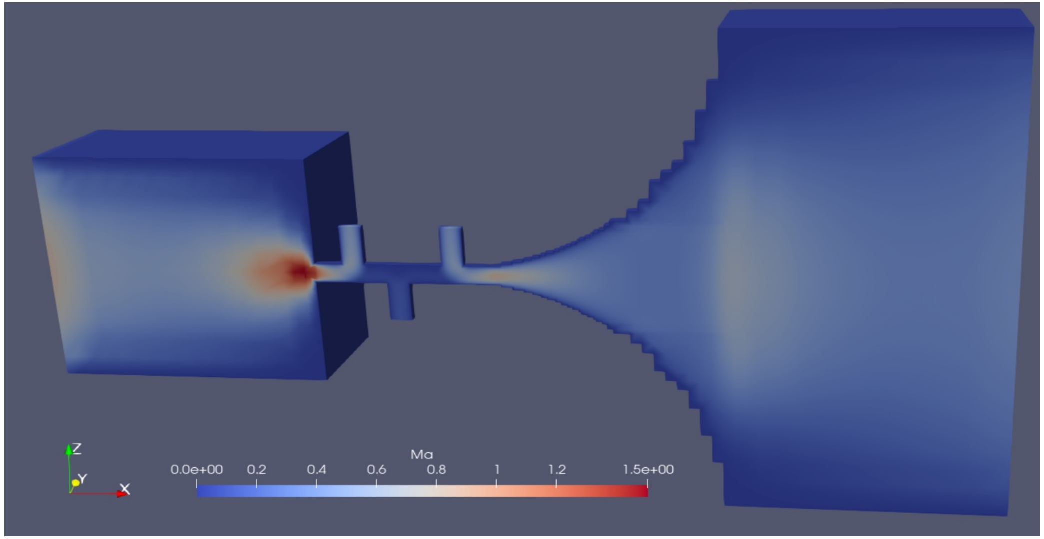
Development of a Two-Stage 150 MeV Laser-Plasma Electron Injector Using Massive Particle-in-Cell Computing Combined with Fluid Simulation



Pierre Drobniak

Thanks to the organisers

Francesco Massimo & Damien Minenna

And many thanks to my collaborators and colleagues

[1] = IJCLab
[2] = LLR
[3] = LPGP
[4] = CEA-Irfu
_ : supervisors

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IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

From theory to experimental electron production

10k+ configurations

Smilei [1]

Development of a Two-Stage 150 MeV Laser-Plasma Electron Injector Using Massive Particle-in-Cell Computing Combined with Fluid Simulation

OpenFOAM [2]

[1] https://smileipic.github.io/Smilei/
[2] https://www.openfoam.com/

2. Project

Multiple laser diagnostics and shaping (Single shot online monitoring: pointing, phase, 3D pulse shape)

High laser stability at 10 Hz

R&D injector for EuPRAXIA [2]

Automatic control and acquisition at 10 Hz

PALLAS [1]

Test facility for plasma cell design

High quality electron beam

E > 150 MeV
Q > 30 pC
$\varepsilon_{tr,norm} < 2\ \mu m$
$\Delta E/E < 5\%$

at 10 Hz

Prototyping **A**ccelerator based on **L**aser-p**LAS**ma technology

[1] https://pallas.ijclab.in2p3.fr/

[2] http://www.eupraxia-project.eu/

Laser parameters (LaseriX platform [1]):

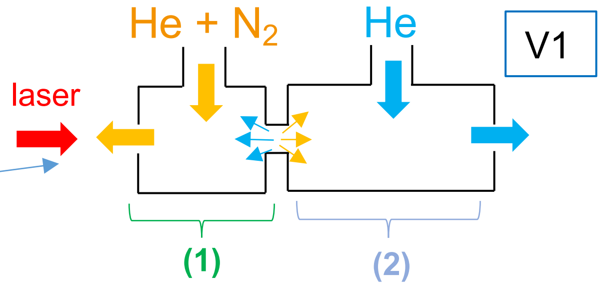
- 810 nm (Δλ = 30 nm)
- 5th order FGB (Flattened Gaussian Beam [2])
- 1.6 ± 0.1 J (on target)
- τ_{FWHM} = 35 ± 5 fs
- f = 1.5 m
- w_0 = 19 µm
- $a_0 \approx 1.40$ (4×10^{18} W/cm²)
- x_R = 1.4 mm

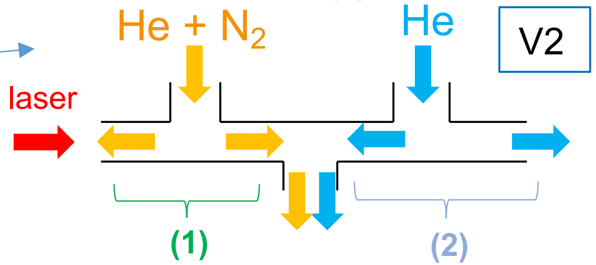
Injection scheme:

- self-truncated ionisation injection [3][4]
- **He** dopped with **N_2**
- $\mathbf{a_{0,BSI,N5+}}$ = 2.21 & $\mathbf{a_{0,BSI,N6+}}$ = 2.77 [5] -> need for **self-focusing**

Cell design

- Inspiration from [3], [4] and [6]
  two-chamber cell (1) + (2)
  (1): self-focusing + injection
  (2): acceleration + filter
- **Prototype V1:**
  - Same pressure in both chambers, to **prevent dopant convection** from (1) to (2)
- **Prototype V2:**
  - **Diffusion** is sucked out by central outlet
- Play with N_2 concentration to shape **overall** electronic density

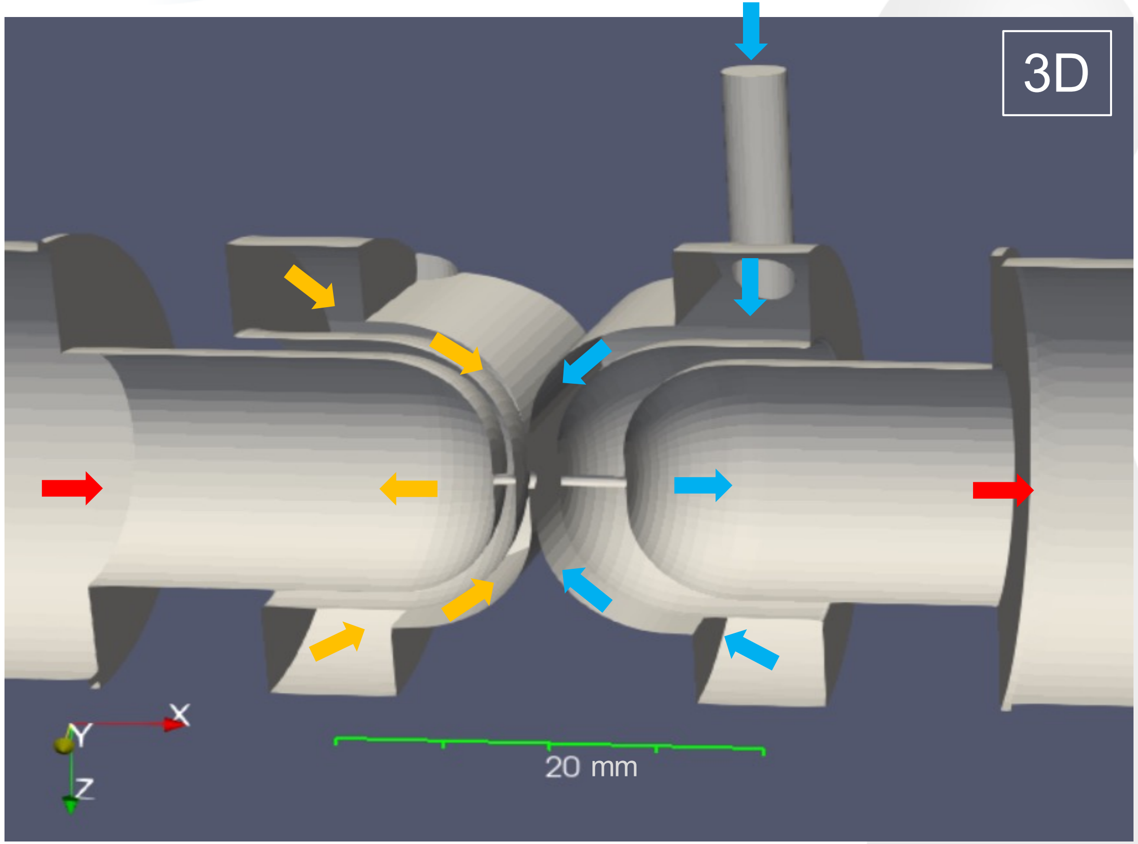


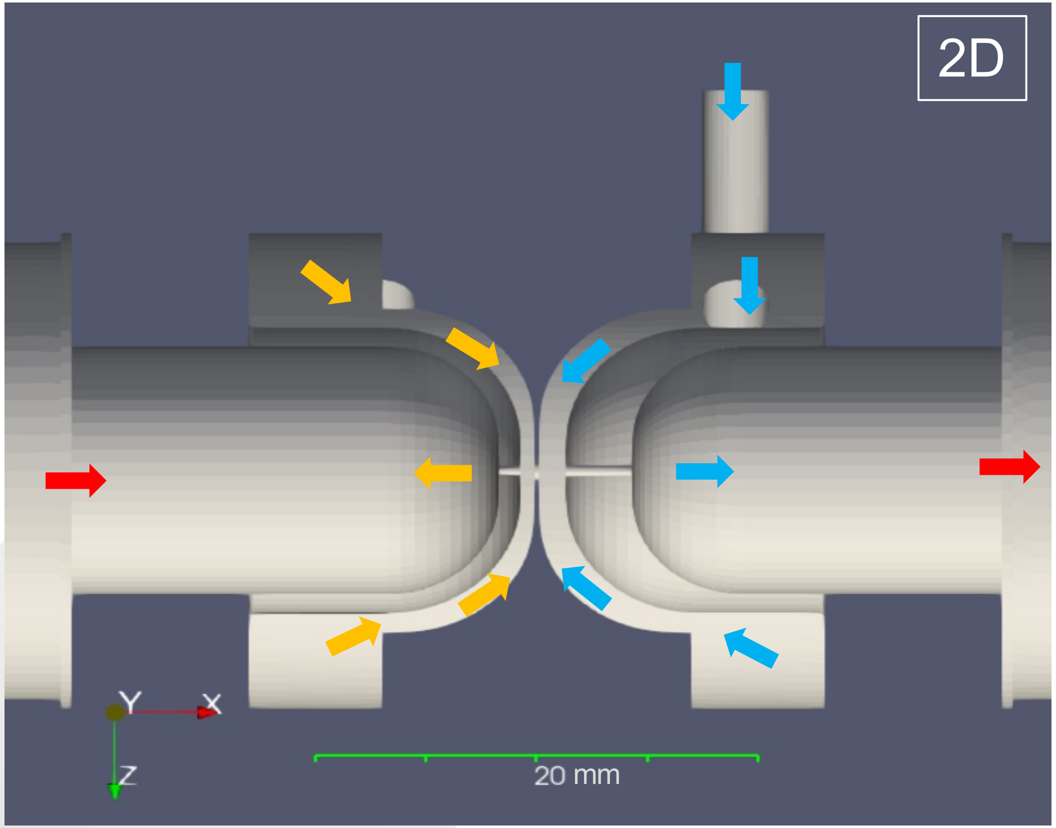


[1] https://www.ijclab.in2p3.fr/en/platforms/laserix/
[2] Gori, F. (1994). Flattened gaussian beams. *Optics Communications*, *107*(5-6), 335-341.
[3] Pak et al. (2010). Injection and trapping of tunnel-ionized electrons into laser-produced wakes. *Physical review letters*, *104*(2), 025003.
[4] Golovin et al. (2015). Tunable monoenergetic electron beams from independently controllable laser-wakefield acceleration and injection. *Physical Review Special Topics-Accelerators and Beams*, *18*(1), 011301.
[5] Couperus, J. P. (2018). *Optimal beam loading in a nanocoulomb-class laser wakefield accelerator* (No. HZDR--093). Helmholtz-Zentrum Dresden-Rossendorf (Germany).
[6] Jalas et al. (2021). Bayesian optimization of a laser-plasma accelerator. *Physical review letters*, *126*(10), 104801.

Prototype V1: two tank chambers, 2 inlets, 2 outlets

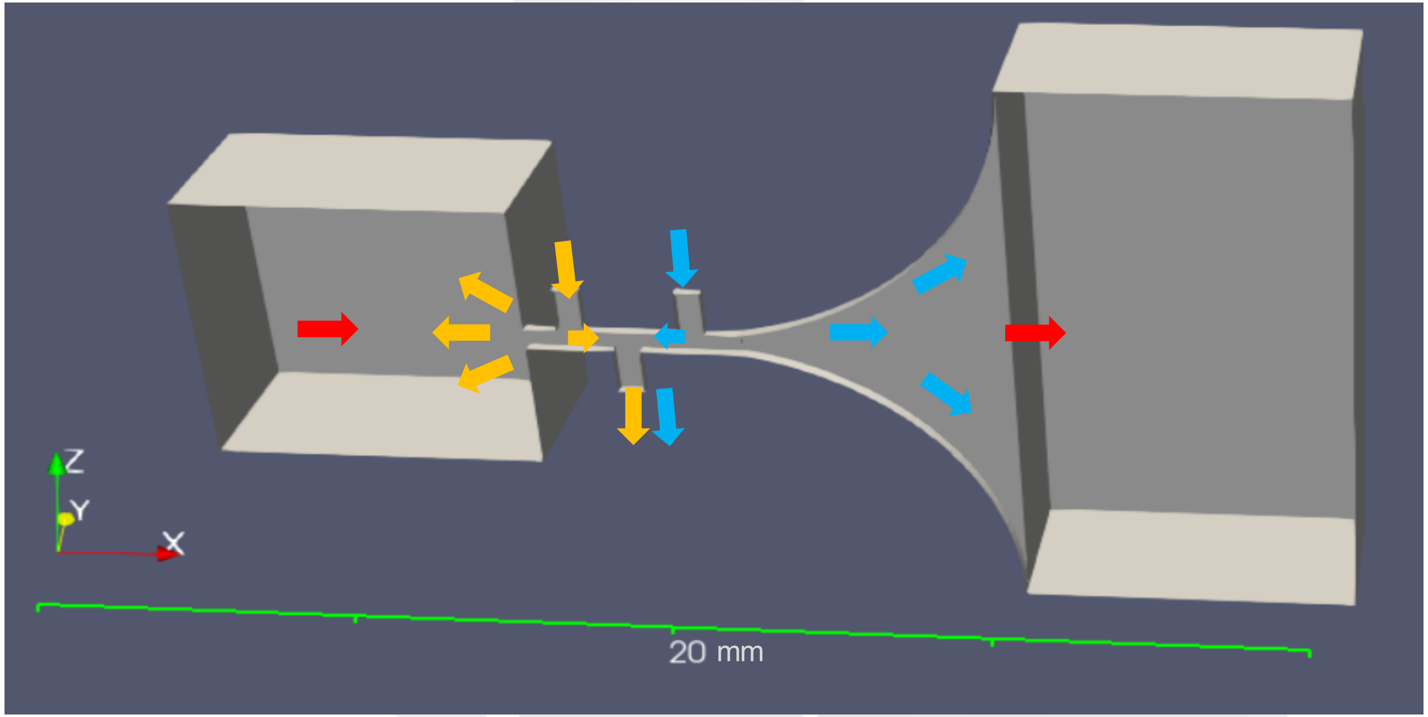
He
He + N_2
laser





Prototype V2: 2 flows, 2 inlets, 3 outlets

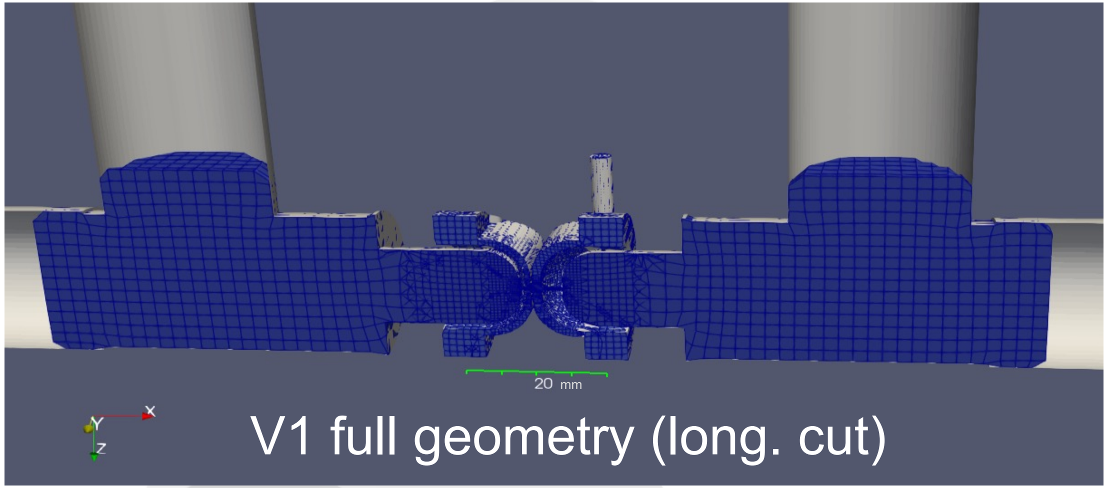
He
He + N_2
laser



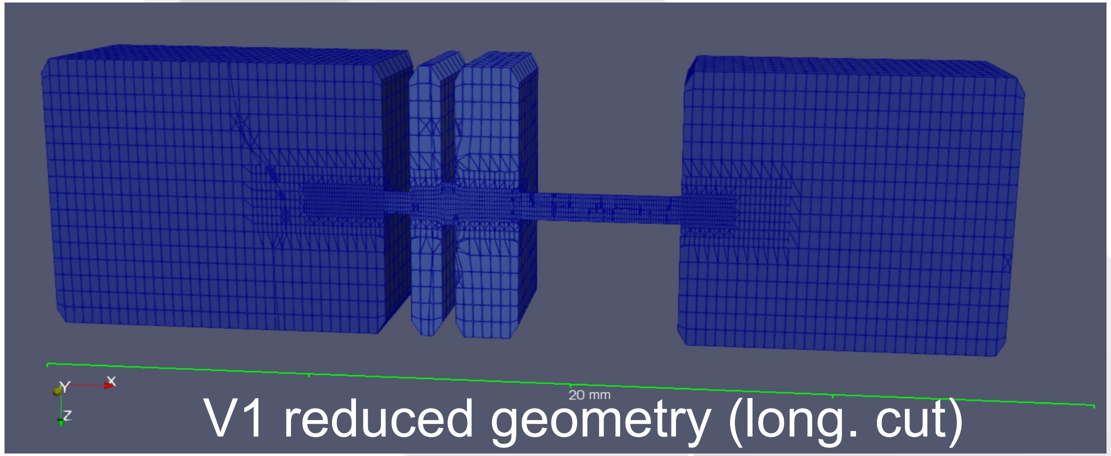
On prototype V1

Meshing tool:
snappyHexMesh

Careful with cells shape
=> Courant Number might explode



Full geometry
70 000 cells
20 sec meshing on 1 proc.



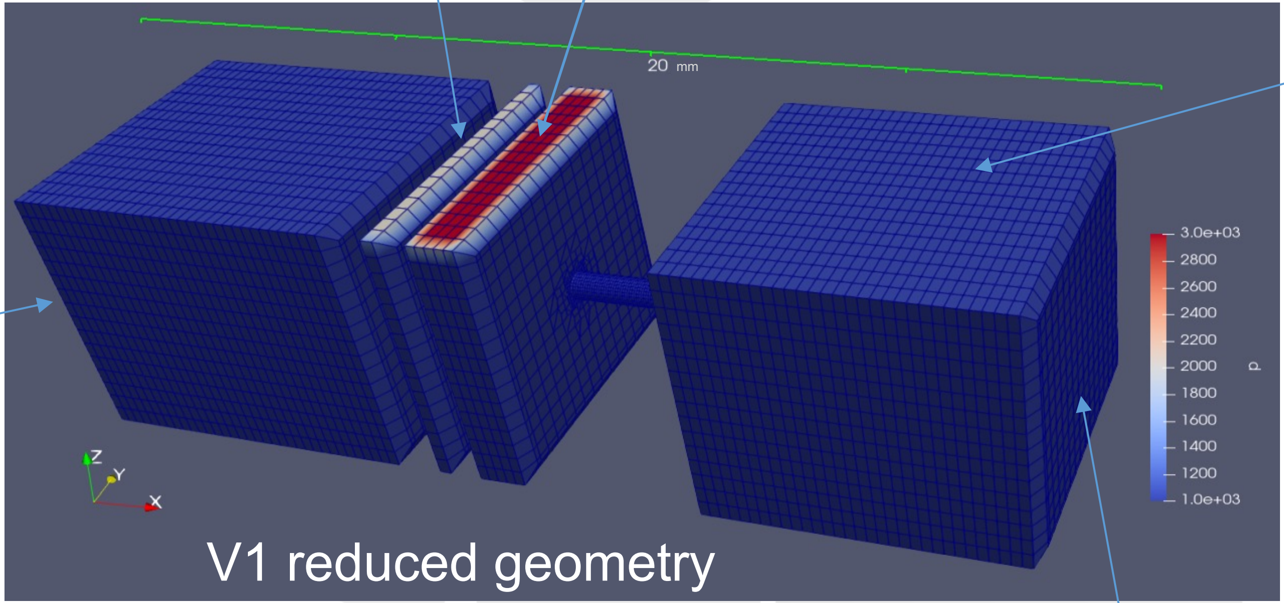
Reduced geometry
50 000 cells
8 sec meshing on 1 proc.

6.1 Definition of patches

Inlet_1 Inlet_2

Walls (everywhere except at inlets and outlets)

Outlet_neg



Outlet_pos

6.2 Set inlets and outlets

Boundary conditions

Walls:
- Pressure P: « zero gradient»
- Velocity U: « no slip»
- Temperature T: « fixed value» (293K)

Inlets:
- P: « zero gradient » & U: « flow rate»

or P: « fixed value » & U: « zero gradient»
- Temperature T: « fixed value» (293K)

Outlets:
- P: « zero gradient » & U: « flow rate»

or P: « fixed value » & U: « zero gradient»
- Temperature T: « fixed value» (293K)

Example: boundary conditions with pressure values only

Walls:
- P: « zero gradient »
- U: « no slip »
- Temperature T: « fixed value» (293K)

Inlets:
- P: « fixed value » for ex. p_inlet_1 = p_inlet_2 = 30 mbar
- U: « zero gradient »
- Temperature T: « fixed value» (293K)

Outlets:
- P: « fixed value » for ex. p_outlet_neg = p_outlet_neg = 1 mbar
- U: « zero gradient »
- Temperature T: « fixed value» (293K)

6.3 Set initial values

Initial values

For patches:

- Same as boundary conditions

For the internal fields:

- P = a few mbar
- U = 0
- T = 293 K

Careful with pressure difference at t = 0

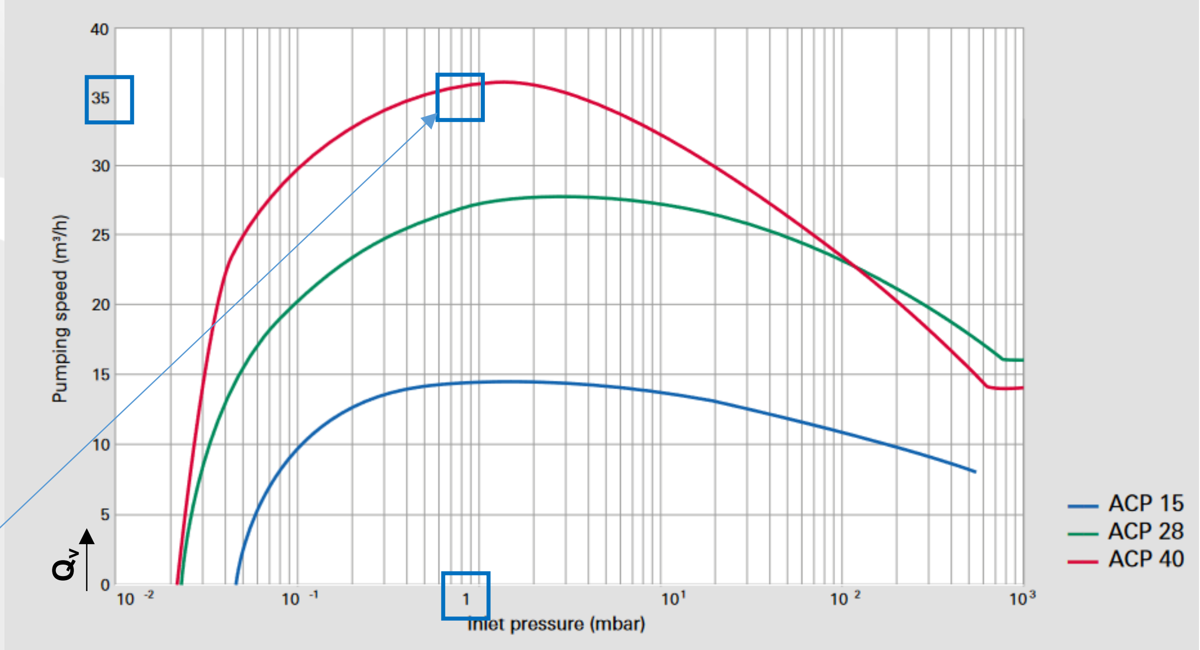
6.4 Check if feasible (at end of simulation)

- Energy sucked out by the pump cannot be higher in simulation than what the curve describes.

-> check that Q_{pV} (throughput [Pa m^3/s] = [J/s]) is not higher than what pump can develop.

- **Example**: for fixed outlet pressure values

(1) note the fixed pressure value
(2) check the simulation flow Q_v
(3) compute $Q_{pV} = Q_v \times p$
(4) Verify Q_{pV} feasible by pump for the given pressure value



Characteristics of primary vacuum pump (Pfeiffer ACP40)

6.5 Comments

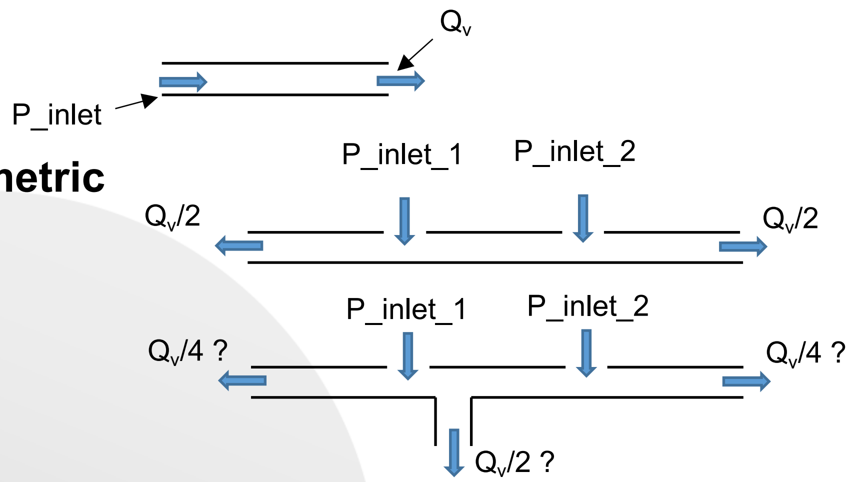
- With a flow pressure in the range of 10-100 mbar, setting a boundary condition at 1 mbar **or lower** does not influence the flow in the channel (only change is in Q_v at the very end + strong gas expansion)
- **Easier to set pressure boundary conditions** at outlet than pumping rates, because pumping rates on different outlets depends on each pipe **conductance** (which might be tricky to compute)

-> simply chose a single primary vacuum pressure for all outlets
(assumes all patches are in the same primary vacuum tank)

For flow boundary conditions (assuming you know the pump characteristics):

- Easy when there is only **one** outlet
  -> Set pumping flow Q_v (m3/s) on the outlet patch
- Easy when the geometry and expected result are **symmetric** (you know how the flow is distributed)
- **Difficult** when geometry is more **complex** (no information on the flow distribution)

-> need for **conductance** values… not direct



7. Flow characteristics

Flow:

- Compressible (Ma ~1 or higher)
- Laminar (Re < 2000)

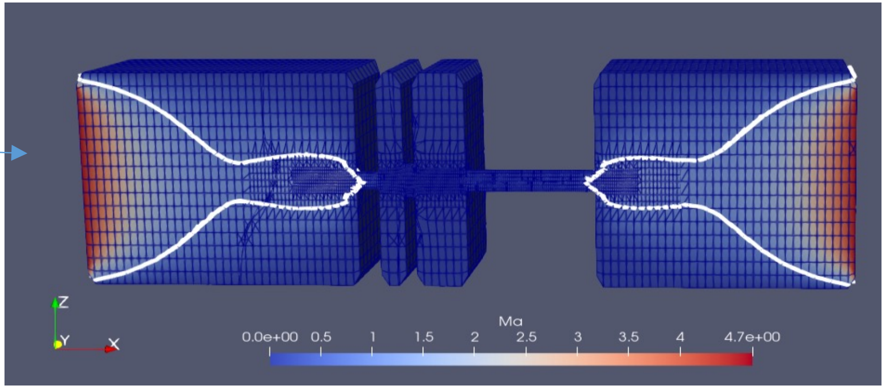
$$Re = \frac{\rho U L}{\mu}$$

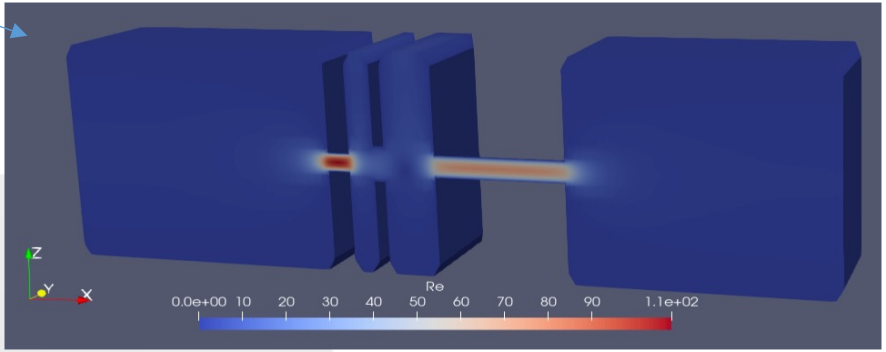
Gas:

- Only Helium (enough for flow modelling)
- Possible to have **multiple** gases but « **non-miscible** » (**diffusion** cannot be modelled with OpenFOAM presently)

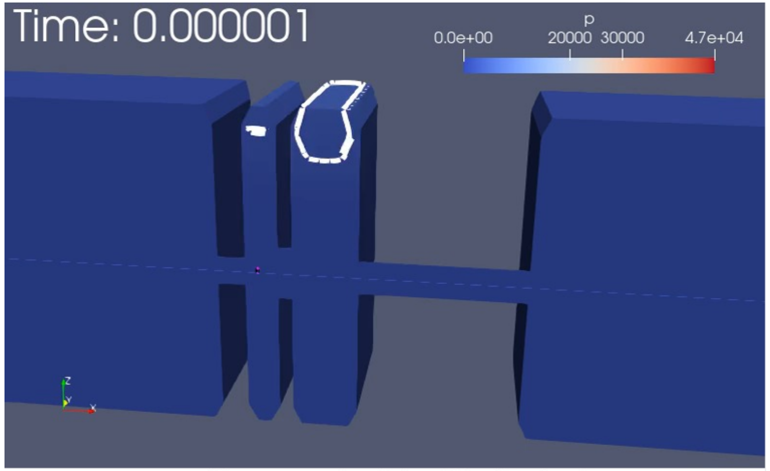
Solver:

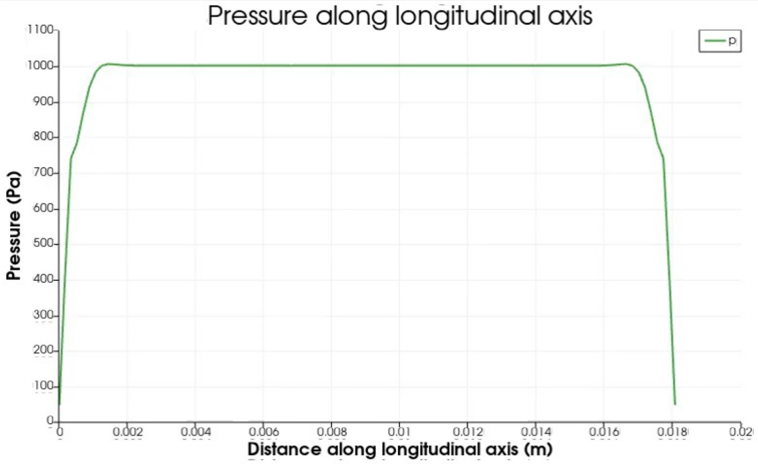
- rhoPimpleFoam

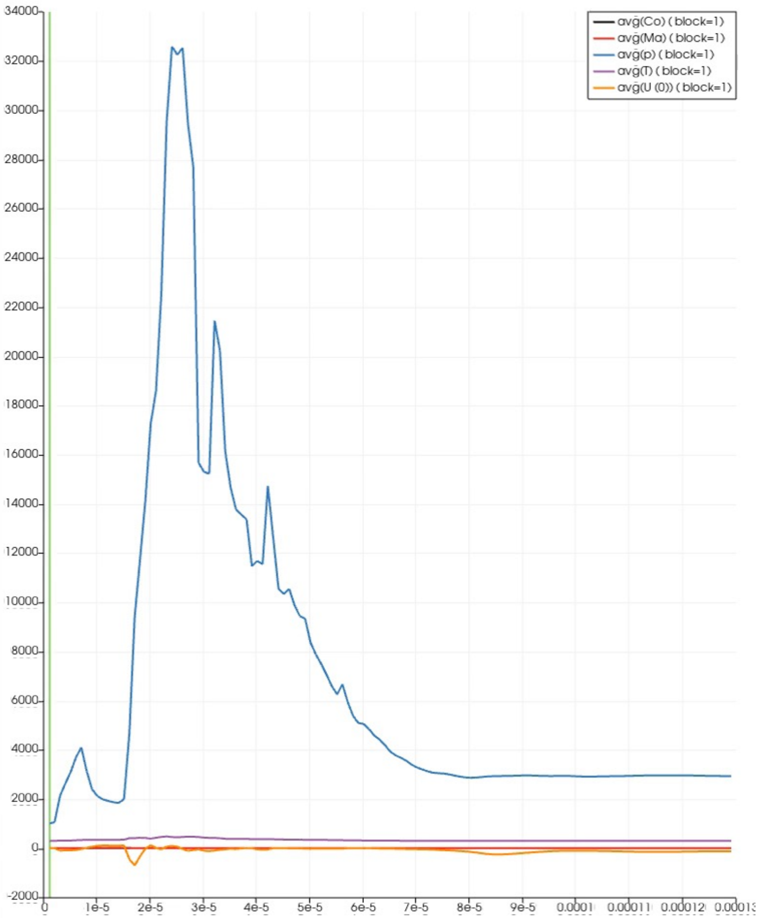




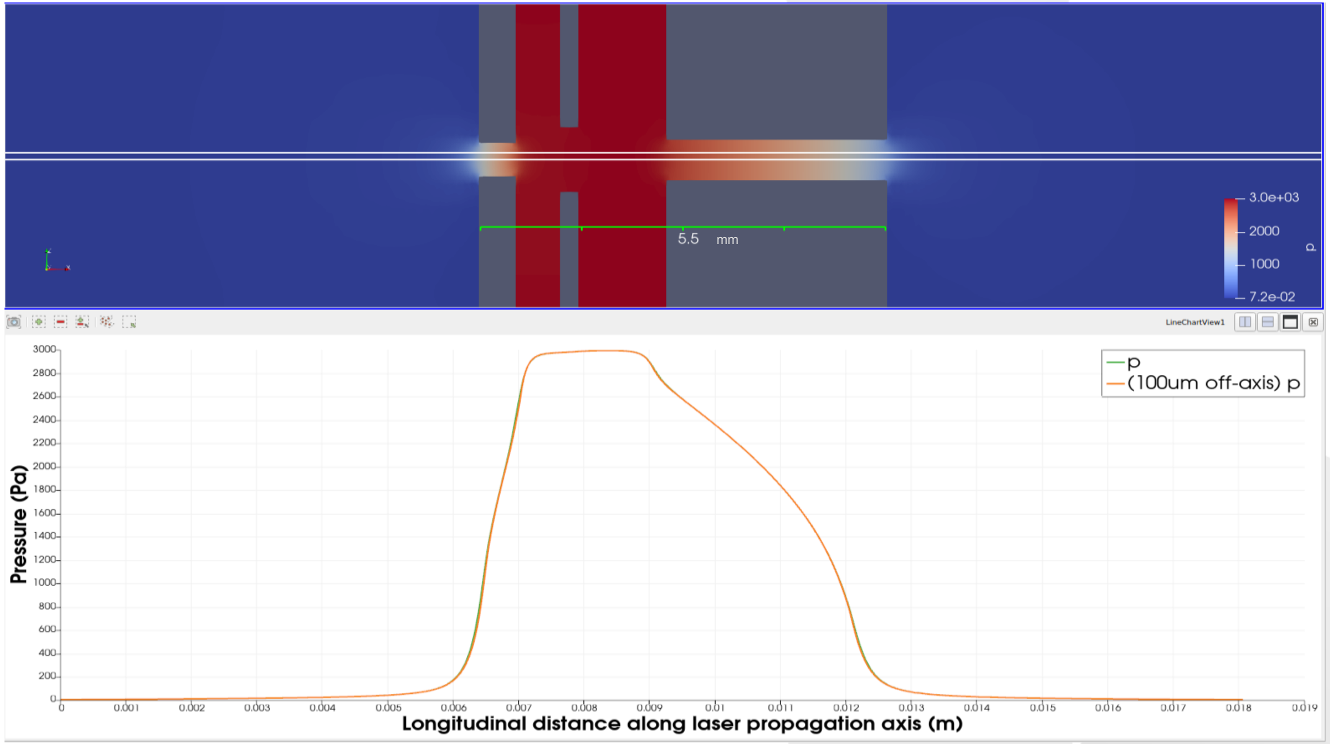
8. Fluid simulations results







Longitudinal plot along laser propagation axis

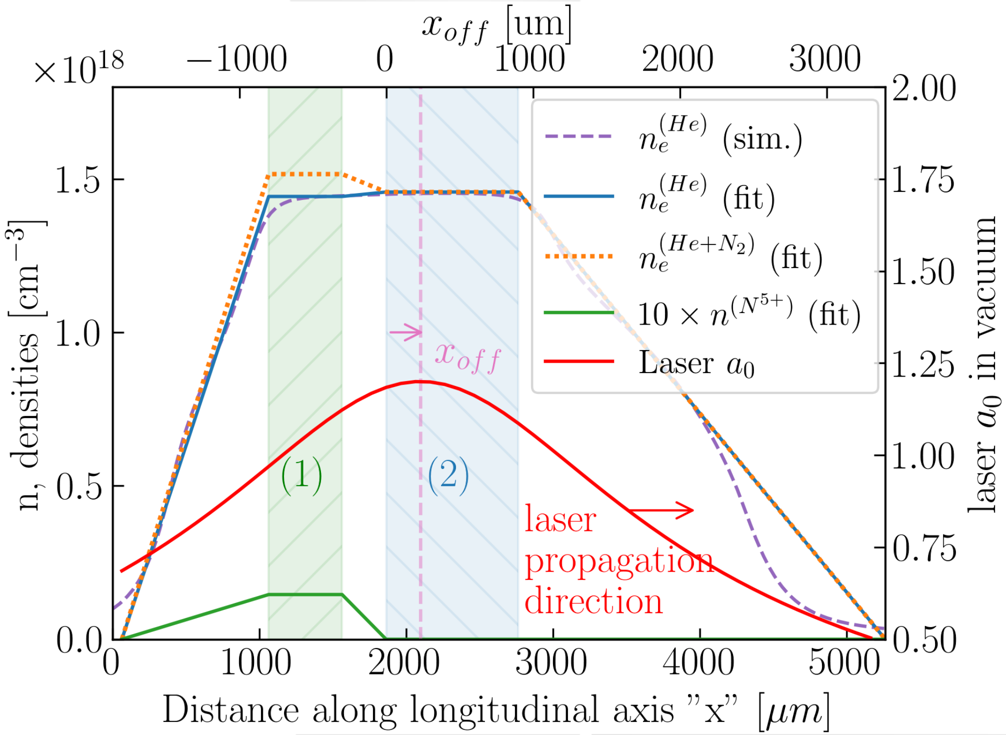


Plot along long. axis:
- no difference with 100µm off-axis curve

Computation time
- On 1 proc ~ 20 min (V1 reduced geometry)
- Simulated time: ~ 100 µs (enough for steady state)

Profile for PIC simulations:

- Polygonal fit to the simulated profile



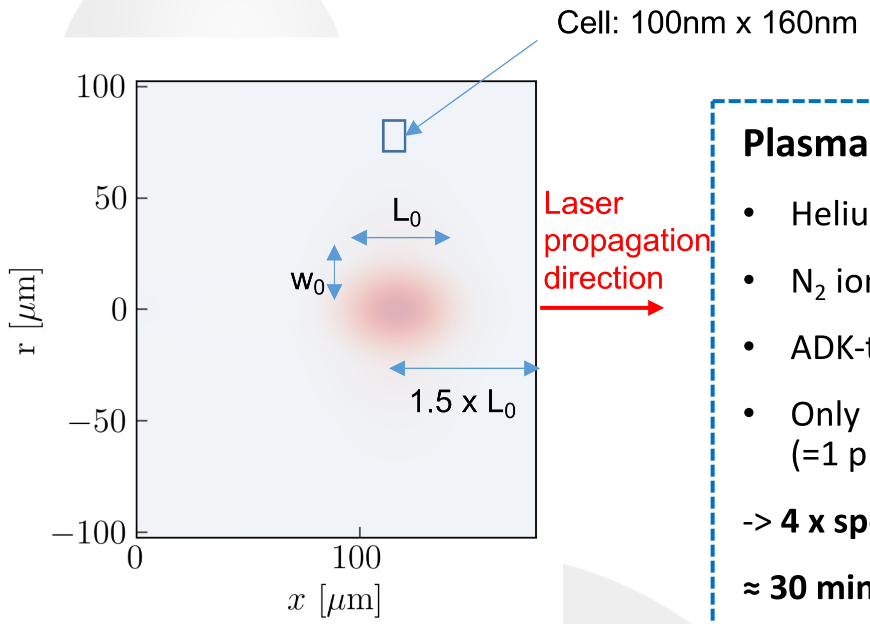
10. Particle-in-Cell configuration

Solver:

- Smilei)
- Cylindrical geometry (with 1 Azimutal Mode)
- Envelope approximation [1]

Laser parameters :

- 810 nm
- 5th order FGB
- τ_{FWHM} = 35 fs (Gaussian, unchirped)
- w_0 = 19 µm
- $a_0 \in [1.10 ; 1.85]$



Plasma parameters:

- Helium fully ionised
- N_2 ionised up to N^{5+}
- ADK-tunnel ionisation of N^{5+} & N^{6+}
- Only 1 **macro Particle Per Cell** (=1 ppc)

-> **4 x speedup** compared to 8 ppc

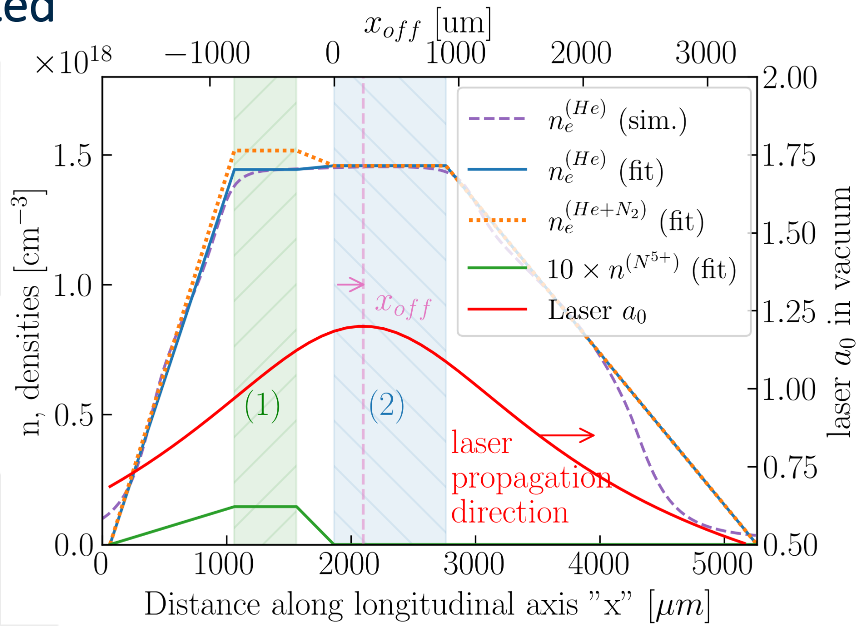
≈ 30 min / sim

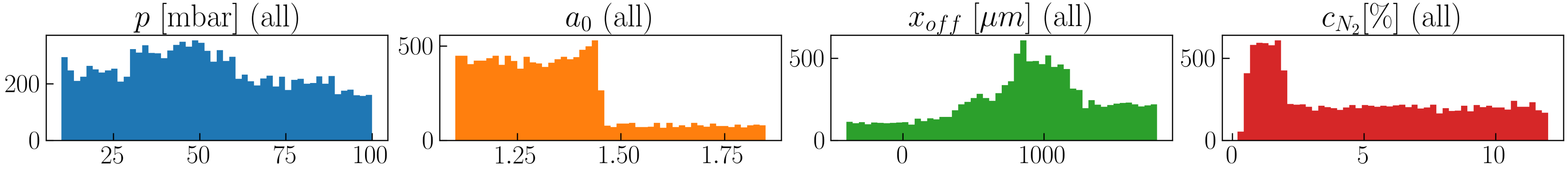
- > ≤ **10%** difference compared to 8 ppc in energy, spread, charge and emittance.

[1] Massimo 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.

11.1 Configurations investigated

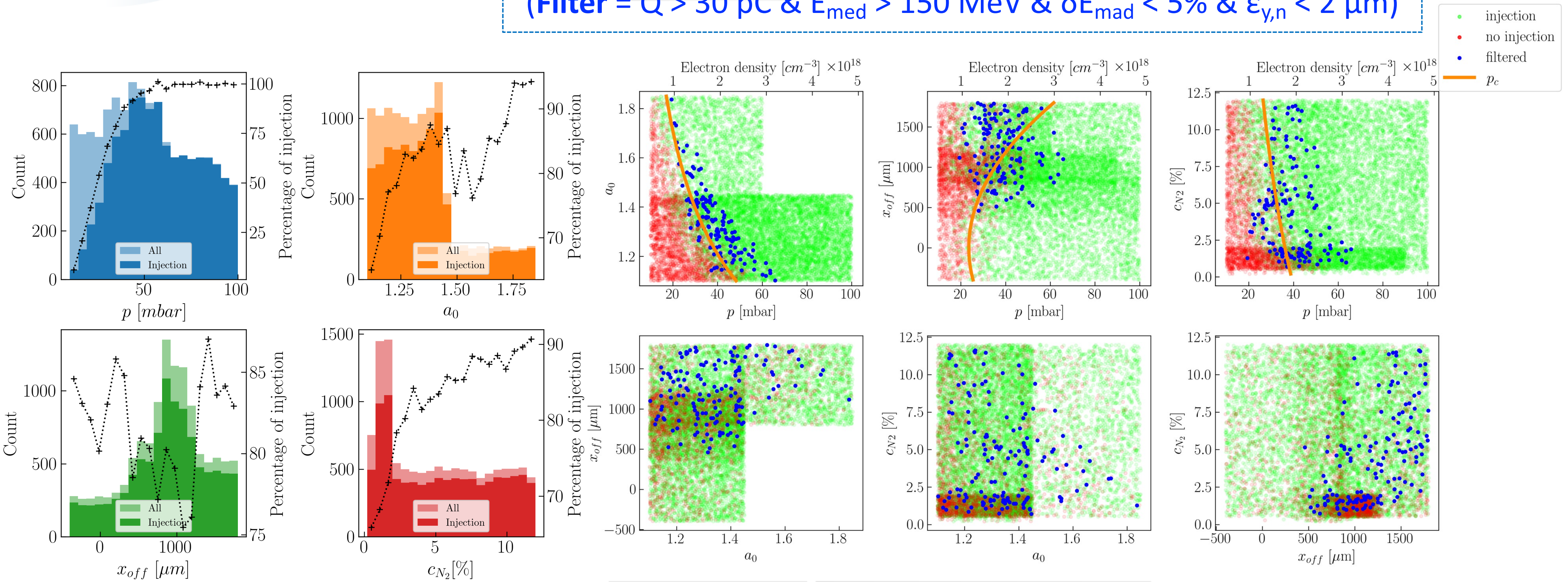
- 5 Random Scans (RS)
- 5 x 2401 = **12 005 configurations**
- 5 x 4 h **< 1 day**





11.2 Injection positions

(Filter = Q > 30 pC & E_{med} > 150 MeV & δE_{mad} < 5% & $\varepsilon_{y,n}$ < 2 µm)



11. Massive scan

11.3 Beams generated

$$f_1 = \frac{E_{med}^2 Q}{\sigma_{mad} \epsilon_{y,n}}$$ S1

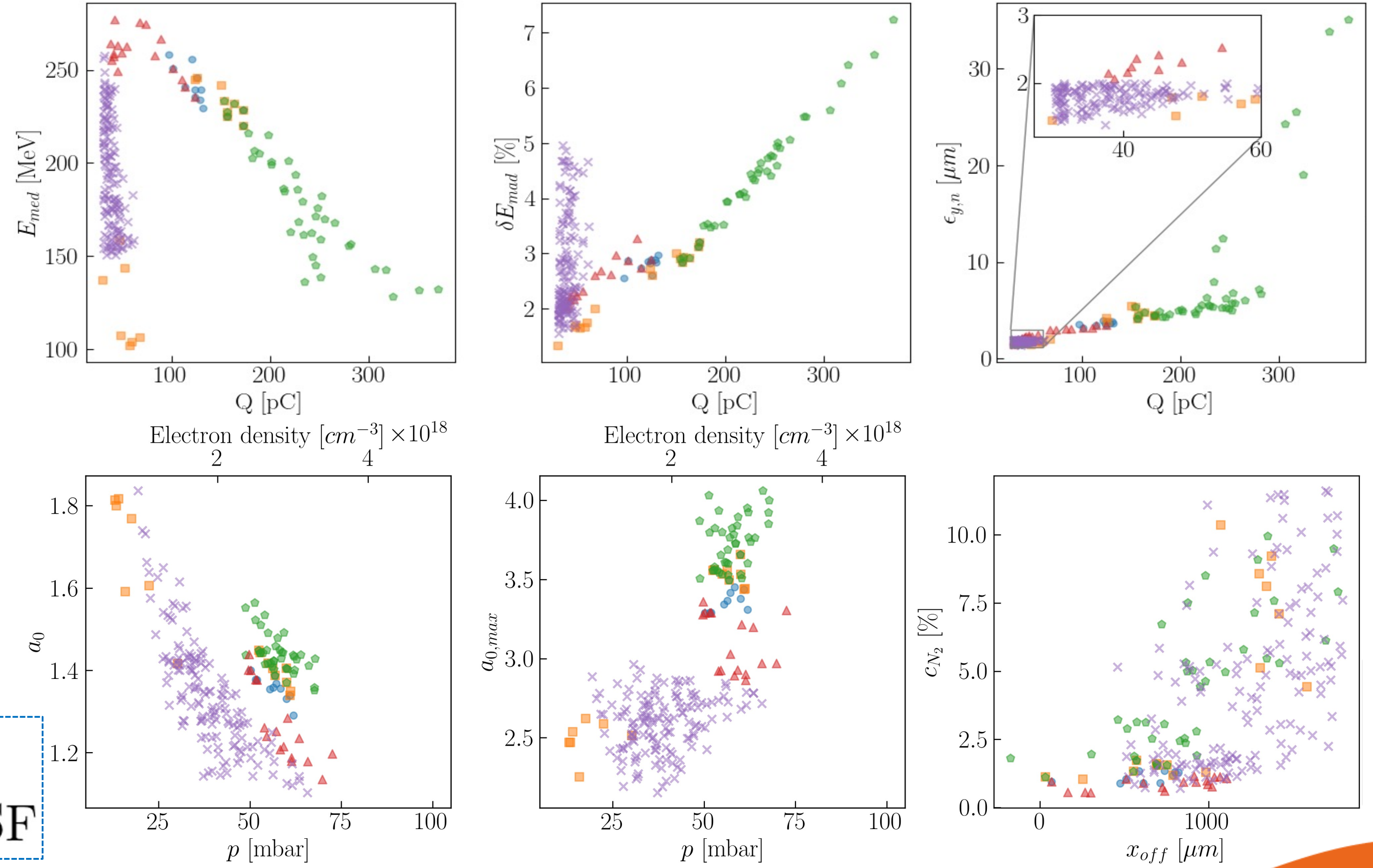
$$f_2 = \frac{E_{med} \sqrt{Q}}{\sigma_{mad}}$$ S2

$$f_3 = \frac{E_{med} Q}{\sigma_{mad}}$$ S3

$$f_4 = \frac{E_{med} Q}{\sigma_{mad} \sqrt{\epsilon_{y,n} \epsilon_{z,n}}}$$ S4

- Set = cut each *f* at 10% of their max.

In **Filter** = Q > 30 pC & E_{med} > 150 MeV & δE_{mad} < **5**% & $\epsilon_{y,n}$ < 2 μm SF



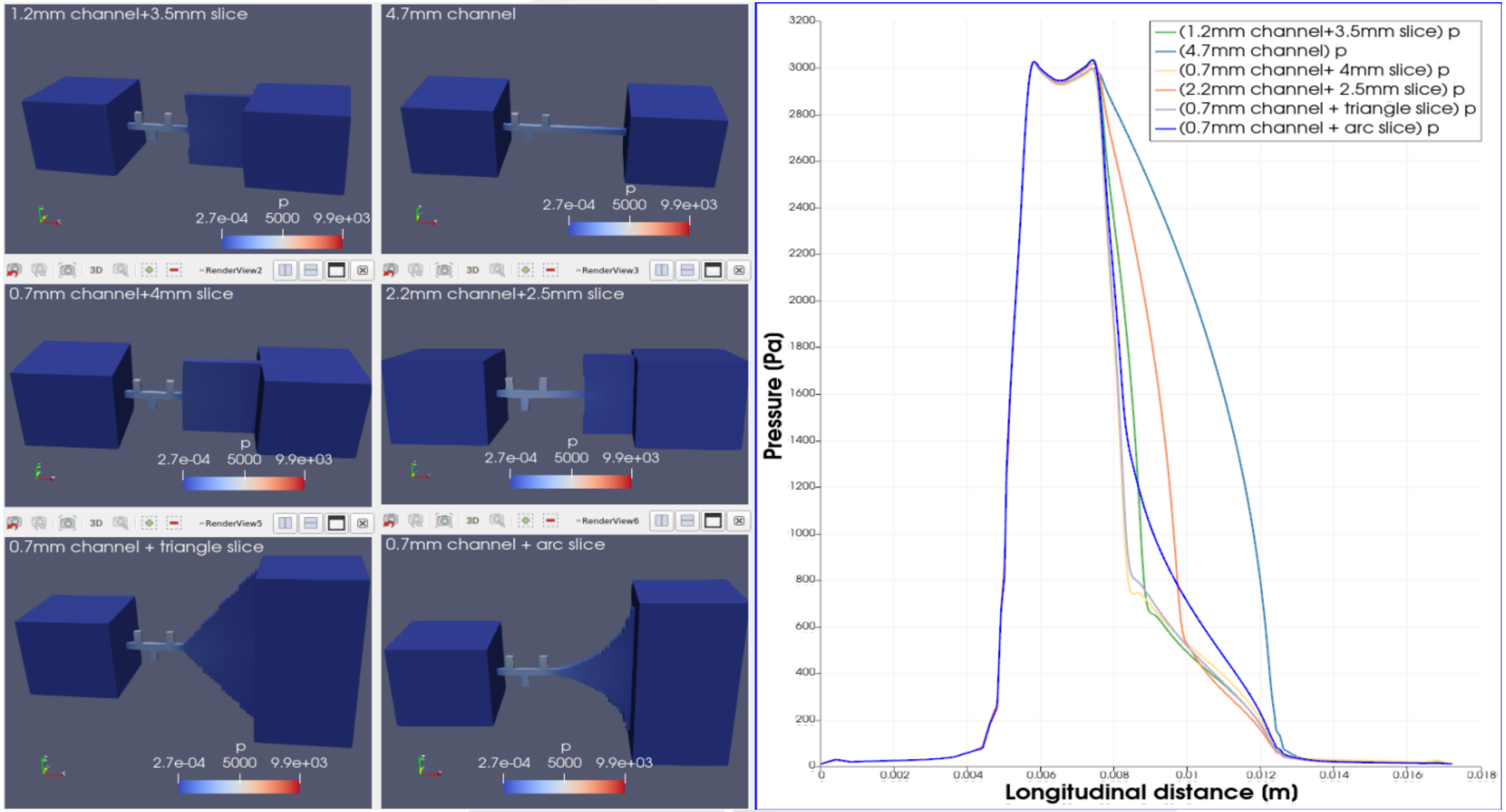
Sum-up

- Ability to generate density profile with fluid simulations
  - Fast meshing (few *s*)
  - Fast simulations (few *min*)
- Applied to massive PIC random scans
- Several beams found which satisfy **Filter** = $Q > 30$ pC & $E_{med} > 150$ MeV & $\delta E_{mad} < 5\%$ & $\varepsilon_{y,n} < 2$ µm
- PIC results open to scientific community

Next steps:

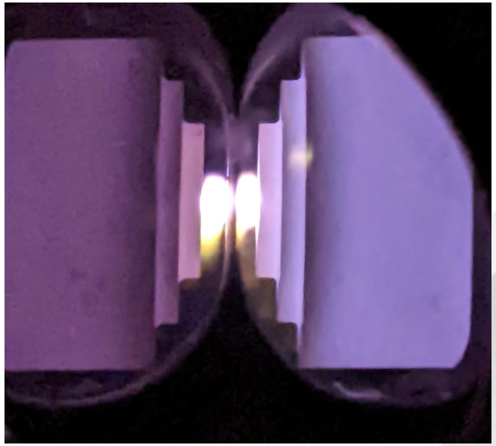
- Compare OpenFOAM results with other codes (Ansys Fluent) + check interface for diffusion
- Shape the plasma outramp…

Outramp optimisation to preserve emittance growth (already investigated in [1][2])

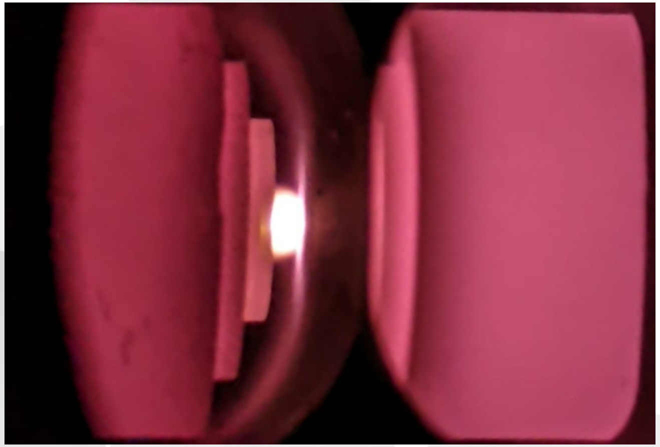


[1] Li, Xiangkun, Antoine Chancé, and Phu Anh Phi Nghiem. "Preserving emittance by matching out and matching in plasma wakefield acceleration stage." *PRAB* 22.2 (2019): 021304.
[2] Dornmair, Irene, K. Floettmann, and A. R. Maier. "Emittance conservation by tailored focusing profiles in a plasma accelerator." *PRSTAB* 18.4 (2015): 041302.

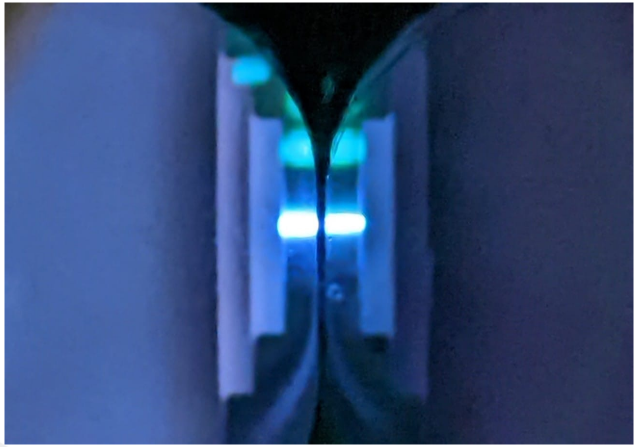
Thank you



Helium plasma
(with IR absorptive filter)



Helium plasma
(no IR absorptive filter)

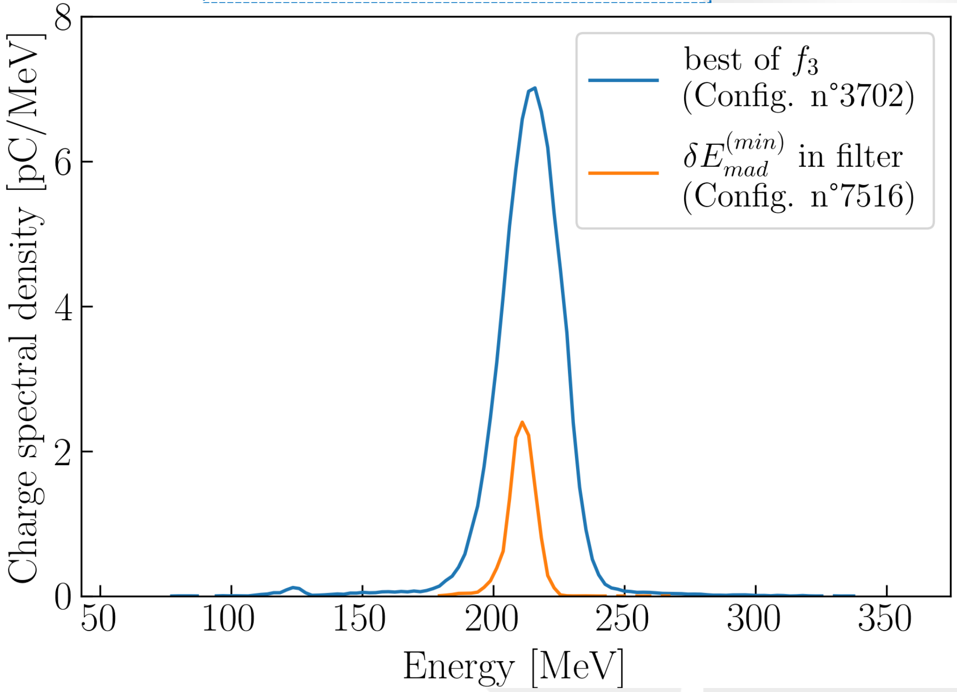


N_2 plasma
(with IR absorptive filter)

Merci

8. Stability study

We select 2 configurations



	Best of f_3 (high charge)	Lowest δE_{mad} in filter
N°	3702	7516
Scan origin	RS3	RS5
p [mbar]	58.6	47.8
a_0	1.43	1.23
X_{off} [µm]	558	1680
c_{N2} [%]	1.88	6.17
$a_{0,max}$	**3.73**	**2.58**
Q [pC]	**198**	**30**
E_{med} [MeV]	215	212
δE_{mad} [%]	3.53	1.55
$\varepsilon_{y,n}$ [µm]	5.03	1.74