PALLAS

laser-plasma accelerator test facility @ IN2P3

Kevin CASSOU

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on behalf ot the team

AG Alex Gonnin, AB Arnaud Beck, AS Arnd Specka, BL Bruno Lucas, BM Bruno Mercier, CB Christelle Bruni, DD Denis Douillet, EB Elsa Baynard, EG Emmanuel Gouttiere, EL Eric Legay, FM Francesco Massimo, FG François Glotin, GI Greg Iaquaniello, HG Hayg Guler, HM Hugues Monard, JC Jean louis Coacolo, JD Julien Demailly, KD Kevin Dupraz, MP Moana Pittman, MA Mohammed Abdillah, ON Olivier Neveu, PD Pierre Drobniak, RP Rui Prazeres, SW Sébastien Wurth, SK Sophie Kazamias, SJ Stephane Jenzer, VK Viacheslav Kubytskyi, VC Vincent Chaumat, YP Yann Peinaud KC Kevin Cassou

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online version

interactive slides, full version available here:

https://s.42l.fr/pallas

A view of present LPA status for FEL

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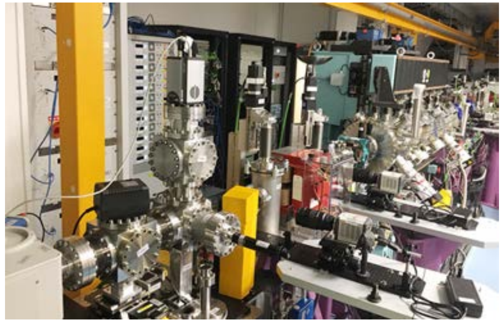
Required beam parameters are : **energy spread <1%; beam brightness 5 pC/MeV; stability ~ 1 %**

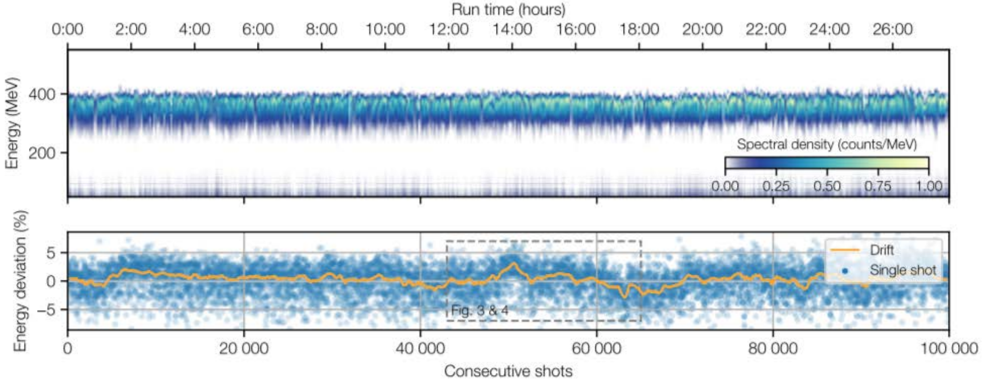
COXINEL (SOLEIL-LOA):

- LPI : injection by ionization / gas jet
- Electron beam brightness issue ~ 0.2-0.3 < 5 pC/MeV [design value] @ 2.5Hz
- LPA beam transport studies [1]
- observation of spontaneous emission



LUX (DESY-UHH):

- LPI : injection by ionization / gas cell
- Effort on reliability and control since 2016
- Electron beam stable energy spread 15%[3] -> ~1%, peak brightness ~0.5 -> 5 pC/MeV @ 1Hz



a transition has started toward potential reliable sources and laser-plasma accelerators

[1] M. Labat et al., Phys. Rev. Accel. Beams, vol. 21, no. 11, p. 114802, Nov. 2018; T. André et al., Nat Commun, vol. 9, no. 1, p. 1334, Dec. 2018

[3] A. R. Maier et al., Phys. Rev. X, vol. 10, no. 3, p. 031039, Aug. 2020, doi: 10.1103/PhysRevX.10.031039; M. Kirchen *et al.* and S. Jalas *et al.* submitted (2021)

National and (international) context

National overview

07/2019: GDR organzed $\longrightarrow$ discussions 2 projects emerged structuring a potential French contribution to EuPRAXIA

Laser-Plasma accelerator center

LAPLACE (INP/IPP)

LPA FEL / kHz LPA

sources for applications

PALLAS (IN2P3/Upsay)

prototype of laser-plasma injector

staging towards GeV

+ PIC code development SMILEI, CALDER_CIRC, HR/HE laser R&D , multi-PW LPA experiments...

01/2020: IJClab commit to support in the infrastructure renewing for PALLAS (CPER)

04/2020: national master project **PALLAS**, CNRS worked for a EuPRAXIA CA, IJClab representing CNRS.

06/2020: **PIA3-PACIFICS** national R&D project for future accelerator submitted, **one axe devoted to LPA R&D**

07/2020: exceptional financial support [COVID19] => important kick start for the project

12/2020: **PIA3-PACIFICS** national project accepted, pending to final financial arbitration 75% funding confirmed.

Laser-plasma R&D @ IN2P3 ?

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LASERIX facility | SMILEI numerical platform | Environment

LASERIX 40 TW, 10 Hz laser driver of the Université Paris Saclay with unique features in the short term project funded research :

- **Constant maintenance and upgrade** by Université Paris Sud over a more than a decade (~130k€/year + >800k€ investment CPER POLA)
- Aggregation of unique competencies in a cohesive team
- Localization close to a **radiation shielded area NEPAL** (PHIL)
- Part of the material to upgrade the laser system to 300 TW[1], 0.1Hz existing

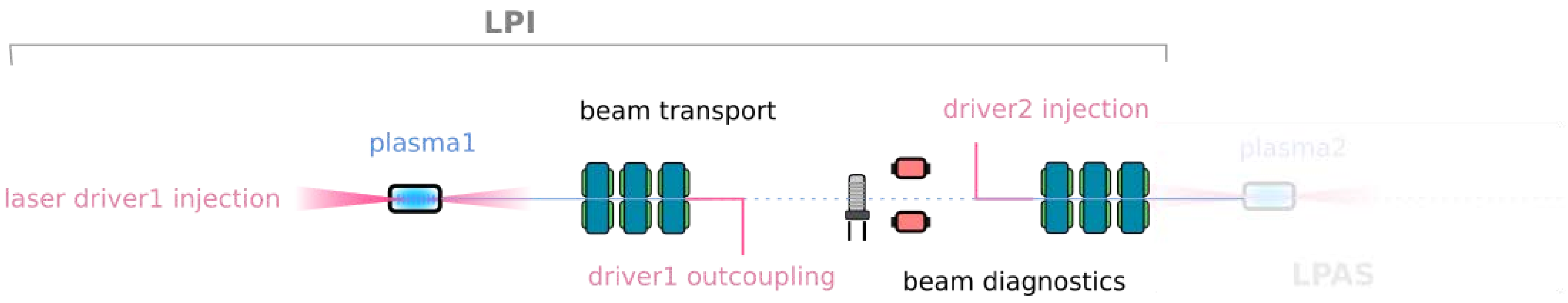
[1] Ref. F. Ple et al., "Design and demonstration of a high-energy booster amplifier for a high-repetition rate petawatt class laser system," Opt. Lett. 32, 238-240 (2007)

PALLAS project

Objectives

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

Push LPA technological development starting with a **laser-plasma injector** (**LPI**) prototype



Research and development lines :

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

Achieved fully optimized and controlled LPI

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

Electron beam parameters

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- 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	<10%	**< 5%**	< 5%	peak (FWHM)
$\varepsilon_{T,n}$	1	**<1**	<1	mm.mrad
stability	5%	**3%**	**1%**	-
reproductibility	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.

LPI parameters

Configuration of the LPI : laser driver, plasma, ...

Parameters	phase 1	phase 2	phase 3	unit
laser strengh, a_0	1.15	**1.97**	**1.97**	
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	STII	STII	STII	-
electron beamline	*TBD*	*TBD*	*TBD*	-

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

Our approach

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Guidelines

- **Modularity** : accelerator divided in module
- **Reliability** : high performances laser optics + over sized optical compressor (350TW-class grating used @ 40TW) + optimized laser-driver diagnostic implementation
- **Compactness** : plasma target integrated in the accelerator beamline
- **Scalable** : to high repetition rate (starting in the middle range 10Hz)

Online control (laser / electron)

- TANGO control command, Ada webpage based UI
- Full 10 GB/s network acquisition, 10Hz time-stamping, automated data-storage
- Design oriented for and to ease application of **Machine Learning** technics

Stepwise approach (cost / complexity)

- **Staged implementation** : from the source characterization to more and more complex electron beamline
- **Parallel development** : plasma cell test bench , online laser field control ML-COLA[1]
- **Simulation support**: reinforce collaboration between experimental and numerical people

Open to the community in the spirit of accelerator development: OpenHardware / OpenData

ML-COLA: P2IO project (2021-2022), V. Kubytskyi and M. Pittman *Proof of the principle experiment of Machine Learning based online Characterization and Optimisation of a high intensity LAser pulse*.

Advanced laser control

Laser performances & control

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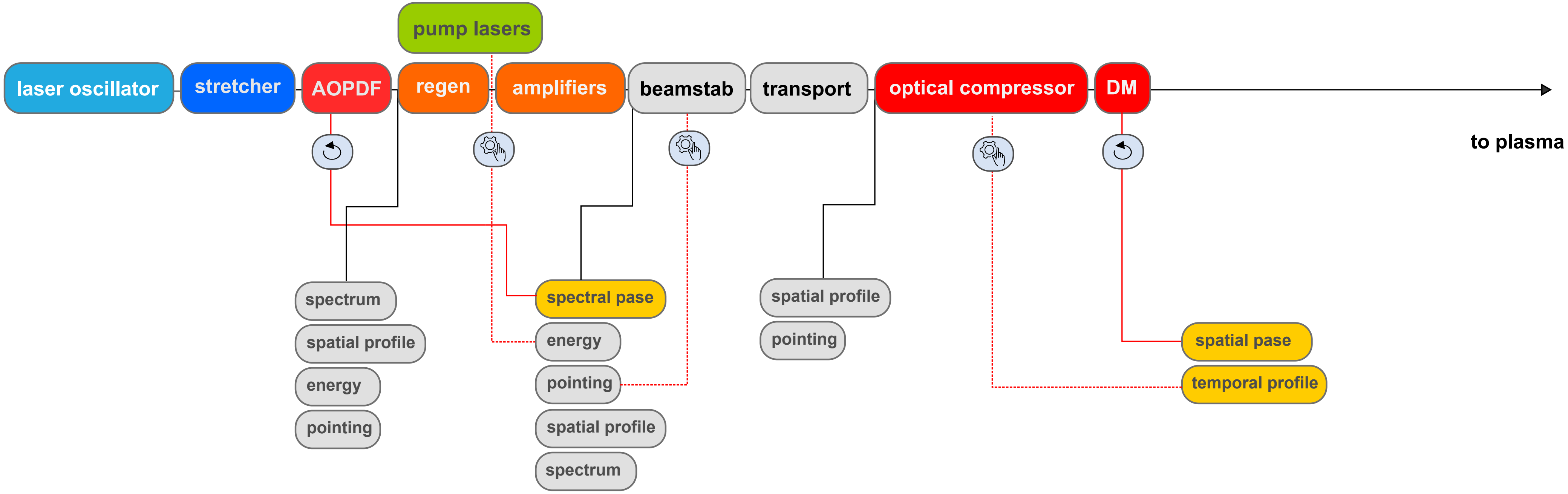
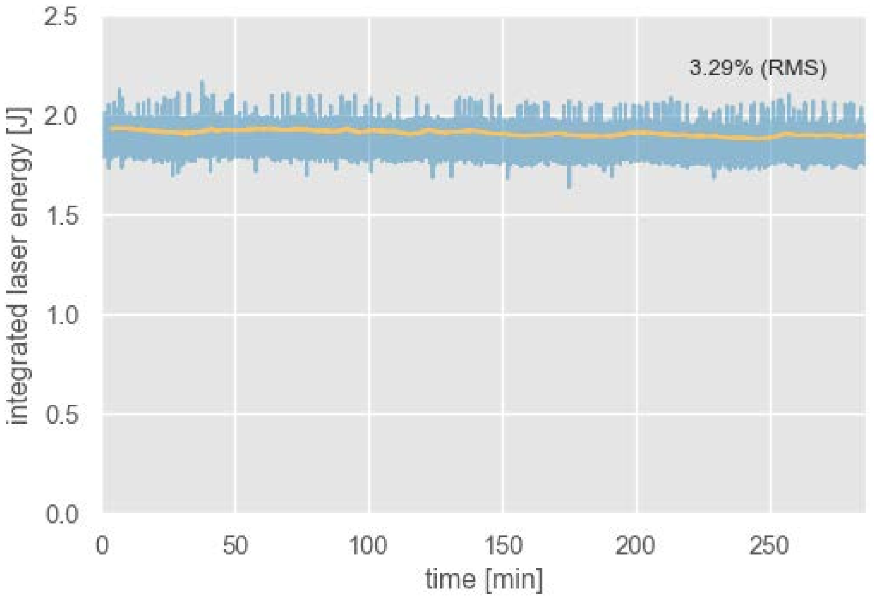
30-100 TW class laser system = complex system

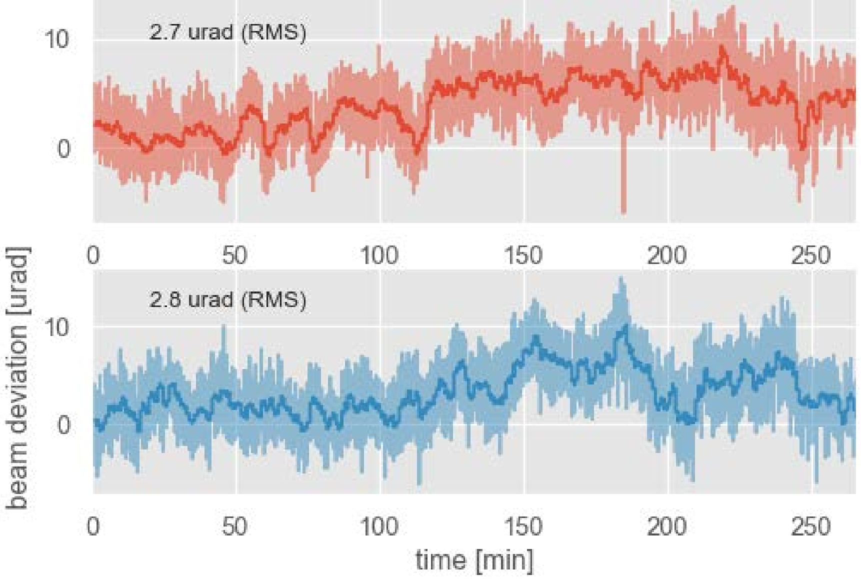
overview of the LASERIX Ti:Sa chirped pulse amplification laser driver system



Laser performances & control

current status without feedback :

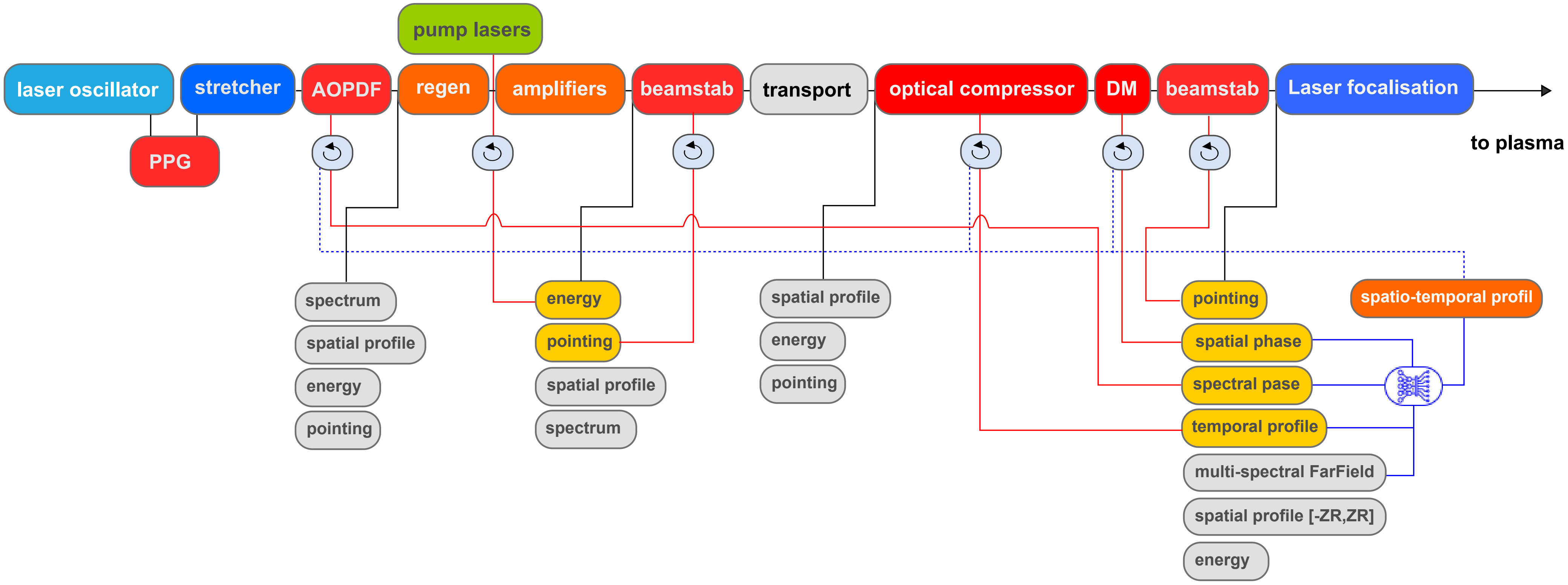




+ laser pulse duration $\tau_l = 40 \pm 3$ fs stability <10% (RMS)

bring **errors** of laser pulse properties (E, t, Sr) **below <1%**

Laser performances & control



- **add** active beam **pointing stabilization**
- **add** online development of **laser field spatio-temporal distortion** monitoring
- **add** longitutinal pulse shaping = controlled pre-pulse for preformed plasma channel (PPG)
- full **data-logging** and **gateway** to accelerator control command

Plasma target

Plasma target

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develop engineering of laser-plasma accelerating structure

Characteristics length of a plasma target for LPI ($10^{18} \leq n_e \leq 10^{19}$ cm $^{-3}$) :

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

Tailoring plasma density profile:

- **to control injection** : density down-ramp assisted truncated ionization injection [1]
  $\Rightarrow$ narrowing of the injection length [2]
- **tune** the injected **charge / beam loading** [3]
- **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).

[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 density profile : an illustration

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Example of simulation:

- LASERIX laser input
- generic shape for $n_e(x)$

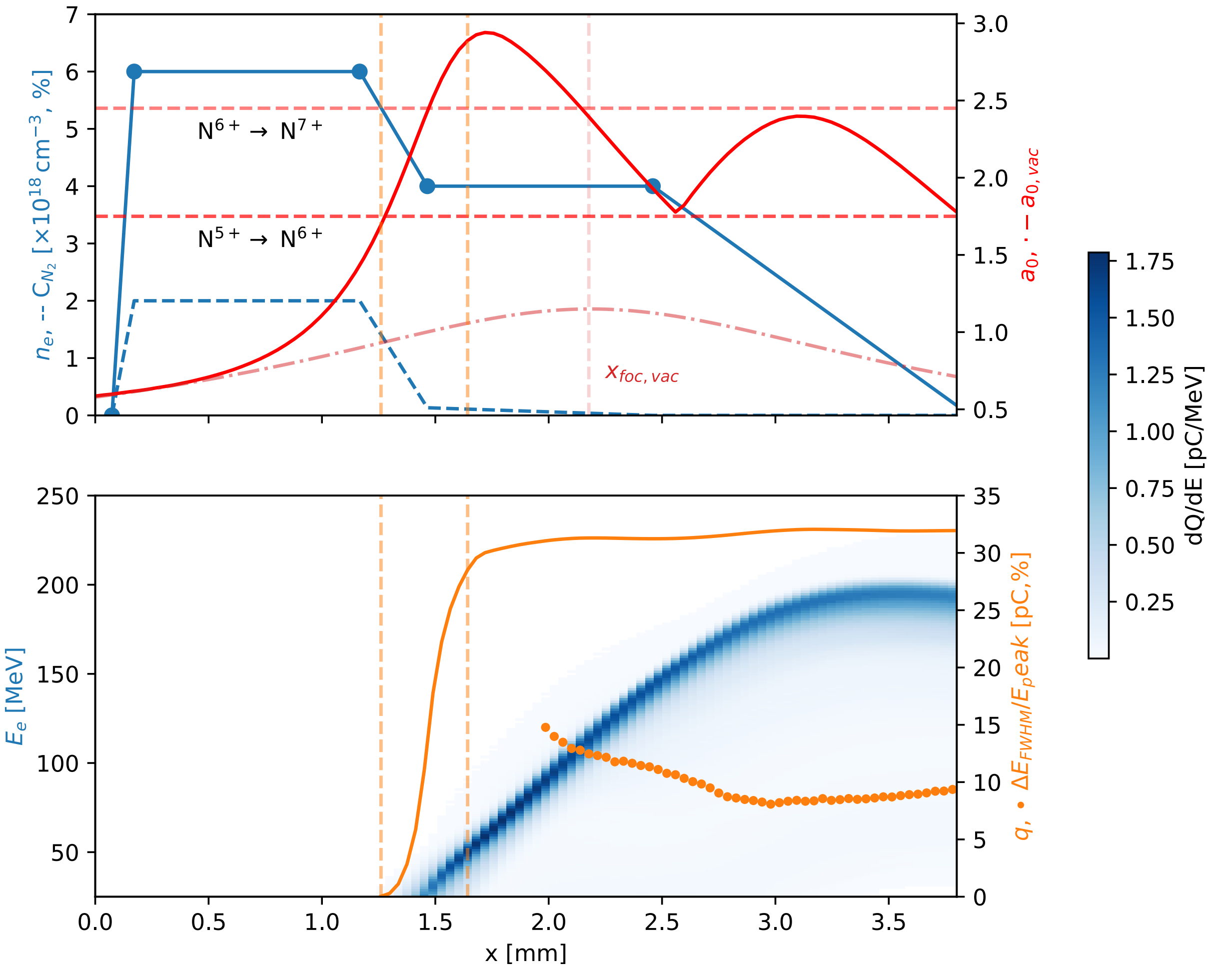
  inspired from various ref[1]
- parameter : $x_{foc,vac}$

mMulti-cell to get access to each region tuning :

- length and density
- dopant $C_{N_2}(x)$

Open ways to:

- Fine optimization
- Control
- Tolerancing



[1] G. Golovin et al., Phys. Rev. ST Accel. Beams,**18**,1,011301,(2015); M. Mirzaie et al., Sci Rep,**5**,1,14659,(2015). ; A. Irman et al., Plasma Phys. Control. Fusion, **60**, 4,044015,(2018), P. Lee, et al., Phys. Rev. Accel. Beams, **21**,5, 052802, (2018).

Optimization of the LPI core

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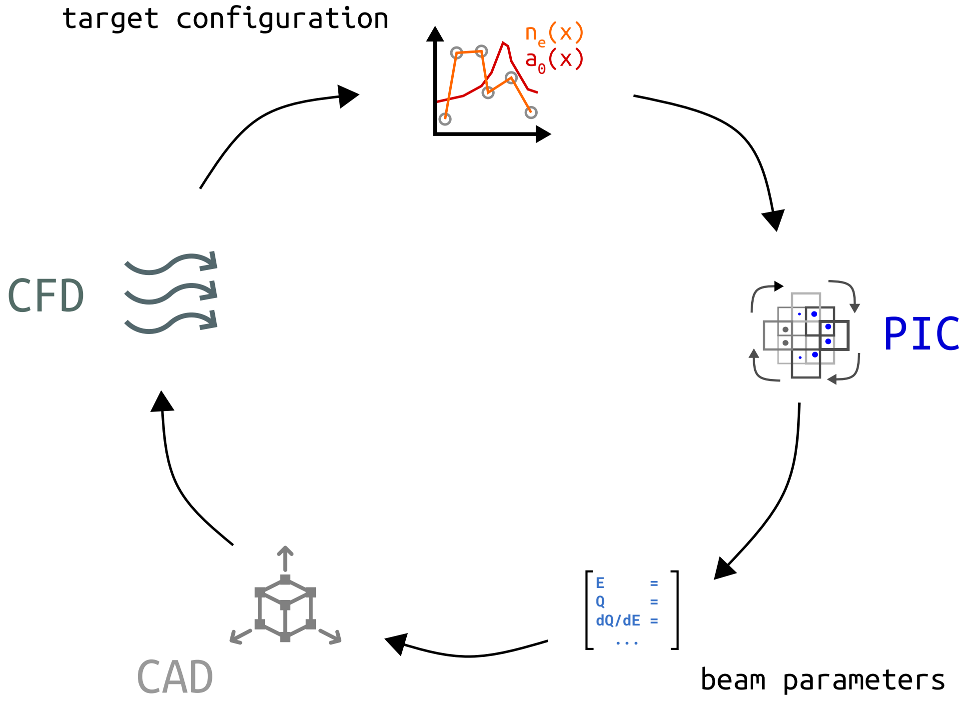
Input

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

Tools:

- **Fast PIC** simulations
  - Azimuthal modes geometry
  - envelope approximation for the laser.
- **Laminar conductance rough model** for cell geometry as CAD input
- **CFD** Openfoam / snappyHexmesh couple to CAD
- Tracking particle code coupling ASTRA/CODAL



all the ingredient for a **full numerical optimization** of the plasma cell ...

[1] in phase 1 : limited to $a_0 = 1.15 \pm 0.8$ and $\tau_L = 40 \pm 3$ fs (FWHM)

Plasma target

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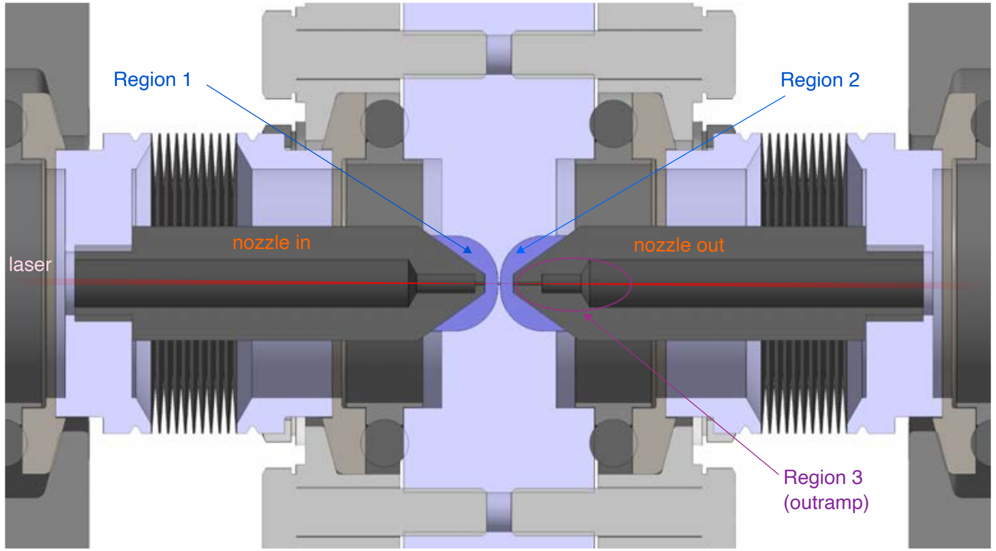
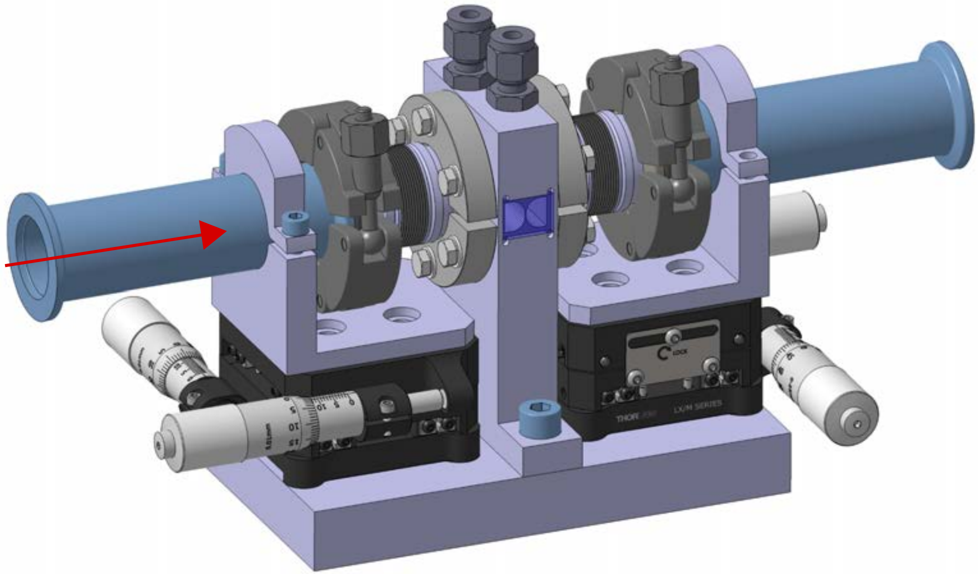
prototype preliminary design

- divide in region / process
- customizable part (nozzle in, central body , nozzle out)
- integrate in the beamline (*10x6x15* cm^3)
- transverse optical access





Plasma cell test bench

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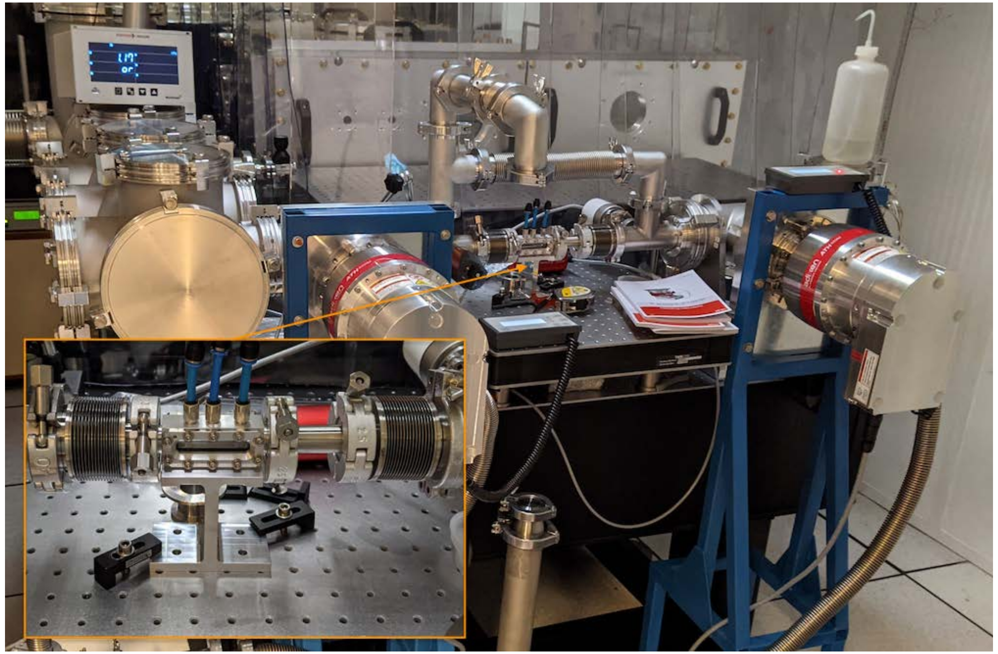
Dedicated test bench for plasma cell:

- **fs intense laser driver** $I \sim 5 \times 10^{16}\, W.cm^{-2}$ for plasma channel generation
- **synchronized probe beam** for time resolved transverse interferometry
- high resolution **plasma density diagnostic** [1] $\delta n_e \sim 5 \times 10^{17} cm^{-3}$
- spectral imaging for **dopant spatial distribution control** [2]
- multiple **mass-flow controlled gas injection**
- continuous flow target operation with **two stages differential pumping**



View of the plasma test bench under commissioning with long testing gas cell from Esculap project (*N. Delerue, K. Wang, S. Jenzer, et al.*) [3]

[1] F. Brandi and L. A. Gizzi, High Pow Laser Sci Eng, vol. 7, p. e26, 2019; Phasics, 'SID4 High resolution wavefront sensor, http://phasicscorp.com/cameras/sid4/ (2020).

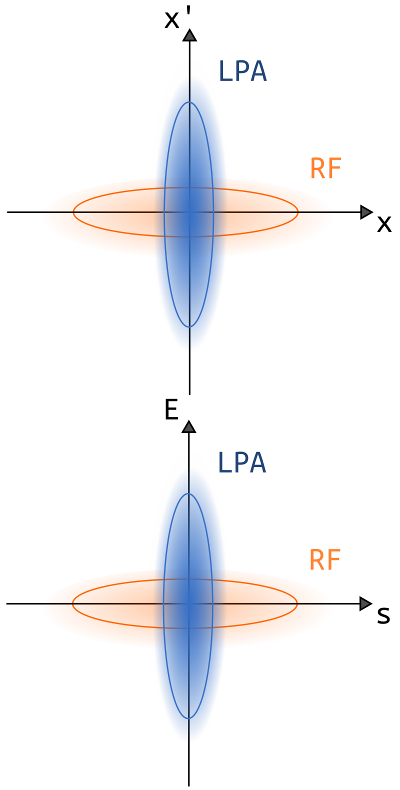
[2] B. B. Pollock et al., Phys. Rev. Lett., vol. 107, no. 4, p. 045001, Jul. 2011.

[3] K. Wang, PhD, 2019 in ESCULAP project, E. Baynard et al, NIMA, vol. 909, p.46, 2018.

Electron beam control and transport

Electron beam line

main challenges



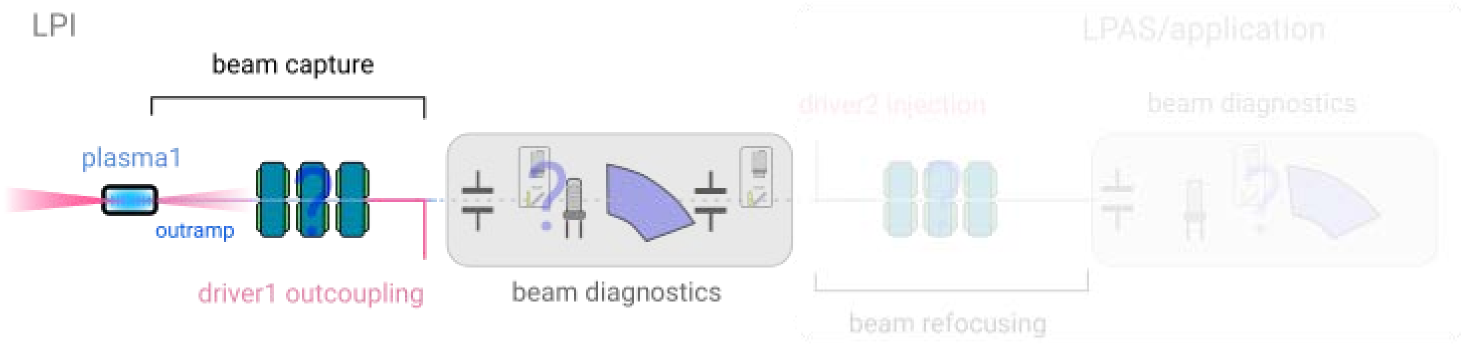
main difficulties already highlighted in the literature:

- laser removal from *e-* path
- *e-* divergence
- large $\Delta E/E$
- low charge and 10-20% fluctuations
- orbit stability
- sensitivity to error
- bunch lengthening

our strategy = stepwise approach

- well known beam properties
- minimize divergence at the source
- energy selection in the peak
- transverse / longitudinal manipulation
- maximize flexibility

Electron beam line : characterization to control



e- beam characterization

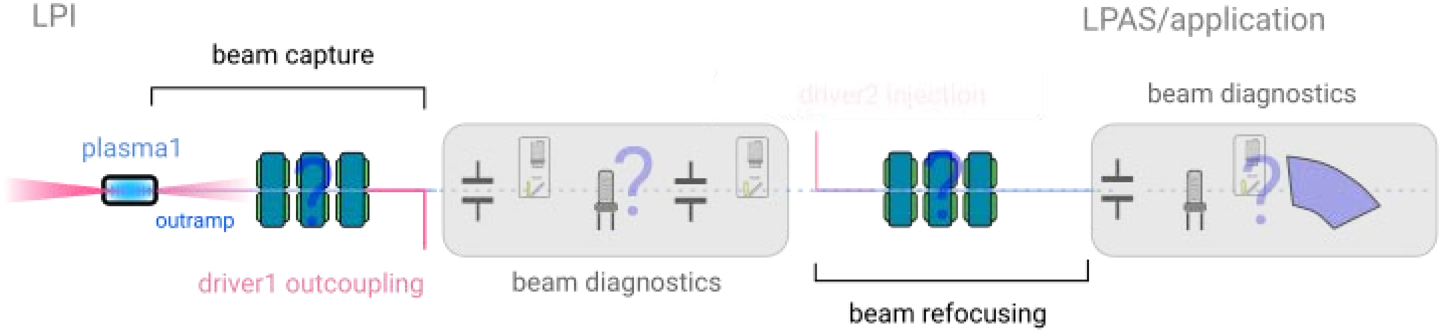
Design: start from PIC simulation parameters
+ explore different capture/focusing scenarii
Beamline: magnets with remote alignment
+ correctors and BPM
Diags: robust diagnostics: Yag screen, faraday cups
+ wide angular acceptance spectrometer
+ emittance measurement

beam/laser/plasma correlations

- **single shot** characterized **diags** / SNR
- **online control** laser/plasma/magnets
- machine learning correction

+ additional diagnostic prevously tested on our photo-injector PHIL for beam duration and **longitudinal phase-space** measurement

Electron beam line: transport



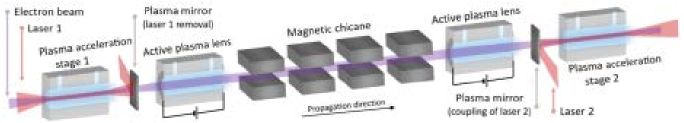
transport line for staging

incoupling/outcoupling driver: chicane,dogleg; plasma mirror

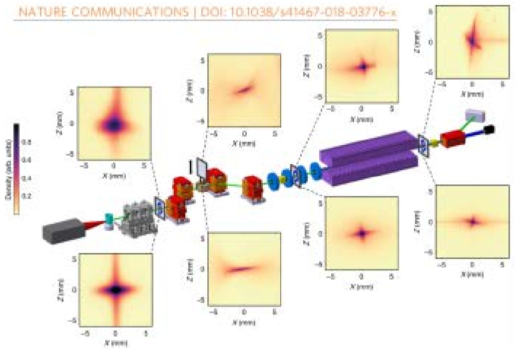
focus close to plasma exit : Quapeva; plasma lens

energy spread: demixing chicane; D-chicane

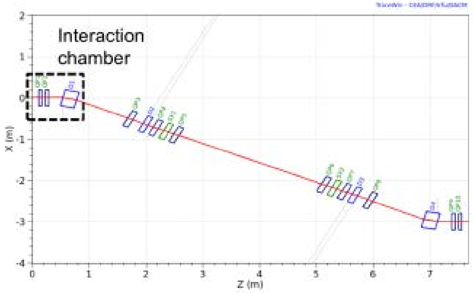
Orbit: Response matrix; lattice optimization in the dogleg



A. Ferran Pousa, et al. Phys. Rev. Lett. 123, 054801 (2019)



T. André, et al. Nature Comm., 9, 1334 (2018)



Antoine CHANCE, Alegro workshop 26-29 march 2019

Development plan

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phase 1 phase 2 phase 3

2020-2022: base of the LPI facility

- **infrastructure upgrade** : renovation, network, PHIL reconfiguration
- **laser driver commissioning** : laser transport, compression, injection and focalisation
- **control command development** : tango laser gateway + tango system / DS and GUI for laser transport and injection control + time stamping and automated storage

=> laser driver optimized

- **optimization of plasma injector design / target development** : PIC simulations optimization studies for injection control and emittance; target prototyping and testing; plasma module

=> target prototype

- **e- characterization beam line**: simple characterization beamline : charge,energy,divergence,emittance dE/E

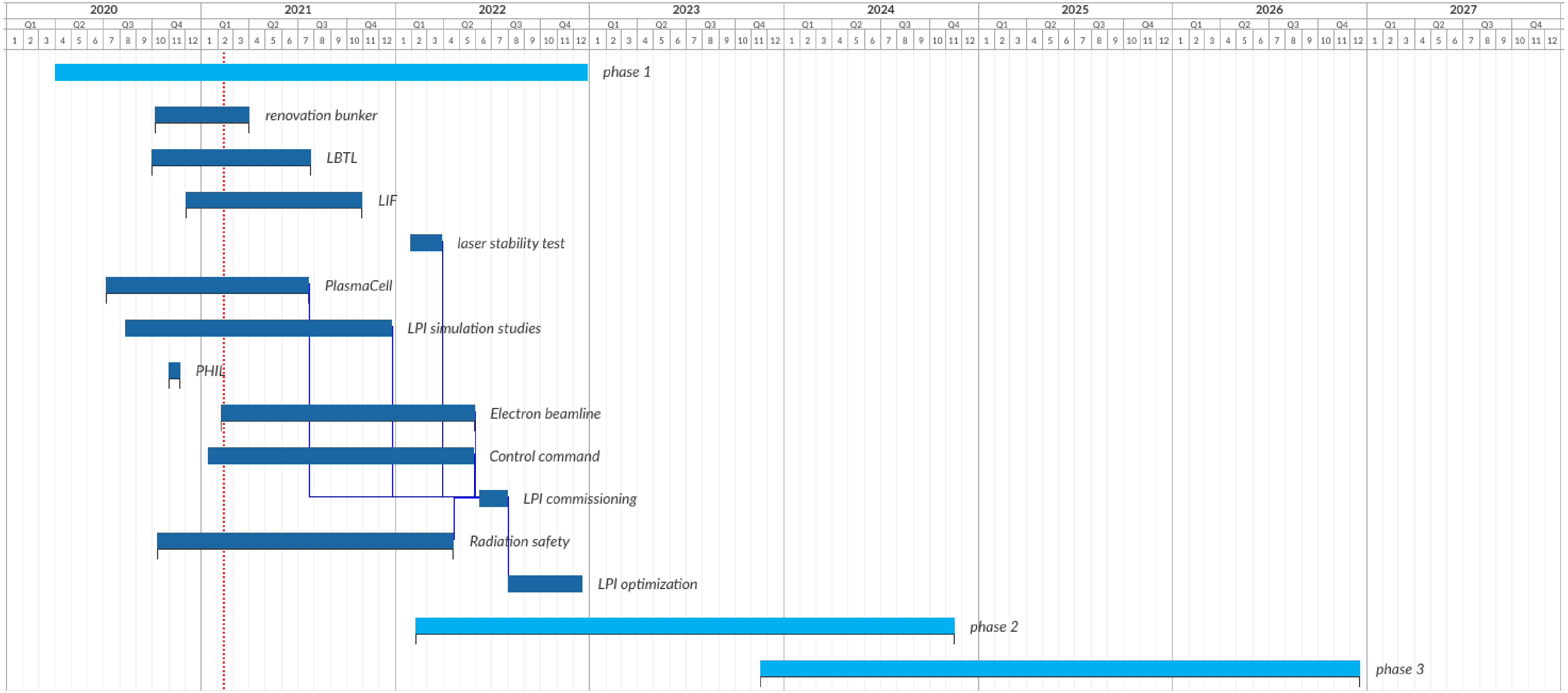
=> first e- beam parameters optimization run at 10Hz.

Budget & costs

- **84 %** of the equipment budget is consolidated.
- budget relies on:
  - substantial support (564k€) from CNRS-IN2P3 to the master project PALLAS
  - projection of last year Université Paris Saclay support despite the growing activities

not available online

Schedule



2020
2021
2022
2023
2024
2025
2026
2027
phase 1
renovation bunker
LBTL
LIF
laser stability test
PlasmaCell
LPI simulation studies
PHIL
Electron beamline
Control command
LPI commissioning
Radiation safety
LPI optimization
phase 2
phase 3

Resources

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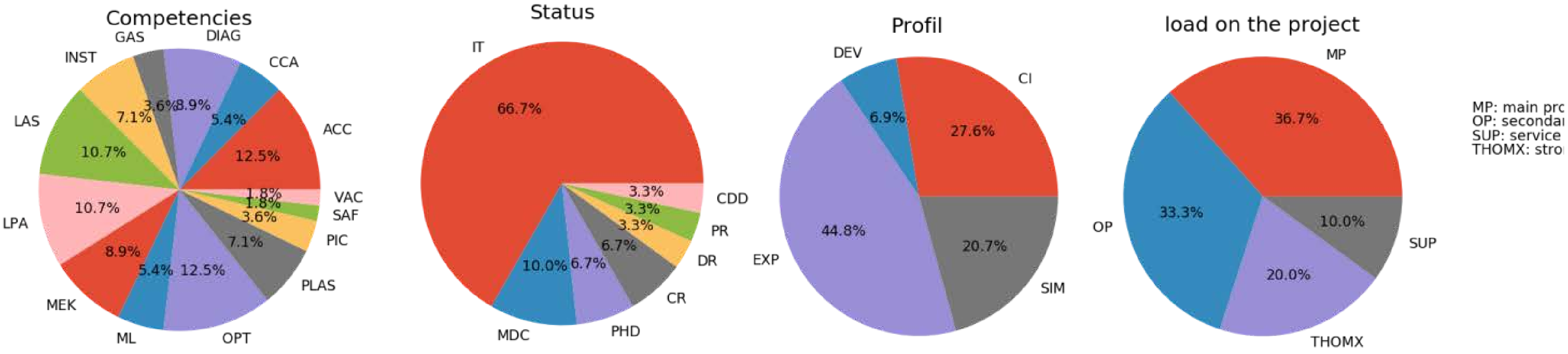
- Project team is about **~30 persons** [IJClab,LLR, LCP, CEA] / average of **7.5 FTE**
- Project team **snapshot for 2021**



- Strong engineering capacities on accelerator, laser, optics, plasma and experimentation
- Delicate situation possible with ThomX delay
- Midterm FTE weakness **PIC code development** for LPA (Smilei 1FTE) and theoretical on laser-plasma interaction must be reinforced

Magnetism and **beam dynamic** must be reinforced at the lab level

SWOT analysis

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Strengths

- Unique 10Hz laser-plasma accelerator test facility with >22 weeks/year beam time
- State of the art laser driver supported (operation) by Université Paris-Saclay
- Strong engineering support

Weaknesses

- No magnet services in the lab.
- Limited funding.
- Starting late in competitive and dynamic domain
- organization/administration.

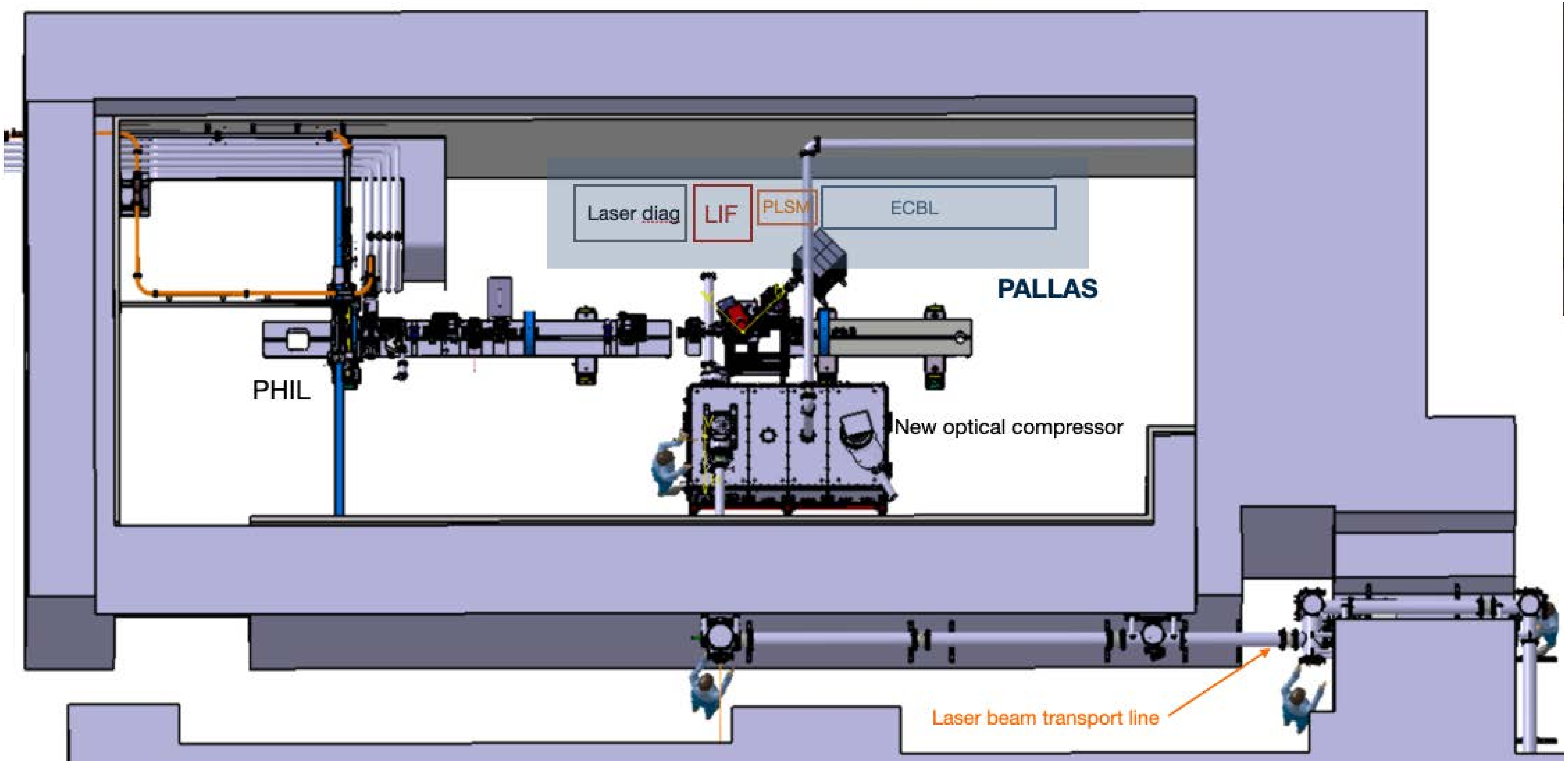
Opportunities

- link with SMILEI team
- EuPRAXIA
- Plasma cell development for other LPA experiments
- Industrial collaboration

Threats

- ASN
- Some spares can not be covered by the budget.

Infrastructures : overview



Infrastructures : overview

Summary

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- Unique opportunities to build a **10Hz laser-plasma accelerator test facility**
- **Push back the laser-plasma technology frontiers** to high reliability and control
- **Complementary** to national effort at CNRS-INP (LAPLACE, ApoLLon) in the **EuPRAXIA context**
- Strategy align with *2020 Update of European Strategy for Particle Physic*, preamble p. 8 :

> Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. **The technologies under consideration include** high-field magnets, high-temperature superconductors, **plasma wakefield acceleration** and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. The European particle physics community **must intensify accelerator R&D and sustain it with adequate resources**. A roadmap should **prioritise the technology**, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.

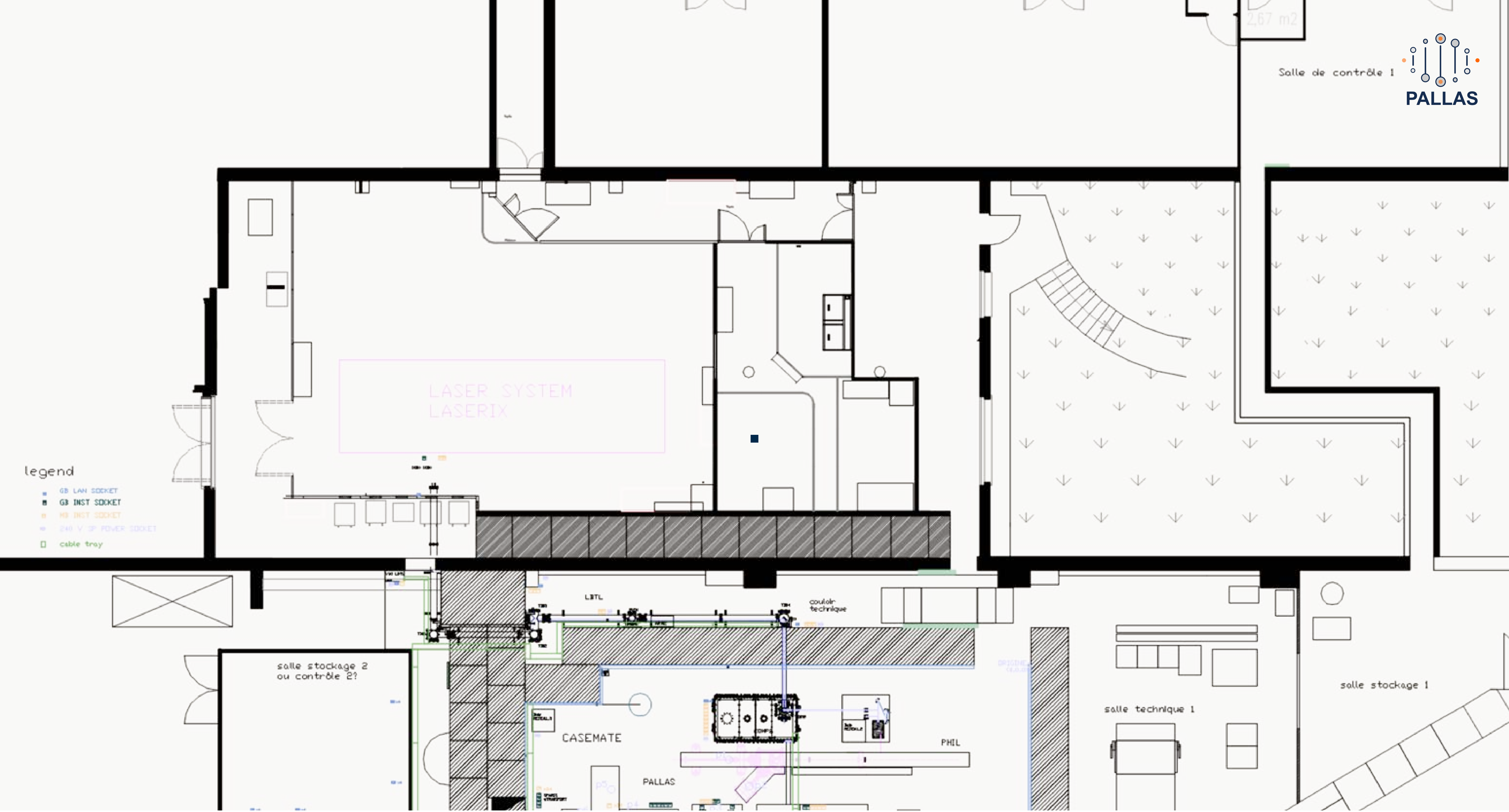
@IN2P3 : Reinforce competences and position in future innovative accelerator technologies

Requirement for IN2P3 : a strong financial support of 564 k€ over 2022-2025 is required to the IN2P3 + 2 post-doc and doc positions.

Thanks !

Contact :

Back slides


Salle de contrôle 1
LASER SYSTEM
LASERIX
legend
GB LAN SOCKET
GB INST SOCKET
cable tray
LBTL
couloir
technique
salle stockage 2
ou contrôle 2?
CASEMATE
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PHIL
salle technique 1
salle stockage 1

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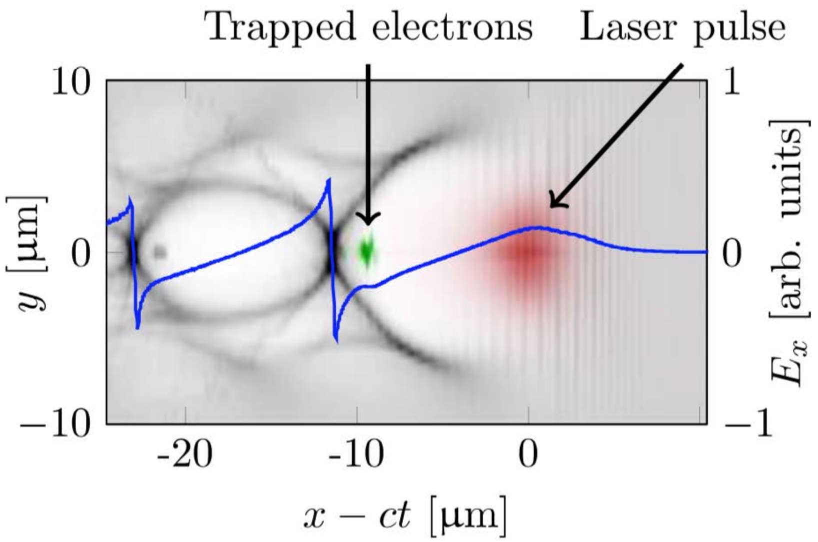
Laser wakefield acceleration

in a bubble

some basics



laser driver in underdense plasma ($n_0 \sim 10^{18}$ cm $^{-3}$) :

$$F_p = -m_e c^2 \nabla(a^2/2)$$

$$a = eE_L/m_e\omega_L c$$

non linear regime $a > 1$, in 1D, plasma wakefield, density pertubation:

$$\frac{\delta n}{n_0} = \frac{1}{2}\left[\frac{1+a^2}{(1+\phi)^2} - 1\right]$$

+ **High accelerating field**, $E_0 \sim 100$ GV/m[1]

+ **ultra short bunches**, ~ 10 fs [2]

- **tiny transient structure** $\sim 10\mu$m

- **hard to control** $\rightarrow$ large fluctuation

[1] E. Esarey, *et al.* (2009), doi: 10.1103/RevModPhys.81.1229

[2] O. Lundh, *et al.* (2011),doi: 10.1038/s41598-020-73805-7, src img Hansson et al. Phd (2016)

Injection ...

so many way to surf the plasma wake waves... when increasing the laser driver intensity (a_0):

external | ionization | density down-ramp | self-injection

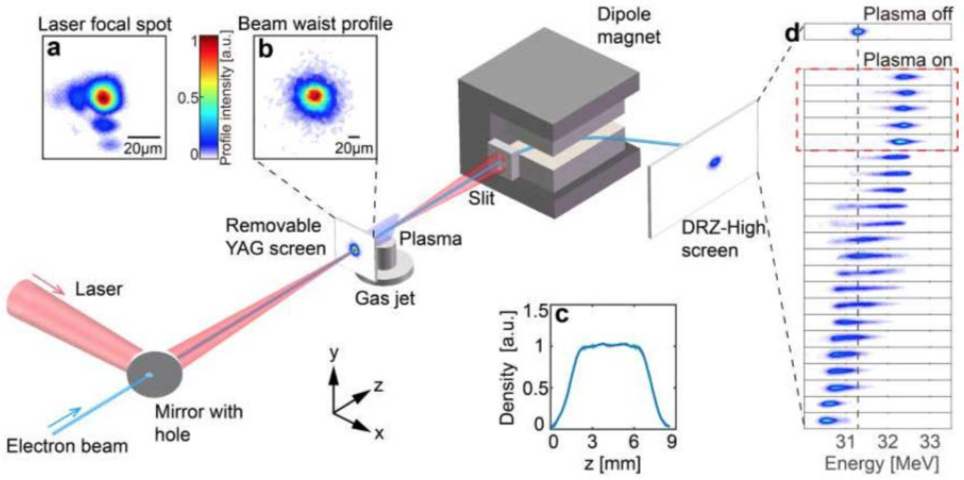
a_0 ~1

+ linear regime control acceleration

- requires a RF linac

- coupling to the plasma wake focusing / timing

  - very low charge ~ 20 fC [1]
  - timing constraints $\sim \lambda_p / c$



[1] B. Marchetti et al.,NIMA vol. 829, pp. 278–283, Sep. 2016

[2] Y. Wu et al. arXiv (2020)

typical laser-plasma experimental setup

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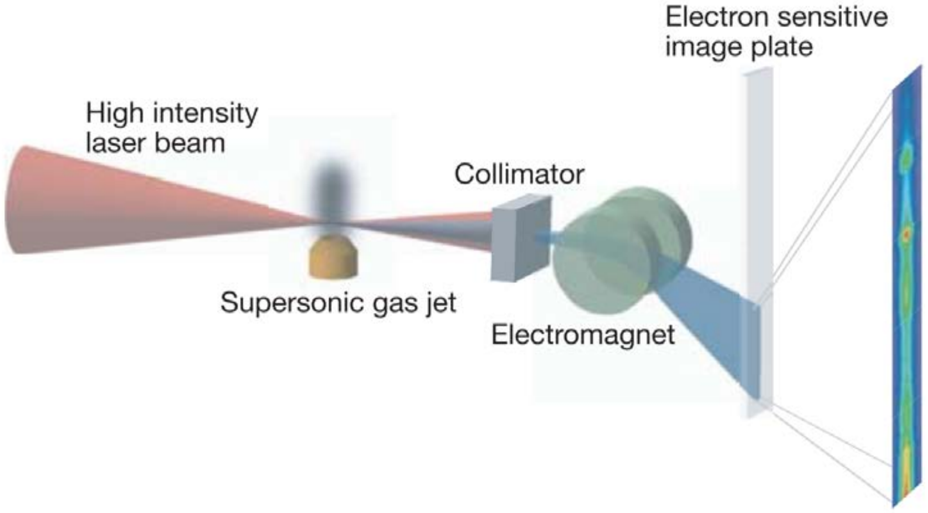
For production of $100 < E < 500$ MeV, in a large vacuum chamber:

laser:

- energy : 0.5-2 J,
- duration: 30-40 fs
- waist : 10-20 um
- repetition rate:1-10 Hz

Plasma:

- target: supersonic gas jet 1-4 mm/gas cell 1-50mm, capillary discharge (>50mm)
- gas: H_2 or He ($+0.1 - 10\% N_2$)
- density: $1 - 50 \times 10^{18}\ cm^{-3}$



src: *Mangles, S. P. D. et al. Nature 431, 535–8 (2004)*

LPA state of the art

PALLAS

LPA a **one** parameter optimization performer

Property	State of the art value [*]	Injection	Laser driver	Target type; density cc; length	Reference	Remarks
Energy	**3 GeV** (± 15%, ~50pC) **7.8 GeV** (± 5%, ~5pC)	Self-injection	26J/30fs/30um 31J/30fs/60um	Gas cell; 1.4e18 / 6mm Capillary discharge; 2.3e17/200mm	Kim (2017) - GIST Gonsalvez (2019) - LBNL	In single stage
Energy spread	**1%** (@ 10pC, 200MeV) **5-30%** (@50-3GeV) **5%**-100% (@ 400MeV, 80pC) **0.4%**-20% (@ 300-350MeV,~10pC)	Colliding pulse self-injection ST-Ionization Downramp	1.1J/35fs/20um 1-5J/20-50fs/15-30um 2-5J/30fs/30um 2-3J/33fs/32um	Gas jet Gas jet, gas cell Gas jet Gas jet	Rechatin (2009) - LOA Many references (2010-2018) Mirzaie (2015) Shangai MOE Wang(2016) Shangai MOE	Still one order from FEL application requiring 0.1%
Normalized transverse emittance	**~ 0.1 π mm.mrad** (@250MeV, ~15pc) **~ 0.01 π mm.mrad** (@200MeV-600MeV)	Self injection Shock injection	1.5J/30fs/20um	Gas jet 5e18/4mm	Weingartner (2012) - MPQ Qin (2018) - Shangai MOE	Measurement at the resolution limit
Bunch length	**5-10 um**	Self-injection	1.1J/35fs/20um	Gas jet	Lundh (2011) - LOA Kaluza(2014) - Jena Heigholt(2015) - UMu	Measurement at the resolution limit
Charge	~ 300 pC (@ 300-350MeV, 12-17%) **>1nC** (@ 330 MeV >15%-)	ST-Ionization Shock injection	2.5J/40fs/20um 10J/40fs/>25um	Gas jet Gas jet	Couperus (2017) - Jena Götzfried(2020) - LMU	Beam loading
Repeatability	**2.4%E, 11%Q** (@1Hz, 368MeV, 25pC) **4%-11% E, 23%Q**(@1kHz, 2.5MeV, 3pC)	Ionization Downramp	2J/42fs/25um 10mJ/25fs/6um	Gas cell SSF; Gast jet; 7e19/ 0.1mm	Maier (2020) - DESY/UHH Rovige (2020) - LOA	
Repetition rate	**~ 1 Hz** @ >1 GeV **~ 1 kHz** @ 1-3 MeV	Self-injection Downramp	>25J/30fs/>30um ~mJ/ <25fs /6um	Gas cell, capillary High density gas jet; 7e19/ 0.1mm	Kim (2017) - GIST, Gonzalves (2019) He (2015)- UMi, Salehi(2017) - UMd Guenot (2017) - LOA	Limited by laser

Note : see last slides for references detail

laser control & diags details

control of the laser driver is the key

- 38 CCDs + (12)
- 6 points energy measurement (+2)
- 3 spectrometers (+1)
- **spectral control loop**: ultra broadband dazzler + additional wizzler => correct high phase order
- **spatial control loop**: large aperture deformable mirror + wavefront sensor => Get high Strehl ratio ($S_r > 0.8$) and work on intermediate field homogeneity.
- **pointing stabilization system** : target value 0.2urad (RMS)!!
  Spectral side band injection from osscillator for high bandwidth (> 400 Hz) pointing correction
  Scanning lightweight SiC mirror for large beam stabilization.

- high accuracy pulse duration measurement in the interaction region : test most reliable technique for fast reconstruction [1] including pulse front-tilt.

[1] N. C. Geib, *et al.* , 'Common pulse retrieval algorithm: a fast and universal method to retrieve ultrashort pulses', Optica, vol. 6, no. 4, p. 495, Apr. 2019

[2] image credits : MERSEN