European Advanced Accelerator Concepts Workshop (**EAAC2019**), 15-21 September 2019 Hotel Hermitage, La Biodola Bay, Isola d'Elba, Italy

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ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

CHALLENGES IN THE DESIGN OF A LASER DRIVER FOR A PLASMA ACCELERATOR

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CNR-*INO*

Intense Laser Irradiation Lab
Pisa, Italy

A node of the Italian ELI Network

A founding member of the EuPRAXIA infrastructure project

http://www.ilil.ino.it

Intense Laser Irradiation Laboratory

Istituto Nazionale di Ottica – Consiglio Nazionale delle Ricerche

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CNR Campus in Pisa

The Intense Laser Irradiation Lab

PEOPLE

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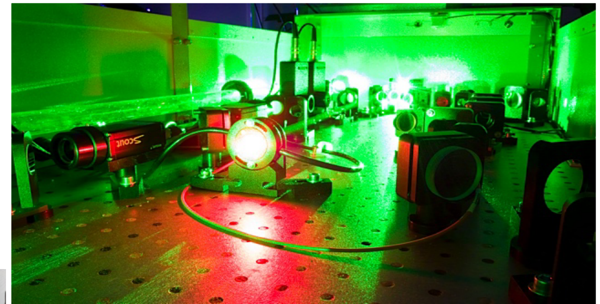

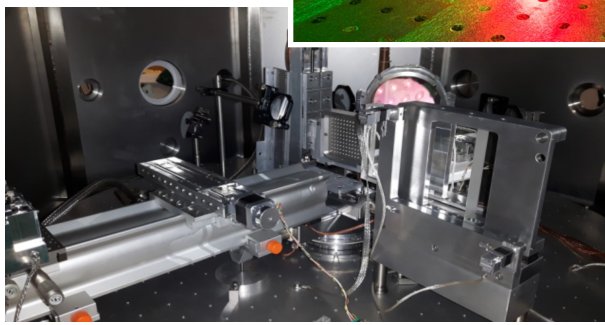

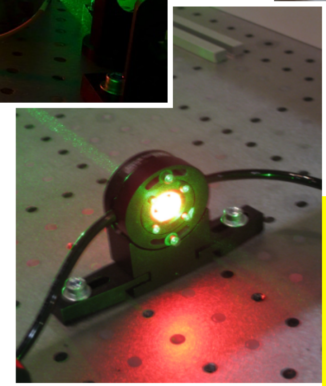

Contributions to this workshop

L. Labate, WG4, Mon. 16.40
L.A. Gizzi, WG7, Mon, 18.20
D. Terzani, WG6, Wed, 18.40
P. Tomassini, Poster, Wed, 19.00
L.A. Gizzi, Poster, Wed, 19.00
F. Brandi, Plenary, Fri, 9am

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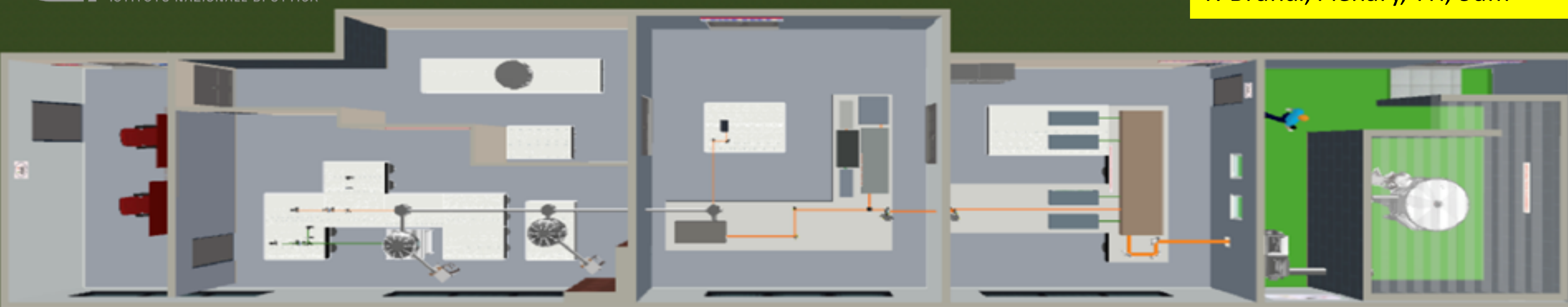
Sub-PW Experimental Laser Facility



Control Room

Radiobiology
Laser-Driven
Particles and Radiation

Laser Front End
10 TW, 10 Hz

Power Amplifier
Up to 250 TW

Shielded target Area LWFA, TNSA, Thomson Scattering, γ-rays …

Roadmap of Advanced and Novel Accelerators

International Committee for Future Accelerators

Panel on Advanced and Novel Accelerators

2017 - 2022	2022 - 2027	2027 - 2032	2032-2037
e- sources: optimization **e+ sources:** Concept devt **Driver development** **Accelerating structures** **Beam transport and coupling**	**e- acceleration :** Optimization of all parameters **e+ acceleration:** demonstration		

5 Ys

Injector, Accelerator stages with controlled parameters

10 Ys

x10 Improved beam quality at higher energy

15 Ys

Reliable staged accelaration, 10 GeV module

20 Ys

Advanced Linear Collider CDR and TDR

Address specific challenges :

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

HOW TO ASSESS DRIVER NEEDS?

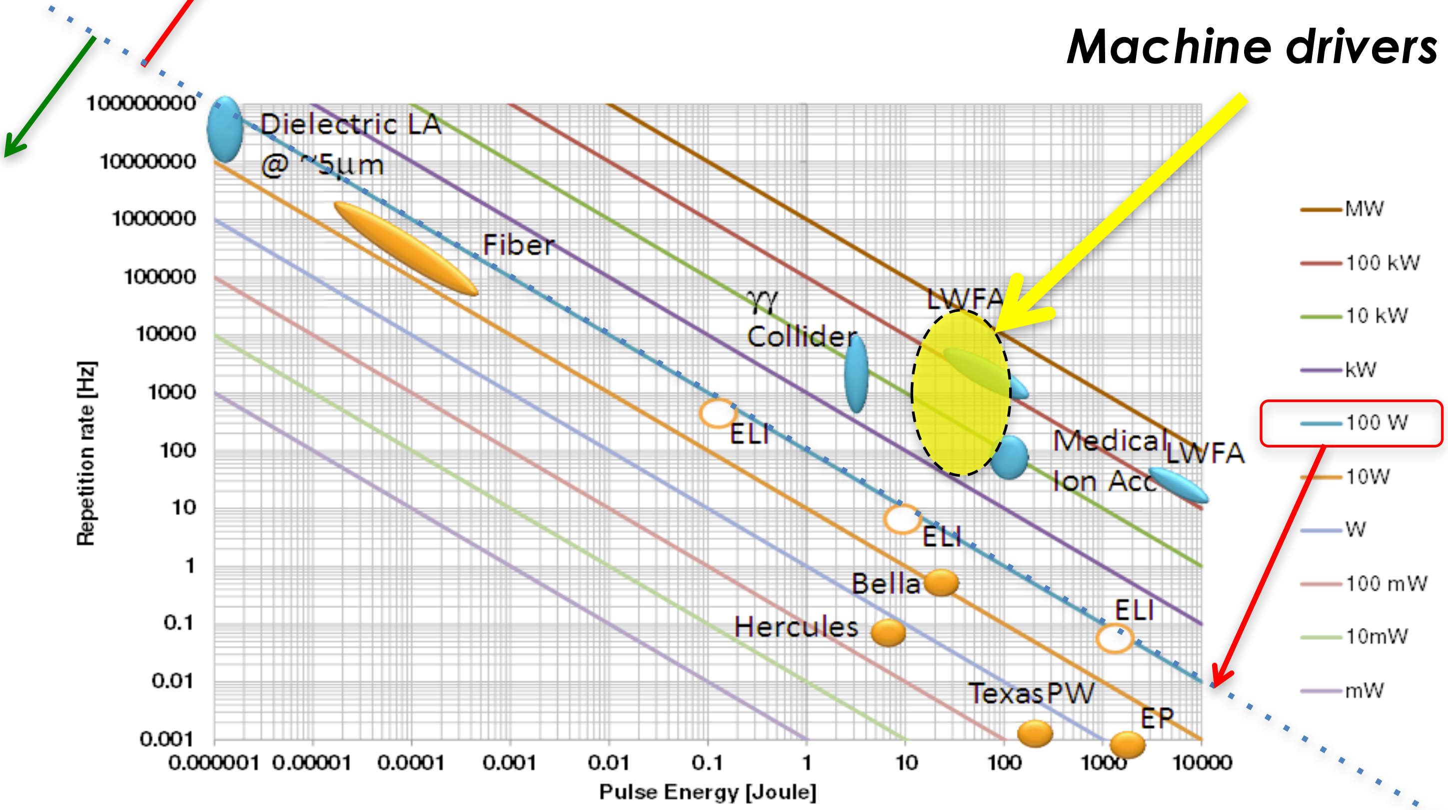
A three years extensive conceptual design work from international leading groups

Detailed concept from lasers to applications

HIGH POWER LASER REQUIREMENTS

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

Machine drivers



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

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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.

DRIVER: STRATEGY 1/2

- **up to ten kW** average laser power with PW peak power and high(est possible) 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 prototype pump lasers offer kW performances at the required Ti:Sa pumping wavelength of 0.5 μm;

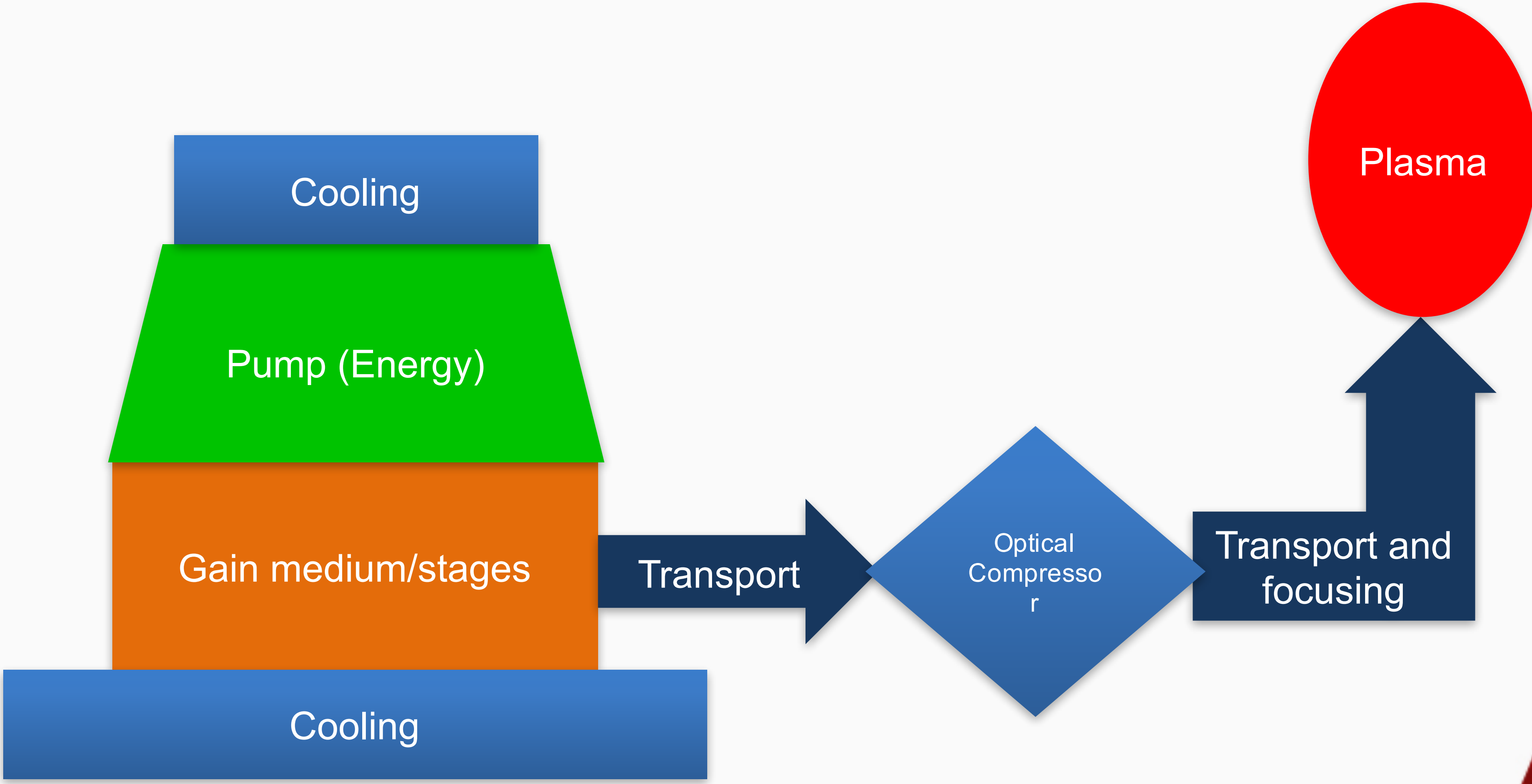
DRIVER: STRATEGY 2/2

- **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;

RELEVANT BLOCKS OF A LASER DRIVER



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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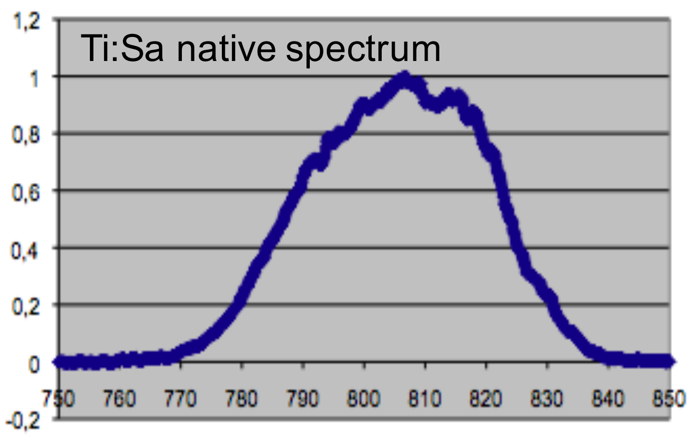
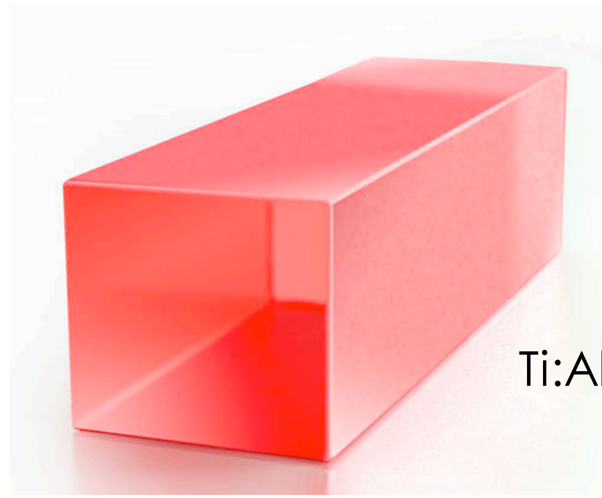
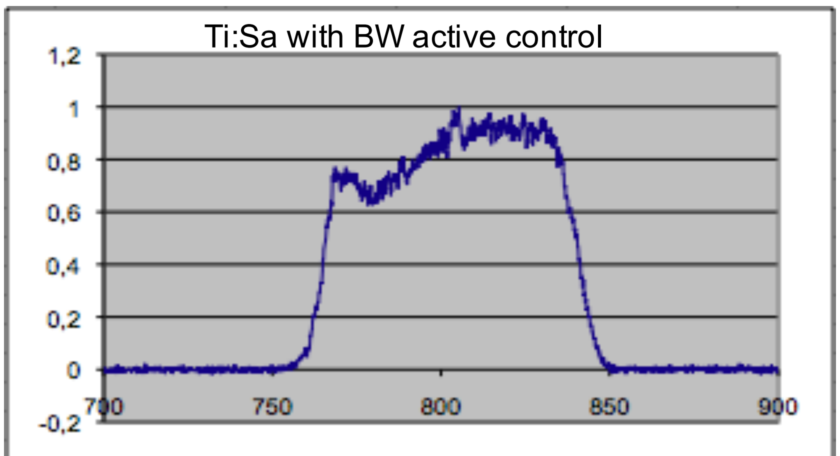
GAIN MATERIAL: TITANIUM SAPPHIRE

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 µs
- 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

EuPRAXIA

EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

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

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

http://eupraxia-project.eu

Goals and challenges

Horizon 2020

- EuPRAXIA is a **conceptual design study** for a **5 GeV electron plasma accelerator** as a European research infrastructure.

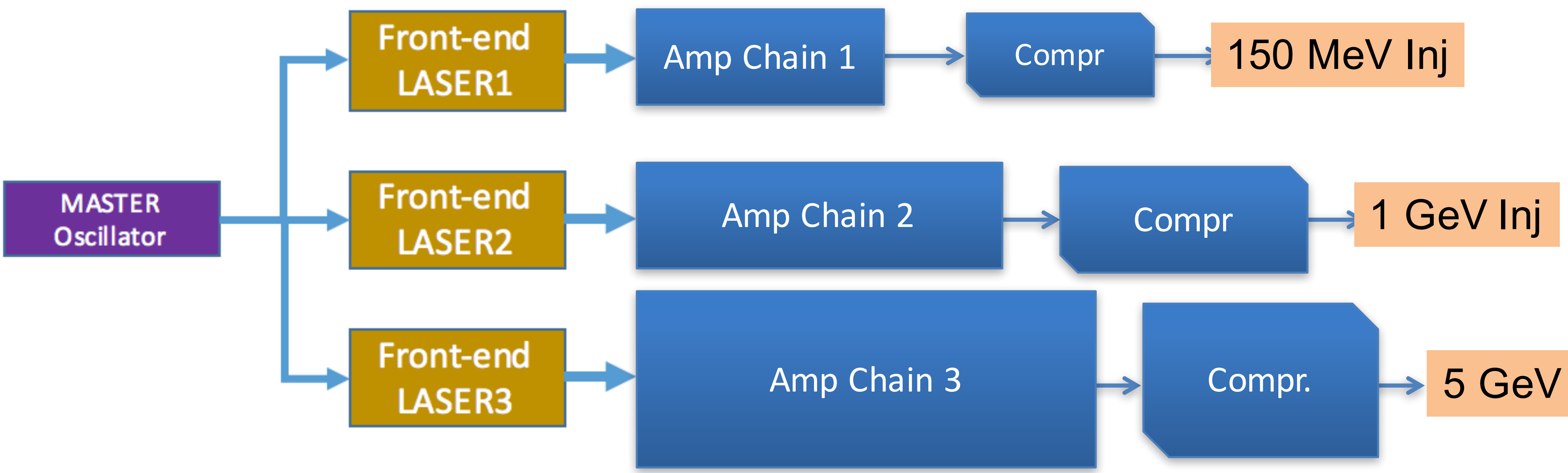
P. Tomassini on "FEL-quality 5GeV e-bunches with the Resonant Multi Pulse Ionization injection scheme (ReMPI).
Poster on Wed

- **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).*

The EuPRAXIA approach

Horizon 2020

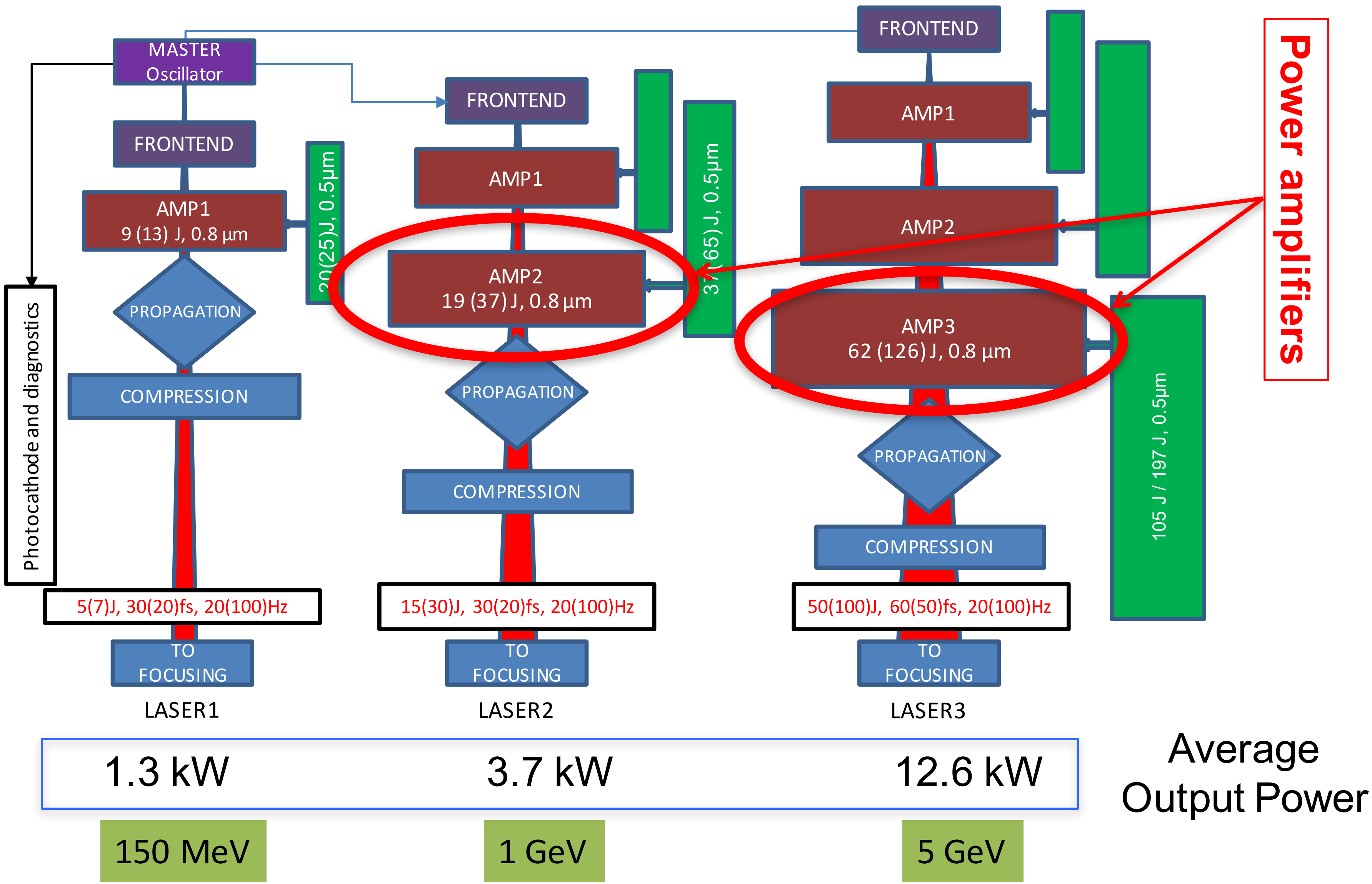
Three independent front-end sections seeded by the same laser oscillator



5GeV: Driver Specifications

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) %	$\sigma_{<W_0>}/W_0$	20	10
Pointing stability (RMS) (µrad)	$\sigma_{<x'>}$, $\sigma_{<y'>}$	5	1

Detailed scheme



Amplifiers design strategy

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);

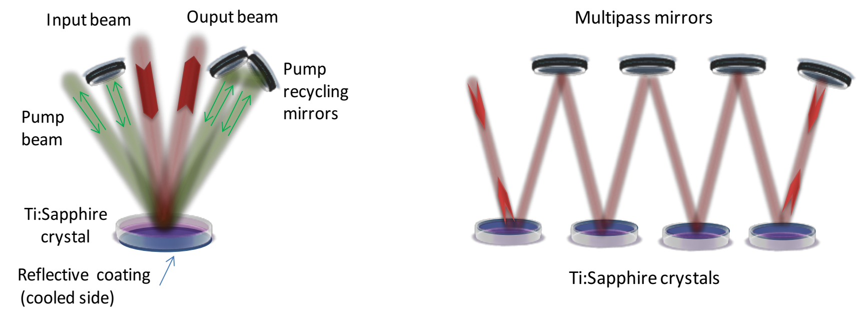
Results

- 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

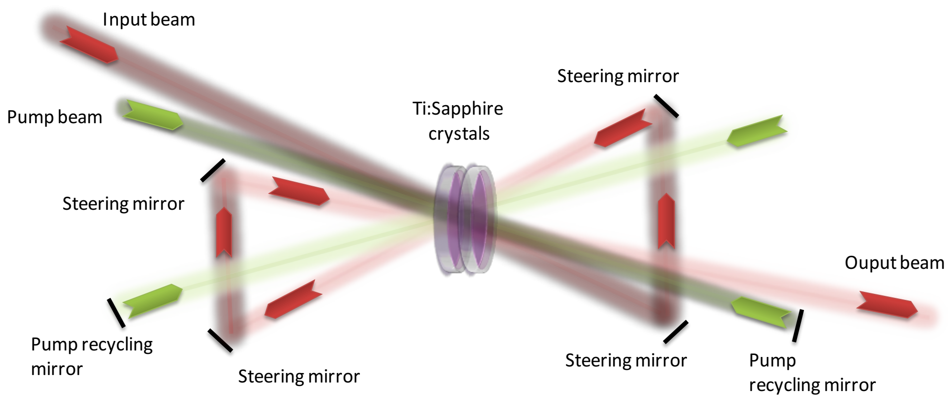
"Active mirror" geometry



Pro: Well established concept with no propagation through cooling fluid

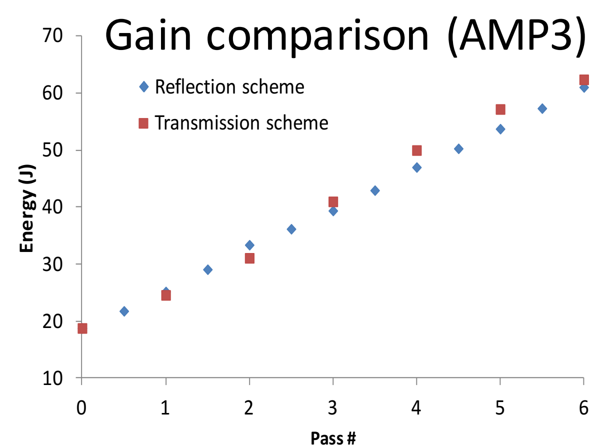
Con: limited cooling (single face), to be modelled

Transmission geometry



Pro: More efficient (double-side) cooling and reduced complexity;

Con: propagation through flowing cooling liquid

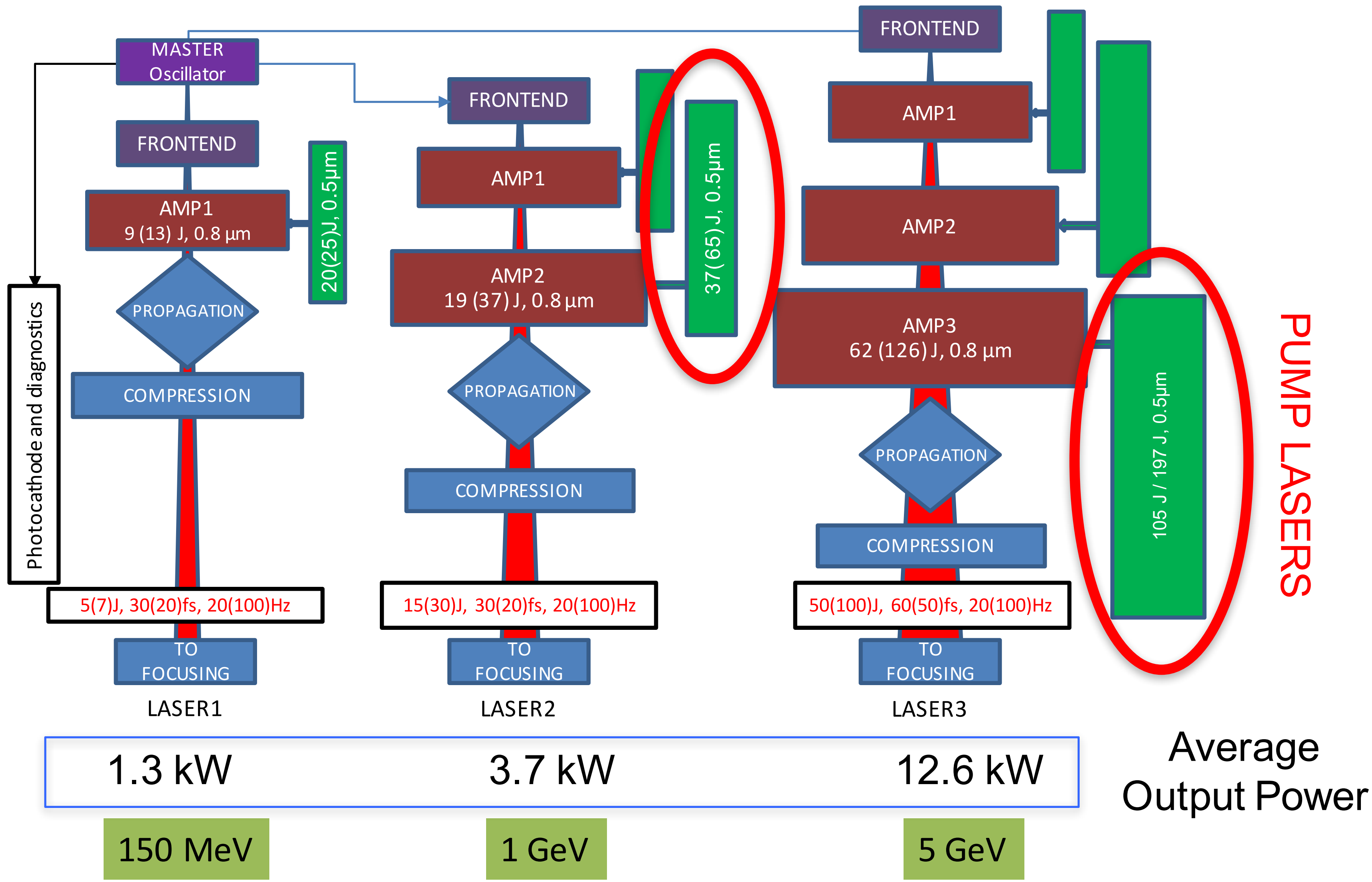


*) Water cooled Ti:Sa amplifier ("Active Mirror" configuration) under development at ELI-HU (After V. Cvhykov *et al.*, Opt. Lett, **41,** 3017, 2016)

) 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

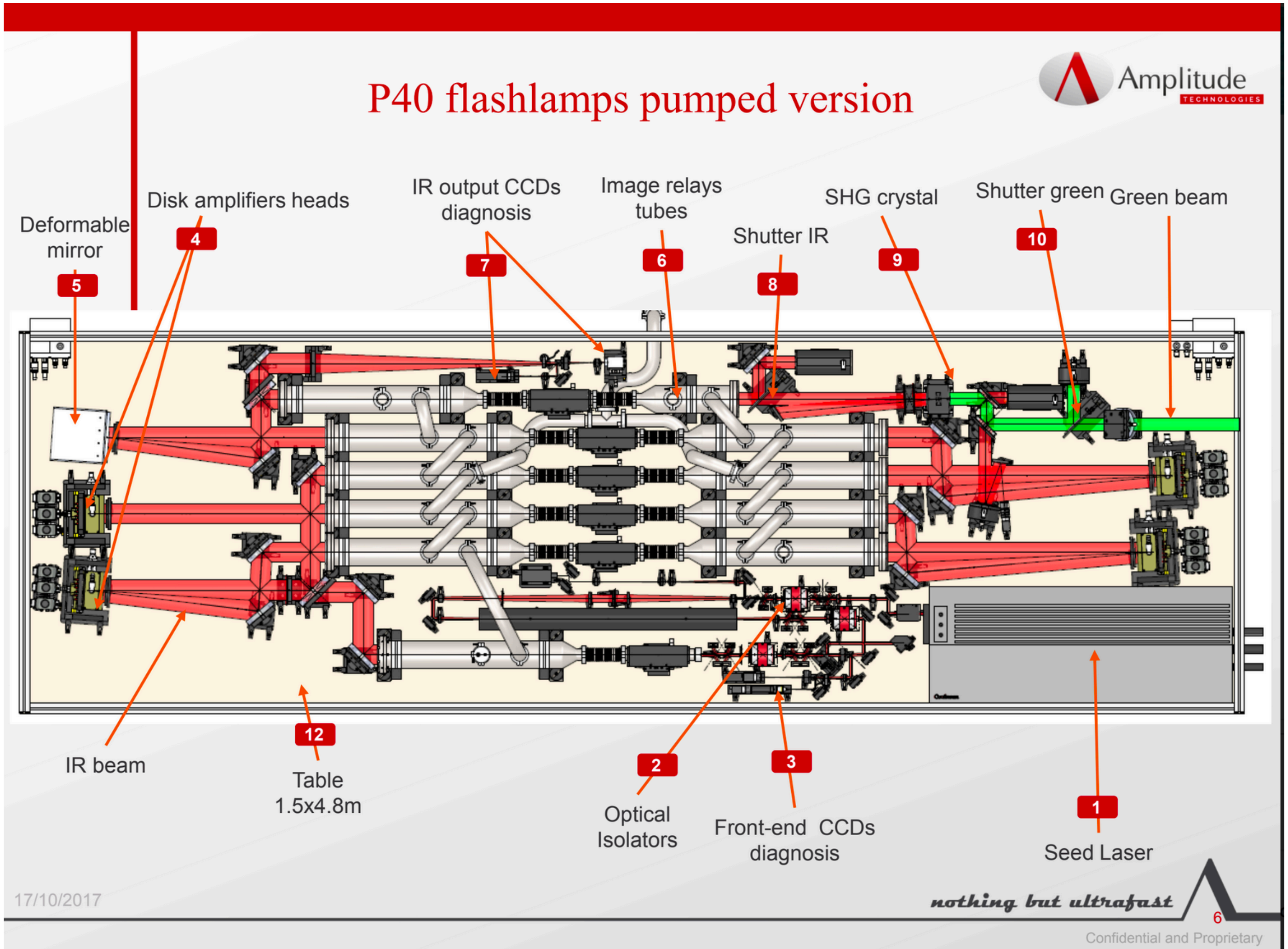
Horizon 2020

- **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

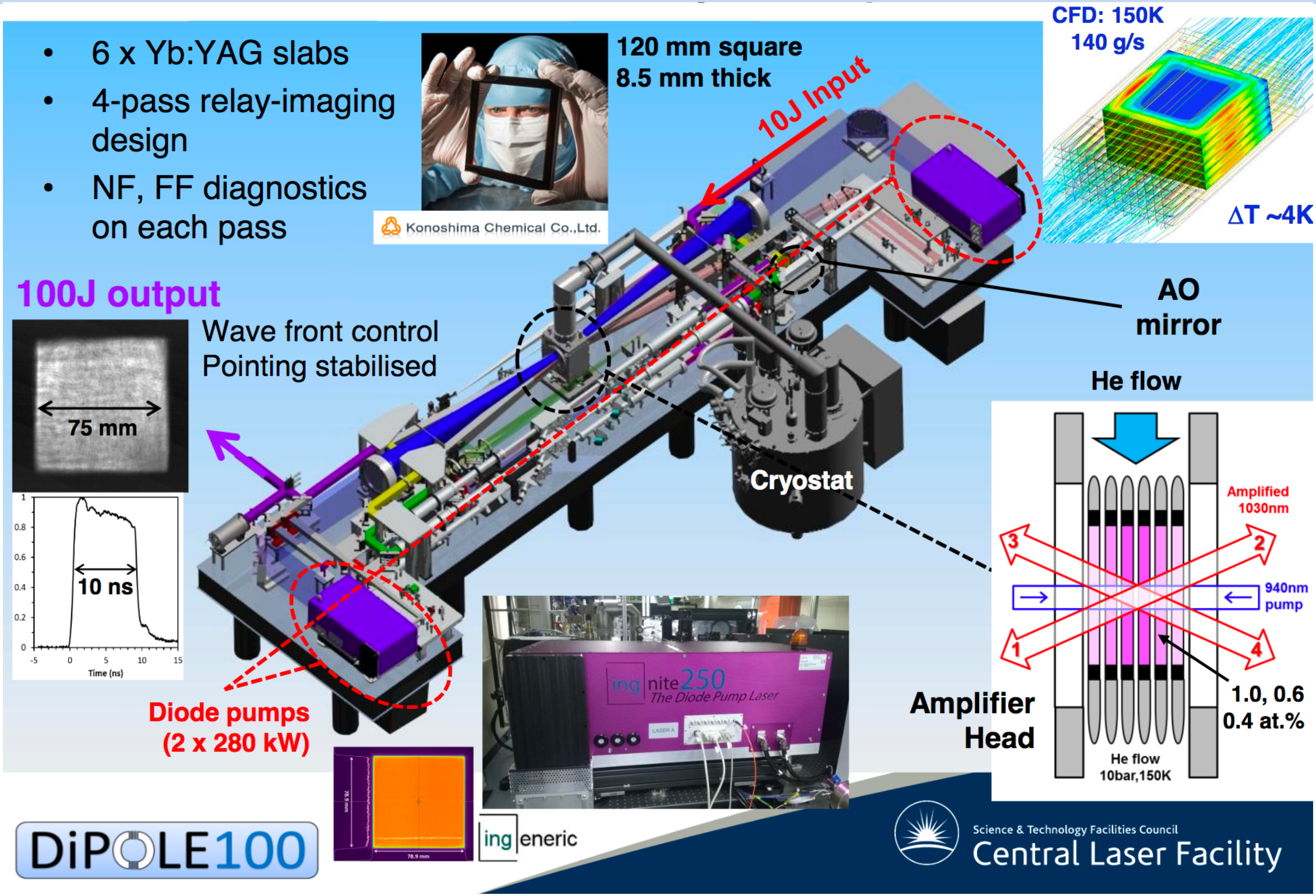


Flashlamp pumped Nd:YAG/
DPSSL possible
80 J output energy demonstrated @ **10 Hz**, 1064 nm
60 J SHG energy @ 532 nm : design target (**40 J** demonstrated)

- **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



DiPOLE100

ing eneric

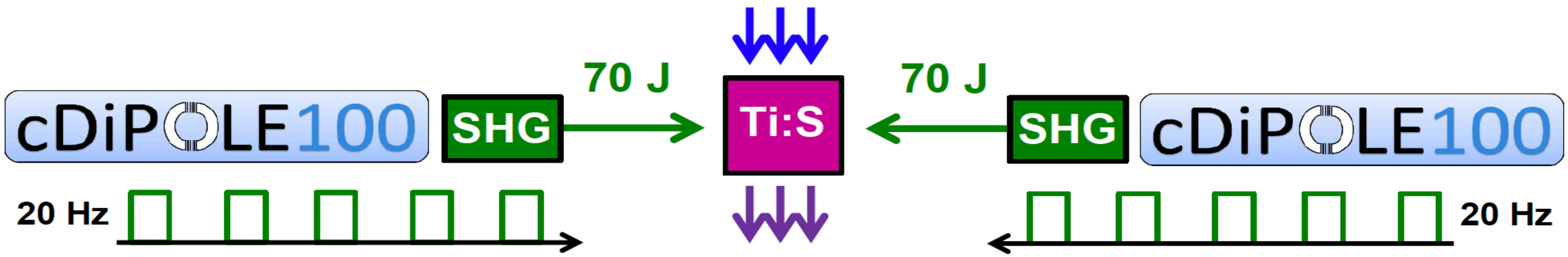
Science & Technology Facilities Council
Central Laser Facility

VIABLE CONFIGURATION

- 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)

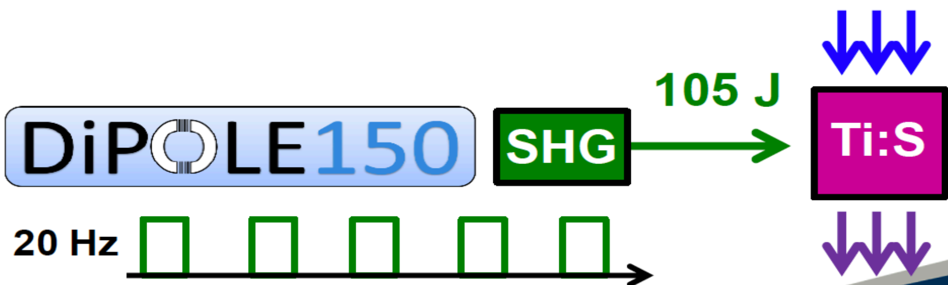
Compact

Simpler & more affordable

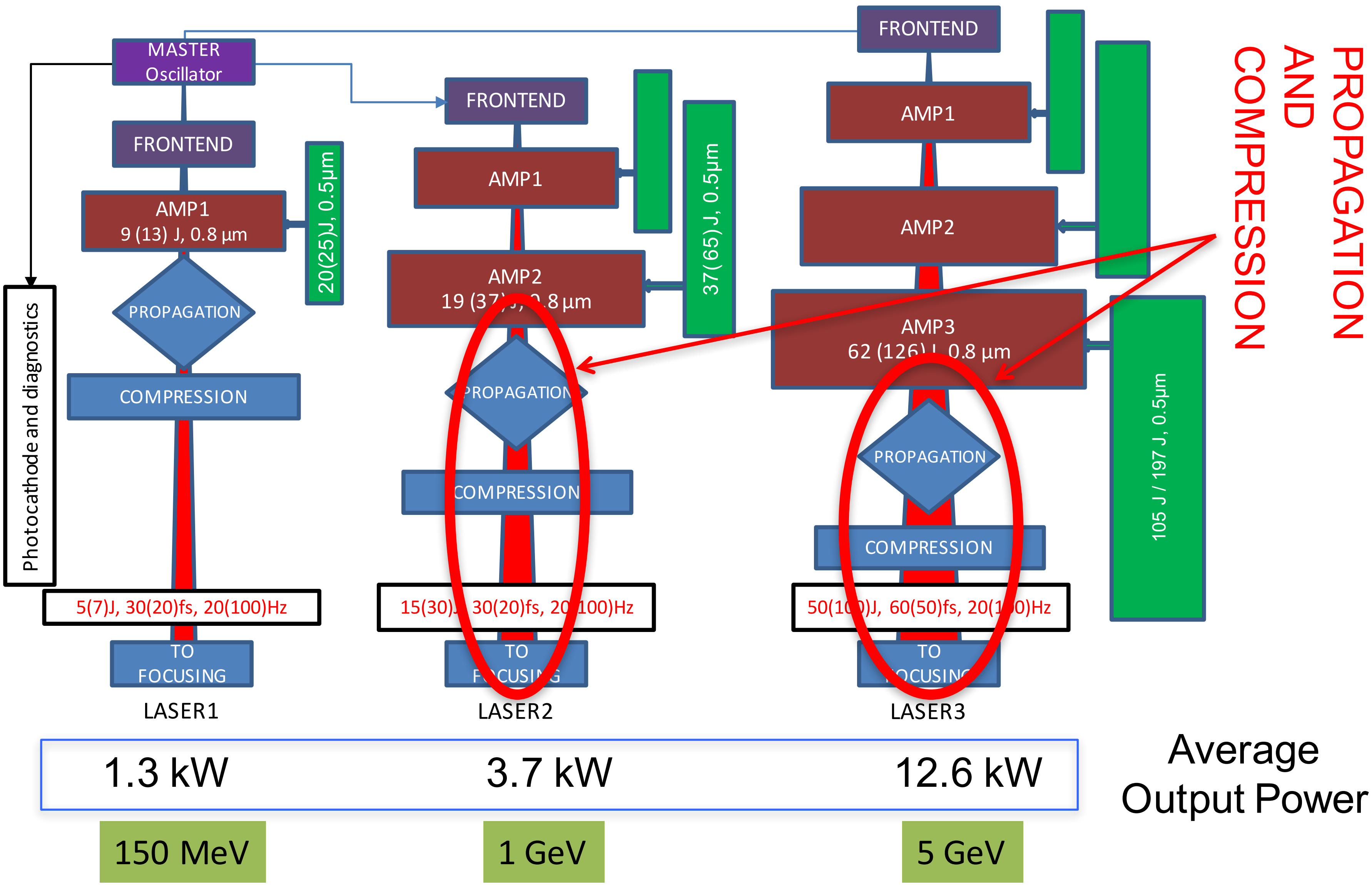


or 1 x DiPOLE150 @ 20 Hz (8 kW load)

Convergence with EPAC Project (UK)



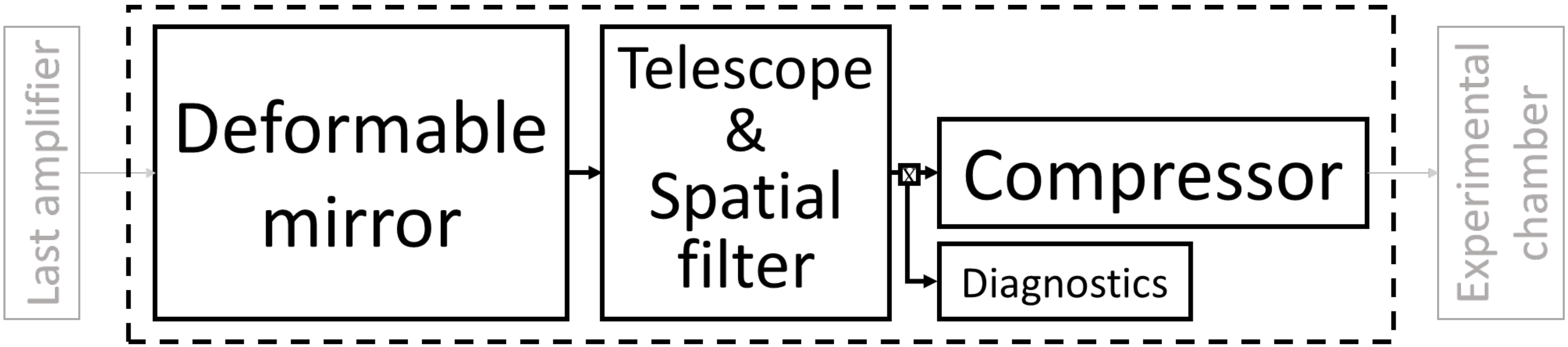
Detailed scheme



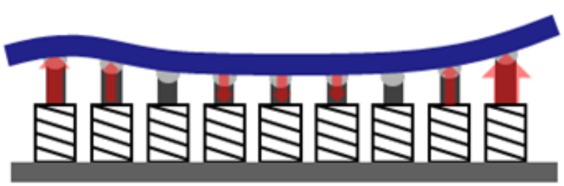
TRANSPORT TO TARGET

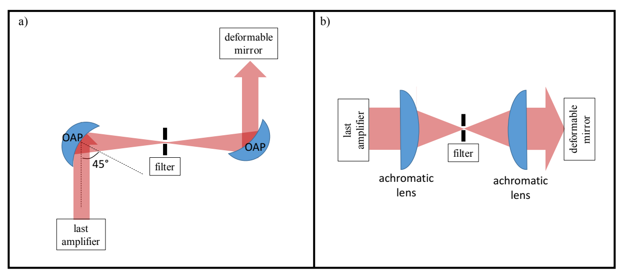
Horizon 2020

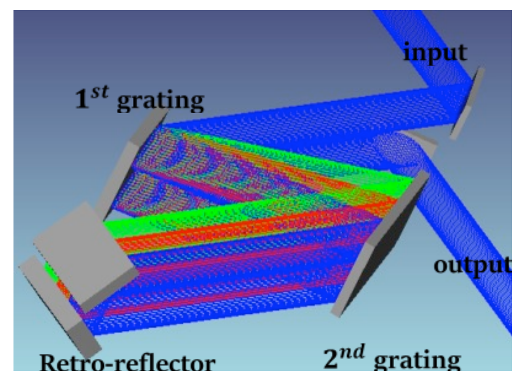
Main challenges: large optics, mechanical stability, cooling of gratings, beam quality control, beam pointing stability …



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







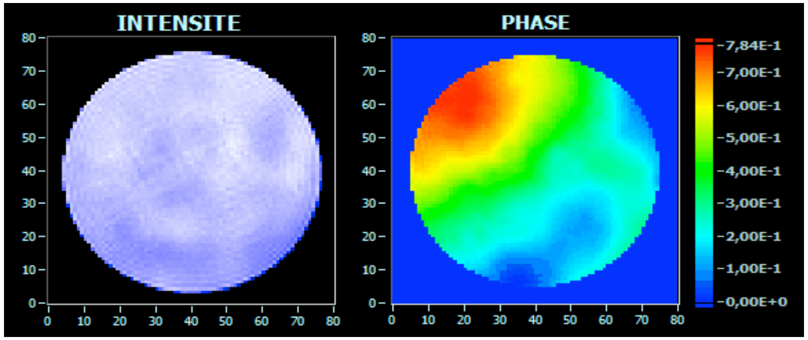
FOCAL SPOT BEAM QUALITY

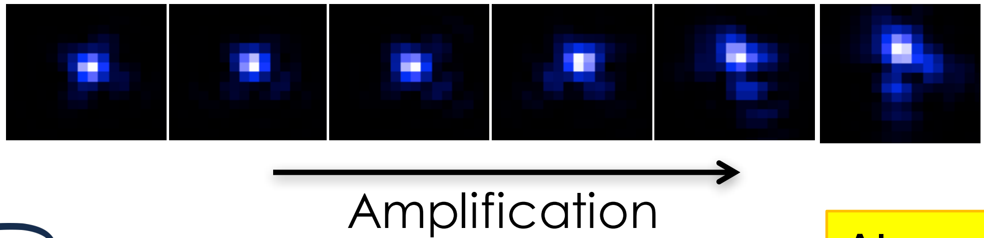
As larger gain media and optics are used, optical aberrations become important and limit the focusability of laser pulses

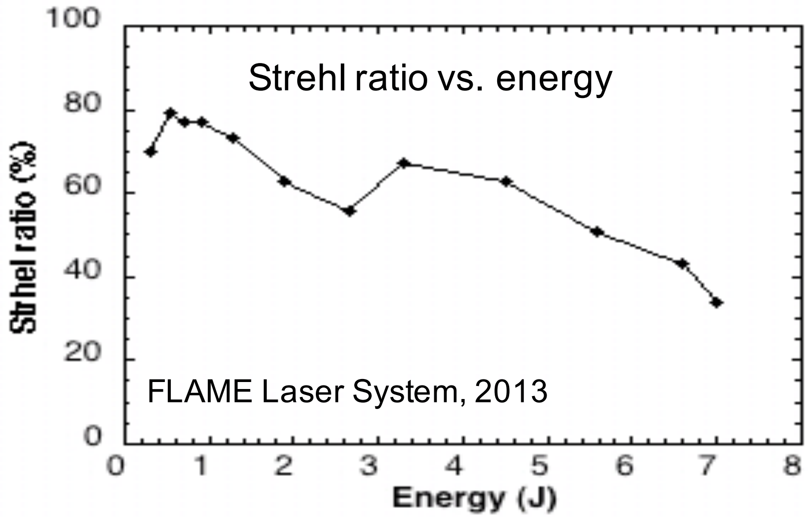
$$S_r = \frac{\textbf{Energy in the focal spot}}{\textbf{Energy in the pulse}}$$

STREHL RATIO

PHASE FRONT DISTORTIONS







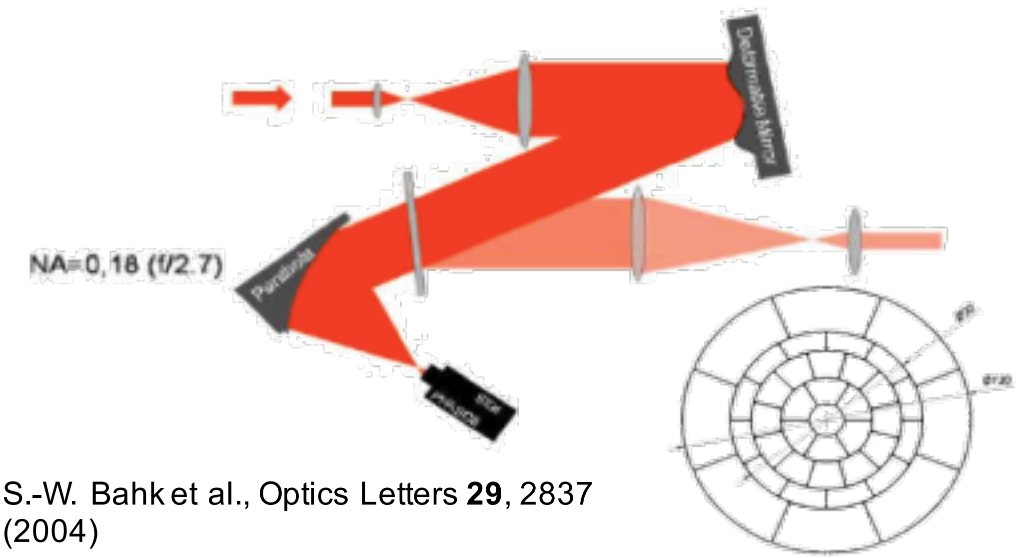
Also: need of Gaussian profile

ADAPTIVE OPTICS for high power lasers

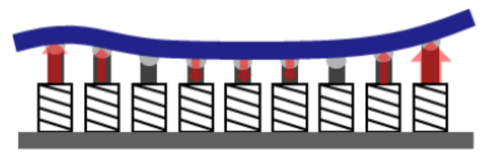
Active spatial phase control technique can be used to **correct severe to moderate phase distortions**;

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

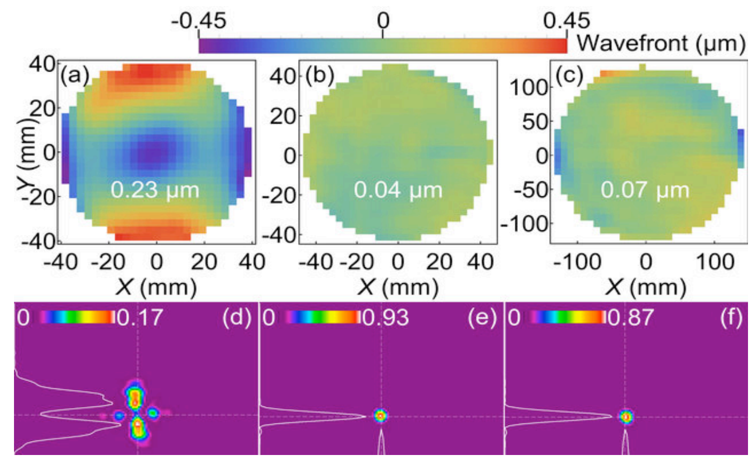
Deformable mirrors are used to correct the measured wave front distortions in a closed loop;



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



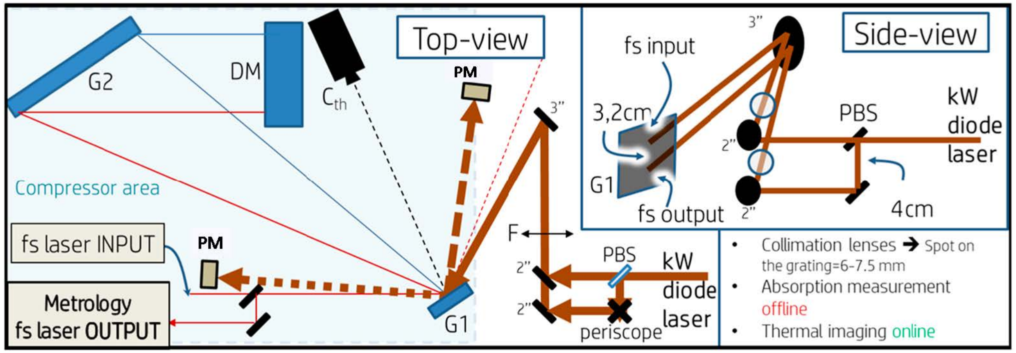
Mechanical actuator modify mirror shape by applying a force on the back of the mirror



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

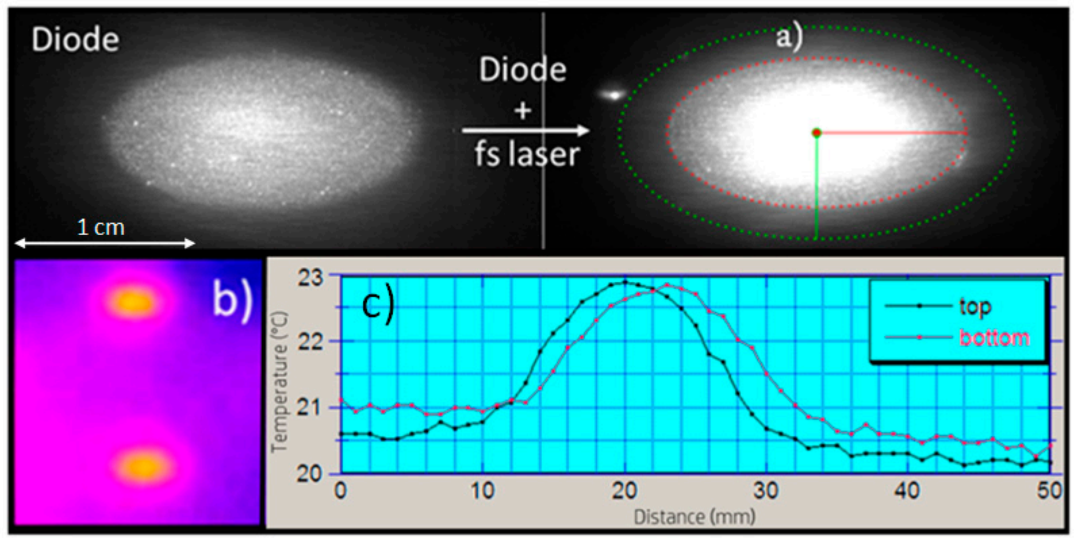
Key enabling component to reach high intensity

Grating heating experiment*



Compressor Area: PM = power meter; Cth = Thermal camera; G1 = first compressor grating; G2 = second compressor grating (gold, 56°,1480l/mm); DM = Dihedral Mirror. Diode Area: F = imaging lens; PBS = Polarizing Beam Splitter.

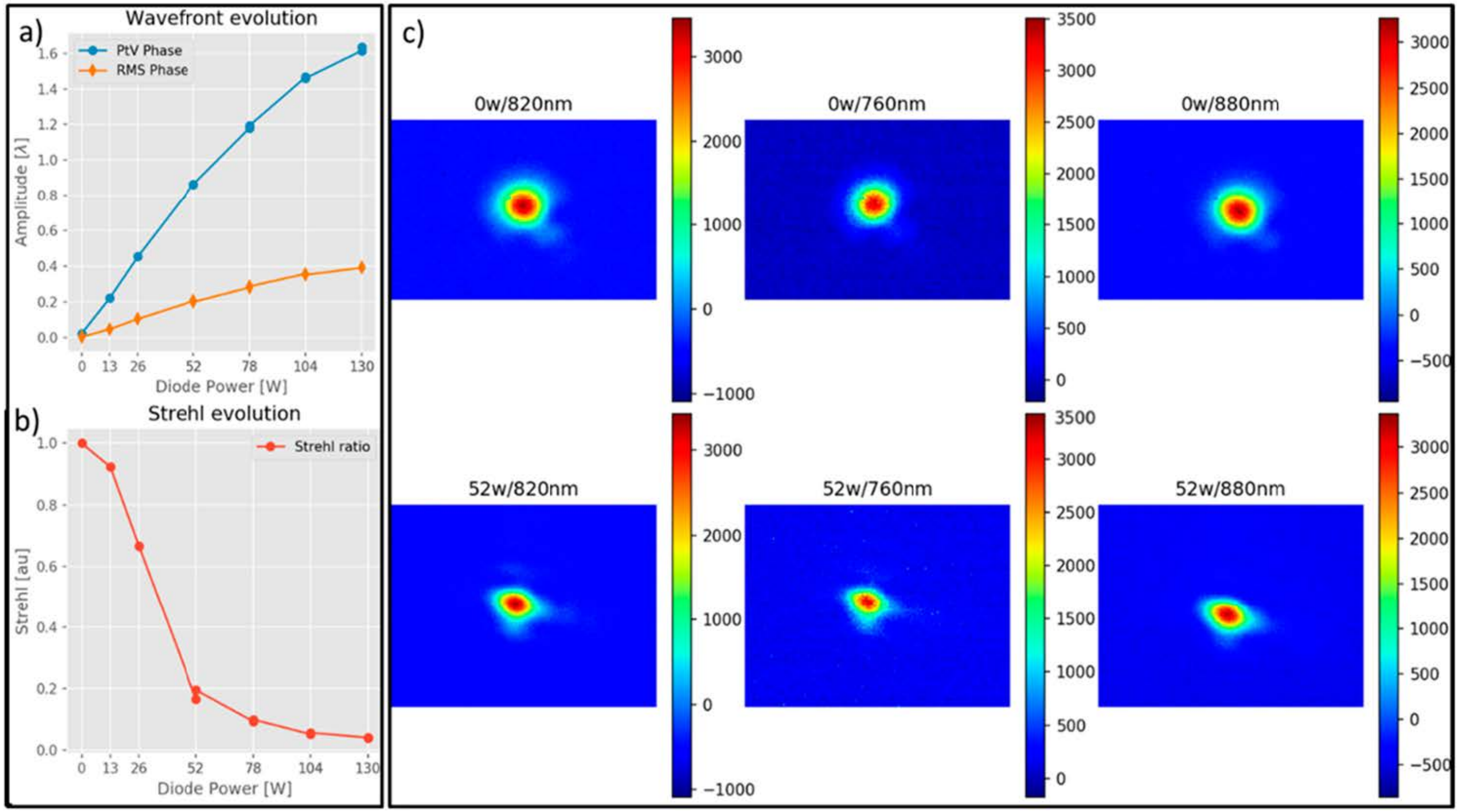
Image of the heating diode laser beam and of the fs laser beam on G1. The laser diode beam has a top hat profile, with a spot size of 0.82 mm x 1.63 mm (surface ~ 1 cm2). (b) G1 thermal image for 130 W sent on each spot. (c) Temperature profiles for the beam spots (b); left profile: input spot; right profile: output spot.



*using *Apollon* front-end test compressor

G. Toci et al. Instruments, **3**, 40 (2019)

Strehl ratio degradation



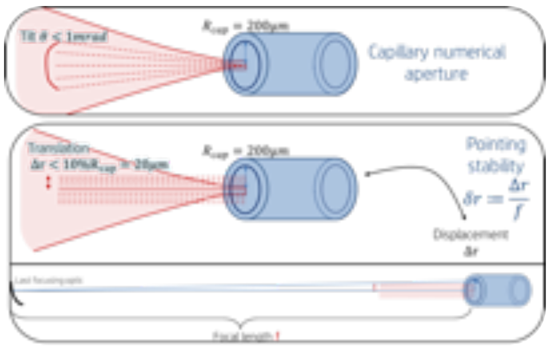
First measurements of phase front distortion by HAP heating of compressor grating

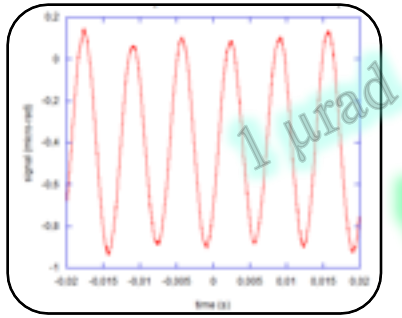
Upper line: far field at 760 nm, 820 nm, 880 nm for 0 W heating power.
Lower line: far field at 760 nm, 820 nm, 880 nm for 52 W heating power.

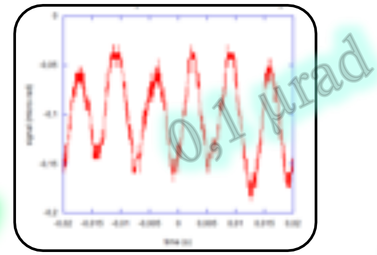
G. Toci et al. Instruments, **3**, 40 (2019)

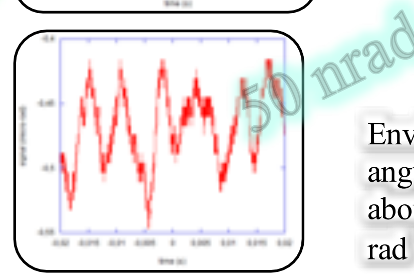
POINTING STABILITY

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.







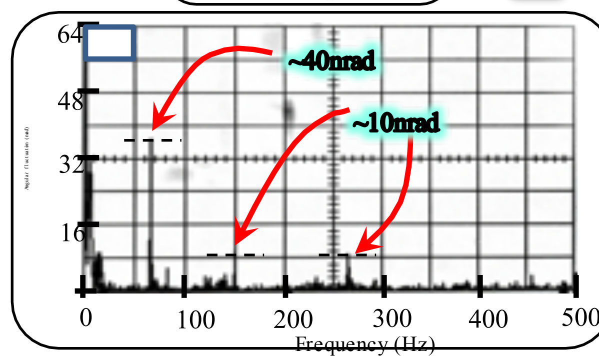


Laser angular fluctuations footprints at 150 Hz

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



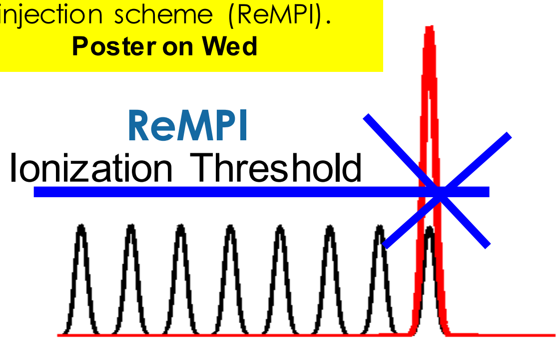
Spectral analysis of the laser fluctuation.

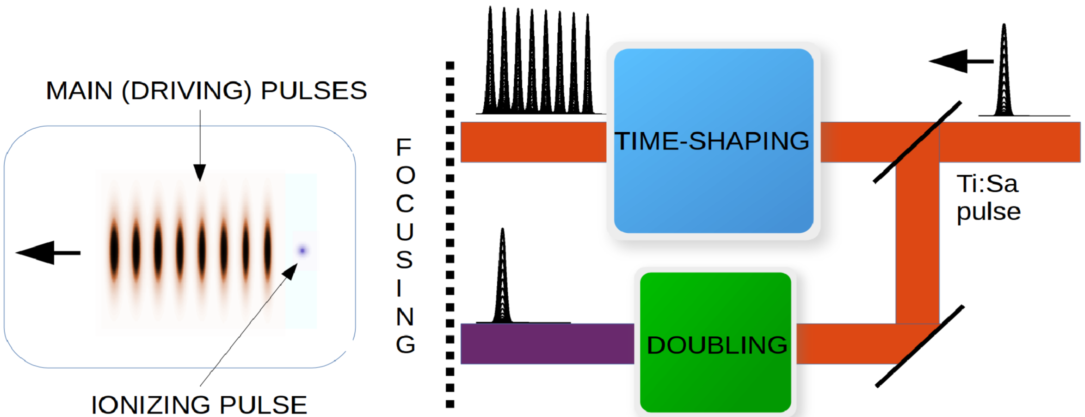
B. Canuel et al., Sub-nanoradiant beam pointing monitoring […], Appl. Opt. 2014, 53, 2906-2916

The Resonant Multi-Pulse Ionization Injection*

- **The Resonant Multi-Pulse Ionization injection [P. Tomassini et al., Phys. Plasmas 24 (2017)] 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.**

P. Tomassini on "FEL-quality 5GeV e-bunches with the Resonant Multi Pulse Ionization injection scheme (ReMPI).
Poster on Wed





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** » has been recently proposed by L. Labate et al. (submitted)

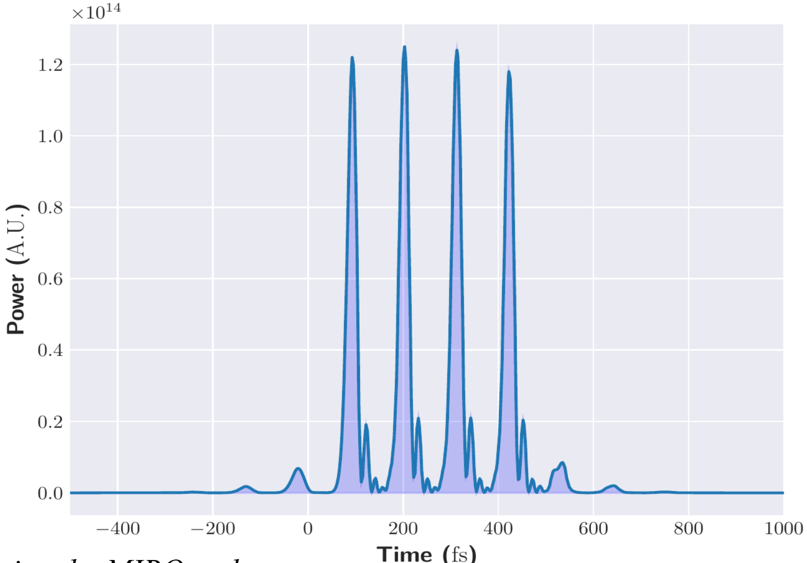
*P. Tomassini et al., *Physics of Plasmas 24, 103120 (2017)*, ***PPCF, 2019 in press***

Pulse train for resonant wakefield

Michelson interferometer approach [1] as a baseline, but needs large optics and leads to significant losses
Use birefringent plates of increasing (doubling) thicknesses and crossed polarization [2].
Complex setup, to be implemented on the compressed (large) beam

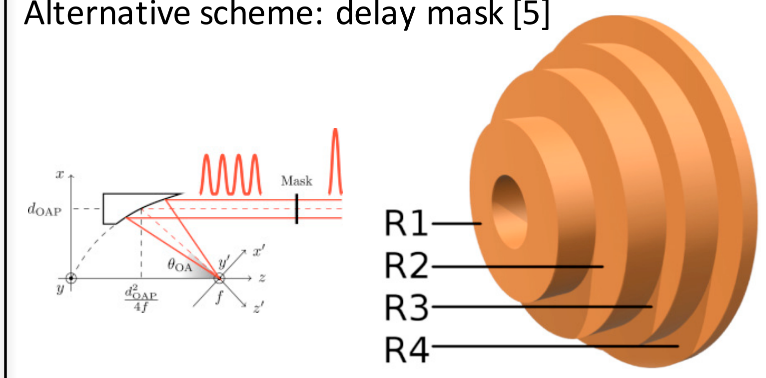
- Intensity homogeneity issues among the different pulses of the same train
- Possibly leading to very high energy losses (up to 50%) ← relevant for the EuPRAXIA laser design

Our approach: quasi lossless Train gEneration by an early aMplitude dIvision (TEMPI) [3,4]:Splitting occurs upstream in the laser chain. Small aperture and negligible energy losses. Effects due to pulse interference manageable.



Simulation carried out using the MIRO code

Alternative scheme: delay mask [5]



Test experiment in progress at CNR ILIL laboratory
Energy losses negligible as compared to the overall pump energy
Compact and simple setup [4]

[1] C. W. Siders *et al.*, Appl. Opt, **37**, 5302–5305 (1998)
[2] B. Dromey *et al., Appl. Opt.* **46**, 5142 (2007)
[3] L. Labate, G. Toci, P. Tomassini, L.A. Gizzi, *submitted*
[4] G. Toci et al. Instruments, **3**, 40 (2019)
[5] G. Vantaggiato et al., NIM-A, 909, 114, (2018)

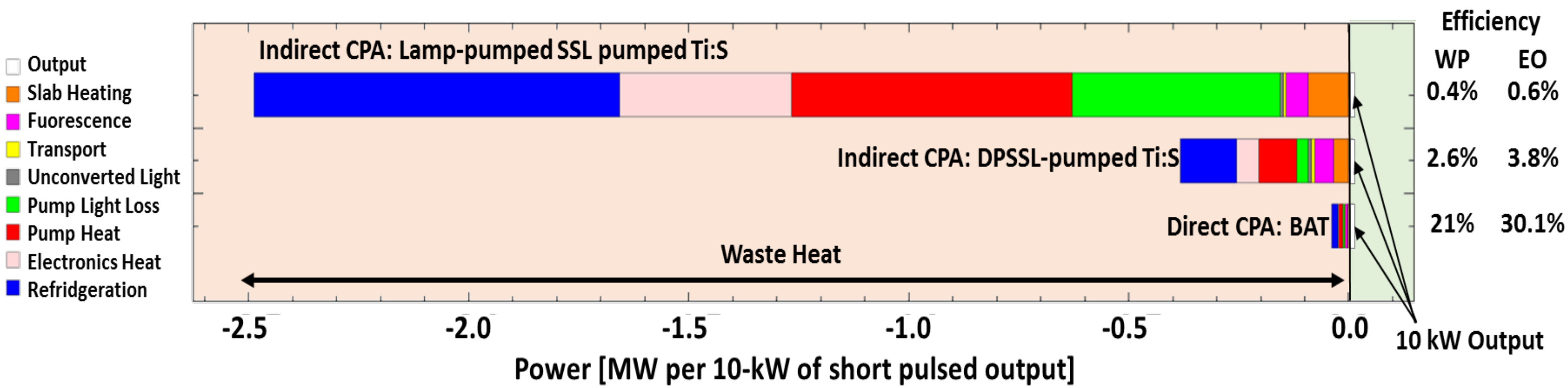
TECHNOLOGY READINESS

- 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.

>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 may become a solution 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.

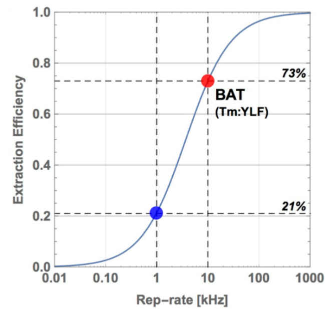
Direct diode pumping

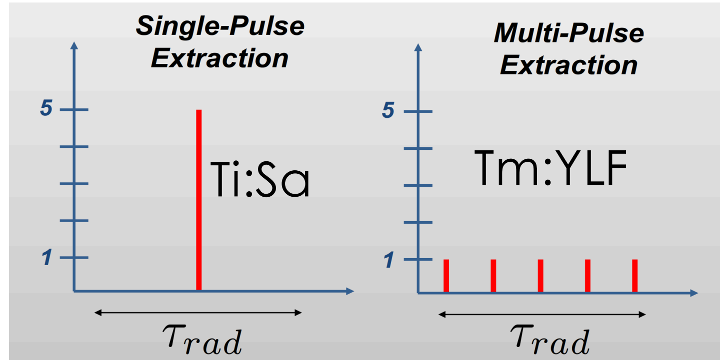
Crystals	Nd: YAG	Yb: YAG	Ti: Sa	Yb: CaF_2
Fluorescence lifetime (ms)	0.23	0.96	0.0032	2.4
Stimulated-em. $\sigma(\times 10^{-20}/cm)$	20 to 30	2.1	30	0.2
Fluorescence wavelengths (nm)	1064	1030	660-1100	1033
Absorption wavelengths (nm)	808	940	514 to 532	980
Fluorescence BW (FWHM) (nm)	0.67	10	440	70
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[1]: 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);





T.C. Galvin et al., Proc . of SPIE Voi. 11033 1103303 (2019)

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 in progress

(1)C. Haefner et al., EAAC 2017

INFN

Lawrence Livermore National Laboratory

CNR-INO ISTITUTO NAZIONALE DI OTTICA CONSIGLIO NAZIONALE DELLE RICERCHE

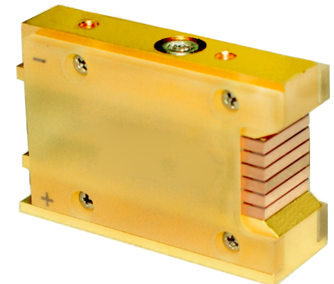
EuPRAXIA

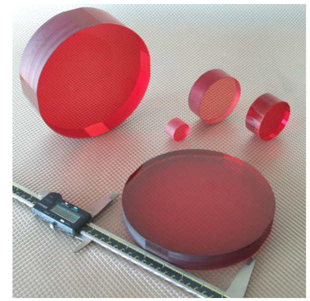
Broader view on driver R&D

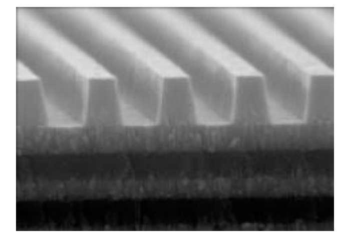
Horizon 2020

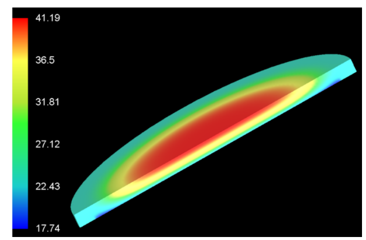
Laser driver relies on industrial development in:

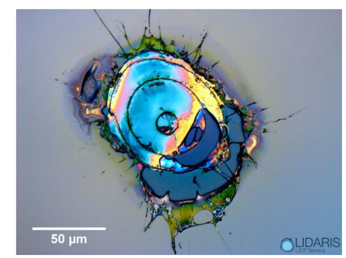
- Pumping technology: diode (direct or indirect) pumping;
- Gain media: material should be industrially available at laser quality, scalable in size and capable of supporting large bandwidth and efficient cooling;
- Grating technology to improve for higher damage threshold and smaller beam size
- Optics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

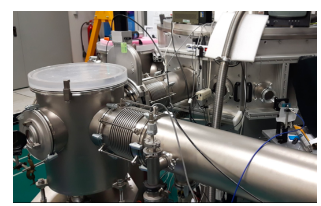












Major R&D and technology transfer to embed in final systems

Cluster on laser technology (EuP-LASTECH):

Main Scientific and Technical issues

Amplifier configuration:

Prototyping of Ti:Sa amplifiers

Build a test amplifier to test Thermal load, Cooling;

Pumping technology:

Scaled 100 Hz rep rep. rate, high energy pumping;

Addressing 100 Hz pump lasers developments

Optical compressor technology:

Thermal management of compressor gratings

Run high average power illumination tests at existing facilities, to make assessments on LIDT, Thermal load, Cooling. Lifetime;

Pointing stability :

Stability (pointing & more) and active control

Build tools and run tests at existing facilities; define route for active stabilization;

Temporal and Spatial Shaping:

Synchronization

Develop efficient pulse train, temporal contrast, AO control and measurements.

Cluster approach

Cluster on laser technology (EuP-LASTECH):

High Repetition Rate Developments

The current layout of the EuPRAXIA laser foresees up to 100 Hz configuration. Beyond this, totally alternative systems based on direct diode pumping of different gain media are being explored like Yb:YAG and Yb:CaF_2 Tm:YLF. Cluster coordination will foster these explorations.

Participating Institutes:

Consiglio Nazionale delle Ricerche; cnrs centre national de la recherche scientifique; FBH Leibniz Ferdinand Braun Institut; Science & Technology Facilities Council; INFN Istituto Nazionale di Fisica Nucleare

Participating Companies:

Amplitude Technologies; THALES; imagine optic; ISP System; Dynamic Optics; SAFRAN; Vacuum FAB Motion Control & Optics; VCS vacuum components & systems; TRUMPF; HORIBA Jobin Yvon

Exploring funding opportunities. Two proposals submitted to TIARA-ARIES.

SUMMARY

- Ti:Sa as a viable options for first generation laser driver
- Addressing open issues
    - Thermal management of
        - Amplifiers
        - Compressor gratings
- Stability (pointing & more) and active control
- Synchronization
- Driver pulse temporal shaping (multi-pulse)
- Longer term solutions with direct diode pumping
- Major need of R&D -> Cluster approach

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shaded: major contributors/collaborators

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THANK YOU FOR YOUR ATTENTION