PALLAS

laser-plasma accelerator test facility @ IN2P3

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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

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
- 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% \( \rightarrow \) ~1%, peak brightness ~0.5 -> 5 pC/MeV @ 1Hz

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


National and (international) context
National overview

07/2019: GDR organized discussions 2 projects emerged structuring a potential French contribution to EuPRAXIA

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 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...
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

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

- **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

- **continuous 10 Hz** beam to enable machine studies

<table>
<thead>
<tr>
<th>Parameters</th>
<th>phase 1</th>
<th>phase 2</th>
<th>phase 3</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td>150</td>
<td>200</td>
<td>200</td>
<td>MeV</td>
</tr>
<tr>
<td>charge</td>
<td>15-30</td>
<td>30</td>
<td>30</td>
<td>pC</td>
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<tr>
<td>frep</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>Hz</td>
</tr>
<tr>
<td>energy spread</td>
<td>&lt;10%</td>
<td>&lt; 5%</td>
<td>&lt; 5%</td>
<td>peak (FWHM)</td>
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<tr>
<td>$\varepsilon_{T,n}$</td>
<td>1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>mm.mrad</td>
</tr>
<tr>
<td>stability</td>
<td>5%</td>
<td>3%</td>
<td>1%</td>
<td>-</td>
</tr>
<tr>
<td>reproductibility</td>
<td>5%</td>
<td>3%</td>
<td>3%</td>
<td>-</td>
</tr>
</tbody>
</table>

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

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## LPI parameters

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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>phase 1</th>
<th>phase 2</th>
<th>phase 3</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>laser strength, $a_0$</td>
<td>1.15</td>
<td>1.97</td>
<td>1.97</td>
<td></td>
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<tr>
<td>laser duration, $t_L$</td>
<td>40</td>
<td>30</td>
<td>30</td>
<td>fs (FWHM)</td>
</tr>
<tr>
<td>laser waist, $w_0$</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>um</td>
</tr>
<tr>
<td>Strehl ratio, $S_r$</td>
<td>&gt; 0.8</td>
<td>&gt; 0.8</td>
<td>&gt; 0.8</td>
<td>-</td>
</tr>
<tr>
<td>beam pointing, $\delta u_i$</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>urad</td>
</tr>
<tr>
<td>stability</td>
<td>1%</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>-</td>
</tr>
<tr>
<td>frep</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>Hz</td>
</tr>
<tr>
<td>target type</td>
<td>multi-cell</td>
<td>multi-cell</td>
<td>multi-cell</td>
<td>-</td>
</tr>
<tr>
<td>injection</td>
<td>STII</td>
<td>STII</td>
<td>STII</td>
<td>-</td>
</tr>
<tr>
<td>electron beamline</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>-</td>
</tr>
</tbody>
</table>

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

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, 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**
- **Simulation support**: reinforce collaboration between experimental and numerical people

Open to the community in the spirit of accelerator development: **OpenHardware / OpenData**
Advanced laser control
Laser performances & control

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** longitudinal pulse shaping = controlled pre-pulse for preformed plasma channel (PPG)
- full data-logging and gateway to accelerator control command 😊
Plasma target
Plasma target

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 \[ Z_r = \frac{\pi w_0^2}{\lambda_0} \sim 1.3 \text{ mm} \]
- 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
  \[ \Rightarrow \text{narrowing of the injection length} \]
- **tune** the injected charge / beam loading
  \[ \Rightarrow \text{Control of the exit down ramp is crucial!} \]

... in only few mm

---

Example of simulation:

- LASERIX laser input
- generic shape for $n_e(x)$ inspired from various ref\(^1\)
- parameter: $x_{\text{foc, vac}}$

Multi-cell to get access to each region tuning:
- length and density
- dopant $C_{\text{N}_2}(x)$

Open ways to:
- Fine optimization
- Control
- Tolerancing

---

Optimization of the LPI core

Input

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

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 ...

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

 prototype preliminary design

- divide in region / process
- customizable part (nozzle in, central body, nozzle out)
- integrate in the beamline \((10 \times 6 \times 15 \text{ cm}^3)\)
- transverse optical access
Plasma cell test bench

Dedicated test bench for plasma cell:

- **fs intense laser driver** $I \sim 5 \times 10^{16} \text{W}. \text{cm}^{-2}$ for plasma channel generation
- **synchronized probe beam** for time resolved transverse interferometry
- high resolution **plasma density diagnostic** $\delta n_e \sim 5 \times 10^{17} \text{cm}^{-3}$
- spectral imaging for **dopant spatial distribution control**
- 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.)


Electron beam control and transport
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** previously tested on our photo-injector PHIL for beam duration and **longitudinal phase-space** measurement
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
Development plan

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

Annexure: Schedule of activities

- Phase 1: 2020-2021
  - Renovation bunker
  - LBTL
  - LIF
  - PlasmaCell
  - LPI simulation studies
  - Laser stability test

- Phase 2: 2022-2023
  - PHIC
  - Electron beamline
  - Control command
  - LPI commissioning
  - Radiation safety
  - LPI optimization

- Phase 3: 2024-2027
  - Accelerator commissioning

Date: 02/09/2021
Resources

- 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

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

Opportunities

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

Weaknesses

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

Threats

- ASN
- Some spares can not be covered by the budget.
Infrastructures: overview
Summary

- 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 Physics**, 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
Laser wakefield acceleration
in a bubble

some basics

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

\[
F_p = -m_e c^2 \nabla (a^2 / 2)
\]
\[
a = e E_L / m_e \omega_L c
\]

non linear regime \(a > 1\), in 1D, plasma wakefield, density perturbation:

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

- High accelerating field, \(E_0 \sim 100 \text{ GV/m}\)
- ultra short bunches, \(\sim 10 \text{ fs}\)

- tiny transient structure \(\sim 10 \mu \text{m}\)
- hard to control \(\rightarrow\) large fluctuation

Injection ...

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

<table>
<thead>
<tr>
<th>external</th>
<th>ionization</th>
<th>density down-ramp</th>
<th>self-injection</th>
</tr>
</thead>
</table>

$a_0 \sim 1$

+ linear regime control acceleration
- requires a RF linac
- coupling to the plasma wake focusing / timing
  - very low charge $\sim 20 \text{ fC}^1$
  - timing constraints $\sim \lambda_p/c$

---

**typical laser-plasma experimental setup**

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

LPA state of the art

LPA a **one** parameter optimization performer

<table>
<thead>
<tr>
<th>Property</th>
<th>State of the art value [*]</th>
<th>Injection</th>
<th>Laser driver</th>
<th>Target type; density cc; length</th>
<th>Reference</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>3 GeV (± 13%, -50°C)</td>
<td>Self-injection</td>
<td>26/30/6/10um</td>
<td>Gas cell; 1.4e18 / 6mm</td>
<td>Kim (2017) - GIST</td>
<td>In single stage</td>
</tr>
<tr>
<td></td>
<td>7.8 GeV (± 5%, -5°C)</td>
<td></td>
<td>31/30/6/10um</td>
<td>Capillary discharge; 2.3e17/200mm</td>
<td>Goncalves (2019) - LBNL</td>
<td></td>
</tr>
<tr>
<td>Energy spread</td>
<td>1% (0.1°C, 200 MeV)</td>
<td>Collision pulse</td>
<td>1.1/1.5/2/1.5/2/1.5/2.0/1.0/2</td>
<td>Gas jet; Gas jet; Gas cell</td>
<td>Rechatin (2009) - LOA</td>
<td>Still one order from FEL</td>
</tr>
<tr>
<td></td>
<td>5-30% (5-50°C)</td>
<td>self-injection</td>
<td>1.5/2/3/1/2/1/3/2/1/6/8/2</td>
<td>Gas jet; Gas jet; Gas jet</td>
<td>Many references (2010-2018)</td>
<td>application requiring</td>
</tr>
<tr>
<td></td>
<td>0.4-20% (0.0-360 MeV)</td>
<td>ST-ionization Down ramp</td>
<td>1.5/2/3/4/1/2/3/4/2/4/2/6/2</td>
<td>Gas jet; Gas jet; Gas jet</td>
<td>Minzale (2015) - Shanghai MOE</td>
<td>0.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Wang (2016) - Shanghai MOE</td>
<td></td>
</tr>
<tr>
<td>Normalized transverse</td>
<td>- 0.1 π mm.mrad (250 MeV, -15πc)</td>
<td>Self injection Shock injection</td>
<td>1.5/3/2/0/2.0</td>
<td>Gas jet; 5e18/4mm</td>
<td>Weingartner (2012) - MPQ</td>
<td>Measurement at the resolution limit</td>
</tr>
<tr>
<td>emittance</td>
<td>~ 0.01 π mm.mrad (200 MeV-600 MeV)</td>
<td></td>
<td></td>
<td></td>
<td>Qin (2018) - Shanghai MOE</td>
<td></td>
</tr>
<tr>
<td>Bunch length</td>
<td>5-10 um</td>
<td>Self-injection</td>
<td>1.1/1.5/3/2/0.5</td>
<td>Gas jet; Gas jet; Gas jet</td>
<td>Lundh (2011) - LOA</td>
<td>Measurement at the resolution limit</td>
</tr>
<tr>
<td>Charge</td>
<td>~ 300 pC (0.300-350 MeV, 12-17%)</td>
<td>ST-Ionization Shock injection</td>
<td>2.5/4/0/1/2/0/2/0</td>
<td>Gas jet; Gas jet; Gas jet</td>
<td>Cooper (2017) - Jena Götzfried (2020) - LUMu</td>
<td>Beam loading</td>
</tr>
<tr>
<td></td>
<td>&gt;=1nC (0.330 MeV &gt;15%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repeatability</td>
<td>2.4% E, 11% Q @1Hz, 368 MeV, 2.5pC</td>
<td>Ionization Down ramp</td>
<td>2.42/9.25/6.8/2/3/4/6/6/6/5/7</td>
<td>Gas cell; SSF; Gas jet; 7e19/0.1mm</td>
<td>Maier (2020) - DESY/UHH</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4% TT E, 23% Q @1kHz, 2.3 MeV, 3pC</td>
<td></td>
<td></td>
<td></td>
<td>Kovac (2020) - LUMu</td>
<td></td>
</tr>
<tr>
<td>Repetition rate</td>
<td>- 1 Hz @ &gt;1 GeV</td>
<td>Self-injection Down ramp</td>
<td>23/30/6/30/30/7/36/6/6/6/6</td>
<td>Gas cell; capillary; High density gas jet; 7e19/0.1mm</td>
<td>Kim (2017) - GIST, Goncalves (2019) He (2015) - LUMU, Salehi (2017) - LUMU, Guerin (2017) - LUMU</td>
<td>Limited by laser</td>
</tr>
<tr>
<td></td>
<td>- 1 kHz @ 1-3 MHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 oscillator 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 including pulse front-tilt.

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[2] Image credits: MERSEN