HD and MHD Plasma Simulations inside Discharge Capillaries with PLUTO

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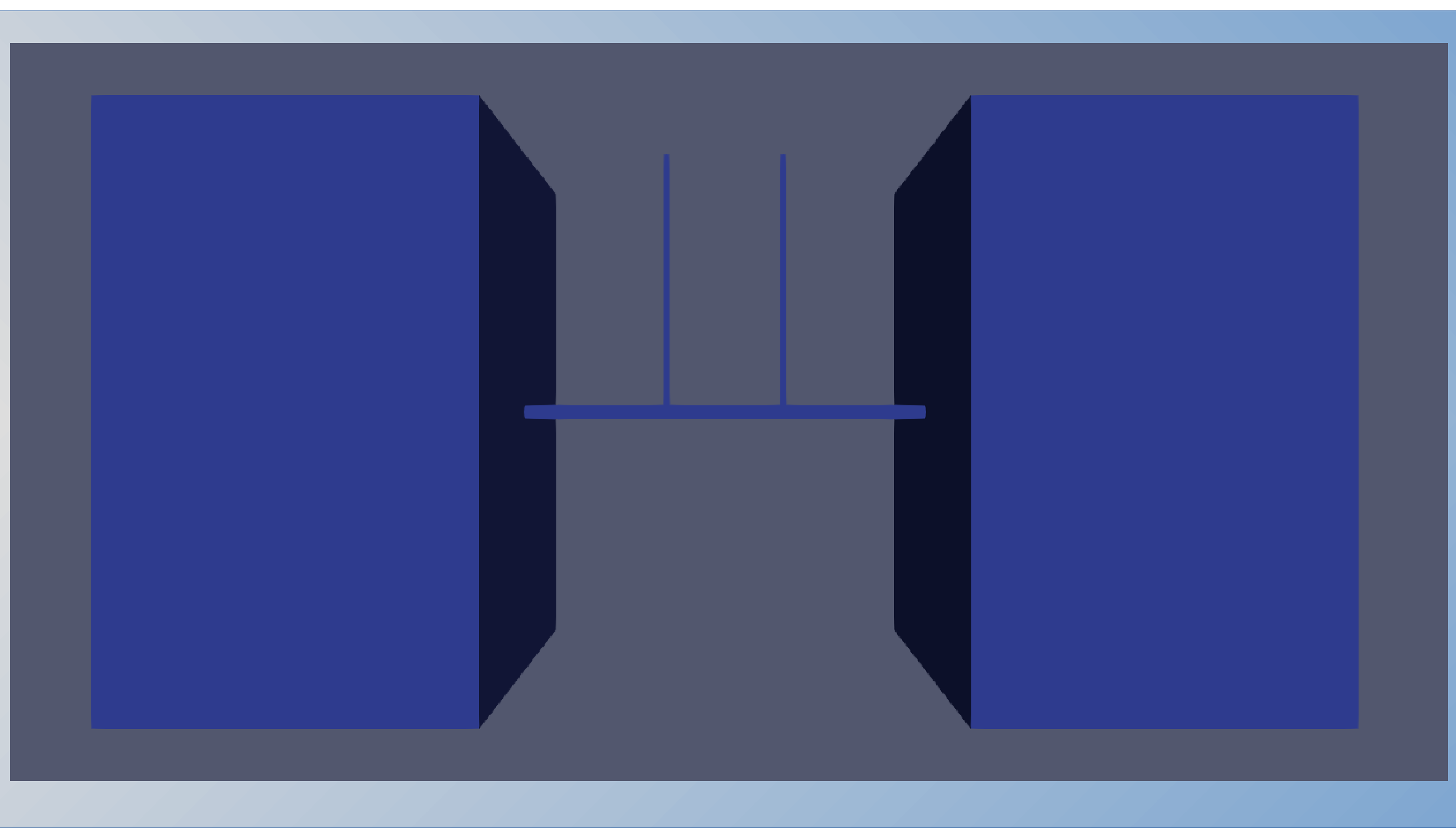
Abstract

Simulations play a key role in the design of plasma sources, employed for plasma-based accelerators [2] and other applications, and it is important to have alternative codes, for simulating the dynamics of the plasma. We propose an open source code, PLUTO [1], which allows to perform 3D, hydrodynamic (HD) and magneto-hydrodynamic (MHD) simulations of gas-filled plasma discharge capillaries. We demonstrate its functionality and its versatility for testing different geometries for the capillary and parameters for the gas injection and discharge generation. PLUTO results to be useful to analyze the behavior of the neutral gas, filling the capillary before ionization, and assess the plasma evolution after ionization, by implementing the time-dependent magnetic field created by the discharge.

PLUTO geometry, initial and boundary conditions

- 3cm capillaries with 1mm diameter
- Square cells with variable size depending on simulation region: 156 um x 156um x 97um inside the capillary, 590um x 590 um x 460 um outside
- 200 mbar , 300K gas from inlet surface during HD simulations, closed for MHD
- 10^{-3} mbar , 300K at outlet surface
- Ideal gas law $pV = nRT$
- Thermal conduction coefficient estimated from

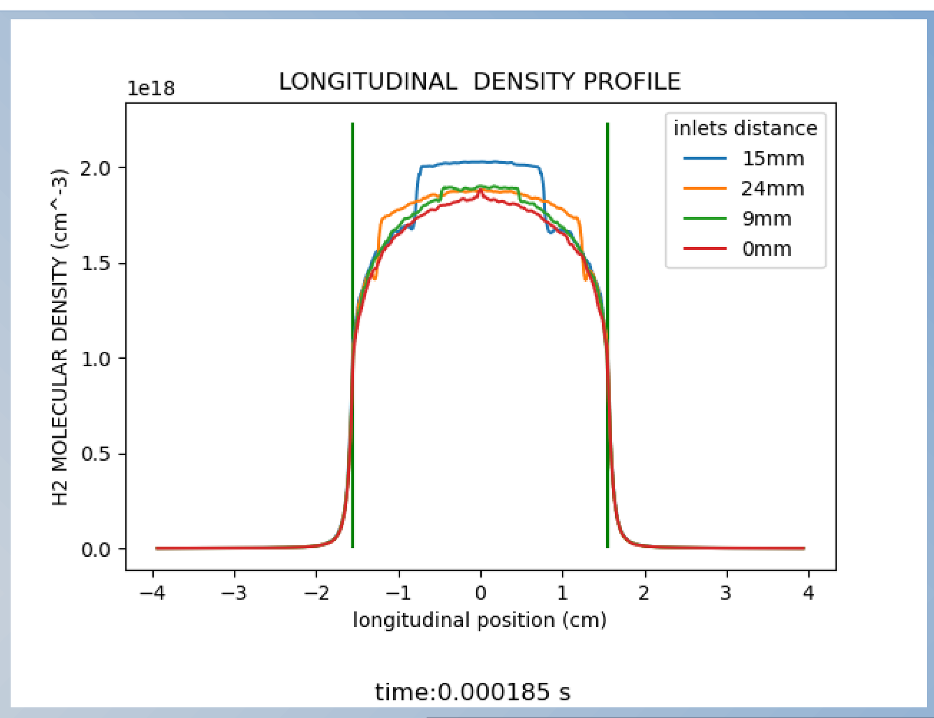
$$\kappa_{\parallel} = 5.6 \cdot 10^{-7} \cdot \mathrm{T}^{5/2}$$

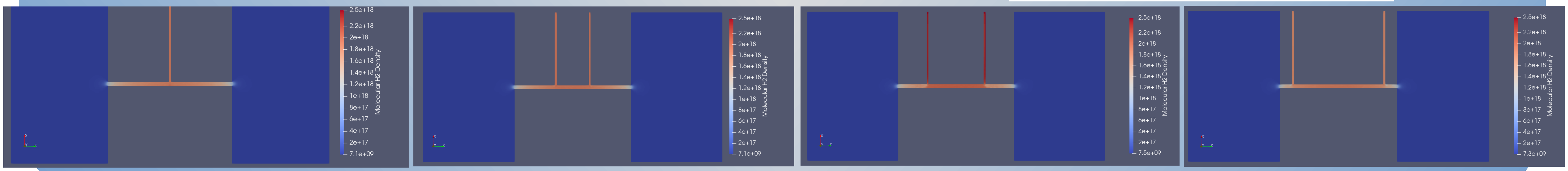


Hydrodynamic simulations

Tested single inlet capillaries and differently spaced symmetrical inlets:

- We compared the molecular hydrogen density profile varying the distance between the inlets from 9mm to 24mm keeping the same radius and injection pressure.
- Stationary flow is reached about 0.1 ms after valve opening.
- The density profile showed a higher uniformity between the inlets when they are closer.
- In addition, the outer regions from the inlets to the ends are characterized by smooth ramps, which can be controlled for beam matching and extraction.





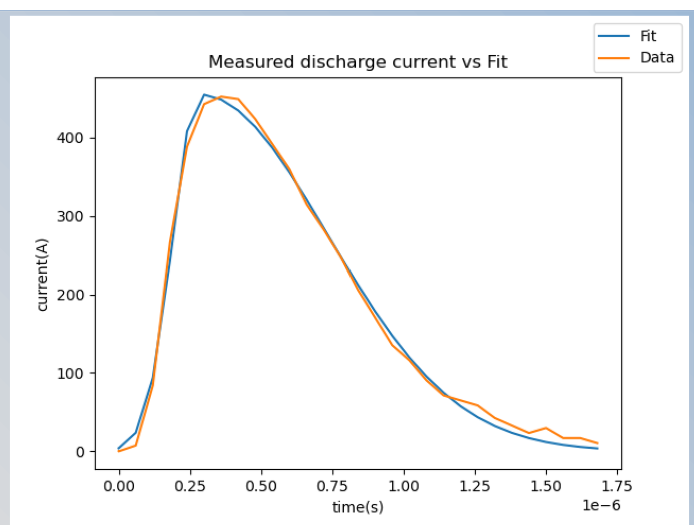
Magneto-Hydrodynamic simulations

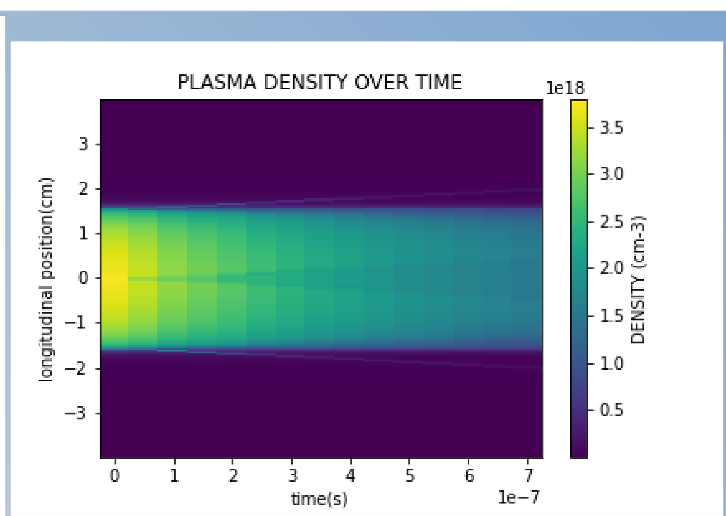
HD simulation results for single inlet configuration are used as a starting condition for the MHD simulation, to analyze the plasma density distribution along the capillary.

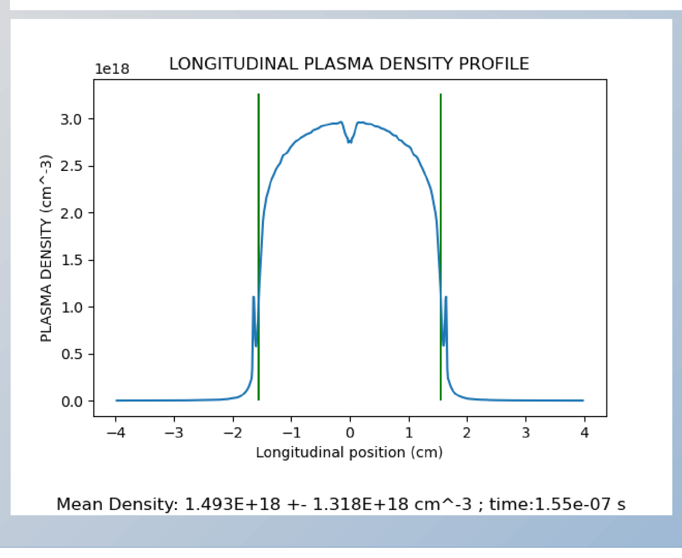
- The gas is initially considered as fully ionized, and simulated from the current peak time
- Boundary conditions on the capillary walls are set considering the azimuthal magnetic field produced by the electrical discharge current according to the Biot-Savart law.
- For this purpose, a 450A-peak discharge current, produced inside a 3cm capillary and measured with an oscilloscope, is used.
- The resistivity is estimated according to:

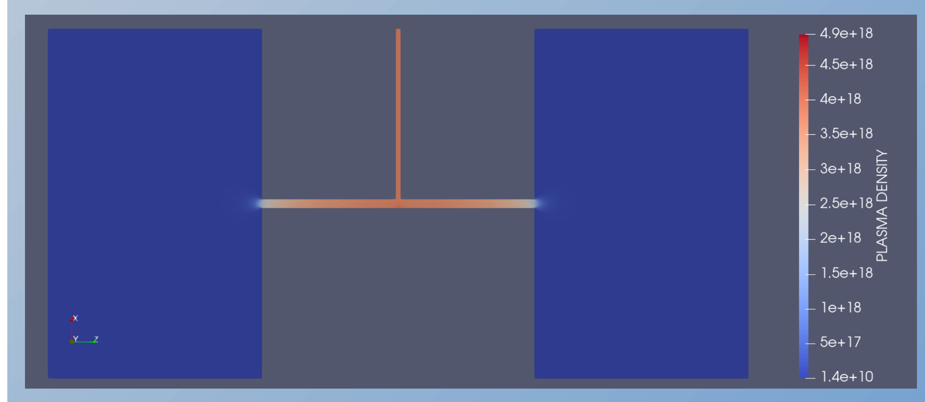
$$\rho_{ei}(t) = \frac{m_e}{n_e(t)e^2}\upsilon_{ei}(t) \quad \upsilon_{ei}(t) = \frac{4}{3}\sqrt{\frac{2\pi}{m_e}}\frac{e^4 n_e(t) ln\lambda_{ei}(t)}{(4\pi\epsilon_0)^2(k_B T(t))^{3/2}} \quad ln\lambda_{ei} = ln\left[\frac{3}{2\sqrt{2\pi}}\frac{(4\pi\epsilon_0)^{3/2}(k_B T(t))^{3/2}}{e^3 n_e^{1/2}(t)}\right]$$

- For the ionization, the module Simplified Non-Equilibrium Cooling (SNEq) is chosen.









Conclusions

In this work we present PLUTO code as an interesting option for hydrodynamics and plasma simulations in the context of plasma discharge capillaries. HD results are in agreement with other simulation codes [3] and first MHD simulations provide useful info in the dynamics of the formed plasma in the recombination phase. Future developments will allow to fully characterize the plasma evolution, including the gas ionization, to give a consistent theoretical support to experimental development of such plasma sources.

References

[1]Mignone, A., Bodo, G., Massaglia, S., Matsakos, T., Tesileanu, O., Zanni, C., & Ferrari, A. (2007). PLUTO: a numerical code for computational astrophysics. The Astrophysical Journal Supplement Series, 170(1), 228–242. https://doi.org/10.1086/513316
[2]Assmann, Ralph & Weikum, M. & Akhter, Tonny & Alesini, D. & Alexandrova, A. & Anania, Maria Pia & Andreev, N.E. & Andriyash, Igor & Artioli, Marcello & Aschikhin, A. & Audet, Thomas & Alberto, Bacci & Barna, I. & Bartocci, Simona & Bayramian, A. & Beaton, Andrew & Beck, A. & Bellaveglia, M. & Beluze, A. & Zigler, Arie. (2020). EuPRAXIA Conceptual Design Report. The European Physical Journal Special Topics. 229. 3675-4284. 10.1140/epjst/e2020-000127-8.
[3]Crincoli, L., Anania, M. P., Biagioni, A., Carillo, M., Costa, G., Del Giorno, M., Galletti, M., Iovine, P., Lollo, V., Mariani, C., Pellegrini, D., Pompili, R., Romeo, S., & Ferrario, M. (2024). Characterization of plasma-discharge Capillaries for Plasma-based Particle Acceleration. Journal of Physics Conference Series, 2687(4), 042006. https://doi.org/10.1088/1742-6596/2687/4/042006
[4]CINECA Supercomputing Centre, SuperComputing Applications and Innovation Department. (2024). "LEONARDO: A Pan-European Pre-Exascale Supercomputer for HPC and AI applications.", Journal of large-scale research facilities, 8, A186. https://doi.org/10.17815/jlsrf-8-186