EUROPEAN UNION

Structural Instruments 2014-2020

Competitiveness Operational Programme (COP)

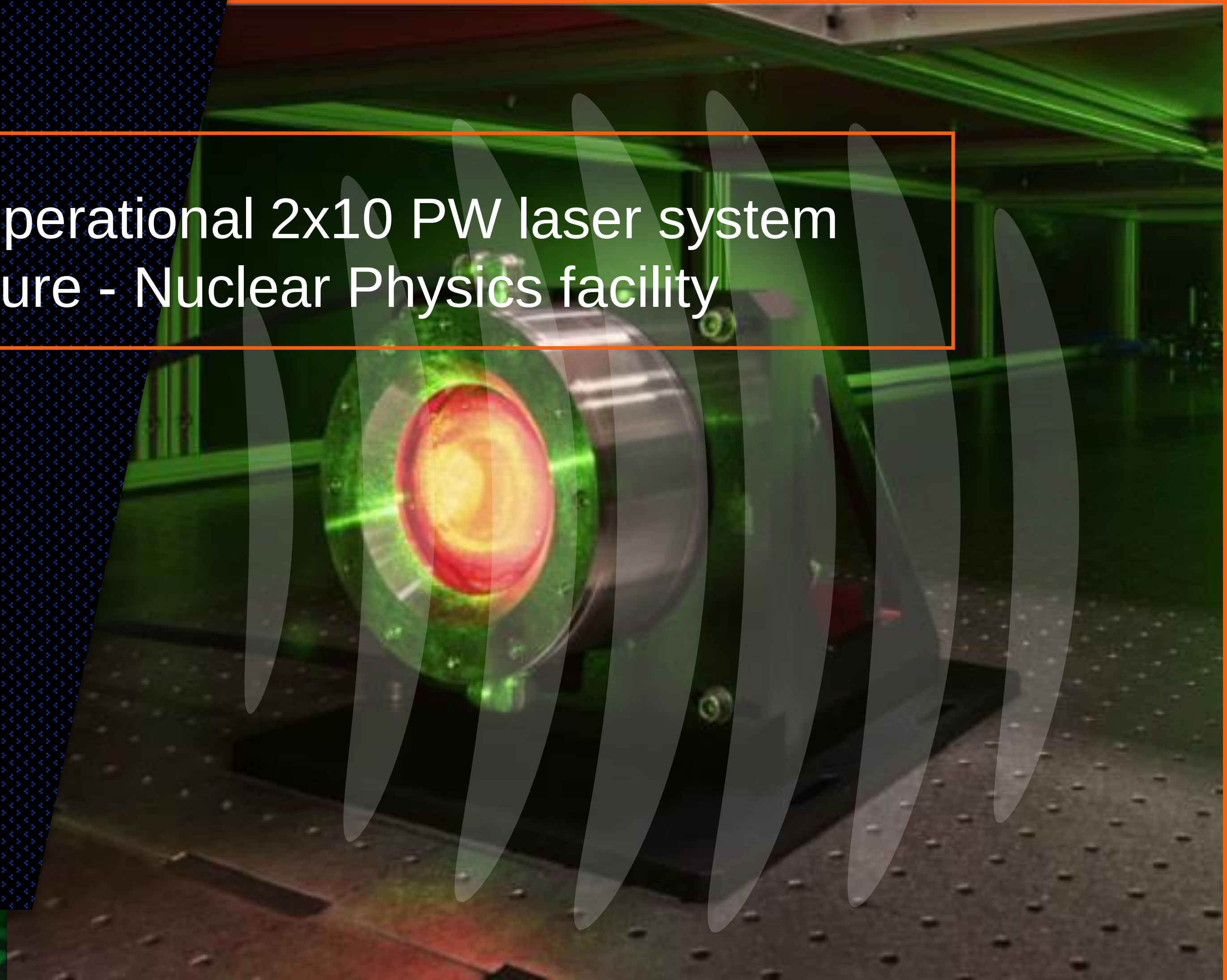
Extreme Light Infrastructure - Nuclear Physics (ELI-NP) – Phase II

Towards experiments with the operational 2x10 PW laser system at the Extreme Light Infrastructure - Nuclear Physics facility

Daniel URSESCU

3.3.2021

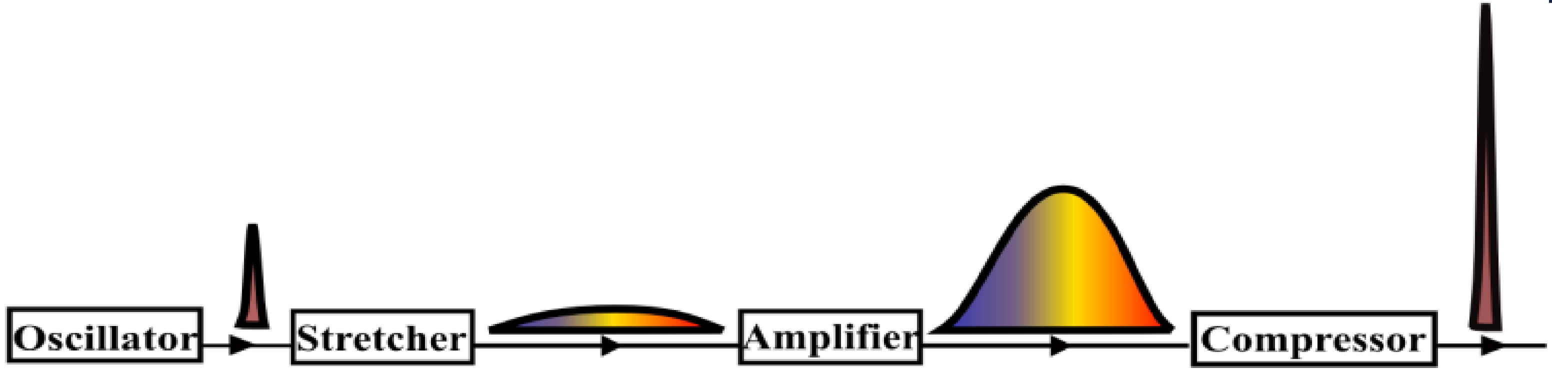
RAL Particle Physics Seminar, via Zoom

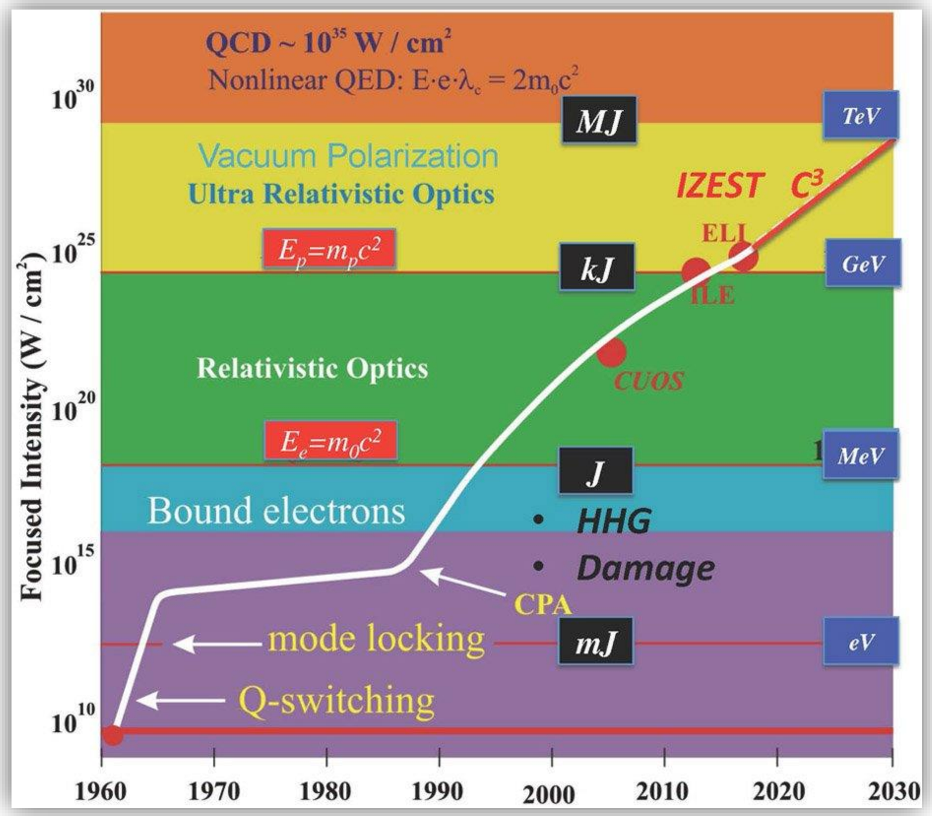


eli nuclear physics

IFIN-HH

Nobel 2018: Chirped Pulse Amplification





GERARD MOUROU
& DONA STRICKLAND
(Nobel 2018)

Towards higher intensity: ideal Gaussian pulses

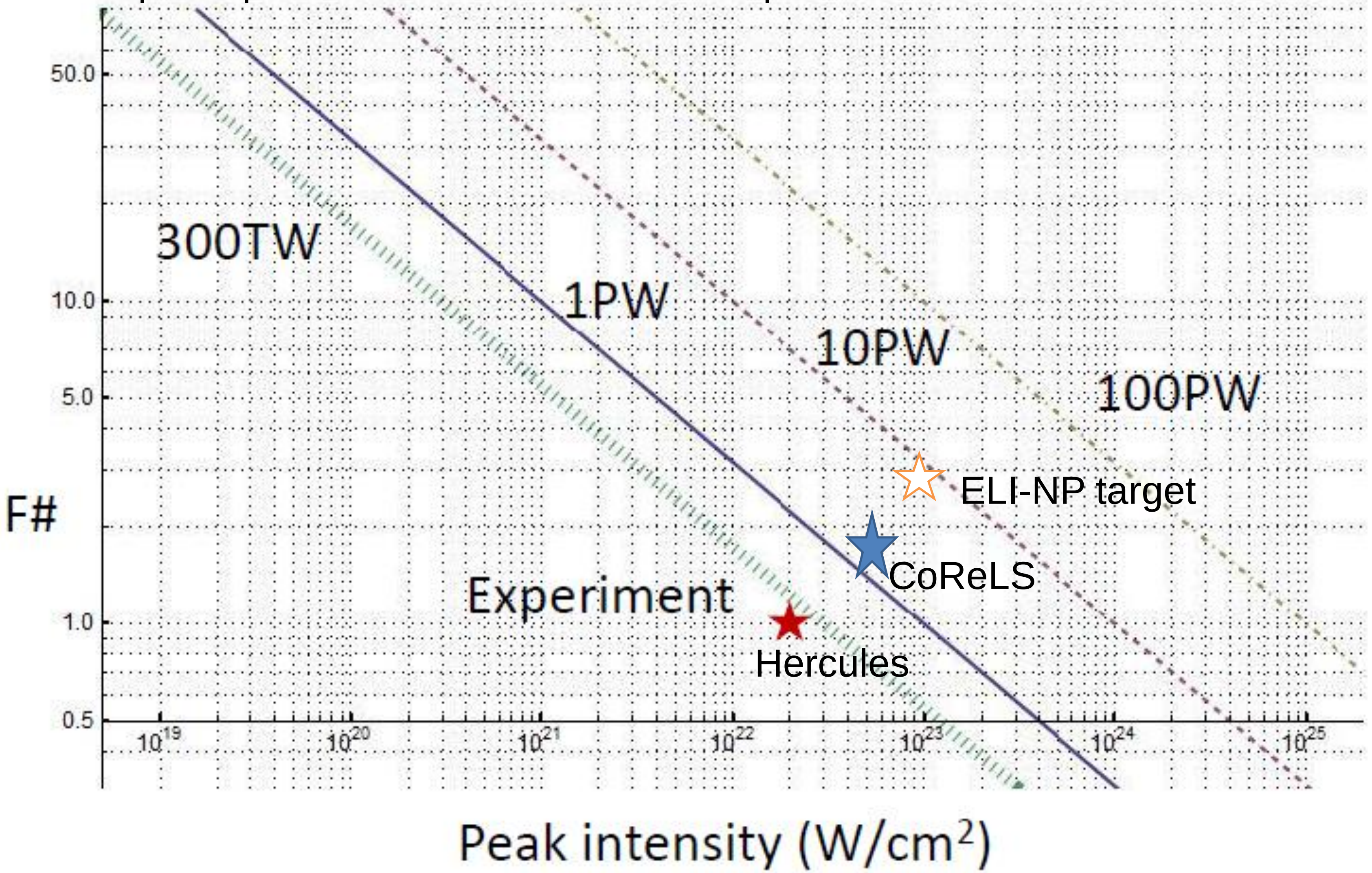
Peak intensity:

$$I = 2P/\pi w_0^2$$

Waist of the pulse:

$$w_0 = f\#\lambda$$

Laser pulse parameters in ideal vs. real experiments



Ionel L., Ursescu D., "*Spatial extension of the electromagnetic field from tightly focused ultra-short laser pulses***"** Laser and Particle Beams, 2014

Contents

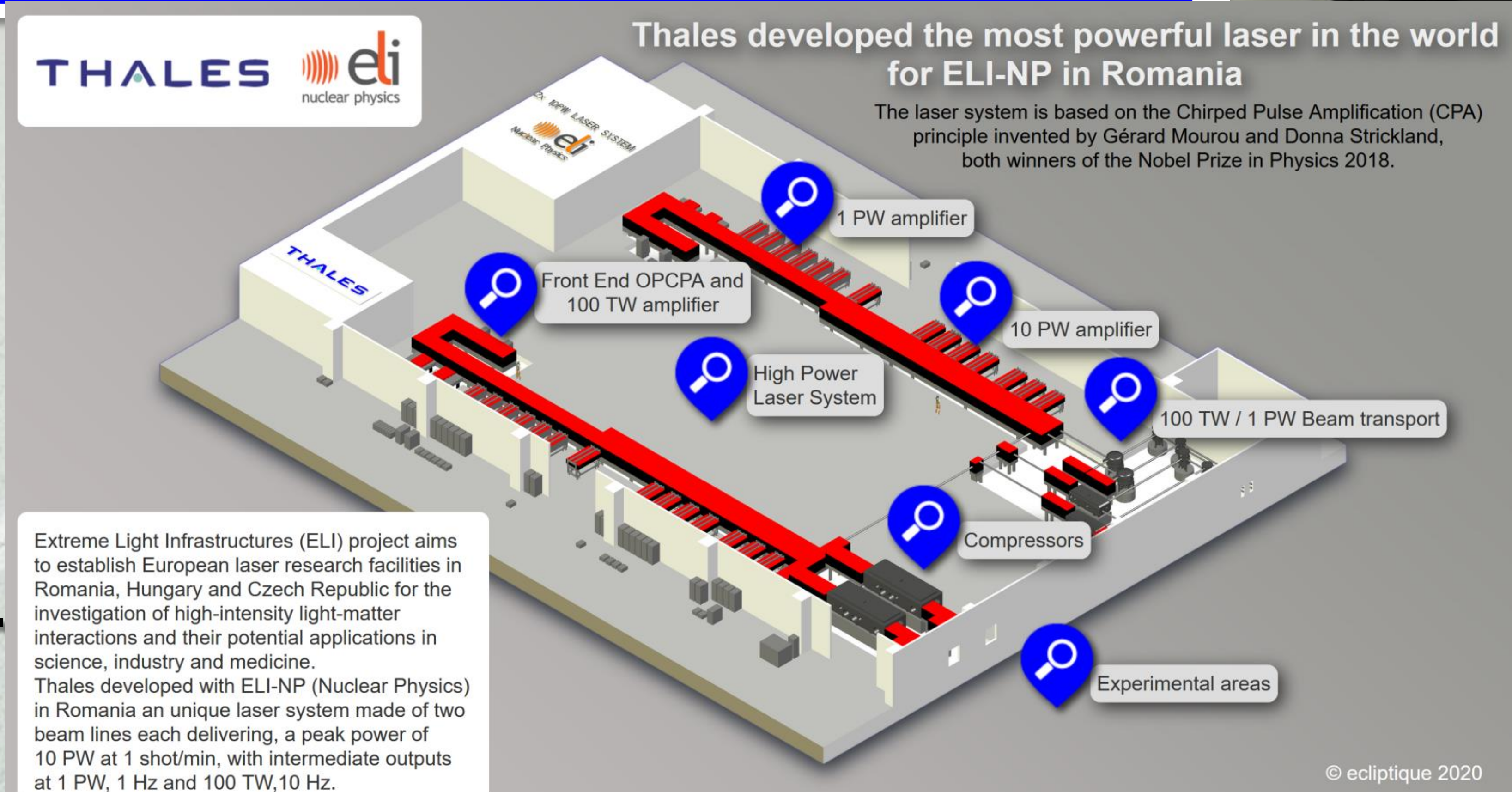
- Architecture of the 2x10PW laser system
- Laser pulse characterization at HPLS
- Experimental areas for laser experiments
- Beamtime request – further technical aspects

Contents

- **Architecture of the 2x10PW laser system**
- Laser pulse characterization at HPLS
- Experimental areas for laser experiments
- Beamtime request – further technical aspects

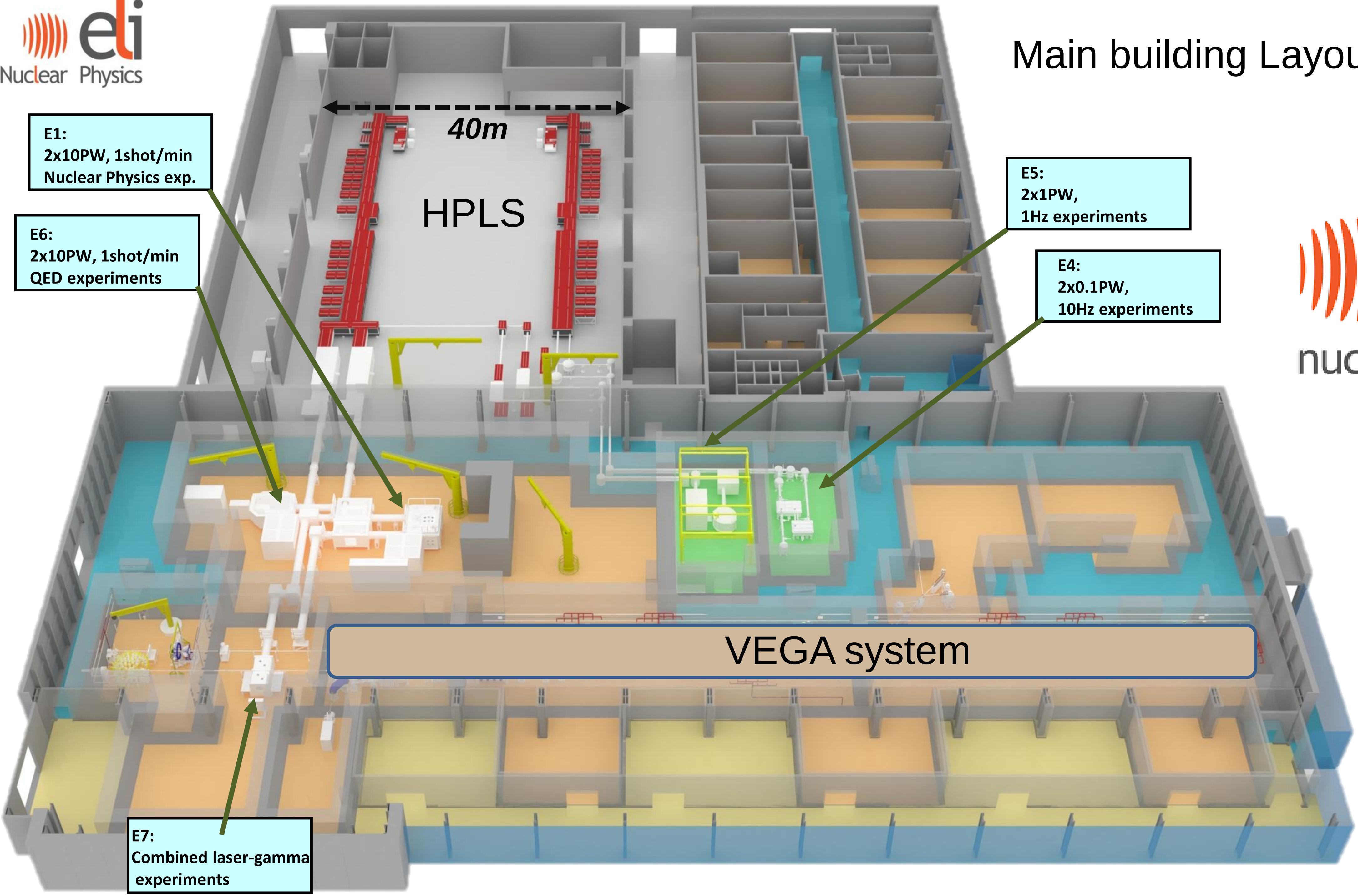
Virtual tour of the ELI-NP laser system

https://www.eli-np.ro/thales_eli-np.php

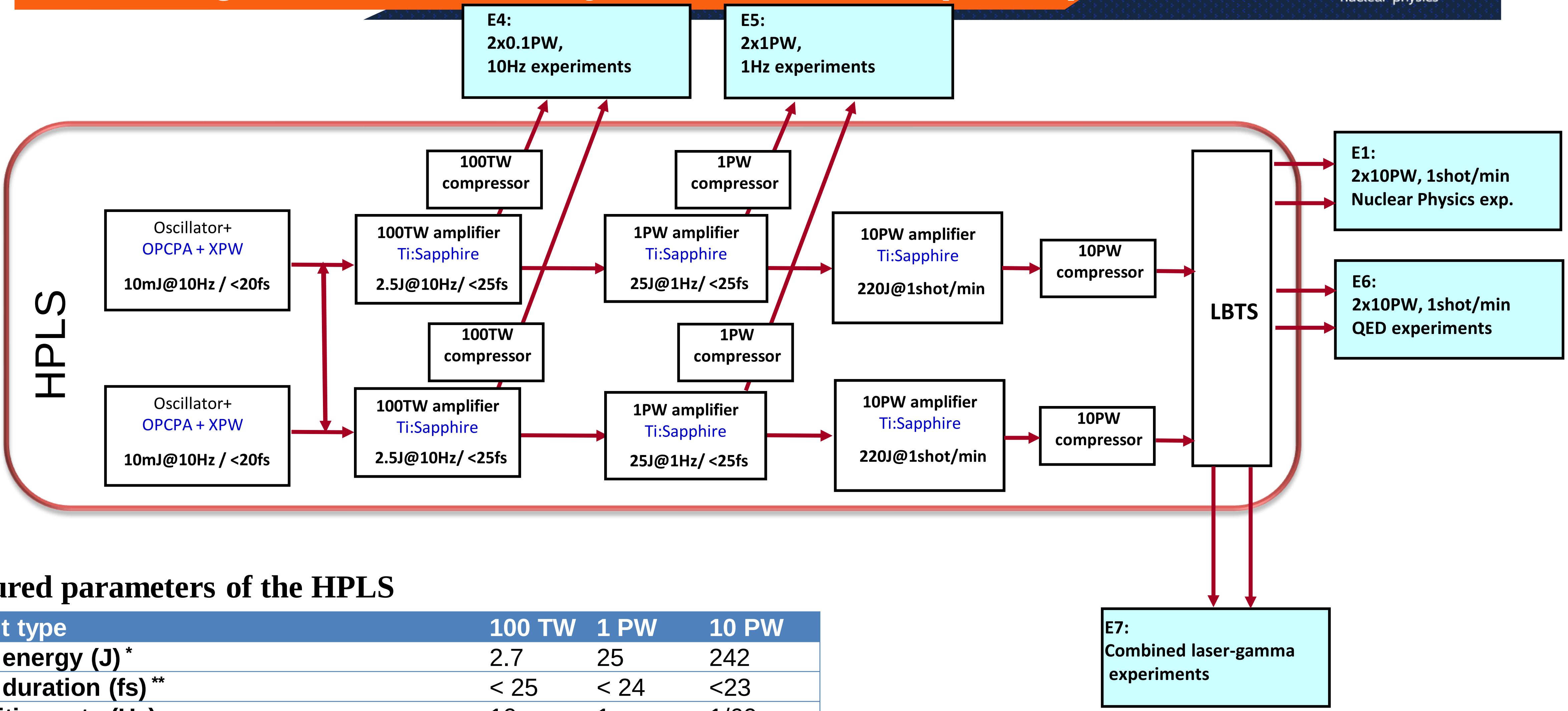


High power laser

Main building Layout



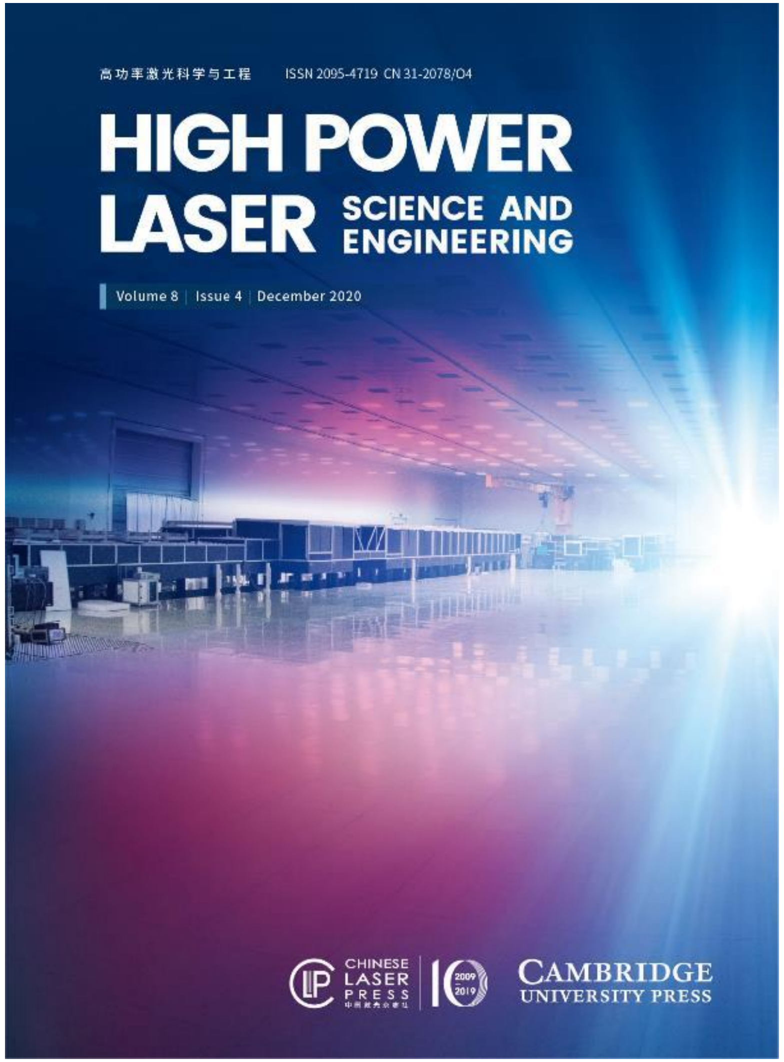
The High Power Laser System at ELI-NP (HPLS)



Measured parameters of the HPLS

Output type	100 TW	1 PW	10 PW
Pulse energy (J) *	2.7	25	242
Pulse duration (fs) **	< 25	< 24	<23
Repetition rate (Hz)	10	1	1/60
Calculated Strehl ratio from measured wavefront	> 0.9	> 0.9	> 0.9
Pointing stability (µrad RMS)	< 3.4	< 1.78	< 1.27
Pulse energy stability (rms)	< 2.6 %	< 1.8 %	< 1.8 %

*Calculated considering the transmission efficiency of temporal compressors
**Measured with attenuated input energy in the compressors
***Front End demonstrated ps contrast - In the range of 10^{13}:1



High Power Laser Science and Engineering, (2020), Vol. 8, e43, 15 pages.
doi:10.1017/hpl.2020.41

HIGH POWER LASER SCIENCE AND ENGINEERING

RESEARCH ARTICLE

High-energy hybrid femtosecond laser system demonstrating 2 × 10 PW capability

François Lureau[1], Guillaume Matras[1], Olivier Chalus[1], Christophe Derycke[1], Thomas Morbieu[1], Christophe Radier[1], Olivier Casagrande[1], Sébastien Laux[1], Sandrine Ricaud[1], Gilles Rey[1], Alain Pellegrina[1], Caroline Richard[1], Laurent Boudjemaa[1], Christophe Simon-Boisson[1], Andrei Baleanu[2], Romeo Banici[2], Andrei Gradinariu[2], Constantin Caldararu[2], Bertrand De Boisdeffre[3], Petru Ghenuche[3], Andrei Naziru[3,4], Georgios Kolliopoulos[3], Liviu Neagu[3], Razvan Dabu[3], Ioan Dancus[3], and Daniel Ursescu[3]

[1]*Thales LAS France, 78990 Élancourt, France*

[2]*Thales Systems Romania, 060071 București, Romania*

[3]*Extreme Light Infrastructure – Nuclear Physics, 'Horia Hulubei' National Institute for Physics and Nuclear Engineering, 077125 Bucharest Magurele, Romania*

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(Received 1 August 2020; revised 22 October 2020; accepted 26 October 2020)

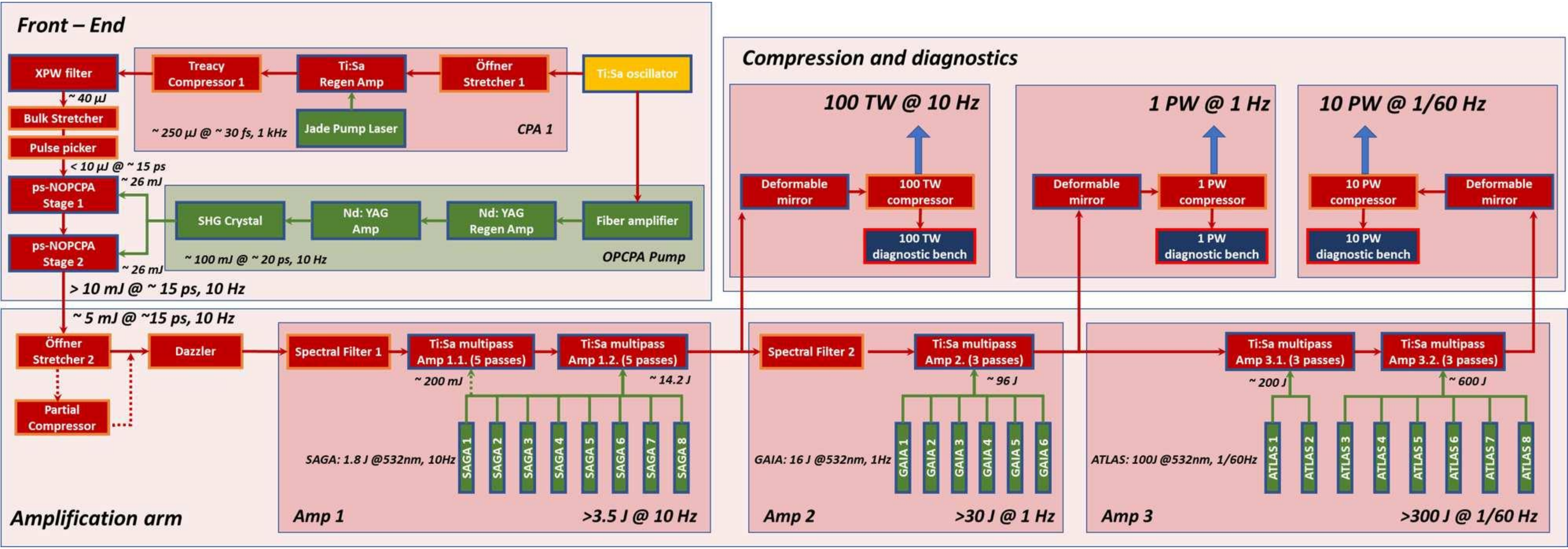
Abstract

We report on a two-arm hybrid high-power laser system (HPLS) able to deliver 2 × 10 PW femtosecond pulses, developed at the Bucharest-Magurele Extreme Light Infrastructure Nuclear Physics (ELI-NP) Facility. A hybrid front-end (FE) based on a Ti:sapphire chirped pulse amplifier and a picosecond optical parametric chirped pulse amplifier based on beta barium borate (BBO) crystals, with a cross-polarized wave (XPW) filter in between, has been developed. It delivers 10 mJ laser pulses, at 10 Hz repetition rate, with more than 70 nm spectral bandwidth and high-intensity contrast, in the range of 10^{13}:1. The high-energy Ti:sapphire amplifier stages of both arms were seeded from this common FE. The final high-energy amplifier, equipped with a 200 mm diameter Ti:sapphire crystal, has been pumped by six 100 J nanosecond frequency doubled Nd:glass lasers, at 1 pulse/min repetition rate. More than 300 J output pulse energy has been obtained by pumping with only 80% of the whole 600 J available pump energy. The compressor has a transmission efficiency of 74% and an output pulse duration of 22.7 fs was measured, thus demonstrating that the dual-arm HPLS has the capacity to generate 10 PW peak power femtosecond pulses. The reported results represent the cornerstone of the ELI-NP 2 × 10 PW femtosecond laser facility, devoted to fundamental and applied nuclear physics research.

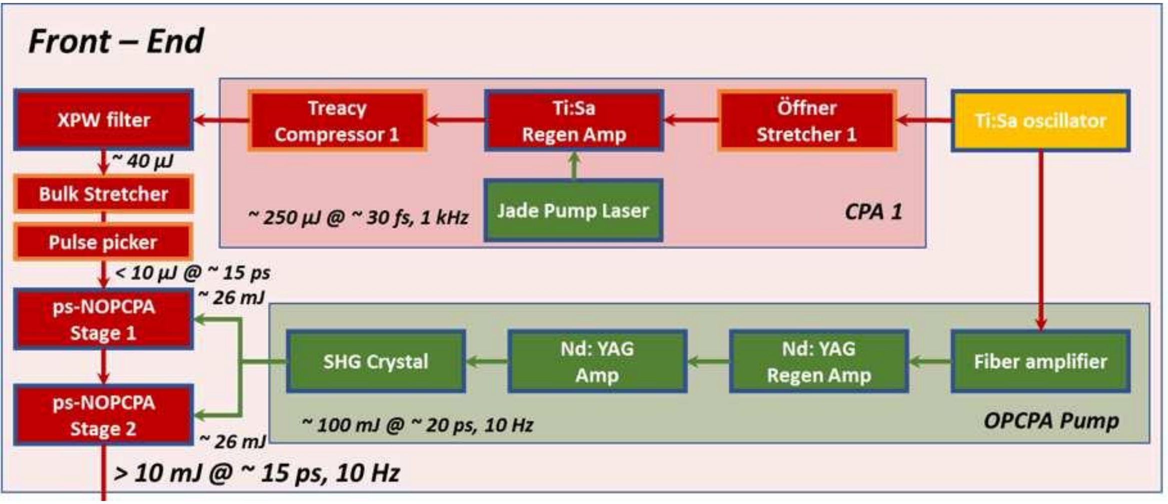
Keywords: lasers; high-power laser pulses; ultra-short laser pulses

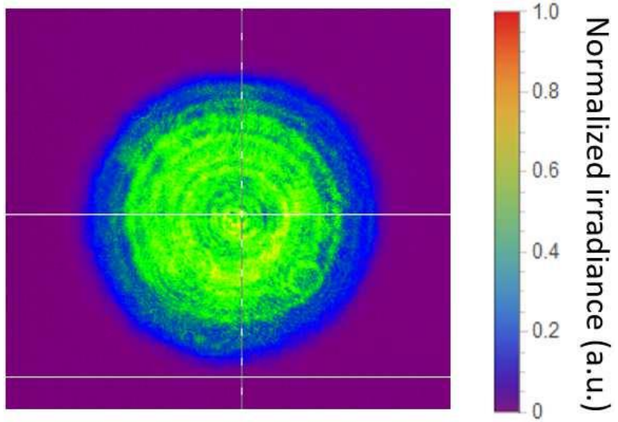
Open access Milestone article on HPLS

HPLS layout

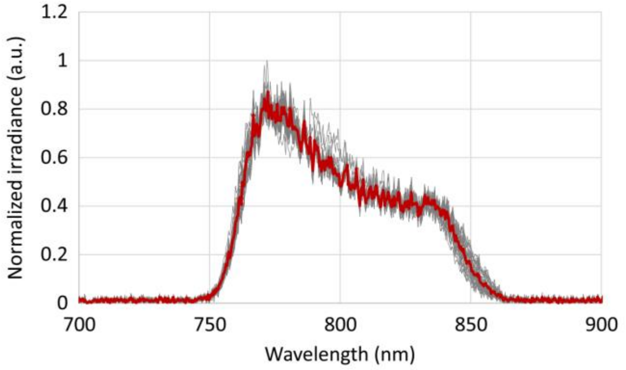

Front – End
XPW filter
~ 40 µJ
Bulk Stretcher
Pulse picker
< 10 µJ @ ~ 15 ps
~ 26 mJ
ps-NOPCPA Stage 1
ps-NOPCPA Stage 2
~ 26 mJ
Treacy Compressor 1
Ti:Sa Regen Amp
Öffner Stretcher 1
Ti:Sa oscillator
Jade Pump Laser
~ 250 µJ @ ~ 30 fs, 1 kHz
CPA 1
SHG Crystal
Nd: YAG Amp
Nd: YAG Regen Amp
Fiber amplifier
~ 100 mJ @ ~ 20 ps, 10 Hz
OPCPA Pump
> 10 mJ @ ~ 15 ps, 10 Hz
Compression and diagnostics
100 TW @ 10 Hz
Deformable mirror
100 TW compressor
100 TW diagnostic bench
1 PW @ 1 Hz
Deformable mirror
1 PW compressor
1 PW diagnostic bench
10 PW @ 1/60 Hz
10 PW compressor
Deformable mirror
10 PW diagnostic bench
~ 5 mJ @ ~15 ps, 10 Hz
Öffner Stretcher 2
Dazzler
Partial Compressor
Spectral Filter 1
Ti:Sa multipass Amp 1.1. (5 passes)
Ti:Sa multipass Amp 1.2. (5 passes)
~ 200 mJ
~ 14.2 J
SAGA: 1.8 J @532nm, 10Hz
SAGA 1
SAGA 2
SAGA 3
SAGA 4
SAGA 5
SAGA 6
SAGA 7
SAGA 8
Amp 1
>3.5 J @ 10 Hz
Spectral Filter 2
Ti:Sa multipass Amp 2. (3 passes)
~ 96 J
GAIA: 16 J @532nm, 1Hz
GAIA 1
GAIA 2
GAIA 3
GAIA 4
GAIA 5
GAIA 6
Amp 2
>30 J @ 1 Hz
Ti:Sa multipass Amp 3.1. (3 passes)
Ti:Sa multipass Amp 3.2. (3 passes)
~ 200 J
~ 600 J
ATLAS: 100J @532nm, 1/60Hz
ATLAS 1
ATLAS 2
ATLAS 3
ATLAS 4
ATLAS 5
ATLAS 6
ATLAS 7
ATLAS 8
Amp 3
>300 J @ 1/60 Hz
Amplification arm

HPLS front-end

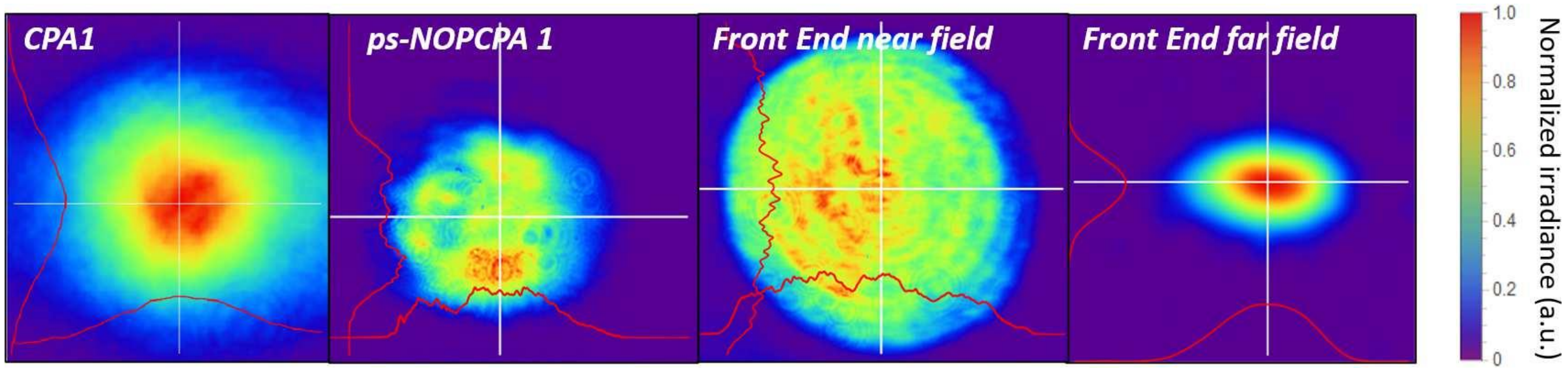


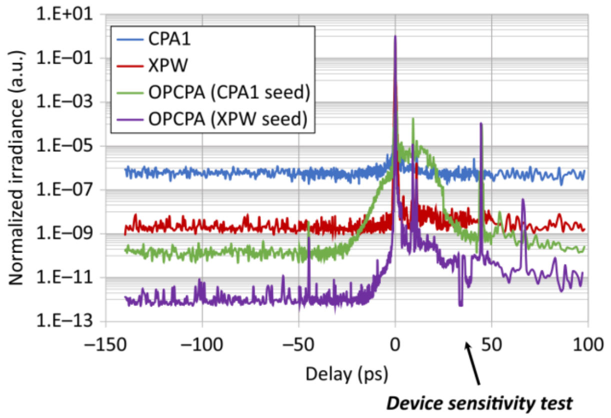


Near-field beam intensity profile of the 532 nm picosecond pump laser for OPCPA

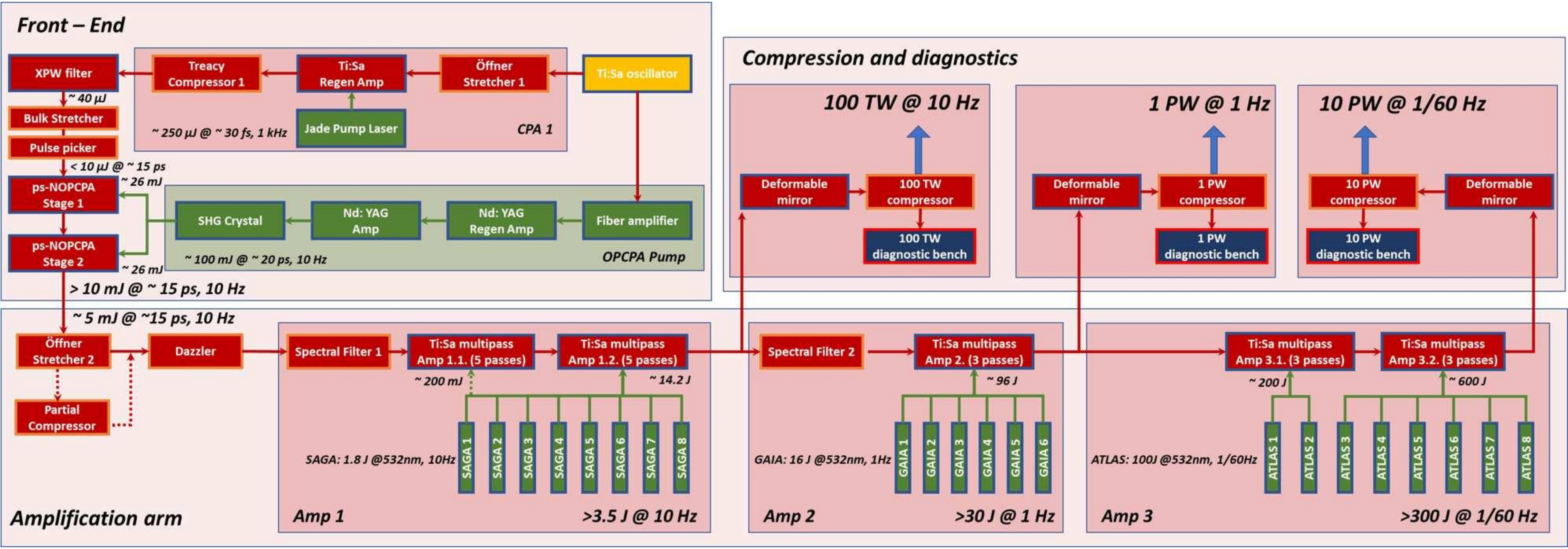


Stability of the OPCPA spectrum over 7 h continuous operation. The red curve is the average (data acquired each 10 min)





HPLS layout



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Ti:Sa oscillator
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Bulk Stretcher
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CPA 1
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SHG Crystal
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Nd: YAG Regen Amp
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ps-NOPCPA Stage 2
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Amp 3
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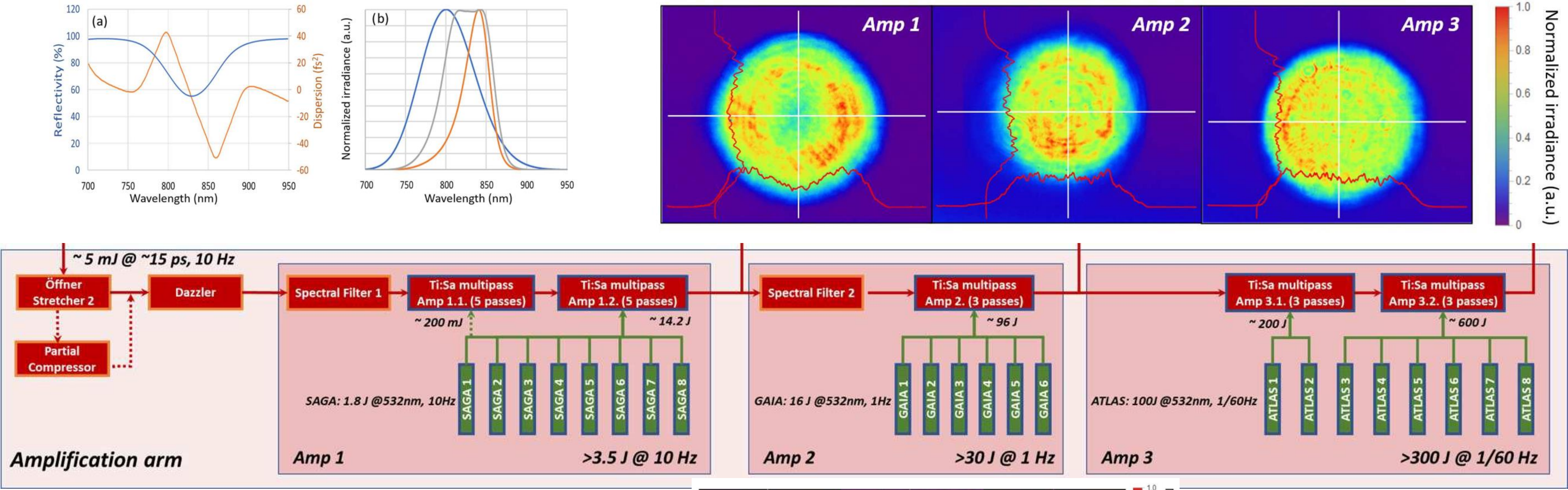
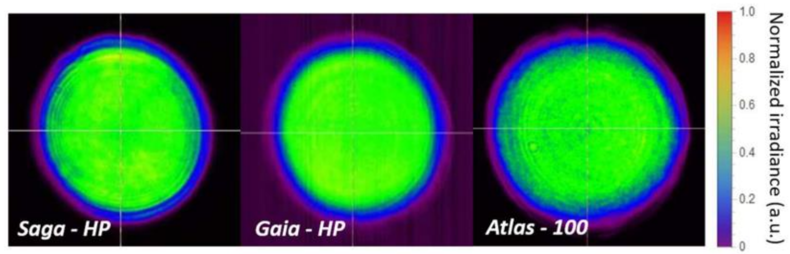
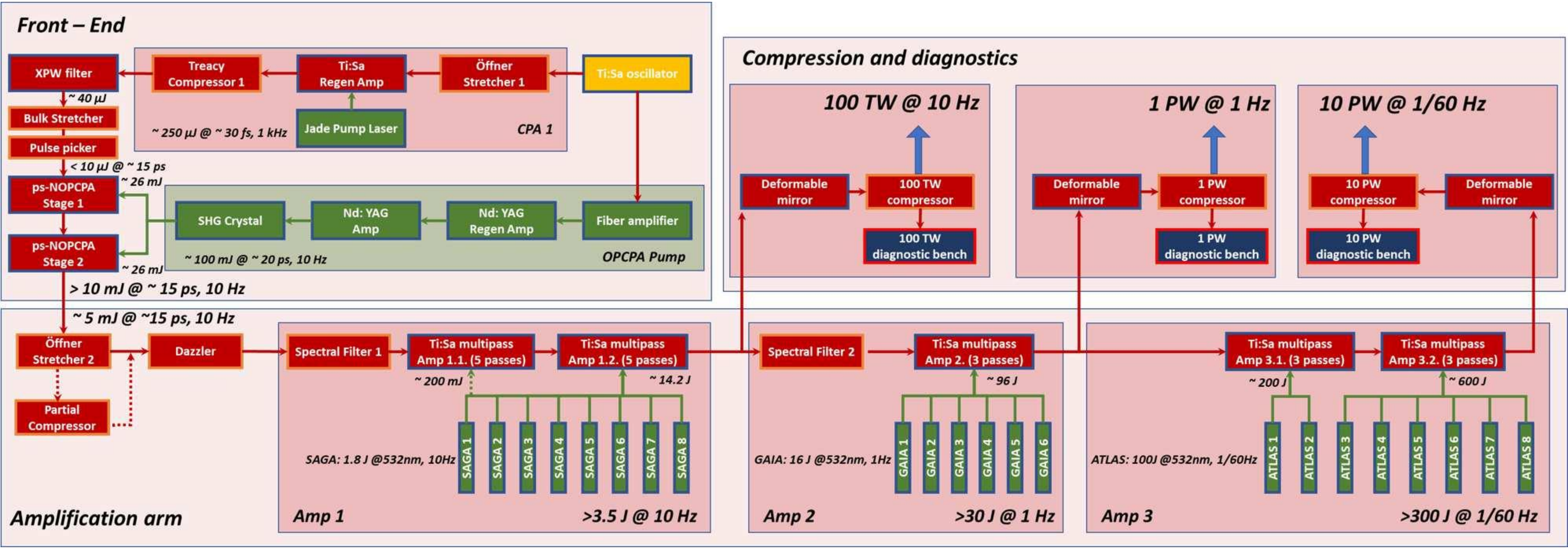
HPLS amplifiers





HPLS layout



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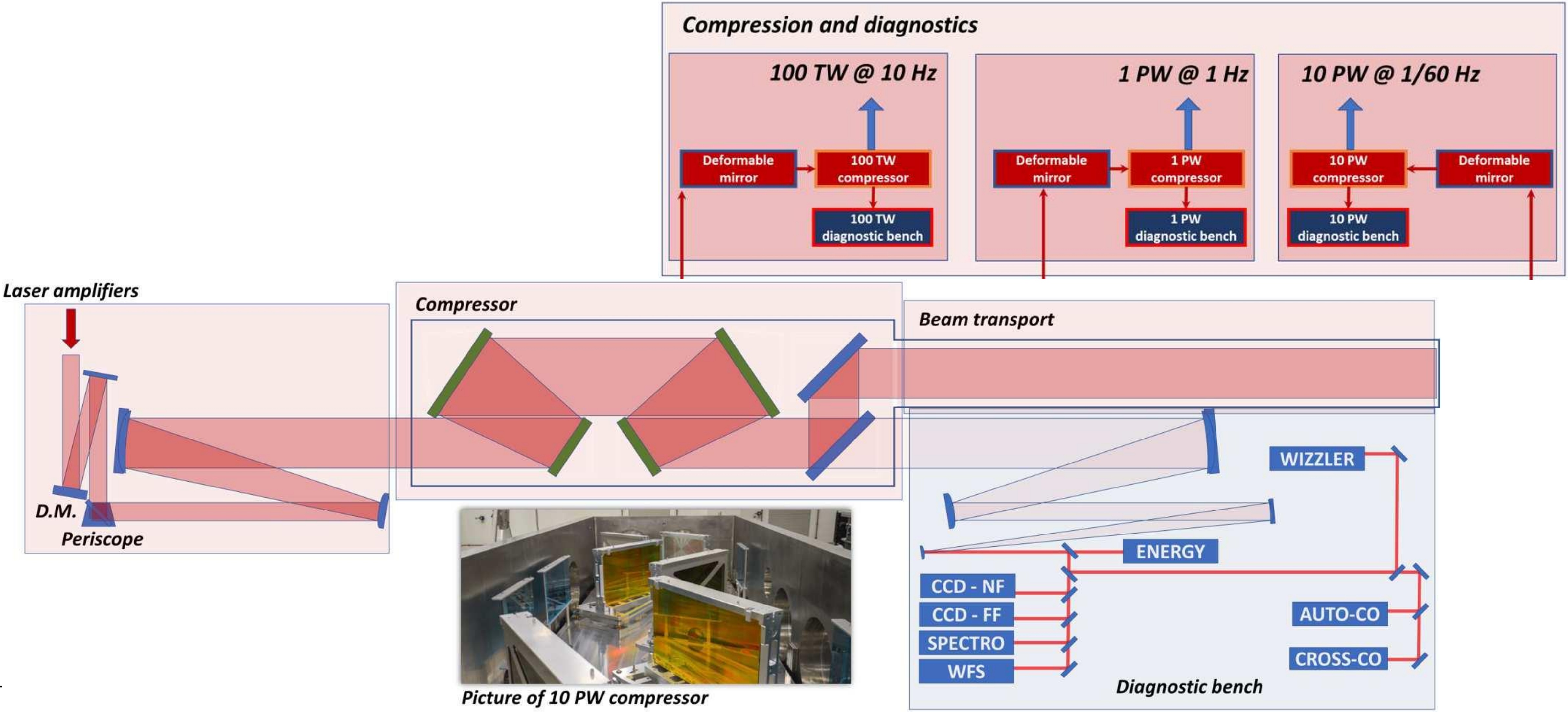
ATLAS 2
ATLAS 3
ATLAS 4
ATLAS 5
ATLAS 6
ATLAS 7
ATLAS 8
Amp 3
>300 J @ 1/60 Hz
Amplification arm

HPLS compressors and diagnostics



Picture of 10 PW compressor

-

Contents

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- Architecture of the 2x10PW laser system
- **Laser pulse characterization at HPLS**
- Experimental areas for laser experiments
- Beamtime request – further technical aspects

Compressor metrology

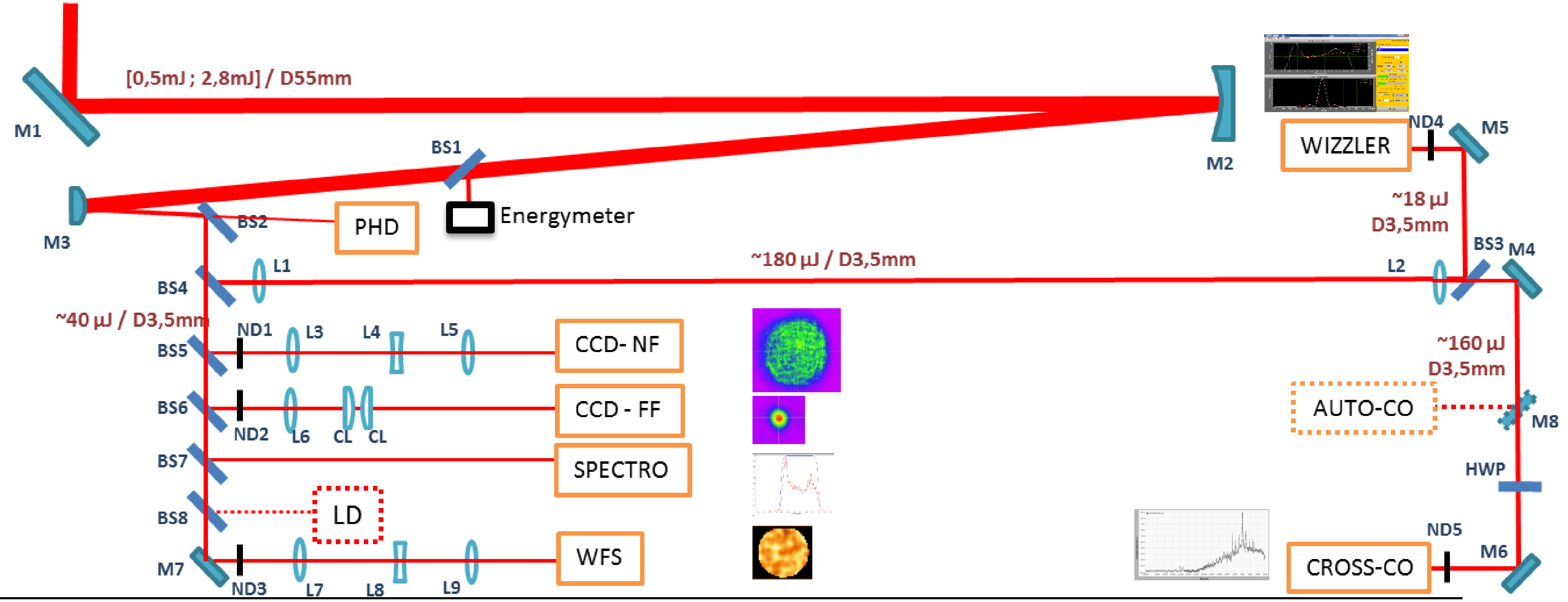
Beam transport

Experiment metrology

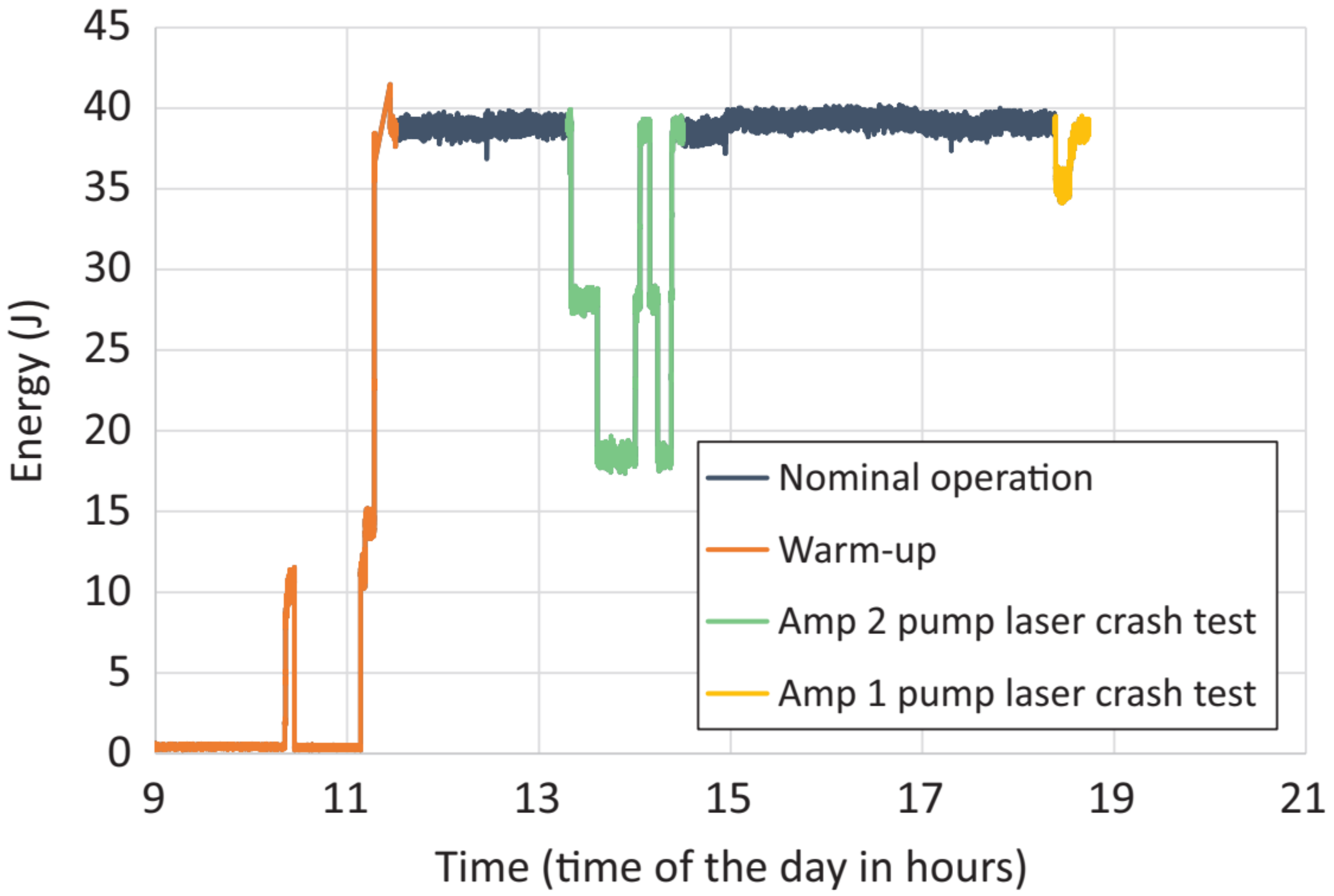
Diagnostics bench

- Parameters
  - Pulse energy using energy-meter
  - Spectral measurement using spectrometer
  - Pulse duration using Phase retrieval device
  - Near and far-field Beam profile using camera
  - Strehl ratio and pointing stability using wavefront sensor
  - Picosecond contrast using cross-correlator

$$\frac{E}{t\,S} = I$$



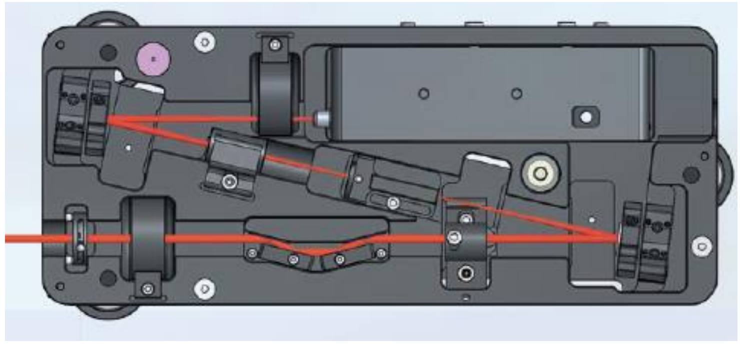
Energy stability for Amplifier 2

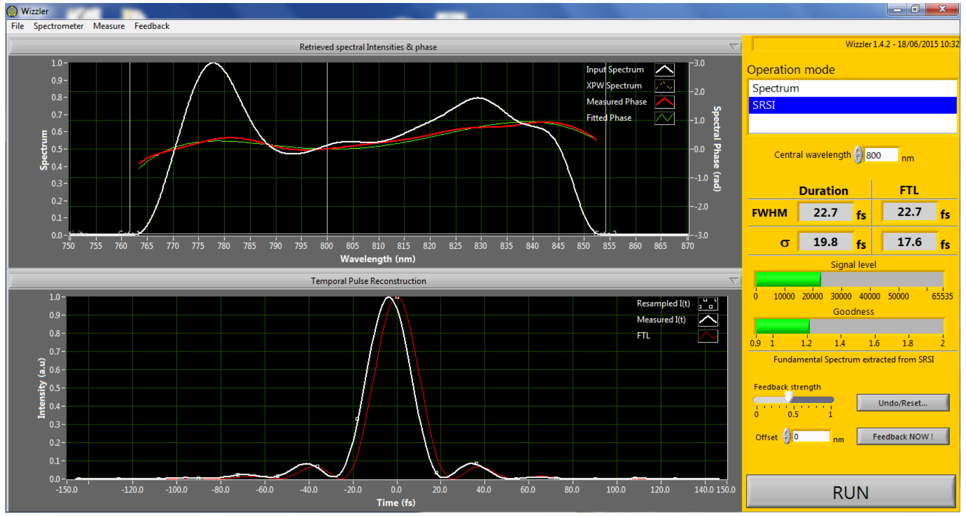


>25000 shots/day

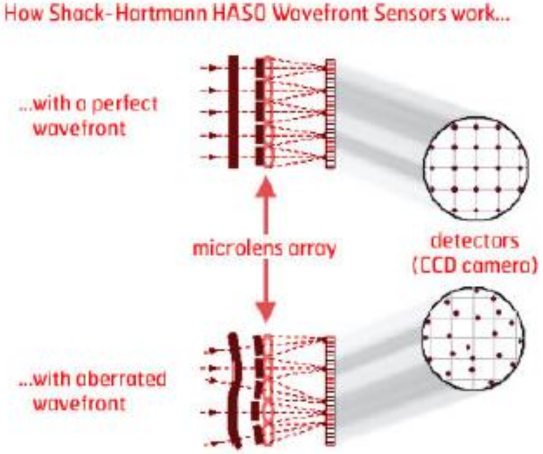
Pulse duration measurement and control

- Pulse width : Wizzler (Fastlite)
  - Pulse duration range : 20-100fs
  - Required pulse energy : 2-20 µJ
- Principle
  - XPW → reference pulse with flat spectral phase generated from the input pulse
  - spectral interference pattern resulting from the combination of the input pulse with reference pulse
  - the reference pulse allows direct retrieval of the spectral phase and intensity
- Pulse duration optimization with Dazzler
  - Wizzler calculates the phase mismatch between the current spectral phase and a flat spectral phase
  - The differences are recorded in a phase file shared with the Dazzler

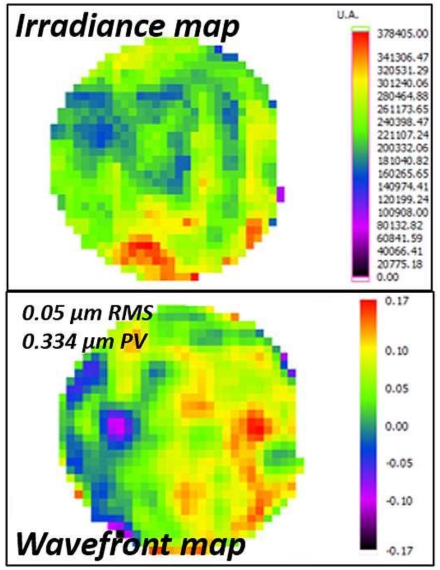


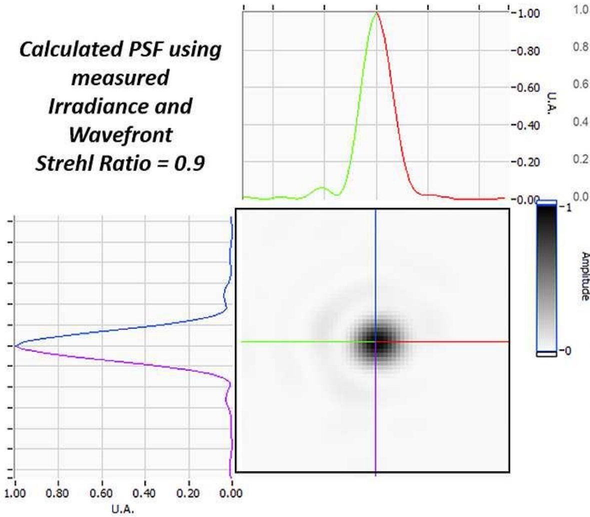


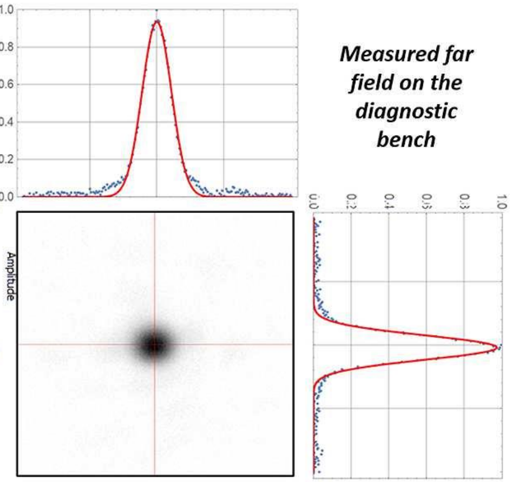
Wavefront measurement and control

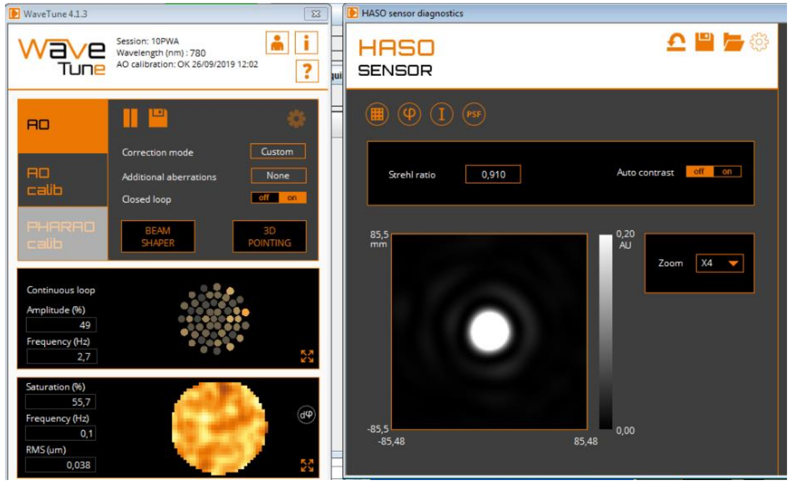


- Wavefront sensor : HASO (Imagine Optics)
  - Shack-Hartmann technology
  - Number of µ-lenses : 32x40
  - Wavefront measurement accuracy (rms) : $\lambda/150$
  - Working wavelength : 400-1100 nm
- Wavefront correction
  - Works in open or closed-loop with deformable mirror placed before each compressor input









Temporal contrast measurement

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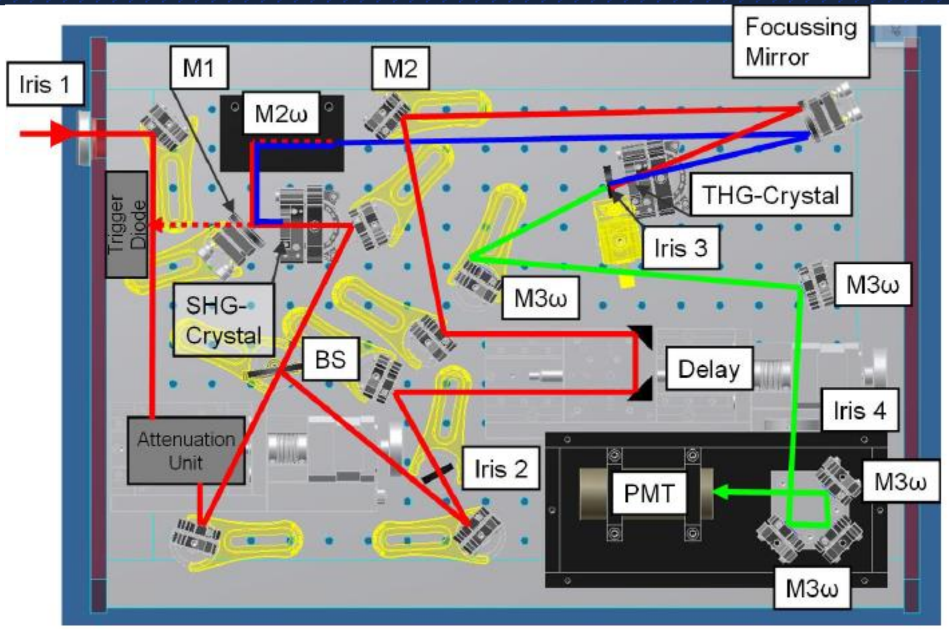
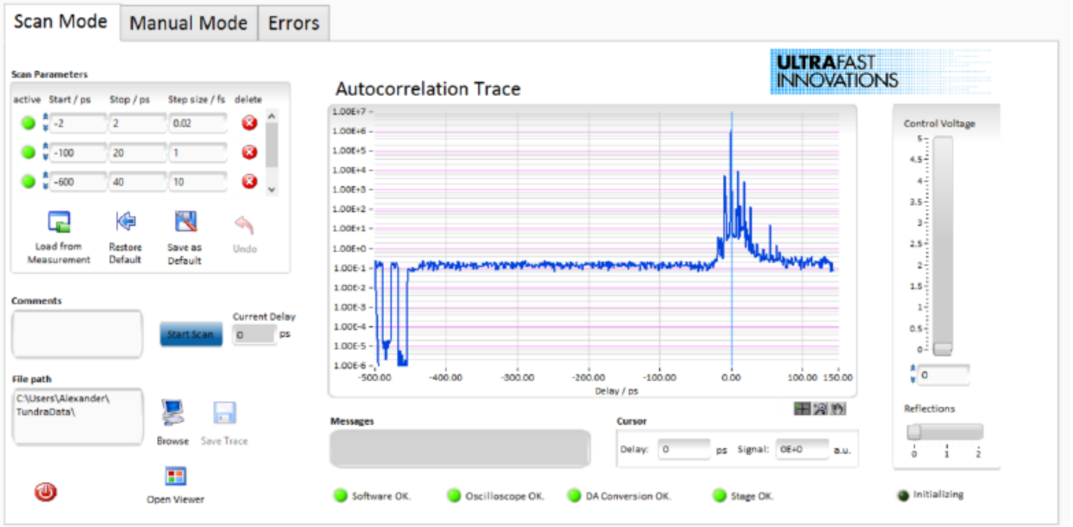
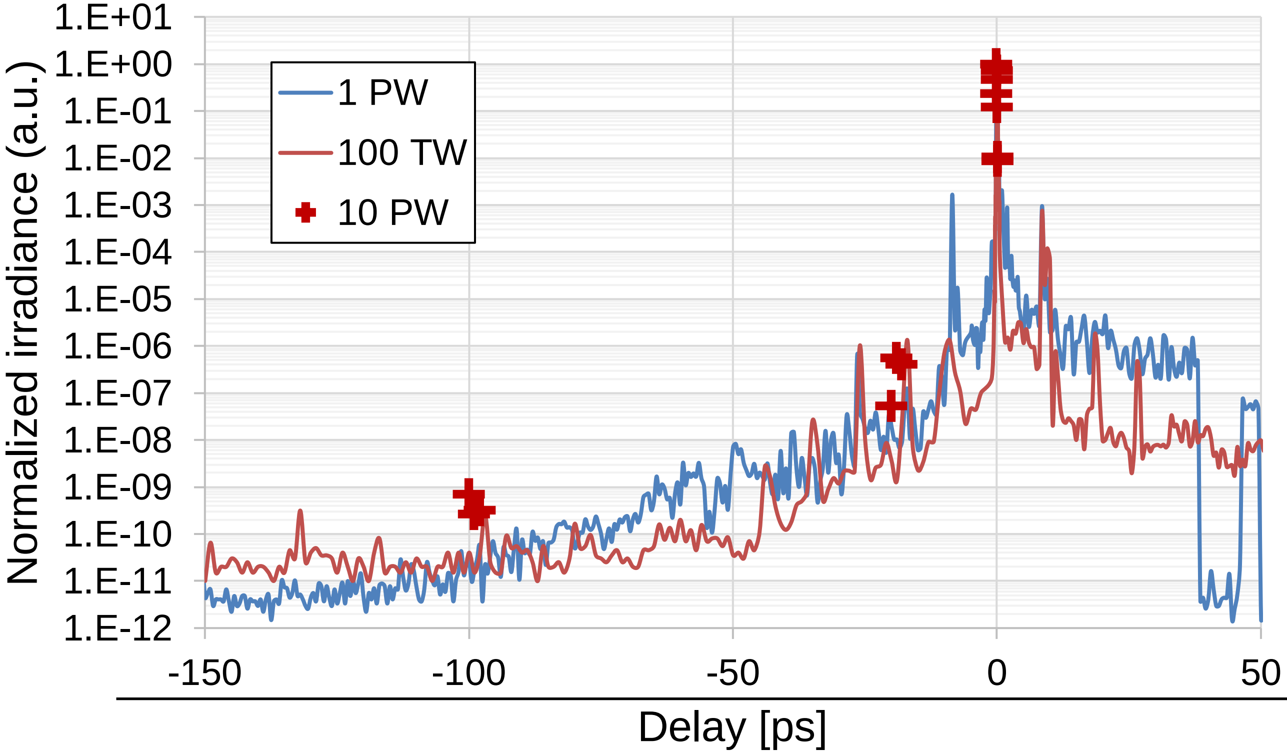
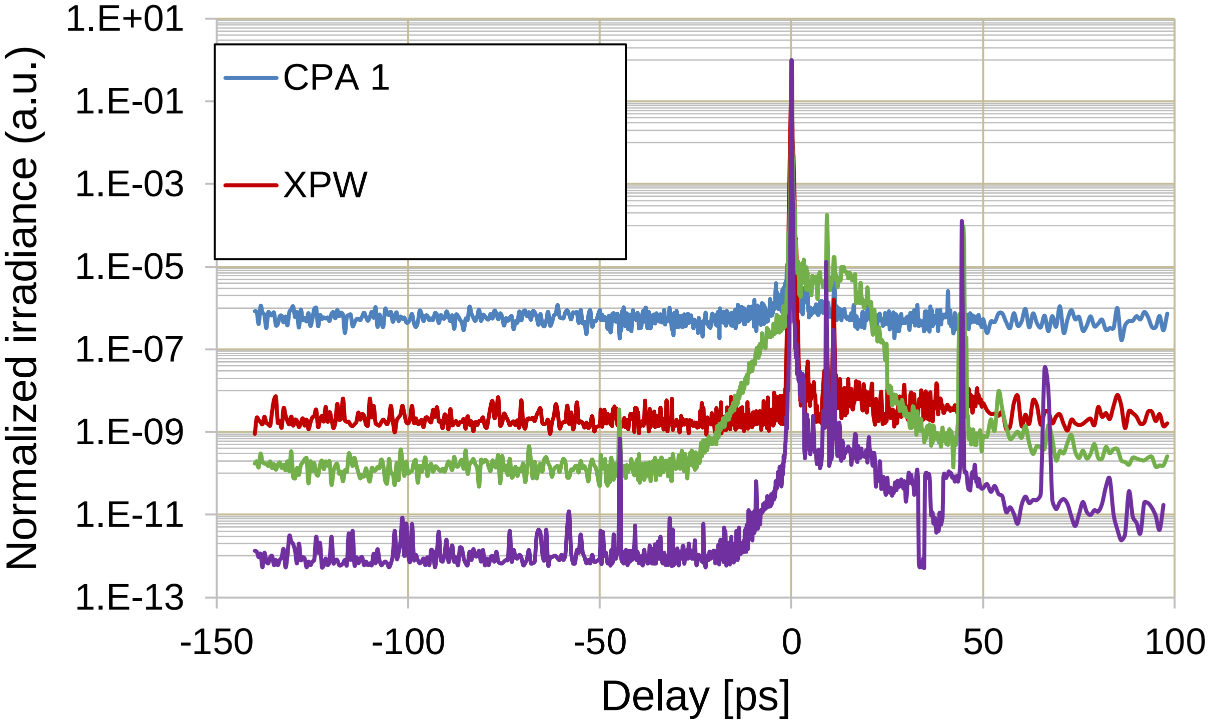
- Picosecond contrast : Tundra (Ultrafast Innovations)
  - Signal dynamic range : up to 11 orders of magnitude
  - Pulse energy range : 50-100µJ
  - Delay range : 633 ps
  - Scan resolution : down to 1 fs





Contrast measurements





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Beam transport

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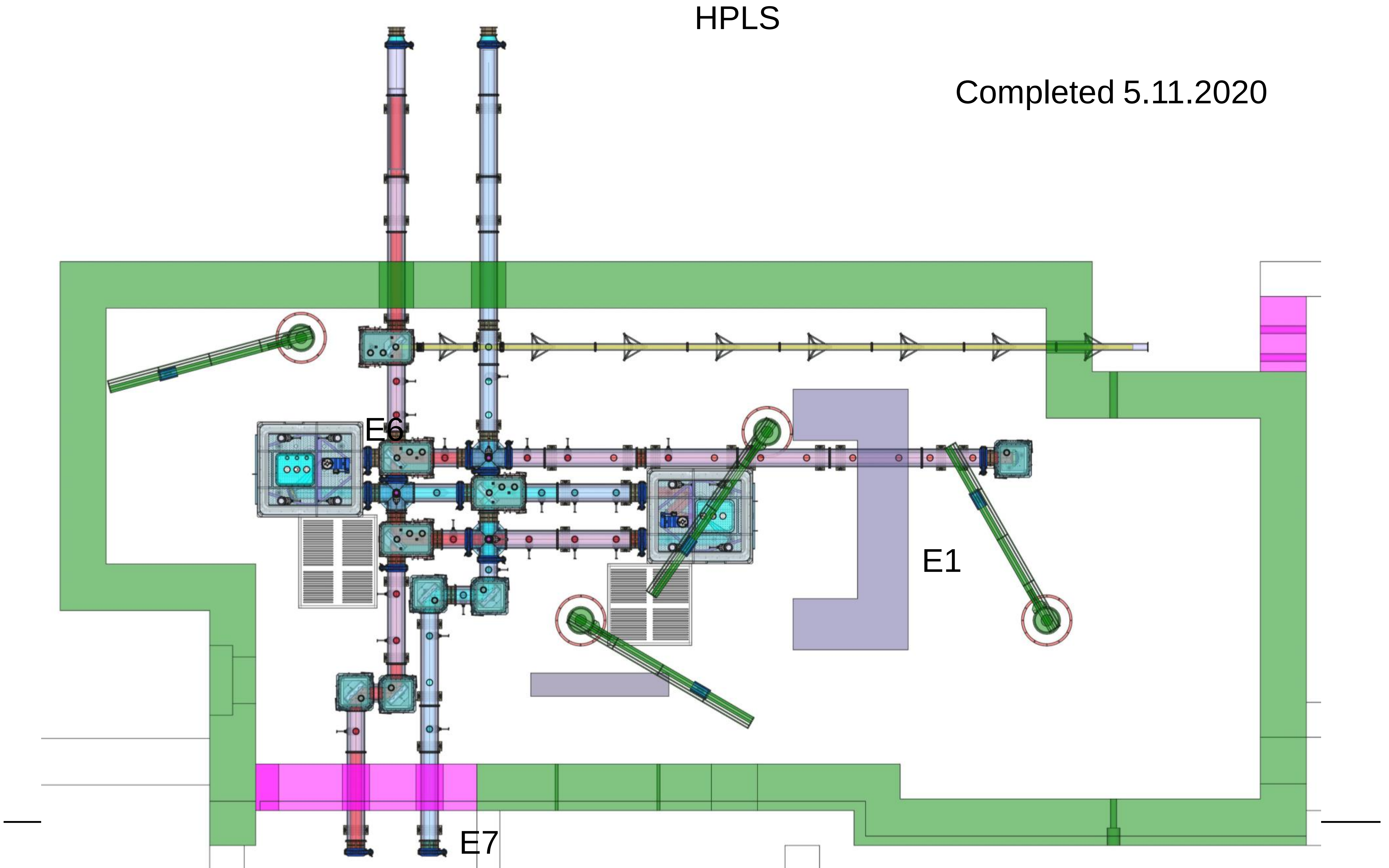
ELI-NP Laser Beam Transport System



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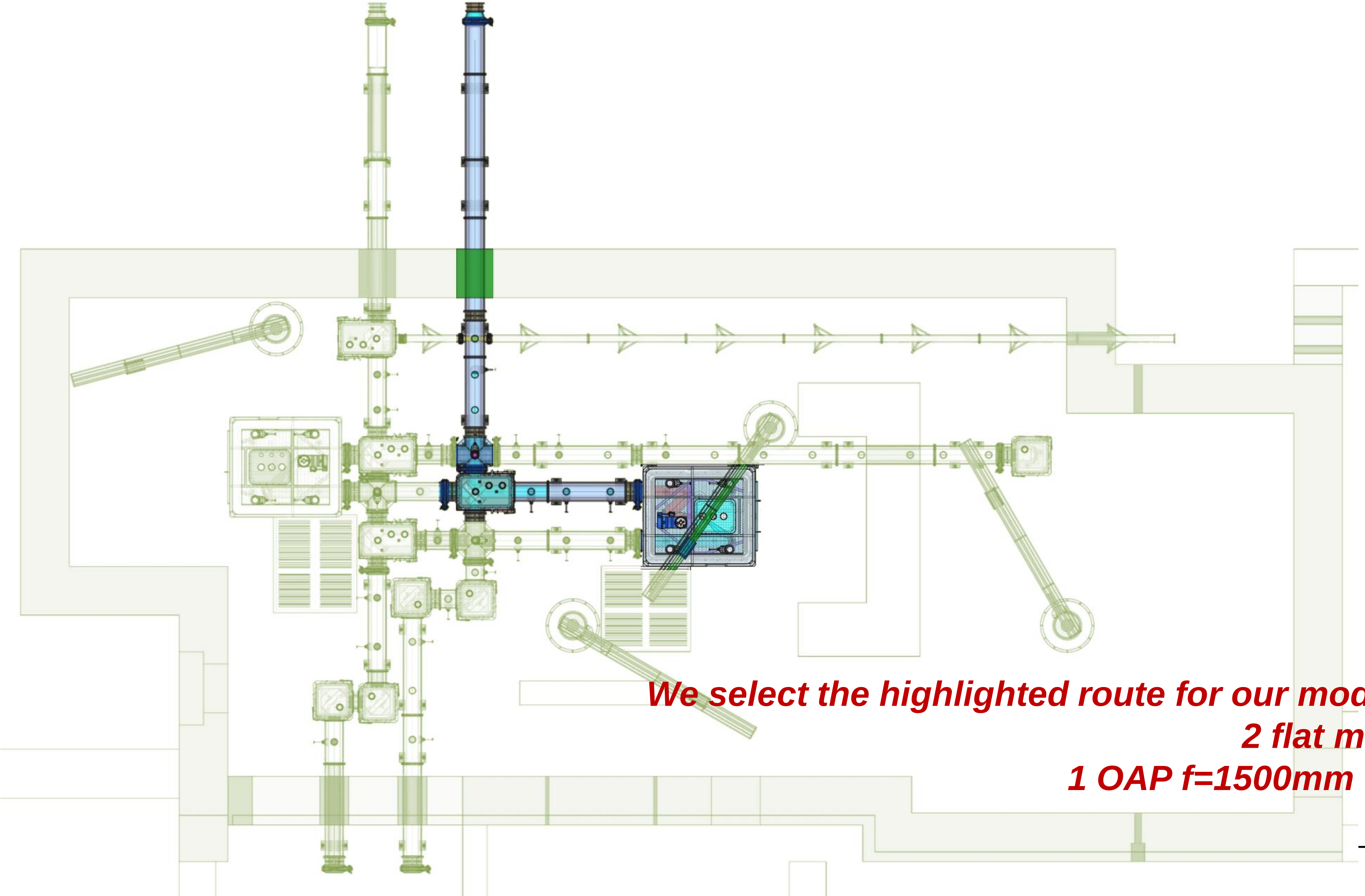
THALES

ALSYOM
ALCEN

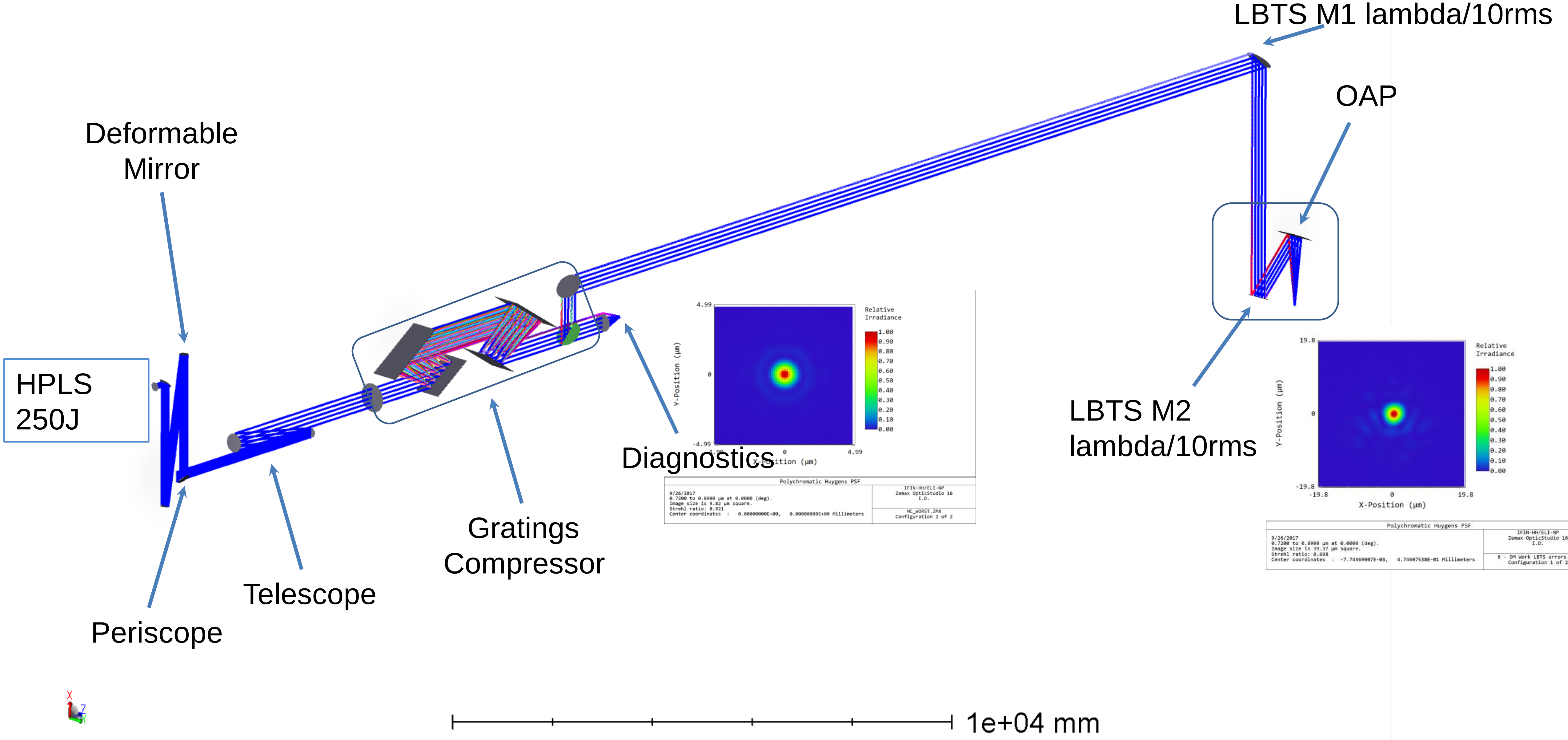
September 2019

LBTS beam quality preservation



We select the highlighted route for our modeling
2 flat mirrors
1 OAP f=1500mm @ 45º

Zemax study



Simulations by Ioan Dancus

Measured beam + OAP with 50 nm RMS wavefront error + 4-8 orders Zernike polynomials correction

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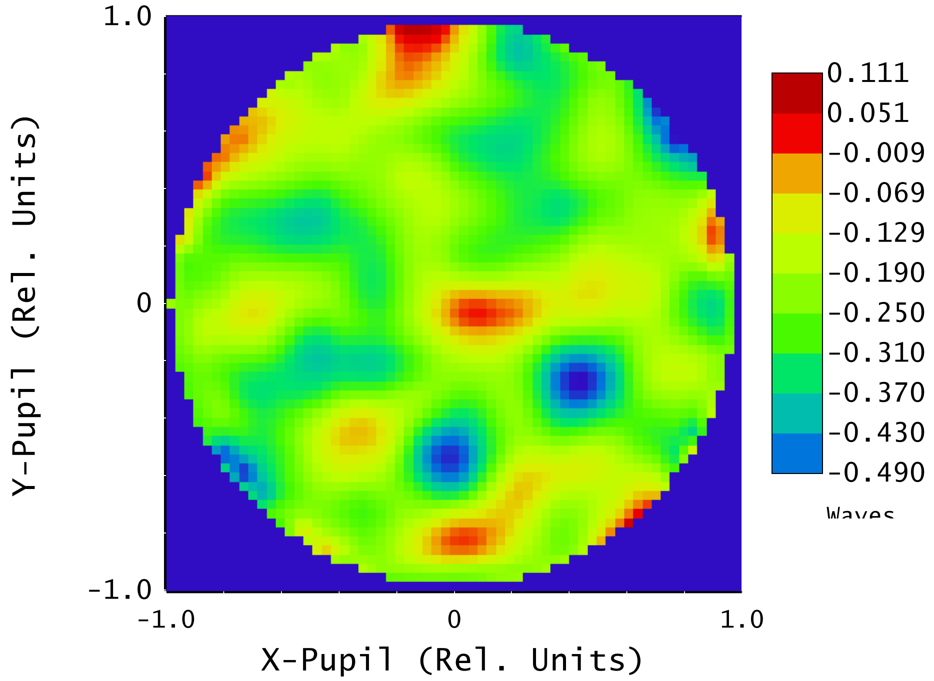
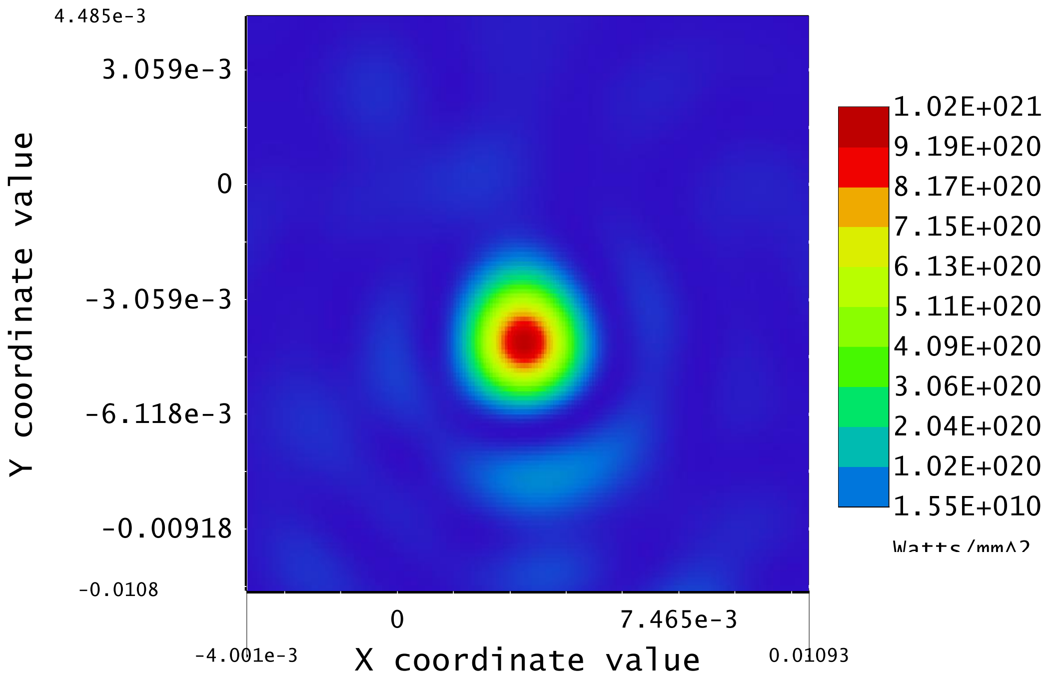
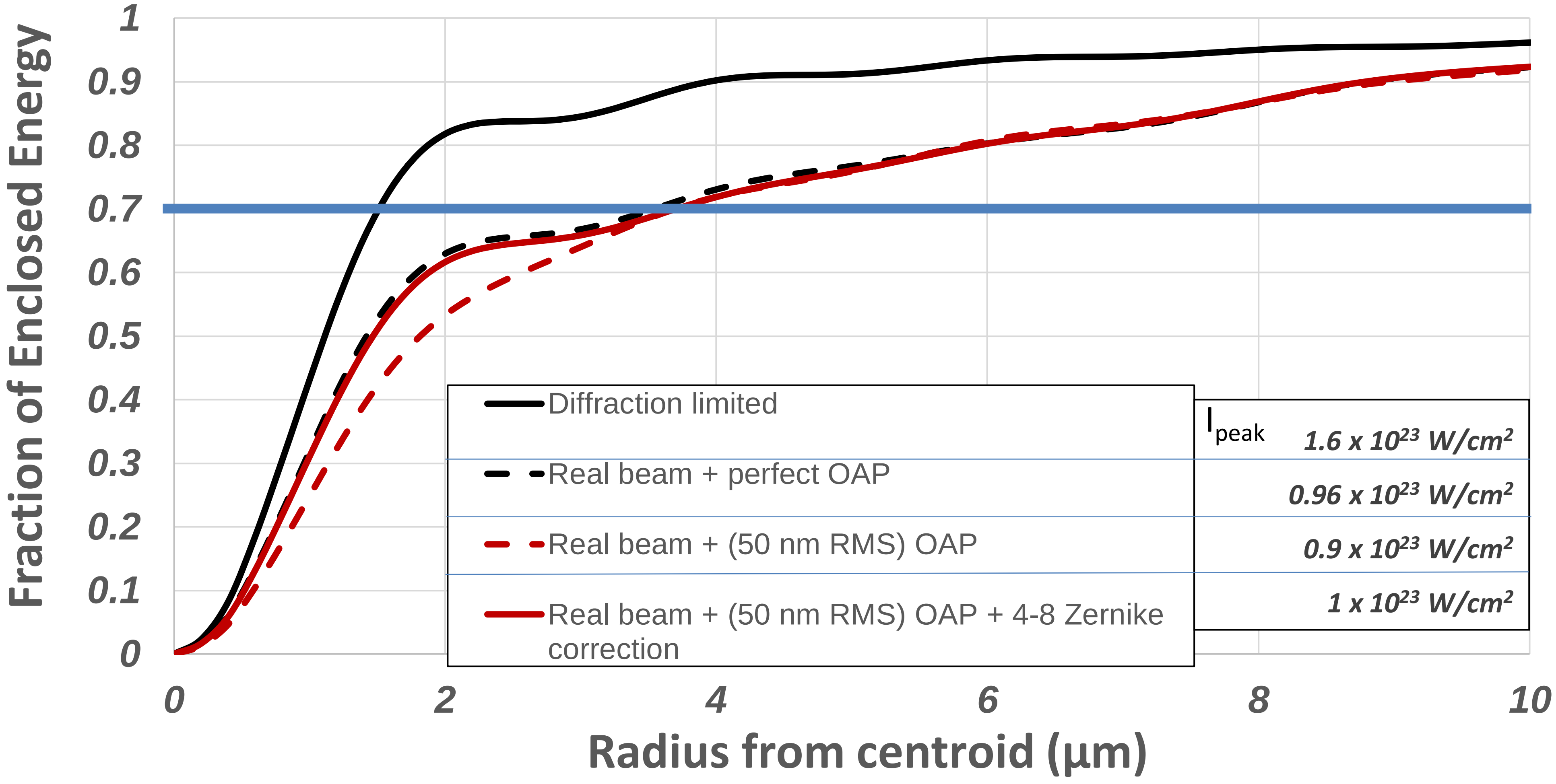




Wavefront Function		Total Irradiance surface 22
9/15/2020 0.8100 µm at 0.0000 (deg) Peak to valley = 0.6014 waves, RMS = 0.0916 waves. Surface: 22 Exit Pupil Diameter: 2.0003E+02 Millimeters Tilt Removed: X = -0.8413, Y = 0.7017 waves	Zemax Zemax OpticStudio 19.4 SP1 Short OAP aberrations + DM correction 1 optimised 50 Configuration 3 of 6	9/15/2020 Beam wavelength is 0.81000 µm in the media with index 1.00000 at 0.0000 (deg) Display X Width = 8.1960E-02, Y Height = 1.2621E-01 Millimeters Peak Irradiance = 1.0214E+21 Watts/Millimeters^2, Total Power = 1.0000E+16 Watts X Pilot: Size= 4.5100E-02, Waist= 1.4064E-03, Pos= +2.4589E-01, Rayleigh= 7.6717E-03 Y Pilot: Size= 6.9428E-02, Waist= 1.4065E-03, Pos= +3.7865E-01, Rayleigh= 7.6721E-03 Beam Width X = 1.26402E-02, Y = 1.59835E-02 Millimeters

Encircled energy



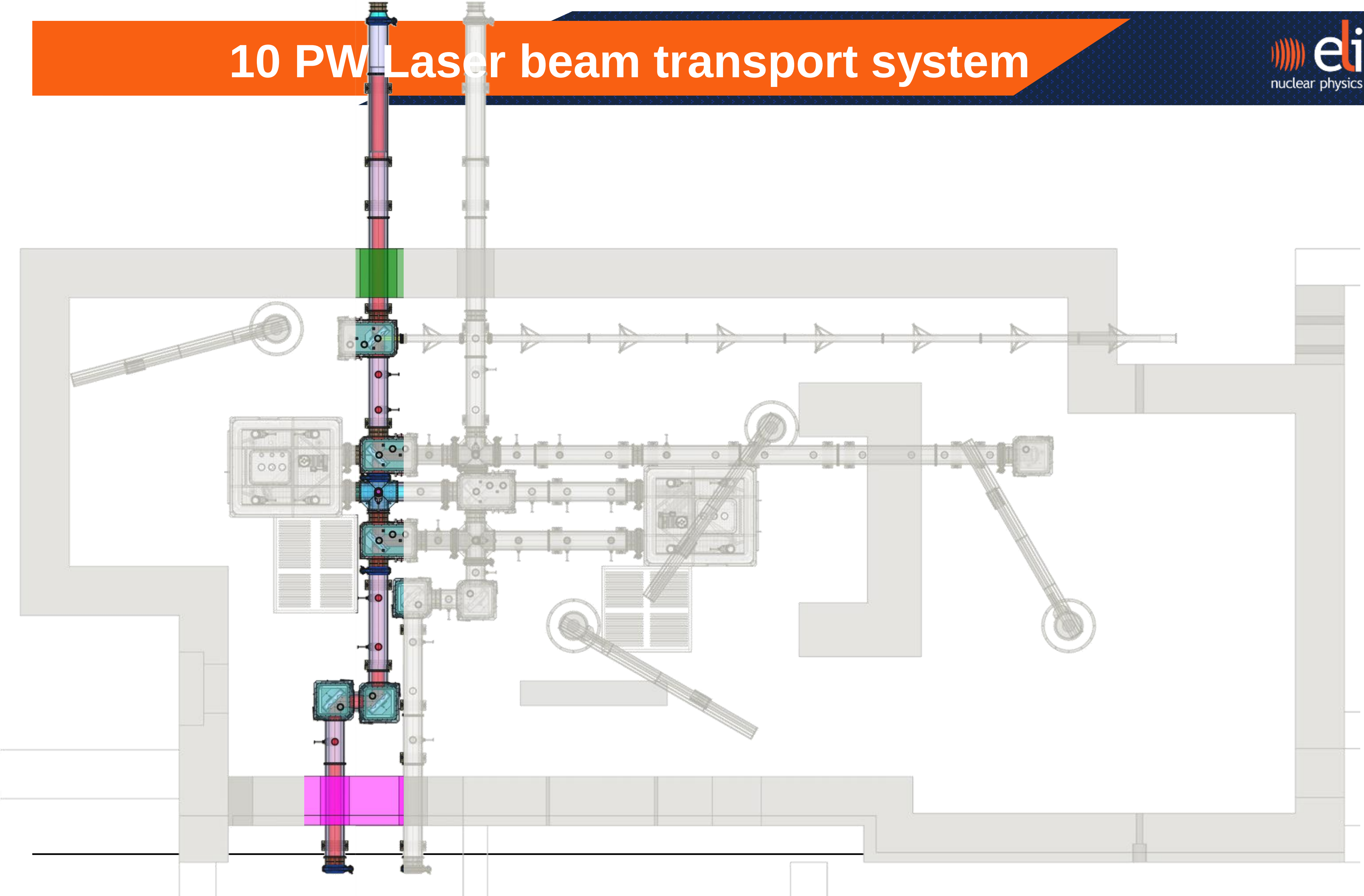
Ioan Dancus et al. FiO+LS 2020

19 August 2020
First 10 PW propagated pulses

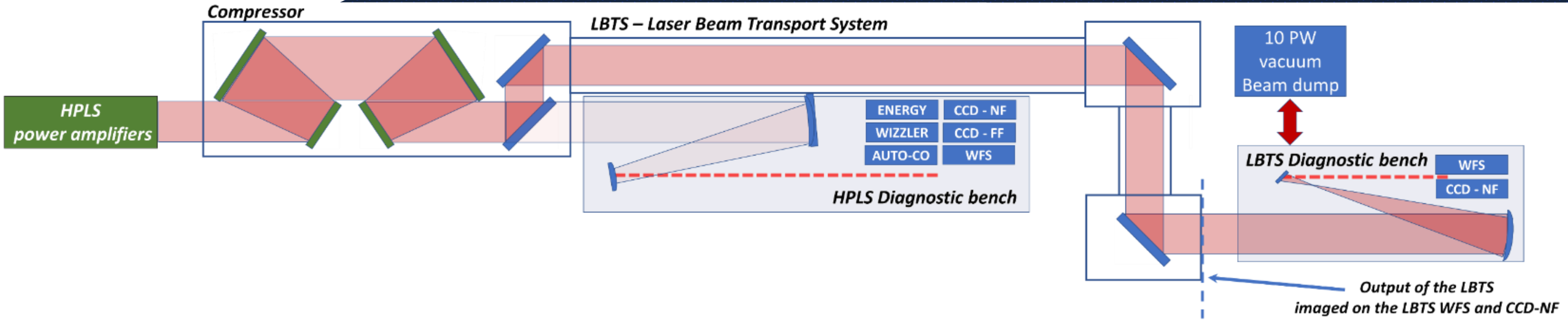
nuclear physics

Part of the LBTS endurance test

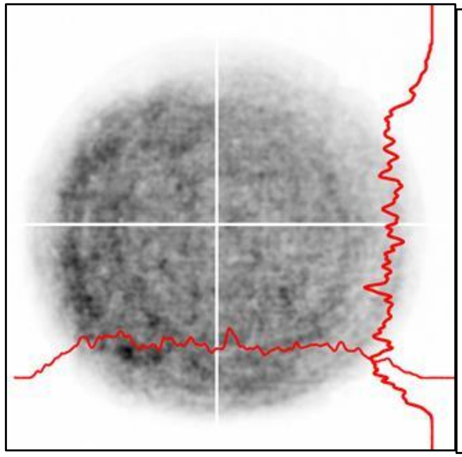
10 PW Laser beam transport system



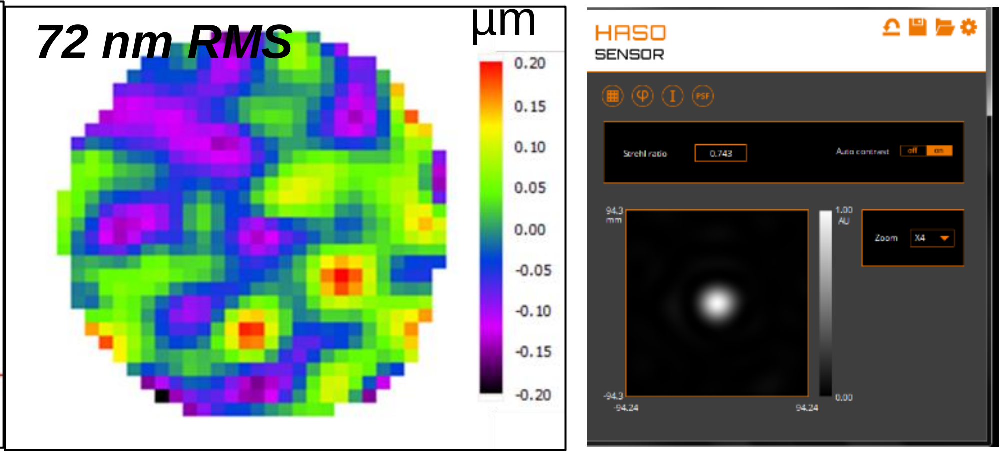
LBTS test configuration – step 1



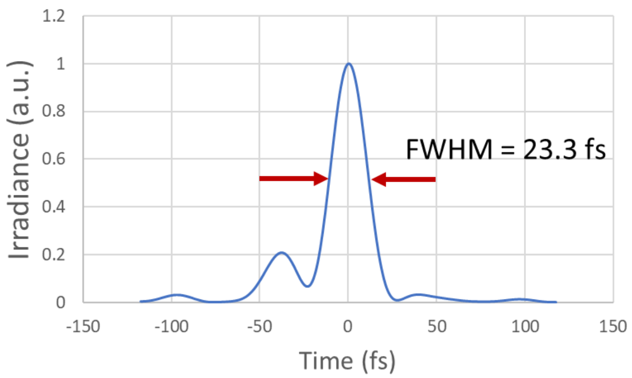
- HPLS laser running at full energy attenuated before compressor for beam profile analysis after propagation through the LBTS and transmission efficiency



NF LBTS output



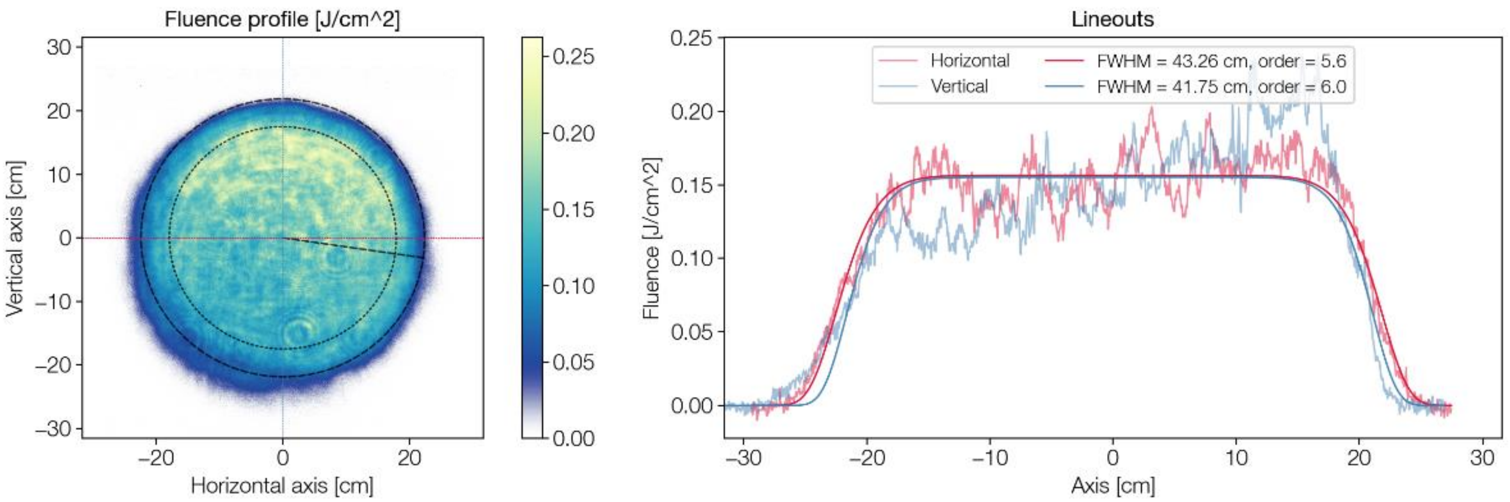
Wavefront map, Strehl ratio > 0,7

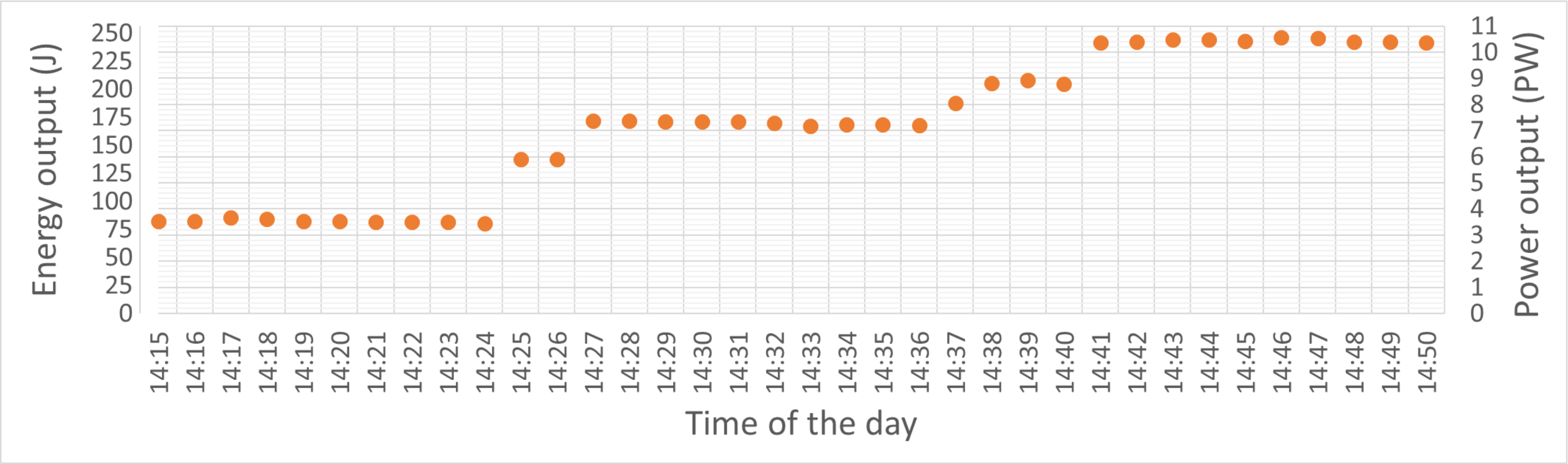


Pulse duration LBTS output

Compressor output - beam line 2
(measurements at full aperture with full energy after compressor)

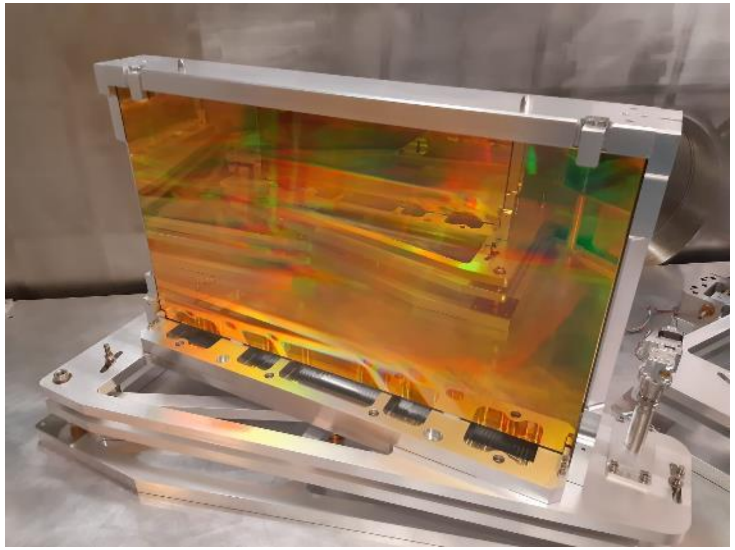
- Calculated peak power = 243 J / 23,4 fs = 10,4 PW



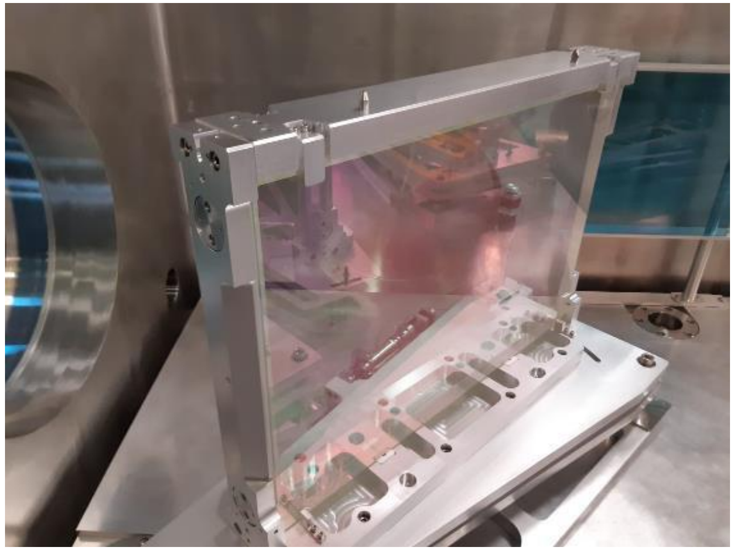


LBTS test configuration – step 3

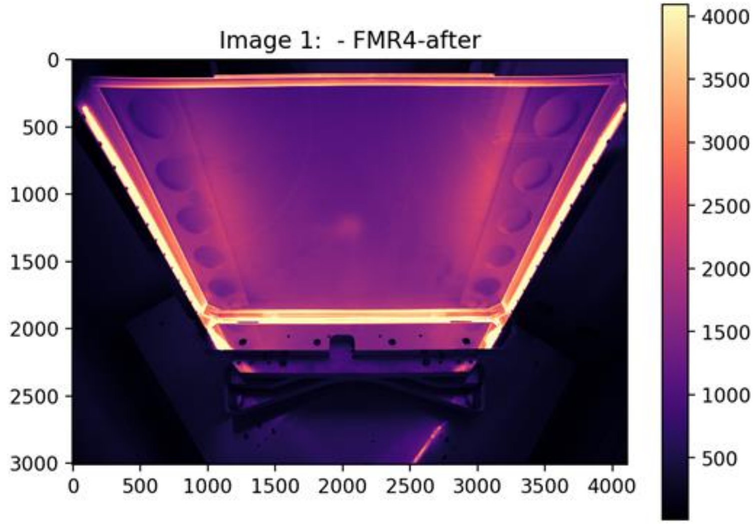
- Verification of transmission efficiency
- Visual inspection of optical components within HPLS compressor and LBTS



Grating



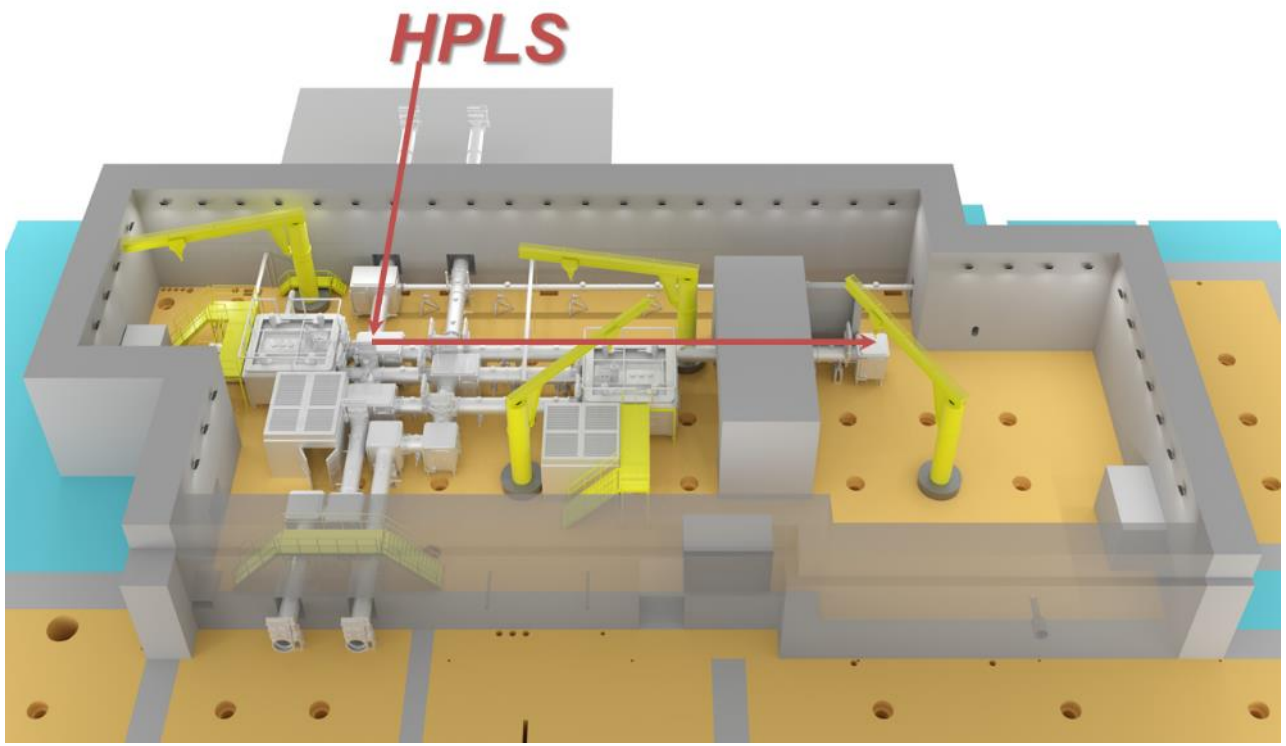
Compressor mirror



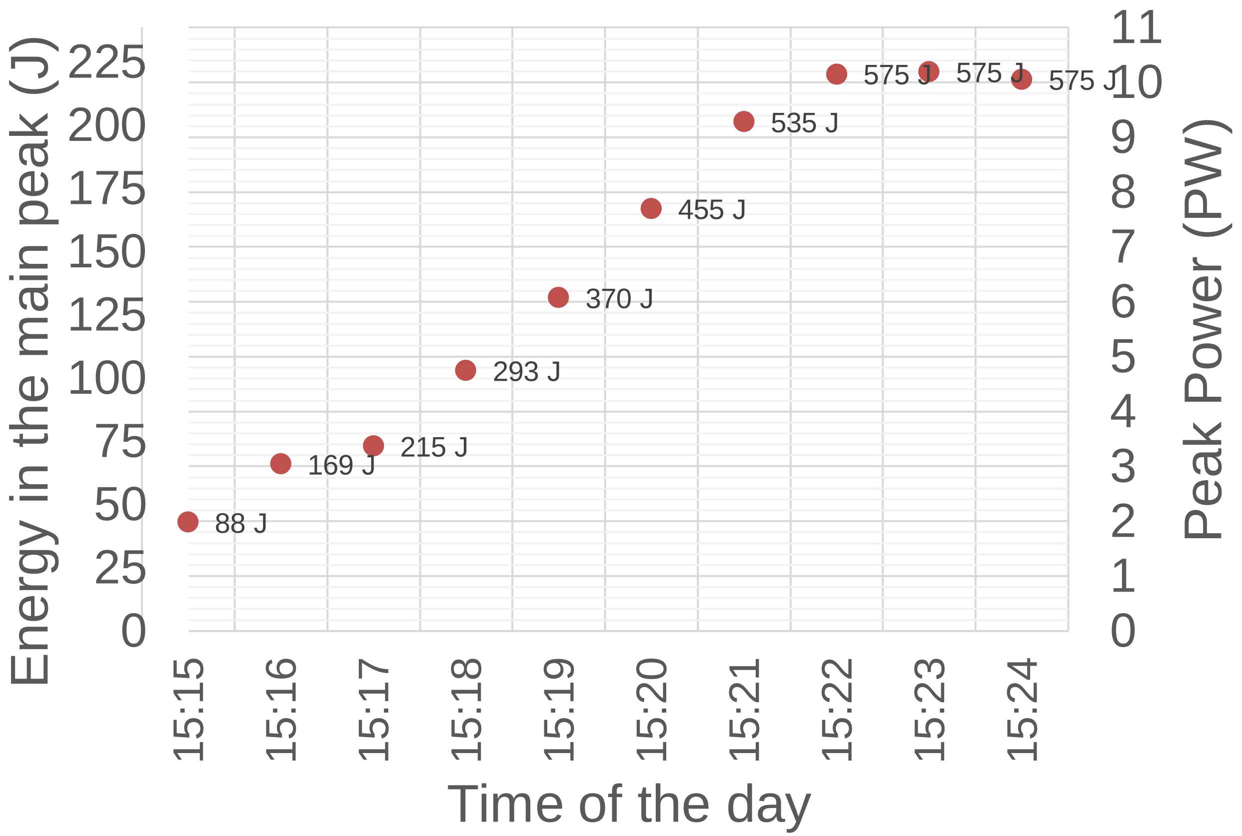
LBTS mirror

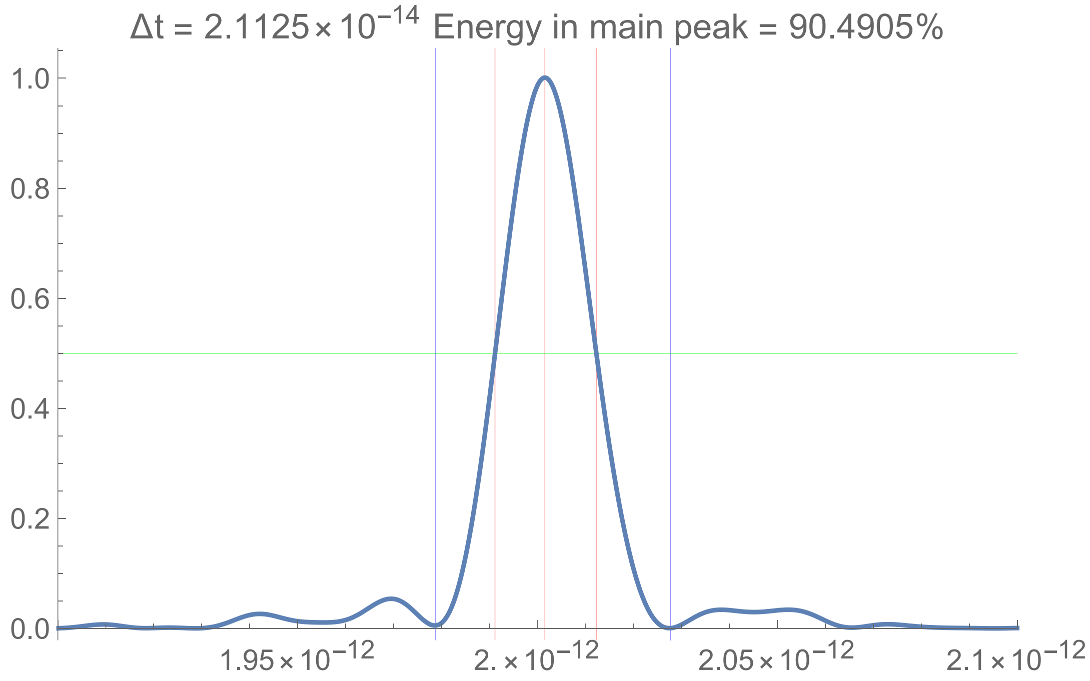
- No losses of efficiency and no damages observed

17 November 2020
Moving into Uncharted Territories



Pulse sequence





Contents

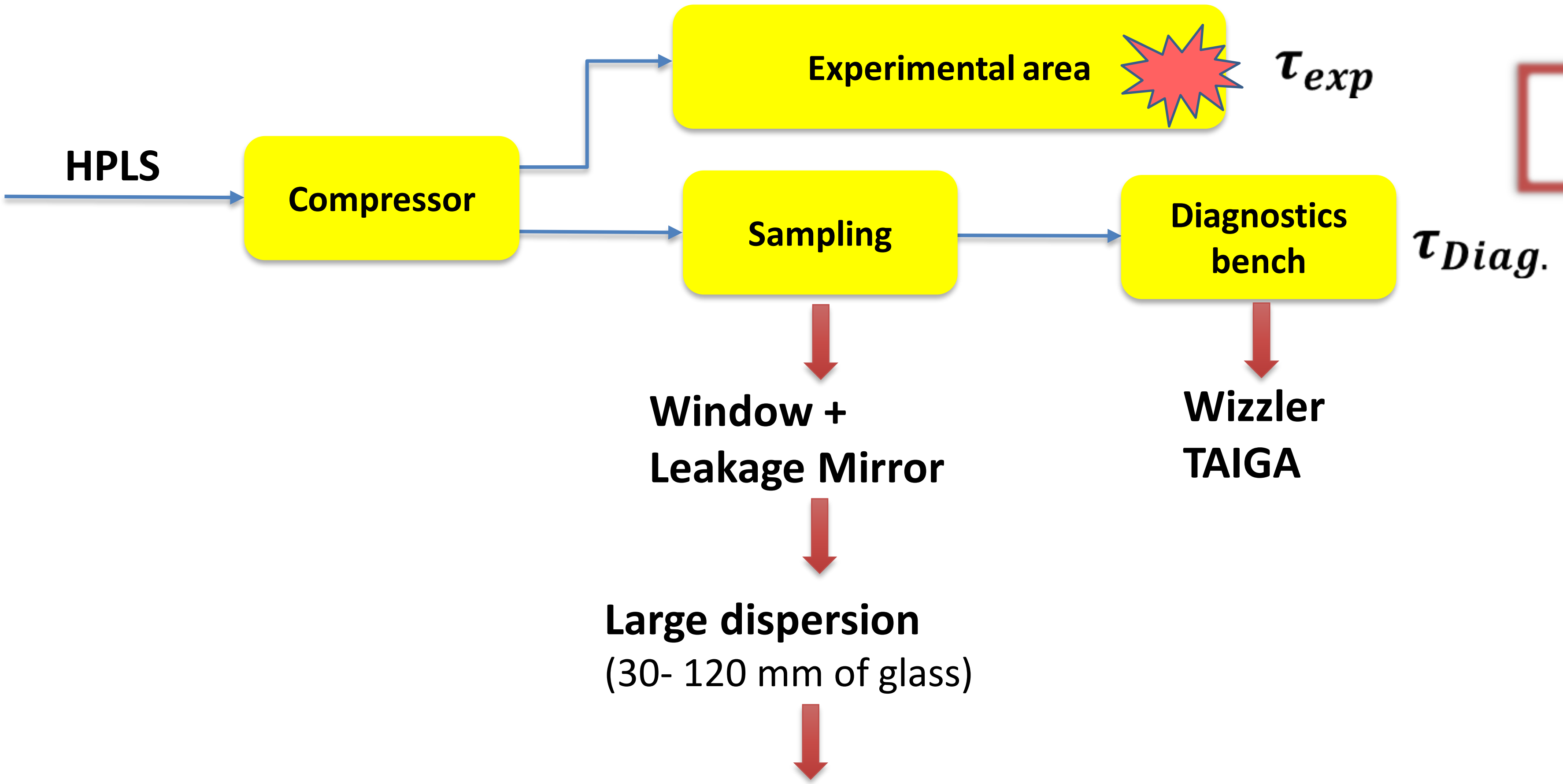
- Architecture of the 2x10PW laser system
- **Laser pulse characterization at HPLS**
- Experimental areas for laser experiments
- Beamtime request – further technical aspects

Compressor metrology

Beam transport

Experiment metrology

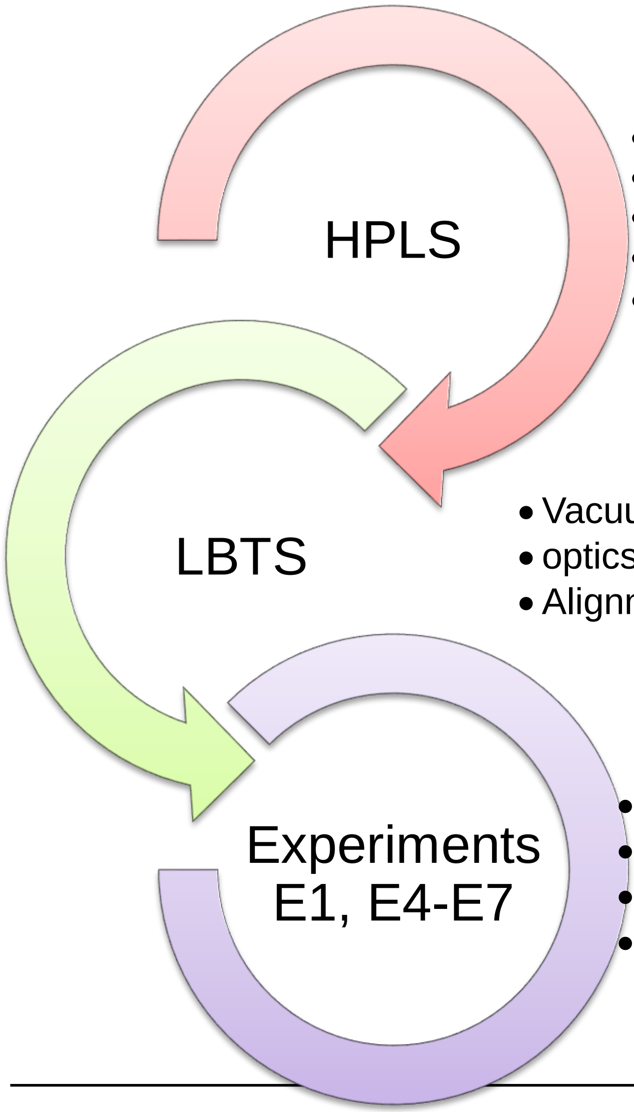
Beam sampling for diagnostics



$\tau_{exp} \neq \tau_{Diag.}$

Positive chirp: $22fs \rightarrow 491\ fs\ @\ 1PW$

ELI-NP diagnostics scenario



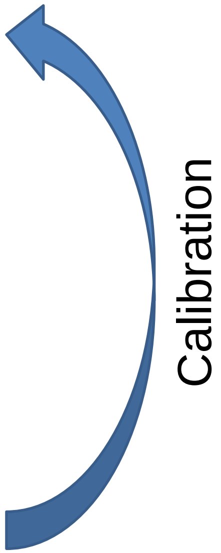
- Control system
- Front End
- amplifiers
- 6x Compressors
- **6x diagnostics benches**

- Vacuum system
- optics
- Alignment control

- Interaction chamber
- target
- **Laser diagnostics**
- Experiment diagnostics

Parameter	Device
Near field	CCD
Far field	CCD
Wavefront	ImaginOptics Wavefront sensor
Pulse duration	Wizzler
Spectral phase	
Spectrum	
ns-contrast	Fast photodiodes and oscilloscope
ps-contrast	Tundra
Energy	Gentec energy-meter

Parameter	Device
Far field	CCD (high resolution)
Pulse duration	Frog or D-Scan or Spider
Spectral phase	
Spectrum	Ocean optics
ns-contrast	Fast photodiodes and oscilloscope
Energy	Gentec energy-meter (Q12)



+ focal spot size

Contents

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E4: 2x100TW@10Hz

E5: 2x1PW@1Hz

E1/E6: 2x10PW@1 shot/min

https://www.youtube.com/watch?v=qBse2Uw2WTQ

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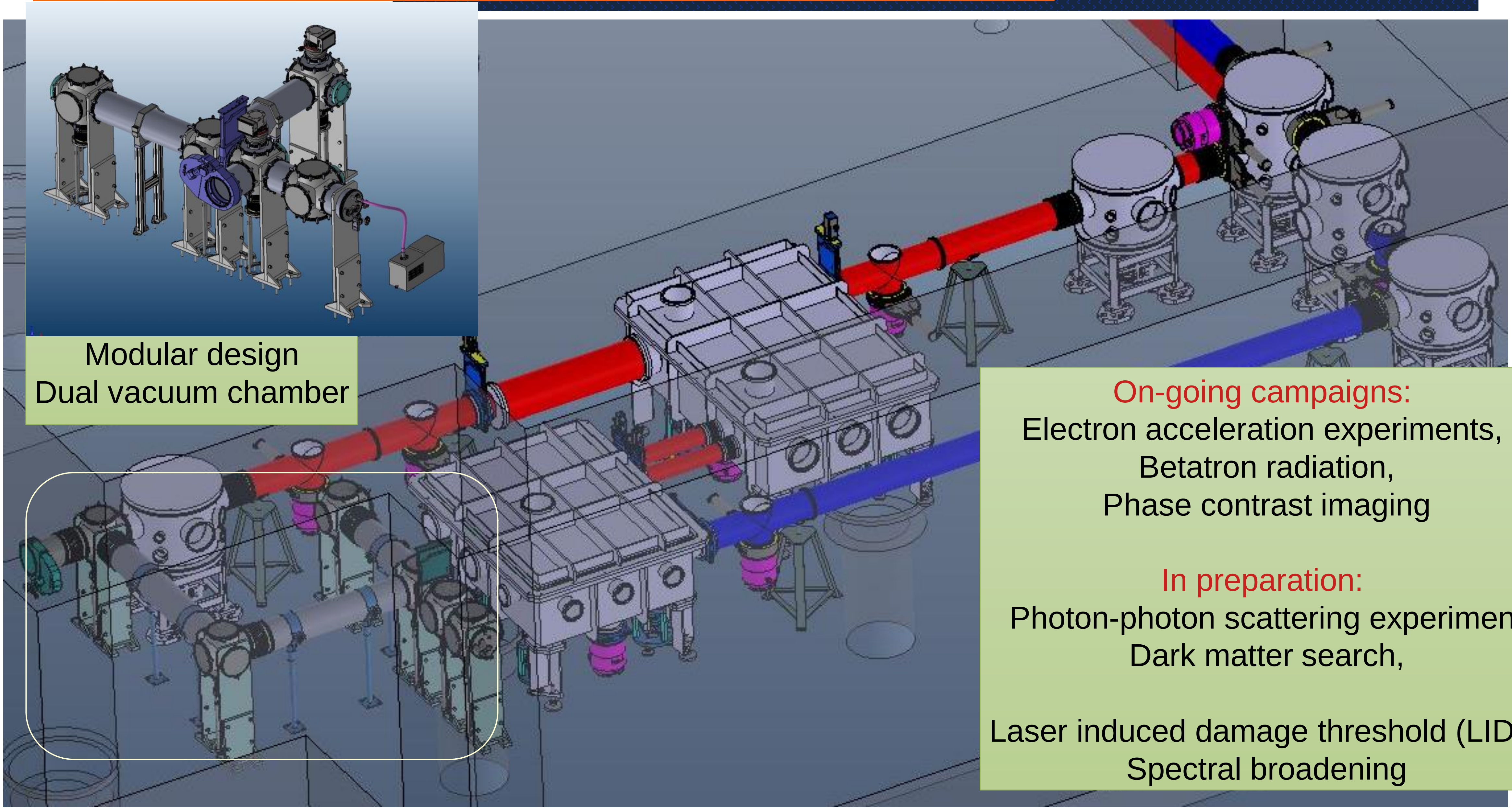
E1/E6: 2x10PW@1 shot/min

E4 2x100TW experimental area



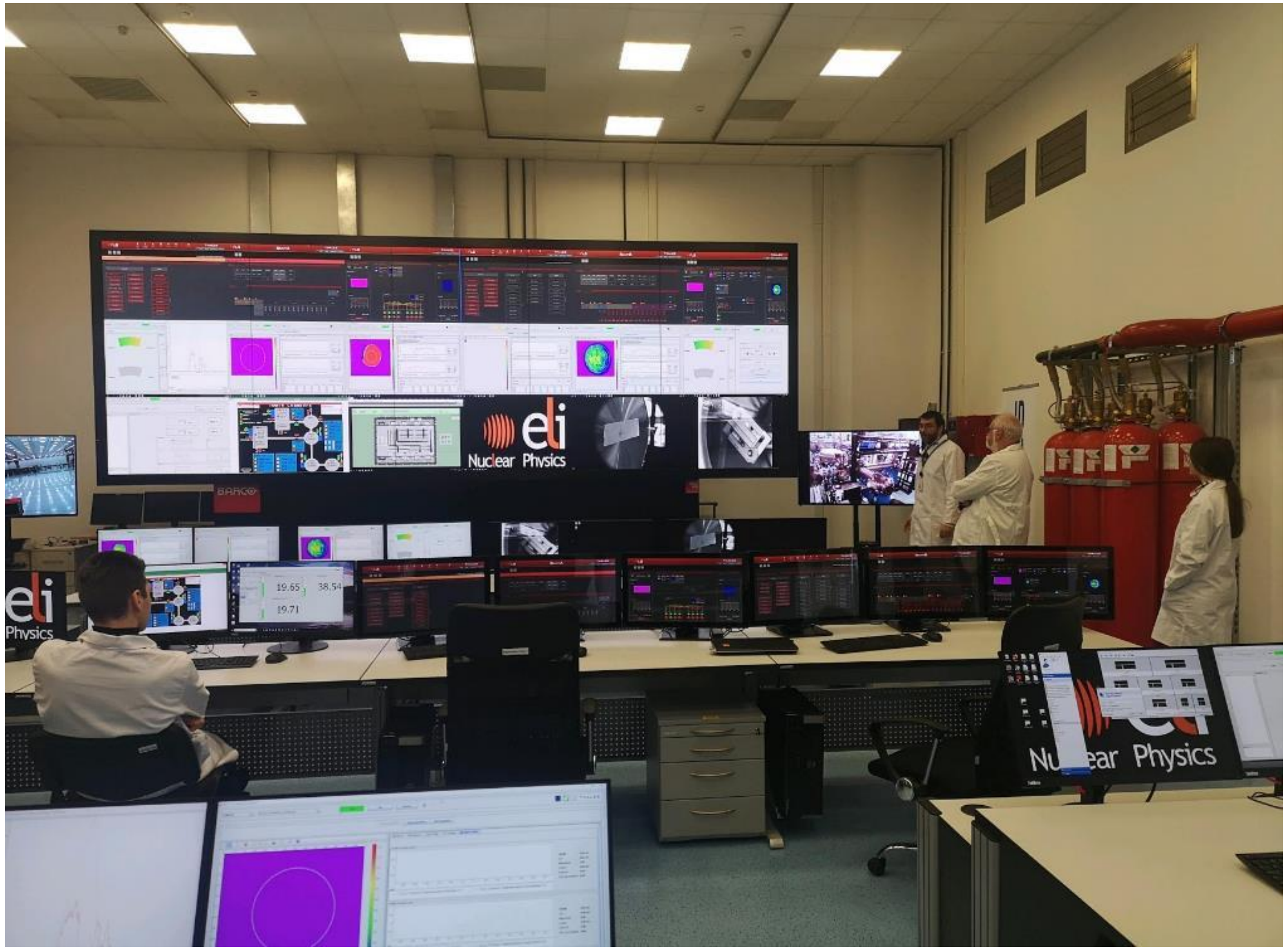
Modular design
Dual vacuum chamber

On-going campaigns:
Electron acceleration experiments,
Betatron radiation,
Phase contrast imaging

In preparation:
Photon-photon scattering experiment
Dark matter search,

Laser induced damage threshold (LIDT)
Spectral broadening

18 March 2020
First HPLS beam on a target



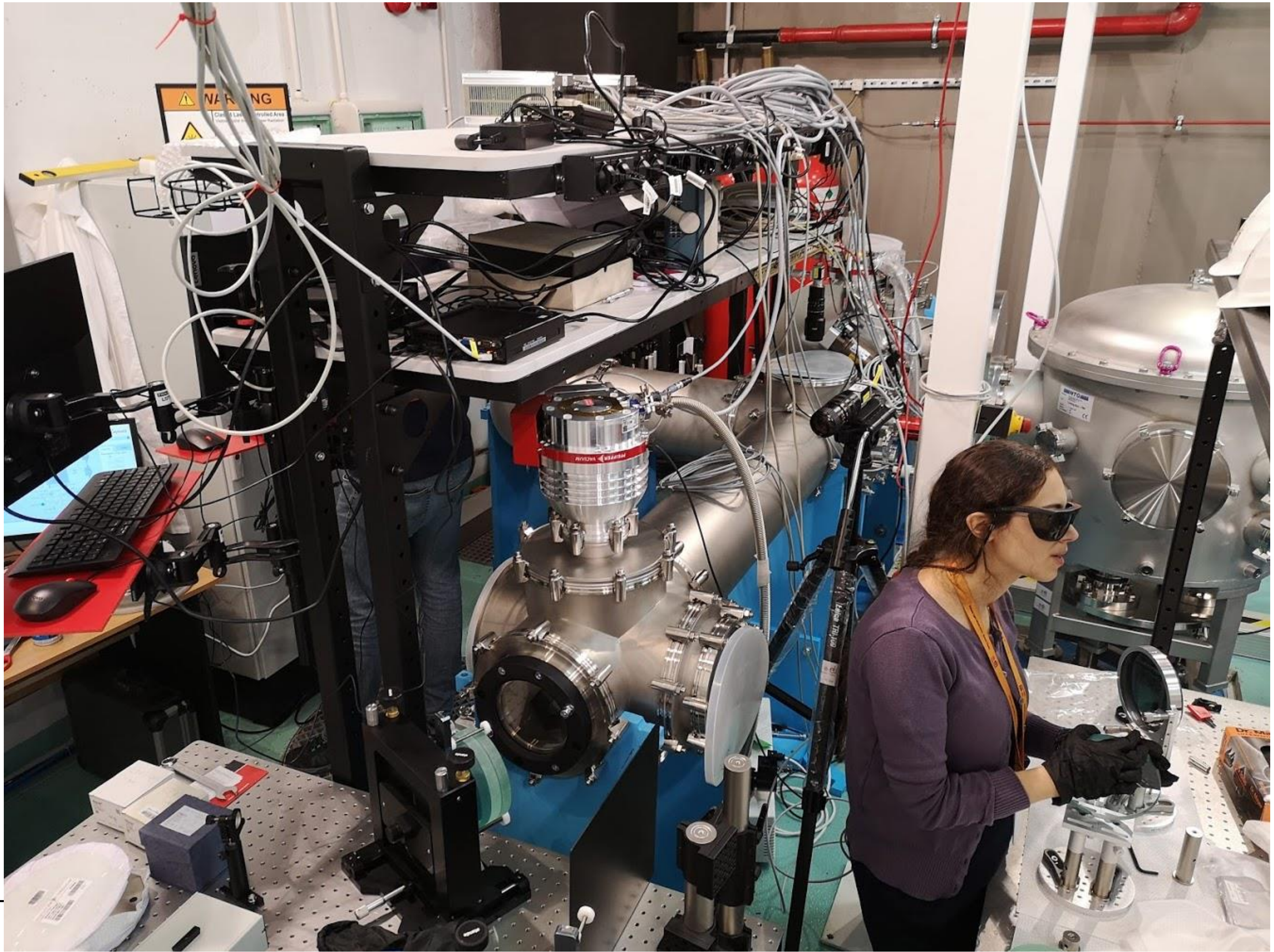
Experiment: Spectral broadening

P.I.: Dr. Daniel Ursescu

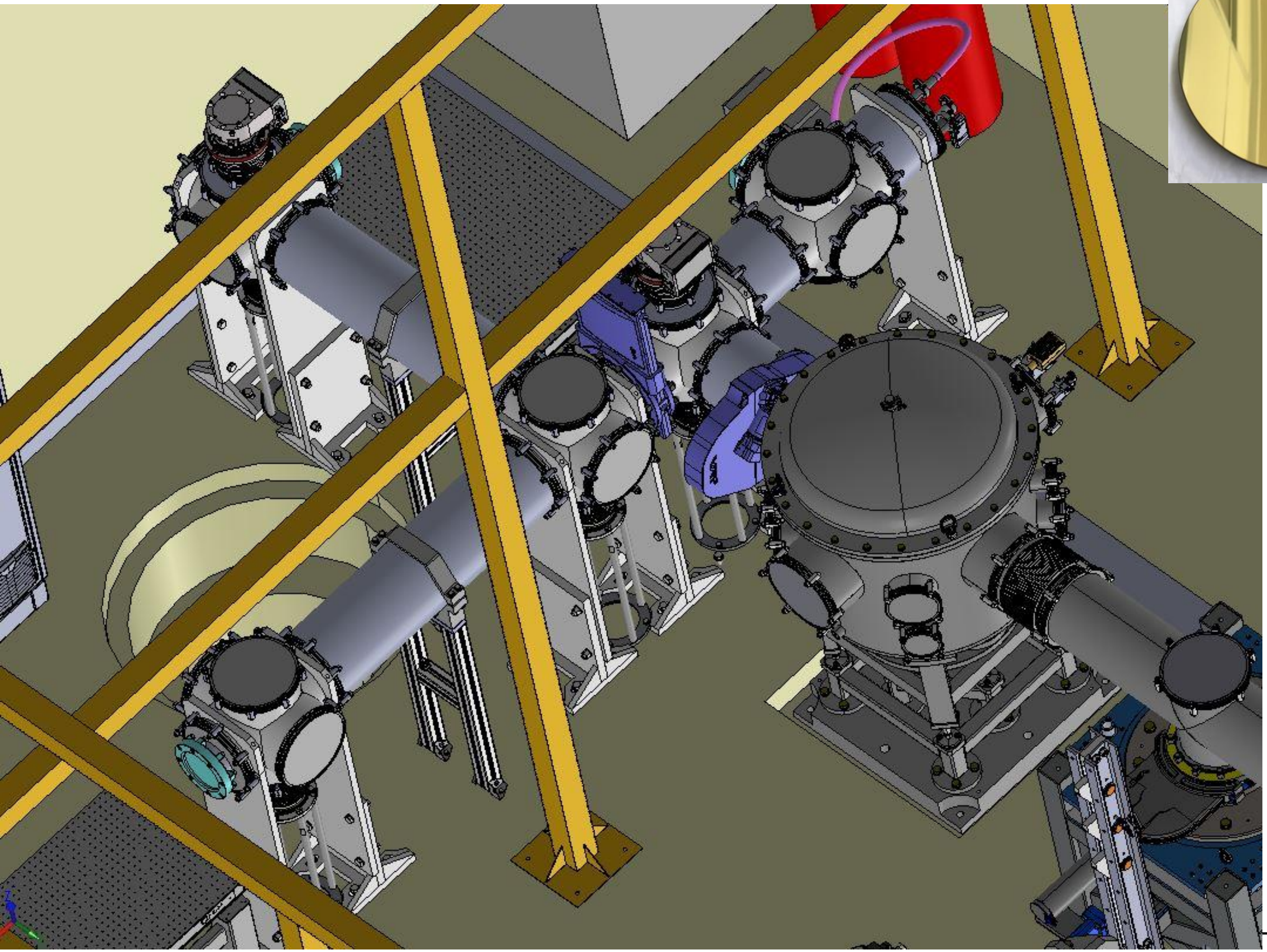
Collaboration: Gerard Mourou (IZEST)

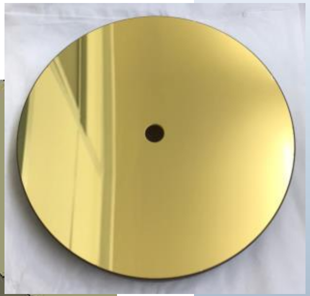
Preliminary results presented at:
FiO+LS – OSA - 14 – 17 September 2020

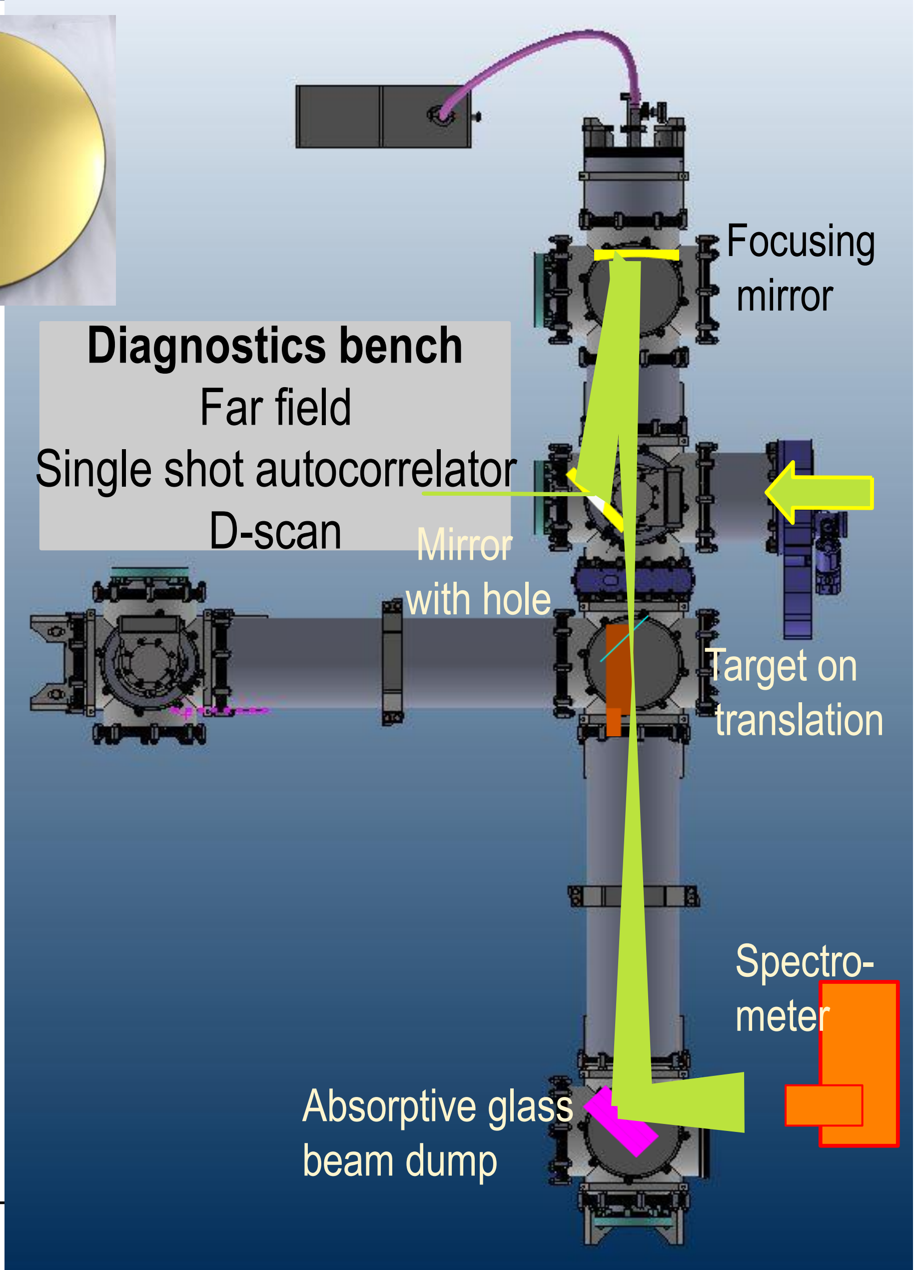
Integration of the experiment



LIDT station



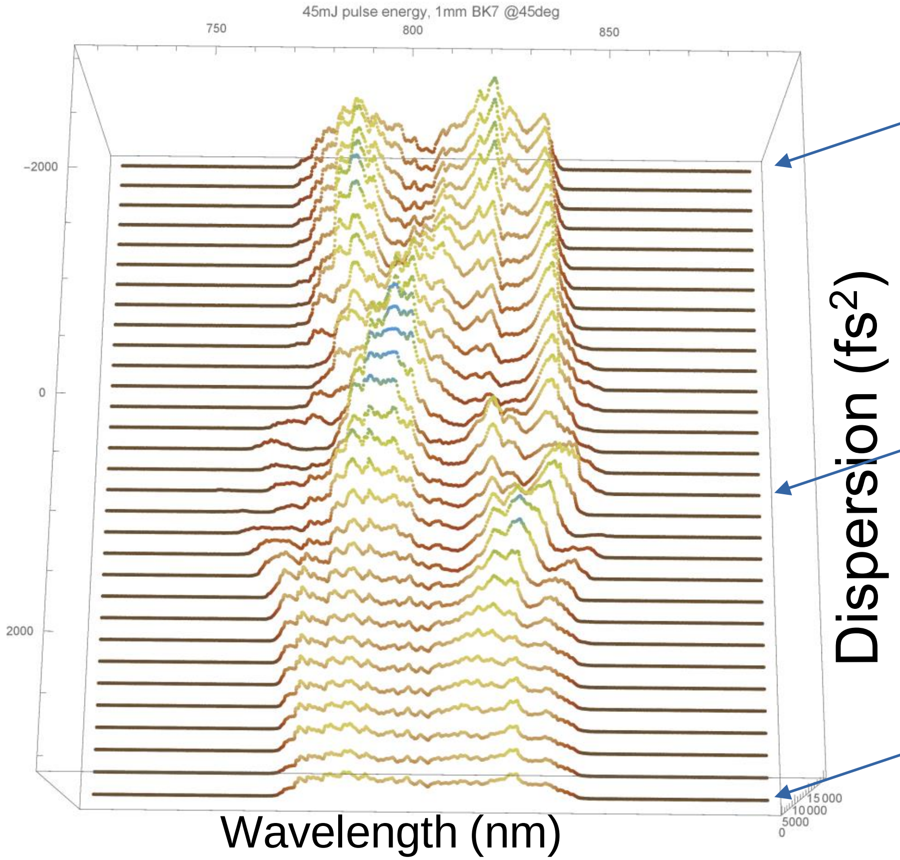




SB coarse adjusting: pulse duration variation

Dispersion variation between -3000fs^2 and 3000fs^2, in steps of minimum 100fs^2

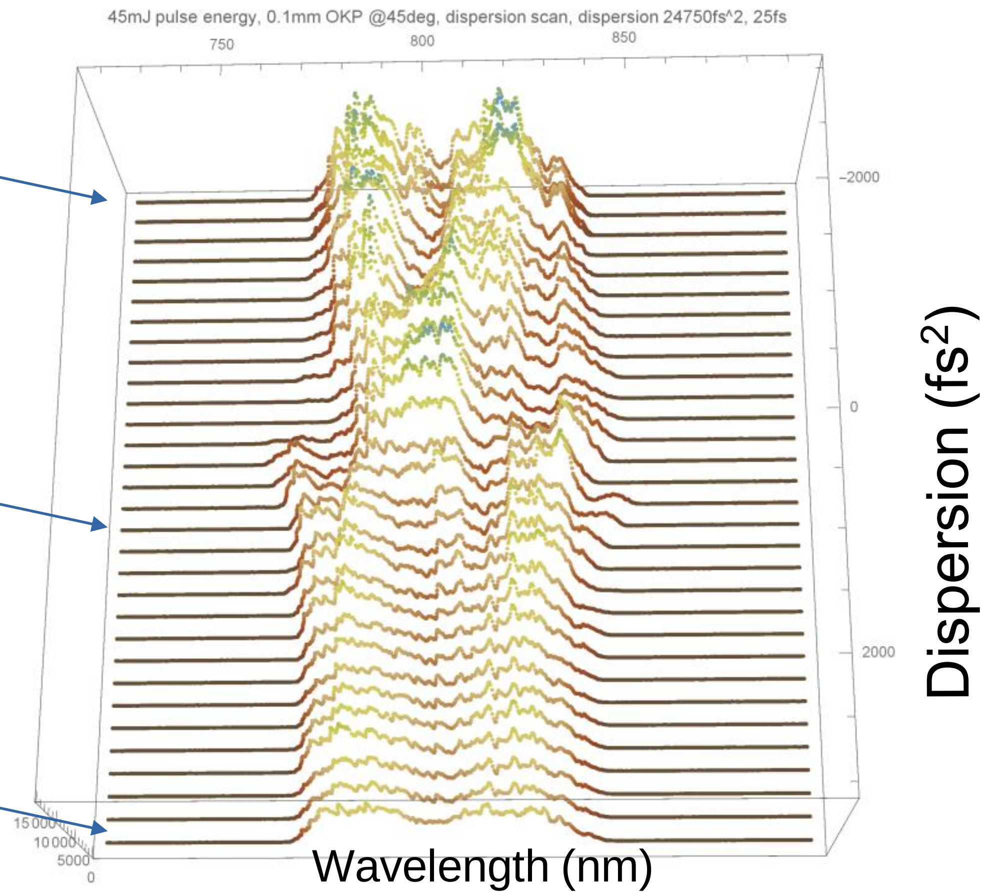
Target position at 250mm from focus. Energy per pulse ~45mJ



~400 fs

23 fs

~400 fs



Glass: BK7 1mm

Plastic: OKP 0.1mm

LWFA Experimental setup of E4

PI: Domenico Doria / Petru Ghenuche

Max Energy: ~ 2.5 J

Pulse duration: ~ 25 fs

Beam diameter: ~ 56 mm

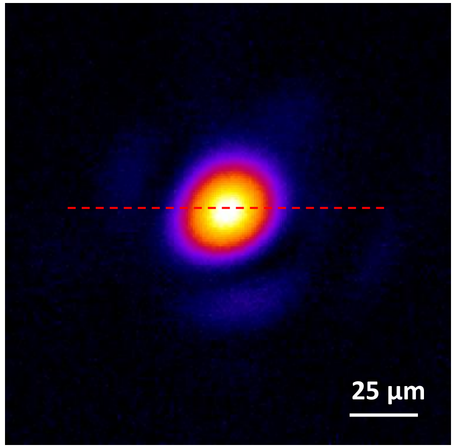
Laser pointing fluctuation: ~ 30 µrad

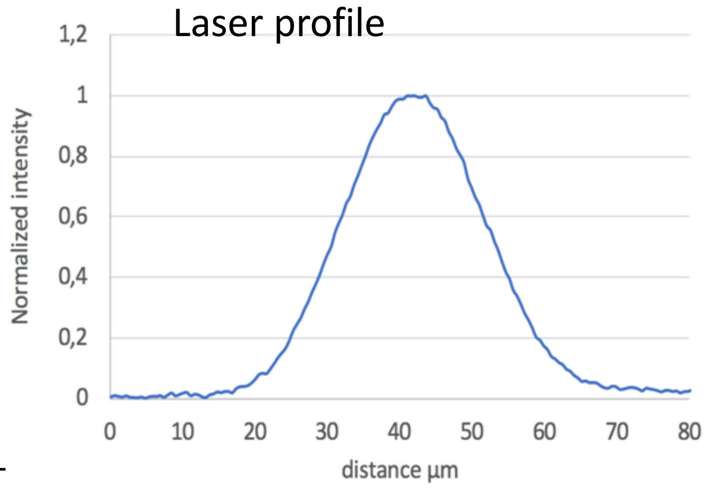
Parabolic mirror: 1.5 m focal length (F# ~27)

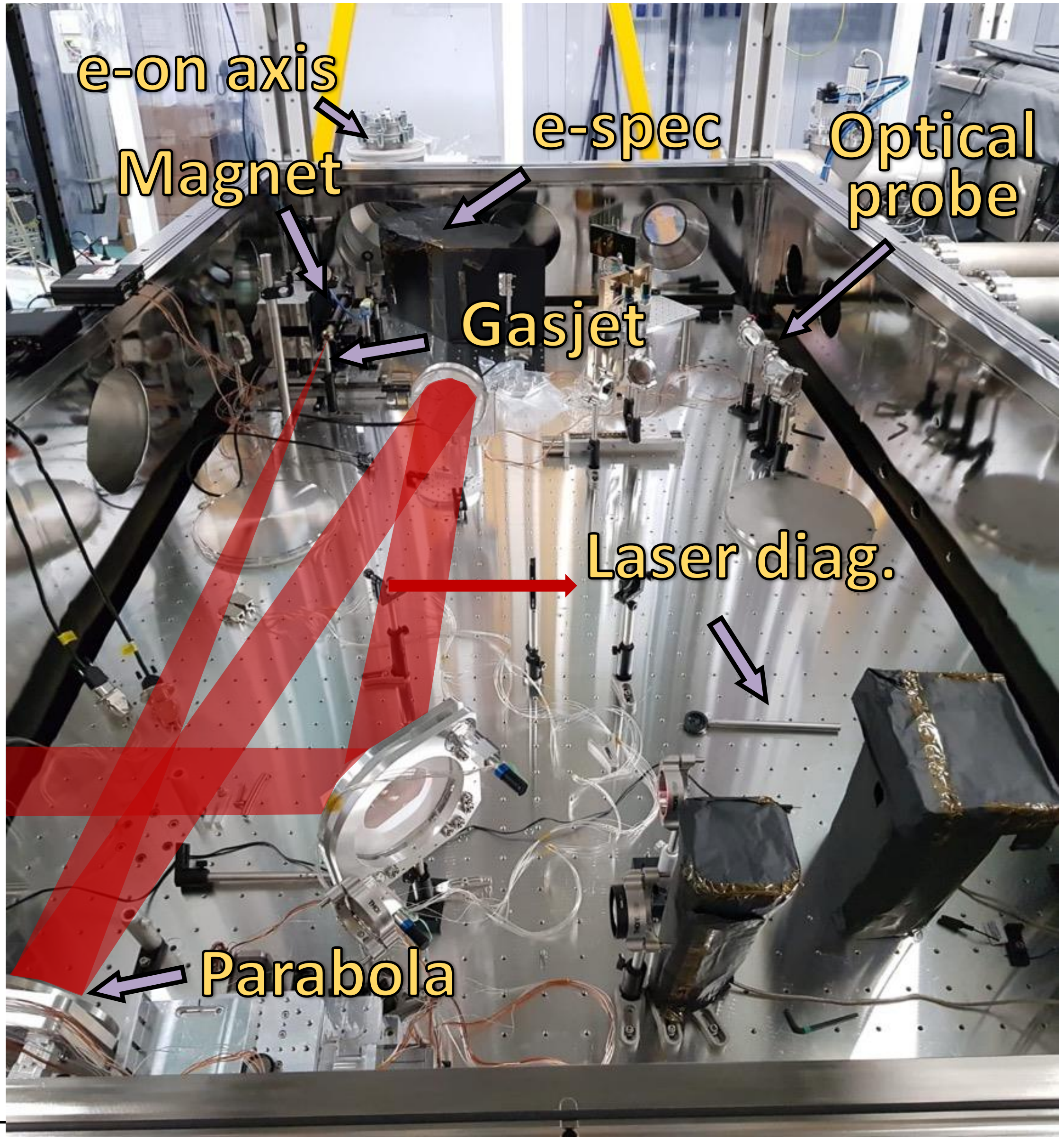
Spot size diameter: ~ 26 µm at FWHM

Encircled energy ~ 67% @ 1/e^2

The laser spot is measured at full power, with attenuation



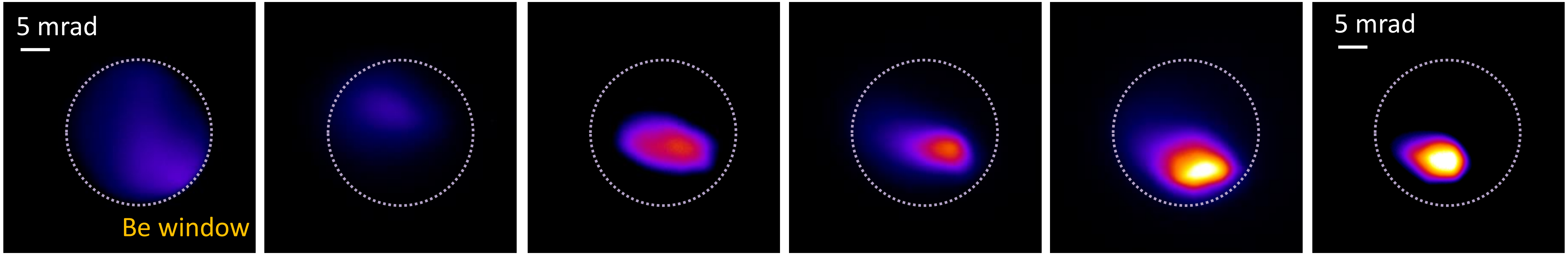




Experimental data for He + 2% N_2

eli nuclear physics

On-axis diagnostics: electron beam profile

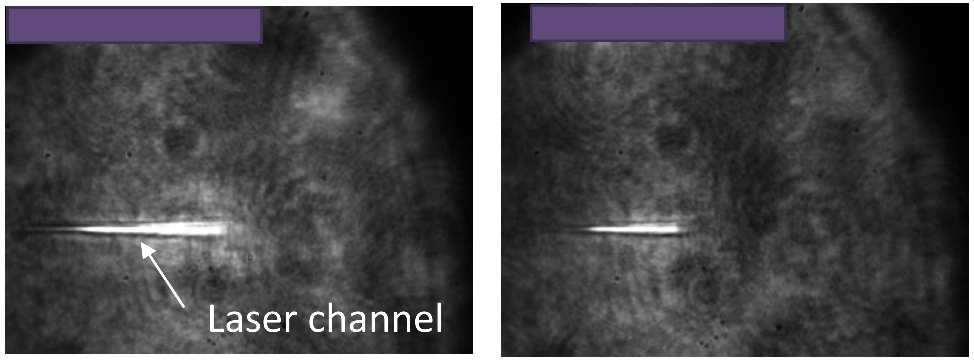


Electron beam profile improvement with further optimization

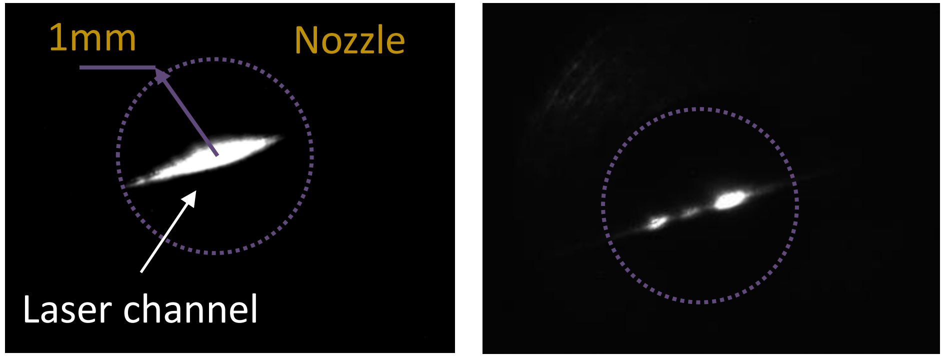
Electron beam divergence ~ 5 mrad, and pointing ~ ±5 mrad

Optical probe

Shadowgraphy



Top view: scattered radiation



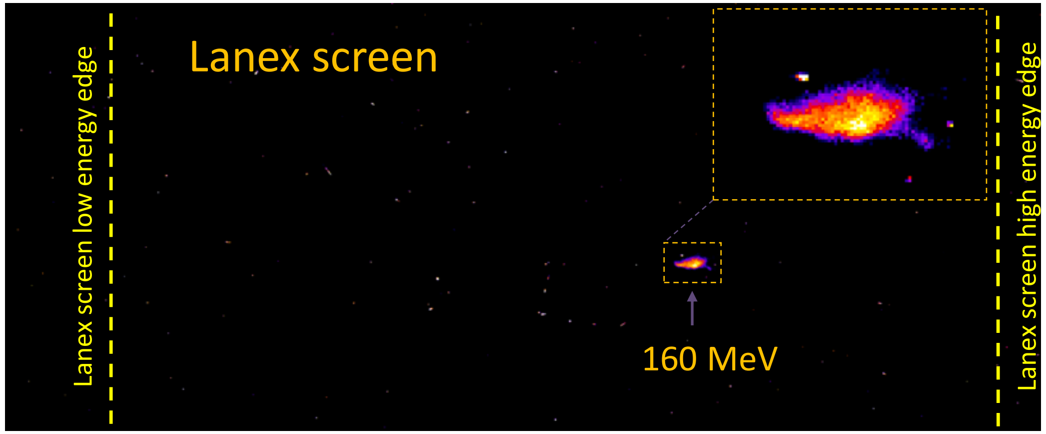
Experimental data

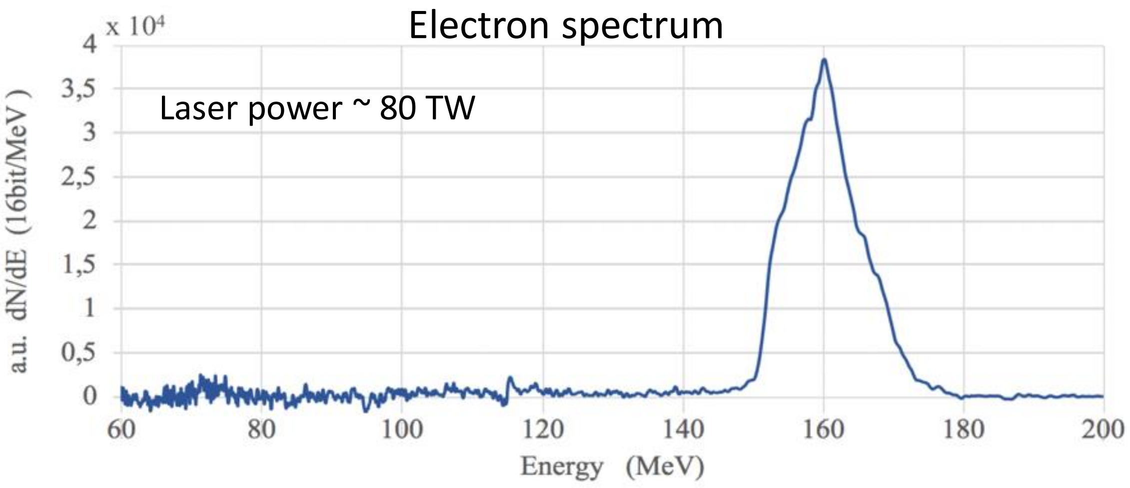
Magnet length: 160 mm
Magnetic field 0.7 T

Nozzle: 2 mm diameter nominal
Gas target: He, He + 2% N_2
Gas density best data ~ $4x10^{18}$ atom/cm^3 @ the plateau

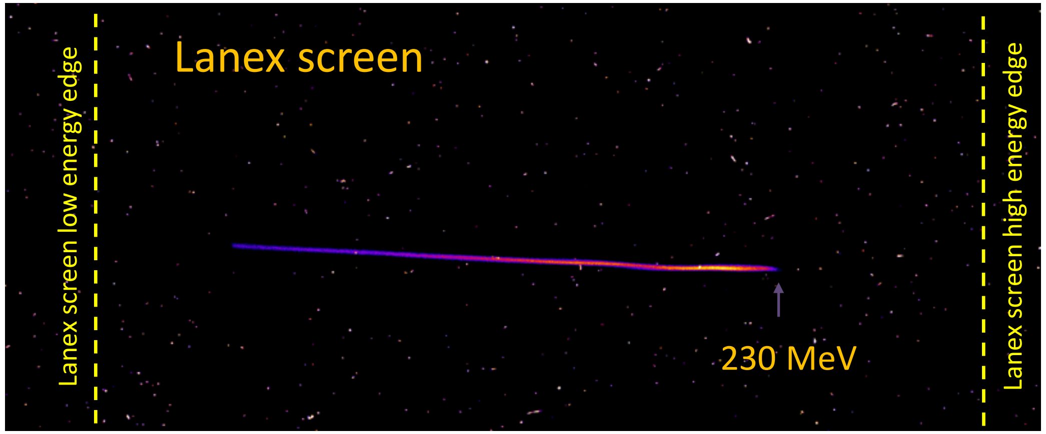
Typical electron spectra obtained

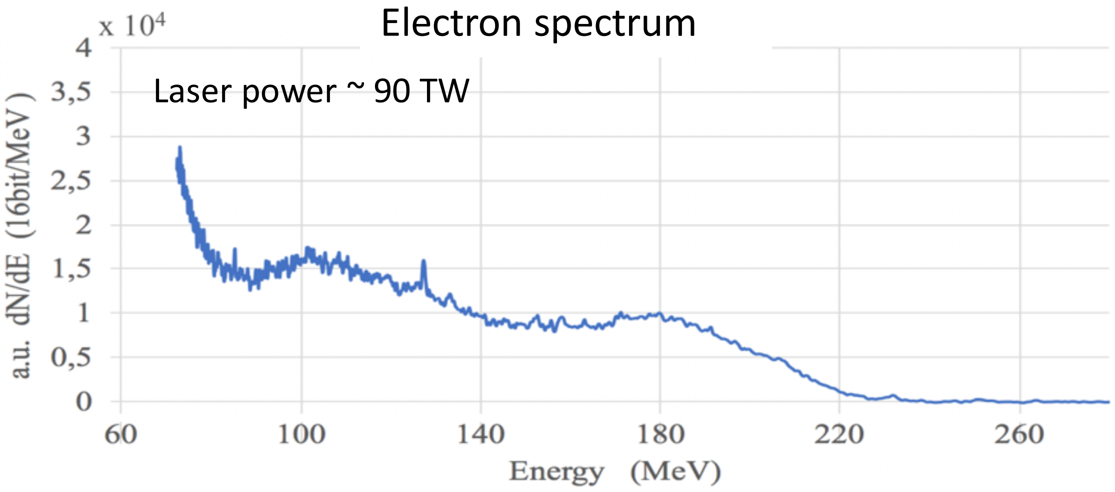
Typical quasi-monoenergetic spectrum with pure **He** gas





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





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E4: 2x100TW@10Hz

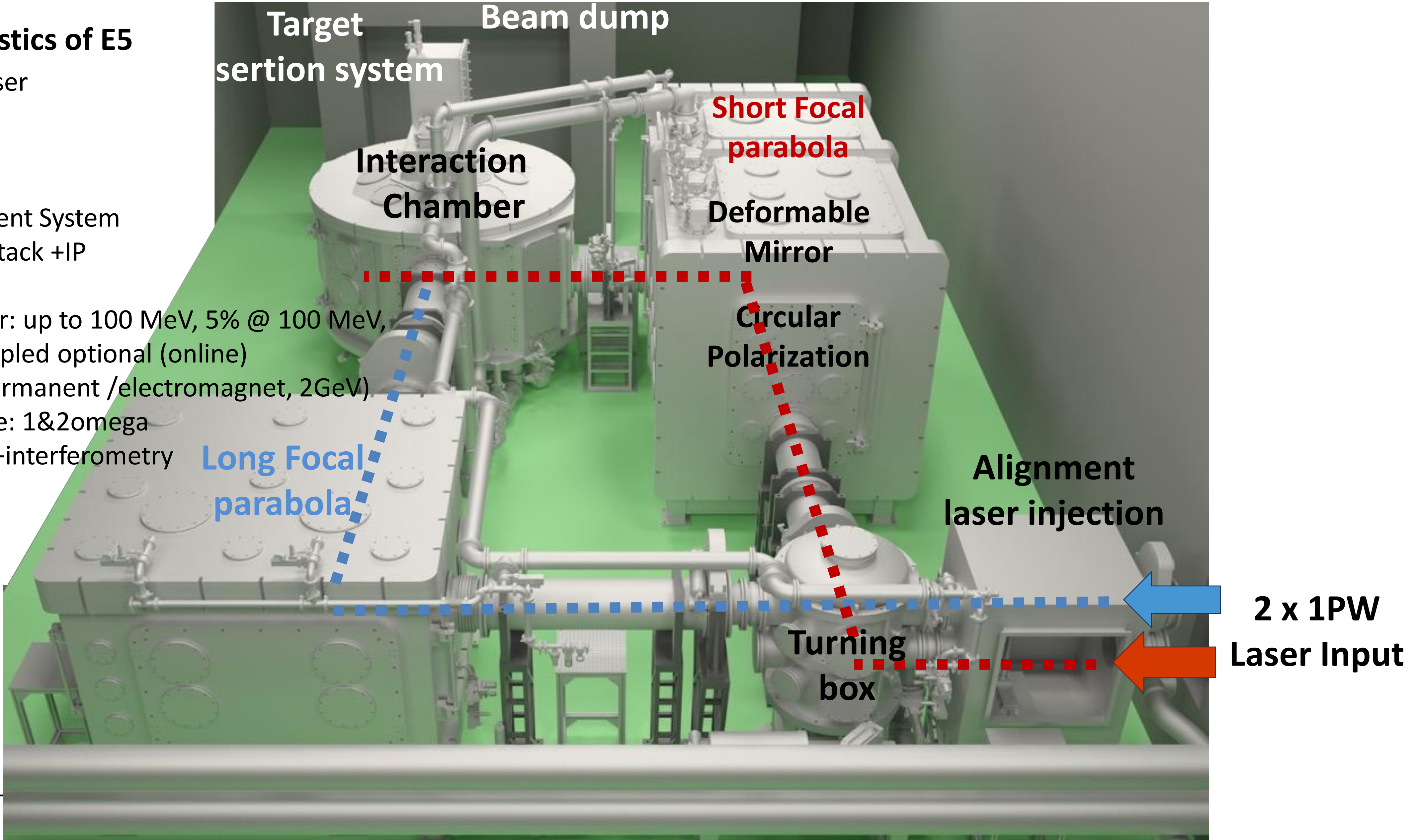
E5: 2x1PW@1Hz

E1/E6: 2x10PW@1 shot/min

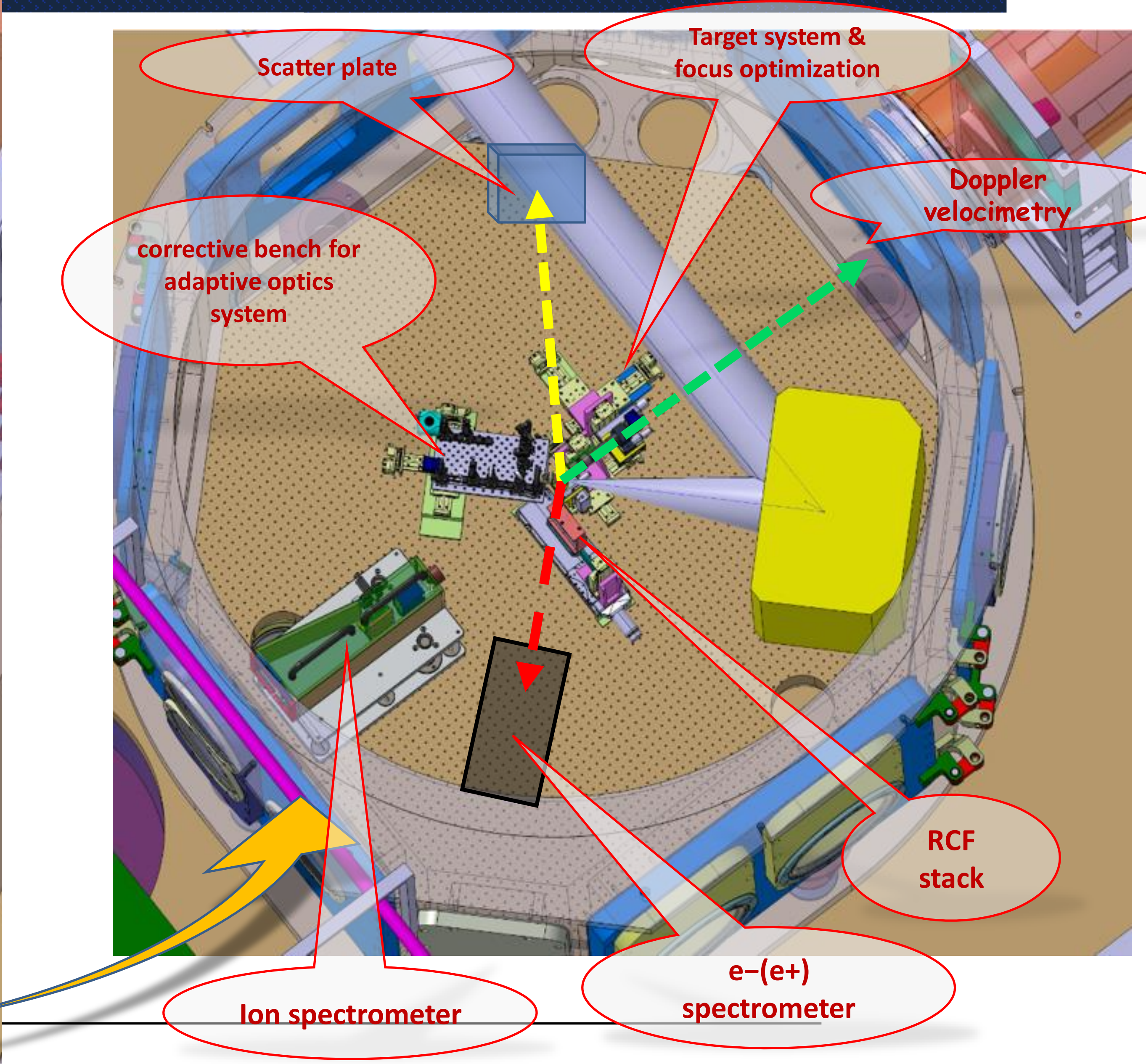
Overview E5 chamber

List of main diagnostics of E5

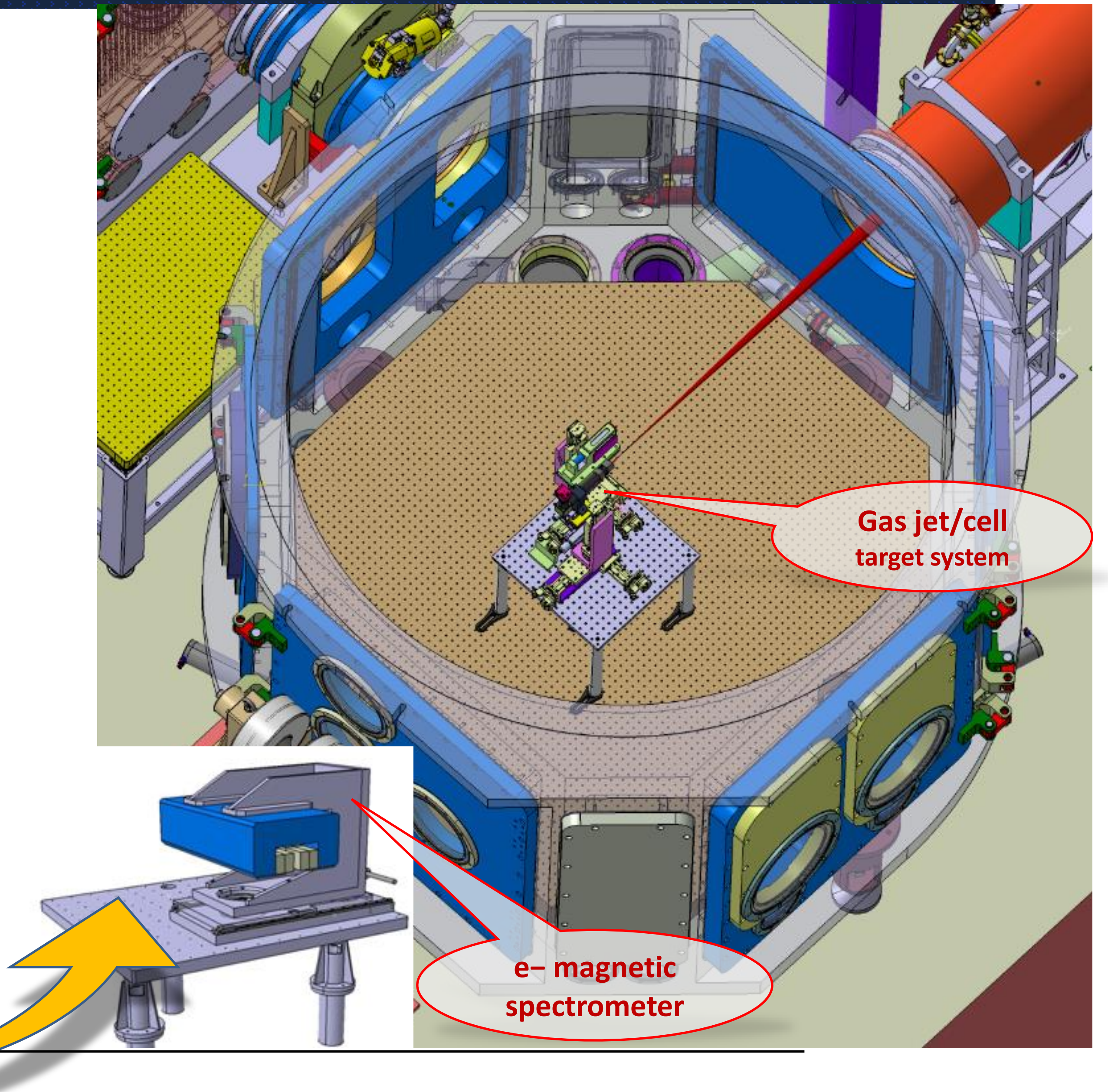
- Internal Injection Laser
- Laser Diagnostics
- Deformable Mirror
- Circular Polarization
- Targetry and Alignment System
- Radiochromic Film Stack +IP
- Thomson Parabola
- e−e+/γ Spectrometer: up to 100 MeV, 5% @ 100 MeV, optically coupled optional (online)
- e− Spectrometer (permanent /electromagnet, 2GeV)
- Optical Plasma Probe: 1&2omega +shadowgraphy +interferometry



E5 chamber: Short Focal Parabola Configuration



E5 chamber: Long Focal Parabola Configuration



E5 on-going proton acceleration experiments preparations

Laser, alignment and target manipulation

Internal Injection Laser: CW 632-800nm, 150mm dia.

Laser Diagnostics: (FF, NF, laser energy at full power, FROG, Stokes Parameters, back-reflection)

Circular Polarization System: Mica waveplates (permanent system upgrade to come)

5X – 20X objectives alignment system, 1µm spatial resolution motion

Deformable Mirror: 52 actuators, 400mm dia. membrane

Shack-Hartmann wavefront sensor λ/100 r.m.s. 32x40 px

Particle detection

Radiochromic Film Stack: 1’’x 1’’, 2’’x 2’’up to 100 MeV proton

Thomson Parabola: up to 60 MeV, 8% res. @ 60 MeV , optically coupled optional (online)

Optical plasma probe: up to 200 mJ, 2w,1’’ dia., ~ µm res., Interferometry, shadowgraphy.

e−p+, Spectrometer: up to 100 MeV, 5% res. @ 100 MeV , optically coupled optional (online)

Streak camera: VIS, 1 ps res.

Optical spectrometer: ANDOR Shamrock (VIS)

Pin-hole cameras: UV-X-ray, ~ 10 - ~ 100 µm res.

Contents

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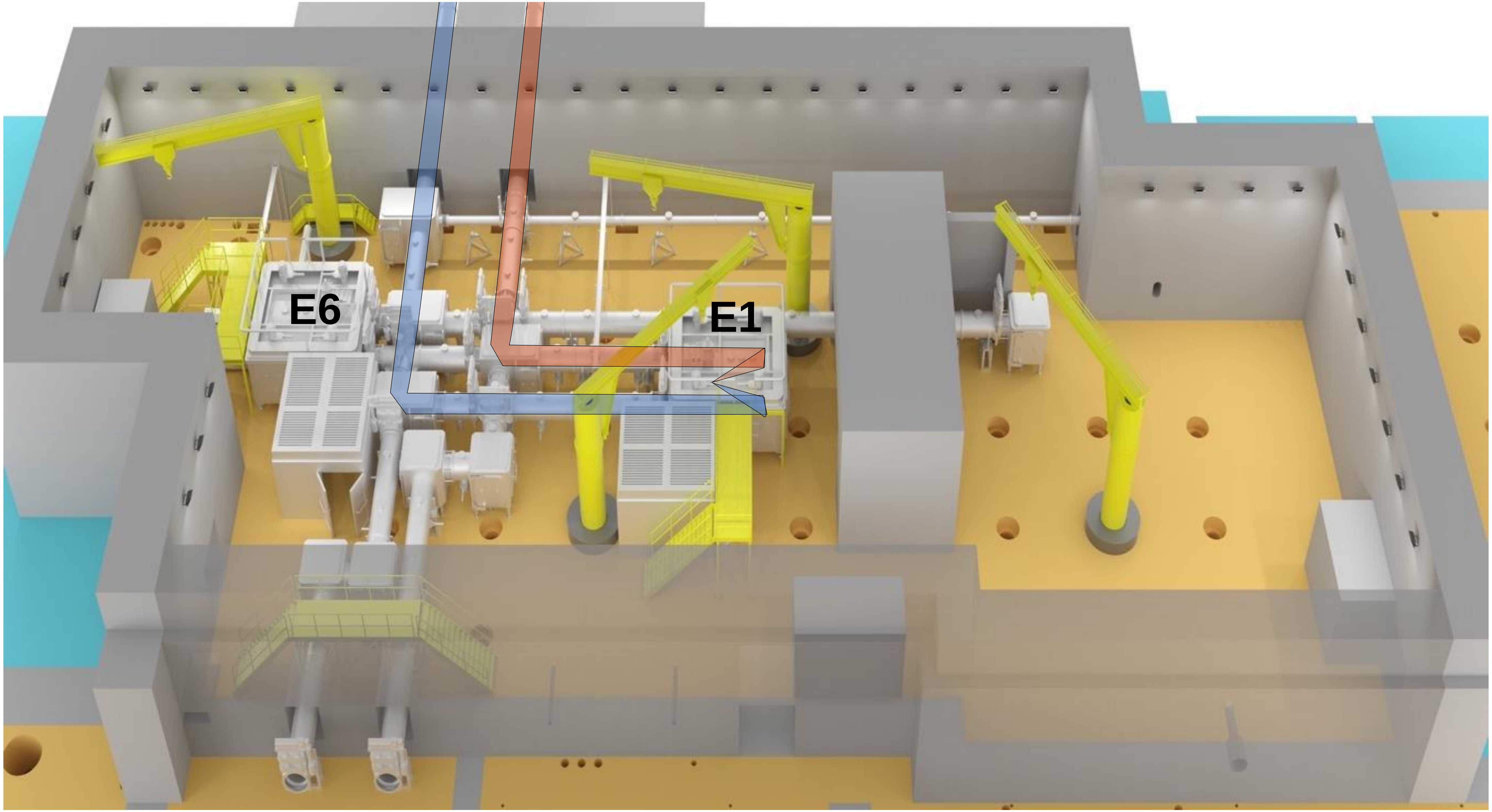
E4: 2x100TW@10Hz

E5: 2x1PW@1Hz

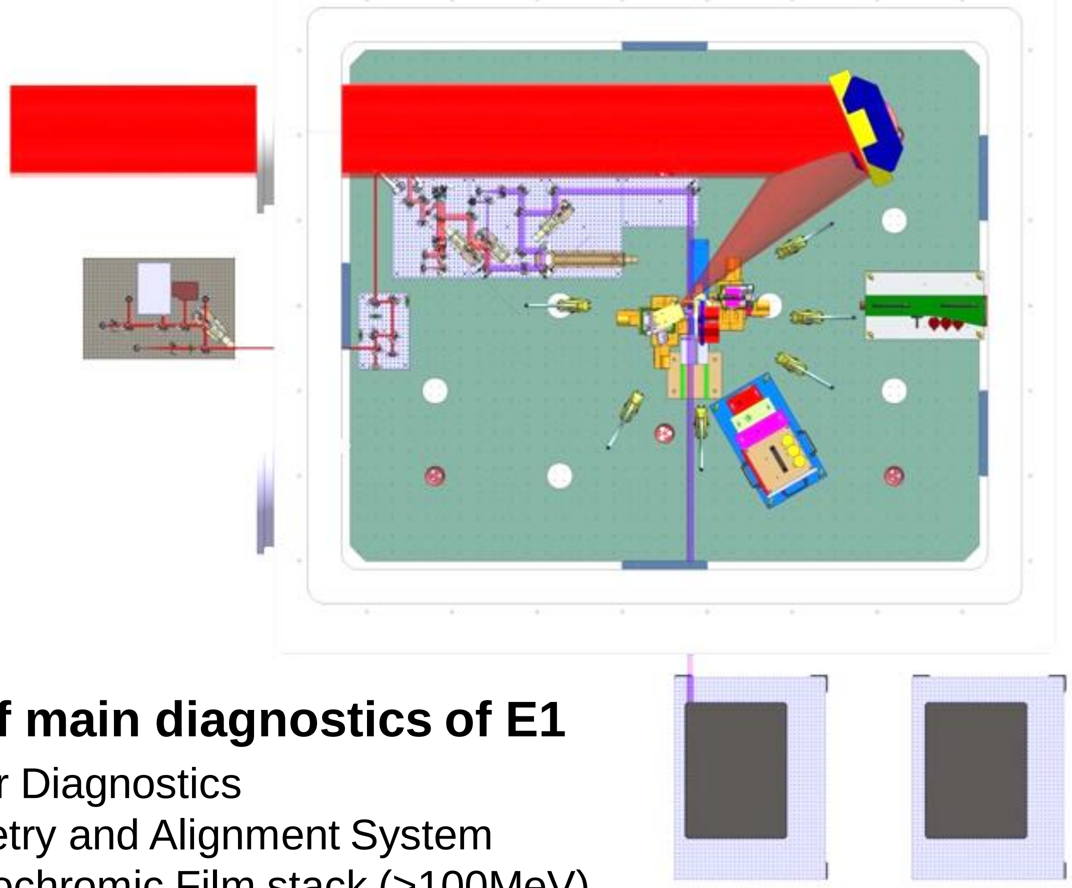
E1/E6: 2x10PW@1 shot/min

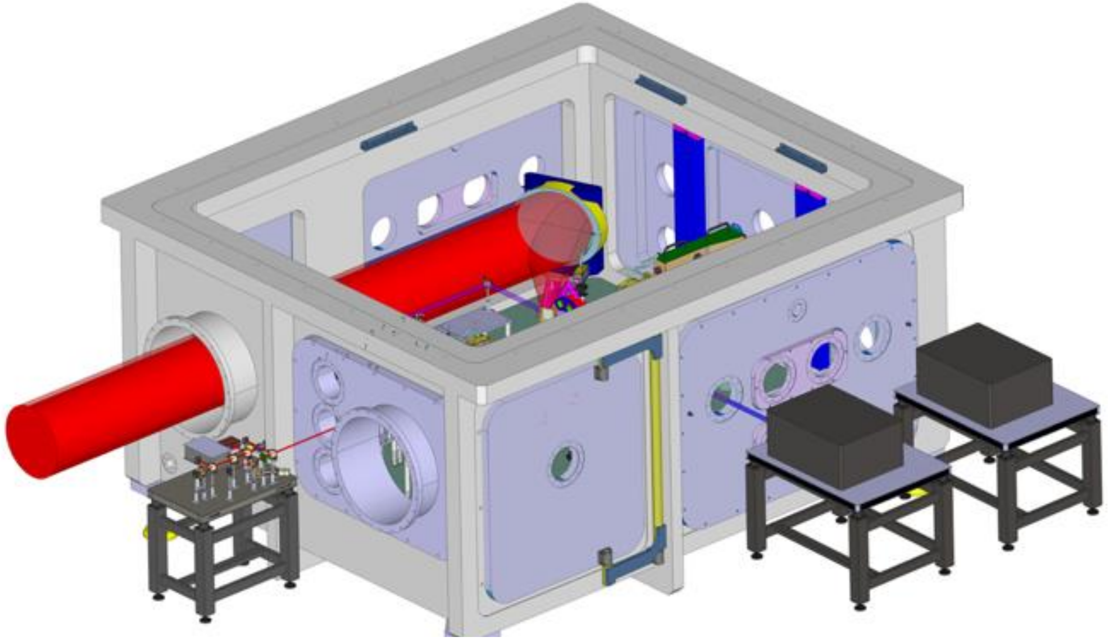
Overview of 10PW Experimental Area

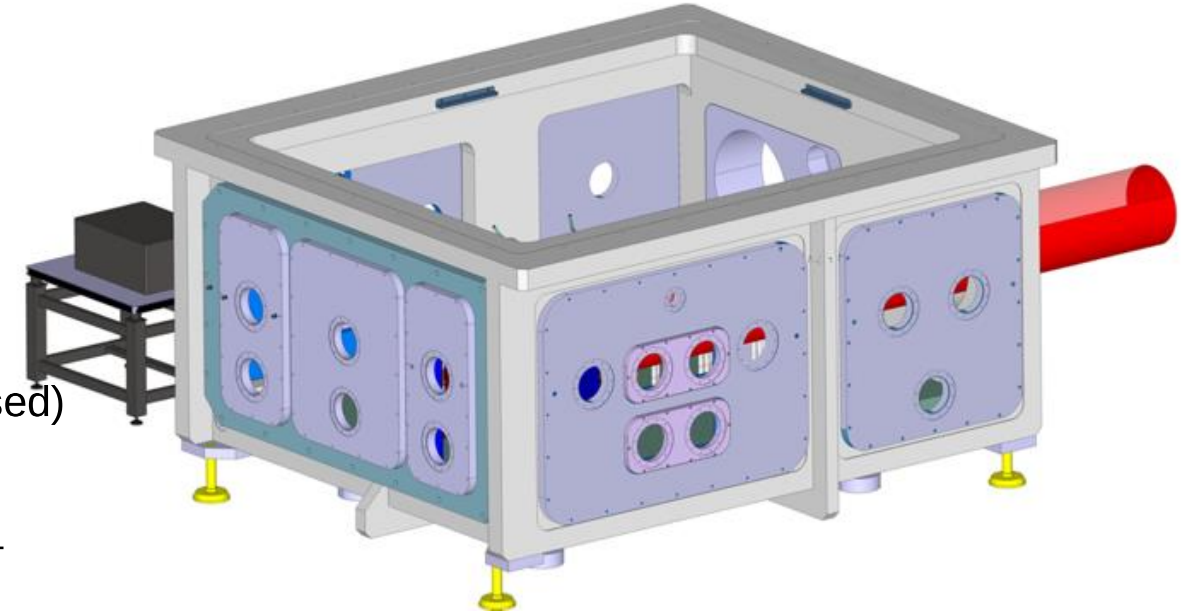


Overview E1 chamber

E1 CAD drawings by Eng. M. Tataru



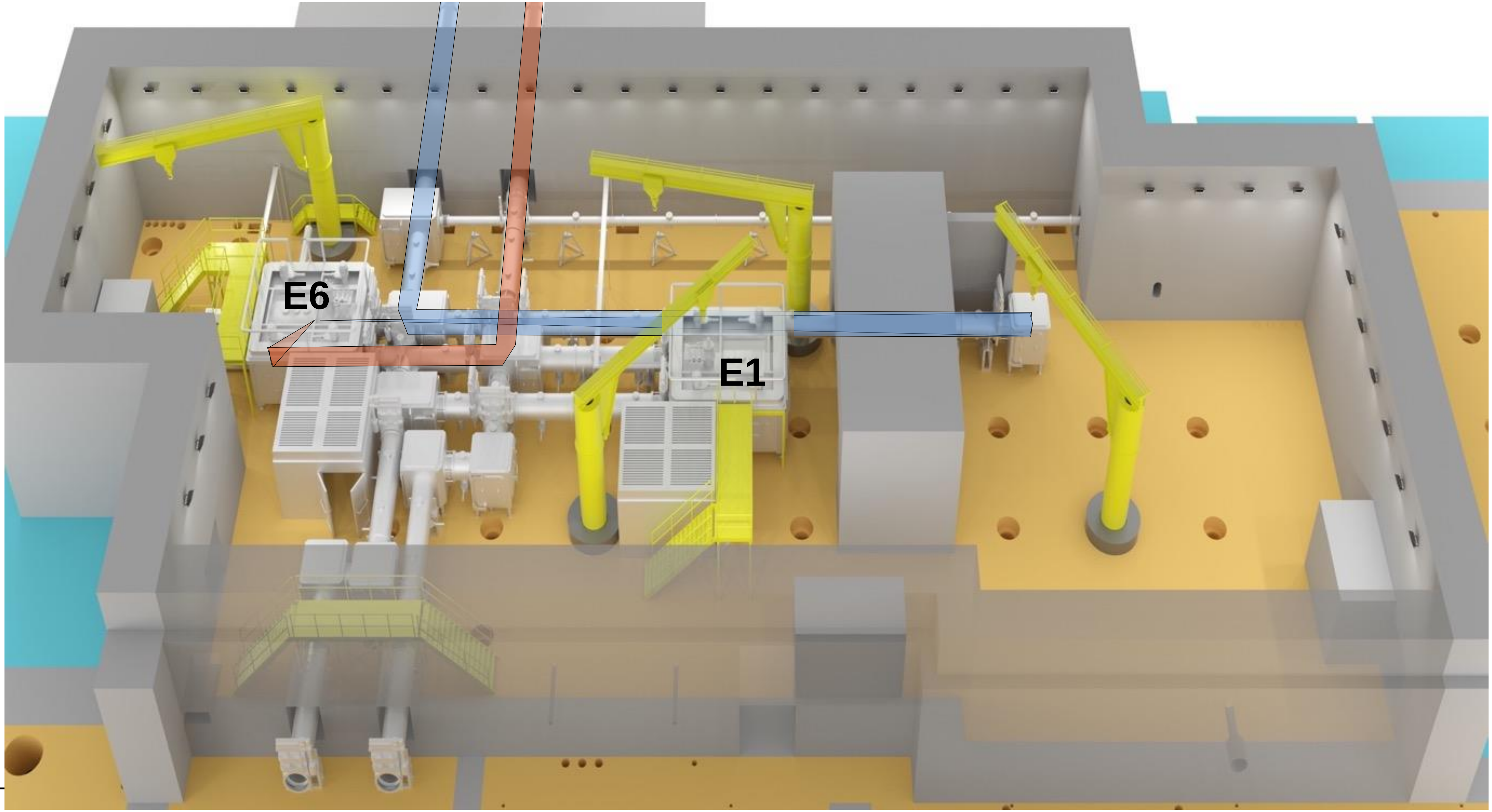




List of main diagnostics of E1

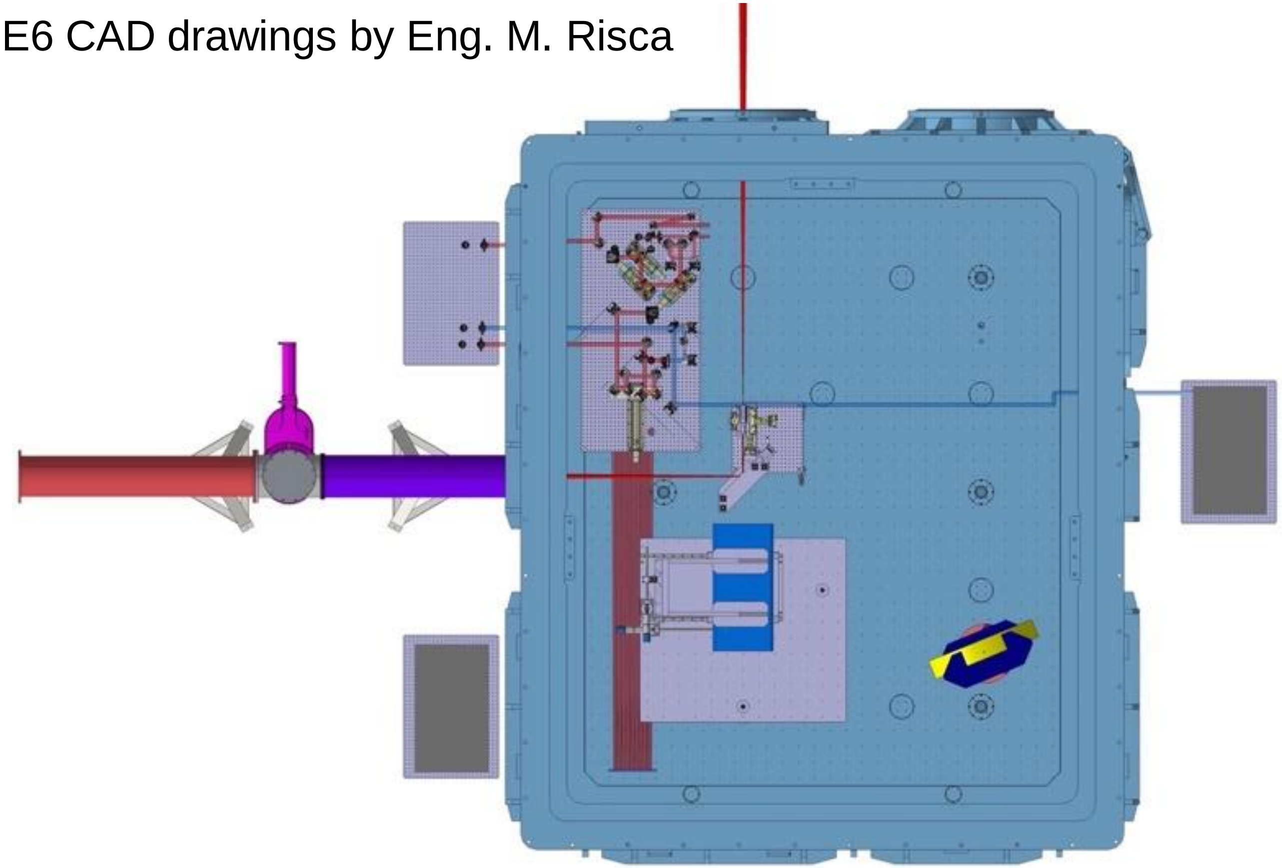
- Laser Diagnostics
- Targetry and Alignment System
- Radiochromic Film stack (>100MeV)
- Thomson Parabola (60MeV/200MeV-250MeV, 8%)
- Forward-Compton gamma spectrometer (10MeV-…; scintillator-based)
- e−, e+ Pair Spectrometer 100MeV
- Angle Resolved Gamma Spectrometer/Calorimeter (CsI)
- ~~Optical Probe/Pump (100mJ)~~

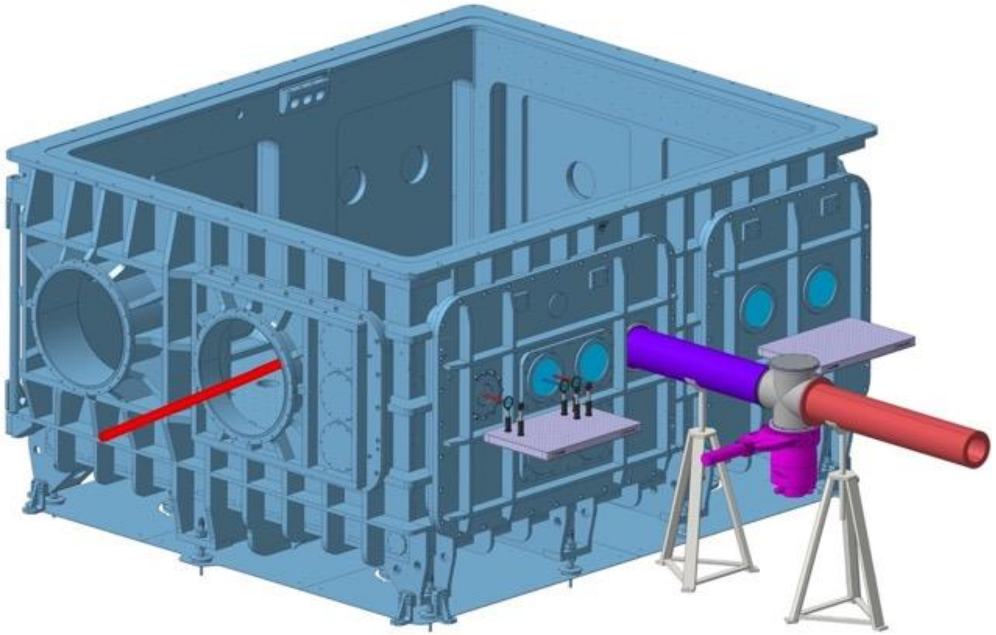
Overview of 10PW Experimental Area

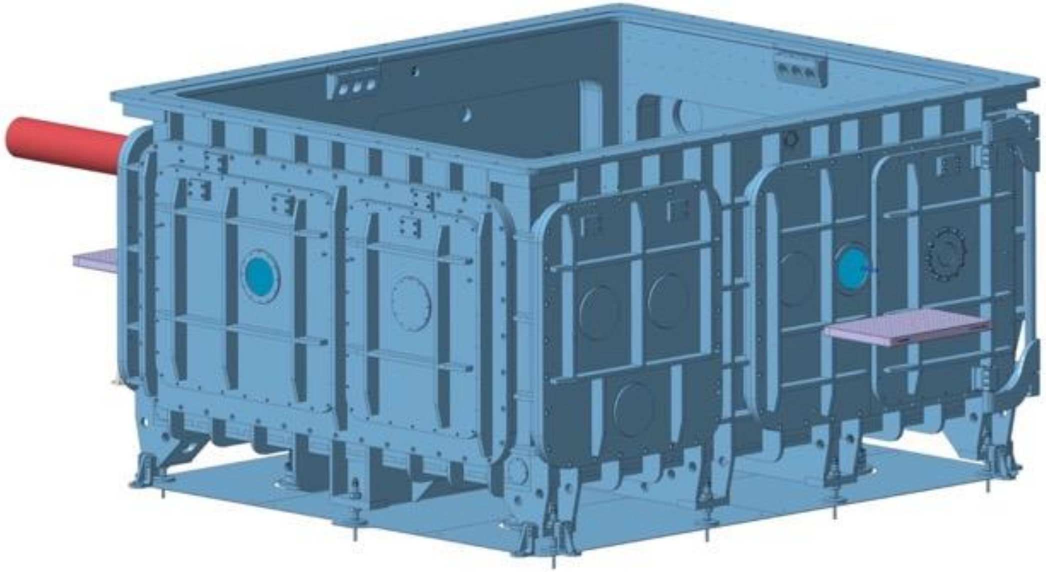


Overview E6 chamber

E6 CAD drawings by Eng. M. Risca







List of main diagnostics of E6

- Laser Diagnostics
- Targetry and Alignment System
- Laser Beam Dump
- e−, e+ Pair Spectrometer
- Optical Probe/Pump

Contents

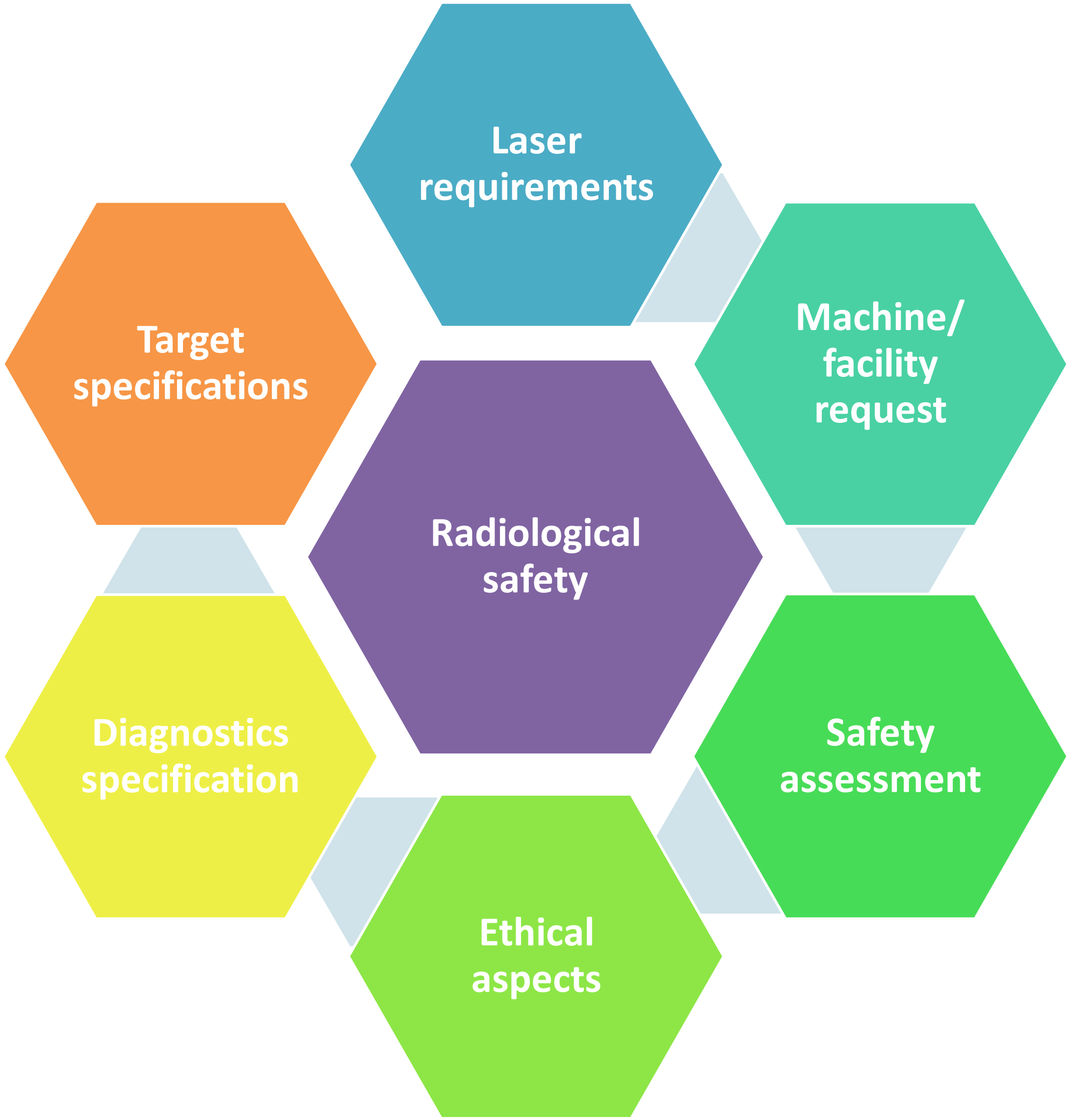
- Architecture of the 2x10PW laser system
- Laser pulse characterization at HPLS
- Experimental areas for laser experiments
- **Beamtime request – further technical aspects**

Beamtime request user application webpage

Home | Beamtime request | Beamtime preparation | Beamtime execution | Data access and publication | ELI-NP Users page

1. **BEAMTIME REQUEST** - guides the user from the application for beamtime until the allocation of the beamtime slot in the schedule of the facility.
2. **BEAMTIME PREPARATION** - Having the allocated beamtime slot, a number of actions related to access clearance, safety training of the user and shipping goods to the ELI-NP have to be performed.
3. **BEAMTIME EXECUTION** - this section reffers to on-site execution of the experiments and includes three parts: experimental area preparation, executing the laser shots and decommissioning of the experiment.
4. **DATA ACCESS AND PUBLICATION** - here the user is guided through the procedures to access the collected data during the beamtime. Also there are general rules to be considered when publishing the outcome of the beamtime.

Beamtime request – technical aspects



Nuclear Physics

Laser requirements

- Parameters for alignment:
- Parameters during the experiments:
- Parameters to be scanned, ranges and steps (shot plan):
- Alignment accuracy:

Machine/facility request

- Specify the beams and the geometry intended:
- Specify the experimental area intended:
- Specify interaction chamber intended (when known)

Target specifications

- Delivery schedule if the targets arrive at ELI-NP
- Target handling specific procedures (avoid damage before the experiment or after)
- Manpower for specific technical works requested (machining, etc)

Diagnostics specification

- List of on-site diagnostics required:
- List of diagnostics devices to be delivered by the users
- Delivery schedule if the diagnostics arrive at ELI-NP
- Utilities requirements for users' devices (specify connector /interface):

Safety assessment

- Assessment of the human safety aspects
- Assessment of the machine safety aspects

Ethical considerations

- Dual use (civilian and military or terrorist):
- Genetic samples manipulation:
- Biological samples (e. g. live animals):

Radiological safety considerations

- Radiological evaluation of materials:
- Uses radioactive isotopes:
- Expected dose during and after experiment:

eli Nuclear Physics

http://www.eli-np.ro/jobs.php

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Structural Instruments 2007-2013

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IFIN-HH

Extreme Light Infrastructure – Nuclear Physics (ELI-NP) – Phase II

eli Nuclear Physics

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Thank you!