Leonida A. Gizzi,
CNR, Istituto Nazionale di Ottica,
& INFN
Pisa, Italy

5th iFAST Annual Meeting, 21–22 Oct 2025, CERN

WP6 - Novel Particle Accelerators Concepts and Technologies

- Task 1 (R.A. + M. Ferrario): **Novel Particle Accelerators Concepts and Technologies** (NPACT – **EuroNNAc4**)
- Task 2 (Leo Gizzi): **Lasers for Plasma Acceleration** (LASPLA)
- Task 3 (Cedric Thaury): **Multi-scale Innovative targets for laser-plasma accelerators** (MILPAT)
- Task 4 (Francois Mathieu): **Laser focal Spot Stabilization Systems** (L3S)

iFAST/EuroNNAc Deliverables

Deliverables related to WP6	
D6.1: EAAC workshops and strategies. *Report on the EAAC workshops as strategic forums for international accelerator R&D and resulting strategies*	M42 Nov. 2024
D6.2: LASPLA Strategy. *Report on a strategy for laser drivers for plasma accelerators.*	M46 Mar. 2025
D6.2: Electron acceleration experiments with new targets. *Report on electron acceleration with micro-scale target at a kHz repetition rate, and with long targets at the multi-Joule level.*	M24 April 2023
D6.4: Improvement of the laser intensity stability on target. *Report showing the stability on two laser facilities before and after improvement.*	M36 April 2024

State of the Art and Identified Challenges

>Current LPA relies on **Ti:Sapphire laser systems**, which provide high peak power but **low average power**, **low repetition rate**, **limited efficiency**,

>Future LPA drivers must provide:

ultrashort pulses (< 50 fs)

high repetition rates (100 Hz → kHz → > 10 kHz)

high average power (multi-kW average, multi-Joule per pulse)

high wall-plug efficiency (> 30%)

scalable, robust architectures

>Key technical challenges include:

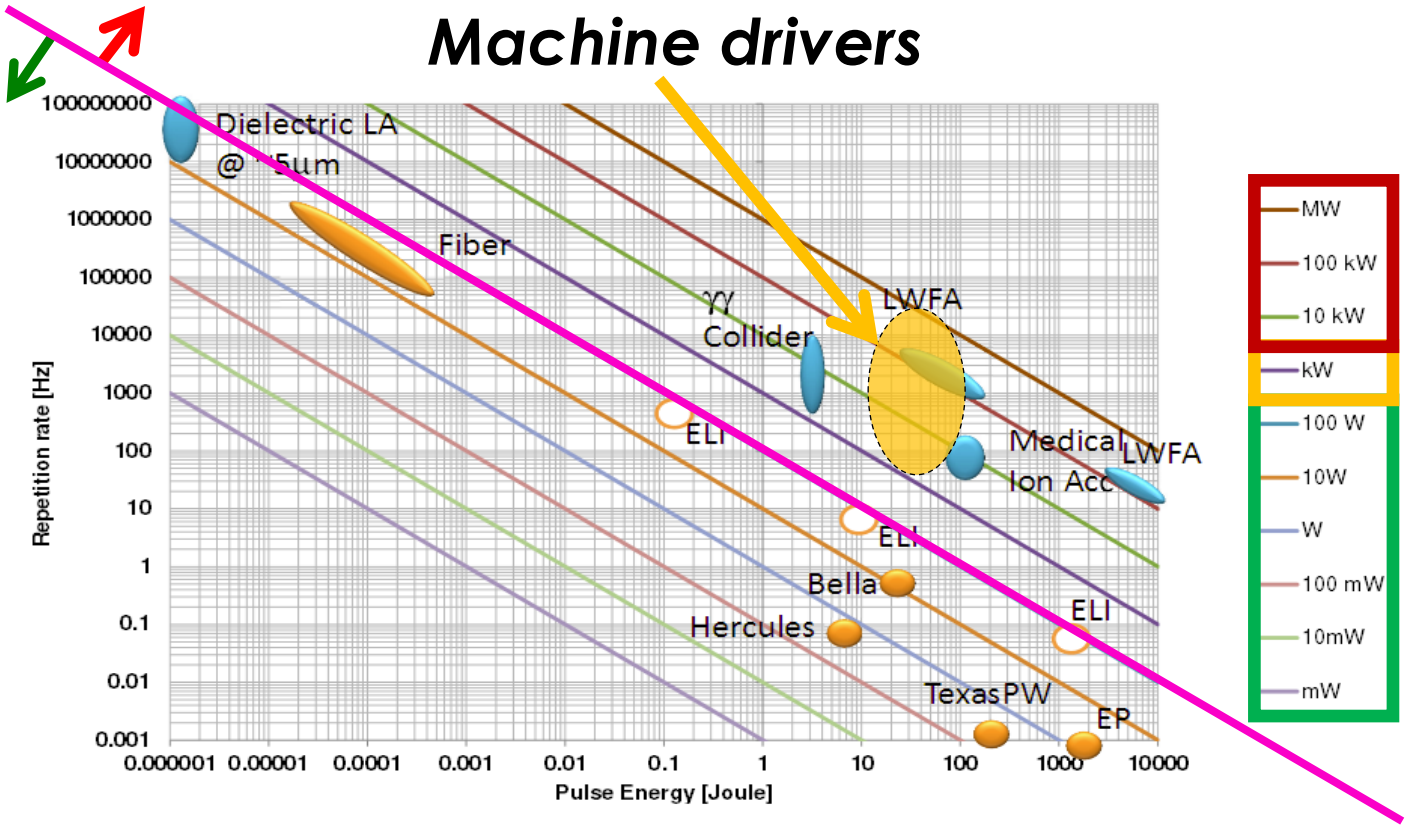
achieving **kHz operation** with stable pulse energy and spatial quality,

shot-to-shot repeatability, **beam pointing stability**, and **thermal management**.

>Industrial involvement is essential to develop **turn-key, high-reliability systems** rather than one-off prototypes.

Objective of the LASPLA Task

Foster development **of** PW-class system, with high repetition rate (≈kHz)



HOW

Establish a **coordination activity with networking** and training of **main laser labs and industrial partners**, focused on laser-driver R&D.

Identify the **key laser architectures and components** required for future LPA drivers: ultra-short pulse lasers (< 50 fs), high repetition rate (100 Hz to kHz), high wall-plug efficiency (> 30%), and scalable gain media (e.g. Tm-doped, ceramics, thin-disk designs).

Major effort required to fill the gap between **existing** and **required** laser technology

L.A. Gizzi et al., A viable laser driver for a user plasma accelerator, NIM **A 909 , 58 (2018); https://doi.org/10.1063/1.4984906

Results

> A **network of laboratories and industrial partners** (CNR, CNRS, DESY, Thales, Amplitude Technologies, etc.) was established under LASPLA.

>Dedicated workshop (Palaiseau, Pisa, @EAAC, @ELISS, @LPAW, Remote) addressed:

high-repetition laser technologies,

novel gain media (e.g. Tm-based, 2 μm lasers),

diode-pumped amplifiers,

and integration with plasma accelerator experiments.

>Conceptual studies and technology developments carried out:

Multi-Pulse Laser Wakefield Acceleration (MP-LWFA) schemes using pulse trains or modulated beams to drive plasma waves — enabling use of high-rep-rate, industrial lasers.

Development of **high-efficiency amplifiers** based on Tm:Lu_2O_3, ceramic disk technology.

>I.FAST societal impact: e.g. **Very High Energy Electron (VHEE) and PIXE;**

>Publications

Results: Publications

List of IFAST publications concerning lasers and plasma accelerators

- Differential pumping for khz operation of a laser wakefield accelerator based on a continuously flowing hydrogen gas jet, J. Monzac, S. Smartsev, J. Huijts, L. Rovige, I. A. Andriyash, A. Vernier, V. Tomkus, V. Girdauskas, G. Raciukaitis, M. Mackeviciute, V. Stankevic, A. Cavagna, J. Kaur, A. Kalouguine, R. Lopez-Martens, and J. Faure, REVIEW OF SCIENTIFIC INSTRUMENTS, 96(4), APR 2025, DOI: 10.1063/5.0246912
- Cross-relaxation and temporal dynamics of lasing at 2 μm in thulium-doped ceramic material, A. Fregosi, F. Brandi, L. Labate, F. Baffigi, G. Cellamare, M. Ezzat, D. Palla, G. Toci, A. Whitehead, and L. A. Gizzi, HIGH POWER LASER SCIENCE AND ENGINEERING, 13, APR 25 2025, DOI: 10.1017/hpl.2025.37
- Sub-2-cycle post-compression of multi-mj energy ti:sapphire laser pulses in a gas-filled multi-pass cell, L. Daniault, J. Kaur, G. Galle, C. Sire, F. Sylla, and R. Lopez-martens, OPTICS LETTERS, 49(23):6833-6836, DEC 1 2024, DOI: 10.1364/OL.544563
- Optical ionization effects in khz laser wakefield acceleration with few-cycle pulses, J. Monzac, S. Smartsev, J. Huijts, L. Rovige, I. A. Andriyash, A. Vernier, V. Tomkus, V. Girdauskas, G. Raciukaitis, V. Stankevic, A. Cavagna, J. Kaur, A. Kalouguine, R. Lopez-Martens, and J. Faure, PHYSICAL REVIEW RESEARCH, 6(4), NOV 5 2024, DOI: 10.1103/PhysRevResearch.6.043099
- Quantitative elemental analysis of a specimen in air via external beam laser-driven particle-induced x-ray emission with a compact proton source, M. Salvadori, F. Brandi, L. Labate, F. Baffigi, L. Fulgentini, P. Galizia, P. Koester, D. Palla, D. Sciti, and L. A. Gizzi, PHYSICAL REVIEW APPLIED, 21(6), JUN 10 2024, DOI: 10.1103/PhysRevApplied.21.064020
- Simple few-shot method for spectrally resolving the wavefront of an ultrashort laser pulse, S. Smartsev, A. Liberman, I. a. Andriyash, A. Cavagna, A. Flacco, C. Giaccaglia, J. Kaur, J. Monzac, S. Tata, A. Vernier, V. Malka, R. Lopez-Martens, and J. Faure, OPTICS LETTERS, 49(8):1900-1903, APR 15 2024, DOI:, 10.1364/OL.502000
- Carrier-envelope phase controlled dynamics of relativistic electron beams in a laser-wakefield accelerator, L. Rovige, J. Monzac, J. Huijts, I. A. Andriyash, A. Vernier, J. Kaur, M. Ouille, Z. Cheng, V. Tomkus, V. Girdauskas, G. Raciukaitis, J. Dudutis, V. Stankevic, P. Gecys, R. Lopez-Martens, and J. Faure, EUROPEAN PHYSICAL JOURNAL-SPECIAL TOPICS, 232(13, SI):2265-2276, SEP 2023, DOI: 10.1140/epjs/s11734-022-00675-7
- A model for pumping optimization in edge-pumped disk amplifiers, D. Palla, L. Labate, F. Balligi, G. Cellamare, and L. A. Gizzi, OPTICS AND LASER TECHNOLOGY, 156, DEC 2022, DOI: 10.1016/j.optlastec.2022.108524
- Axiparabola: a new tool for high-intensity optics, K. Oubrerie, I. A. Andriyash, R. Lahaye, S. Smartsev, V. Malka, and C. Thaury, JOURNAL OF OPTICS, 24(4), APR 1 2022, DOI: 10.1088/2040-8986/ac57d2
- Waveform control of relativistic electron dynamics in laser-plasma acceleration, J. Huijts, L. Rovige, I. A. Andriyash, A. Vernier, M. Ouille, J. Kaur, Z. Cheng, R. Lopez-Martens, and J. Faure, PHYSICAL REVIEW X, 12(1), FEB 24 2022, DOI: 10.1103/PhysRevX.12.011036
- Symmetric and asymmetric shocked gas jets for laser-plasma experiments, L. Rovige, J. Huijts, A. Vernier, I. Andriyash, F. Sylla, V. Tomkus, V. Girdauskas, G. Raciukaitis, J. Dudutis, V. Stankevic, P. Gecys, and J. Faure, REVIEW OF SCIENTIFIC INSTRUMENTS, 92(8), AUG 1 2021, DOI: 10.1063/5.0051173

Outcomes

Successful development of high-repetition, high-efficiency laser drivers will enable:

Compact plasma accelerators with high gradients

Applications in medicine, notably **FLASH/VHEE radiotherapy**, benefiting from ultra-high-dose-rate electron beams.

Compact photon and particle sources for materials science, non-destructive testing, and industry.

Further Integration with **European infrastructures** such as **ELI** and **EuPRAXIA**, designed for laser-driven plasma-based accelerators.

Identified challenges:

Achieving **long-term, stable operation** at kHz repetition rates (AI loop)

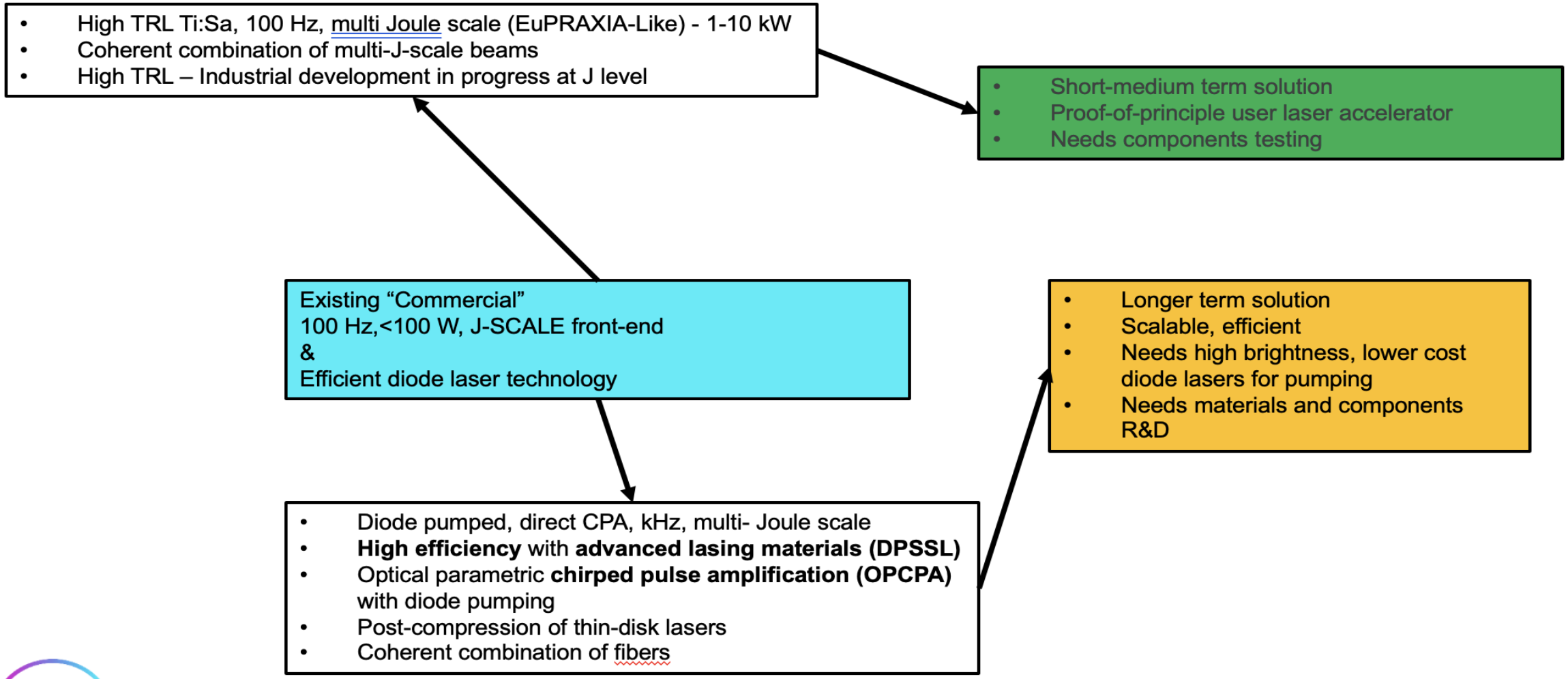
Improving **thermal management** and **component lifetime**

Reaching **industrial maturity** (TRL 5–6).

Coordinating progress across laser technology, plasma targets, beam diagnostics, and user-facility standards.

Outcome: LASPLA Strategy

Strong IFAST contribution to the delivery of a STRATEGY for laser drivers for plasma accelerators



Outcome: LASPLA Strategy

Strong IFAST contribution to the delivery of a STRATEGY for laser drivers for plasma accelerators

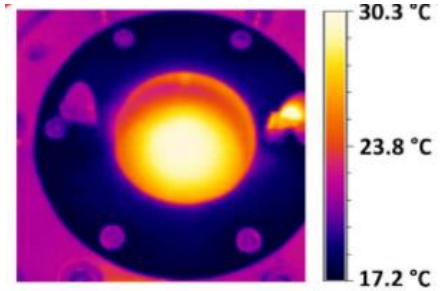
1 Introduction
2 Pillars of strategy
2.1 Overview
2.2 Key Technologies
- 2.2.1 Cooling architectures
- 2.2.2 Pump lasers
- 2.2.3 High Quality Front-end
- 2.2.4 100 Hz Ti:Sa Technology
- 2.2.5 Diode laser technology
- 2.2.6 Thulium doped gain media
- 2.2.7 Exploitation of industrial kHz systems

3 Planned developments
3.1 Funded Laser Activities
- 3.1.1 Ti:Sa amplifier modules
- 3.1.2 Efficient kHz laser drivers
- 3.1.3 High Rep-rate pump sources
- 3.1.4 High average power compressors
- 3.1.5 System Architectures

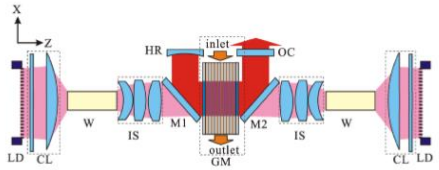
4 Future plans / Conclusion / relation to other IFAST work

Ongoing technology developments

THERMAL MANAGEMENT OF POWER AMPLIFIERS



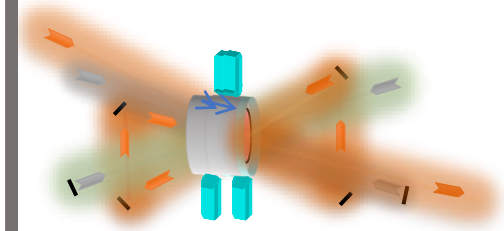
WATER/GAS COOLING



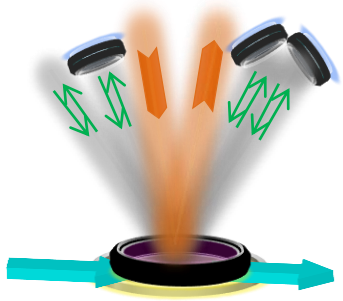
Prototyping needed

AMPLIFIER GEOMETRY TRANSMISSION VS. REFLECTION

Multipass transmission

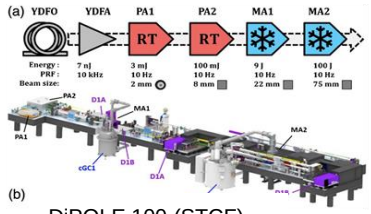


Multipass reflection

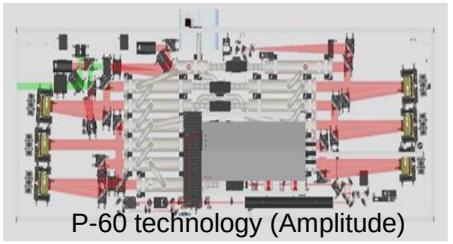


Prototyping needed

DPSSL PUMP SOURCES TECHNOLOGY



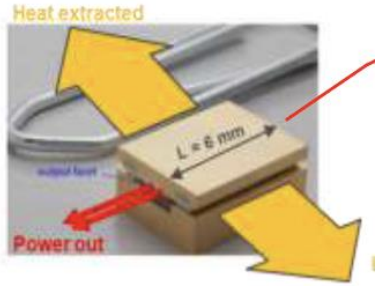
DiPOLE 100 (STCF)

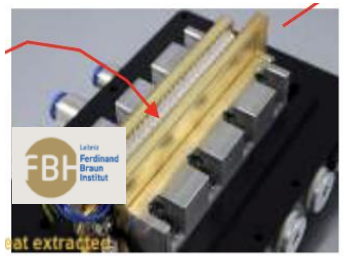


P-60 technology (Amplitude)

Currently no solution for full system specs (P1): development

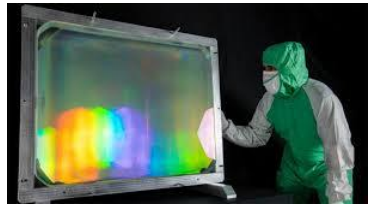
DIODE LASERS EFFICIENCY, BRIGHTNESS AND LIFETIME





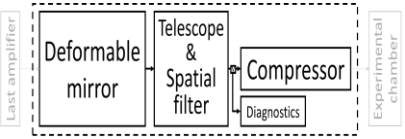
Needs development

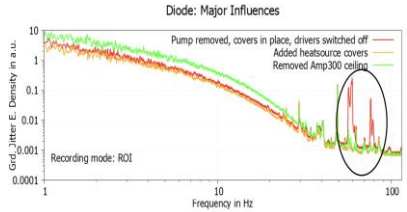
COMPRESSOR AND TRANSPORT: THERMAL AND MECHANICAL



Gold -> MD, MLD, MMLD

reduction of the thermal load
cooling of residual heat
control of thermal effects





Main challenges: large optics, mechanical stability, beam quality control, pointing stability

Impact on

Demonstration of kHz-class laser systems meeting target specifications (multi-J, < 50 fs, > 30% efficiency).

Industrial partnerships for upscaling and commercialization.

Integrated LPA operation using these systems showing stable, reproducible plasma acceleration suitable for continuous operation.

Alignment of development with user-driven requirements to address scientific excellence along with industrial and medical needs

Important Milestone Achieved in LPA

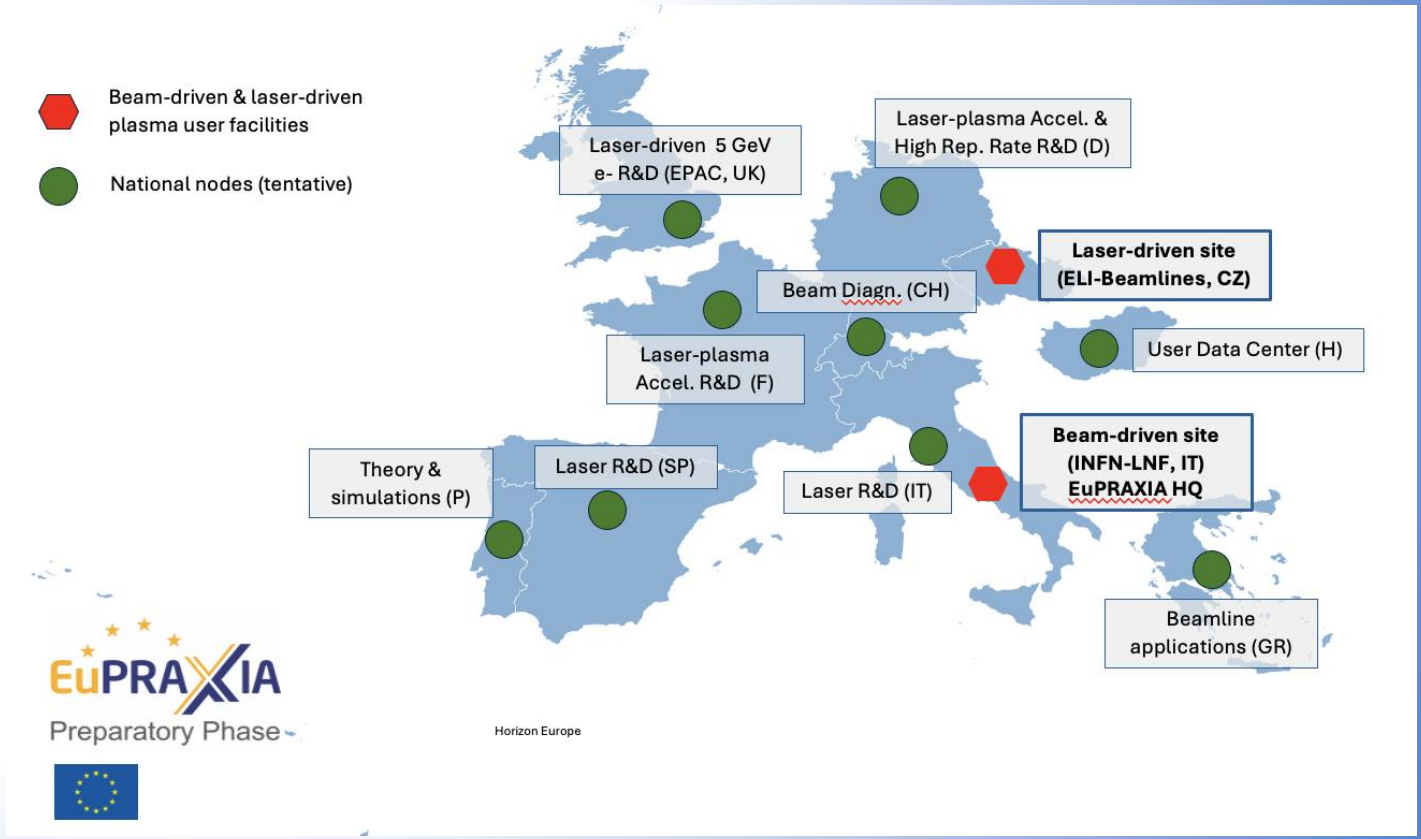
EuPRAXIA selects ELI for the Laser-Driven Accelerator Site

https://www.eupraxia-facility.org/post/eupraxia-selects-eli-for-second-laser-driven-accelerator-site

The EuPRAXIA Consortium selected the ELI Beamlines Facility in Dolní Břežany, Czech Republic, as the site for its laser-driven plasma accelerator pillar. ELI Beamlines was selected for its infrastructure readiness, state-of-the-art laser systems, and comprehensive technical expertise.

EuPRAXIA also recognises the important roles of the other candidates for the second site, EPAC and CNR-INO.

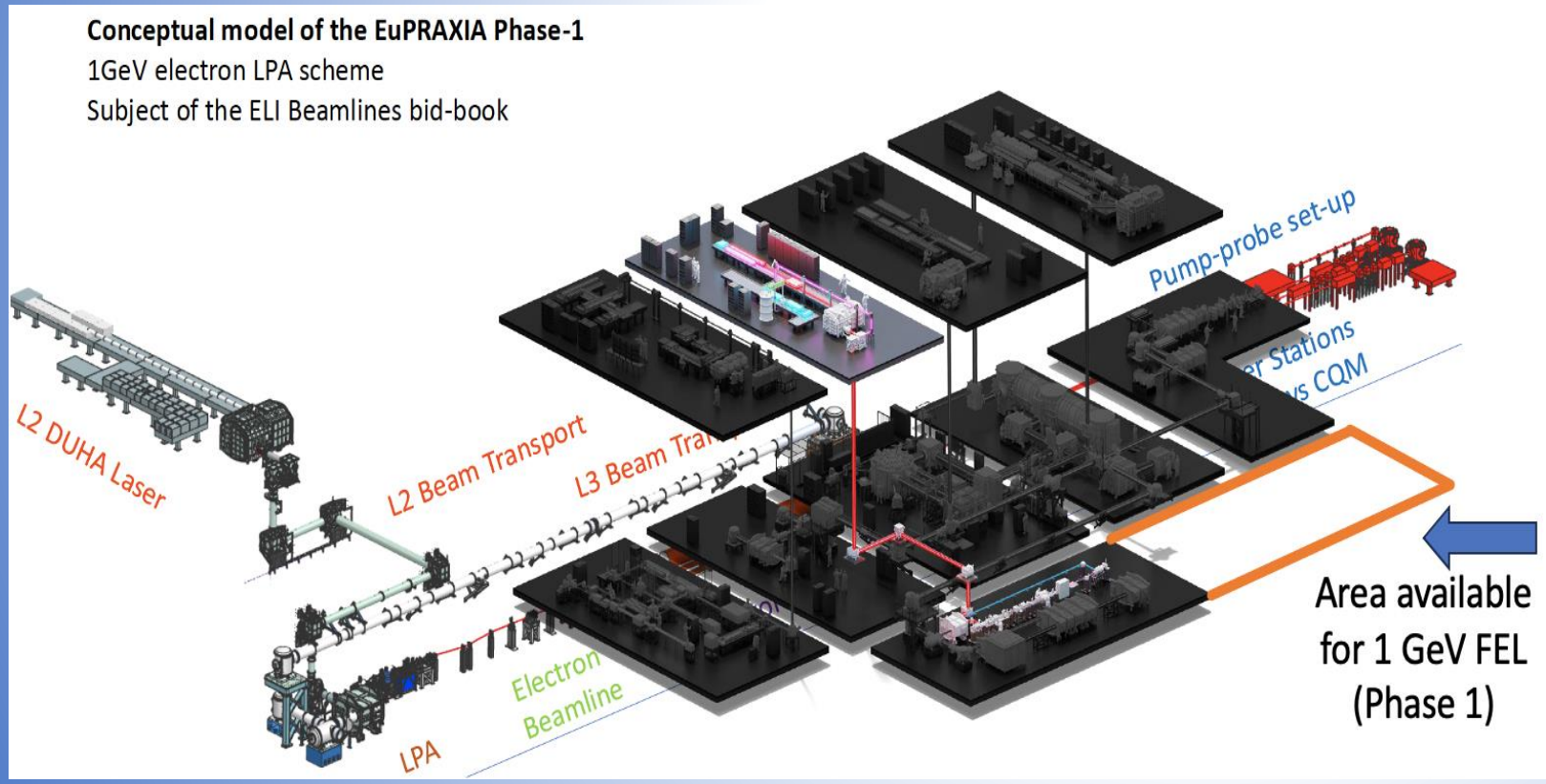
EPAC will contribute to EuPRAXIA as a centre for R&D, focusing on advancing research towards achieving a high-quality 5 GeV electron beam. While **CNR-INO** will function as EuPRAXIA's National Node in Italy and laser test facility.

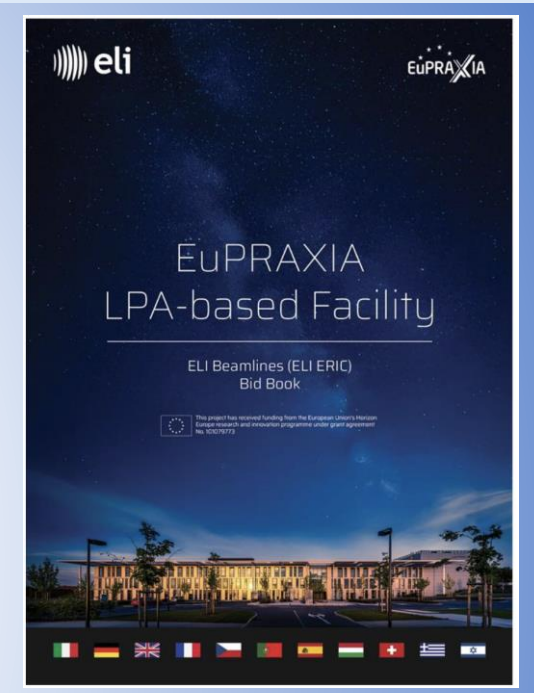


EuPRAXIA@ELI LPA based facility

Funded by the European Union

With it's advanced high-power, high-repetition-rate laser systems, including the newly developed L2 DUHA laser (aiming to 200 TW, 100 Hz) , and versatile experimental setups, ELI is ideally equipped to implement and operate the Laser-Plasma-Accelerator-based 1-GeV Free-Electron Laser (FEL) envisioned by EuPRAXIA.





PHASE-1		
Soft X-ray FEL (W_e = 1GeV)	~ 4 nm / 100 Hz	L2-laser
Low-energy POSITRON source	YES / 1000 Hz	ALLEGRO laser
PHASE-2		
Hard X-ray FEL (W_e ~ 2 GeV)	~ 0.3 nm / 100 Hz	L2-laser
High-energy electron beam Up to 5 GeV	YES 100 Hz	**NOVEL** PW-class laser system

PACRI

IMPACT: *PACRI* PROJECT

Funded by the European Union

Funding for scaleup of collaborative EuPRAXIA TDR development (within Infratech proposal PACRI)

PACRI WP10

High repetition rate High power Ti:Sa amplifier module

PACRI WP12

High repetition rate pump sources for laser drivers

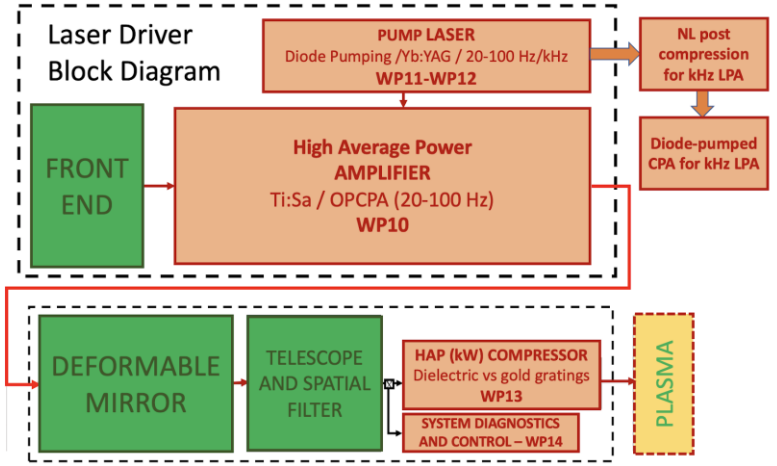
PACRI WP13

Prototype of High average power optical compressor

PACRI WP14

Laser driver System Architecture, transport and engineering

EuPRAXIA laser driver (100 Hz) and longer term options (1 kHz)



PACRI WP11

Efficient kHz laser driver modules for plasma acceleration

Conclusions on LASPLA

High-repetition, efficient laser drivers are key to advancing high gradient laser–plasma accelerators toward real-world applications.

The **LASPLA network** has gathered European labs and Industry around a shared roadmap for scalable, high-performance laser systems.

Progress in **materials, amplifier design, and thermal management** is enabling operation at kHz rates with improved stability.

Applications such as **FLASH and VHEE radiotherapy** and **compact particle and X-ray sources** drive strong motivation for continued investment.

Industrial collaboration and system integration are essential for the transition from experimental setups to robust, multi-purpose **user-facilities**.