A fluid formalism for low-temperature plasma flows dedicated to space propulsion in an unstructured high performance computing solver

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E×B

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Motivation

Development cycle of Hall thruster is very long and expensive for companies

Simulation might alleviate this problem but are expensive too

- Different simulation methods
  - PIC [1,2,3,4,5]
  - DK [6,7]

Limited to small and simplified geometries [8,9]

Fluid models have a priori the potential to scale to provide global characteristics of the plasma in a reasonable computational time

[1]: Guarrigues et al. (2000) Plasma Sources Science and Technology, 23(5):053502

[2]: Adam et al. (2004). Physics of Plasma. 11(1):295–305

[3]: Taccogna et al.(2008). Plasma Sources Science and Technology, 17(2):024003

[4]: Coche et al. (2014). Physics of Plasma. 21(2):023503

[5]: Croes, V. (2017). PhD thesis, Ecole Polytchnique.

[6]: Hara, K. et al. (2012). Physics of Plasma, 19(11):113508

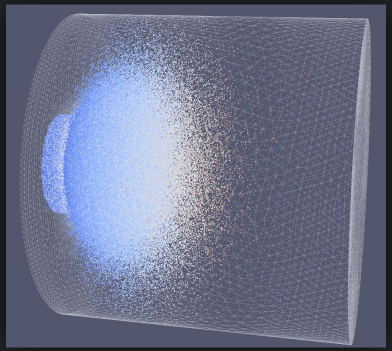
[7]: Raisanen, A. et al. (2018). AIAA Joint Propulsion Conference, 4809

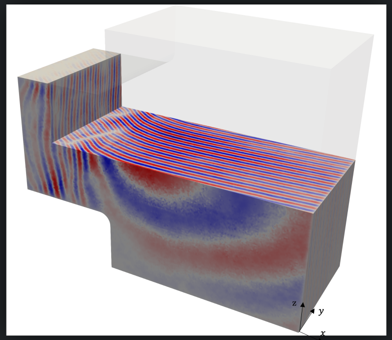
[8]: Minelli et al. (2018). IEEE Transaction on plasma science, vol.46 of 2 , pp. 219-224

[9]: Taccogna et al. (2018). Physics of Plasmas. 25(061208)

AVIP – A 3D plasma solver for HETs

- Unstructured
- Massively parallel
- PIC, fluid and hybrid approaches





Poisson equation E B = cte	⟺	neutrals	ions	electrons
	⟺	neutrals	ions	electrons
	⟺	neutrals	ions	electrons

Lagrangian (PIC) | Eulerian (fluid)

A 10-moment fluid model

Electrons

$$\partial_t \rho_e + \nabla.(\rho_e \vec{u}_e) = S^0_{e,ioniz}$$

$$\partial_t(\rho_e \vec{u}_e) + \nabla.(\rho_e \vec{u}_e \vec{u}_e + k_B T_e n_e \bar{\bar{I}}) = -en_e(\vec{E} + \vec{u}_e \times \vec{B}) + S^1_{e,ioniz} + S^1_{e,en}$$

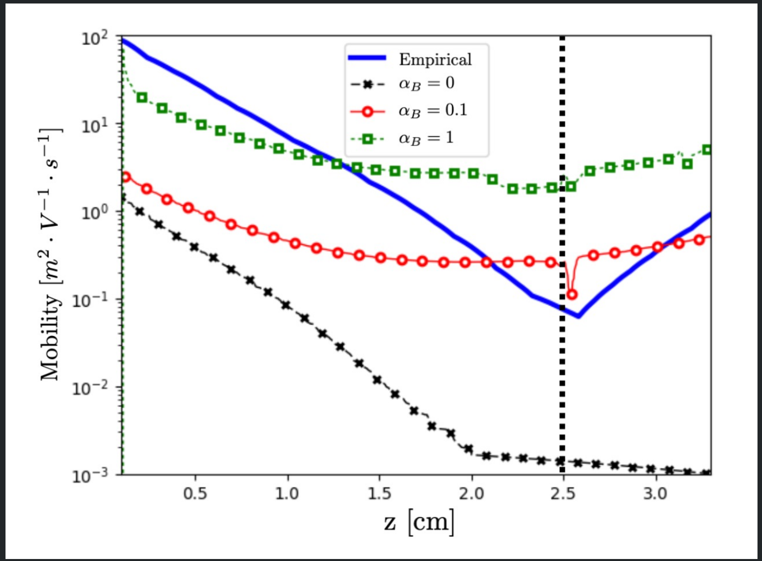
$$\partial_t(\epsilon_e) + \nabla.\left((\frac{1}{2}\rho_e \vec{u}_e^2 + \frac{\gamma}{\gamma - 1} k_B T_e n_e).\vec{u}_e \right) = -en_e \vec{E}.\vec{u}_e + S^2_{e,ioniz} + S^2_{e,en} + S^2_{e,exc}$$

Ions

$$\partial_t \rho_i + \nabla.(\rho_i \vec{u}_i) = S^0_{i,ioniz}$$

$$\partial_t(\rho_i \vec{u}_i) + \nabla.(\rho_i \vec{u}_i \vec{u}_i + k_B T_i n_i \bar{\bar{I}}) = en_i(\vec{E} + \vec{u}_i \times \vec{B}) + S^1_{i,ioniz} + S^1_{i,in}$$

$$\partial_t(\epsilon_i) + \nabla.\left((\frac{1}{2}\rho_i \vec{u}_i^2 + \frac{\gamma}{\gamma - 1} k_B T_i n_i).\vec{u}_i \right) = en_i \vec{E}.\vec{u}_i + S^2_{i,ioniz} + S^2_{i,in}$$



Neutrals

$$\partial_t \rho_n + \vec{u}_{0,n} \nabla.(\rho_n) = S^0_{n,ioniz}$$

- $S_{en}, S_{in}, S_{iz,e}, S_{iz,i}$: loss/gain of energy via inelastic/elastic collisions for ions and electrons
- Constant magnetic field $\vec{B}(\vec{x}, t) = \vec{B}(\vec{x})$
- Poisson equation

- Azimuthal velocity is taken into account

$$u_{\theta,e} = \frac{-e}{m_e \nu_{en}} B_r u_{z,e}$$

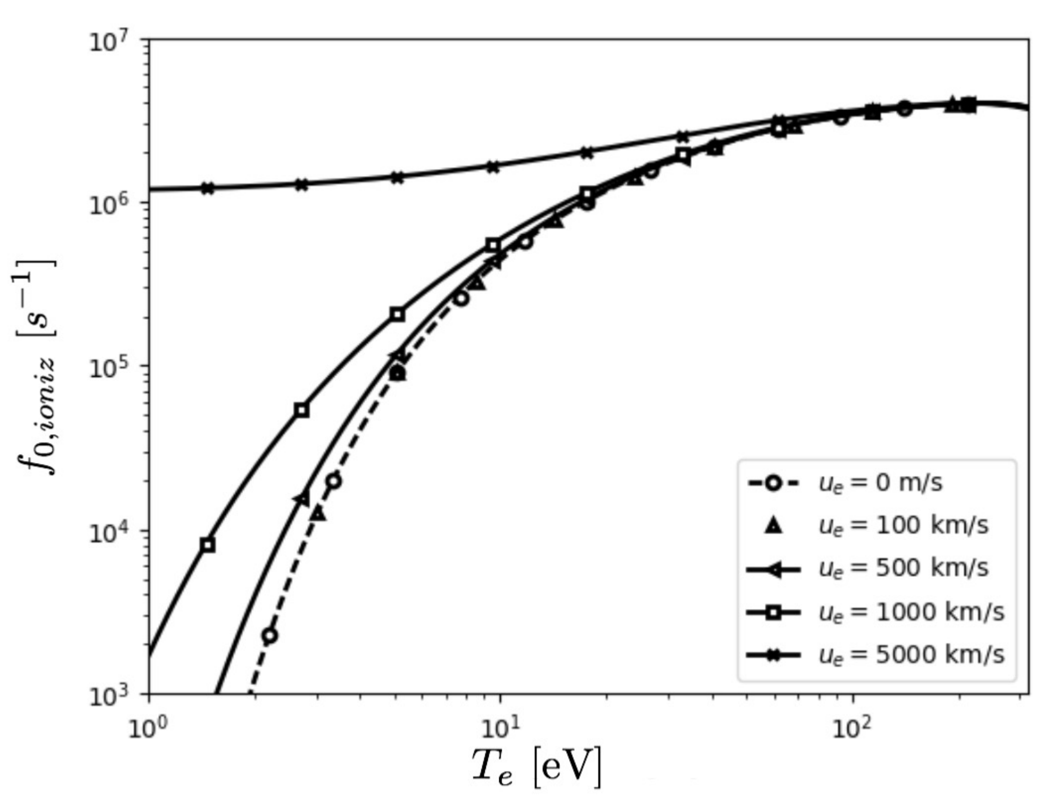
- Bohm law for anomalous transport

$$\nu_{anom} = \frac{\alpha_B \omega_B}{16}$$

Collision source terms

- Collision rates are integrated considering a Maxwellian distribution depending on the temperature and the Mach number of the species:

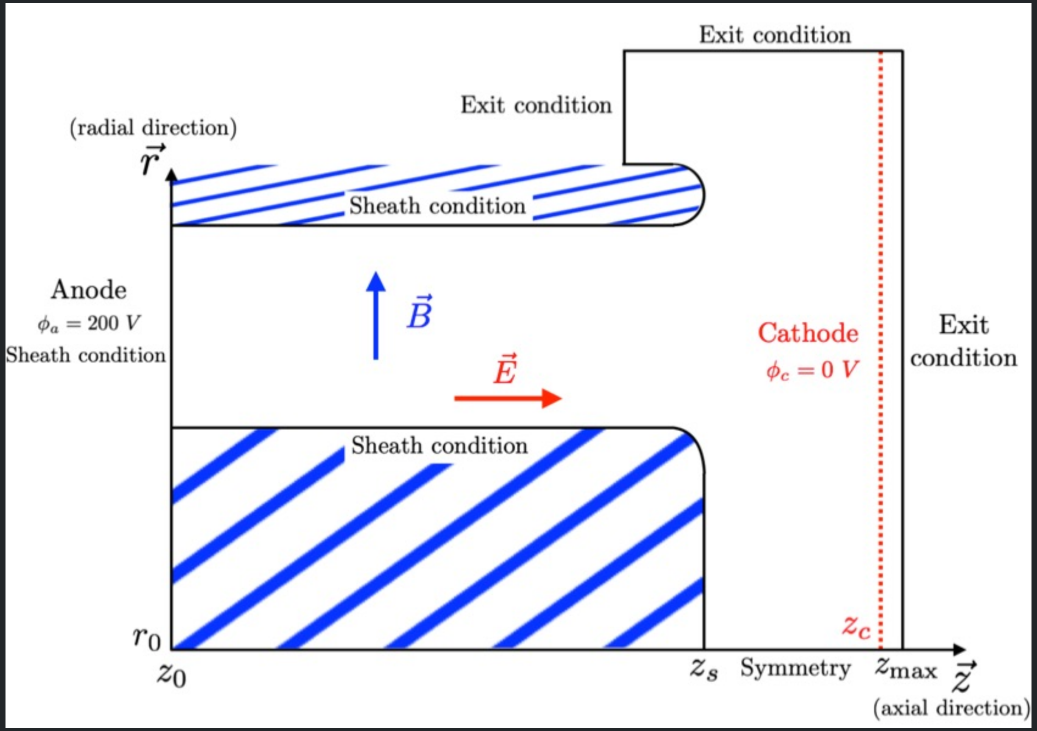
$$
\begin{aligned}
S^0_{e,ioniz} &= \frac{m_i}{m_e} S^0_{i,ioniz} = -\frac{m_i}{m_e} S^0_{n,ioniz} \\
&= n_e f_{0,ioniz} \\
&= n_e n_n 2 \left(\frac{2k_B T_e}{\pi m_e}\right)^{\frac{1}{2}} \frac{e^{-M_e^2}}{M_e} \int \sigma_{ioniz}(x) x^2 e^{-x^2} sinh(2M_e x) dx
\end{aligned}
$$



For HET chambers, the electron velocity should be included in the computation of the ionization frequency

M. S. Benilov. *A kinetic derivation of multifluid equations for multispecies nonequilibrium mixtures of reacting gases*. Physics of Plasmas, 4(3):521–527, 1997.
H. Le and J-L. Cambier. *Modeling of inelastic collisions in a multifluid plasma: Excitation and deexcitation*. Physics of Plasmas, 22(093512), 2015.
LXCAT Database

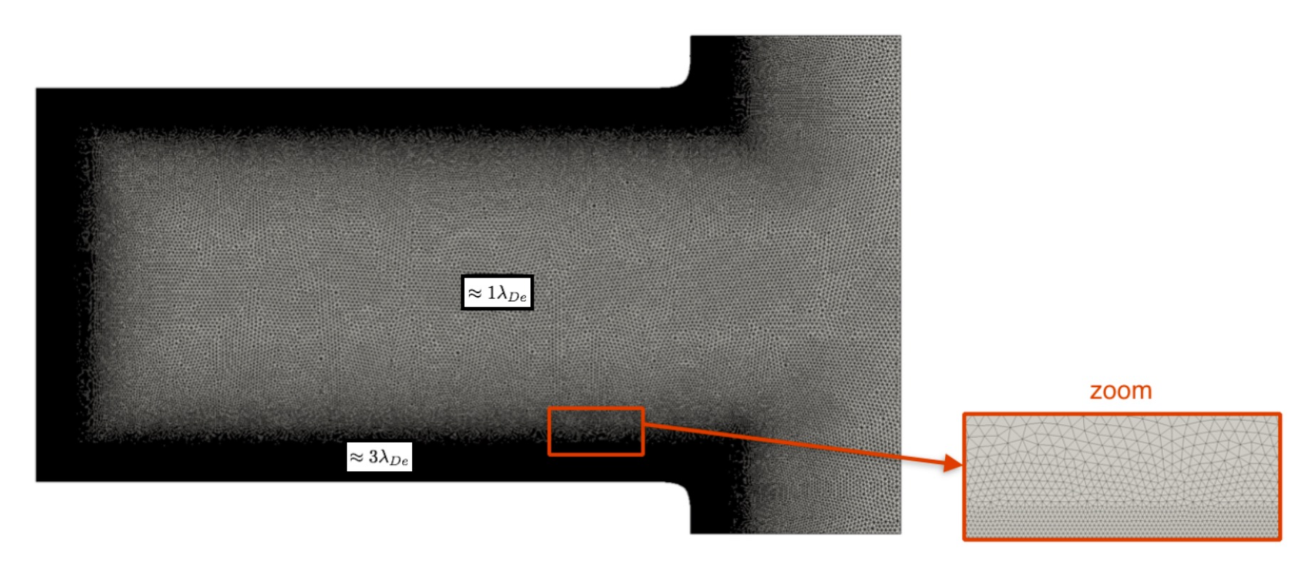
A 2D radial-axial test case



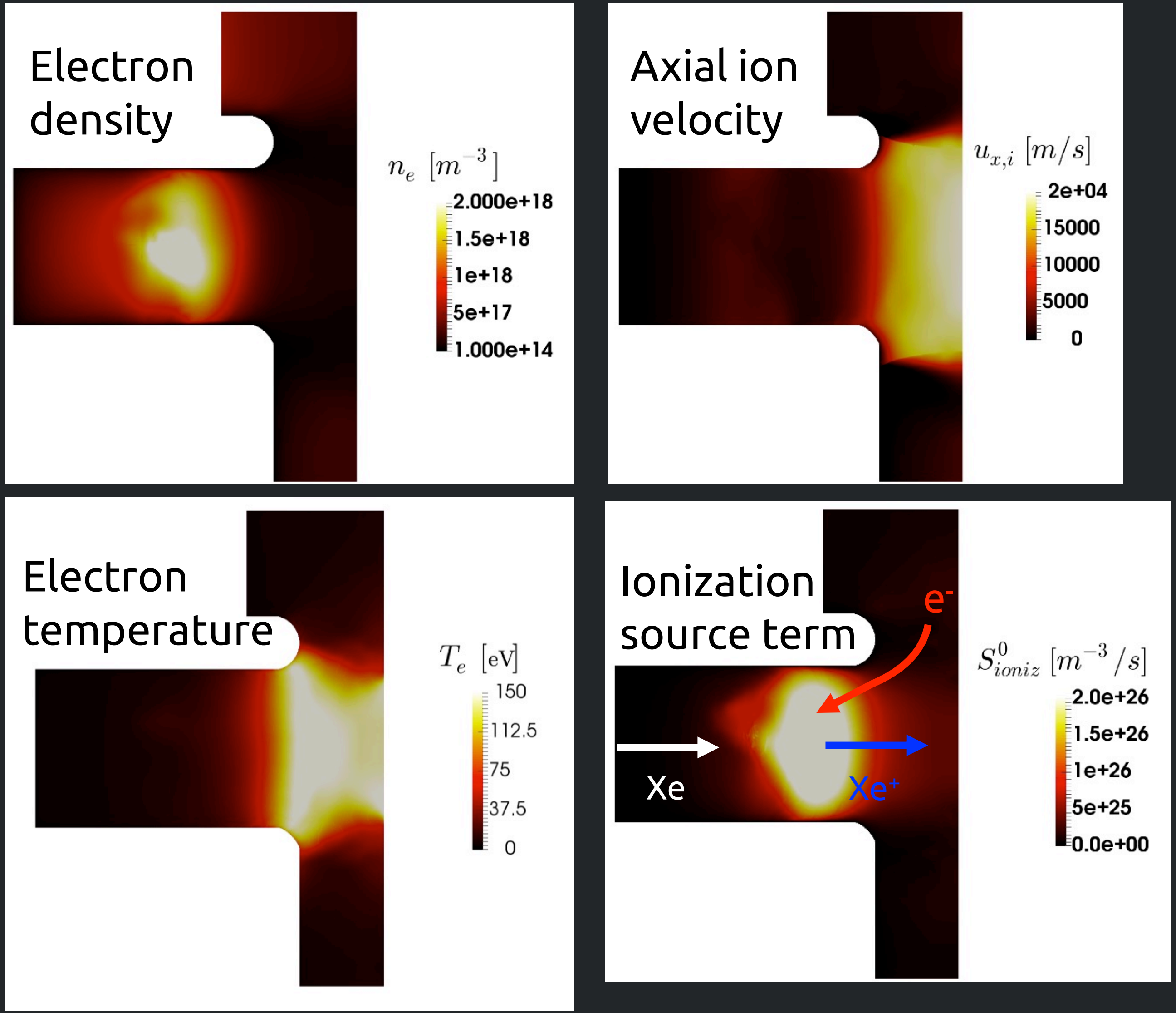
Parameters are representative of a SPT-100 thruster

$\dot{m}_n$	$4.85\ mg/s$	$u_{0,n}$	$300\ m/s$
B_{max}	$237\ G$	ϕ_a	$300\ V$
L_{AC}	$33\ mm$	$L_{channel}$	$25\ mm$
$h_{channel}$	$15\ mm$	$n_{0,e}$	$10^{17}\ m^{-3}$
$T_{0,e}$	$5\ eV$	$T_{0,i}$	$0.1\ eV$

Fully unstructured mesh



A 2D radial-axial test case



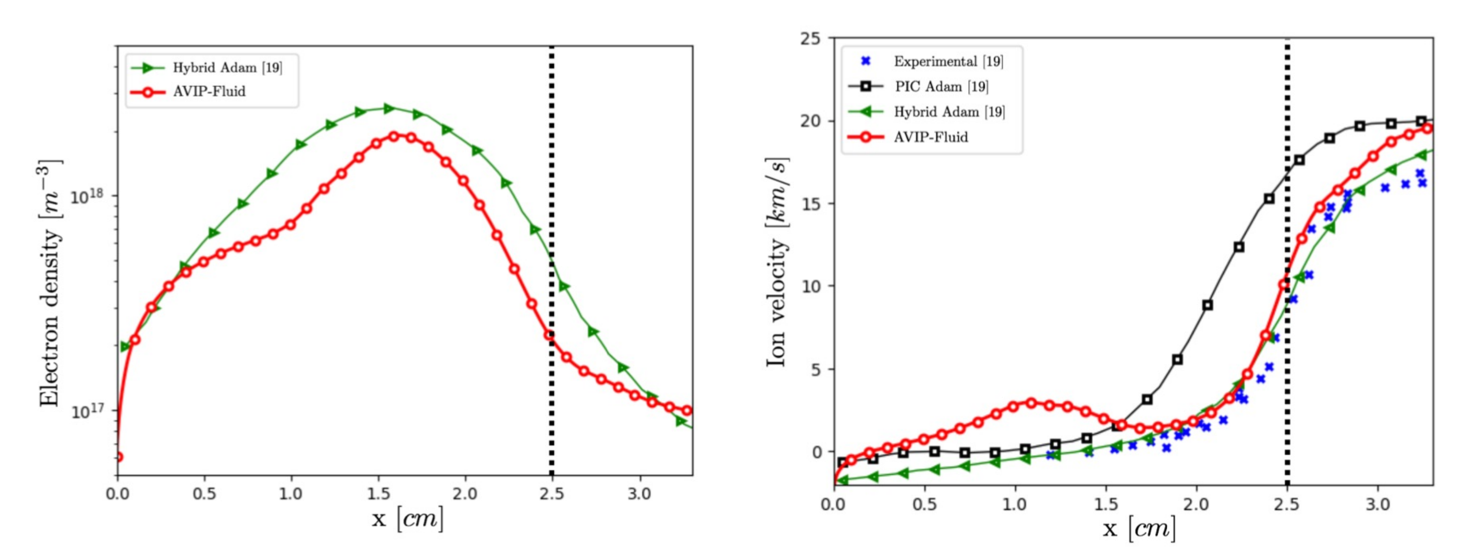
- Global parameters of the plasma inside the discharge chamber are well reproduced
- Correct prediction of the behavior of electric sheaths in the vicinity of walls, without any modeling
- Reliable prediction of the ionization zone and the acceleration of ions through the exit plane

A 2D radial-axial test case

- Comparison with hybrid and PIC results from Adam *et. al. 2008: Physics, simulation and diagnostics of Hall effect thrusters*
- Good agreement also on potential, electric field and ionization source term

Performances	Experimental	AVIP-Fluid
Isp	1734 s	1937 s
Discharge current I_d	5 A	3.6 A
Divergence efficiency η_d	0.93	0.76
Voltage efficiency η_v	0.89	0.94
Current efficiency η_b	0.775	0.78
Mass efficiency η_m	0.86	0.42
Total efficiency η_t	0.59	0.24

R. Hofer and A. Gallimore. Efficiency analysis of a high-specific impulse hall thruster. In AIAA Joint Propulsion Conference, Fort Lauderdale USA, 3602, 2004.



- Global parameters match experimental measurements of NASA-173Mv2 Hall thruster
- Lower mass efficiency due to ion losses at the metallic walls

Conclusion

- AVIP is an unstructured massively parallel solver dedicated to Hall Thrusters
- It uses a 10 moments fluid formalism, validated on a 1D benchmark

- Improved accuracy compared to the drift-diffusion methodss
- But typical weaknesses of fluid methods appear for low densities and high Knudsen, which is problematic for temperature prediction

- We managed to reproduce the basic global characteristics of the plasma in the discharge chamber
- Ionization zone and acceleration of ions through the exit plane are correctly predicted
- However the electron mean energy does not reach the expected values

- Improvement needed on the heat flux model and suitable dielectric boundary conditions at the walls are needed

Acknowledgments

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