Eupraxia Laser design optimization and industry

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Sebastien LAUX, Thales Group
Oliver KARGER Hamburg University (UHH)
Alexander KNETSCH Hamburg University (UHH)
• An industrial laser for EuPRA-XIA?
• Strategy for a rep-rated PW laser
• Technology down-selection criteria
• Preliminary laser design
  – Main candidate components
  – Outstanding issues
• Transport and Interaction point challenges
  – Stability and reproducibility
D4.1 (M12) Benchmarking of existing technologies and comparison with EuPraxia requirements

*Explore and identify promising technologies*

D4.2 (M24) Preliminary laser design

To be developed with an eye to perspective industrial development

D4.3 (M24) Preliminary design of transverse functions

To account for final use of EuPRAXIA (user facility)
D4.4 (M36) Final requirements of laser system

To comfortably accommodate LWFA design and other laser based activities

D4.5 (M36) Control command design system

To enable turn-key-like operation of the laser system
Engage key players

• World-wide scenario in Petawatt scale laser development is seeing major contributions from industry and research labs involved in challenging projects;

• After a first exploration meeting (Saclay, May 18°, 2016), potential contributors were identified and invited to contribute to the Eupraxia design.
Strategy: main laser systems

Starting point:
Laser system requirements emerged in WP 2 Physics and Simulation (A.Mosnier, L. Silva) and WP3 High Gradient Laser Plasma Accelerator Structure (B.Cros, Z.Najmudin)

Three main lasers envisaged:

Laser 1: drive a 150 MeV injector
Laser 2: drive a 1 GeV accelerator
Laser 3: drive a 5 GeV accelerator

Strategy:
• Analysis of the available technologies for PW-class lasers,
• Comparison with the requirements of Eupraxia,
• Evaluation of the suitability for the given time frame for construction (<5 yrs)

L.A.Gizzi, EAAC2017, Elba
• Discussion about detailed laser parameters and interaction with laser-plasma acceleration workpackages (WP2-3) to identify laser parameters for the most challenging performance (5GeV);
  • Minimum required pulse duration: 60 fs
  • Minimum required pulse energy: 50 J
• High repetition rate to enable active stabilization via feedback loops;
  • Ideally 1kHz, minimum 20 Hz, but exploring 100 Hz option
• Challenging problems in beam transport, focusing, diagnostics: a key part of the reliability of the laser system as a whole;
  • Extensive data acquisition from existing systems needed.
Produce a credible laser design to meet project specifications for a PW-class system, with demanding high average power (>1 kW, ideally 10 kW).

Major effort required to fill the gap between existing and required laser technology.
## Laser 1 Specs: 150 MeV injector

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Label</th>
<th>P0*</th>
<th>P1**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>$\lambda_1$(nm)</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>Maximum energy on target (J)</td>
<td>$E_{\text{target}}$</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Energy tuning resolution (% of targeted value)</td>
<td>$dE$</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Total output energy (incl. Diagnostic beams)</td>
<td>$E_{\text{tot}}$</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>Pulse length (FWHM) (fs)</td>
<td>$\tau_1$</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>$f_1$</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Contrast at 100 ps</td>
<td>$C_1$(100 ps)</td>
<td>1,00E+11</td>
<td>1,00E+12</td>
</tr>
<tr>
<td>Contrast at 50 ps</td>
<td>$C_1$(50 ps)</td>
<td>1,00E+10</td>
<td>1,00E+11</td>
</tr>
<tr>
<td>Contrast at 10 ps</td>
<td>$C_1$(10 ps)</td>
<td>1,00E+09</td>
<td>1,00E+10</td>
</tr>
<tr>
<td>Contrast at 1 ps</td>
<td>$C_1$(1 ps)</td>
<td>1,00E+06</td>
<td>1,00E+08</td>
</tr>
<tr>
<td>Contrast at 100 fs</td>
<td>$C_1$(100 fs)</td>
<td>1,00E+02</td>
<td>1,00E+03</td>
</tr>
<tr>
<td>Number of beams</td>
<td>$N_1$</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Synchro. to global reference (P-V) (fs)</td>
<td>$\sigma_{\Delta t}$</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Beam intensity distribution (x-y) in focal plane</td>
<td>-</td>
<td>Gaussian</td>
<td>Supergaussian (n=10)</td>
</tr>
<tr>
<td>Polarization in focal plane</td>
<td>$P_1$</td>
<td>linear</td>
<td>linear, circular</td>
</tr>
<tr>
<td>Max ellipticity of focal spot (Am/AM)</td>
<td></td>
<td>0.8</td>
<td>0.95</td>
</tr>
<tr>
<td>Polarization purity (%)</td>
<td>$\sigma_{&lt;E&gt;}$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Requirement on energy stability (RMS) %</td>
<td>$\sigma_{&lt;E&gt;}$</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Requirement on focal size &amp; $Z_L$ stab. (RMS) %</td>
<td>$\sigma_{&lt;Z_L&gt;}$</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Focal spot size stability (on target plane) (RMS) %</td>
<td>$\sigma_{&lt;w_0/w_0&gt;}$</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Pointing stability (RMS) (µrad)</td>
<td>$\sigma_{&lt;x'&gt;}$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Required lab room space (m²) including technical rooms but no beam transport</td>
<td>$A_1$</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

*This value is mandatory*

**This value is a goal that we will try to reach**
<table>
<thead>
<tr>
<th>Parameter</th>
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<th>$P_0^*$</th>
<th>$P_1^{**}$</th>
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<tr>
<td>Wavelength (nm)</td>
<td>$\lambda_2$ (nm)</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>Maximum energy on target (J)</td>
<td>$E_2$</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>Energy tuning resolution (% of targeted value)</td>
<td>$dE$</td>
<td>7</td>
<td>5</td>
</tr>
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<td>Shortest pulse length (FWHM) (fs)</td>
<td>$\tau_2$</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
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<td>$f_2$</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Contrast at 100 ps</td>
<td>$C_1(100 \text{ ps})$</td>
<td>1,00E+11</td>
<td>1,00E+12</td>
</tr>
<tr>
<td>Contrast at 50 ps</td>
<td>$C_1(50 \text{ ps})$</td>
<td>1,00E+10</td>
<td>1,00E+11</td>
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<tr>
<td>Contrast at 10 ps</td>
<td>$C_1(10 \text{ ps})$</td>
<td>1,00E+10</td>
<td>1,00E+10</td>
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<tr>
<td>Contrast at 1 ps</td>
<td>$C_1(1 \text{ ps})$</td>
<td>1,00E+06</td>
<td>1,00E+08</td>
</tr>
<tr>
<td>Contrast at 10 fs</td>
<td>$C_1(100 \text{ fs})$</td>
<td>1,00E+02</td>
<td>1,00E+03</td>
</tr>
<tr>
<td>Number of beams</td>
<td>$N_2$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Synchro. to global reference (P-V) (fs)</td>
<td>$\sigma_{At}$</td>
<td>10</td>
<td>5</td>
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<td></td>
<td>1</td>
<td>1</td>
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<td>Requirement on energy stability (RMS) (%)</td>
<td>$\sigma_{E}$</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Requirement on focal size &amp; $Z_L$ stab. (RMS) (%)</td>
<td>$\sigma_{2L}$</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Focal spot size stability (on target plane) (RMS) (%)</td>
<td>$\sigma_{W0}/w_0$</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Pointing stability (RMS) ($\mu$rad)</td>
<td>$\sigma_{x'&gt;}, \sigma_{y'}$</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Required lab room space (m2)</td>
<td></td>
<td>$A_1$</td>
<td>600 400</td>
</tr>
</tbody>
</table>

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### Laser Driver 5 GeV (Laser 3)

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<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>$\lambda_2\ (\text{nm})$</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>Maximum energy on target (J) *</td>
<td>$E_2$</td>
<td>50</td>
<td>100</td>
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<td>Energy tuning resolution (% of targeted value)</td>
<td>$dE$</td>
<td>7</td>
<td>5</td>
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<tr>
<td>Shortest pulse length (FWHM) (fs)</td>
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<td>60</td>
<td>50</td>
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<td>100</td>
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<td>1.00E+02</td>
<td>1.00E+03</td>
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<tr>
<td>Number of beams</td>
<td>$N_2$</td>
<td>1</td>
<td>1</td>
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<td>1</td>
</tr>
<tr>
<td>Required lab room space (m²) Including technical rooms but no beam transport</td>
<td>$A_1$</td>
<td>700</td>
<td>500</td>
</tr>
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Hold-ups for scalability of current systems include:

- Pumping technology: diode (direct or indirect) pumping;
- Gain media: material should be industrially available at laser quality, scalable in size and capable of supporting large bandwidth and efficient cooling;
- Grating technology to improve for higher damage threshold and smaller beam size
- Optics Damage threshold
- Thermal load, management, dissipation
TWO POSSIBLE SCENARIOS identified:

- Medium risk: TiSa with DPSSL pump lasers;
- High risk: Direct CPA with new materials (required for >100Hz);

Scenarios matching large programmes at other institutions (e.g. LLNL, LBNL, STFC ...);
Available subsystems (injector)

**LWFA injector:** required 7J @ 800 nm, 30 fs, 20 Hz (minimum)

May become available at industrial level from different suppliers e.g.:

- **Amplitude Technologies**
  - PULSAR: 5 J, <25 fs, 5-10 Hz
  - Ti:Sapphire

- **Thales**
  - ALPHA5/XS: 20 J, 25 fs, 5 Hz
  - Ti:Sapphire

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Available subsystems (front-end)

300 mJ, 100 Hz, 25 fs

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L.A.Gizzi, EAAC2017, Elba

**STFC DiPOLE 100 (HiLASE)**

- Diode pumped Yb:YAG slab, He-cooled
- >100 J output energy demonstrated @ 10 Hz, 1030 nm
- >60 J conversion @ 515 nm expected

**LLNL HAPLS L3 (ELI-Beamlines)**

- Diode pumped Nd:APG-1 glass, He-cooled
- 75 J output energy demonstrated @ 3.3 Hz, 1053 nm
- 45 J SHG energy @ 526.5 nm demonstrated
- Ramping up to 10 Hz, 200 J (design limit): in progress

**Amplitude P-60 (ELI-ALPS HF)**

- Flashlamp pumped Nd:YAG/DPSSL possible
- 45 J output energy demonstrated @ 10 Hz, 1064 nm
- 60 J SHG energy @ 532 nm: design target
- Ramping up to 10 Hz, full energy (design limit): in progress

**HZDR PEnELOPE**

- Developed by Dresden Helmholtz Institute
- Diode-pumped Yb:CaF$_2$ slabs, He cooled
- 150 J, 150 fs, 1 Hz, 1030 nm
- Expected optical to optical conversion efficiency 5-10% before compression (unsaturated amplification)

Laser driver: DPSSL(upgradable) pump sources
Block diagram of EuPRAXIA laser

Master oscillator → Front end → Amplification stage (>7J) → Small Compressor → 7 J, 30 fs

Front end → Amplification stage (7 J) → Medium Compressor → 30 J, 30 fs

Front end → Amplification stage (7 J) → 100 J, 50 fs

Amplification stage (7 J) → Medium Compressor
Amplification stage (>30 J) → Large Compressor
100Hz, high contrast ratio ($>10^{12}$ at ps) front-end (very) preliminary layout

Preliminary scheme: double CPA scheme with XPW pulse cleaning

European companies potentially interested

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A set of development activities have been identified to address main issues and proceed towards the construction of a driver for a plasma-based accelerator with the performance and quality as required by EuPRAXIA

- **Driver pulse temporal shaping and synchronization**
- **High repetition rate driver pulse: towards 100 Hz**
- **High repetition rate driver pulse: dpssl pumping**
- **Laser Driver design and test on LPA**
- **Laser Driver stability and active control**

**Collaborating Institutes**

IEP: Institute of Electrophysics (IEP), UD RAS, Russia  
FBH: Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik  
OX: Oxford University  
IOQ: Institut für Optik und Quantenelektronik Jena  
UHH: Hamburg University

**Collaborating Industry**

Amplitude Technologies  
Thales: Thales Lasers

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At each compressor we will arrive with an average power of:

- **Injector 150MeV**
  - 1 kW (10J @ 100Hz), needed 25 fs after compression (38nm bandwidth), spectral acceptance required: 120 nm

- **Injector 1GeV**
  - 4 kW (40J @ 100Hz), needed 30-35 fs after compression (32nm bandwidth), spectral acceptance required: 100 nm

- **Accelerator 5GeV**
  - 16 kW (160J @ 100Hz), needed 60 fs after compression (16nm bandwidth), spectral acceptance required: 60 nm

LIDT determines the laser fluence arriving on the compressor: $100\text{mJ/cm}^2$. This sets the value of the average intensity reaching the three compressors: $10\text{ W/cm}^2$
Compressor issues

INDUSTRIES and LABS

Gold Coated Grating without epoxy resin for lower thermal stress

Plymouth Grating Laboratory
World record for the largest MultiLayer Dielectric (MLD) diffraction grating

Work in progress at DESY (V. Leroux, WG7)

Lawrence Livermore National Laboratory
Photoresist-Free High Average Power Compressor Gratings

Transport issues

High beam quality and pointing stability, optomechanics, mirrors, actuators

Passive stabilization

In contact with an industry whose action is to stabilize optic mountings in a “definitive” way.

Active stabilization

Adaptive Optics
ILAO deformable mirror + HASO wavefront sensor

Close loop that allows for active (but also passive) correction of the beam spatial profile.

... and many more
SUMMARY

• EuPRAXIA design study progressing rapidly;
• Mandatory laser specs set highly demanding kW system;
• Aiming at Ti:Sa with DPSSL pump lasers;
• Current DPSSL pump systems exceeding kW;
• Major effort required to meet focusing stability;
• Building on the experience of current PW facilities;
• Strong involvement of European industry and labs.
16 Participants

22 Associated Partners
(as of October 2016)
www.eupraxia-project.eu

#EuPRAXIA
#plasma
#acclerator