EuPRAXIA
Advanced Photon Sources

WP4: High Repetition Rate Laser Beamline

Luca Labate

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Also at INFN, Sezione di Pisa

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

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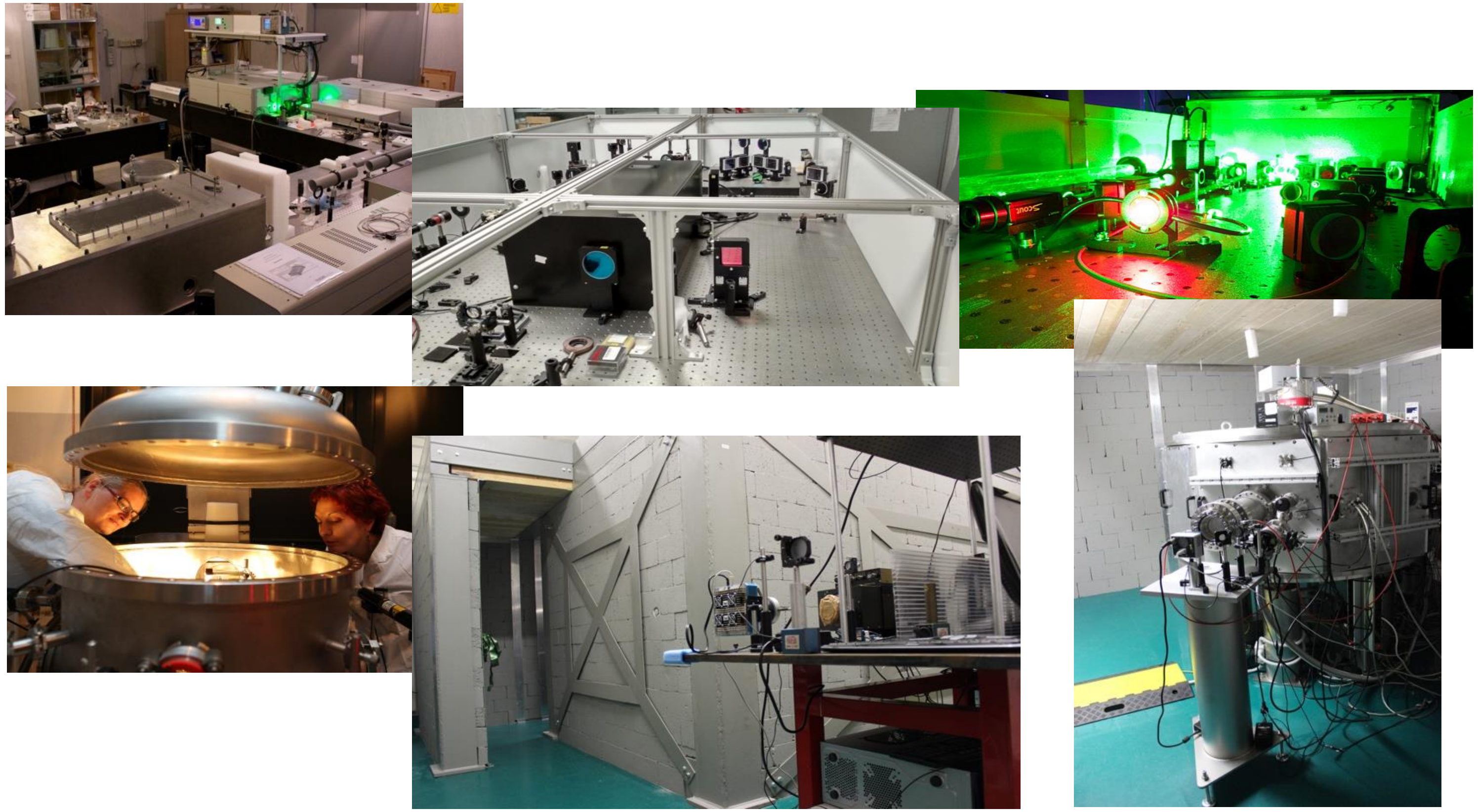
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
CNR-INO ISTITUTO NAZIONALE DI OTTICA CONSIGLIO NAZIONALE DELLE RICERCHE

The ILIL (*Intense Laser Irradiation* Laboratory) group

Scientific team

Leonida A. **GIZZI*** (Head of lab)
Fernando **BRANDI**
Gabriele **CRISTOFORETTI**
Petra **KOESTER**
Luca **LABATE***
Federica **BAFFIGI**
Lorenzo **FULGENTINI**
Gabriele **BANDINI** term ← ***EuAPS***
Alessandro **FREGOSI** term ← ***EuAPS***
Daniele **PALLA** term
Costanza **PANAINO** term
Simona **PICCININI** term
Martina **SALVADORI** term
Emma **HUME** postdoc
Federico **AVELLA** PhD student
David **GREGOCKI** PhD student
Simon **VLACHOS** PhD student
Gianluca **CELLAMARE** (associated)

**Also at Istituto Nazionale di Fisica Nucleare*



The ILIL lab

NEW: HAP kHz LASER DEV. LAB

USER CONTROL ROOM

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

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PNRR (“Piano Nazionale di Ripresa e Resilienza”)

NEW: UNDER-GROUND BUNKER

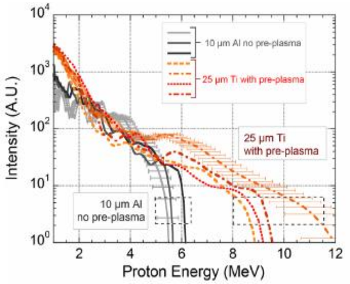
Motivations (1). Toward applications of laser-driven particle accelerators: Proton beams

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]
Pablo I. Bilbao[3], Fernando Brandi[1], Gabriele Cristoforetti[1]

Scientific Reports | (2021) 11:13728

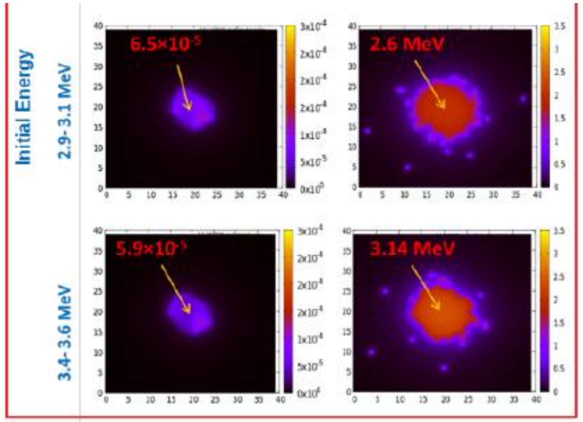


Article

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

Fernando Brandi [1,*], Luca Labate [1,2,*], Daniele
Petra Koester [1], Federica Baffigi [1], Massimo Chia

applied sciences



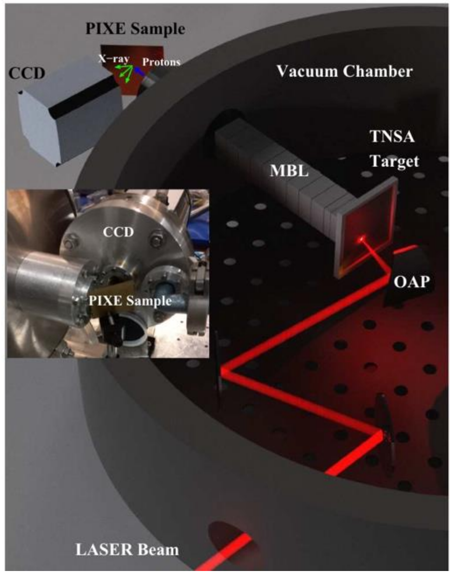
PHYSICAL REVIEW APPLIED **21**, 064020 (2024)

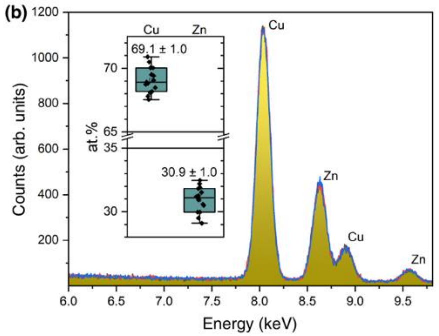
Quantitative elemental analysis of a specimen in air via external beam laser-driven particle-induced x-ray emission with a compact proton source

Martina Salvadori,[1,*] Fernando Brandi,[1,†] Luca Labate,[1,‡,§] Federica Baffigi,[1]
Lorenzo Fulgentini,[1] Pietro Galizia,[2] Petra Koester,[1] Daniele Palla,[1] Diletta Sciti,[2] and
Leonida A. Gizzi[1,§]

[1] *Consiglio Nazionale delle Ricerche, Istituto Nazionale di Ottica (CNR-INO), Pisa, Via Moruzzi, 1, Pisa 56124, Italy*

[2] *Consiglio Nazionale delle Ricerche, Istituto di Scienza, Tecnologia e Sostenibilità per lo Sviluppo dei Materiali Ceramici (CNR-ISSMC), Faenza, Italy*





Missione 4 • Istruzione e Ricerca

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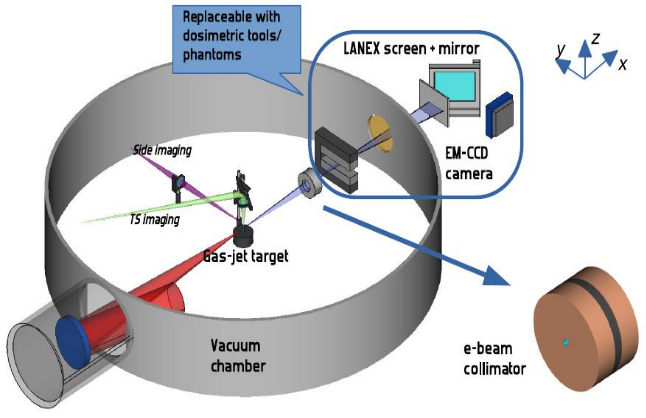
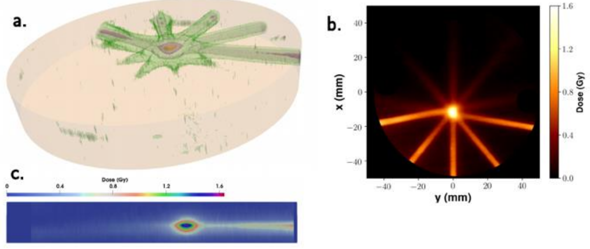
Motivations (2). Very High Energy Electrons (VHEE) for radiotherapy

Very High Energy Electrons (~100-250MeV) for direct radiotherapy?
Toward FLASH-effect based modalities…

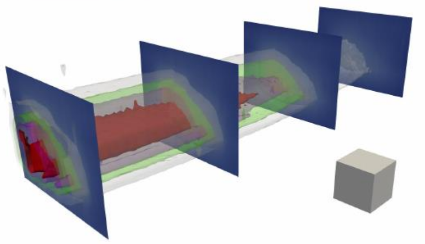
Recent experiments aimed at demonstrating the feasibility of advanced irradiation modalities (similar to current photon based radiotherapy) with laser-driven VHEE pencil beams



Multi-field irradiation



Intensity modulation (IMRT-like dose painting)

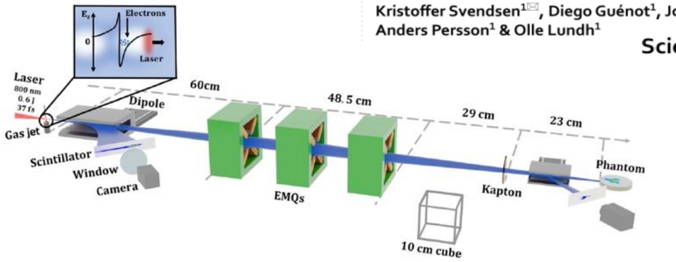


L. Labate *et al.*, Sci. Rep. **10**, 17307 (2020)

OPEN **A focused very high energy electron beam for fractionated stereotactic radiotherapy**

Kristoffer Svendsen[1], Diego Guénot[1], Jonas Björklund Svensson[1,2], Kristoffer Petersson[3,4], Anders Persson[1] & Olle Lundh[1]

Scientific Reports | (2021) 11:5844

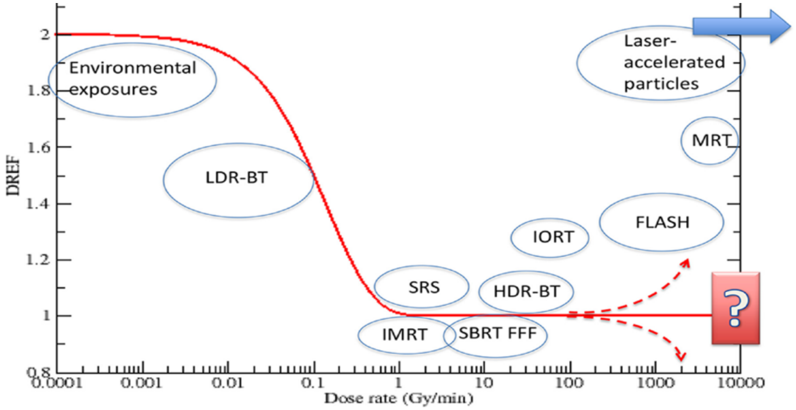


Cite this article as:
Durante M, Bräuer-Krisch E, Hill M. Faster and safer? FLASH ultra-high dose rate in radiotherapy. *Br J Radiol* 2018; **91**: 20170628.

COMMENTARY

Faster and safer? FLASH ultra-high dose rate in radiotherapy

[1]MARCO DURANTE, PhD, [2]ELKE BRÄUER-KRISCH, PhD and [3]MARK HILL, PhD

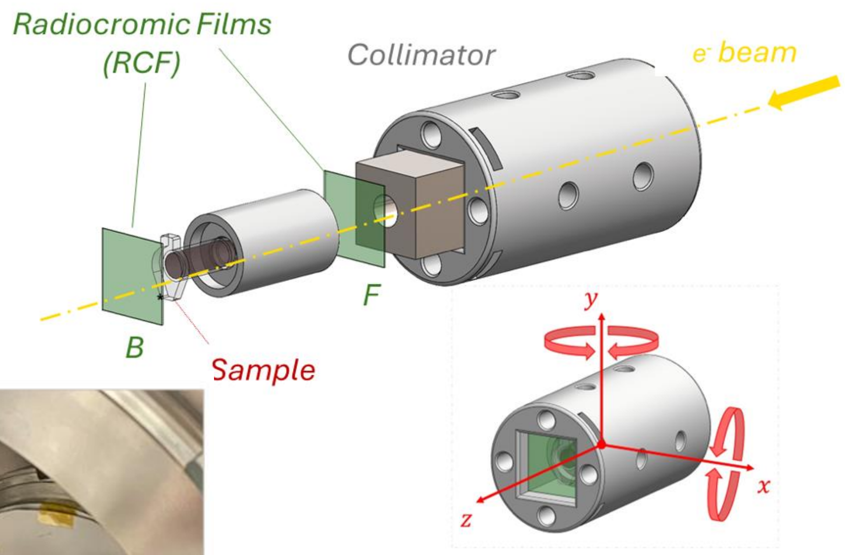


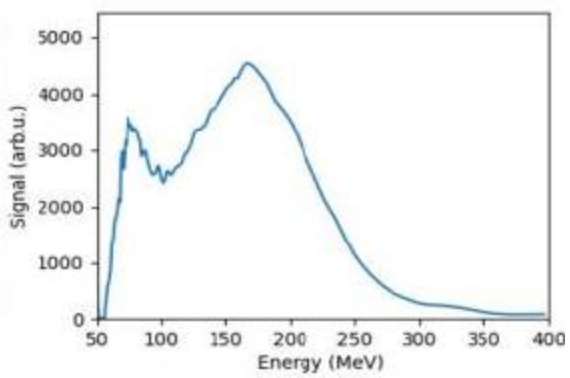
Motivations (3). Very High Energy Electrons (VHEE) for radiotherapy: Recent experiments @ ILIL-INO-CNR

RUN50 del 02 Luglio 2024

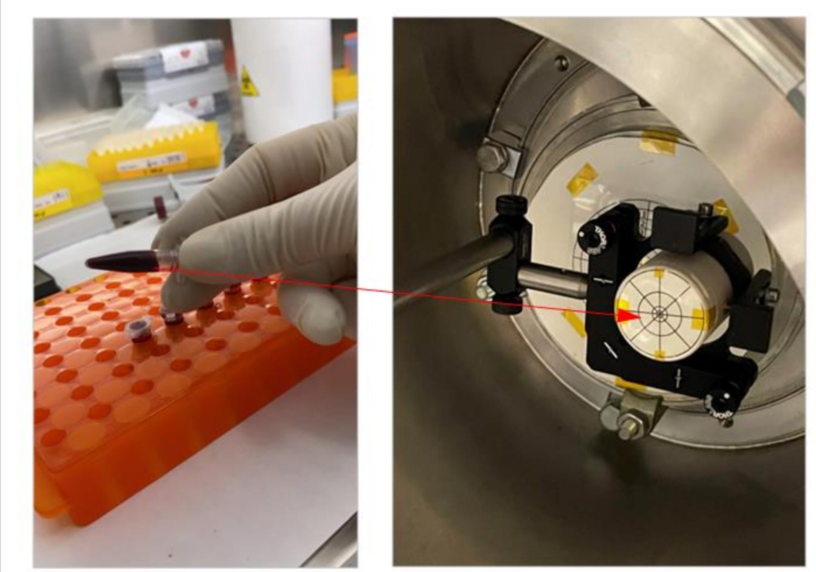
SAMPLE	RCF (F-B)	COMMENTS	RCF	D Media Cal 2025 (Gy)		
2	13-14		F			one shot
3	15-16	faint	B	0,27	0,3±0,1	one shot
8	29-30		F			one shot
1	11	homogeneus	F	1,25	1,3±0,2	

3D printed sample holder with 0.5 ml Eppendorf tube adapter



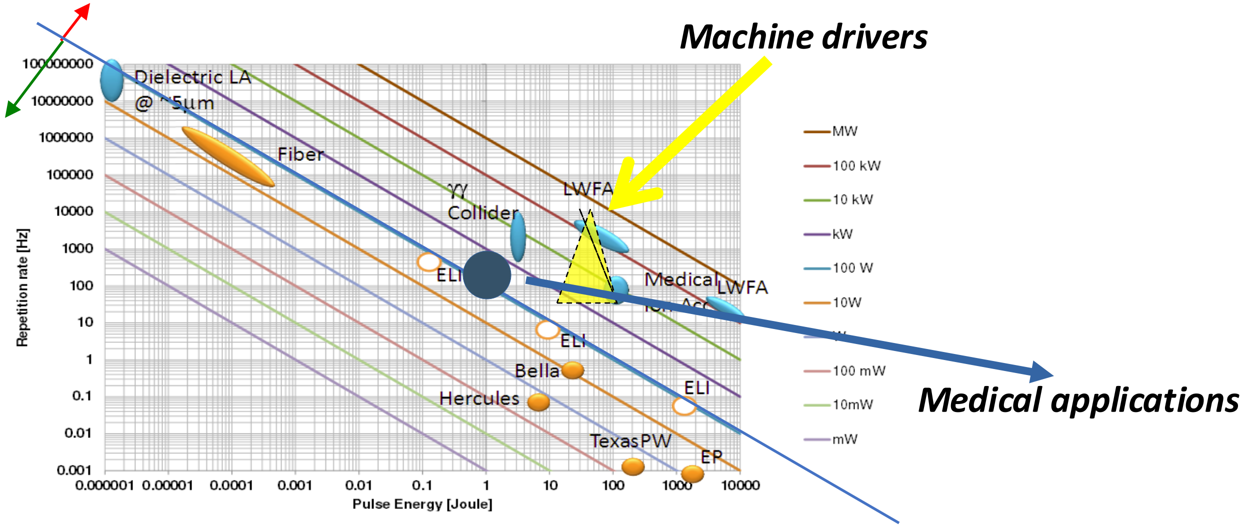


Path for reaching FLASH-ready dose rates with ~100Hz rep rate systems



Context: The need for high rep rate/high average power ultrashort/ultraintense lasers

Most of the foreseen applications of laser-driven particle accelerators requires particle (or secondary X/gamma-ray photon) beams with a high average flux
This requires high repetition rate laser systems, beyond the ~10Hz level of nowadays ultrashort/ultraintense systems, which translates into high average power lasers



The EuPRAXIA laser(s)

Quantity	Baseline Value
Laser 1 - Energy on target	≤ 5–7 J
Laser 1 - Pulse duration	≥ 20–30 fs
Laser 2 - Energy on target	≤ 15–30 J
Laser 2 - Pulse duration	≥ 20–30 fs
Laser 3 - Energy on target	≤ 50–100 J
Laser 3 - Pulse duration	≥ 50–60 fs
Wavelength	800 nm
Repetition rate	20–100 Hz
Energy stability (RMS)	0.6–1 %
Pointing stability (RMS)	~1 µrad

Average power ranging from 1kW to 10kW

Current TiSa-based CPA technology (TiSa pumped by frequency doubled, flashlamp pumped Nd lasers) is not foreseen to be scalable to the ~kHz rep rate, basically due to thermal management issues

Major efforts required to fill the gap between existing and required laser technology

EuAPS system at CNR paving the way to the EuPRAXIA laser driver

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%)

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

EuAPS

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

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

"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, as well as of applications of high average flux laser-driven particle beams

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 to provide users with a state of the art characterization of the beam features, as well as flexibility for parameter adjustment/tuning

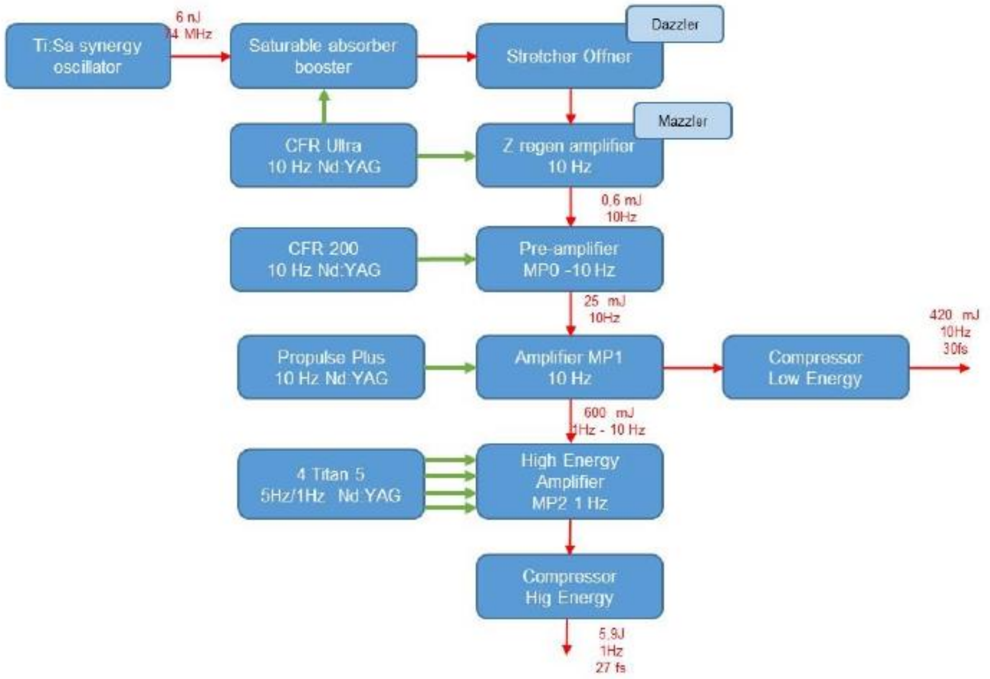
Full set of longitudinal functions diagnostics (WIZZLER or similar, 3rd order autocorrelation, …)

Wavefront characterization and correction

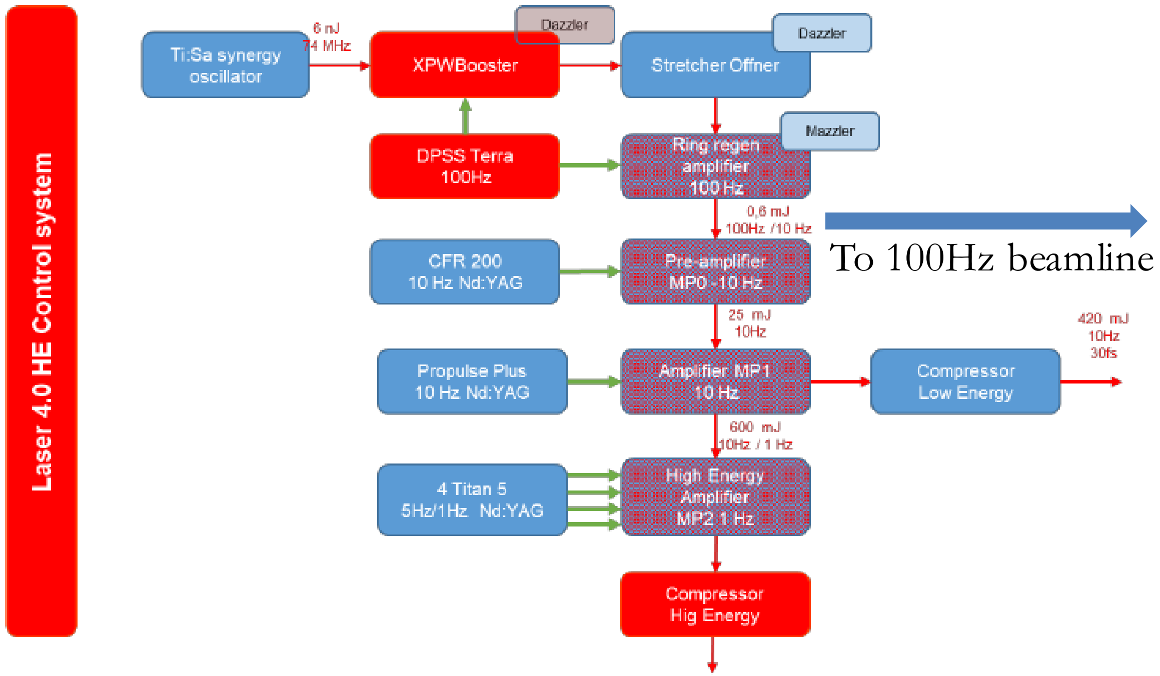
TiSa laser system upgrade at ILIL: The final layout

After upgrade (PNRR projects):
Common front-end (@100Hz) driving a) a >200TW, 1Hz system, and b) >40TW, 100Hz system

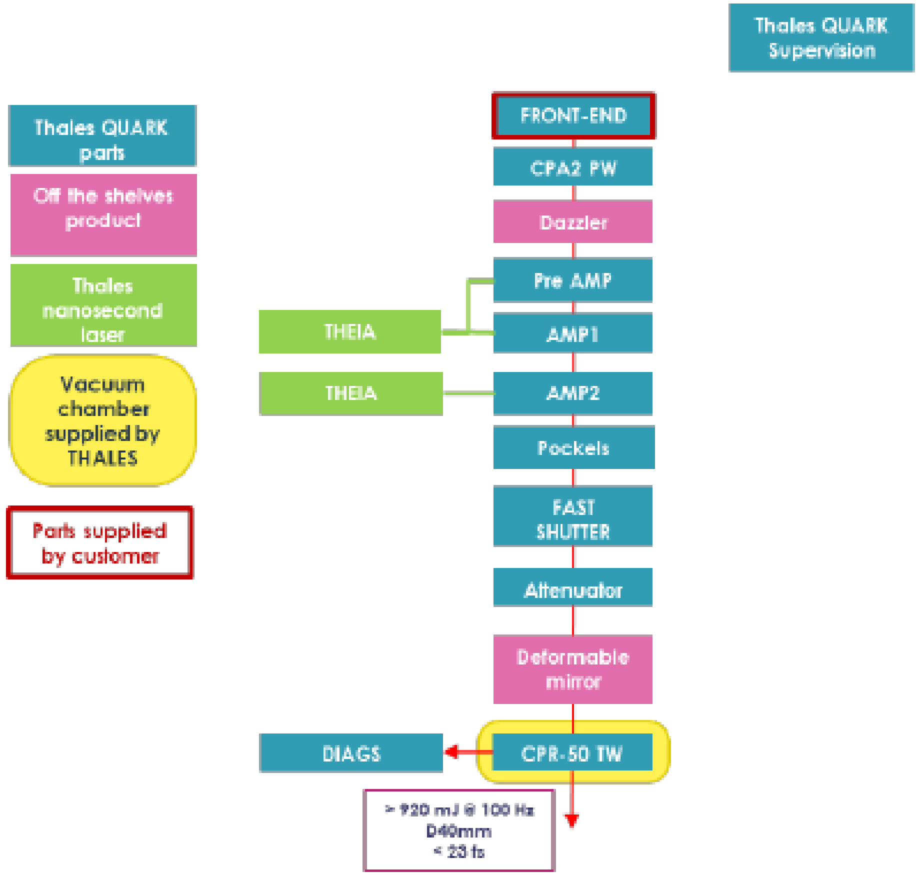
Current layout (up to a few weeks ago)



Front-end (and 220TW) layout (Amplitude Technologies)



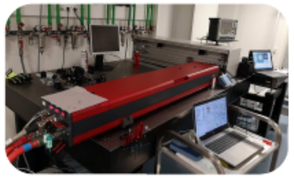
The 100Hz amplifier's optical layout (awarded to Thales)



Specification	unit	Requirement	Thales commitment	Comments
Output energy	mJ	> 650	≥ 920	
Pulse duration	fs	≤ 25	< 23	
Peak power	TW	≥ 25	> 40	
Repetition rate	Hz	100	100	
Central wavelength	nm	800 nm +/- 40 nm	800 nm +/- 10 nm	
Strehl ratio	%	> 85	≥ 90	
Contrast:				
- ns		> 10^8	≥ 5x10^8	
- @5 ps		> 10^6	> 10^7	
- @30 ps		> 10^8	> 10^9	
- @100 ps		> 10^10	> 10^10	
Energy stability	% RMS	< 1.5	< 1.5	over 2000 shots
Long-term energy stability (over 2h)	% RMS	< 2	< 1.5	excluding ramp-up time
Pointing stability	µrad RMS	< 5	< 5	over 2000 shots

Thales "THEIA" pumps

THEIA PRODUCT



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

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

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

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CIVIL DEFENCE & SECURITY

THALES

THEIA SPECIFICATIONS

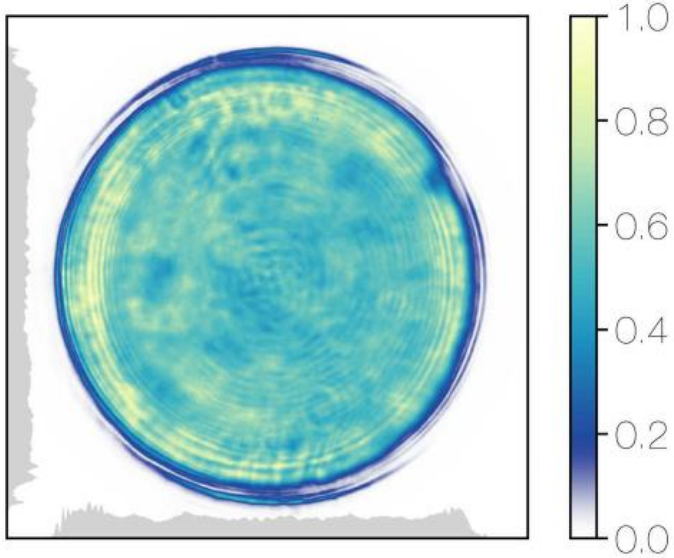
Specifications

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

CIVIL DEFENCE & SECURITY



THALES

Courtesy of Christophe Simon-Boisson (Thales)

Thales MP amplifiers: "Active mirror" architecture

TI:SA GAIN MODULE

Concept

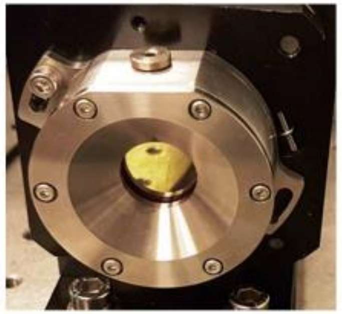
- Cristal use as **active mirror**
- **Efficient cooling system** to keep crystal temperature < 50°C and maximize gain
- **Limit thermal lens** to keep simple amplifier architecture

Caracterization

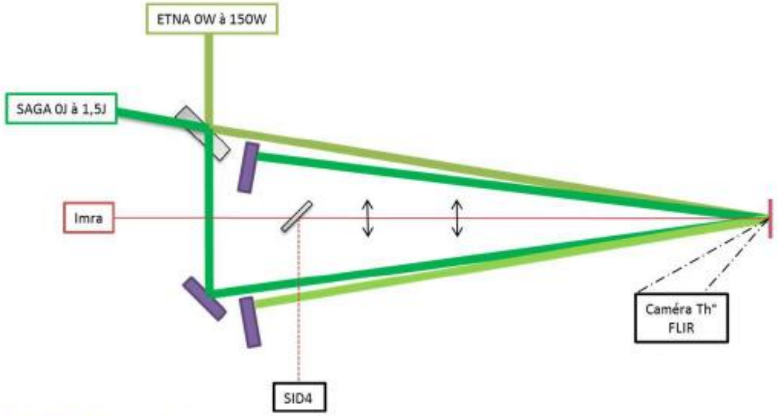
- Crystal design = Thales patent
- Pumped with THEIA laser 100Hz 750mJ @532nm, but not yet available
- Thermal lens measurement with ETNA HP laser at 80 average power
- Gain measurement with ETNA HP laser at 80W average power
- Temperature measurement with ETNA HP laser at 80W average power

CIVIL

THALES

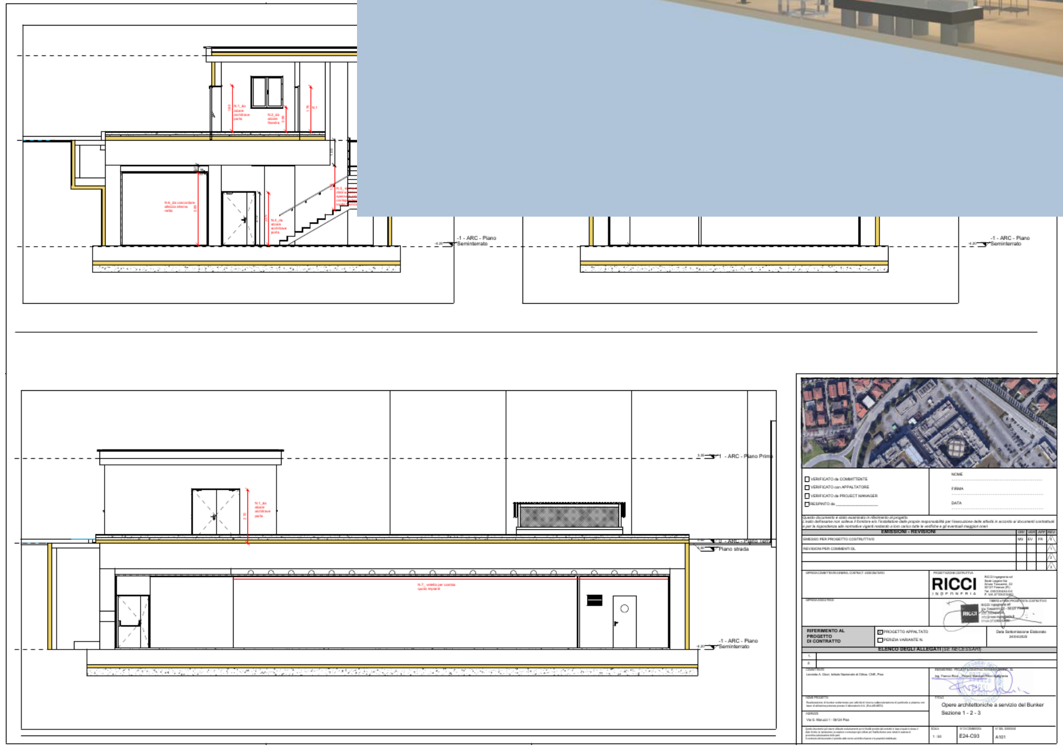


The CNR-INO laser will feature two active mirror amplification stages

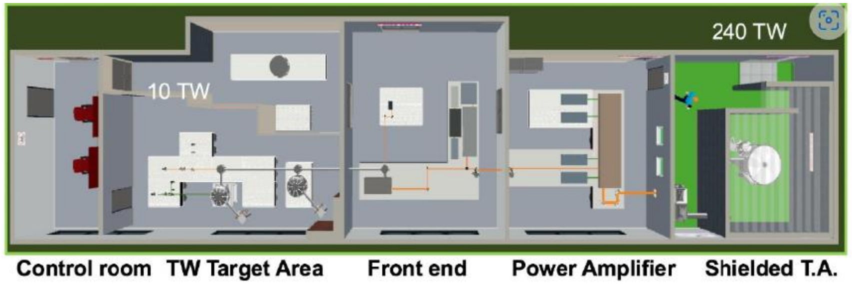


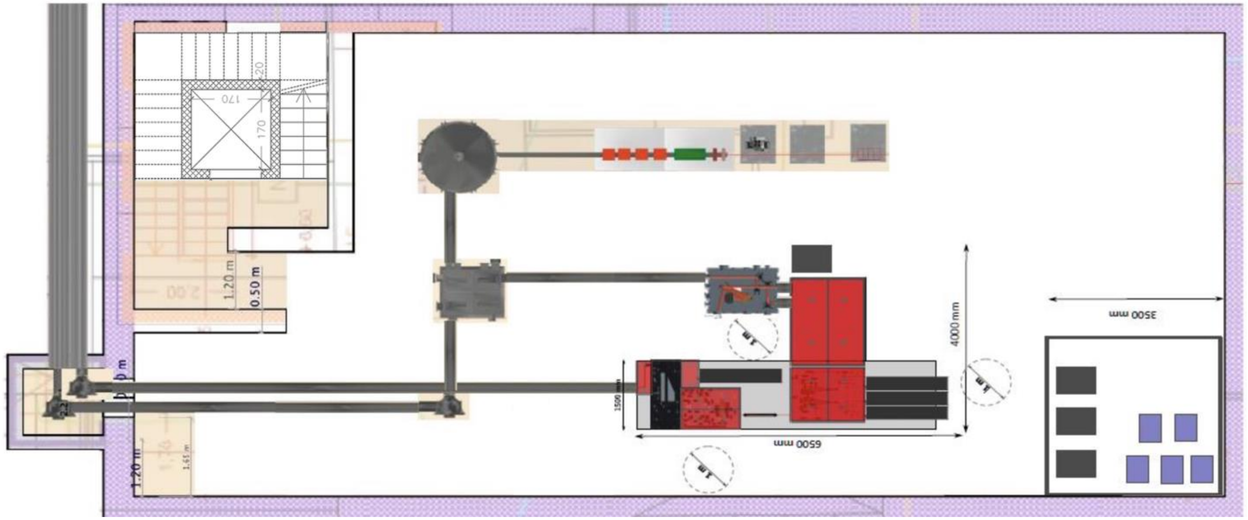
Courtesy of Sandrine Ricaud/ Christophe Simon-Boisson (Thales)

Final positioning of the 100Hz system



Laser initially hosted in a new clean room close to the FE





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

Underlying process(es) of LPA intrinsically nonlinear, and depending on several parameters

- Laser: Energy/pulse, focusing conditions, pulse duration, pointing, spectrum, spectral phase, …
- Plasma: Density, density gradients, density profiles, gas species (ionization, injection, laser guiding)
- Particle beam transport parameters,

PHYSICAL REVIEW X **10**, 031039 (2020)

Decoding Sources of Energy Variability in a Laser-Plasma Accelerator

Andreas R. Maier[1,2,*] Niels M. Delbos,[1] Timo Eichner,[1] Lars Hübner,[1,2] Sören Jalas,[1] Laurids Jeppe,[1] Spencer W. Jolly,[1,3] Manuel Kirchen,[1] Vincent Leroux,[2,1,3] Philipp Messner,[4,1] Matthias Schnepp,[1] Maximilian Trunk,[1] Paul A. Walker,[2,1] Christian Werle,[1] and Paul Winkler[2,1]

[1]*Center for Free-Electron Laser Science and Department of Physics Universität Hamburg,*

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-020-20245-6 OPEN

Check for updates

Automation and control of laser wakefield accelerators using Bayesian optimization

R. J. Shalloo[1✉], S. J. D. Dann[2], J.-N. Gruse[1], C. I. D. Underwood[3], A. F. Antoine[4], C. Arran[3],

NATURE COMMUNICATIONS | (2020)11:6355 | https://doi.org/10.1038/s41467-020-20245-6 | www.nature.com/naturecommunications

High Power Laser Science and Engineering, (2023), Vol. 11, e55, 41 pages.
doi:10.1017/hpl.2023.47

HIGH POWER LASER SCIENCE AND ENGINEERING

REVIEW

Data-driven science and machine learning methods in laser–plasma physics

Andreas Döpp[1,2], Christoph Eberle[1], Sunny Howard[1,2], Faran Irshad[1], Jinpu Lin[1], and Matthew Streeter[3]

[1]*Ludwig-Maximilians-Universität München, Garching, Germany*
[2]*Department of Physics, Clarendon Laboratory, University of Oxford, Oxford, UK*

Infrastructure for high-speed data acquisiton and transfer acquired (optical fiber backbone + server for ML-based optimization)
Expected to enable >~100MB/s data acquisition (based on laser operation at 100Hz)

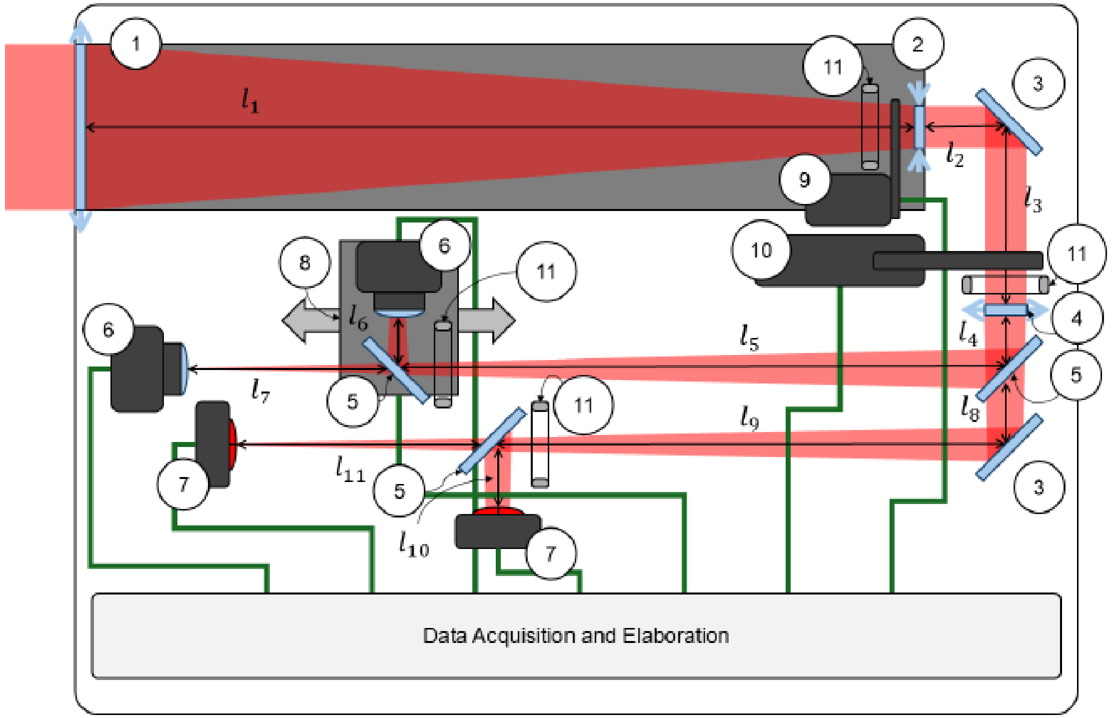
Thanks to the unprecedented rep rate (with this class of lasers), the beamline will make up an ideal test bench for ML optimization

Care have been paid 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 IJCLab (CNRS), CNR-ISTI, CNR-IIT

Active beam pointing stabilization

Project ongoing to develop an active pointing stabilization system able to cope with the long optical path toward the bunker (collaboration with italian companies)



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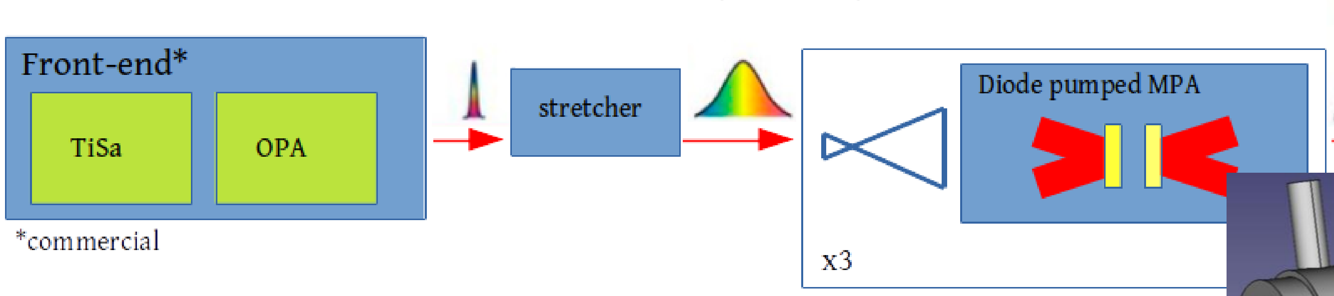
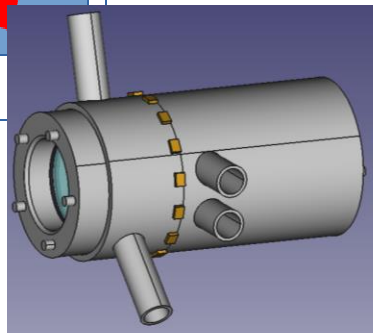
R&D on ultrashort lasers at ILIL-INO-CNR:
The APOLLO laser (kHz rep rate, ~1kW average power)

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

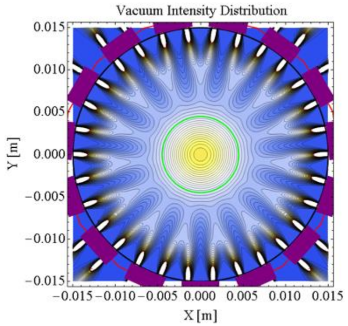




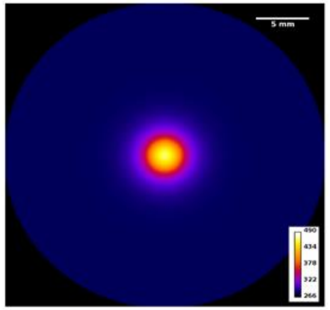
APOLLO system design specs: pulse duration ~50-100fs (potential), pulse energy > 500mJ, repetition rate 1kHz

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

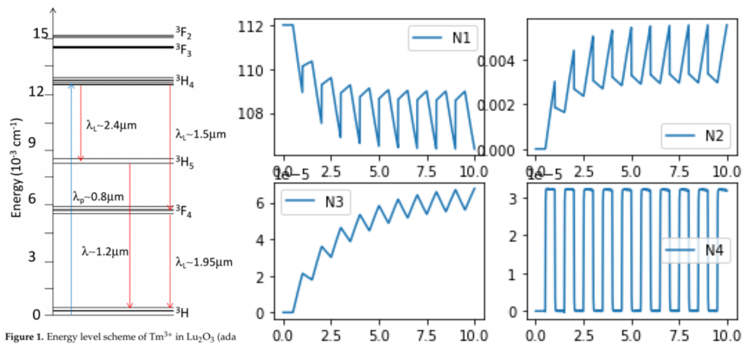
Edge diode pumping



Thermal load



Multi-Pulse Extraction: time dependent level dynamics



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

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Accepted Manuscript

Article submitted to: High Power Laser Science and Engineering, 2025 *April 3, 2025*

A study of cross-relaxation and temporal dynamics of lasing at 2 microns in Thulium doped ceramic

Alessandro Fregosi[1], Fernando Brandi[1], Luca Labate[1], Federica Baffigi[1], Gianluca Cellamare[1], Mohamed Ezzat[1], Daniele Palla[1], Guido Toci[2], Alex Whitehead[1], and Leonida A. Gizzi[1]

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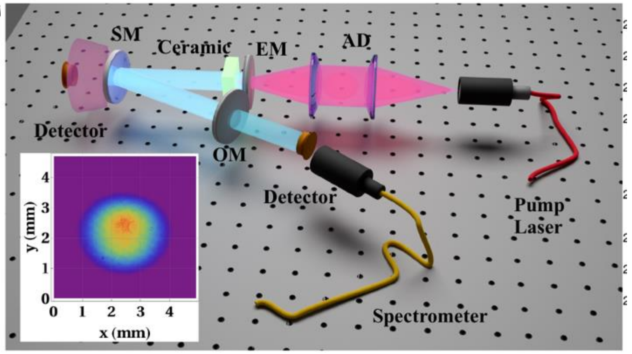

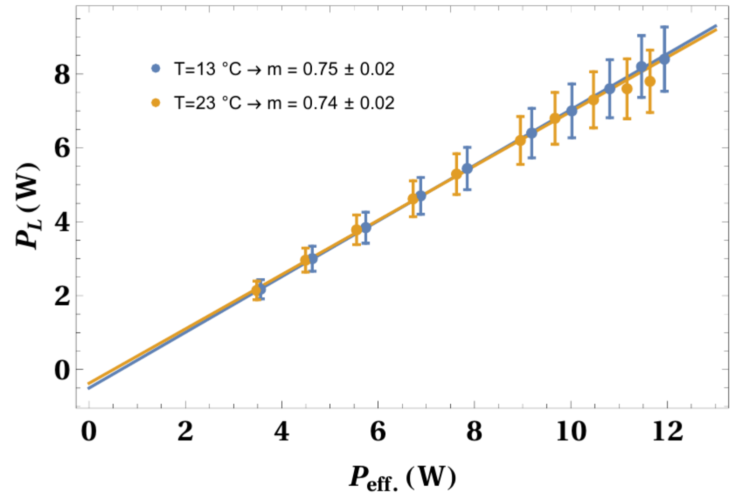

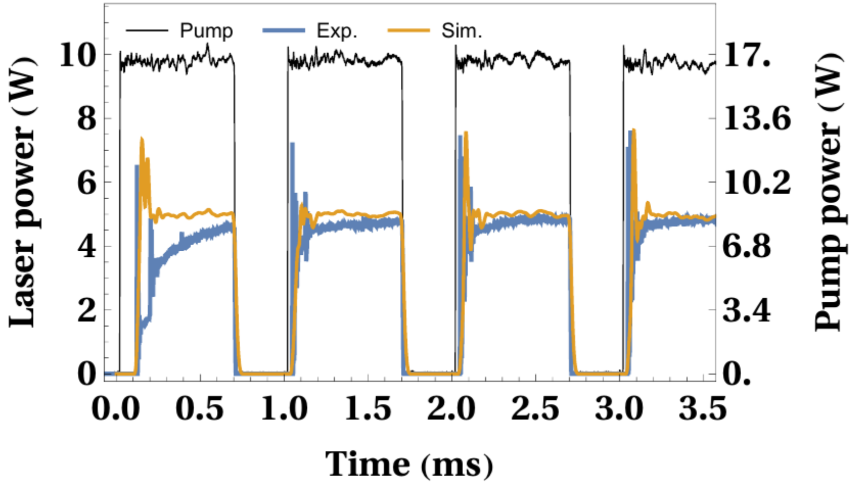

Remarkably high slope-efficiency demonstrated (with a cross-relaxation close to the theoretical maximum value)

Temporal dynamics modelled → material parameters measured

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 as for the average power, will match the performances required for the EuPRAXIA front-end laser

Budget-wise: All available fundings (apart ~32k + overhead) recently allocated

Initial commitment on average power fulfilled thanks to synergy with the other IR project (IPHOQS)

Laser commissioning expected to be completed within november

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 (toward FLASH radiotherapy), material studies with charged particles (for instance, PIXE), study of novel materials for advanced applications (fusion science, space applications, …)

ML techniques for stabilizing laser-driven particle sources