High average power laser technologies for LPA-based FELs

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European Advanced Accelerators Conference
22/09/2025

www.thalesgroup.com

Summary of Thales laser activity

A world leader in high-power solid-state laser systems

- Over **30 years of laser expertise**
- **World record 1 petawatt (PW) laser** with the BELLA system (USA) in 2012
  World record 10 PW with ELI-NP system (Romania) with one beam in 2019
- Laser solutions for **industrial processes** and new **medical applications**
- **World's only company** to send operational laser to Mars (with CNES and NASA) in 2011 and 2020
- Long-standing laser research partnership between Thales and Gérard Mourou, winner of 2018 **Nobel Prize in Physics**

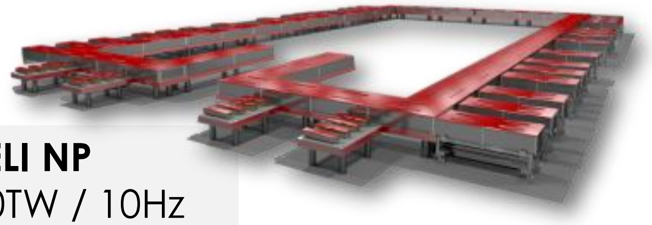
Gérard Mourou
2018 Nobel Prize in Physics

QUARK COMMUNITY

A.Gonsalves, PRL 122, 084801 (2019): **8 Gev**
A.Picksley, PRL 133, 255001 (2024): **10 GeV**
A. Picksley, EAAC 2025

CALA (3PW)
90J / 1Hz

ELI NP
2x 100TW / 10Hz
2x 1PW / 1Hz
2x 10PW / 1sh/min



10 PW

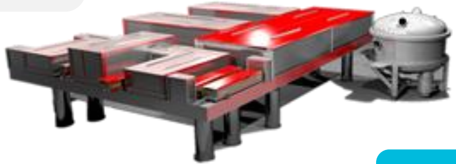
LBNL BELLA
1,3PW / 1Hz

3 PW

1 PW

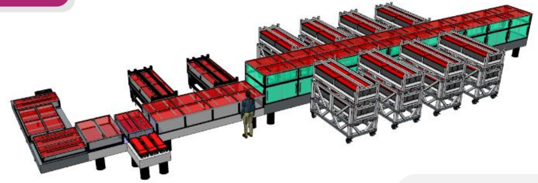
2 PW

SCAPA
350TW / 5Hz



350 TW

500 TW



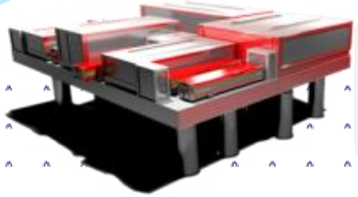
Peking Uni.
2PW / 1Hz

Riken Harima
2x 500TW / 1Hz

45 TW

USC
45TW / 10Hz

200 TW



DESY 200TW / 5Hz
Peking Uni. 200TW / 5Hz
Weizmann 2x100TW / 1Hz

HPLS 10 PW laser at ELI-NP - *« The most powerful laser in the world »*

System aiming to deliver two laser beams with three possibe peak power

2x10 PW, 1 tir/min
2x1 PW, 1 Hz
2x100 TW, 10 HZ

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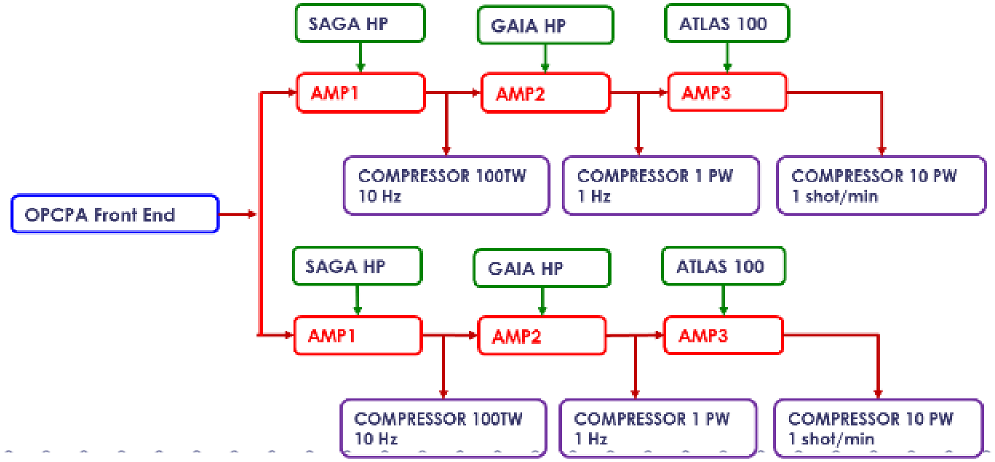
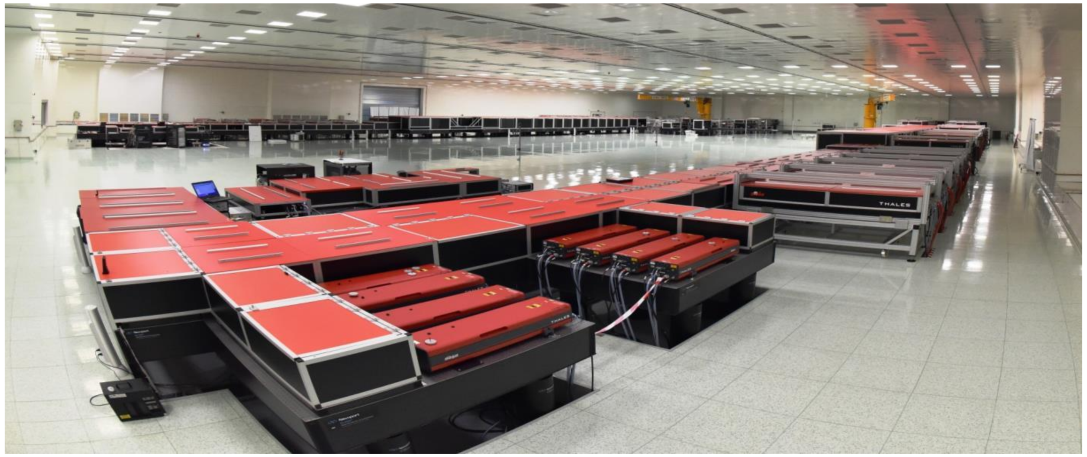
48 pump lasers

A dedicated clean room (ISO7)
2 400 m²

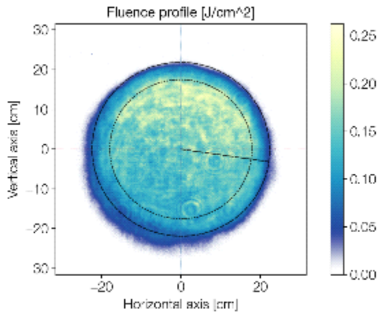


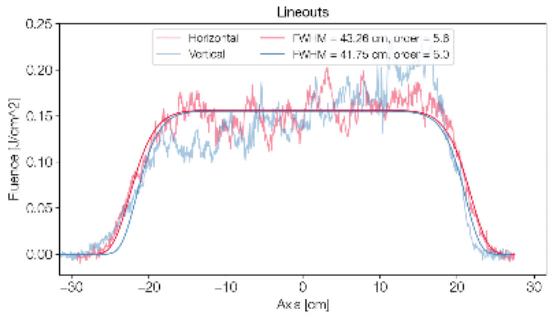


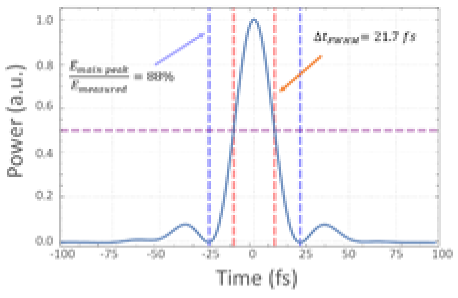
[THALES - ELI ; the most powerful laser in the world (ecliptique.com)]

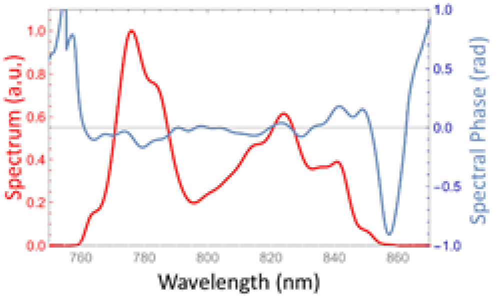
HPLS 10 PW laser at ELI-NP - *« The most powerful laser in the world »*

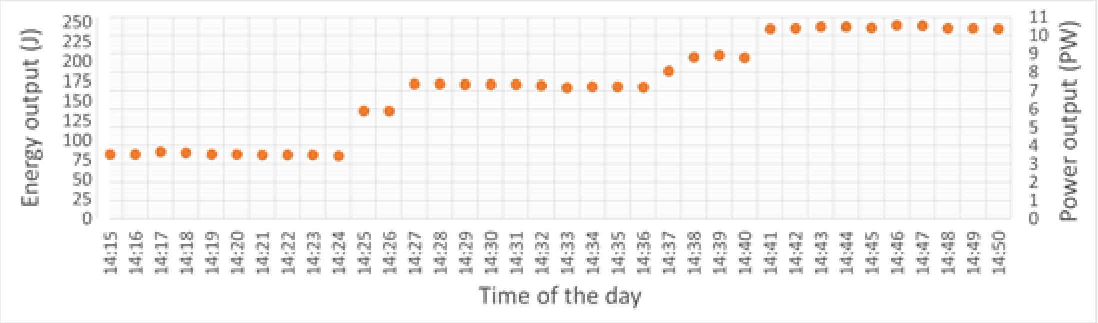
Retrieved peak power (from energy and duration measurements) = <u>10,2PW</u> (in the main pulse)



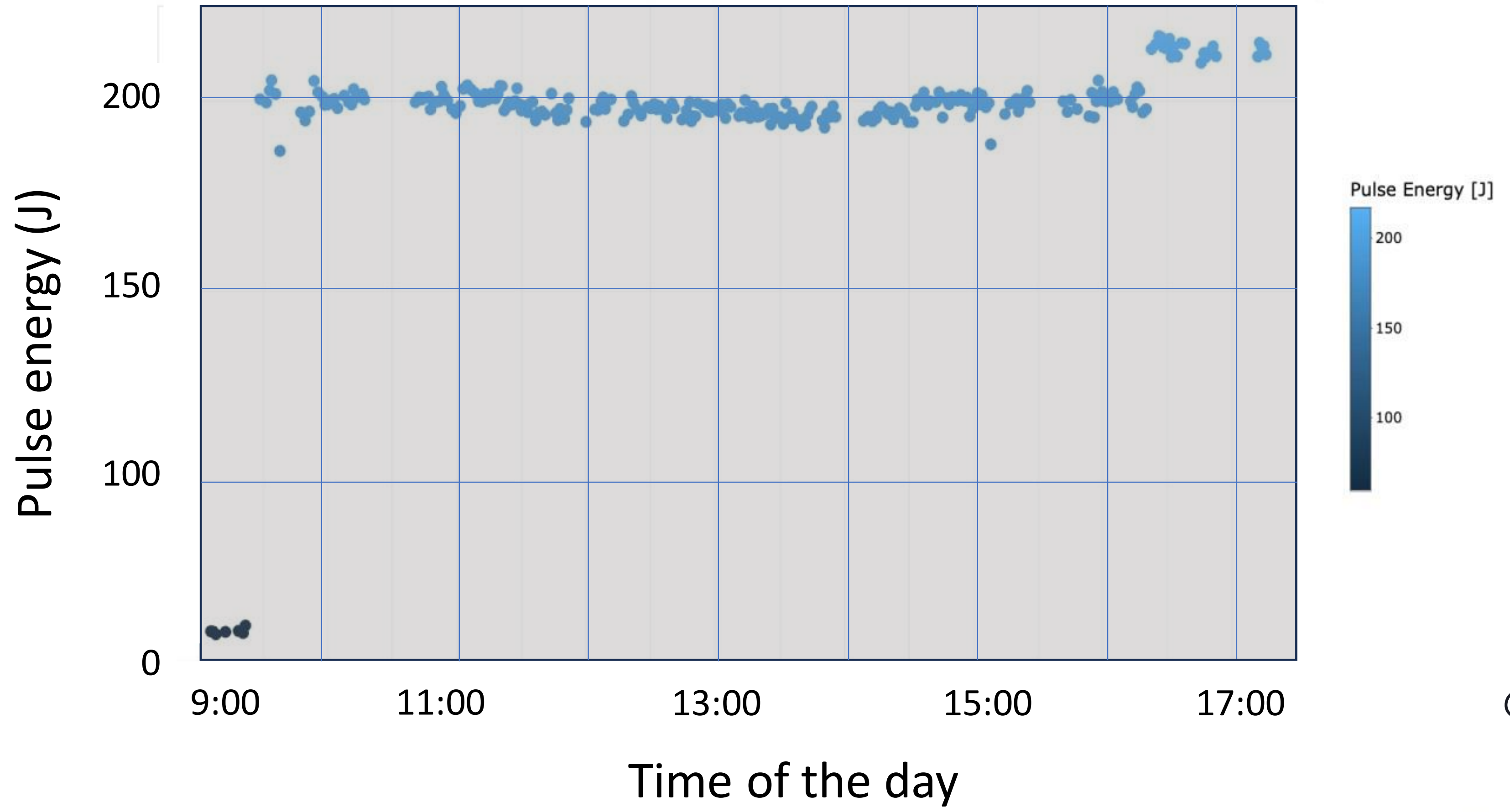








HPLS 10 PW laser at ELI-NP - *« The most powerful laser in the world »*



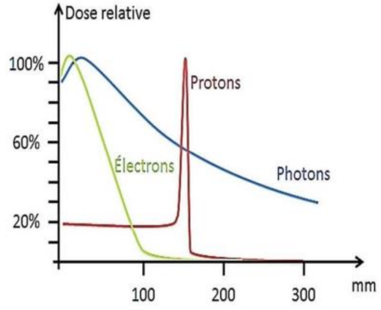
Courtesy of ELI-NP

World Record, ELI-NP delivers 274 shots in one day at 10 PW output of its High Power Laser System

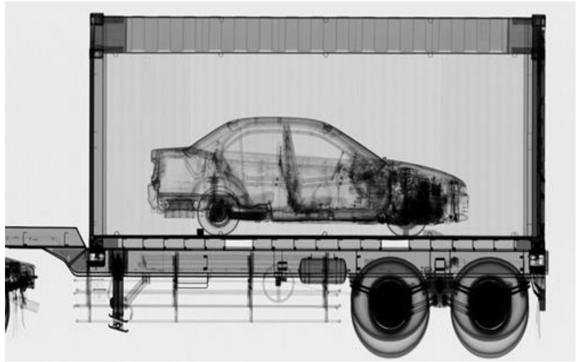
Increase the repetition rate of lasers: a need for industrial & medical applications

Rationale

- Titanium Sapphire is confirmed as the ideal technology for producing high-energy ultrashort pulses (< 30 fs)
- Development of 1J / 100 Hz laser system for scientific, industrial and medical applications



Home - Multiscan3D (multiscan3d-h2020.eu)



Revolutionising the way we treat cancer - Ebeam4Therapy

LAPLACE HC platform at LOA for electron acceleration (within Heracles joint research lab)

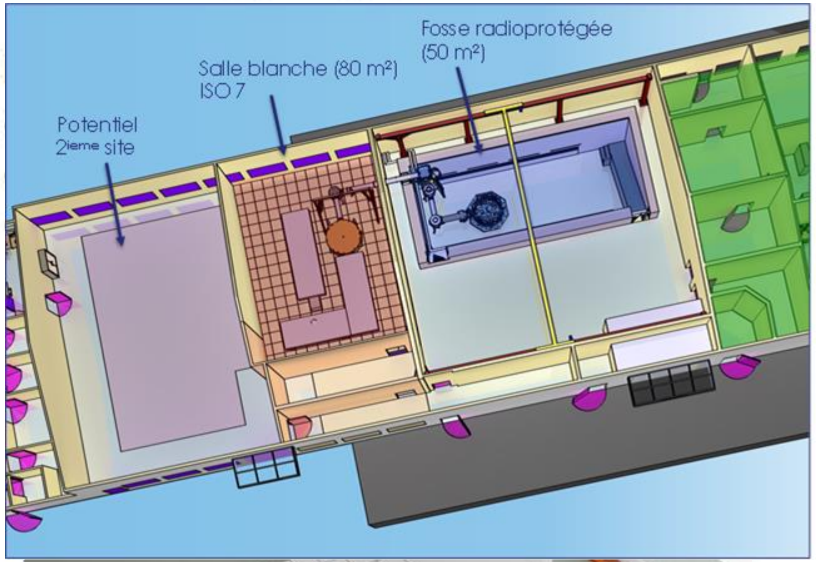
The LAPLACE Project

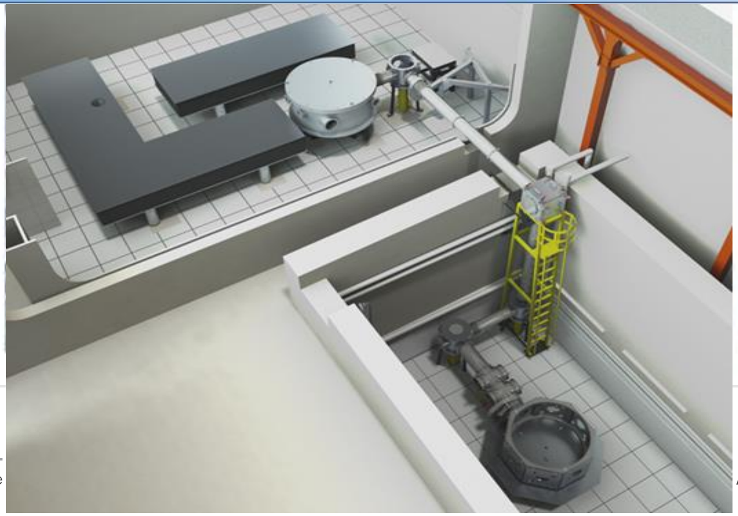
LAPLACE HC

- 80 m² clean room
- Laser 1 J @ 100 Hz
- 50 m² radioprotected area
- 2nd radioprotected area in option

Average power of ~ 100 W (vs 1 W now)

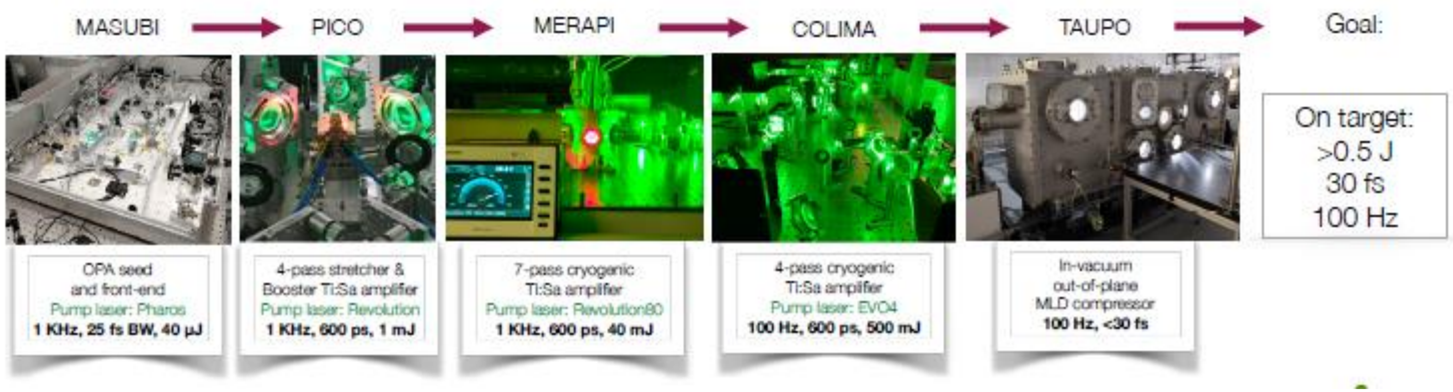
O. Chalus , WG2 Th. (THALES LAS)

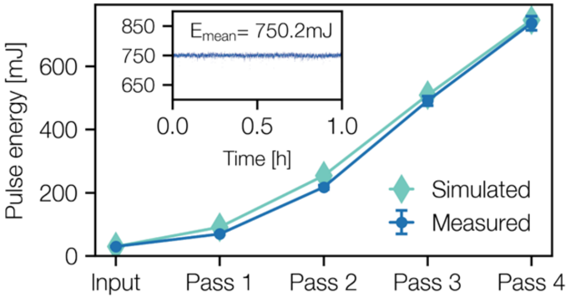




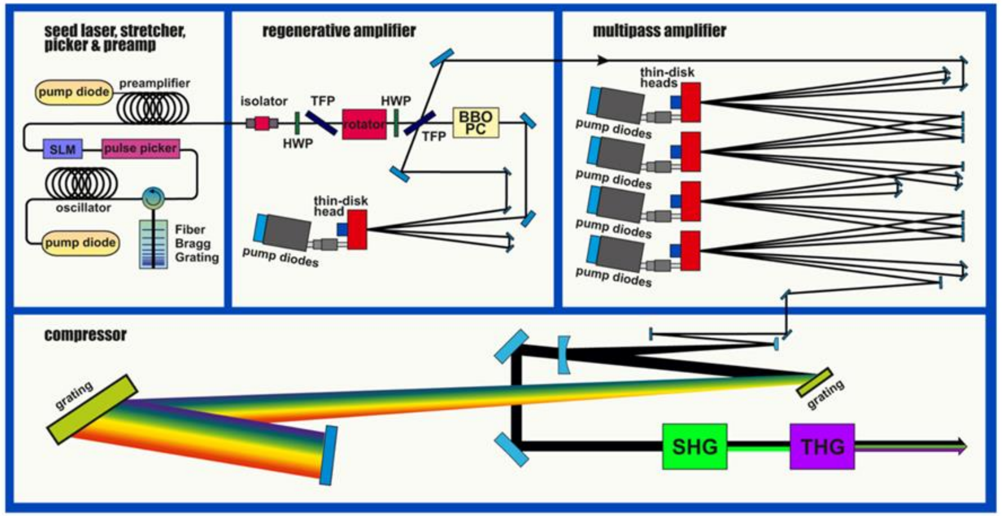
[LAPLACE – Laser Plasma Acceleration Center at LOA (laplace-loa.fr)](laplace-loa.fr)

State of the art of high average power Joule class subpicosecond lasers





DESY – Phase 1 of KALDERA project
500 mJ – 34 fs – 100 Hz
Andreas Maier – EAAC 2025
Eichner & al – Optics Letters, 50, 16, 5890 (2025)
https://doi.org/10.1364/OL.564062



Trumpf Scientific - Laser Lightning Rod EU project
720 mJ _ 920 fs – 1 kHz
Herkommer & al – Optics Express 2020
https://doi.org/10.1364/OE.404185)

High rep-rate Ti:Sa

200 mJ 100 Hz

New High rep-rate Ti:Sa laser system: **200 mJ @ 100 Hz**

> Front-end adapted to contrast need

- single CPA – double CPA w/ XPW – **OPCPA based** – …

> Diode-pumped pump laser for amplifiers: THEIA

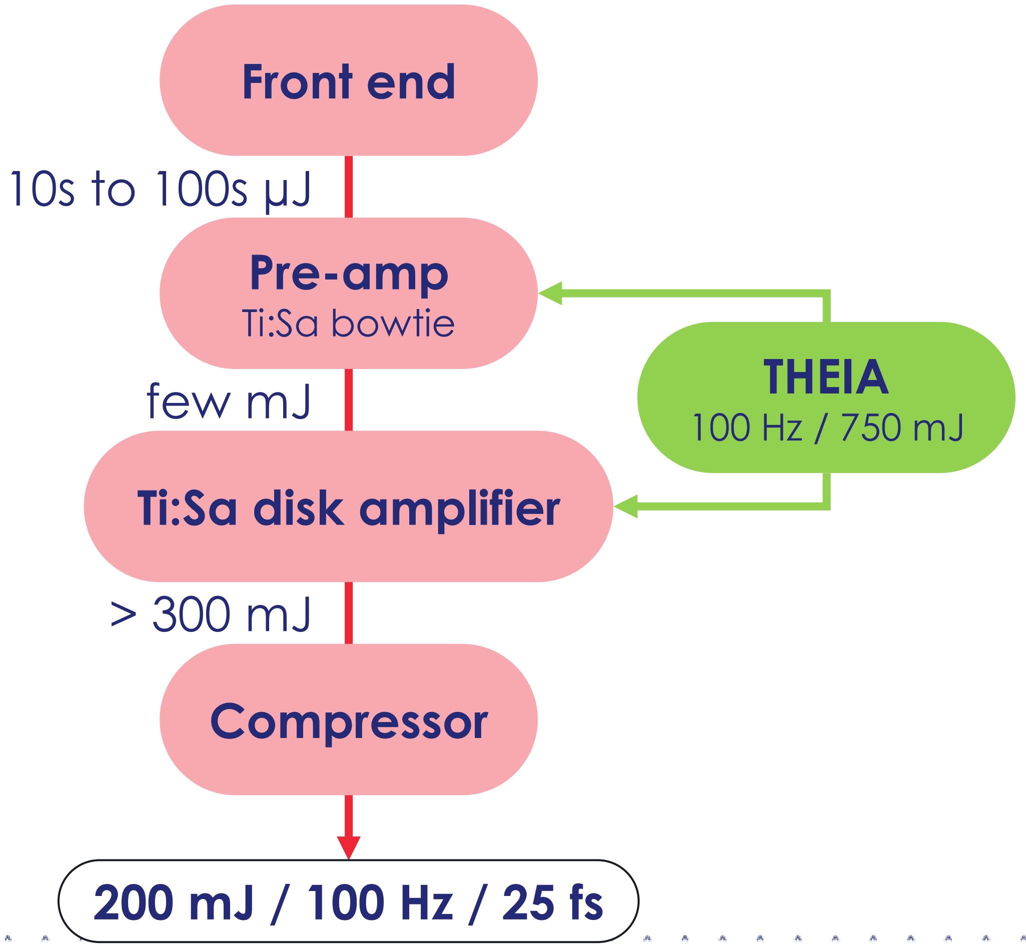
- **750 mJ** @ 532 nm, 100 Hz, ~10 ns

> New Ti:Sa disk amplifier at room temperature

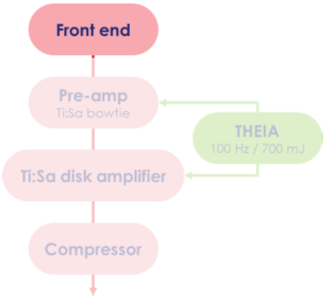
- Active mirror configuration for effective cooling with **water @ 20°C**
- Fully qualified at **300 mJ**

> "Standard" compressor

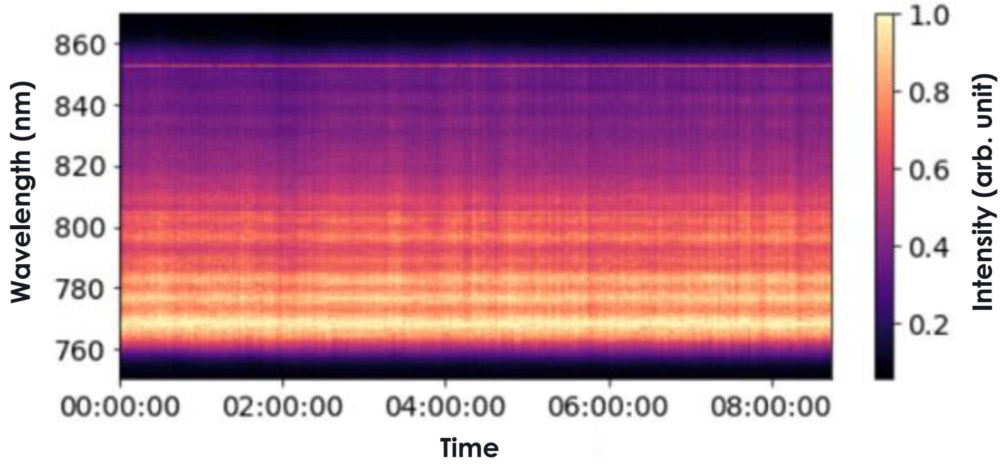
- No cooling required at this average power



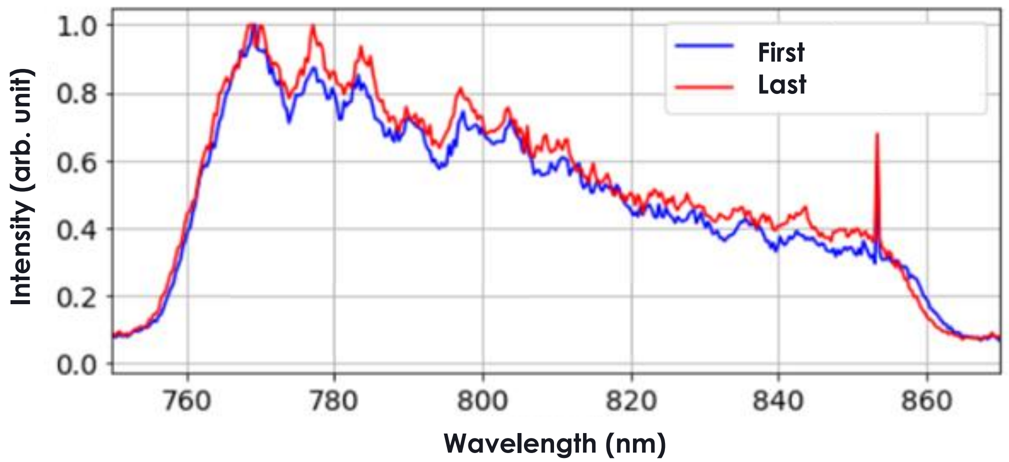
OPCPA Frontend



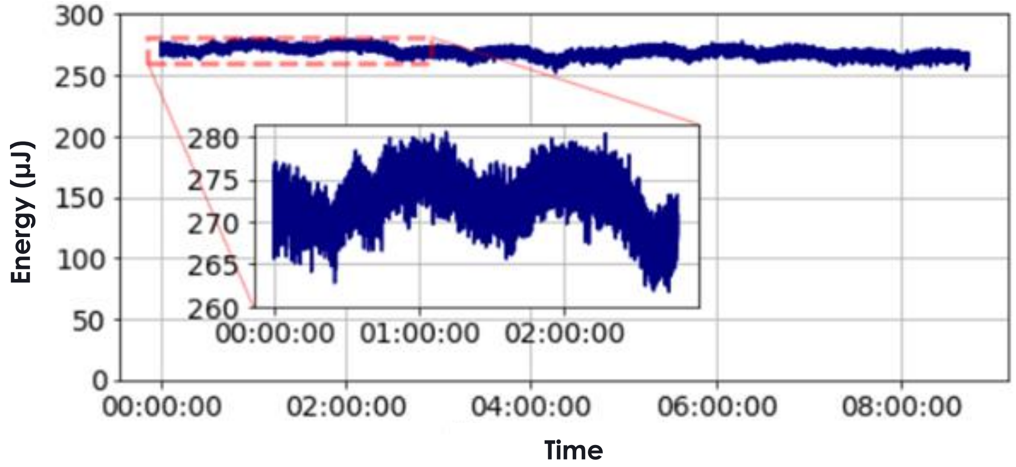
Spectral evolution OPCPA frontend



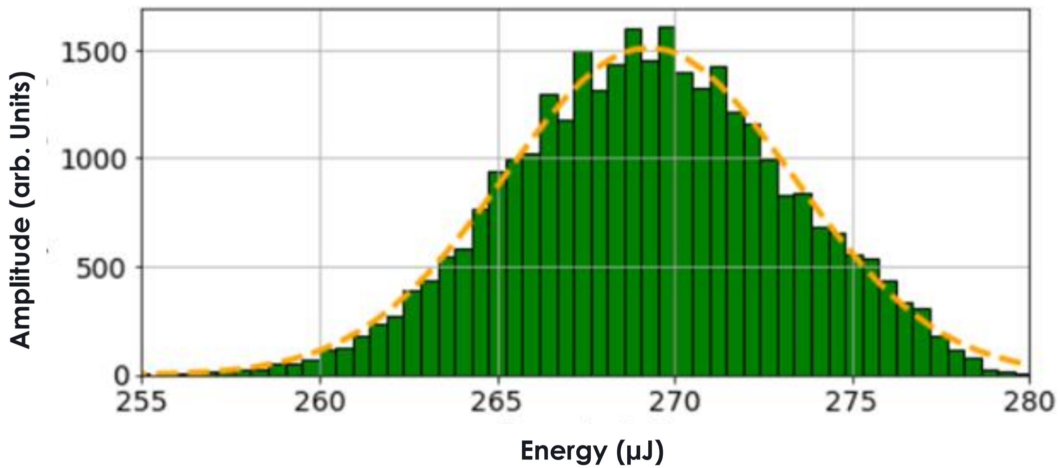
Spectrum OPCPA frontend



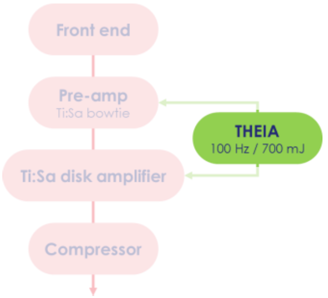
Energy OPCPA frontend: average = 270 µJ



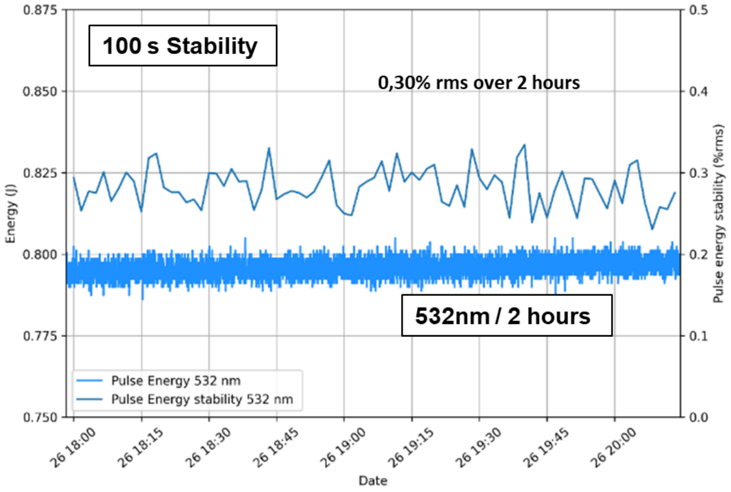
Energy histogram: 1.4% RMS

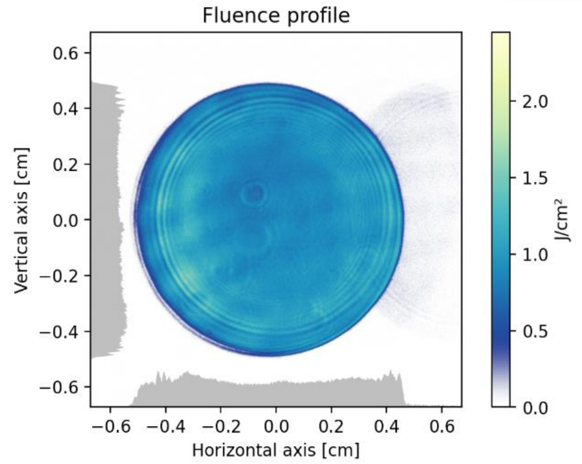


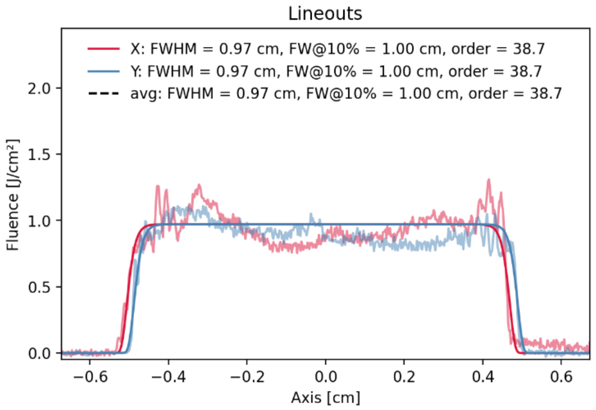
THEIA Performances



THEIA 500 @532nm: **< 0.3 % RMS over 2h**

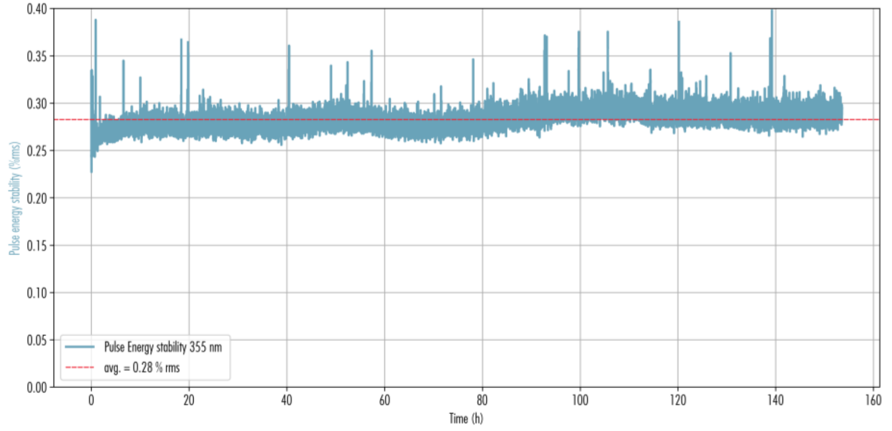






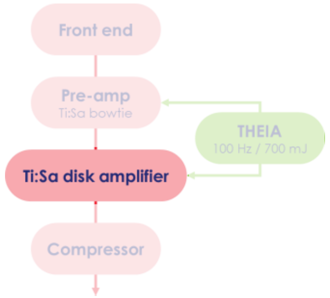
- Top-hat NF profile
- 750 mJ @ 532 nm
- 0.3% stability (short and long term)
- ~ 10 ns pulse duration

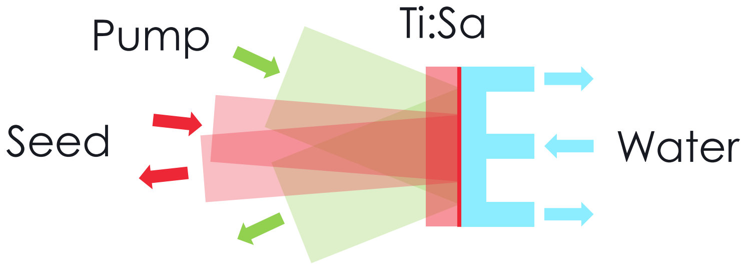
THEIA 500 @355nm: **< 0.3 % RMS over 150h**

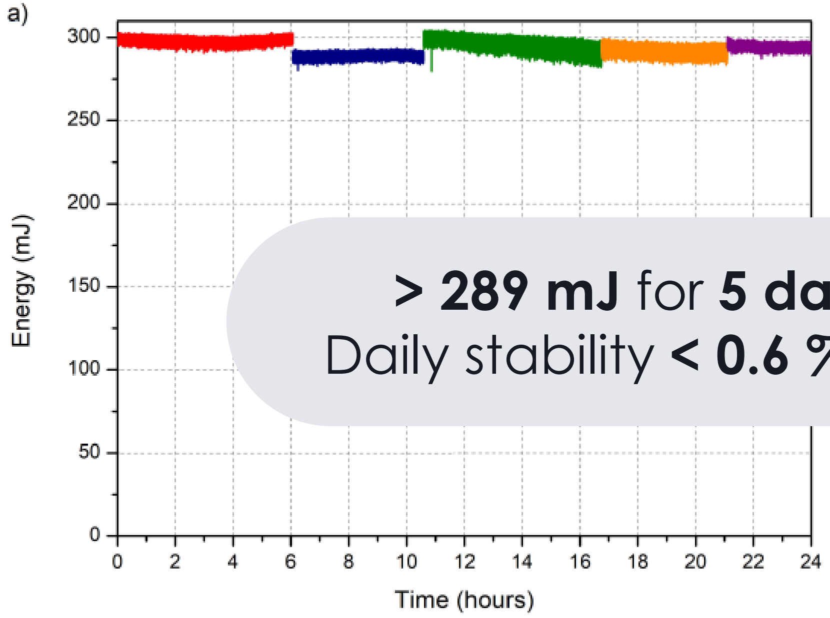


Ti:Sa disk amplifier

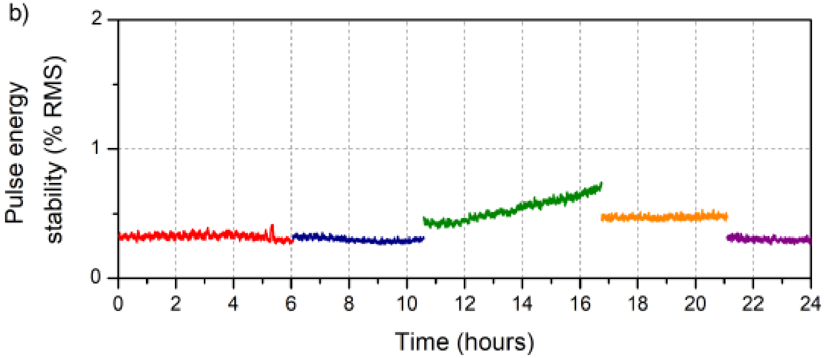
See more details in
Kabacinski & al, Optics Letters, 50, 18, 5630 (2025)

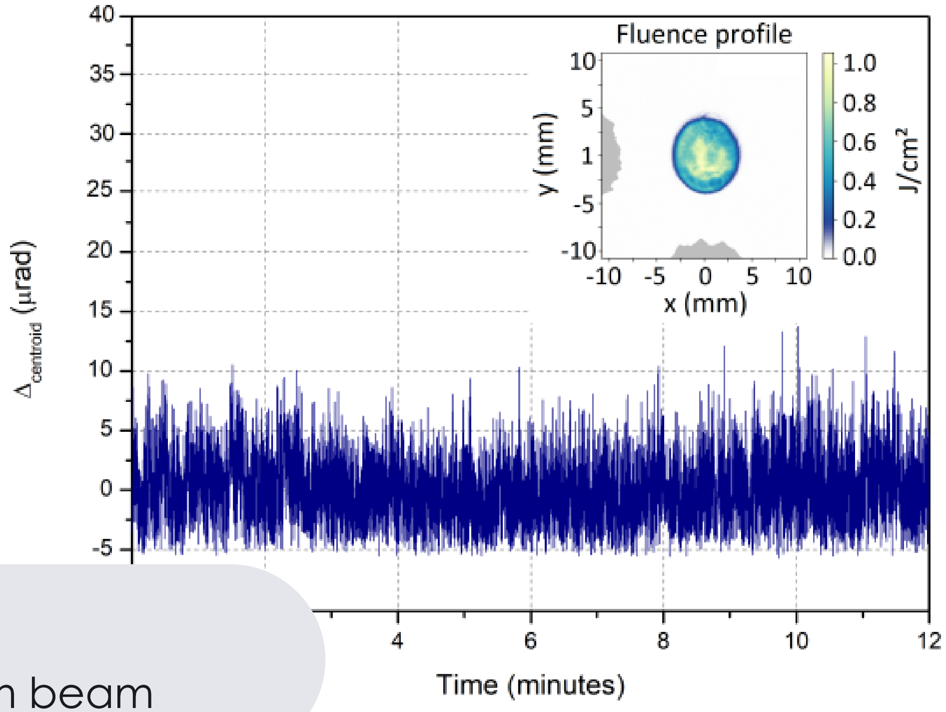






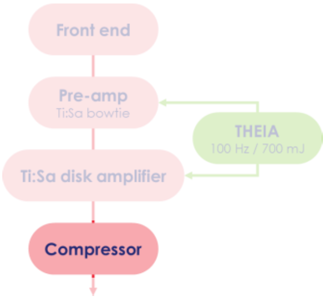
> 289 mJ for **5 days**
Daily stability **< 0.6 % rms**





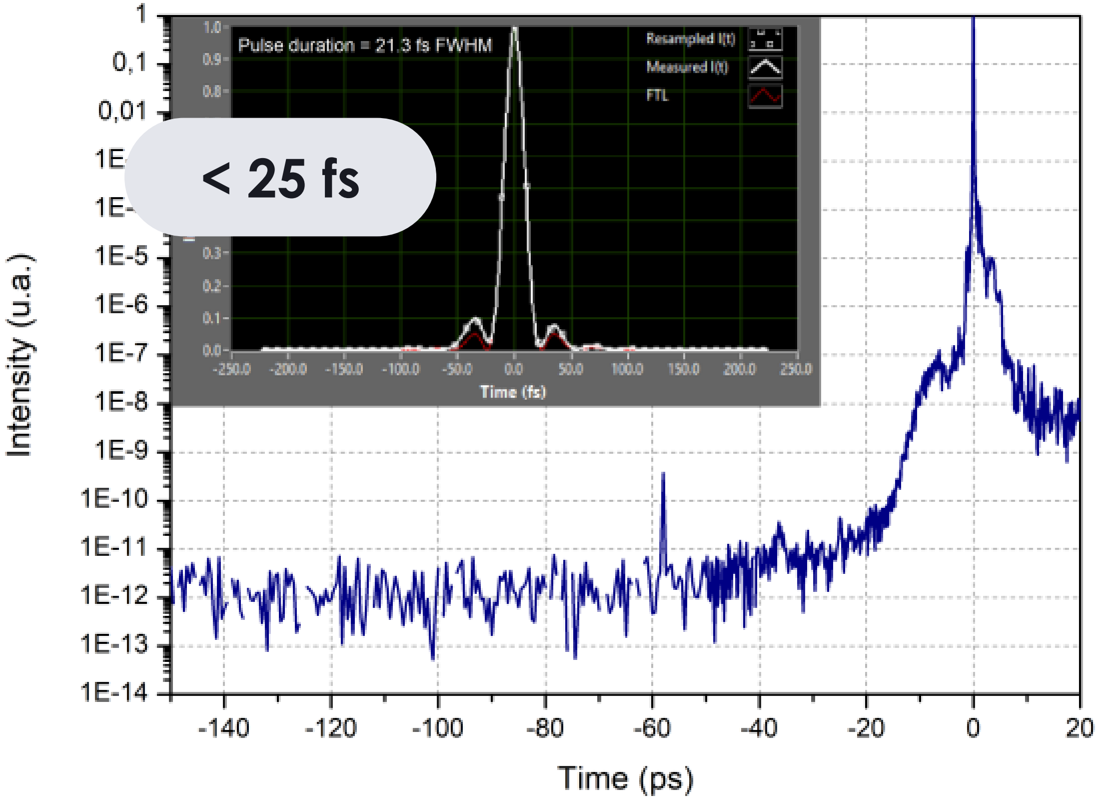
< 3 µrad
12 min on Ø 8 mm beam

Compression

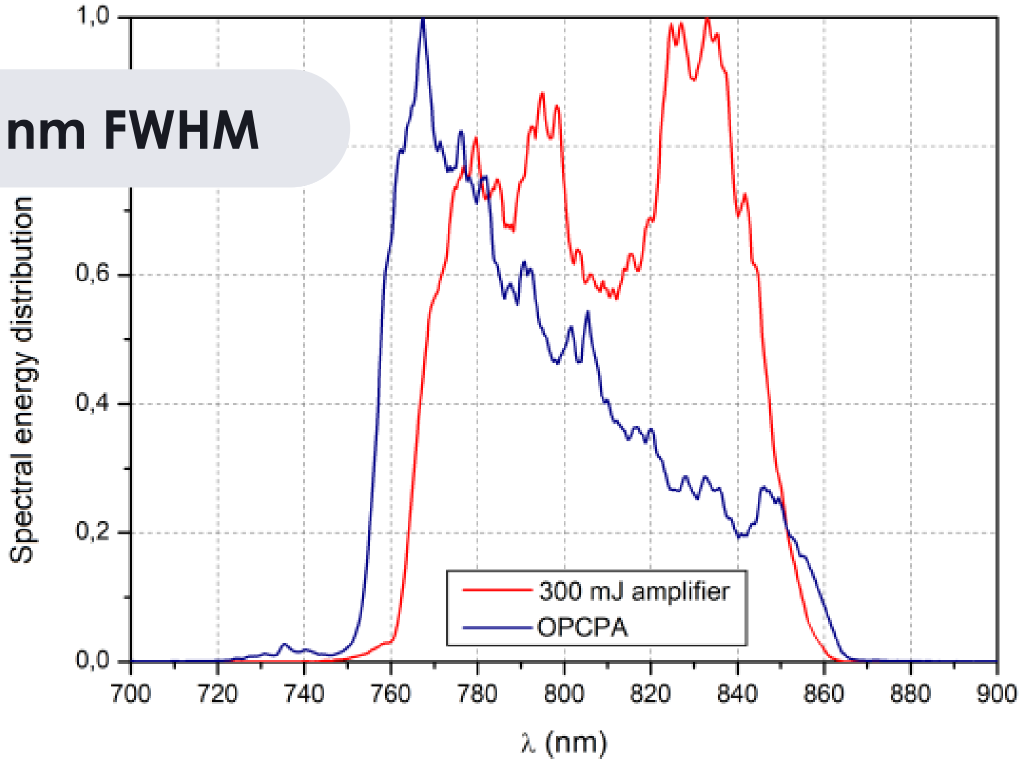


1×10^{-8} @ 10 ps
3×10^{-11} @ 30 ps

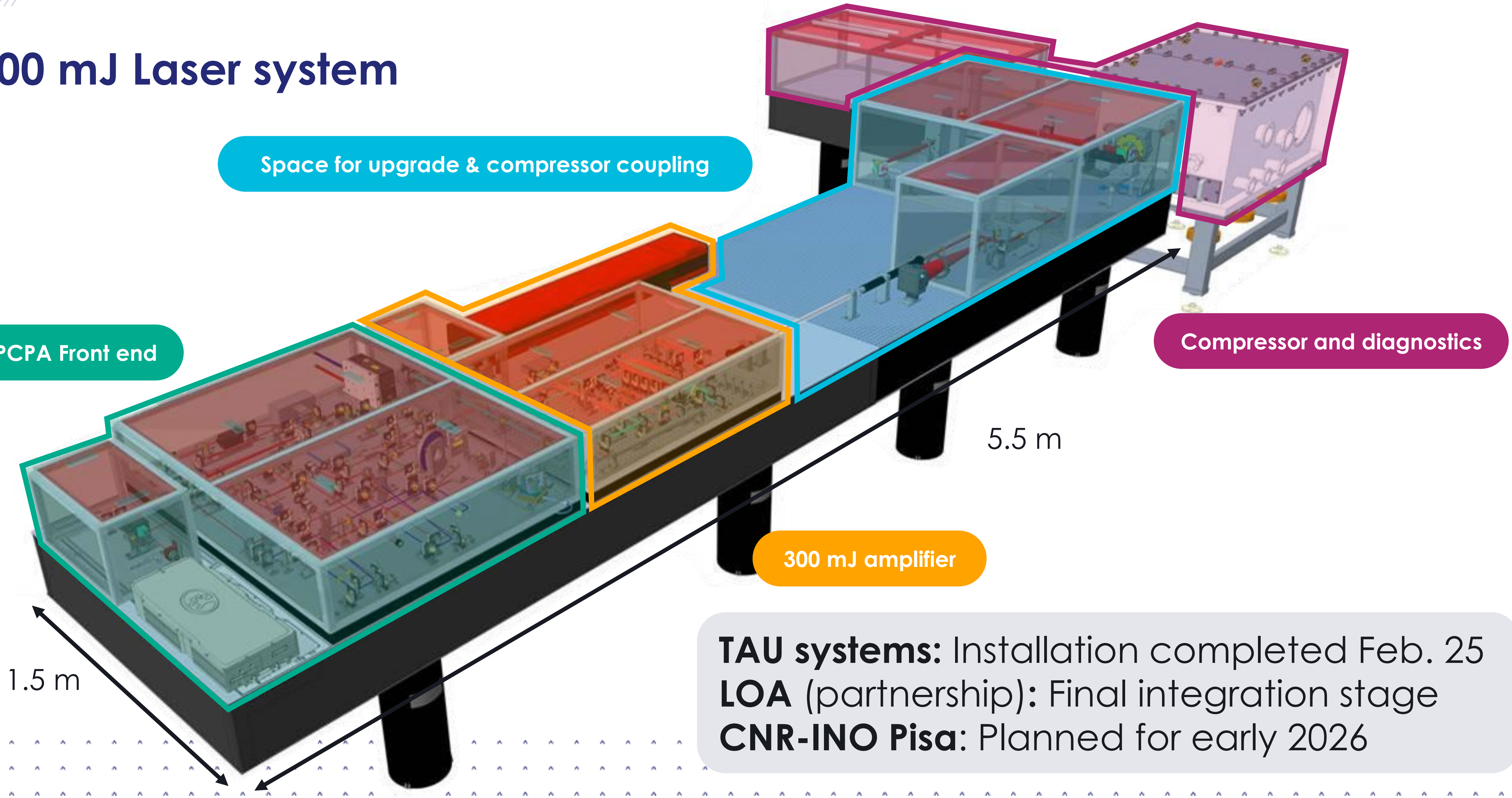
< 25 fs



80 nm FWHM

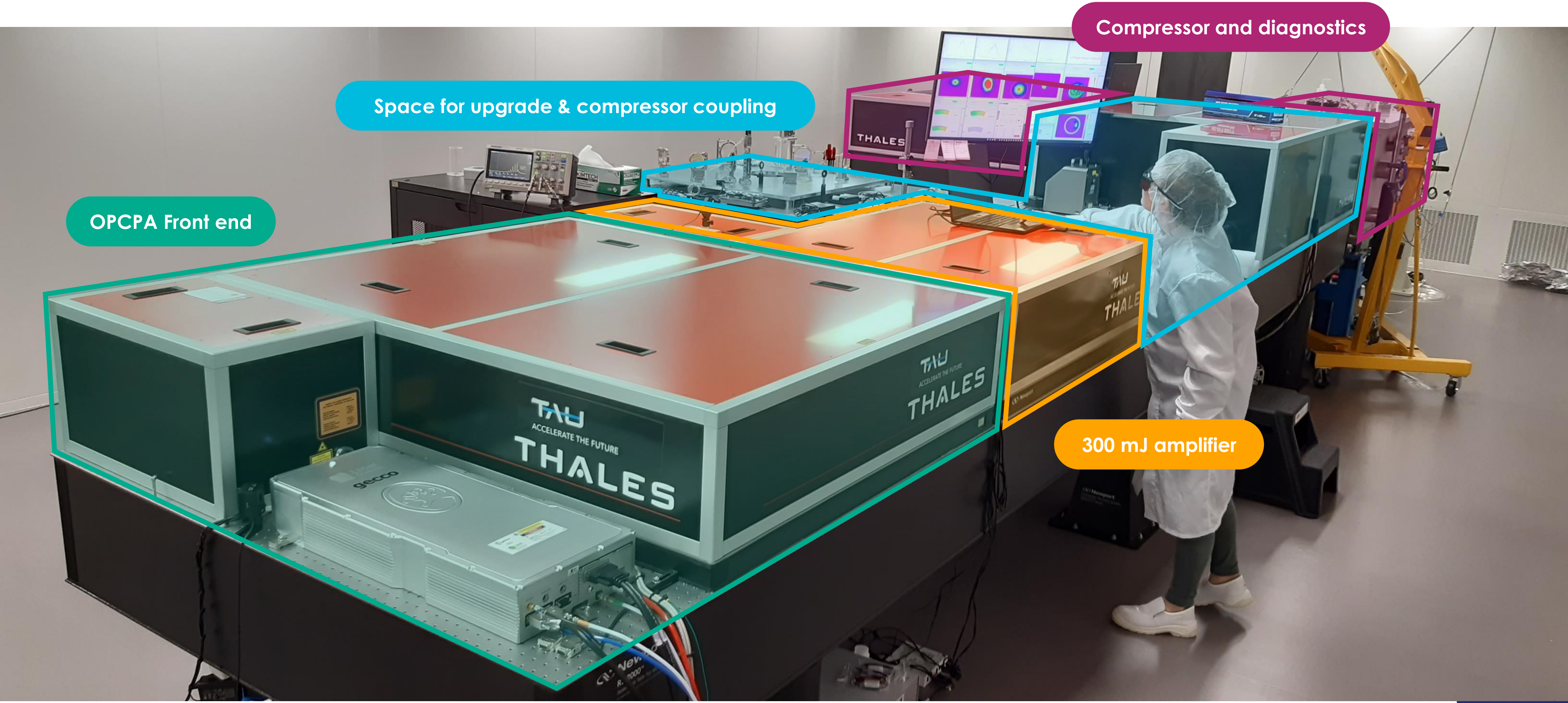


Full 200 mJ Laser system



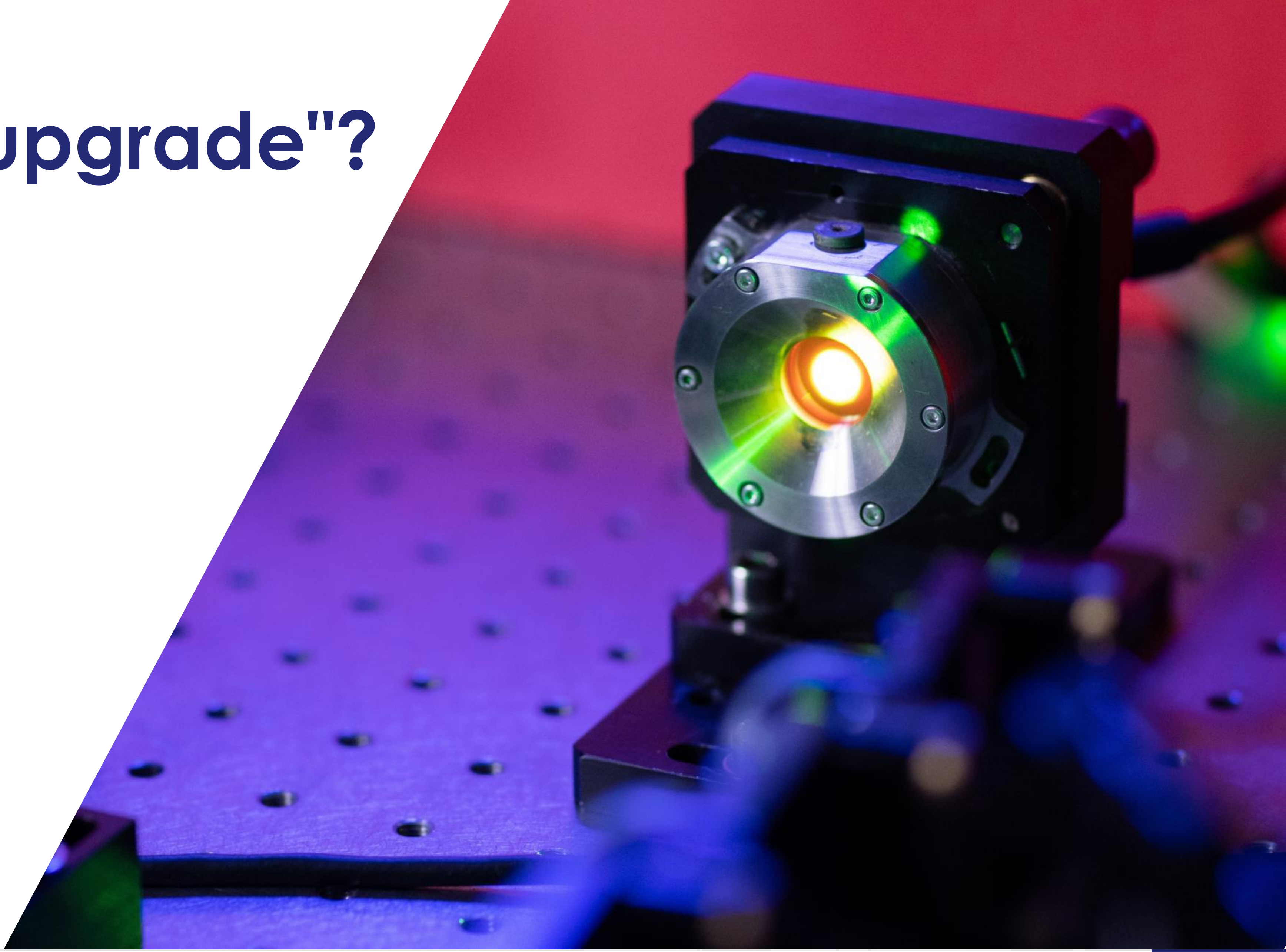
TAU systems: Installation completed Feb. 25
LOA (partnership)**:** Final integration stage
CNR-INO Pisa: Planned for early 2026

TAU systems: commisionned in Feb. 2025



"Space for upgrade"?

1 J 100 Hz



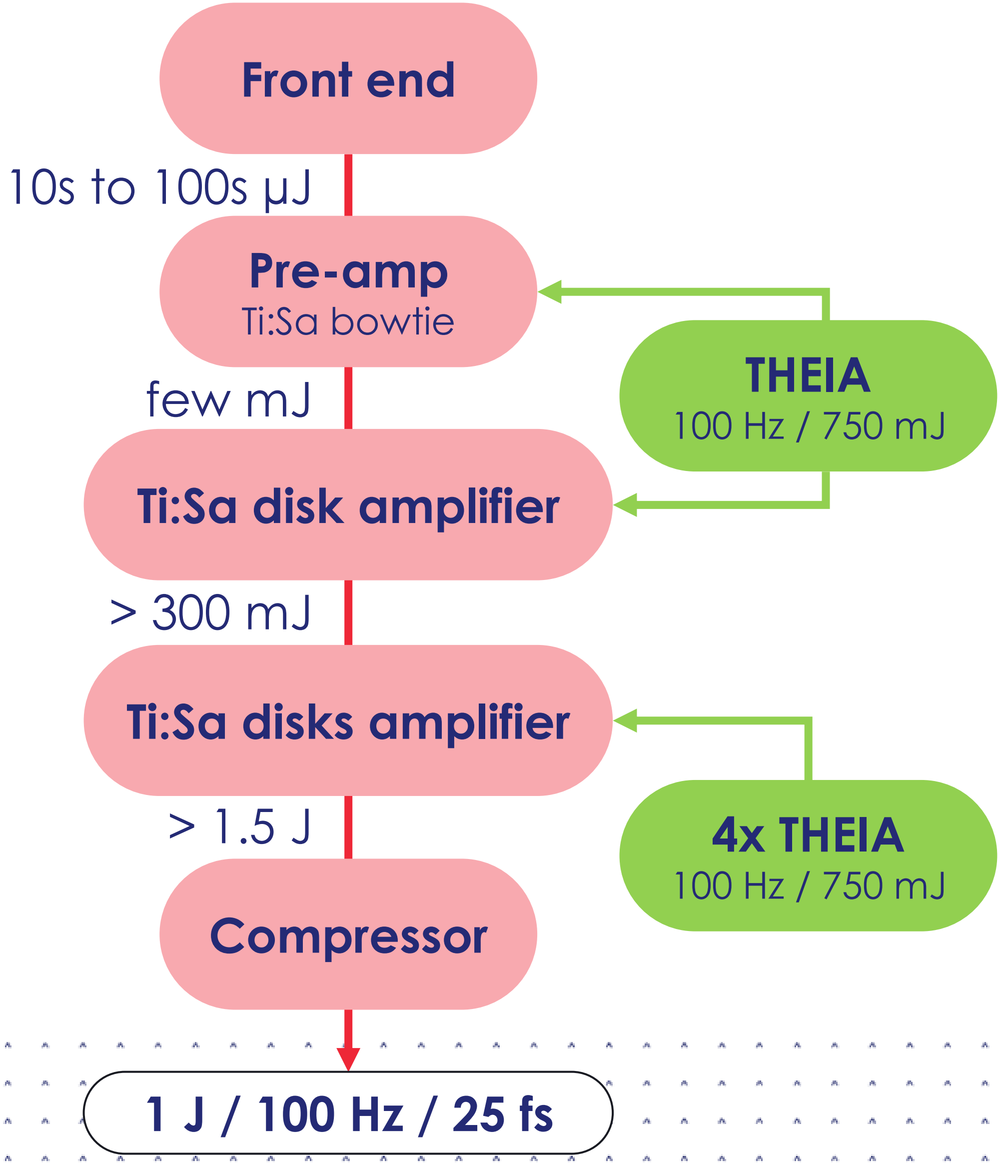
Upgrade to **1 J @ 100 Hz**

> Amplification with active mirrors

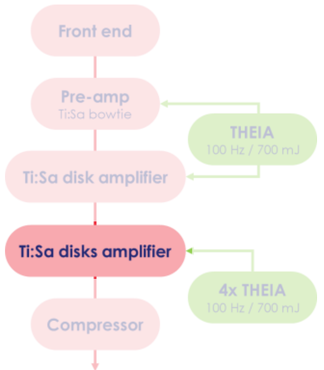
- > 850 mJ with 2 THEIAs on one crystal achieved (R&D)
- Thermal lens characterized
- ➔ Solution validated for integration

> Compression

- Simulation of grating heating and deformation to design cooling solution
- First tests on mirror substrate to validate solution

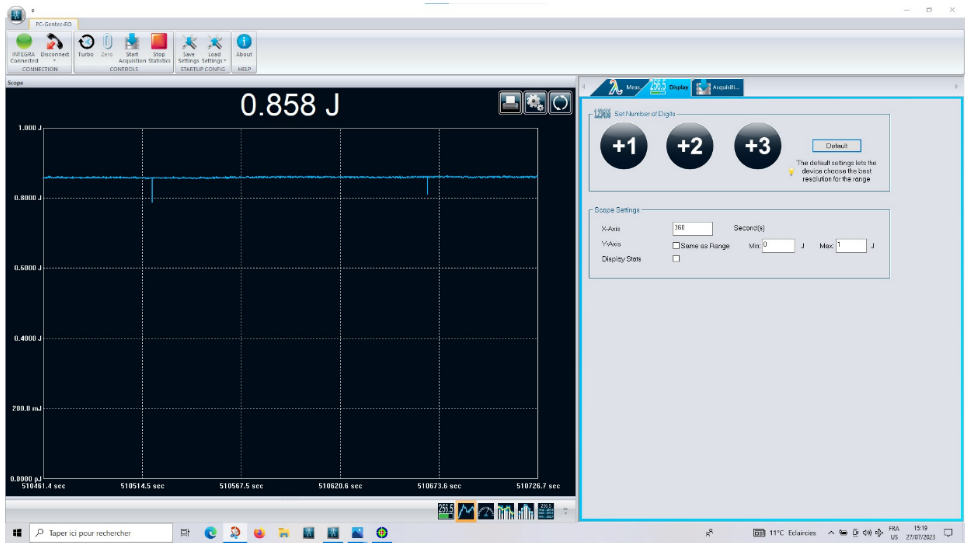


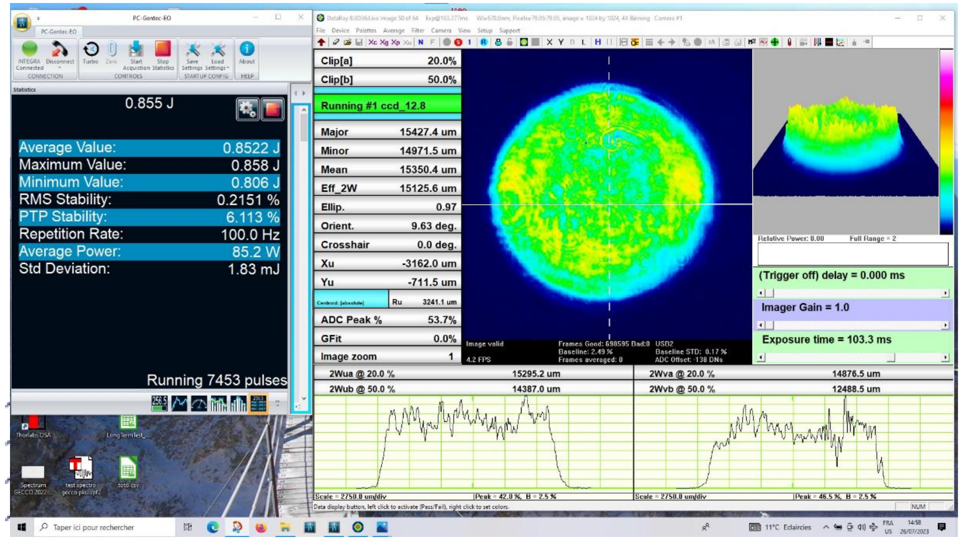
Upgrade to 1 J: Amplification



> R&D validation: ½ Joule amplifier

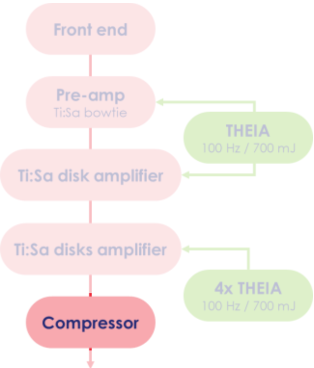
- Seeding with ~ 250 mJ
- Pumped by 2 THEIAs (1.5 J)
- 40 % extraction ➔ **> 850 mJ @ 100 Hz**, short-term stability < 0.3 % rms
- No ASE or transverse lasing
- 20°C water cooling, crystal temperature similar to 300 mJ amplifier
- Resulting total **thermal lensing > 20 m**





> 1.5 J amplifier ➔ 2 amplification stages

Upgrade to 1 J: Compression

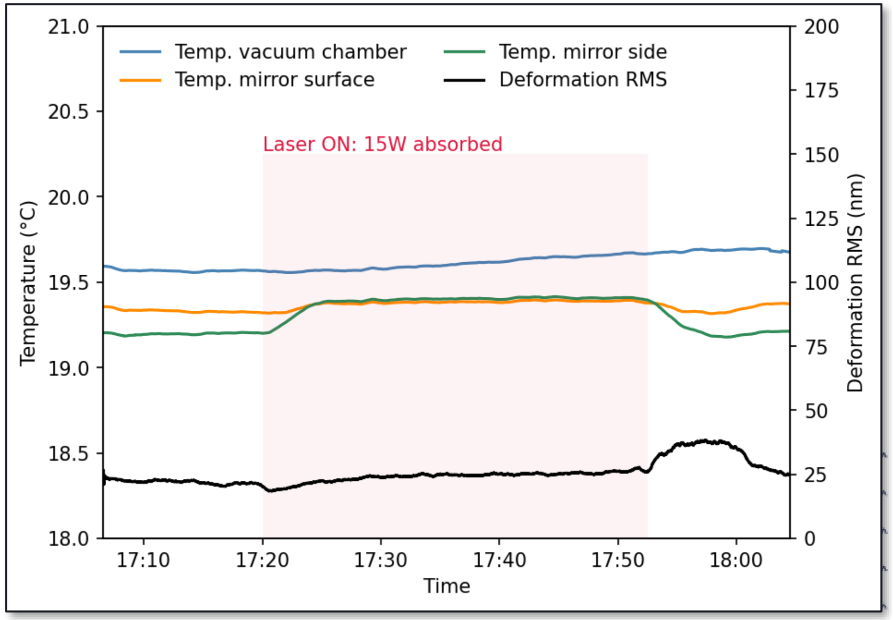


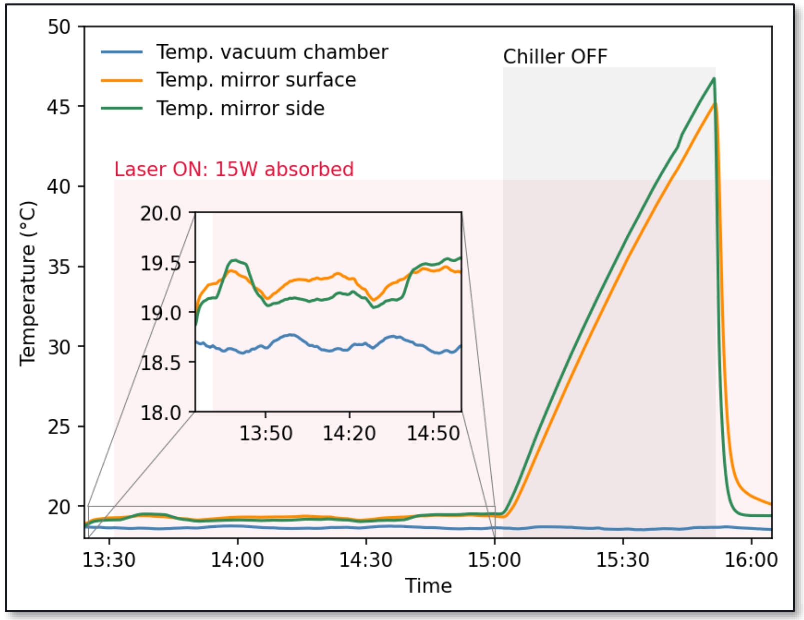
> Gold gratings for < 25 fs, ~ 12 W absorbed heat ➔ cooling required!

- Experiment on gold coated mirror, using THEIA as heating laser at LOA
- Monitoring of temperature and deformation

> 15 W absorbed ➔ ΔT < 1°C, RWFE < λ/30 rms

- Efficient and fast cooling





What's Next ?

> Flagship is EuPRAXIA laser-driven machine to be installed at ELI-ERIC Prague site

EuPRAXIA at ELI Beamlines will extend USER-oriented operation.		
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

PHASE-2: NOVEL high-power high-repetition-rate laser system

Aiming 800 TW / 100 Hz

Key information	Planned	Collaboration
Laser type	*DPSSL-pumped OPCPA*	*STFC (UK), HiLASE (CZ), IoP CAS (CZ) Lithuania, CNR (Italy), Thales (France)* Annex-13
Energy per pulse [J]	*20*	
Repetition rate [Hz]	*100*	
Pulse duration [fsec]	*25*	
Laser power [TW]	*800*	
Laser beam quality		
Contrast ratio [-]	*TBD*	
Pointing stability [μrad]	*< 2*	
Beam profile	*Round (D=300mm)*	
Energy stability [%]	*TBD*	
Temporal characteristics	*TBD*	

Extract from final version of ELI-ERIC bid book release on March 25, 2025

> Also next generation of fully diode-pumped PetaWatt class lasers (typ 30 J / 10 Hz / sub-100 fs)

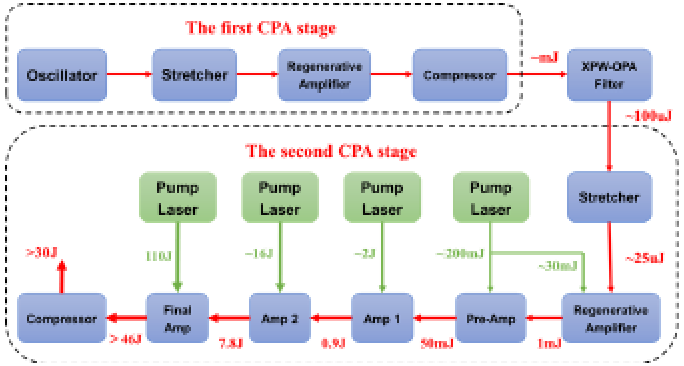
Laser design considerations for 10-20 Hz operation

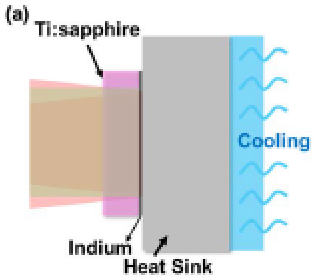
> Titanium Sapphire still the premium solution to produce multi-10s of Joule with sub-100 fs output

- OPCPA is also working but at half the efficiency & increased complexity of pump laser (< 3 ns)
- Ytterbium technology not yet mature for multi-10s of Joule output + requires huge post-compression cells
- Thulium concepts (BAT) not mature and optimised for 10 kHz+ operation

> Titanium Sapphire under validation for hundreds of Watt operation in ongoing & short term projects

- KALDERA phase 1 : 50 W (0.5 K @ 100 Hz)
- KALDERA phase 2 : 300 W (3 J @ 100 Hz) ongoing work
- Our work: 100 W expected to be fully demonstrated before mid-2026)
- Theoretical modelling by SIOM of 1 kW average power TiSa amplifiers *[Sun & al, Optics Express, 33, 6, 13205 (2024)]*





Paper concludes on the feasability of 46 kW (46 J @ 1 kHz) final amplifier based on cryo-cooled TiSa disks active mirror amplifiers

Thales RTD roadmap overview (1/3)

> Titanium Sapphire amplifiers

- Ongoing extended numerical modelling activity of TiSa amplifiers in the range of 100 W – 5 kW average power
- Exploration of both 10-20 Hz & 100-500 He repetition rate ranges
- Investigations done on both usual amplifier with TiSa crystal in transmission and active mirror amplifiers based on TiSa disks
- Using both ANSYS & COMSOL for these numerical simulations

> Compressors

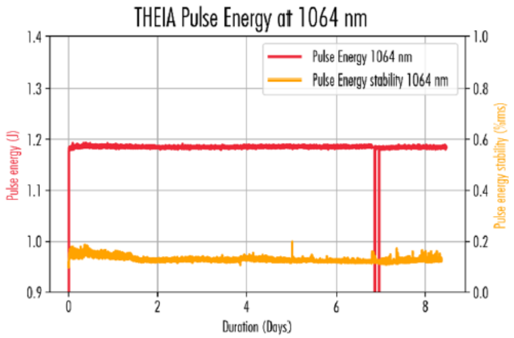
- Implementation of active cooling of gold-coated gratings for 100 W systems & further investigation of the average power limits for active cooling
- Ongoing studies of pulse compressors design based on the use of MLD-coated gratings
- Subject of WP13 of PACRI projects who starded in March 2025

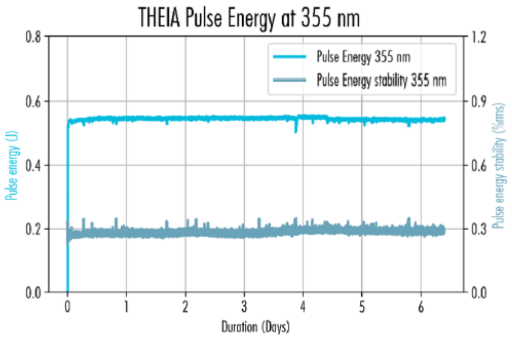
Thales RTD roadmap overview (2/3)

> For flashlamp pumped lasers, portfolio is already available (GAIA HP up to 1 Hz, SAGA & RHEA up to 10 Hz)

> For diode-pumped lasers we have also catalog lasers

- THEIA 100/200 : for operation at 100 or 200 Hz (same energy at each rep rate)
- THEIA 500: DPSS laser developed for highly demanding industrial applications in semiconductor and display





Bruel & al , EuroPhoton conference (Oct 2024)
https://doi.org/10.1051/epjconf/202430704050

TARANIS: theInertial Confinement Fusion project in France

GenF
Fusion Generated Energy

- The Taranis project lead by GenF (a Thales spin-off) and supported by French government is a public-private partnership aiming at developping an ICF based reactor

cea | CELIA | THALES | assystem

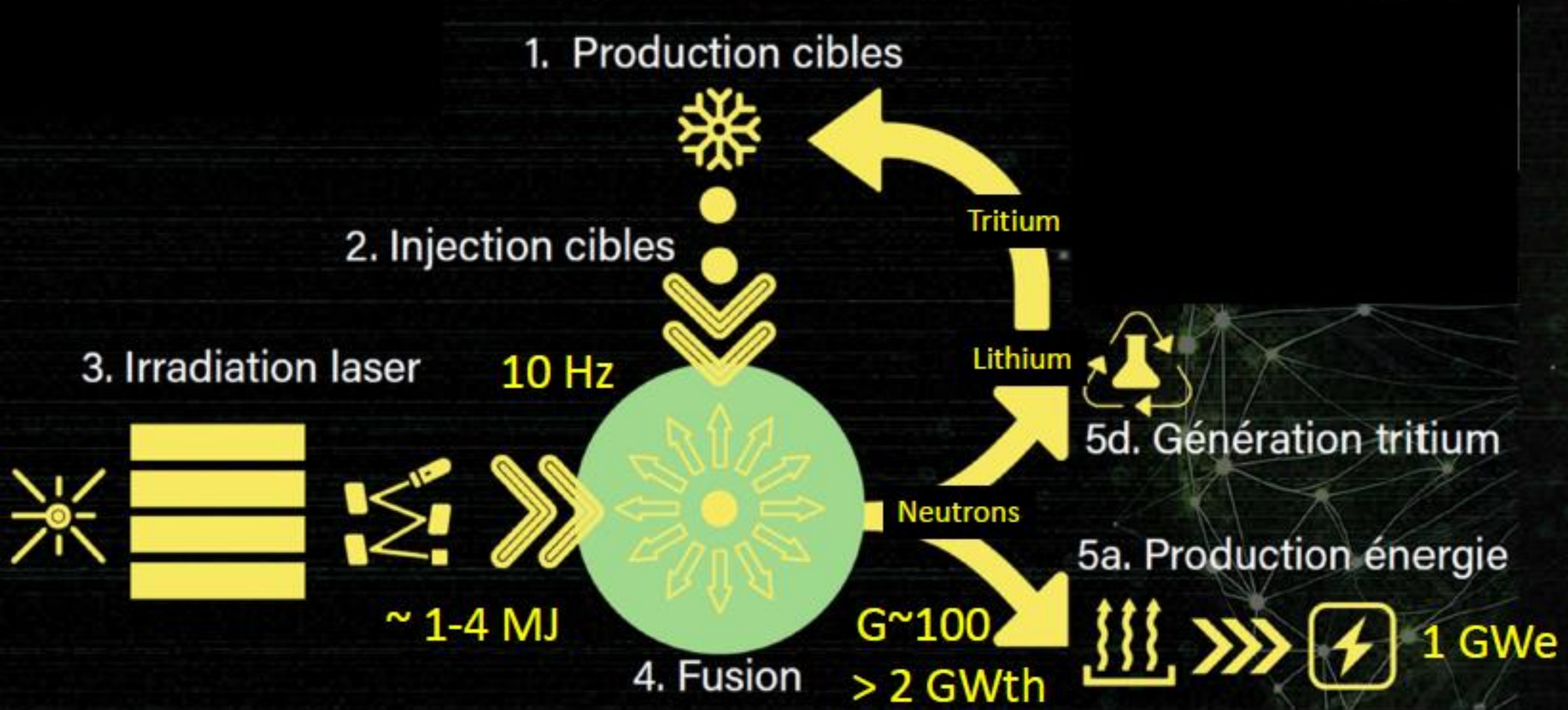
Soutenu par GOUVERNEMENT Liberté Égalité Fraternité FRANCE 2030

~ 40 FTE (laboratories + industries)

~ 18 M€ seed funding

Access to unique facilities (ex LMJ)

General principles



Thales RTD roadmap overview (3/3)

> Within TARANIS project, design of high energy diode pumped lasers (DPSSL) optimised for IFE

> Large number of individual lasers to reach several MegaJoules of overall laser energy for the fusion reactor

> Energy quantum to be likely comprised between 100 J & 10 kJ of UV light with a repetition rate around 10 Hz

> These developments could highly benefit to the development of pump lasers required for phase 2 of EuPRAXIA laser-driven machine

Conclusion

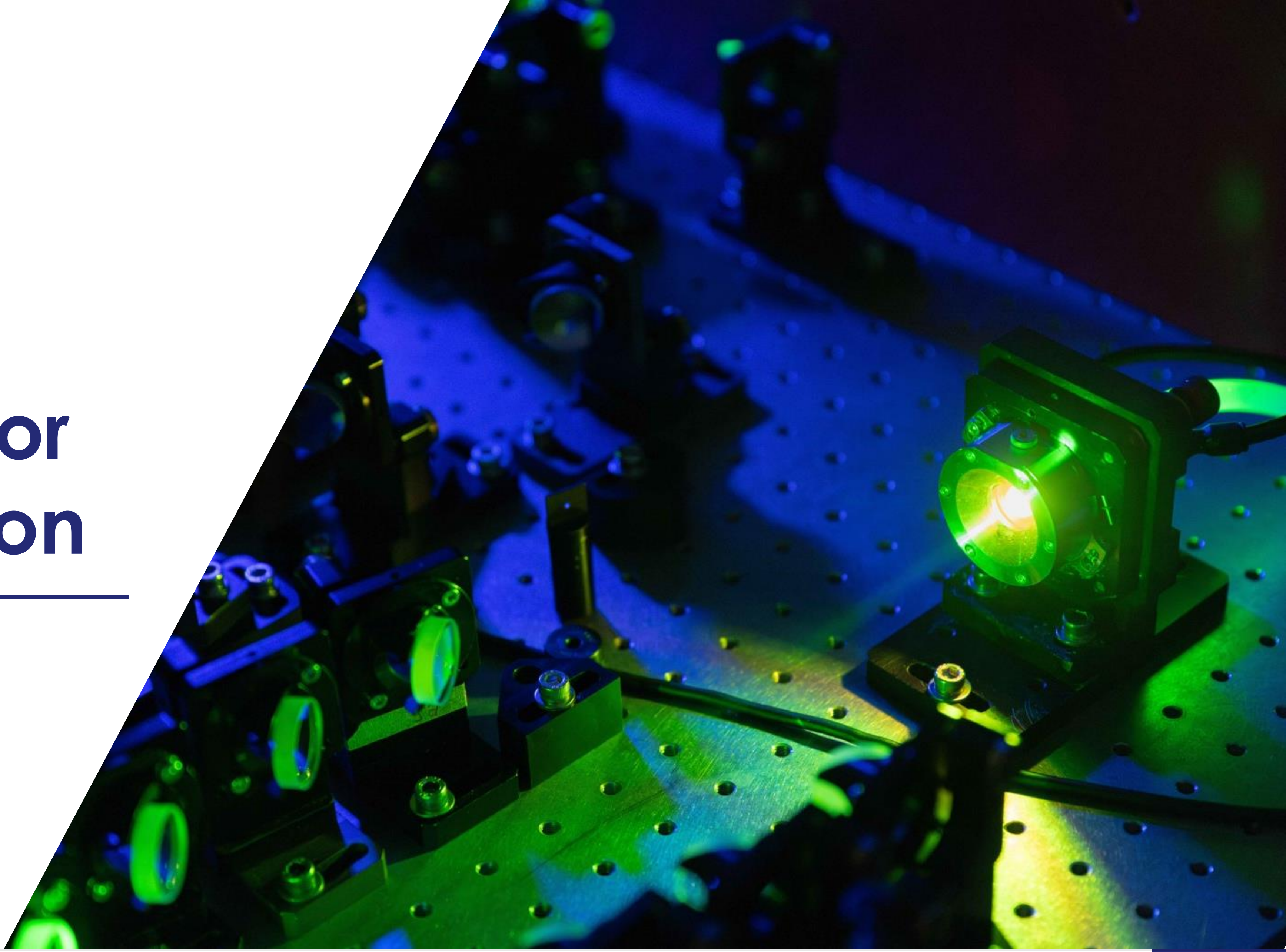
> Thales has delivered first 200 mJ / 100 Hz Titanium Sapphire based lasers pumped by DPSS lasers

> We have derisked the technical bricks for 1 J / 100 Hz operation & will demonstrate soon the full capability at this level

> Further developments will consist to increase the average power of 100-500 Hz systems and to adapt the high average power technology to lower repetition rate systems (10-20 Hz)

> This will require new high energy diode-pumped lasers whose design has started within IFE projects (French project TARANIS) and which could benefit to phase 2 of EuPRAXIA laser-driven machine

Thank you for your attention



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