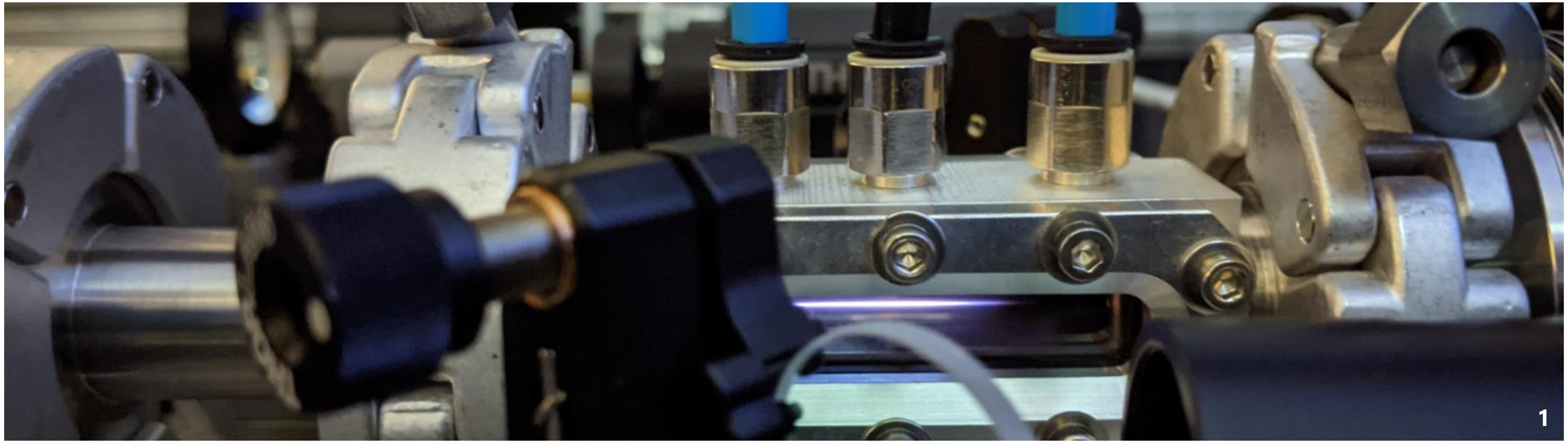
Development of a 150 MeV laser-plasma injector



Pierre Drobniak

Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

[1] developped in the frame of the ESCULAP project (N. Delerue, K. Wang, J. Jenzer et al.), used as a test cell [1]

[1] Baynard, E. *et al.* Status report of the ESCULAP project at Orsay: External injection of low energy electrons in a Plasma. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **909**, 46–48 (2018).

1. Explanation of the title
2. Why do we need accelerated electron bunches ?
3. What is the particularity of laser-plasma injection ?
4. Project and working principle
5. Present set-up
6. Plasma cell optimisation
7. Results
8. Conclusion and future developments

Development of a 150MeV laser-plasma injector

1) First stage of an **accelerator** (in our case an **electron** accelerator)

2) Technique used to **create** the **electron** bunch

3) Average energy of the bunch

$$E_c = (\gamma - 1)mc^2 \longrightarrow v = 99{,}9994\%\ c\ !$$

« Some » examples

Tool for Applied Research

- Medecine
  - Indirect use -> X-Ray source for radiotherapy in hospitals
  - Direct use -> Flash Therapy with fs beams [2]
- Free electron laser development
  - Indirect use as coherent X-Ray source [3]

Tool for Fundamental Research

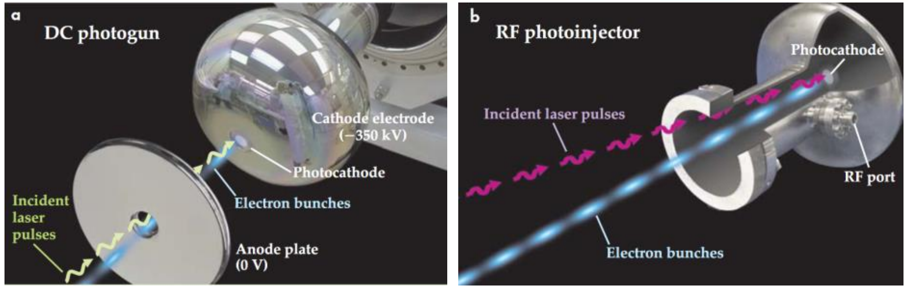
- Particle physics
- Accelerator physics
  - Driver for novel particle accelerators (e.g. Beam Driven Wakefield Acceleration [4])

[2] Moeckli R, Gonçalves Jorge P, Grilj V, Oesterle R, Cherbuin N, Bourhis J, Vozenin MC, Germond JF, Bochud F, Bailat C. Commissioning of an ultra-high dose rate pulsed electron beam medical LINAC for FLASH RT preclinical animal experiments and future clinical human protocols. Med Phys. 2021 Jun;48(6):3134-3142. doi: 10.1002/mp.14885. Epub 2021 May 14. PMID: 33866565.
[3] https://www.xfel.eu/
[4] https://home.cern/fr/science/awake

3. What is the particularity of laser-plasma injection ?

Conventional electron injection = use of **photoelectric** effect …

in our case: **ionisation** injection in a **plasma** using a **laser source**



Photoemission using DC and RF electron sources [5]

Advantages:

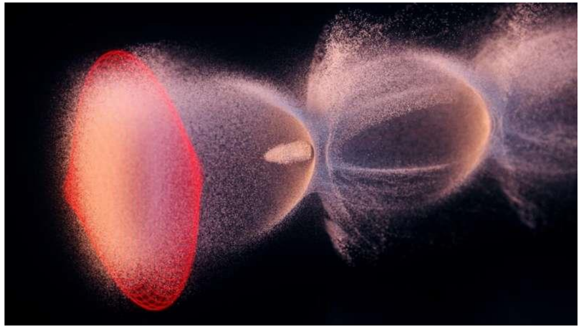
- **High accelerating gradients**

~ 100 GV/m > 100 MV/m (Radio-frequency accelerators)

- **Compactness of the device**

Few millimeter < several meters (conventional LINACs)
-> reduction by a factor of 1 000 !
-> lower radio protection cost

- **Very short in time electrons bunches (high peak current)**



Example of laser-plasma injection [6]

[5] Hernandez-Garcia, Carlos, Patrick G. O Shea, and Marcy L. Stutzman. "Electron sources for accelerators." Physics today 61.2 (2008): 44.
[6] https://scx1.b-cdn.net/csz/news/800a/2021/plasma-acceleration-it.jpg

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cnrs IN2P3 — université PARIS-SACLAY — FACULTÉ DES SCIENCES D'ORSAY — Université de Paris

Laboratory project

Stability at 10 Hz

Plasma Cell design

PALLAS

Beam transport -> multi-stage

high quality electron beam

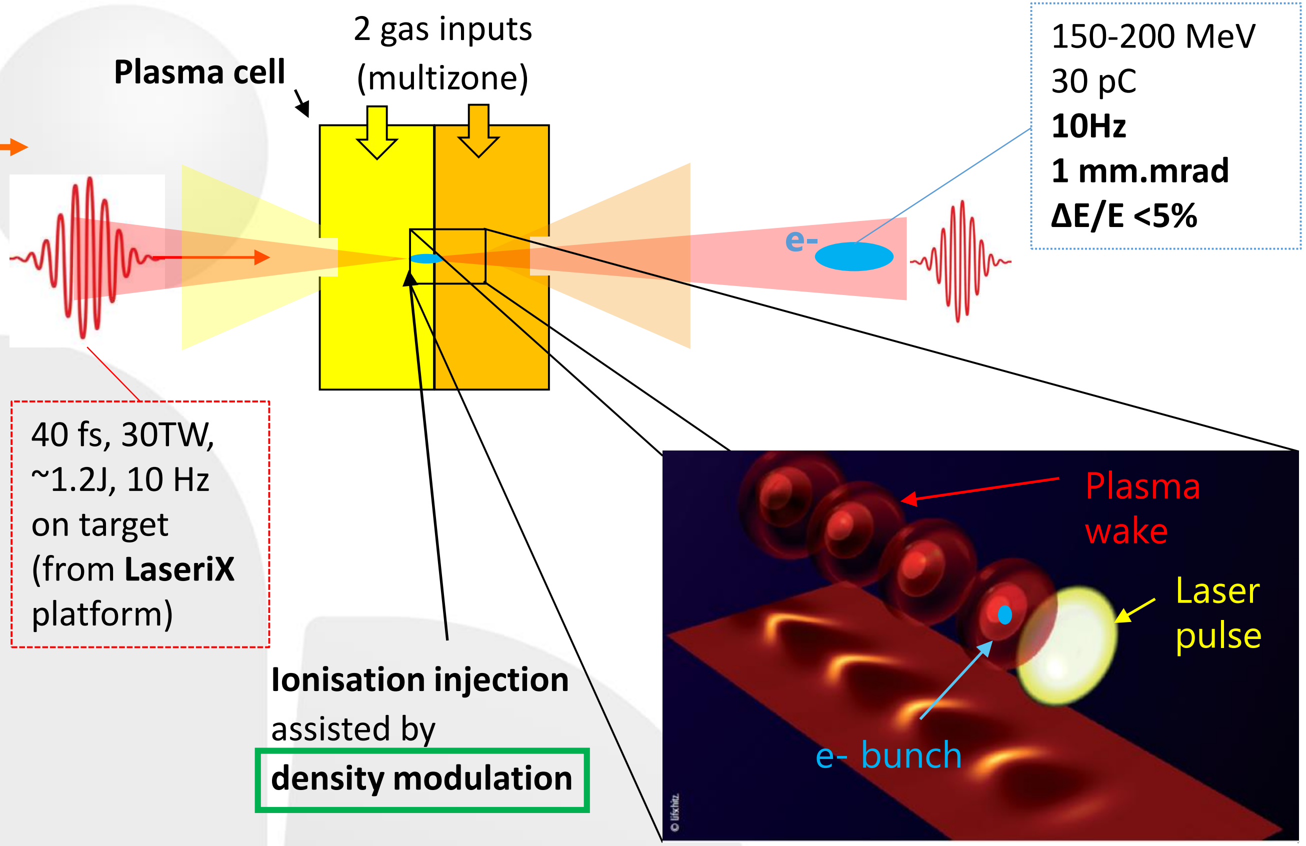
Prototyping **A**ccelerator based on **L**aser-p**LAS**ma technology

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

EuPRAXIA

https://pallas.ijclab.in2p3.fr/
http://www.eupraxia-project.eu/

Plasma Cell design

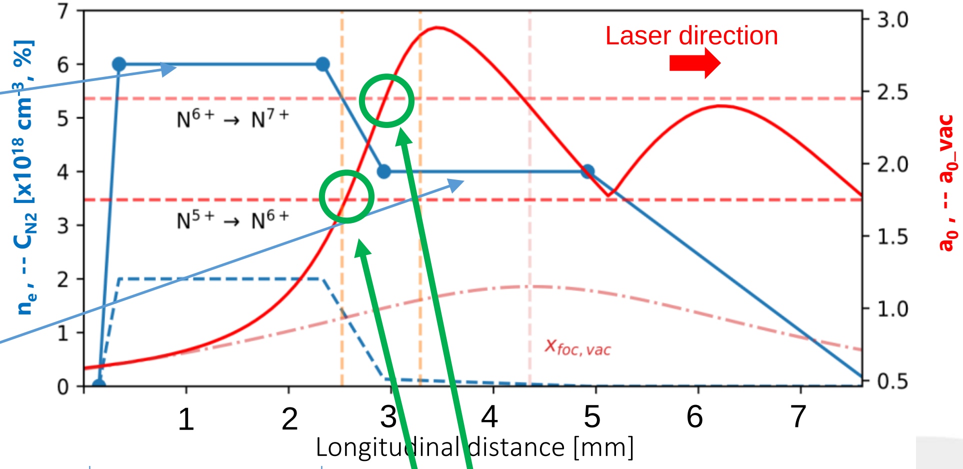


Laser **W**ake **F**ield **A**cceleration **(LWFA)** [7]

[7] Malka et Al. (2013). Accélérateurs à plasma laser: principes et applications. *Reflets de la physique*, (33), 23-26.

4. Project and working principle

Electronic density profile and PIC (Particle-In-Cell) simulated laser



1st plateau

2nd plateau

Zone 1

Injection zone

Zone 2

a0 high enough to « peel » the two last electrons of N2

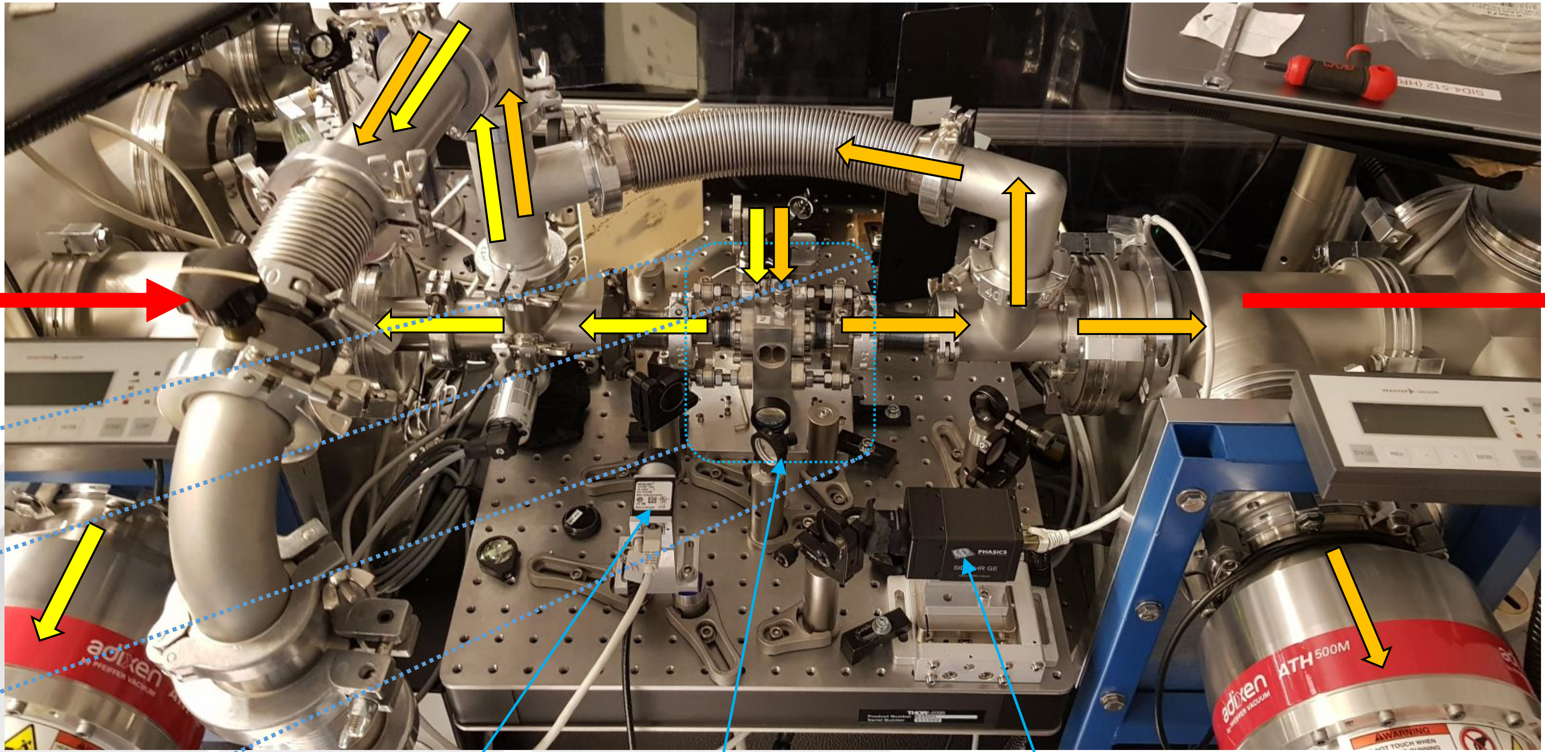
Zone 1: laser autofocalisation + plasma wave electrons from Helium and 5 first levels of N2.

Between 1 and 2: injection of the two last electrons of N2 in the plasma wave

Zone 2: energy filter and acceleration

5. Present set-up

Gas 1	Gas 2	Laser



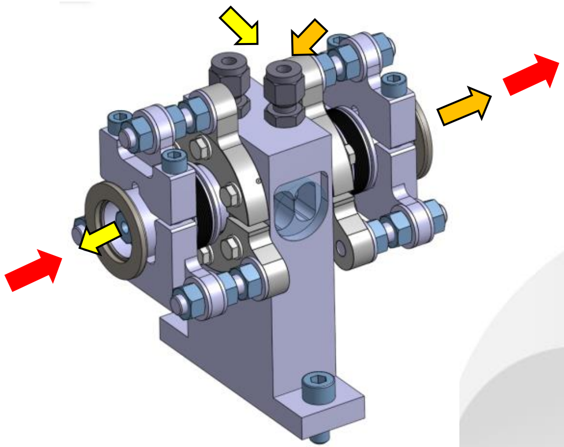
Camera

Plasma cell

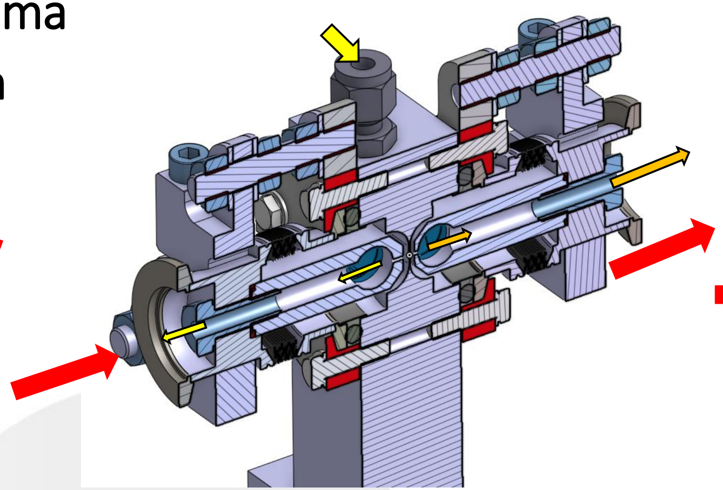
Wavefront sensor

N2 plasma, at 20mbar, 60mJ, 40fs

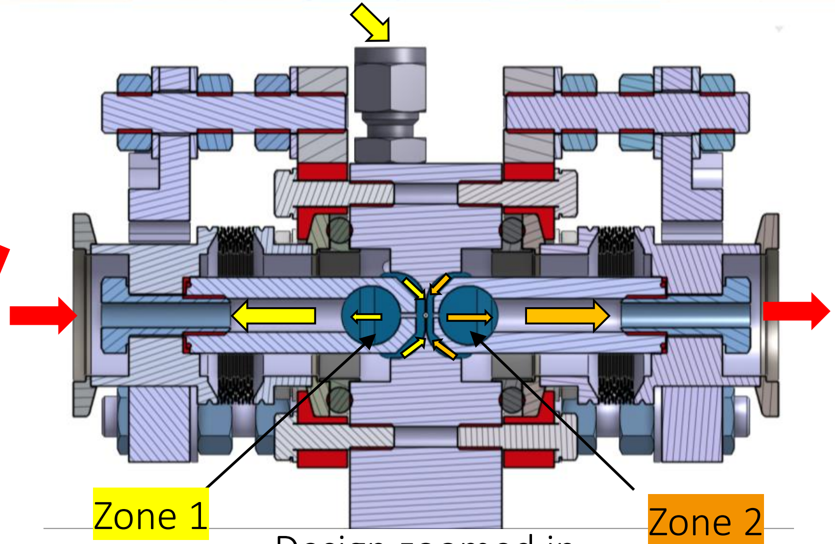
Latest Plasma Cell design



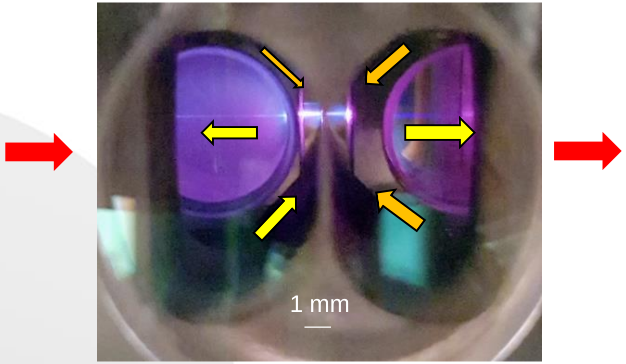
Two-gas prototype



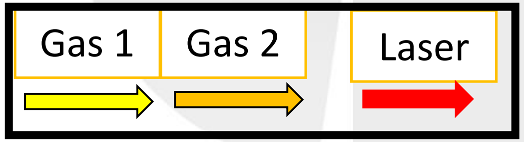
Longitudinal cut



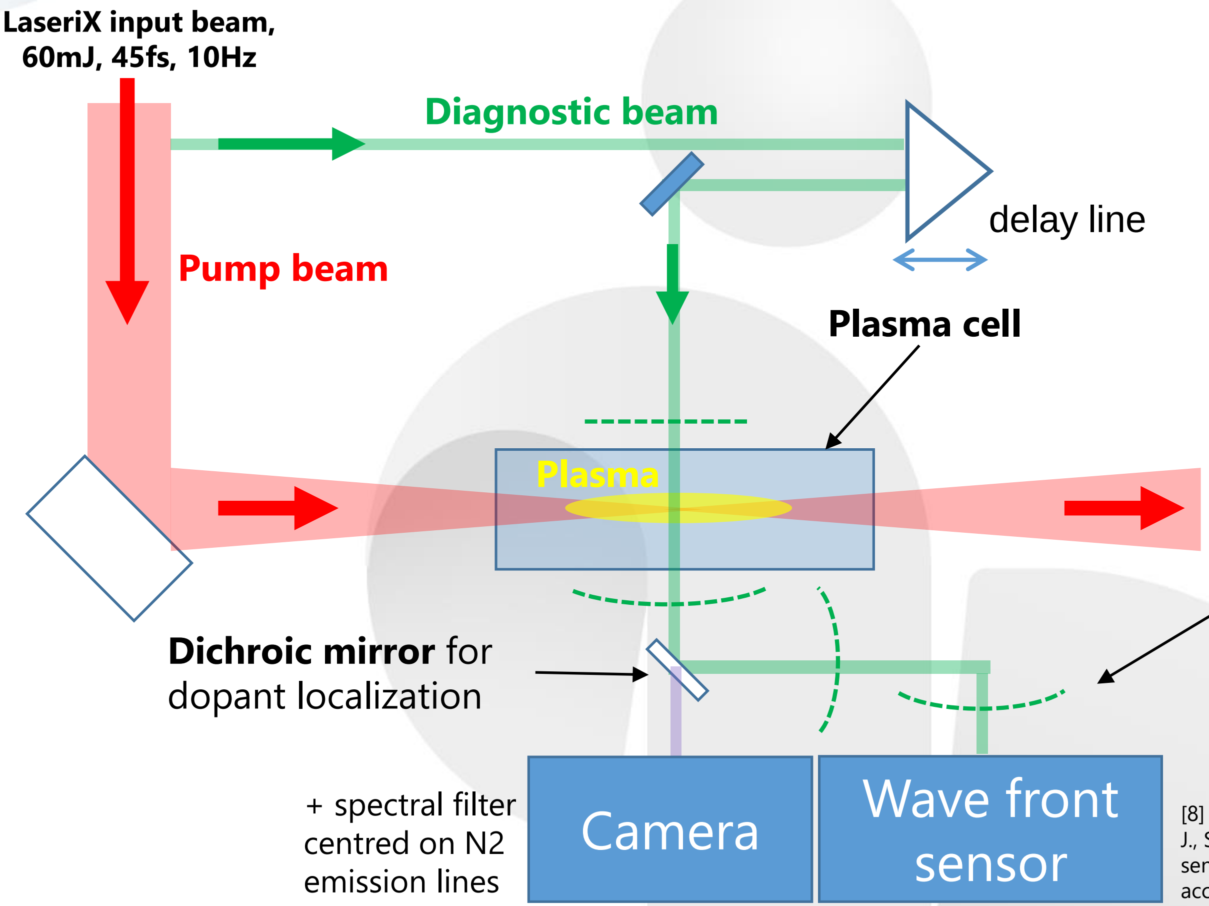
Design zoomed in



Actual cell zoomed in



Set-up scheme



Plasma induced **phase shift** in the diagnostic beam wave front

$$\phi(x,y)=\omega/c\int(1-\sqrt{1-n_e(x,y)/n_c(\omega)})dl$$

Reconstruction of the **absolute phase shift** (Abel inversion)

$$\Phi(x,r)=-1/\pi\int_r^R\partial\phi(x,y)/\partial y\cdot(y^2-r^2)^{-1/2}dy$$

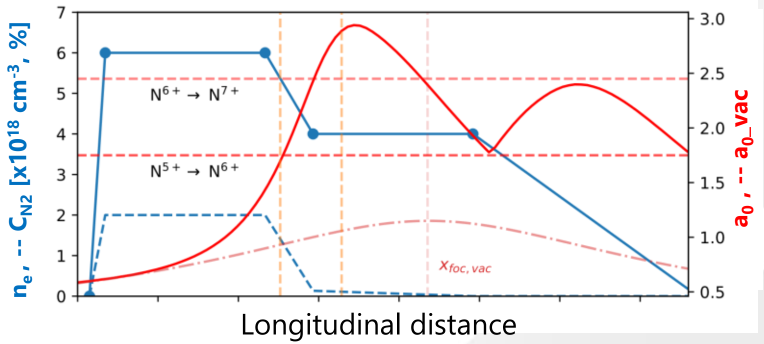
Reconstruction of the **plasma density**

$$n_e(x,r)=n_c(\omega)\{1-[1-c/\omega\cdot\Phi(x,r)]^2\}$$

[8]

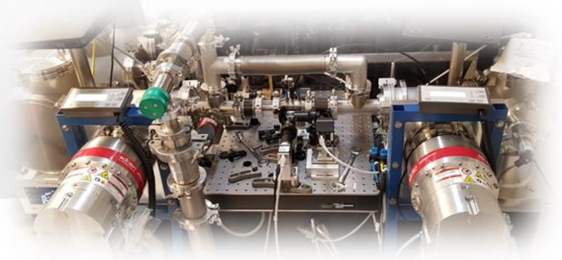
[8] Plateau, G. R., Matlis, N. H., Geddes, C. G. R., Gonsalves, A. J., Shiraishi, S., Lin, C., ... & Leemans, W. P. (2010). Wavefront-sensor-based electron density measurements for laser-plasma accelerators. *Review of Scientific Instruments*, *81*(3), 033108.

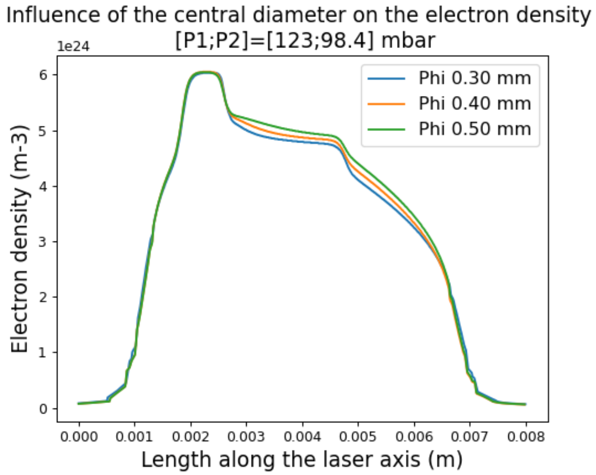
Theoretical profile and PIC simulated laser variation



Smilei [9]

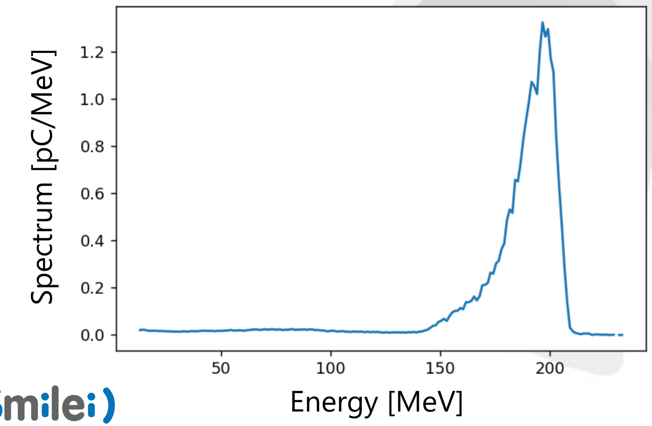
Experimental qualification on test bench



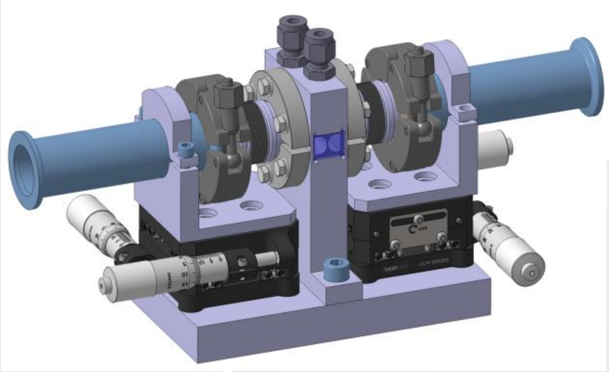


OpenFOAM-simulated electronic density

OpenFOAM® [10]



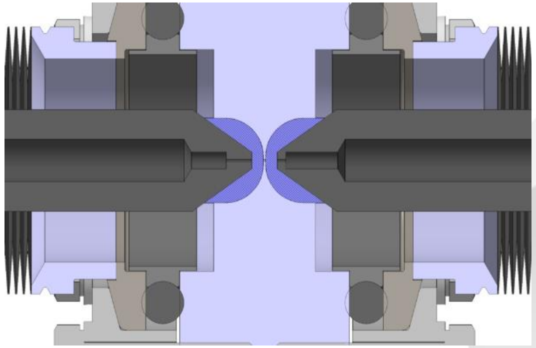
Smilei



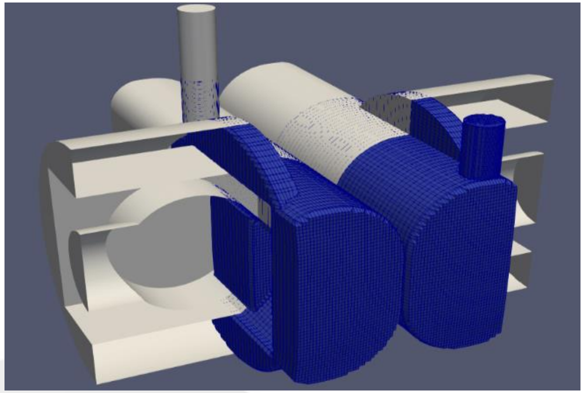
Cell design

[9] https://smileipic.github.io/Smilei/
[10] https://www.openfoam.com/

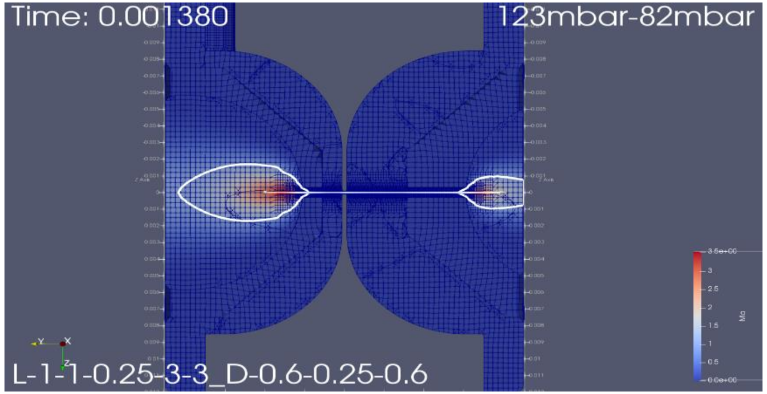
CFD simulations
Open∇FOAM®



1. Design zoomed in

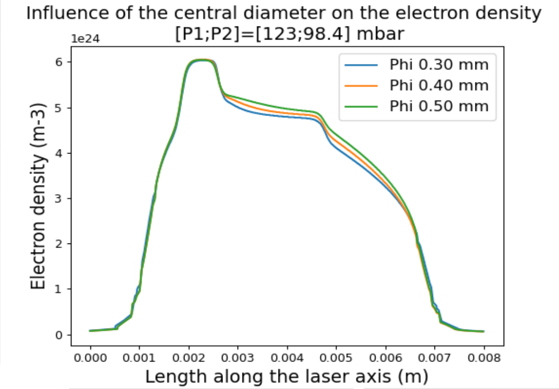


2. Automatic meshing (snappyHexMesh utility)



3. Compressible flow simulation

- 200 000 cells
- Optimized mesh
- Compressible simulation
- 1 processor
- 1 hour simulation (with optimized geometry)



4. Gas density plot along propagation axis

Particle-In-Cell (PIC) plasma simulations with Bayesian Optimization

Smilei)

Sim. characteristics:

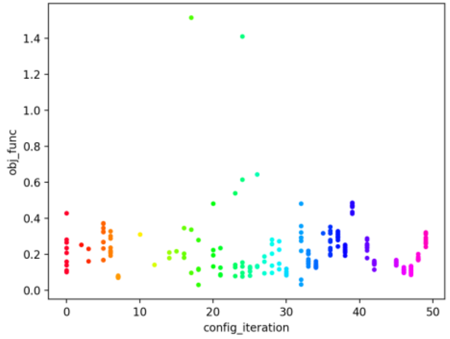
- Sim. time: **2,5h** (large window + density distribution length 12mm) -> **80 µm/min**
- **Total**: approx. 50 x 2,5h = **125h** = 5 days
- Size: 30 GB per sim

Comments:

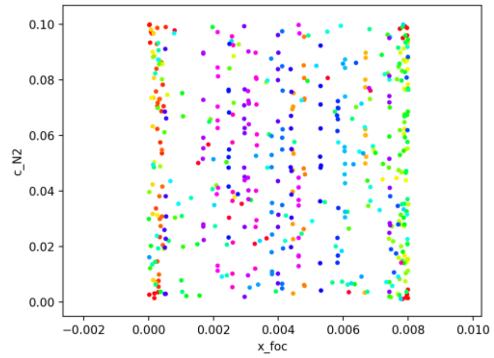
- Higher a0 -> higher charge
- **Broad search**

	x_foc	c_N2	a_0	q_end	E_mean	E_med	E_std	E_peak	emit_y	emit_z	dQdE_max	obj1
172	0.006160	0.026470	1.317068	24.358028	272.817961	271.015189	10.788528	271.854592	3.134120	1.489322	0.782828	1.516903
243	0.006132	0.032520	1.341563	33.773650	257.560331	256.827345	11.074599	259.694592	4.903707	2.571796	0.893735	1.411860
269	0.005758	0.020192	1.044194	4.036363	285.346130	288.922249	7.566086	293.742592	1.157413	0.266049	0.123687	0.644761
242	0.006270	0.066085	1.341438	17.800926	300.059452	293.944101	15.117617	288.878592	3.836440	2.037670	0.272049	0.616445
235	0.005738	0.068639	0.991944	0.952936	292.626316	293.791617	3.637747	293.742592	5.642029	2.365243	0.052928	0.539945

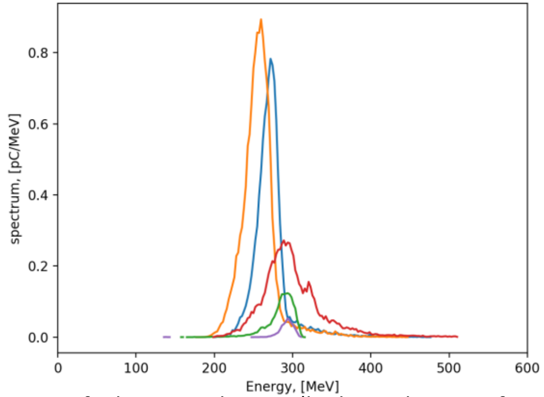
$$\text{obj1} = \frac{q\,E_{med}}{E_{mad}}$$



Objective function distribution after each iteration



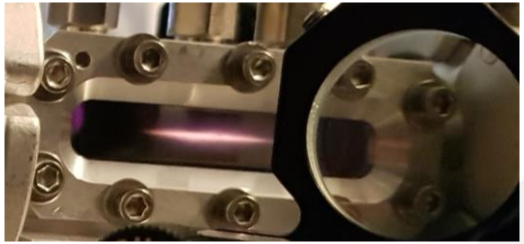
2D view (cN2,xfoc) of parameter search



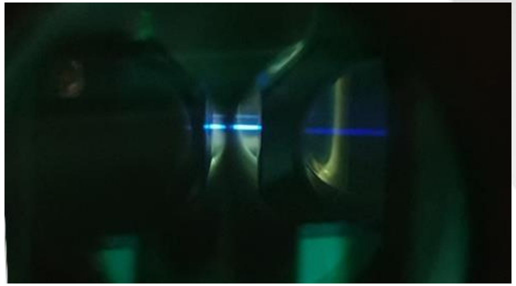
Spectrum of 5 best simulations (highest objective function)

Experimental

1) Plasma ignition for Helium and Nitrogen, using different plasma cells

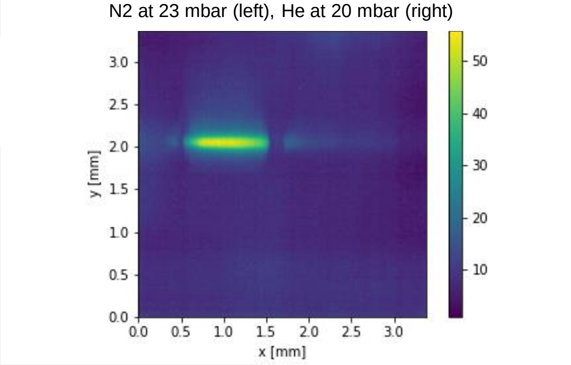


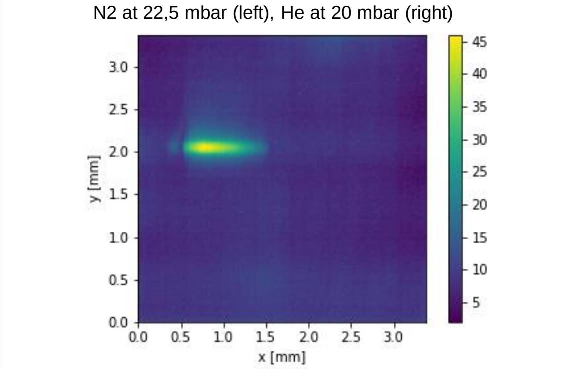
He plasma, at 15mbar (1 chamber cell)



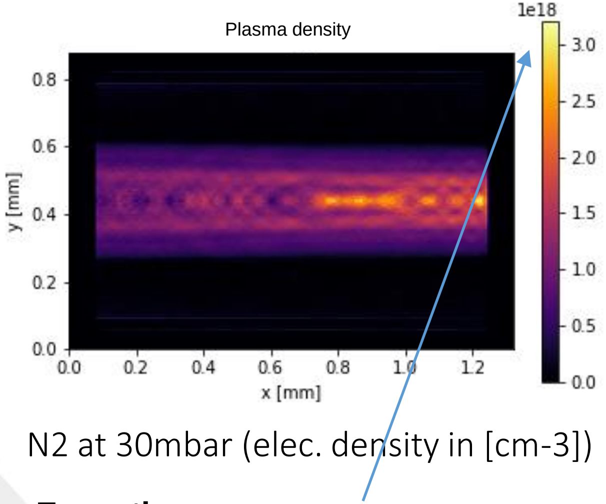
N2 plasma, at 20mbar (2 chamber cell)

2) Confinement of N2





3) Measurement of plasma density



N2 at 30mbar (elec. density in [cm-3])

Expecting:

- 7,5 e18 (if 5 1st levels ionised)

-> autofocalisation too strong + non gaussian beam

Conclusion

- **PIC-Simulation**: I am now able to perform numerical simulations of my future experiments.
- **Fluid simulations:** running well and yielding interesting results (but not calibrated with real measurement yet!)
- **Set-up**: continuously being upgraded. Hard to understand
  - the autofocalisation strength
  - the effective laser parameters
- Most results so far are very qualitative -> need for more quantitative results

Future development

- **Simulations**:
  - PIC-Simulations, using Bayesian Optimisation and realistic laser profile (Flattened Gaussian Beam)
  - Calibrate fluid simulations with experimental data

- **Experiment**:
  - Test new plasma nozzles
  - Understand the autofocalisation caused by gas leak
  - Implement new diagnostics (imaging spectrometer for plasma)
  - Automation of the pressure record
  - Implementation of a more complete injection system (gas mixture)

Thank you

And many thanks to

Kevin CASSOU, Viacheslav KUBYTSKYI, Sophie KAZAMIAS, Bruno LUCAS, Yann PEINAUD, Moana PITTMAN, Elsa BAYNARD, Julien DEMAILLY, Alexandre GONNIN, Stéphane JENZER