ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

TO PAY A PERMANENT TRIBUTE TO ARCHIMEDES AND GALILEO GALILEI, FOUNDERS OF MODERN SCIENCE AND TO ENRICO FERMI, THE "ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

INFN ACCELERATORI ERICE Accelerator School

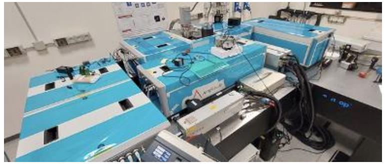
Science and Technology of laser drivers for plasma accelerators

Leonida Antonio GIZZI, CNR-INO, Pisa, Italy
also at INFN, Pisa, Italy

Intense Laser Irradiation Laboratory
Istituto Nazionale di Ottica – Consiglio Nazionale delle Ricerche

CNR INO
CONSIGLIO NAZIONALE DELLE RICERCHE
ISTITUTO NAZIONALE DI OTTICA

The Intense Laser Irradiation Laboratory (ILIL)



NEW HAP LASER DEV. LAB

LASER CAPABILITIES:

- 240 TW, Ti:Sa, up to 5 Hz, 27 fs;
- 1kHz, >20 mJ, Ti:Sa + OPA
- 100 Hz, >1J, TiSA (procurement in progress)

USER CONTROL ROOM

TESTING AND PROTOTYPING

LASER FRONT END 10 TW, 10 Hz

POWER AMPLIFIER Up to 240 TW

SHIELDED TARGET AREA FOR PARTICLE ACCELERATION

NEW BEAMLINE for PRE-CLINICAL STUDIES

NEW HIGH DOSE UNDERGROUND BUNKER

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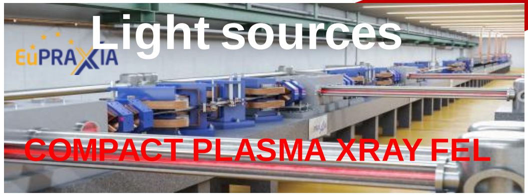
Grand challenges of laser-plasma science

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

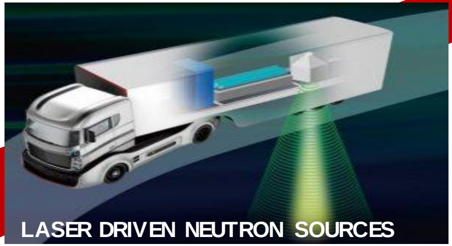
Limited by laser technology

LASER LIGHTENING ROD
A. Houard. *Nat. Photon.* **17**, 231–235 (2023).



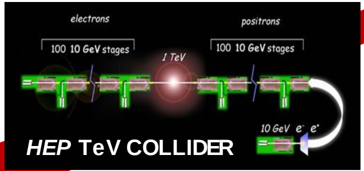
EuPRAXIA PP

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



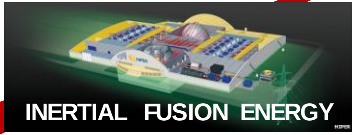
https://www.ile.osaka-u.ac.jp/eng/research/project/project-lans/index.html

R&D



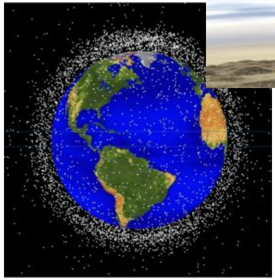
C. Benedetti et al.,
https://doi.org/10.48550/arXiv.2203.08366

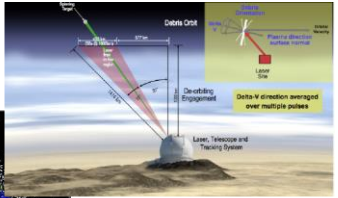
Towards CDR



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

Towards CDR





SATELLITE DEBRIS REMOVAL

C. Phipps , .Advances in Space Research. ***49*** *(9): 1283–1300. (2011)*

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

Contents

- **High power lasers**
- **Short Pulse Ultraintense Lasers**
- **Amplifying lasing media**
- **Ultraintense Lasers: overview**
- **From amplification to plasma**
  - Focal spot quality
  - Temporal contrast
  - Multipulse generation
- **Scaling laser drivers to large accelerator systems**
  - Potential and limits of existing Ti:Sa technology
  - New schemes for high rep-rate and WPE
- **kHz laser driver for LPA**
  - A case study

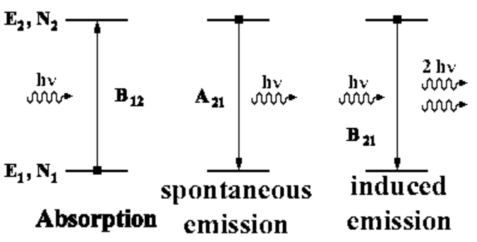
High power lasers

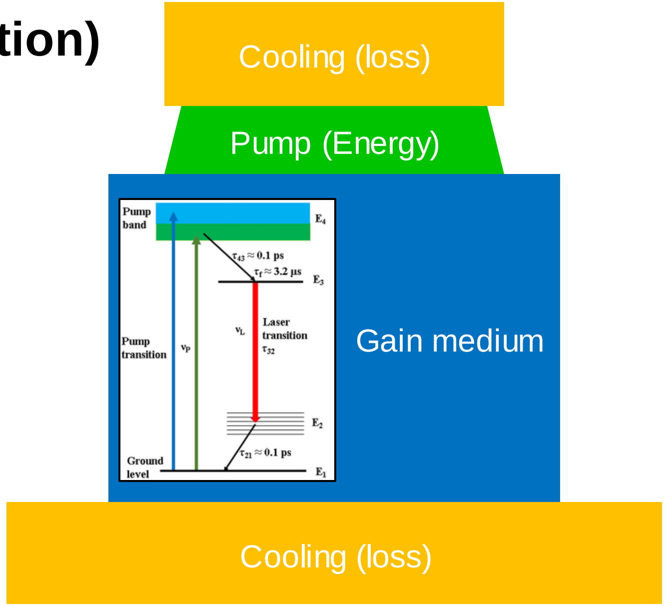
la.gizzi@ino.cnr.it http://ilil.ino.it

Main principles of a laser

Solid state laser for high power amplification

1) **Excitation (pump radiation)**
2) **population inversion**
3) ***spontaneous emission***
4) **stimulated emission**





einstein coefficients

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3}$$

$$\frac{B_{21}}{A_{21}} = \left(\frac{c^3}{8\pi h}\right)\frac{1}{\nu^3}$$

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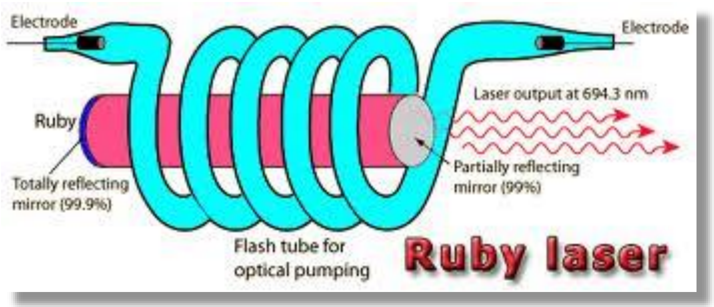
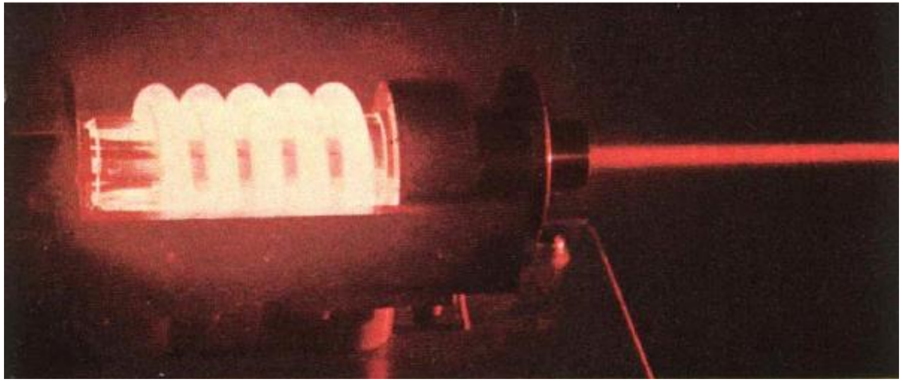
The origin of lasers in the lab



Theodore Maiman, 1960



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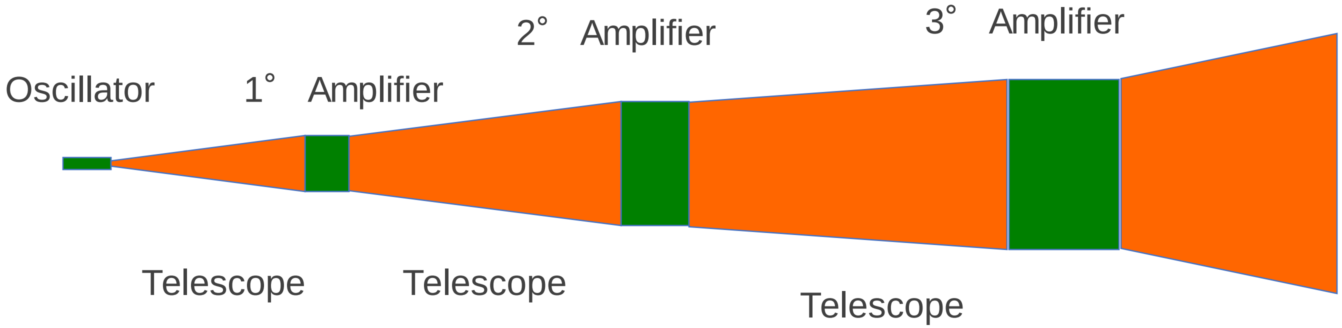
MATERIAL DAMAGE LIMITS AMPLIFICATION

To avoid damage of optics and gain materials due to the growing electric field, laser intensity must be distributed over progressively larger diameters



Consequence? "Gigantism" of high power, high energy lasers …

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Conventional high power (high energy) lasers have huge size

Fusion ignition scale laser

Lawerence Livermore National Lab. California, USA

Pulse energy:
2 MJ

Pulse duration:
4 ns

Peak power:
≈500 TW

Alternative approach to laser-matter interaction? High power at low energy per pulse and ultrashort pulse duration.

Short pulse, ultraintense lasers

ORIGINAL PAPER

Volume 56, number 3 OPTICS COMMUNICATIONS 1 December 1985

COMPRESSION OF AMPLIFIED CHIRPED OPTICAL PULSES ☆

Donna STRICKLAND and Gerard MOUROU

Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, NY 14623-1299, USA

Received 5 July 1985

We have demonstrated the amplification and subsequent recompression of optical chirped pulses. A system which produces 1.06 μm laser pulses with pulse widths of 2 ps and energies at the millijoule level is presented.

The onset of self-focusing of intense light pulses limits the amplification of ultra-short laser pulses. A similar problem arises in radar because of the need for short, yet energetic pulses, without having circuits capable of handling the required peak powers. The solution for radar transmission is to stretch the pulse by passing it through a positively dispersive delay line before amplifying and transmitting the pulse. The pulse would be free from gain saturation effects, because the frequency varies along the pulsewidth and each frequency component sees gain independently.

A schematic diagram of the amplifier and compression system is shown in fig. 1. A CW mode-locked, Nd : YAG laser (Spectra-Physics Series 3000) is used to produce 150 ps pulses at an 82 MHz repetition rate. Five watts of average power are coupled into 1.4 km

D. Strickland and G. Mourou, “Compression of amplified chirped optical pulses”, Opt. Commun. 56, **219** (1985)

INSPIRATION from other field

Phased-Array Radars

Such a radar can track or search for objects without moving its antenna. To steer the beam it relies on wave interactions among signals from a multitude of small antenna elements

by Eli Brookner

The ceaselessly turning radar dish, sweeping its beam of microwave radiation along the horizon in search of distant objects, is a staple of motion pictures and, in the form of airport radar, of everyday experience. Yet in many of the most familiar uses of radar, such as aviation, air defense and intelligence, the mechanically steered dish is giving way to a new kind of device. A flat bank of small, identical antennas, each one capable of transmitting and receiving signals, takes the place of the concave reflector, and even as its beam scans expanses of sky the radar itself does not move. Instead the signal is deflected from target to target electronically, steered through the principle of wave interference. This new technology is ergy rather than a continuous signal, the lag between the transmission of a pulse and its echo indicates the object's distance. Some radars are also designed to gauge the Doppler shift of the echo: the change in the frequency of a signal that occurs when the source (in this case the target) and the receiver (the radar installation) are moving with respect to each other. From the Doppler shift such radars derive the object's velocity toward or away from the antenna.

For a given distance the strength of the echo gives some indication of the object's size. The word "indication" is used advisedly; two objects of the same size, if they are shaped differently or made of different materials, will return echoes that differ sharply in green stripe that sweeps around the cathode-ray-tube display, leaving behind it updated positions and other information about the aircraft within the range of the radar, turns at the same rate as the physically rotating radar dish. The update rate of such radars is typically only about once every six seconds, and even advanced military radars rarely achieve update rates greater than twice a second.

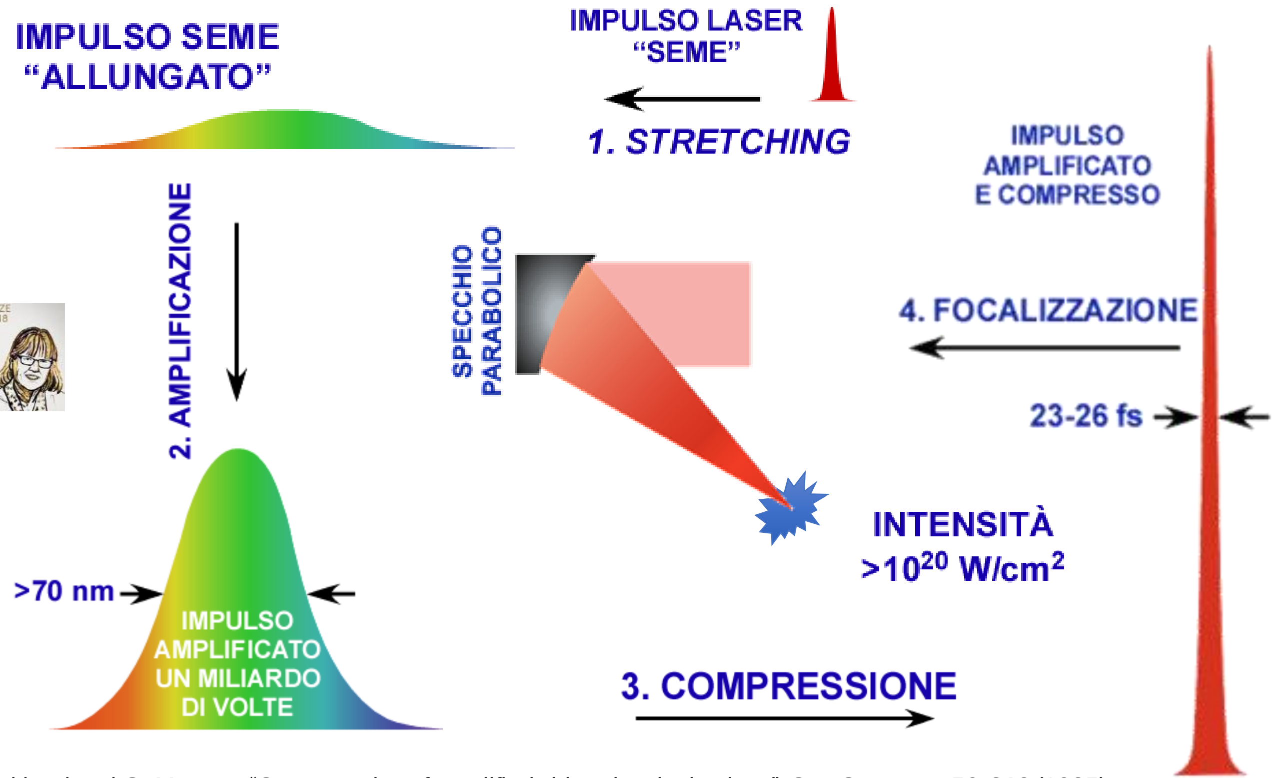
There are circumstances that demand more frequent readings of target position and movement. A single mechanically steered radar can provide continuous data on one or a few closely spaced objects by tracking them, rotating to match their movement. For many military and intelligence purposes, however—shipboard tracking of

Feb 1985

CNR-INO ISTITUTO NAZIONALE DI OTTICA CONSIGLIO NAZIONALE DELLE RICERCHE

Chirped Pulse Amplification

A change of paradigm in high power lasers



Higher peak-power to date: 10 PW Achievedn at the ELI-NP laser installation in Magurele (Romania)

C. Radier et al., HPLSE, **10**, 21 (2022).

D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses", Opt. Commun. 56, **219** (1985)

The original *CPA* EXPERIMENT

Volume 56, number 3 OPTICS COMMUNICATIONS 1 December 1985

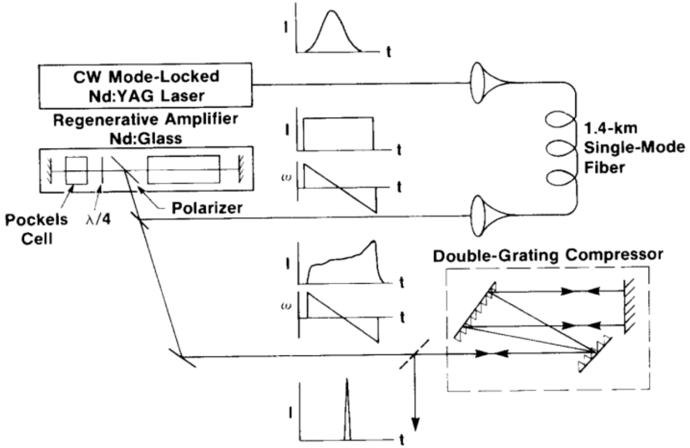
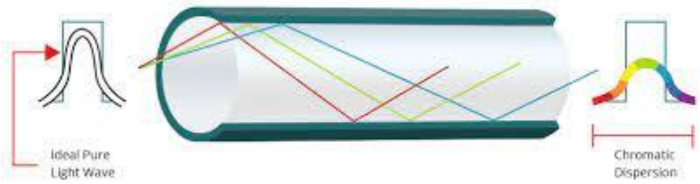


Fig. 1. Amplifier and compression system configuration.

Dispersion in fibers

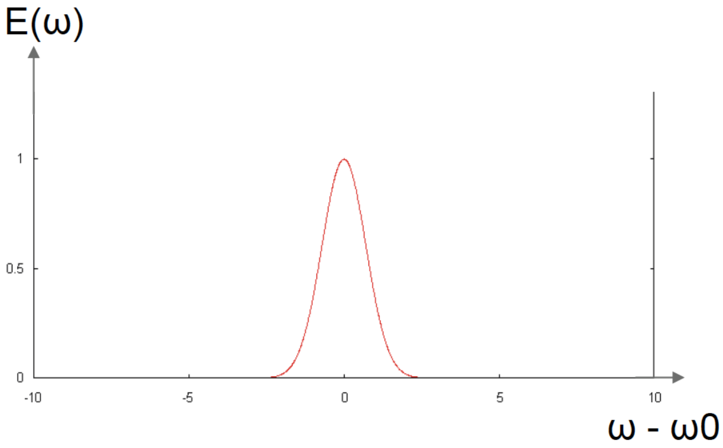


PULSE DURATION AND Bandwidth

$$E(t) = E_0 * e^{-\Gamma t^2} * \cos(\omega_0 t)$$

fourier transformation

$$E(\omega) \propto e^{-\frac{(\omega-\omega_0)^2}{(4\Gamma)}}$$



We need a spectrum with a large bandwidth to achieve a short pulse

VIA UNCERTAINTY PRINCIPLE

→ estimation via uncertainty relation

$$\hbar \Delta\omega * \Delta t \geq \frac{\hbar}{2}$$

$$\rightarrow \Delta\omega \geq \frac{0.5}{\Delta t}$$

$$\Delta t = 10\ fs$$

$$\rightarrow \Delta\omega \geq 5 * 10^{13}\ Hz$$

exact value for gaussian pulses:

$\Delta\omega\ \Delta t \geq 0.441$

WAVELENGTH-WISE

In wavelength this means:

$$\Delta\lambda = c\frac{\Delta\omega}{\omega_c^2 - \Delta\omega^2} \neq \frac{c}{\Delta\omega} \quad \triangle!$$

$$\omega_c = \frac{c}{\lambda_c} = \frac{c}{790\text{nm}} \approx 3.79 * 10^{14}\, Hz$$

$$\Rightarrow \Delta\lambda \approx 106\, nm$$

We need a broadband *seed pulse and a* laser medium capable of amplifying wavelengths from 740 nm to 840 nm: very challenging

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Amplifying lasing media

Key parameters of lasing media

Main parameters governing laser amplifiers:

- Spectral gain **bandwidth**: short pulse duration
- **Thermal conductivity**: limits repetition rate
- Abs. and emis. **cross sections**: gain, pump absorption and saturation
- **Fluorescence lifetime**: sets conditions on pumping
- **dn/dT**: limits beam quality

Crystals	Nd: YAG	Yb: YAG	Ti: Sa	Yb: CaF_2
Fluorescence lifetime (ms)	0.23	0.96	0.0032	2.4
Stimulated-em. $\sigma(\times 10^{-20}/cm)$	20 to 30	2.1	30	0.2
Fluorescence wavelengths (nm)	1064	1030	660-1100	1033
Absorption wavelengths (nm)	808	940	514 to 532	980
Fluorescence BW (FWHM) (nm)	0.67	10	440	70
Absorption BW (FWHM) (nm)	1.9	>10	200	10
Pumping quantum efficiency	0.76	0.91	0.55	0.5
Saturation fluence (J/cm^2)	0.67	9.2	0.9	80
Thermal conductivity (W/m/°K)	0.14	11	35	9.7
dn/dT (1E-6/K)	7.3	7.8	13	-11.3

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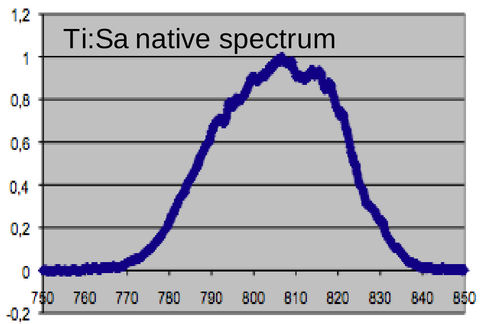
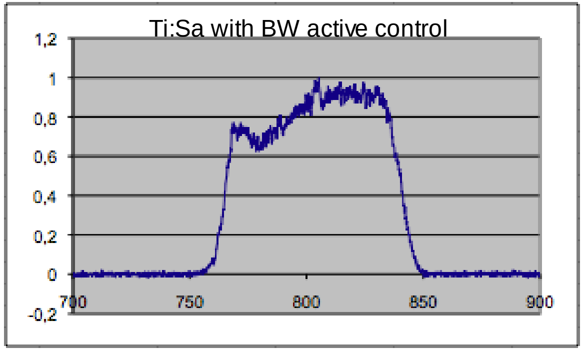
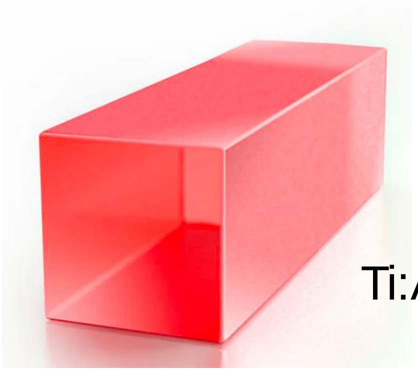
Key GAIN MATERIAL: Titanium doped Sapphire

Currently, most CPA lasers are based on Ti:Sapphire







Ti:Al_2O_3

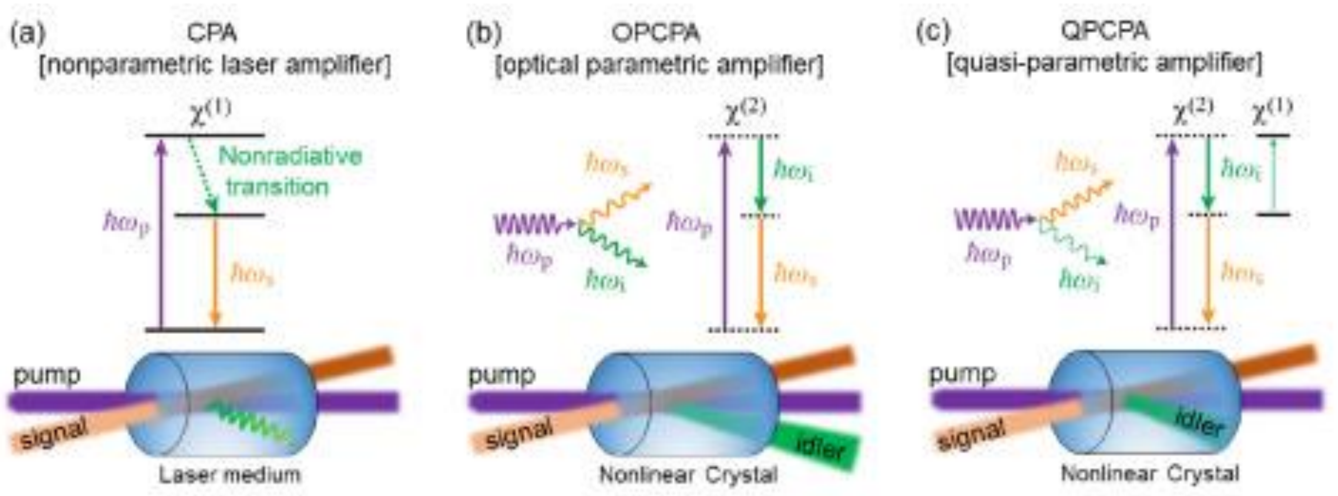
Large gain bandwidth (680 nm – 1080 nm)
- High quantum efficiency

Thermal conductivity: 35 $WK^{-1}m^{-1}$
- **Relatively long lifetime: 3 μs**
- Typically pumped in the green with ns Q-switched pulses

Active bandwitdth control crucial to overcome gain narrowing (non linear process) and enable sub-50 fs pulses

ALTERNATIVE APPROACH

Optical Parametric Chirped Pulse Amplification



Mainly for ultra-broad-band front-end preamplifiers

A. Dubietis et al. "Powerful femtosecond pulse generation by chirped and stretched pulse parametric amplification in BBO crystal," Opt. Commun. **88**, 437 (1992).
I.N. Ross et al. "The prospects for ultrashort pulse duration and ultrahigh intensity using optical parametric chirped pulse amplifiers," Opt. Commun. **144**, 125 (1997).

Ultraintense lasers: overview

See also:
C.N. Danson, C. Haefner, J. Bromage, T. Butcher, J.-C.F. Chanteloup, E.A. Chowdhury, A. Galvanauskas, L.A. Gizzi, J. Hein, D.I. Hillier, N.W. Hopps, Y. Kato, E.A. Khazanov, R. Kodama, G. Korn, R. Li, Y. Li, J. Limpert, J. Ma, C.H. Nam, D. Neely, D. Papadopoulos, R.R. Penman, L. Qian, J.J. Rocca, A.A. Shaykin, C.W. Siders, C. Spindloe, S. Szatmári, R.M.G.M. Trines, J. Zhu, P. Zhu, and J.D. Zuegel, High Power Laser Science and Engineering **7**, 54 (2019).

High intensity lasers: evolution

Major breakthrough following Chirped Pulse Amplification

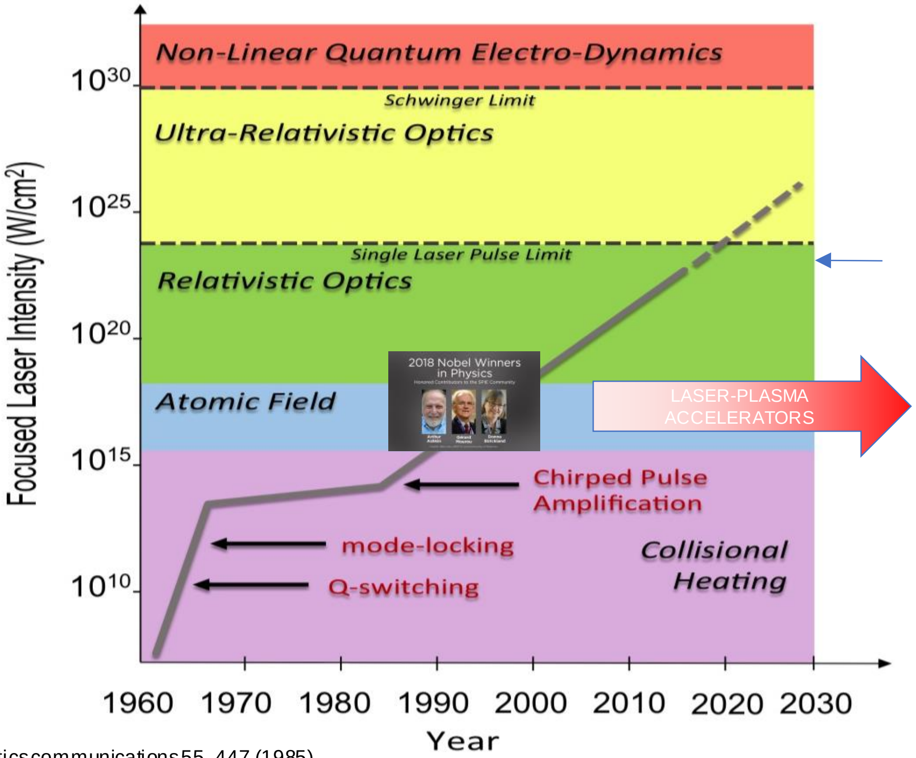
Current laser technology developmentof CPA lasers [1] mainly driven by **extreme intensity** applications;

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;

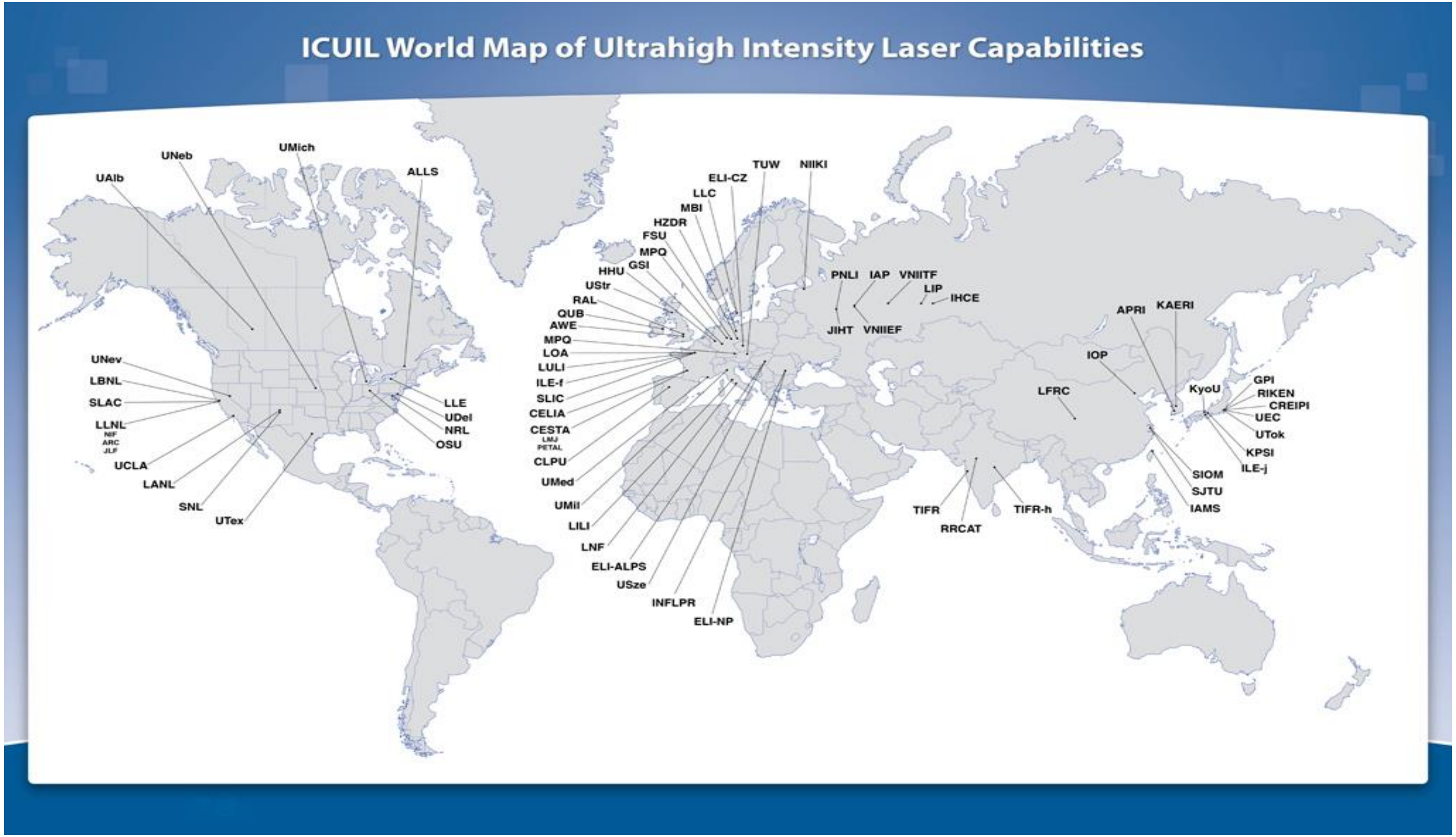
Key role of industry to establish turn-key, high average/peak power ultrashort pulse technology;



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

ULTRAINTENSE LASERS



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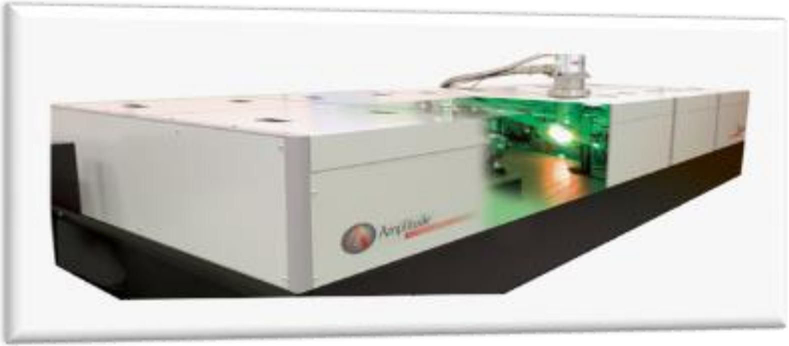
AVAILABLE INDUSTRIAL SYSTEMS

Current EU industrial systems offer robust solutions, incorporating ultrashort pulse capabilities at the PW level, in a compact footprint

Amplitude Technologies
PULSAR: 5 J, <25 fs, 5-10 Hz
Ti:Sapphire



Thales
ALPHA5/XS: 20 J, 25 fs, 5 Hz
Ti:Sapphire

Scientific lasers: still require expert users

Many PW-CLASS lasers worldwide

Almost unique systems built upon specifications of scientific cases

And many more … ≈ 20

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EXTREME LIGHT INFRASTRUCTURE(s)

A joint effort of the whole community

eXtreme light infrastructure

- **ELI-Beamlines facility**, Prague, Czech Republic
- **ELI Attosecond Light Pulse Source** (ELI-ALPS) in Szeged, Hungary
- **ELI Nuclear Physics** (ELI-NP), Magurele, Romania

(Approx 1 Bln € investment)

Currently entering operation phase

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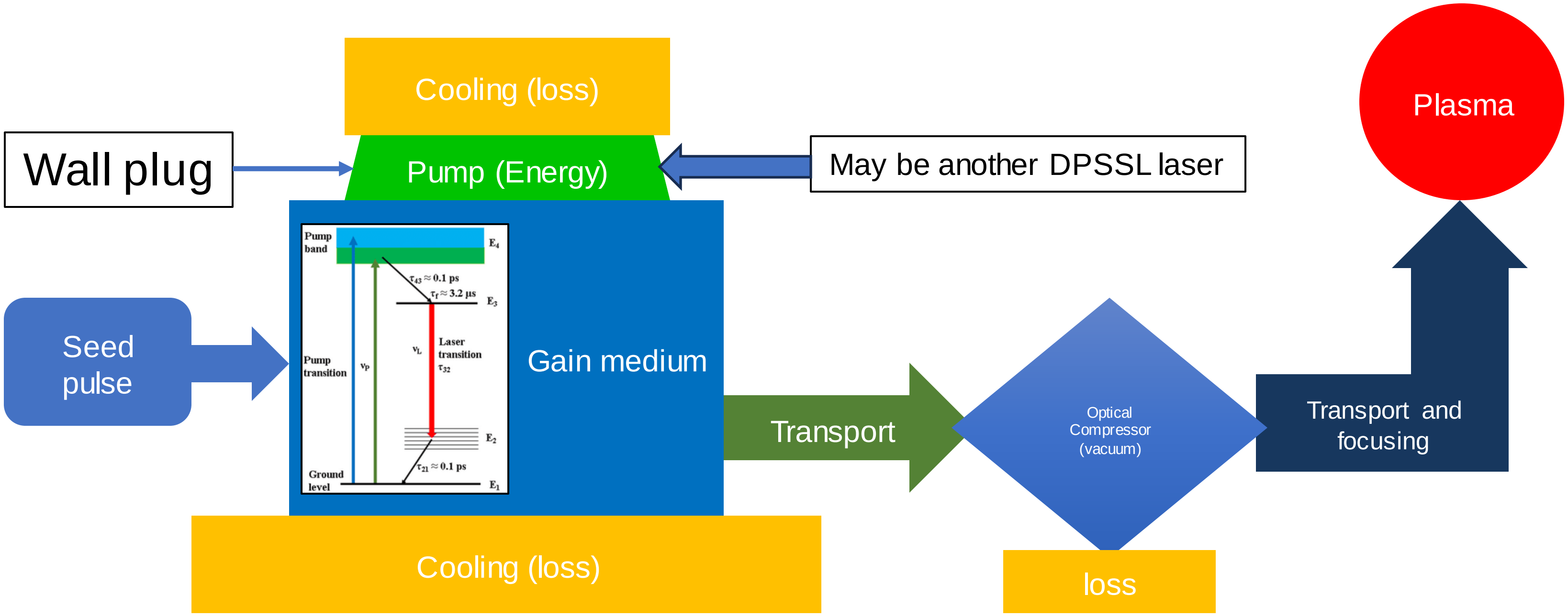
From laser pulse amplification and compression to interaction with plasma

Relevant blocks of a laser driver

Tackle power and coupling efficiencies and losses



All blocks from oscillator to focusing are key for stable electron acceleration

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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)

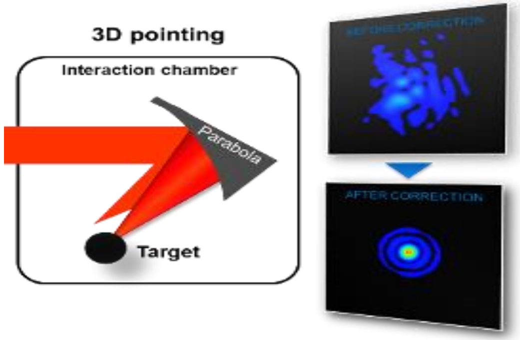
2006: Energy gain: 1 GeV
W.P. Leemans et. al, Nature Physics 696 (2006)

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%
10 PW	



Phase front correction with adaptive optics (from astronomy)

+ several additional quality parameters

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From laser pulse amplification and compression to plasma irradiation

Focal spot quality

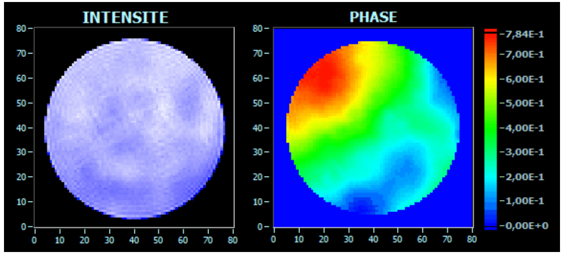
FOCAL SPOT BEAM QUALITY

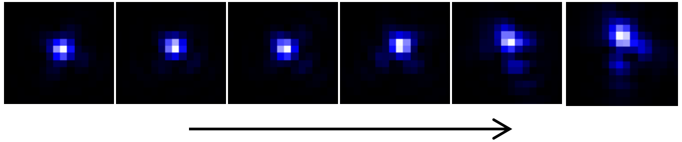
As larger gain media and optics are used, optical aberrations become important and limit the focusability of laser pulses

$$S_r = \frac{\text{Energy in the focal spot}}{\text{Energy in the pulse}}$$

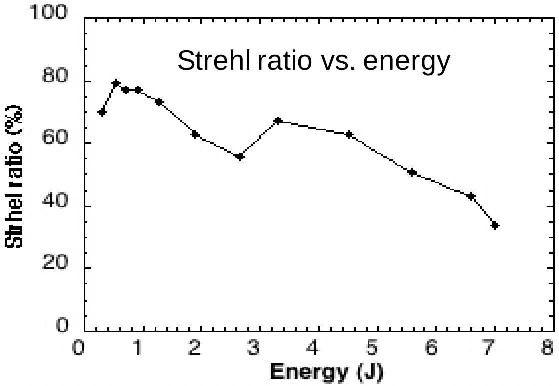
STREHL RATIO

PHASE FRONT DISTORTIONS





Amplification



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Borrowing Astronomy Adaptive Technology

ESO's Very Large Telescope (Paranal, Chile)

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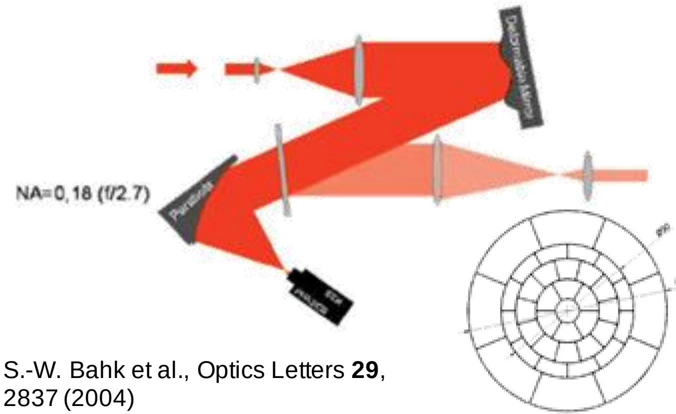
ADAPTIVE OPTICS for high power lasers

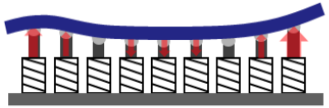
Active spatial phase control technique can be used to correct severe to moderate phase distortions;

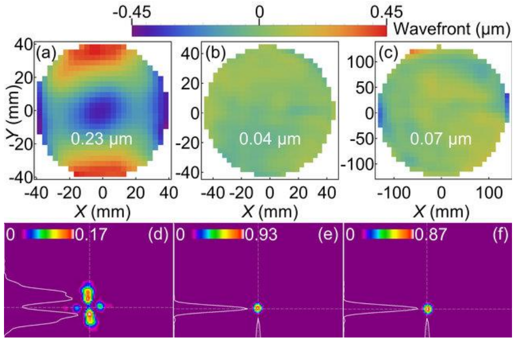
Sensors are used to measure intensity and phase map of the beam;

Deformable mirrors are used to correct the measured wave front distortions in a closed loop;



S.-W. Bahk et al., Optics Letters **29**, 2837 (2004)





A. PIROZHKOV et al., Optics Express 25, 17 (2017)

Key enabling component to reach high intensity

From laser pulse amplification and compression to plasma irradiation

Temporal contrast

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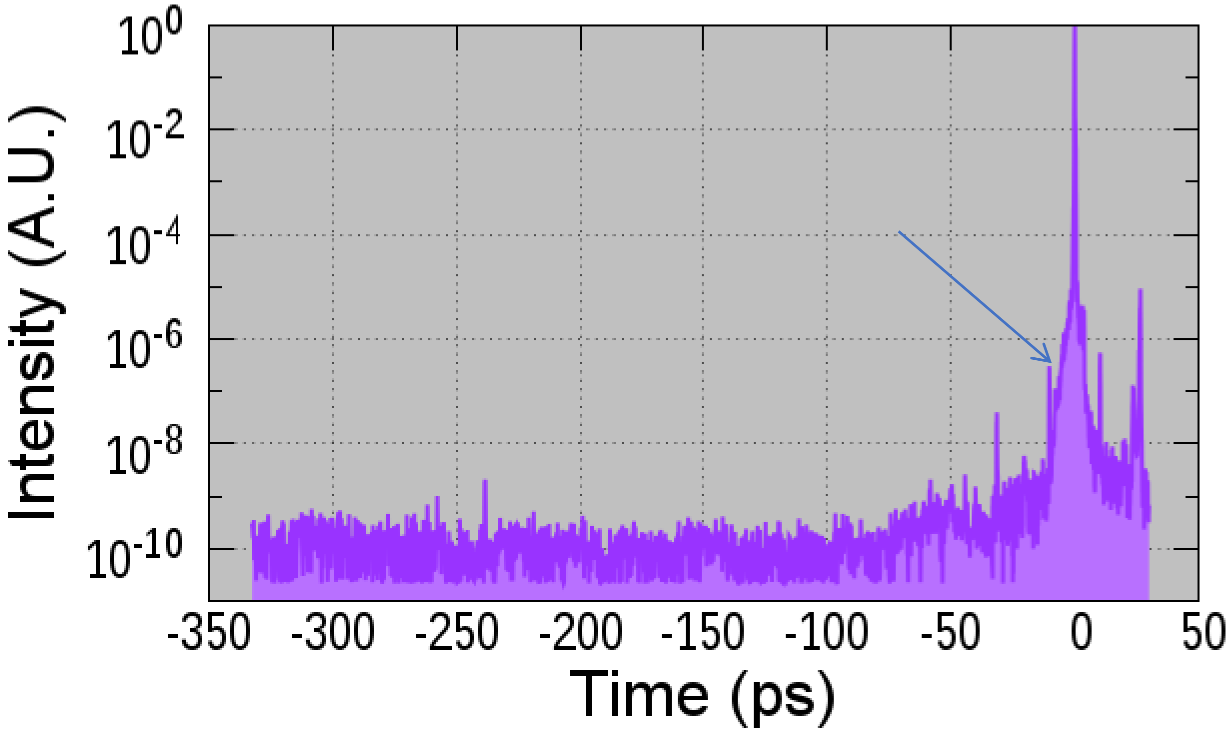
Temporal features: contrast



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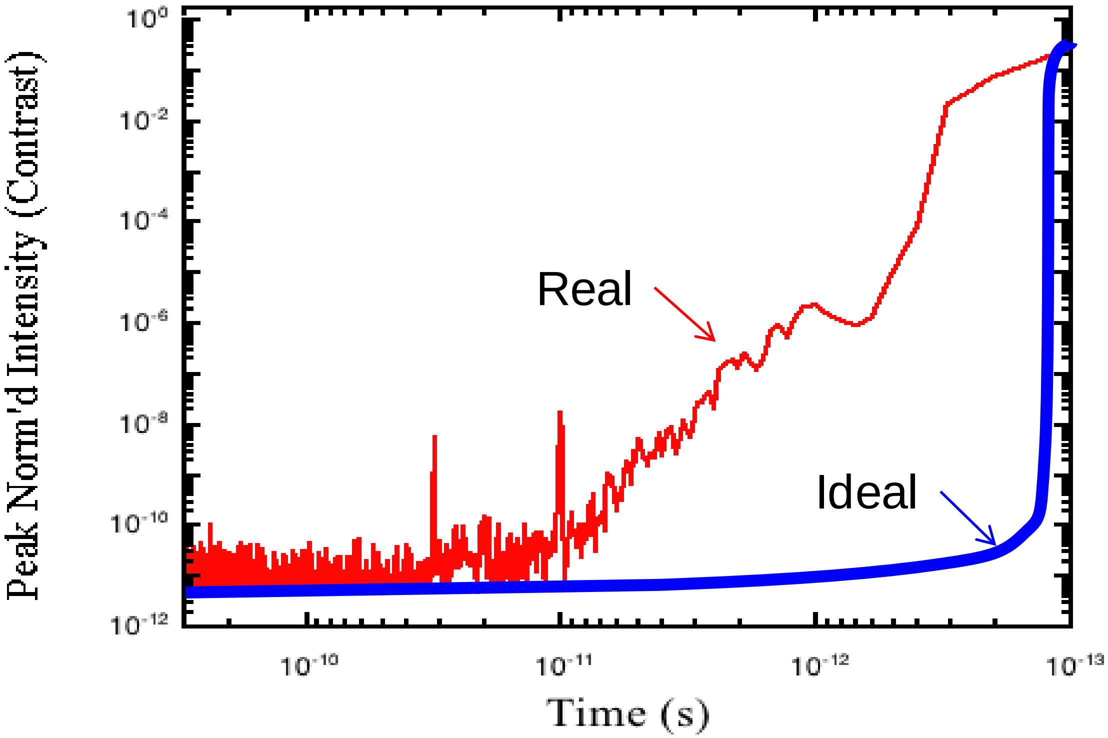
Laser contrast: sub-ps time scale



Gizzi, L.A et al., Role of laser contrast and foil thickness in target normal sheath acceleration
Nuclear Instruments and Methods in Physics Research A829, 144–148 (2016)

TEMPORAL Contrast enhancement

High contrast is crucial to **prevent plasma heating and expansion** prior to the ultraintense interaction.

- IMPORTANT for laser-plasma acceleration schemes based upon gas targets, but standard contrast (≈10^7 or more) is normally sufficient;

- CRITICAL for current schemes of ion acceleration based on laser solid interaction and in particular for **nanostractured targets**;

Solutions have been developed based on several principles:

- **Saturable absorber (SA)** is the basic solution for a standard pulse cleaning;
- Better control of ASE can be obtained using **Optical Parametric Amplification (OPCPA)**;
- **Plasma mirror (PM)** can provide excellent contrast down to the ps range;
  - Limits the repetition rate of the laser;
- Crossed polarized wave **(XPW)** generation is another solution[1] for suppression of prepulse and amplified spontaneous emission;
- Non-linear (**frequency doubling**) conversion.

[1]A. Jullien et al.,Opt. Lett., vol. 30, pp.920–922 (2005),
G. I. Petrov et al., Opt. Lett. 26, 355–357 (2001)

ACCESSIBLE Laser specs on plasma

a) **Pulse duration as short as 15 fs at multi-PW power**; band narrowing is managed by using OPCPA and/or bandwidth control/shaping capabilities;

b) **Temporal contrast as high as 10^{12}-10^{13}**, at ps timescale to prevent premature disruption of plasma conditions, using contrast enhancement;

c) **Repetition rate ≈10 Hz at PW level;**

d) **Focusability close to diffraction limit**, using wavefront correction;

e) **Focused Intensity >10^{22} W/cm^2;**

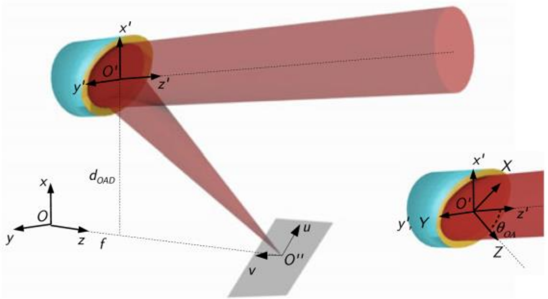
Relativistic parameter $a_0 \equiv \frac{eE_0}{m_e \omega c} = 0.85 \left(\frac{I\lambda^2}{10^{18}\ \mathrm{W\ cm^{-2}}} \right)^{1/2}$ **>>1**

"A Superintense Laser-Plasma Interaction Theory Primer," Andrea Macchi, Springer, 2013

PARTICLE ACCELERATION WITH LASERS AND PLASMAS

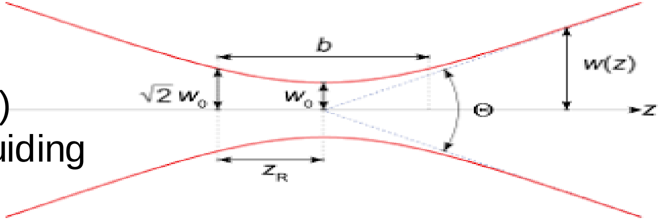
Acceleration of ions: interaction of tightly focused laser pulses at ultra-high (ultrarelativistic) intensities on **high density (solid) targets**:

- Short focal length focusing optics
- Small focal spot
- Short Rayleigh length
- Polarization distortions effects*



Acceleration of electrons: interaction of ultrashort laser pulses at (moderately) relativistic intensities with **underdense (gas) targets**;

- Very long focal length optics
- Larger focal spot diameter (30-50 µm)
- Long Rayleigh length – channeling/guiding



* **L. Labate, G. Vantaggiato, L.A. Gizzi,** Intra-cycle depolarization of ultraintense laser pulses focused by off-axis parabolic mirrors, ***High Power Laser Science and Engineering, 6, 32 (2018)***.

OPEN ISSUES OF Laser Plasma Acceleration

Since 2004, systematic production of electron bunches with energy in the hundreds of MeV range to 10 GeV and moderate energy spread (5-10%)*
Exploration of applications ongoing worldwide – focusing on Xray FEL (EuPRAXIA)

OPEN ISSUES

QUALITY: energy spread, beam divergence, emittance, self-injection dynamics, plasma shaping
=>understanding of the physics of laser-plasma acceleration in real conditions

STABILITY: and control of bunch parameters, pointing
=>improve quality of lasers and laser-target coupling

SCALABILITY: staging (phase space matching) + higher energy, high repetition rate, high average power
=>develop new laser schemes for efficient high average power.

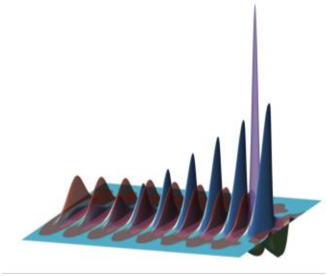
From laser pulse amplification and compression to plasma irradiation

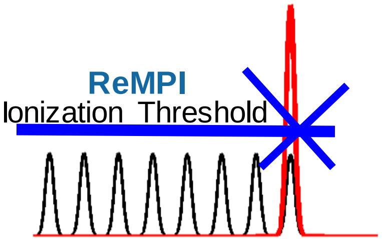
Multipulse generation

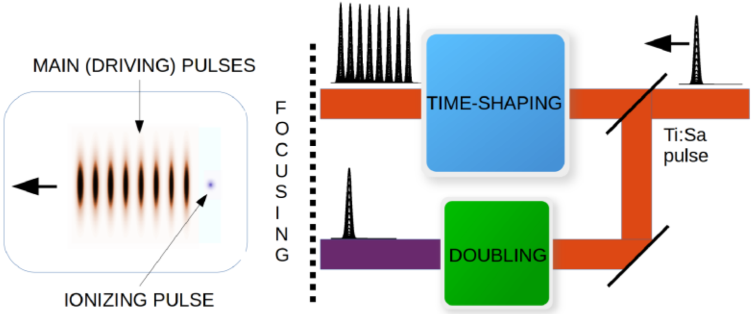
la.gizzi@ino.cnr.it http://ilil.ino.it

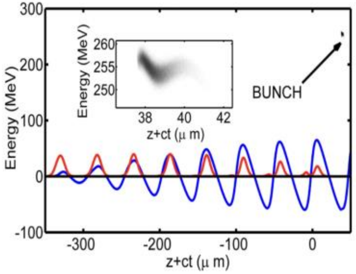
The Resonant Multi-Pulse Ionization Injection

- **The Resonant Multi-Pulse Ionization injection is a new bunch injection scheme aiming at generating extremely low-emittance bunches [as low as 0.06 mm mrad]**
- **ReMPI requires ONE short-pulse 100-TW class (e.g Ti:Sa) laser system. Since a unique very large-amplitude Ti:Sa pulse would fully ionize the atoms (N5+ or Ar8+), the pulse is shaped as a resonant sequence of sub-threshold amplitude pulses.**









EuPRAXIA

A new scheme to generate the train of pulse in a stable, efficient and feasible way
« **Quasi Lossless Pulse Train generation by Early Amplitude division** »

- P. Tomassini et al., Phys. Plasmas 24 (2017)

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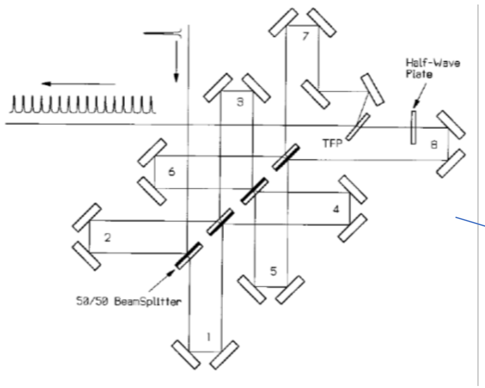
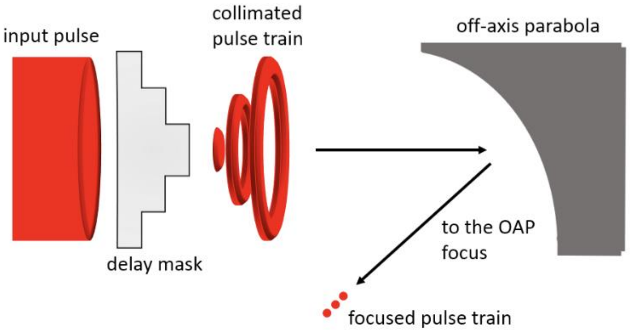
MULTI-PULSE LASER GENERATION

N-Michelson interferometers



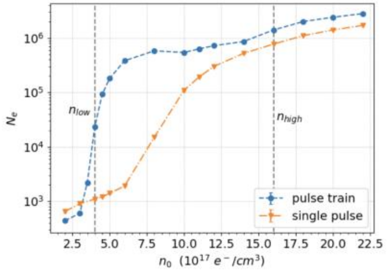
C. W. Siders et al., "Efficient high-energy pulse-train generation using a 2n-pulse Michelson interferometer," Applied Optics Vol. 37, Issue 22, 1998.

Large beams: Delay mask

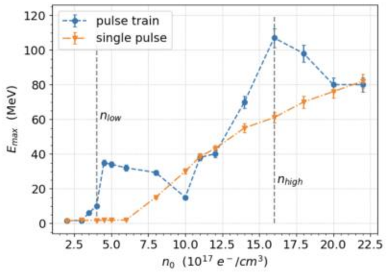


A. Marasciulli, PhD thesis, 2023

Proof of principle validation using a two-pulse "train", in progress



(a) Number of accelerated electrons versus target density



(b) Maximum electron energy versus target density

Proof of principle demonstration

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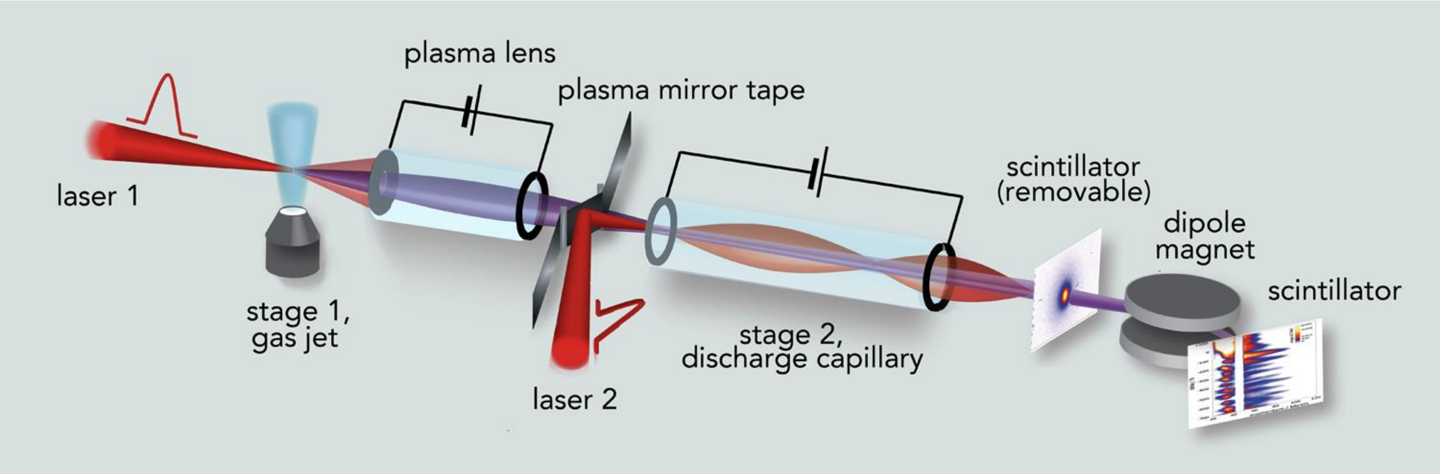
NEXT STEP: STAGING OF ACCELERATING SECTIONS

Advanced staged acceleration with lasers



Multiple stages need multiple laser pulses: scaling of energy and repetition rate

Scaling lasers drivers to large accelerator systems

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TOWARDS HIGH AVERAGE POWER

Future installations will require multi 100J, fs pulses with kHz rep-rate (multi 100kW) lasers with high efficiency

Ti:Sa requires pumping with green laser light with high power and high quality- no existing diode lasers can fulfill these requirements

↓

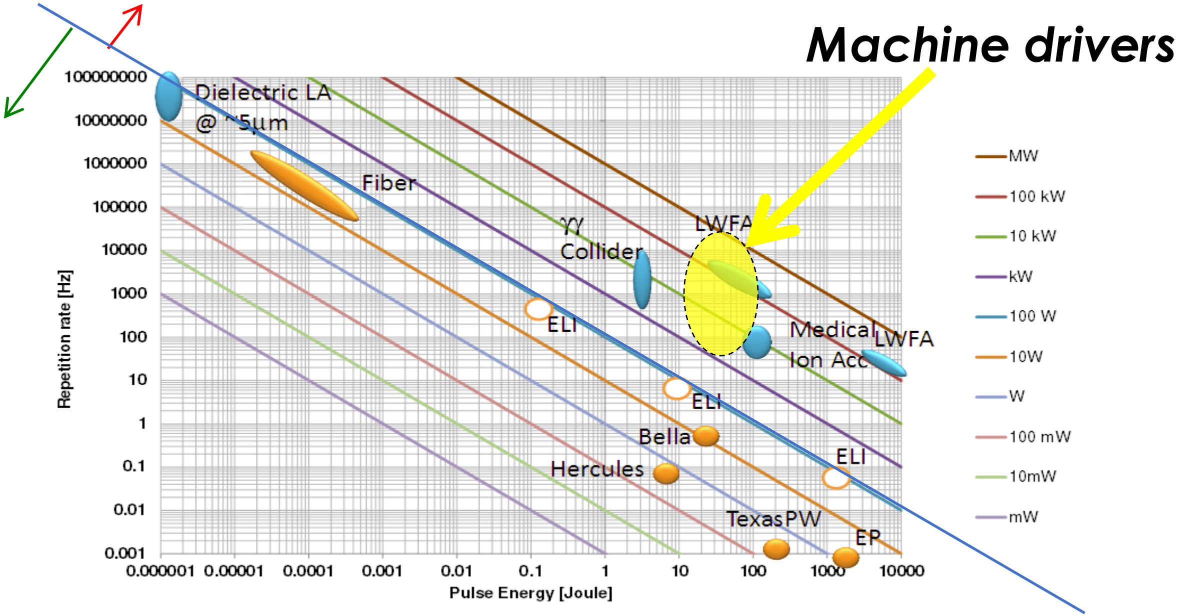
Choose different gain medium for future multi-kW laser systems

Aim at laser architectures that can exploit diode lasers.

Average power

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

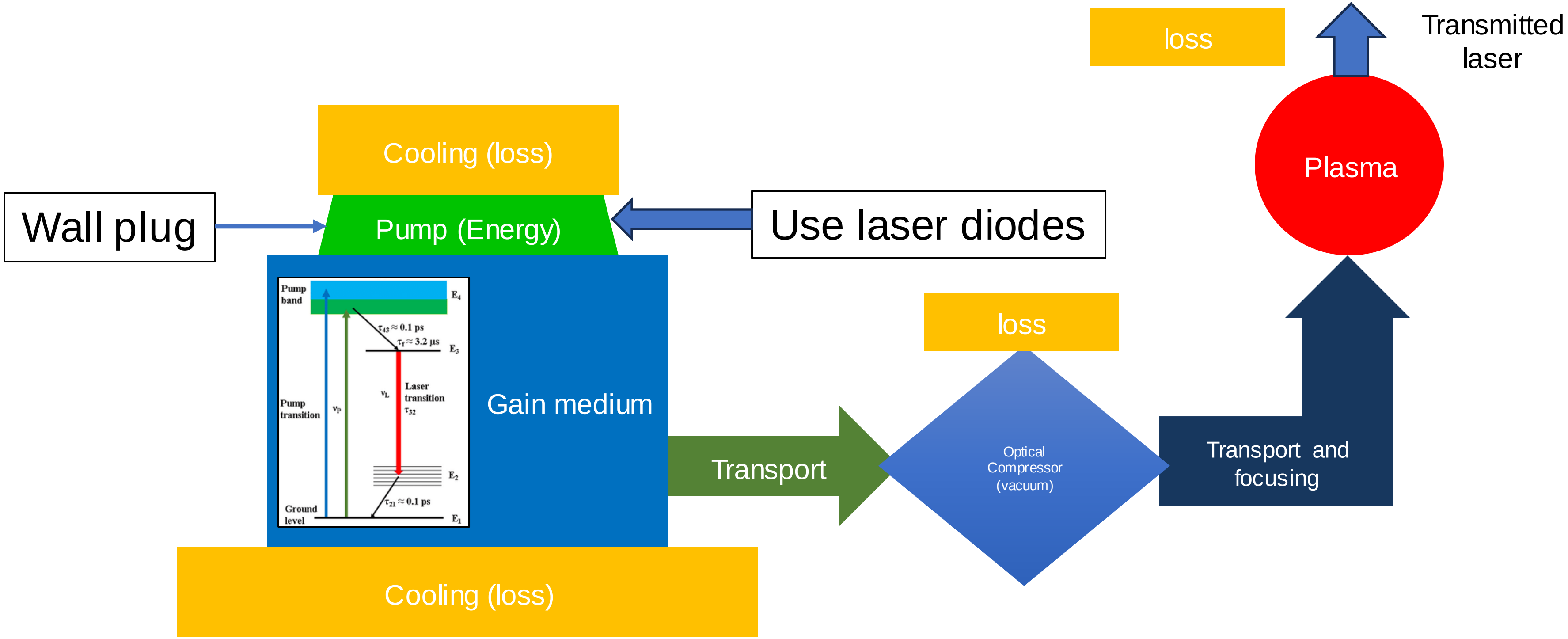
Demanding high average power (1-10 kW)



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

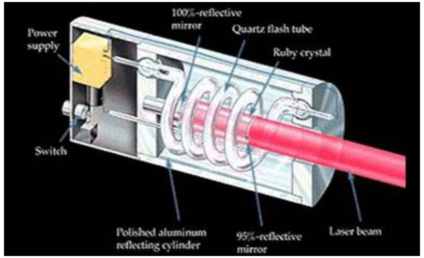
Relevant blocks of a laser driver

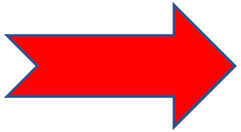
Tackle power and coupling efficiencies and losses

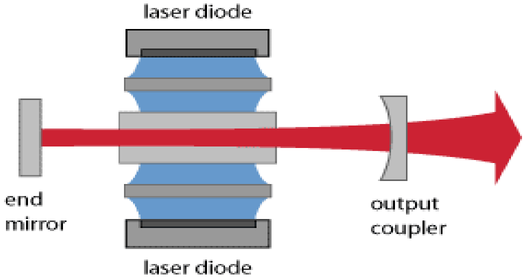


CHANGE OF OPTICAL PUMPING TECHNOLOGY

- Analysis of available technologies for PW-class, multi kW average power lasers;
- Comparison with the requirements of user beamlines;
- Current option: TiSa pumped with **diode pumped solid state lasers** (DPSSL) – robust;
- In progress: Direct CPA for higher rep-rate, higher efficiency.







PUMP SOURCE: Flashlamp

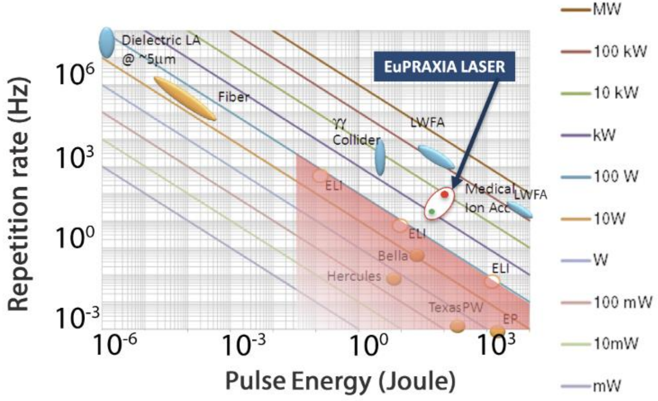
PUMP SOURCE: Diode laser

Major developments in laser technology occurring now!

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)

Scaling lasers drivers to large accelerator systems

Scaling existing Ti:Sa technology

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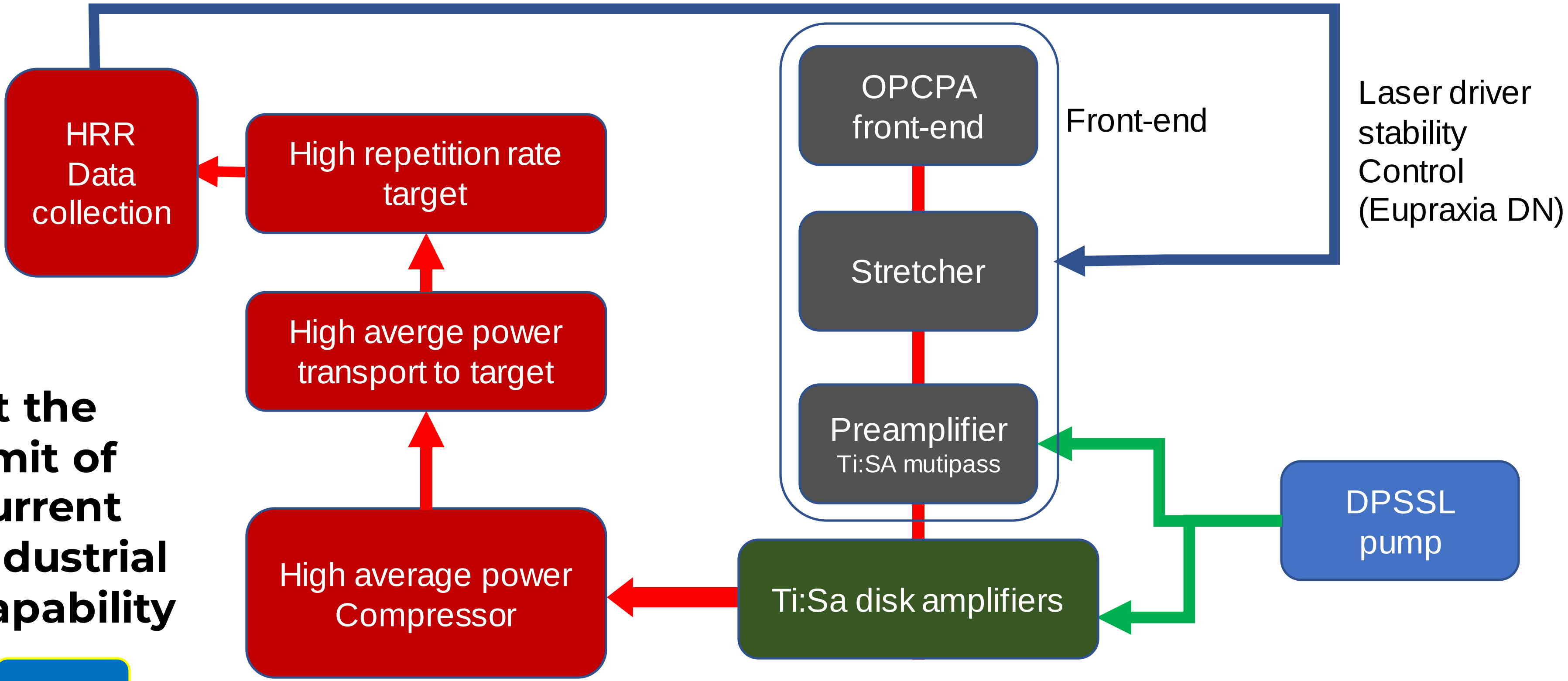
100 Hz, J-scale laser beamline

Funded by the European Union
NextGenerationEU



At the limit of current industrial capability

100 W

Joule scale / 100 Hz / > 100 W

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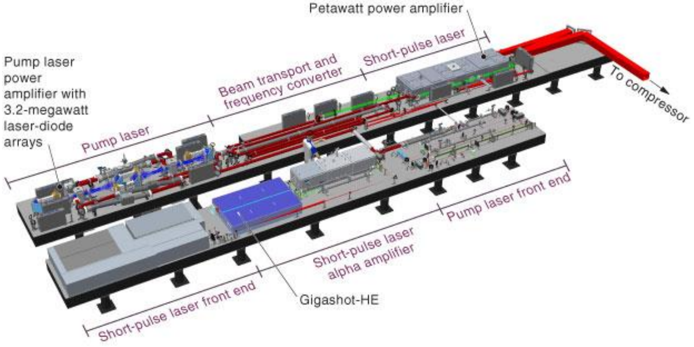
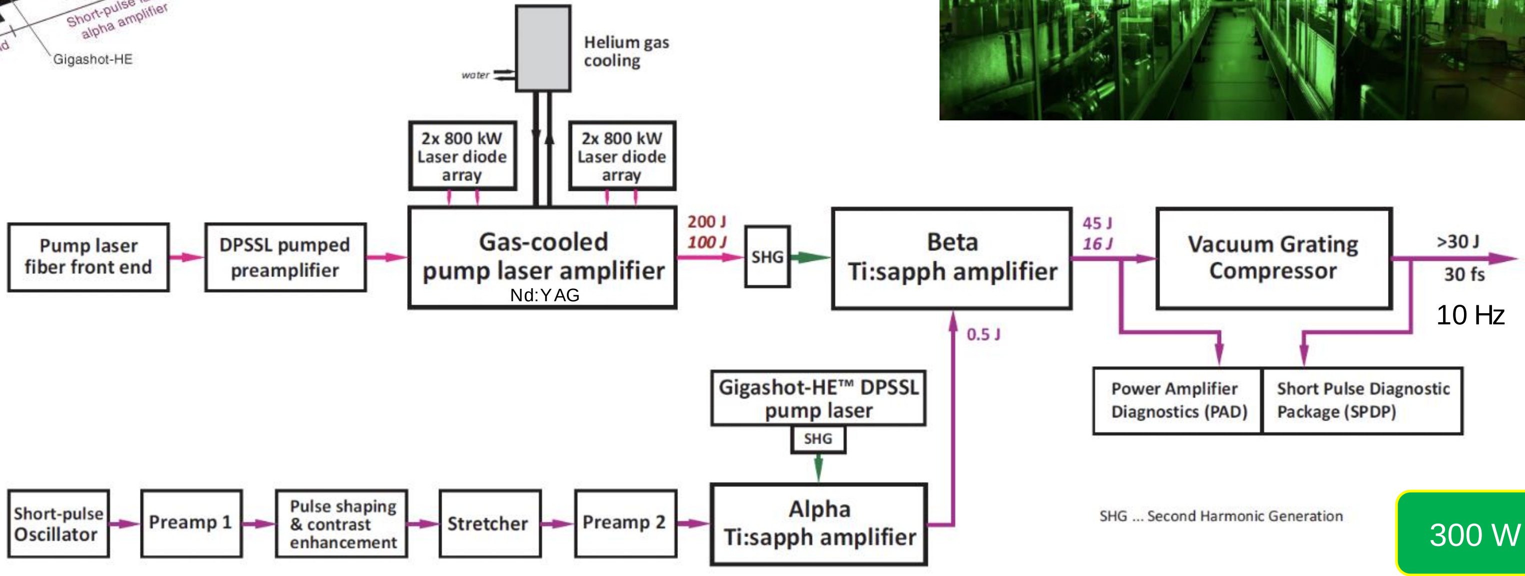
HAPLS: Fully diode-pumped reprated PW system



Beamline (Prague)



300 W

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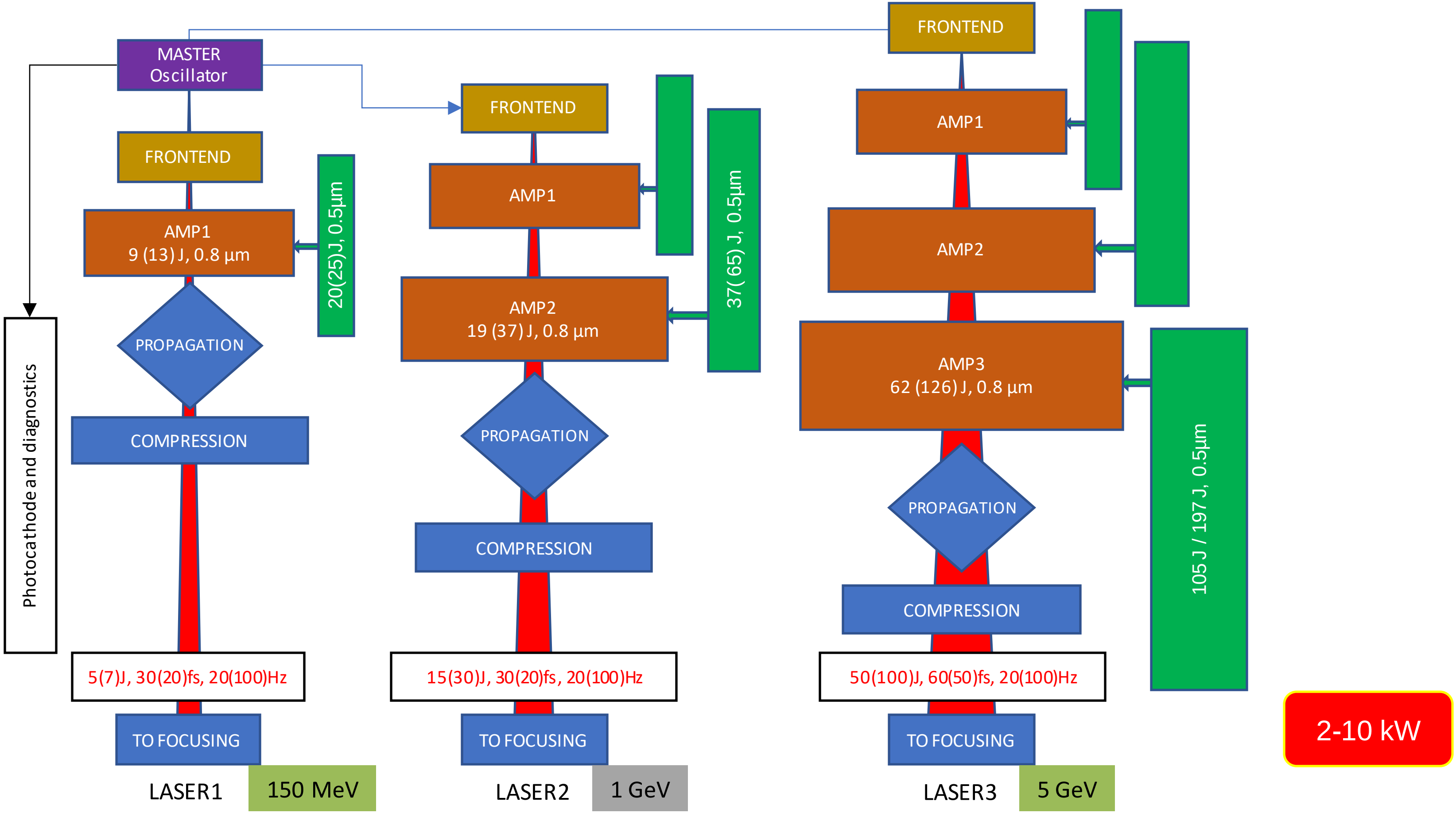
EuPRAXIA LASER (Ti:Sa)



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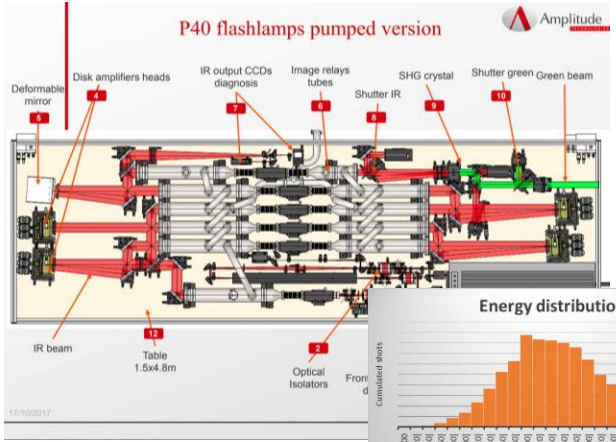
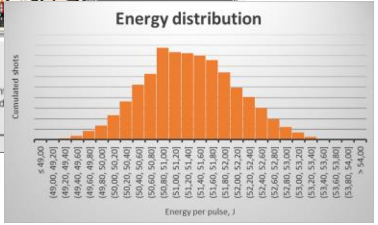
EuPRAXIA Laser Driver: pump lasers

Developments based on diode pumping technology are in progress, progressively matching requirements



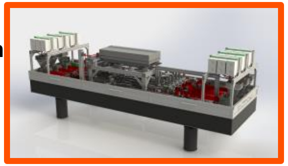


Amplitude P60

Flashlamp pumped Nd:YAG

Design: 60 J @ 10 Hz, 532 nm

Conversion to diode pumping fully designed - **Premiumligh**



Expected specs: **100 Hz – 10 kW** (100 J/pulse @ 1µm)

Cost of diode still an issue

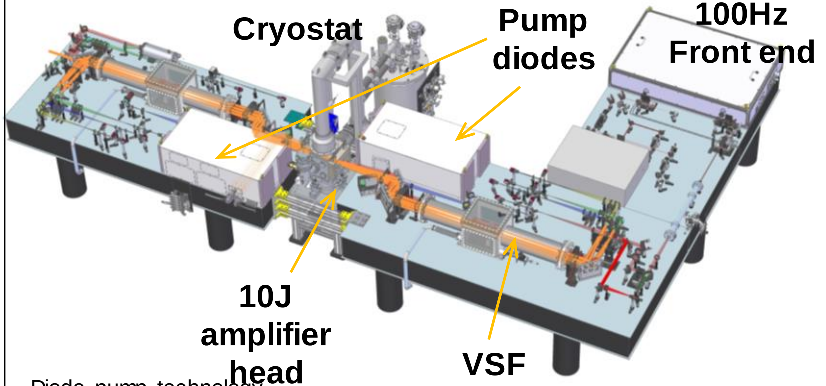
currently 5x compared to flash-lamps.

expected to decrease.

Maintenance free operation for 25-30 yrs.

Amplitude *Courtesy of F. Falcoz*

Schematic of DiPOLE 100Hz



Diode pump technology

100J @ 10Hz

Summer 2019 demonstrated 60J @ 10Hz, 515nm in LBO with 66% efficiency (91J @ 1030nm)

Commissioning of DiPOLE100 @ XFEL commenced Q1 2020 – completion end 2021

Energy scaling 145J @ 10Hz, 1030nm @ HiLASE in January 2021

10J (

Build @ CLF near completion – commissioning Q4 2021

central laser facility · UKRI · Science and Technology Facilities Council

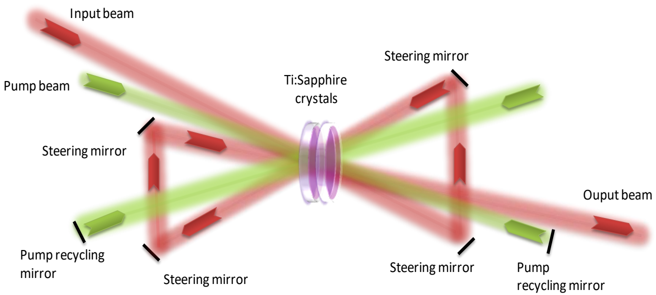
Courtesy of P. Mason

More options available and further developing.

Thermal management

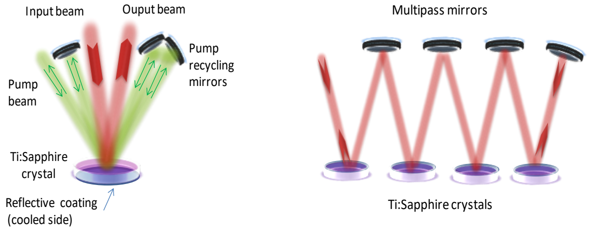
Transmission vs. "active mirror" configuration is currently being evaluated to account for thermal management

Transmission geometry

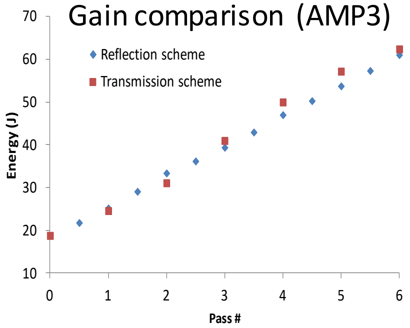


Pro: More efficient (double-side) cooling and reduced complexity;
Con: propagation through flowing cooling liquid

"Active mirror" geometry



Pro: Well established concept with no propagation through cooling fluid
Con: limited cooling (single face), to be modelled



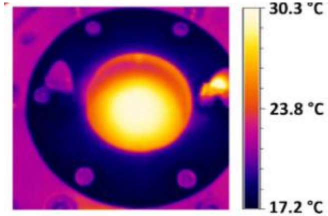
*) Water cooled Ti:Sa amplifier ("Active Mirror" configuration) under development at ELI-HU (After V. Cvhykov *et al.*, Opt. Lett, **41,** 3017, 2016)
) Fluid (D_2O) cooled Nd:YAG laser, 20 kW CW pump power, D_2O (After X. Fu *et al.*, Opt. Express, **22, 18421 (2014)
***) Fluid (Siloxane) cooled Nd:YLF laser, 5 kW CW pump power (After Z. Ye *et al.*, Opt. Express, **24**, 1758 (2016)

Underpinning EuPRAXIA-like Laser driver

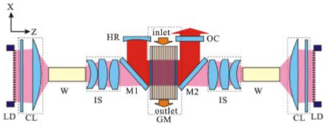
EuPRAXIA Advanced Photon Source

Funded by the European Union

THERMAL MANAGEMENT OF POWER AMPLIFIERS



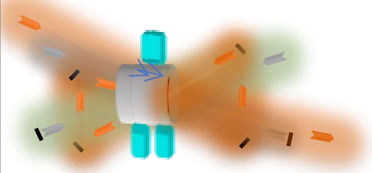
WATER/GAS COOLING



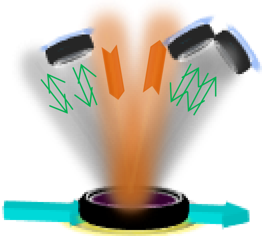
Prototyping needed

AMPLIFIER GEOMETRY TRANSMISSION VS. REFLECTION

Multipass transmission

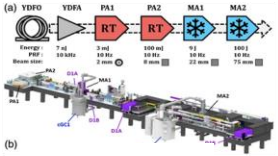


Multipass reflection



Prototyping needed

DPSSL PUMP SOURCES TECHNOLOGY

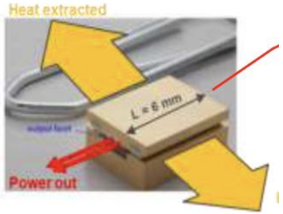


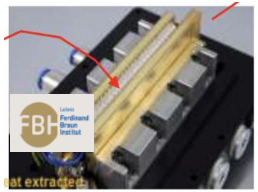
DiPOLE 100 (STCF)

P-60 technology (Amplitude)

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

DIODE LASERS EFFICIENCY, BRIGHTNESS AND LIFETIME



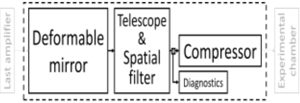


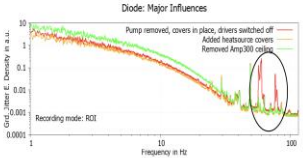
Needs development

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

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Scaling lasers drivers to large accelerator systems

New schemes for high repetition rate and high WPE

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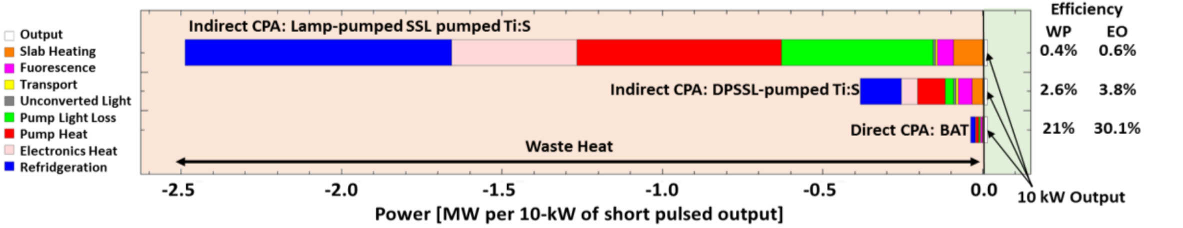
Efficiency path

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:

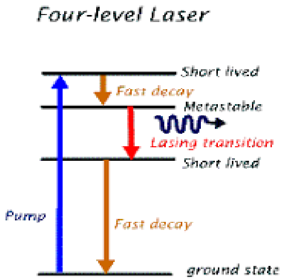
Direct CPA is a solution for wall-plug (WP) efficiency and high rep-rate.

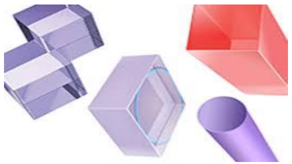
From flashlamp to indirect to direct diode pumping



C. Siders et al., EAAC 2017

Quantum defect





WP Efficiency > 20% possible:

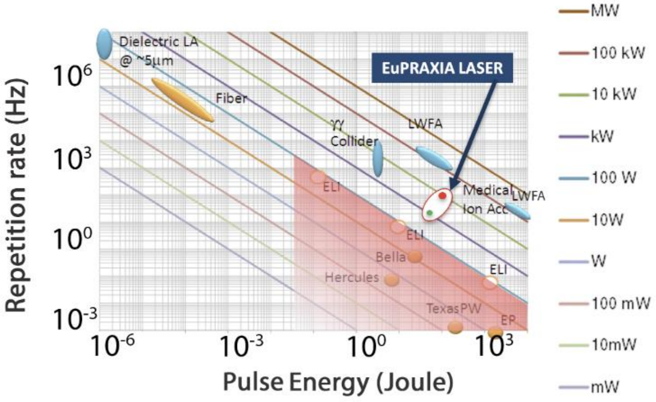
We need a **gain medium** that can support amplification on a large bandwidth, has a **low quantum defect** and can be pumped **directly** with **diode lasers**: **endless quest for the perfect laser medium!!**

la.gizzi@ino.cnr.it http://ilil.ino.it

Roadmap on LPA Laser Driver technology

Laser-driven plasma acceleration needs ultrashort, high power lasers with <u>high average power</u>

- **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)

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).

Coherent Combination in Fibers

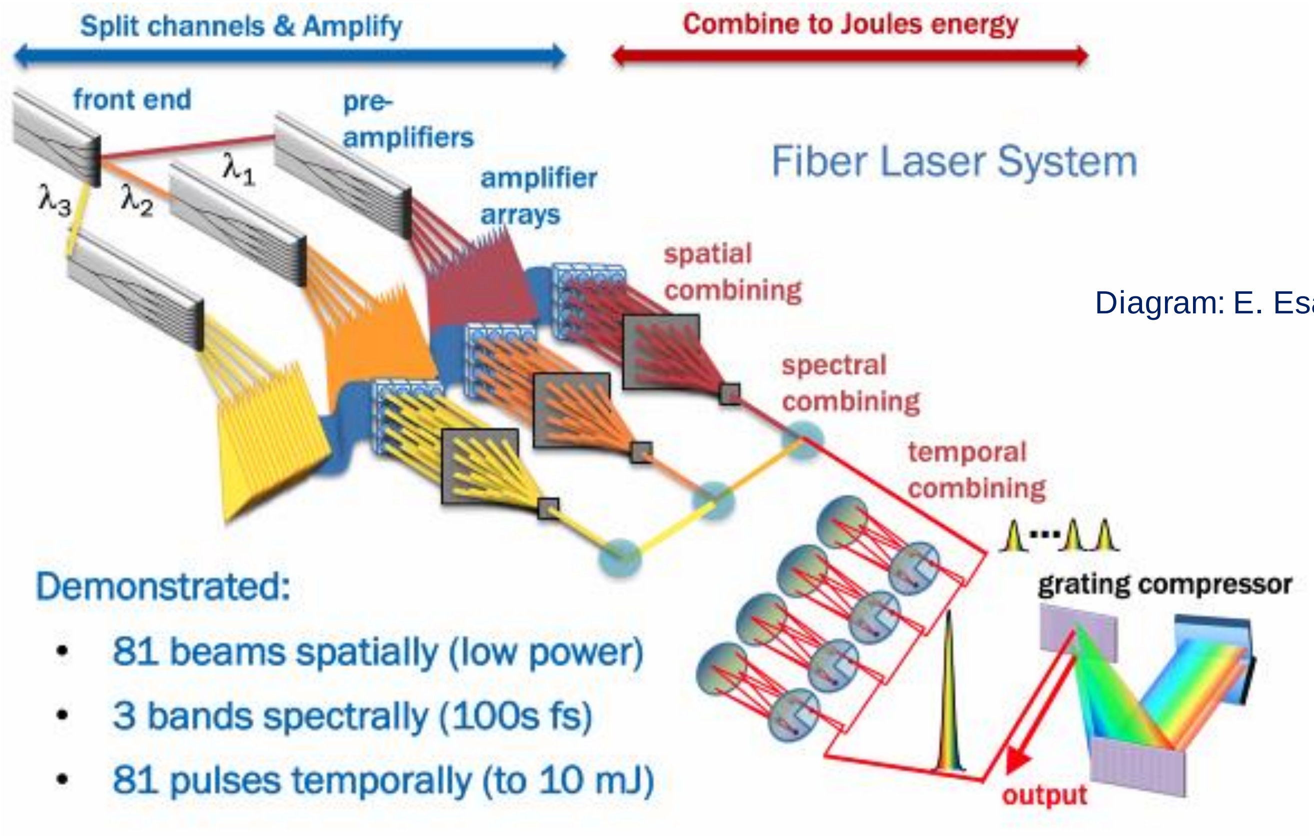
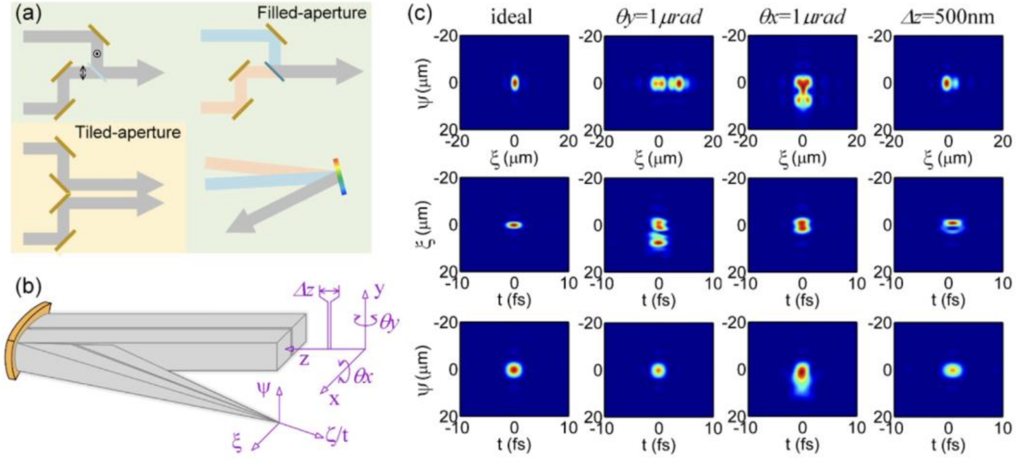


Diagram: E. Esarey, LBNL

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

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kHz laser driver development for LPA

A case study: direct DPSSL CPA with Thulium

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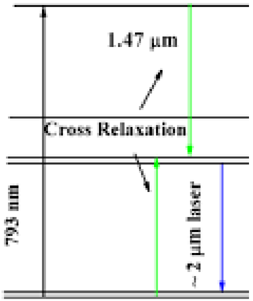
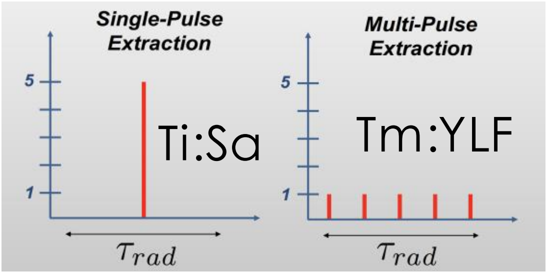
Thulium based laser gain materials

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

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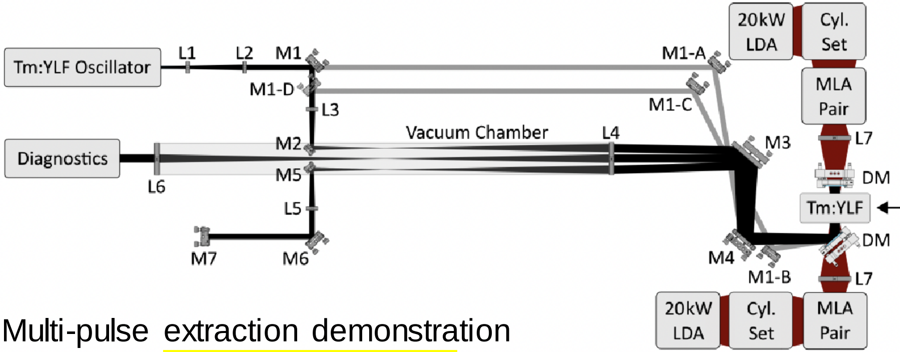
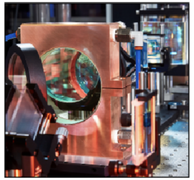
Recent advances with Tm:YLF

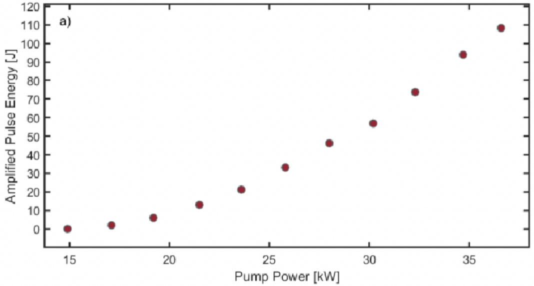
Energy density storage and extraction capabilities of Diode pumped Tm:YLF (narrowband)



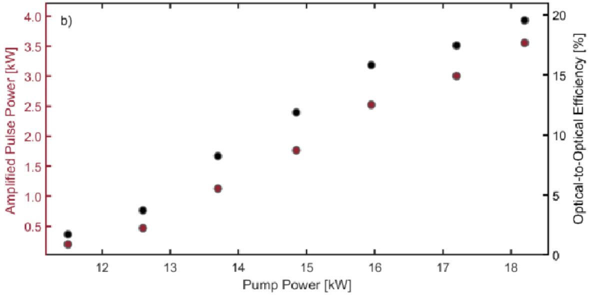
Mounted Tm:YLF Crystal



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."

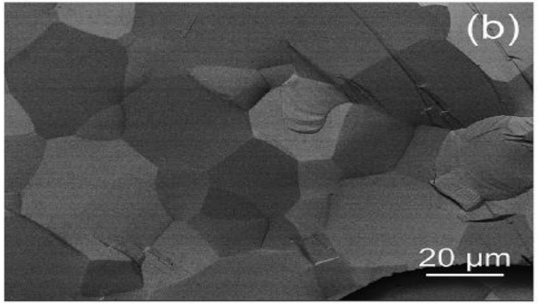
Issa Tamer, et al., "High energy operation of a diode-pumped Tm:YLF laser," Proc. SPIE 12401, High Power Lasers for Fusion Research VII, 1240109 (14 March 2023); doi:10.1117/12.2649103

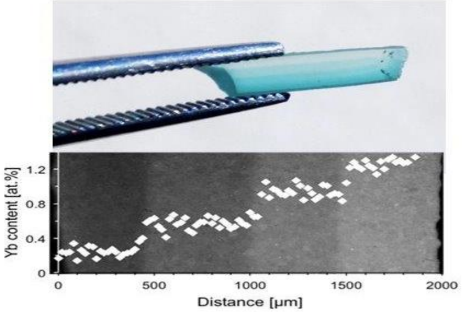
Laser grade ceramic option

- 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





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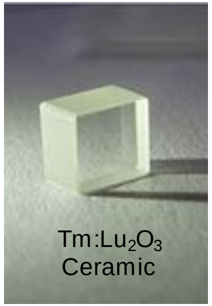
Ceramic option: Tm Lu_2O_3



Sample from Konoshima

Laser material: Tm:Lu_2O_3

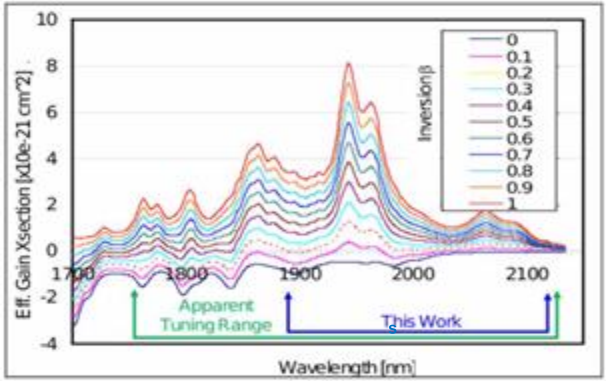
- Emission at 2 μm;
- Large amplification bandwith
- Direct pumping at 800 nm, using diodes operating in CW mode (available and scalable);
- Cross relaxation partially compensates quantum defect – option of in-band pumping.
- Multi-pulse extraction at high repetition rate > 10 kHz; Ideal for accelerator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

Commercial diode lasers

[Scholle et al., 2010]



[Antipov, 2011]

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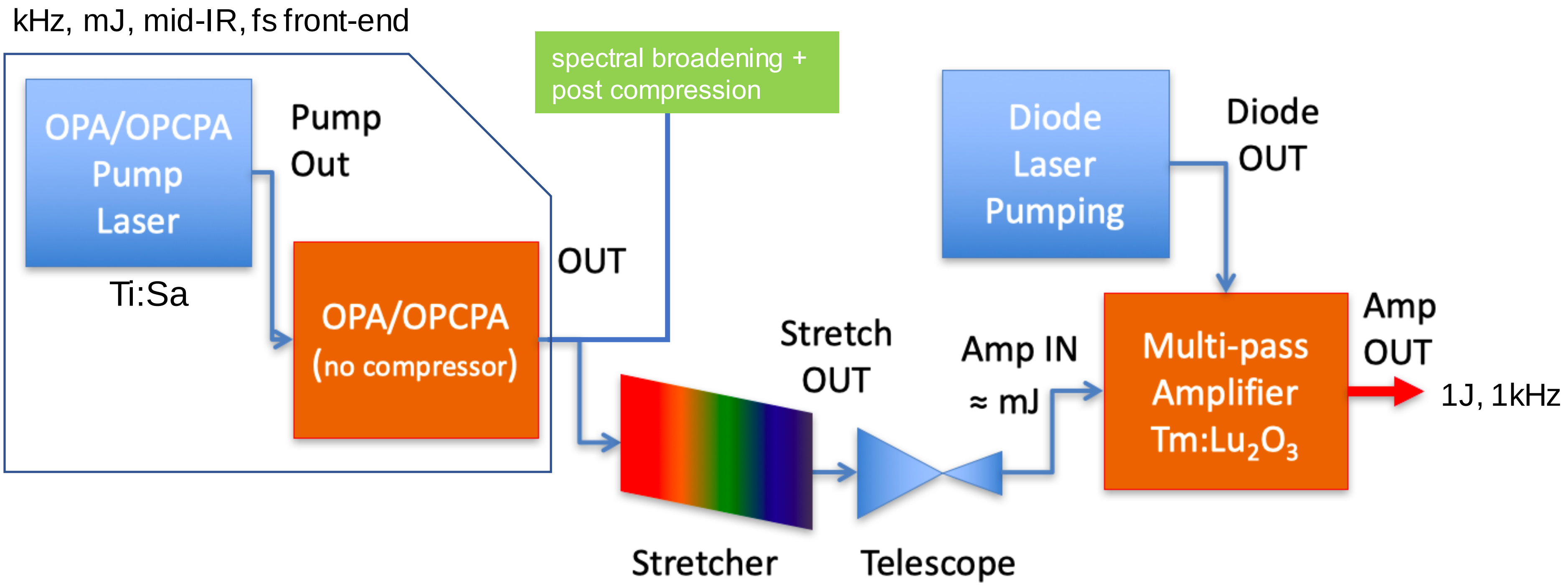
kHz laser development at ILIL

A kW-kHz CPA laser development with direct diode pumping



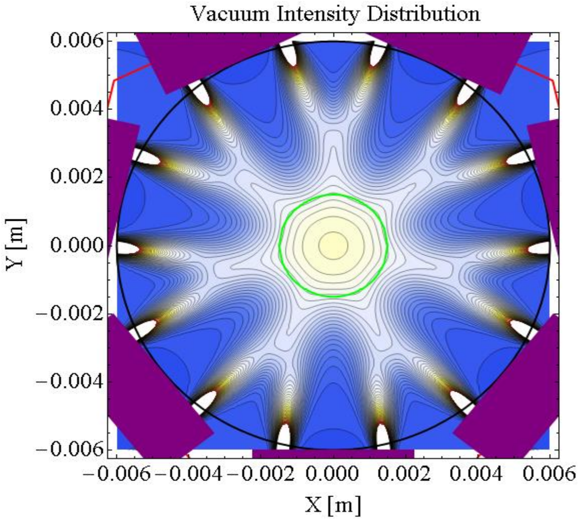
Main development effort in amplifier modules: ELI_{IT}/APOLLO project (CNR)

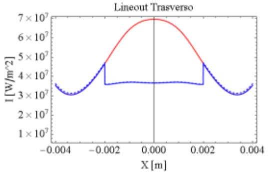
Gain medium design and pumping

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

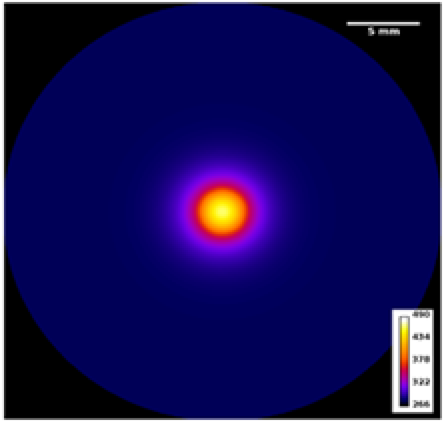
Geometry

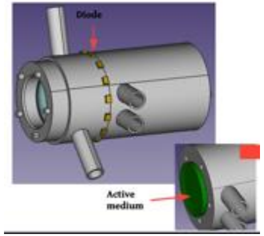
Edge diode pumping





Thermal load





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

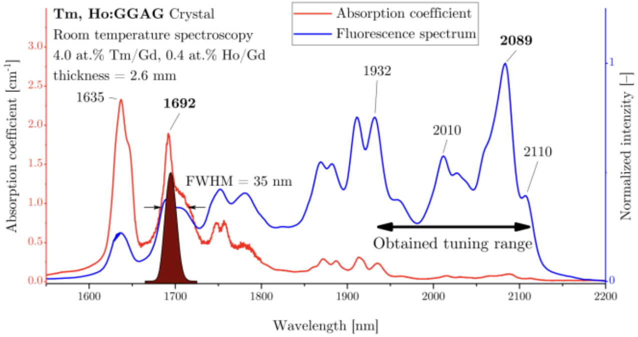
Now finalizing technical design and starting construction and tests

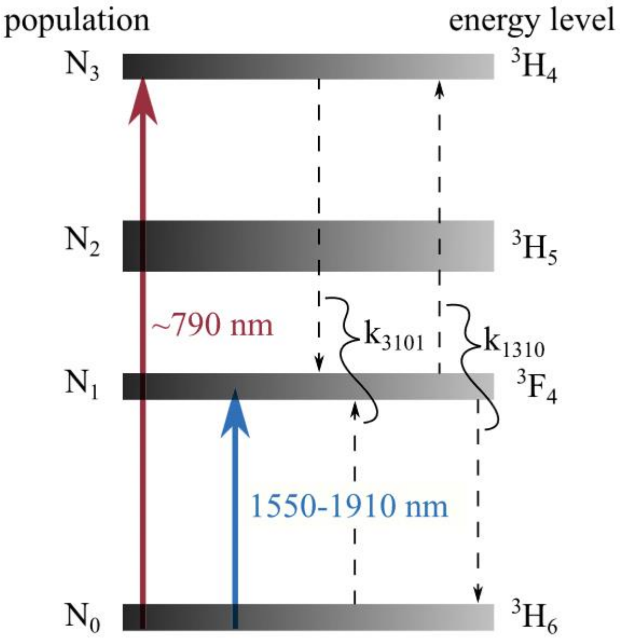
[1] J. Vetrovec, et al., “Wide-Bandwidth Ceramic Tm:Lu2O3 Amplifier”, Proc. SPIE 9834, 983407 (2016); https://doi.org/10.1117/12.2224411
[2] J. Vetrovec, et al., “2-micron lasing in Tm:Lu2O3 ceramic:initial operation”, Proc. SPIE 10511, 1051103 (2018); https://doi.org/10.1117/12.2291380
[3] D. Palla,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

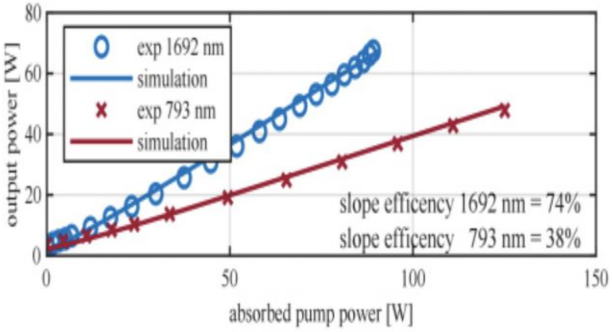
Higher WPE: In-band pumping for low *QD*

WPE: wall plug efficiency
QD: Quantum Defect

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 considerations on lasers for LPA

- **CPA laser technology is mature for LPA studies;**
  - **Scientific lasers are being optimized;**
  - **Suitable for high quality plasma acceleration (FEL);**
- **Limited scaling (thermal, wpe) for HEP accelerator drivers;**
- **New laser technology is needed for high WPE and >kW average power;**
- **Efficient diode pumping is replacing flashlamps;**
- **Suitable schemes and materials are emerging and under investigation.**