Electron Kinetics in Magnetic nozzles

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Propulsive Magnetic Nozzle (PMN) Theory

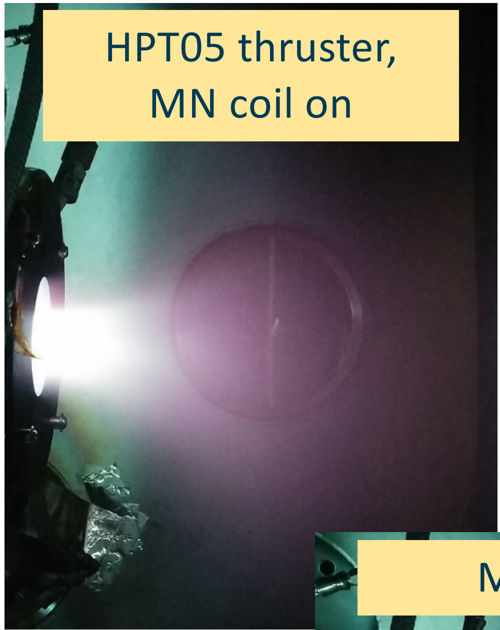
- **Since 2009, EP2 is developing a complete theory of PMNs**
  - ‘Propulsive’ MN means that we look for
    - Supersonic acceleration of plasma beam in divergent MN
    - Creation of magnetic thrust
- **Multi-fluid stationary models**
  - 2Dax: **DIMAGNO**: main MN physics
  - 3D: **FUMAGNO**: MN near-region, no detachment
- **Kinetic models (quasi-1D)**
  - Steady-state: **AKILES**
  - Time-dependent: **VLASMAN**

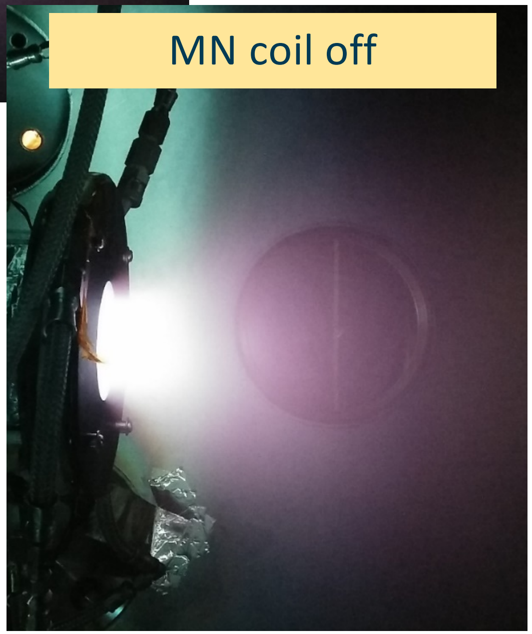
EP2 open source codes are available on GitHub: https://github.com/ep2lab

EPIC Lecture series 2017, Madrid:
Watch the lecture on MN at www.youtube.com/watch?v=IEpd1ME2P30

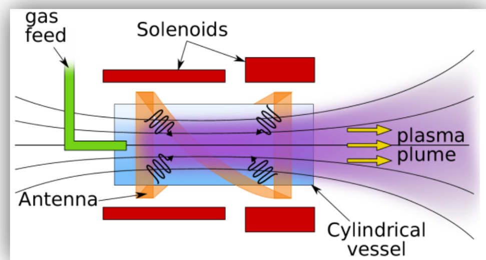
Lecture notes:
M. Merino, E. Ahedo, “*Magnetic Nozzles for Space Plasma Thrusters*” Encyclopedia of Plasma Technology, 2016

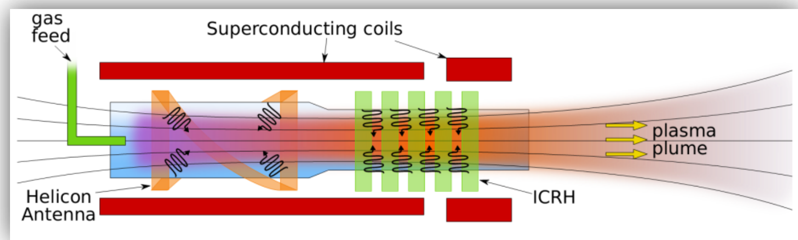
MN in experiments

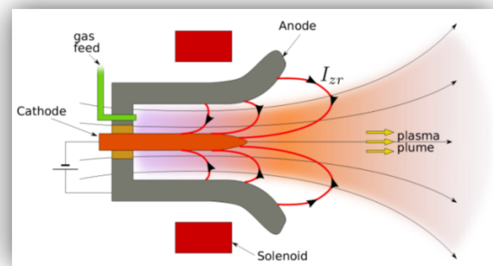




DIMAGNO (2010)







- Fully 2D model of divergent MN
  - No self-similarity
  - No ambipolar condition on current
  - Increase of beam momentum in MN through magnetic force

$$\nabla \cdot (m_i n \boldsymbol{u_i} \boldsymbol{u_i} + \bar{\bar{P}}) = \boldsymbol{j} \times \boldsymbol{B}$$

    - Magnetic thrust (i.e. reaction), $j_\theta B_r$, based on beam θ- current
    - Better operation at low plasma-β
    - *e*-momentum/energy $\xrightarrow{\mathbf{E}\text{ ambipolar}}$ *i*-momentum/energy
- Partially-magnetized ions
  - Detachment via ion demagnetization
  - For fully-magnetized ions & current ambipolarity → FUMAGNO 3D

DIMAGNO (2010)

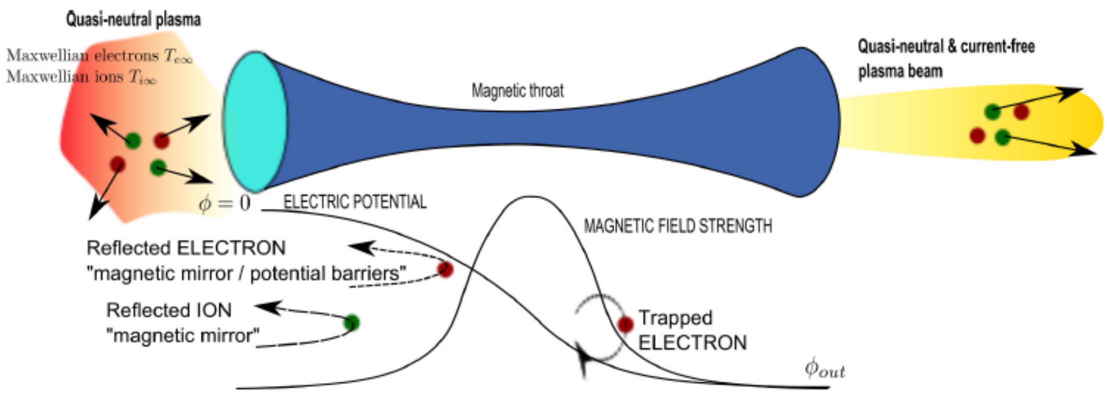
- Collisionless (i.e. rarefied beam)
  - Beam θ- current must be created inside source
  - Conservation of beam energy

$$\nabla \cdot \sum \left[\left(\frac{1}{2} m_\alpha n u_\alpha^2 + \frac{5}{2} T_\alpha\right) n \boldsymbol{u}_\alpha + \boldsymbol{q}_\alpha \right] = \boldsymbol{j} \cdot \boldsymbol{E} \simeq j_\theta E_\theta = 0$$

    - Internal energy $\xrightarrow{\text{MN expansion}}$ Axially directed energy
- Electron thermodynamics
  - Assumption: Isotropic $\bar{\bar{P}}_e$ + isothermal/polytropic behavior:
    - $\nabla \cdot \bar{\bar{P}} \simeq \nabla \cdot \bar{\bar{P}}_e \simeq \nabla p_e \simeq n_e \nabla h_e,$
    - barotropic function: $h_e \propto T_e^{\gamma-1}, \ \ln n$
  - No justification for a magnetized free-molecular $(Kn \gg 1)$ flow
    - This is DIMAGNO's current weak point
  - Extension to anisotropic $\bar{\bar{P}}_e$ is on the tasks' list
- Assistance on $\bar{\bar{P}}_e$ sought in kinetic models

Stationary kinetic model

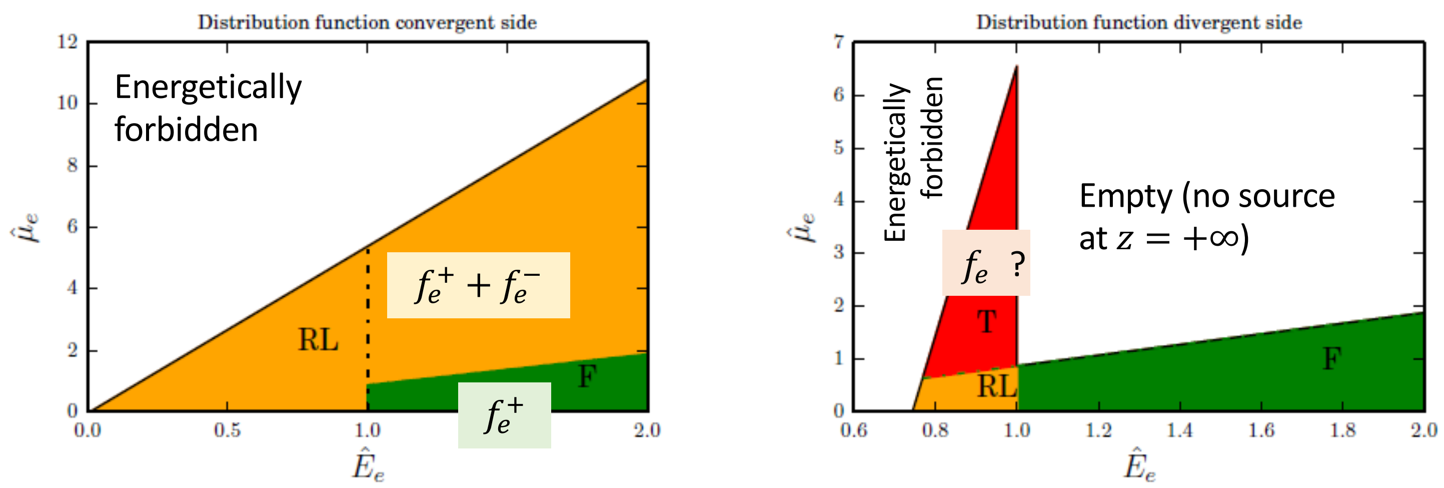
Martínez-Sánchez, Navarro, Ahedo, PoP 22, 053501 (2015)



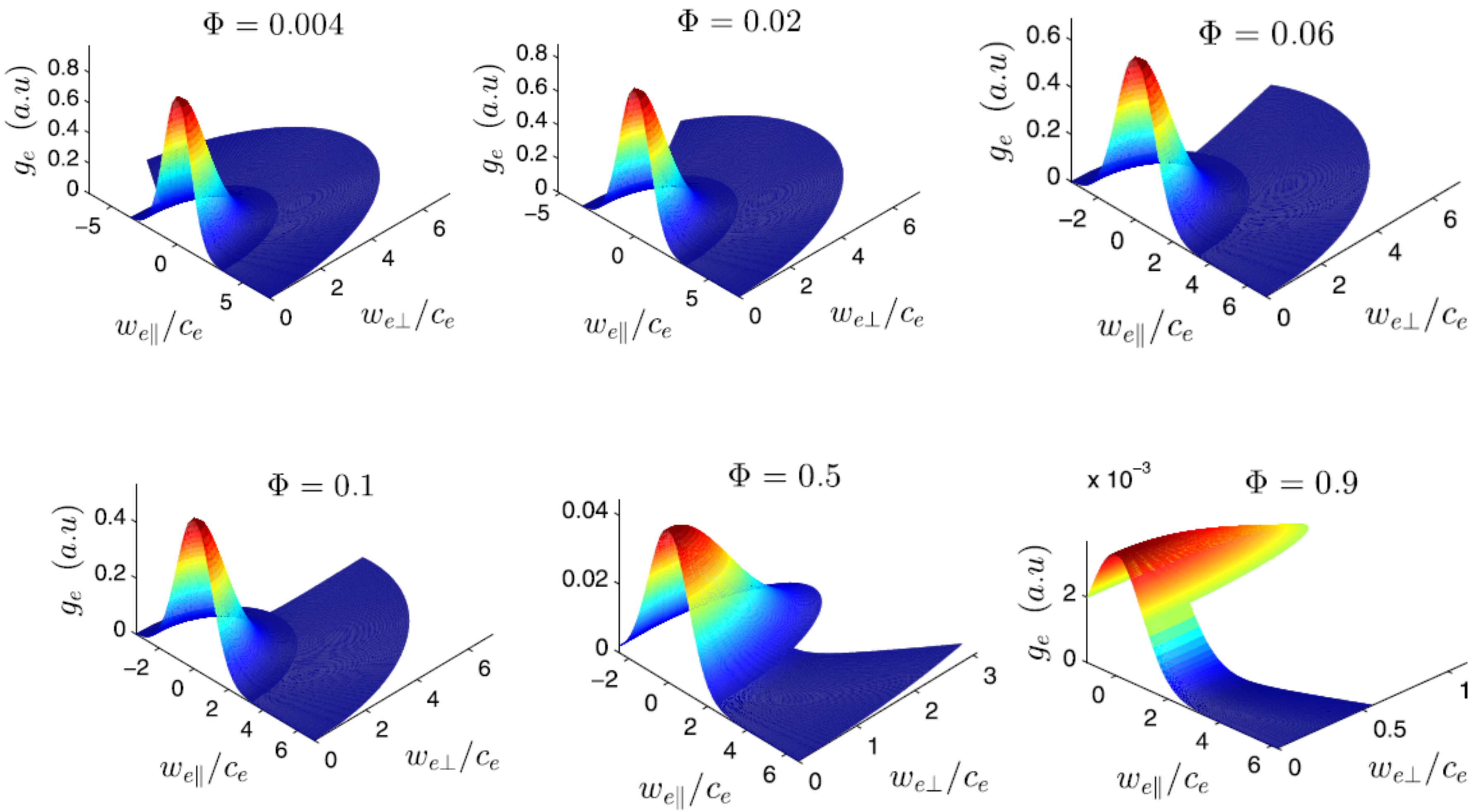
- Semi-analytical solution for VDF
- Discussion here focused on electron dynamics
- Upstream: semi-Maxwellian source of electrons, $f_e^+ \propto \exp\left(-\frac{m_e v^2}{2T_e}\right)$
- Convergent side of MN:
  - Both $\boldsymbol{E}$ and $\boldsymbol{B}$ tend to confine electrons
  - Most electrons are reflected back $\Rightarrow$ $f_e \simeq \text{Maxw.}$, $T_e \simeq \text{const}$
    - **No macroscopic B-mirror effect in convergent geometry**

Stationary kinetic model

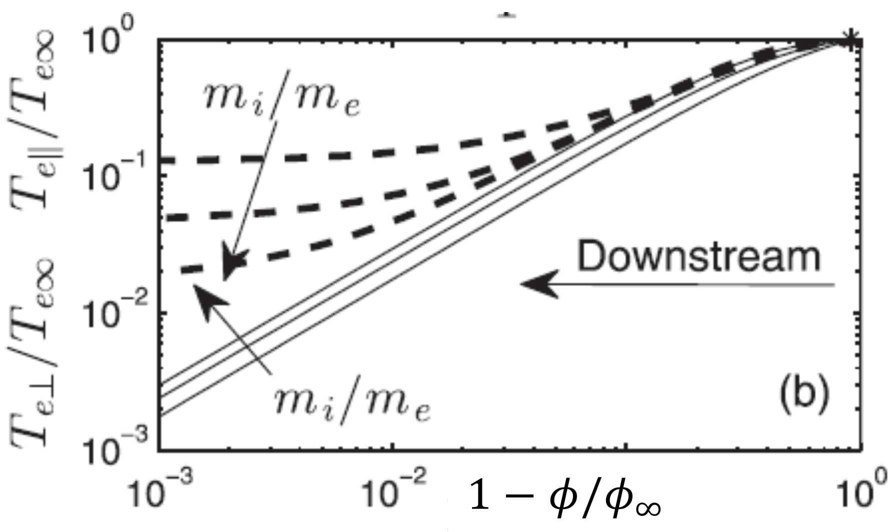
- Divergent side of MN:
  - $\boldsymbol{E}$ is confining; $\boldsymbol{B}$ increases parallel energy
  - Maxwellianicity is lost: there are regions of v –space:
    1. Empty $\Rightarrow$ Cooling + anisotropy $(\frac{T_\perp}{T_\parallel} < 1)$
    2. Unconnected with $z = \pm\infty$
       - These are isolated regions of doubly-trapped electrons
         - Similar case in probe theory
       - Stationary model is unable to determine f_e there

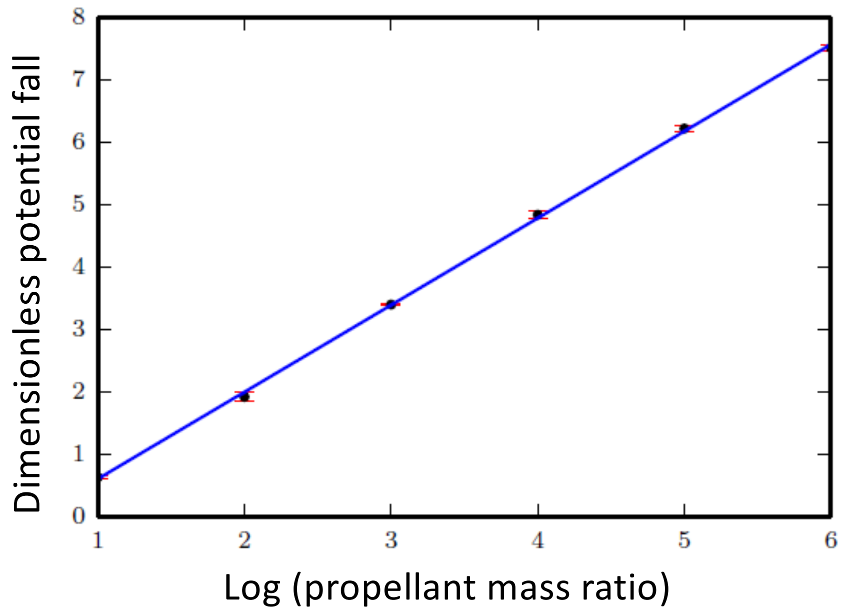


Stationary kinetic model



Stationary kinetic model





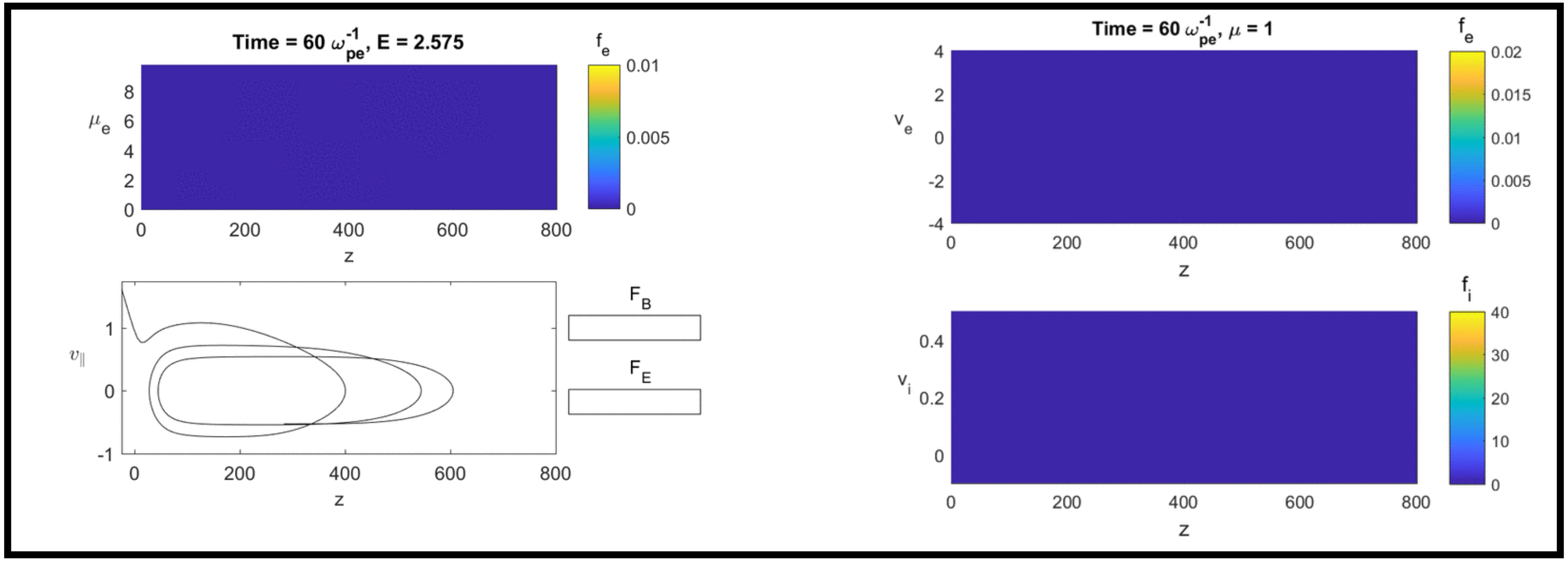
Merino, Mauriño, Ahedo, PSST 27, 035013 (2018)

- AKILES: Quasi-axial kinetic code for magnetized & unmagnetized plumes
  - Magnetic Moment, $\mu = \frac{mv_\perp^2}{B}$, and Radial Action Integral, $J_r = \oint mv_r dr$, are the respective adiabatic invariants
  - Main issue of stationary model: Double trapped electrons might be majority and dominate ϕ profile

VLASMAN

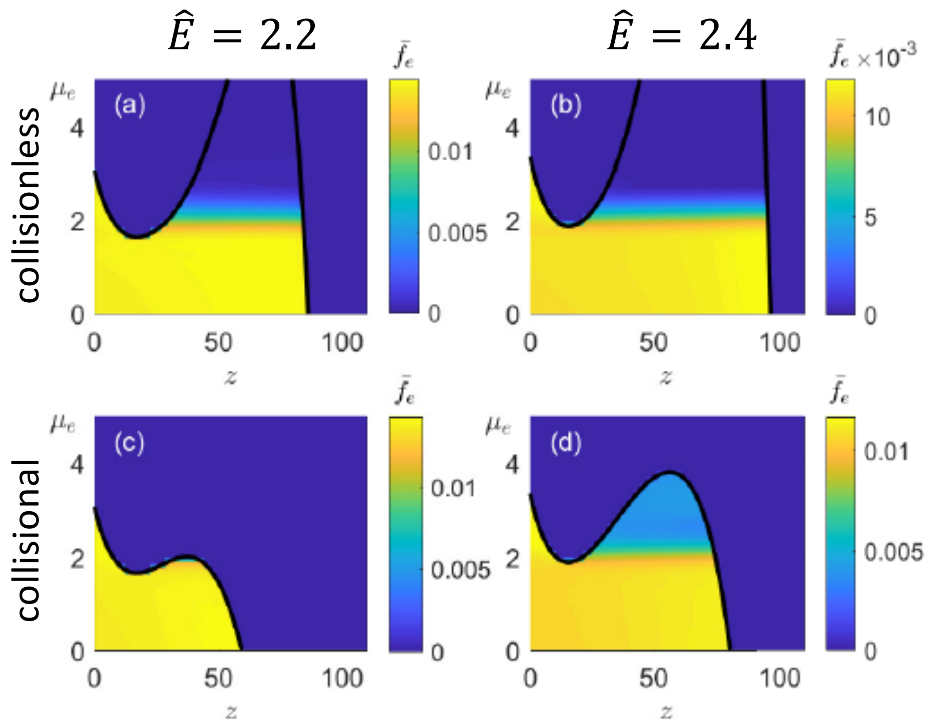
S.-Arriaga, Zhou, Ahedo, M.-Sánchez, Ramos, PSST 27, 035002 (2018)

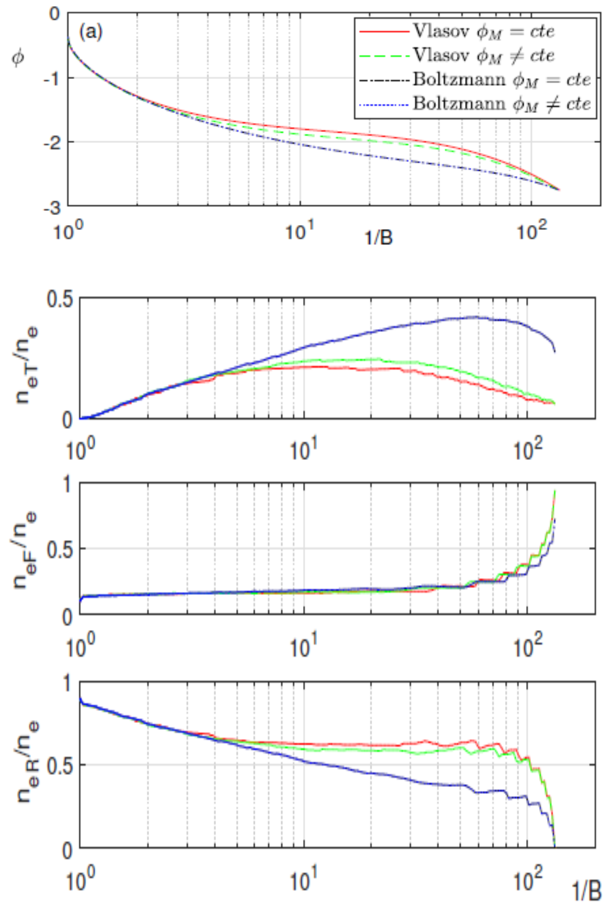
- Time-dependent kinetic Vlasov problem in a quasi-axial divergent MN
  - Motivation: doubly-trapped region is likely filled (a) by sporadic collisions and (b) in the transient formation of MN
  - Goals: 1) to determine doubly-trapped f_e from transient period
    2) to confirm f_e anisotropic cooling
    3) to understand MN formation



VLASMAN extension:

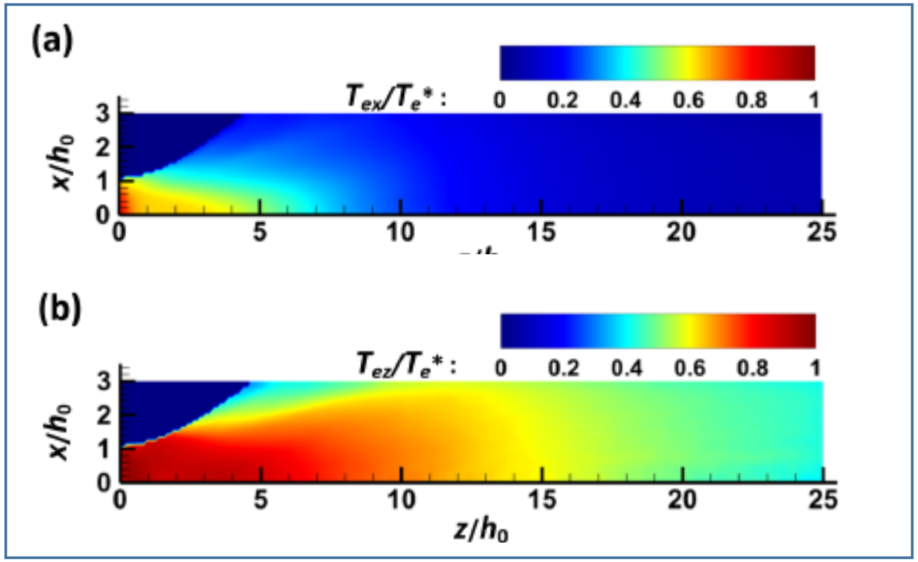
- Inclusion of collisionality effects (Space Propulsion 2018, Seville)
  - Doubly-trapped electron regions get filled thanks to collisions
    - Characterization of $f_e^{trapped}$ is pending
  - Axial profiles of ϕ and n get modified

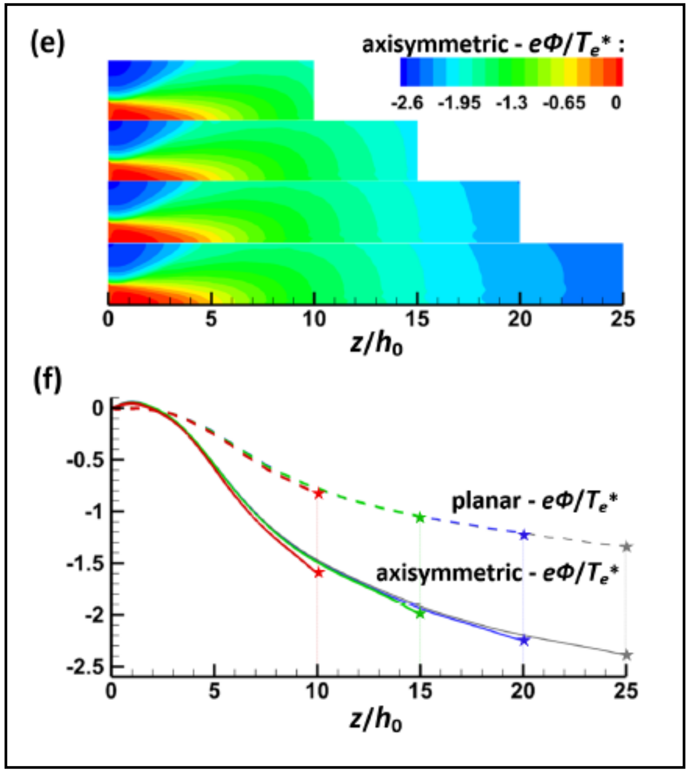




Magnetized vs unmagnetized plumes

- AKILES showed comparable cooling process in mag. & unmag. plumes
- Full-PIC unmagnetized plume (Li, Merino, Ahedo, etal.; PSST submitted) and VLASMAN (kinetic, magnetized) confirm the same
  - Numerically: VLASMAN, no statistical noise but simpler geometries
  - Both use a finite spatial domain and try to solve pending issues on
    - Downstream conditions for electrons
    - Extrapolation of results to $z \to \infty$ and steady-state





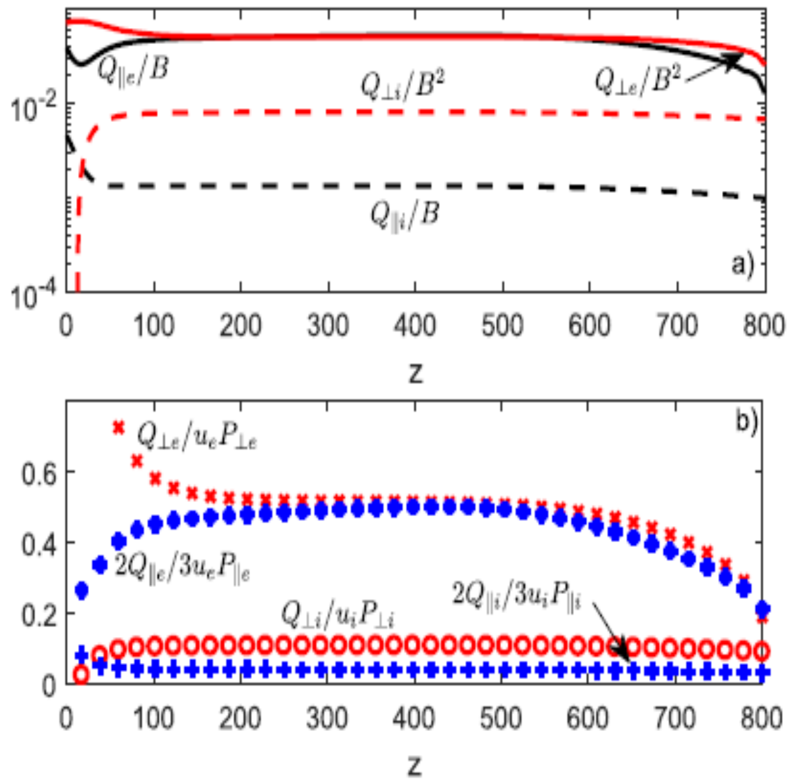
On heat fluxes

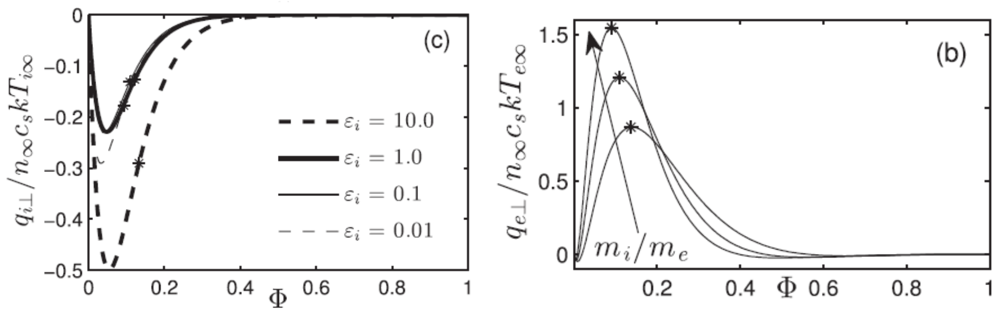
- For a collisionless electron beam it is better to close fluid equations:
- at 2nd v-moment, which requires finding tensor $\bar{\bar{P}}_e$, than at 3rd v-moment, which requires $\boldsymbol{q}_e$, and this does not satisfy Fourier-type laws. (Indeed, closure at 4th v- moment is suggested)
- For VLASMAN case, we find

$$q_{\parallel e} \approx \frac{3}{4} u_e n T_{\parallel e} \propto B$$

$$q_{\perp e} \approx \frac{1}{2} u_e n T_{\perp e} \propto B^2$$

- In collisionless flows, there are no simple physical interpretation of $\boldsymbol{q}$
  - Indeed, in some cases $\boldsymbol{q} \cdot \nabla T > 0$





Thank you! Questions?

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