EuPRAXIA
Advanced Photon Sources

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

INFN

WP4: Laser development and controls

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The ILIL (*Intense Laser Irradiation* Laboratory) group

Scientific staff

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- Gianluca **CELLAMARE** PhD student
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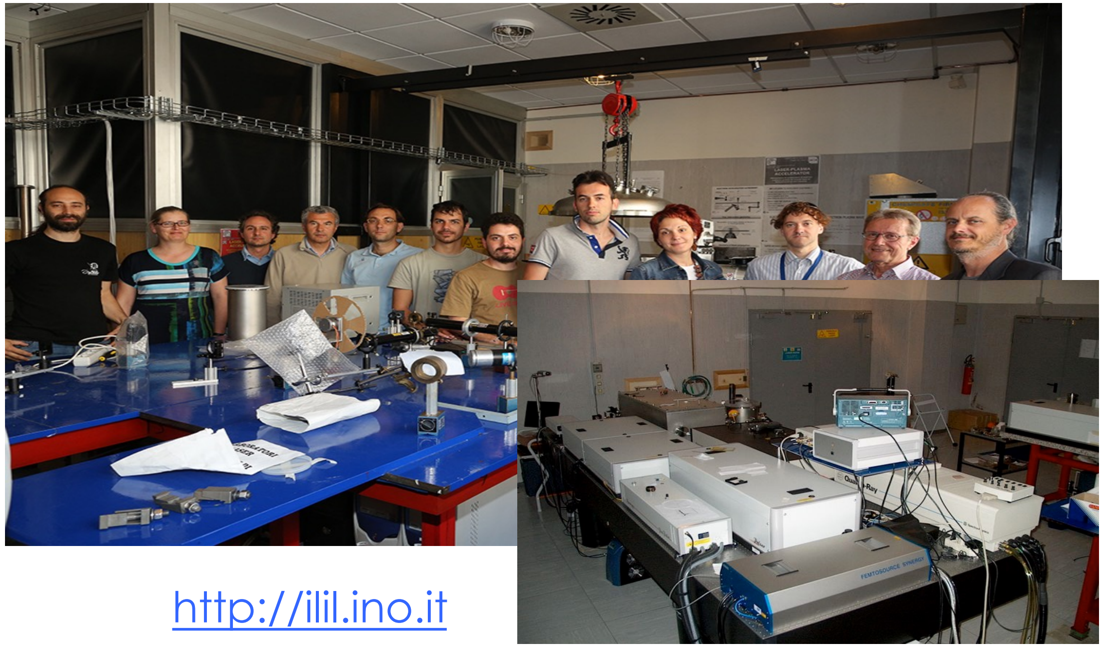

http://ilil.ino.it

Finanziato dall'Unione europea
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PIANO NAZIONALE DI RIPRESA E RESILIENZA

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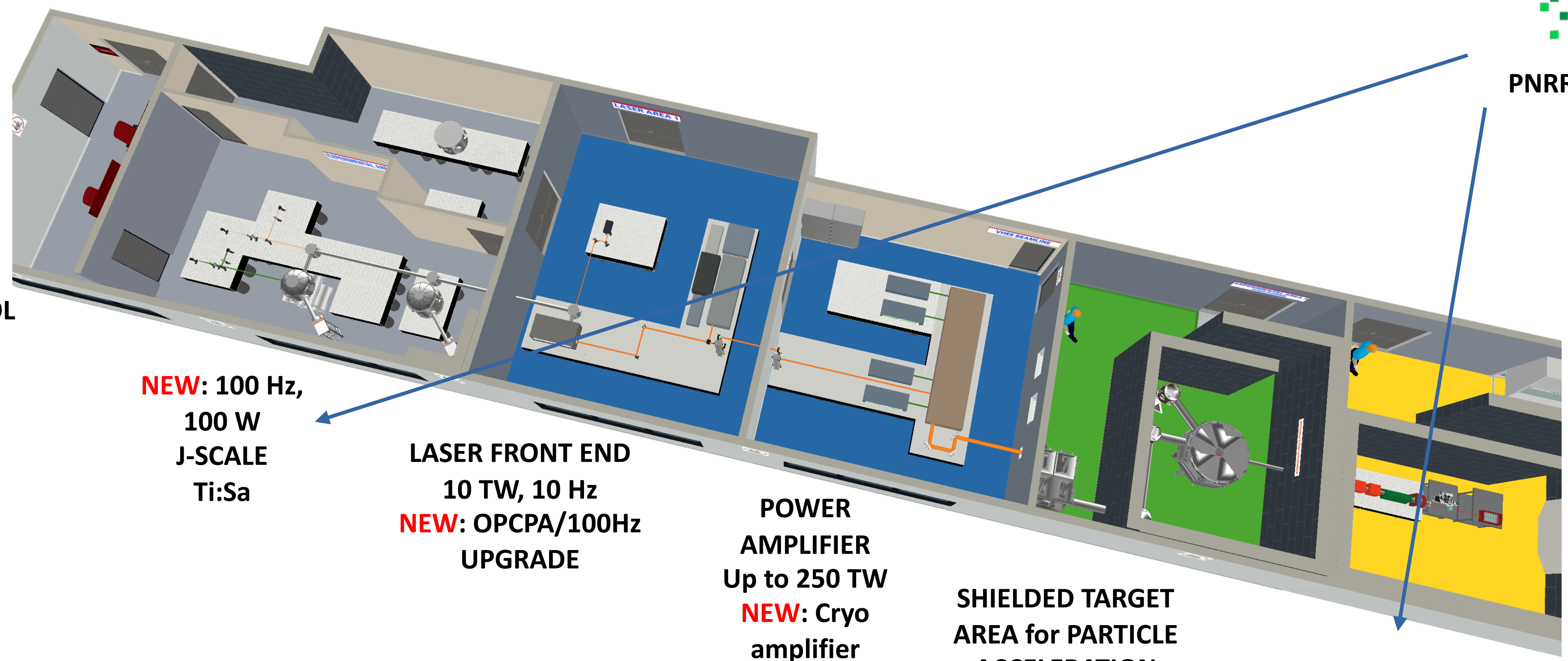
CONSIGLIO NAZIONALE DELLE RICERCHE

The ILIL lab

NEW: HAP kHz LASER DEV. LAB

USER CONTROL ROOM



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PIANO NAZIONALE DI RIPRESA E RESILIENZA

PNRR ("Piano Nazionale di Ripresa e Resilienza")

NEW: 100 Hz, 100 W J-SCALE Ti:Sa

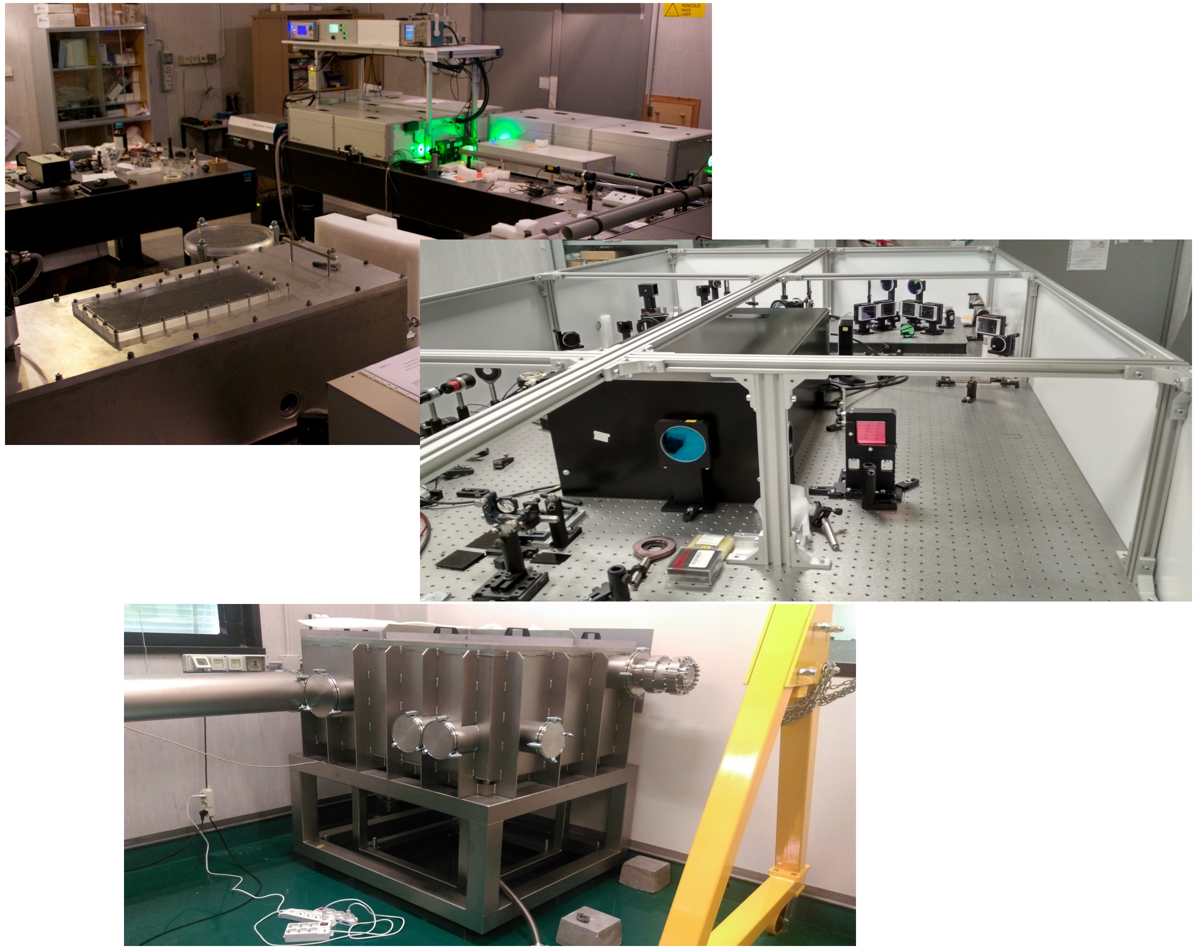
LASER FRONT END
10 TW, 10 Hz
NEW: OPCPA/100Hz UPGRADE

POWER AMPLIFIER
Up to 250 TW
NEW: Cryo amplifier upgrade

SHIELDED TARGET AREA for PARTICLE ACCELERATION

NEW: BEAMLINE for *FLASH* PRE-CLINICAL STUDIES

NEW: UNDER-GROUND BUNKER



Main research fields

Laser-driven particle accelerators
- Electron acceleration and X-rays radiation sources
- Light Ion acceleration

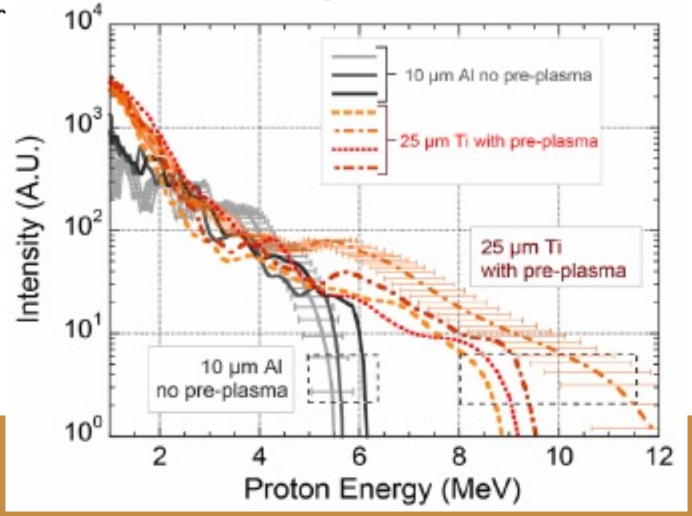
Applications in medicine, material science, ...

Laser-plasma interactions in ICF and Shock ignition*
Laser-driven instabilities and plasma characterization
Diagnostics of ICF-relevant plasmas

OPEN **Enhanced laser-driven proton acceleration via improved fast electron heating in a controlled pre-plasma**

Leonida A. Gizzi[1,2], Elisabetta Boella[3,4], Luca Labate[1,2], Federica Baffigi[1], Pablo J. Bilbao[3], Fernando Brandi[1], Gabriele

Scientific Reports | (2021) 11:13728

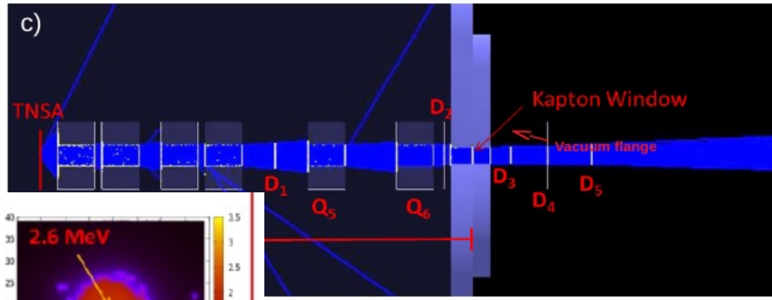


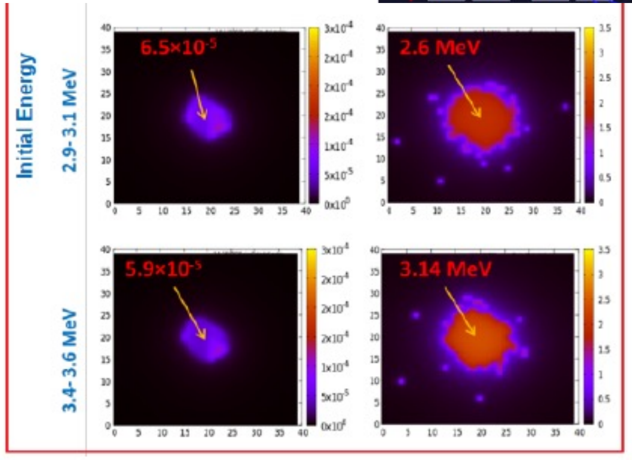
Article

A Few MeV Laser-Plasma Accelerated Proton Beam in Air Collimated Using Compact Permanent Quadrupole Magnets

Fernando Brandi [1,*], Luca Labate [1,2,*], Daniele Palla [1,†], Sanjeev Kumar [1,†,‡], Lorenzo Fulgentini [1], Petra Koester [1], Federica Baffigi [1], Massimo Chiari [3], Daniele Panetta [4] and Leonida Antonio Gizzi [1,2]

applied sciences





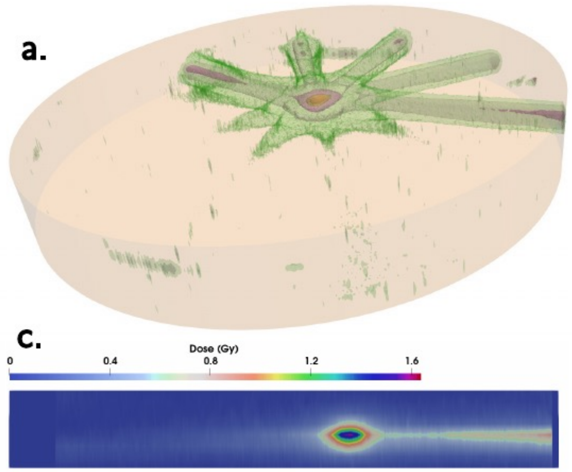
R&D on laser-driven VHEE sources for advanced radiotherapy protocols (FLASH radiotherapy)

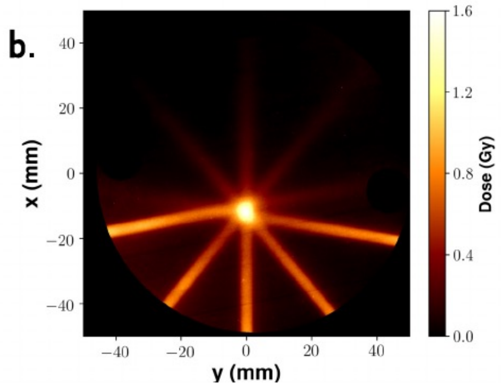
RT modalities/protocols exploiting the FLASH effect (>~40Gy/s, ~200ms irradiation time) require high charge/(average)current particle beams, with the required penetration depth to allow deep seated tumors to be treated

Laser-driven VHEE beams among the most promising candidates for FLASH RT

RT approaches with LWFA VHEE pencil beams

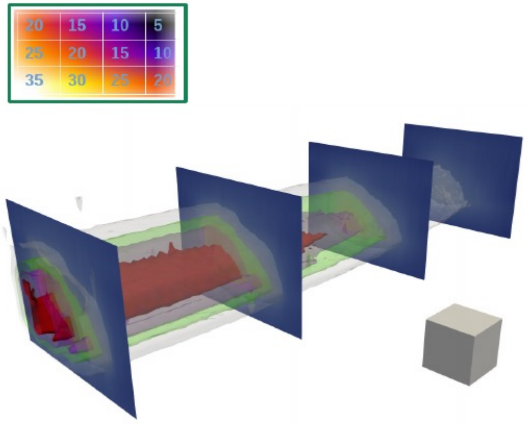
Multi-field irradiation of a mm-sized target volume





L. Labate *et al.,* Sci. Rep. 10, 17307 (2020)

IMRT-like dose painting



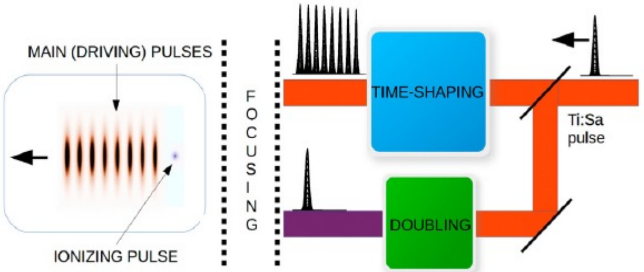
Maximum dose on the "target" volume 2.5x the dose at the entrance and 4x the dose a few mm apart

- Dose up to 2 Gy (using 200 laser shots) delivered in a 2 mm diameter pencil beam at 50mm water depth.
- Dose "painting" with sub-mm resolution demonstrated.
- In perspective, FLASH-RT needs therapeutic doses **(tens of Gy)** in a short time (**200 ms)**
- This is challenging for all accelerators (including RF)
- LPA can address with compact footprint, with highest charge per bunch and high repetition rate (>100 Hz).

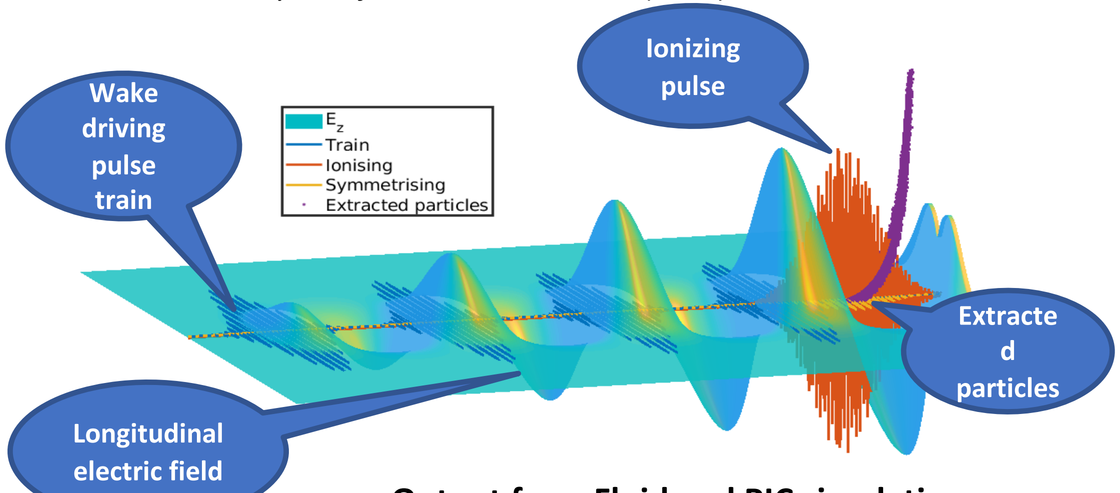
R&D on high quality laser-driven electron beams: The REMPI LWFA scheme and advanced optical schemes for ultrashort pulse train generation

Motivation: Generating high quality LWFA beams for FEL (EuPRAXIA)

The REMPI scheme combines some of the most advanced concepts conceived to date in LWFA to deliver high quality electron beam to drive an X-ray FEL

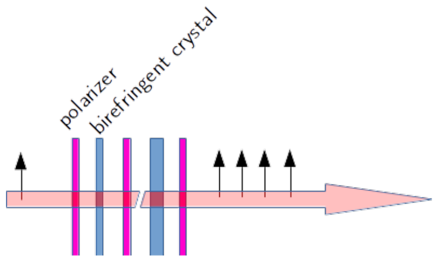


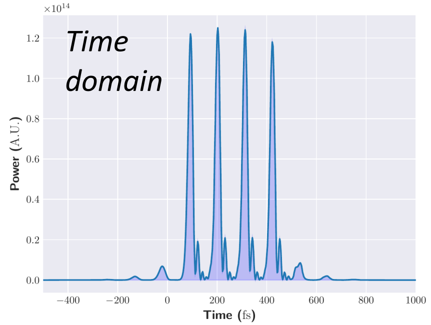
P. Tomassini et al., *Physics of Plasmas 24, 103120 (2017)*

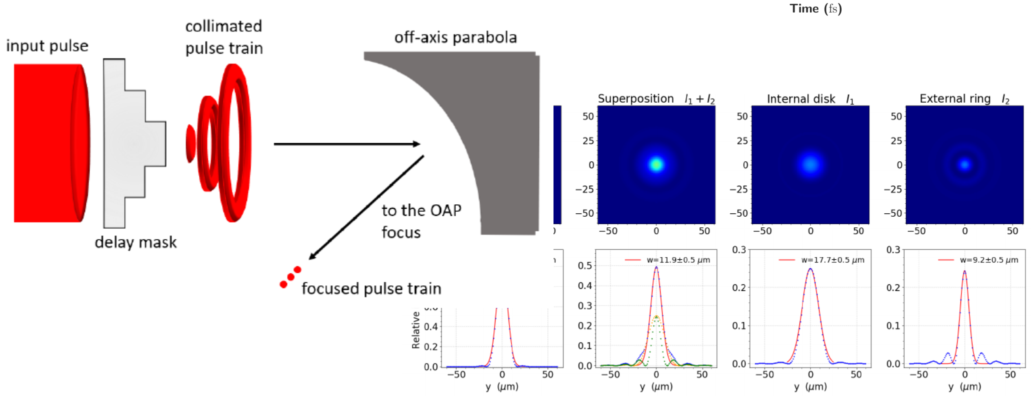


Output from Fluid and PIC simulations

Novel concepts for ultrashort pulse train generation



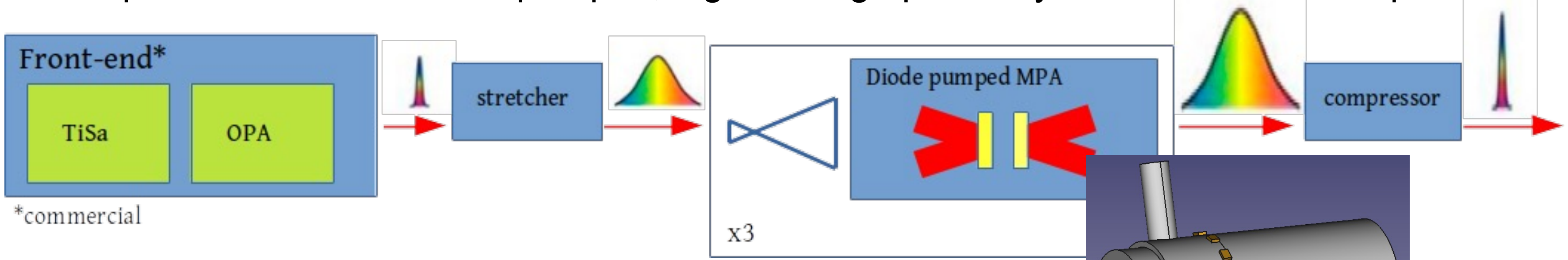


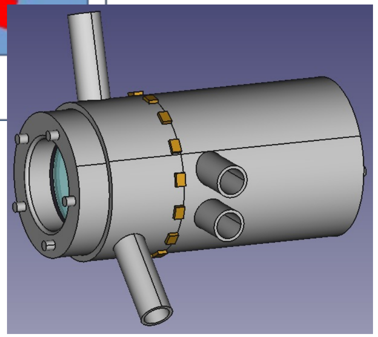


G. Vantaggiato *et al.*, NIM A 909, 114 (2018)

R&D on ultrashort lasers at ILIL-INO-CNR:
The APOLLO laser (kHz rep rate, ~1kW average power)

Development of a direct diode pumped, high average power system based on multipulse extraction and ceramic active materials

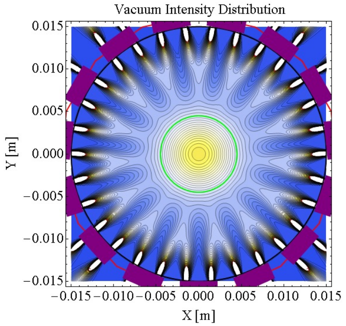




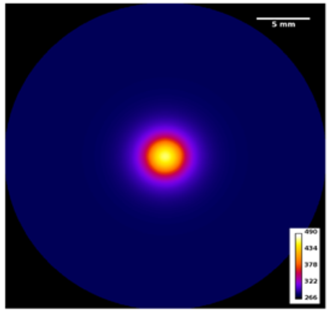
APOLLO system design specs: pulse duration ~50-100fs (potential), pulse energy > 500mJ, repetition rate 1kHz

Selected material: *Tm:Lu2O3*
- Emission at 2 μm (eye-safe)
- Large amplification bandwidth
- Direct pumping at 800 nm, using diodes operating in (quasi) CW mode (available and scalable)
- Multi-pulse extraction at high repetition rate > 1 kHz; Ideal for accelerator technology
- Mature ceramic production technology

Edge diode pumping



Thermal load



Multi-Pulse Extraction: time dependent level dynamics

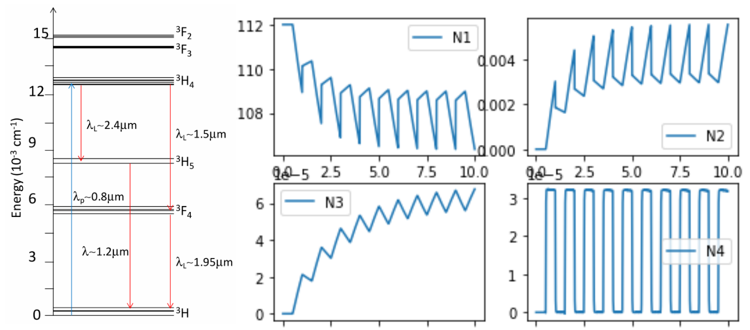


Figure 1. Energy level scheme of Tm^{3+} in Lu_2O_3 (ada

D. Palla, L. Labate*, F. Baffigi, G. Cellamare, L.A. Gizzi, Optics & Laser Technology, **156**, 108524 (2022)

EuAPS – WP4: High Repetition Rate Laser Beamline

Activity of CNR-INO mostly framed within WP4

COSTS (€) WORK PACKAGE [WP.4 - High Repetition Rate Laser Beam Line]			
	Costs included in the request for funding		
	To be located within the eight southern Regions	To be located outside the eight southern Regions	Total requested grant
a. Fixed term personnel specifically hired for the project	0,00	240.000,00	240.000,00
b. Scientific instrumentation and technological equipment, software licenses and patent	0,00	4.024.986,00	4.024.986,00
c. Open Access, Trans National Access, FAI principal implementation	0,00	0,00	0,00
d. Civil infrastructures and related systems	0,00	280.000,00	280.000,00
e. Indirect costs, including running costs	0,00	318.164,00	318.164,00
f. Training activities	0,00	0,00	0,00
Total	0,00	4.863.150,00	4.863.150,00

Design and construction of a high average power/rep rate laser infratsructure, featuring a 100Hz, J-class, ultrashort duration, TiSa based (800nm) system

Advanced laser architecture, boasting
- diode pumping technology for Nd pumps
- final amplifier based on active mirror concept

Active spectral amplitude/phase correction

User oriented approach: efforts will be undertaken to provide users with a state of the art characterization of the beam features, as well as flexibility for parameter adjustment/tuning

Full set of longitudinal functions diagnostics (WIZZLER or similar, 3rd order autocorrelation, …)

Wavefront characterization (full correction to be tentatively carried out using ILIL equipment)

Challenges on laser-drivers for future LPAs

Most of the current PW-scale facilities worldwide use indirect pumping CPA architectures, based on TiSa (~30fs, ~10J, up to 10Hz), with flashlamp based pump lasers (notable exception HAPLS@ELI (ELI laser L3))

A major limitation to the increase of the rep rate toward the 100Hz level is due to the management of the thermal load on gain media (on both pumps and TiSa), as well as on the transport optics, gratings, …

Other (possibly related issues): thermal lensing/wavefront aberrations, pointing stability, ...

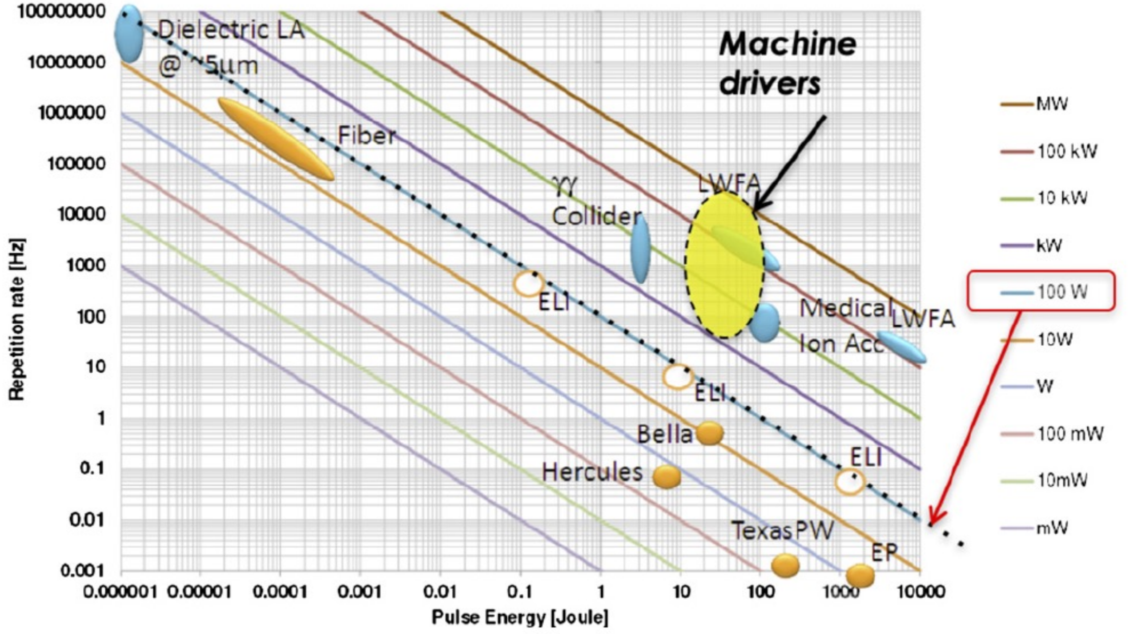


Figure 17. Repetition rate vs pulse energy of high intensity laser systems. The dotted line separates the existing systems with average power below approximately 100 W, with systems envisaged for applications and for laser–plasma acceleration drivers.

The laser system to be installed in the EuAPS facility pillar at CNR-INO in Pisa will allow some of these issues to be investigated

L.A. Gizzi *et al.,* in F. Albert *et al.,* 2020 roadmap on plasma accelerators, New J. Phys. 23, 031101 (2021)

- **EuPRAXIA**
- PW class,
- 100 Hz repetition rate,
- multi kW average power,
- diode pumped

Required specs of the EuPRAXIA laser very challenging

Eupraxia laser development is aimed at delivering more efficient, kW class PW laser driver for plasma acceleration at >100 Hz rate

Ultrashort pulses (large bandwidth <50 fs)
High repetition rate (100 Hz – 10 kHz)
High average power (~kW -10 kW)
High wall-plug efficiency (>30%)

EuAPS

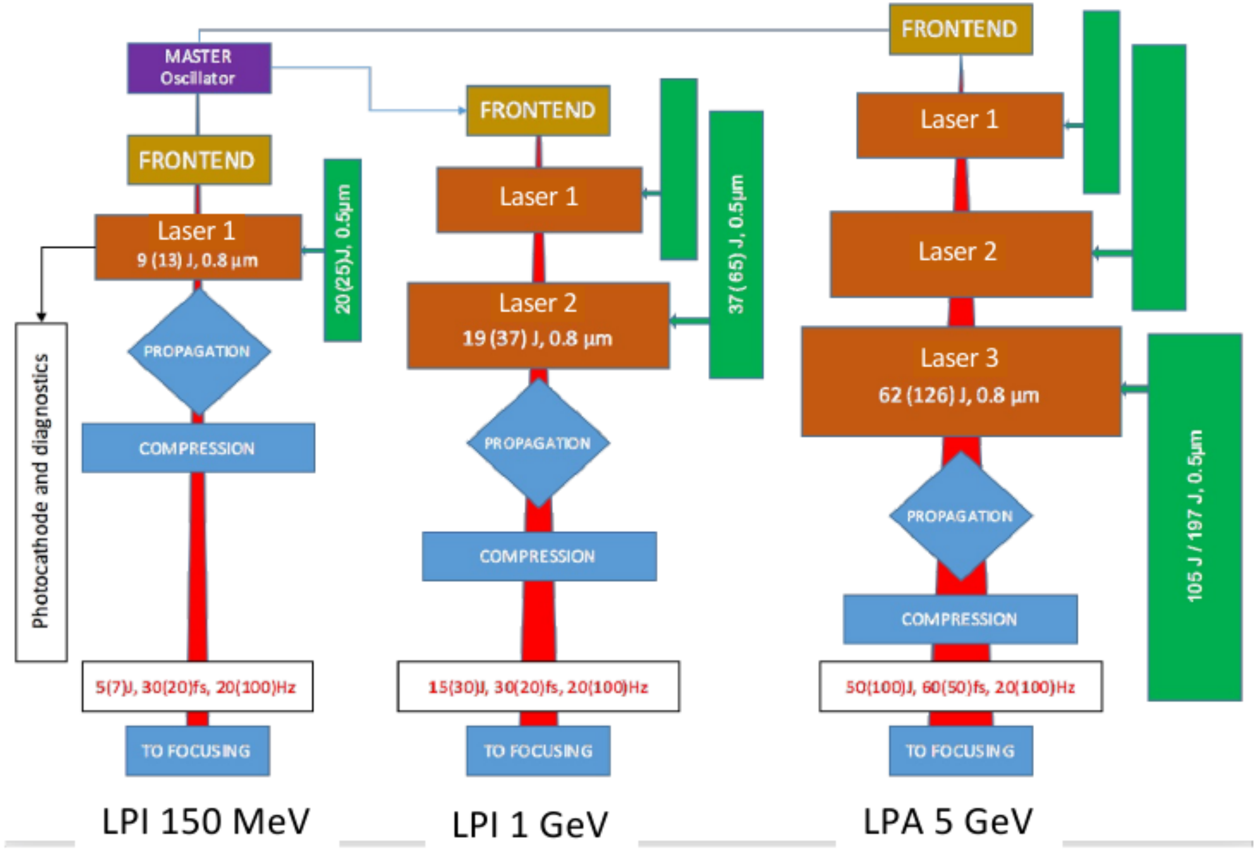
- **EuAPS@CNR-Pisa**
- 30 TW peak power
- 100 Hz repetition rate
- 100 W average power
- Diode pumped
- Thermal load effects

"EuAPS" system at CNR: expected to match the final EuPRAXIA front-end laser specs

Research platform for studies in the field of high average power (high rep rate) laser optics, amplification and control

- **CURRENT**
- **PW class,**
- **Hz repetition rate,**
- **≈10 W average power**
- **flashlamp pumped**
- **No thermal load transport**

General architecture of the EuPRAXIA laser systems

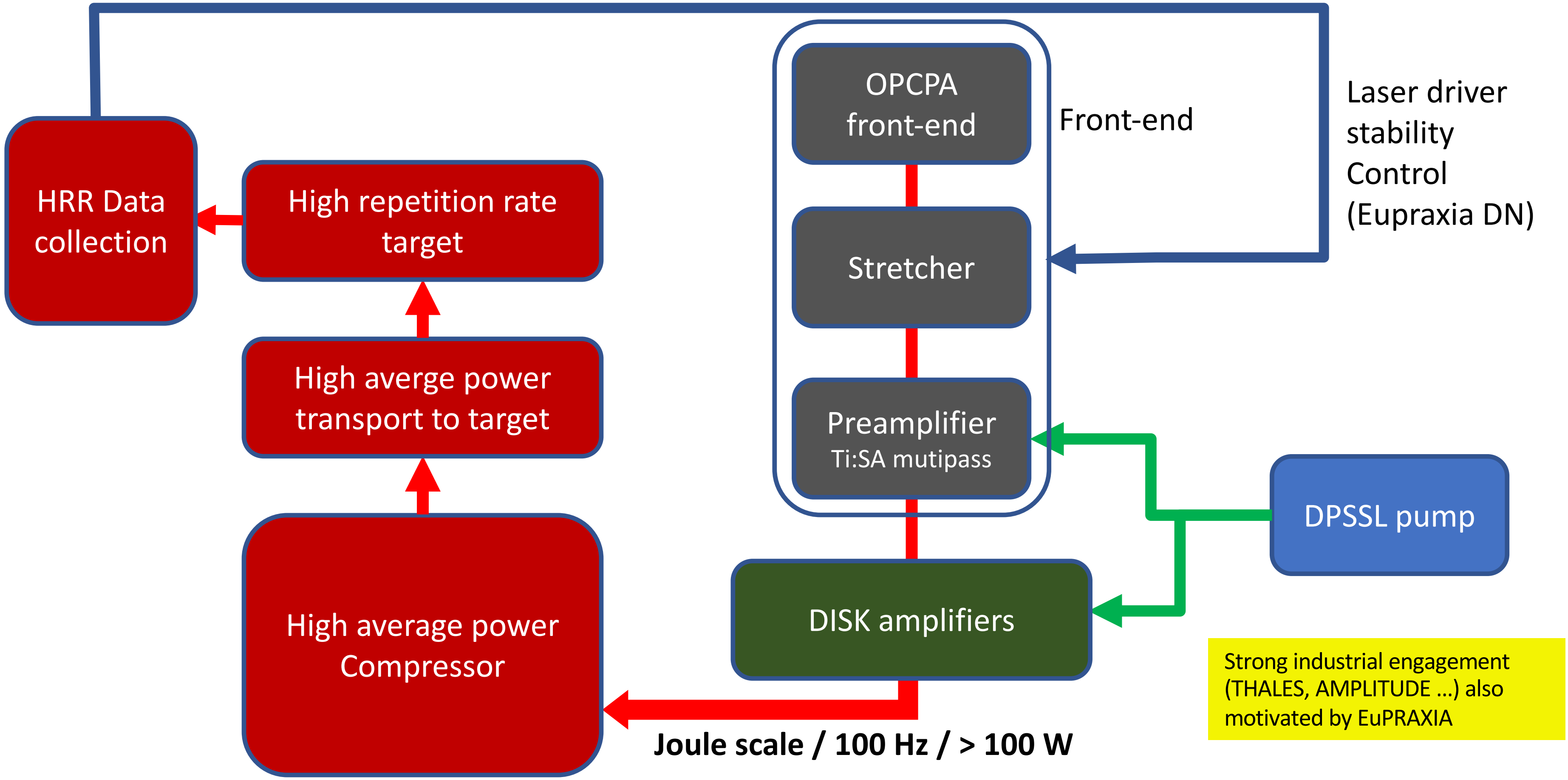


Modularity of amplification stages:

LPI 150 MeV	⇒	Laser1
LPI 1 GeV	⇒	Laser1 + Laser2
LPA 5 GeV	⇒	Laser1 + Laser2 + Laser3

- adjustments on pulse duration/bandwidth
- Synchronization: common master oscillator
- Pulse duration/wavelength tailoring : separate front end
- Scalability: possibility to upgrade from P0 to P1 performance levels without a major changes

Optical architecture of the EuAPS 100Hz system at CNR



100 Hz, >100 W average power – Eupraxia front end and HAP R&D
High repetition rate target and data collection (with possible ML stability loop)

EuAPS – WP4 outcomes/time schedule

List of WP deliverables

Laser

D4.1.1 **Laser system design (report) M6**. Report on the laser architecture selected, including expected figures
D 4.1.2 **Laser system specifications (report) M20**. Report on the final specs of the commissioned laser system

Transport

D4.2.1 **Laser beam transport (report) M12**. Design of the laser beam transport to the user's end station
D4.2.2 **User's beam specs and available operation modes (report) M22**. Report on the expected laser figures at the user's end station, which includes the possibility of beam longitudinal/transverse functions tailoring according to the user's needs

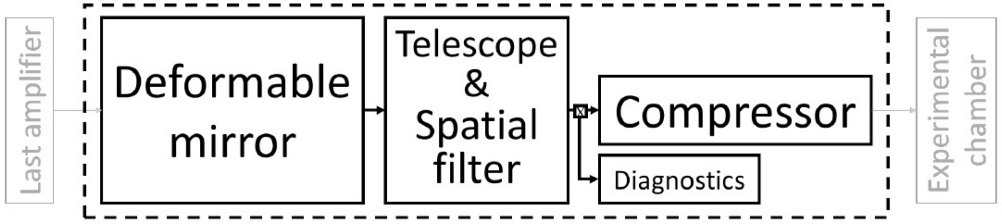
Infrastructure

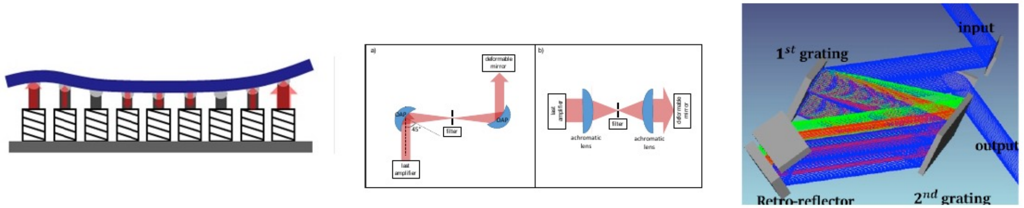
D4.3.1 **Infrastructure design (report) M8**. Preliminary design report of the whole infrastructure
D4.3.2 **User's area capability design (report) M22**. Report on the user's area, including the expected user's station and related facilities/devices, timing/synchronization capabilities, irradiation station(s) characteristics/footprints
D4.3.3 **Final infrastructure report, including full beam line specs and available options (report) M30**. Final report on the infrastructure, including all beam line specifications, with a user-oriented approach

Expected studies to be carried out at the EuAPS high average power beamline

Ultrahigh average/peak power laser beam transport

Main challenges: large optics, mechanical stability, cooling of gratings, beam quality control …

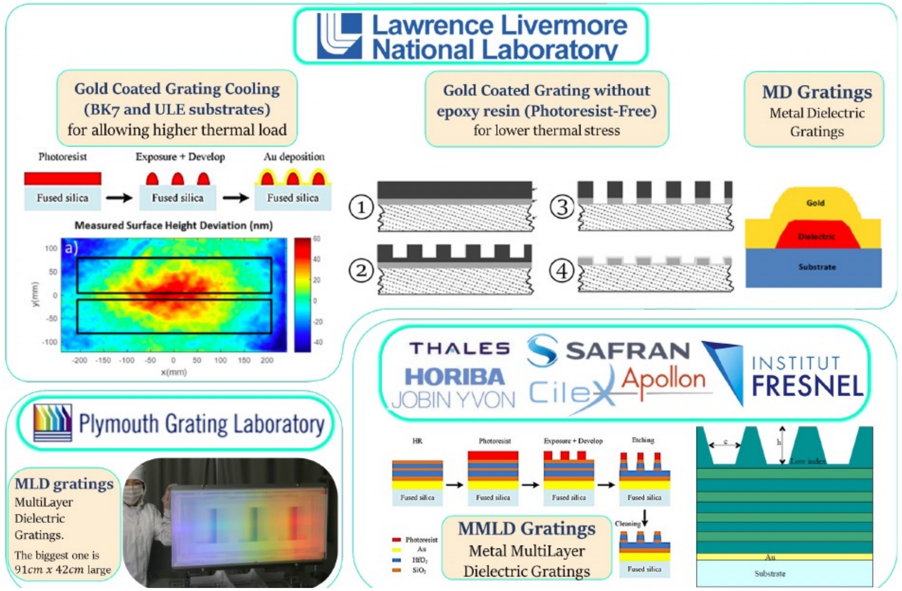




Wavefront aberration characterization (thermal lensing, high order aberrations, …)
Beam size manipulation, focusing
Beam diagnostics/manipulation at high rep rate (high frequency feedback loops)

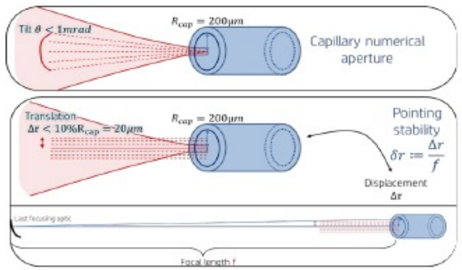
Compressor grating technology

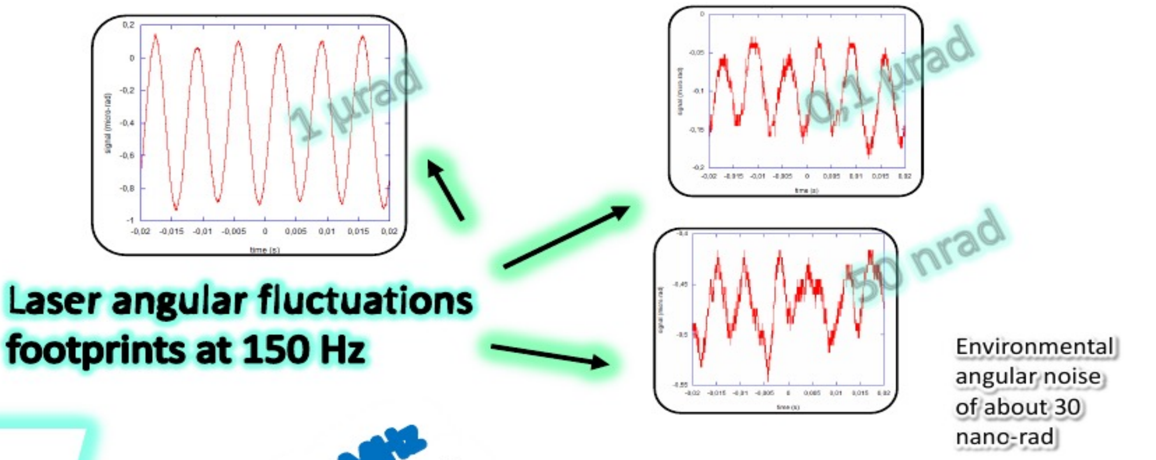
Different technologies under evaluation to address main issues with higher repetition rate. Strategy includes reduction of the thermal load at high average power, cooling of residual heat and control of thermal effects on compression quality.



Expected studies to be carried out at the EuAPS high average power beamline: pointing stability in high power laser and active stabilization techniques

Eupraxia requirements for beam pointing stability are extremely demanding. Both passive and active control will be required. Prior to the implementation of control strategies, tools are being developed to **measure pointing stability** performances at EuPRAXIA facilities and labs.



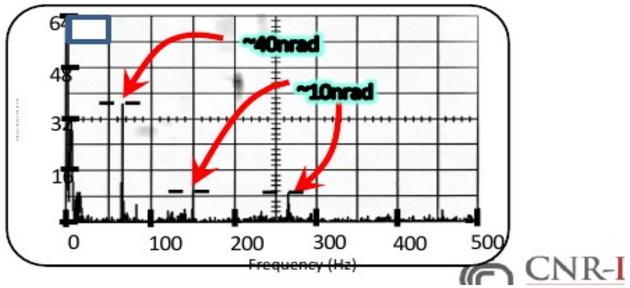


We already detect
<100nrad fluctuations

Z. Mazzotta, F. Mathieu
in collaboration with
S. Cialdi, D. Cipriani, S. Capra
of Università degli studi di Milano.

up to the MHz regime and more

Spectral analysis of the laser fluctuation.



"EuAPS" system at CNR: expected to match the final EuPRAXIA front-end laser specs

Research platform for studies in the field of high average power (high rep rate) laser optics, amplification and control

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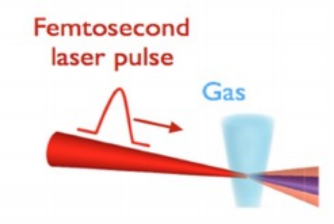
EuAPS high average power beamline: Ideal test bench for LWFA stabilization methods based on ML

Machine Learning for control/tuning of plasma-based accelerators

Set the right **control parameters**

- Gas pressure
- Laser energy
- Laser focal position
- Laser spectral properties
- Laser waist
- ...



in order to **maximize one (or several) objectives**:

- Electron emittance
- Electron energy
- Electron energy spread
- Electron charge
- Combinations thereof
- ...

In high-dimensional parameter space:

$$x = \begin{pmatrix} \text{Laser energy} \\ \text{Gas density} \\ \text{Laser chirp} \\ \dots \end{pmatrix}$$

Find $\boldsymbol{x}_{best}$ such that $f(\boldsymbol{x}_{best})$ is maximal.

R. Lehe, EURONNAC 2022

Stabilization:
The (uncontrolled) properties of the system change in time (e.g. thermal drifts)

The previously-found optimal point $\boldsymbol{x}_{best}$ becomes obsolete after some time.

Aim: Find the correction $\Delta\boldsymbol{x}$ that recovers the optimal behavior.

ML techniques can "recognize" patterns in the system changes (drifts, ...) and apply corrections

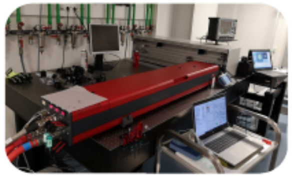
Thanks to the unprecedented rep rate (with this class of lasers), the beamline will make up an ideal test bench for ML optimization

Care will be paid to the development of the beamline to implement laser diagnostic techniques, data acquisition platforms, data transfer, ... which will eventually allow ML optimization techniques to be studied in future users' experiments

Collaboration established on that with LASERIX and CNR-ISTI

Industry activity on 100Hz rep rate, J-class amplifiers: Thales

THEIA PRODUCT



New product : diode pumped developed by Thales for **industral and scientific applications**

Des
get
reli

Joule class system running at 100 and 200Hz for right now

Future developments will allow it to run **at 500Hz**

Usi
inc

We
art

CIVIL
DEFENCE & SECURITY

THALES

THEIA SPECIFICATIONS

Specifications

MODEL	THEIA
Repetition Rate (Hz)	Up to 200
Energy per pulse (mJ)	
-> At 1064 nm	≥ 1000
-> At 532 nm	≥ 700
-> At 355 nm	≥ 500
Pulse to pulse energy stability (% rms)	< 1
Typical pulse duration (ns)	10

Physical characteristics

Power supply	20.9 x 22 x 31.1 in	65 x 60 x 83 cm
Cooling unit	14.6 x 17.4 x 28.4 in	37 x 44 x 72 cm
Laser Head	63 x 11.34 x 7.4 in	160 x 28.8 x 18.8 cm

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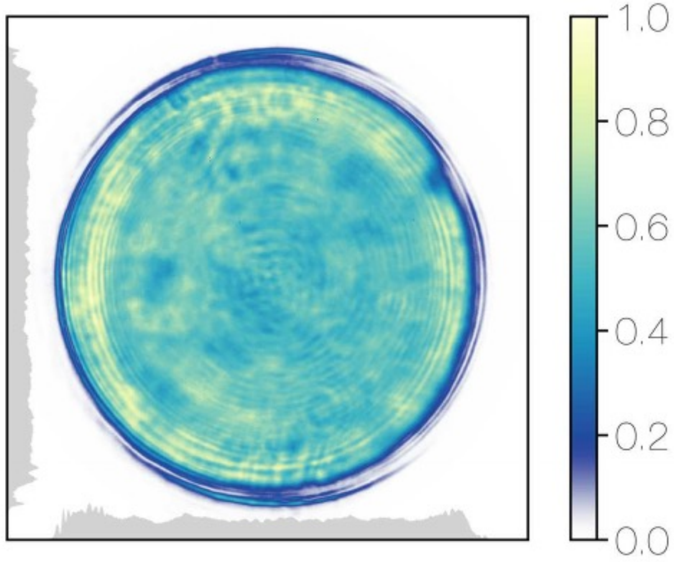


THALES

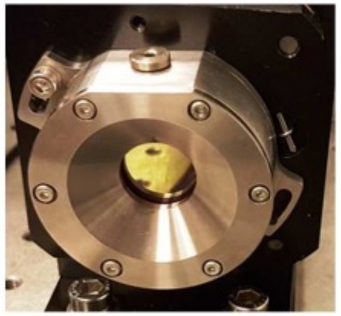
Courtesy of Christophe Simon-Boisson (Thales)

Industry activity on 100Hz rep rate, J-class amplifiers: Thales

TI:SA GAIN MODULE

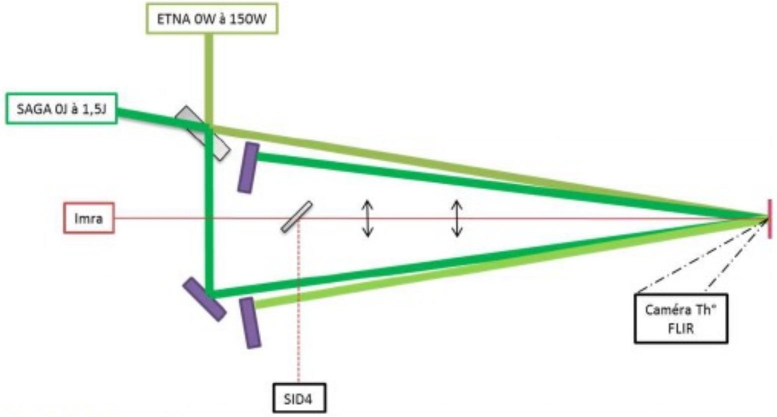
Concept

- Cristal use as **active mirror**
- **Efficient cooling system** to keep crystal temperature < 50°C and maximize gain
- **Limit thermal lens** to keep simple amplifier architecture



Caracterization

- Crystal design = Thales patent
- Pumped with THEIA laser 100Hz 750mJ @532nm, but not yet available
- Thermal lens measurement with ETNA HP laser at 80 average power
- Gain measurement with ETNA HP laser at 80W average power
- Temperature measurement with ETNA HP laser at 80W average power



CIVIL

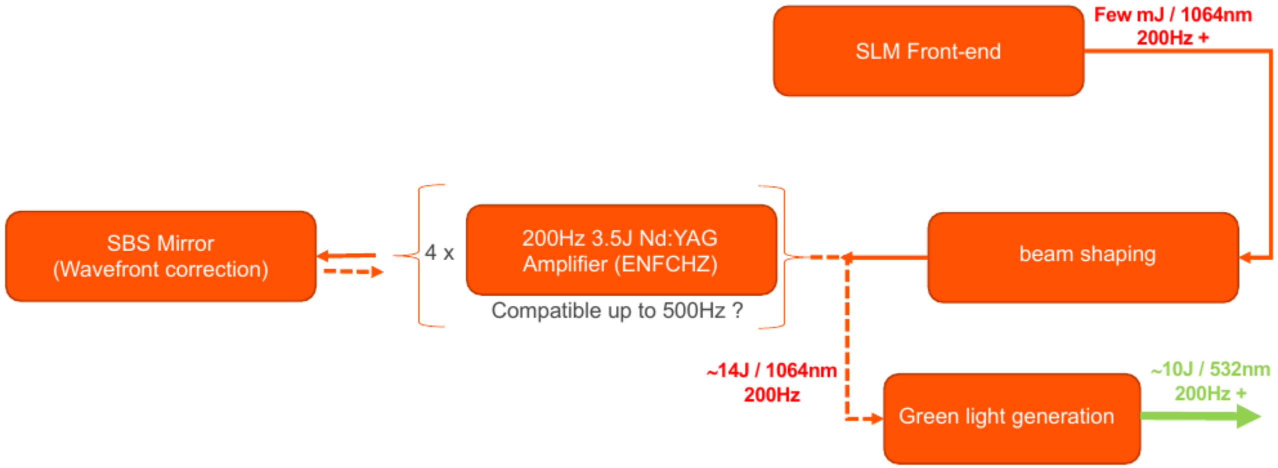
THALES

Courtesy of Sandrine Ricaud/ Christophe Simon-Boisson (Thales)

Industry activity on 100Hz rep rate, J-class amplifiers: Amplitude

Route to >100Hz pump Lasers for Particle acceleration

Block diagram of the future Laser 10J - 200Hz @ 532nm



The key challenge is **THERMAL MANAGEMENT** **(aberrations issues + depolarization)**

Designed for industrial & reliable operation:

- The solution is based on Longitudinal heat extraction and multi-disks concept like Premiumlite
- Liquid-cooling for better heat extraction efficiency
- But with renewed pumping scheme requesting only 2kWc/cm² pumping density (no diodes collimation)
- Ultra-simple doping scheme for the Nd-doped disks (simpler maintenance constraints)

Amplitude

25

Courtesy of Franc Falcoz/Stephane Branly (Amplitude)

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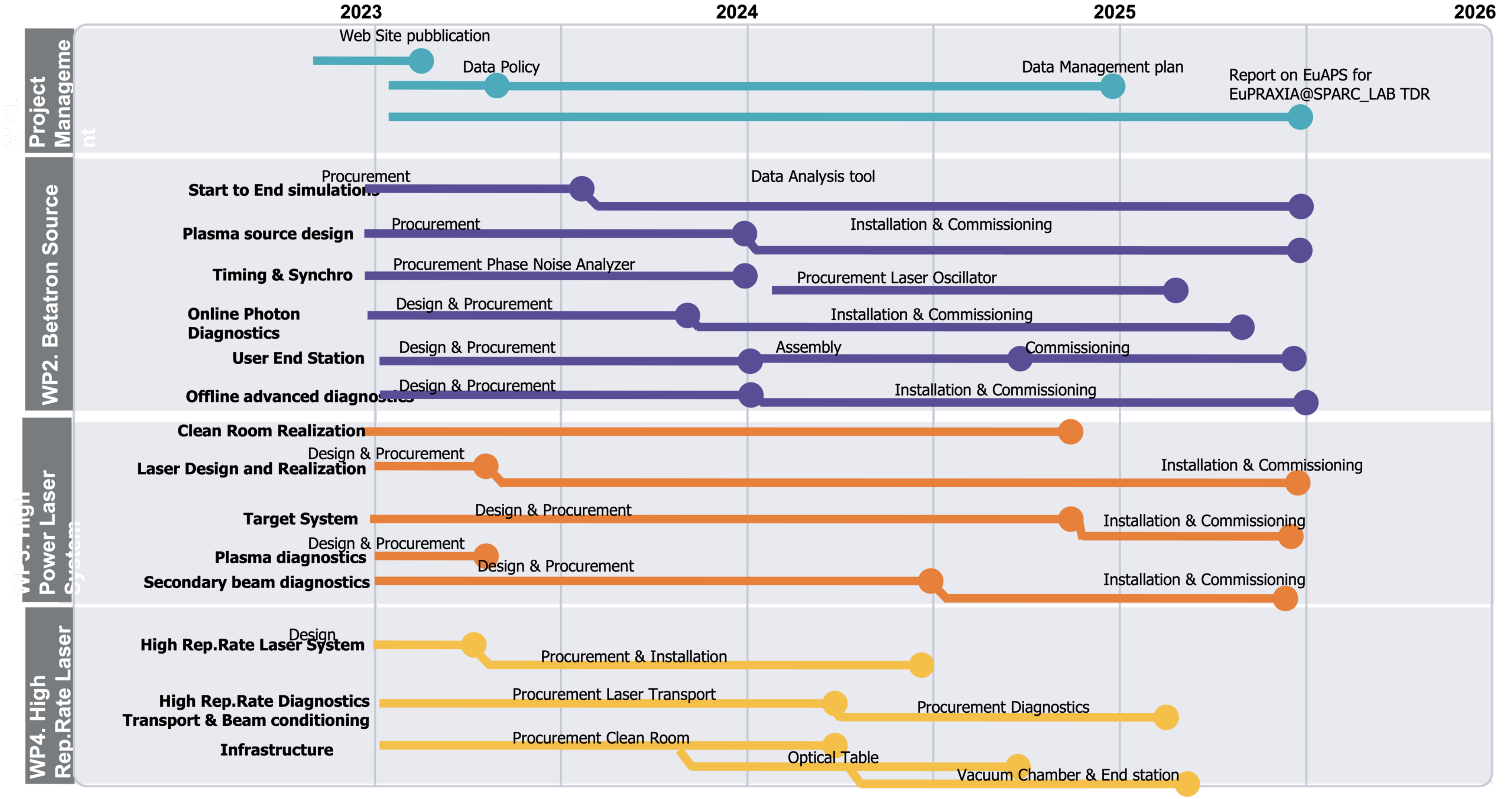
Ministero dell'Università e della Ricerca

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

Time Schedule EuAPS



WP4 – 1/2

Deliverable	Due Date	% Complete
4.1 High rep.rate laser system		
Laser system design (report) (first payment)	01/06/2023	50%
Laser system design (report) (second payment)	01/04/2024	0%
Laser system specifications (report) (final payment)	01/08/2024	0%
4.2 High rep.rate laser system diagnostics transport and beam conditioning		
Laser beam transport (report) (Laser transport and manipulation full-scale modelling)	01/04/2023	25%
Laser beam transport (report) (Definition and procurement of optics, optomechanics, etc. for laser beam transport)	01/10/2024	0%
Laser system specifications (report) (Definition and procurement of laser beam temporal diagnostics)	01/10/2024	0%

WP4 – 2/2

Deliverable	Due Date	% Complete
4.3 High rep. rate laser infrastructure and users end station		
Infrastructure design (report)	01/04/2024	25%
Laser beam transport (report1) (procurement of optical tables)	01/08/2024	0%
Laser beam transport (report2) (procurement of vacuum pipes/pumps/steering chambers for beam transport)	01/02/2025	0%
User's area capability design (report)	01/04/2025	0%

Summary

A new high average power laser beamline, featuring ultrashort duration, J-class energy laser system at high rep rate (100Hz), to be installed at the Intense Laser Irradiation Laboratory of CNR-INO in Pisa

The new laser system, at the forefront of current ultrashort/ultraintense laser technology, will match the performances required for the EuPRAXIA front-end laser

Beamline accessible via a dedicated user station in a new underground area, built taking advantages of synergies with another NG-EU infrastructure (IPHOQS).

Studies in the following fields (among others) will be made possible:

Ultrashort and ultraintense laser development

Among others: high power optics, laser damage, new laser and optical materials/coatings, laser components, thermal management

Established sources of energetic particles with high average flux

Among others: particle beams for applications in radiobiology and medicine, material studies with charged particles (for instance, PIXE), study of novel materials for advanced applications (fusion science, space applications, ...)