"EuPRAXIA Advanced Photon Sources"
Introductory Meeting
LNF-INFN 27 june 2022

EuAPS
High Repetition Rate Laser Program at CNR-INO

L. Labate

Intense Laser Irradiation Laboratory
Consiglio Nazionale delle Ricerche
Istituto Nazionale di Ottica
Sezione di Pisa, Italy

Also at
Istituto Nazionale di Fisica Nucleare
Sezione di Pisa, Italy

The ILIL (*Intense Laser Irradiation* Laboratory) group

PEOPLE

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Petra **KOESTER**
Luca **LABATE***
Federica **BAFFIGI** term
Lorenzo **FULGENTINI**
Paolo **TOMASSINI** term
Daniele **PALLA** postdoc
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Gianluca **CELLAMARE** PhD student
Andrea **MARASCIULLI*** PhD student
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**Also at Istituto Nazionale di Fisica Nucleare*

CNR-INO

http://ilil.ino.it

Main activities and lab

Laser-plasma interactions in ICF and Shock ignition*

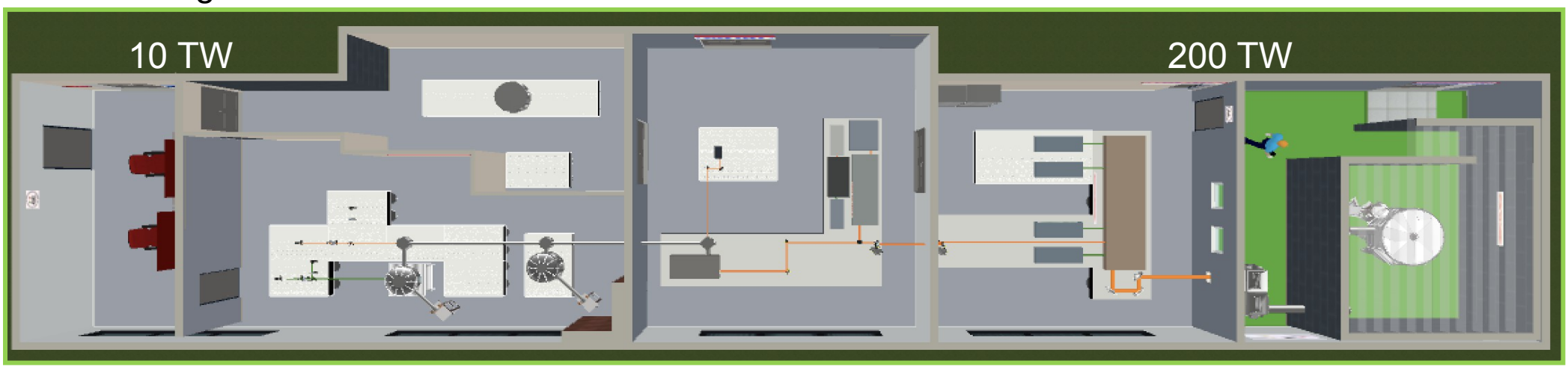
Laser-driven instabilities and plasma characterization

Diagnostics of ICF-relevant plasmas

Laser-driven particle accelerators

Electron acceleration and X-rays radiation sources

Light Ion acceleration

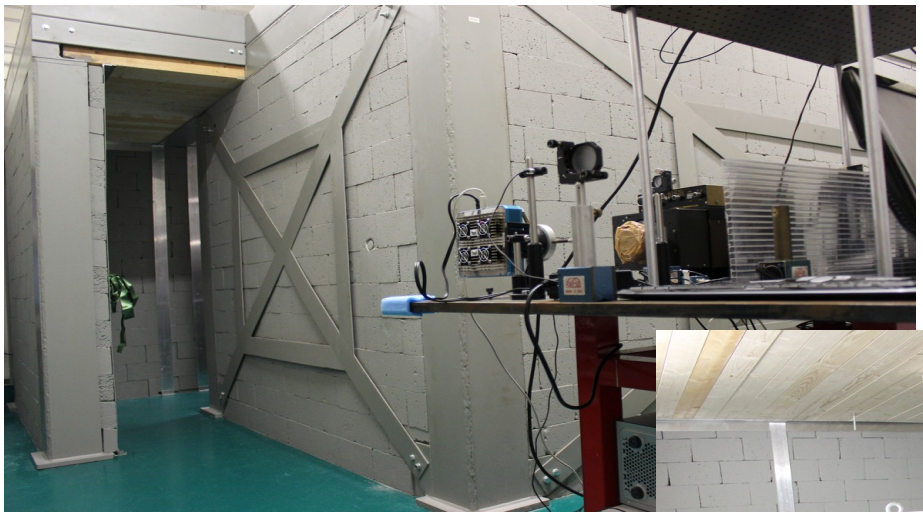


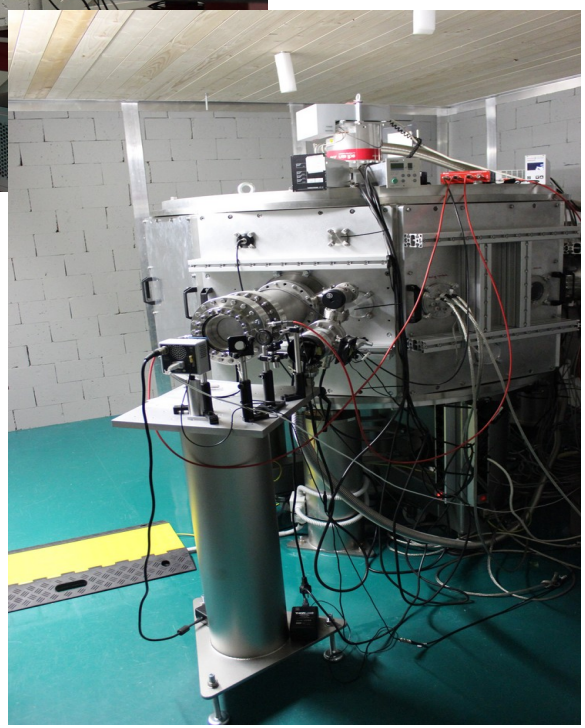
*Also through LASERLAB access to Laser facilities (RAL-CLF(UK), PALS (CZ) and within EURATOM Collaboration)

CNR-INO

The lab: the 220TW Target Area

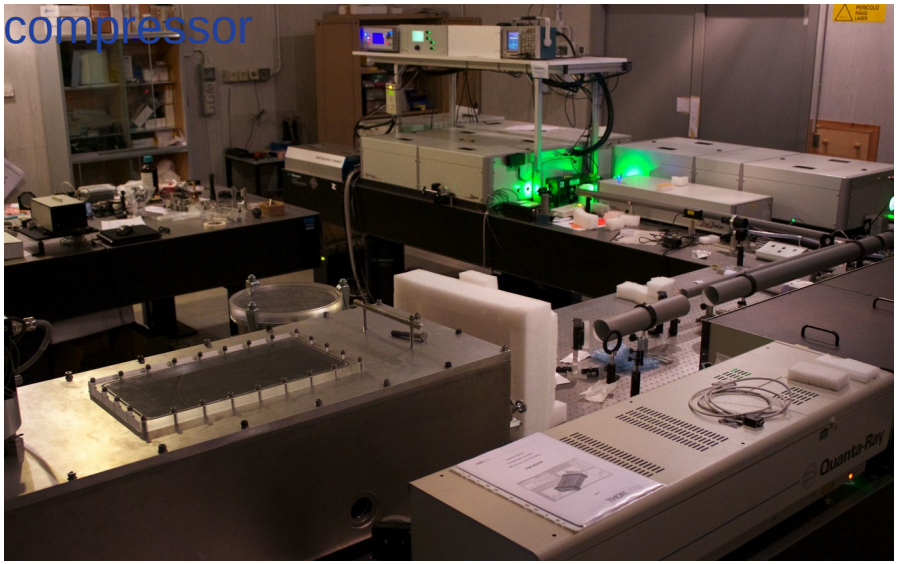
Target Area with radiation shielding inaugurated on March 2018



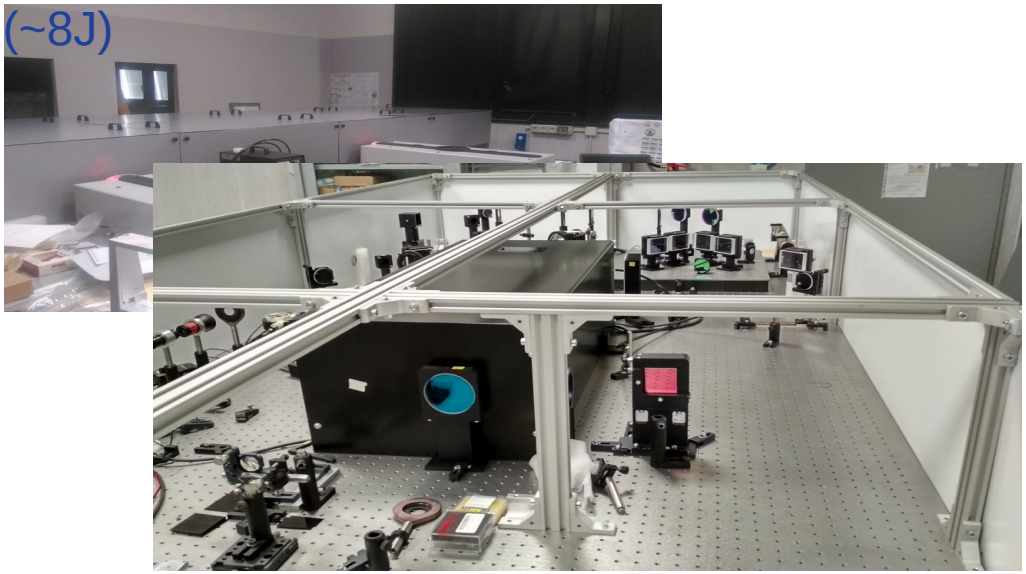


The lab: the laser system

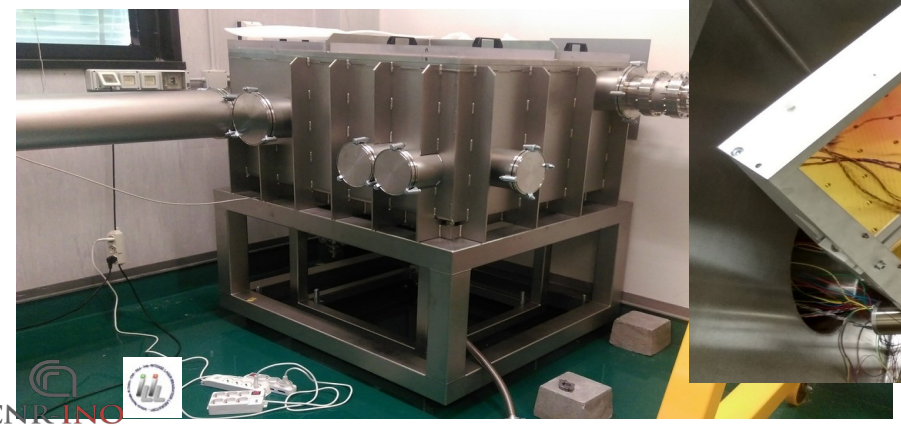
Front-end and 10TW compressor

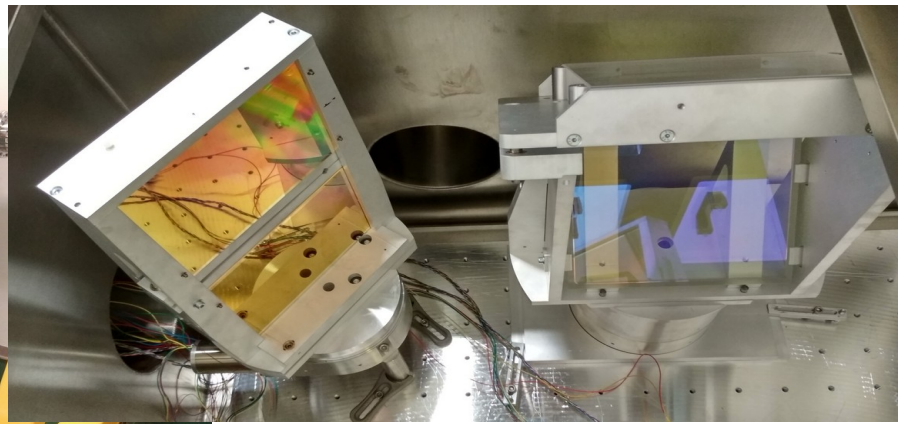


ILIL 220TW final amplifier (~8J)



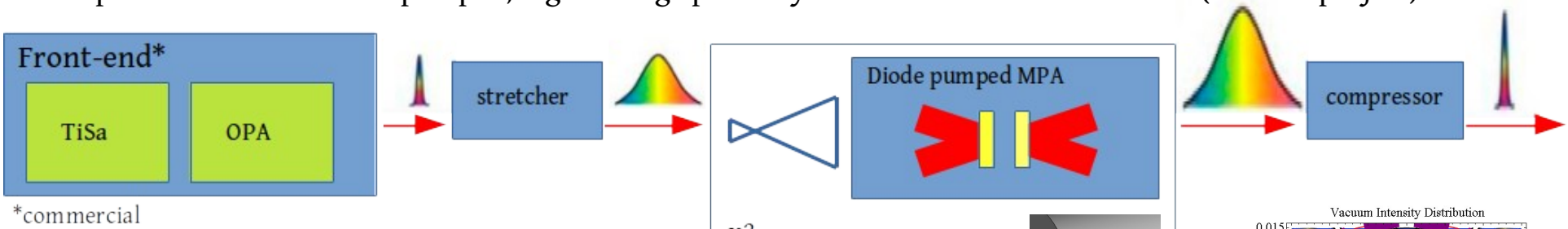
220TW compressor





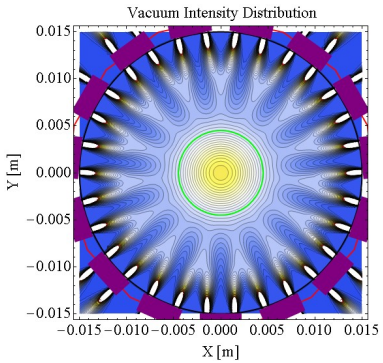
R&D on high average power/high rep rate lasers at CNR-INO

Development of a direct diode pumped, high average power system based on novel materials (APOLLO project)



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



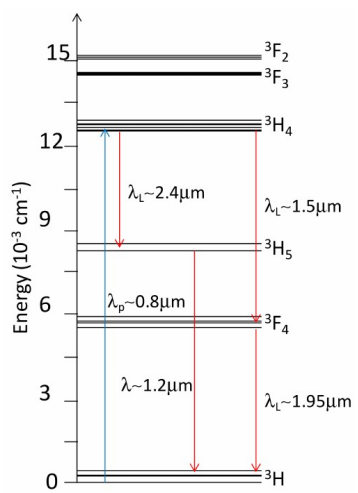
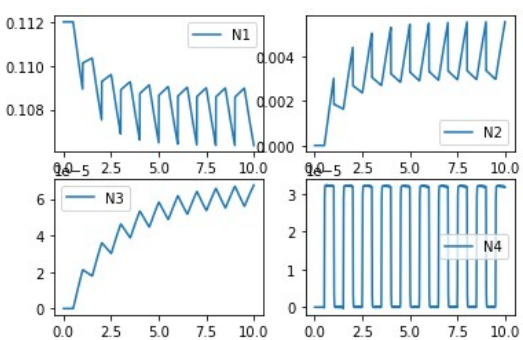


Figure 1. Energy level scheme of Tm^{3+} in Lu_2O_3 (ada



Multi-Pulse Extraction: long lifetime upper level(s), extraction occurs on multiple pulses at high rep rate

CNR-INO

Overview of EuPRAXIA lasers specs

LASER1 - Injector 150 MeV			
Parameter	**Unit**	**P0**	**P1**
Wavelength	nm	800	800
Max Energy on Target	J	5	7
Max Total Output Energy	J	8.8	12.5
Shortest Pulse Duration	fs	30	20
Repetition Rate	Hz	20	100
Energy Stability RMS	%	1	0.6
LASER2 - Injector 1 GeV			
Parameter	**Unit**	**P0**	**P1**
Wavelength	nm	800	800
Max Energy on Target	J	15	30
Max Total Output Energy	J	18.8	37.5
Shortest Pulse Duration	fs	30	20
Repetition Rate	Hz	20	100
Energy Stability RMS	%	1	0.6
LASER3 - Accelerator 5 GeV			
Parameter	**Unit**	**P0**	**P1**
Wavelength	nm	800	800
Max Energy on Target	J	50	100
Max Total Output Energy	J	62.5	125
Shortest Pulse Duration	fs	60	50
Repetition Rate	Hz	20	100
Energy Stability RMS	%	1	0.6

EuPRAXIA CDR

Three laser systems envisaged, to drive three stages:
- Laser Plasma Injector at 150 MeV (LPI 150MeV)
- Laser Plasma Injector/Accelerator at 1 GeV (LPI 1GeV)
- Laser Plasma Accelerator at 5 GeV (LPA 5GeV)

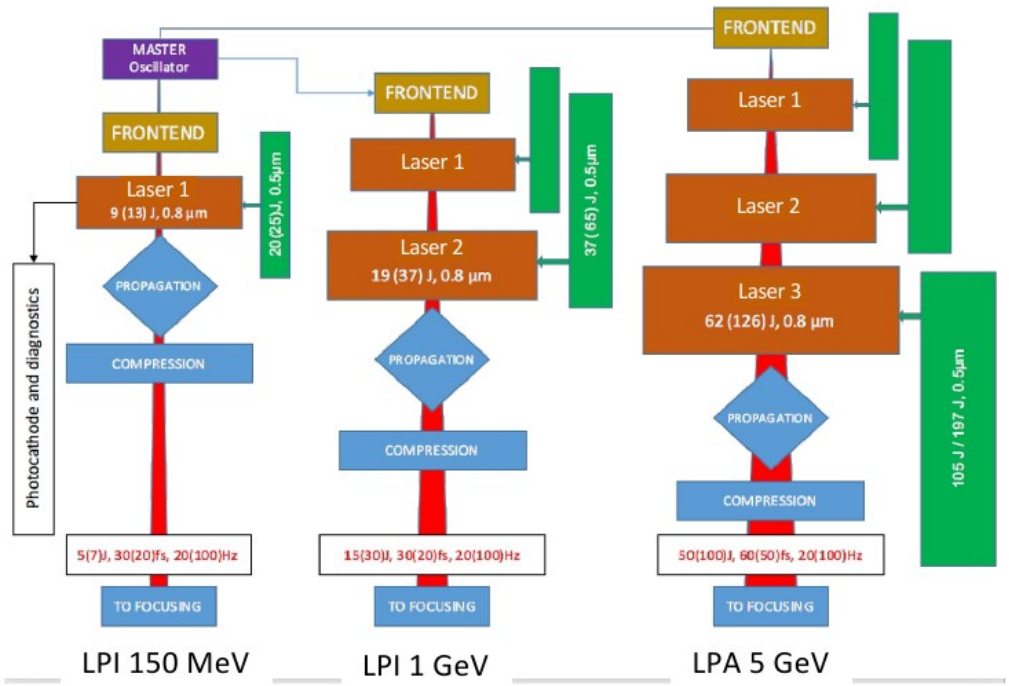
For each system, two levels of performances considered:
P0: low energy, 20 Hz rep rate
P1: high energy, 100 Hz rep rate

Key figures
Ultrashort pulses/large bandwidth (20 – 50 fs)
High rep rate (20 – 100 Hz)
High average power (sub-kW – 10 kW)
High wall-plug efficiency (1 – 30%)

The combination of all these parameters results in performances never achieved so far

The performance level P0 is less challenging in terms of required technologies. According to our study, it can be implemented with the currently available technologies, requiring mainly integration efforts and optimisation. Level P1 is more challenging and can be considered as lying one step ahead with respect to the current technological capabilities, in particular regarding the repetition rate of the pump sources. The target performances of the three laser chains, at the level

General architecture of the EuPRAXIA laser systems



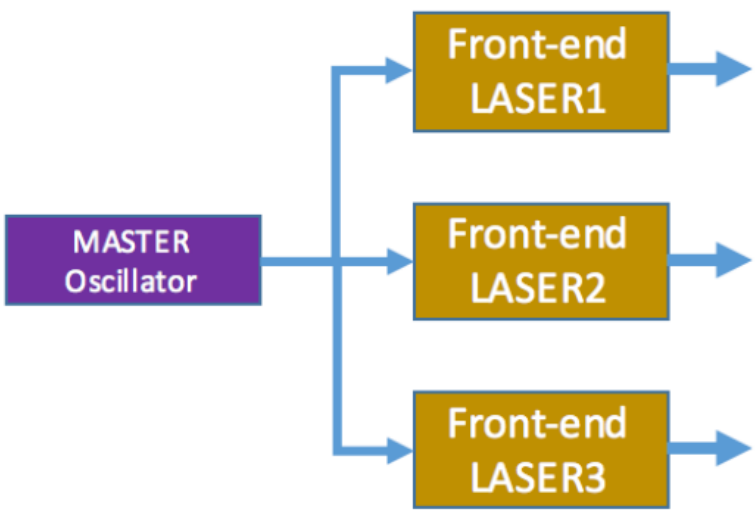
Modularity of amplification stages:

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

The EuPRAXIA laser(s) front-end(s)

Each laser beamline required independent spectral amplitude/phase control that is carried out in the front-end: EuPRAXIA required three independent front-end sections seeded by the same laser oscillator independently as per the requirements of the seeding of each of the three amplification chains



- Overall synchronization: single master oscillator, broadband
- Independent adjustment of spectral amplitude for each amplification chain: separate front –ends, with the same architecture
- Pulse energy 1.0-1.5 J
- Stretched pulse duration ~ 500 ps
- Main requirement: high pre-pulse contrast

Each of these front-end will deliver stretched pulses with ~1J energy to the subsequent amplification stages

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 propagation optics, gratings, ...

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

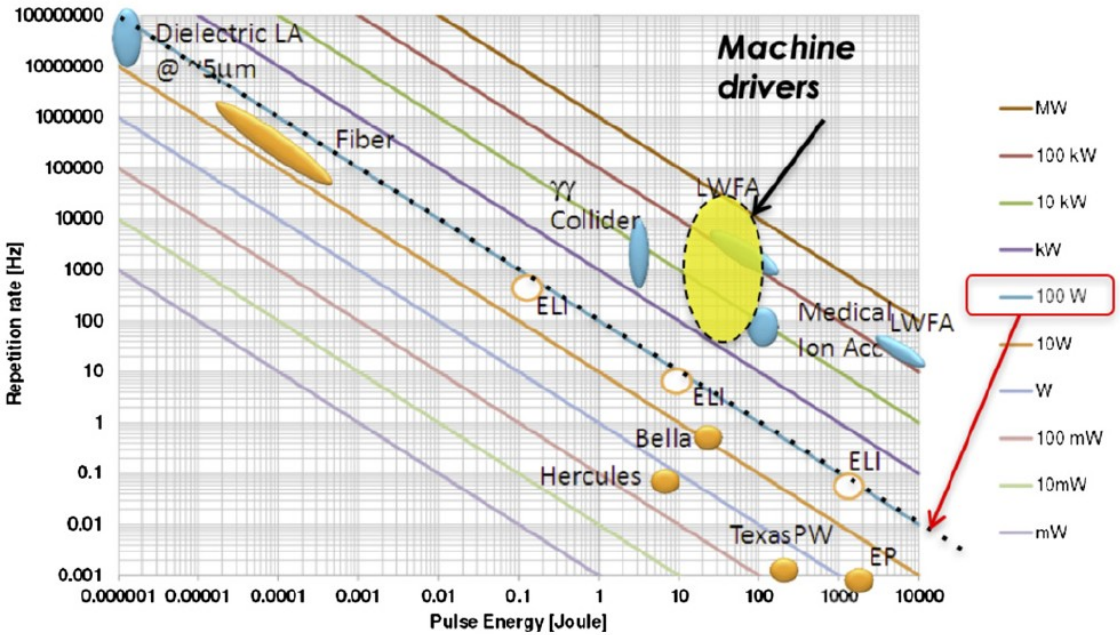


Figure 17. Repetition rate vs pulse energy of high intensity laser systems. The dotted line separates the existing systems with average power below approximately 100 W, with systems envisaged for applications and for laser–plasma acceleration drivers.

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
EuAPS@CNR specs: sub-J energy level, <30fs pulse duration, 100Hz rep rate, main amp based on diode technology

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

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

Laser architecture (tentative):
- double CPA with XPW pulse cleaning (contrast expected 10^{11}-10^{12} at 100ps)
- diode pumping technology for Nd pumps
- final amplifier based on active mirror concept

Active spectral amplitude/phase correction

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

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

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

EuAPS – WP4 outcomes/time schedule

Most relevant outcomes

New laser laboratory with clean room installation (for the laser system)

Ultrashort, high rep rate laser, J-class laser system (pulse duration <25fs, pulse energy sub-J, 100 Hz repetition rate). The system is expected to boast parameters similar to those expected for the 100 Hz option of the front-end laser system of the EuPRAXIA laser, and will thus allow the development of further amplification stages of interest for the final EuPRAXIA laser to be carried out.

Laser beam transport vacuum line up to the users end station.

HPC (GPU based) cluster to be used for advanced, full temporal/spatial scale optical simulations and thermomechanical modelling, shared for developments needed by users.

Users end station equipped with a vacuum chamber for testing high power, ultrashort laser optics

EuAPS – WP4 outcomes/time schedule

List of WP deliverables

D4.1.1 **Laser system design (report) M6**. Report on the laser architecture selected, including oscillator specs, booster/multipass amplification stages, contrast enhancement, (diode) pumping for each amplifier

D 4.1.2 **Laser system specifications (report) M20**. Report on the final specs of the commissioned laser system; this will include pulse duration, pulse energy, ASE/ps pedestal contrast, short/long term energy stability, pulse spectrum, pointing stability

D4.2.1 **Laser beam transport (report) M12**. Design of the laser beam transport to the user's end station, including expected performances regarding pulse duration, pointing diagnostics and so on

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

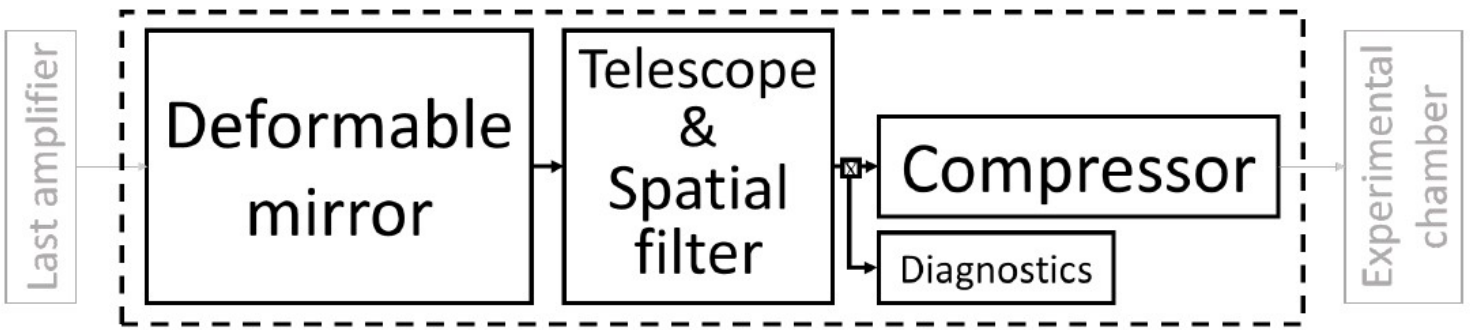
D4.3.1 **Infrastructure design (report) M8**. Preliminary design report of the whole infrastructure

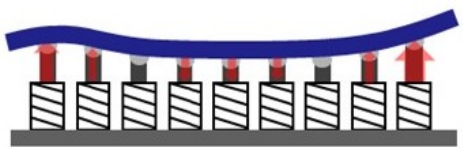
D4.3.2 **User's area capability design (report) M22**. Report on the user's area, including the expected user's station and related facilities/devices, timing/synchronization capabilities, irradiation station(s) characteristics/footprints

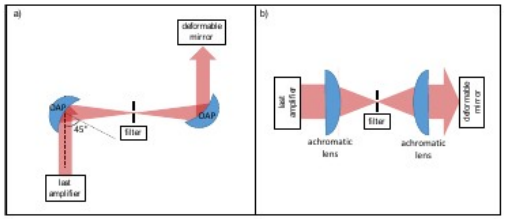
D4.3.3 **Final infrastructure report, including full beam line specs and available options (report) M30**. Final report on the infrastructure, including all beam line specifications, with a user-oriented approach

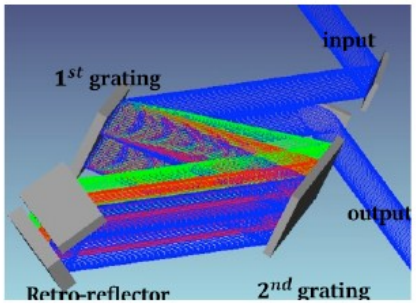
Studies related to the EuPRAXIA laser development: transport to target

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





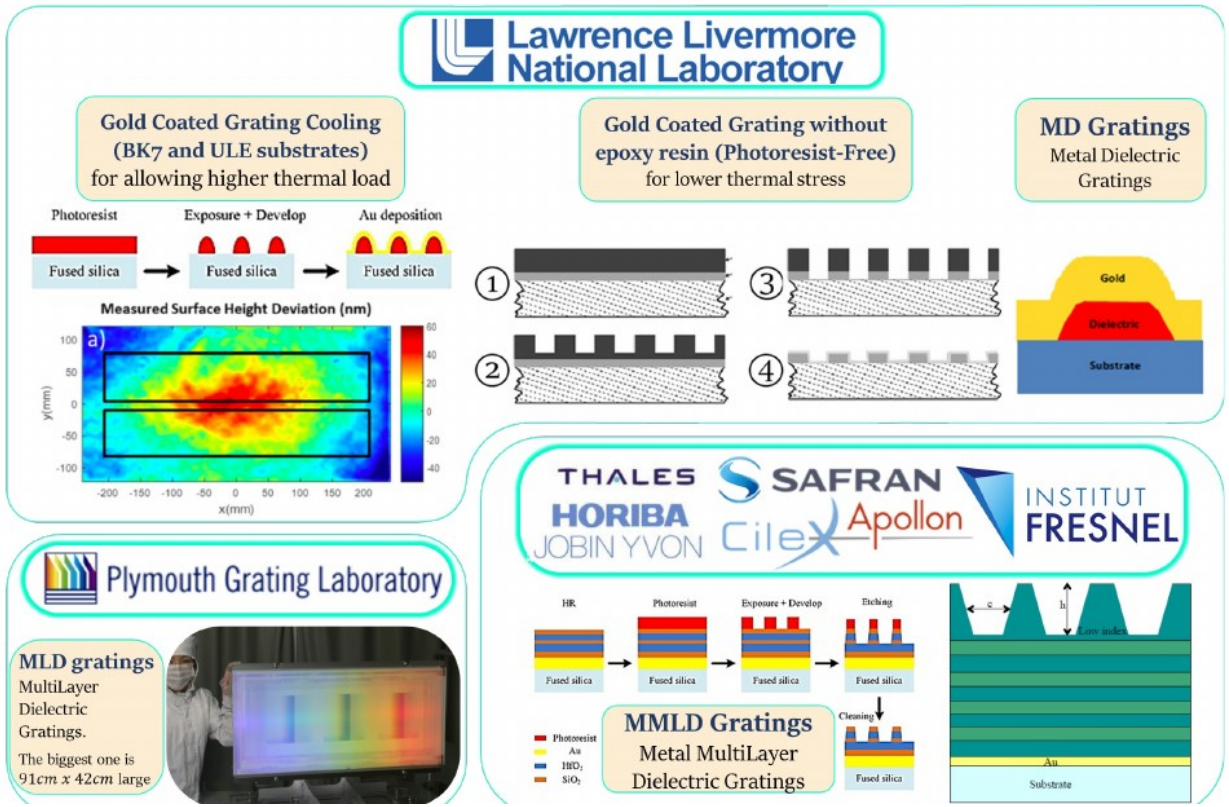




Wavefront aberration characterization (thermal lensing, high order aberrations, …)
Beam size manipulation, focusing
Beam diagnostics/manipulation at high rep rate (high frequency feedback loops)

Studies related to the EuPRAXIA laser development: compressor grating technology

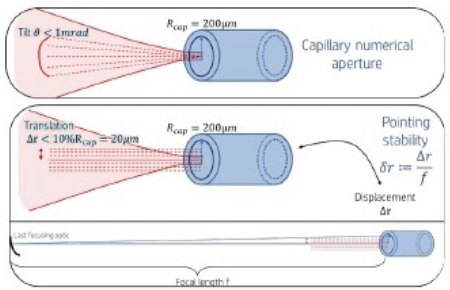
Different technologies under evaluation to address main issues with higher repetition rate. Strategy includes **reduction** of the thermal load at high average power, **cooling** of residual heat and **control** of thermal effects on compression quality.

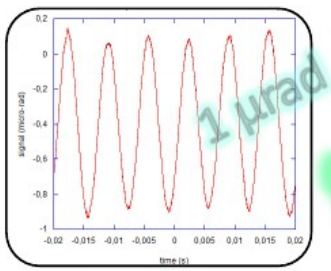


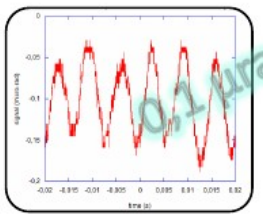
Wavefront aberration characterization (thermal lensing, high order aberrations, ...)
Beam size manipulation, focusing

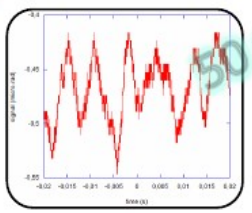
Studies related to the EuPRAXIA laser development: beam pointing stability

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.









Laser angular fluctuations footprints at 150 Hz

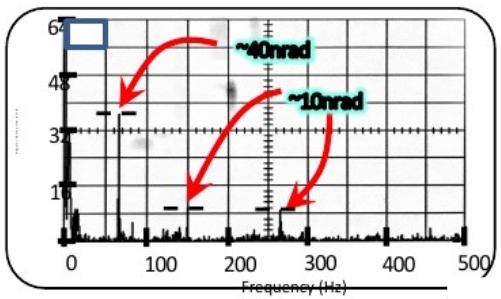
Environmental angular noise of about 30 nano-rad

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 kHz region and more

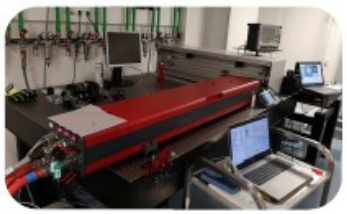
Spectral analysis of the laser fluctuation.



CNR-INO

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

THEIA PRODUCT



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

Design has been made to get the most **robust** and **reliable system**

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

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

Using diodes for pumping will **increase the lifetime**

We estimate as state of the art **5 to 10 billions shots**

CIVIL DEFENCE & SECURITY

THALES

Courtesy of Christophe Simon-Boisson (Thales)

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

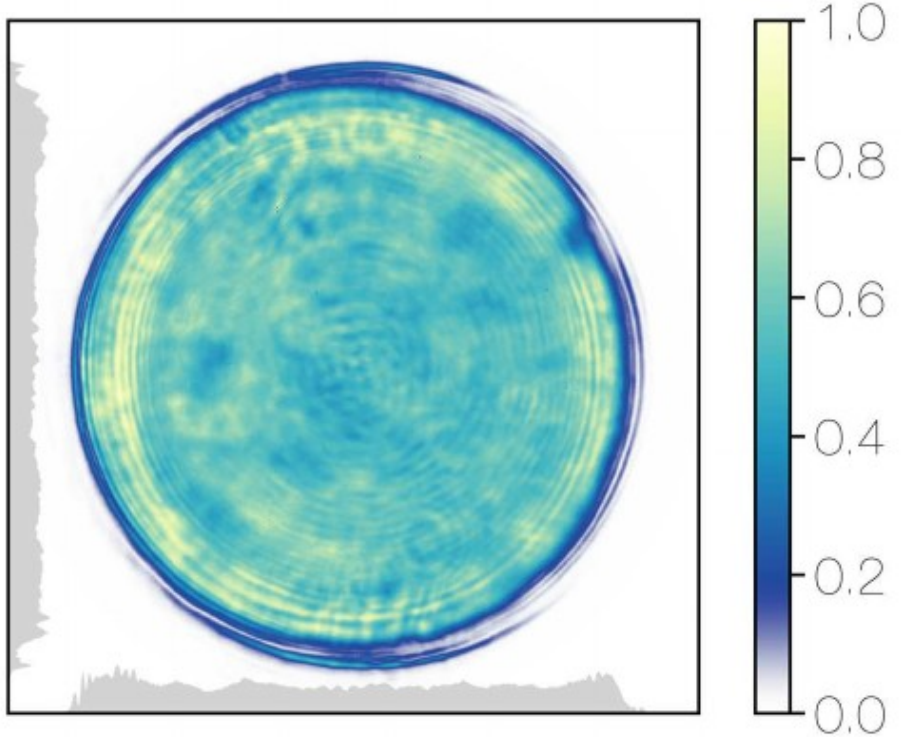
THEIA SPECIFICATIONS

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



THALES

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

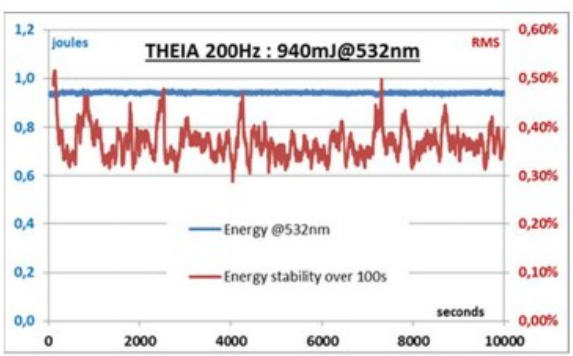
Industry activity on 100Hz rep rate, J-class amplifiers: Thales

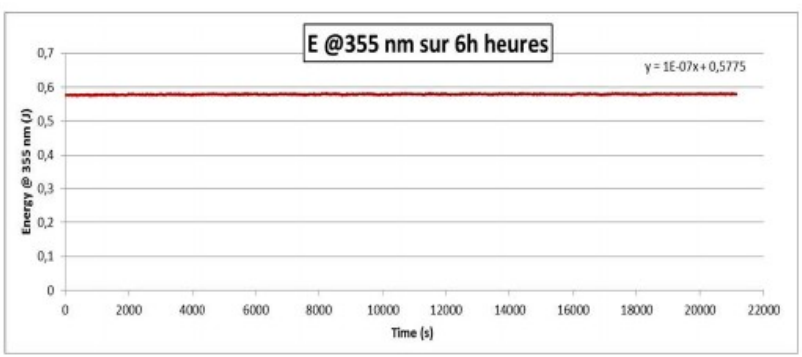
LAB RESULTS

Lab results @532 nm (lab demonstrator)

Same IR configuration & SHG with adapted LBO crystal

- Up to 940 mJ @532nm vs target >700 mJ
- SHG efficiency : 75%
- Energy stability : <0,5% rms





CIVIL DEFENCE & SECURITY

THALES

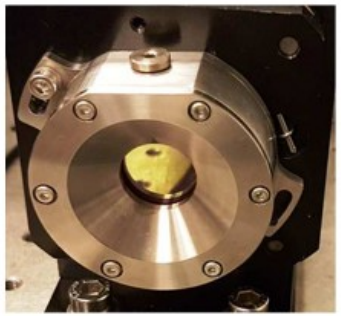
Courtesy of Sandrine Ricaud/ Christophe Simon-Boisson (Thales)

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

TI:SA GAIN MODULE

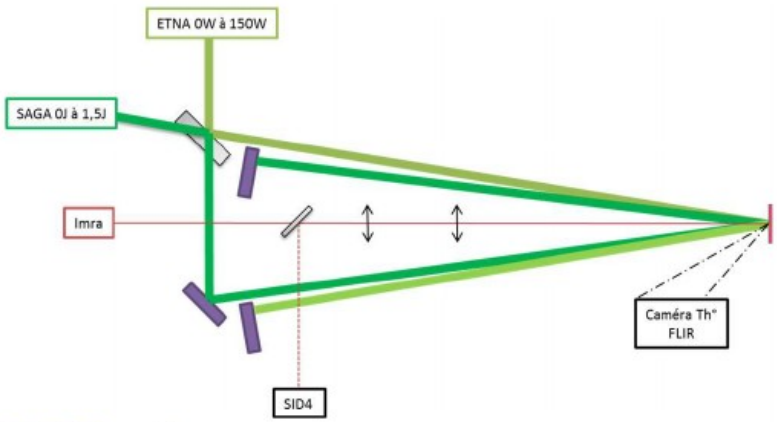
Concept

- 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 DEFENCE & SECURITY

THALES

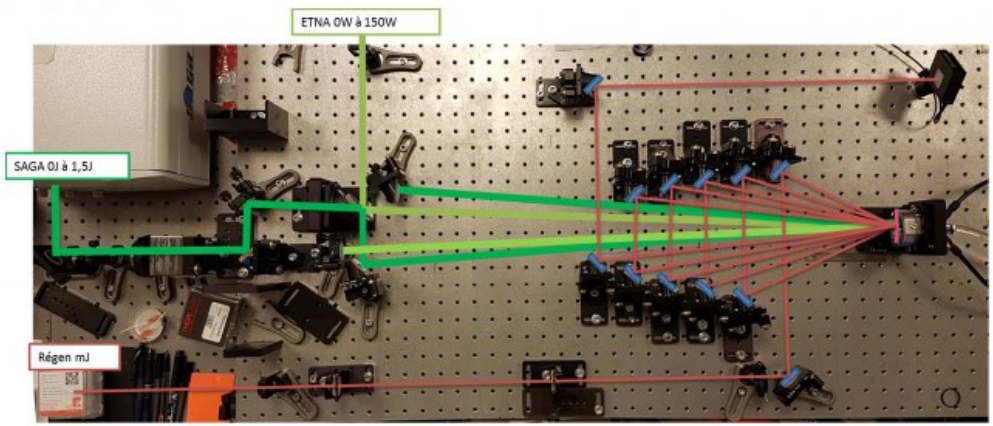
Courtesy of Sandrine Ricaud/ Christophe Simon-Boisson (Thales)

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

TI:SA GAIN MODULE

Multi-pass amplification

- **Tests done at 10 Hz** (Theia not available at the time) but **with additionnal 75 W** laser to provide **equivalent thermal load**
- At 10Hz with thermal load up to 75W : **250mJ output for 750mJ pump energy** (2mJ Input energy) = ~33 % extraction but beam size can be optimized
- Thermal lens measured : manageable up to 75 W
- **Next steps: repeat tests at 100 Hz with Theia laser**



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

TI:SA DISK AMPLIFIER

Advantages

- Good overlap between pump and signal beams
- Really compact amplifier
- Focal lens longer than 1m
- Crystal wedged, no contrast degradation

Next steps

- Amplification with THEIA laser @ 100Hz
- Thermal lens characterization with THEIA laser
- Goal : amplification > 250mJ with THEIA laser

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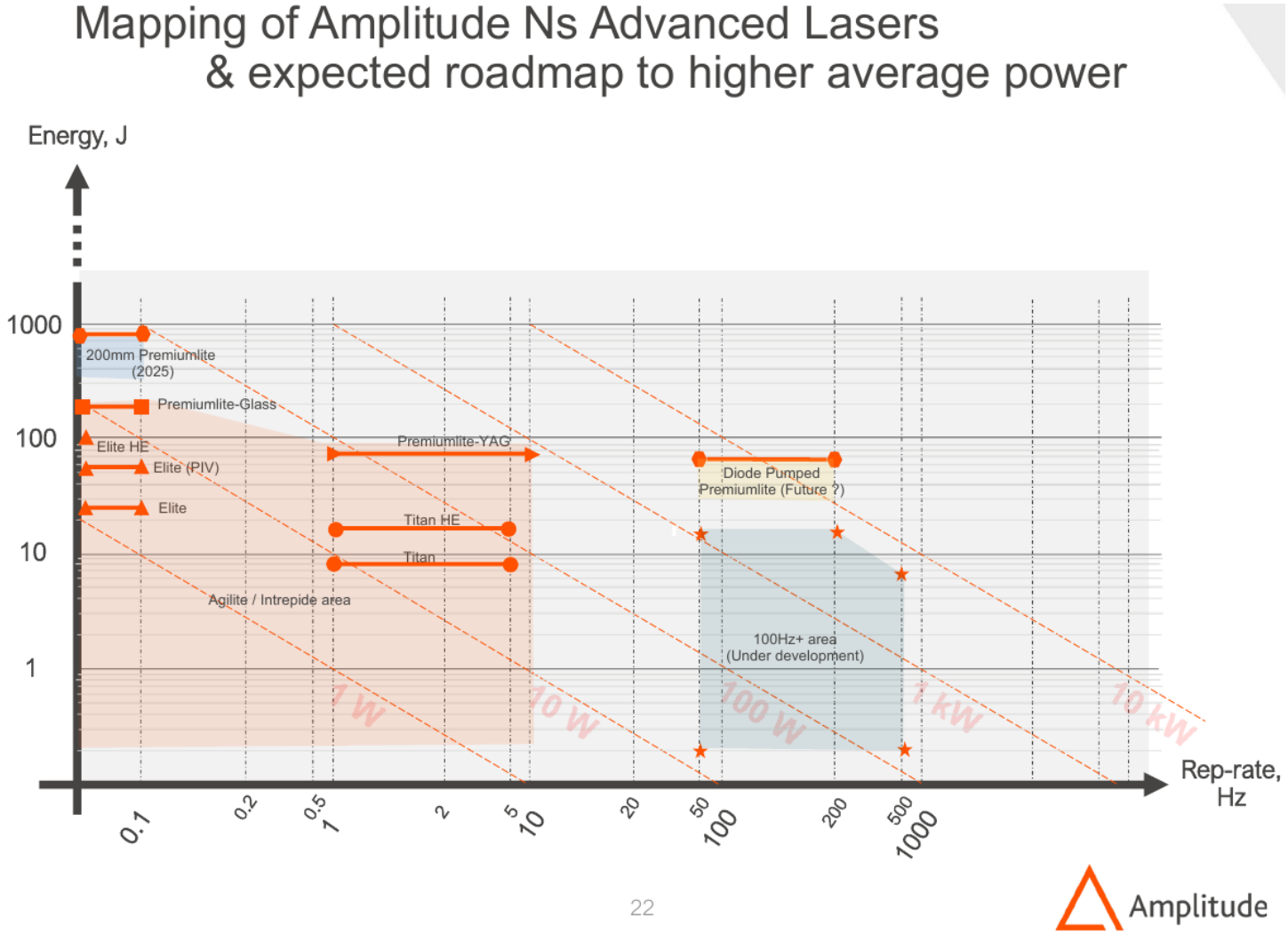
Industry activity on 100Hz rep rate, J-class amplifiers: Amplitude

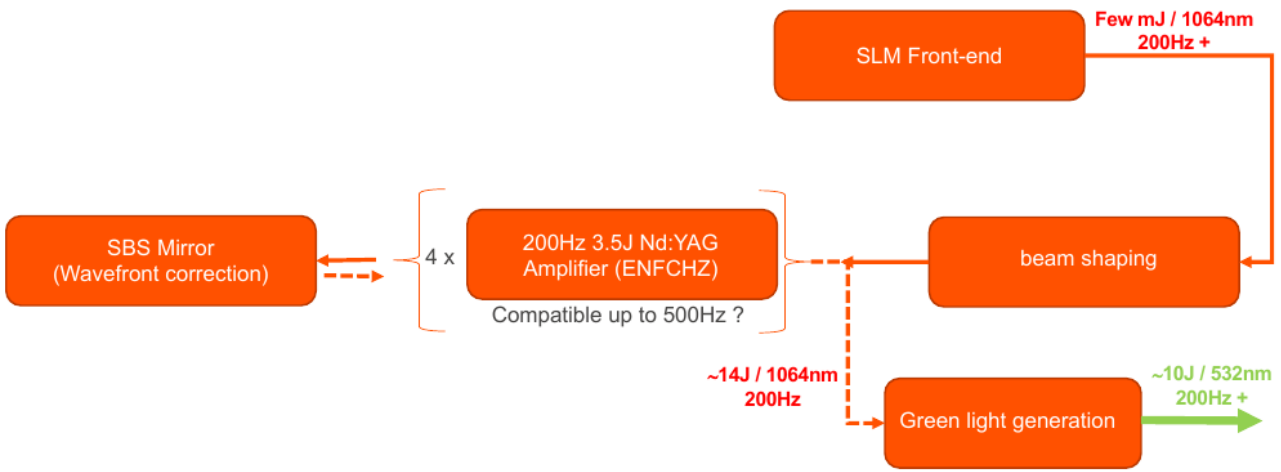


Courtesy of Franc Falcoz/Stephane Branly (Amplitude)

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)

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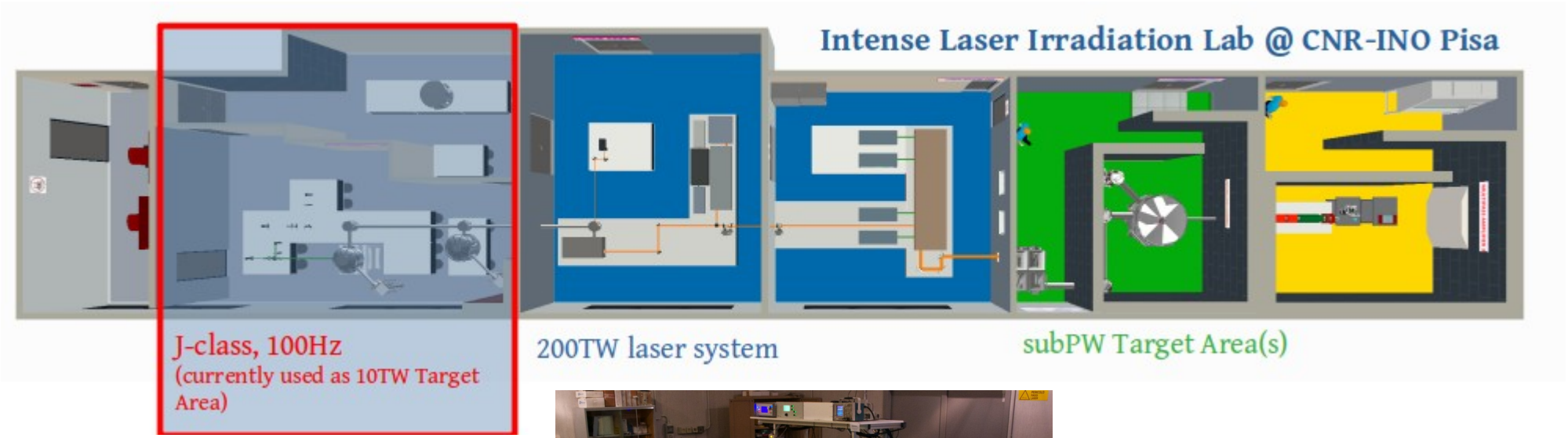
Amplitude

Courtesy of Franc Falcoz/Stephane Branly (Amplitude)

EuAPS – High Rep Rate Laser Beamline Infrastructure



The new ultrashort, J-class, high rep rate laser system is tentatively expected to be hosted in the 10TW Target Area (~100m2 excluding room for ancillaries) currently available.