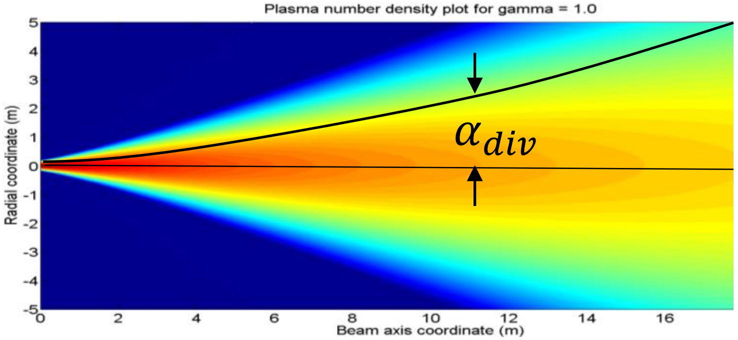
- **EP2 group in numbers**
  - About 40 R&D projects (FP7/H2020, ESA, AFOSR,...)
  - 150+ papers in journals and conference proceedings
  - 4 (+3) recent PhD Theses and ~10 research awards

EP plasma plumes

- Electric propulsion systems generate thrust by creating and ejecting a plasma at high velocities → plasma plume
- Plasma plumes expand into vacuum and have dramatically varying properties:
  - Ion velocities u_i from ~10 km/s to ~100 km/s
  - Plasma densities n_e from $\sim 10^{18} - 10^{15}\ \mathrm{m}^{-3}$ to 0
  - Electron temperatures T_e from ~ 20 eV to ~0



- Important plume numbers:
  - Ion Mach number: $M^2 = m_i u_i^2 / T_e$
  - Divergence half-angle: $\alpha_{95\%}$



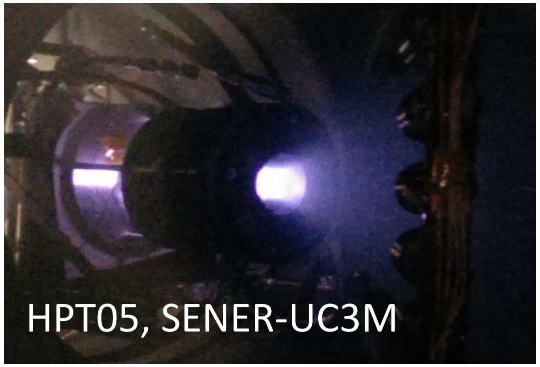
Two fundamental families of plasma plumes

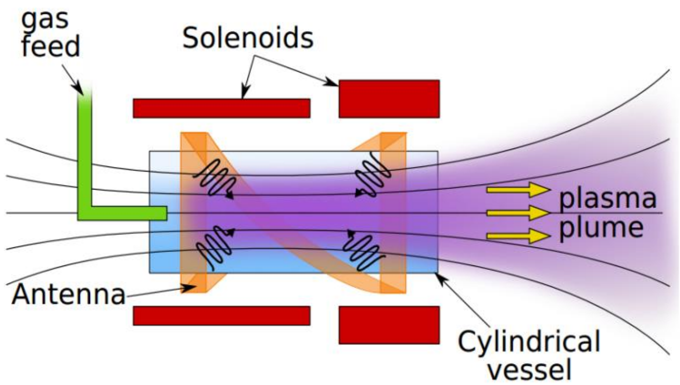
Plasma Plumes

Unmagnetized

- Ion thruster plumes
- Hall effect thruster plumes beyond near region
- **The topic of this talk**

Magnetically guided

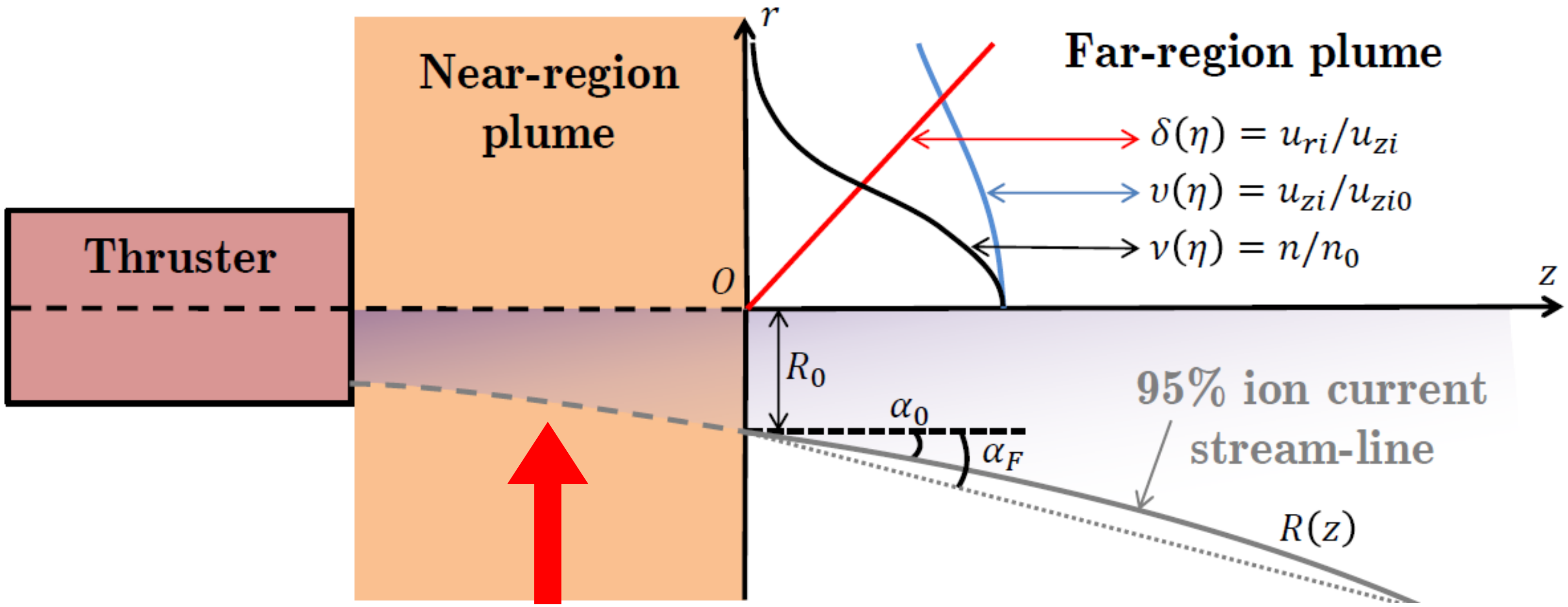




- Magnetic nozzles
- Present in Helicon plasma thruster, AF-MPD, ECR thruster, VASIMR
- Core topic of my phd thesis and an active research line in EP2

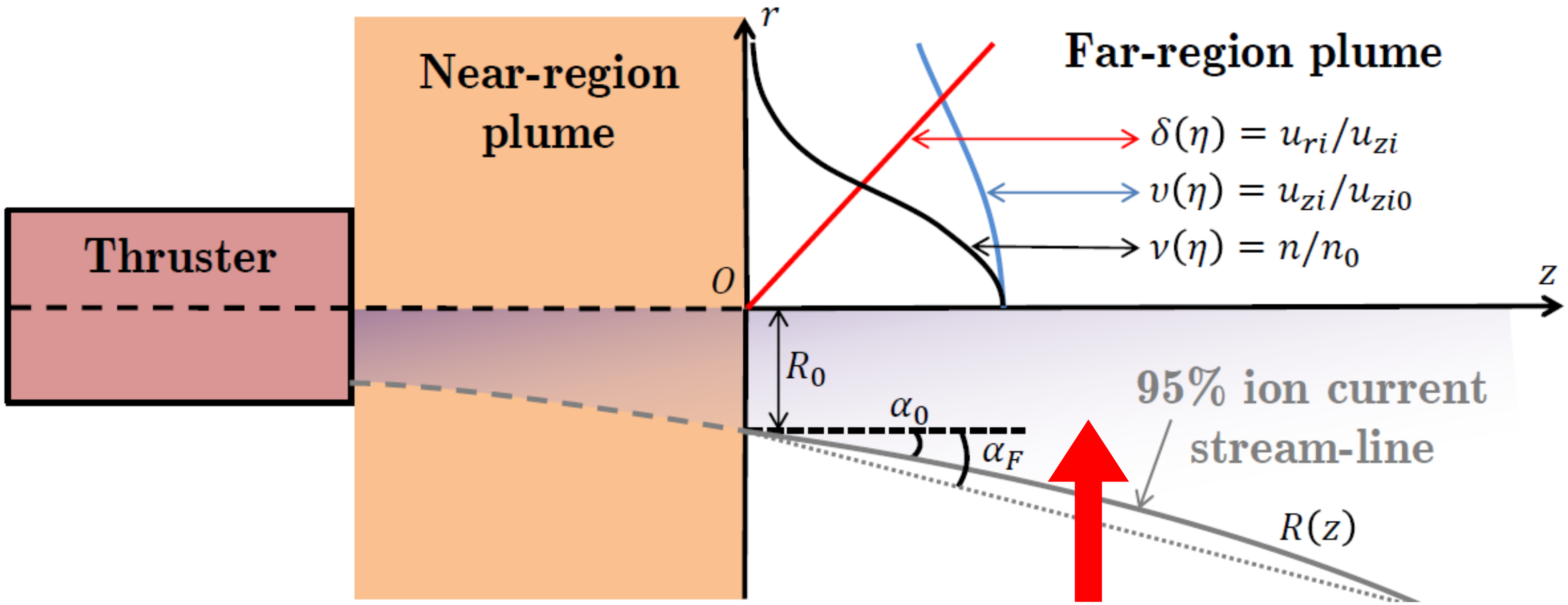
Unmagnetized EP plasma plumes

- Physical phenomena in a plasma plume can be complex. Luckily we can distinguish two qualitatively different regions:
  - Near plume:
    - neutral density is still large; large n_e → collisions, creation of secondary plasma (CEX).
    - Important influence of neutralizer, 3D plume inhomogeneities, residual electric and magnetic fields from the thruster
    - Easy to measure experimentally; hard to model and simulate



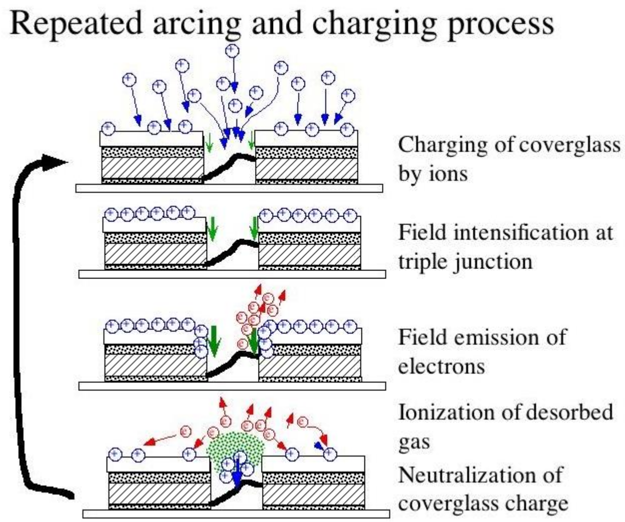
Unmagnetized EP plasma plumes

- Physical phenomena in a plasma plume can be complex. Luckily we can distinguish two qualitatively different regions:
  - Far plume (starts a few thruster radii away from the exit):
    - Collisions are negligible → near-collisionless expansion
    - Thruster and neutralizer influence become insignificant
    - Plume has developed a single-peaked profile and becomes smooth, 2D
    - Hard to measure in the lab; easy to model and simulate



Why study plasma plumes? S/C interaction

- A small fraction of plasma hits the sensitive surfaces of the spacecraft (optical devices, solar arrays, etc)
    - Ions can chemically and mechanically damage them → erosion (sputtering, etching) and contamination (deposition)
    - Plasma can affect electric charging and induce currents in different parts of the S/C
    - The denser plasma (compared to the background plasma) increases the risk of unwanted discharges (arcing) at solar cell interconnectors

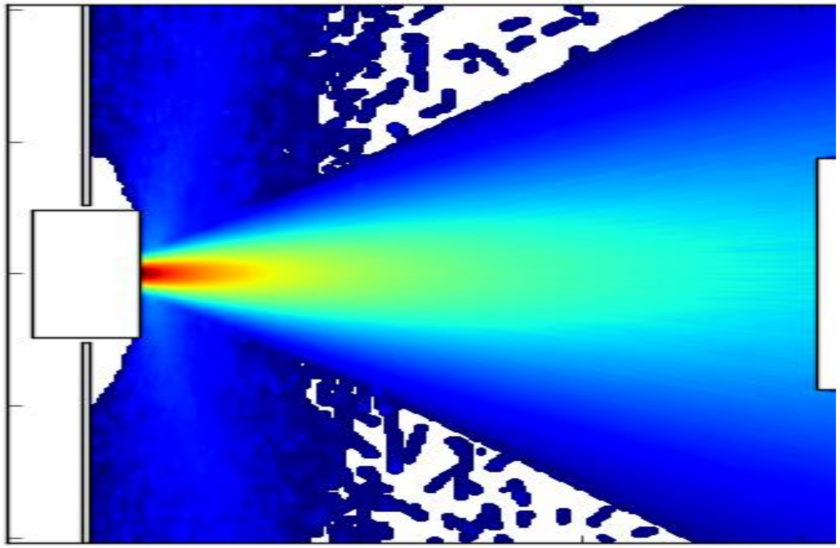


- Plasma plume can interfere with telecommunications too

- Also, characterizing the plume helps understand and optimize the operation of a plasma thruster
    - Thrust and thrust efficiency can be estimated from plume measurements and the operating point of the thruster
    - A wide plume results in reduced thruster efficiency due to divergence losses

Why study plasma plumes? S/C interaction

- Charge-exchange collisions in the near-plume region generate a low energy secondary plasma
  - In contrast to fast primary ions, CEX ions are slow and are deflected strongly by the electric field inside the plume: $\phi(z,r)$ dictates their trajectories
  - CEX ions tend to be accelerated radially to 10s or 100s of eV before impacting on the surfaces of the S/C, and they are a major cause for erosion and contamination

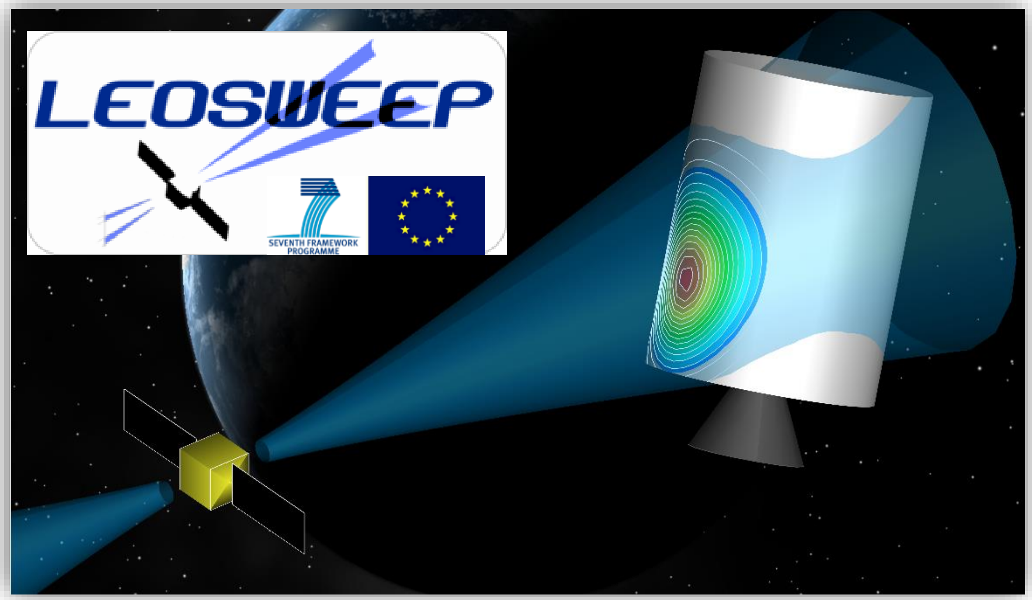


- These problems make plasma plumes a great S/C integration concern → need for detailed plasma plume characterization with experiments and simulation

Deorbiting space debris plasma plumes

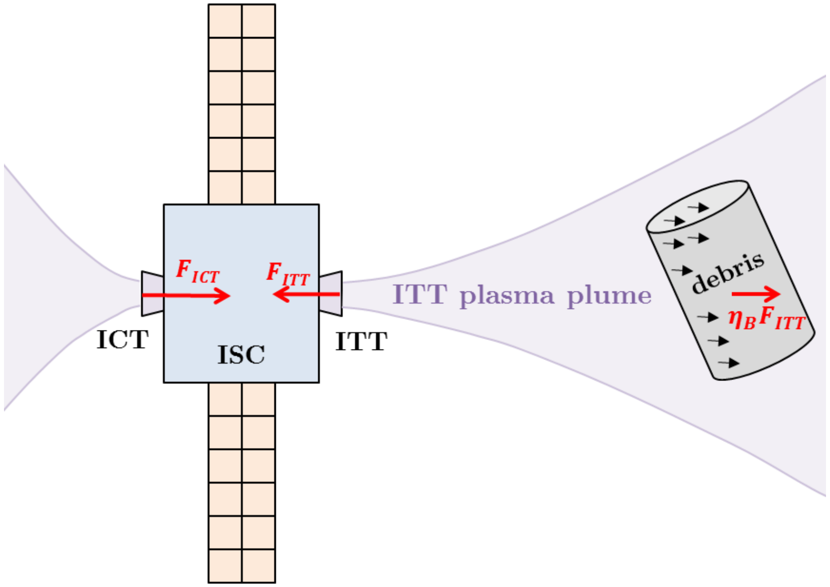
- Plasma plumes can also be used for other purposes: contactless deorbiting of space debris (Ion Beam Shepherd active deorbiting system)
  - ESA Projects (ARIADNA, IBSIOD)
  - LEOSWEEP (FP7 project)
- IBS requires accurate calculation of the momentum transmitted (force and torque) to the target object, as well as the erosion and backflow of material to the IBS

Artist impression of the space debris. Credit by ESA



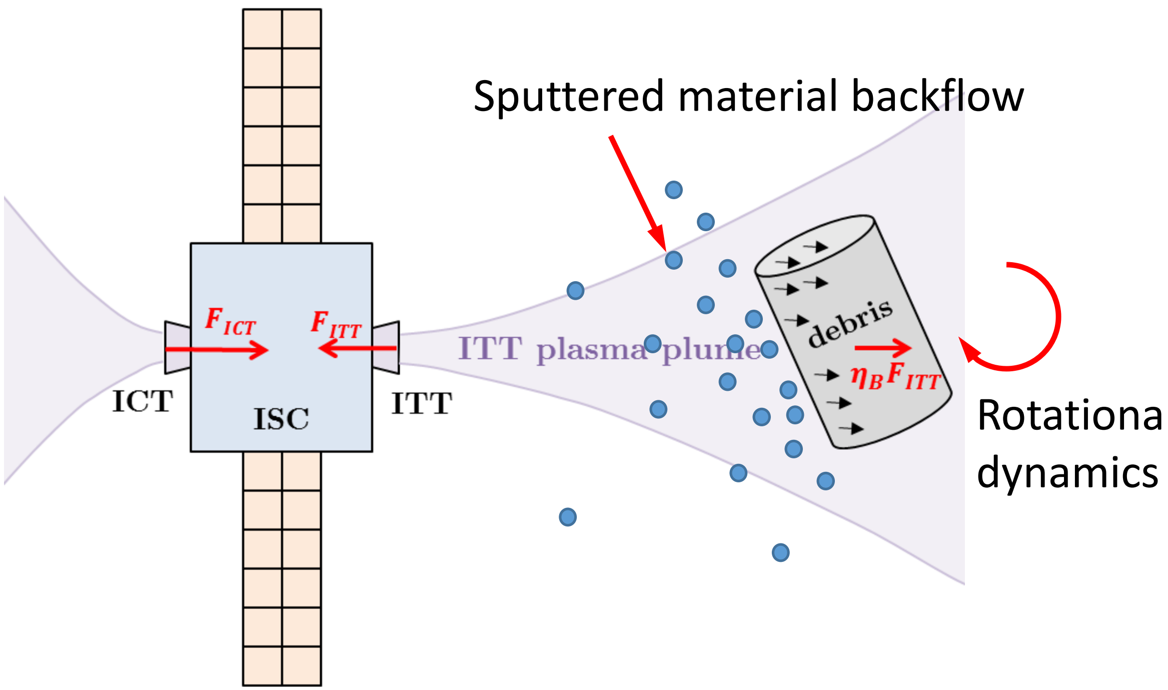
Ion Beam Shepherd

- Thrust on target F_{TG} depends on the momentum of the plasma jet intercepted by the target, and on the accommodation process of high-energy ions on the surface
- We define the plasma plume momentum transfer efficiency as
  - $\eta_B = F_{TG}/F_{ITT}$
  - Large dependence on plume divergence angle!
- To maintain distance during deorbiting, an impulse compensation thruster must fire in the opposite direction:
  - $\vec{a}_{TG} = \vec{a}_{SC}$
    $\Rightarrow \quad F_{ICT} = \left(1 + \eta_B \cdot \frac{m_{SC}}{m_{TG}}\right) \cdot F_{ITT}$
  - $F_{ICT} > F_{ITT}$
  - If $m_{TG} \gg m_{SC} \rightarrow F_{ICT} \simeq F_{ITT}$

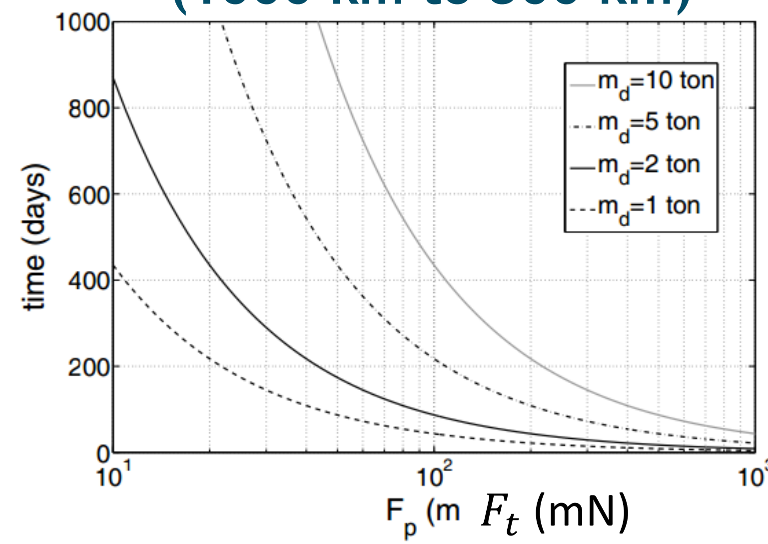


Ion Beam Shepherd

- Other concerns created by the plasma plume – target interatcion:
  - Formation flying stability
  - Rotational state of target (torque on target)
  - Interaction with ambient plasma and geomagnetic field (plume deflection?)
  - Sputtering of target (small contribution to thrust but risk of contaminating IBS)

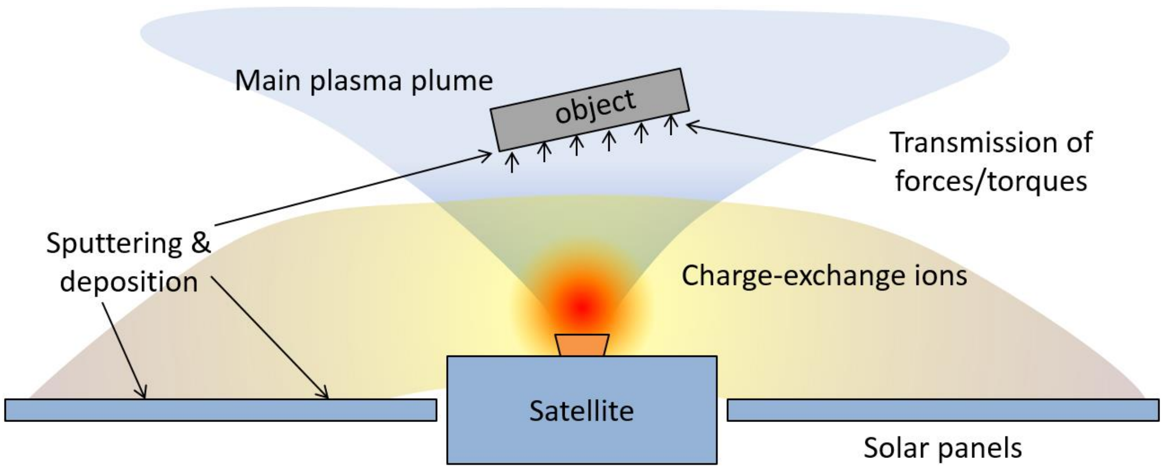


IBS Deorbiting Time (1000 km to 300 km)



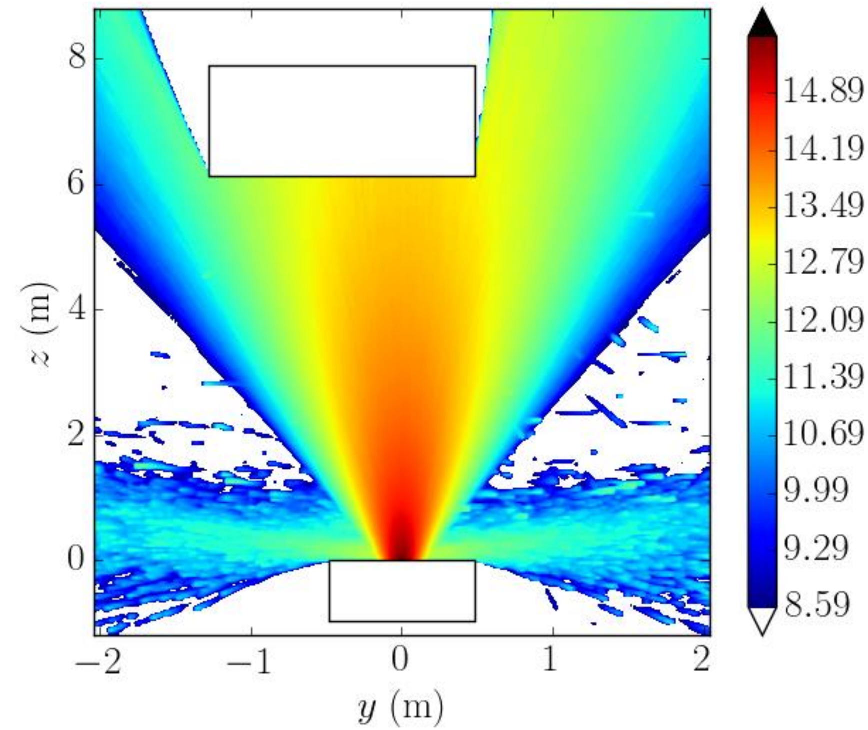
Modeling plasma plume expansions

- There are several ways to model a plasma plume:
  - Fluid models (single-fluid, two/three-fluid models):
    - Simple and computationally fast
    - Can recover most physics of interest of the far region
    - Limited use to study CEX ions and near region phenomena. Cannot study kinetic effects
    - Example: EASYPLUME code
  - Particle-in-cell methods (all species modeled as macroparticles; fields are computed on a mesh):
    - Computationally very expensive; not suited for large domains
    - Timestep and cell size constrained by λ_D and ω_{pe} (critical!)
    - Can address most physical phenomena



Modeling plasma plume expansions

- Hybrid PIC/fluid codes (heavy species are particles; electrons are fluid)
  - Eliminates the need of solving λ_D and ω_{pe}: much faster
  - Allows to recover the distribution function of heavy species (ions, neutrals) and most physical phenomena related to them
  - Limited electron physics
  - Example: EP2-PLUS code
- Direct kinetic codes (solve f_e, f_i directly)
  - Can address most physical phenomena, but computationally expensive: use restricted to studying specific problems
  - Example: AKILES2D code

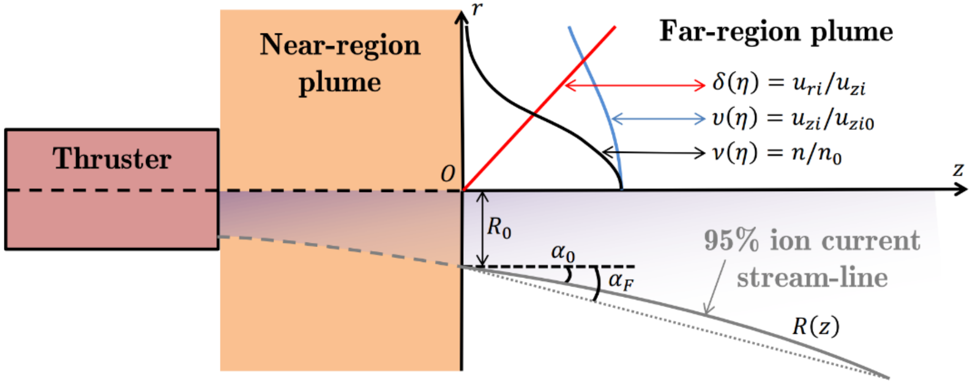


Ion density with EP2-PLUS

Fluid model of the plasma plume far region

Two-fluid model: EASYPLUME

- Two-fluid code of the far-region plasma plume expansion
  - Two-fluid, collisionless, quasineutral
  - Solution of fluid equations with three methods:
    - Self-similar methods
    - Asymptotic expansions
    - Method of characteristics



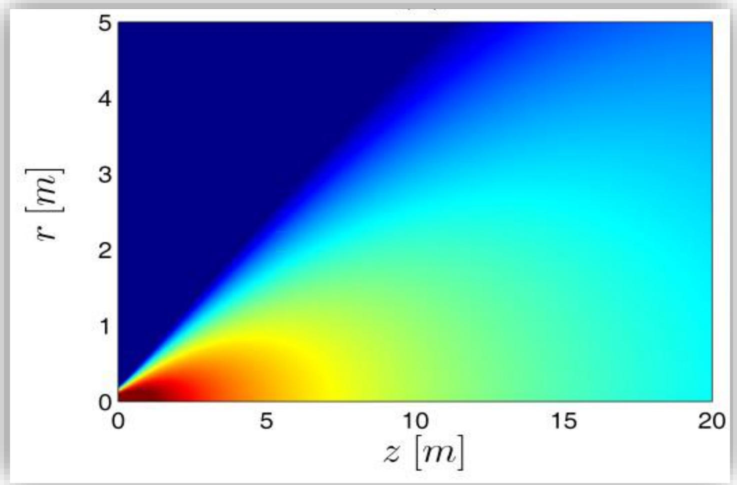
- Continuity and momentum equations for ions (normalized):

$$\tilde{u}_{zi}\frac{\partial \ln \tilde{n}}{\partial \tilde{z}} + \tilde{u}_{ri}\frac{\partial \ln \tilde{n}}{\partial \tilde{r}} + \frac{\partial \tilde{u}_{zi}}{\partial \tilde{z}} + \frac{1}{\tilde{r}}\frac{\partial\left(\tilde{r}\tilde{u}_{ri}\right)}{\partial \tilde{r}} = 0,$$

$$\tilde{u}_{zi}\frac{\partial \tilde{u}_{zi}}{\partial \tilde{z}} + \tilde{u}_{ri}\frac{\partial \tilde{u}_{zi}}{\partial \tilde{r}} = -\frac{\tilde{n}^{\gamma-1}}{M_0^2}\frac{\partial \ln \tilde{n}}{\partial \tilde{z}},$$

$$\tilde{u}_{zi}\frac{\partial \tilde{u}_{ri}}{\partial \tilde{z}} + \tilde{u}_{ri}\frac{\partial \tilde{u}_{ri}}{\partial \tilde{r}} = -\frac{\tilde{n}^{\gamma-1}}{M_0^2}\frac{\partial \ln \tilde{n}}{\partial \tilde{r}},$$

Ideal EP Plasma plume expansion into vacuum (EASYPLUME)



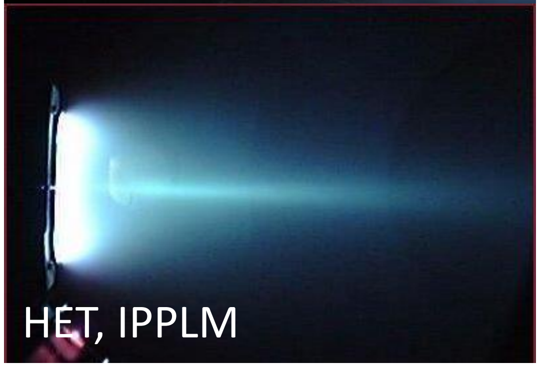
Two-fluid model: EASYPLUME

- Two fundamental parameters control the far-region expansion:
  - **Plasma cooling** (approximated with a polytropic law with specific heat ratio γ):

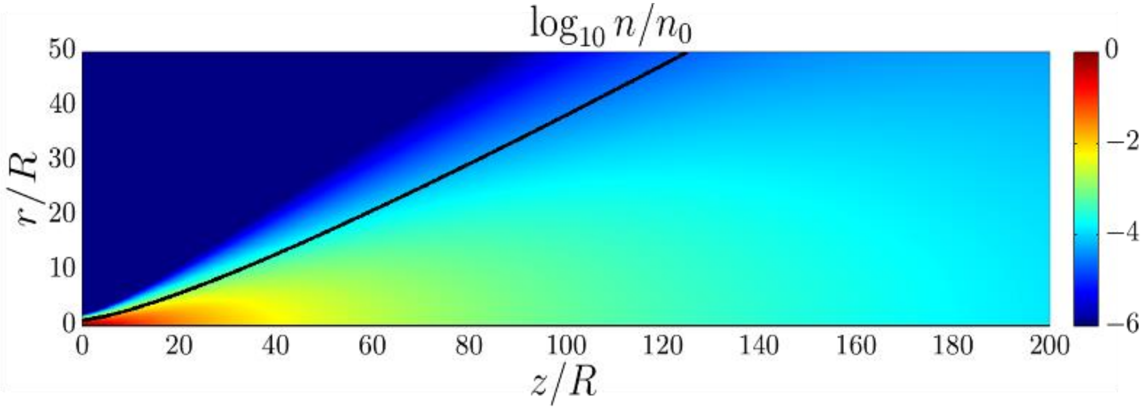
$$T_e \propto n^{\gamma-1}$$

  - Main parameter: **Ion beam energy** to **electron thermal energy ratio** (or: squared Mach number):

$$(eV_{beam})/T_{e0} = \left(m_i u_i^2/2\right)/T_{e0} = \frac{\gamma}{2} M_0^2$$



≫ **1 for EP plasma plume**



EASYPLUME enables:
- Fast iteration in preliminary design
- Understanding dominant physics
- Identifying the role of main parameters
- Validation of advanced codes

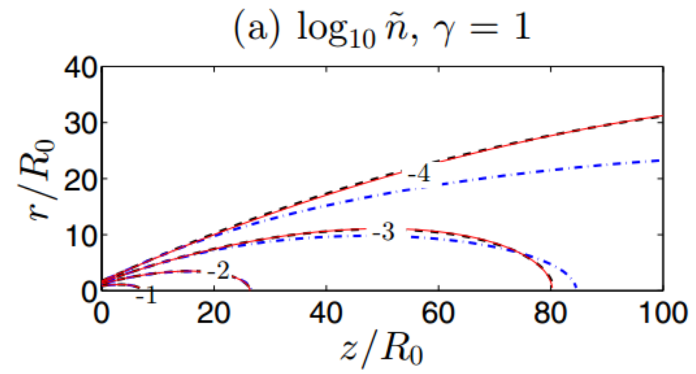
Two-fluid model: EASYPLUME

- Asymptotic expansion model (AEM)
  - Expand solution in the small parameter $\varepsilon = 1/M_0^2$
  - Each order can be solved by integrating an ode along straight lines

$$\tilde{u}_{zi} = \tilde{u}_{zi}^{(0)} + \varepsilon \tilde{u}_{zi}^{(1)} + \varepsilon^2 \tilde{u}_{zi}^{(2)} + \cdots ,$$

$$\tilde{u}_{ri} = \tilde{u}_{ri}^{(0)} + \varepsilon \tilde{u}_{ri}^{(1)} + \varepsilon^2 \tilde{u}_{ri}^{(2)} + \cdots ,$$

$$\ln \tilde{n} = \ln \tilde{n}^{(0)} + \varepsilon \ln \tilde{n}^{(1)} + \varepsilon^2 \ln \tilde{n}^{(2)} + \cdots ,$$

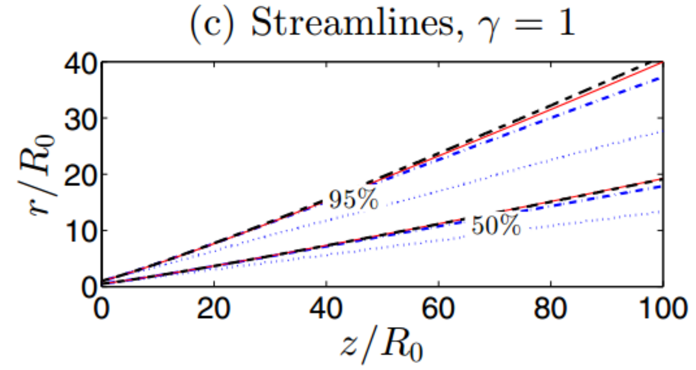


- Self-similar model
  - Separation of variables and self-similarity assumption lead to an approximated solution (accurate when $M_0^2 \gg 1$

$$\tilde{n} = \nu(\eta) \tilde{n}_c(\zeta),$$

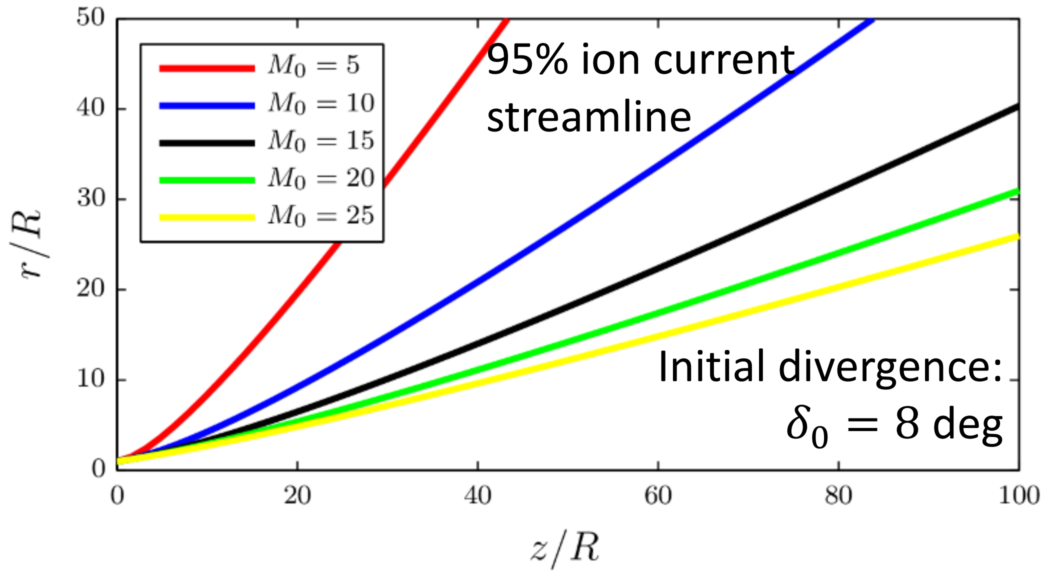
$$\tilde{u}_{ri} = \tilde{u}_{zi} \eta h',$$

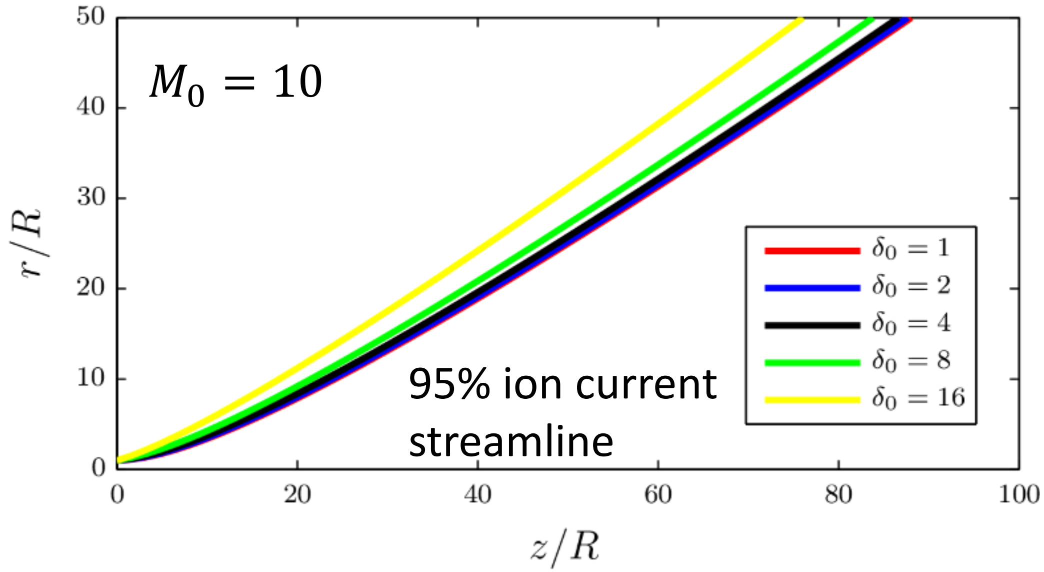
$$\tilde{u}_{zi} = \upsilon(\eta) \tilde{u}_c(\zeta),$$



- Method of characteristics
  - Full integration of fluid equations

Plume divergence growth in the far region

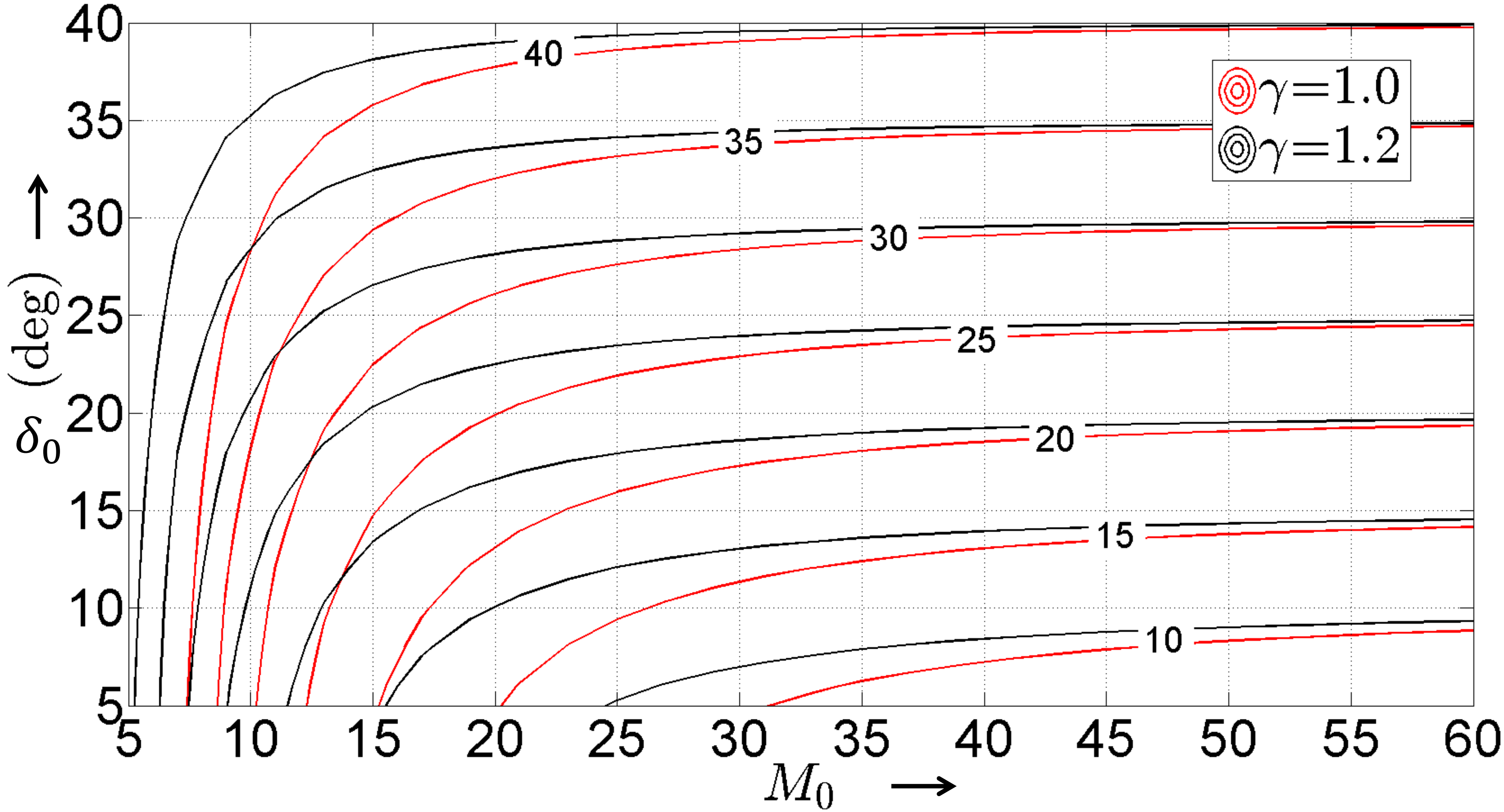




- The residual **electron pressure** is the main driver of divergence growth in the far plume
  - Ion-electron energy ratio $\boldsymbol{M_0^2}$ **determines far-region divergence**
  - **Increasing acceleration voltage increases $\boldsymbol{M_0}$** and reduces divergence growth
- Effort to decrease the initial divergence angle at the exit of the thruster may not pay off – especially at low-medium M_0

Effect of M_0, δ_0, and γ (cooling rate)

DIVERGENCE ANGLE AT 20 METRES (useful for IBS missions)



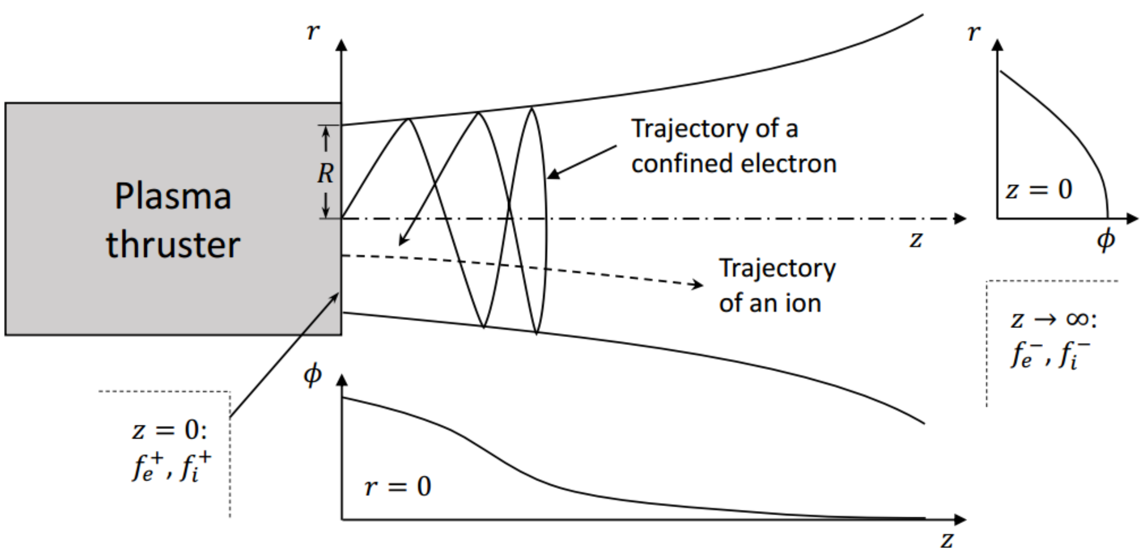
Kinetic model of the plasma plume far region

Motivation

- The electron cooling rate γ in a plasma plume is important, as it dictates the profile of the plasma electric potential ϕ
- Too simplistic electron models are commonly used in the study of plasma plumes (e.g. hybrid PIC/fluid codes)
  - Isothermal and polytropic closure relations are used ubiquitously
- However, the expansion is near-collisionless: electron response is *global* as electrons are far from local thermodynamic equilibrium (LTE)
  - Simple closure models based on LTE are not physically justified
- A kinetic treatment is required to resolve the electron distribution function in the plume and understand the collisionless electron cooling mechanisms
  - Goal: to inform fluid and PIC/fluid models with a better justified electron model
  - AKILES2D: Advanced Kinetic Iterative pLasma Expansion Solver 2D
  - Effort funded by ESA project 4000116180/15/NL/PS

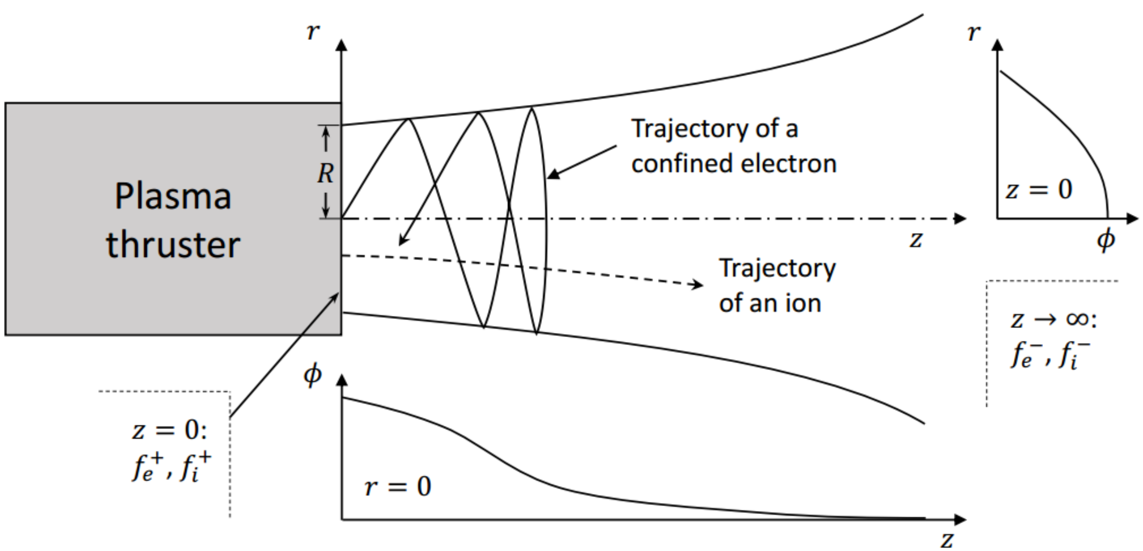
Definition of the problem

- In the plasma plume, the electric potential decreases downstream and is paraxial (ε)
- Except for the few escaping electrons, the electric field confines most of them axially and radially. Their trajectories bounce radially back and forth
- Ions, on the contrary, are accelerated downstream
- Collisionless plasma, steady state



Kinetic plume model

- A potential $\phi(z, r)$ is assumed as initial guess
- Electron model and ion model are solved for that ϕ: n_e, n_i are computed at the plume axis
- The error in $n_i - n_e$ (quasineutrality) and in $j_i - j_e$ (current-free plume) are used to recompute $\phi(z, r)$ and iterate
- After convergence, any moment of the EVDF can be computed



Electron kinetic model

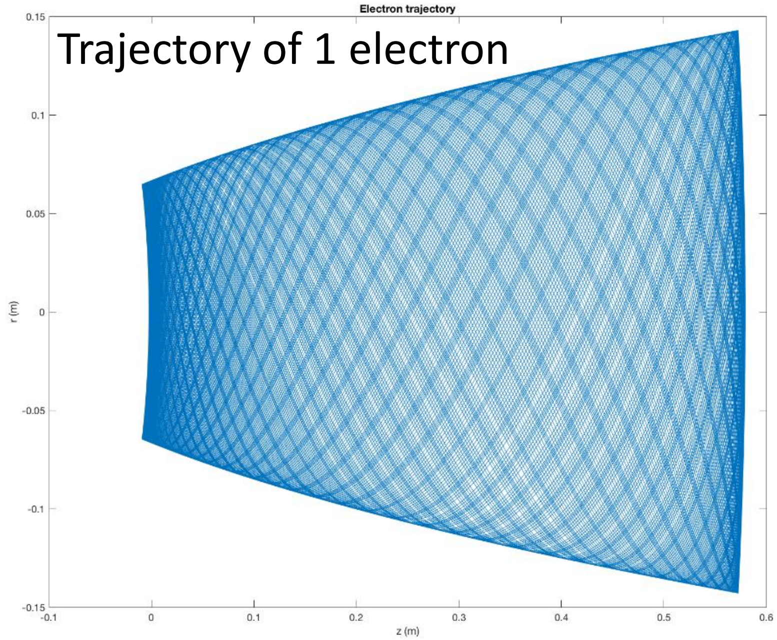
- In a steady-state, axisymmetric, collisionless plume, each electron conserves exactly:
  - The mechanical energy E,
  - The angular momentum about the axis p_θ
- In a paraxial plume ($\partial/\partial z \sim \varepsilon\, \partial/\partial r$) the radial-orbit-averaged electron action integral is conserved to order ε^2:
  - Action integral associated to radial motion: $J_r = \oint p_r dr$
    - Conjugated angle variable: β_r
- We perform a change of variables from $(z, r, \theta, v_z, v_r, v_\theta)$ to $(z, \beta_r, \theta, E, J_r, p_\theta)$
- We decompose the EVDF into its radial-orbit-averaged value $\bar{f}$ and a zero-average radial variation $\hat{f}$ of order ε:

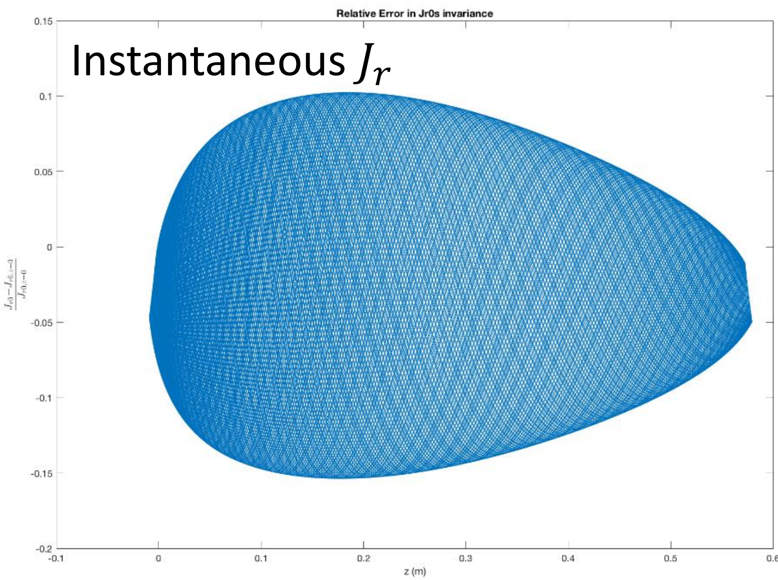
$$\boxed{f(z, \beta_r, E, J_r, p_\theta) = \bar{f}(z, E, J_r, p_\theta) + \varepsilon \hat{f}(z, \beta_r, E, J_r, p_\theta)}$$

with $\bar{f} = \int_0^1 f d\beta_r;\ 0 = \int_0^1 \hat{f} d\beta_r$

Numerically testing the conservation of J_r

- Numerically checked by propagating single electrons in a paraxial electric potential map
- Conservation is exact in the limit $\varepsilon \to 0$
- For a 20 deg divergence case, the **radial-orbit-averaged J_r used in the model deviates less than 1%**





Electron kinetic model

- The radial-orbit-averaged evolution equation for $\bar{f}$ (Vlasov's equation) in these variables simplifies substantially:

$$\cancel{\frac{\partial \bar{f}}{\partial t}} + v_z \frac{\partial \bar{f}}{\partial z} + \dot{\beta}_r \cancel{\frac{\partial \bar{f}}{\partial \beta_r}} + \dot{\theta} \cancel{\frac{\partial \bar{f}}{\partial \theta}} + \dot{E} \cancel{\frac{\partial \bar{f}}{\partial E}} + \underbrace{\int_0^1 \dot{J}_r \frac{\partial \bar{f}}{\partial J_r} d\beta_r}_{O(\varepsilon^2)} + \dot{p}_\theta \cancel{\frac{\partial \bar{f}}{\partial p_\theta}} = 0$$

- To order ε, then:

$$\boxed{v_z \frac{\partial \bar{f}}{\partial z} = 0}$$

  - In these variables, $\bar{f}$ is merely convected along z as a constant
  - Equation $v_z = 0$ divides phase space into different regions according to their connectivity to the upstream and downstream boundary conditions
    - Passing, reflected, doubly-trapped, empty, forbidden regions

Electron kinetic model

- For a **radially-parabolic potential**,

$$\phi(z,r) = -\frac{ar^2}{h^2(z)} + \phi_z(z)$$

with:

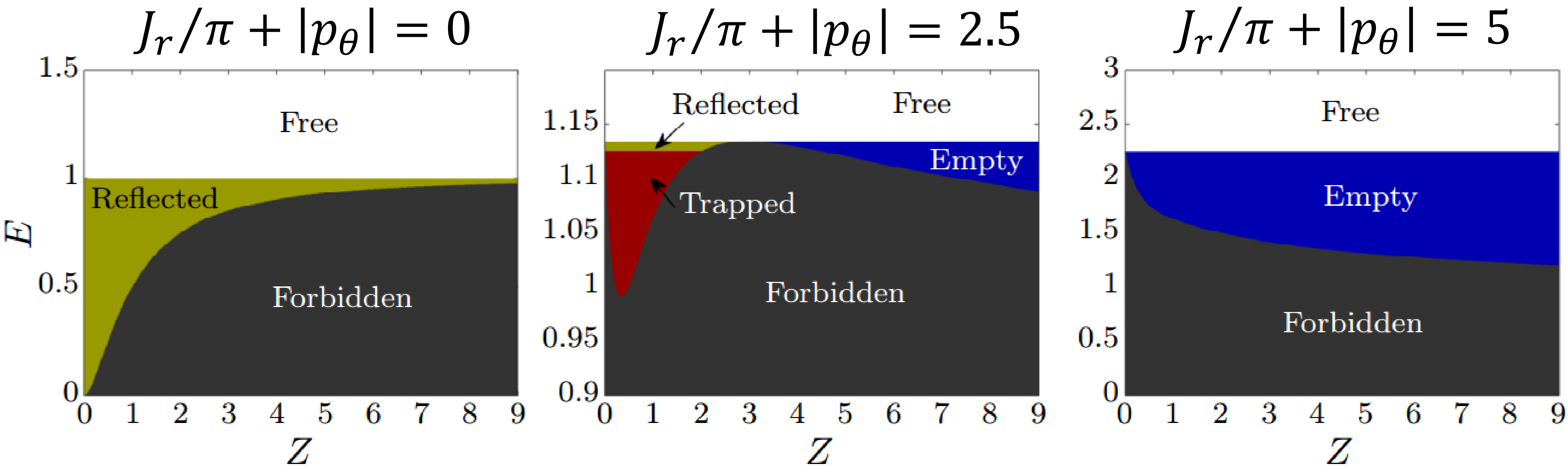
- $h(z)$: function that represents effective beam radius at z,
- $\phi_z(z)$: electric potential at the axis,

setting $v_z = 0$ in the resulting energy equation gives the phase-space region boundaries in terms of the **effective potential U_{eff}**:

$$E = \frac{1}{2} m_e v_z^2 \underbrace{- e\phi_z(z) + \sqrt{\frac{2ea}{m_e}} \frac{J_r/\pi + |p_\theta|}{h(z)}}_{U_{eff}(z, J_r, p_\theta)}$$

Electron kinetic model

- Example of U_{eff} plots and **phase-space regions** for different values of $J_r/\pi + |p_\theta|$:



- Once $\bar{f}$ is propagated in z, **any moment of the distribution** can be computed:

$$M_{ijk} = \int \bar{f} v_z^i v_r^j v_\theta^k dv_z dv_r dv_\theta$$

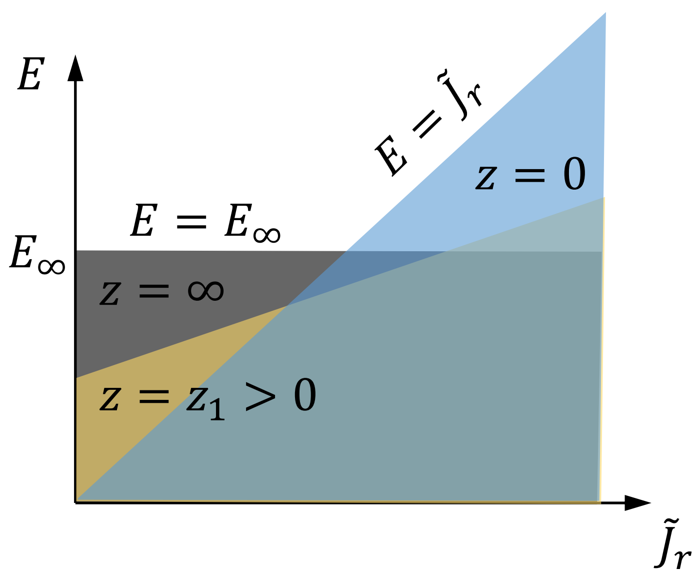
  - The computation involves changing variables to E, J_r, p_θ
  - The error committed is of order ε due to $\hat{f}$

Electron kinetic model

- Further insight on the electron kinetic model is obtained by looking at **phase-space regions** in the $(E, \tilde{J}_r)$ plane, where:

$$\tilde{J}_r = \sqrt{\frac{2ea}{m_e}}(J_r/\pi + |p_\theta|)$$

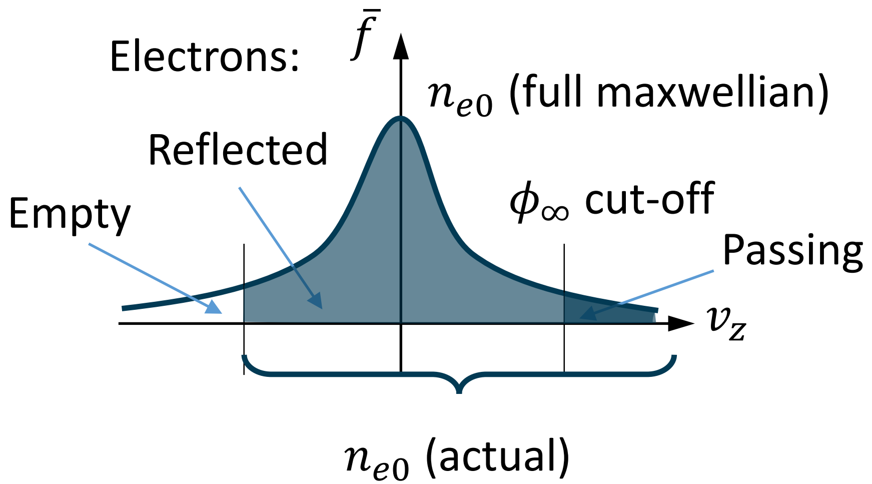
- The effective potential is $U_{eff} = -e\phi_z(z) + \tilde{J}_r/h(z)$
  - At each z, the forbidden region is limited by a **straight line** in this plane



  - The **envelopes** of the forbidden region for $z \in (0, z_1)$ (behind of z_1) and for $z \in (z_1, \infty)$ (ahead of z_1) define the phase-space regions
  - In particular, the only **electrons reaching** ∞ are those in the white region: they must have $E > E_\infty$

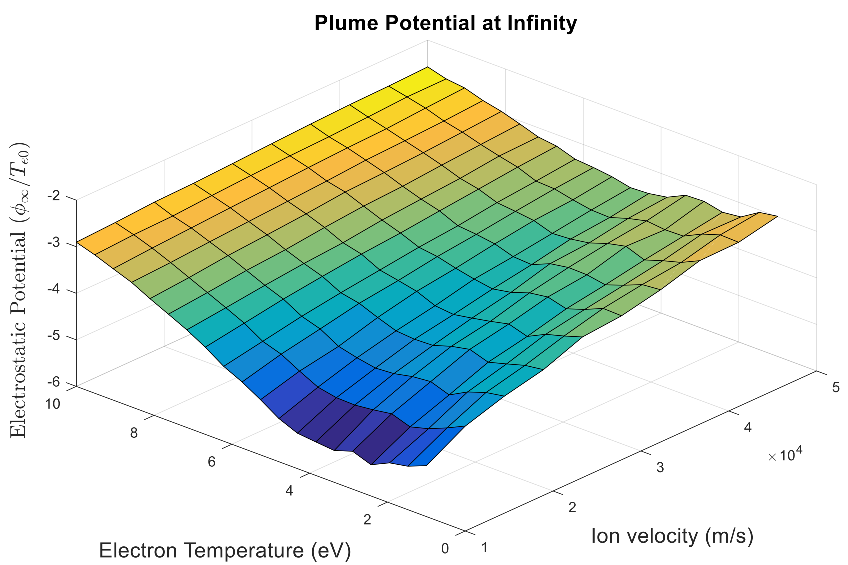
Electron kinetic model

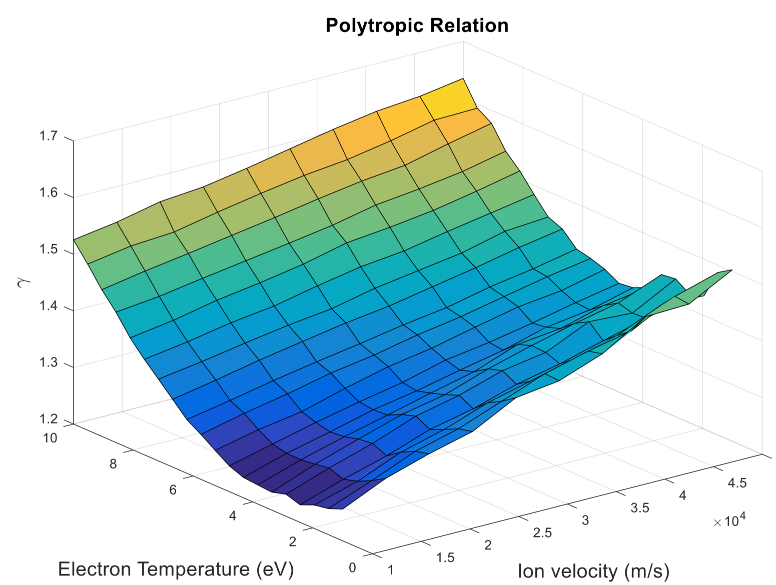
- Electron model **boundary conditions**:
  - Assume a Maxwellian population at $z = 0$ for $v_z > 0$
    - The **full Maxwellian** (i.e., extended to $v_z < 0$ too) has a temperature T_{e0} and a density n_{e0} at the origin
    - Note that these values **will differ** from those of the *actual* distribution at $z = 0$, since $\bar{f}$ for $v_z < 0$ is **unknown** until the solution of the problem.



Iterator solver and preliminary results

- The electron model is complemented with a simple fluid model and made non-dimensional with $m_e, e, T_{e0}, R_0,\ n_{i0}$. The model has the following parameters:
  - m_i/m_e: mass ratio. Only relevant at low ion Mach numbers
  - $u_{zi0}\sqrt{m_i/T_{e0}}$: ion Mach number at origin
- A pseudo-Newton-Raphson algorithm can be used to iterate on the initial guess of the potential and the initial EVDF until convergence is reached
- Preliminary results (work in progress):





Thank you! Questions?

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