PW-class Lasers for Accelerators – Overview and an Industry Perspective

O. CHALUS, THALES LAS

NAPAC 2022 08TH AUGUST 2022

THALES


THALES
GROUP

OVERVIEW

Over

80,000

employees

68

Countries of operation

1 Bn €

self-funded R&D*

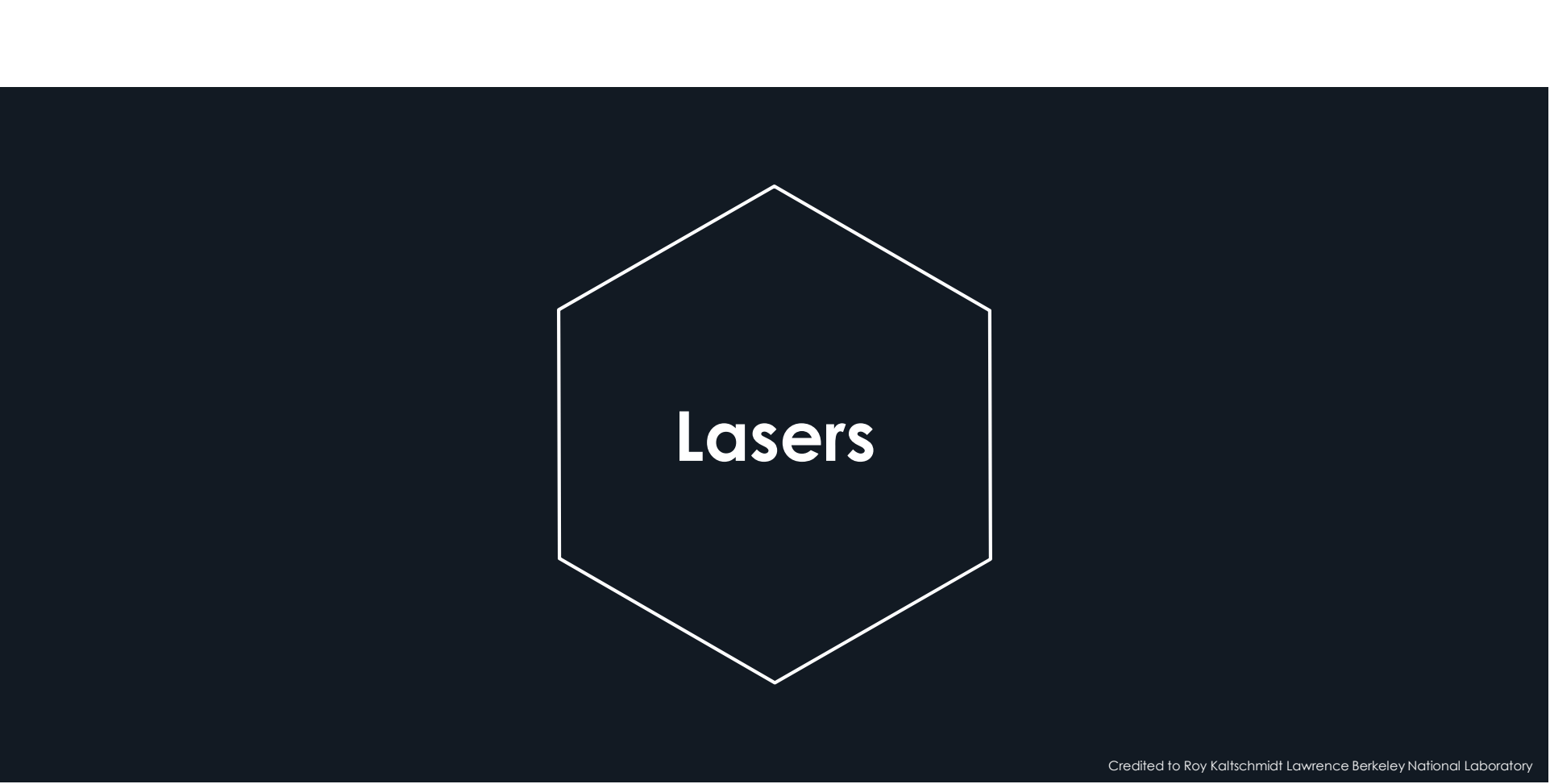
* Does not include externally financed R&D

19

sales in 2018

bn €

Lasers



Credited to Roy Kaltschmidt Lawrence Berkeley National Laboratory

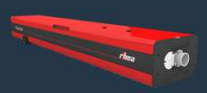
LASER SOLUTIONS

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**

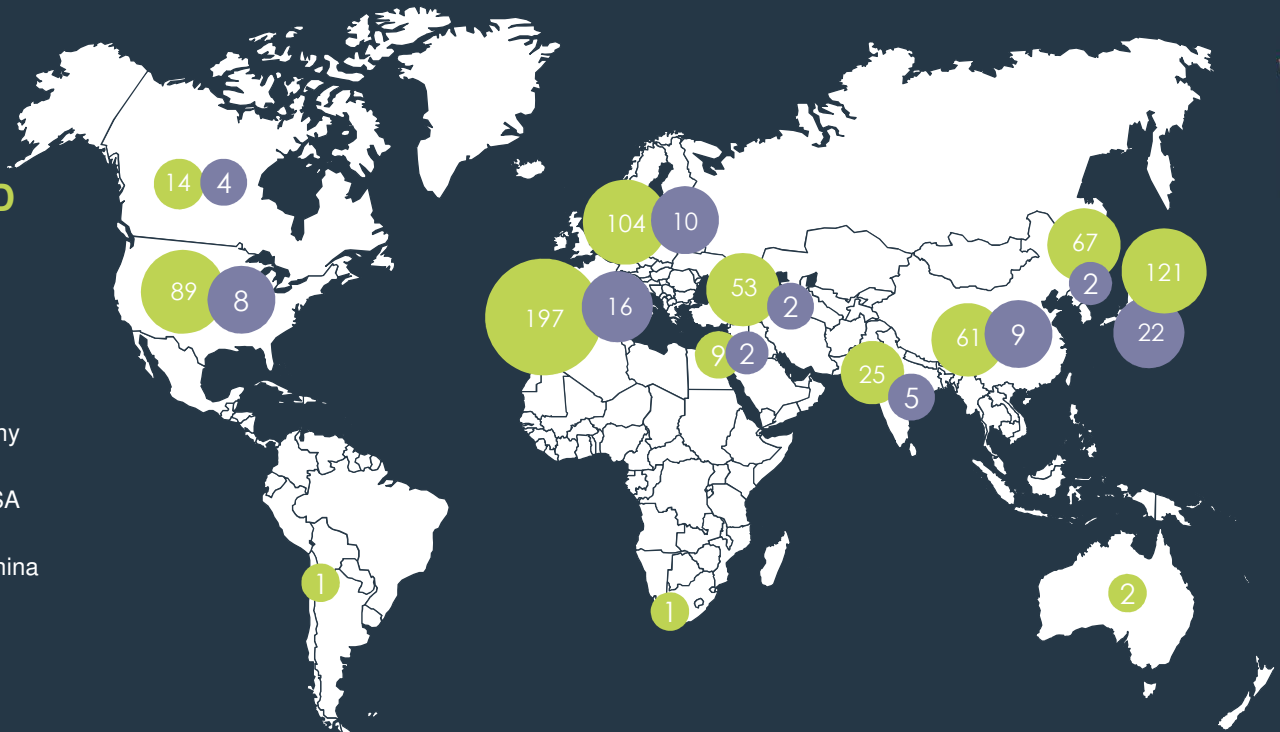
Gérard Mourou
2018 Nobel Prize in Physics

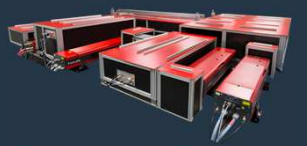
WORLDWIDE PRESENCE



NANOSECOND

APOLLON France
CEA France
CSIR South Africa
DRDC Canada
GIST South Korea
Jena University Germany
LOA France
Nebraska University USA
STFC UK
Shenzhen University China
SIOM China
SLAC USA
Texas University USA

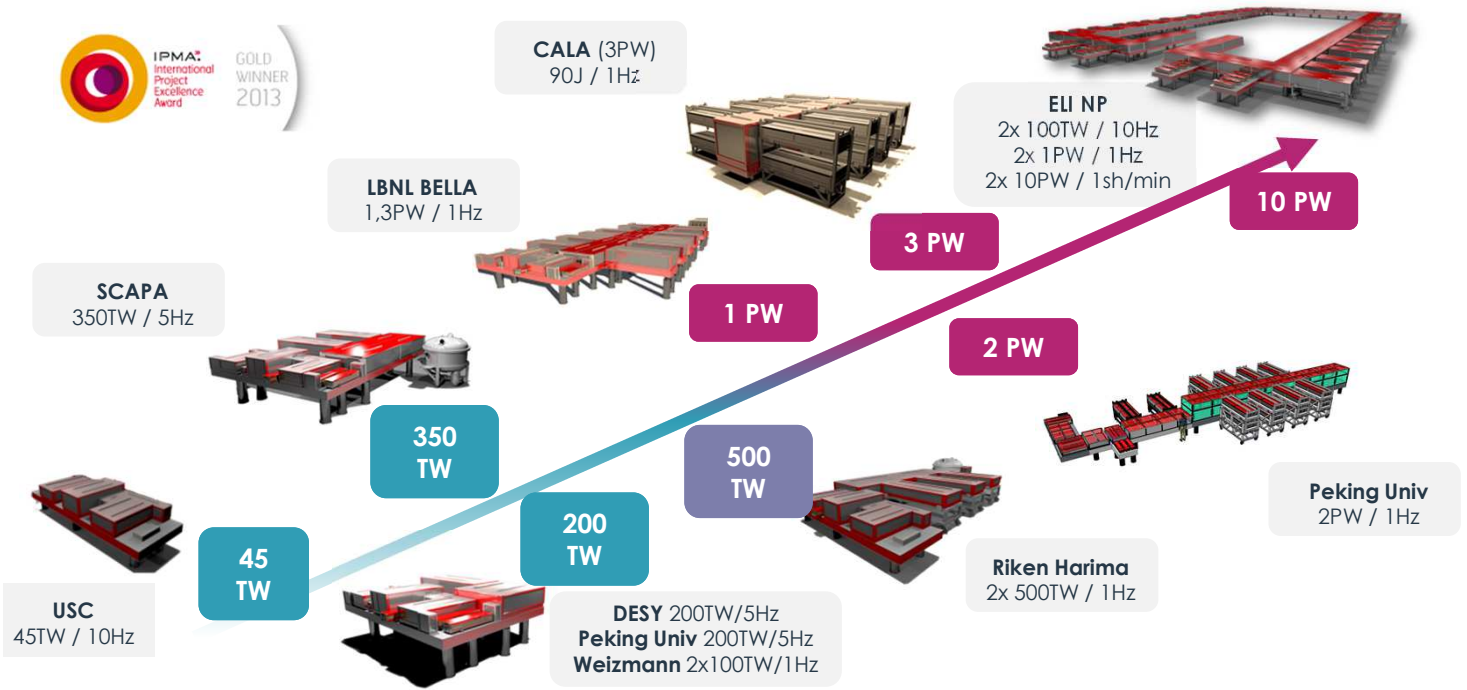




FEMTOSECOND

CALA Germany
CETAL Romania
DESY Germany
ELI NP Romania
Julich University Germany
LBNL USA
Peking University China
Riken Harima Japan
RRCAT India
SCAPA UK
SWJT China
Universidade de Santiago de Compostela Spain
University of Michigan USA
Weizmann Institute of Science Israel

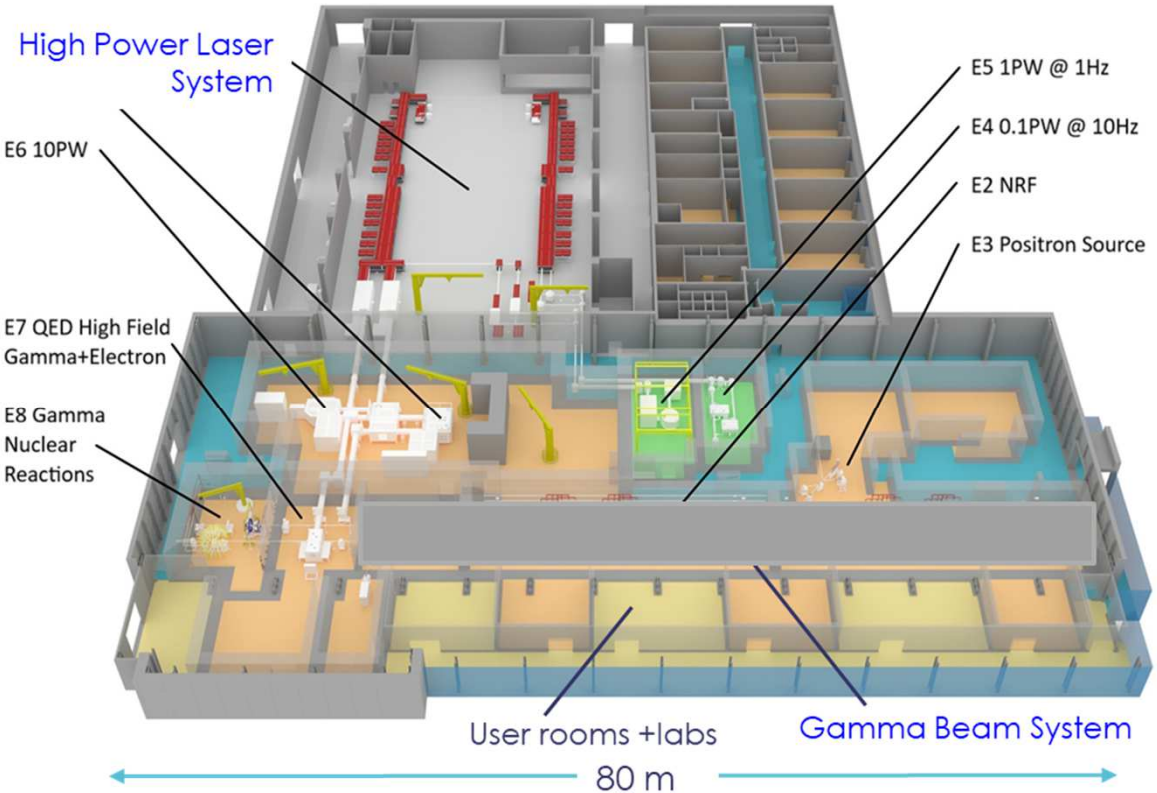
AMPLIFICATION OF HIGH-ENERGY FEMTOSECOND PULSES FOR SCIENCE



High-energy pumping lasers are designed and produced in Thales:

SAGA – GAIA – ATLAS – THEIA

ELI NP - INFRASTRUCTURE



ELI NP SYSTEM

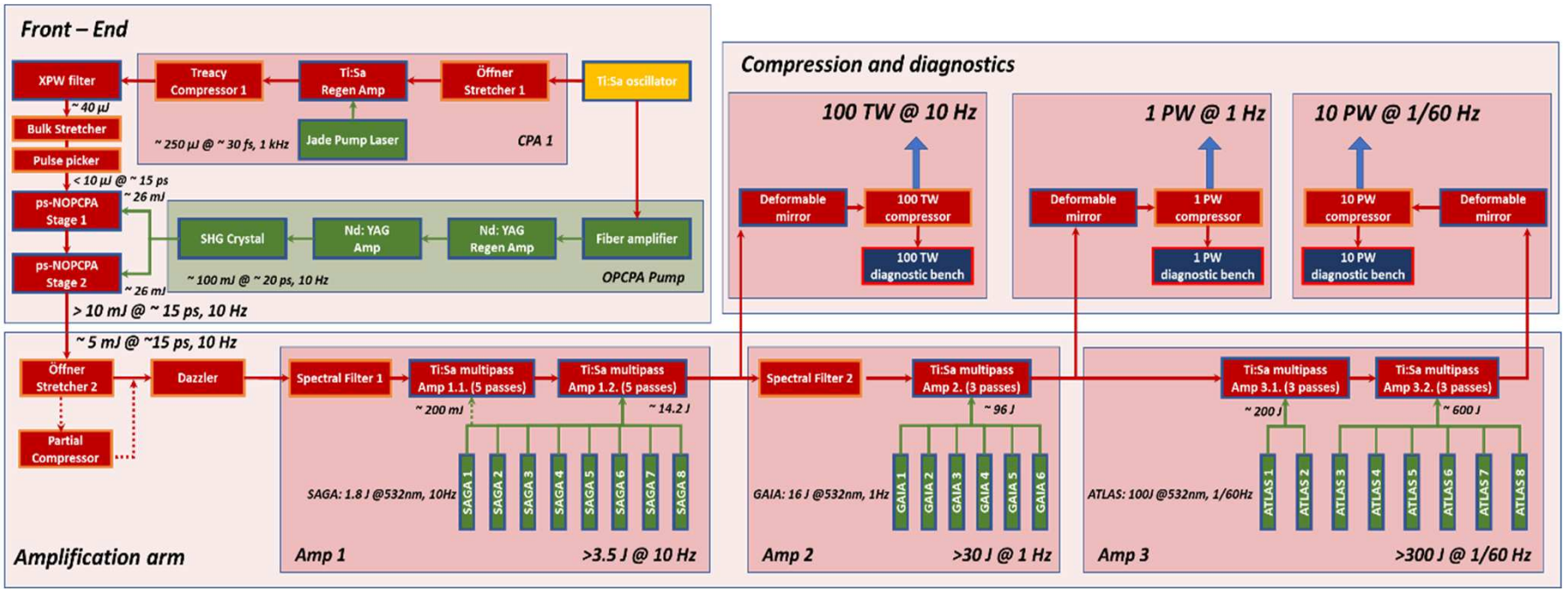
Thales joined the Extreme Light Infrastructure for Nuclear Physics (**ELI-NP**) program in 2013 to develop the High Power Laser System (HPLS), the **most powerful system of its kind in the world**.

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 10am to 6pm for 100TW beamline and 10.30am to 6.30pm for 1PW beam
- **Training** ELI NP team regarding our dedicated program launched in 2019 for our users
- **Maintaining** the system with preventive and corrective maintenance

SYSTEM BREAKDOWN STRUCTURE



3 crystals produced

All size of Ti:Sa crystals for amplification on the system : up to 200 mm in diameter
Manufacturer GTAT, USA

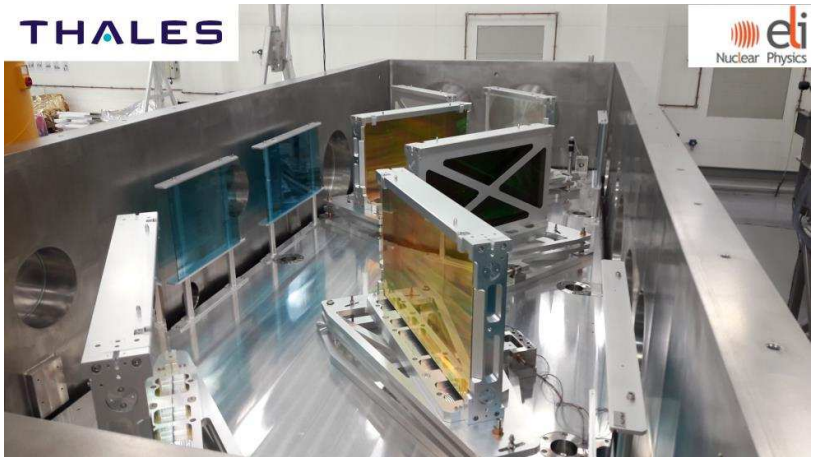
200 mm Ti:Sa crystals on the amplifier

Thales rented a 11 inch furnase for the development of crystals

- Furnase now available for the community

9 gratings produced

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

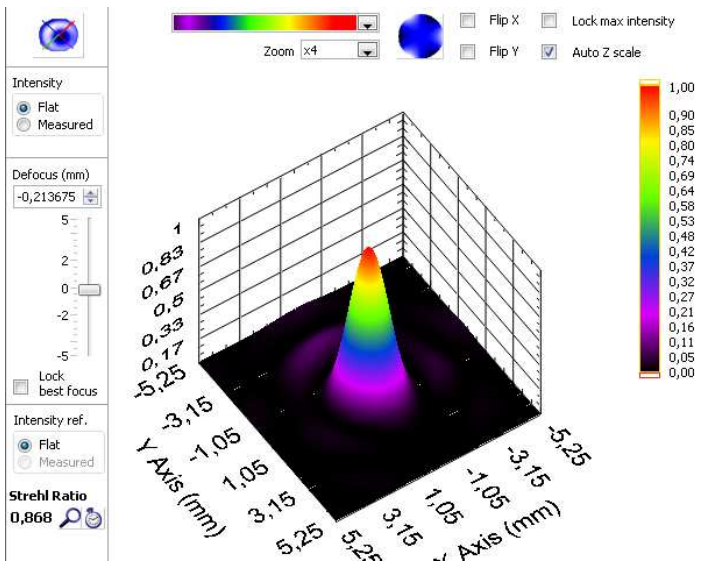


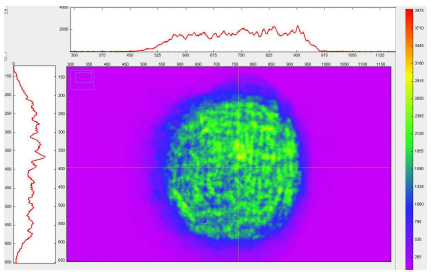
Gratings integrated in the vacuum vessel

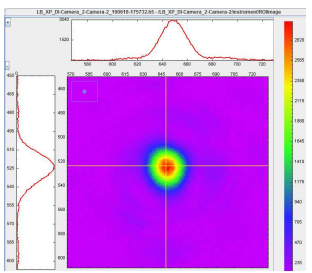
Grating size : 1015 x 575 mm²

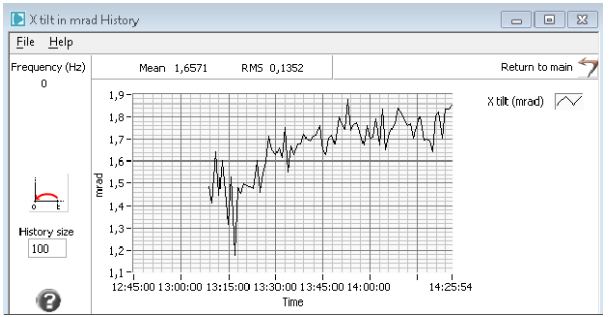
Compressor output - beam line 2

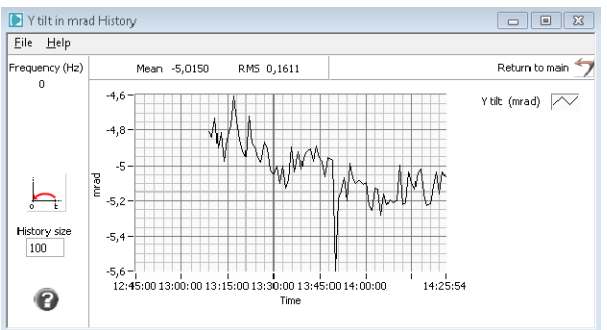
(measurements at full aperture with energy 310J attenuated before compressor)











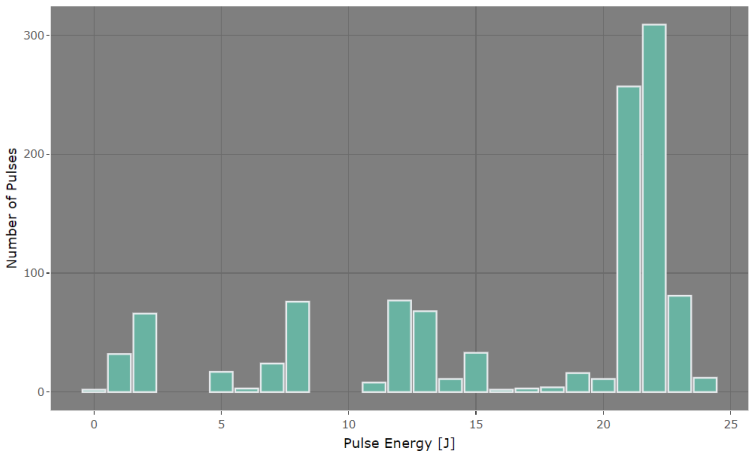
D=450mm FWHM / reduction factor 180x

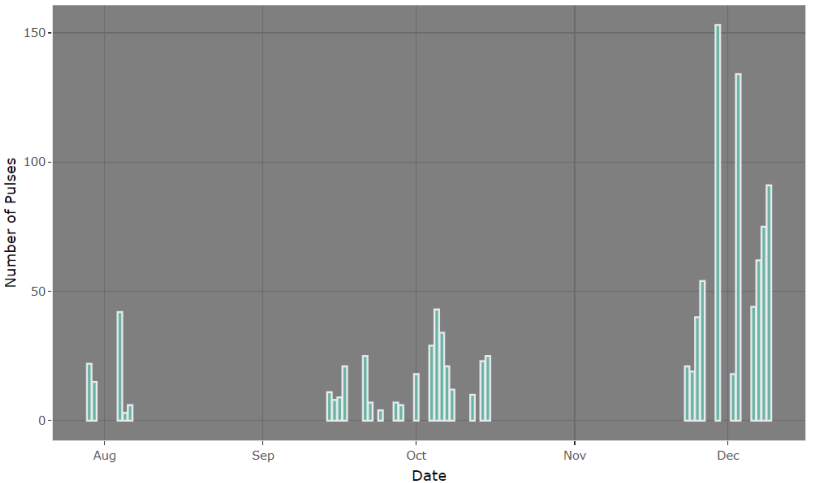
100TW / 1PW OPERATION

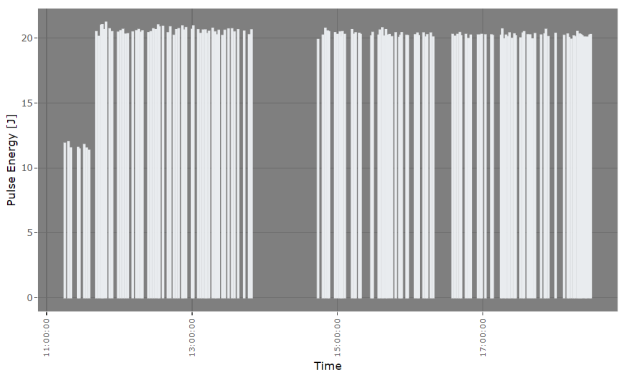
Beam time for comissionning operation

- During second half of 2021 THALES and ELI-NP operation team delivered beam for a total **484 number of hours from the HPLS 100 TW output to E4 experimental area**.
- During second half of 2021 THALES and ELI-NP operation team delivered beam for a total **721 number of hours from the HPLS 1 PW output to E5 experimental area**. A total number of 1112 pulses on target were delivered during this time.

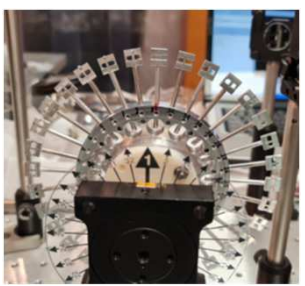
HPLS 1 PW OUTPUT TO E5 AREA



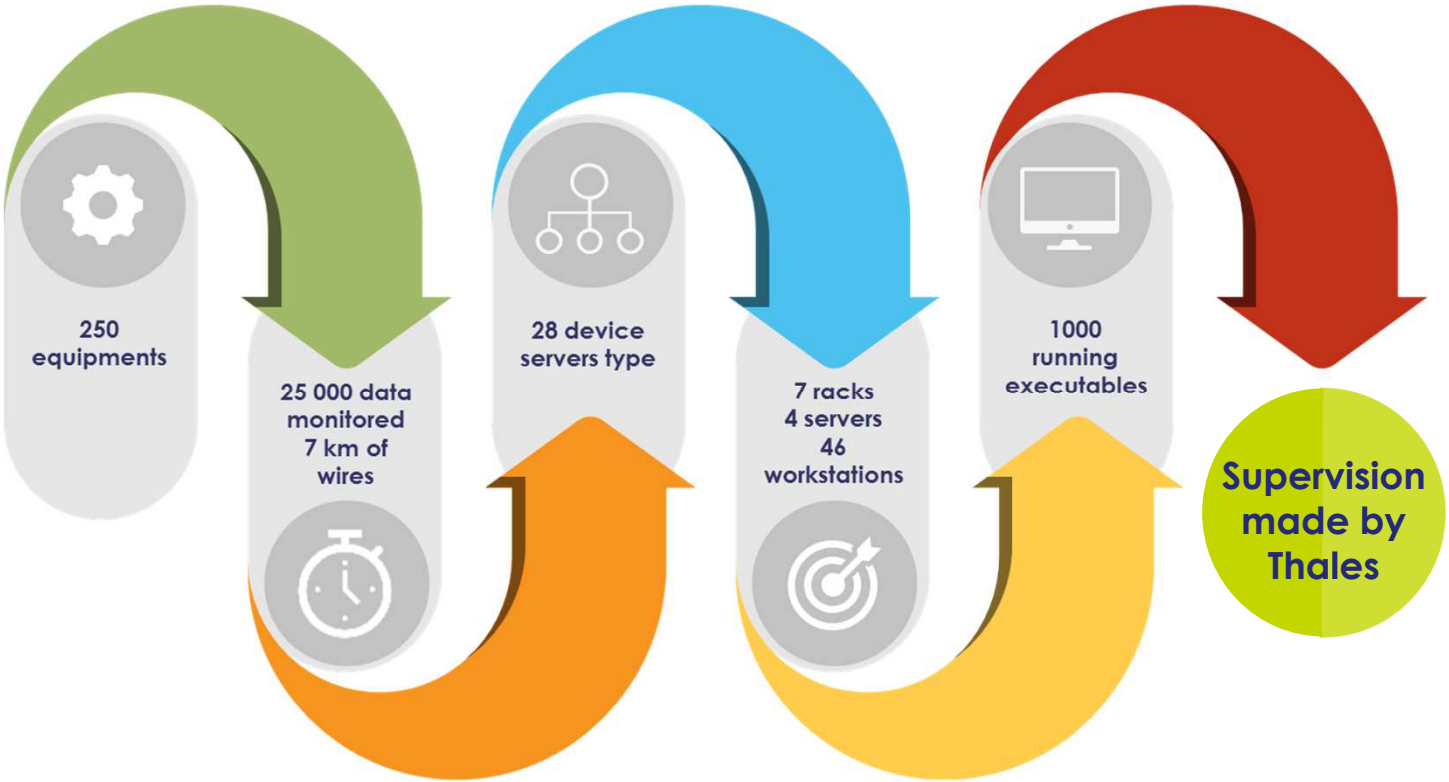




- Maximum number of shots/day on gas target = 153
- Maximum number of shots/day on solid target = 43



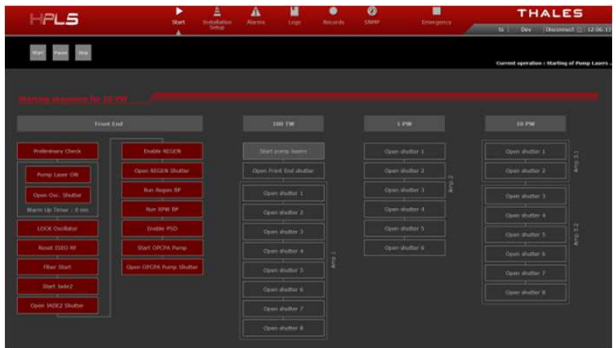
DATA MANAGEMENT



=> 300 GB data per day!

SYSTEM DETAILED CHARACTERISTICS

Full supervision software coupled with internal diagnostics



Left screen, available views

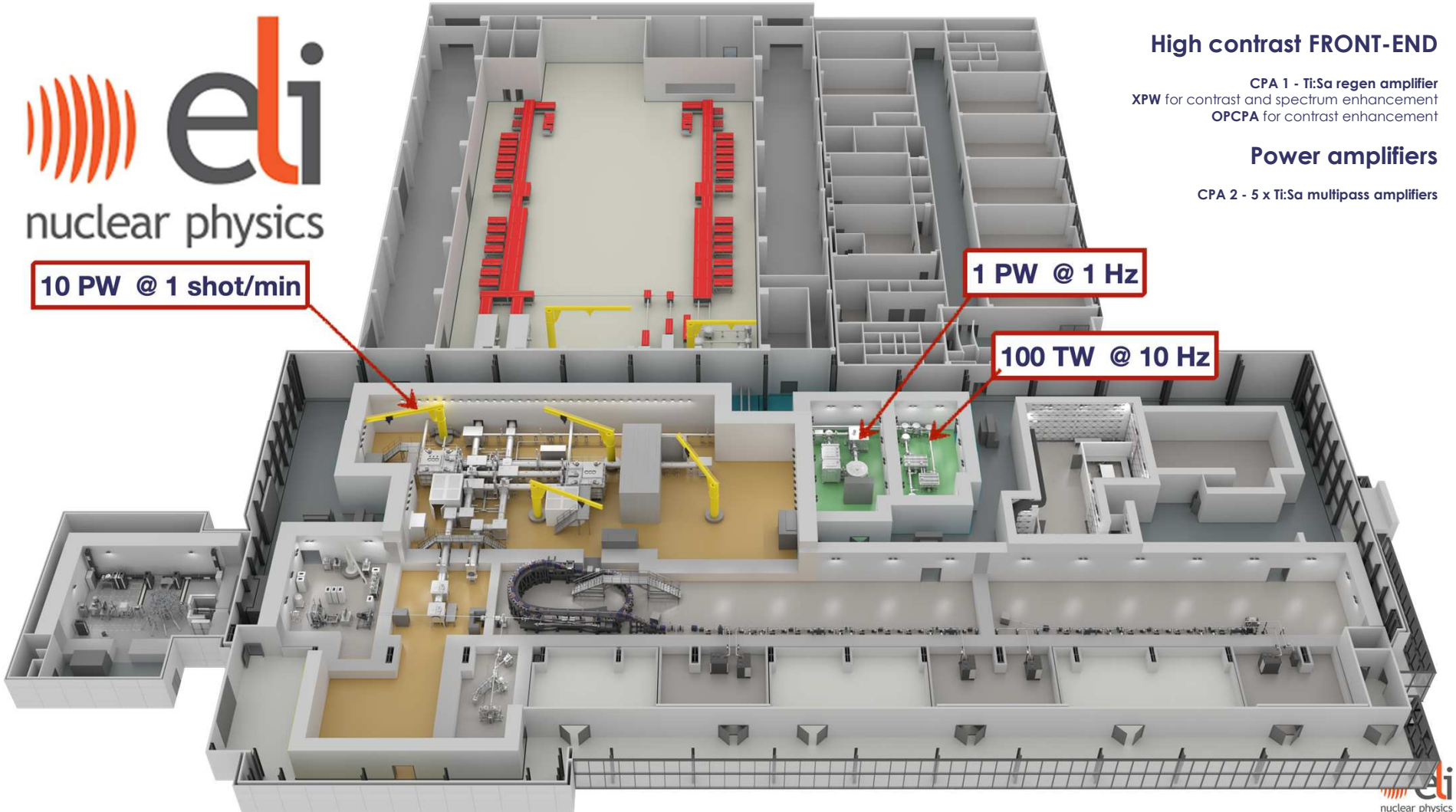
- Start
- Installation setup
- Alarms
- Logs

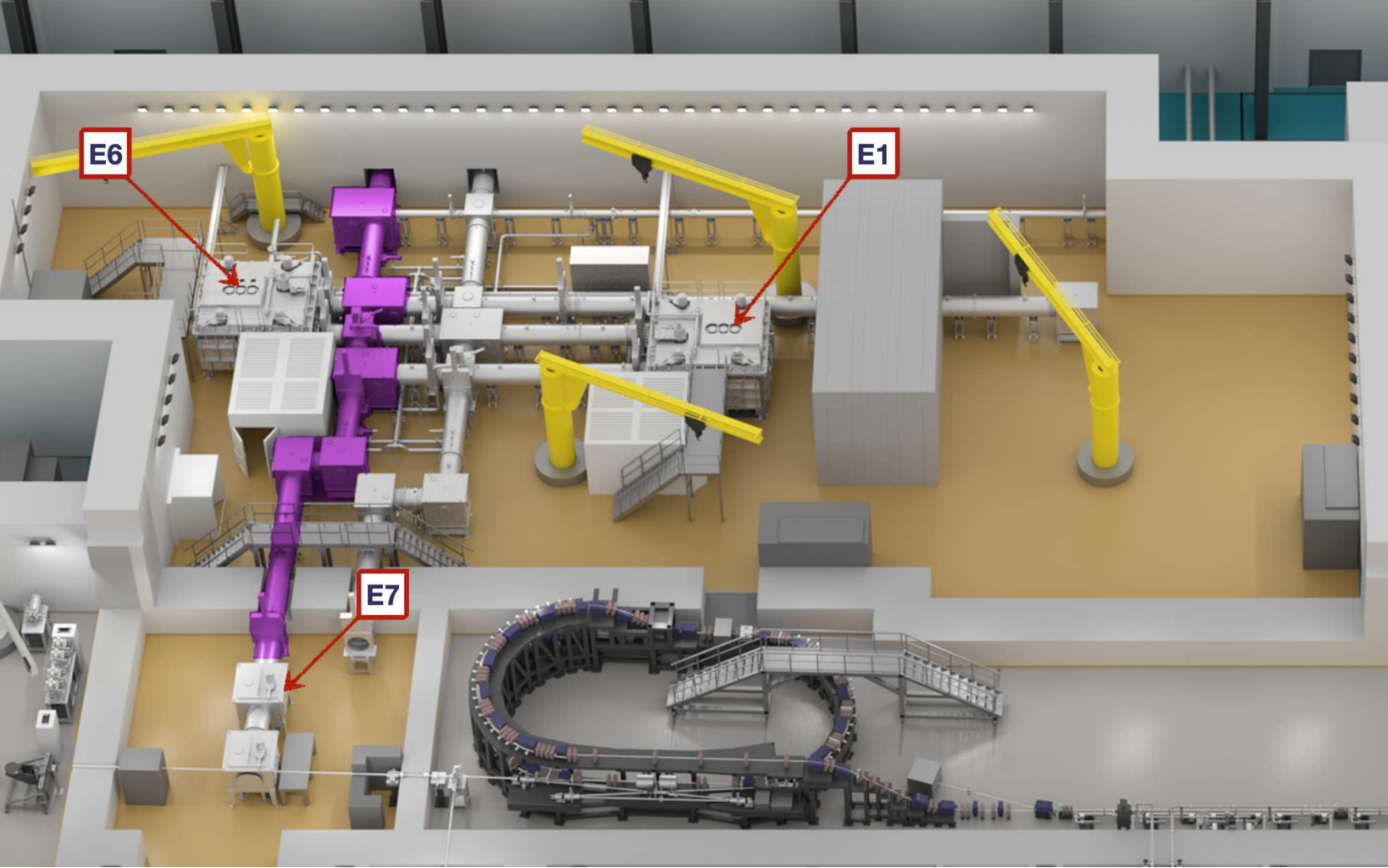
Middle screen, one single view

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

Right screen, available views

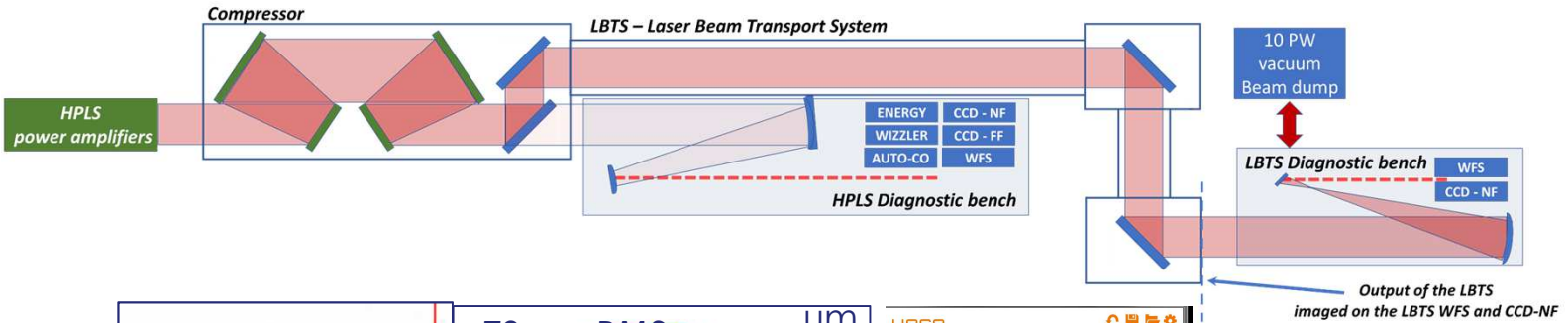
- Stage synthetic view
- Diagnostic bench synthetic view
- CSCI detailed view

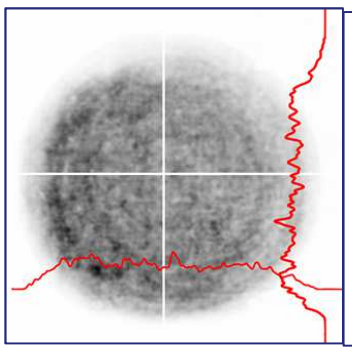

nuclear physics
10 PW @ 1 shot/min
1 PW @ 1 Hz
100 TW @ 10 Hz
High contrast FRONT-END
CPA 1 - Ti:Sa regen amplifier
XPW for contrast and spectrum enhancement
OPCPA for contrast enhancement
Power amplifiers
CPA 2 - 5 x Ti:Sa multipass amplifiers
nuclear physics


E6
E1
E7

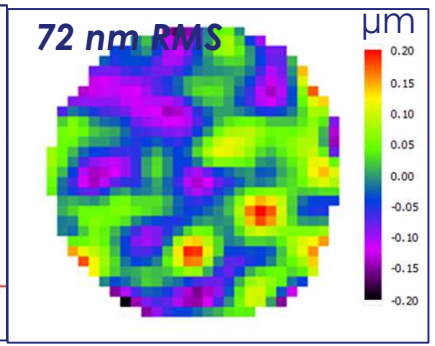
ELI NP - LBTS TEST CONFIGURATION – STEP 1

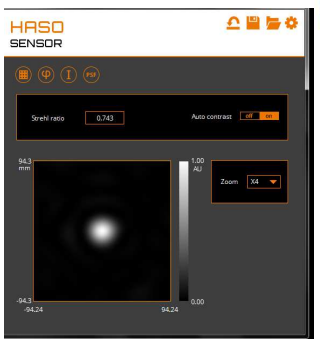
HPLS laser running at full energy attenuated before compressor for beam profile analysis after propagation through the LBTS and transmission efficiency





NF LBTS output

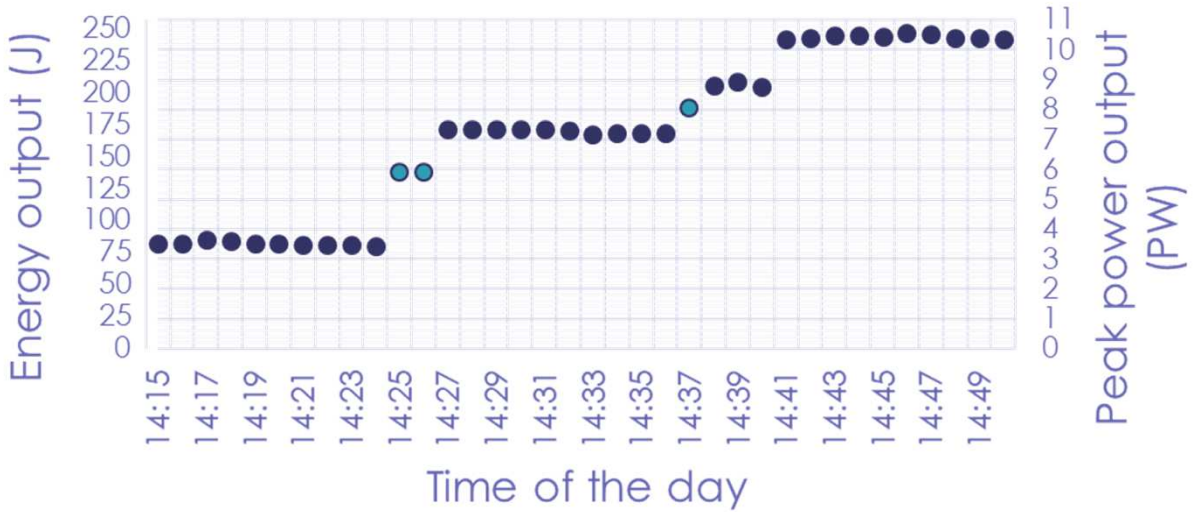




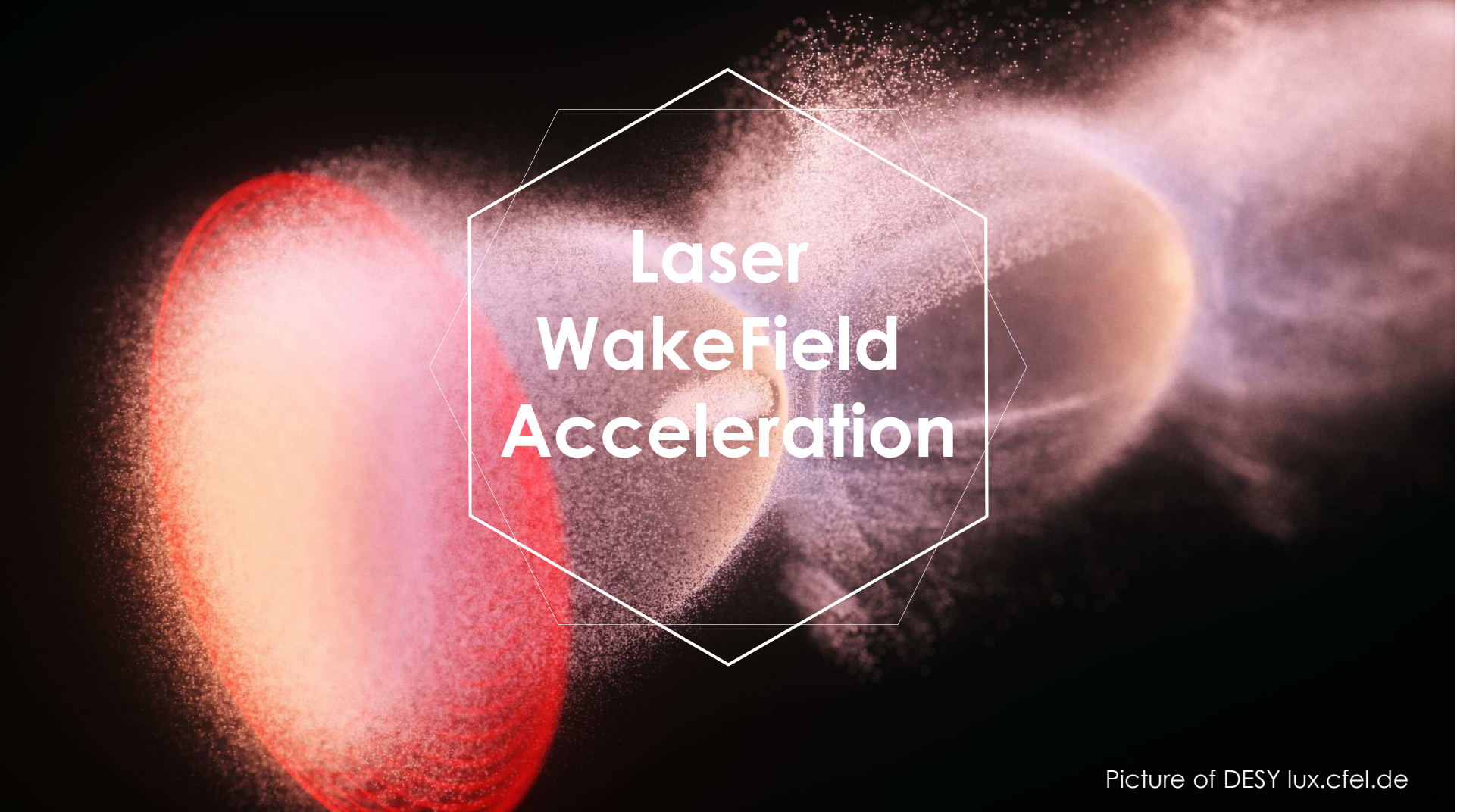
Wavefront map, Strehl ratio > 0,7

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



Picture of DESY lux.cfel.de

Laser WakeField Acceleration (LWFA)

The LWFA was proposed in 1979!

T. Tajima **J.M. Dawson**

Phys. Rev. Lett **43**, 267(1979)

Laser field
Transverse field

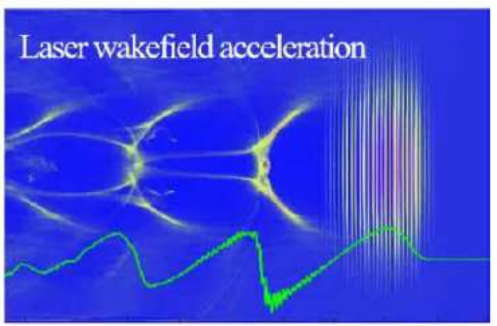
plasma

Without breakdown voltage

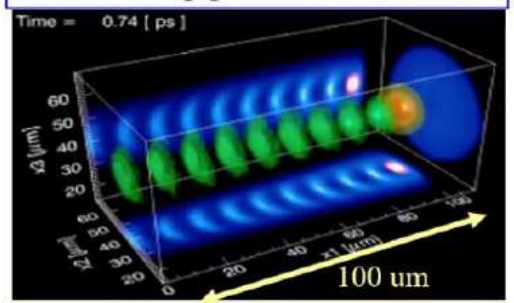
Plasma wakefield
Longitudinal field

Accelerating gradient~**100MV/m**

Radiofrequency cavity (1 m-long)



Accelerating gradient~**100GV/m**



3D PIC simulation of a plasma wave (UCLA)

2004 The Dream Beam

Monoenergetic beams of relativistic electrons from intense laser–plasma interactions

S. P. D. Mangles[1], C. D. Murphy[1,2], Z. Najmudin[1], A. G. R. Thomas[1], J. L. Collier[2], A. E. Dangor[1], E. J. Divall[2], P. S. Foster[2], J. G. Gallacher[3], C. J. Hooker[2], D. A. Jaroszynski[3], A. J. Langley[2], W. B. Mori[4], P. A. Norreys[2], F. S. Tsung[4], R. Viskup[3], B. R. Walton[1] & K. Krushelnick[1]

[1]The Blackett Laboratory, Imperial College London, London SW7 2AZ, UK
[2]Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK
[3]Department of Physics, University of Strathdyde, Glasgow G4 0NG, UK
[4]Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA

High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

C. G. R. Geddes[1,2], Cs. Toth[1], J. van Tilborg[1,3], E. Esarey[1], C. B. Schroeder[1], D. Bruhwiler[4], C. Nieter[4], J. Cary[4,5] & W. P. Leemans[1]

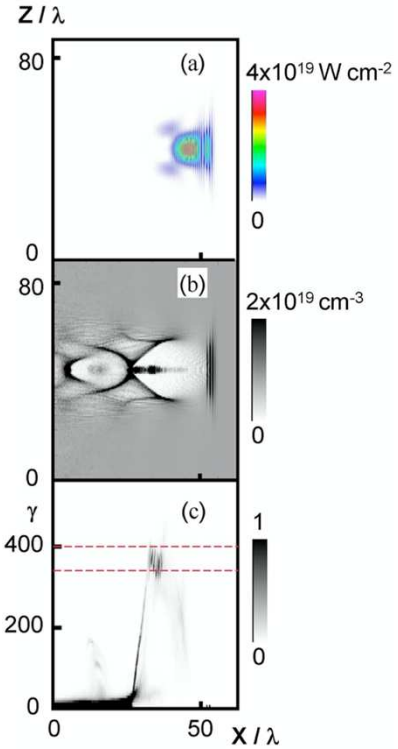
[1]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
[2]University of California, Berkeley, California 94720, USA
[3]Technische Universiteit Eindhoven, Postbus 513, 5600 MB Eindhoven, the Netherlands
[4]Tech-X Corporation, 5621 Arapahoe Ave. Suite A, Boulder, Colorado 80303, USA
[5]University of Colorado, Boulder, Colorado 80309, USA

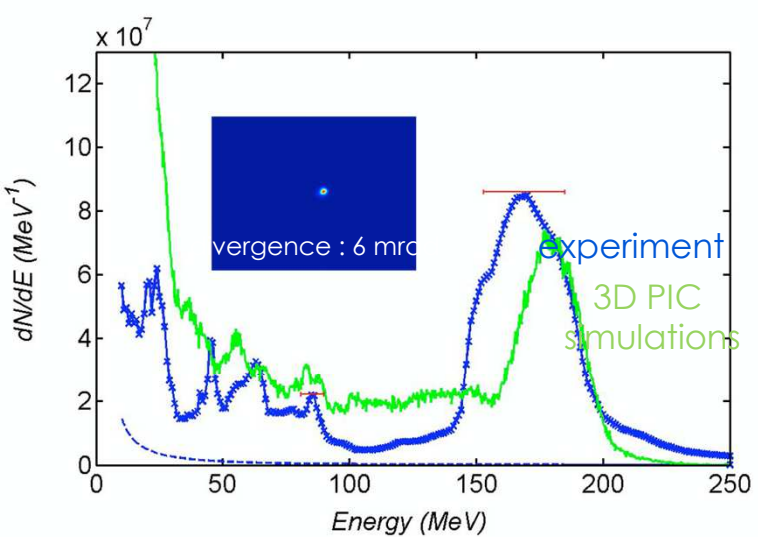
A laser–plasma accelerator producing monoenergetic electron beams

J. Faure[1], Y. Glinec[1], A. Pukhov[2], S. Kiselev[2], S. Gordienko[2], E. Lefebvre[3], J.-P. Rousseau[1], F. Burgy[1] & V. Malka[1]

[1]Laboratoire d'Optique Appliquée, Ecole Polytechnique, ENSTA, CNRS, UMR 7639, 91761 Palaiseau, France
[2]Institut für Theoretische Physik, 1, Heinrich-Heine-Universitat Duesseldorf, 40225 Duesseldorf, Germany
[3]Département de Physique Théorique et Appliquée, CEA/DAM Ile-de-France, 91680 Bruyères-le-Châtel, France

2005 The Bubble regime : theory/experiments

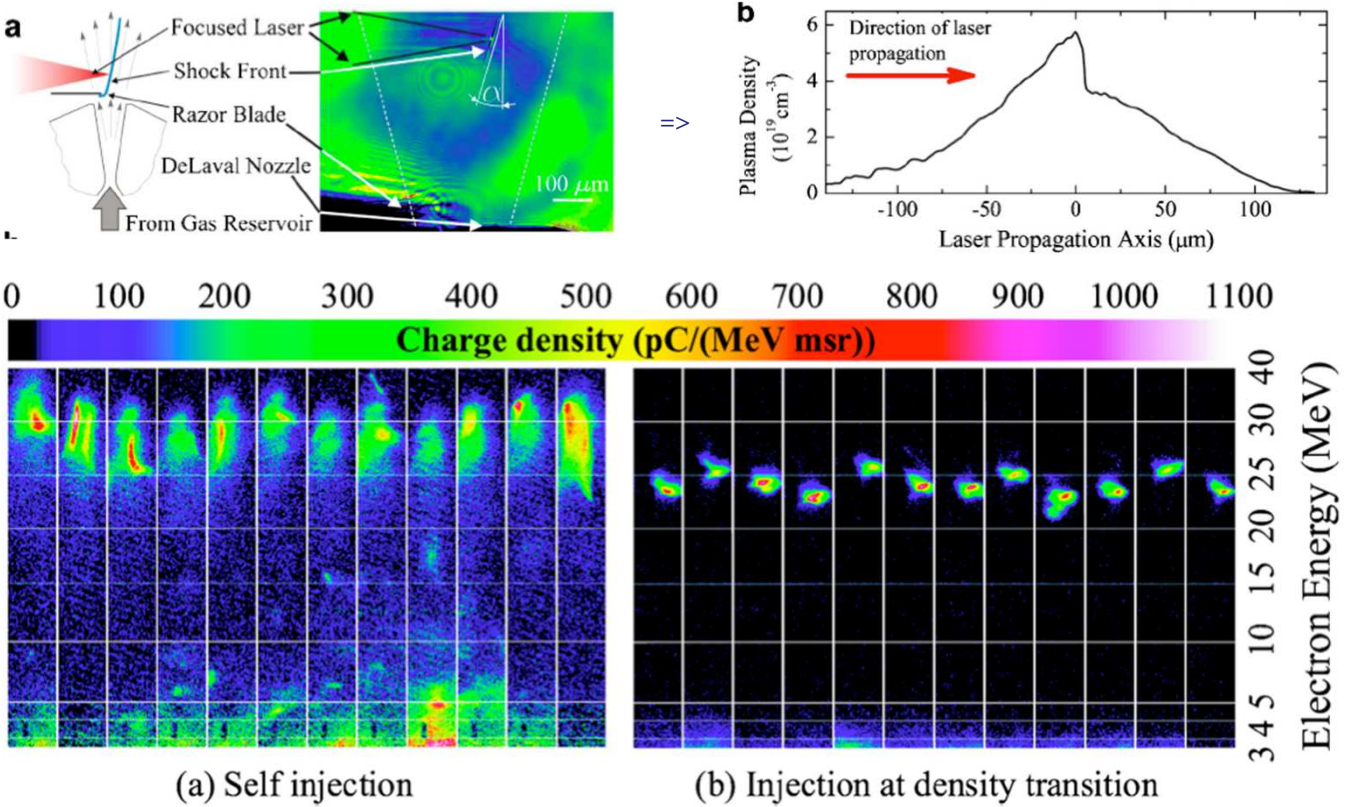




Experimental parameters : E=1J,
τ_L=30fs, λ_L=0.8μm, I_L=3.2×10^{19}W/cm^2,
n_e=6×10^{18}cm^{-3}

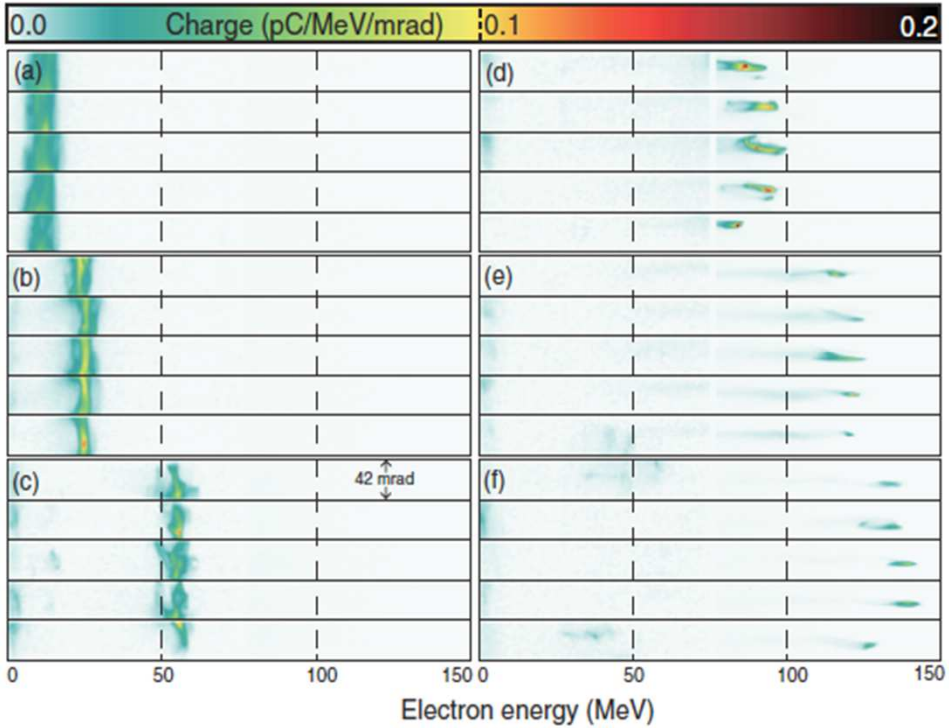
J. Faure *et al.*, Nature **431**, 7008 (2004)

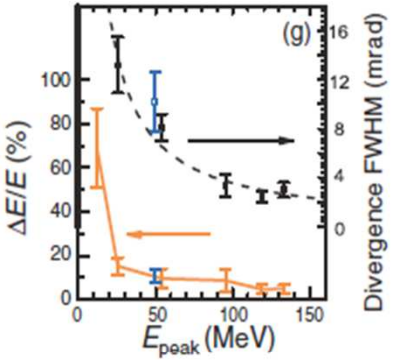
2010 Sharp density ramp injection

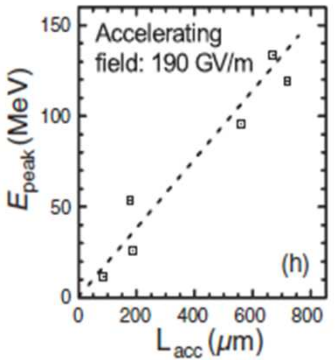


K. Schmid et al., PRSTAB 13, 091301 (2010)

2013 Shock front injection

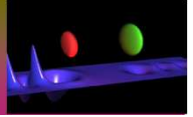




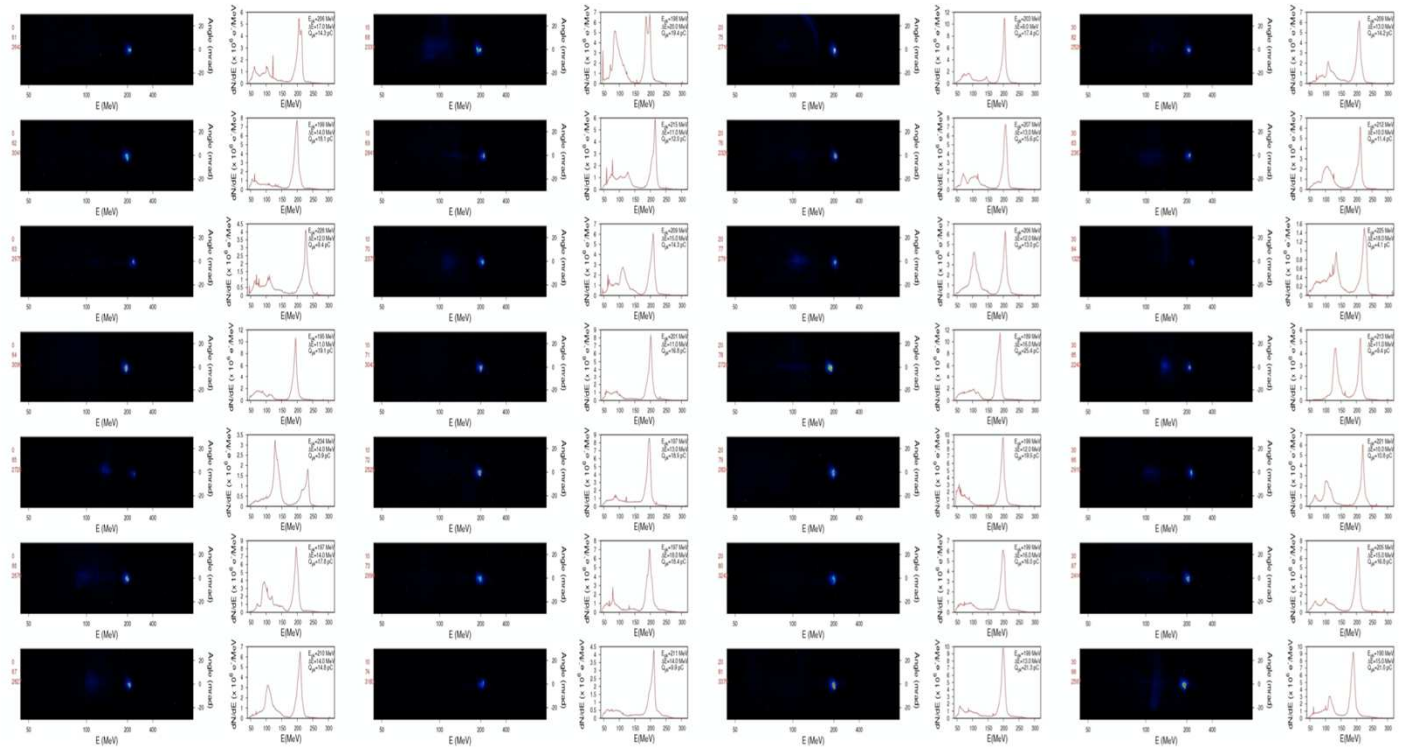


A. Buck *et al.*, PRSTAB 13, 091301 (2010)

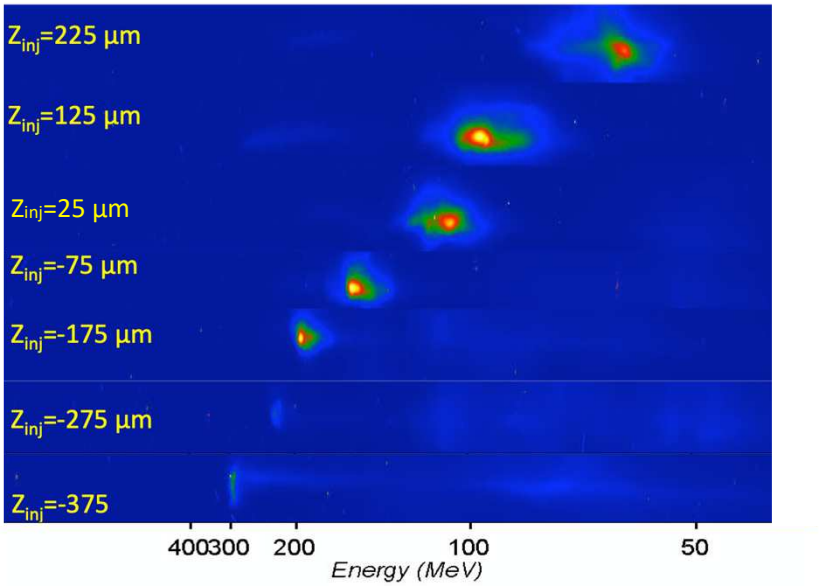
Colliding laser pulses scheme : Stable

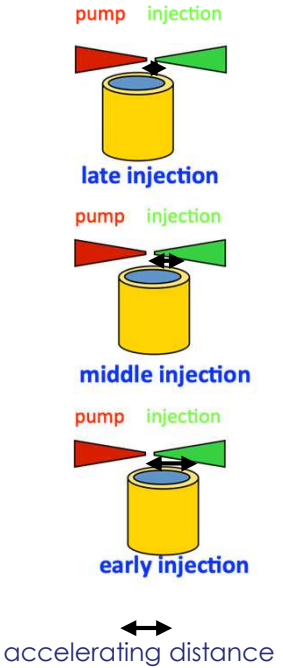


Series of 28 consecutive shots with : a_0=1.5, a_1=0.4, n_e=5.7×$10^{18}$$cm^{-3}$



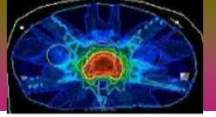
Colliding laser pulses scheme : Tunable





J. Faure *et al.*, Nature **444**, 737 (2006)

Laser beam parameters for electron-RT



Considered cases	Robustness	Maturity	Cost
1 mJ/10kHz/ 3fs	-	Low	?
10mJ/1 kHz/few fs	-	Low/medium	?
100mJ/100Hz 20fs	++	medium	?
1J/10Hz 30fs	++	High	1-1.5 M€

Reduction of the laser energy (assuming the photon to electron efficiency the same) requires higher repetition rate

Few 100'smJ/few 10'sHz/ 20 fs seems to be a good compromise on the basis on the present technology

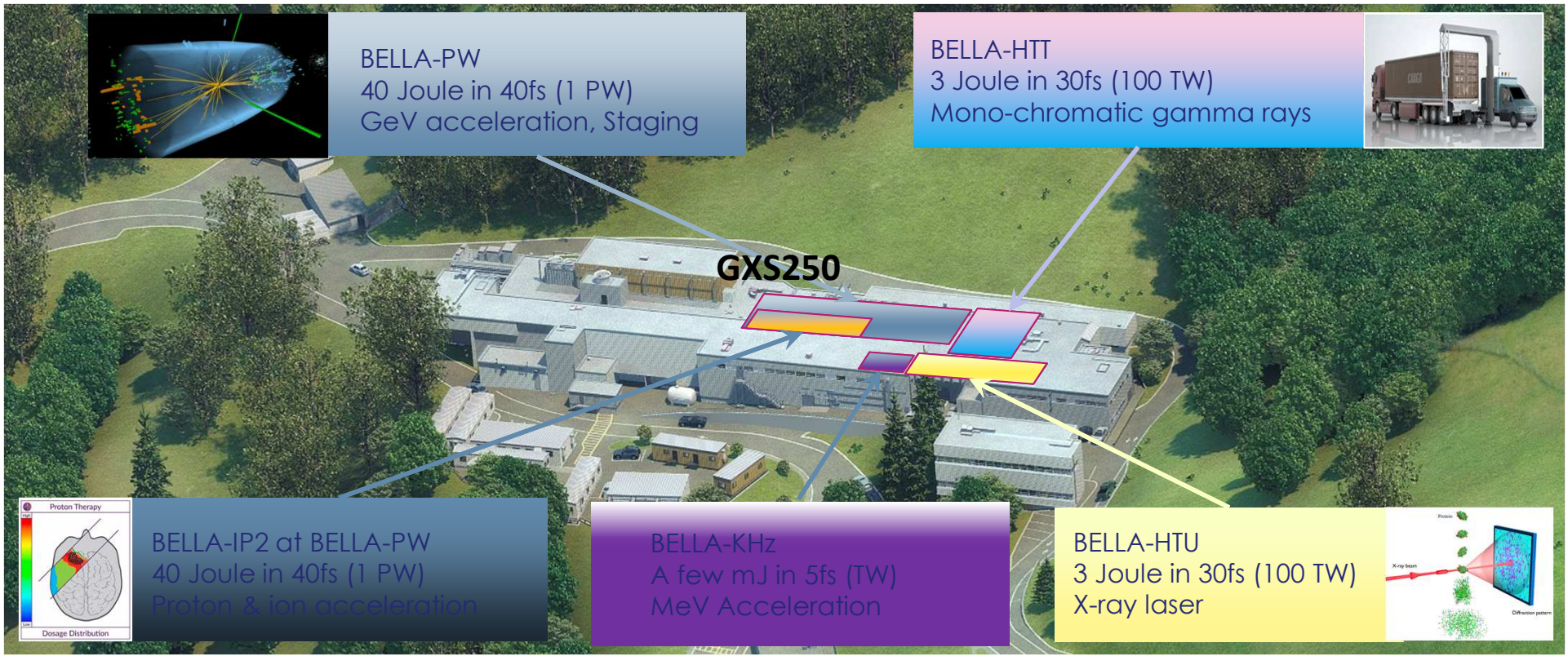
Conclusions

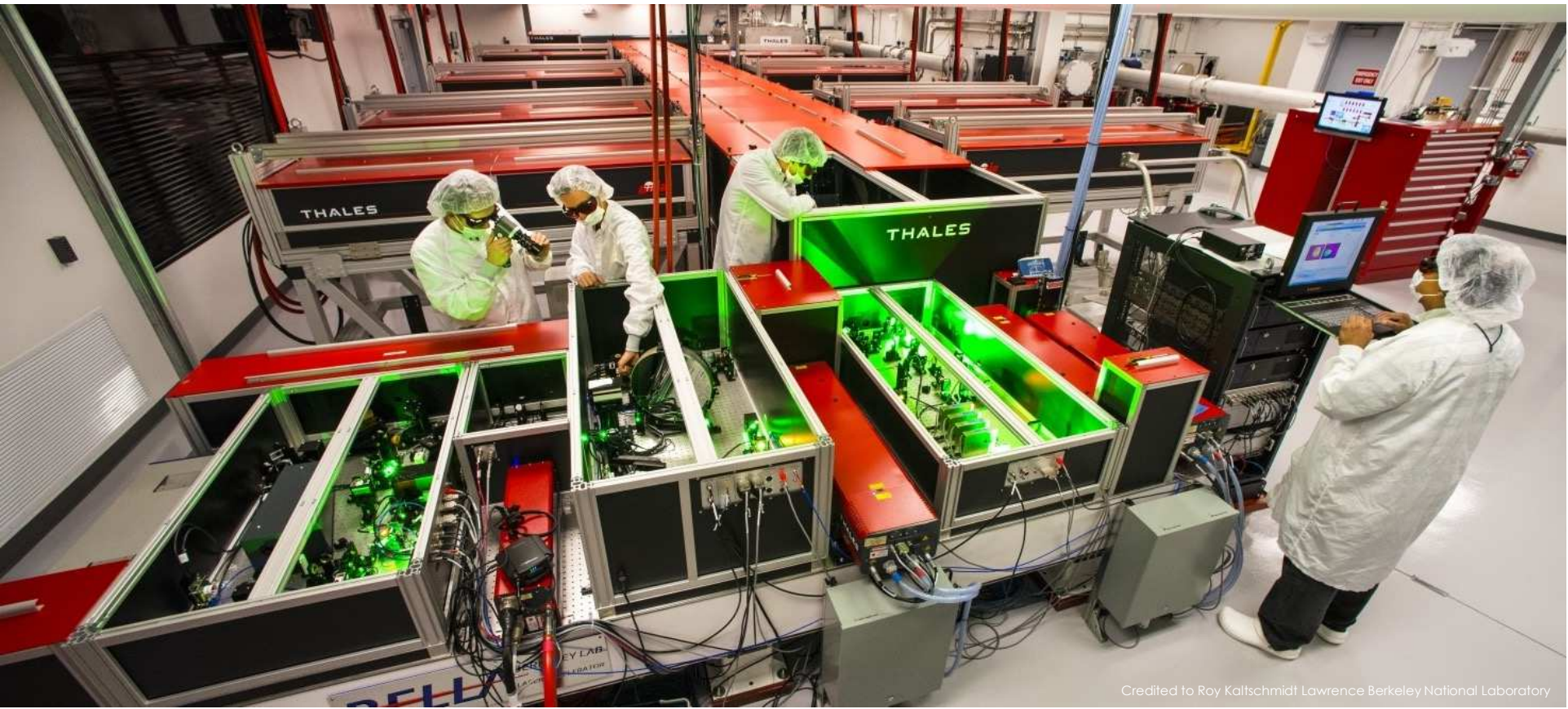
Accelerators point of view :

- Good beam quality & Monoenergetic dE/E down to 1 % √
- Beam is very stable √
- Energy is tunable: up to 400 MeV √
- Charge is tunable: 1 to tens of pC √
- Energy spread is tunable: 1 to 10 % √
- Ultra short e-bunch : 1,5 fs rms √
- Low divergence : 2 mrad √
- Low emittance[1-3] : < π.mm.mrad √
- With PW class laser : peak energy at 8 GeV √

[1]S. Fritzler *et al.*, Phys. Rev. Lett. **92**, 165006 (2004), [2]C. M. S. Sears *et al.*, PRSTAB **13**, 092803 (2010), [3]E. Brunetti *et al.*, Phys. Rev. Lett. **105**, 215007 (2010)

BELLA Center: 4 unique Laser-driven Accelerator systems

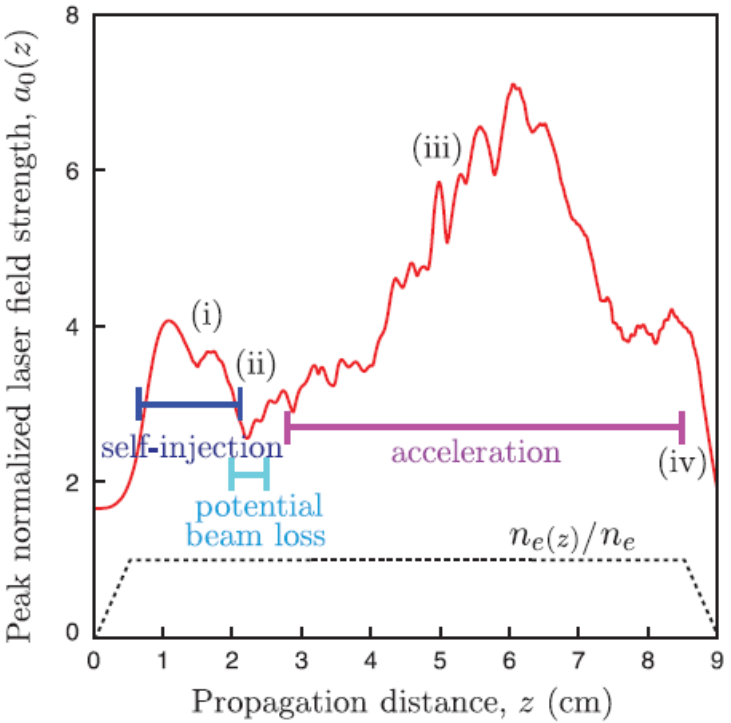


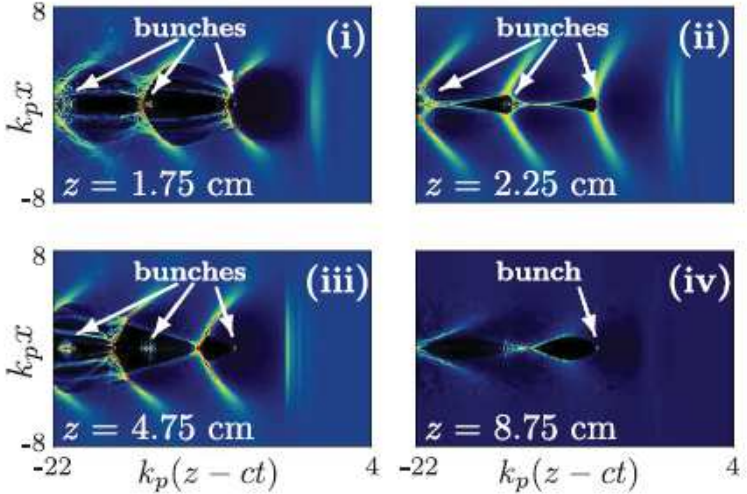


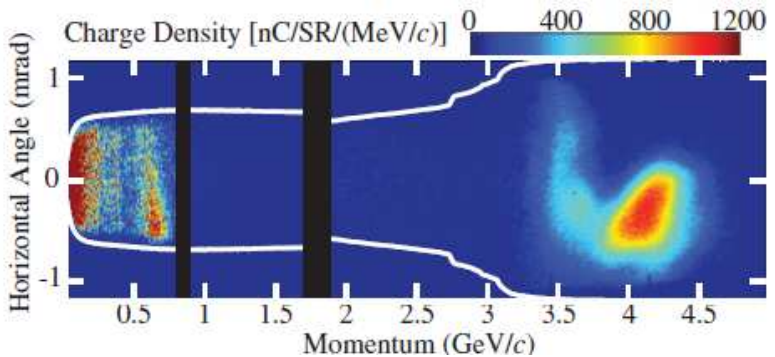
Credited to Roy Kaltschmidt Lawrence Berkeley National Laboratory

BELLA Results (2014 4.2GeV)

PRL **113,** 245002 (2014)

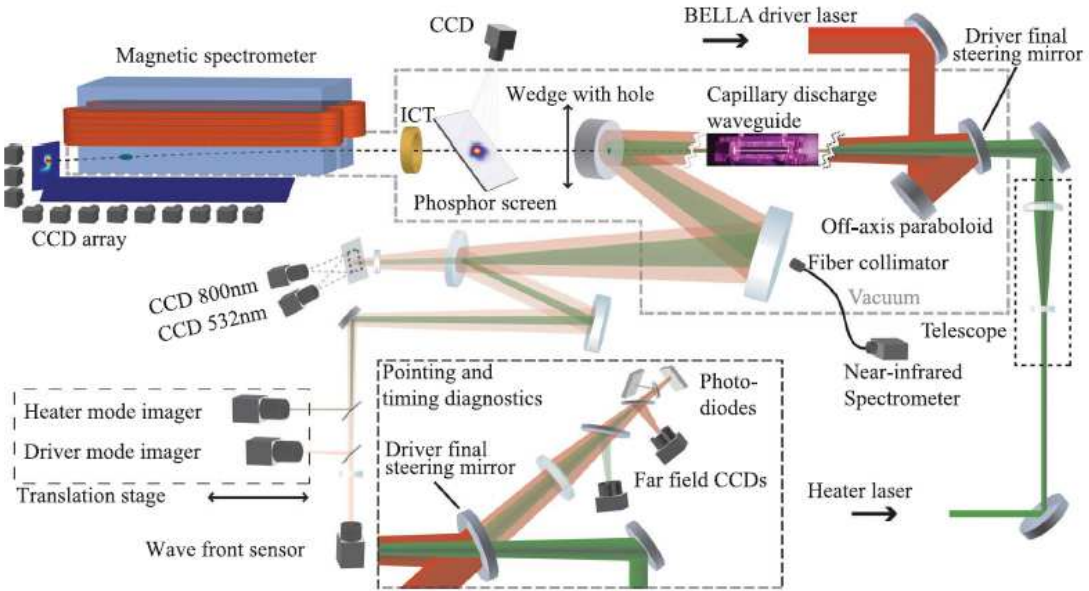


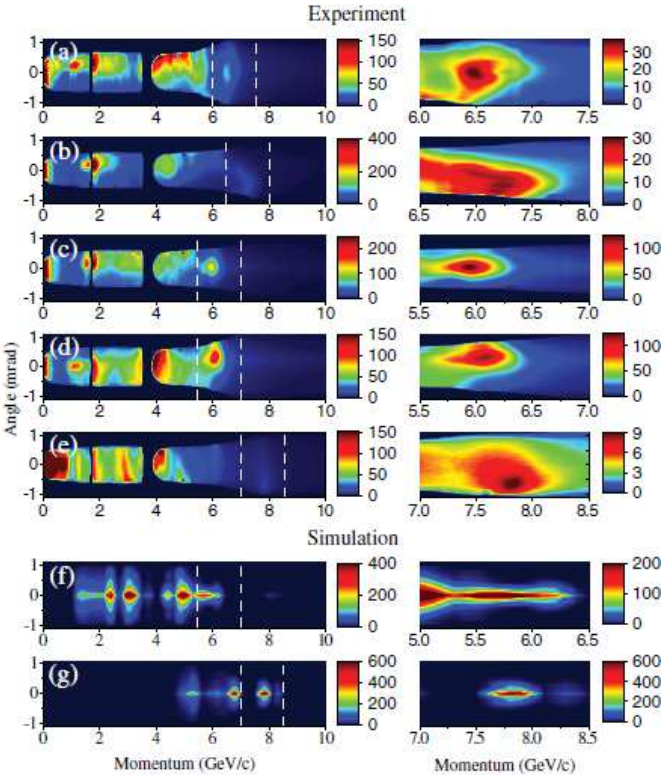




BELLA Results (2018 7.8GeV)

PHYSICAL REVIEW LETTERS **122,** 084801 (2019)

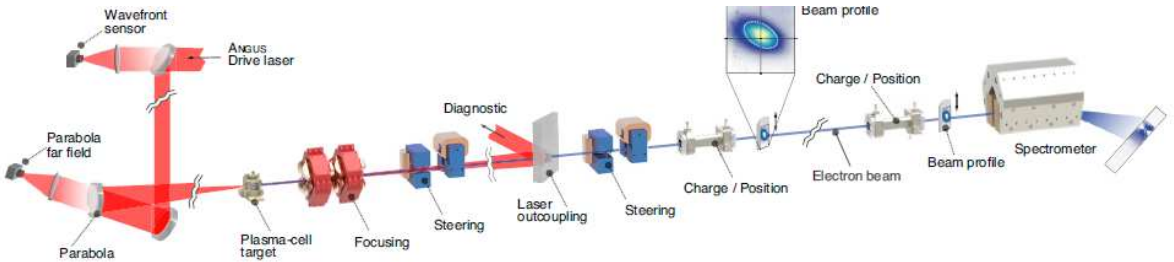


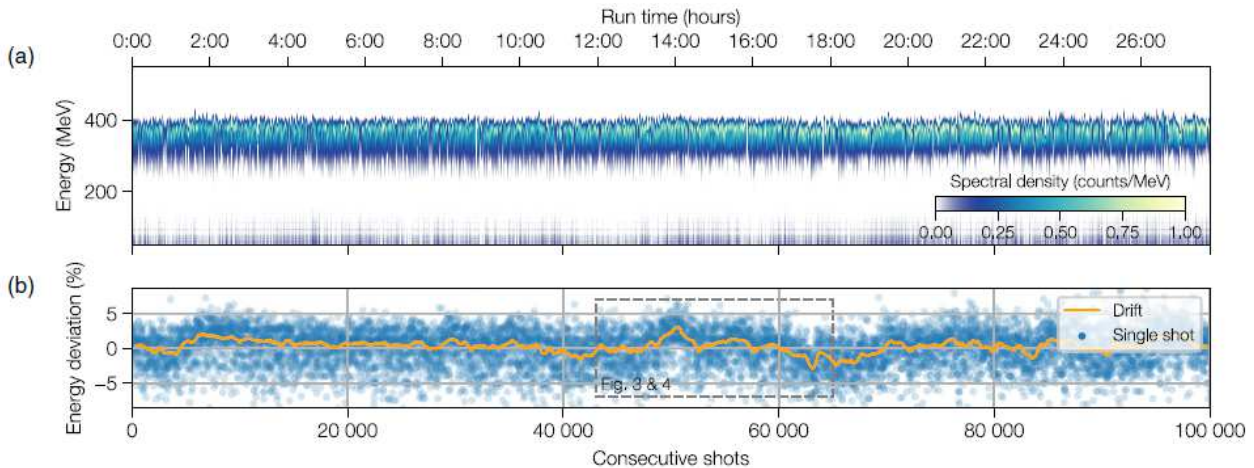


Toward Loading an Accelerator

Andreas Maier's Group (DESY)

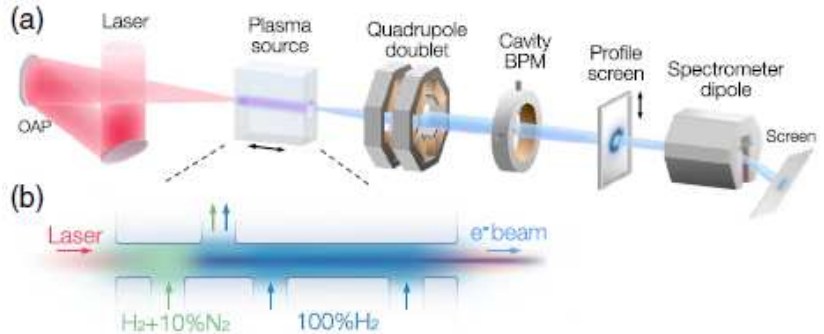
PHYS. REV. X 10, 031039 (2020)

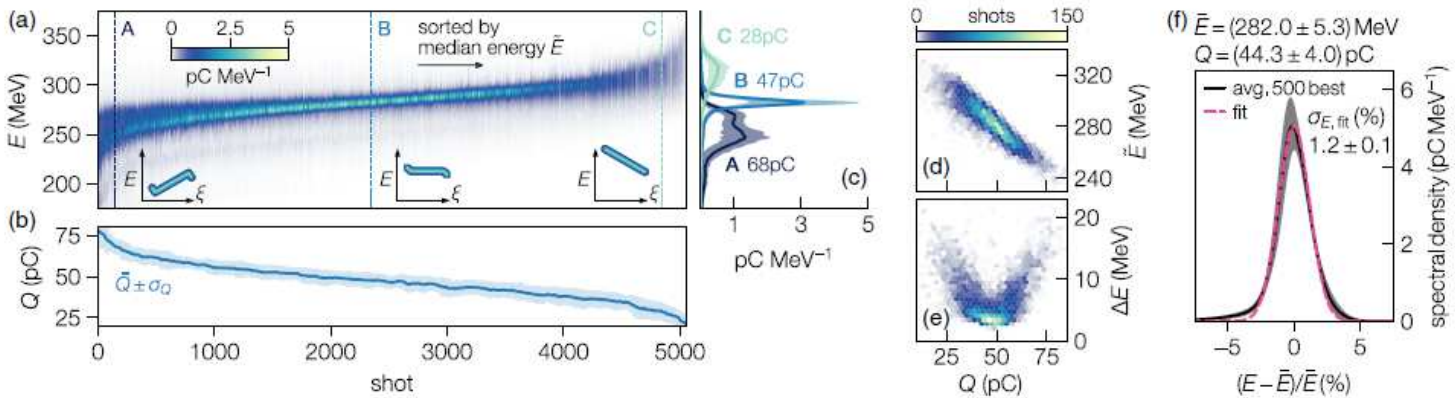




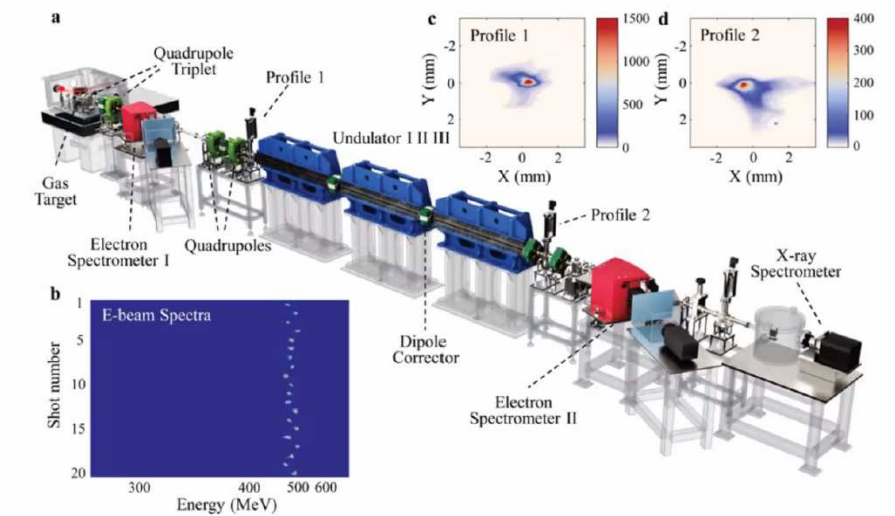
Toward Loading an Accelerator

Andreas Maier's Group (DESY) PHYSICAL REVIEW LETTERS **126,** 174801 (2021)

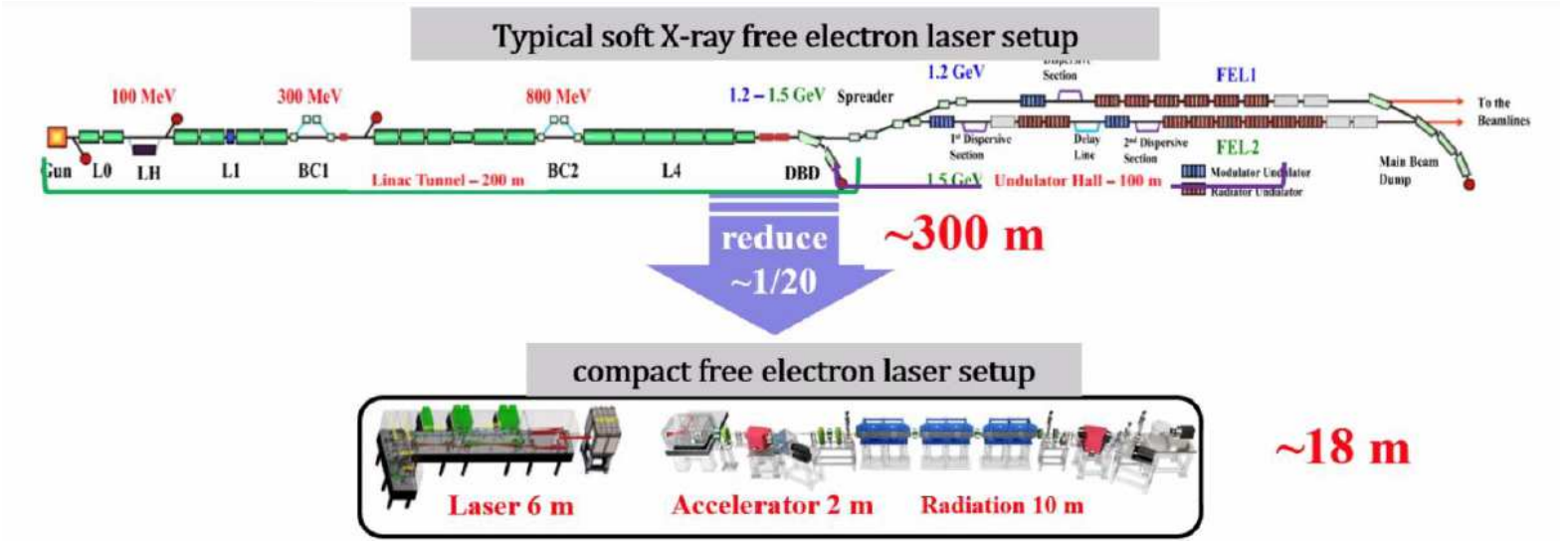




Seeded FEL (2020)

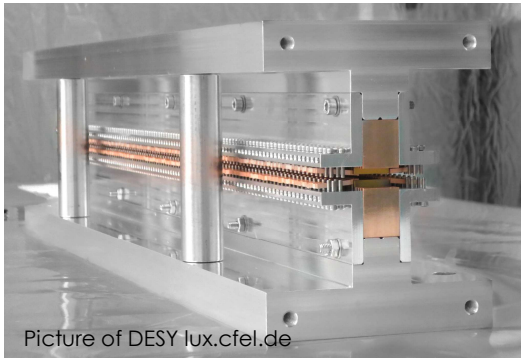


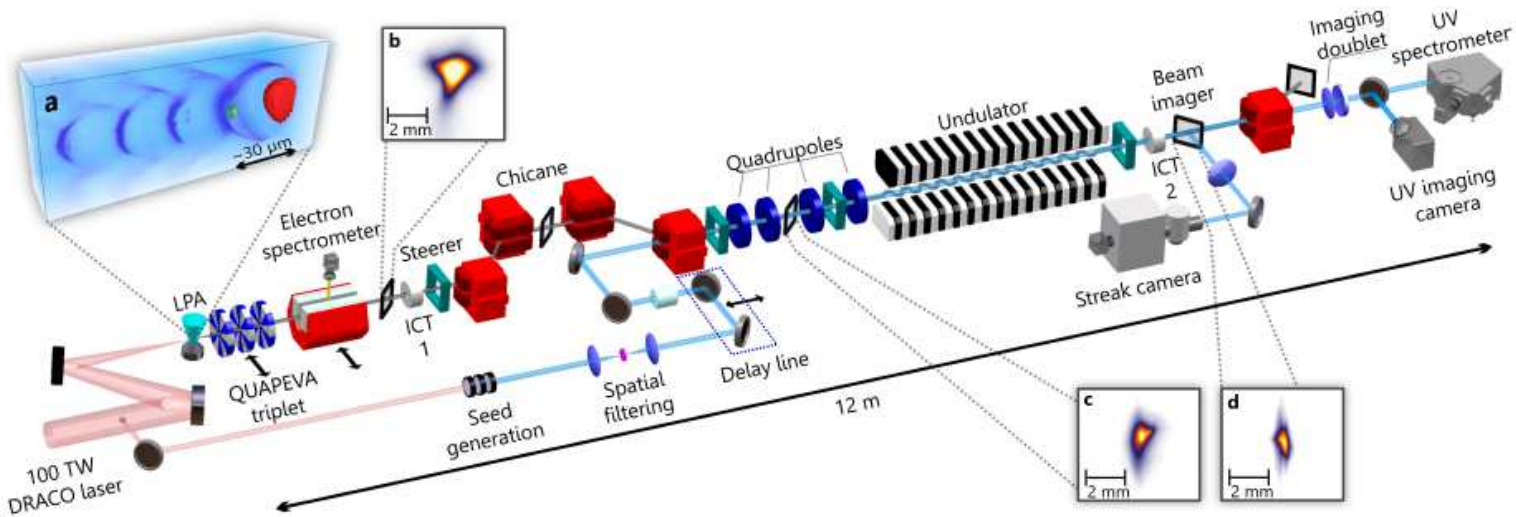
100nJ



Seeded FEL

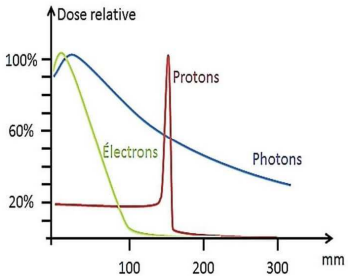
Marie LABAT et Al. 2022: Seeded free-electron laser driven by a compact laser plasma accelerator


Picture of DESY lux.cfel.de



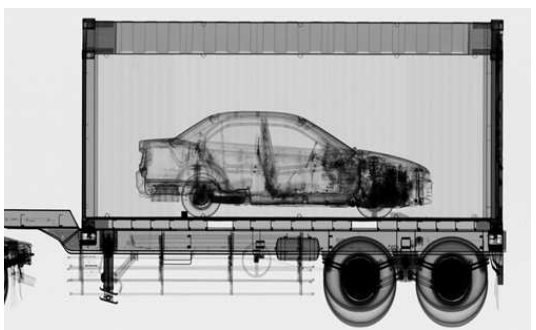
Short term roadmap

INCREASING REPETITION RATE OF OUR FEMTOSECOND SYSTEMS: A NEED FROM INDUSTRIAL & SCIENTIFIC APPLICATIONS



Current work in progress

- TiSa is confirmed as the ideal technology for producing high-energy ultrashort pulses
- Development of 1J / 100 Hz laser system for scientific and industrial applications



HERACLES³

INSTITUT POLYTECHNIQUE DE PARIS

ENSTA

ÉCOLE POLYTECHNIQUE

cnrs

THALES

OME – TRT – AVS

HERACLES 3

(Hautes Energies pour la Recherche en ACcélération Laser d'Electrons et Sources Secondaires à Saclay)

HERACLES3 JOINT LAB

THALES

- **THALES LAS** : Bulk laser expert at Elancourt
- **THALES SA :** Thales Research Center at Palaiseau, fiber laser experts
- **THALES AVS :** Microwave and Imaging Sub-systems at Velizy

ACADEMIC PARTNERS

- **Ecole Polytechnique**
- **ENSTA** → **LULI and LOA**
- **CNRS**

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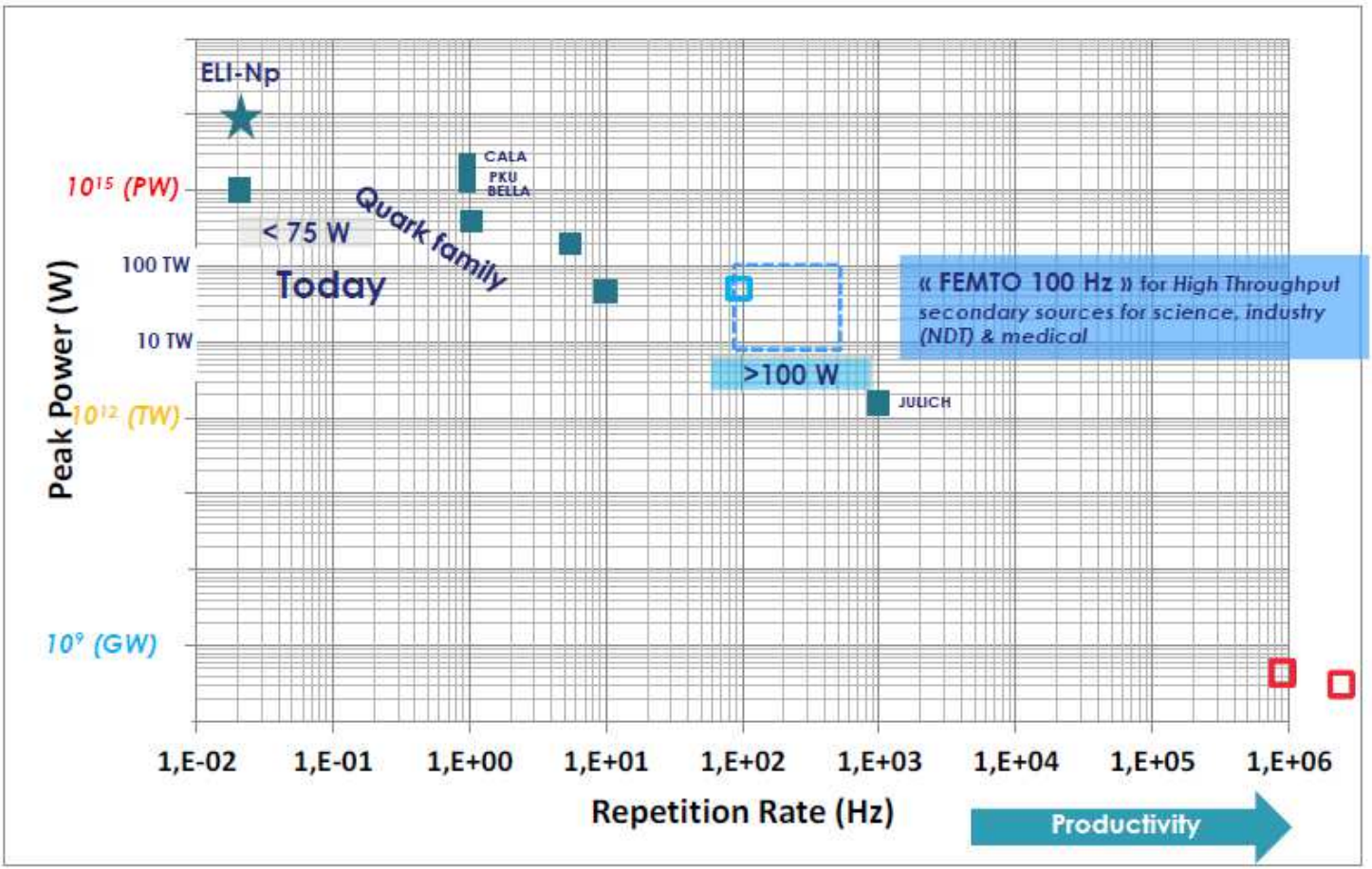
THALES

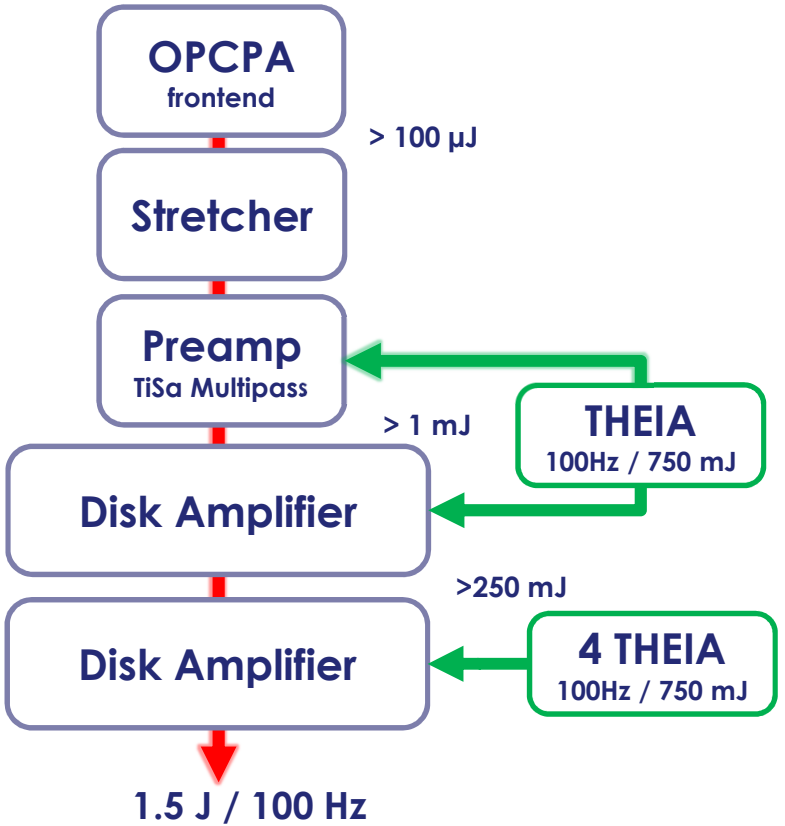

ELI-Np
CALA
PKU
BELLA
Quark family
< 75 W
Today
>100 W
JULICH
« FEMTO 100 Hz » for High Throughput secondary sources for science, industry (NDT) & medical
« X-CAN »
Peak Power (W)
10¹⁵ (PW)
100 TW
10 TW
10¹² (TW)
10⁹ (GW)
1,E-02
1,E-01
1,E+00
1,E+01
1,E+02
1,E+03
1,E+04
1,E+05
1,E+06
Repetition Rate (Hz)
Productivity

100Hz laser architecture

FROM HIGH PEAK POWER TO HIGH REPETITION RATE

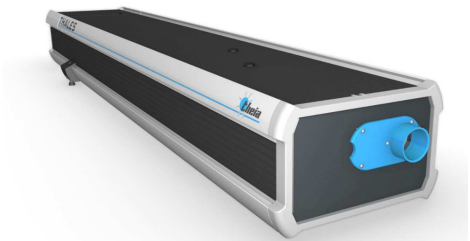
New TiSa laser architecture – In development

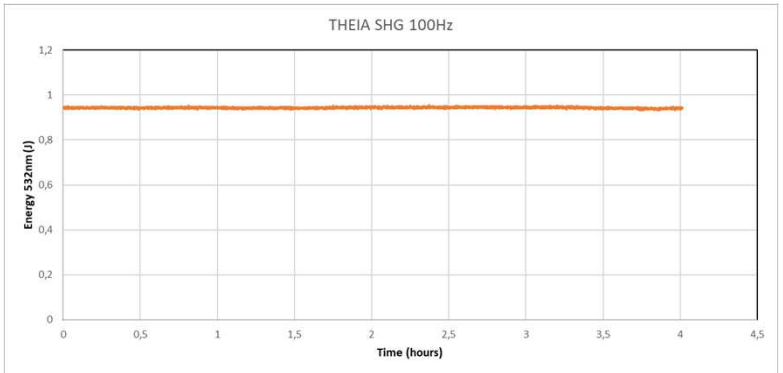
- **Robust OPCPA FE** : 100Hz / 300µJ demonstrated
- New ns diode-pumped laser : **THEIA family qualified**
- 2020-2021 / New TiSa amplifier architecture : **Qualification @ 300mJ 100Hz**
- 2022-2023 / Design and qualification of **1.5J amplifier 100Hz**

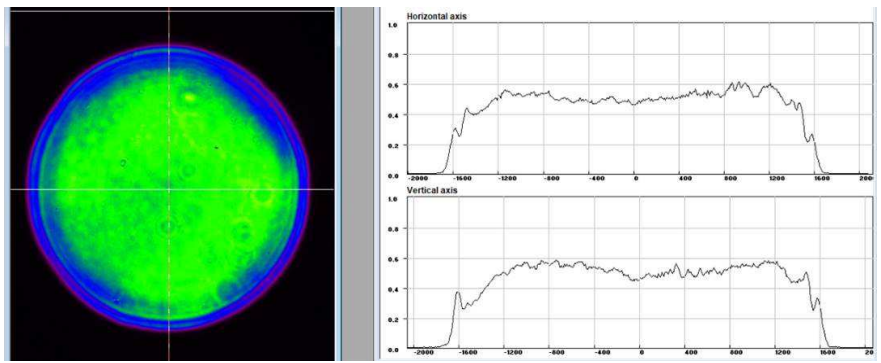


100/200 HZ THEIA LASER

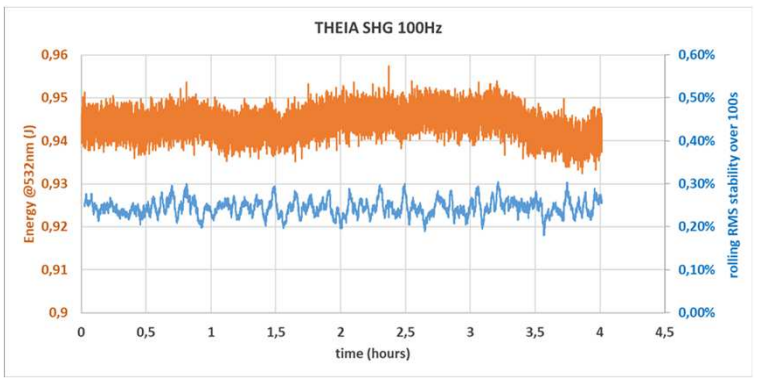
- Energy : 1µm >1J / 532nm > 700mJ / 355nm > 500mJ
- Pulse duration : 10-15 ns
- Bench size : 160*30*20 (L*l*H)





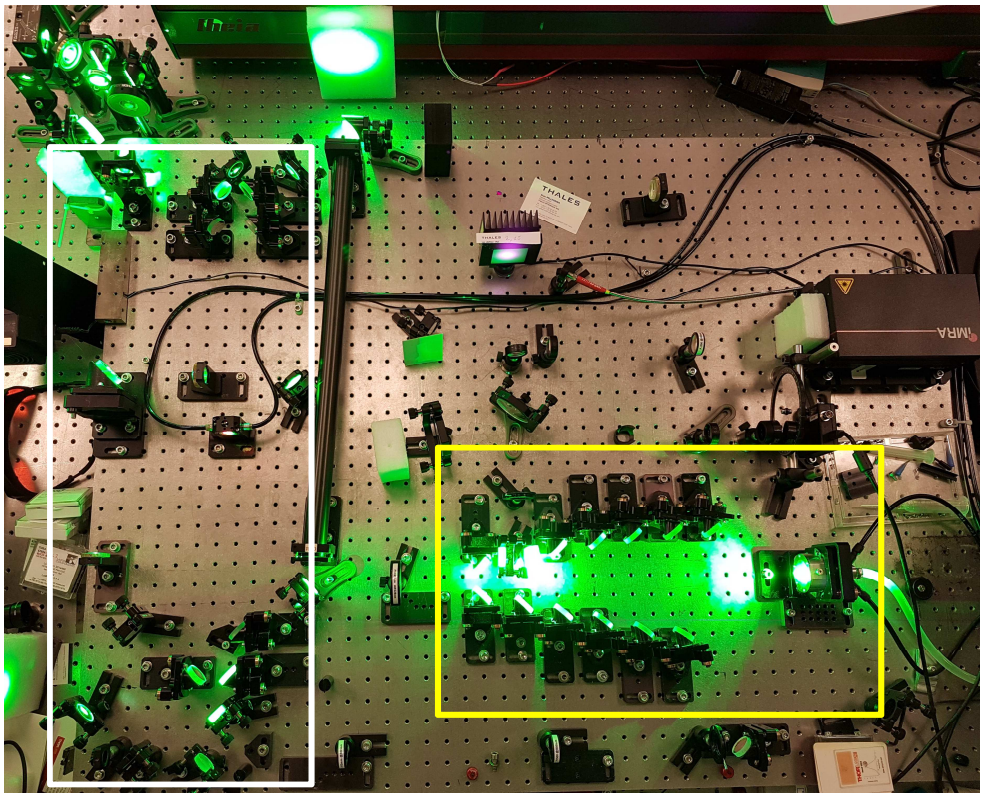


Beam profile at the output of the THEIA



Four hours stability @ 100Hz

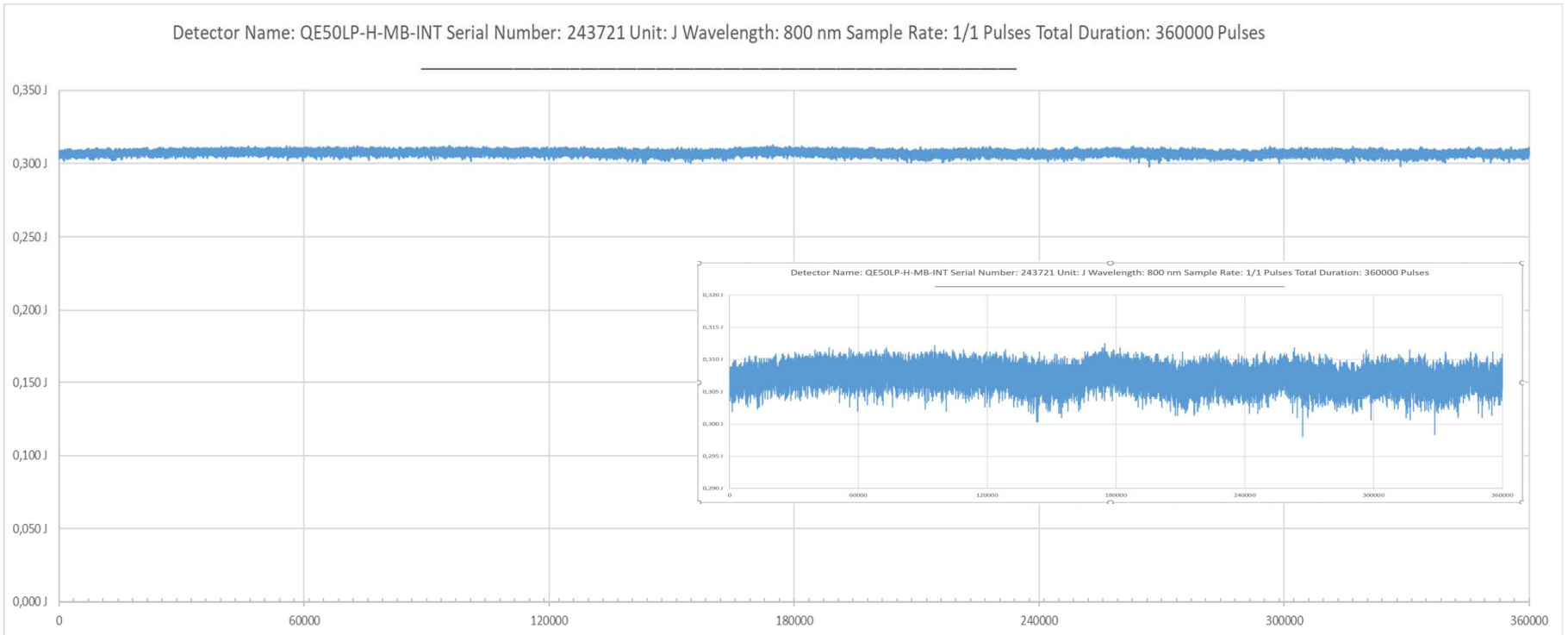
THICK DISK TISA PUMPED BY THEIA LASER



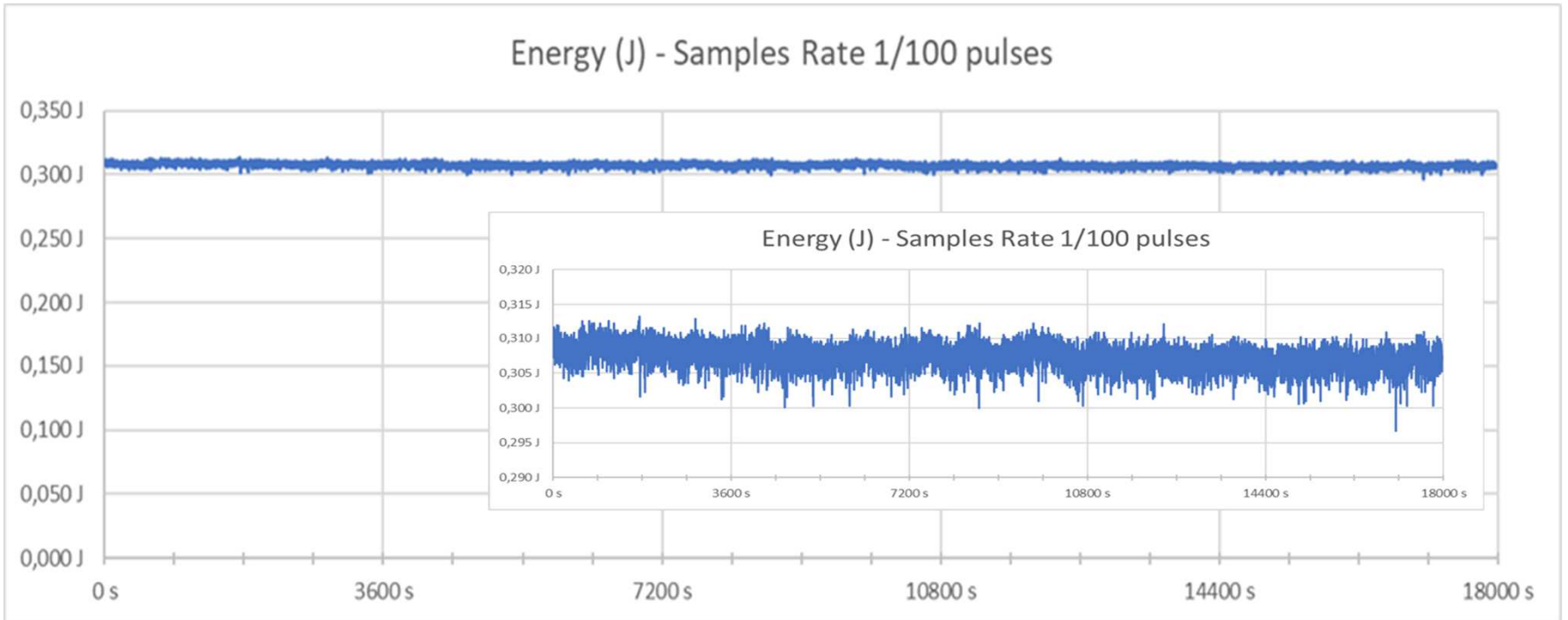
Multi-pass amplifier seed by XPW

- Seed 10µJ
- Standard 4 passes preamplifier : output energy 3mJ
- Thick-disk TiSa amplifier : output energy > 300mJ, stability < 0.5%rms for an hour

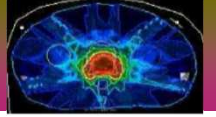
THICK DISK TISA PUMPED BY THEIA LASER : 1 HOUR OPERATION



THICK DISK TISA PUMPED BY THEIA LASER : 5 HOURS OPERATION 1/100 PULSES



Laser beam parameters for electron-RT



Considered cases	Robustness	Maturity	Cost
1 mJ/10kHz/ 3fs	-	Low	?
10mJ/1 kHz/few fs	-	Low/medium	?
100mJ/100Hz 20fs	++	medium	?
1J/10Hz 30fs	++	High	1-1.5 M€

1kHz 40mJ + Post Comp

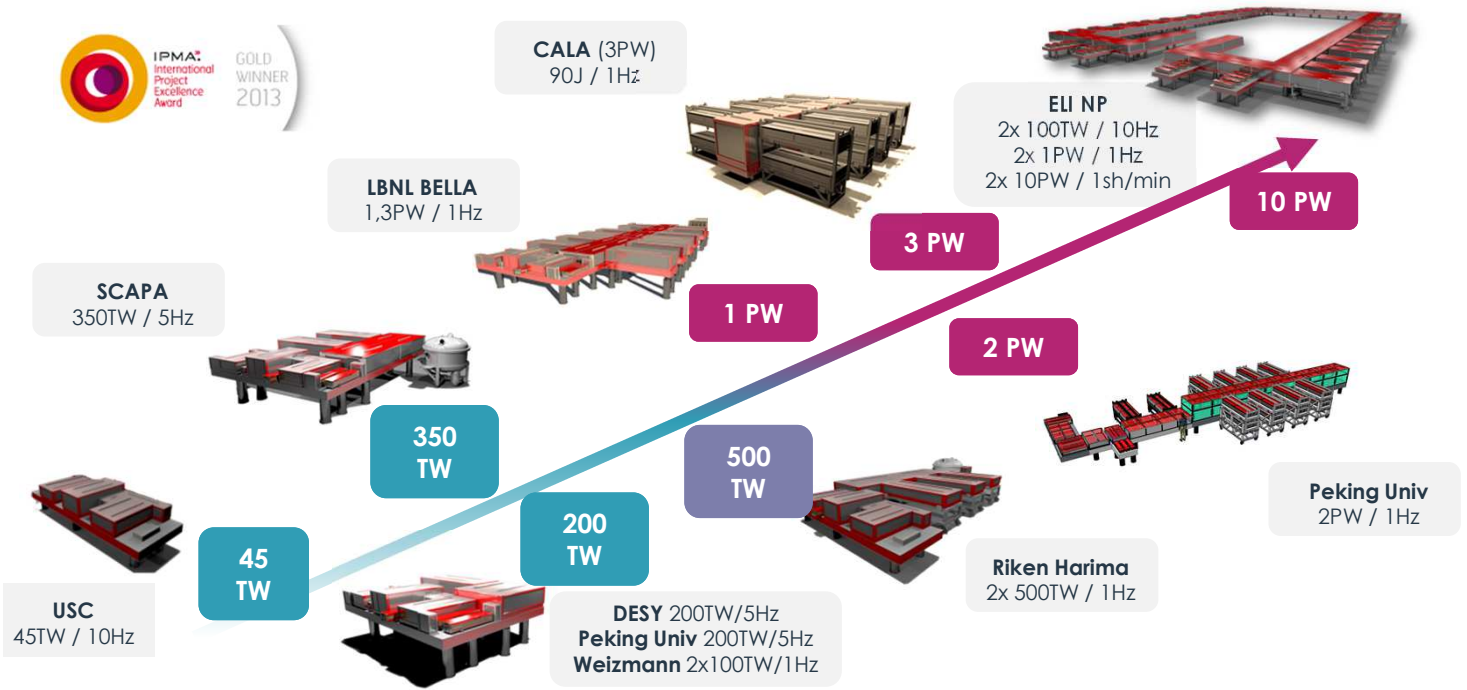
2023

OK

Reduction of the laser energy (assuming the photon to electron efficiency the same) requires higher repetition rate

Few 100'smJ/few 10'sHz/ 20 fs seems to be a good compromise on the basis on the present technology

AMPLIFICATION OF HIGH-ENERGY FEMTOSECOND PULSES FOR SCIENCE



High-energy pumping lasers are designed and produced in Thales:

SAGA – GAIA – ATLAS – THEIA


Thank You