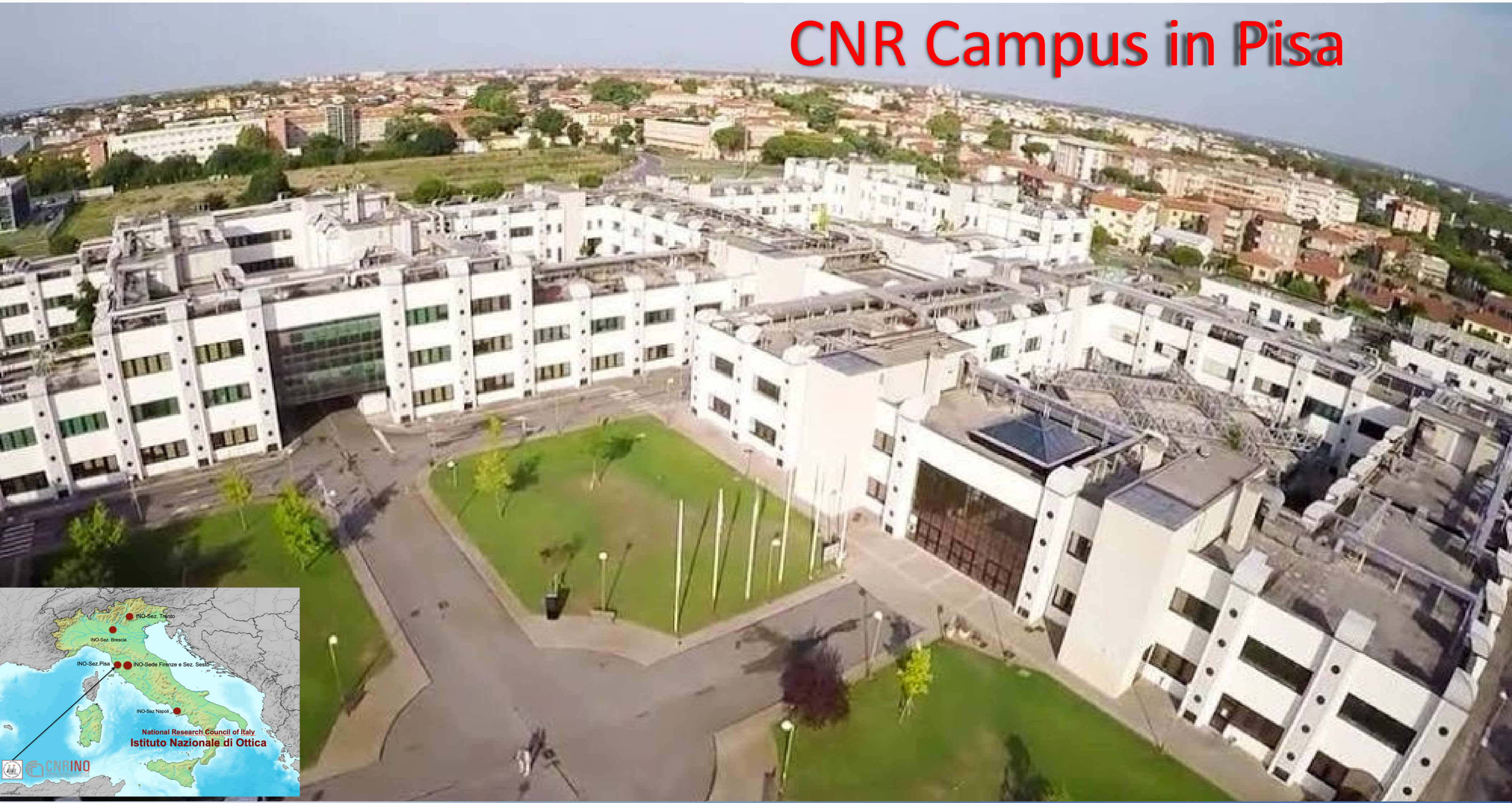
LASERS FOR NOVEL ACCELERATORS

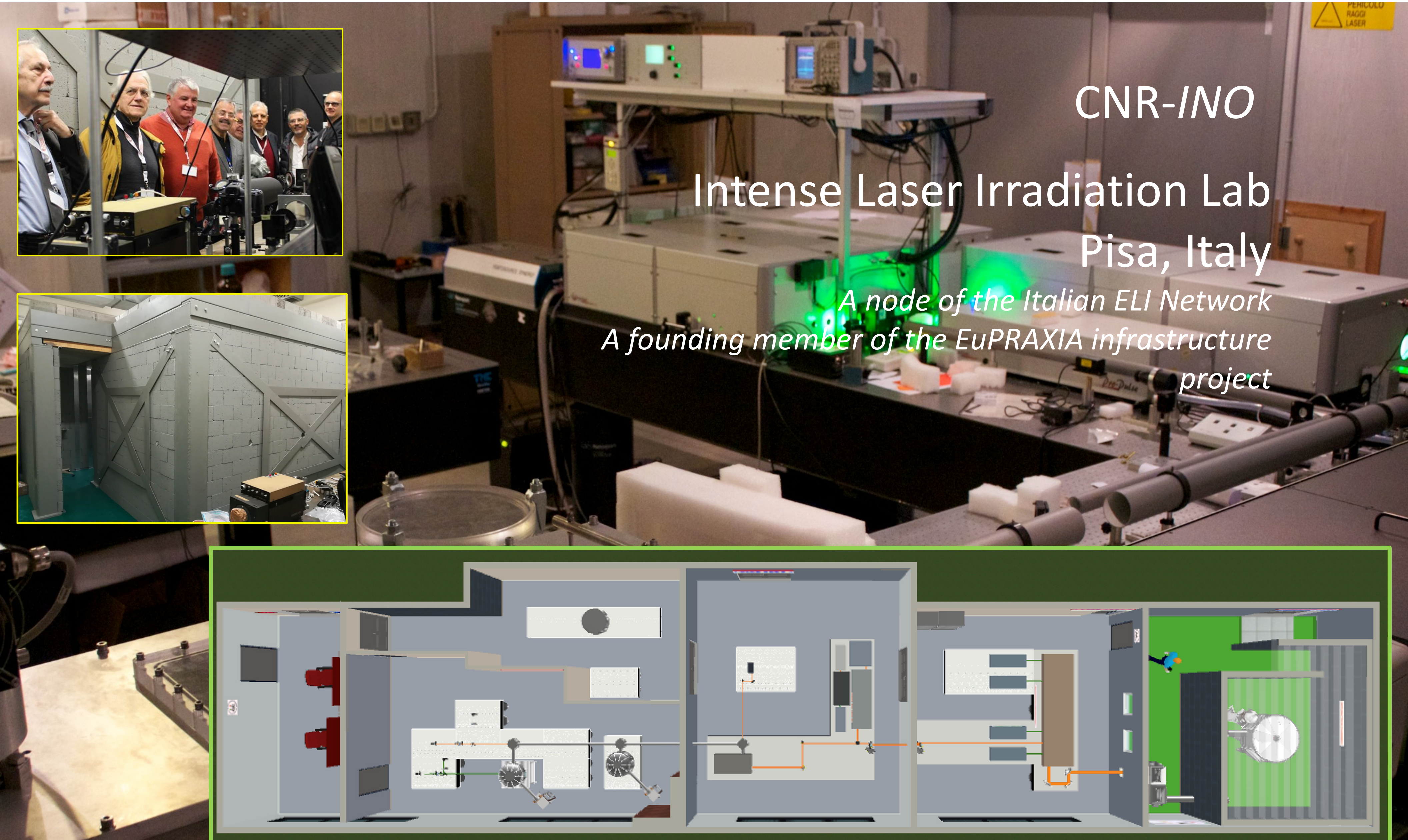
Leonida Antonio GIZZI
Istituto Nazionale di Ottica, CNR, Pisa, Italy
and
INFN, Sezione di Pisa, Italy

10th International Particle Accelerator Conference IPAC19
MELBOURNE CONVENTION & EXHIBITION CENTRE, AUSTRALIA
19 – 24 MAY 2019

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

CNR Campus in Pisa





http://www.ilil.ino.it

Intense Laser Irradiation Laboratory

Istituto Nazionale di Ottica – Consiglio Nazionale delle Ricerche

CNR INO
CONSIGLIO NAZIONALE DELLE RICERCHE
ISTITUTO NAZIONALE DI OTTICA

Contents

- High Intensity Lasers
- Laser drivers for plasma accelerators
- Today's viable solution
- Next steps
- Summary

Laser, “a solution seeking for a problem”*

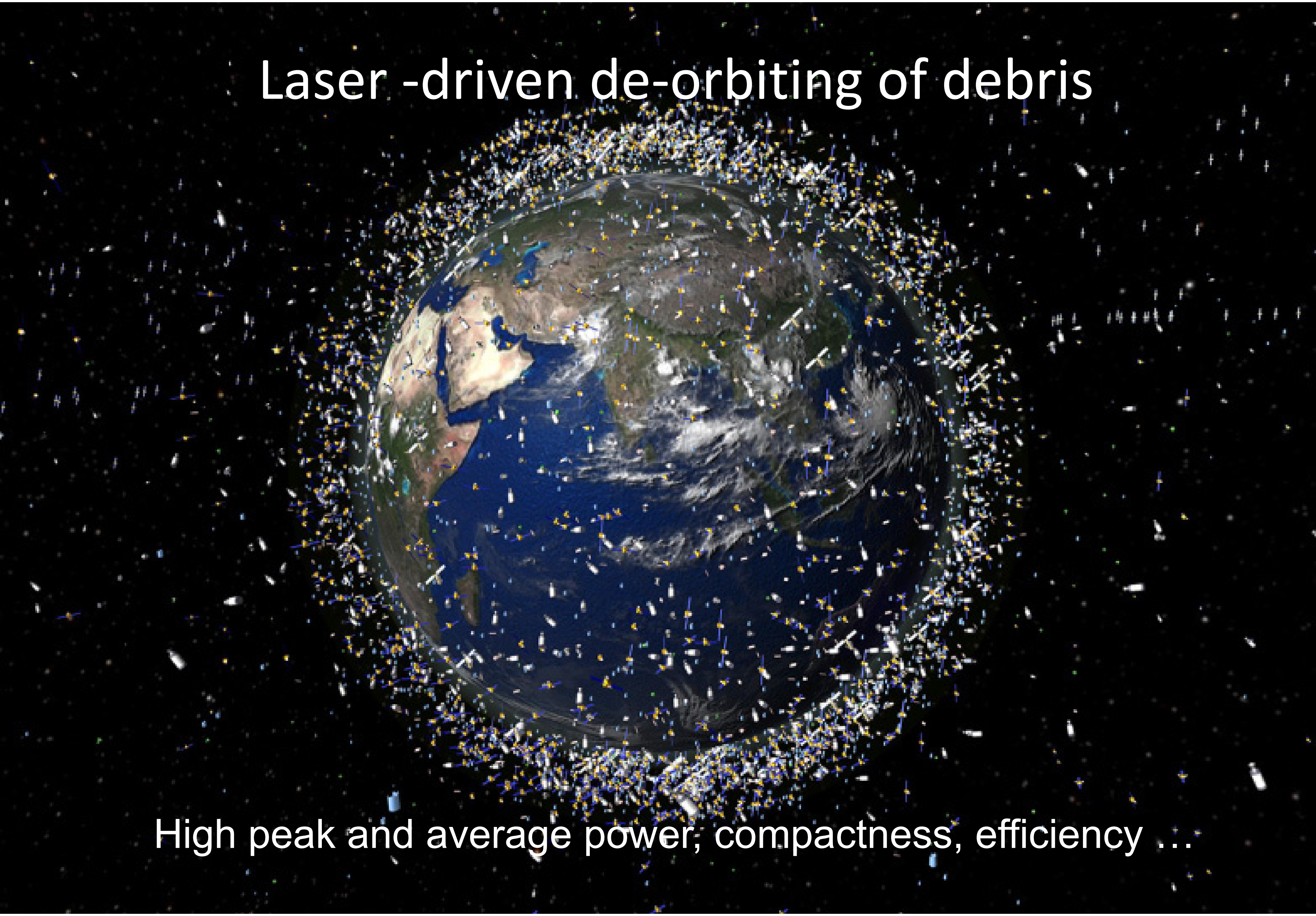
T. Maiman, New York Times, May 6, 1964

LASER DRIVER FOR FAST MINI-PROBES TO EXTRASOLAR PLANETS

Needs: High average power, high beam quality, coherent “combination” ..

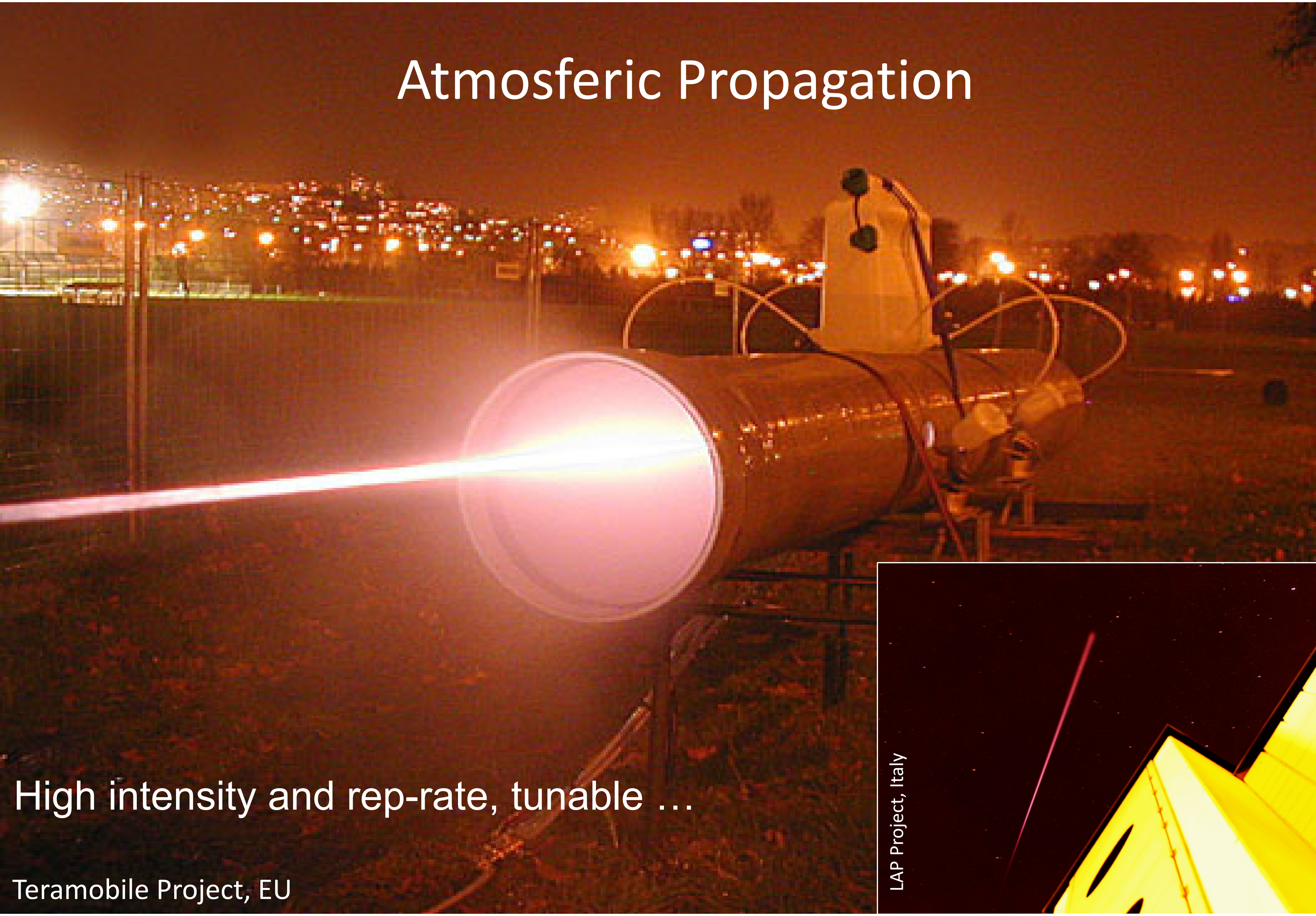
https://breakthroughinitiatives.org/about

Laser -driven de-orbiting of debris



High peak and average power, compactness, efficiency …

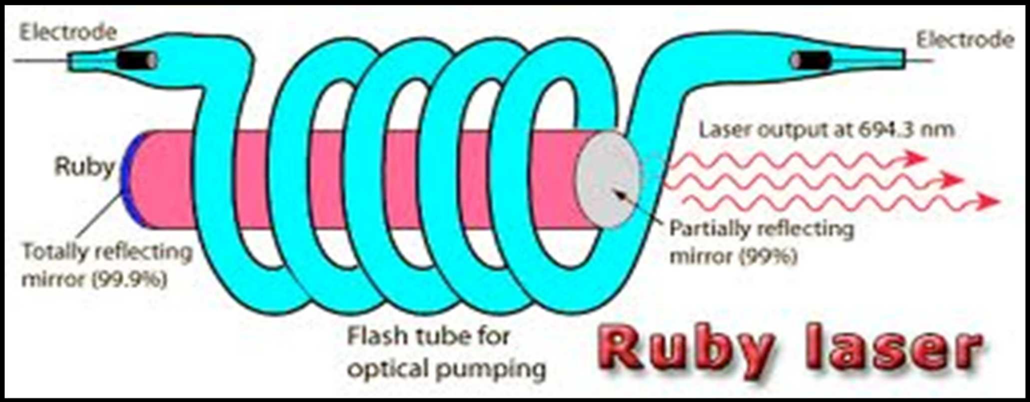
Atmosferic Propagation



Lightnening control

AIP Advances 2, 012151 (2012); doi: 10.1063/1.3690961

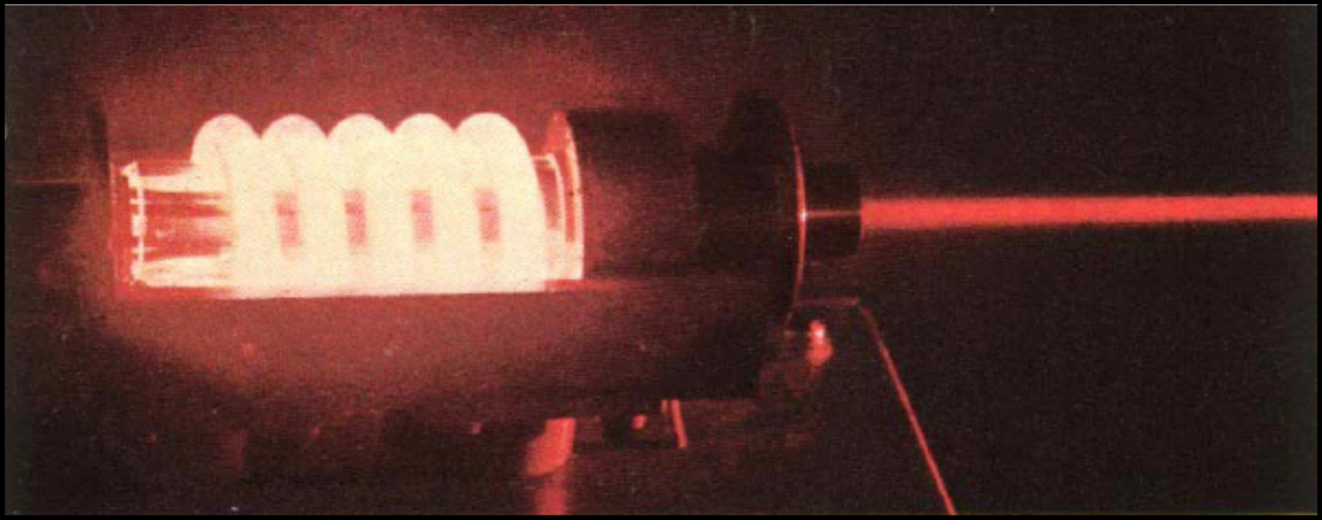
The origin of lasers in the lab



High power laser pulses
≈ nanosecond pulse duration Q-switch
Power: ≈ GW

Theodore Maiman, 1960

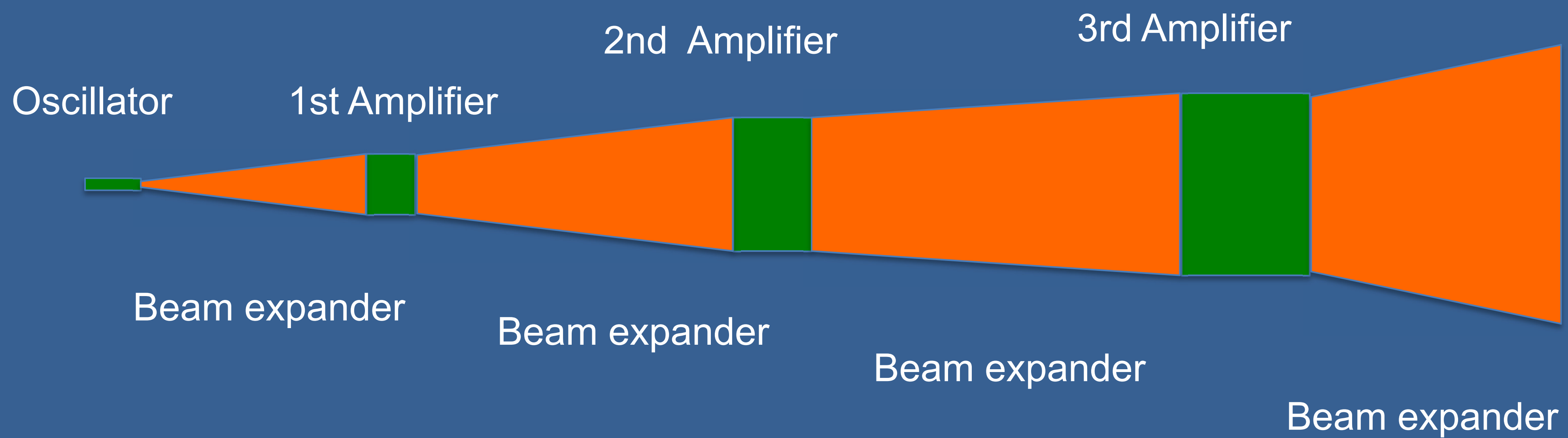
C.H. Townes, N.G.Basov and A.M.Prokhorov, Phisics Nobel prize, 1964



Orazio Svelto, La storia del Laser, in Il Laser, Cinquant'anni di idee luminose, CNR, ISBN 987-88-8080-120-7

DAMAGE contraints FOR AMPLIFICATION

To avoid damage of optics and gain materials, laser intensity must be distributed over progressively larger diameters



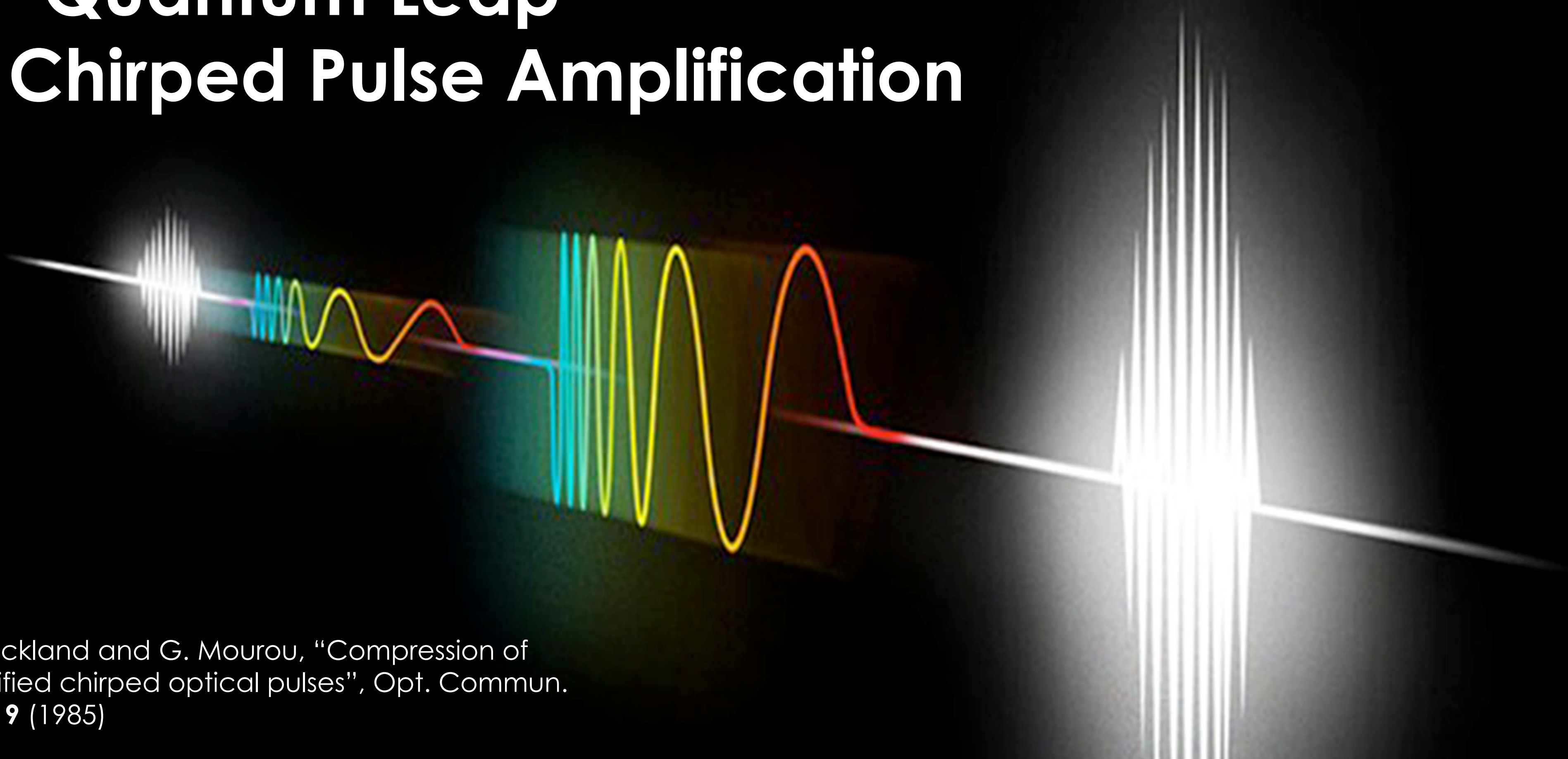
Consequence? "Gigantism" of high power, high energy lasers …

Conventional high power (high energy) lasers have a huge size

Lawerence Livermore National Lab. California, USA

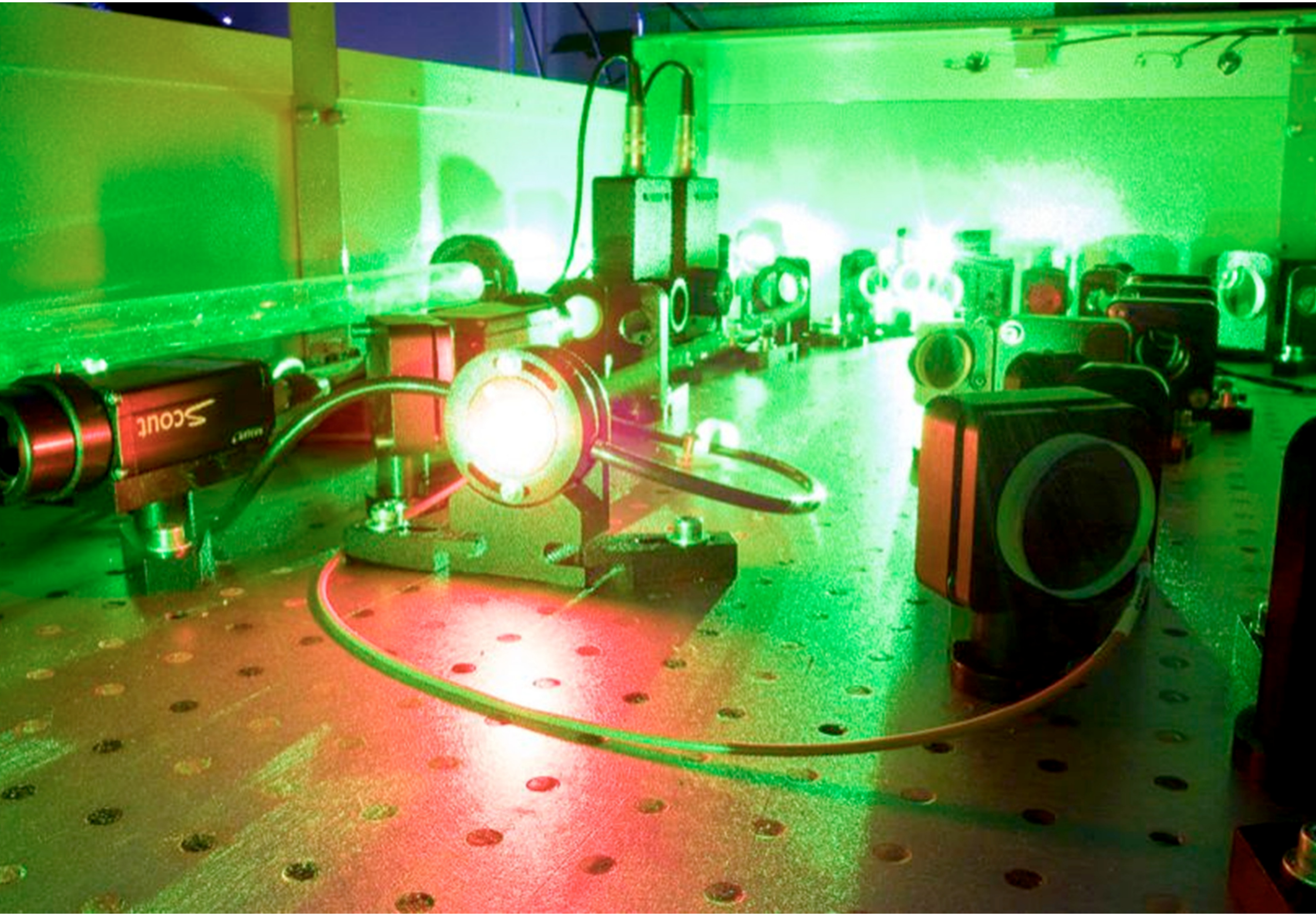
Alternative approach to some laser-matter interaction applications? High power at low energy per pulse.

“Quantum Leap”
Chirped Pulse Amplification

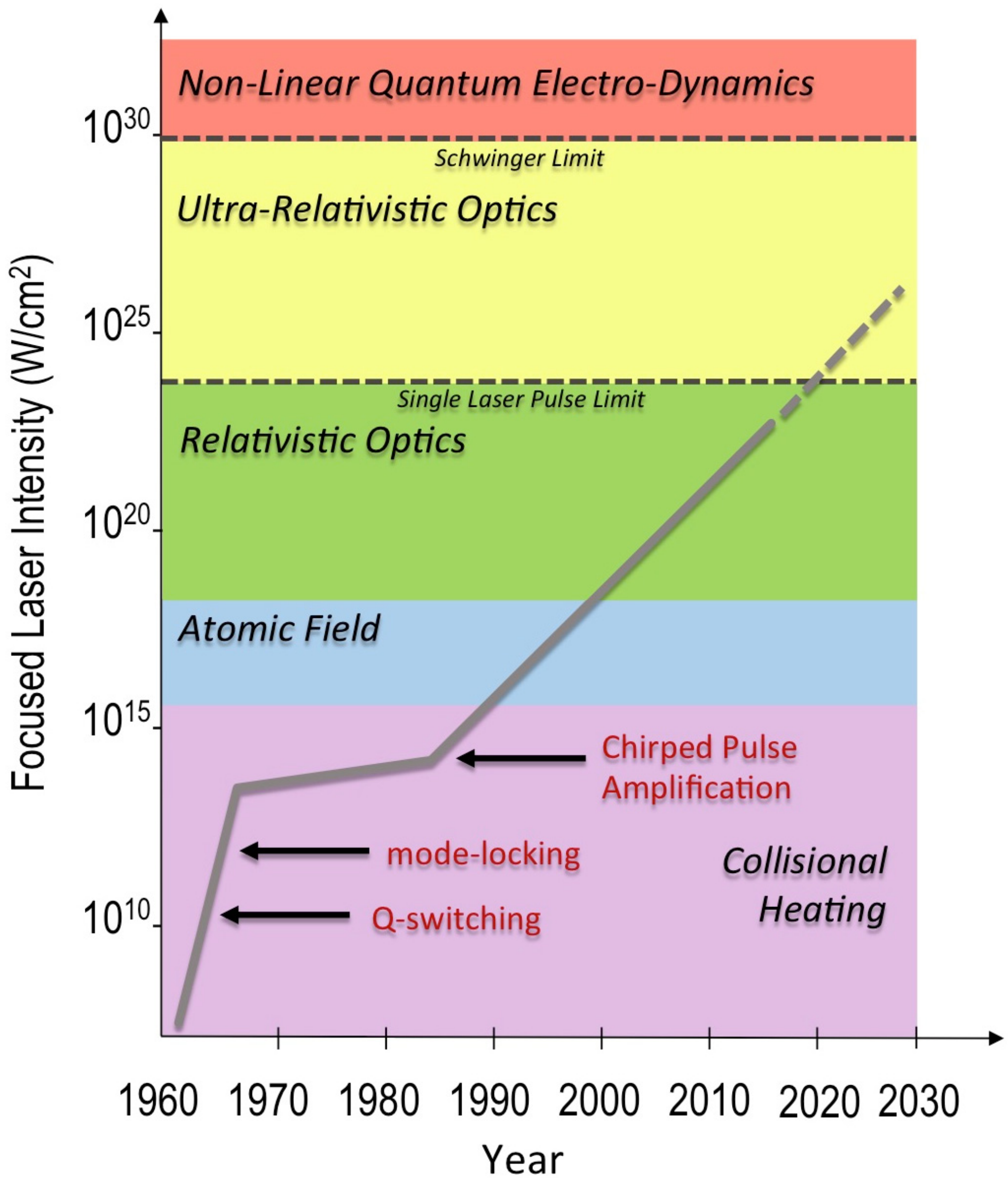


D. Strickland and G. Mourou, “Compression of amplified chirped optical pulses”, Opt. Commun. 56, **219** (1985)

“Quantum Leap”
Chirped Pulse Amplification



Evolution of high intensity lasers



ICUIL World Map of Ultrahigh Intensity Laser Capabilities

The original idea of Laser driven acceleration

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

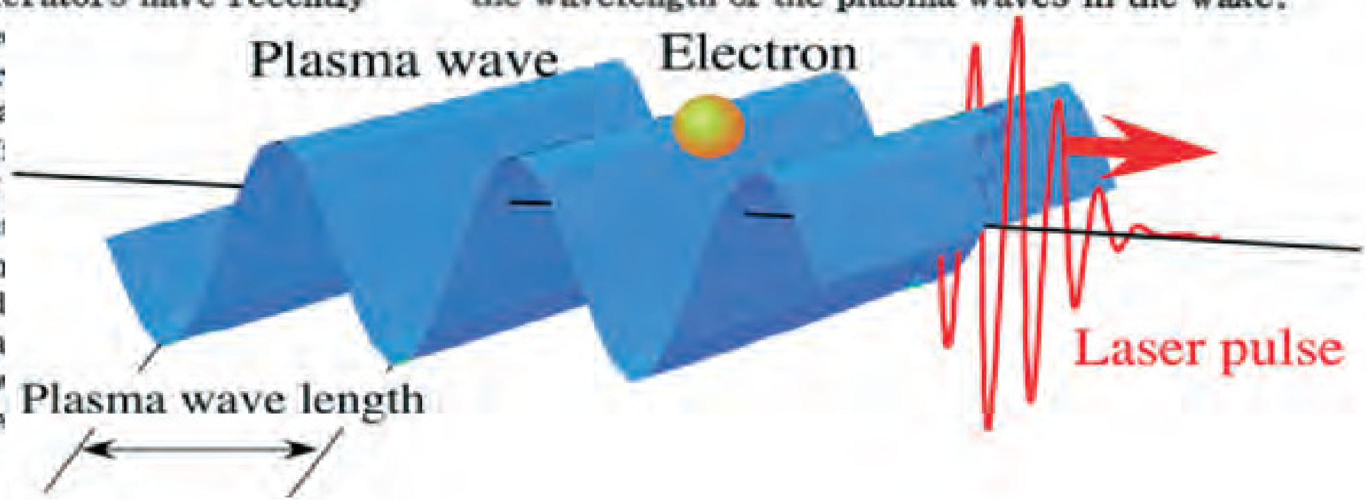
Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

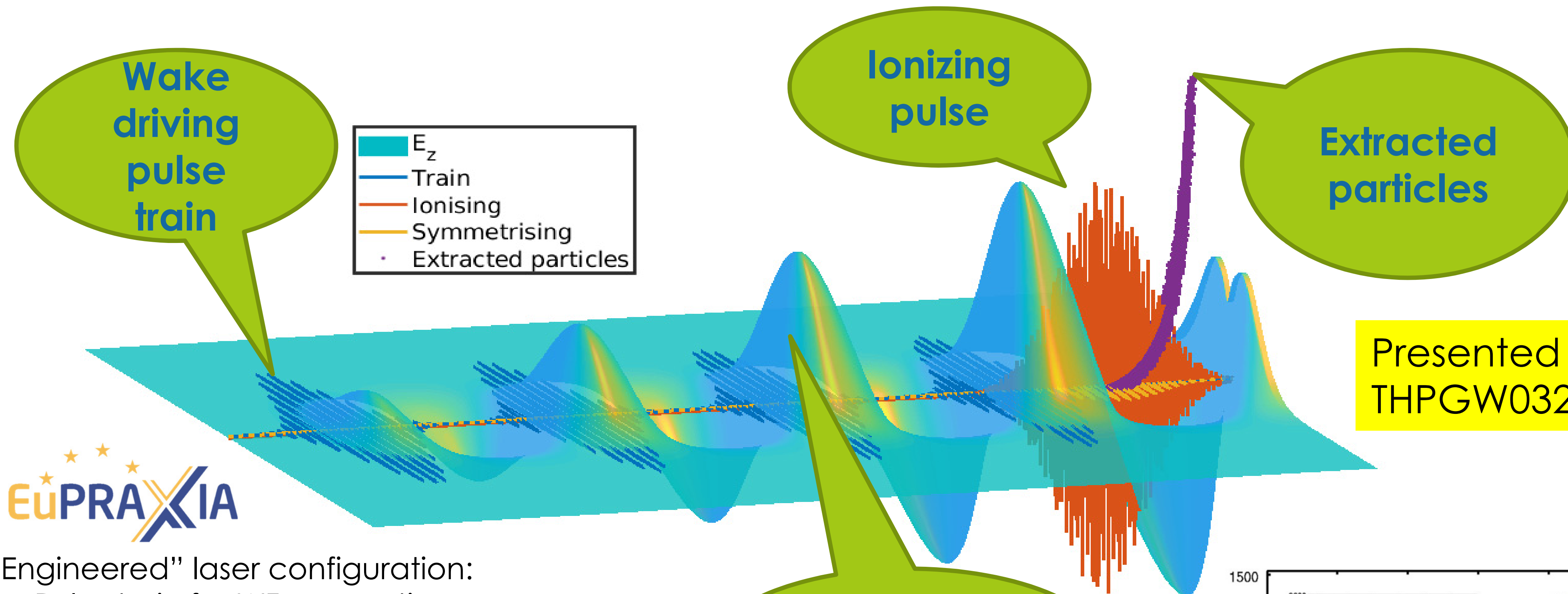
Collective plasma accelerators have recently received considerable the mental investigation. Ear lan[2] considered cosmic-r tion by moving magnetic f netic waves.[2] In terms of tory technology for collec present-day electron bean of ~10^7 V/cm and power d On the other hand, the gla capable of delivering a po cm^2, and, as we shall see

the wavelength of the plasma waves in the wake:



Advanced LWFA schemes

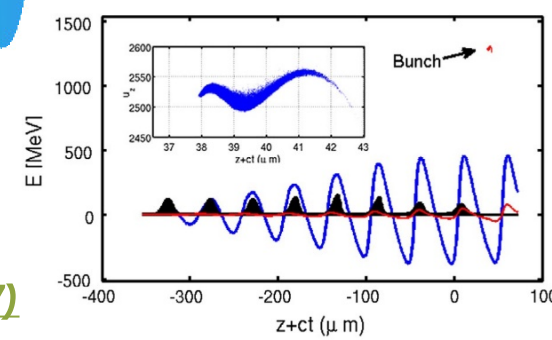
Example of advanced scheme for high quality laser-plasma acceleration: REMPI(1)



Presented at THPGW032

"Engineered" laser configuration:

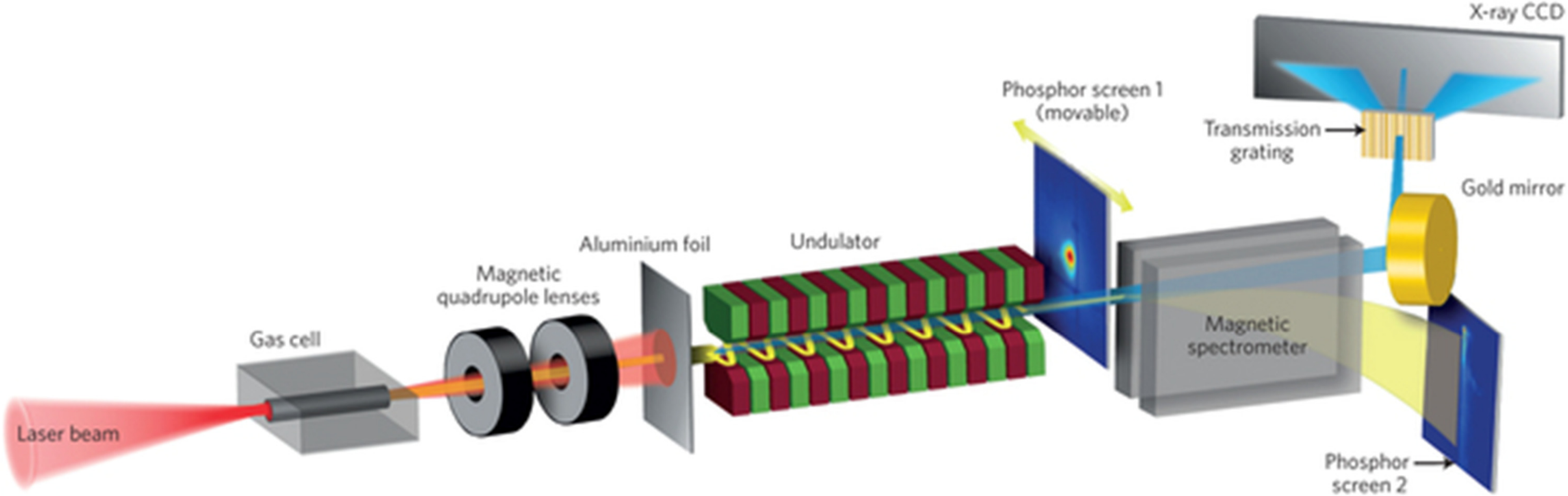
- Pulse train for WF generation
- Frequency-doubled ionization injection pulse
- High stability



P. Tomassini et al., *Physics of Plasmas 24, 103120 (2017)*

Plasma based X-Ray Free Electron Laser?

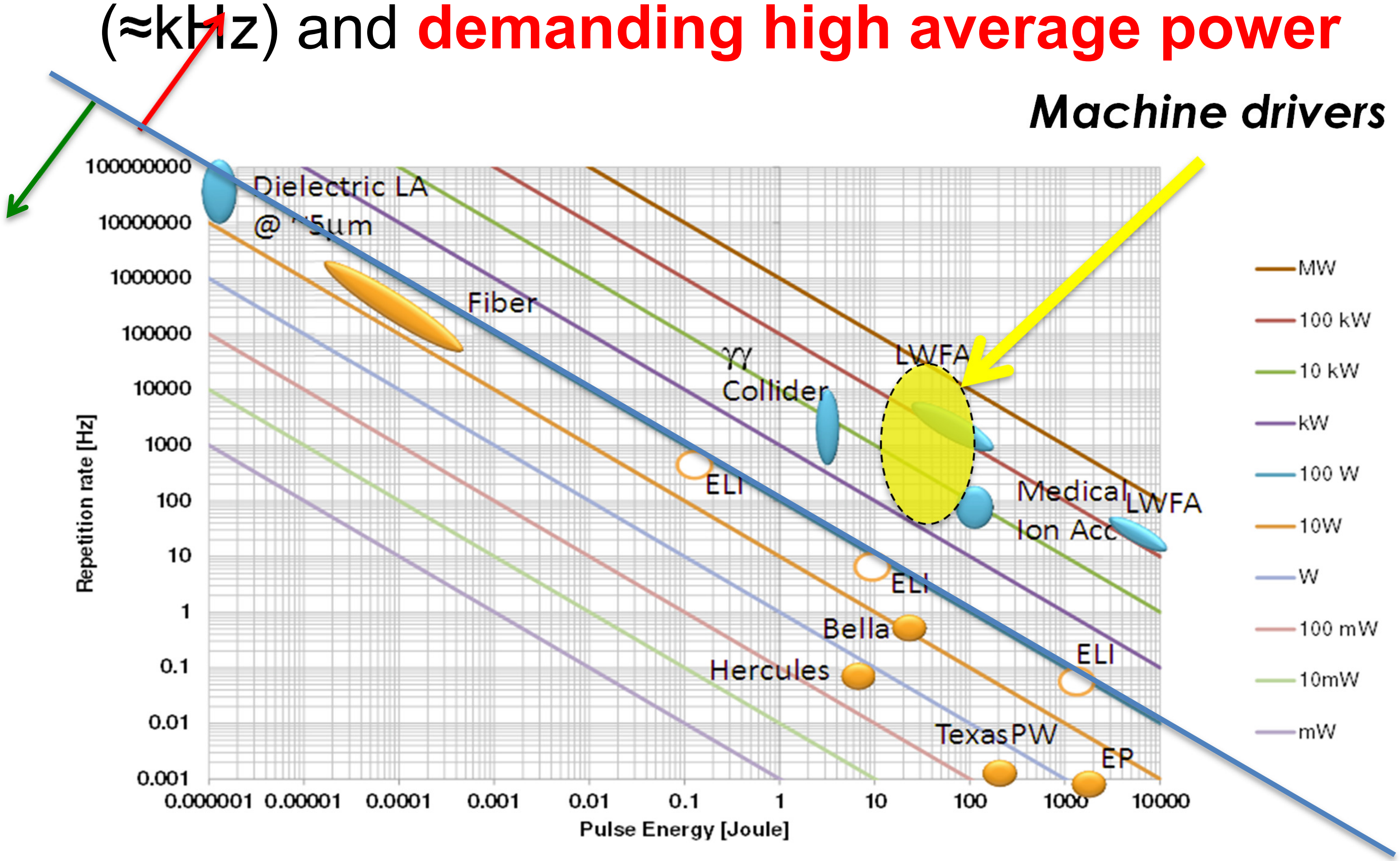
High quality GeV electron beam needed: **a test bed for plasma acceleration**
Great effort world-wide towards this challenging objective (see ME Cuprie's slides)



Aiming at user operation sets mandatory operation boundaries in terms of rep-rate, reliability, up-time, flux excetera. **Driving laser is a key enabling component**.

NEEDED HIGH POWER LASERS

Needs emerging for a PW-class system, with high repetition rate (≈kHz) and **demanding high average power**



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

KEY REQUIRED LASER FEATURES

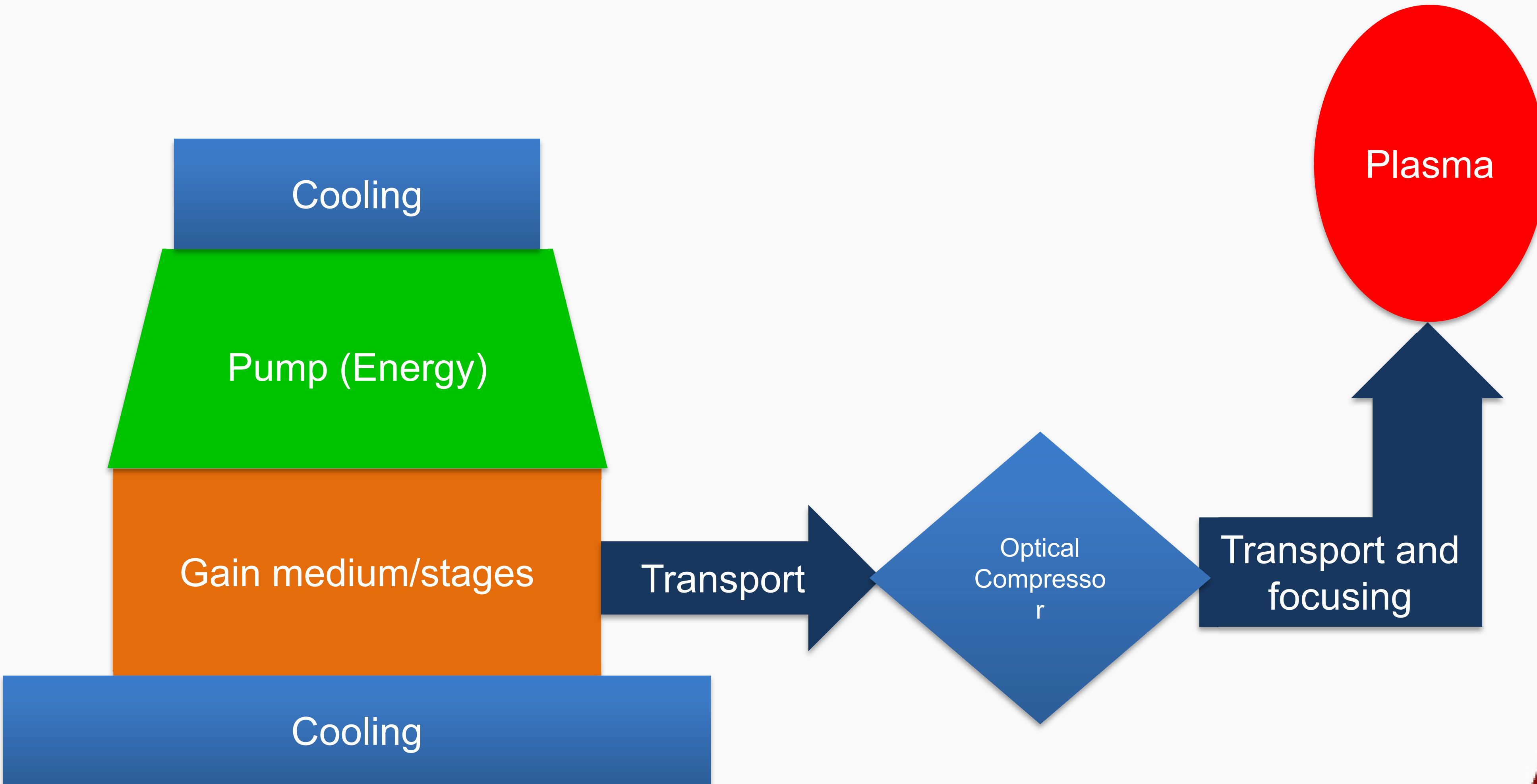
- Short pulse **PW-kW** laser technology (CPA, diode pumping);
- **High repetition rate** to allow user operation while enabling active stabilization via feedback loops;
- **Average power** ranging from 1kW to 10 kW;
- Controlled **beam transport**, focusing, diagnostics.
- Main **issues**: pump lasers, amplifiers heat management and compressor gratings at high rep-rate.

INFN

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

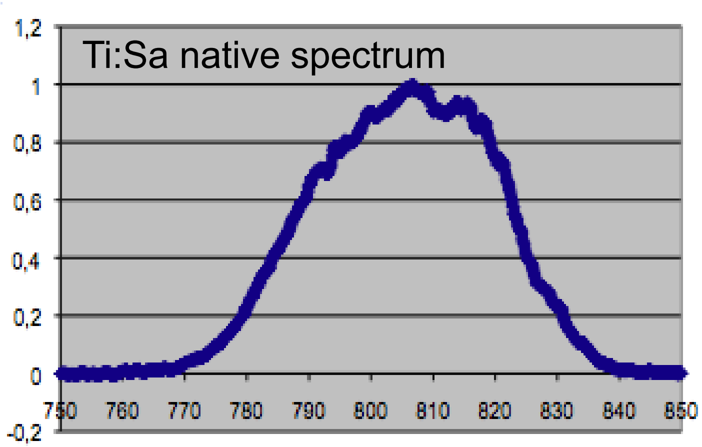
INO-CNR Istituto Nazionale di Ottica

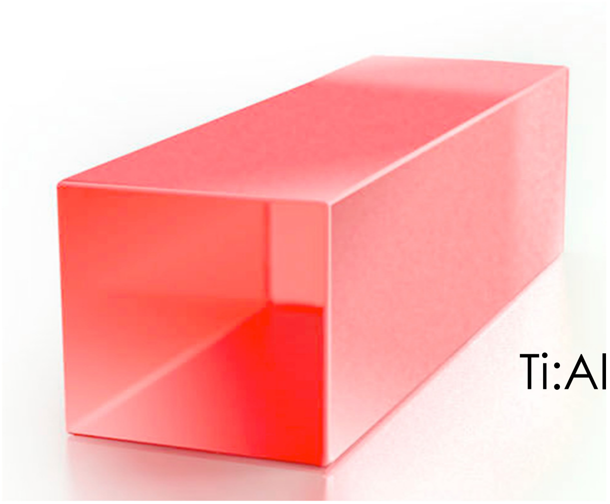
RELEVANT BLOCKS OF A LASER DRIVER



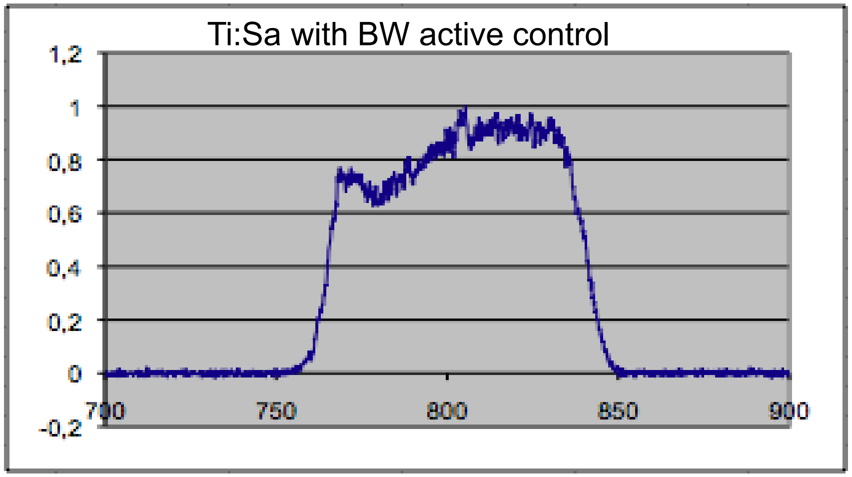
GAIN MATERIAL: TITANIUM SAPPHIRE

Currently, most PW-scale CPA lasers are based on Ti:Sapphire pumped by frequency doubled Nd:YAG lasers





$Ti:Al_2O_3$



Large gain bandwidth (680 nm – 1080 nm)

- High quantum efficiency
- Long lifetime: 3 **μ**s
- Thermal conductivity: 35 $WK^{-1}m^{-1}$
- Pumped in the green

Active bandwitdth control crucial to overcome gain narrowing and enable sub-50 fs pulses

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

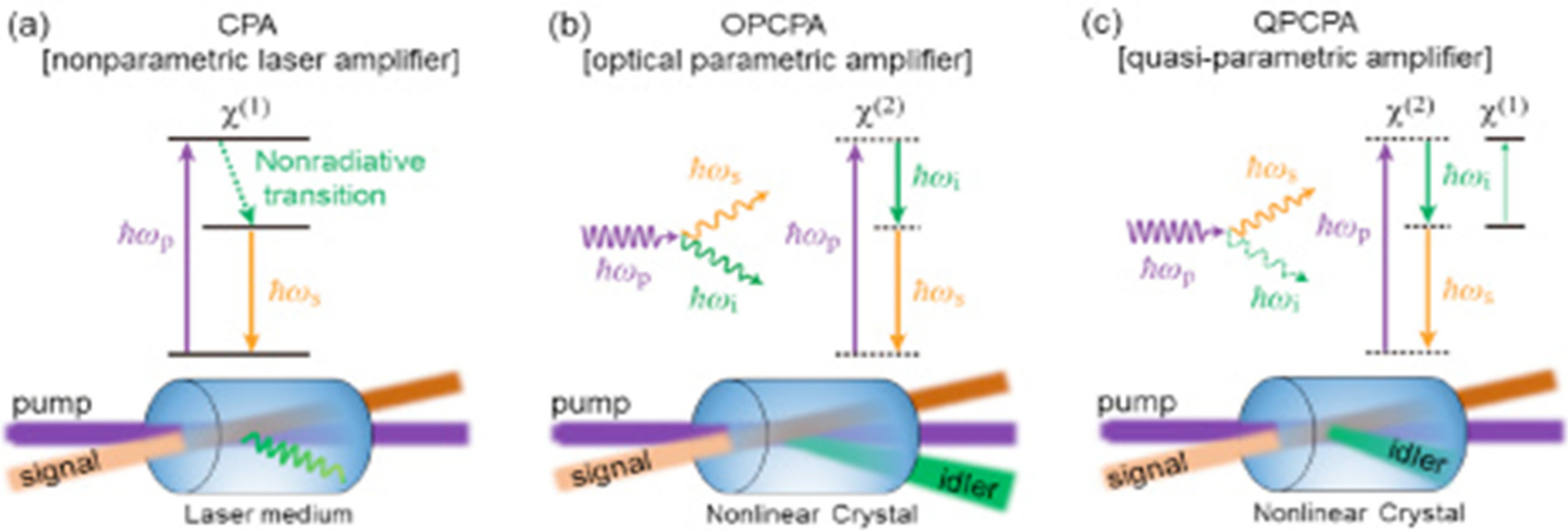
Crystals	Nd: YAG	Yb: YAG	Ti: Sa	Yb: CaF_2
Fluorescence lifetime (ms)	0.23	0.96	0.0032	2.4
Stimulated-em. $\sigma(\times 10^{-20}/cm)$	20 to 30	2.1	30	0.2
Fluorescence wavelengths (nm)	1064	1030	660-1100	1033
Absorption wavelengths (nm)	808	940	514 to 532	980
Fluorescence BW (FWHM) (nm)	0.67	10	440	70
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

INFN

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

ALTERNATIVE APPROACH

Optical Parametric Chirped Pulse Amplification



Mainly for ultra-broad-band front-end preamplifiers

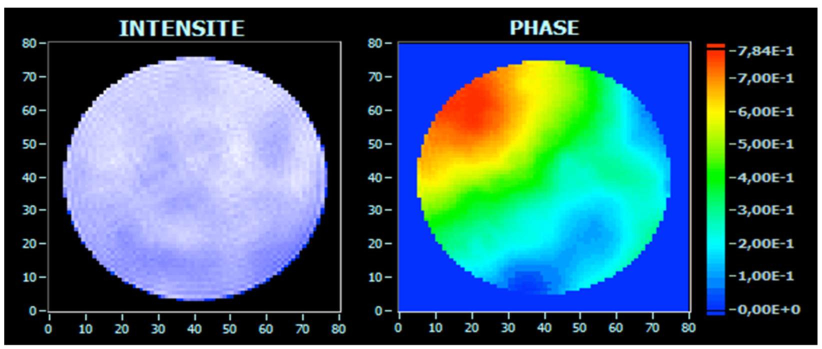
FOCAL SPOT BEAM QUALITY

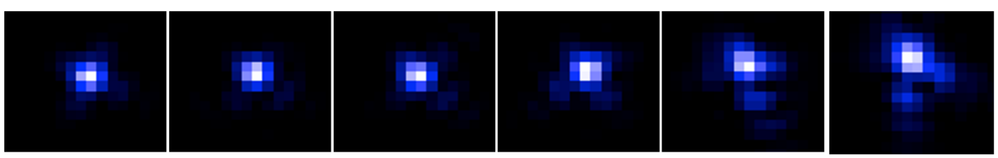
As larger gain media and optics are used, optical aberrations become important and limit the focusability of laser pulses

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

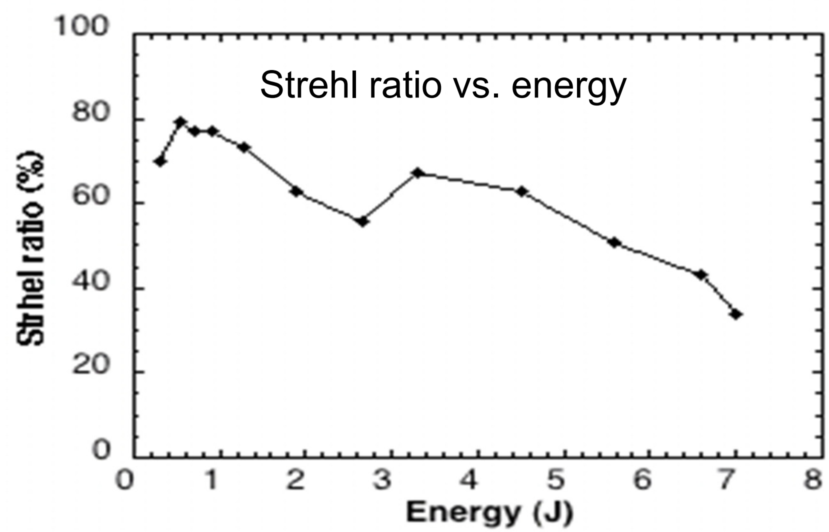
STREHL RATIO

PHASE FRONT DISTORTIONS





Amplification



Borrowing Astronomy Adaptive Technology

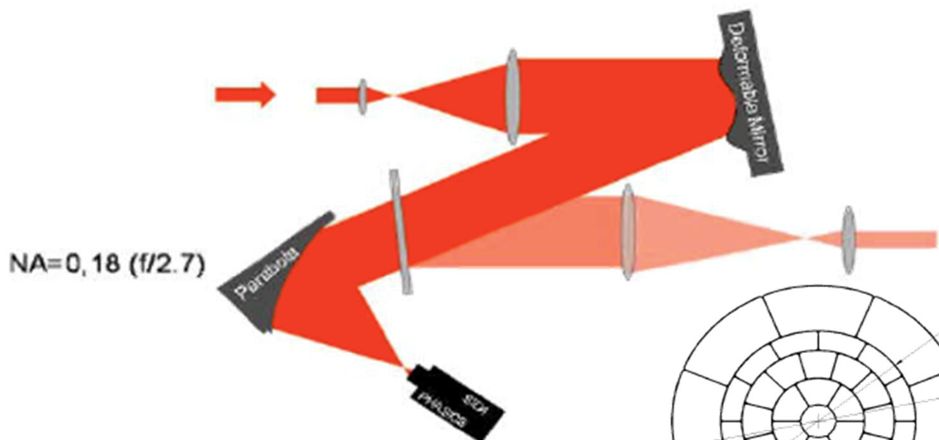
ESO's Very Large Telescope (Paranal, Chile)

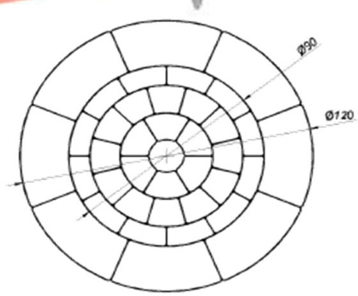
ADAPTIVE OPTICS for high power lasers

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

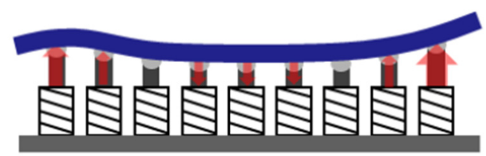
Sensors are used to measure intensity and phase map of the beam;

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

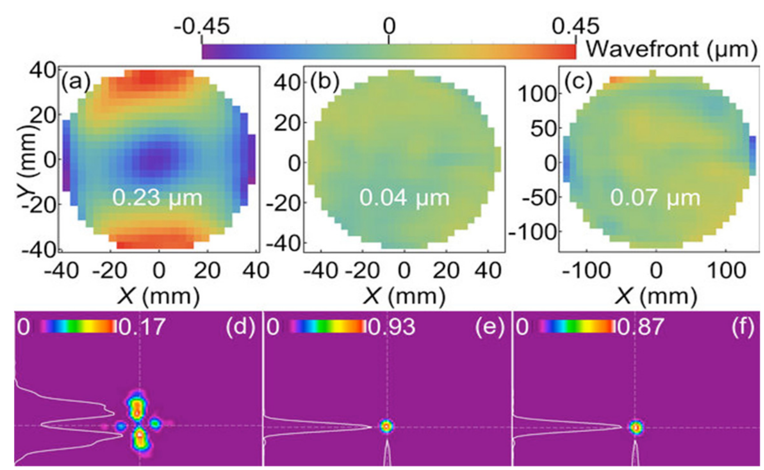




S.-W. Bahk et al., Optics Letters **29**, 2837 (2004)



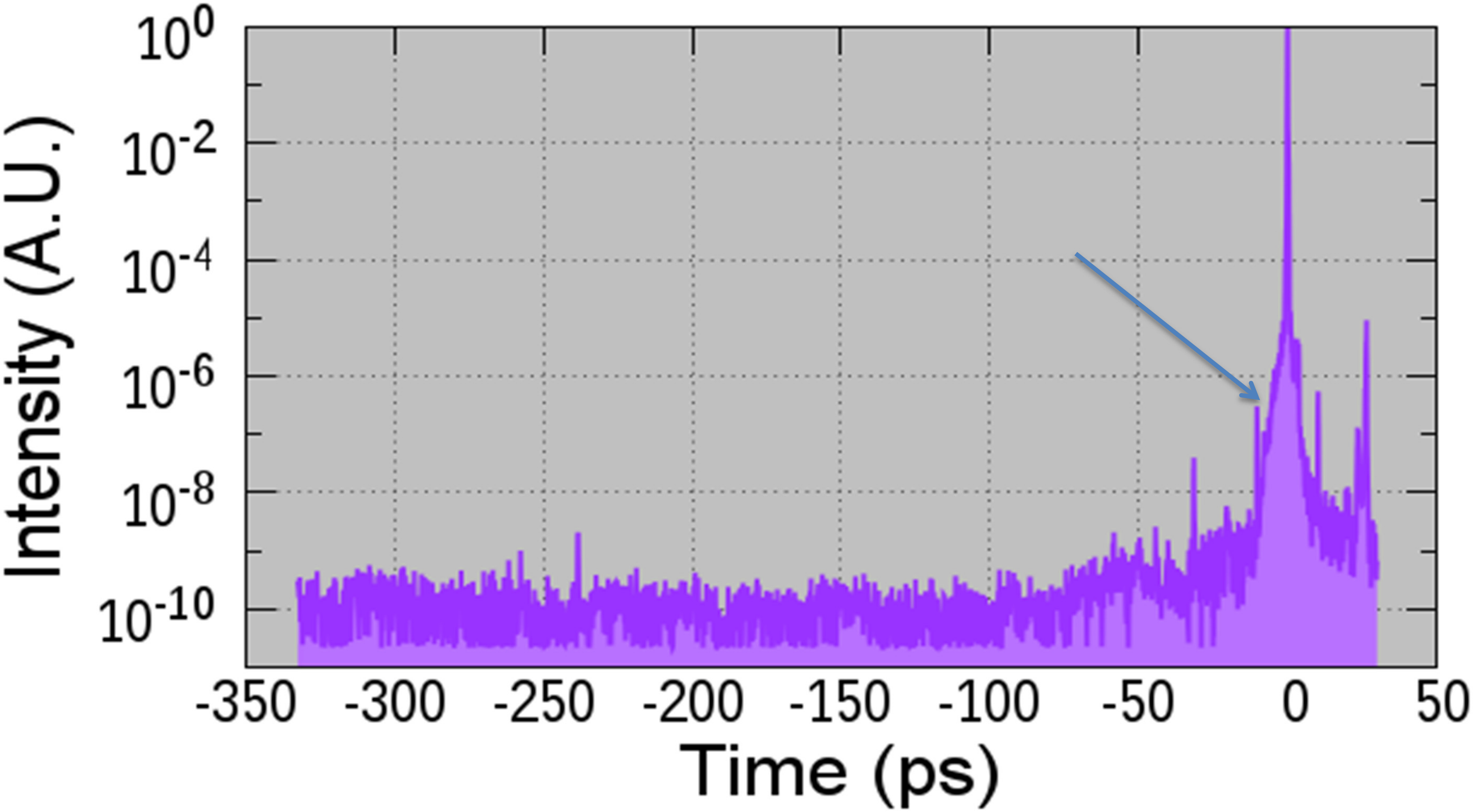
Mechanical actuator modify mirror shape by applying a force on the back of the mirror



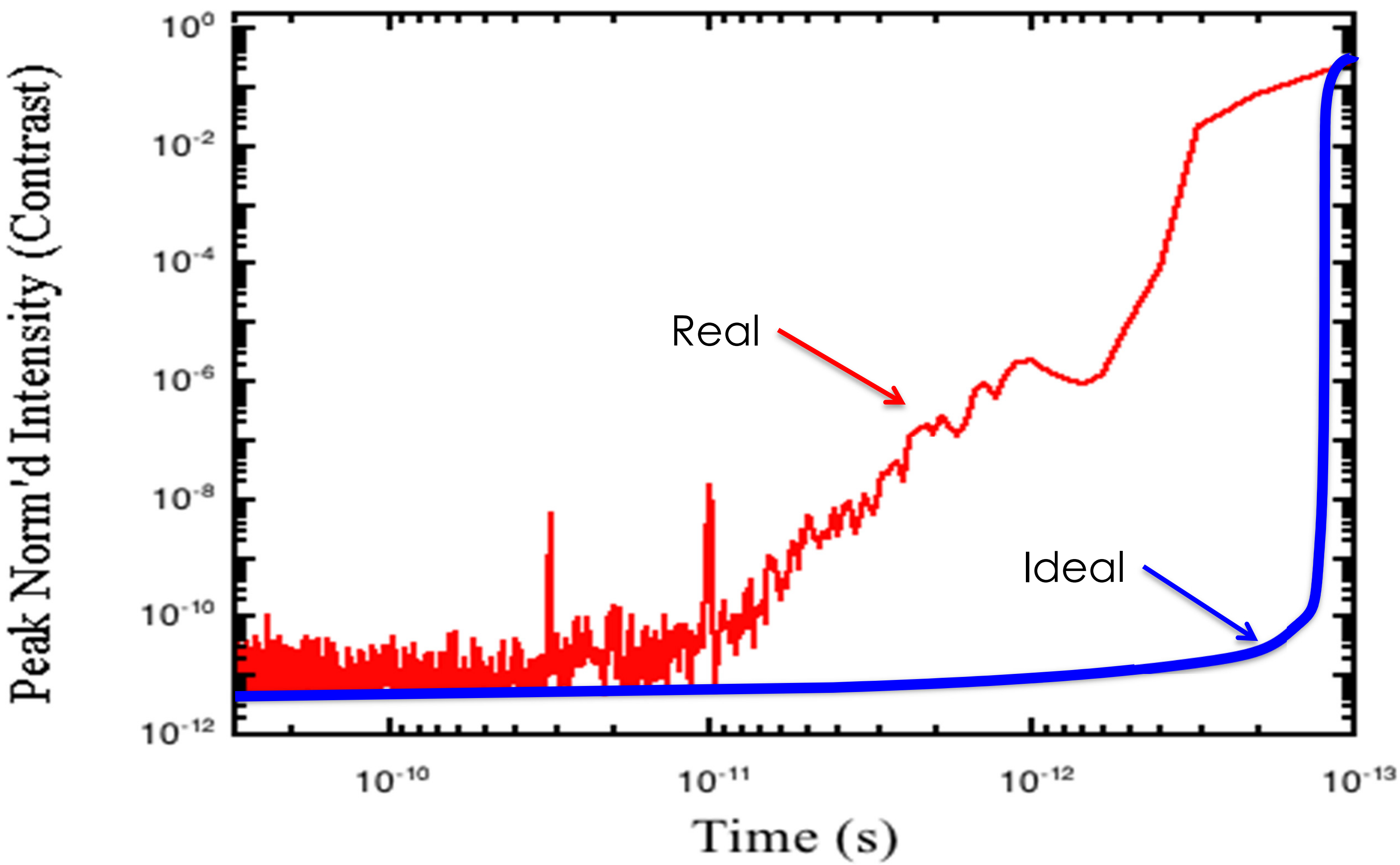
A. PIROZHKOV et al., Optics Express 25, 17 (2017)

Key enabling component to reach high intensity

TEMPORAL FEATURES: CONTRAST



LASER CONTRAST: SUB-PS TIME SCALE

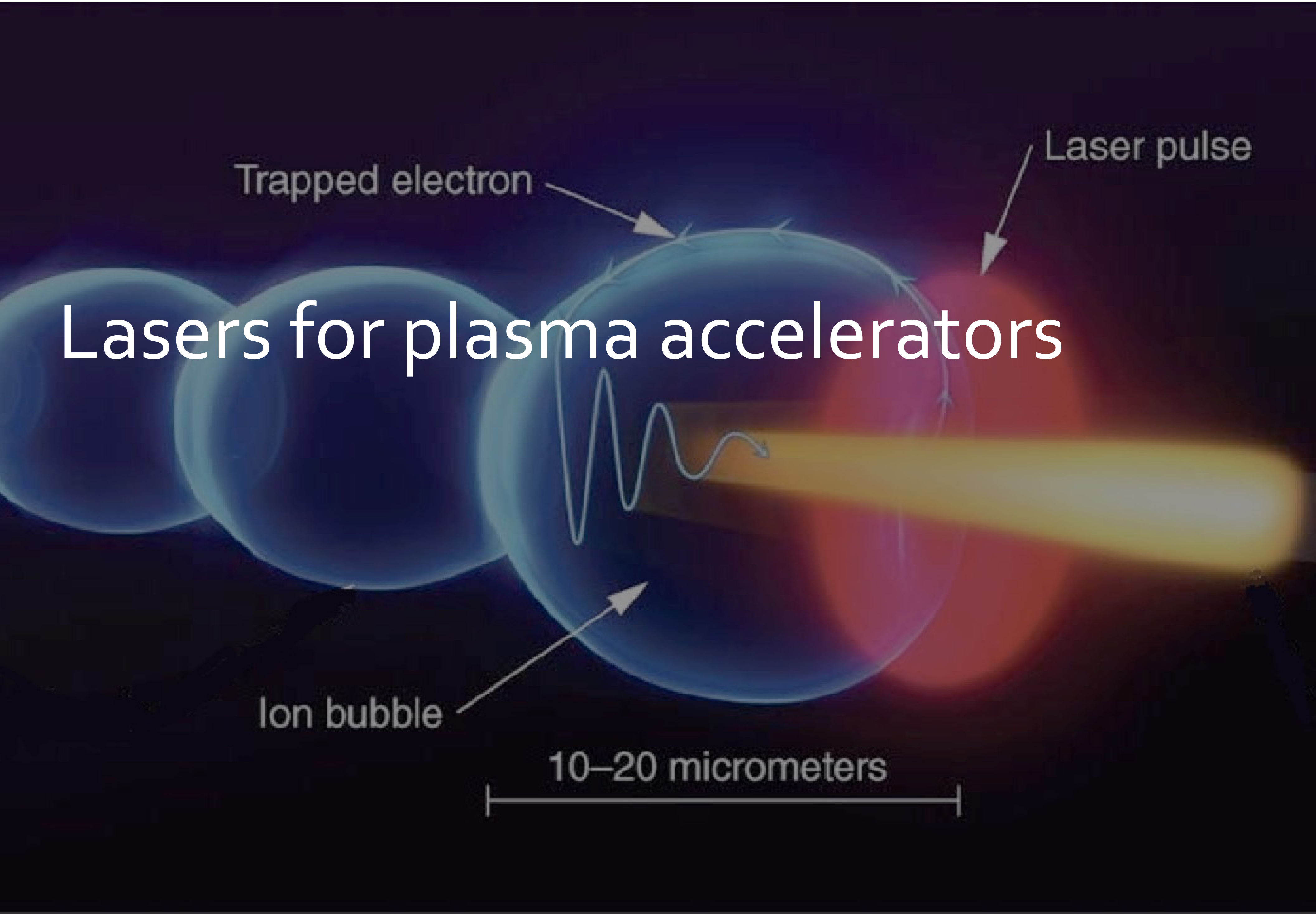


Gizzi, L.A et al., Role of laser contrast and foil thickness in target normal sheath acceleration
Nuclear Instruments and Methods in Physics Research A829, 144–148 (2016)

INFN

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

Lasers for plasma accelerators



Roadmap of Advanced and Novel Accelerators

International Committee for Future Accelerators

Panel on Advanced and Novel Accelerators

2017 - 2022

e- sources: optimization

e+ sources: Concept devt

Driver development

Accelerating structures

Beam transport and coupling

5 Ys — Injector, Accelerator stages with controlled parameters

2022 - 2027

e- acceleration : Optimization of all parameters

e+ acceleration: demonstration

10 Ys — X10 Improved beam quality at higher energy

2027 - 2032

15 Ys — Reliable staged accelaration, 10 GeV module

2032-2037

20 Ys — Advanced Linear Collider CDR and TDR

Address specific challenges :

- Staging →
- Reliability →
- Polarization →
- Efficiency →
- Beam Delivery System →

EuPRAXIA

EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

The EuPRAXIA Project: COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

http://eupraxia-project.eu

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

Goals and challenges

Horizon 2020

- EuPRAXIA is a **conceptual design study** for a **5 GeV electron plasma accelerator** as a European research infrastructure.
- **FEL requires low (total) energy spread (<1%) and low emittance (<1mm mrad):**
  - **<u>Validate</u> technical components and schemes in plasma accelerator** concepts producing already GeV class beams:
  - **<u>Establish</u> laser driver technology**
  - *Combine efforts with* ***laser industry and laser institutes*** *to improve rep. rate & efficiency (incorporate all viable laser technologies with higher efficiency).*

5GeV L. Driver Specifications

Horizon 2020

Laser Driver 5 GeV (Laser 3)			
Parameter	**Label**	**P0***	**P1****
Wavelength (nm)	$\lambda_{2\ (nm)}$	800	800
Maximum energy on target (J) *	E_2	50	100
Energy tuning resolution (% of targeted value)	dE	7	5
Shortest pulse length (FWHM) (fs)	τ_2	60	50
Repetition rate (Hz)	f_2	20	100
Contrast at 100 ps	C_1(100 ps)	1,00E+11	1,00E+12
Contrast at 50 ps	C_1(50 ps)	1,00E+10	1,00E+11
Contrast at 10 ps	C_1(10 ps)	1,00E+10	1,00E+10
Contrast at 1 ps	C_1(1 ps)	1,00E+06	1,00E+08
Contrast at 100 fs	C_1(100 fs)	1,00E+02	1,00E+03
Number of beams	N_2	1	1
Synchro. to global reference (P-V) (fs)	$\sigma_{\Delta t}$	10	5
Beam intensity distribution (x-y) in focal plane	-	Gaussian	Supergaussian (n=10)
Polarization in focal plane	P_1	linear	linear, circular
Max ellipticity of focal spot (Am/AM)		0.8	0,95
Polarization purity (%)		1	1
Requirement on energy stability (RMS) %	$\sigma_{<E>}$	5	1
Requirement on focal size & Z_L stab. (RMS) %	$\sigma_{<ZL>}$	10	5
Focal spot size stability (on target plane) (RMS) %	$\sigma_{<w0>}/w_0$	20	10
Pointing stability (RMS) (µrad)	$\sigma_{<x'>}$, $\sigma_{<y'>}$	5	1

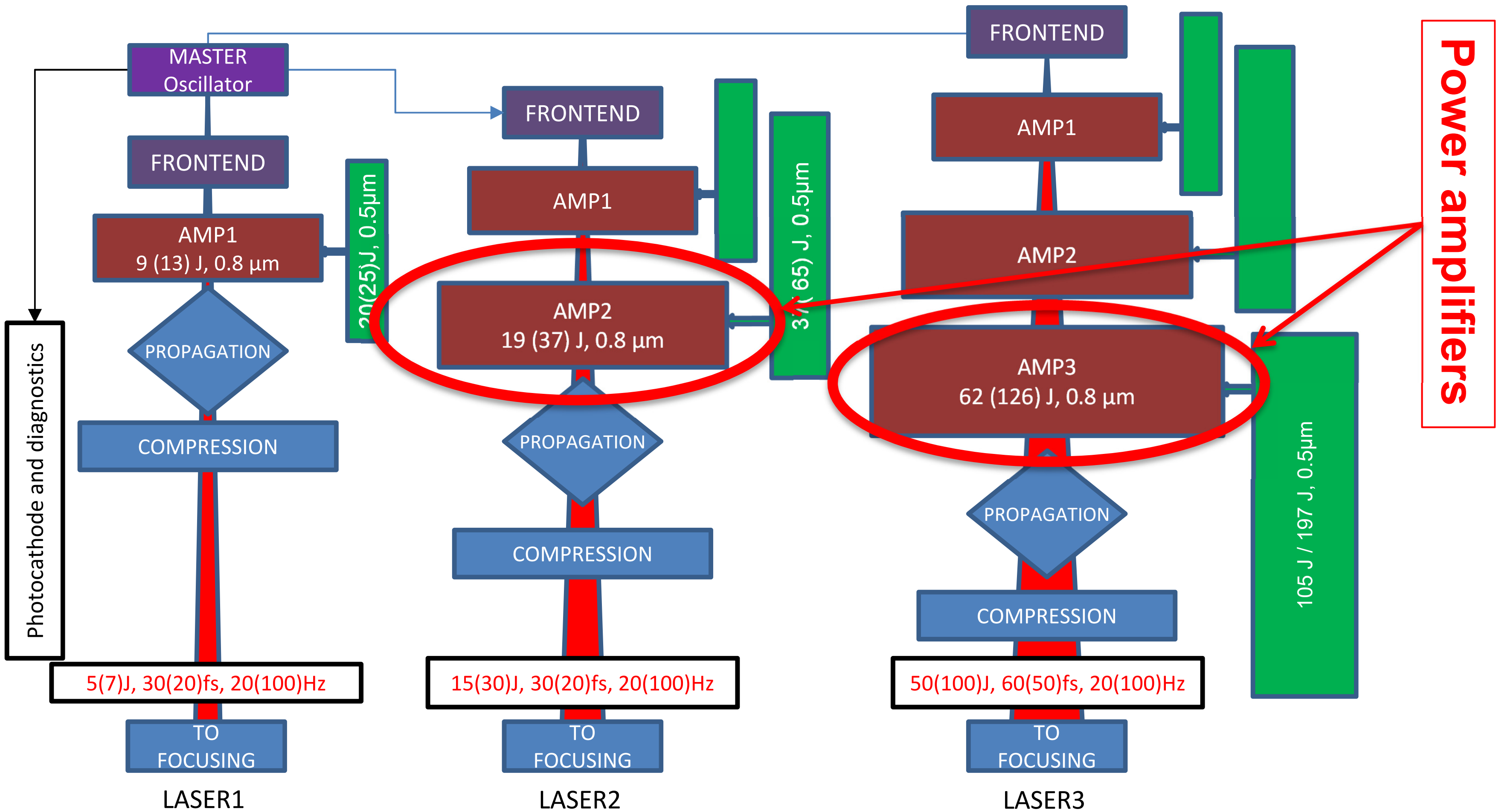
DRIVER: STRATEGY 1/2

Horizon 2020

- **up to ten kW** average laser power with PW peak power and high repetition rate;
- **Ti:Sa technology pumped by diode-pumped solid state (DPSSL)** lasers provides a relatively safe ground, with major **industrial** and research endeavour in place;
- **Recent developments**, with DPSSL prototypes pump lasers offer kW performances at the required Ti:Sa pumping wavelength of 0.5 µm;

Detailed scheme

Horizon 2020



1.3 kW	3.7 kW	12.6 kW	Average Output Power
150 MeV	1 GeV	5 GeV	

Amplifiers design strategy

Horizon 2020

Design guidelines

- Modularity: same amplification stages in the different laser chains;
- Scalability: upgrade “simply” by increasing pump energy and rep rate
- **High extraction efficiency (esp. at P1) to reduce pump energy requirements**
- **Thermal management issues**

Design methodology

- Evaluation of the amplification parameters (energy, spectrum, beam size, stability, parasitic lasing) with **numerical simulations** (MIRO – CEA);
-Validation of modelling with existing systems up to multi-J level;
- Preliminary thermomechanical evaluation by means of FEA simulations (LAS-CAD);

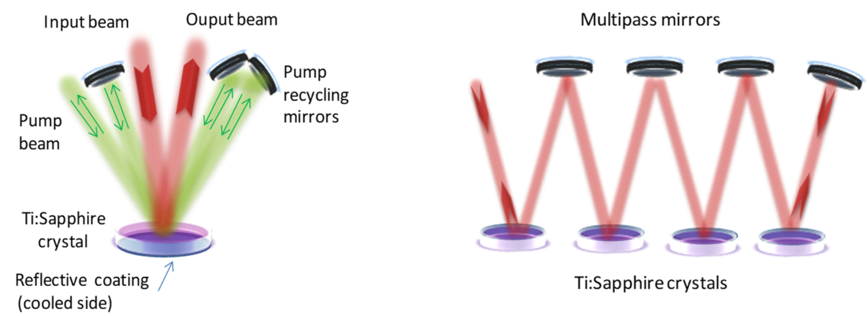
Results

- Main parameters for each stage: pump energy, extracted energy, beam size, spectral shift, parasitic gain …
- Energy stability vs pump and seed energy fluctuations
- Evaluation of thermal aberrations
- Cooling strategies: liquid flow cooling
- ASE/PL mitigation strategies: Extraction during pumping

Thermal management

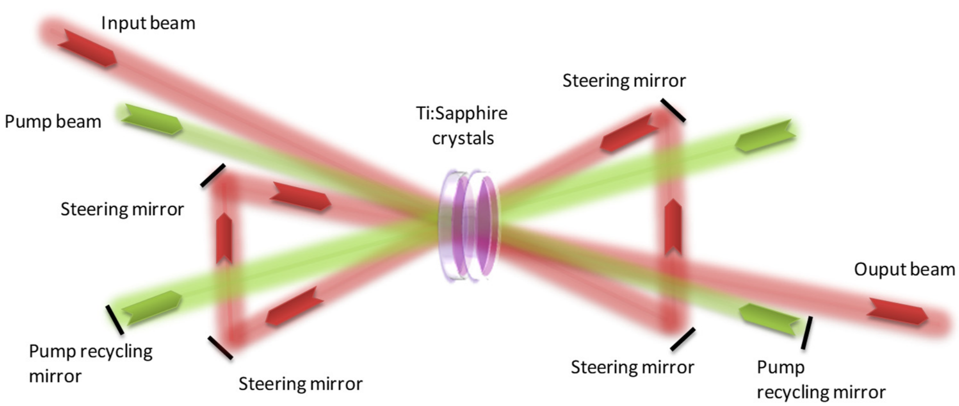
Transmission vs. "active mirror" configuration is currently being evaluated to account for thermal management

"Active mirror" geometry

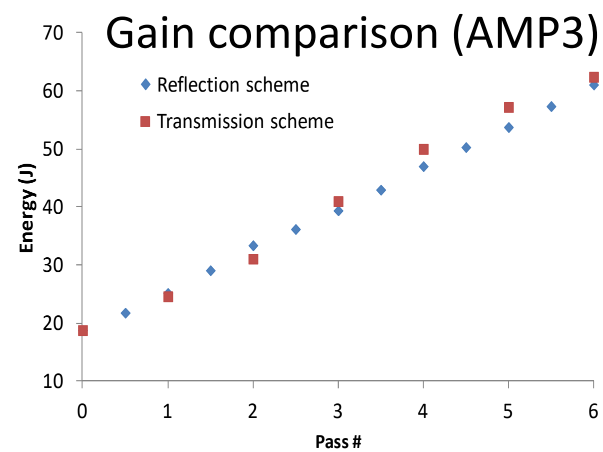


Pro: Well established concept with no propagation through cooling fluid
Con: limited cooling (single face), to be modelled

Transmission geometry

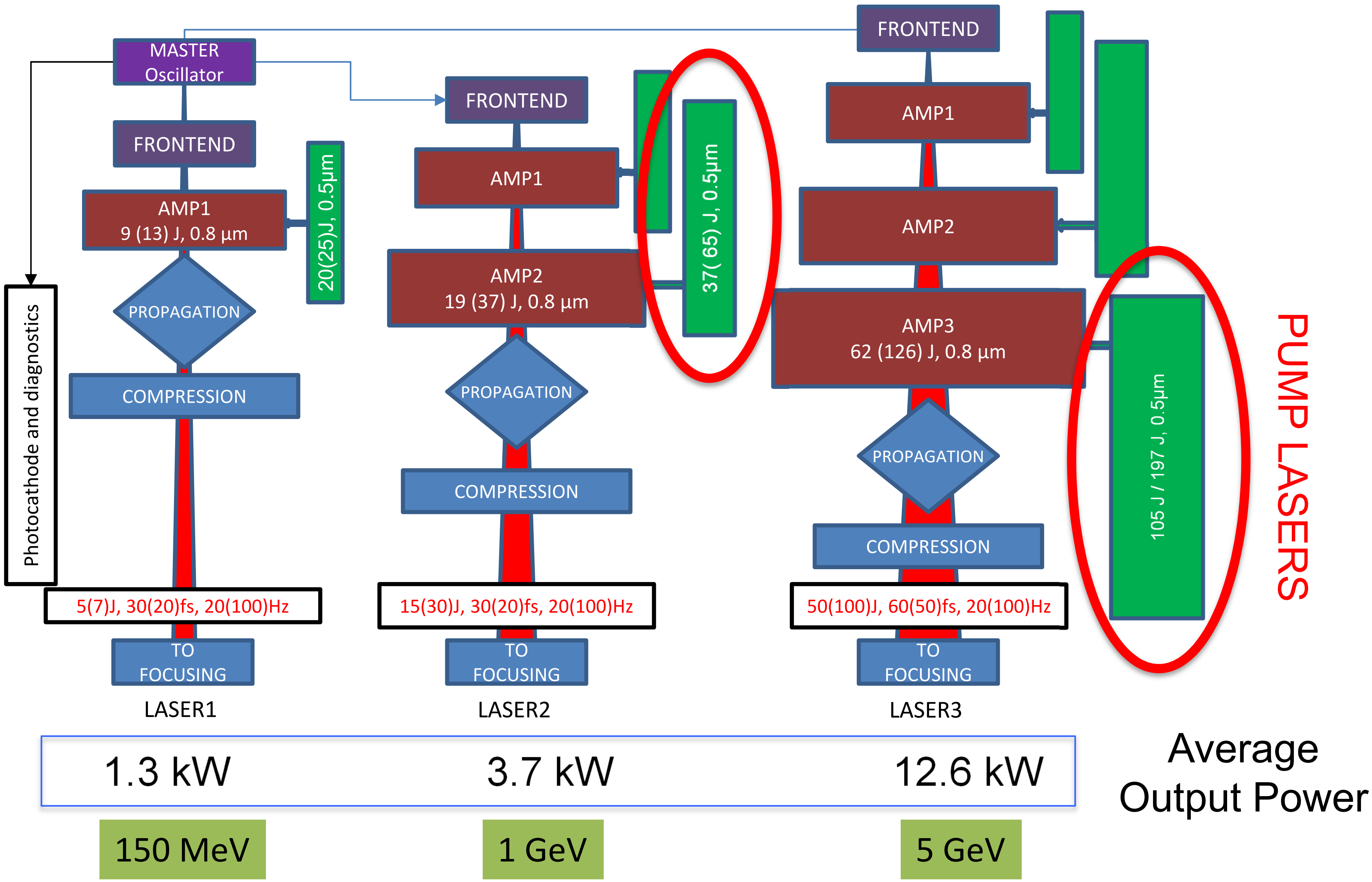


Pro: More efficient (double-side) cooling and reduced complexity;
Con: propagation through flowing cooling liquid



*) 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)

Detailed scheme



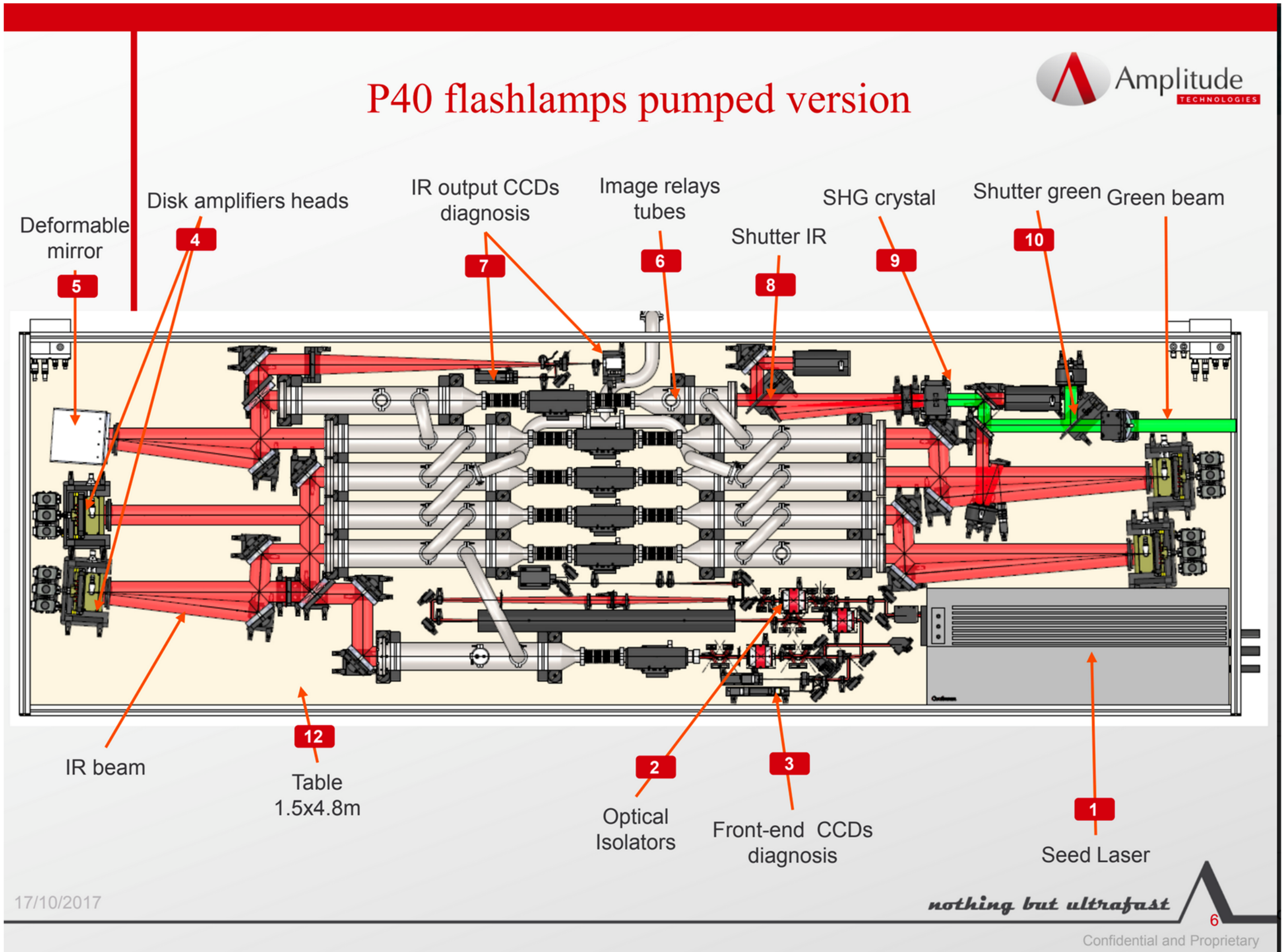
PUMP LASERS: STRATEGY

- **Industrial** developments of high average power pump lasers;
- DPSSL implementation on currently available **industrial** flash-lamp pumped systems for 20-50 Hz performance;
- Link to available effort in prototyping from **industry** and research labs for enhanced performance;
- High power diode developments for future 100 Hz / 1 kHz upgrade.

INDUSTRIAL SUBSYSTEMS: PUMP LASERS

Horizon 2020

Industrial unit (P60): conversion to diode pumping fully designed



Flashlamp pumped Nd:YAG/ **DPSSL possible**

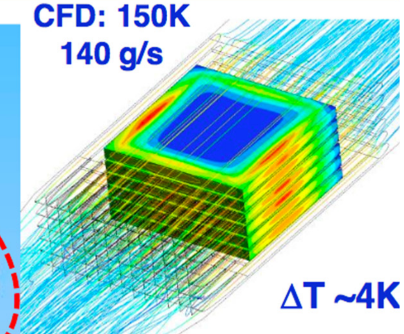
80 J output energy demonstrated @ **10 Hz**, 1064 nm

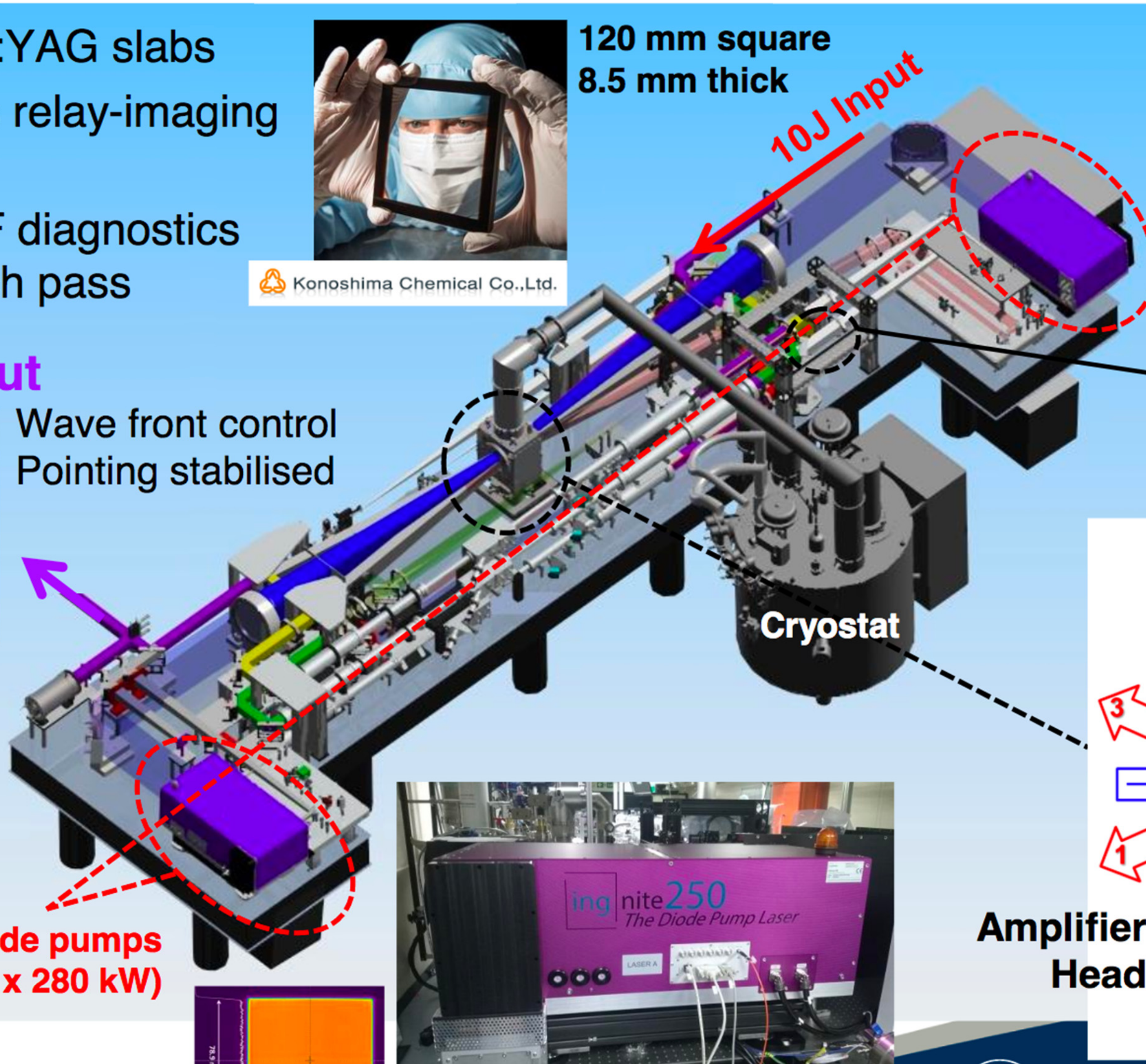
60 J SHG energy @ 532 nm : design target (**40 J** demonstrated)

- **Cost of diode still an issue** – currently 5x total (including operational) costs compared to flashlamps.
- Expected to decrease in 5-10 yrs.
- Maintenance free operation for 25-30 yrs.

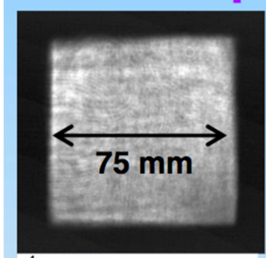
DiPOLE 100

- 6 x Yb:YAG slabs
- 4-pass relay-imaging design
- NF, FF diagnostics on each pass

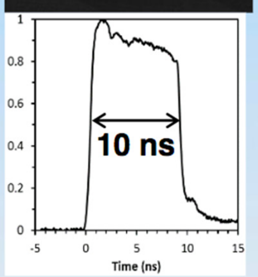


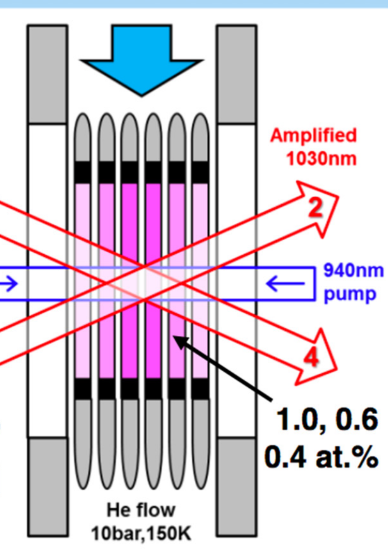


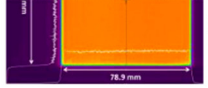
100J output



Wave front control
Pointing stabilised







ingeneric

DiPOLE100

Science & Technology Facilities Council
Central Laser Facility

EuPRAXIA

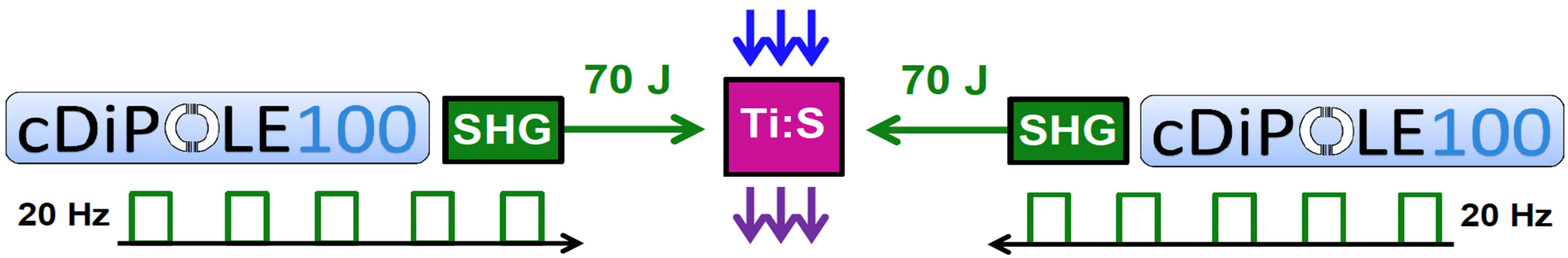
VIABLE CONFIGURATION

Horizon 2020

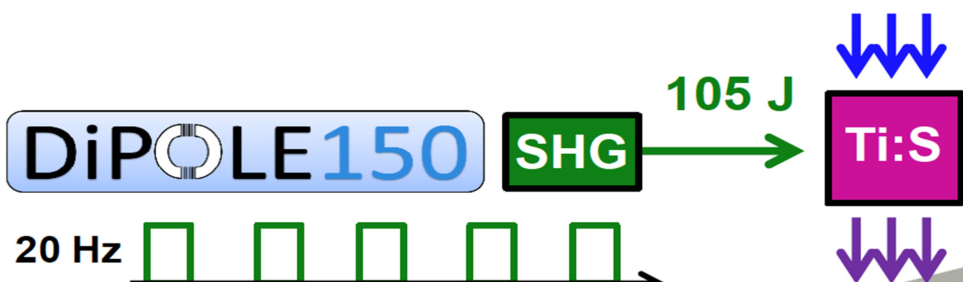
- L3 Baseline: 105 J @ **515 nm**, 20 Hz
  - Operate @ higher fluence ⇒ reduce aperture
  - Higher gain ⇒ fewer amplifier stages
  - Relax beam quality ⇒ higher thermal load (P_{avg}, PRF)
  - 2 x compact-DiPOLE100 @ 20 Hz (5.5 kW load)

Compact

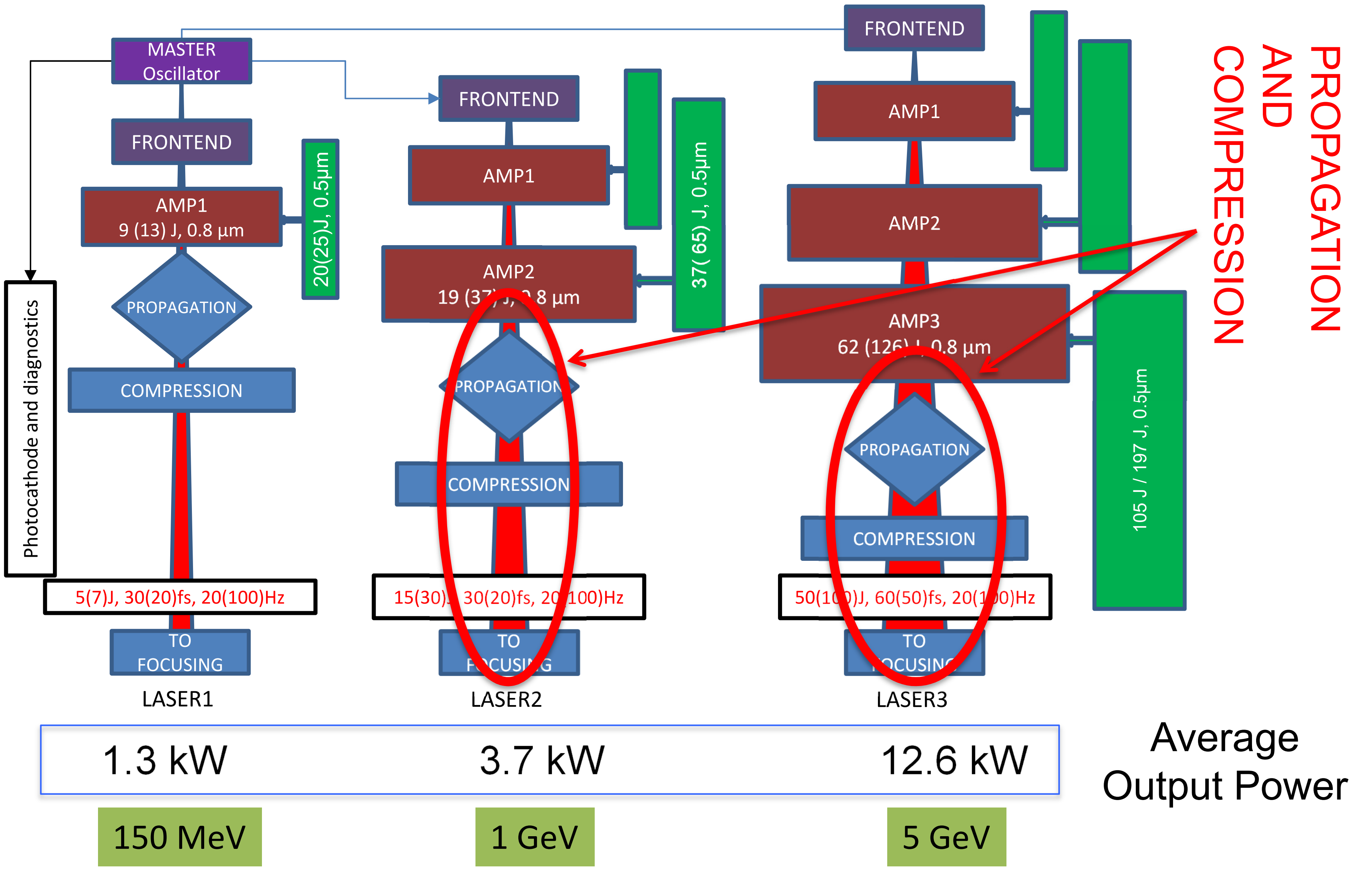
Simpler & more affordable



or 1 x DiPOLE150 @ 20 Hz (8 kW load)

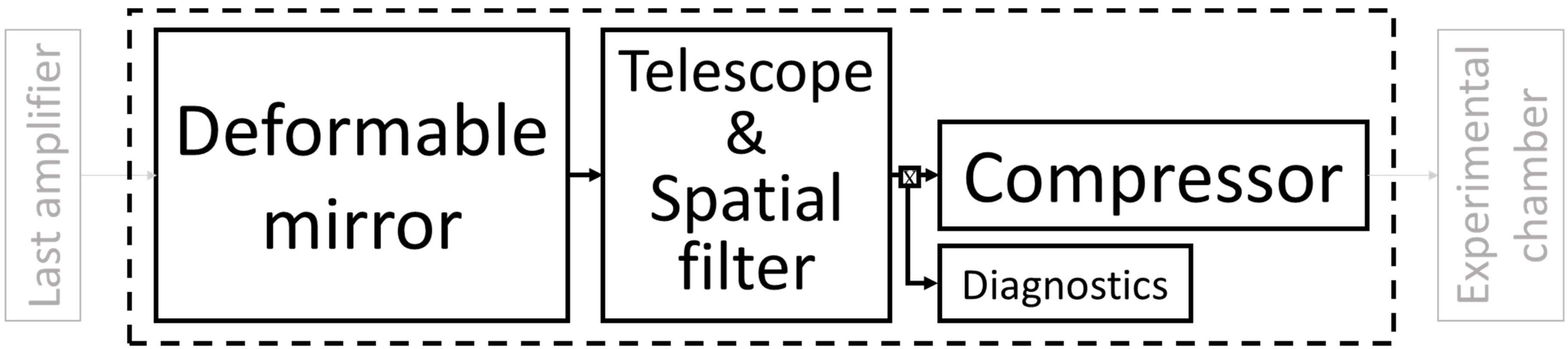


Detailed scheme

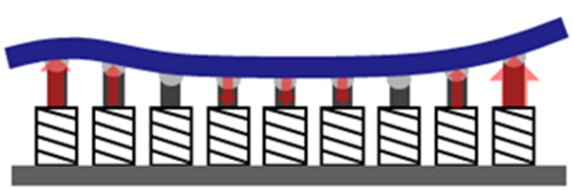


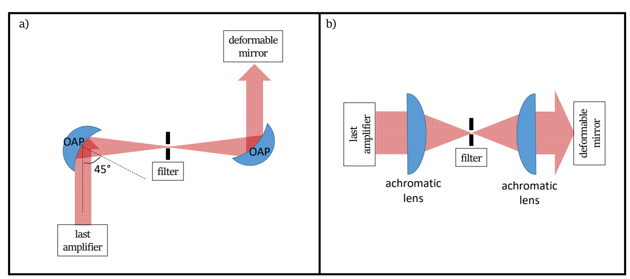
TRANSPORT TO TARGET

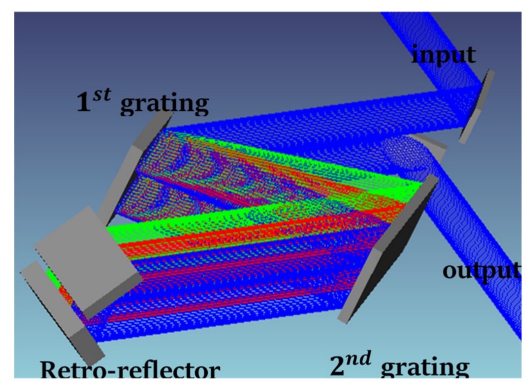
Main challenges: large optics, mechanical stability, cooling of gratings, beam quality control, beam pointing stability ...



R&D at existing laser labs (APOLLON(FR), RAL(UK), ILIL(IT) etc …)



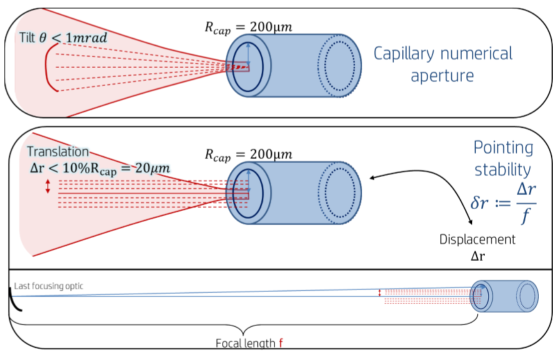


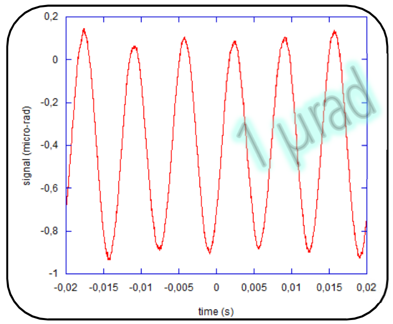


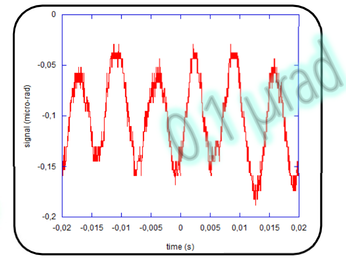
POINTING STABILITY

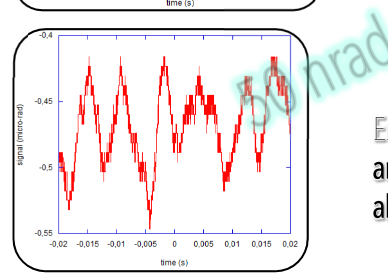
Horizon 2020

Requirements for beam pointing stability are extremely demanding (1-5 µrad). Both passive and active control will be required. Prior to the implementation of control strategies, tools are being developed to **measure pointing stability** performances at EuPRAXIA facilities and labs.









Laser angular fluctuations footprints at 150 Hz

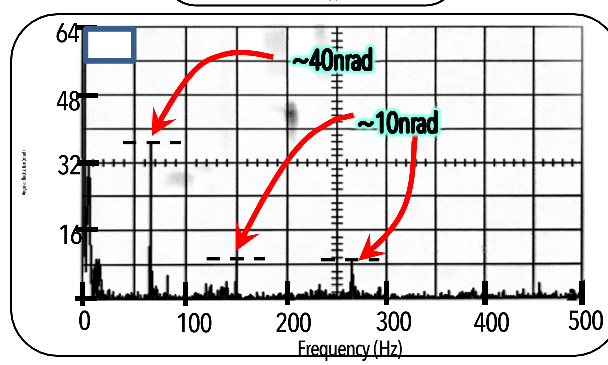
Environmental angular noise of about 30 nano-rad

We already detect

<100nrad fluctuations

Z. Mazzotta, F. Mathieu
in collaboration with
S. Cialdi, D. Cipriani, S. Capra
of Università degli studi di Milano.

up to the **MHz regime** and more



Spectral analysis of the laser fluctuation.

B. Canuel et al., Sub-nanoradiant beam pointing monitoring […], Appl. Opt. 2014, 53, 2906-2916

TECHNOLOGY READINESS

- Laser driver for a plasma accelerator designed to **seamlessly drive** a user laser-plasma accelerator;
- Current required drivers, 100-1kHz Hz, 10-100J, is **beyond existing technologies**;
- Conceptual design relies on the **latest industrial** and lab components of high power lasers;
- 20 Hz operation relies on demonstrated components (**TRL 5** to **TRL 7)**;
- 100 Hz operation (**TRL2 to TRL3**) is evolving along with **diode pumping developments (prototyping);**
- Heat management of amplifier head (**TRL3-TRL4**) requires validation at the relevant component scale.

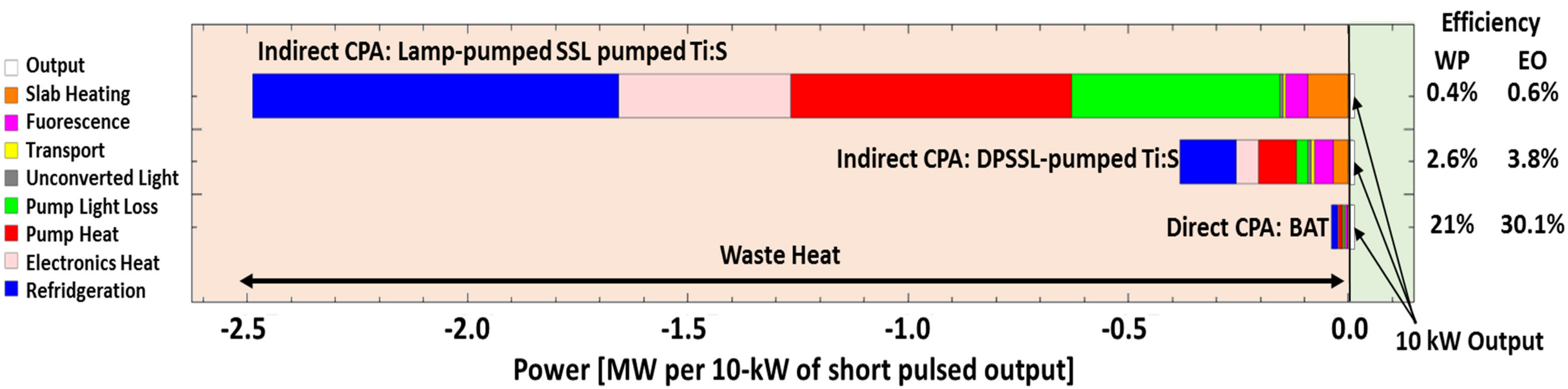
DRIVER: STRATEGY 2/2

- **Other technologies are developing** aiming at >kW, higher rep. rates, higher average power levels and even more efficient configurations (k-BELLA@LBNL, Kaldera@Desy, LEAP@CELIA …);
- **Fiber laser technology** offers the best WPE >50% in CW mode and **coherent combination** is being developed (FSU Jena-Fraunhofer IOF and Ecole Polytechnique-Thales in France). Suited for lower energy per pulse >10 kHz or for future upgrades; see anso XCAN project;
- **Direct Chirped Pulse Amplification** with lasing media **pumped directly by diodes** is ideal for higher efficiency and higher rep-rate;

>kHz repetition rate ?

- Plasma accelerators will require higher and higher repetition lasers with high efficiency. Direct pumping of lasing medium with diodes is most efficient:

Direct CPA required for >100Hz due to wall-plug efficiency limitations.



C. Siders et al., EAAC 2017

We need a **gain medium** that can support amplification on a large bandwidth and can be pumped **directly** with diode lasers.

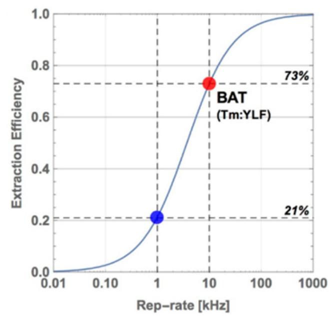
Direct diode pumping

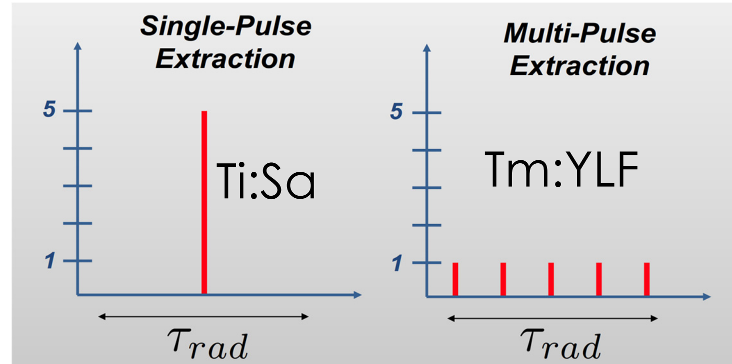
Crystals	Nd: YAG	Yb: YAG	Ti: Sa	Yb: CaF_2
Fluorescence lifetime (ms)	0.23	0.96	0.0032	2.4
Stimulated-em. $\sigma(\times 10^{-20}/cm)$	20 to 30	2.1	30	0.2
Fluorescence wavelengths (nm)	1064	1030	660-1100	1033
Absorption wavelengths (nm)	808	940	514 to 532	980
Fluorescence BW (FWHM) (nm)	0.67	10	440	70
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

- **Available direct CPA concepts (Yb:CaF_2, Yb:YAG …)** limited in pulse duration, heat extraction and scaling;
- Developments in progress also with Tm:YLF

A possible solution: 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);





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

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

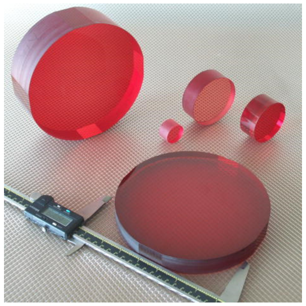
C. Haefner et al., EAAC 2017

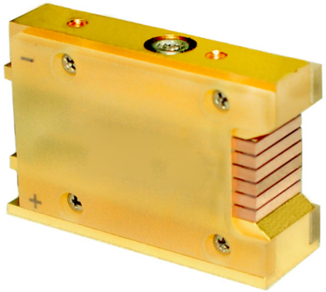
(*) Lawrence Livermore National Laboratory

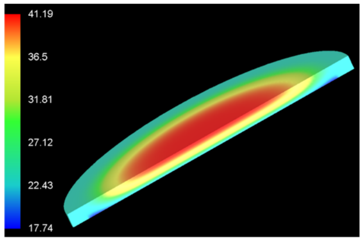
Broader view on driver R&D

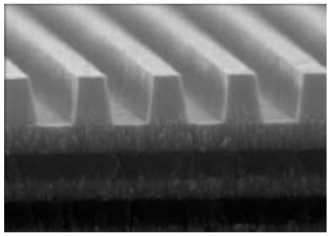
EuPRAXIA laser relies on industrial development in:

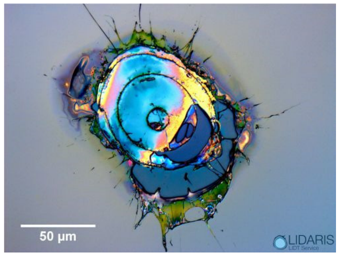
- Pumping technology: diode (direct or indirect) pumping;
- Gain media: material should be industrially available at laser quality, scalable in size and capable of supporting large bandwidth and efficient cooling;
- Grating technology to improve for higher damage threshold and smaller beam size
- Optics Damage threshold
- Thermal load, management, dissipation
- Vacuum technology
- Mechanical stabilization (active and passive);











Major R&D and technology transfer to embed in final systems

SUMMARY

- *Nobel winning, ultraintense CPA laser technology:*
    - *30+ years of impressive developments;*
- *Correlated progress of laser-plasma acceleration;*
- *FEL-quality Laser-Plasma acceleration approaching;*
- *Today's technology leading to viable driver (EuPRAXIA);*
- *Progressing towards kW-kHz with higher efficiency;*
- *Building a credible route for first generation of high quality, laser-driven plasma accelerators.*

Contributors

CNR – Italy

Leonida A. GIZZI, Istituto Nazionale di Ottica-CNR, Pisa
Petra KOESTER INO-CNR, (EuPRAXIA contract), Pisa
Luca LABATE, INO-CNR, Pisa
Fernando BRANDI, INO-CNR, Pisa
Gian Carlo BUSSOLINO, INO-CNR, Pisa
Barbara PATRIZI, INO-CNR, Firenze
Guido TOCI, INO-CNR, Firenze
Matteo VANNINI, INO-CNR, Firenze

CNRS – France

François MATHIEU, CNRS, Ecole Polytechnique
Zeudi MAZZOTTA, CNRS, Ecole Polytechnique (Eupraxia contract)
Dimitrios PAPADOPOULOS, CNRS, Ecole Polytechnique
Catherine LE BLANC, CNRS, Ecole Polytechnique
Bruno LE GARREC, CNRS, Ecole Polytechnique
Audrey BELUZE, CNRS, Ecole Polytechnique
Jean-Luc PAILLARD, CNRS, Ecole Polytechnique

Collaborators

Franck FALCOZ — *Amplitude Technologies*

Christophe SIMON BOISSON
Sandrine RICAUD
Sebastien LAUX
Thales Group

Paul CRUMP — *Ferdinand-Braun-Institut, Germany*

Rajeev PATTATHIL
Klaus ERTEL
Paul MASON
Marco GALIMBERTI
STFC Rutherford Appleton Laboratory

Andy BAYRAMIAN
Constantin HAEFNER
Craig W. SIDERS
Tom SPINKA
K. CHESTNUT
E. ERLANDSON
T. GALVIN
K. SHAFFERS
E. SISTRUNK
Lawrence Livermore National Laboratory

Oliver KARGER
Alexander KNETSCH
Hamburg University

Maria Pia ANANIA
Fabrizio BISESTO
Dario GIOVE
M. BELLAVEGLIA
S. GALLO
INFN LNF

industries
laboratories
shaded major contributors/collaborators

55


THANK YOU FOR YOUR ATTENTION
ANL