Installation laser Apollon : dernières améliorations et perspectives

D. N. Papadopoulos

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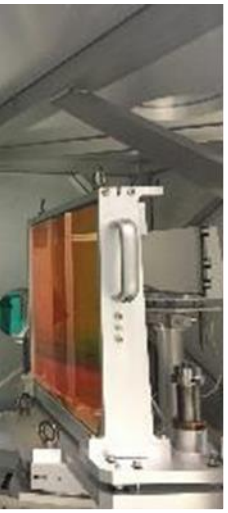



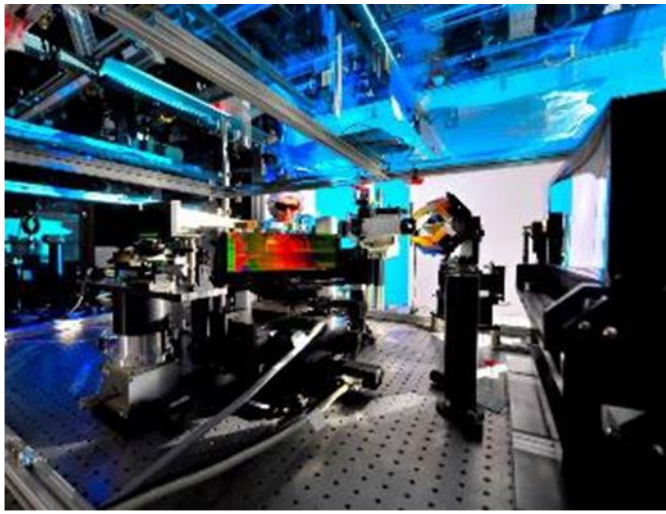

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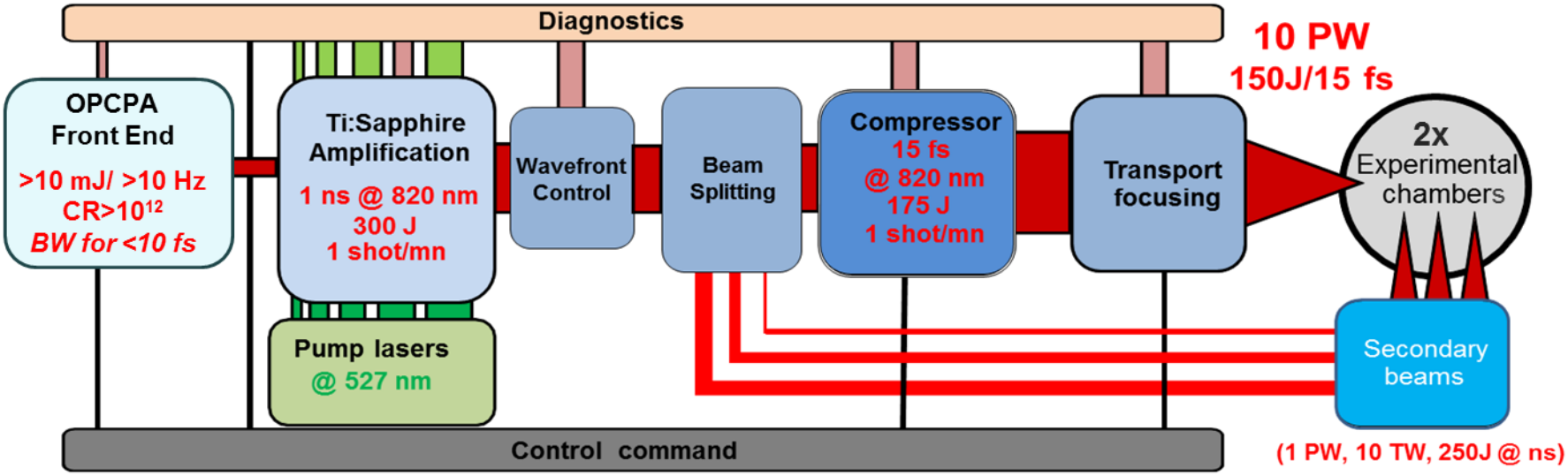
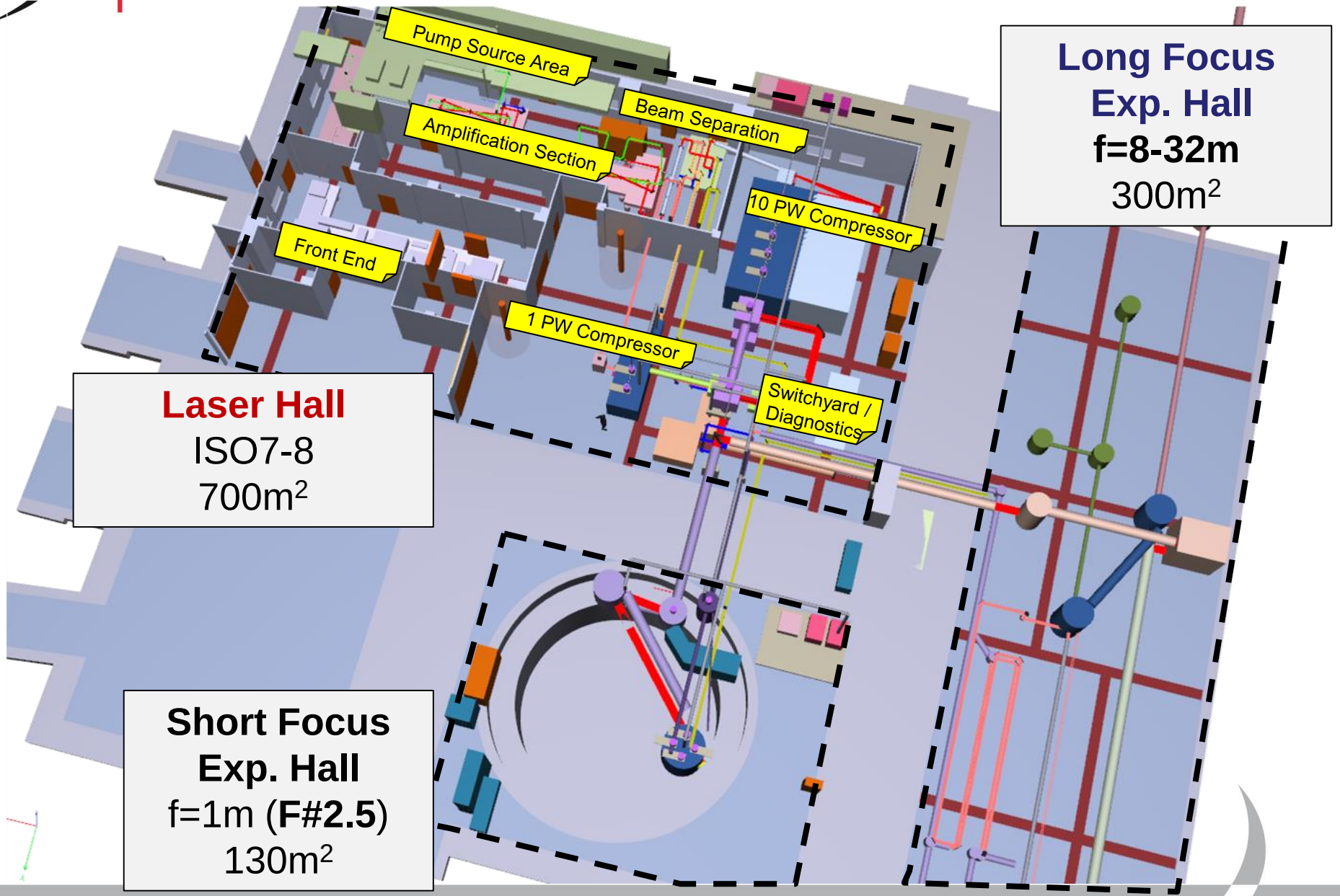
- R&D activities
  - Wavefront stabilization
  - Laser metrology

The Apollon laser

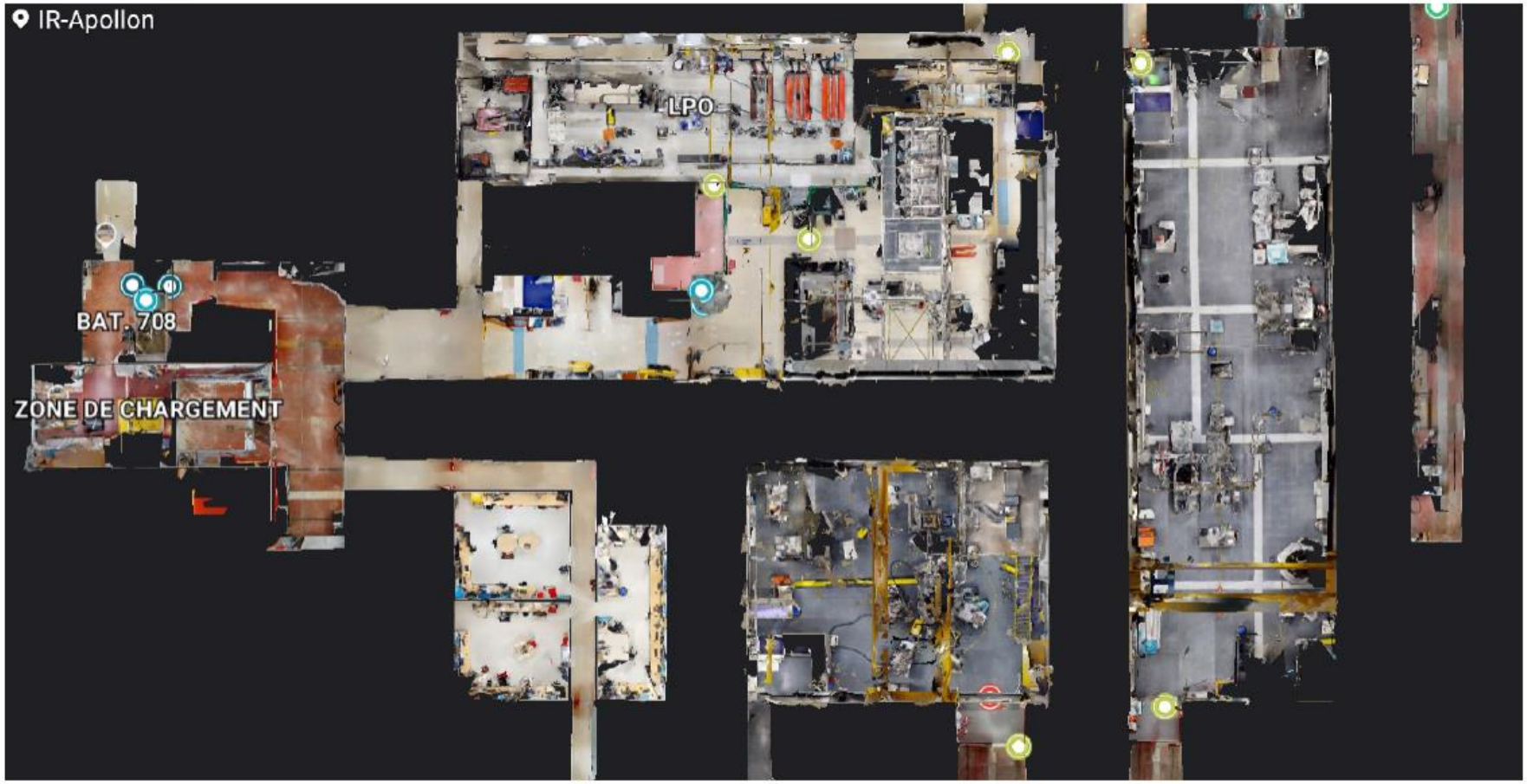


- **Extreme performances:**
  - **10 PW - 150 J/15fs / I>2*10^{22} W/cm^2 / High contrast >10^{12} / 1 shot/min**
- **Apollon key features:**
  - **Hybrid architecture**: OPCPA + Ti:Sa ➔ Contrast + Bandwidth + Energy
  - **Unique Materials**: Φ10-200mm Ti:Sa crystals, Meter size gratings, state-of-the-art optics
  - **4 beam lines/2 experimental areas**

The Apollon Facility



The Apollon Facility: virtual visit



https://my.matterport.com/show/?m=WzYCqomWH4o

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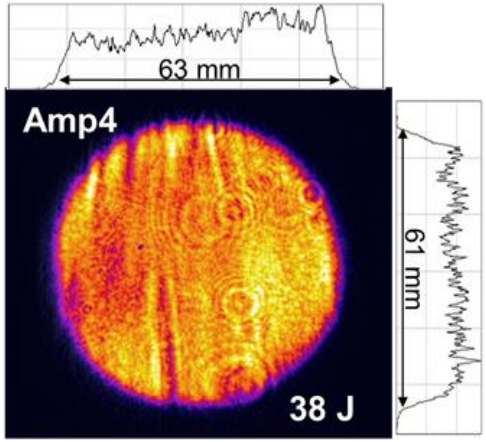
1 PW beamline performances: amplification

- 1st commissioning phase of Apollon with only 4/5 amplifiers

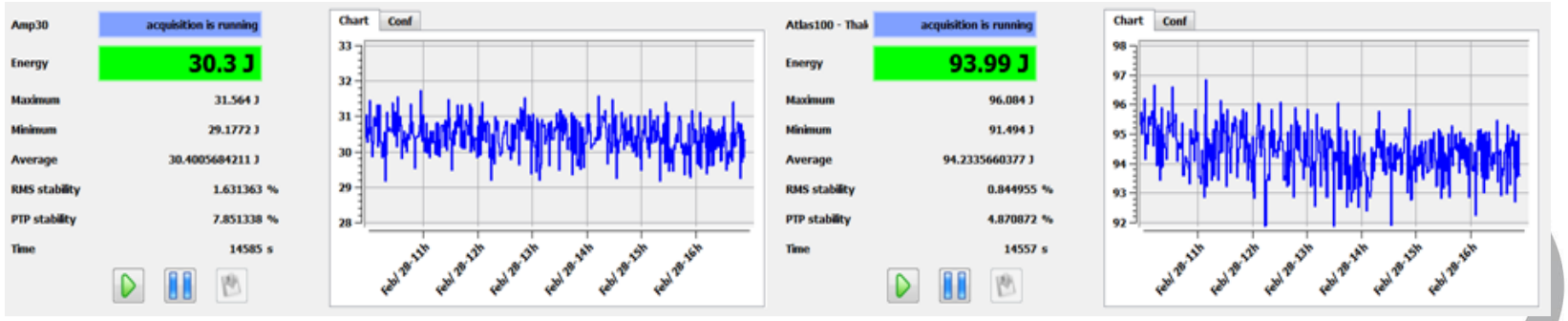


- **ATLAS100** Thales pump source: **100 J/min**
- Output energy: >**38 Joules** for **82 Joules** of pump on the Ti:Sa crystal ⇔ **~44%** efficiency
- Beam quality: **Uniform flat-top like beam**

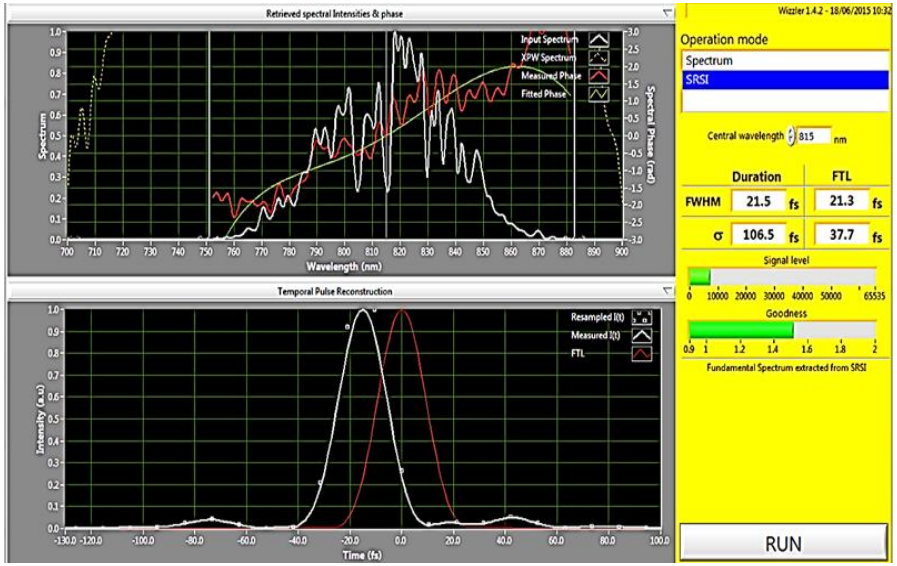
- Highly reliable operation:

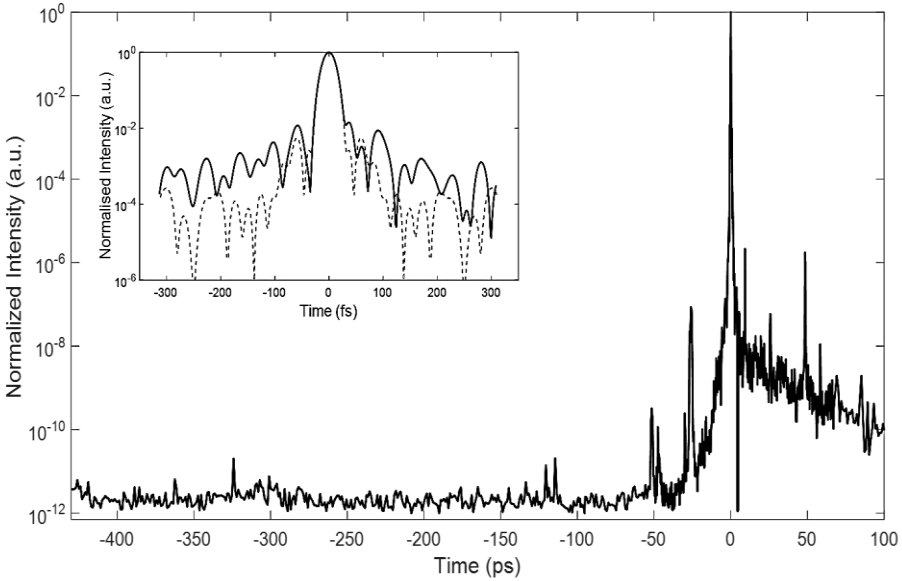
AMP-4
E_{ave} = **30.5J /** 1.6% rms / 7.8% PtP

ATLAS100
E_{ave} = **94J /** 0.8% rms / 4.8% PtP



Compression of the 1 PW beam

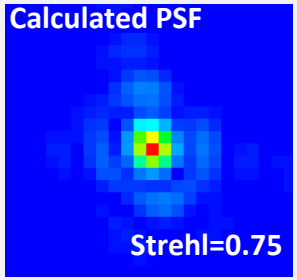


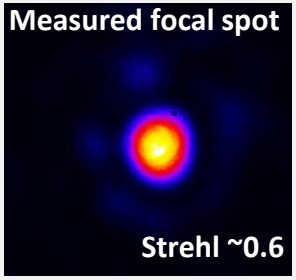


- ✓ Compression + Adaptive spectral phase optimization (b2-b4) ➔ **21.5 fs / 21.3 fs FTL (2019)**
- ✓ Progressive loss of bandwidth in the Front end (aging on the oscillator) ➔ **23-24 fs routinely (2023)**
- ✓ High Temporal contrast : **ASE<10^{-12}**, few prepulses <**10^{-11} (>50 ps)**, <**10^{-6} (<50 ps)**, fast rising edge *(measured at 10 Hz after the 1 st TiSa amplifier + Required characterization at 1 shot/minute)*

1 PW Beam quality on target /stability

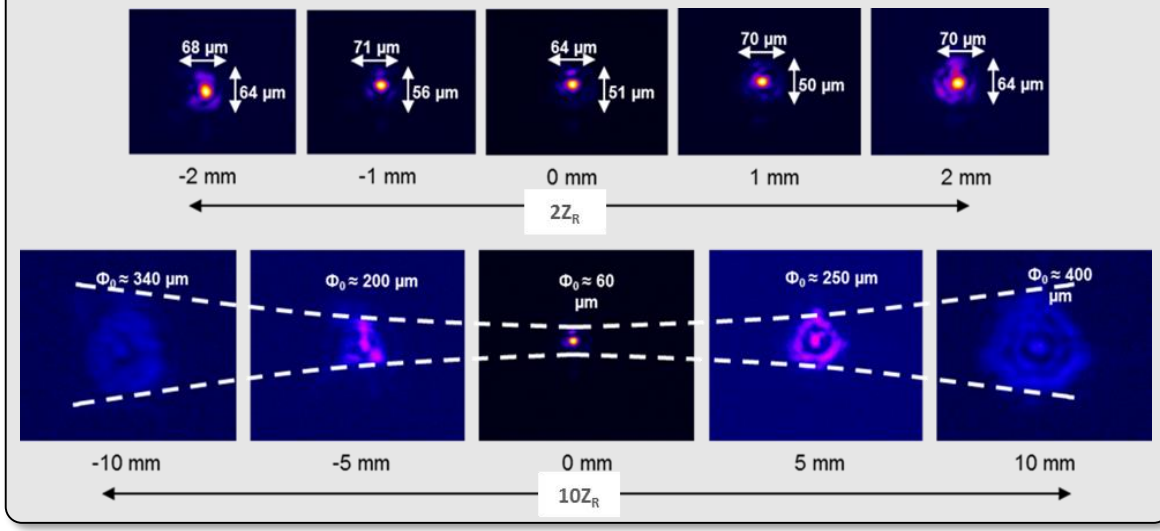
- On target wavefront correction:



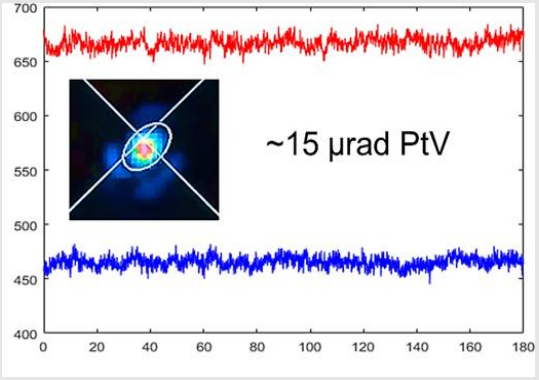


<λ/8 rms residual error / **Strehl > 50%** ➔ I_{max}**>3*10²¹ W/cm²** (F#3, 15J, 25 fs) on the target

- Excellent beam caustic through focus



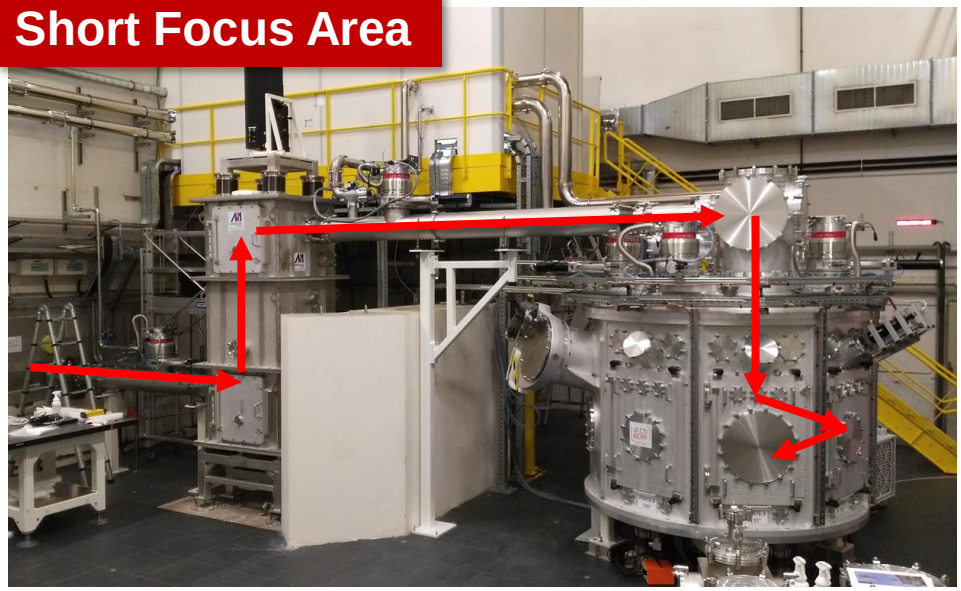
- Excellent pointing stability



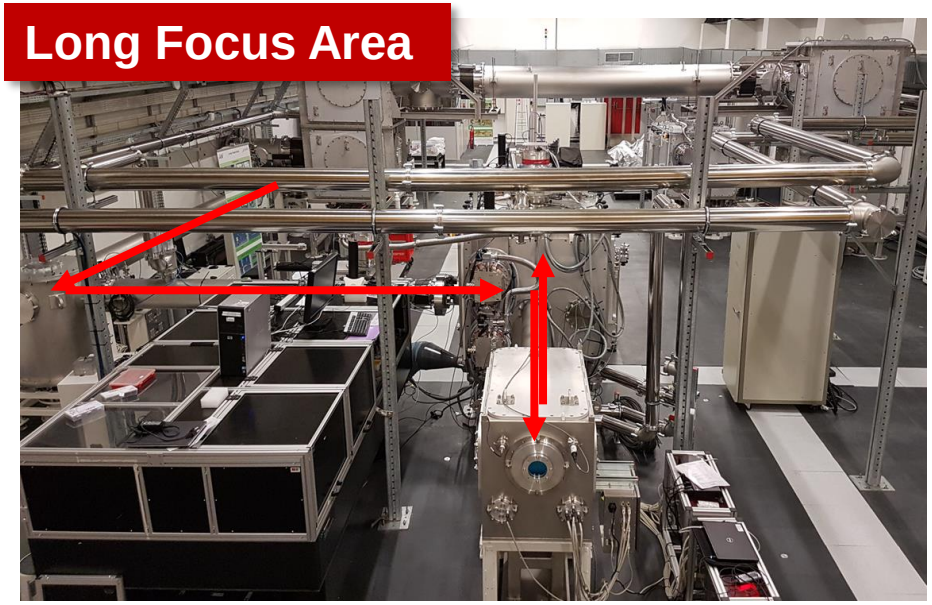
- **±1/2 focal spot** fluctuations PtV
- Practically **no drift** (misalignment) over 3 hours

Experimental campaigns with the 1 PW beam

Short Focus Area



Long Focus Area



- ✓ **First commissioning experiments in both areas:** Nov. 2020-July 2021
- ✓ **Two external calls campaigns 2021-2023 (6+6 campaigns):**
  - Progressively more and more complex configurations / High satisfaction level from the users
  - High quality results: >2.5 Gev in LFA, GeV scale positrons, >25 Mev protons…
  - Many lessons learned / continuous improvement of performances and procedures

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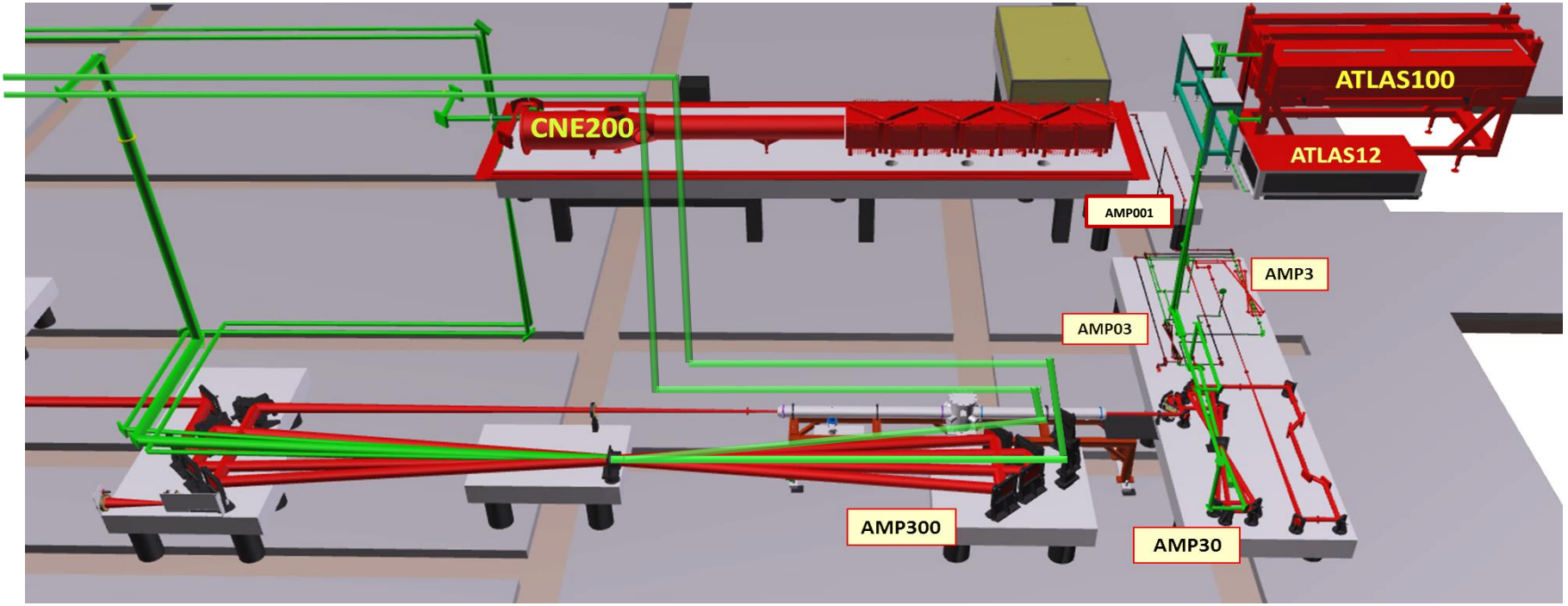
The final Amplifier integration



5x "low-gain" / image-relayed multi-pass amplifiers: Φ3-Φ140 mm => **0.01-300 Joules**

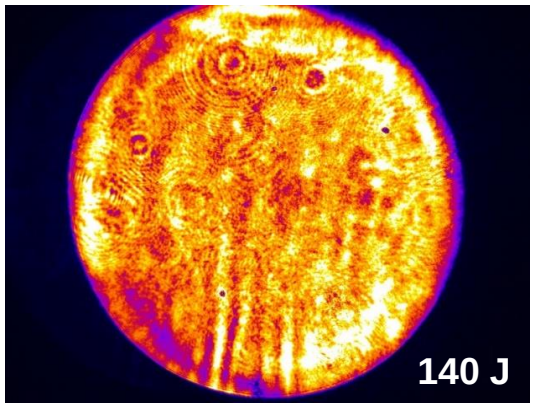
Last amplification stage: Challenging but very flexible design for **high gain & high energy** operation / Very **long beam path** + **7 pump beamlines** in a very specific **spatiotemporal multiplexing configuration**

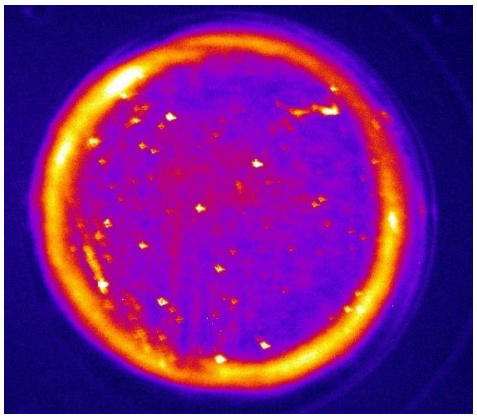
Operation status:

- ✓ **Currently fully operational**: E_{pump}=**300 J** ➔ E_{max}=**140 J** ➔ **3.7 PW** (since 2023)
  - ➢ **1st step of the Pump area upgrade**: E_{pump}=**600 J** ➔ E_{max}>250 J ➔ **>7 PW** (2024)

Performances

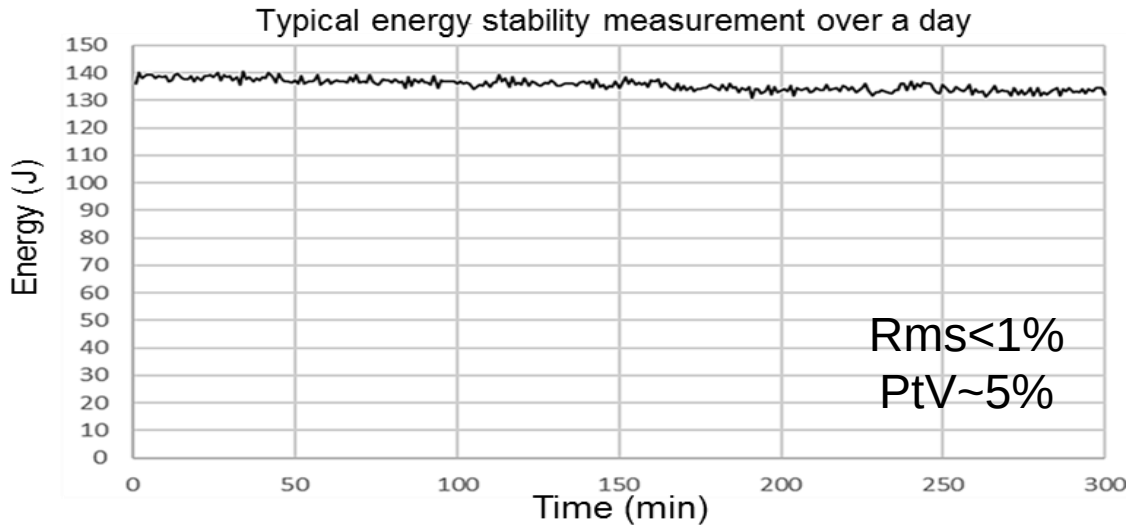
- Final amplifier operation





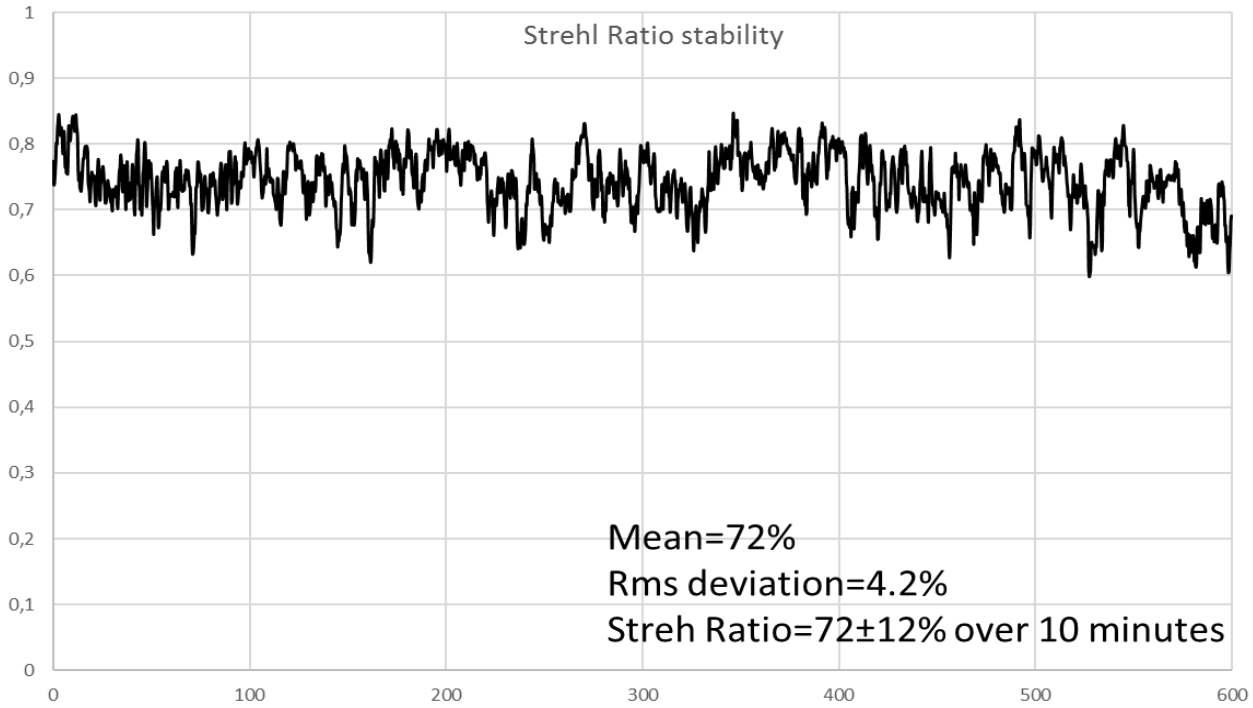
- E_{out}= **140 Joules** (E_{in}=25 Joules)
- E_{pump}=**270 Joules** (6 beamlines)
- Energy Extraction efficiency=**43%**

- Reliability tests: Over 1 week / 5 hours/day => **1500 shots**



Wavefront stability: covering the last amplifier

- The last amplifier adds about **50 m of free beam propagation**
- First tests with large volume global covering➔ **Strehl ratio 55±30%**
- Preliminary « Tight » covering closer to the beam ➔ **Strehl ratio ~70±10%** about a **3-fold improvement** but still not « satisfactory »
- Better (more hermetic) solid covering + Active wavefront stabilization (THRILL project)



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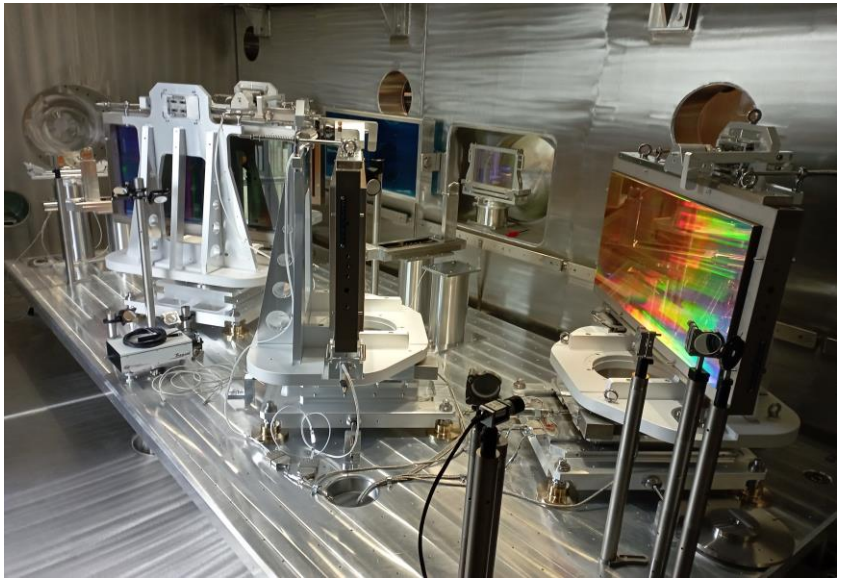
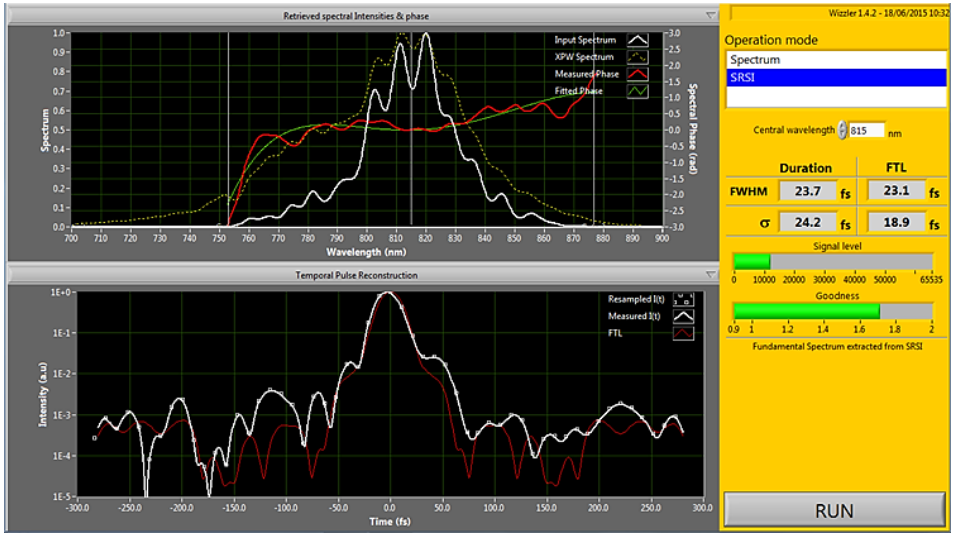
Pulse compression



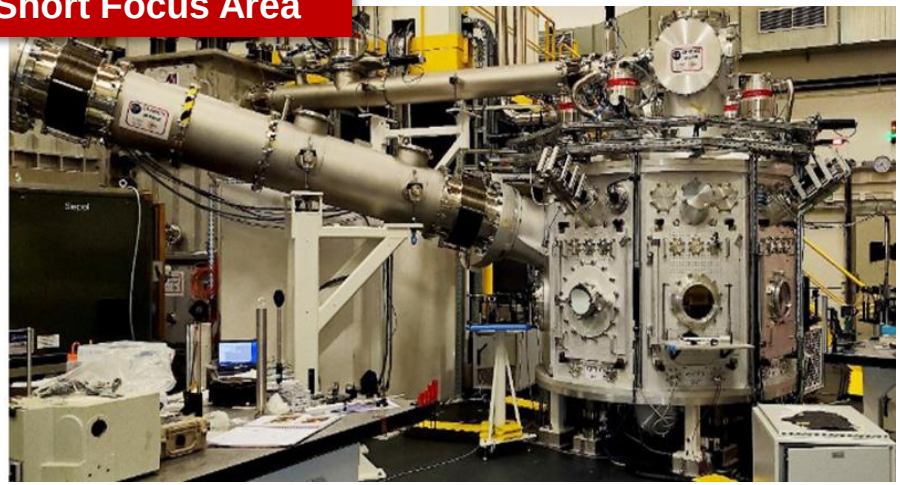


- **10 PW compressor:** 4 gold gratings, **910 mm x 455 mm** (**LLNL**), 1480 t/mm, ~**70% efficiency**
- Full energy compression at **~24 fs (23.1 FTL)**
- **High contrast:** Estimated **ASE<10^-12, prepulses <10^-8** *(work in progress for the complete characterization and further optimization… Summer 2024)*

Experimental qualification

- Experimental areas

Short Focus Area



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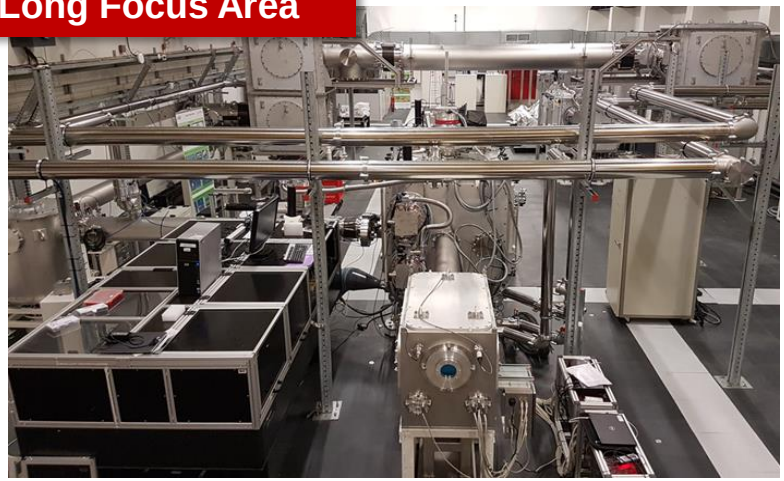
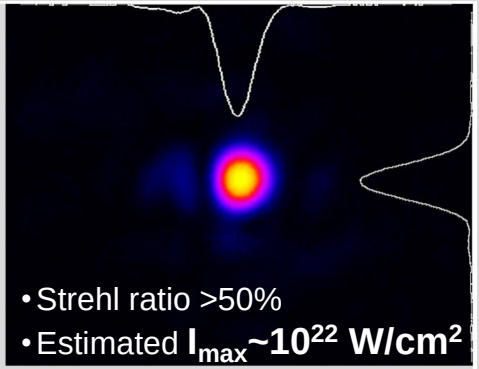


- **Short focus area (SFA)**: F#2.5
  - ✓ *Minimal laser optimization and commissioning time… about 75 J in the chamber, 50% Strehl ratio… STILL A LOT TO BE DONE!!!*
    ➔ ***July-October 2024 detailed F1 laser commissioning in SFA***
  - ✓ *First commission campaigns at ~**2 PW on the target** due to parabola protection losses (June 2023… see presentation of Weipeng YAO tomorrow)*

- **Long focus area (LFA):** F up to 32 m
  - ➢ *Beam transport in construction… end of 2024*

Typical multi-PW focal spot in SFA



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Next steps

- **Increase of the pump energy**:

  CNE upgrade (ongoing)➔ **300 Joules** Beginning 2024 ➔ Total pump energy of **600 Joules** ➔ Further increase to 650 J possible…

- **Commissioning of the Amp5 at full energy**:

  Eout > 250 Joules (2024)

  Peak power capacity:

  7 PW (0.65%*250J/22fs) 2024
  9 PW (0.65%*250J/**18fs**) 2025
  10 PW (0.65%***280J**/**18fs**) …2026
  10 PW on the target… **280J/15 fs** *…possible but requires several upgrade steps on the spectral management of the chain*

- **Upgrade of the Front End** (January 2024): Thales system/Apollon design➔ Stability+Performances+SAV

- **Experimental campaigns with F1 in LFA**:

  Internal PI commissioning experiments up to 7 PW beginning 2025
  1st external users call: May 2025 – May 2026

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CONSORTIUM

The project consortium is composed of eight partners from four European countries:

- **Strong involvement (4 years) of LULI in 3-axes:**
  - High energy coherent beam combination (nanosecond/KJ systems)
  - Active stabilization of wavefront in UHI lasers (Apollon/LULI)
  - Improvement of laser beam transport systems (Apollon/LULI)

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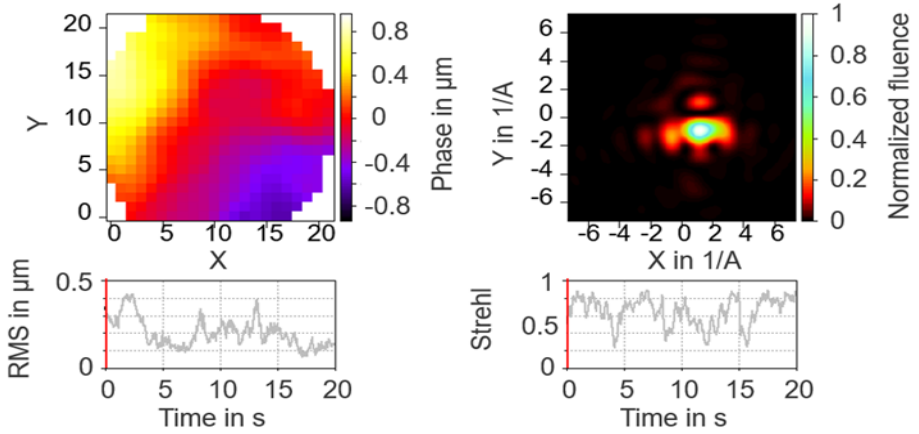
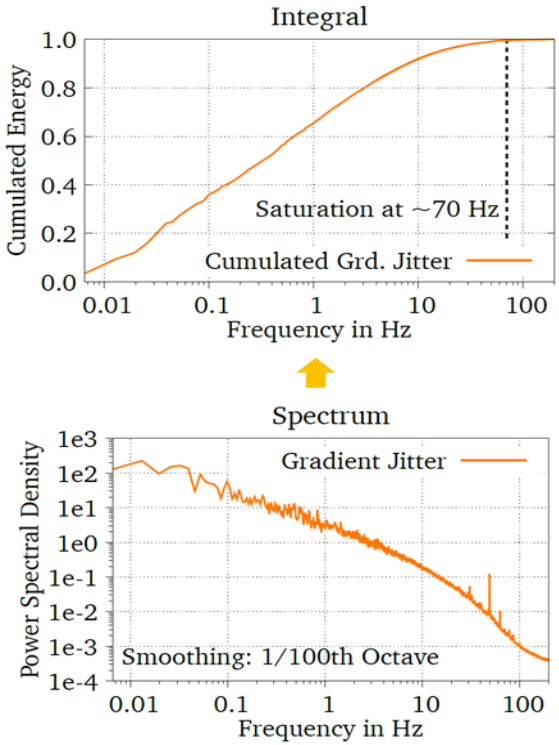
Wavefront stability of the Apollon laser

- Measurements in the amplification area including the last amplifier (no cover)





Characterization:

- Spatial saturation: 20 Eigenmodes / Temporal saturation: 70 Hz / 3σ amplitude: 3 µm Peak-to-Valley

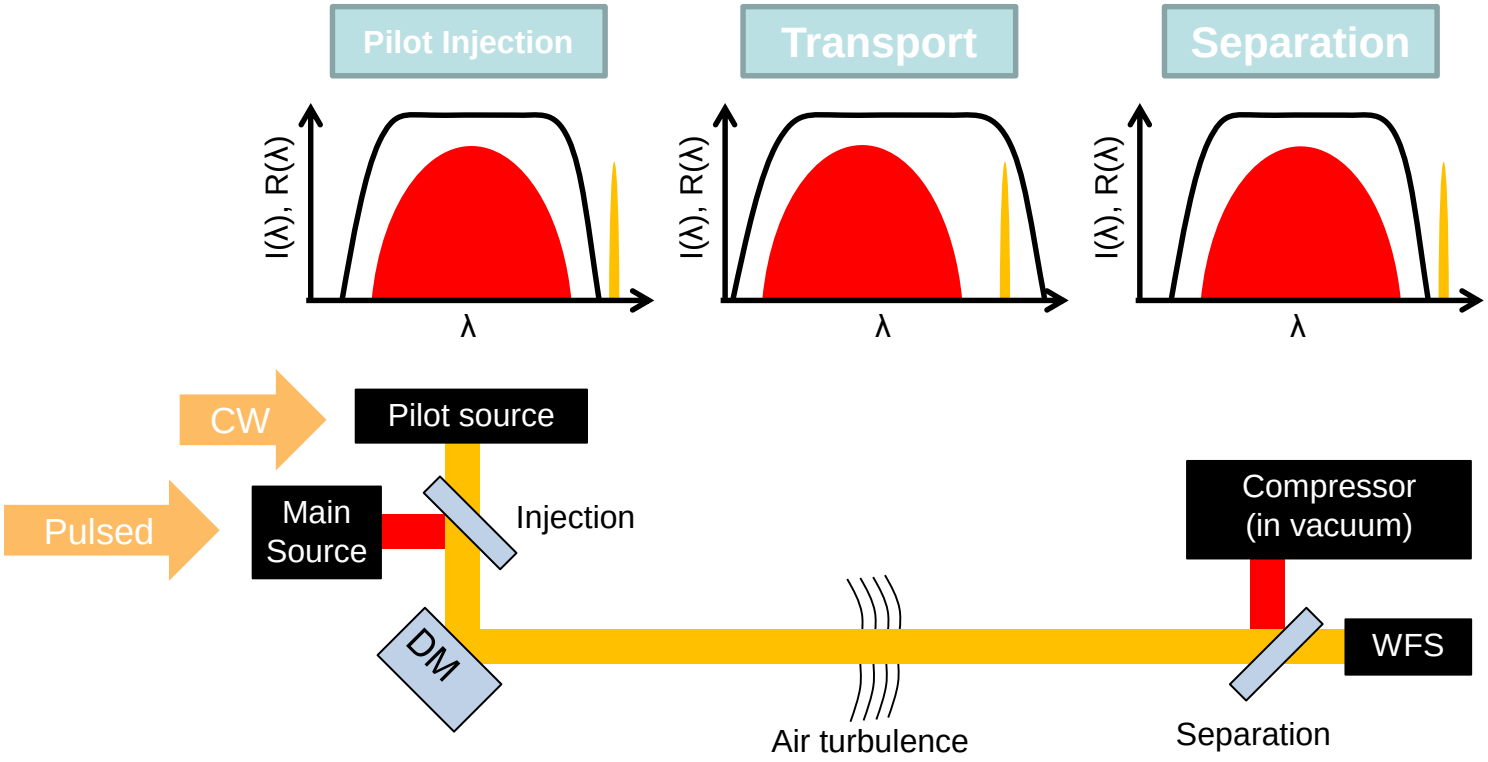
Requirements for AO:

- Min. 50 actuators / Min. 1 kHz (15 steps / period) / Max. 2.4 ms latency [1/(6*f)]

“Single shot” active correction idea

- **The challenge:** compensate the air turbulence for the 1 shot/min beam at 1 kHz rate…

➢ Use of a spectrally separated (905nm) CW « pilot » beam for the fast correction.



Customized high end equipment

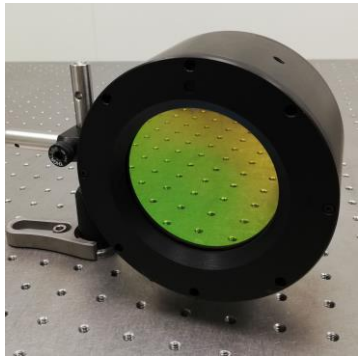
Wavefront Sensor

Camera from XIMEA:
- PCIe 3.0 x8 interface
- Shack-Hartmann Sensor with custom MLA
- **WF acquisition up to 7 kHz**

Controller

Real Time Computer (RTC):
- Consumer grade hardware
- OS: Ubuntu
- AO control based on open source framework „cacao“
- **GPU-based SHS evaluation in < 100 µs**

Deformable Mirror



DM from Dynamic Optics:
- Bimorph Piezoelectric DM
- 55 mm active area
- 96 actuators
- **1 ms latency @ 1 kHz**

- Test bench experiments in the laser development hall of LULI **November-December 2023**
- Implementation in the Apollon system **February-March 2024**
- On shot stabilization in SFA/LFA **… 2024**

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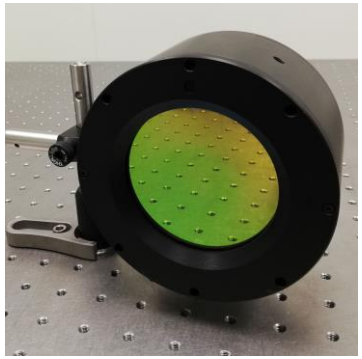

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- **Multispectral phase sensing for metrology and imaging**

Consortium

F. Harms

imagine optic — *Orsay*

- Coordination projet
- Entreprise parmi les leaders en **analyse de front d'onde et optique adaptative**
- Grande expérience du domaine de la **microscopie** (fluo, OCT, endoscopie)

M. Guillon

SPPIN — *Paris*

- **Co-inventeur de la technologie**
- Expert en optique singulière, milieux diffusants, imagerie basée sur le speckle

D. Papadopoulos

Palaiseau

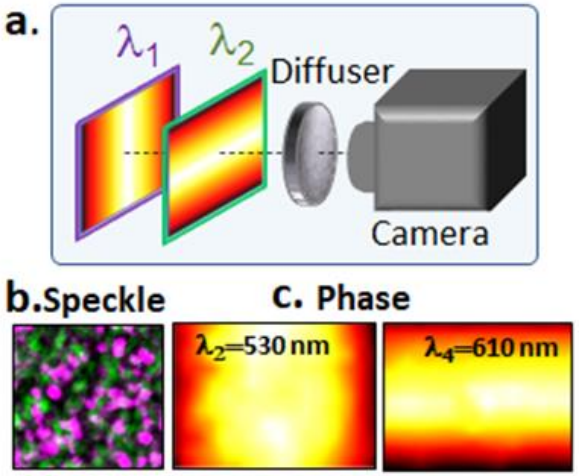
- **Co-inventeur de la technologie**
- Expert en **optique ultrabrève et lasers de puissance**
- Responsable partie laser - Apollon

P. Berto

INSTITUT DE LA VISION — *Paris*

- **Co-inventeur de la technologie**
- Expert en microscopie holographique et en ingénierie du front d'onde

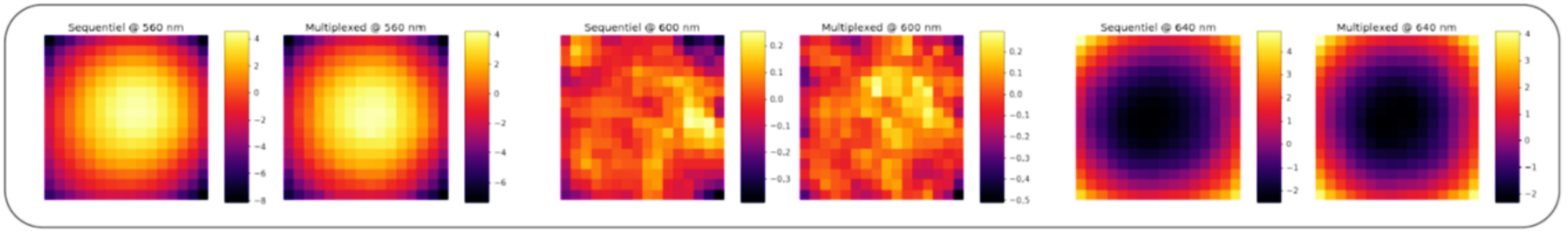
Développement d'une **nouvelle méthode d'analyse de front d'onde**, basée sur l'encodage de la phase par une figure de speckle, délivrant une haute résolution spatiale, sensibilité, une capacité de mesure multiplexée en une seule acquisition:

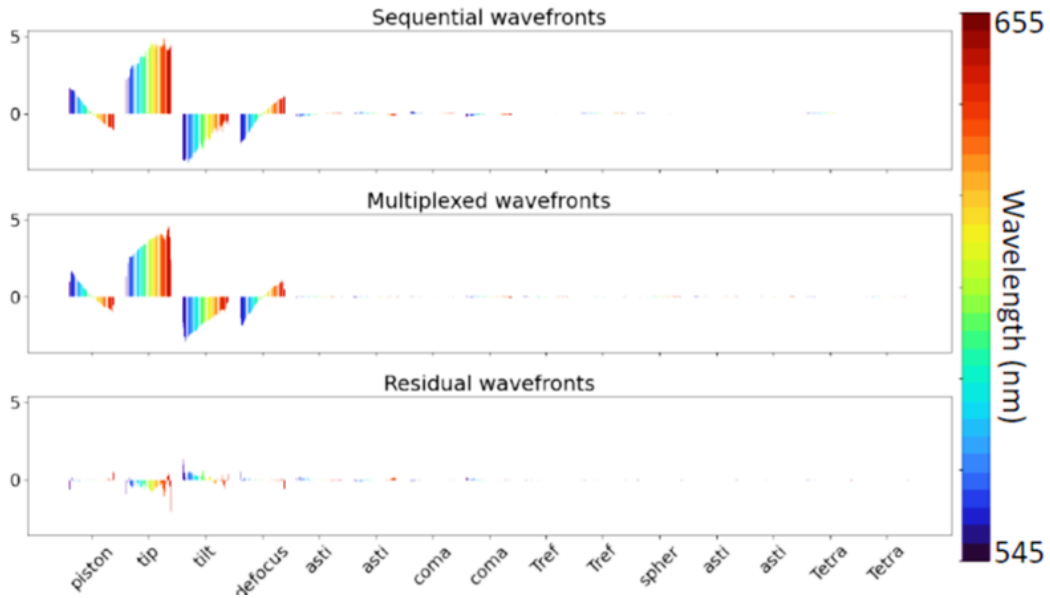


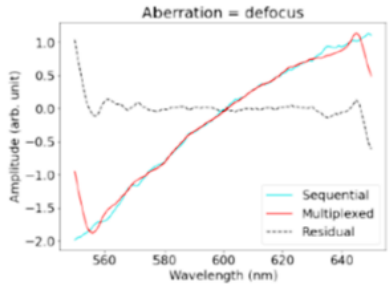
Test bench experiments

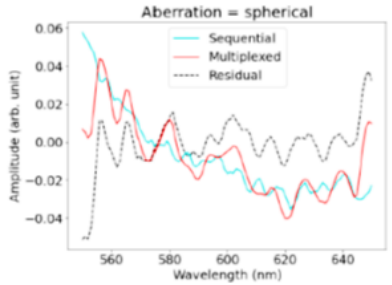
Afocal N-SF11 / f = 50mm / beam diameter = 4.5mm

Reconstructed wavefronts (tip-tilt removed)





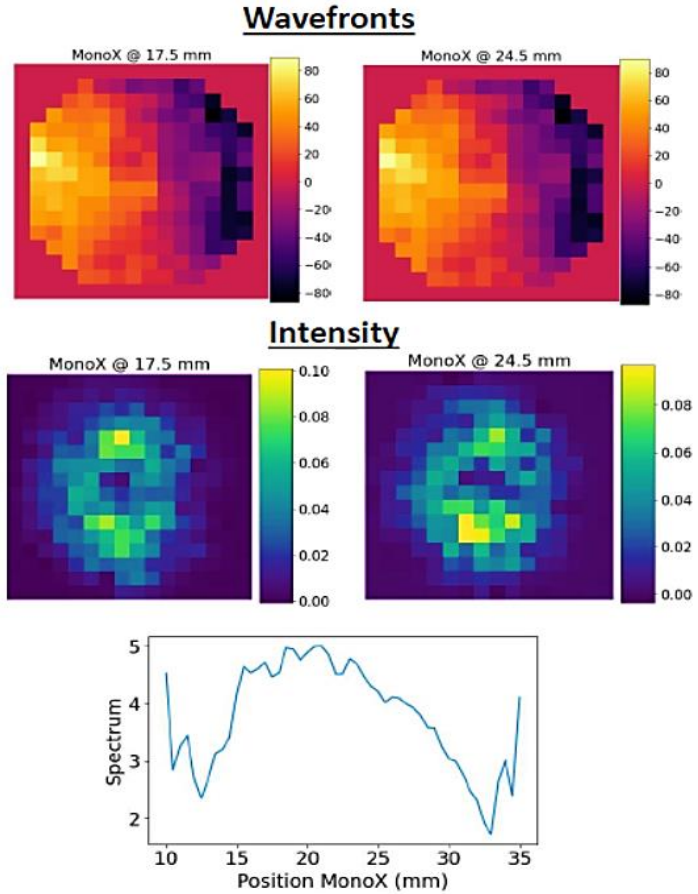


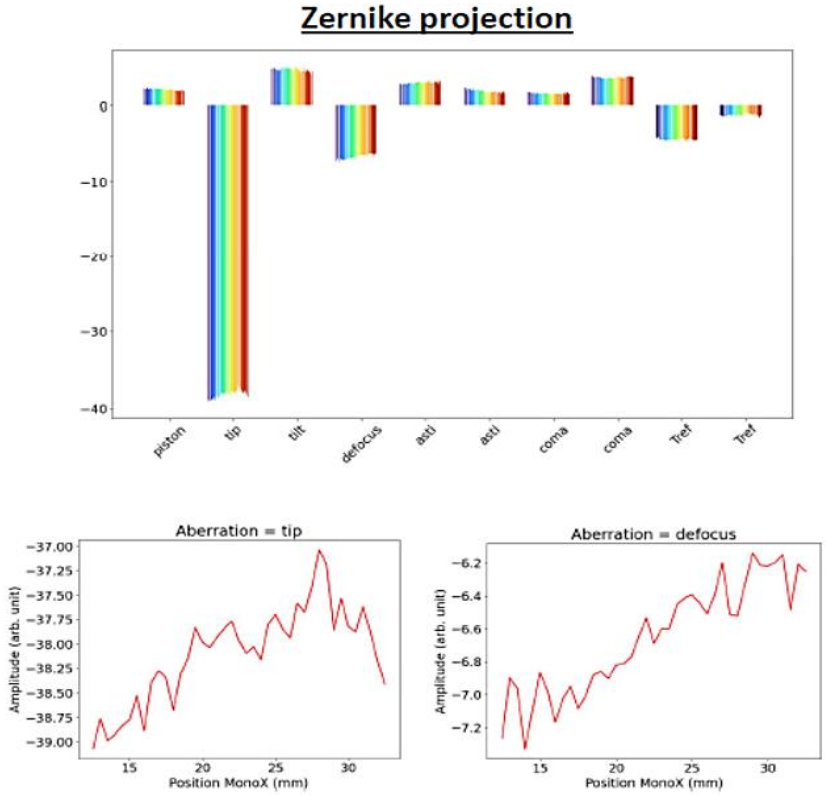


- Excellent spatial and spectral resolution to resolve defocus and spherical chromatique aberrations in a know optical system (*…in preparation for publication*)

Preliminary tests in LFA of Apollon

Multispectral reconstruction : beam 10Hz





- Successful measurement of chromatic tilts and defocus… and higher terms *(to verify)*
- Further optimization of imaging and calibration ➔ Increase of the spatial resolution
- Scheduled tests with the F1 beam line in SFA 2024

Conclusions

- The Apollon laser **joins the multi-PW-class** facilities
- Up to **75 Joules** in SFA at **24 fs**
- **1st experimental campaign** already successfully realized (2023)
- Final amplifier in preparation for up **250 Joules** (2024)

- **Multi-PW LFA commissioning** (**2025**)
- **Multi-PW external calls** (**2025**)

Apollon

Laboratoire pour l'Utilisation des Lasers Intenses

Scientific opportunities with APOLLON facilities: from fundamental physics to societal applications

Save the date of the workshop : **November 29 and 30, 2023**

As the Apollon Research Infrastructure (RI*, https://apollonlaserfacility.cnrs.fr) is building up its capability as a multi petawatt, multibeams facility, it is time to reflect on the scientific challenges that the Apollon facility is best suited to tackle in the coming years (5-10 years). The community is invited to contribute to this process by participating to the workshop that will take place 29-30 November 2023 in Paris at Sorbonne University.

https://luli.cnrs.fr/scientific-opportunities-with-apollon-facilities/

https://indico.mathrice.fr/event/428/

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Thank you

Avec le soutien de