PALLAS project development status

laser-plasma injector test facility

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on behalf ot the team

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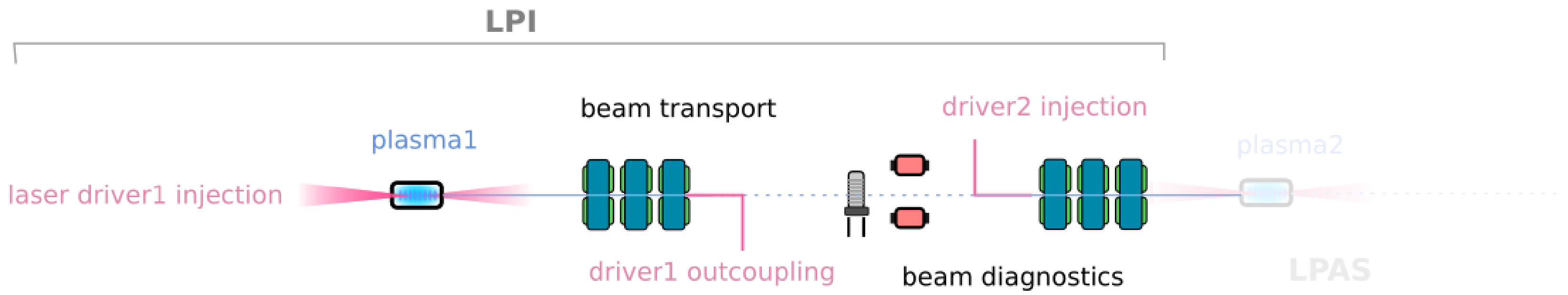
PALLAS project

Objectives

Build a laser-plasma **accelerator test facility** aiming to achieve **reliability** and **control** comparable to conventional **RF accelerator** standards.

Push **technological development** starting with a **10 Hz** 150-250 MeV *"high-quality beam"* **laser-plasma injector** (**LPI**) prototype for staging to high energy



Research and development lines :

1. advanced **laser control**
2. development of **plasma targetry**
3. electron **beam control and transport**

Achieved fully optimized and controlled LPI operating at 10Hz with a scalability to higher repetition rate

First brick of a more ambitious beamline with second plasma stage (LPAS) or applications

PALLAS : Electron beam parameters

Staged effort:

- **phase 1**: laser optimization & control, **target**
  first electron characterization
- **phase 2**: laser and beamline upgrade
  electron beam optimization
- **phase 3**: transport beamline
  full LPI optimization

EuPRAXIA parameters for technical design study [1]

continuous 10 Hz beam to enable machine studies

Parameters	phase 1	phase 2	phase 3	unit
energy	150	**200**	200	MeV
charge	15-30	**30**	**30**	pC
frep	10	10	10	Hz
energy spread	<5%	**< 5%**	**< 2%**	peak (std)
ε_n^{rms}	1	**<1**	?	μm
stability	5%	**3%**	**1%**	-
reproducibility	5%	**3%**	3%	-

Nota bene : **value phase 3** are considered at the virtual entrance of a second laser-plasma accelerating stage.

[1] R. Assmann, 'EuPRAXIA Conceptual Design Report', Hamburg, 2019. [Online]. Available: https://desycloud.desy.de/index.php/s/X37pwaJxEGi2God.

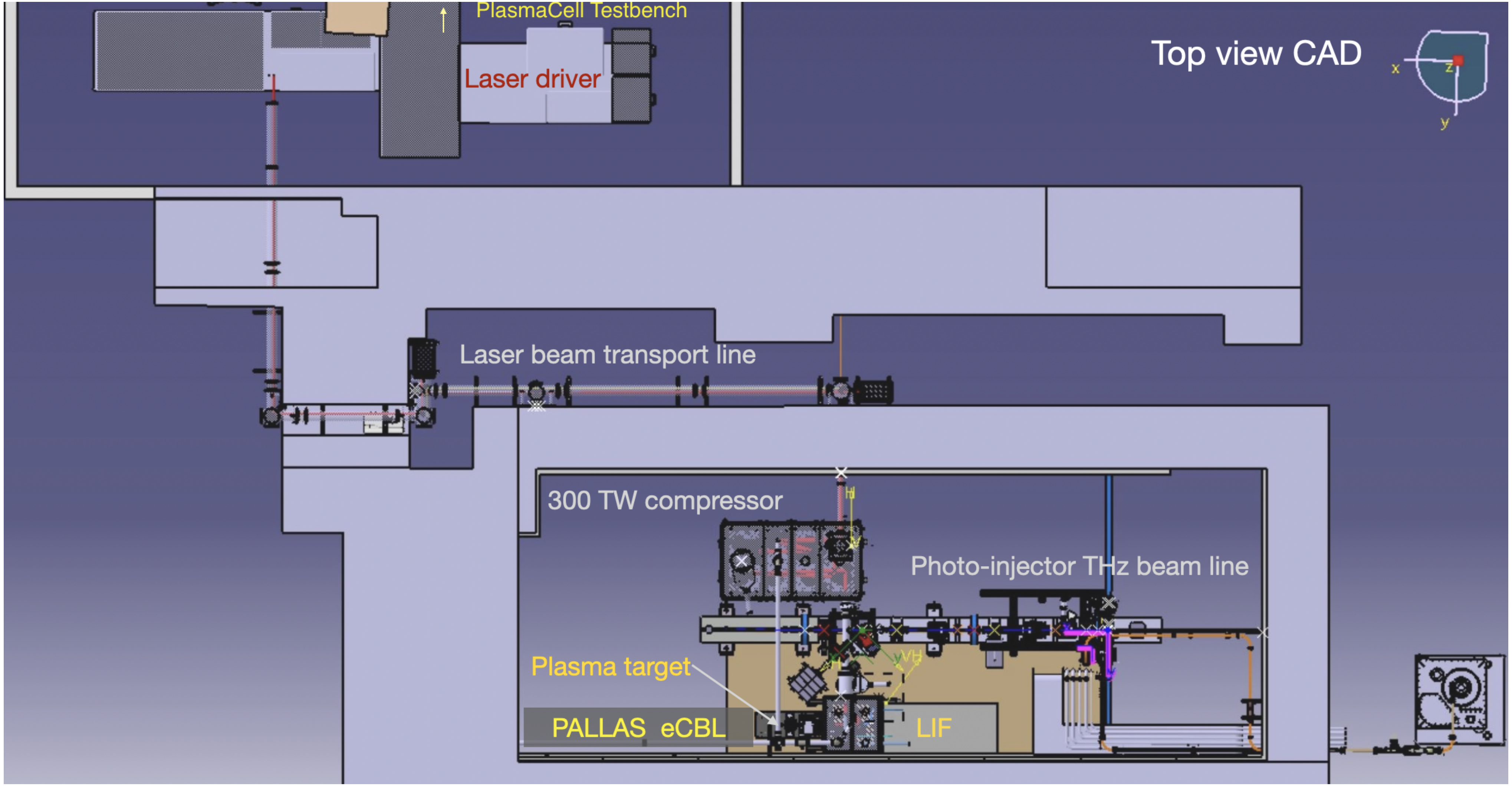
PALLAS : LPI source parameters

Configuration of the LPI : laser driver (40-50 TW), plasma, ...

Parameters	phase 1	phase 2	phase 3	unit
laser strengh, a_0	1.15-1.4	1.15-1.4	**>1.8**	
laser duration, t_L	40	**30**	**30**	fs (FWHM)
laser waist, w_0	18	18	18	um
Strehl ratio, S_r	**> 0.8**	**> 0.8**	**> 0.8**	-
beam pointing, δu_i	**<0.5**	**<0.5**	**<0.5**	urad
stability	1%	**<1%**	**<1%**	-
frep	10	10	10	Hz
target type	multi-cell	multi-cell	multi-cell	-
injection	ionisation	ionisation	ionisation	-
electron beamline	*CL1*	*CL1*	*TBD*	-

STII : Self truncated injection / downramp assisted ionization injection to be optimized
CL1 : characterization beamline.
TBD : to be defined.

PALLAS installation overview



Plasma target

Plasma target for LWFA

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Characteristics length of a plasma target for LPI ($10^{17} \leq n_e \leq 10^{19}$ cm $^{-3}$) :

- Rayleigh length of the laser $\rightarrow$ $Z_r = \pi w_0^2/\lambda_0 \sim 1.3$ mm
- Plasma wavelength $\rightarrow$ $\lambda_p \approx 10 - 30\,\mu m$
- Betatron wavelength $\rightarrow$ $\lambda_\beta = \sqrt{2\gamma_e}\lambda_p \sim 250 - 800\,\mu m$

with laser a laser having $\lambda_0 = 0.8\,\mu$m and $w_0 = 19\,\mu$m

Tailoring gas species density profiles

- **to control injection** : localized ionization injection [1,2]
- **tune** the injected **charge / beam loading** [3]

Tailoring plasma density profile:

- **tune** e- **beam energy** / acceleration length
- **limit emittance growth** at the exit of the plasma / minimized Twiss parameters

$\Rightarrow$ Control of the exit down ramp is crucial ! [4]

... in only few mm

[1] M. Zeng, et al., Physics of Plasmas, **21**, 3, p. 030701,(2014). [2] J. P. Couperus, et al., , Nat Commun, **8**,1, p. 487,(2017),

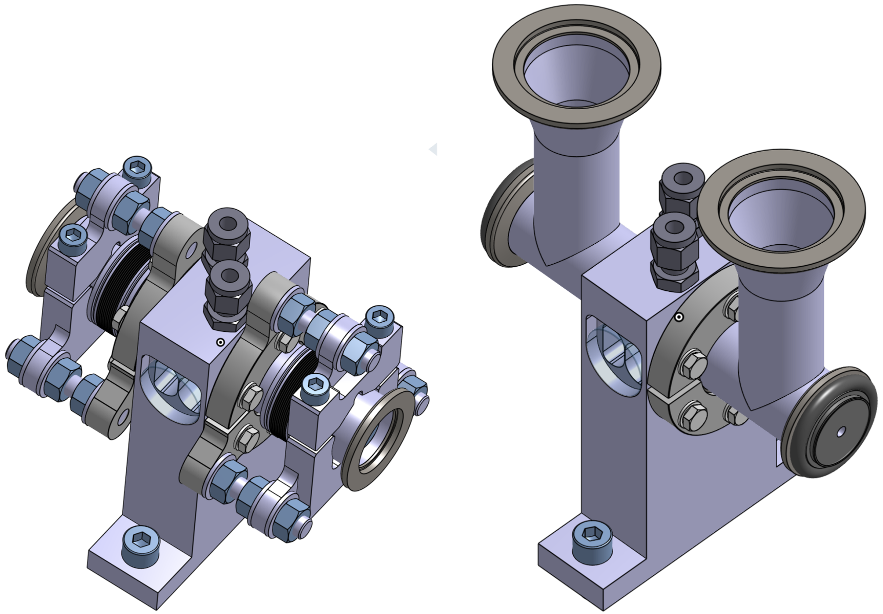
[3] P. Lee, et al., Phys. Rev. Accel. Beams, **21**,5, 052802, (2018), M. Kirchen et al., "Optimal Beam Loading in a Laser-Plasma Accelerator," Phys. Rev. Lett., **126**,17, p.174801, (2021)

[4] M. Migliorati, et al., Phys. Rev. ST Accel. Beams, **16**,1, p. 011302, (2013); X. Li,et al.,Phys. Rev. Accel. Beams, **22**, 2, p. 021304, (2019).

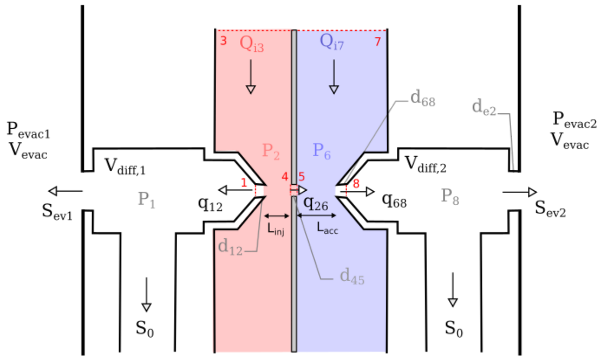
Plasma target design approach

prototype requirements

1. divide in region / process
    - localized High-Z gas dopant ✓
    - tune independently pressure ✗
2. customizable parts (nozzle in/out, central body) ✓
3. removable wear parts with high LIDT
4. stable density profile ($\delta n_e < 1$ %)✓
5. integrated in the beamline[1] ✓
6. compact (*10x10x15* cm^3) ✓
7. transverse optical access for plasma diags ✓
8. scalability to high average power operation

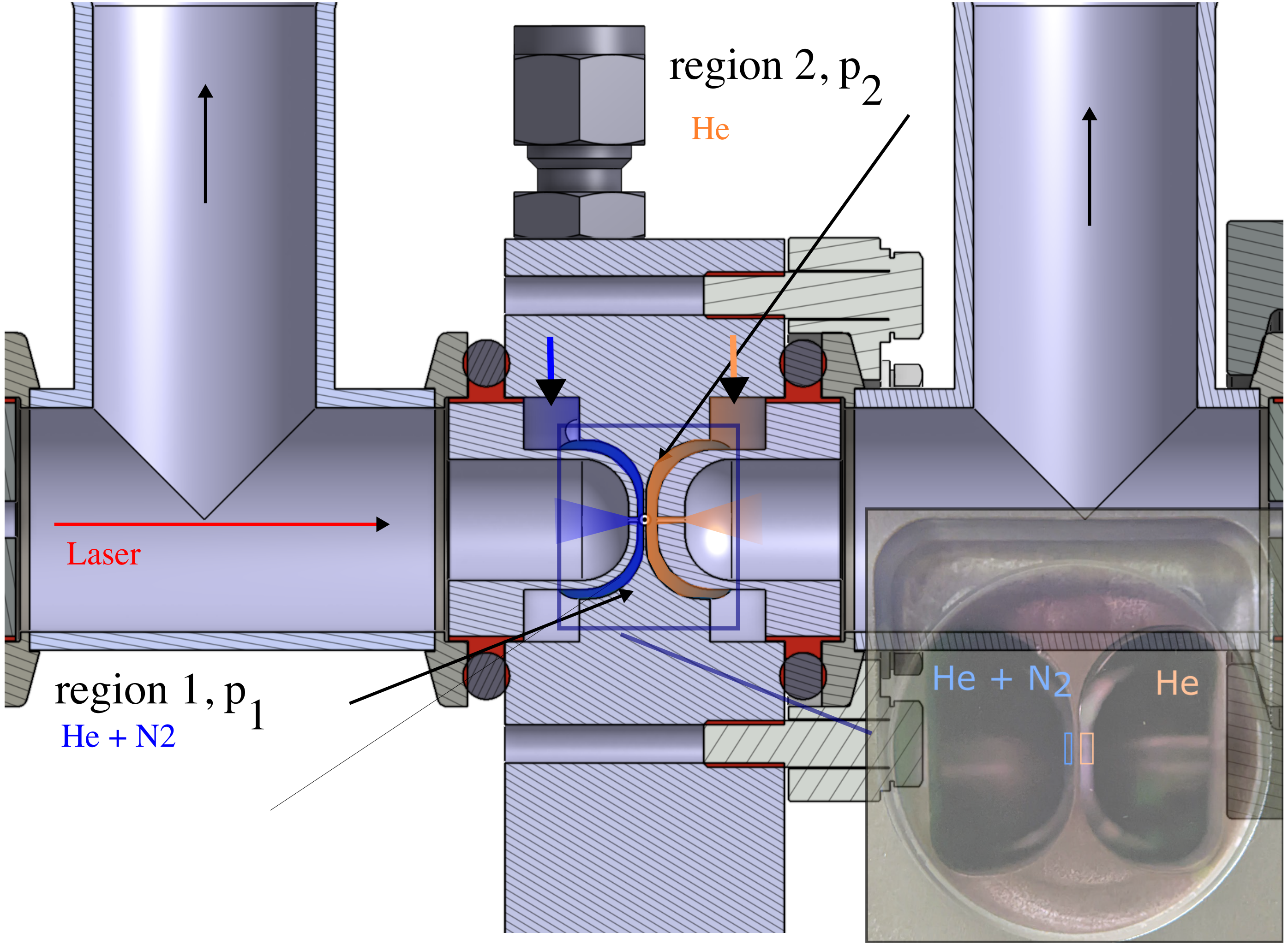


=> slab of gas approach in multi-cell arrangement



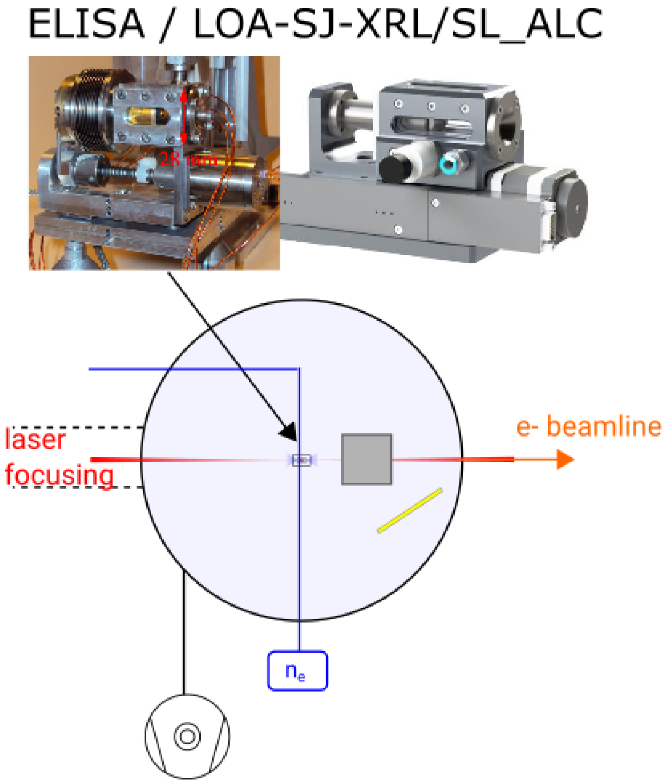
[1]: design inspired from experience from previous project:
K. Wang, PhD, 2019 in ESCULAP project N. Delerue, E. Baynard et al, NIMA, vol. 909, p.46, 2018.

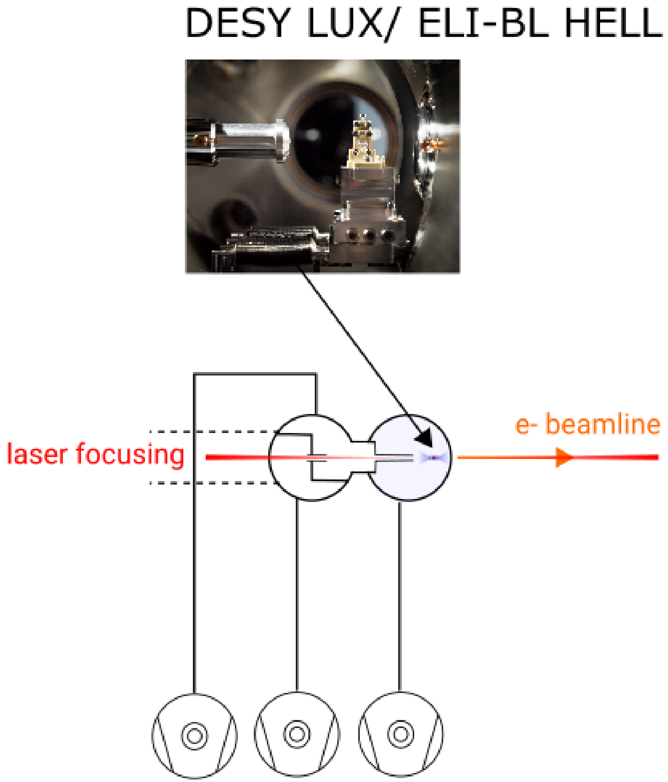
PALLAS current prototype

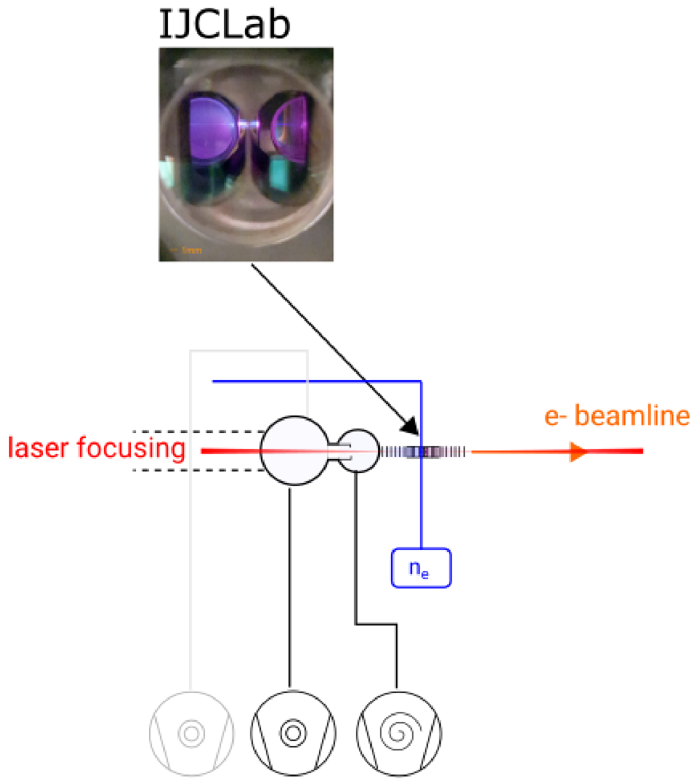


Plasma target : beamline integration

- Various configurations exists for plasma target gas-cell type integration :





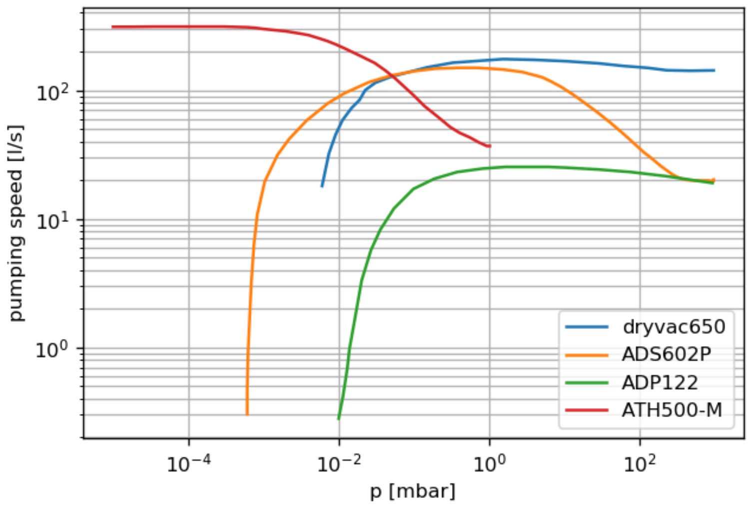


- ... and local evacuation for high pressure operation gas operation, kHz regime at LOA [1] and 10 Hz operation gas jet at DESY [2] see S.Bolen presentation link

[1] J. Faure, slides IFAST 2022
[2] S. Bolen *et al.* PRAB 2022 10.1103/PhysRevAccelBeams.25.031301

Plasma target: gas flow and vacuum

- In continuous flow, flow rate are typically : $5 < q_{ij} < 30$ mbar.l/s
- Flow rates depend on cell aperture : $300 < d_{ij} < 1000$ um
- Match pump pumping speed to pressure stages :



- Allow a decrease by 2-3 order of magnitude the pressure at the entrance ant output of the target
- Support high flow and 10^{-4} mbar (depending on turbo molecular pump type) after < 20 cm in the pipe

Optimization of the LPI plasma target

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Input

- a lot of bibliography [1]
- **laser parameters** in vacuum (a_0,t_0,w_0,x_0) [2]
- **plasma target**: continuous laminar flow gas cell $\Rightarrow n_e(x) \propto$ cell geometry + Q_i gas flow

Fast PIC simulations

CAD cell design integration

CFD Openfoam / snappyHexmesh couple to CAD

prototype experimental characterization on dedicated testbench ...[⚠ validation on LD?]

all the ingredient for a **almost full optimization** of the plasma target ...

see Pierre Drobniak Poster

[1] figure 3 of M. C. Downer et al. “Diagnostics for plasma-based electron accelerators,” Rev. Mod. Phys.,**90**,3, p. 035002,(2018) is a good start even if good points are now missing ...

[2] in phase 1 : limited to $a_0 = 1.35 \pm 0.2$ and $\tau_L = 35 \pm 3$ fs (FWHM)

Fast PIC simulations for target configuration optimization

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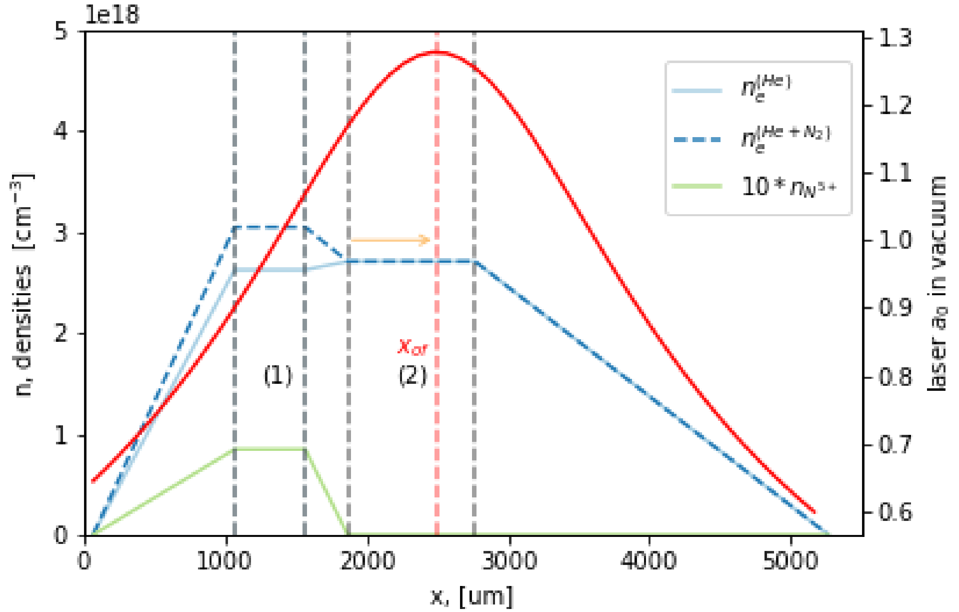
Numerical setup

- target configuration $x = [\, a_0, x_{of}, p_1 = p_2, c_{N_2} \,]$
- Smilei) open source PIC code with envelop approximation coupled to ionization[1], azimuthal modes[2] and low ppc :
  ~ **12-24 h.cores/mm**.(*running with 240 cores on 96k computing-core HPC SKL*)
- simplified profiles from CFD simulations and confined high-Z dopant.



Two types of complementary approach:

- **random scan**
- bayesian optimization

https://smileipic.github.io/Smilei/

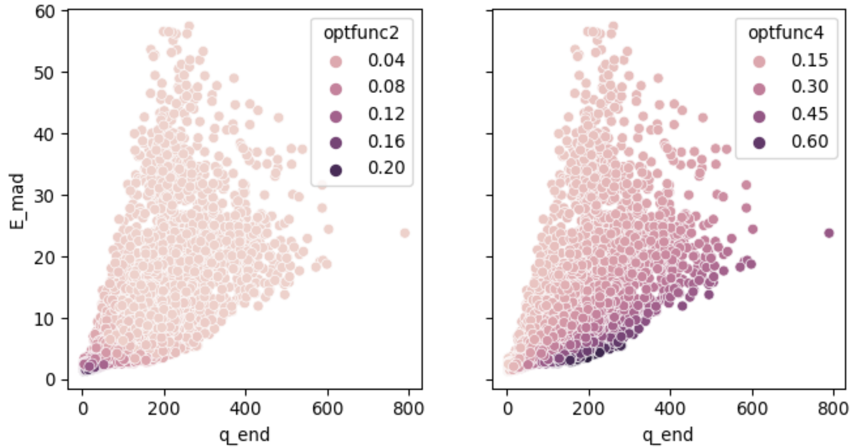
[1]: F. Massimo, et al. “Efficient cylindrical envelope modeling for laser wakefield acceleration,” J. Phys.: Conf. Ser., **1596**,012055, (2020)

[2]: I. Zemzemi, F. Massimo, and A. Beck, “Azimuthal decomposition study of a realistic laser profile for efficient modeling of Laser WakeField Acceleration,” arXiv:2001.04771 (2020)

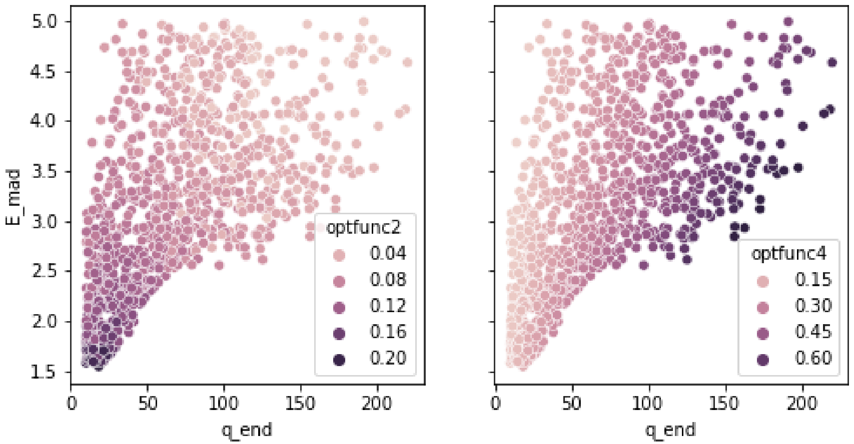
Fast PIC random scan (1)

- 4800 configuration simulations
- Injection rate: 73%;
- Some example of objectives functions: $f_2^{opt} \propto E^2\sqrt{q}/(\sigma_E^{mad}\cdot\epsilon_n^{rms})$, $f_4^{opt} \propto \sqrt{q}\cdot E/\sigma_E^{mad}$ [1,2]

`full data set`



`.query(E_peak>150 and q_end> 10 and E_mad<5)`

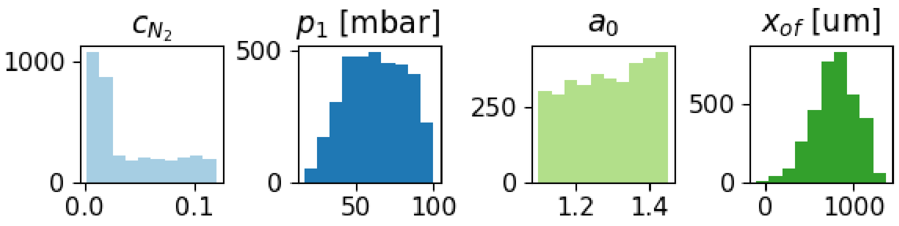


❗ triplet optimization ($\sigma_E, \epsilon_{n,rms}, q$)

Various approach already possible considering the *"complete"* source optimization including beam dynamics with high quality beam at the start or cleaning high-spectral brightness beams.

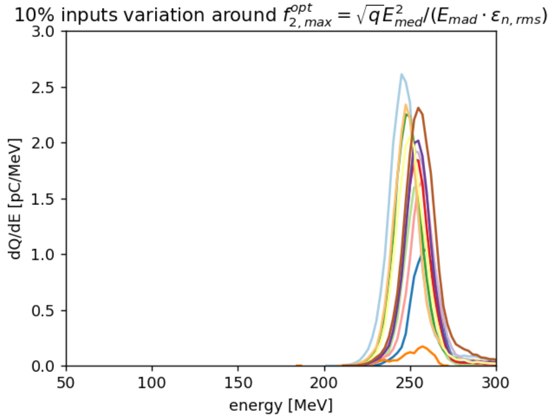
[1] M. Kirchen et al. Phys. Rev. Lett.,**126**, 17, p. 174801, (2021) [2] S. Jalas et al., Phys. Rev. Lett., **126**, 10, p. 104801, (2021)

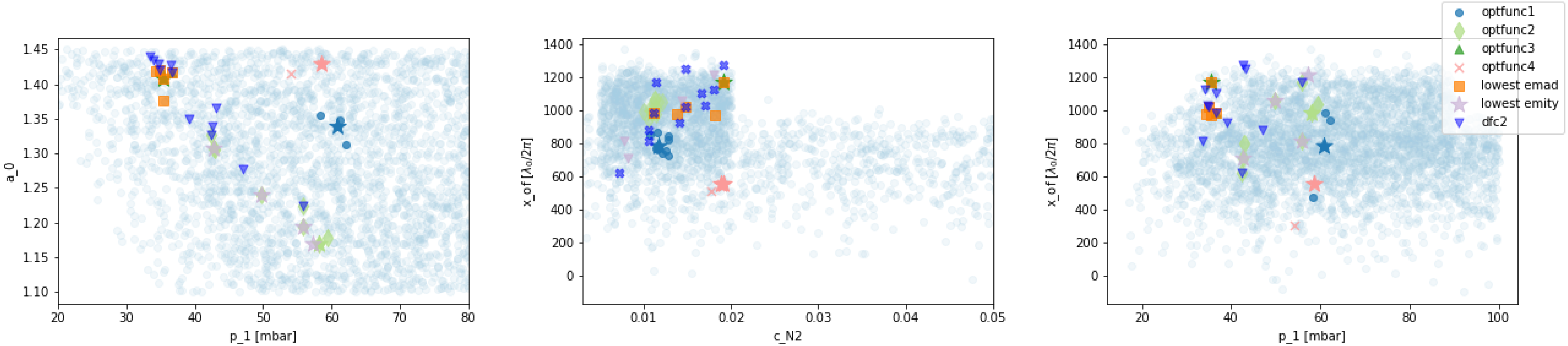
Fast PIC random scan (2)



- Observed tendencies in the hyper-parameter space similar to already published work (Jalas, Kirchen *et al.*)
- Example of projections of the parameter space and various beam optimum positions.

- On going study of inputs variation sensitivity of optimum





Plasma cell test bench

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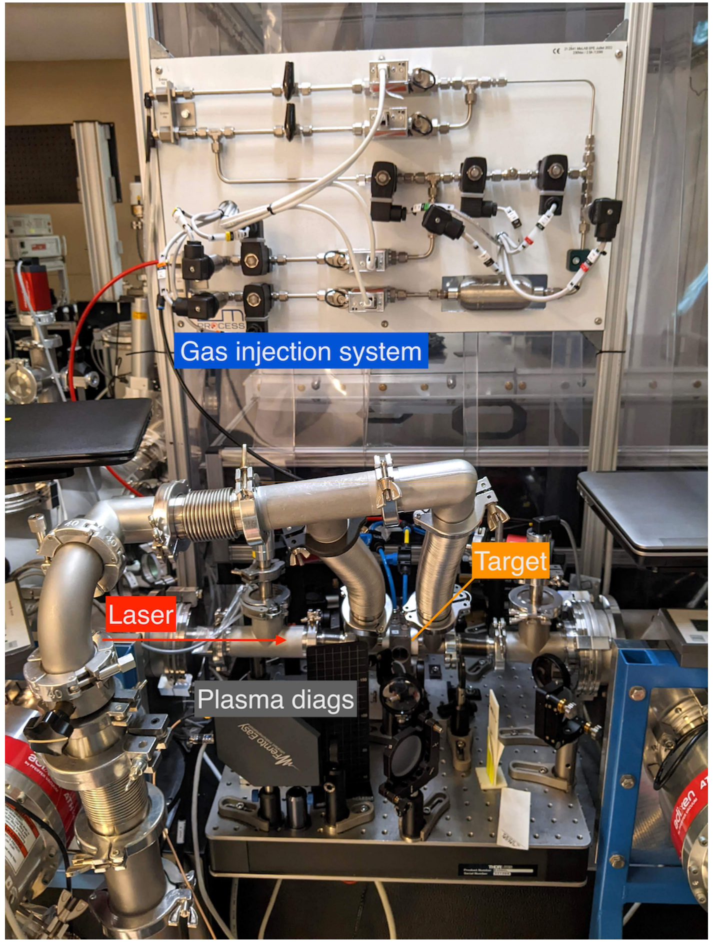
Dedicated test bench for plasma target cell:

- **fs intense laser driver** $I \sim 1 \times 10^{16}\, W.cm^{-2}$ for plasma channel generation
- **synchronized probe beam** for time resolved transverse interferometry
- high resolution **plasma density diagnostic** [1] $\delta n_e < 3 \times 10^{17} cm^{-3}$
- spectral imaging for **dopant distribution control** [2]
- multiple **mass-flow controlled gas injection**
- continuous flow target operation with **two stages differential pumping**



[1] F. Brandi and L. A. Gizzi, High Pow Laser Sci Eng, vol. 7, p. e26, 2019;
Phasics, 'SID4 High resolution wavefront sensor (2020).
[2] B. B. Pollock et al., Phys. Rev. Lett., vol. 107, no. 4, p. 045001, Jul. 2011.

Ionization injection High-Z dopant confinement

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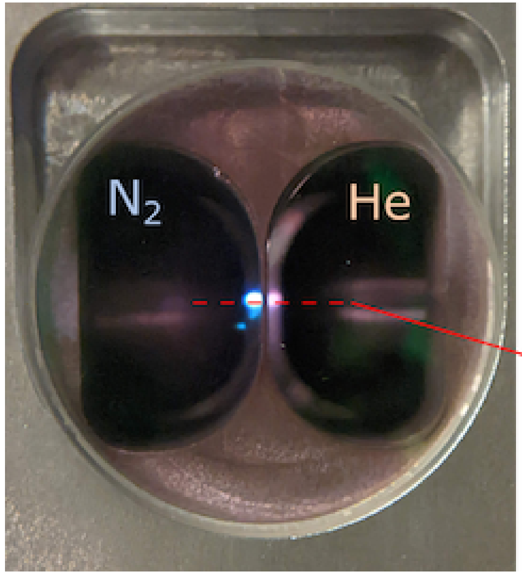
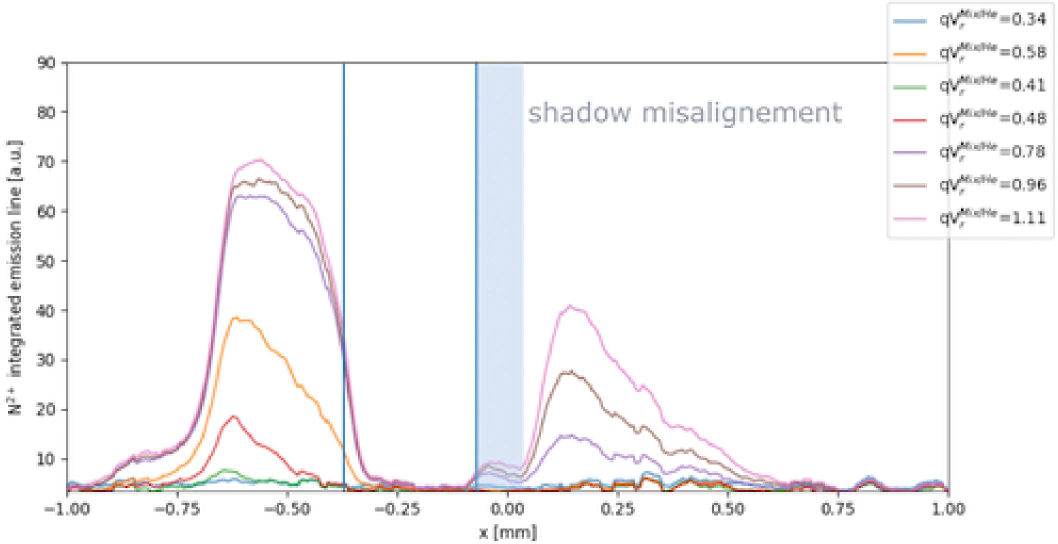
- Pressure operation : 5 mbar to ~120 mbar in continuous flow.
- Localization of High-Z dopant (N_2) in region 1 for controlled injection.
- **[PRELIMINARY]** results from spectrally resolved imaging region 1/2 looking to N^{2+} (triplet lines $2s^22p3s \rightarrow 2s^22p3p$) @ 40 mbar $\pm$ 1.5





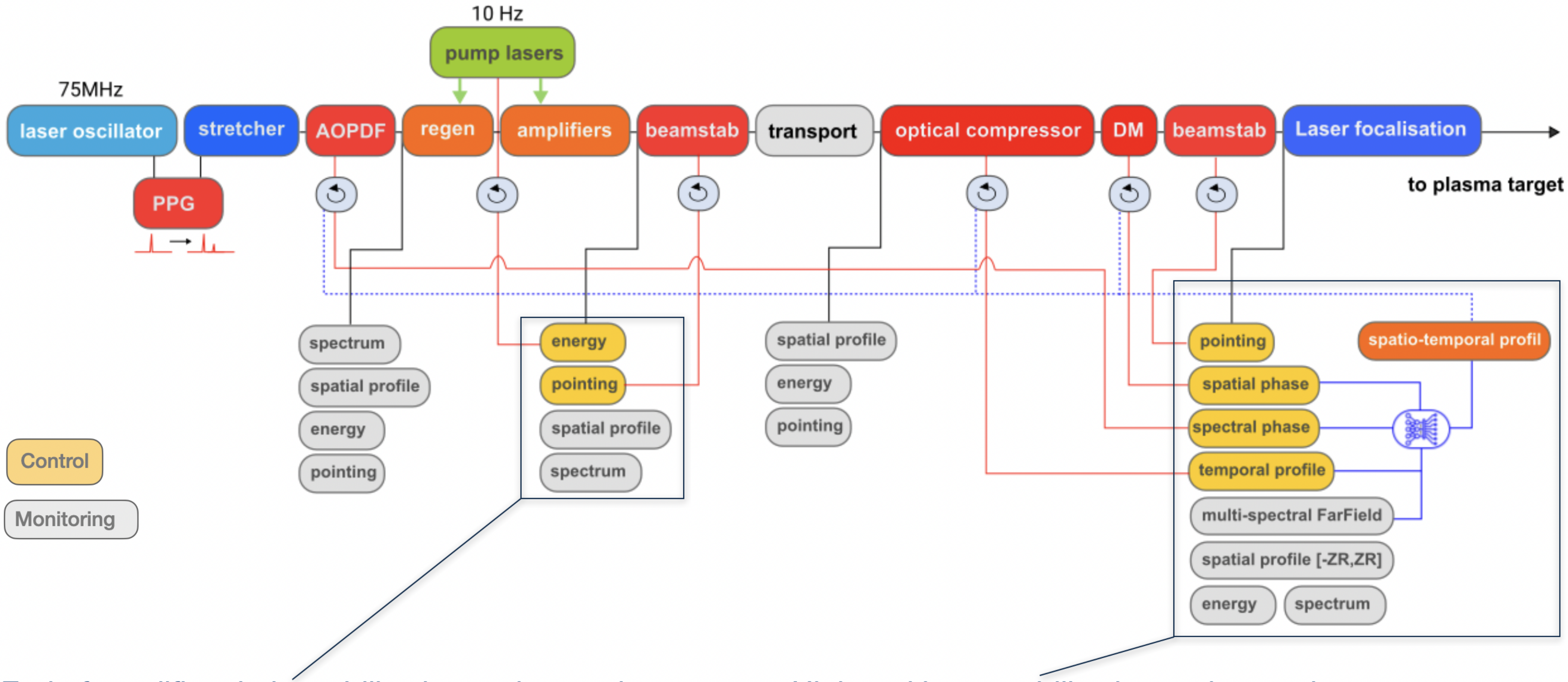
=> successful stable tailoring of high-Z dopant distribution in stationary continuous flow regime by direct flow control.

see poster by PhD Pierre Drobniak

Laser advanced control

PALLAS Laser Driver

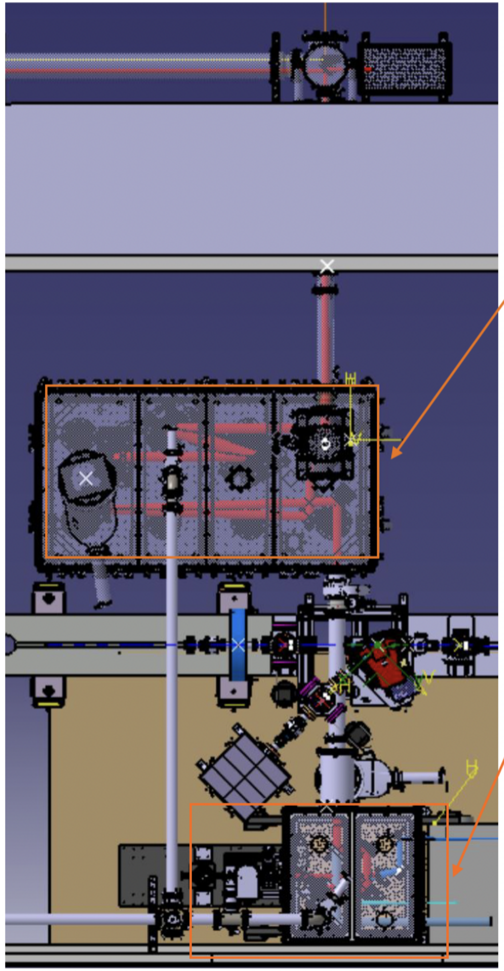
Tentative of stabilization of 40-50TW 10Hz LASERIX laser system @ IJClab, collaboration with Amplitude Laser



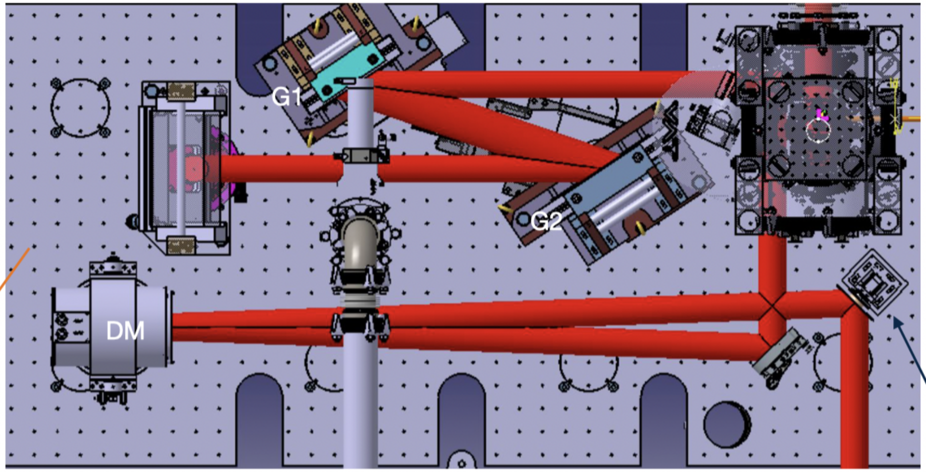
End of amplifier chain stabilization and control

High end laser stabilization and control

Laser driver control at the target level

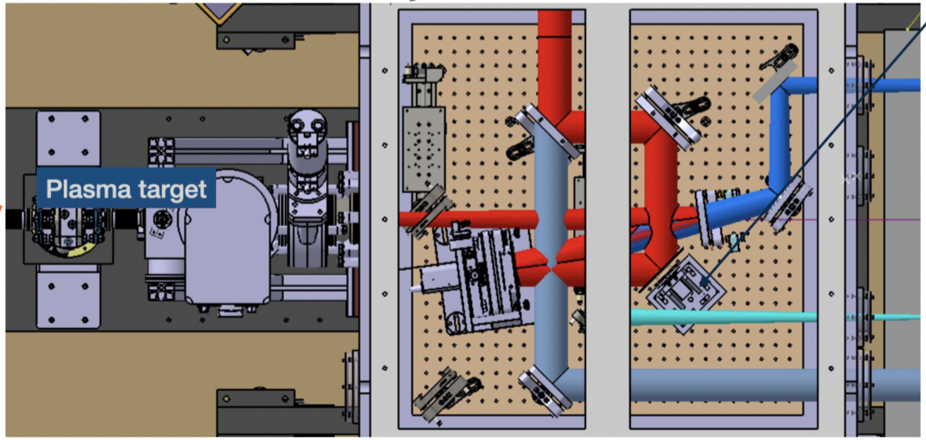


Compressor module



High speed large aperture mirror

Laser injection focalisation module



Laser diagnostics @ focus station
- FF laser beam stabilization
- WFS
- FROG
- 2 imaging spectrometer
- Multi-spectral diags [ML-COLA]

Laser diagnostics direct focus

NF laser beam stabilization

courtesy design office IJCLab, G; Iaquanello, D; Douillet, Y. Peinaud et al.

Active beam pointing stabilization (1)

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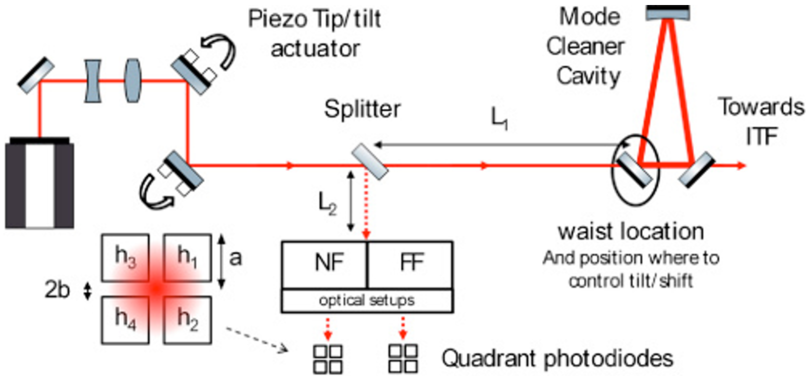
Typical active beam pointing system are composed by :

- 2 piezo tip tilt stages [cut off frequency ~1Hz]
- 2 fast positions sensor : 4 QD or PSD
- Electronic driver

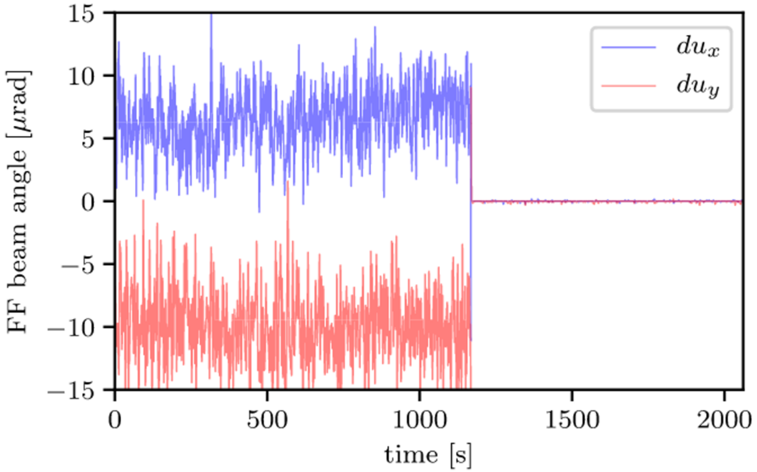
Beam pointing is critical for **plasma target life time** and electron beam stability

Various demonstration and implementation can be found in literature [1,2,3]

- Witness beam are required for sub kHz laser system
- Witness vs main beam selection (shutter, band selective beam splitter combination …)
- Check out of the loop main pulse vs witness pulse



src: Canuel, B. et al. s. Appl. Opt. 53, 2906 (2014).



src: out of the loop FF measurement, piezo tiptilt activated at 1170s, sampling 10Hz [3]

[1]: Genoud, G., et al. Review of Scientific Instruments 82, 033102 (2011).

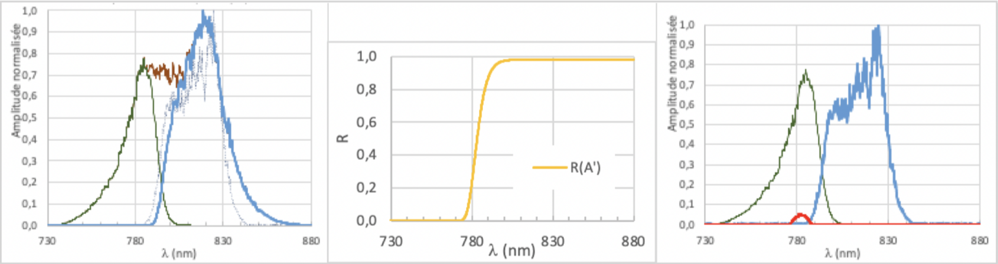
[2]: Isono, F. et al. High Pow Laser Sci Eng 9, e25 (2021).

[3]: Ndiaye, C. F. et al. Phys. Rev. Accel. Beams 22, 093501 (2019).

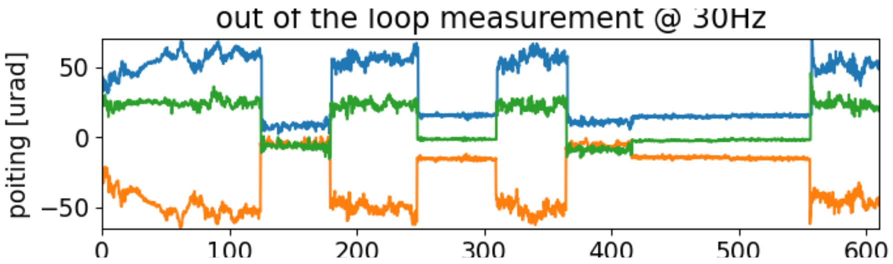
Active beam pointing stabilization (2)

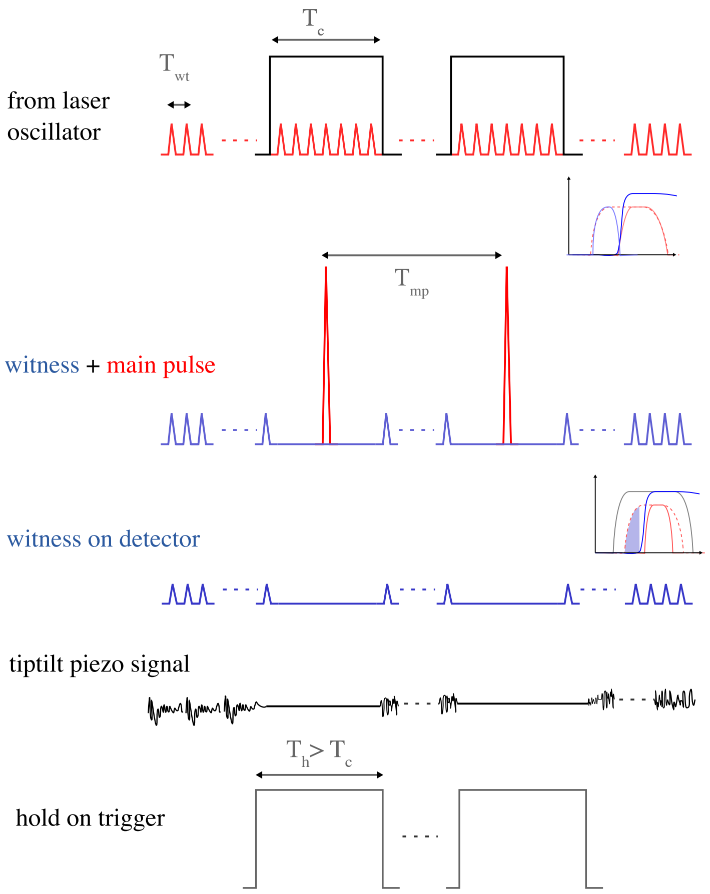
Lower rep-rate LD systems require witness beam

- **Witness beam:** MHz pulse train from the blue part of the oscillator spectrum
- **Witness selection vs main pulse:** cut-on wavelength optimization with specific dichroic coating along the system



- Piezo-driver integrated in the Tango control system
- Integration FF/NF optimization $\sigma_u = 0.6$ urad (RMS)

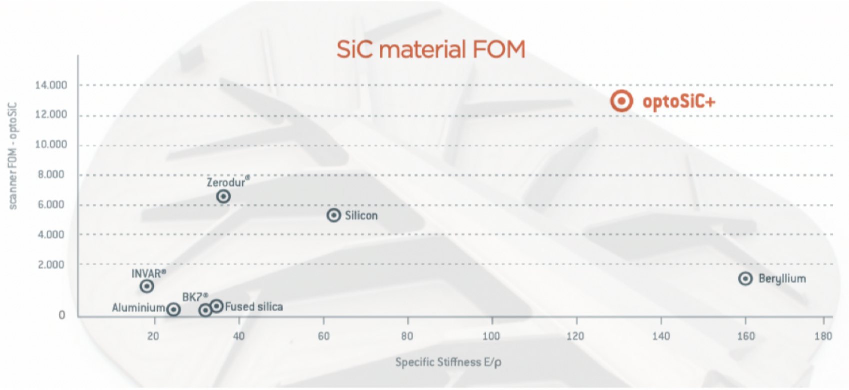




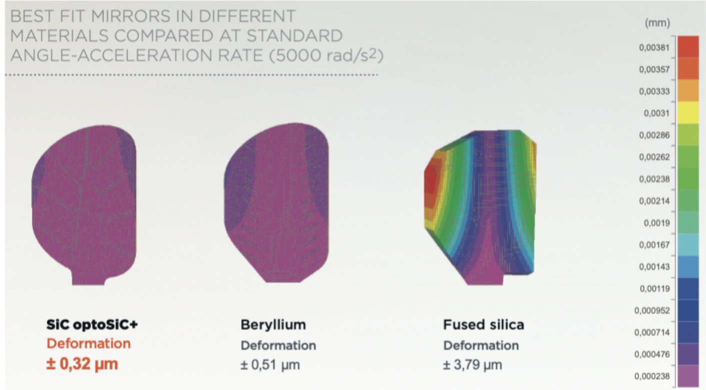
High speed large aperture mirror final focus stabilization

For large aperture mirror are required min 90x130mm aperture for 50 TW pulses => ultra lightweight mirror

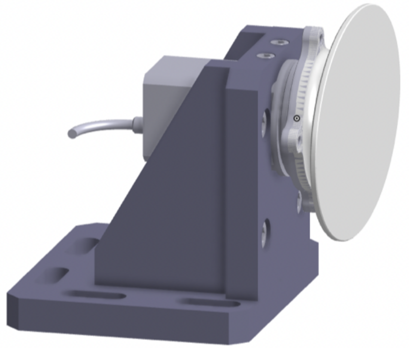
Combine SiC + boostec [1] : < 150 g with SFE< 80 nm



src: http://www.mersen.com, *gs-optosic-optics-high-end-laser-process-galvo-scanning-mersen*



src: http://www.mersen.com *gs-optosic-optics-high-end-laser-process-galvo-scanning-mersen*



src: courtesy of MRC / MERSEN

- Test on piezo tip-tilt for optimal bandwidth [~400Hz] validated [1]
- On going qualification test of femtosecond broadband coating on SiC: IBS stress compensation and LIDT under vacuum [2]

[1]: MRC gmbh

[2]: MERSEN/OPTOMAN/LIDARIS

Conclusions

PALLAS

Just a selected overview of work ongoing on PALLAS:

- Target development workflow is set :
  - moving to test new prototype based on Kim *et al.*[1] approach
  - adding diagnostics to monitor target lifetime (aperture ablation)

- LPI simulations next steps:
  - optimization: train ML model on the dataset
  - make dataset open to public for the community
  - speed up (< 4 h.core/mm ?) approach of sequential modelling injection / acceleration /extraction

- Electron characterization beamline capture section design complete moving to magnet design

- Control-command development oriented for machine optimization at 10Hz
  - About 70% of the device server developed
  - first elements are to be connected
  - archiving time-stamping to be implemented (TimeScaledb)

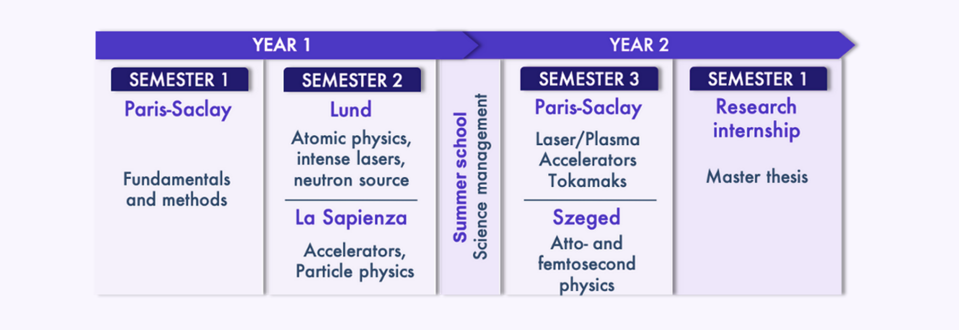
- Expected laser-driver injection and focalization module installed with active beam stabilization in June 2023.

- Still on road for being able to produce first electron by end of 2023...depending procurement delay hazard.

Seeking for collaborations

Future

The students did lab work at Frascati or Lund, will spend another one semester in Paris Saclay With specific lectures and practicals on LPA and french laser installations, they are 20 !



PLEASE send internship offers or any further question to : sophie.kazamias@universite-paris-saclay.fr We will put them on the master website for all the students

Thanks !