Non-Maxwellian electron VDF features in a Hall thruster chamber

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Motivation

- HYPHEN: Multi-thruster simulation platform
  - ☐ for electromagnetic thrusters,
  - ☐ operating with weakly-collisional plasmas
- Thruster family
  - ☐ EMT with electrodes: HET, HEMPT, AF-MPDT
  - ☐ EMT with EM emission: HPT, ECRT, VASIMR
- To be developed next year
- From converging ongoing EP2 developments for individual thrusters:

☐ NOMADS	within H2020-CHEOPS
☐ SURFET	within H2020-MINOTOR
☐ HELPIC	within AirbusDS (F) funded project

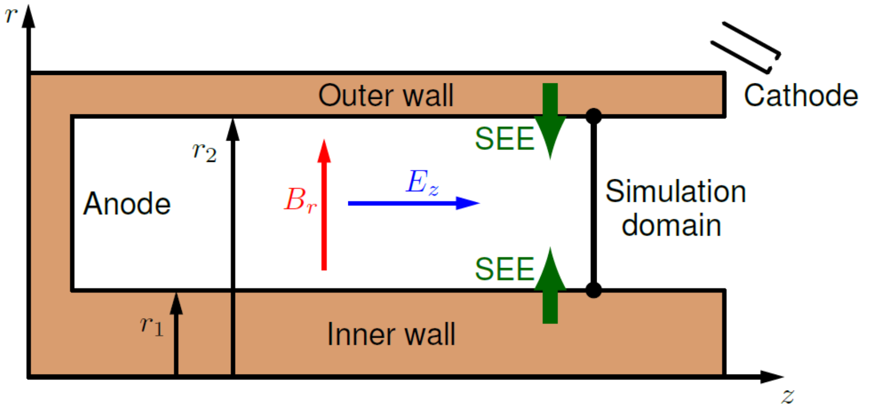
- Why?
  - ☐ More global understanding of thruster physics
  - ☐ Quicker code development & validation
- Our choice: modular 2D **hybrid (PIC-MC/fluid) code**

Motivation

- Hybrid code → Electrons treated as a single magnetized fluid
- $Kn \gg 1$ → **Maxwellian VDF non assured** → uncertainties in fluid eqs.
- **Plasma-wall interaction** is largely responsible
  - ☐ Depletion of high-energy primary (main) electrons
  - ☐ Presence of counter-streaming near-monoenergetic SEE beams
- Magnetic field topology too ?
  - ☐ Magnetic mirror effects
  - ☐ B-field angle of incidence
- A full-PIC 1D model can provide (a) VDF and (b) macroscopic trends:
  - ☐ Temperature anisotropies → magnetic mirror effects
  - ☐ Depletion fraction of p-electron tails → wall energy losses
  - ☐ Recollection-thermalization fractions of s-electrons
- This can then be implemented in hybrid code
- The hybrid/full-PIC association can be very cost-effective an reliable

The 1D radial PIC model

Domínguez, Taccogna, Ahedo, PSST 27, 064006, 2018



- ❑ Acceleration region of a HET

Prescribed fields
$$\begin{cases} E_z = \text{const.} \\ B_r(r) = B_{r_1}\dfrac{r_1}{r} \end{cases}$$

Poisson equation $\longrightarrow E_r$

- ❑ Particle populations:
  - ❖ Singly charged ions
  - ❖ Primary electrons (p)
  - ❖ Secondary electrons (s1,s2) ⟶ BS + TS

Initial populations (ions, primary electrons): T_{i0}, n_{i0} T_{e0}, n_{e0}

- ❑ Neutral background $T_n, n_n(t)$

- ❑ Collisions
  - e-n
    - Elastic
    - Ionization
    - Excitation
  - Coulomb (e-i, e-e, i-i)

s1,s2 ⇩ p

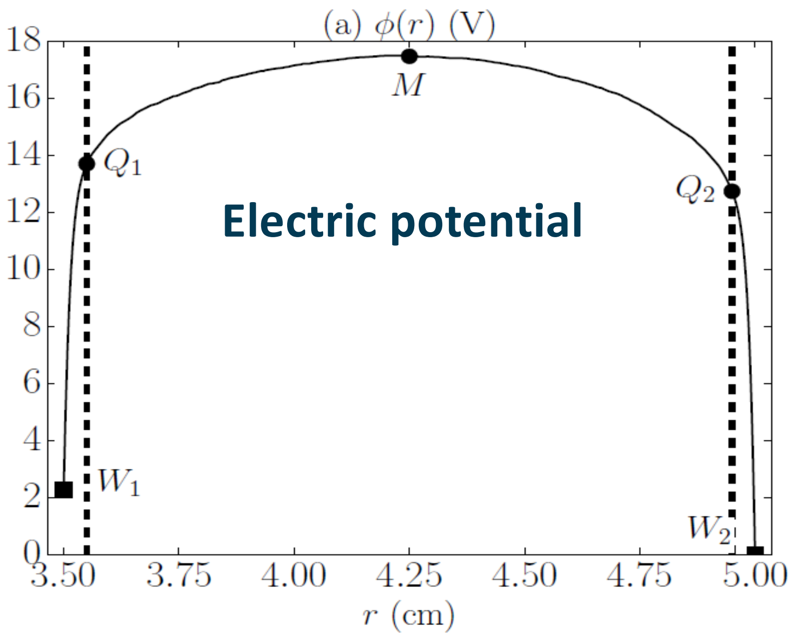
- ❑ Unmagnetized ions: E_r
  - ❖ Only accelerated by u_{zi}
  - ❖ Generated with
  - ❖ No secular effects on axial motion

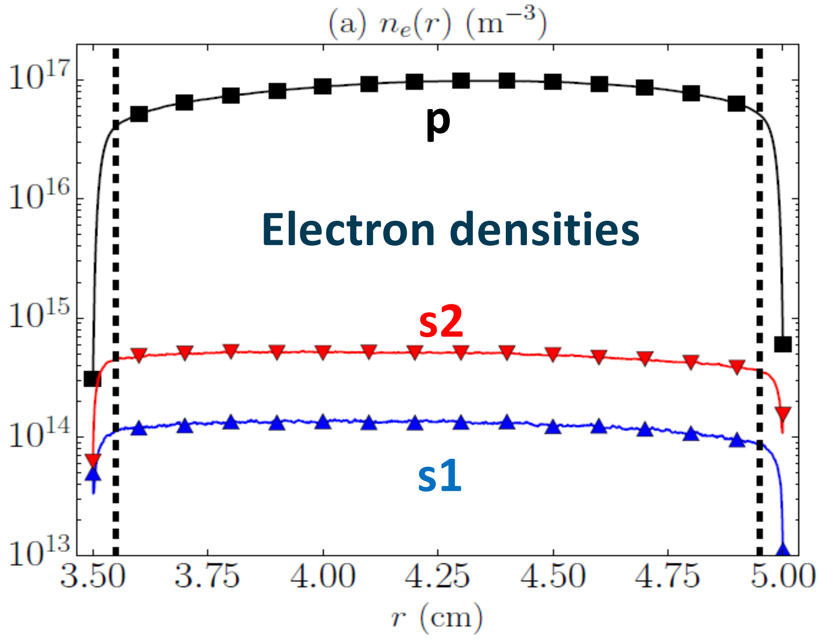
- ❑ Magnetized electrons:
  - ❖ Azimuthal ExB drift
  - ❖ Magnetic mirror effect
  - ❖ Sources: ionization + SEE
  - ❖ Sinks: walls

Previous work: Ahedo etal.; Sydorenko, Kaganovich, etal.; Taccogna etal.

Results: asymmetries

- **Cylindrical effects introduce significant asymmetries in radial profiles**

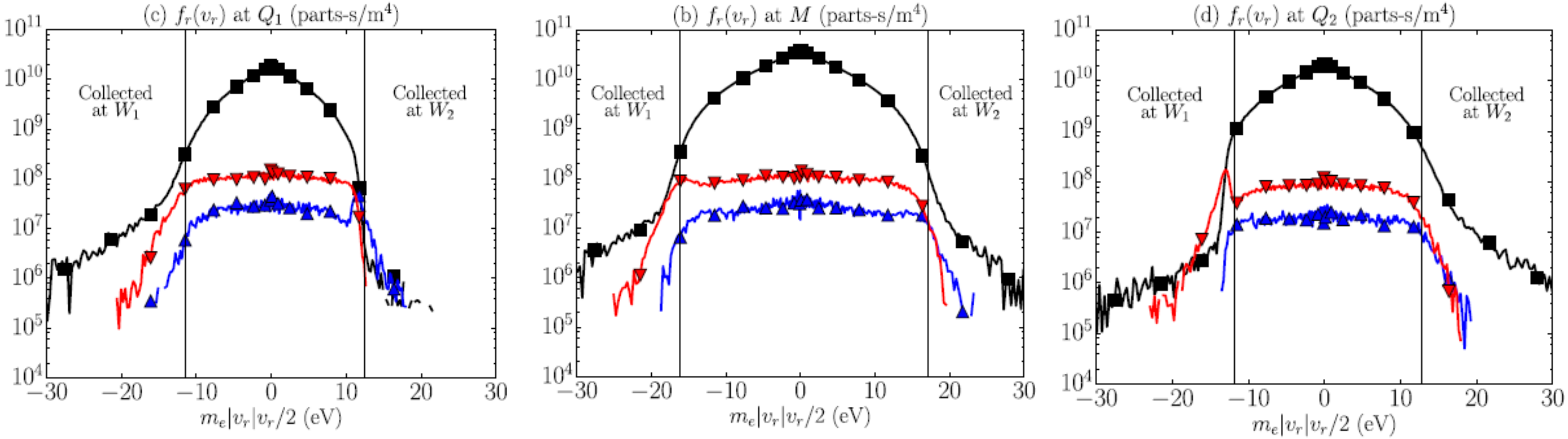




  - ❑ Since $n_{s1} + n_{s2} \ll n_p$, the response is dominated by p-electrons
- Impact properties at inner and outer walls ($r_1 = 35mm, r_2 = 50mm$)
  - ❑ $j_{p1} = 12.8\ A/m^2$, $j_{p2} = 24\ A/m^2$
  - ❑ $E_{imp,1} = 8.1\text{eV}$, $E_{imp.2} = 15.7\text{eV}$, (mean impact energy)
  - ❑ $\langle \delta_{SEE,1} \rangle$ =15%, $\langle \delta_{SEE,2} \rangle = 29\%$,

Results: tail depletion

- **Depletion of p-electron tail is significant**



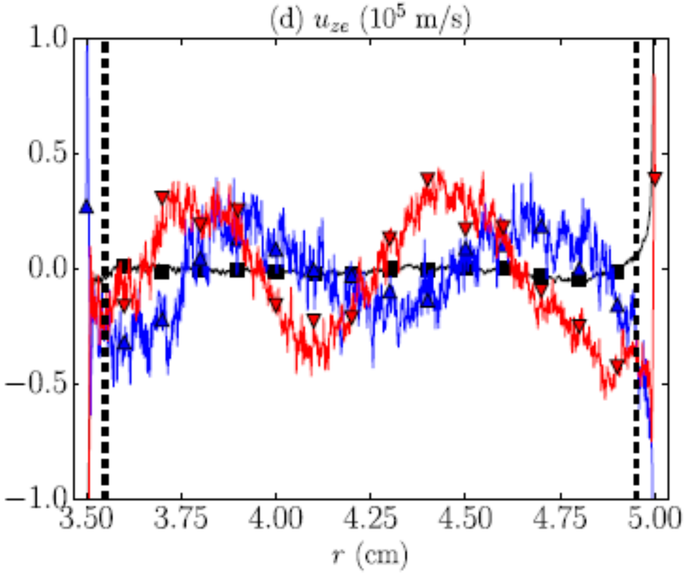
- Thermalization fraction: $\sigma_{t,1} = \dfrac{|j_{\mathrm{pW_1}}|}{j_{\mathrm{ther},1}}$ with $j_{\mathrm{ther},1} = e n_{\mathrm{pQ_1}} \exp\left(-e\dfrac{\phi_{\mathrm{W_1Q_1}}}{T_{\mathrm{pQ_1}}}\right)\sqrt{\dfrac{T_{\mathrm{pQ_1}}}{2\pi m_e}}$,

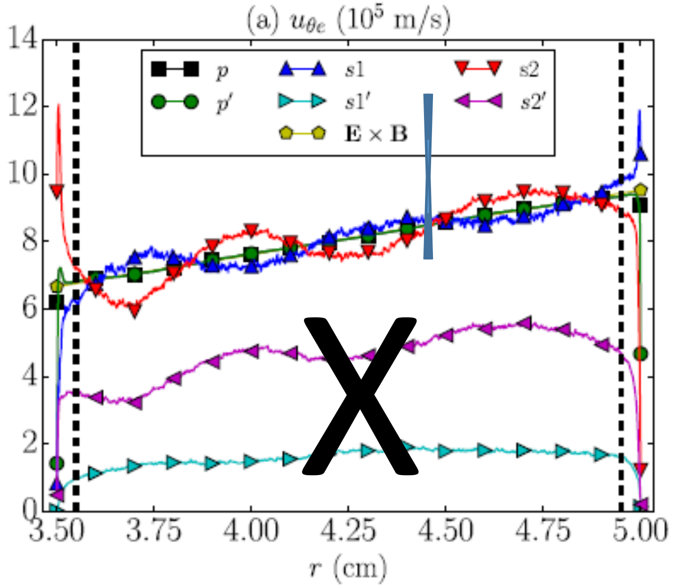
  - ❑ $\sigma_{t1} \approx 4\%,\ \sigma_{t2} \approx 5\%$
  - ❑ This data is central for wall losses in electron model of hybrid code

Results: s-electrons fate

- **Fate of secondary electrons: wall-recollection or conversion-to-p?**
  - Collisional conversion to p-electrons$\approx$ 60%
  - Recollection in opposite wall $\approx$ 30%
  - Recollection in same wall $\approx$ 10%
  - This data is again central for electron model in hybrid code

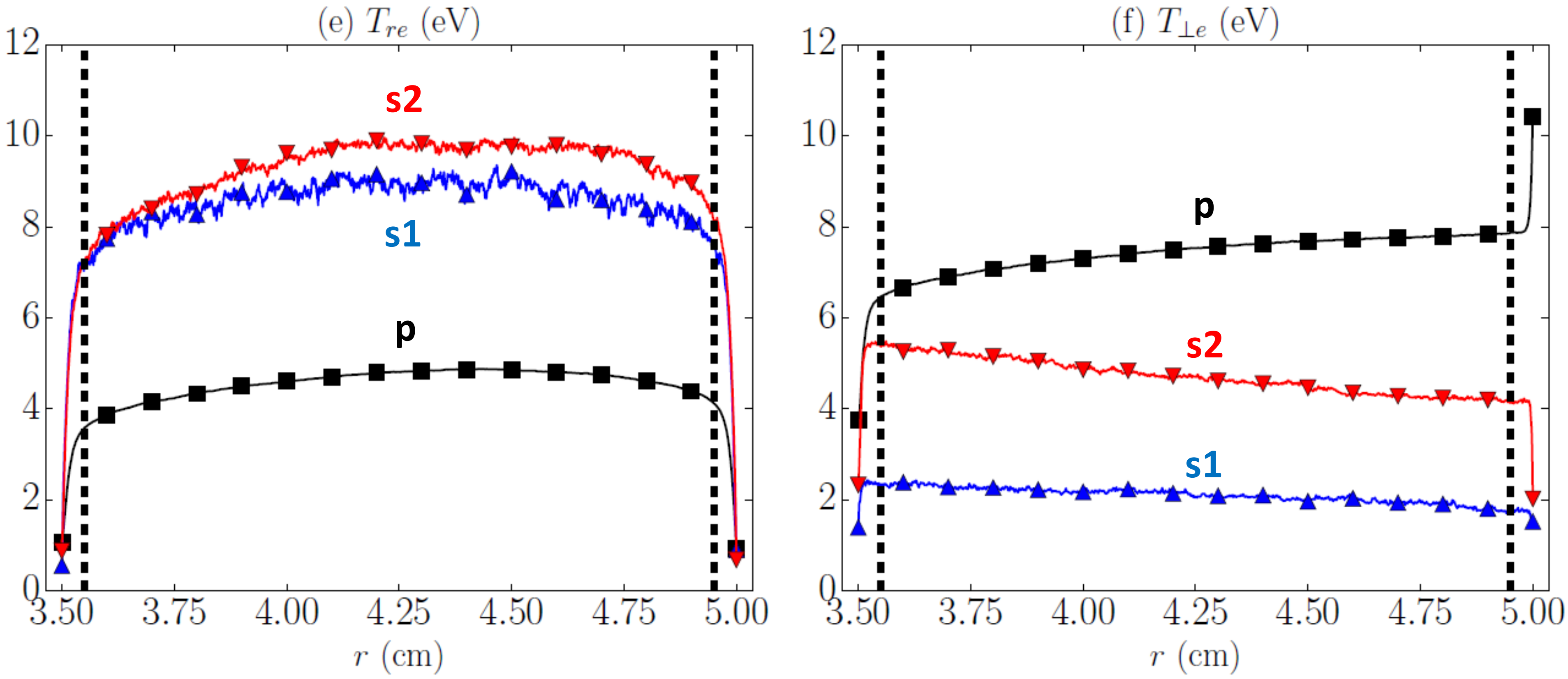
    (Fluid models usually assume total conversion to p in plasma bulk)
- Tincidentally, t××races of 'near-wall conductivity' are observed





Results: temperature anisotropies

- **Temperature anisotropy is significant** and population dependent
  - ☐ $\frac{T_{\parallel pM}}{T_{\perp pM}} \approx 0.64,\quad \frac{T_{\parallel s1M}}{T_{\perp s1M}} \approx 4.35,\quad \frac{T_{\parallel s2M}}{T_{\perp s2M}} \approx 2.08$
- Radial non-uniformity on *T* is non-negligible



Results: momentum equilibrium

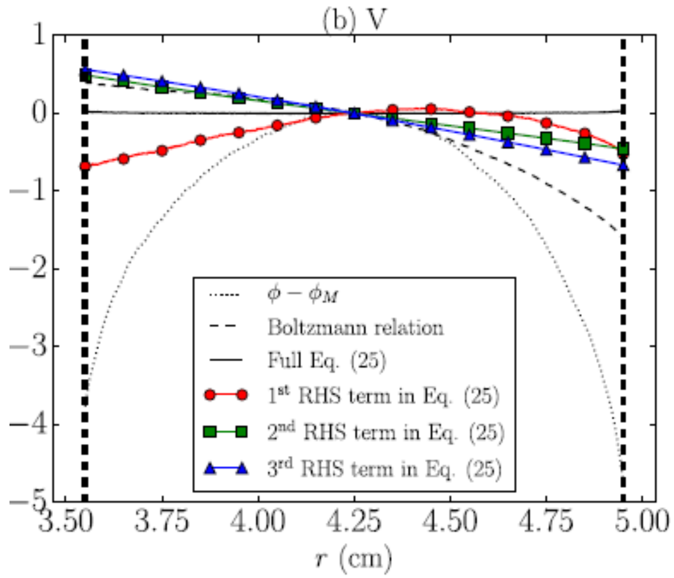
- **Deviations from Maxwell-Boltzmann relation** are significant

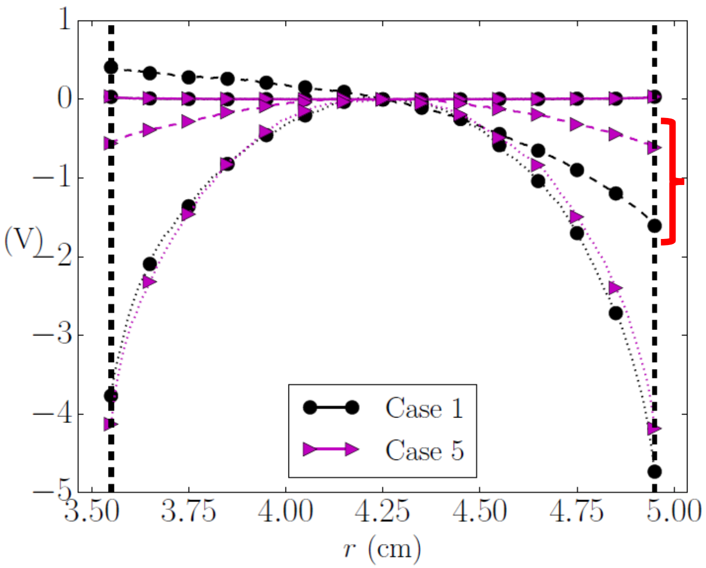
$$\underbrace{e\frac{\partial\phi}{\partial r}}_{\text{Electric force}}\underbrace{-T_{rp}\frac{\partial\ln n_p}{\partial r}-\frac{\partial T_{rp}}{\partial r}+\boxed{\frac{T_{\perp p}-T_{rp}}{r}}}_{\text{Pressure gradient}}+\underbrace{\frac{m_e u_{\theta p}^2}{r}}_{\text{Centrifugal force}}=\cancel{F_r}$$

Collisions + other inertia terms

Magnetic mirror effect

$$\underbrace{e\phi-e\phi_M-T_{rpM}\ln\frac{n_p}{n_{pM}}}_{\text{M.-B. relation}}=\underbrace{\left[T_{rp}-T_{rpM}+\int_{r_M}^{r}dr\,(T_{rp}-T_{rpM})\frac{d\ln n_p}{dr}\right]}_{\text{Non-uniform } T_{\parallel}}+\underbrace{\int_{r_M}^{r}dr\frac{T_{rp}-T_{\perp p}}{r}}_{T\text{ anisotropy, B mirror}}-\underbrace{\int_{r_M}^{r}dr\frac{m_e u_{\theta p}^2}{r}}_{\text{Centrifugal force}}$$





M.-B. relation

Case 1: cylindrical

Case 2: planar

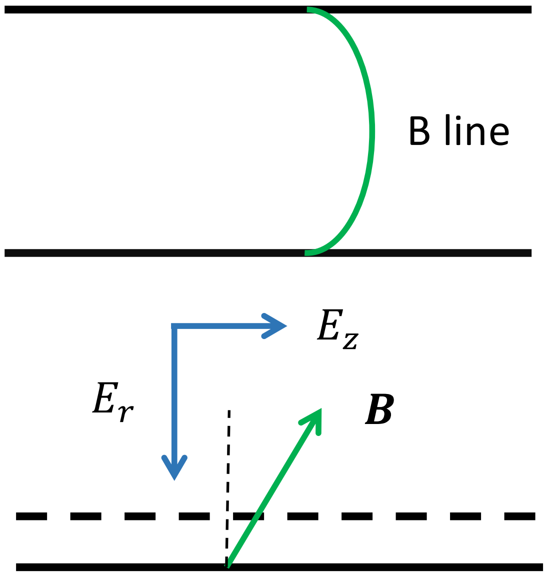
Work in progress

Domínguez, Taccogna, Ahedo, Space Propulsion, Seville, May 2018

- Parametric investigation on $E_z,\ B_r,\ r_1/r_2,\ \delta_{SEE},\ T_{sW}$
  - According to trends, simulation results seem robust

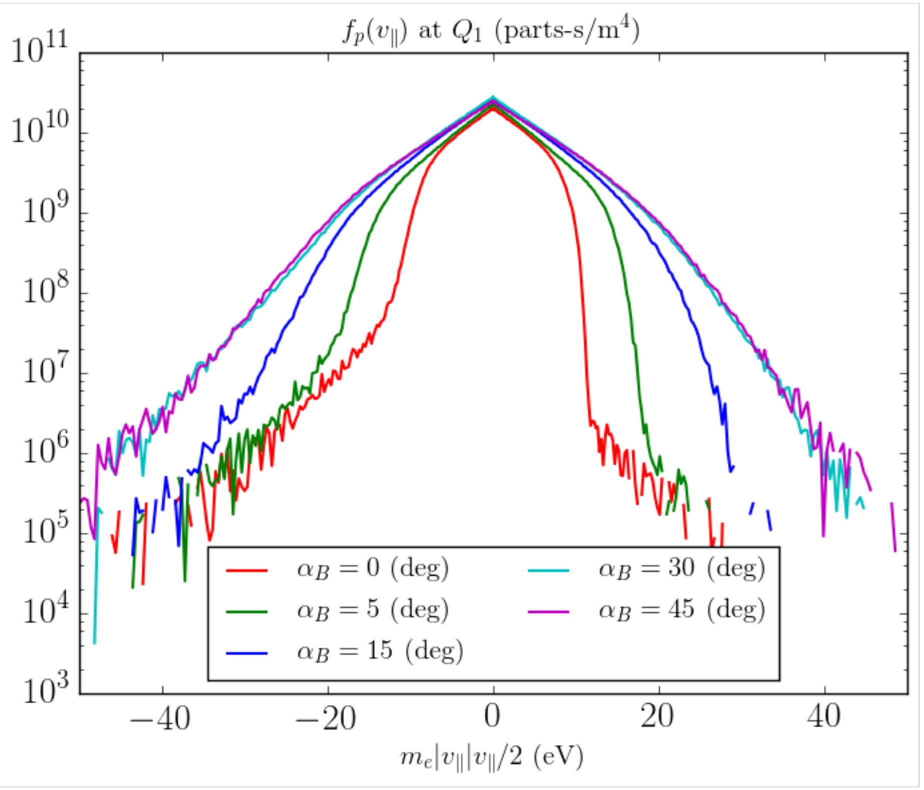
On-going work at UC3M

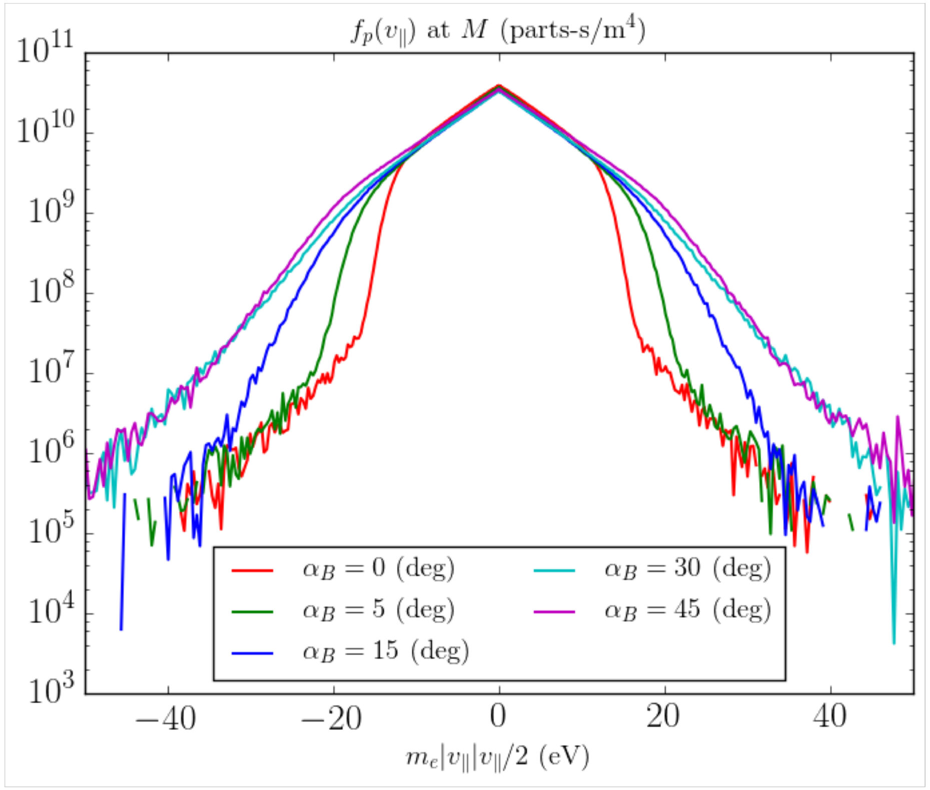
- Towards sheath charge-saturation limit (CSL) -…and sheath instability?-
  - CSL is very local → Concerns on spurious ‘numerical effects’
  - More careful simulations are needed
- Oblique B-field
  - How parallel B-guiding affects to
    - p-VDF radial depletion
    - azimuthal velocity
    - pressure tensor
    - macroscopic magnitudes



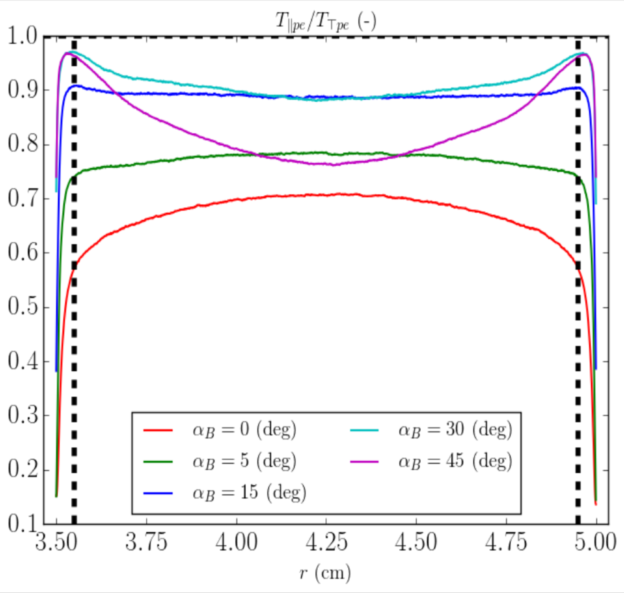
Work in progress: Oblique B-field

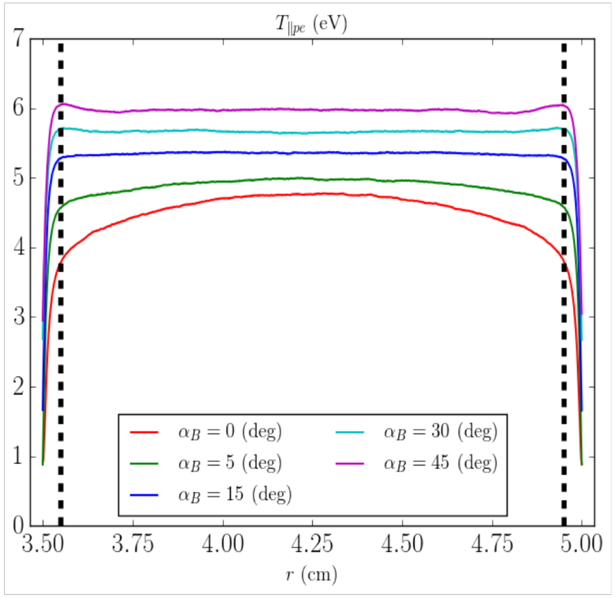
- Planar channel is used here to avoid mixing with cylindrical effects
- Oblique B-field **reduces significantly** (near the walls)
  - ❑ radial depletion of VDF
  - ❑ temperature anisotropy

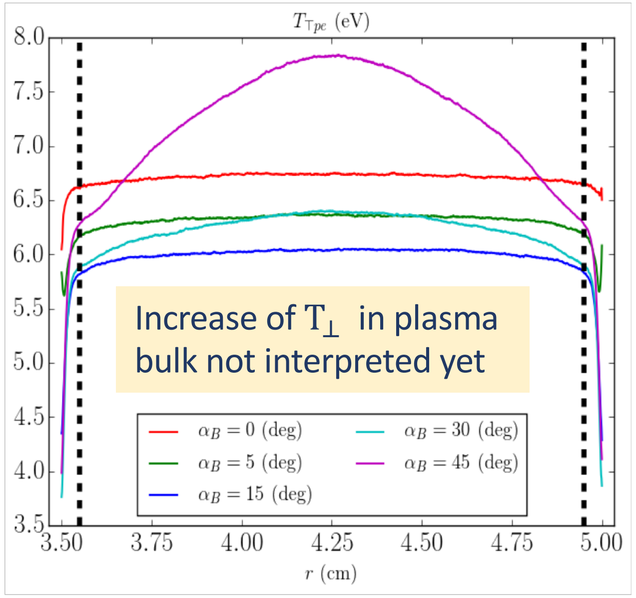




Work in progress: Oblique B-field







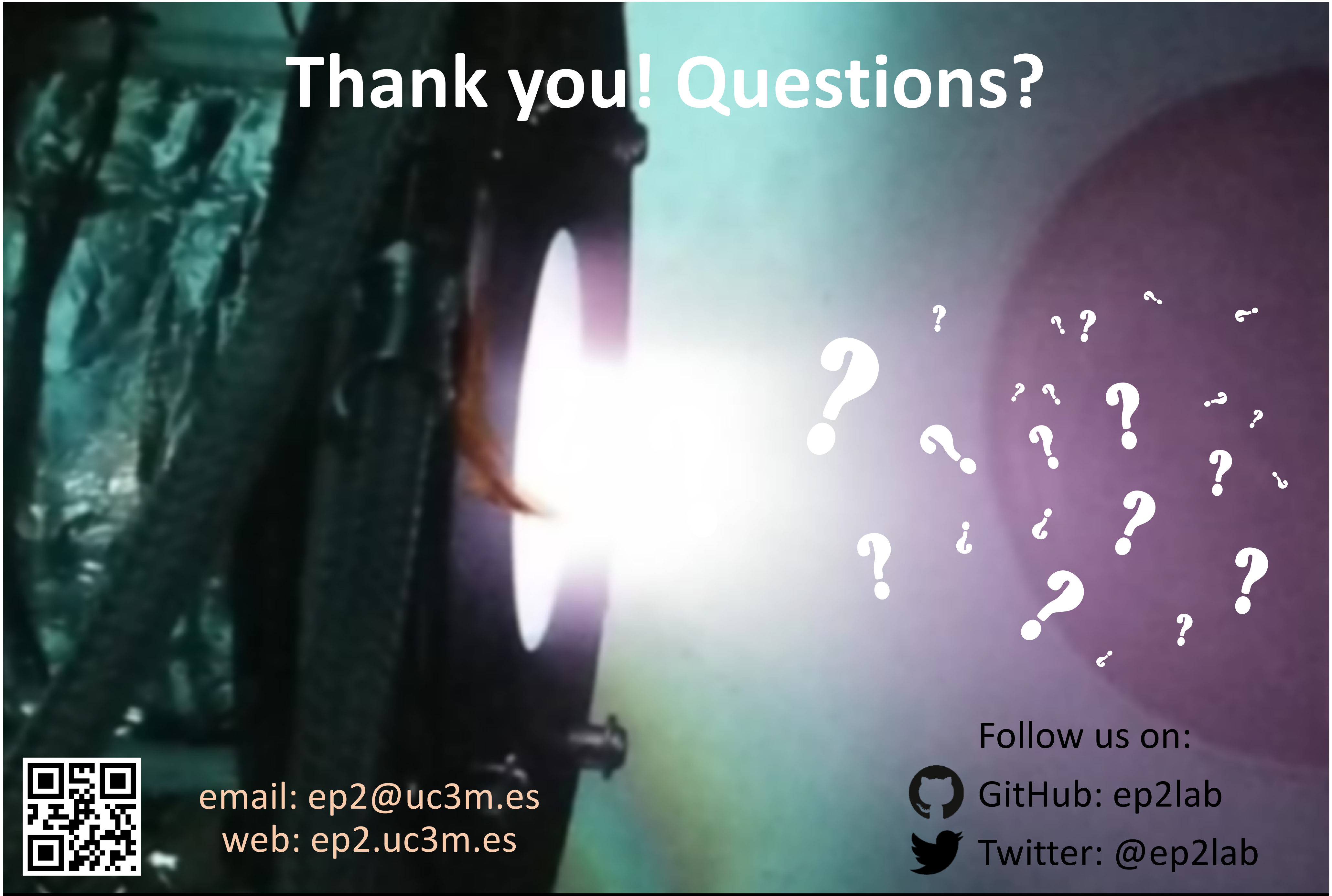
Increase of $T_\perp$ in plasma bulk not interpreted yet

- $\bar{\bar{P}}_e$ at reference $(1_\parallel, 1_\theta, 1_\perp)$ for $\alpha = 5º$, at sheath edge and centerline

$$\frac{\bar{\bar{P}}_e}{p_e}\Big|_{Q1} \simeq \begin{bmatrix} 0.82 & -1.8\,10^{-2} & 1.7\,10^{-2} \\ & 1.09 & 7.4\,10^{-4} \\ & & 1.09 \end{bmatrix} \qquad \frac{\bar{\bar{P}}_e}{p_e}\Big|_{M} \simeq \begin{bmatrix} 0.84 & -7.1\,10^{-5} & 1.5\,10^{-4} \\ & 1.08 & -2.9\,10^{-4} \\ & & 1.08 \end{bmatrix}$$

- For $\bar{\bar{P}}_e$ in all cases:
  - ☐ Very small differences at reference $(1_r, 1_\theta, 1_z)$
  - ☐ Non-diagonal terms are negligible

Thank you! Questions?



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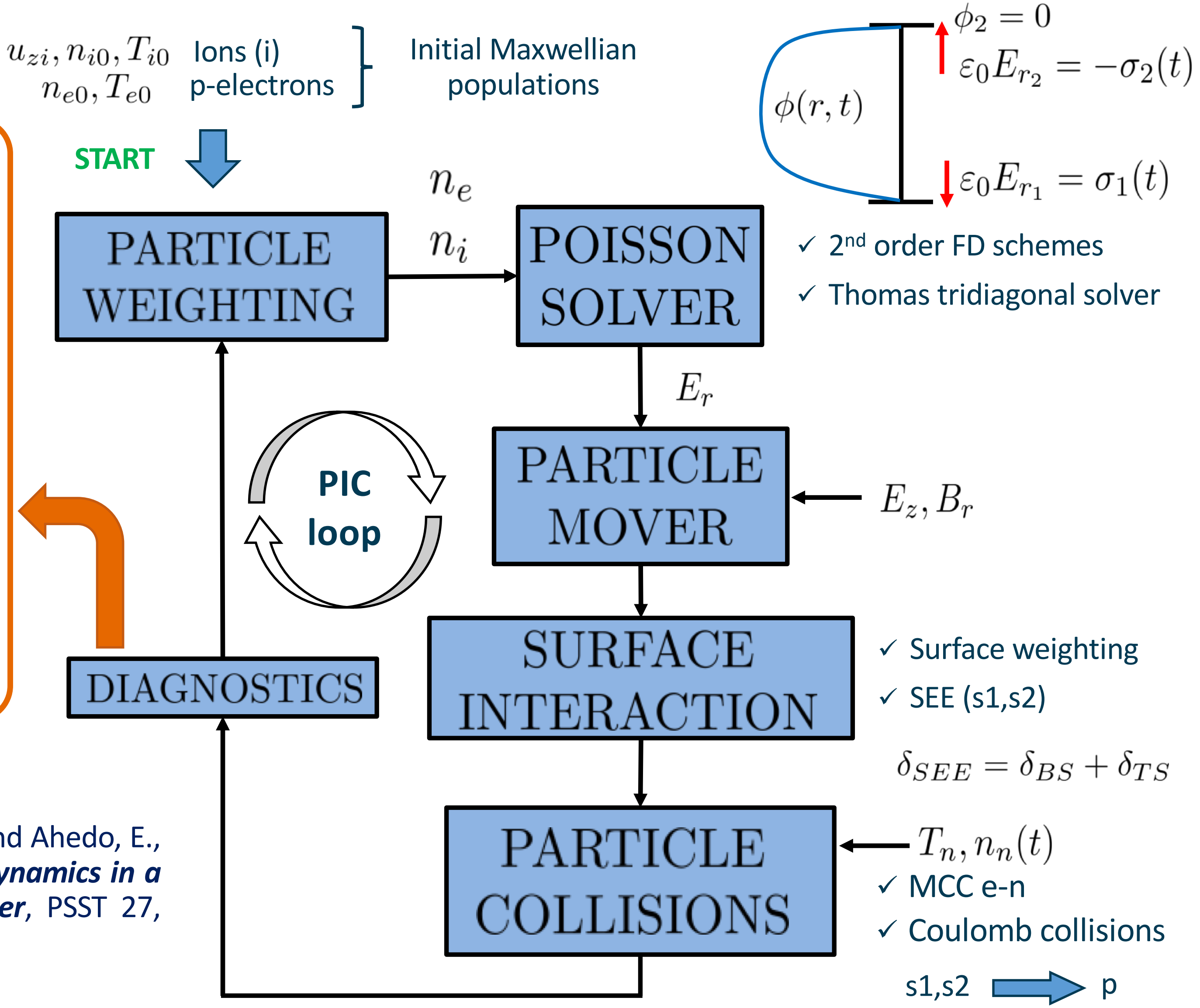
Code structure and improvements

Main code improvements

- ➢ ICD algorithm
  - ❑ Acts on neutral density
  - ❑ Ionization = wall loses
  - ❑ No axial injection/removal of particles
  - ❑ Constant the number of particles per cell
- ➢ EVW algorithm
  - ❑ Improved macroscopic magnitudes calculation for low populated species



u_{zi}, n_{i0}, T_{i0} Ions (i)
n_{e0}, T_{e0} p-electrons
Initial Maxwellian populations

START

PARTICLE WEIGHTING

n_e
n_i

POISSON SOLVER

- ✓ 2nd order FD schemes
- ✓ Thomas tridiagonal solver

$\phi(r,t)$
$\phi_2 = 0$
$\varepsilon_0 E_{r_2} = -\sigma_2(t)$
$\varepsilon_0 E_{r_1} = \sigma_1(t)$

E_r

PARTICLE MOVER

E_z, B_r

PIC loop

SURFACE INTERACTION

- ✓ Surface weighting
- ✓ SEE (s1,s2)

$$\delta_{SEE} = \delta_{BS} + \delta_{TS}$$

PARTICLE COLLISIONS

$T_n, n_n(t)$

- ✓ MCC e-n
- ✓ Coulomb collisions

s1,s2 ⇨ p

DIAGNOSTICS

Further details

Domínguez-Vázquez, A., Taccogna, F., and Ahedo, E., ***Particle modelling of radial electron dynamics in a controlled discharge on a Hall thruster***, PSST 27, 064006, 2018.