EUROPEAN NETWORK FOR NOVEL ACCELERATORS

EuroNNAc4

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IJCLab Irène Joliot-Curie

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Gas cell target development for laser-plasma electron injector using OpenFOAM fluid dynamics solver and dedicated test bench

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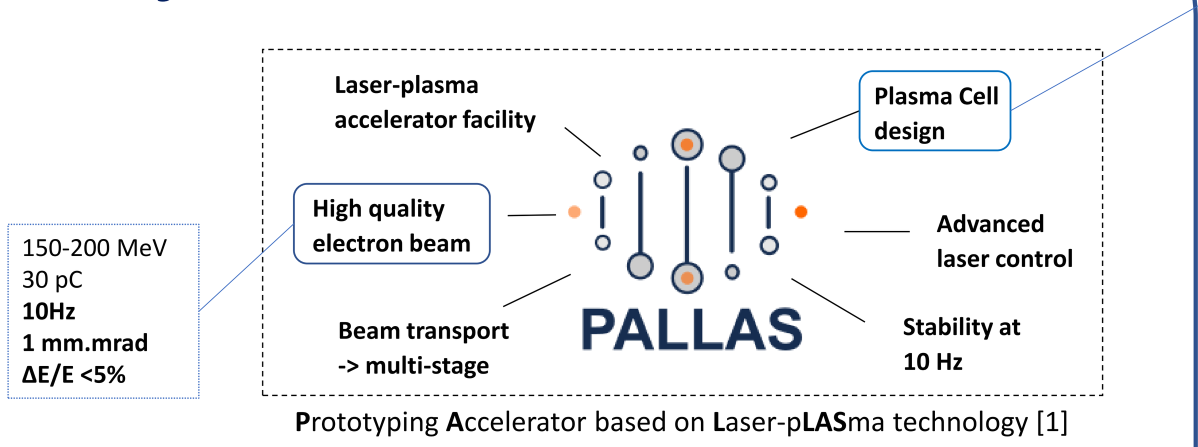
Project



Prototyping Accelerator based on Laser-pLASma technology [1]

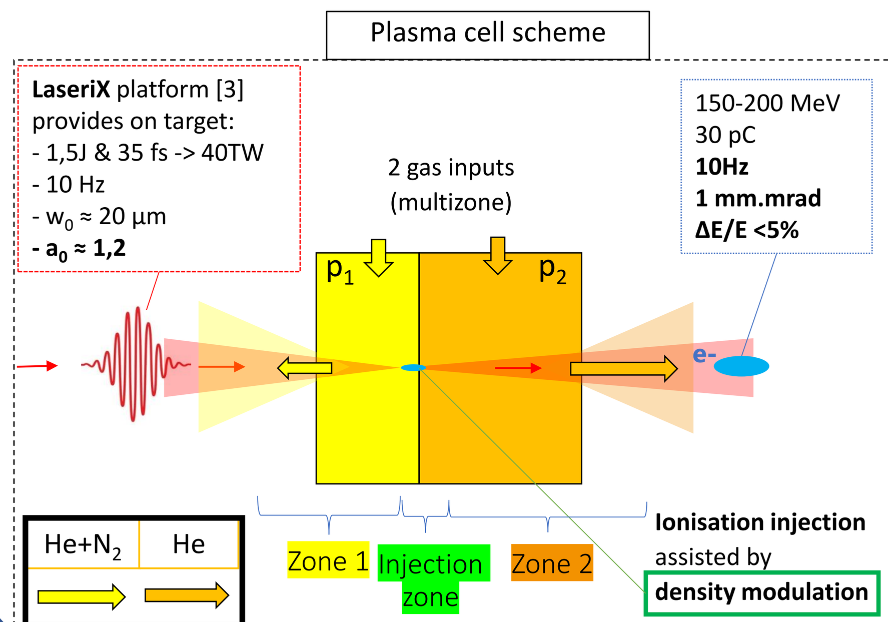
Participation to R&D Technical Design Report in preparatory phase on **high-quality laser-plasma injector (LPI)** for EUPRAXIA Horizon 2020 European project [2]

EuPRAXIA

My PhD

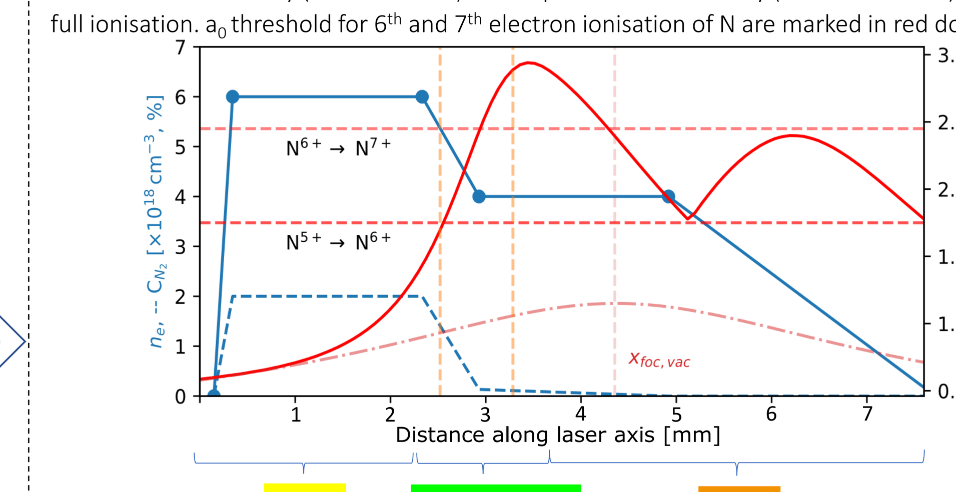
Development of the electron injector (plasma cell)

Plasma cell scheme



Injection principle

Laser a_0 (red lines) in vacuum and in plasma along longitudinal axis (laser travels from left to right). Overall electron density (blue solid line) and dopant electron density (blue dotted line) assuming full ionisation. a_0 threshold for 6th and 7th electron ionisation of N are marked in red dotted line.



Zone 1: laser autofocalisation

Between 1 and 2: injection of the two last e^- of N_2 ($N^{5+} \rightarrow N^{6+} + e^-$, $N^{6+} \rightarrow N^{7+} + e^-$) when a_0 high enough, stops when there is no dopant.

Zone 2: energy filter, acceleration and preservation of emittance (avoid explosion)

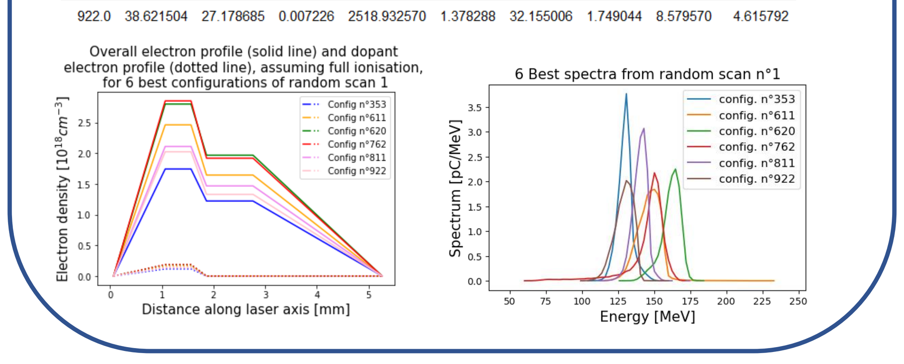
PIC simulations

Smilei

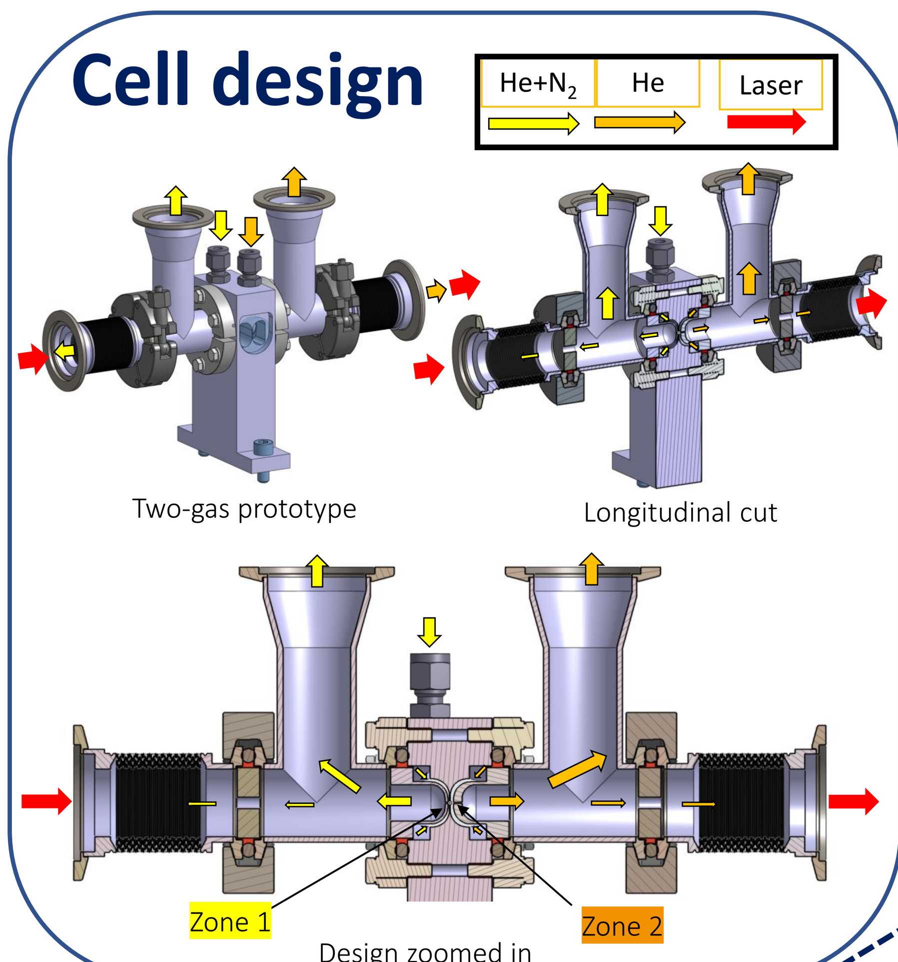
Fast Particle-in-Cell (PIC) simulations with code SMILEI [4] using: enveloppe approximation [8], Azimutal mode decomposition and Flattened Gaussian Beam (FGB) [9][10]

Example of results from Random Scan in 5-D space (p_1, p_2, c_{N2}, x_{foc_vac}, a_0) (assuming dopant confinement in 1st chamber)

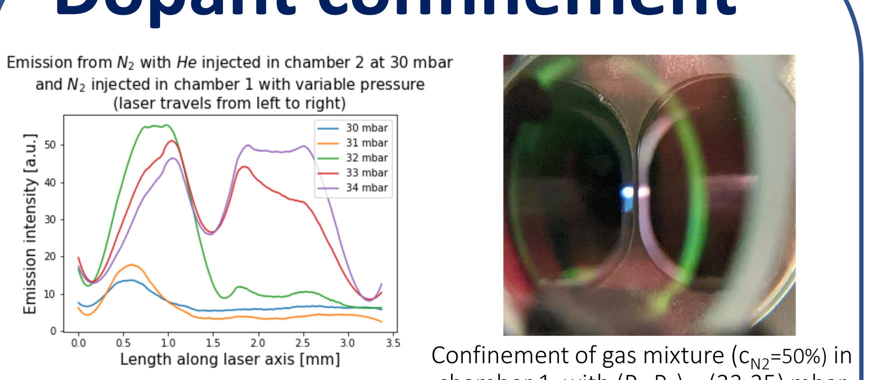
Config	p_1	p_2	c_N2	x_foc_vac	a_0	q_end	emit_y	div_rms	E_std
353.0	33.270554	24.969215	0.006086	2052.575162	1.437473	37.221302	1.908809	8.267781	4.238315
611.0	46.980406	33.596067	0.006949	2647.155282	1.312578	35.740663	1.932915	7.788671	5.933231
620.0	53.460179	40.210503	0.006045	2346.609664	1.210567	32.340157	1.943061	8.093554	5.184536
762.0	54.430189	39.211528	0.006820	1938.115692	1.156289	33.453681	1.891028	8.209600	14.748088
811.0	40.277936	29.988372	0.006231	2186.621522	1.346453	35.962269	1.895663	7.874558	3.588984
922.0	38.621504	27.178685	0.007226	2518.932570	1.378288	32.155006	1.749044	8.579570	4.615792



Cell design



Dopant confinement



Confinement of gas mixture (c_{N2}=50%) in chamber 1, with (P_1;P_2) = (33;35) mbar

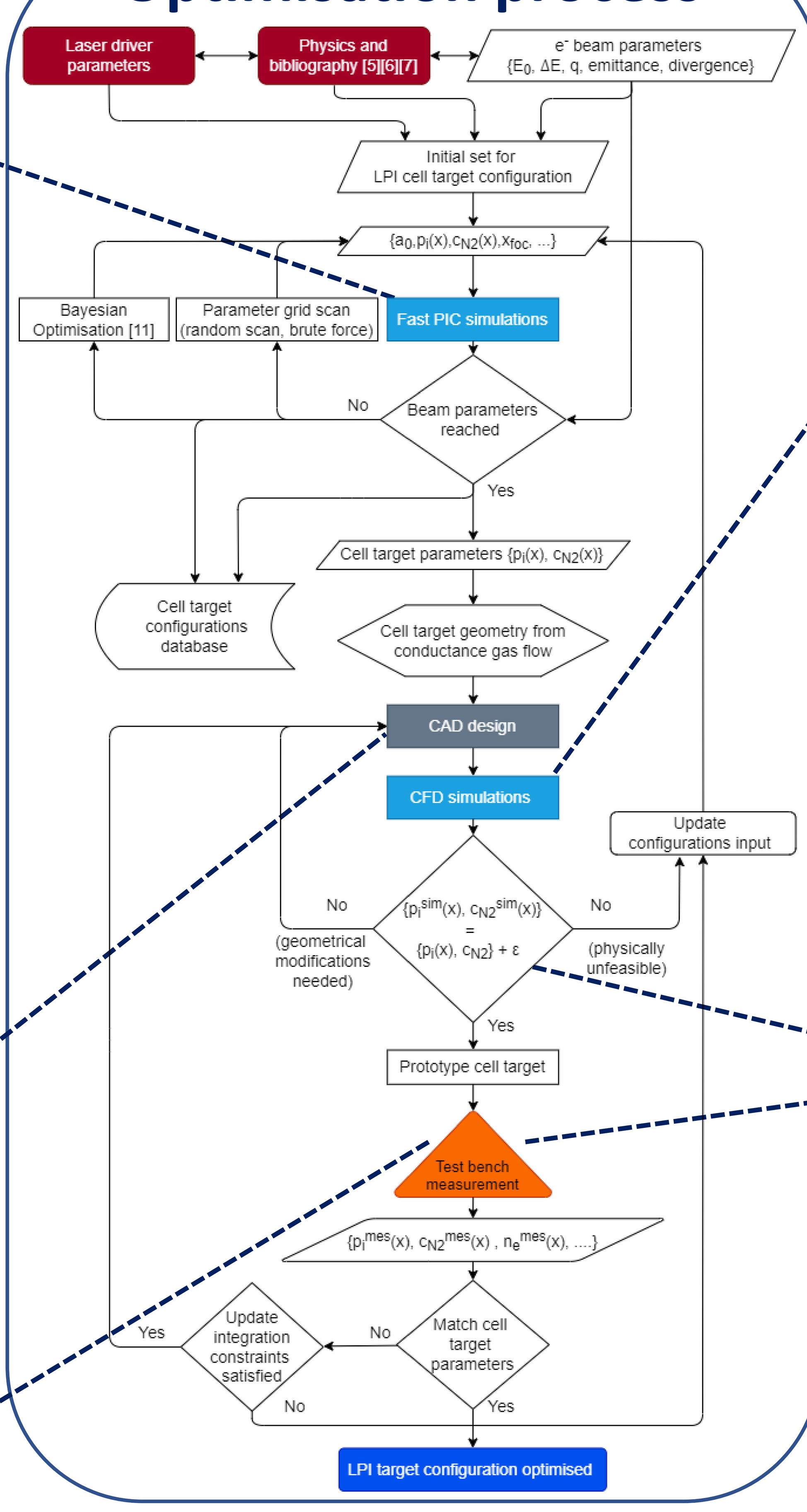
Interrogation: since chamber 1 is under higher pressure than chamber 2 (see best configurations from random scan 1), will the dopant N_2 remain in chamber 1 ?

Experiment: He injected in chamber 1, N_2 injected in chamber 2. Measurement of N_2 emission to see confinement at different pressure differences ΔP between chamber 1 and 2.

Results: if $\Delta P = P_1 - P_2 < 2$ mbar, N_2 is confined (diffusion does not seem to be problematic). For higher ΔP, strong leak from 1 to 2 (convection and diffusion)

-> new pressure profile, with $P_1 = P_2$ but $n_{e,1} \neq n_{e,2}$ by varying c_{N2} (no convection, only diffusion)

Optimisation process



Conclusion

Positive results:

- Calibration of simulation with experimental data
- OpenFOAM simulations in combination with fast PIC simulations allow for the optimisation of a 2 chamber gas cell -> PIC-simulated electron beams acceptable

Problems encountered:

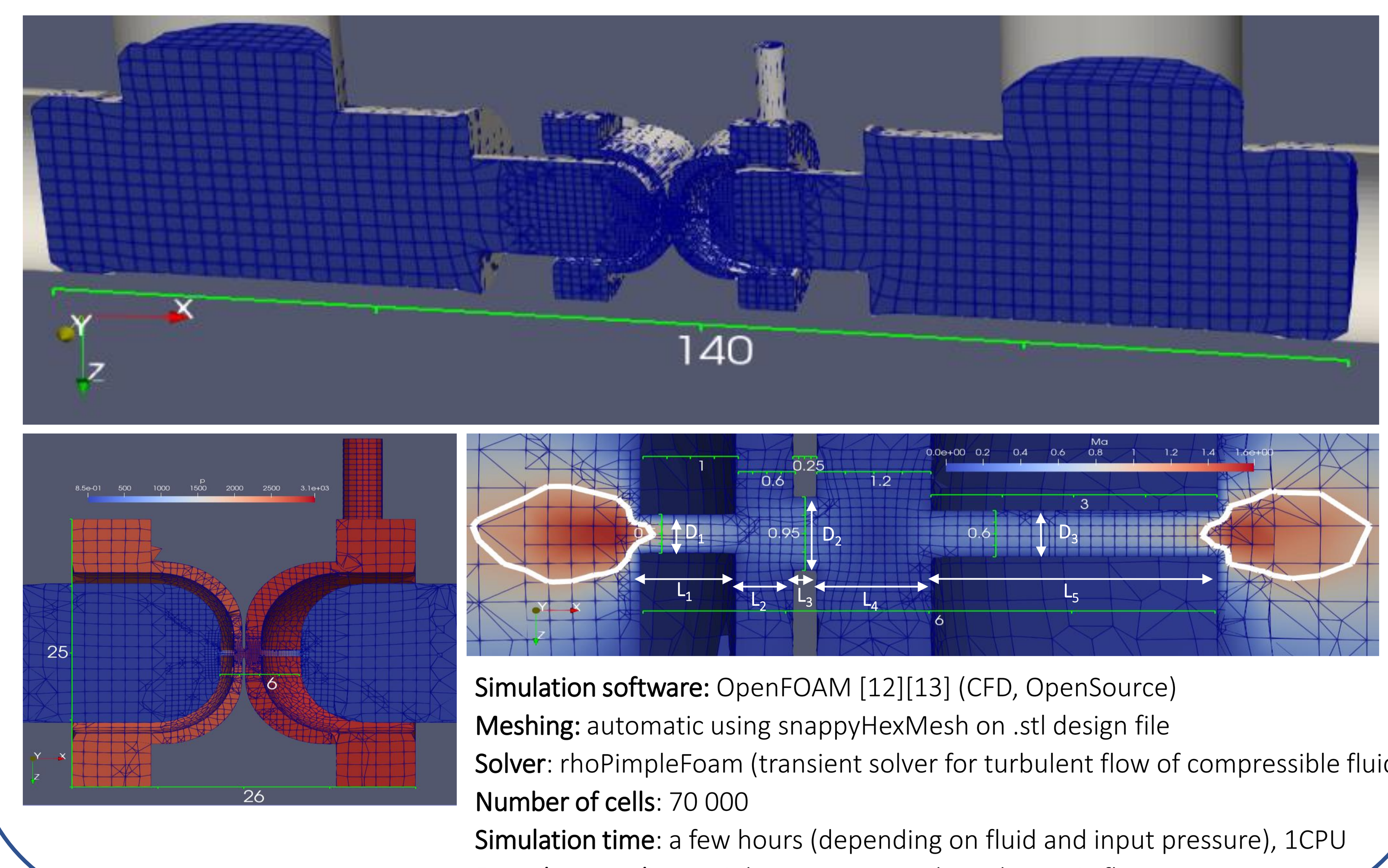
- Hard to mesh (even wih automatic meshing tools) complex geometries
- In a 2 chamber gas cell, if the dopped chamber is under excess pressure (a few mbar), one can expect leaks (convection and/or diffusion) -> essential to stop the injection.
- Present design uses a lot of metal, is hard to align and wears out very quickly.

Conclusion:

- New design to come ([6][14]) to facilitate fluid simulation meshing and prevent diffusion and convection of dopant from chamber 1 to chamber 2.

Model, mesh and solver

OpenFOAM®



Simulation software: OpenFOAM [12][13] (CFD, OpenSource)

Meshing: automatic using snappyHexMesh on .stl design file

Solver: rhoPimpleFoam (transient solver for turbulent flow of compressible fluids)

Number of cells: 70 000

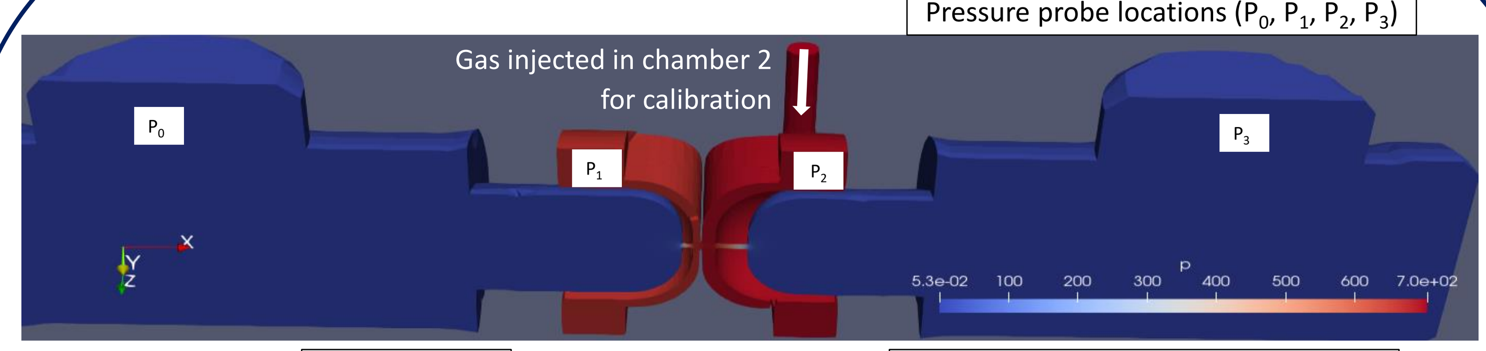
Simulation time: a few hours (depending on fluid and input pressure), 1CPU

Boundary conditions: inlet pressure, outlet volumetric flow

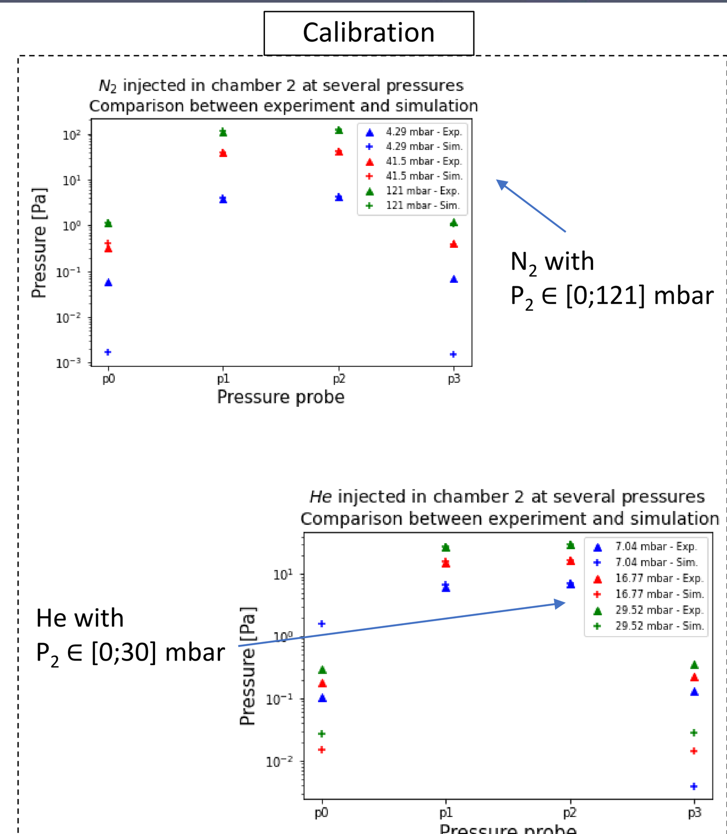
Calibration and results

OpenFOAM®

Pressure probe locations (P_0, P_1, P_2, P_3)



Calibration



N_2 with $P_2 \in [0;121]$ mbar

He with $P_2 \in [0;30]$ mbar

Comments :

Good for N_2 for all input pressure (validity limit reached when vacuum < 1 mbar)

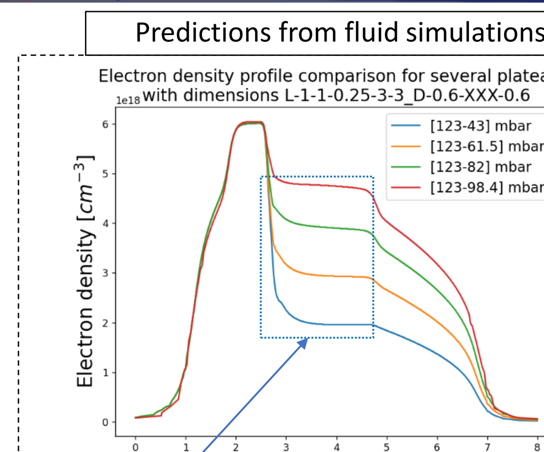
Good for He at low pressure

Missing data for He at high pressure:

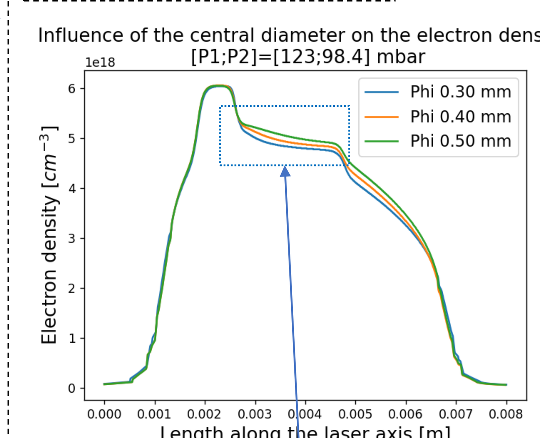
- thiner cells required… then Courant Number explodes !
- simulations are very long (maybe not stationnary yet ?)

Hard to exactly know cell dimensions (material wear)

Predictions from fluid simulations



Pressure gap between P_1 & P_2 not changing plateau shape



Central diameter not strongly changing leak from chamber 1 to chamber 2

[1] https://pallas.ijclab.in2p3.fr/
[2] http://www.eupraxia-project.eu/
[3] https://www.ijclab.in2p3.fr/en/platforms/laserix/
[4] https://smileipic.github.io/Smilei/
[5] Pak et Al. (2010). Injection and trapping of tunnel-ionized electrons into laser-produced wakes. Physical Review Letters, 104(2), 025003.
[6] Kirchen et Al. (2021). Optimal Beam Loading in a Laser-Plasma Accelerator. Physical review letters, 126(17), 174801.
[7] Lee et Al. (2016). Dynamics of electron injection and acceleration driven by laser wakefield in tailored density profiles. Physical Review Accelerators and Beams, 19(11), 112802.
[8] Massimo, Francesco, et al. "Numerical modeling of laser tunneling ionization in particle-in-cell codes with a laser envelope model." Physical Review E 102.3 (2020): 033204.
[9] Gori, F. "Flattened gaussian beams." Optics Communications 107.5-6 (1994): 335-341.
[10]https://fbpic.github.io/api_reference/lpa_utilities/laser_profiles/flattened.html
[11] Jalas, Sören, et al. "Bayesian optimization of a laser-plasma accelerator." Physical review letters 126.10 (2021): 104801.
[12] https://www.openfoam.com/
[13] Audet, T. L., et al. "Gas cell density characterization for laser wakefield acceleration." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 909 (2018): 383-386.
[14] Kim, J., et al. "Development of a density-tapered capillary gas cell for laser wakefield acceleration." *Review of Scientific Instruments* 92.2 (2021): 023511.

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