10 PetaWatt Laser System for Extreme Light Physics

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THALES

ELI NP - EXTREME LIGHT INFRASTRUCTURE NUCLEAR PHYSICS ROMANIA

eli nuclear physics

Budget
310 M€
2013-2022

Large Instruments

- **High power laser system : Laser system 2x10 PW**
- High intensity gamma beam system

Experiment

- 8 experimental rooms for gamma, laser and gamma-laser
- Laboratories

Building (2013-2016)

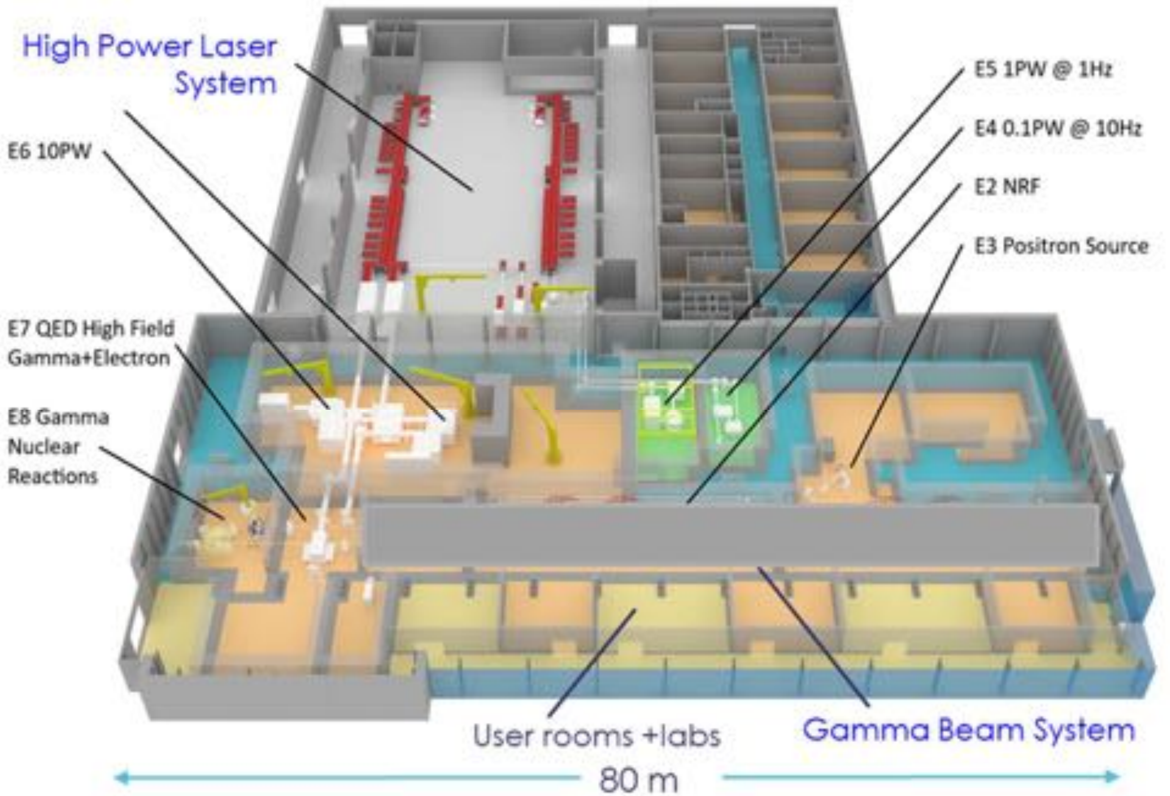
33 000 m²

LBTS

10PW beams transportation

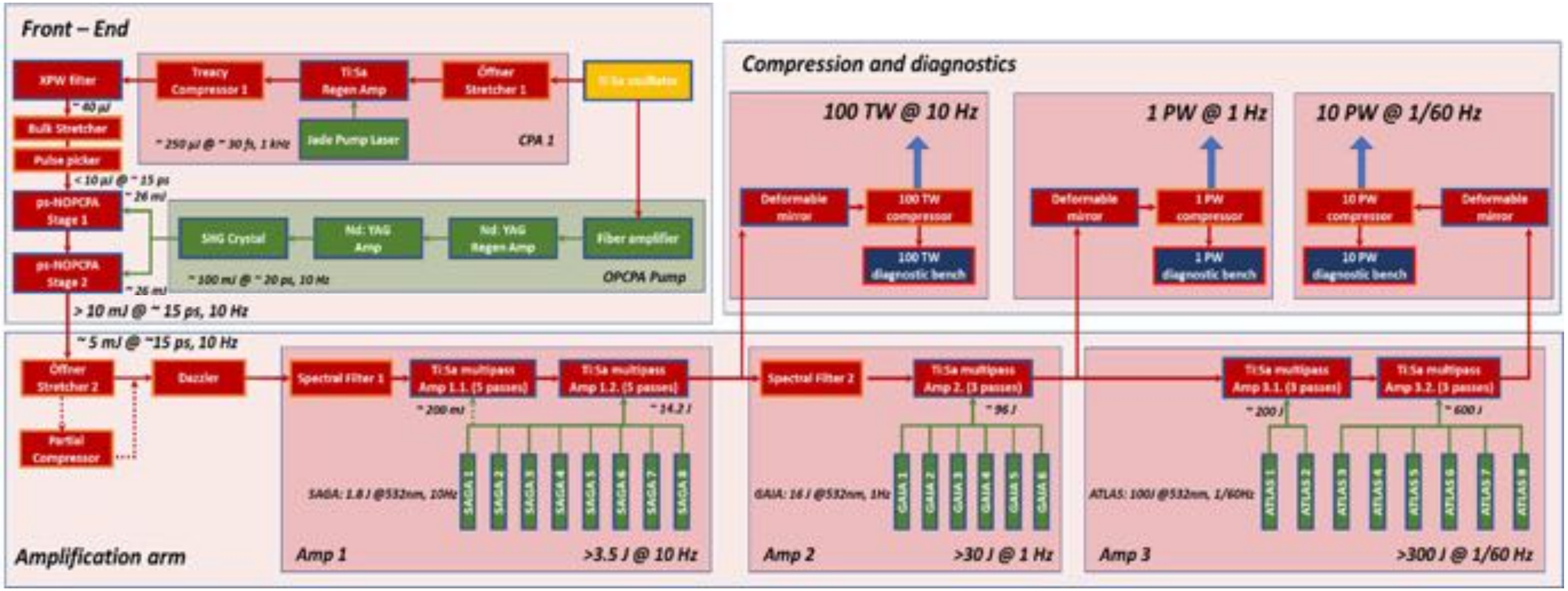
IFIN-HH

ELI NP - INFRASTRUCTURE



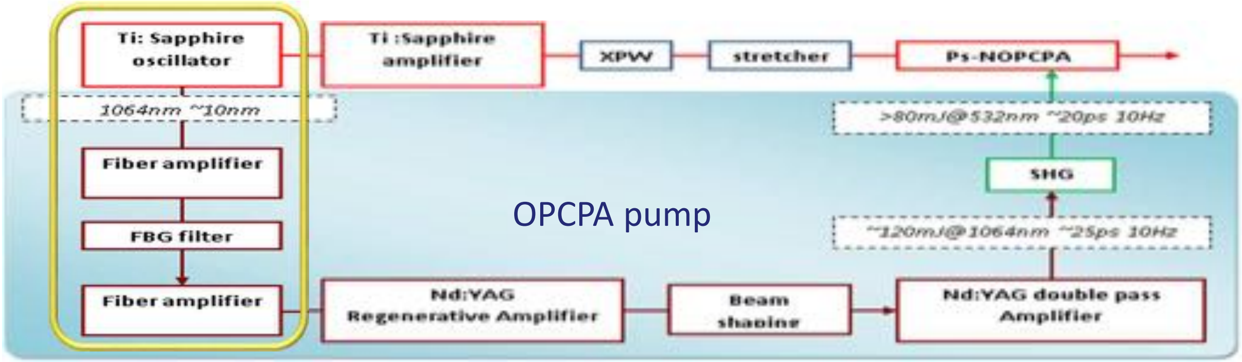
HPLS performances

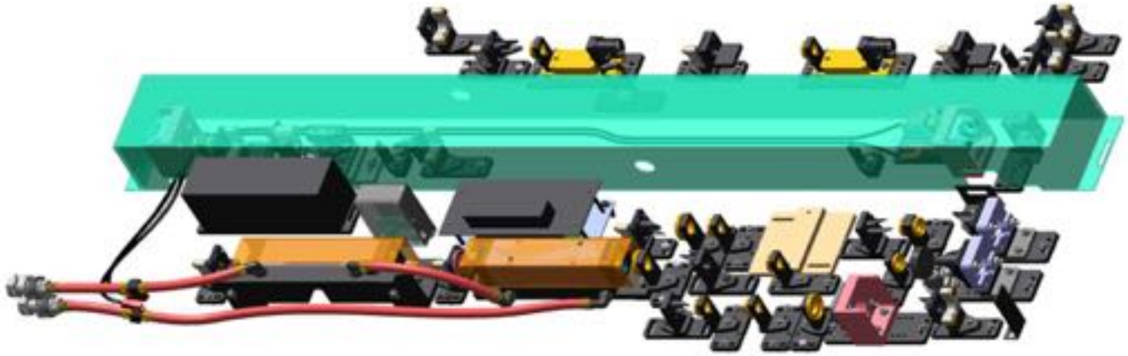
SYSTEM BREAKDOWN STRUCTURE

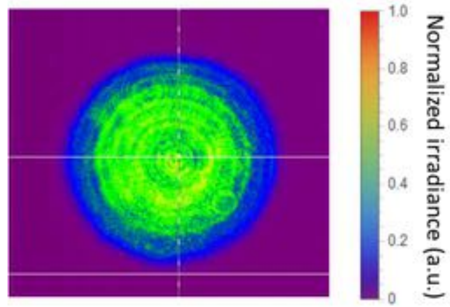


HIGH CONTRAST FRONT-END

From oscillator supplier



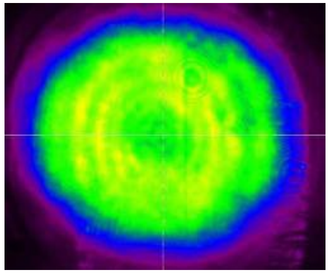


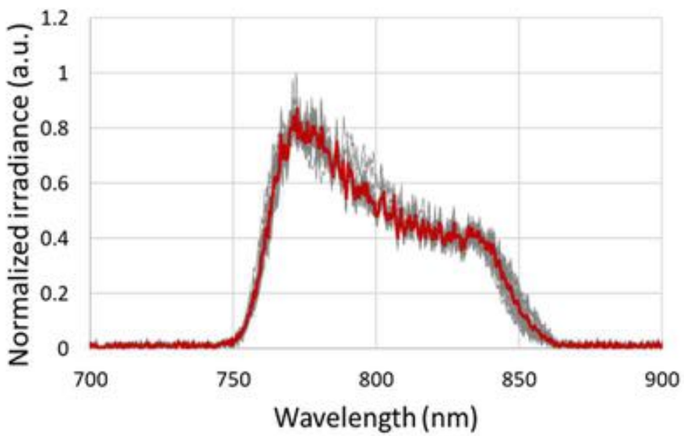


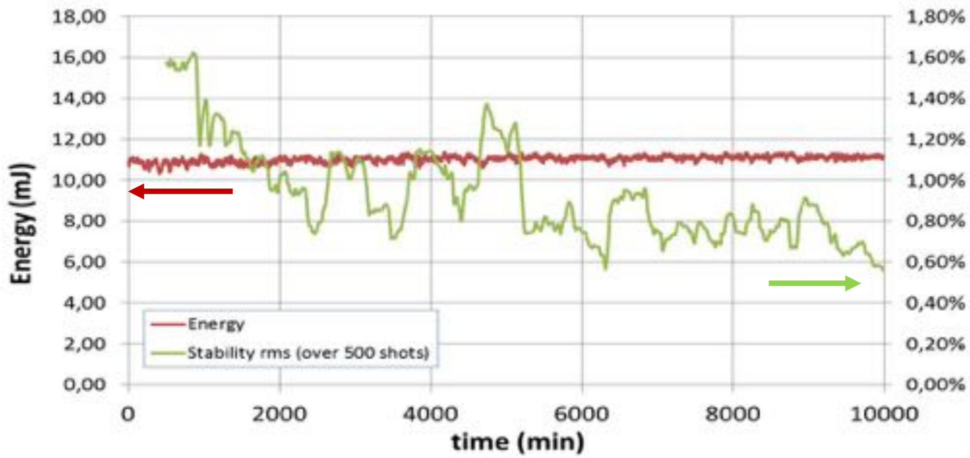
EXPERIMENTAL RESULTS

OPCPA

- Energy > 10 mJ
- Pulse duration ~ 20 ps
- Bandwidth FWHM > 75 nm (FT < 20 fs)
- Repetition rate : 10 Hz
- Short term stability < 1 % rms over 500 shots.



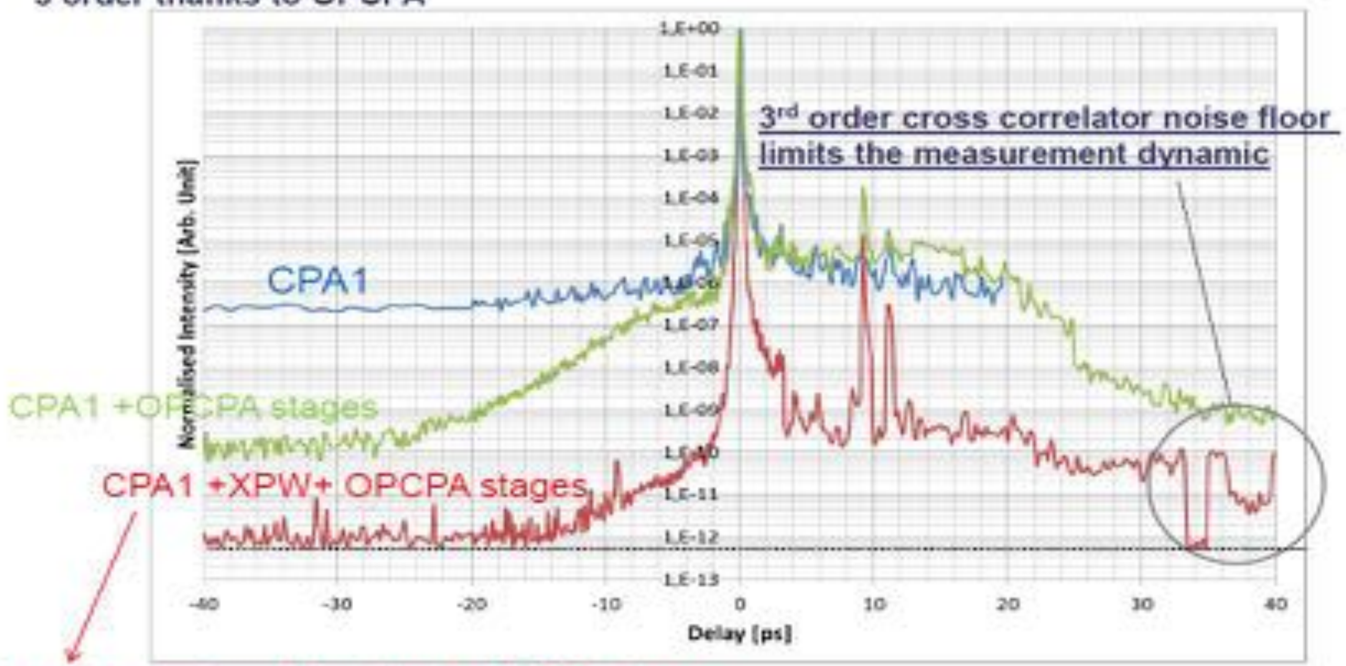




CONTRAST RESULTS

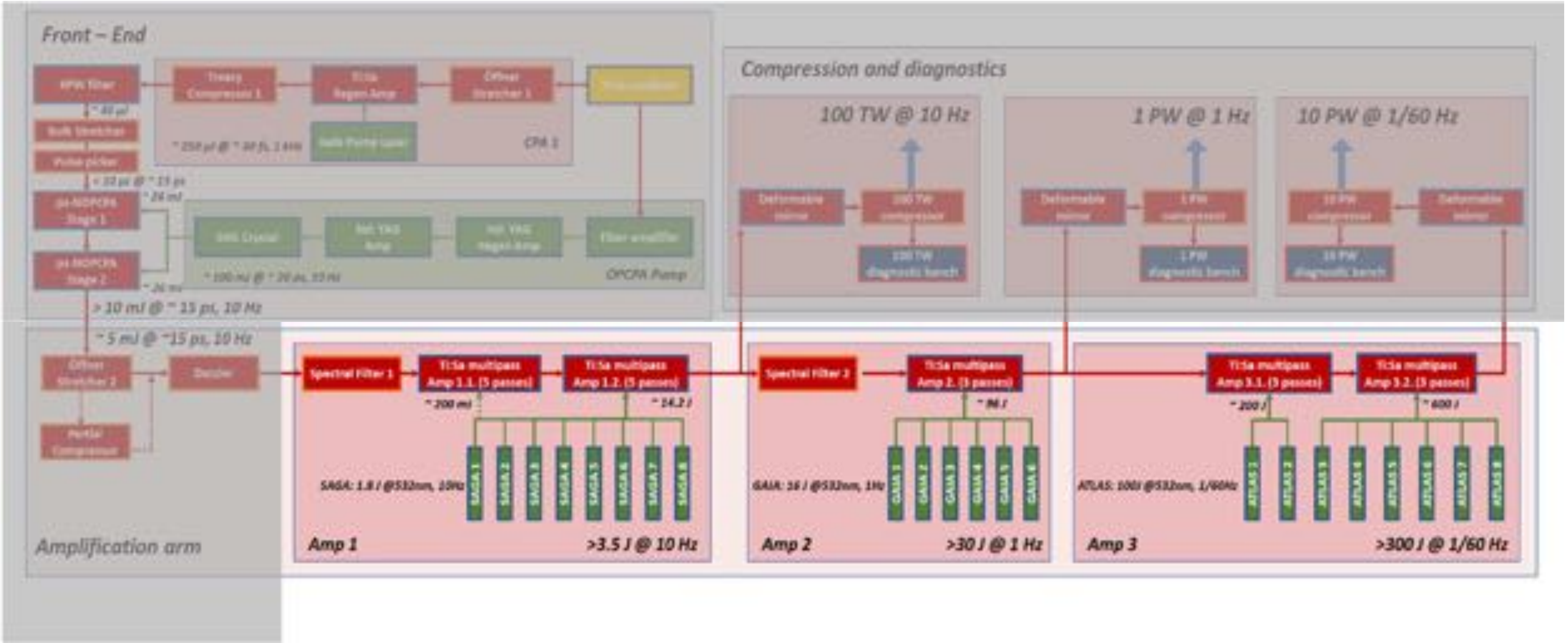
Contrast improvement by 7 order of magnitude:

- 4 order thanks to XPW
- 3 order thanks to OPCPA

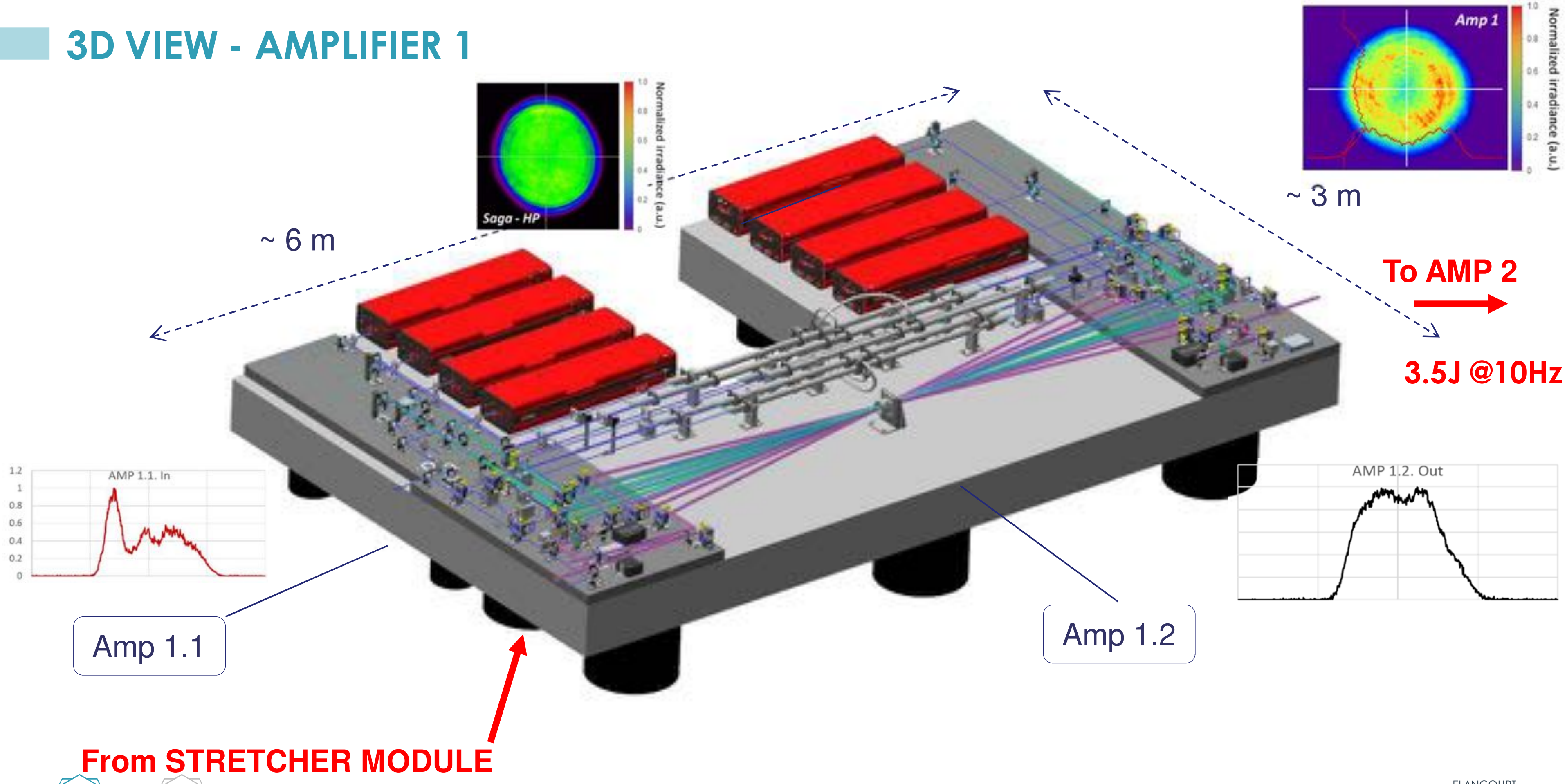


Compression achieved directly out of OPCPA stages

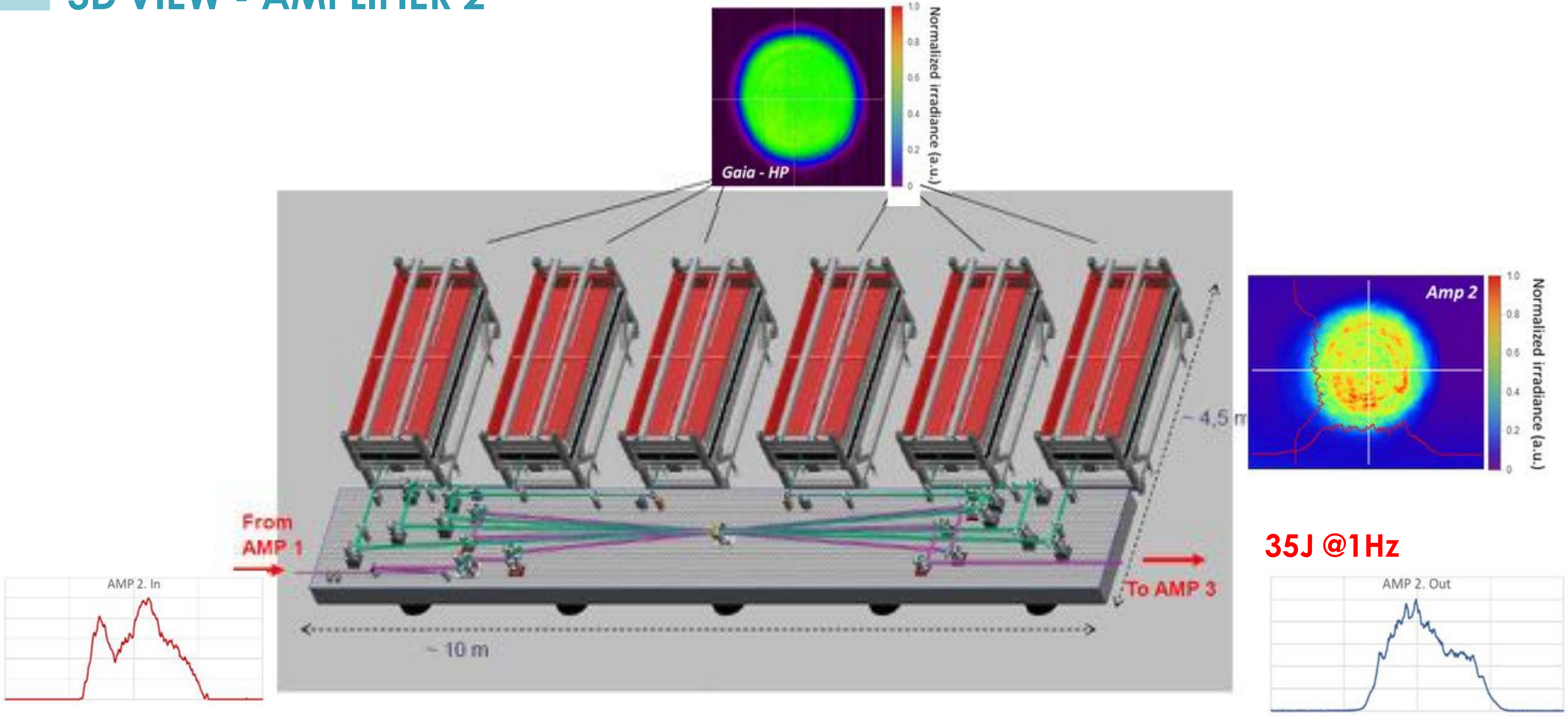
POWER AMPLIFIERS CHAIN BREAKDOWN STRUCTURE



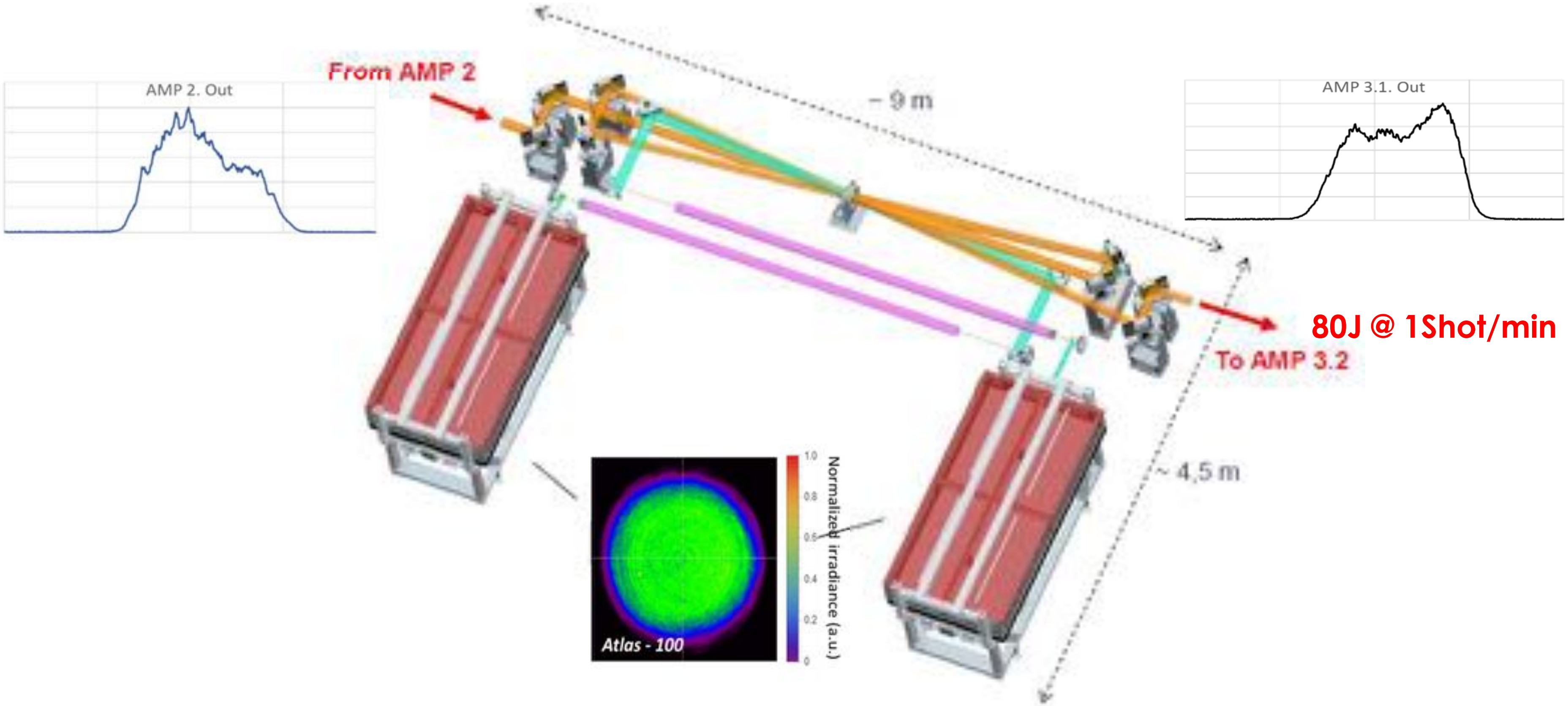
3D VIEW - AMPLIFIER 1



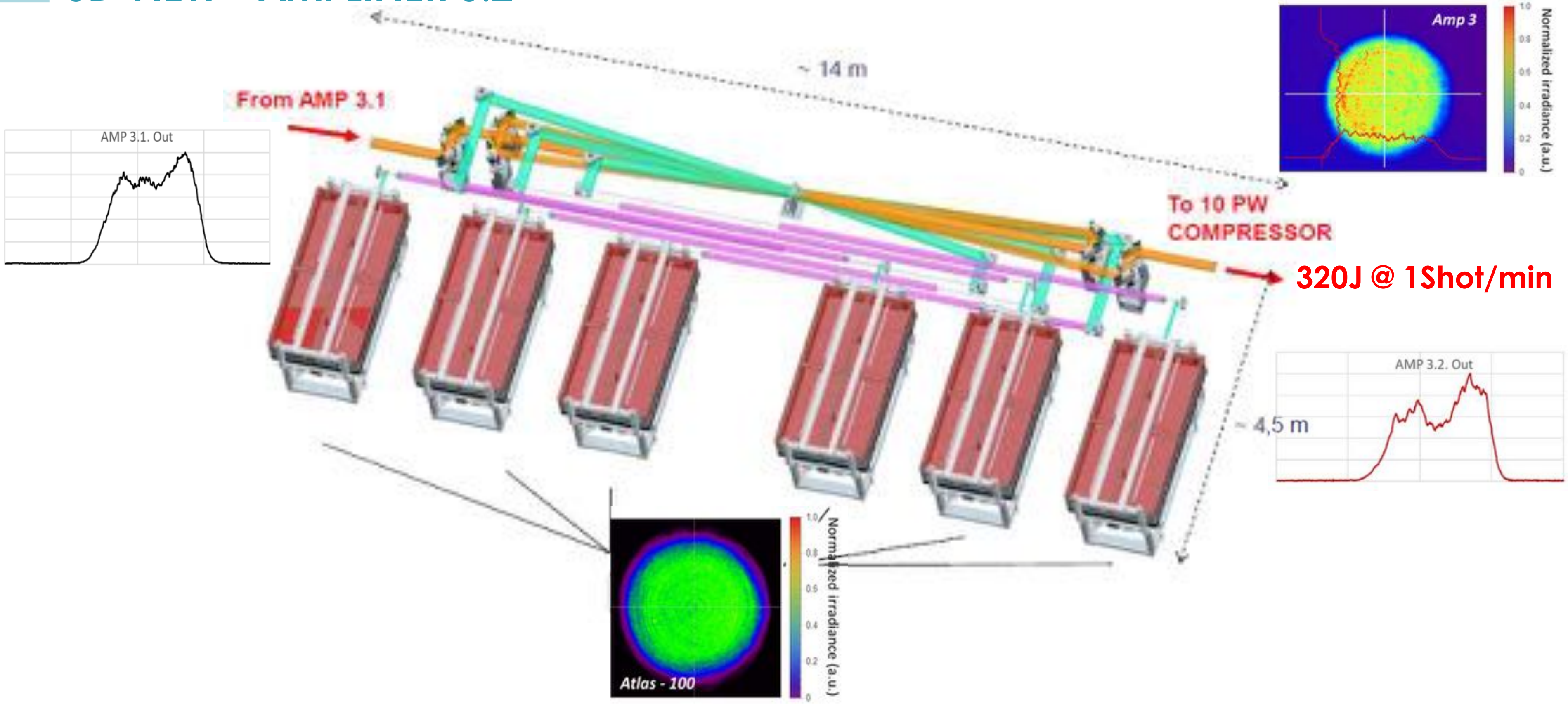
3D VIEW - AMPLIFIER 2



3D VIEW - AMPLIFIER 3.1



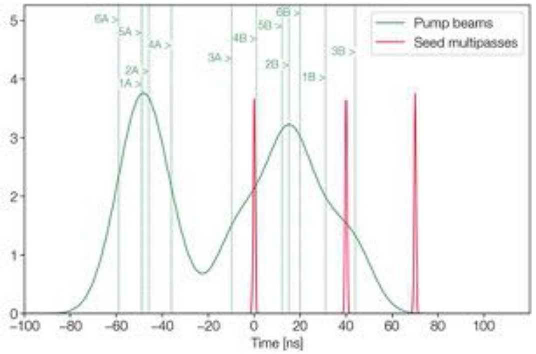
3D VIEW - AMPLIFIER 3.2



AMPLIFIER 3.2 DETAILED CHARACTERISTICS

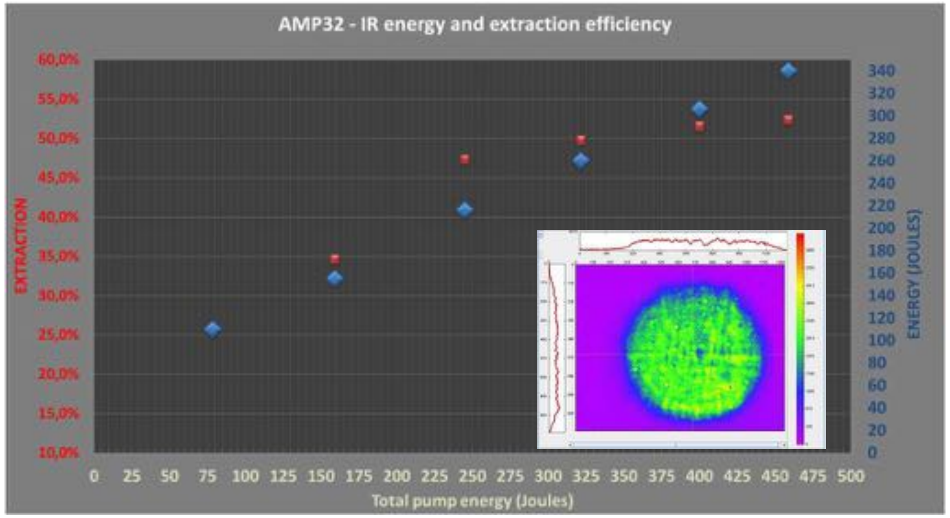
- **Multipass amplifier in bow-tie configuration :**
  - Input fluency close to Ti:Sa fluency of saturation : **0,7 J/cm²**.
    - ⇒ **3 passes** to reach expected specifications.
    - ⇒ Amplifier in **saturation regime**.
  - Pumped by **6 ATLAS 100** on both side of the Ti:Sa crystal : **~ 600 J**.
  - Thermal focal length **~ 10 km** ⇒ thermal load is not an issue.
  - Transverse Lasing Threshold ⇒ «Perfect» index matching and pump delaying required.

- **Performances :**
  - Repetition Rate — **1/60 Hz**
  - Crystal diameter — **200 mm**
  - Output Energy — **~ 300 J**
  - Output fluency @ 45 — **~ 1,6J/cm²**
  - Extraction Ratio — **~ 38 %**

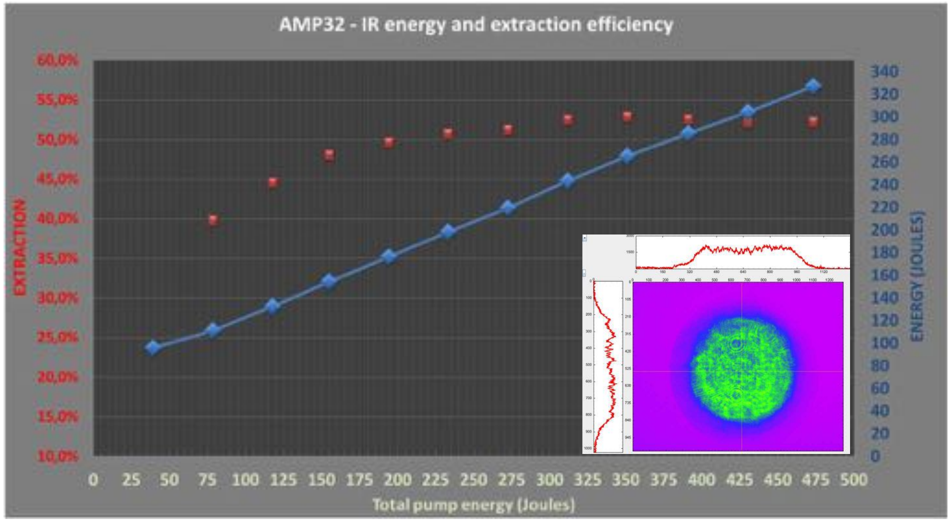


AMPLIFIER OUTPUT

Beam line 1: 340 J



Beam line 2: 327 J

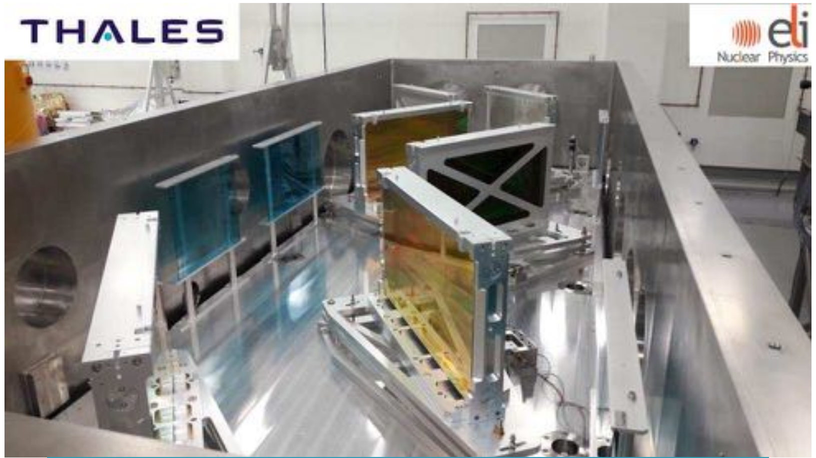


Long term energy stability over 90 minutes at 300J
- **average energy = 300J**
- **energy stabilty < 2 % rms**

UNIQUE OPTICAL COMPONENTS WORLDWIDE FOR ELI NP

Diffractive optical gratings for pulse compression up to 1 meter size
Manufacturer HORIBA France

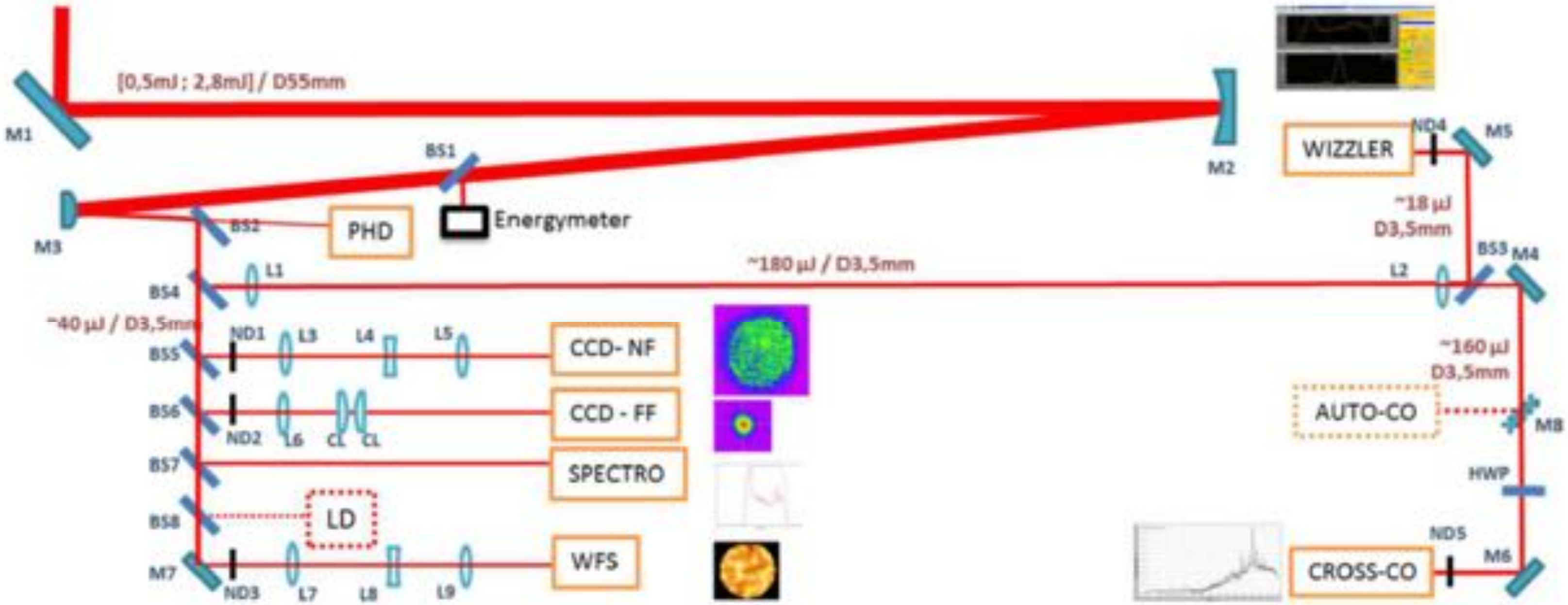
Grating size : 1015 x 575 mm²



Gratings integrated in the vacuum vessel

9 gratings manufactured

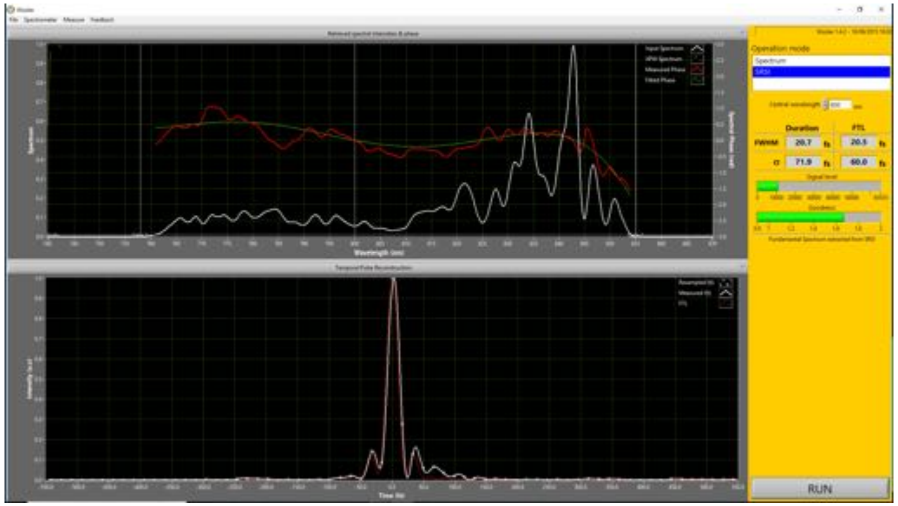
DIAGNOSTIC BENCH – 10 PW



COMPRESSOR OUTPUT - BEAM LINE 2

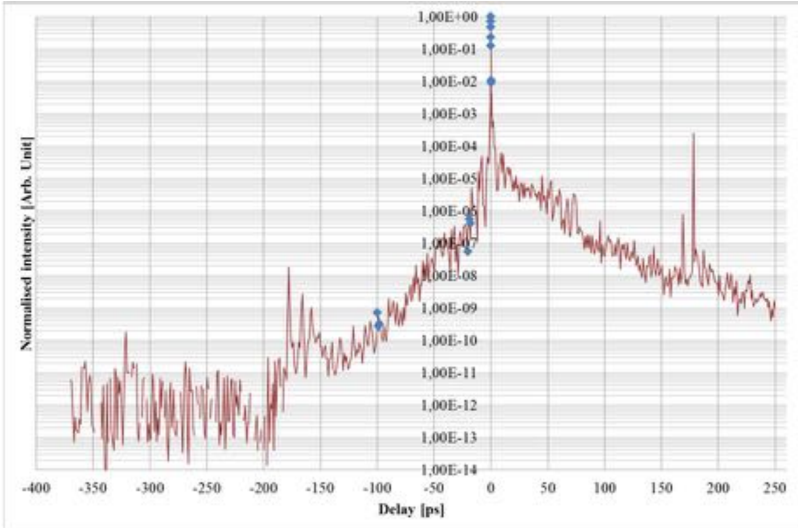
(MEASUREMENTS AT FULL APERTURE WITH ENERGY ATTENUATED BEFORE COMPRESSOR)

Pulse compression 21.7 fs



- Compressor efficiency 74 % / Amplifier output = 327 J

Picosecond contrast > 10^{13}:1 before -200 ps



* : measurements made at 1Hz 22 J and 1shot/Min 320 J

Measured in partnership with

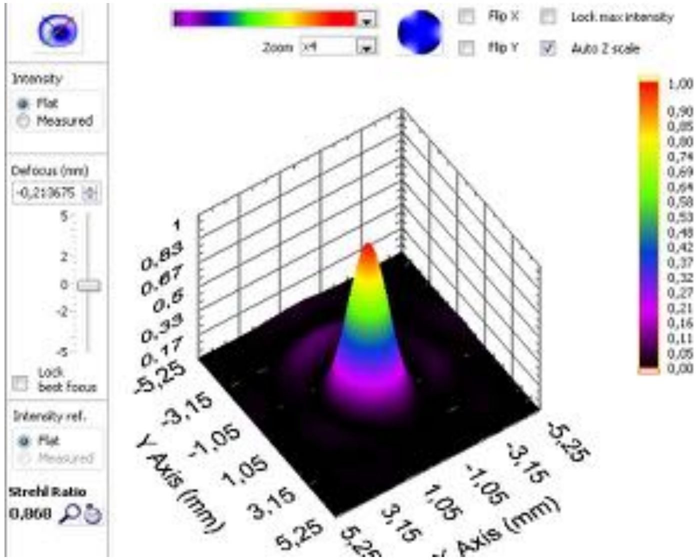
ULTRAFAST INNOVATIONS

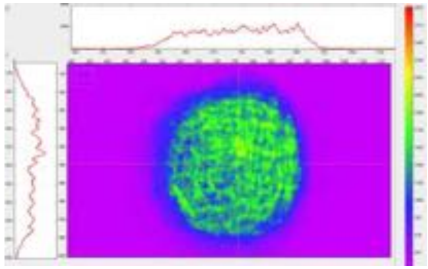
Dr. Daniel Cardenas
Dr. Hans Koop

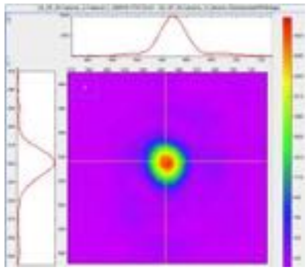
ELI NP - 10 PW BEAM LINES CHARACTERISATION – SPATIAL PARAMETERS

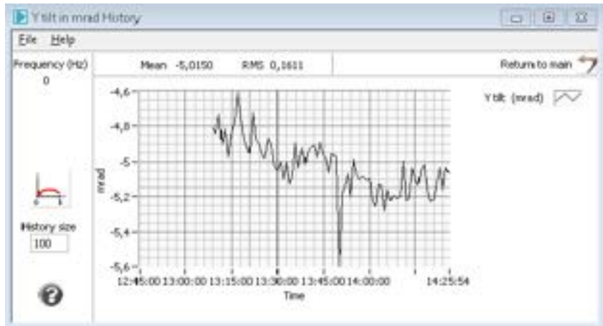
Wavefront and beam pointing stability

- Strehl ratio > 0,8 with deformable mirror
- Beam pointing stability < 1,2 µrad rms over 100 minutes





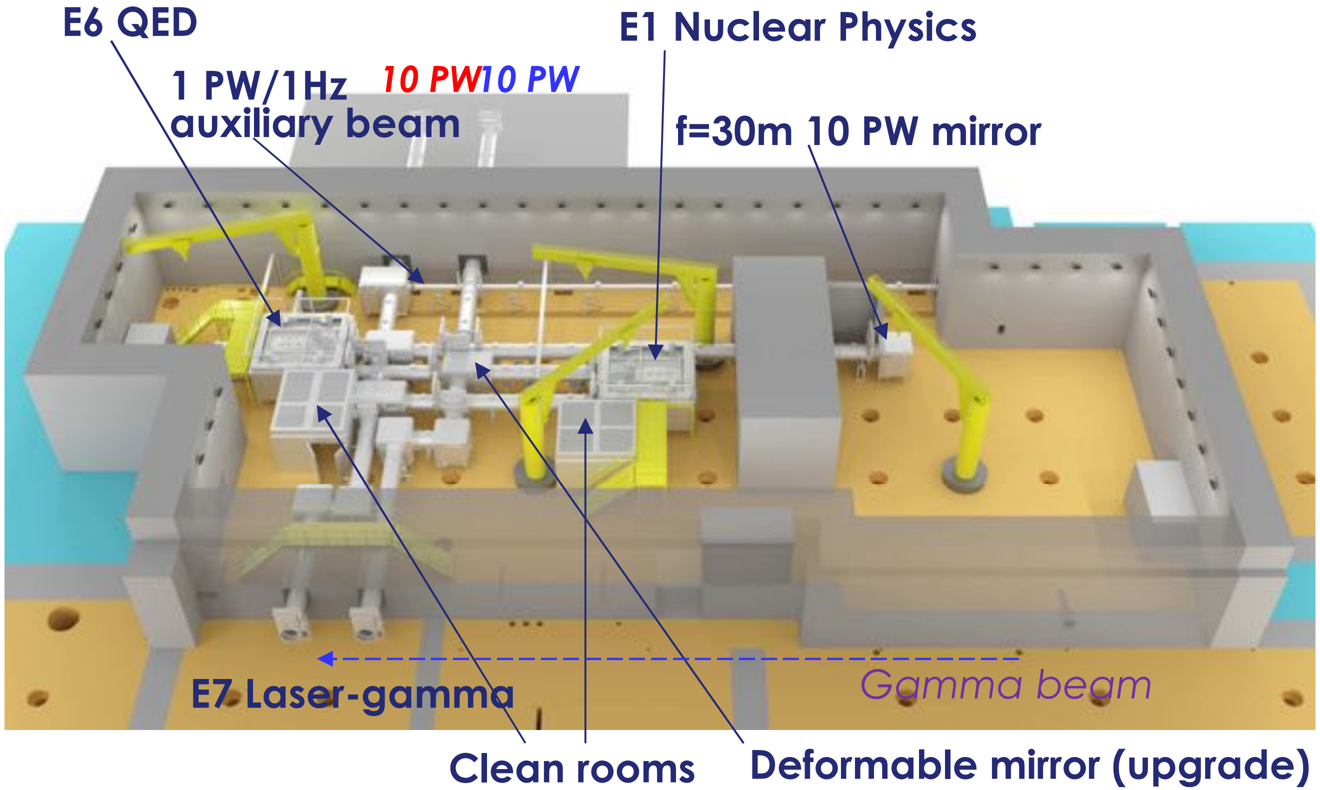




D=450mm FWHM / reduction factor 180x

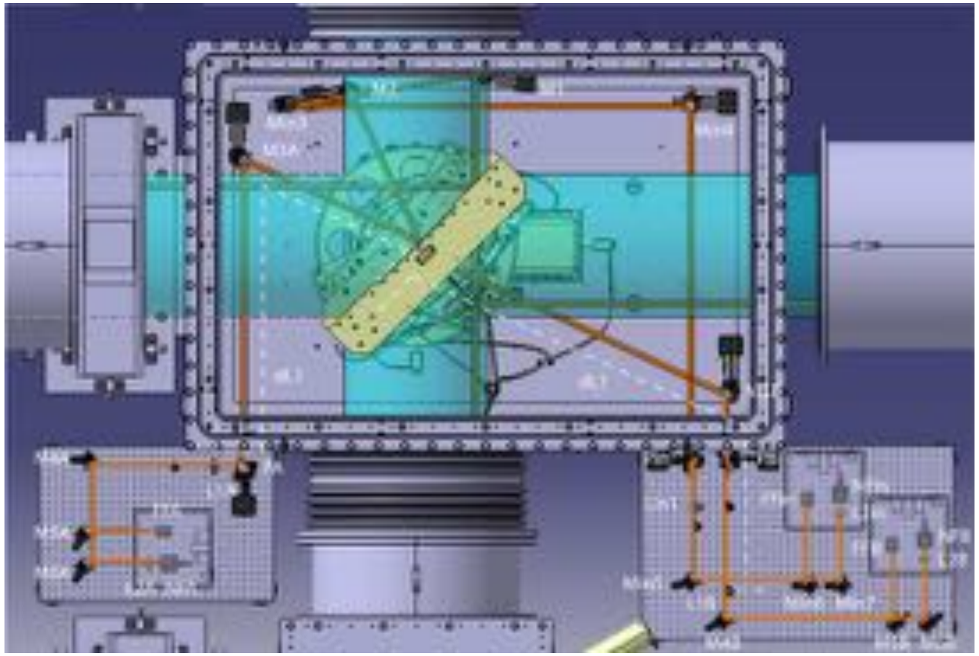

LBTS

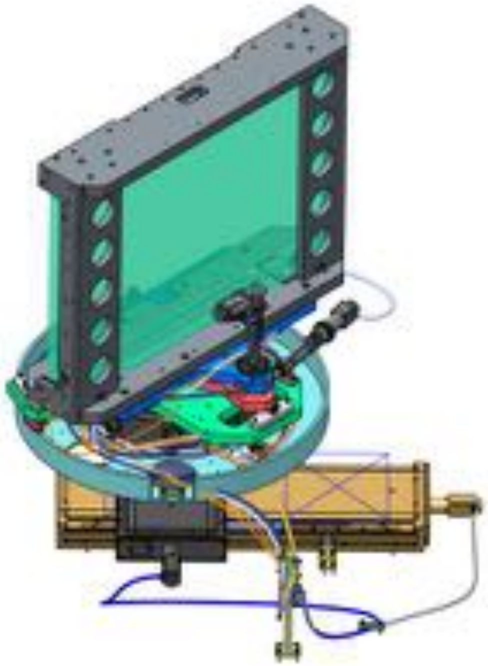
ELI NP - EXPERIMENTAL AREAS LASER MATTER INTERACTION



ELI NP - LASER BEAM TRANSPORT SYSTEM

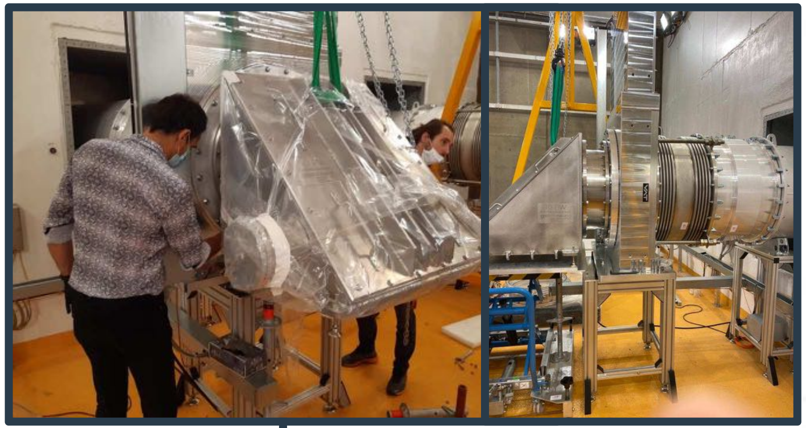
- Mirrors with motorization stages and monitoring of the positions

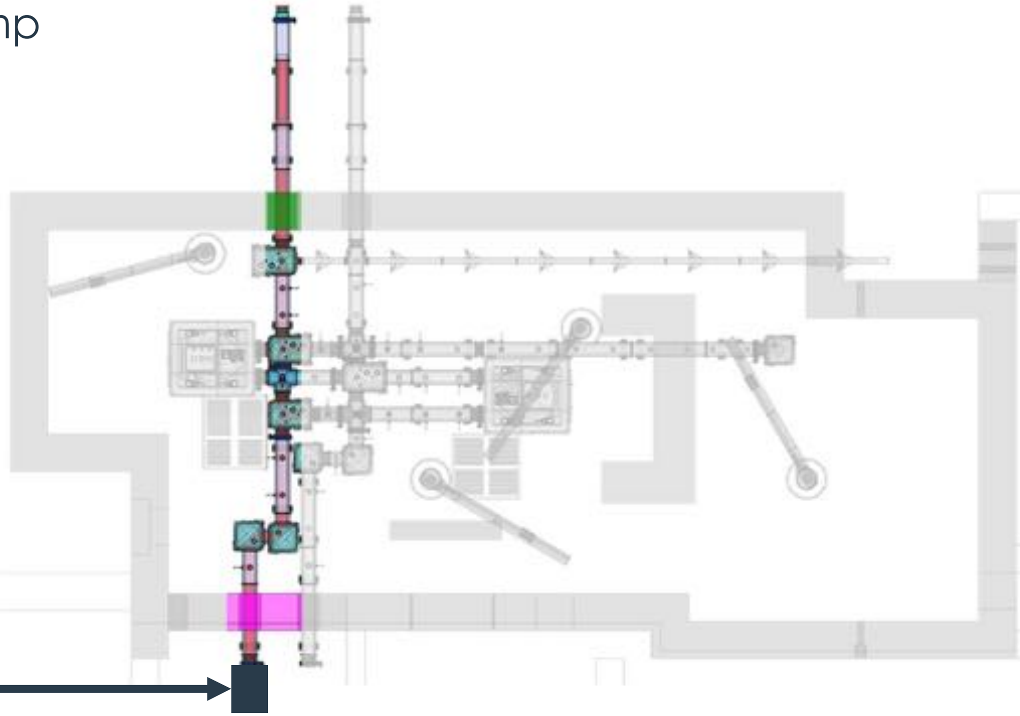




ELI NP - LBTS TEST PURPOSE

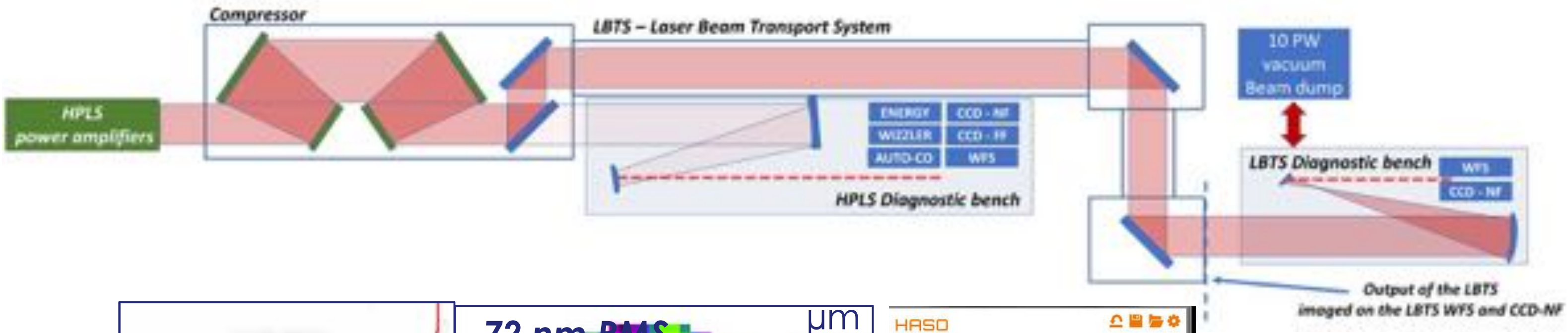
- Full power beam propagation through LBTS
- Beam blocked with a dedicated dump

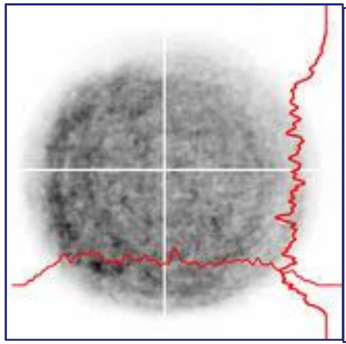




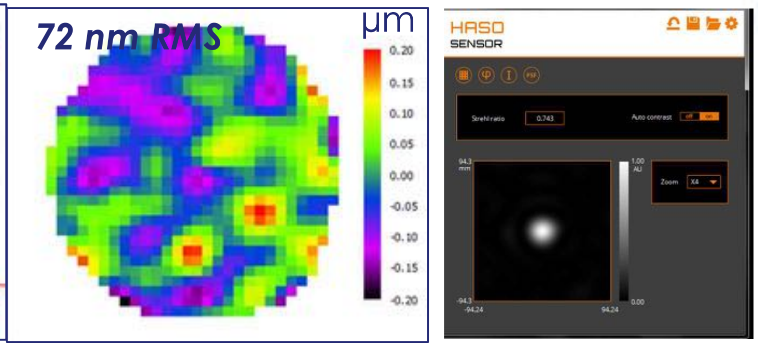
ELI NP - LBTS TEST CONFIGURATION – STEP 1

HPLS laser running at full energy attenuated before compressor for beam profile analysis after propagation through the LBTS and transmission efficiency





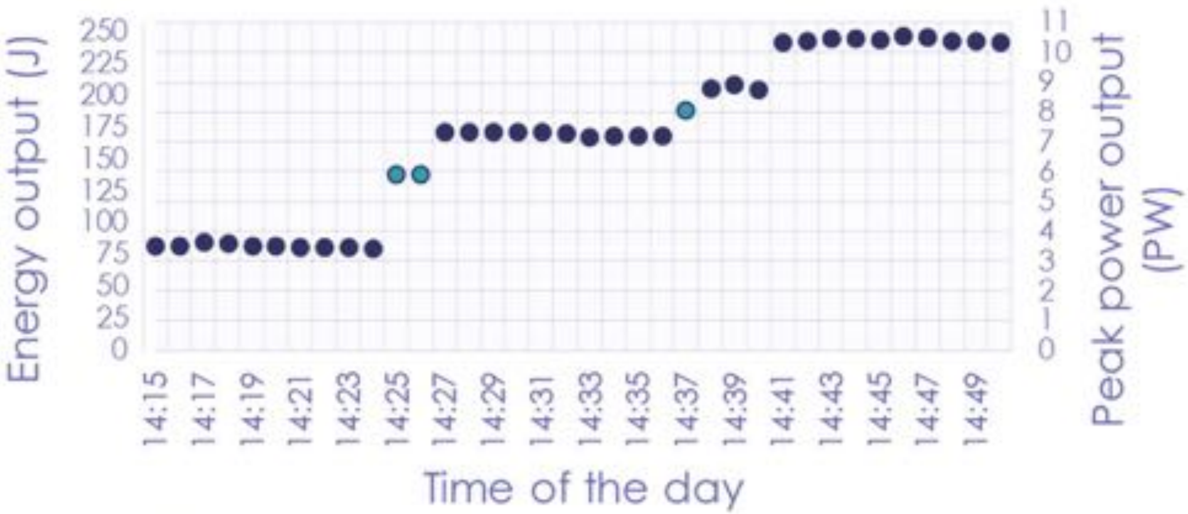
NF LBTS output



Wavefront map, Strehl ratio > 0,7

ELI NP - LBTS TEST CONFIGURATION – STEP 2

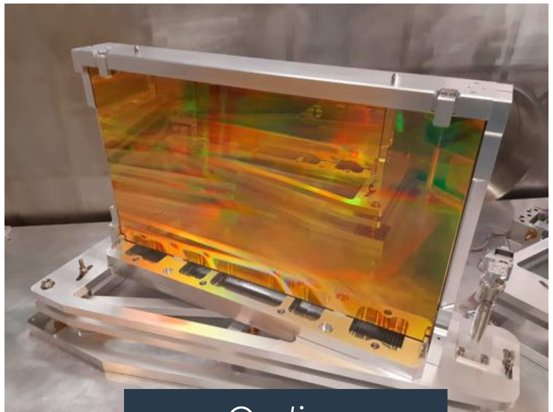
- Beam dump installation replacing the diagnostic bench
- HPLS running at full energy/full power sent through the compressor and the LBTS



- Several shots at 3PW, 7PW and 10 PW (energy/power increase by turning on pump laser on the last amplifiers

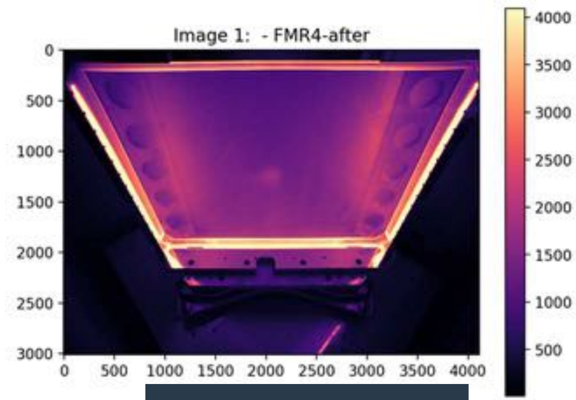
ELI NP - LBTS TEST CONFIGURATION – STEP 3

- Verification of transmission efficiency
- Visual inspection of optical components within HPLS compressor and LBTS



Grating

Compressor mirror

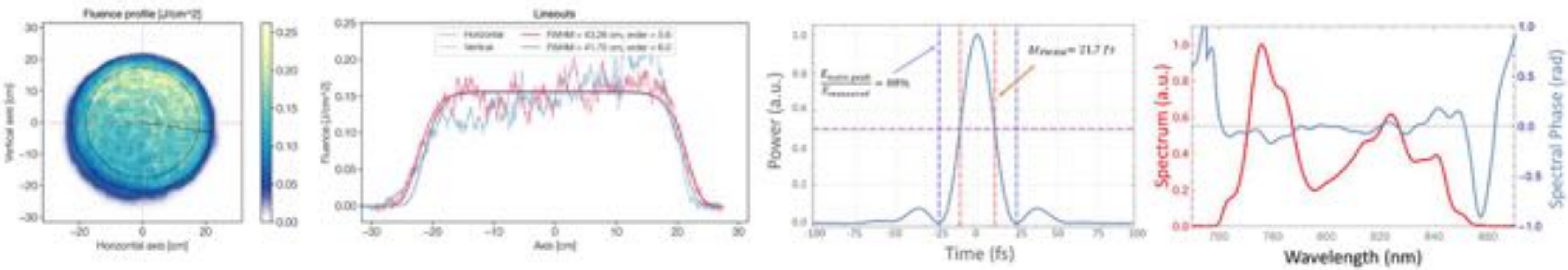


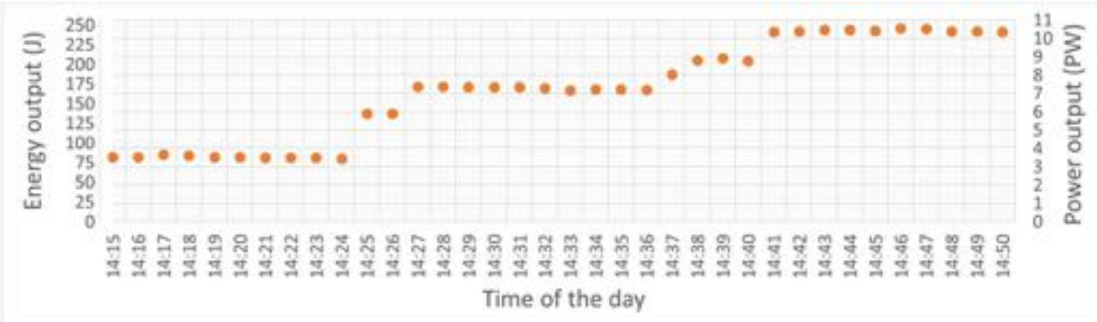
LBTS mirror

- No losses of efficiency (~ 60%) and no damages observed

COMPRESSOR OUTPUT - BEAM LINE 2

Calculated peak power = 10,2PW (in the main pulse)





10PW Focusing optics

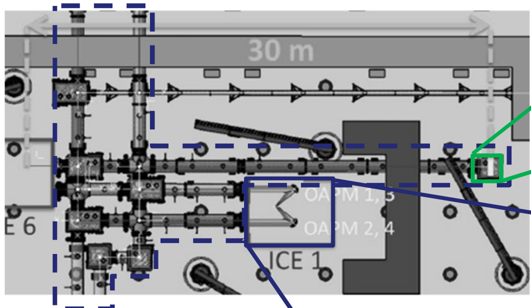
ELI NP - ELI A EUROPEAN PROJECT

Delivery of set of optics for focusing the 10PW beams

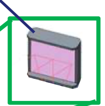
- Q=2 OAPM + 2 spare
- Q=1 LFM + 1 spare

Parabola - OAPM – Off-axis Parabola & Frame
Short Focal Length Mirrors
Dimension : 700x650mm (150kg)
Focal : 1,5m (numerical aperture f/2,1)
Deviation : + & - 45°
LIDT : 250mJ/cm²
WFE : <50nm

LFM -Long focal Sphere
(mirror with frame only)



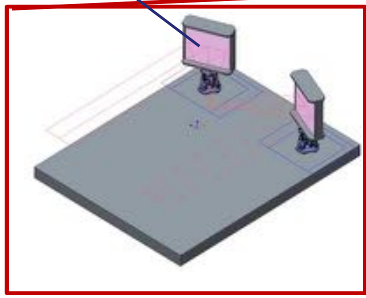
LBTS

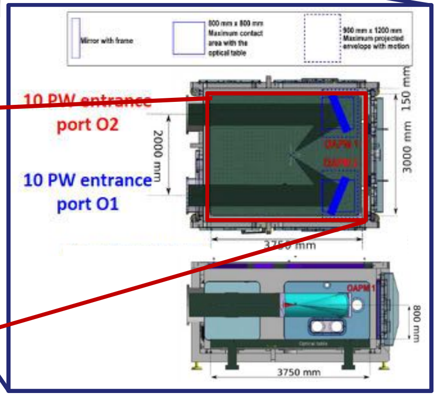


Sphere – LFM Long Focal Length Mirrors
Square Spherical Mirror
Dimension : 650x650mm (150kg)
Focal : 30,5m (numerical aperture f/46)
Deviation : 0°
LIDT : 250mJ/cm²
WFE : <50nm

To be installed on the mechanical motorized mount delivered through LBTS

OAPM- Short focal Parabola Mirror and hexapods





Customer Furnished Item

Operation contract

ELI NP SYSTEM

eli nuclear physics

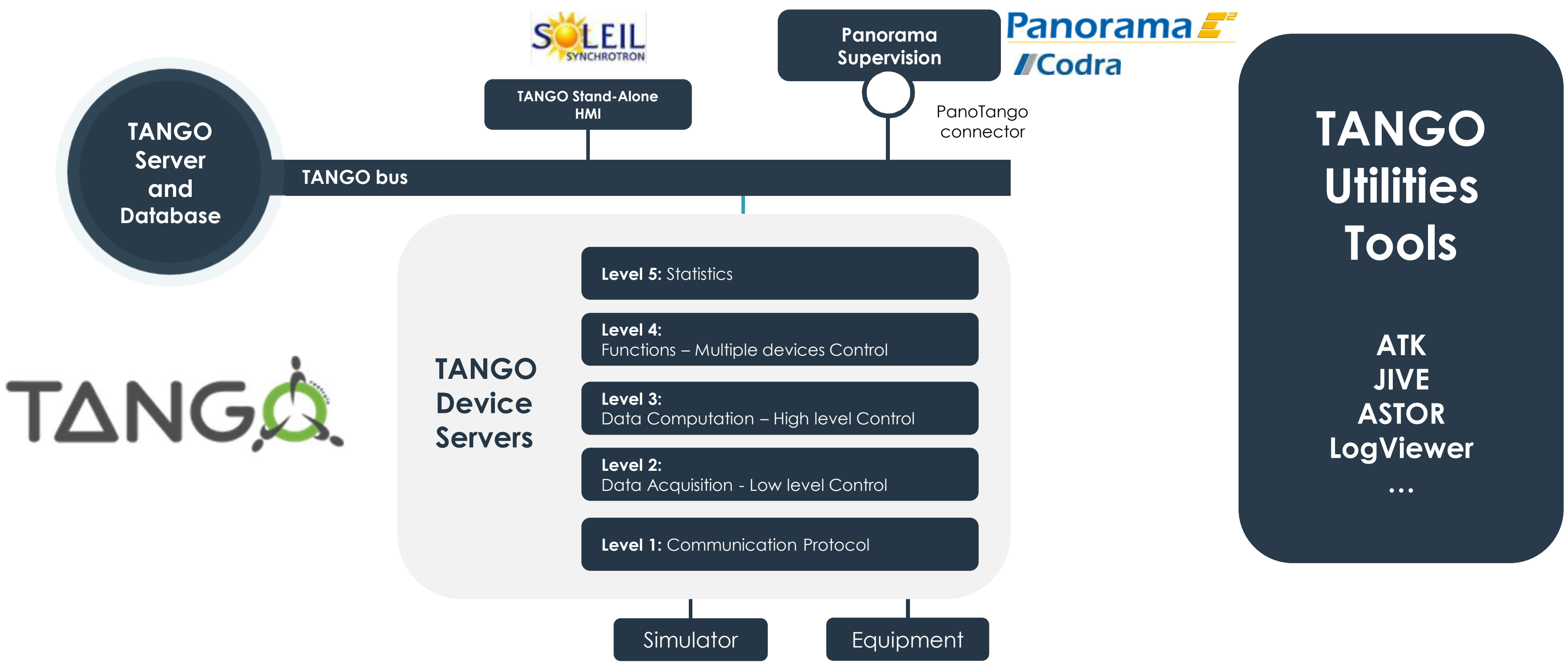
Thales joined the Extreme Light Infrastructure for Nuclear Physics (**ELI-NP**) program in 2013 to develop the High Power Laser System (HPLS), the **most powerful system of its kind in the world.**

This laser will support research in nuclear physics and help advance human understanding of the physics of matter

Thales intervene by

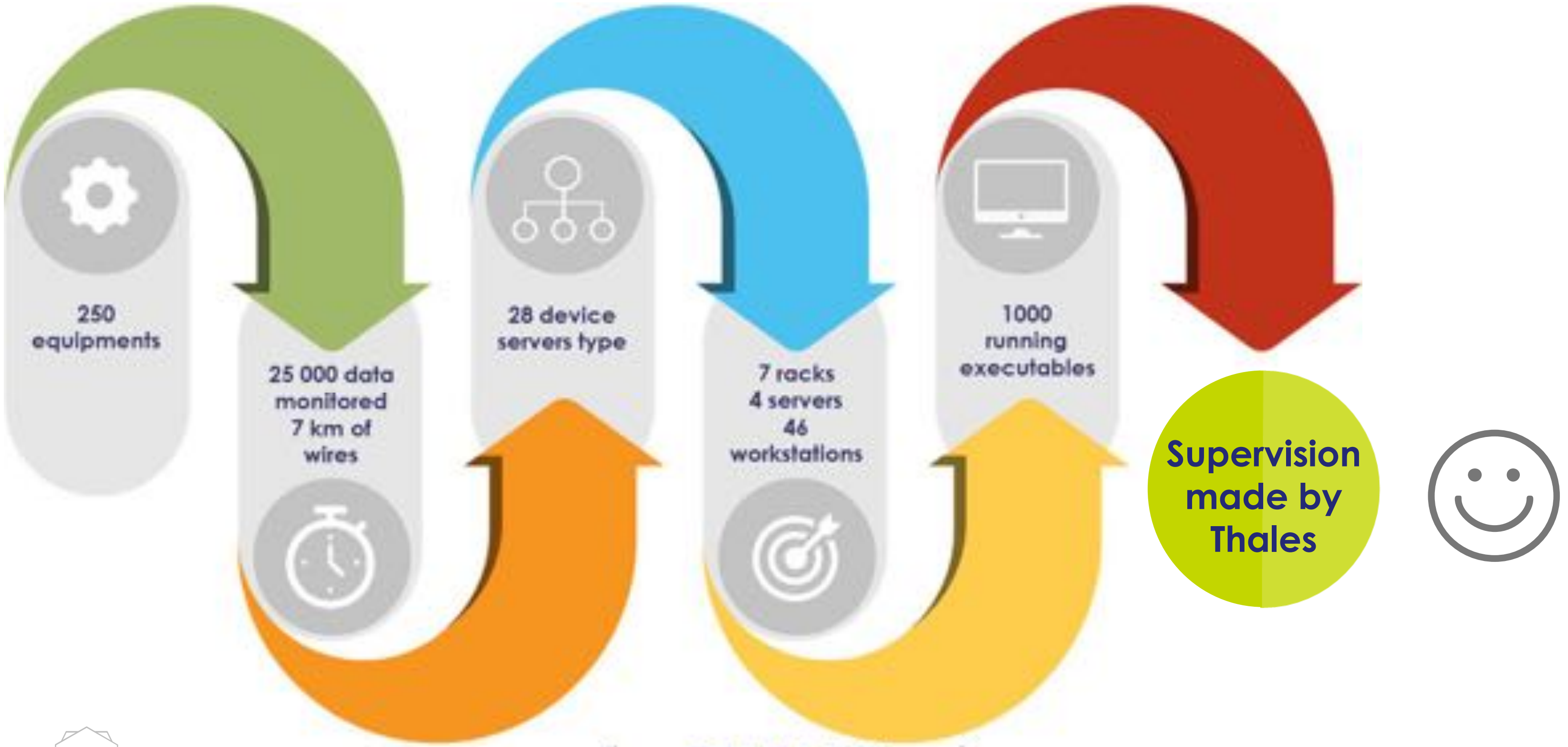
- **Operating** the system from laser preparation to experiences management (beam available from 9am to 6pm)
- **Training** ELI NP team regarding our dedicated program launched in 2019 for our users
- **Maintaining** the system with preventive and corrective maintenance

ELI NP - FROM LABVIEW HMI TO FULLY ERGONOMIC SUPERVISON



SYSTEM CONTROL

High number of equipment : not easy to control by one person



SYSTEM DETAILED CHARACTERISTICS

Full supervision software coupled with internal diagnostics

Left screen, available views

- Start
- Installation setup
- Alarms
- Logs

Middle screen, one single view

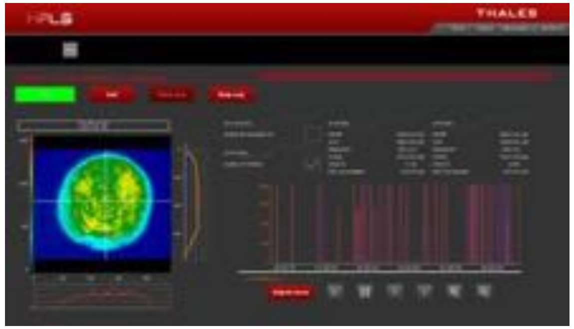
- **Upper part:** global view with energies
- **Lower part:** global view with alarms

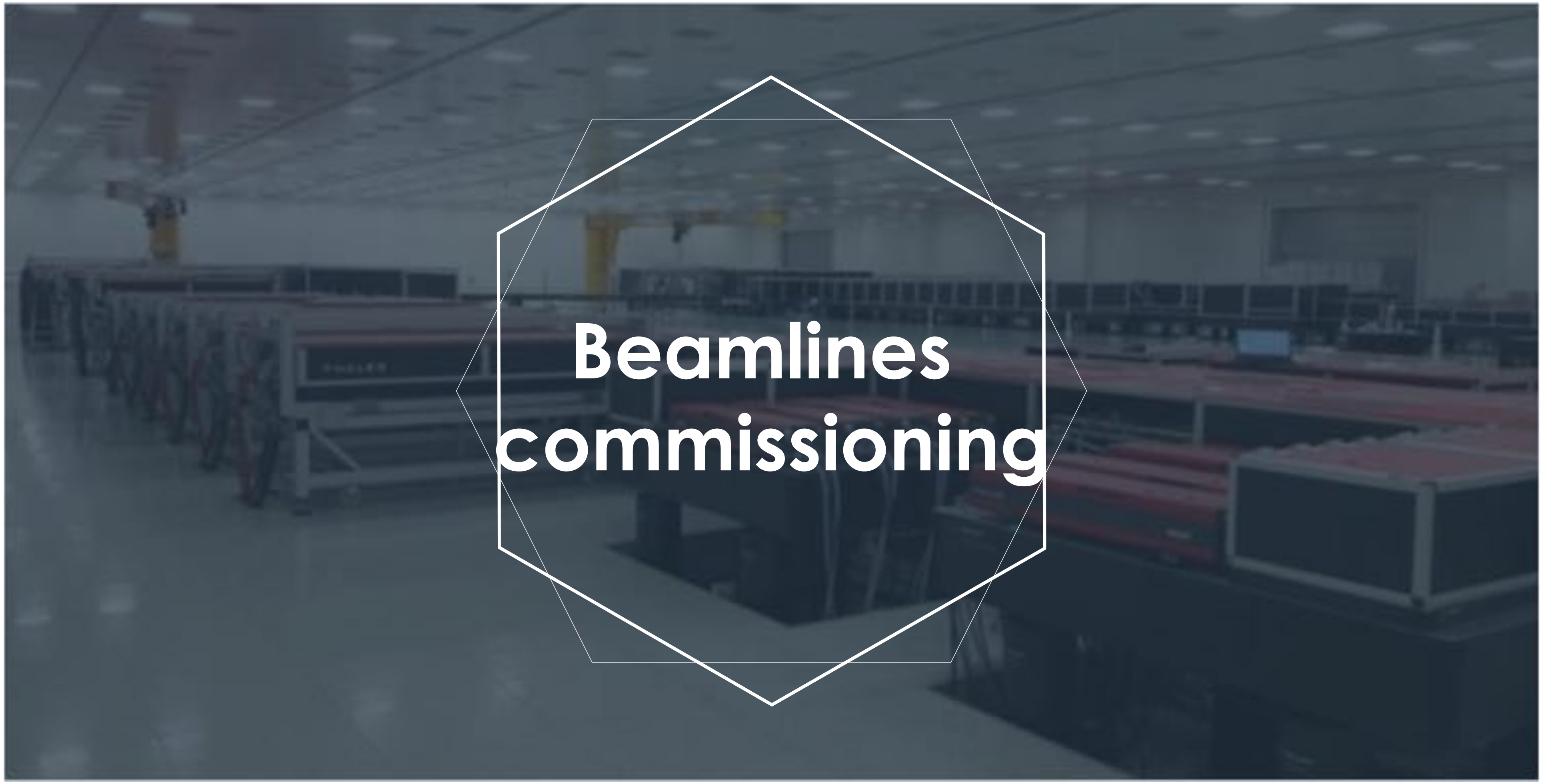
Right screen, available views

- Stage synthetic view
- Diagnostic bench synthetic view
- CSCI detailed view

ELI NP - CONTROL ROOM

Dedicated Supervision software solution developed by Thales to start, operate, monitor and diagnose Thales systems and subsystems



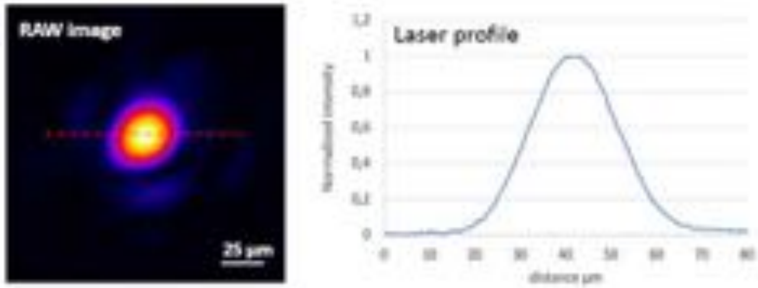


Beamlines commissioning

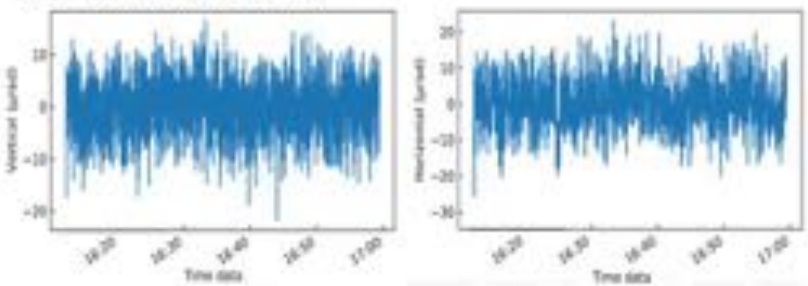
100TW COMMISSIONING

Max Energy:	< 2.5 J
Pulse duration:	~ 25 fs
Central wavelength	~ 810 nm
Beam diameter:	~ 54 mm
Laser pointing fluctuation:	~ ±7 µrad
Parabolic mirror:	1.5 m focal length (F# ~28)
Spot size diameter:	~ 22±2 µm at FWHM
Encircled energy	~ 75% @ $1/e^2$

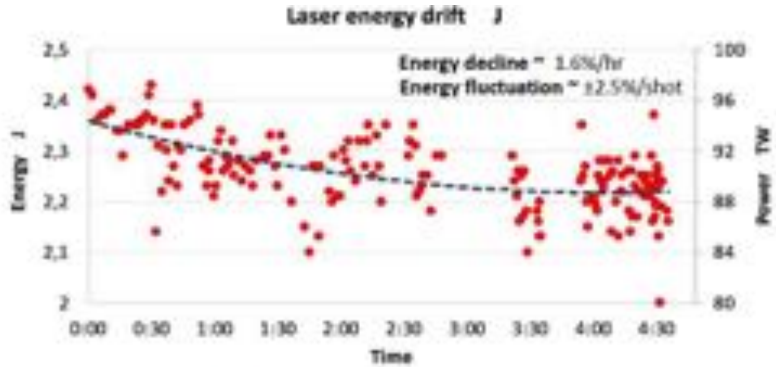
The laser spot is measured at full power, with attenuation wedges



Laser pointing fluctuation



Laser pointing stability representing the laser far-field horizontal and vertical pointing fluctuation as function of time. The r.m.s. of the fluctuations is ±7 µrad.



Stability of the laser pulse energy as function of time. The corresponding power is represented on the right axis.

100TW COMMISSIONING

Experimental setup for LWFA (E4 Area)

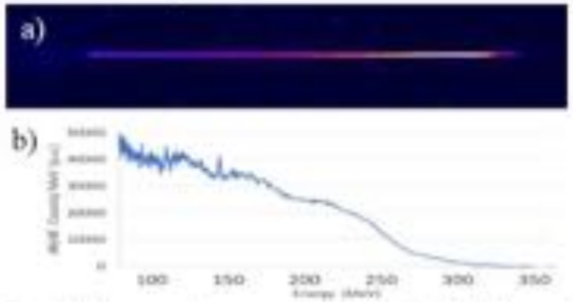
Diagnostics (all at full power shot)

- Electron spectrometer (~0.7 Tesla magnet)
- Laser FarFiled and NearField monitoring
- Optical probing of gas jet
- Top view of gas jet self-emission
- Electron beam pointing/divergence
- Optical spectrometer for laser pulse
- Pulse duration

Target: 2mm dia. gas-jet
Gas: He, He + 2%N
Electron density scan in the range of 10^{18} e/cm^3

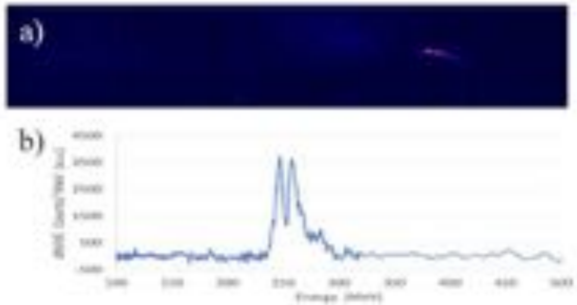
100TW COMMISSIONING

Gas: He + 2% N_2



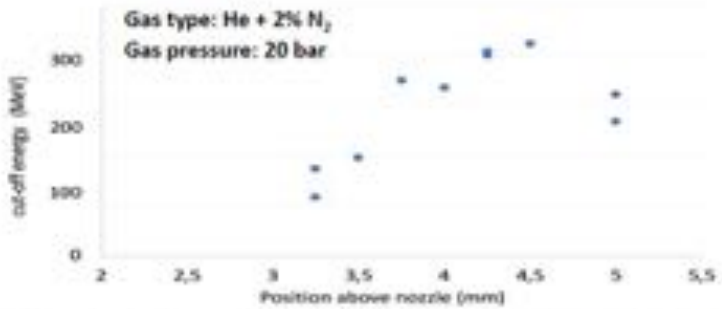
Typical electron continuum spectrum obtained with gas admixture of He and 2% N_2 : a) Lanex image; b) analyzed energy spectrum.

Gas: He



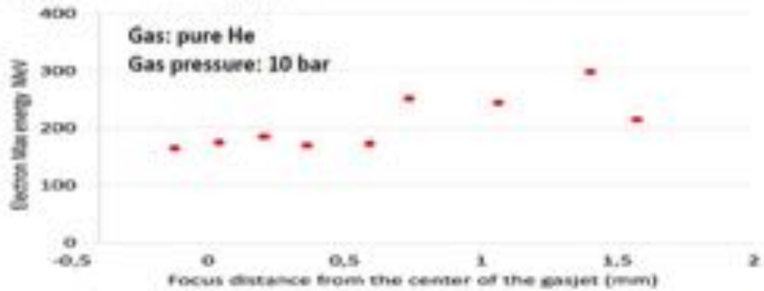
Typical electron peak spectrum obtained with pure He gas: a) Lanex image; b) analyzed energy spectrum.

Electron cut-off energy scan



Vertical scan for several distances from the nozzle taken to map the trend for the maximum electron energy at a fixed gas pressure of 20 bar.

Electron cut-off energy scan



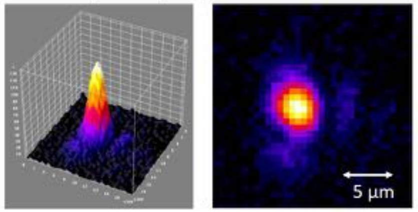
Electron maximum energy versus laser focal position from the center of the gas jet. The scan was done at 2.4 mm above the nozzle (i.e., $n_e \sim 7 \times 10^{18}$ cm^{-3}).

1PW COMMISSIONING

Phase 1

- TNSA proton acceleration, commissioning experiment to assess the HPLS 1 PW performance and test diagnostics, following the ELI-NP ISAB plan
- Improved ion acceleration (TNSA/RPA) in 2 steps, by using a deformable mirror before the focusing mirror and a single plasma mirror, in preparation for the 10 PW experiments.

Best focal spot: 3.5 µm at FWHM



Laser intensity at 1 PW ~ sub-10^{22} W/cm^2

The focal spot was measured at full power using wedges

Target wheel: up to 32 targets

Phase 2

- LWFA commissioning experiment at 1 PW by using a gas cell, step towards the10 PW experiments.

10 PW COMMISSIONING (APPROVED BY ISAB)

nuclear physics

E1 experimental area

- Laser beam: 2 x 10 PW (~250 J, ~25 fs, 810nm, 1/60 Hz)
- OAP mirror: 2 x F/2.7 (laser beam diameter ~ 55cm)
- Laser intensity expected: ~ sub-10^{23} W/cm^2
- Laser-driven ion acceleration / accelerating protons above 200 MeV
- ϒ-flash generation / Showing the fast scaling growth of gamma yield..

E6 experimental area

- Laser beam: 2 x 10 PW (~250 J, ~25 fs, 810nm, 1/60 Hz)
- One short, one long focal / OAP mirror: ~ F/52 for 10 PW and ~ F/150 for 1 PW
- Laser intensity expected : up tp a few10^{20} W/cm^2
- LWFA / accelerating electrons in the GeV energy range


Thank You !

E4 Experiment: laser characteristics

100 TW Laser nominal parameters

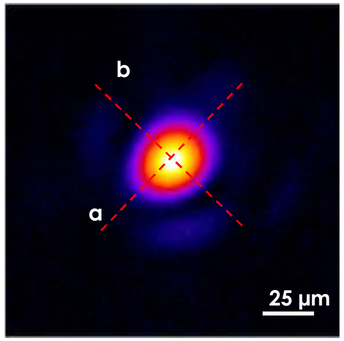
Max Energy: ~ 2.5 J (max, after compressor)
Pulse duration: ~ 25 fs
Beam diameter: ~ 56 mm
Laser pointing fluctuation: ~ 30 µrad

100 TW Laser experimental parameters

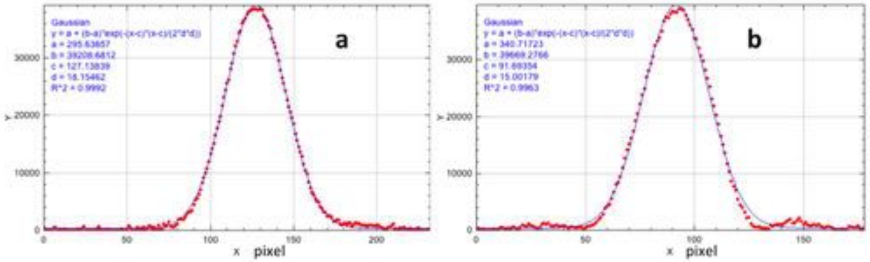
Max Energy: ~ 1.9 J (max on gas target)
Pulse duration: ~ 25 fs
Parabolic mirror: 1500 mm focal length (F# ~28)
Spot size diameter: ~ 18 µm at FWHM
Encircled energy : ~ 70 - 75% @ 1/e^2

Laser focal spot

The laser spot is measured at full power

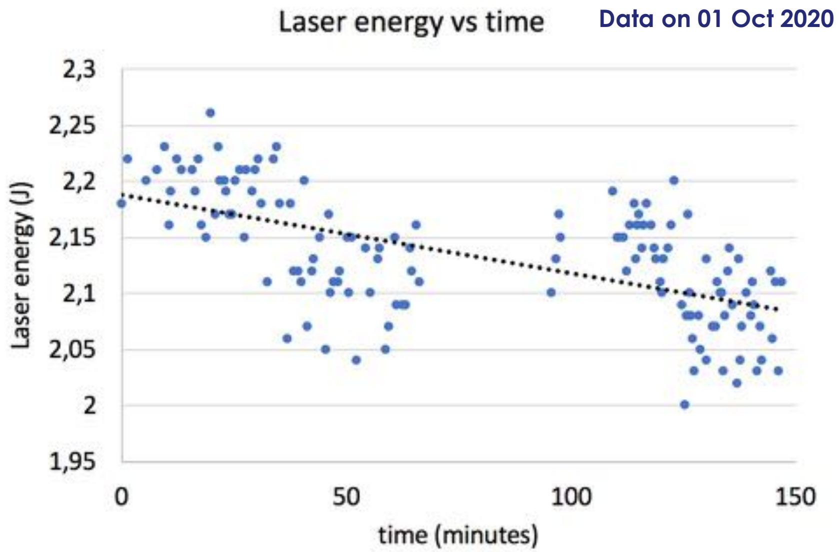


Laser focal spot profiles

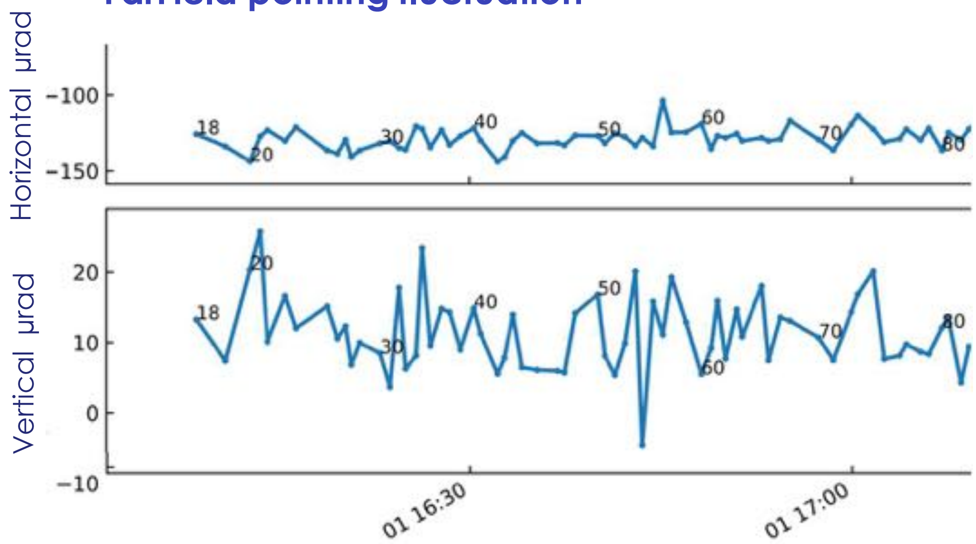


E4 Experiment: laser statistic

100 TW Laser energy variation



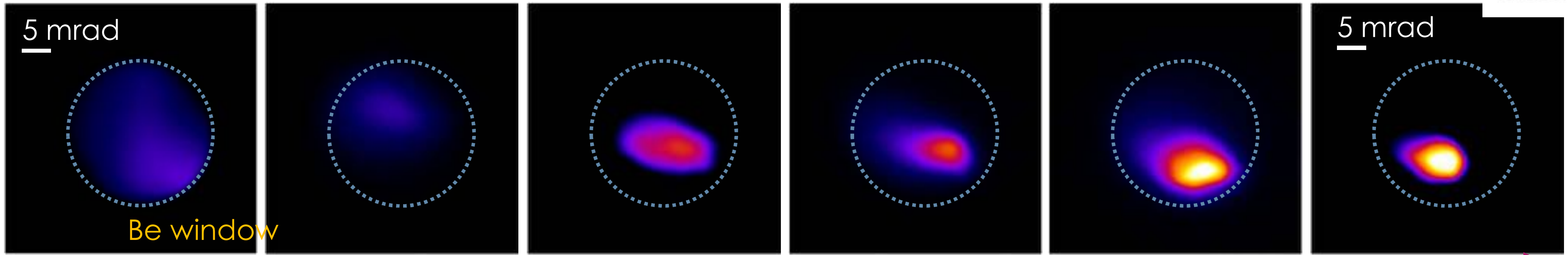
FarField pointing fluctuation Data on 01 Oct 2020



- Laser mean energy ~ 2.15 J
- Energy shot-to-shot fluctuation ~ 1.7 %
- Energy drift during the day ~ -42 mJ/hr

Experimental data for He + 2% N

On-axis diagnostics: electron beam profile

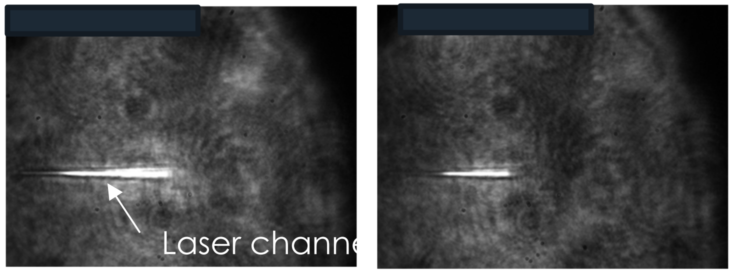


Electron beam profile improvement with further optimization

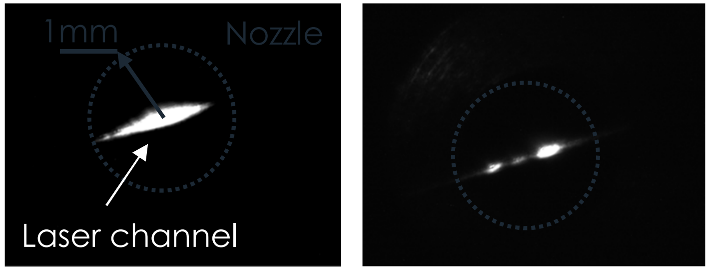
Electron beam divergence ~ 5 mrad, and pointing ~ ±5 mrad

Optical probe

Shadowgraphy



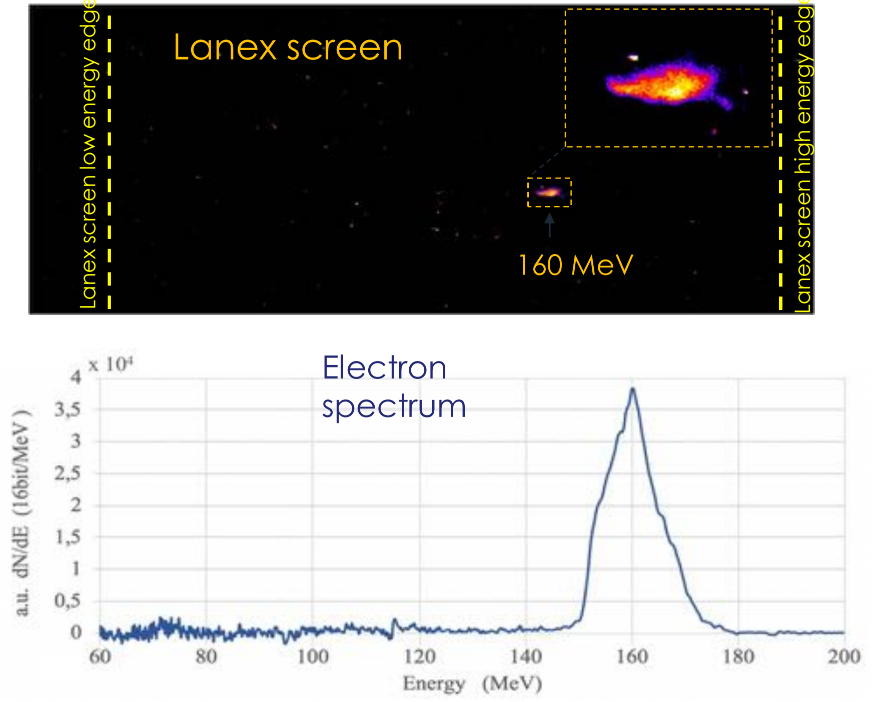
Top view: scattered radiation



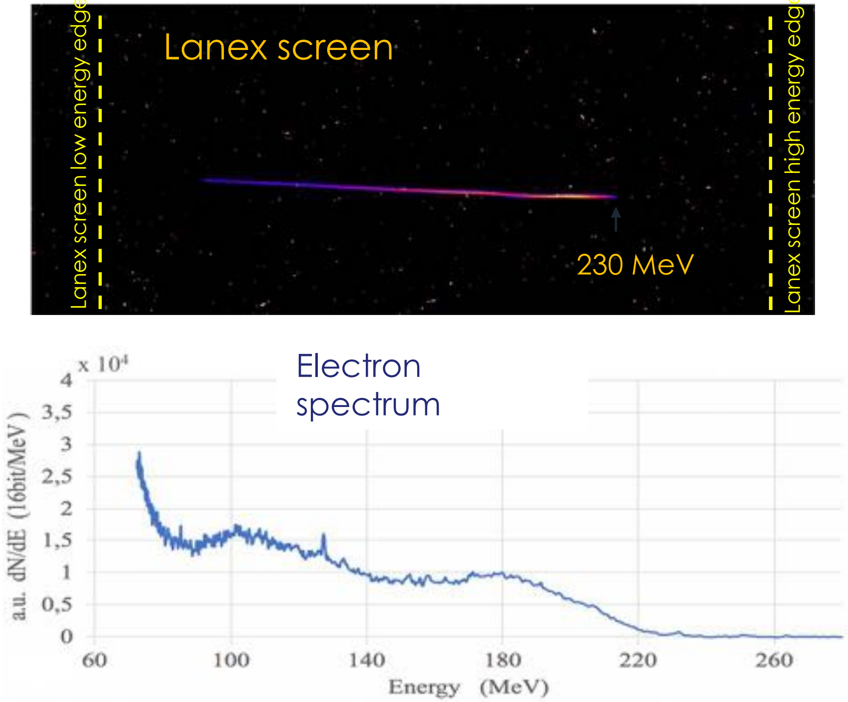
Experimental data for He and He + 2%N

Typical electron spectra obtained with gas density of ~ 3.5 x 10^{18} atom/cm^3

Typical quasi-monoenergetic spectrum with pure **He** gas



Typical broadband spectrum with **He + 2% N_2** gas



ELI NP - ELI A EUROPEAN PROJECT

nuclear physics

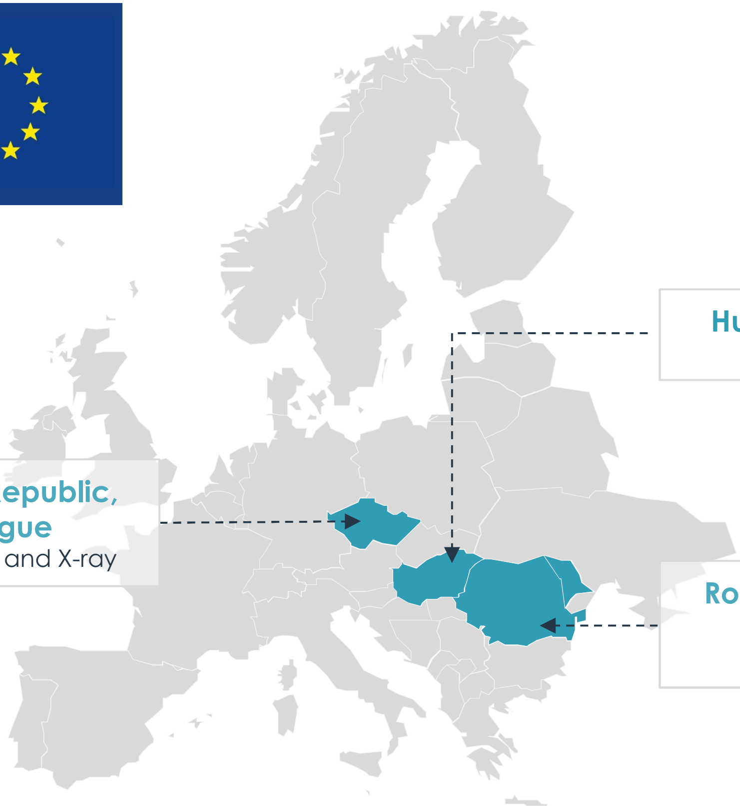
ELI – Extreme Light Infrastructure

850 millions euros

from ERDF (European Regional Development Fund) raised to develop four ELI laboratories

GERARD MOUROU & DONA STRICKLAND

Inventor of the CPA with Dona Strickland and both Winners of the 2018 Nobel Prize

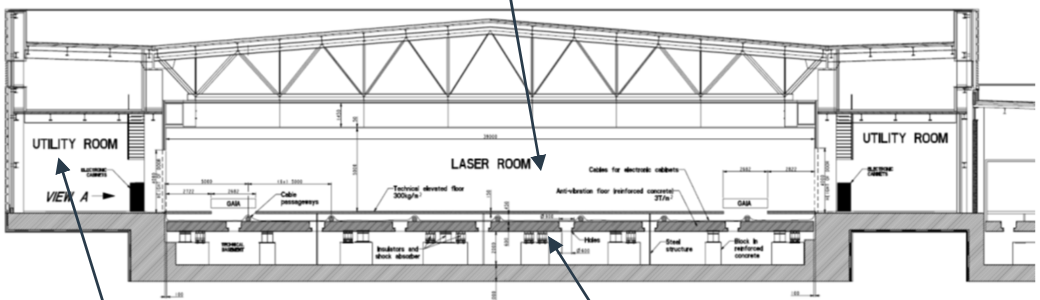


Czech Republic, Prague
Particules and X-ray

Hungaria, Szeged
Attosecond

Romania, Bucarest Magurele
Photonuclear

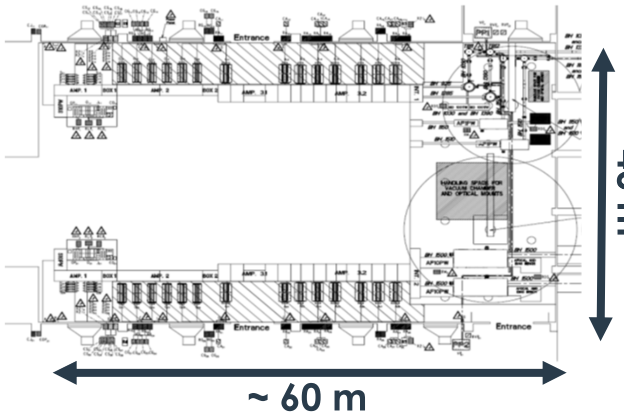
ELI NP - LASER ROOM



eli nuclear physics

Laser room 2400 m²

- Clean room: ISO7
- Temperature regulation: 22°C +/- 0.5°C
- Humidity regulation: [35%-50%]
- Floor stability: VC-E (3 µm/s) according to the ASHRAE criteria
- Flatness default lower than 9 mm



ELI NP - HPLS ARCHITECTURE : TI:SA LASER, DOUBLE CPA CONFIGURATION

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