Laser drivers for plasma accelerators
State-of-the-art and its relevance to collider development

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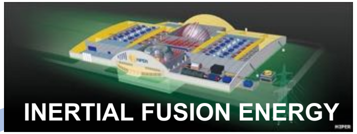
OUTLINE

- Intro on relevant laser needs and features
- Roadmap for laser driver development
- Short-medium term options
- Constraints and high efficiency options
- Engaged developments
- Summary

Grand challenges of laser-plasma technology

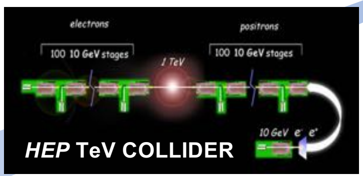
Aiming at extensive use of multiple (hundreds of) laser units at high average power

Limited by laser technology



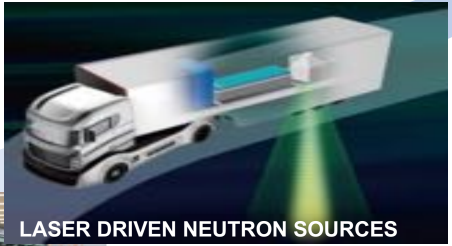
Towards CDR

S. Atzeni et al., https://doi.org/10.1017/hpl.2021.41



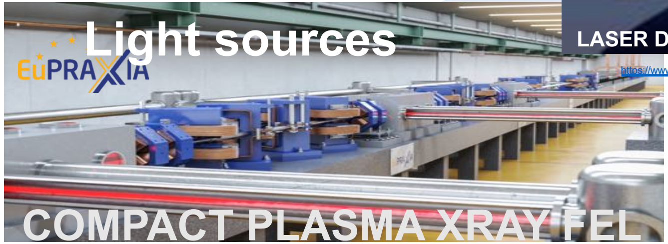
Towards CDR

C. Benedetti et al., https://doi.org/10.48550/arXiv.2203.08366



https://www.ile.osaka-u.ac.jp/eng/research/project/project-lans/index.html

R&D



EuPRAXIA Preparatory phase

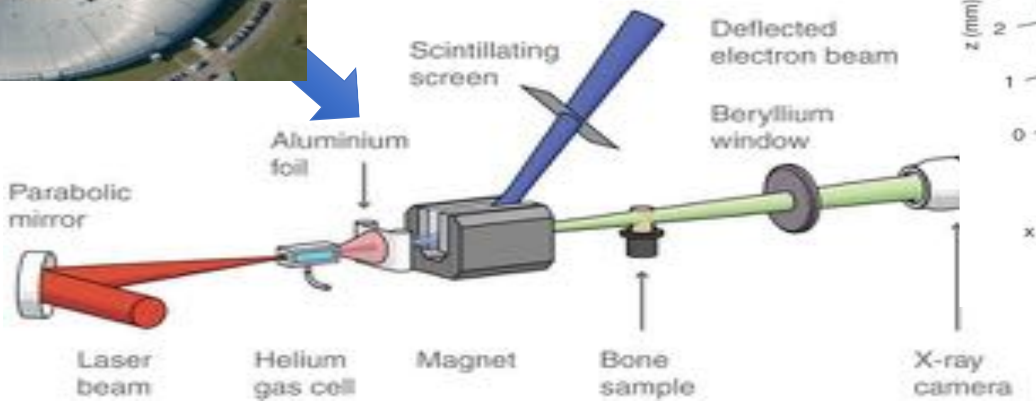
R. Assmann et al., https://doi.org/10.1140/epjst/e2020-000127-8

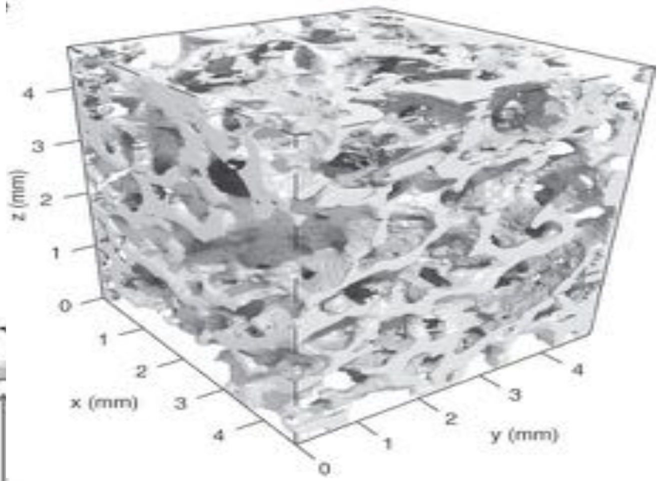
Cost, durability, energy efficiency, mass production of underlying laser components key to enable these developments.

Mature applications: X-ray imaging

X-ray imaging for compact, high resolution (phase contrast imaging) bio-medical diagnostics

Address some of the needs of large SR facility users





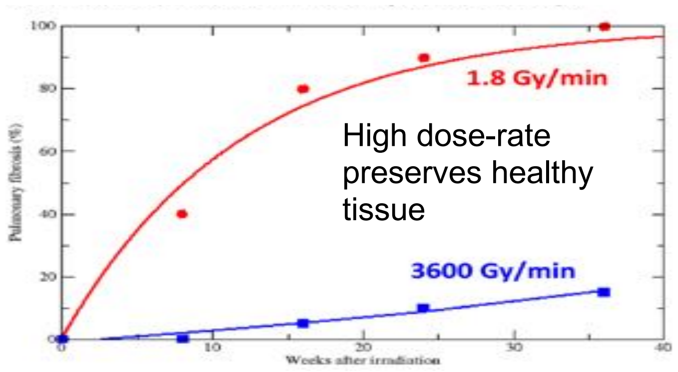
J.M.Cole et al., Scientific Reports 5, 13244 (2015)

Needs next generation high repetition rate kW laser driver

Emerging applications: radiotherapy

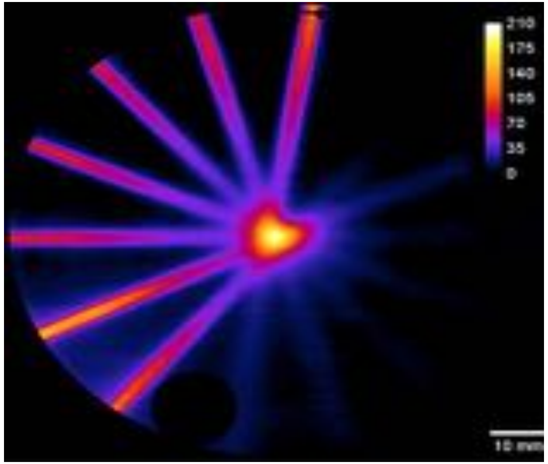
LPA beams can meet specifications of advanced radiotherapy approaches

Laser-driven electron beams can provide ultra-high dose-rate to meet requirements of future "**FLASH" radiotherapy with Very High Energy electrons (VHEE) in a compact size**:



V. Favaudon et al., Sci Transl Med. 2014 Jul 16;6(245):245ra93

VHEE with Laser driven: Dosimetry



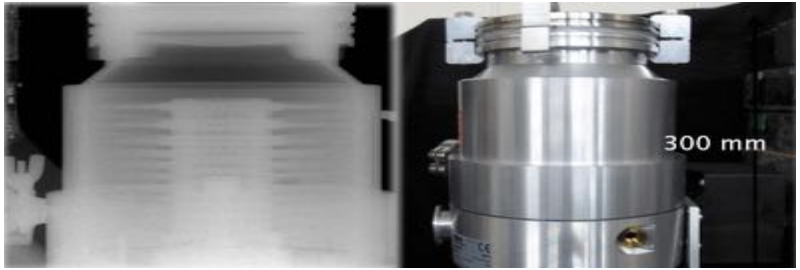
Proof of principle Multi-Field Radiation Therapy Very high energy electrons. (L.Labate et al. Sci Rep, 2020)

Almost none of the 13000 radiotherapy linacs worldwide can deliver FLASH beams: a huge potential still to be addressed, with major R&D in RF accelerators and novel accelerators, including laser-driven LPA.

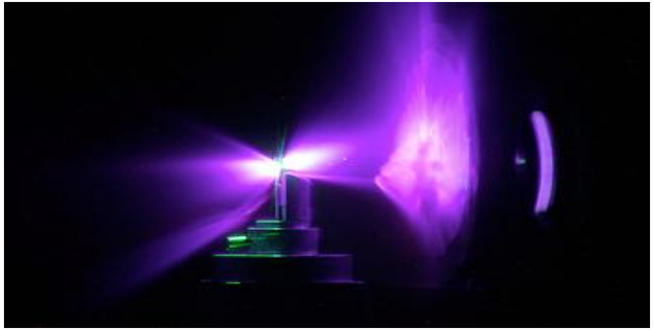
Needs next generation of high repetition rate <kW laser driver

Emerging applications: industry and security

High energy X-rays or neutron sources are being developed for industry and security



Industrial high temporal resolution X-ray imaging - C. M. Brenner et al, PPCF, 58 014039, (2015)



Laser driven neutron sources at Los Alamos

New high intensity laser based facility (80M GPB investment) to support science, technology, innovation and industry.

The Extreme Photonics Applications Centre, CLF, UK

Moving to implementation of kW laser technology for users

High intensity lasers: evolution

Major breakthrough following Chirped Pulse Amplification

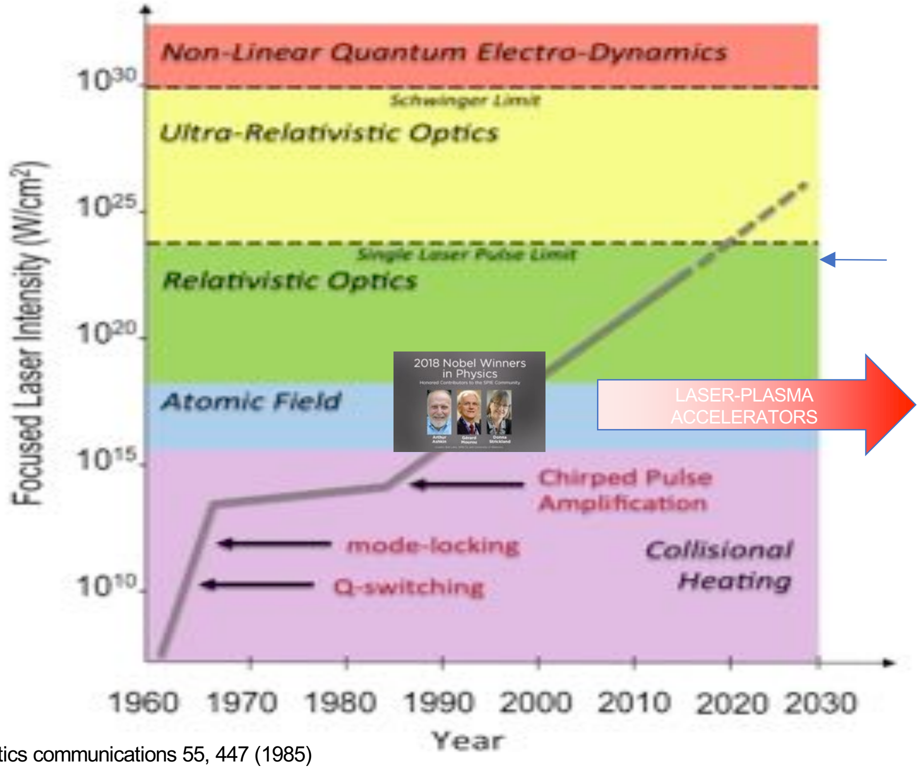
Current laser technology developmentof CPA lasers [1] mainly driven by **extreme intensity** applications;

Laser-Plasma acceleration has developed along with progress in laser performance;

Recent LWFA-FEL demonstration [2] highlights the role of laser stability and control;

Need to focus on the technology required to achieve high-repetition rate at multi-joule (≈100 TW) scale [3], with high quality and enhanced control and stability;

Key role of industry to establish turn-key, high average/peak power ultrashort pulse technology;



1E23 W/cm2 Current highest intensity in the lab [4]

[1] D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses." Optics communications 55, 447 (1985)
[2] W. Wang, K.Feng et al., Free-electron lasing at 27 nanometres based on a laser wakefield accelerator, *Nature* **595**, 516–520 (2021)
[3] L.A. Gizzi et al., A viable laser driver for a user plasma accelerator, NIM **A 909** , 58 (2018); https://doi.org/10.1063/1.4984906
[4] J. W. Yoon et al., "Realization of laser intensity over 1023 W/cm2," Optica 8, 630-635 (2021), https://doi.org/10.1364/OPTICA.420520

LWFA: laser power and quality control

Progress in laser specs is key to the development o Laser Wakefield Acceleration

LWFA: Theoretical model
T. Tajima, J. M. Dawson PRL 43, 267 (1979)

CPA Laser invention,
D. Strickland and G. Mourou" Optics communications 55, 447 (1985)

1995: First electron beam
A. Modena et al., Nature 377 (606) 1995

2004: first monoenergetic electron beam 100 MeV
J. Faure et al., C.G.R. Gedders et al., S. Mangles et al., Nature 431 (2004)

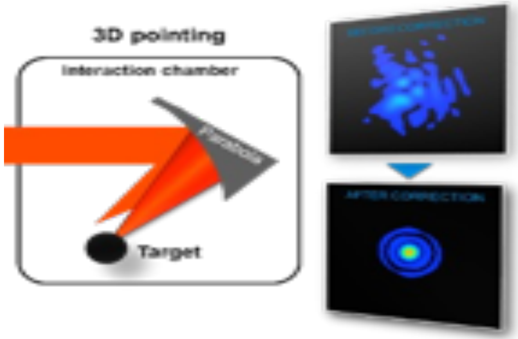
2006: Energy gain: 1 GeV
W.P. Leemans et. al, Nature Physics 696 (2006)

2014: Energy gain: 4.3 GeV
W.P. Leemans et. al, PRL 113 (2014)

+ staging (proof of principle)
S. Steinke et al., Nature 530 (2016)

2019: Energy gain: 8 GeV
A. Gonsalves et. al, PRL 122(2019)

Peak Power	Beam Quality (Energy in the focal spot)
1 TW	30%
10 TW	50%
100 TW	70%
1 PW	90%



Phase front correction with adaptive optics (from astronomy)

+ several additional quality parameters

What laser driver specs for future LPAs

Rapidly evolving scenario for laser technologies relevant for plasma acceleration towards multi-stage accelerators design:

Pillars for a STRATEGY for laser drivers for plasma accelerators:

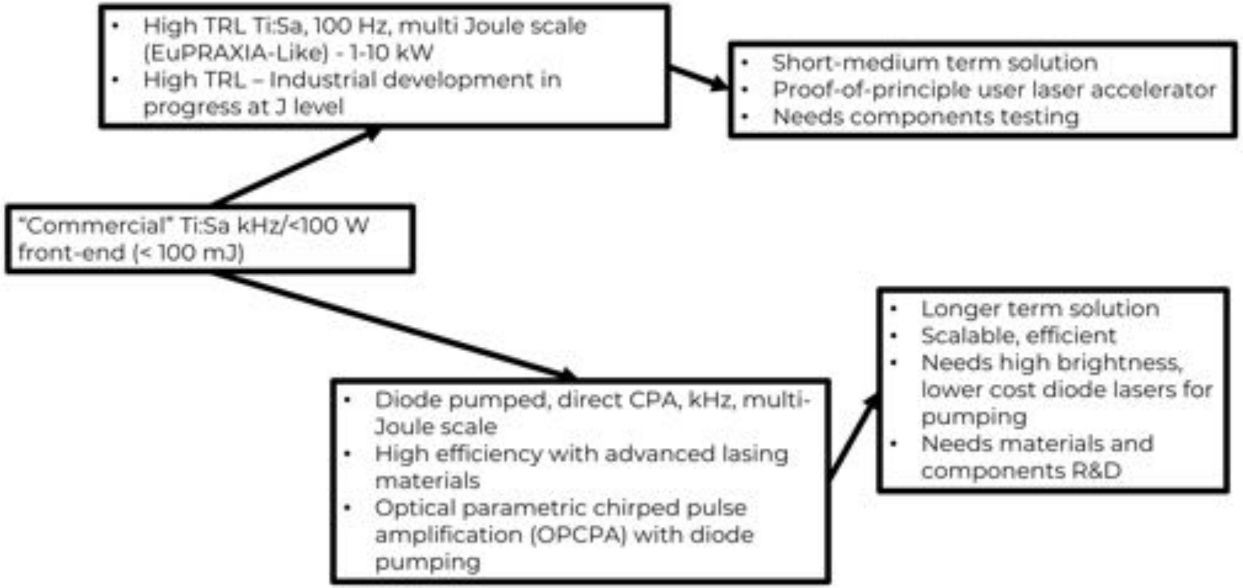
Ultrashort pulses (large bandwidth <50 fs)
High Repetition rate (100 Hz – 50 kHz)
High average power (kW -10s kW)
High wall-plug efficiency (>10%)

- IFAST EU project on novel accelerator techniques just funded (Coordinated by CERN): https://ifast-project.eu/
- Task on "Lasers for Plasma Acceleration (LASPLA)"
  - Roadmap to foster delivery of industrial laser drivers for the plasma-based accelerator.
  - Networking among main laser lab working on LPA laser-driver R&D.

L.A. Gizzi, F. Mathieu, P. Mason, P P Rajeev, *Laser drivers for Plasma Accelerators*, in Félicie Albert et al, *2020 roadmap on plasma accelerators*, 2021 New J. Phys. 23 031101, https://doi.org/10.1088/1367-2630/abcc62

Roadmap for laser driver development

Parto of the **WP6: Novel Particle Accelerators Concepts and Technologies of i.FAST**

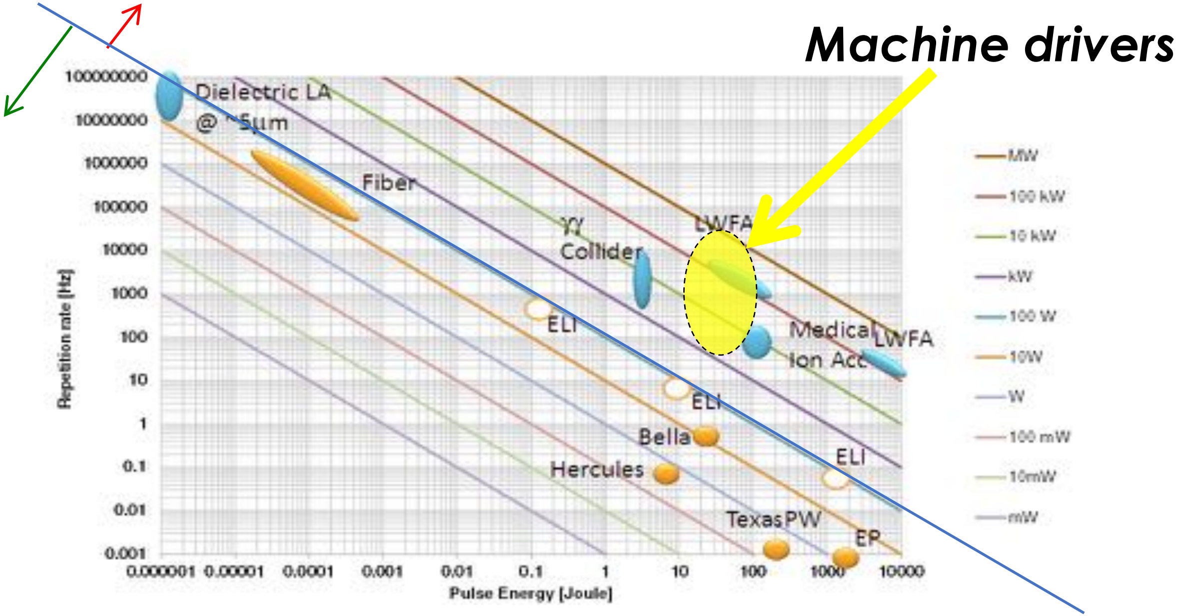


Innovation Fostering in Accelerator Science and Technology (I.FAST) coordinated by CERN https://ifast-project.eu/

Average power

Current reqirement for LPA driver: PW-class system, with high repetition rate (≈kHz)

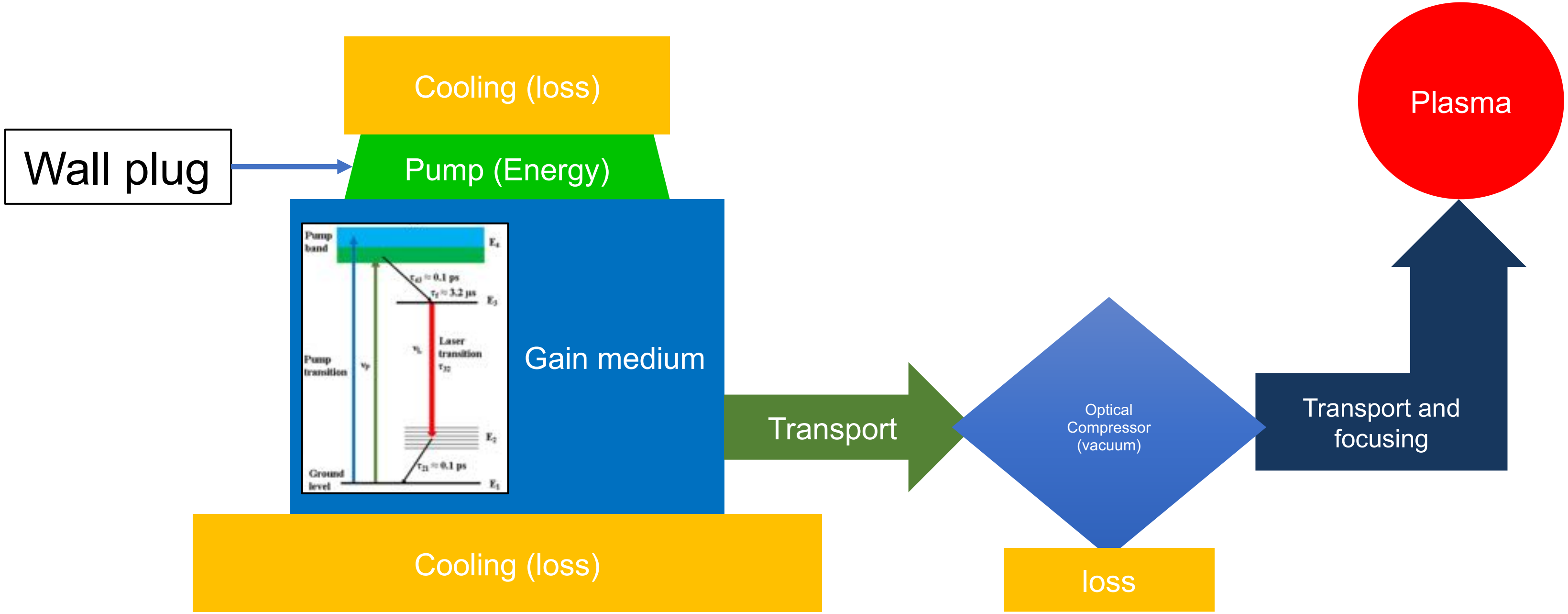
Demanding high average power



Major effort required to fill the gap between **existing** and **required** laser technology

Relevant blocks of a laser driver

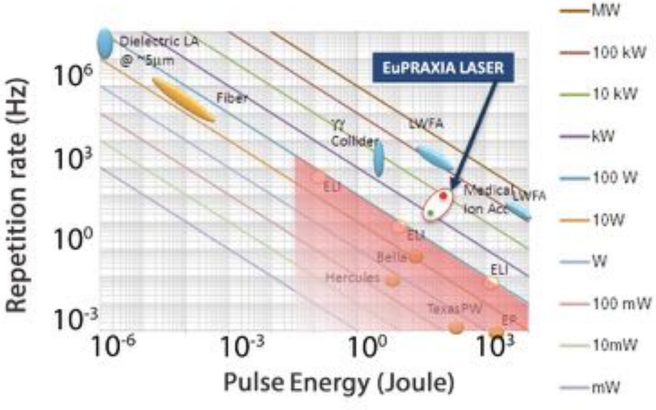
Tackle power and coupling efficiencies and losses



Roadmap on LPA Laser Driver technology

Laser-driven plasma acceleration needs ultrashort, high power lasers with high average power

- **Current industrial technology: ≈ Ti:Sa technology, pumped by flash-lamp pumped lasers**
  - Robust, reliable industrial technology
- **Mature technology: ≈ Ti:Sa technology, pumped by diode-pumped lasers**
  - Strong R&D effort in place (e.g HAPLS@ELI)
  - ≈ 3-5 years to go to first industrial LWFA demonstrator (e.g. Eupraxia) [1]



- **Beyond TiSA: targeting higher wall-plug efficiency and rep. rate, kHz and beyond, stability, control (space, time, spectral)**;
  - **5-10 yrs for first efficient**, multi-kW-scale demonstrator,
  - A strategy is needed to steer effort in the LPA laser driver direction: LASPLA

The L3-HAPLS at ELI Beamlines Research Center in the Czech Republic. Credit: ELI Beamlines*

[1] R. Assmann et al., EuPRAXIA Conceptual Design Report, The European Physical Journal Special Topics **229**, 3675–4284 (2020)
[2] C. Danson et al., Petawatt and exawatt class lasers worldwide High Power Laser Sci. and Eng. **7**, e54 (2019)

The EuPRAXIA Project

With the inclusion in ESFRI and the approval of the Preparatory Phase Project, EuPRAXIA must rapidly move from the conceptual design to a viable technical design of the laser driver.

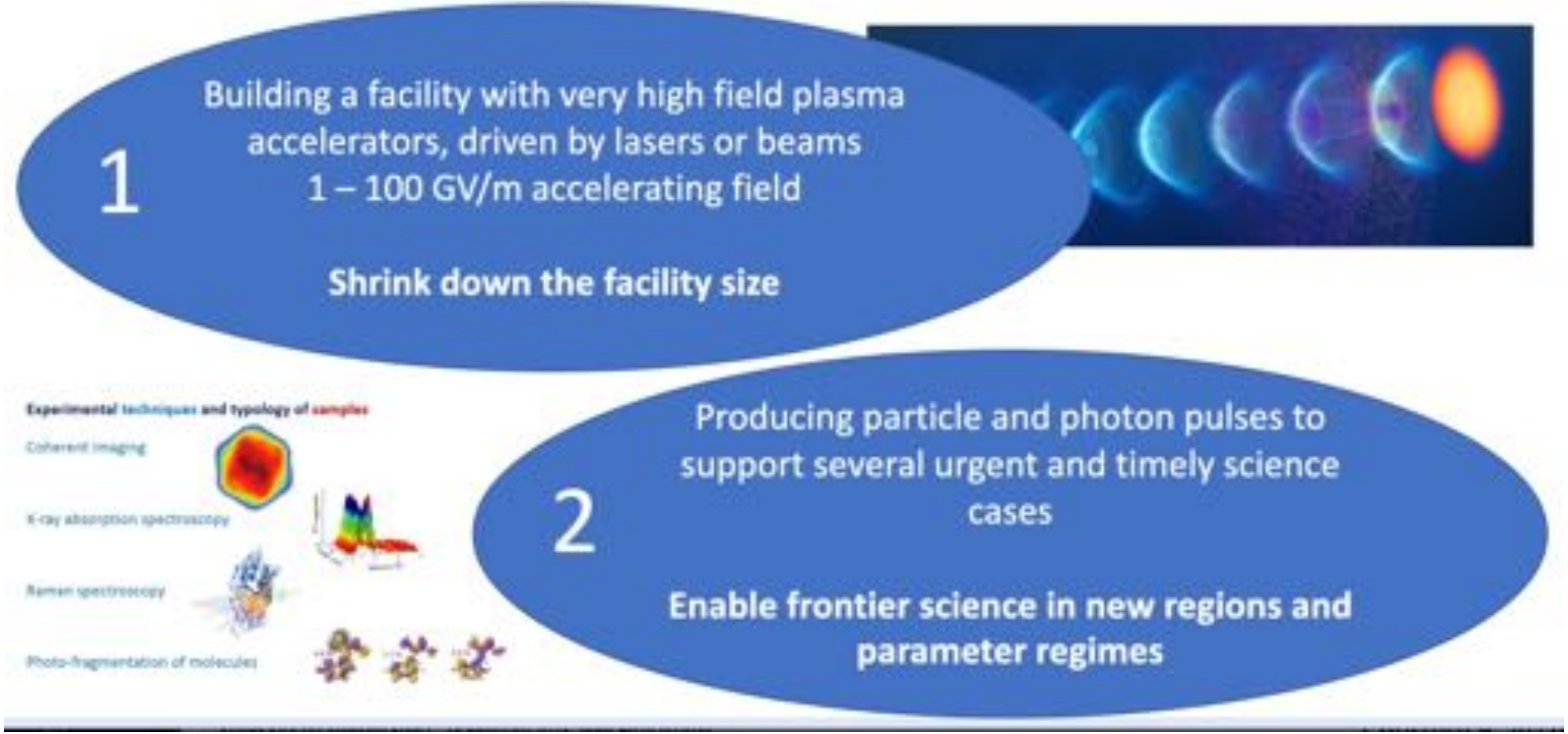
EuPRAXIA

R. W. Assmann, M. K. Weikum, T. Akhter, D. Alesini, A. S. Alexandrova, M. P. Anania, N. E. Andreev, I. Andriyash, M. Artioli, A. Aschikhin, T. Audet, A. Bacci, I. F. Barna, S. Bartocci, A. Bayramian, A. Beaton, A. Beck, M. Bellaveglia, A. Beluze, A. Bernhard, A. Biagioni, S. Bielawski, F. G. Bisesto, A. Bonatto, L. Boulton, F. Brandi, R. Brinkmann, F. Briquez, F. Brottier, E. Bründermann, M. Büscher, B. Buonomo, M. H. Bussmann, G. Bussolino, P. Campana, S. Cantarella, K. Cassou, A. Chancé, M. Chen, E. Chiadroni, A. Cianchi, F. Cioeta, J. A. Clarke, J. M. Cole, G. Costa, M. -E. Couprie, J. Cowley, M. Croia, B. Cros, P. A. Crump, R. D'Arcy, G. Dattoli, A. Del Dotto, N. Delerue, M. Del Franco, P. Delinikolas, S. De Nicola, J. M. Dias, D. Di Giovenale, M. Diomede, E. Di Pasquale, G. Di Pirro, G. Di Raddo, U. Dorda, A. C. Erlandson, K. Ertel, A. Esposito, F. Falcoz, A. Falone, R. Fedele, A. Ferran Pousa, M. Ferrario, F. Filippi, J. Fils, G. Fiore, R. Fiorito, R. A. Fonseca, G. Franzini, M. Galimberti, A. Gallo, T. C. Galvin, A. Ghaith, A. Ghigo, D. Giove, A. Giribono, L. A. Gizzi, F. J. Grüner, A. F. Habib, C. Haefner, T. Heinemann, A. Helm, B. Hidding, B. J. Holzer, S. M. Hooker, T. Hosokai, M. Hübner, M. Ibison, S. Incremona, A. Irman, F. Iungo, F. J. Jafarinia, O. Jakobsson, D. A. Jaroszynski, S. Jaster-Merz, C. Joshi, M. Kaluza, M. Kando, O. S. Karger, S. Karsch, E. Khazanov, D. Khikhlukha, M. Kirchen, G. Kirwan, C. Kitégi, A. Knetsch, D. Kocon, P. Koester, O. S. Kononenko, G. Korn, I. Kostyukov, K. O. Kruchinin, L. Labate, C. Le Blanc, C. Lechner, P. Lee, W. Leemans, A. Lehrach, X. Li, Y. Li, V. Libov, A. Lifschitz, C. A. Lindstrøm, V. Litvinenko, W. Lu, O. Lundh, A. R. Maier, V. Malka, G. G. Manahan, S. P. D. Mangles, A. Marcelli, B. Marchetti, O. Marcouillé, A. Marocchino, F. Marteau, A. Martinez de la Ossa, J. L. Martins, P. D. Mason, F. Massimo, F. Mathieu, G. Maynard, Z. Mazzotta, S. Mironov, A. Y. Molodozhentsev, S. Morante, A. Mosnier, A. Mostacci, A. -S. Müller, C. D. Murphy, Z. Najmudin, P. A. P. Nghiem, F. Nguyen, P. Niknejadi, A. Nutter, J. Osterhoff, D. Oumbarek Espinos, J. -L. Paillard, D. N. Papadopoulos, B. Patrizi, R. Pattathil, L. Pellegrino, A. Petralia, V. Petrillo, L. Piersanti, M. A. Pocsai, K. Poder, R. Pompili, L. Pribyl, D. Pugacheva, B. A. Reagan, J. Resta-Lopez, R. Ricci, S. Romeo, M. Rossetti Conti, A. R. Rossi, R. Rossmanith, U. Rotundo, E. Roussel, L. Sabbatini, P. Santangelo, G. Sarri, L. Schaper, P. Scherkl, U. Schramm, C. B. Schroeder, J. Scifo, L. Serafini, G. Sharma, Z. M. Sheng, V. Shpakov, C. W. Siders, L. O. Silva, T. Silva, C. Simon, C. Simon-Boisson, U. Sinha, E. Sistrunk, A. Specka, T. M. Spinka, A. Stecchi, A. Stella, F. Stellato, M. J. V. Streeter, A. Sutherland, E. N. Svystun, D. Symes, C. Szwaj, G. E. Tauscher, D. Terzani, G. Toci, P. Tomassini, R. Torres, D. Ullmann, C. Vaccarezza, M. Valléau, M. Vannini, A. Vannozzi, S. Vescovi, J. M. Vieira, F. Villa, C. -G. Wahlström, R. Walczak, P. A. Walker, K. Wang, A. Welsch, C. P. Welsch, S. M. Weng, S. M. Wiggins, J. Wolfenden, G. Xia, M. Yabashi, H. Zhang, Y. Zhao, J. Zhu & A. Zigler
EuPRAXIA Conceptual Design Report
The European Physical Journal Special Topics 229, 3675–4284 (2020);
https://doi.org/10.1140/epjst/e2020-000127-8

The EuPRAXIA Project

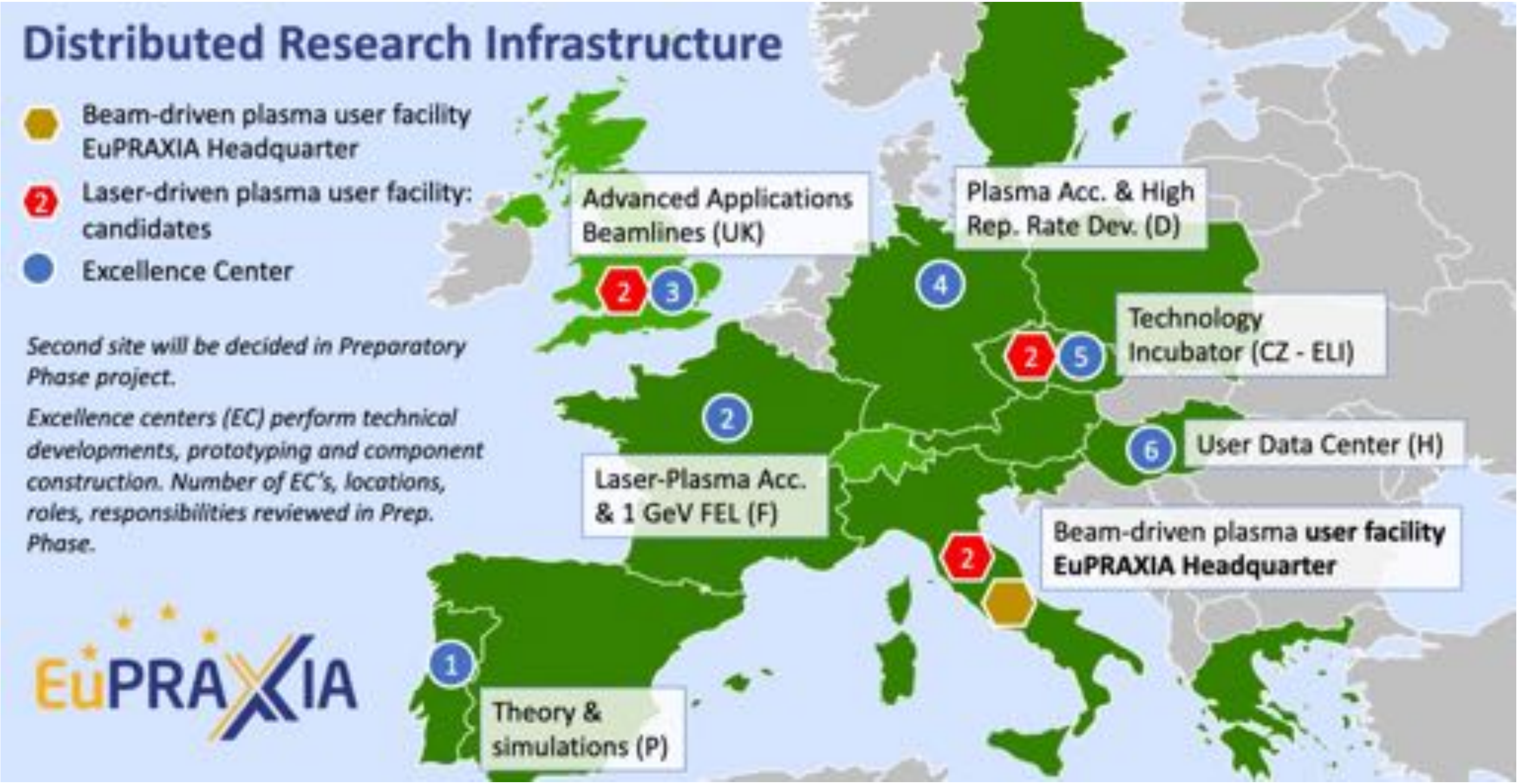
Funded by the European Union

A New European High-Tech Research Facility Delivering Frontier Science



EuPRAXIA is an ESFRI Distributed Facility

Funded by the European Union

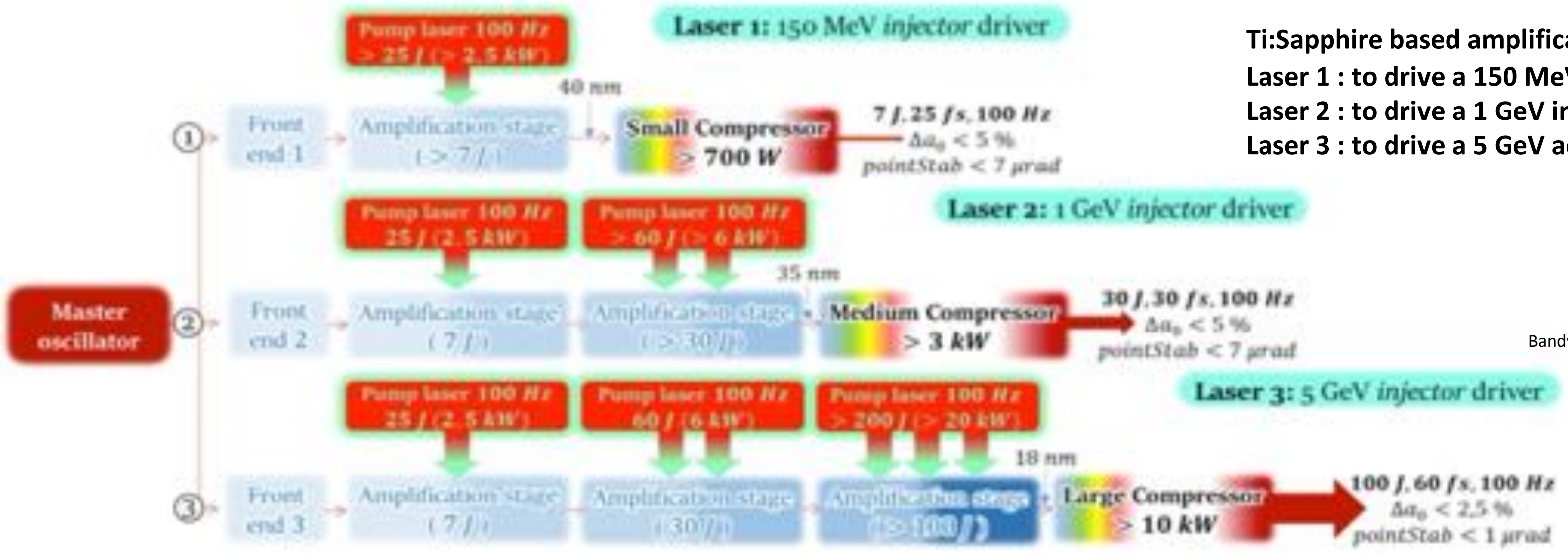


EuPRAXIA: Baseline Laser Design

EuPRAXIA Advanced Photon Source

Funded by the European Union

The current EuPRAXIA laser design relies on Titanium Sapphire technology to address average (10 kW) and peak (PW) power as required by the project (1-5GeV LWFA).



EuPRAXIA baseline laser systems:

Ti:Sapphire based amplification chains
Laser 1 : to drive a 150 MeV injector
Laser 2 : to drive a 1 GeV injector
Laser 3 : to drive a 5 GeV accelerator

MAIN CHALLENGES

Pumping technology:
High rep. rate, high energy

Gain media:
Bandwidth, Size, Thermal load, Cooling

Grating technology
Size, LIDT, Thermal load, Cooling

Pointing stability
Transport

•L.A. Gizzi, et al., A viable laser driver for a user plasma accelerator, NIMA **909** , 58 (2018); https://doi.org/10.1063/1.4984906
•R. Assmann et al., EuPRAXIA Conceptual Design Report, The European Physical Journal Special Topics **229**, 3675–4284 (2020); https://doi.org/10.1140/epjst/e2020-000127-8
•Water cooled Ti:Sa amplifier under development at ELI-HU (After V. Cvhykov *et al.* , Opt. Lett, **41,** 3017, 2016)
•Fluid (D_2O) cooled Nd:YAG laser, 20 kW CW pump power, D_2O (After X. Fu *et al.* , Opt. Express, **22**, 18421 (2014)
•Fluid (Siloxane) cooled Nd:YLF laser, 5 kW CW pump power (After Z. Ye *et al.* , Opt. Express, **24**, 1758 (2016)

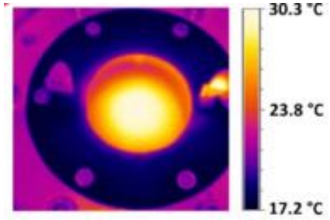
Main outputs of the EuPRAXIA design study

- Requirements on energy, pulse duration, stability etc set by the LPA working point
- Design based on CPA in Ti:Sapphire, dictated by requirements vs. time scale
- Thermal management issues to be addressed by means of liquid cooling
- Main developments required:
  - Prototyping of Ti:Sa amplifiers: fluid cooling: pilot studies
  - Addressing 100 Hz pump lasers developments
  - Thermal management of compressor gratings
  - Stability (pointing & more) and active control
  - Driver pulse temporal shaping and synchronization
- Construction
- Integration Issues

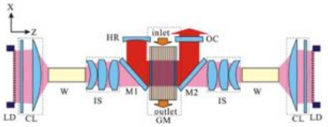
Underpinning EuPRAXIA-like Laser driver TDR

Funded by the European Union

THERMAL MANAGEMENT OF POWER AMPLIFIERS



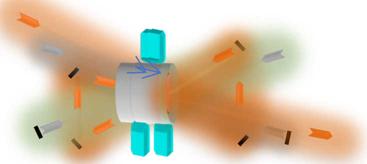
WATER/GAS COOLING



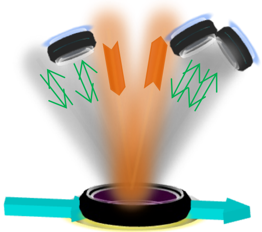
Prototyping needed

AMPLIFIER GEOMETRY TRANSMISSION VS. REFLECTION

Multipass transmission

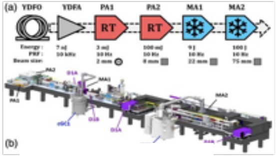


Multipass reflection

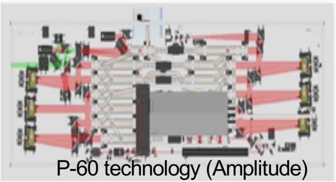


Prototyping needed

DPSSL PUMP SOURCES TECHNOLOGY



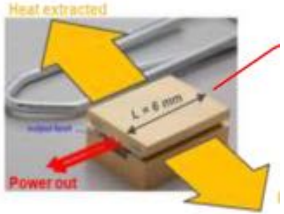
DiPOLE 100 (STCF)

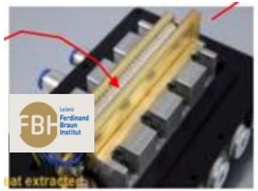


P-60 technology (Amplitude)

Currently no solution for full system specs (P1): development

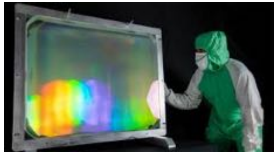
DIODE LASERS EFFICIENCY, BRIGHTNESS AND LIFETIME





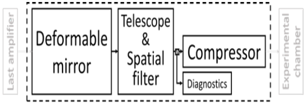
Needs development

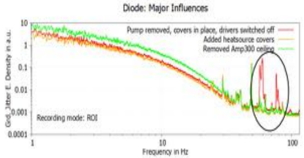
COMPRESSOR AND TRANSPORT: THERMAL AND MECHANICAL



Gold -> MD, MLD, MMLD

reduction of the thermal load
cooling of residual heat
control of thermal effects



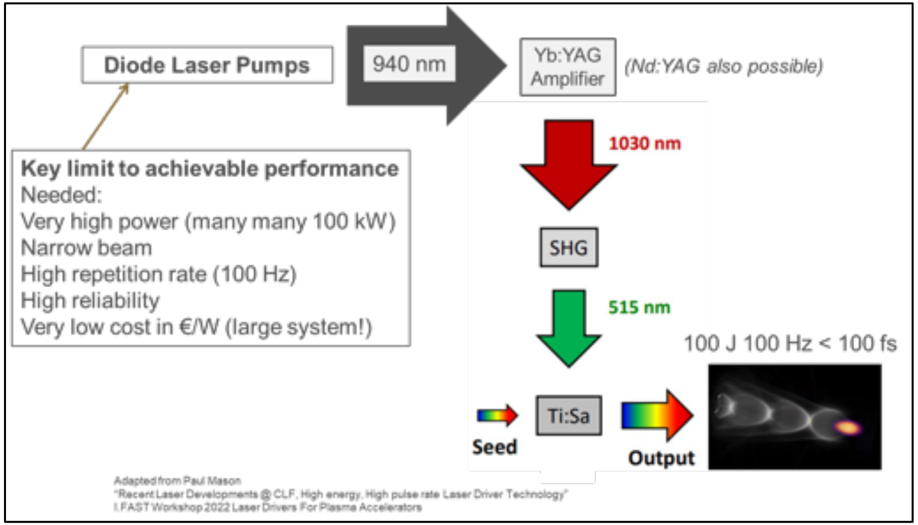


Main challenges: large optics, mechanical stability, beam quality control, pointing stability

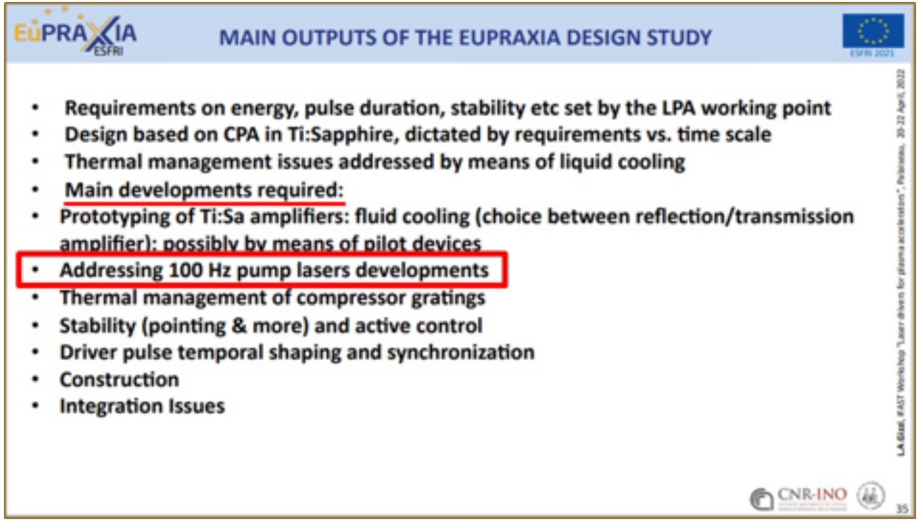
L.A. Gizzi, 24 Mar 2023, Alegro Workshop, DESY, Hamburg, Germany

Diode laser pump challenge: viable 100 Hz

Diode lasers source of all optical power in EuPRAXIA



Challenge: 100 Hz pump supply



Preparatory review with Industry Berlin, held 5 October 2022 „Berlin Laser Tech Symposium“

- Large industry: Coherent, Leonardo, Lumibird, Jenoptik, Hamamatsu, High-tech SMU: Lastronics
- Research: CNR (L. Gizzi). Chair: FBH Berlin (P. Crump)

Consensus: **Economic high duty cycle diode laser pumps remain extremely challenging**

- Improved packaging and diodes and their reliability assurance strongly demanded

Leibniz Ferdinand Braun Institut

Diode specifications: known and open issues

Diode pump laser technical specs

- 20…100 Hz
- ~ 80 cm^2 square flat-top beam, imaged into amplifier, with up to several meters offset
- < 6° divergence angle, high polarization purity
- Multiple 500 kW units needed for largest system
- Yb:YAG: λ = 940 nm, ~ 500 μs pulses (5% duty cycle) – high duty cycle packaging needed
- Nd:YAG: λ = 800 nm, ~ 200 μs pulses (2% duty cycle) – higher power diodes needed

Key open topics:

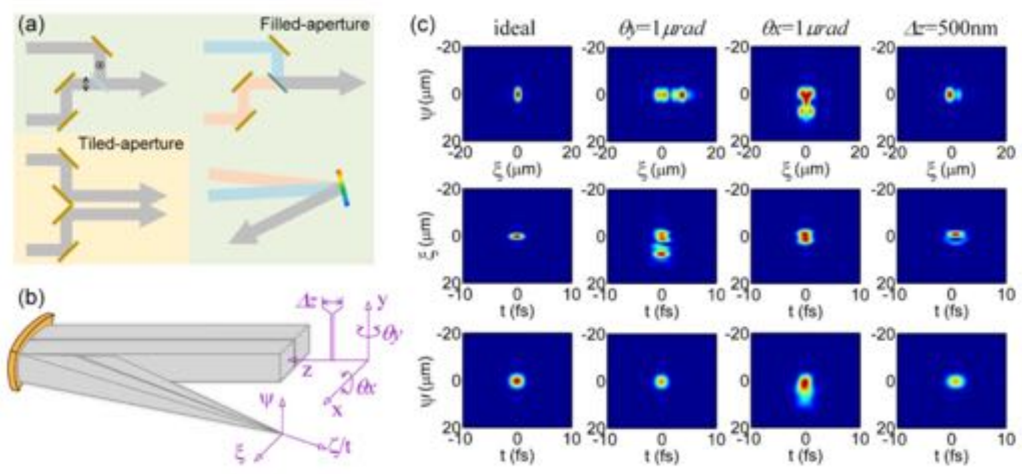
- Lifetime requirements (uptime, system size, replacement rates / failure rate)
- Costs (purchase, maintenance, operation)
- Efficiency (energy cost of operation)
- Specifications / requirements for alternative wavelengths

Needed diode laser pump development goals and research efforts (3 y technology, 3 y qualification)

- Improved diode laser performance: higher efficiency, higher power
- Improved packaging: high performance economical cooling
- Cost reduction: higher power (€/W), yield (€)
- **Prototyping of new concepts (e.g 780 nm or 1600 nm for Thulium)**
- Reliability assurance (low failure rate)
- Security of supply: standardization, assurance of supply chain; European supply

Coherent Combination

Coherent combination has been proposed for Ti:Sa beamlets, in a similar approach as fiber combination, but with tiled-aperture.



Z. Li, et al., Laser Photonics Rev.2023,17, 210070

- Significant engineering issues to be overcome, but in line with current active control approach
- Could relax constraints on heat load management of >kW beamline and need of large optics
- Needs CDR

Ongoing 100 Hz developments

Intermediate milestone

Funded by the European Union

Eupraxia laser development is aimed at delivering more efficient, kW-PW laser driver for plasma acceleration at >100 Hz rate

- **EuPRAXIA**
- PW class,
- 100 Hz repetition rate,
- multi kW average power,
- diode pumped
- Full therma load transport

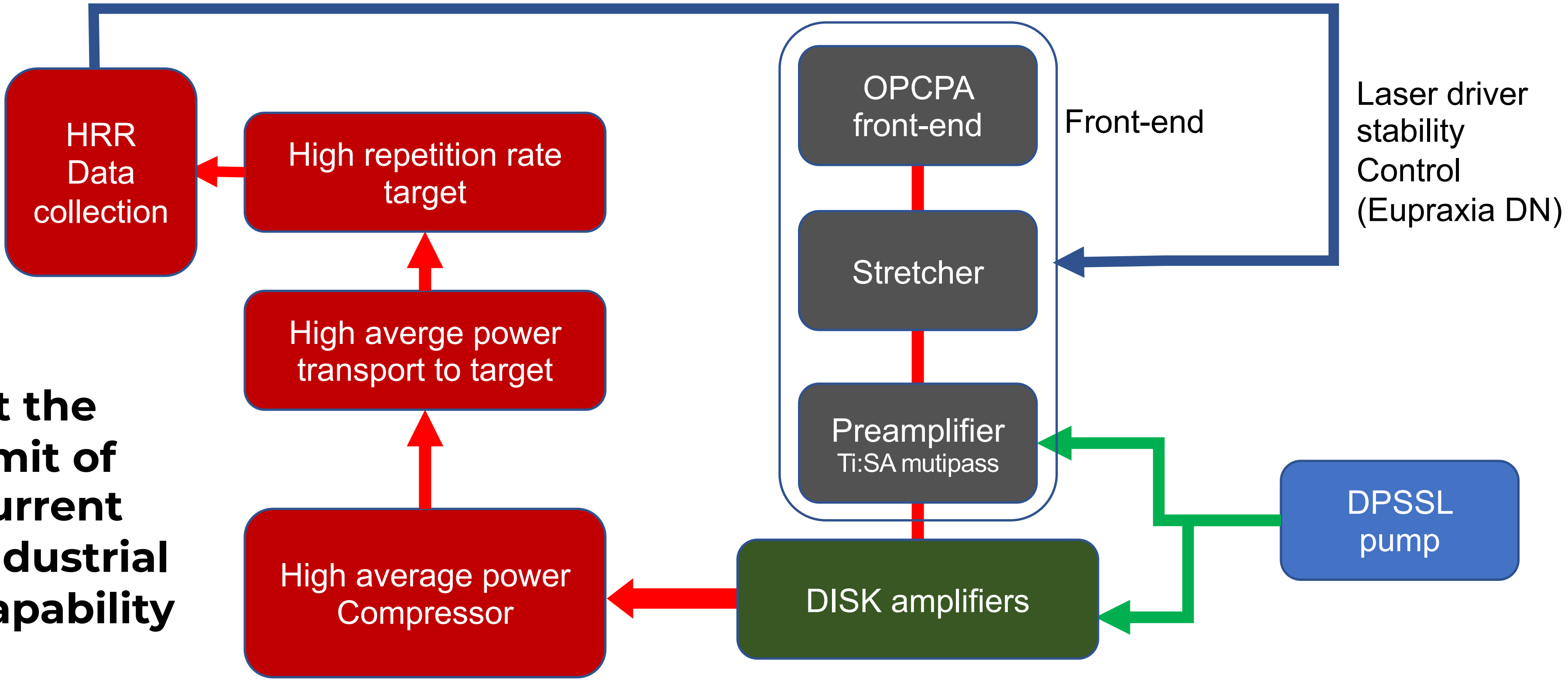
EuAPS

- **EuAPS@CNR-Pisa**
- 30 TW peak power
- 100 Hz repetition rate
- 100 W average power
- Diode pumped
- Thermal load effects

- **CURRENT**
- **PW class,**
- **Hz repetition rate,**
- **≈10 W average power**
- **flashlamp pumped**
- **No thermal load transport**

100 Hz, J-scale laser beamline

Funded by the European Union
NextGenerationEU

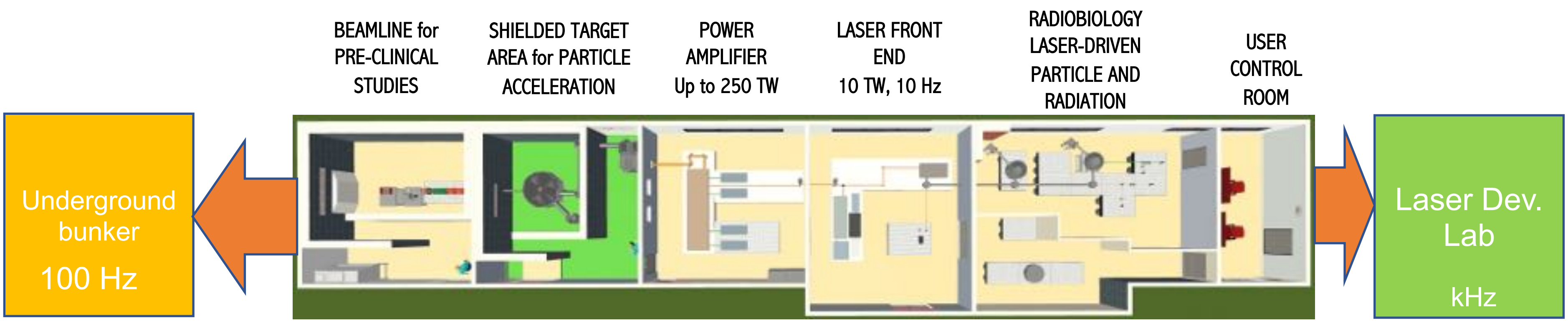


At the limit of current industrial capability

Joule scale / 100 Hz / > 100 W

Funded by the European Union
NextGenerationEU

100 Hz beamline upgrade at ILIL



UPGRADE OF ILIL FACILITY FOR:

1. Upgrade of existing laser system (240 TW) for enhanced stability and control
2. New laser systems for high repetition rate operation (100 Hz-1J, 1kHz-20 mJ)
3. New Infrastructure development for user access to beamlines

Part of : PNRR, I-PHOQS INTEGRATED INFRASTRUCTURE INITIATIVE IN PHOTONIC AND QUANTUM SCIENCES

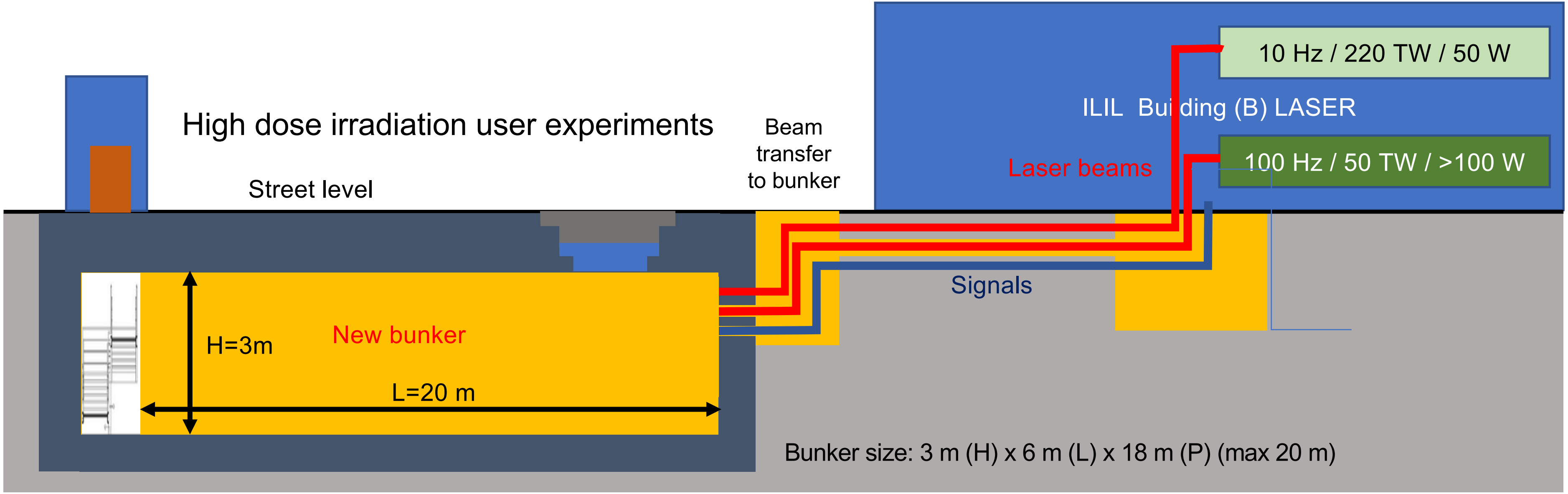
Strong link with eli, ESFRI

Part of : PNRR, EuPRAXIA Advanced Photon Source

User Infrastructure Upgrade

Funded by the European Union
NextGenerationEU

- **EuPRAXIA Advanced Photon Sources (EUAPS) project (NG-EU, INFN-CNR-UTV)**
- **Photonics and Quantum Science (IPHOQS) project (NG-EU, CNR, POLIMI, LENS)**



EUAPS WP2: High average power, high repetition rate laser beamline: 4.8 M€
IPHOQS A3.6 Ultrafast, high repetition rate radiation beamlines: 1.4 M€
IPHOQS A3.5:* High Intensity, extreme laser beamlines*: 1.5 M€

EuAPS
I-PHOQS
INTEGRATED INFRASTRUCTURE INITIATIVE IN PHOTONIC AND QUANTUM SCIENCES

New High Repetition Rate Target Area

Funded by the European Union
NextGenerationEU

EuPRAXIA
Advanced Photon Source

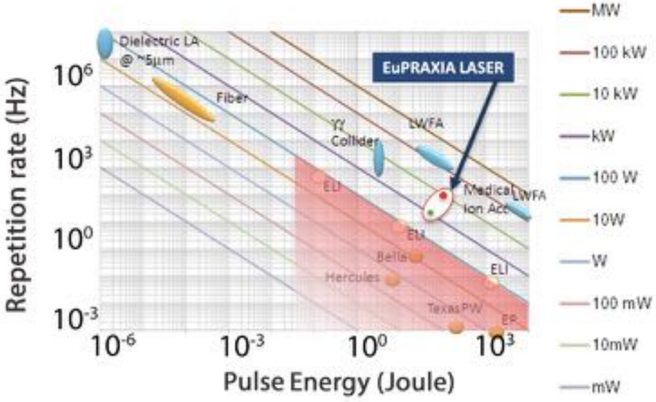
I-PHOQS
INTEGRATED INFRASTRUCTURE INITIATIVE IN PHOTONIC AND QUANTUM SCIENCES

kHz laser driver development for LPA

Roadmap on LPA Laser Driver technology

Laser-driven plasma acceleration needs ultrashort, high power lasers with high average power

- **Current technology: ≈ Ti:Sa technology, pumped by flash-lamp pumped lasers**
  - Robust, reliable industrial technology
- **Mature technology: ≈ Ti:Sa technology, pumped by diode-pumped lasers**
  - Strong R&D effort in place (e.g HAPLS@ELI)
  - ≈ 3-5 years to go to first industrial LWFA demonstrator (e.g. Eupraxia) [1]



- **Beyond TiSA: targeting higher wall-plug efficiency and rep. rate, kHz and beyond, stability, control (space, time, spectral);**
  - **5-10 yrs for first efficient**, multi-kW-scale demonstrator,
  - A strategy is needed to steer effort in the LPA laser driver direction: LASPLA

The L3-HAPLS at ELI Beamlines Research Center in the Czech Republic. Credit: ELI Beamlines*

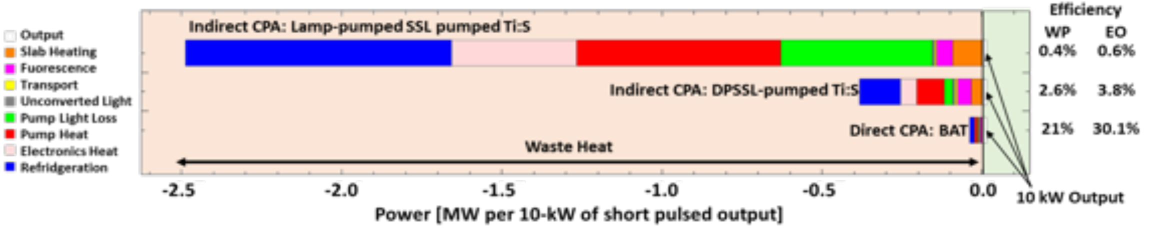
[1] R. Assmann et al., EuPRAXIA Conceptual Design Report, The European Physical Journal Special Topics **229**, 3675–4284 (2020)
[2] C. Danson et al., Petawatt and exawatt class lasers worldwide High Power Laser Sci. and Eng. **7**, e54 (2019)

Efficiency path

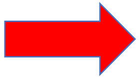
TiSa technology is prompt and will demonstrate repetitive operation 24/7 and stability, but not scalable with poor efficiency (% level) due to the indirect pumping architecture:

Direct CPA is a solution for wall-plug (WP) efficiency and high rep-rate.

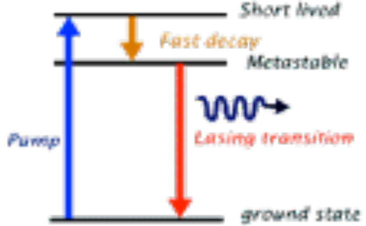
From flashlamp to indirect to direct diode pumping



C. Siders et al., EAAC 2017



Quantum defect



WP Efficiency > 20% possible:

We need a **gain medium** that can support amplification on a large bandwidth, has a **low quantum defect** and can be pumped **directly** with diode lasers: **endless quest for the perfect laser medium!!**

Several options under development

Fiber laser technology targeting the best WPE 30% in CW mode and coherent combination is being developed (FSU Jena-Fraunhofer IOF and Ecole Polytechnique-Thales in France).

Suited for moderate energy per pulse/high rep-rate (10s of kHz);

Now 96 fibers delivering 23 mJ and 674 W in a 235 fs pulse

Direct Chirped Pulse Amplification with lasing media pumped directly by diodes is ideal for higher efficiency and higher rep-rate;

several materials under consideration, Yb:CaF2, Tm:YLF, Tm:Lu2O3 (with cross-relaxation and multi-pulse extraction) …

PENELOPE (Jena) 150 J, 1 Hz, at 1030 nm

Available ps kW thin disk lasers using plasma modulation (Oxford[2])

OPCPA optical parametric amplification within large-aperture lithium triborate (LBO) crystals;

ELI-Beamlines facility, L1 ALLEGRA (100 mJ at 1 kHz) and L2 AMOS (100 TW, 2 to 5 J between 10 and 50 Hz), and the Shenguang II Multi-PW beamline(SIOM, China) …

Thin Disk ps Lasers **+** spectral broadening + post compression[3]

Industrial technology with demonstrated >kW operation ar ≈J per pulse energy.

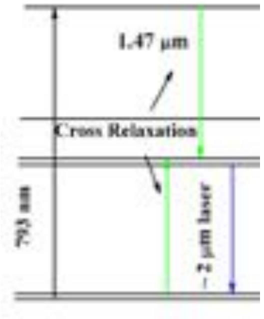
1. L.A Gizzi, F. Mathieu, P. Mason, P P Rajeev, *Laser drivers for Plasma Accelerators*, in Félicie Albert et al, *2020 roadmap on plasma accelerators*, 2021 New J. Phys. 23 031101, https://doi.org/10.1088/1367-2630/abcc62;
2. O. Jakobsson, S. M. Hooker and R. Walczak, PRL, (2021)
3. A.L. Viotti et al., Optica **9**, 197-216 (2022).

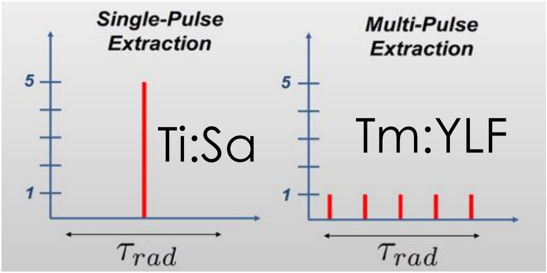
Thulium based gain materials: Tm:YLF

Currently under investigation(*): Tm:YLF

- Emission at 1,9 µm, eye safe;
- Ultrashort pulse (<100 fs);
- High peak power ≈ PW;
- High average power(scalable from kW to 300 kW);
- Direct pumping at 808 nm, using diodes operating in CW mode (available and scalable);
- Multi-pulse extraction at high repetition rate
- 10 kHz; Ideal for accelerator technology;
- High efficiency;
- Mature material technology (crystal growth);

C. Haefner et al., EAAC 2017





Tm: YLF Full specifications

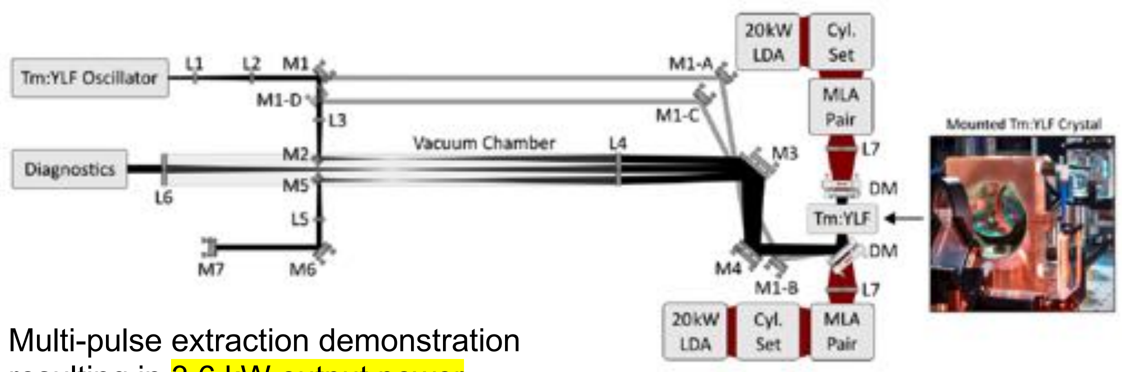
Absorption peak wavelength	792 nm
Absorption cross-section at peak	0.55 × 10-20 cm2
Absorption bandwidth at peak wavelength	16 nm
Laser wavelength	1900 nm
Lifetime of 3F4 thulium energy level	16 ms
Emission cross-section @1900 nm	0.4 × 10-20 cm2
Refractive index @1064 nm	no=1.448, ne=1.470
Crystal structure	tetragonal
Density	3.95 g/cm3
Mohs' hardness	5
Thermal conductivity	6 Wm-1K-1
dn/dT	-4.6 × 10-6 (//c) K-1
Thermal expansion coefficient	10.1 × 10-6 (//c) K-1
Typical doping level	2-4 at.%

High Efficiency enabled by multipulse extraction (energy storage)

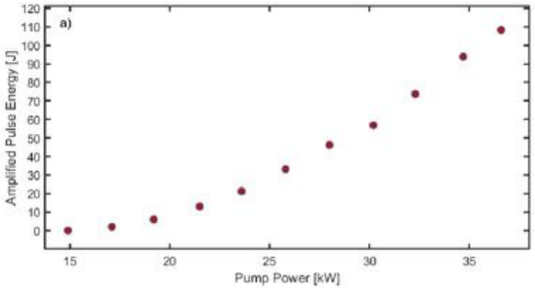
Relatively new approach for short pulse operation: needs R&D, but promising

Recent advances with Tm:YLF

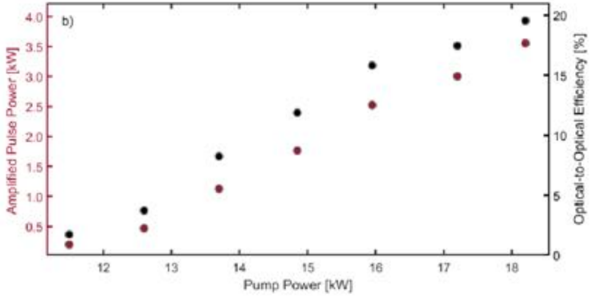
Energy density storage and extraction capabilities of Diode pumped Tm:YLF (narrowband)



Amplified pulse energy measurements up to **108.3 J** for the 6-pass Tm:YLF power amplifier



Multi-pulse extraction demonstration resulting in 3.6 kW output power



- "The multiple proof-of-principle demonstrations [..] reveal the potential for high efficiency, high energy density extraction using Tm:YLF for future high peak and average power laser systems."
- "Additional efforts are currently in progress to conduct chirped pulse amplification of ultrashort pulses using Tm:YLF at the joule-level for the first time."

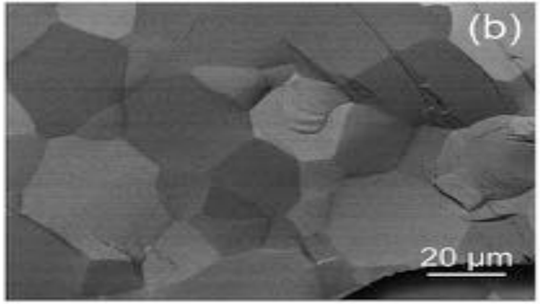
Issa Tamer, et al., "High energy operation of a diode-pumped Tm:YLF laser," Proc. SPIE 12401, High Power Lasers for Fusion Research VII, 1240109 (14 March 2023); doi:10.1117/12.2649103

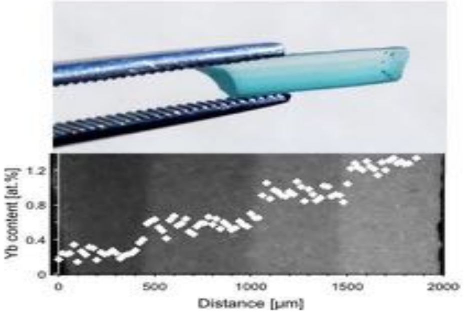
Laser grade ceramic option

- Faster and cheaper vs. single crystal growth process – for cubic crystalline structure.
- Large components, -shaping, -graded doping also optimized for thermal management – **features not available for single crystals.**
- Several compositions (e.g. **YAG, LuAG , Sc_2O_3, Lu_2O_3**) and dopants (**Nd, Yb, Er, Tm**…) already available
- Spectroscopic and thermomechanical properties similar to those of the corresponding single crystals
- Better uniformity of dopant distribution on large gain elements

Industrial and R&D effort: KONOSHIMA (Japan); Research in China, Japan, Russia, USA, France and Italy (ISTEC-CNR) (ZENITH Smart Polycrystals)

ZENIT Smart Polycrystals





Ceramic option: Tm in sesquioxide host

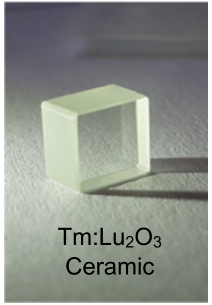
Sesquioxides doped with Tm3+, such as Tm:Lu2O3, Tm:Y2O3, and Tm:Sc2O3, are also emerging materials: their better thermo-optical properties make them promising for power scaling applications.

The growth of sesquioxide single crystals is very complicated, while it is possible to produce them in transparent ceramic form thanks to their cubic crystalline structure and optical isotropy.

Advantages of ceramic medium:
High thermal and mechanical features
Scalable size
Custom doping
Optimize energy efficiency

Best "hosts" for Thulium:

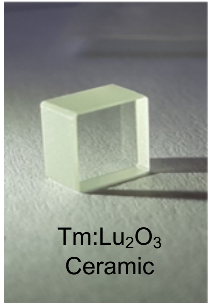
- yttrium lithium fluoride (YLF),
- yttrium aluminum garnet (YAG)
- → Lutetium oxide (Lu_2O_3)



Sample from Konoshima

C. Krankel, IEEE J. Sel. Topics Quantum Electro 21, Art. no. 1602013 (2015)

Ceramic option: Tm Lu_2O_3



Laser material: Tm:Lu_2O_3

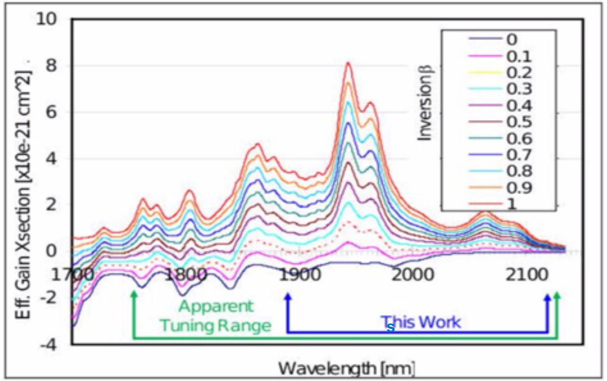
- Emission at 2 μm;
- Large amplification bandwith
- Direct pumping at 800 nm, using diodes operating in CW mode (available and scalable);
- Cross relaxation partially compensates quantum defect – option of in-band pumping.
- Multi-pulse extraction at high repetition rate > 10 kHz; Ideal for accelerator technology;
- Mature material technology (large ceramic).

laser host material	σ_{abs} (10^{-21} cm^2)	λ_{em} (nm)	σ_{em} (10^{-21} cm^2)	λ_{th} (W m^{-1} K^{-1})	τ (ms)	reference
YAG	7.5	2013	1.8	13	10	Heine, 1995
YLF	σ pol 3.6 π pol 8.0	1910 1880	2.35 3.7	6	15.6	Payne et al., 1992 Walsh et al., 1998
Lu_2O_3	3.8	2070 1945	2.3 8.5	13	3.8	Koopmann et al., 2009a

laser host material	λ_p (nm)	λ_{em} (nm)	cw output power (W)	slope eff. (%)	reference
YAG	805	2013	115	52	Honea et al., 1997
YAG	800	2013	120		LISA laser products OHG *
YLF	792	1910	55	49	Schellhorn, 2008
YLF	790	1912	148	32.6	Schellhorn et al., 2009
Lu_2O_3	796	2070	1.5	61	Koopmann et al., 2009a

[Scholle et al., 2010]

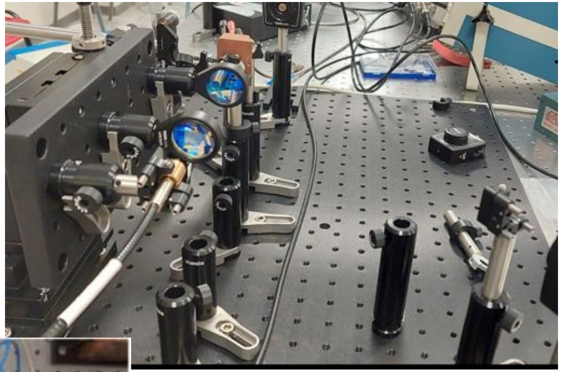
Commercial diode lasers

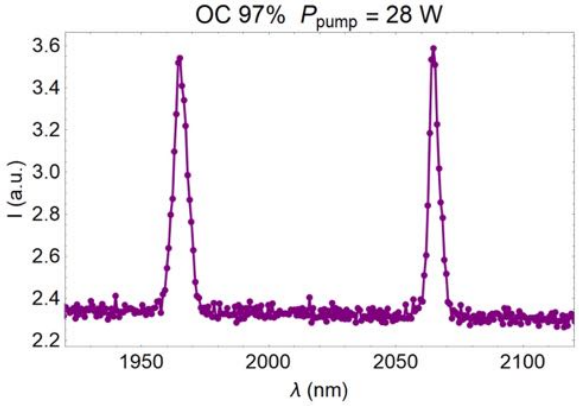


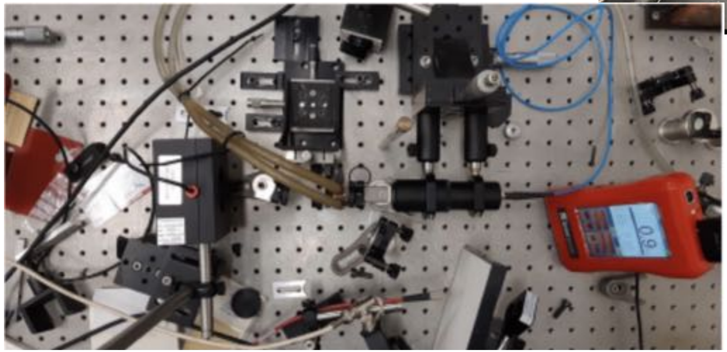
[Antipov, 2011]

Test platform for slope efficiency

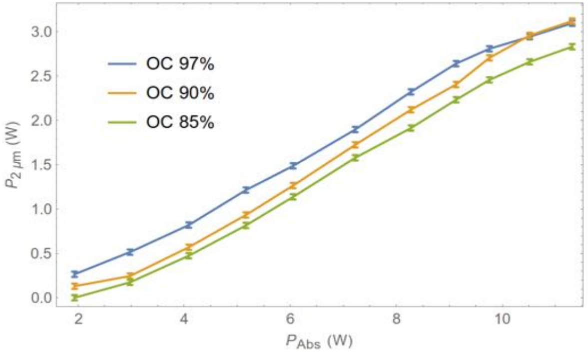
An oscillator cavity has been set up for $Tm:Lu_2O_3$ gain material characterization







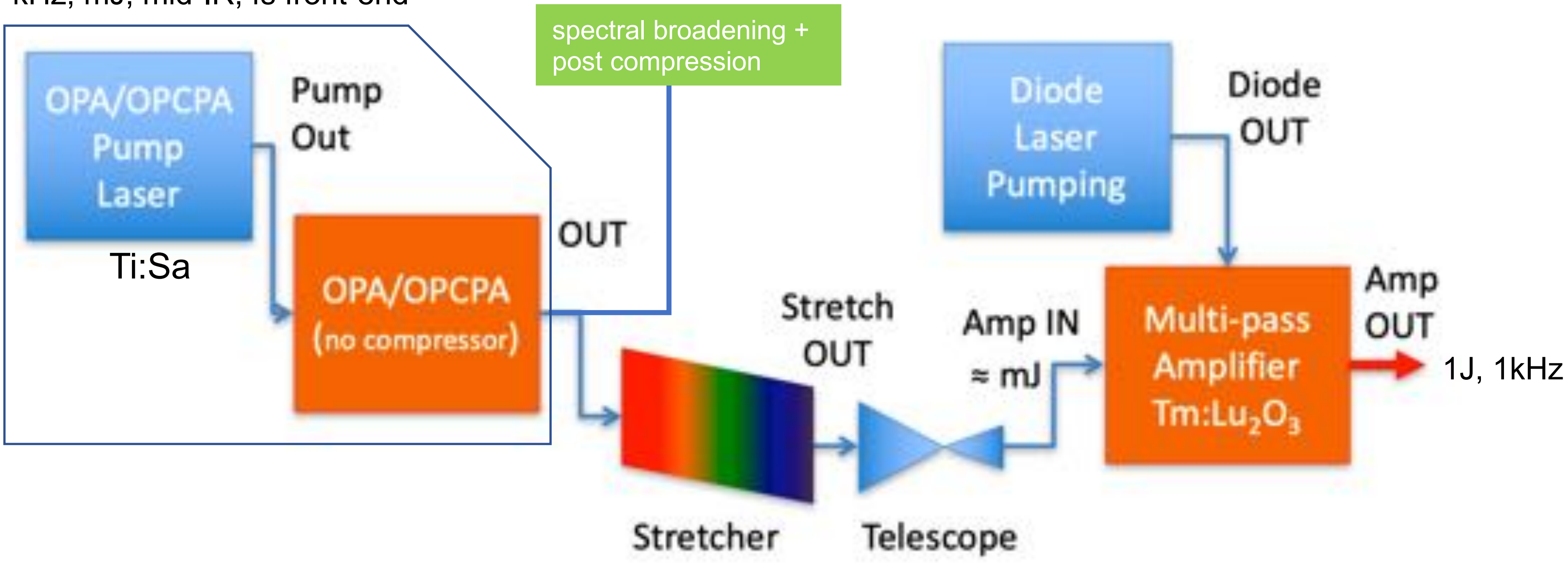
Slope Efficiency > 40% (work in progress)



kHz laser development at ILIL

A kW-kHz CPA laser development with direct diode pumping

kHz, mJ, mid-IR, fs front-end

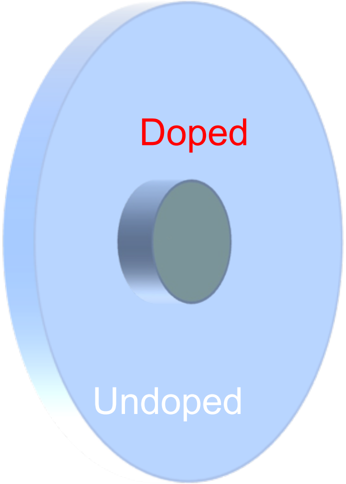


Main development effort in amplifier modules: ELI_{IT}/APOLLO project (CNR)

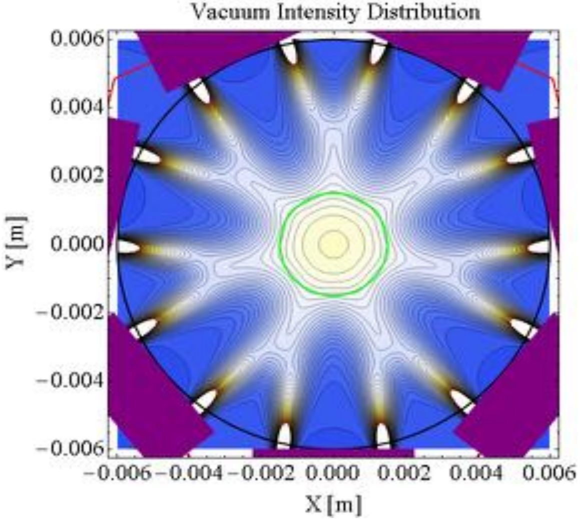
Gain medium design and pumping

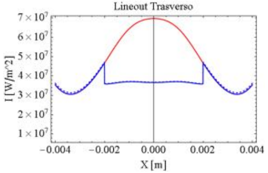
Side/edge pumped thin disk active mirror configuration [1,2]

Geometry

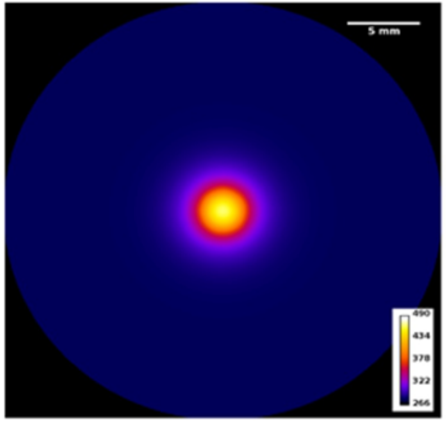


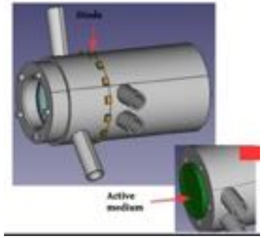
Edge diode pumping





Thermal load





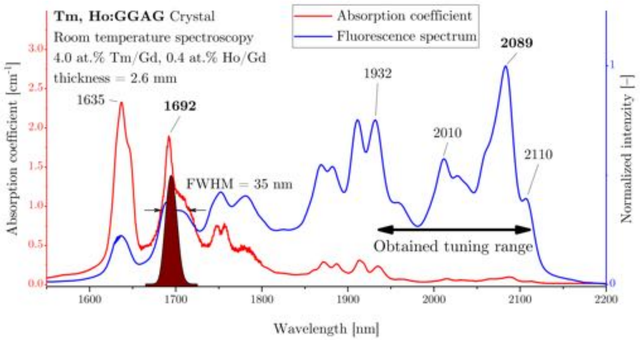
Diodes total power: >**2kW,** Diodes energy (1ms): **1.95 J,** Linear bar power: **19.4 W/mm => 1 J output**

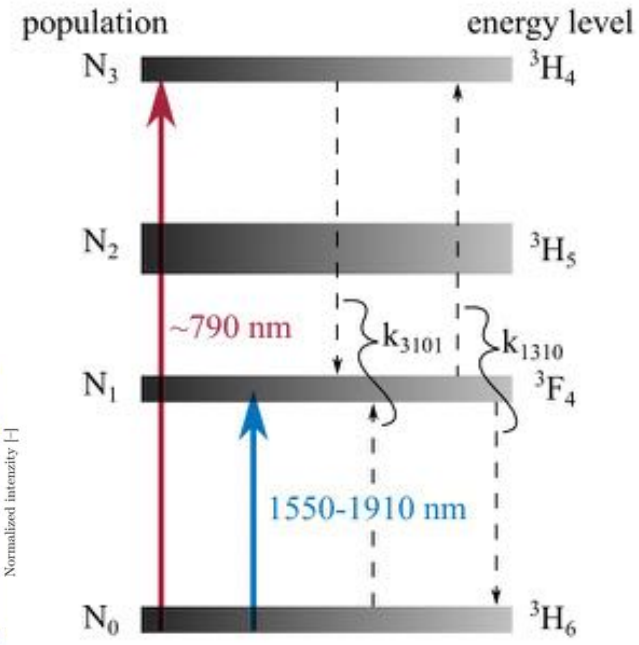
Now finalizing technical design and starting construction and tests

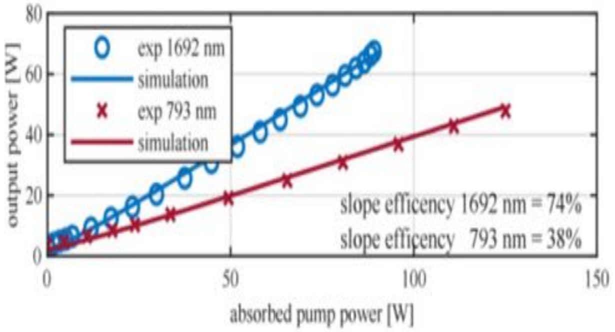
[1] J. Vetrovec, et al., "Wide-Bandwidth Ceramic Tm:Lu2O3 Amplifier", Proc. SPIE 9834, 983407 (2016); https://doi.org/10.1117/12.2224411
[2] J. Vetrovec, et al., "2-micron lasing in Tm:Lu2O3 ceramic:initial operation", Proc. SPIE 10511, 1051103 (2018); https://doi.org/10.1117/12.2291380
[3] D. Palla, L. Labate, F. Baffigi, G. Cellamare, L.A. Gizzi, Optics & Laser Technology, **156**, 108524 (2022), https://doi.org/10.1016/j.optlastec.2022.108524

Higher wpe: In-band pumping for low *qd*

Thulium based gain medium can also be pumped with in-band absorption with virtually marginal quantum defect: High efficiency and lower heat deposition.







>80% slope efficiency demonstrated in fibers

M. Lenski et al., Opt. Express **30**, 44270-44282 (2022)

New path for intra-band pumping and marginal quantum defect: step change in wpe?

Summary

Grand challenges of laser-plasma technologies (including collider) are **limited by laser technology** and cost;

LWFA accelerators require industrial-strength PW-kW laser system, **beyond current state-of-the-art** ;

Industry delivering PW systems now entering development of kW regime with higher efficiency (≈% level) **with diode pumping of Ti:Sa based systems;**

Short term **medical and industrial applications** are now mature and can motivate industrial investments;

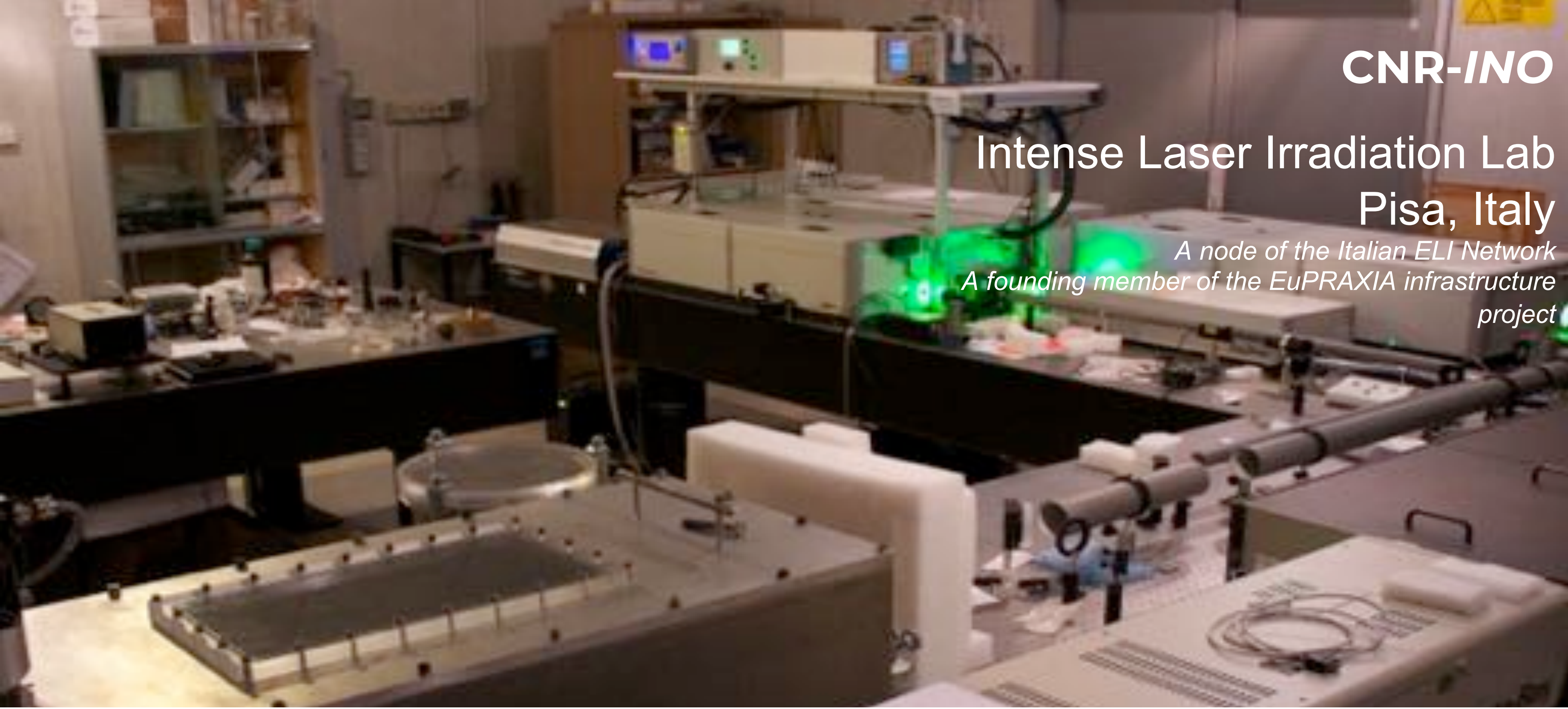
Future large-scale needs >1 kW average power, already under development, aiming at >**20% WP efficiency**;

DPSSL with new materials (Tm:XX) among possible high efficiency solutions, scalable at high average power and high repetition rate;

Infrastructure development and operation a major **thrust** for laser R&D and TRL

Thank you

www.ino.cnr.it



CNR-*INO*

Intense Laser Irradiation Lab
Pisa, Italy

A node of the Italian ELI Network
A founding member of the EuPRAXIA infrastructure project

Intense Laser Irradiation Laboratory

Istituto Nazionale di Ottica – Consiglio Nazionale delle Ricerche

CNR INO
CONSIGLIO NAZIONALE DELLE RICERCHE
ISTITUTO NAZIONALE DI OTTICA

INTENSE LASER IRRADIATION LABORATORY

CNR, Pisa, Italy

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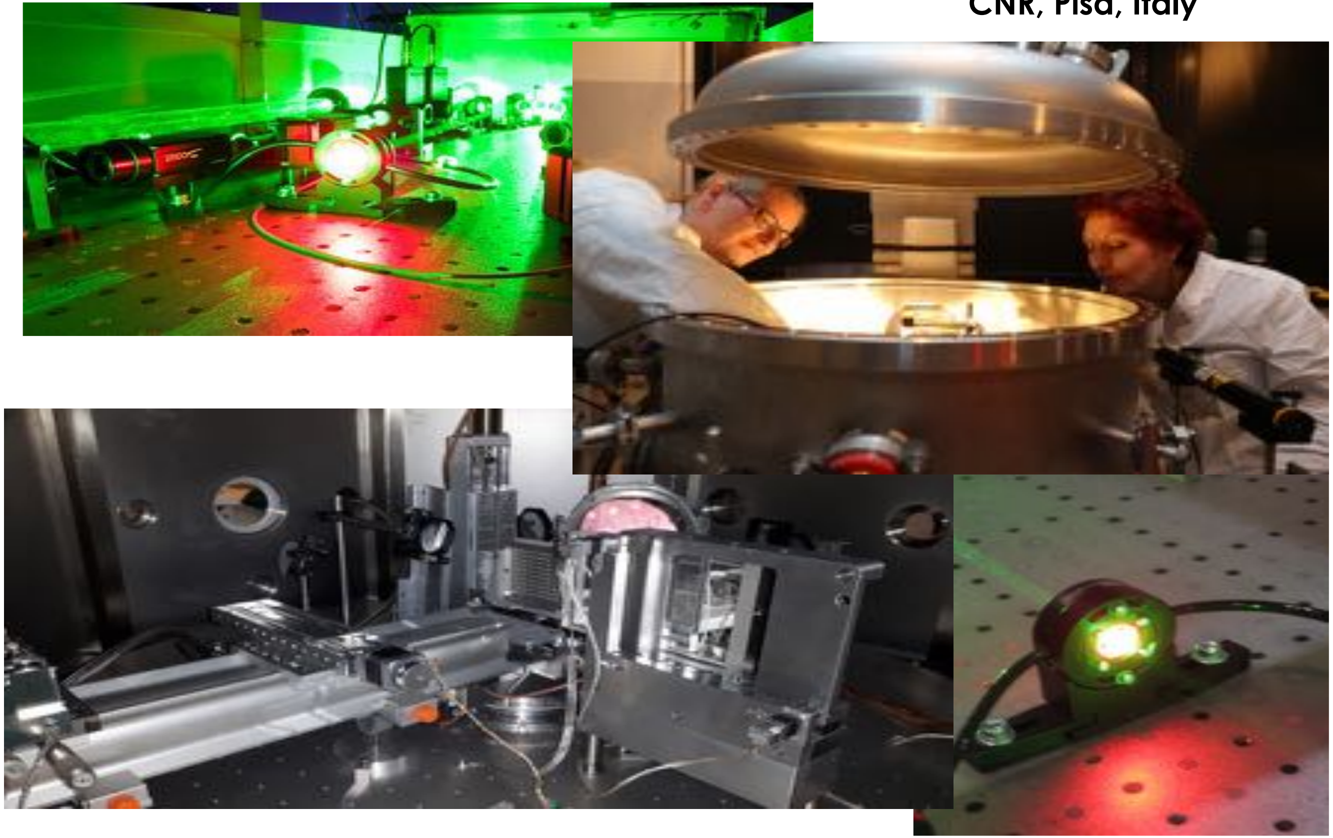
Andrea MARASCIULLI (PhD)
Gianluca CELLAMARE (PhD)
Federico AVELLA (PhD)



http://www.ilil.ino.it