ALEGRO 2018 workshop, 26 March - 29 March 2018, Oxford, UK

EUROPEAN
PLASMA RESEARCH
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EXCELLENCE IN
APPLICATIONS

EuPRAXIA

Laser Drivers for the EuPRAXIA beamlines

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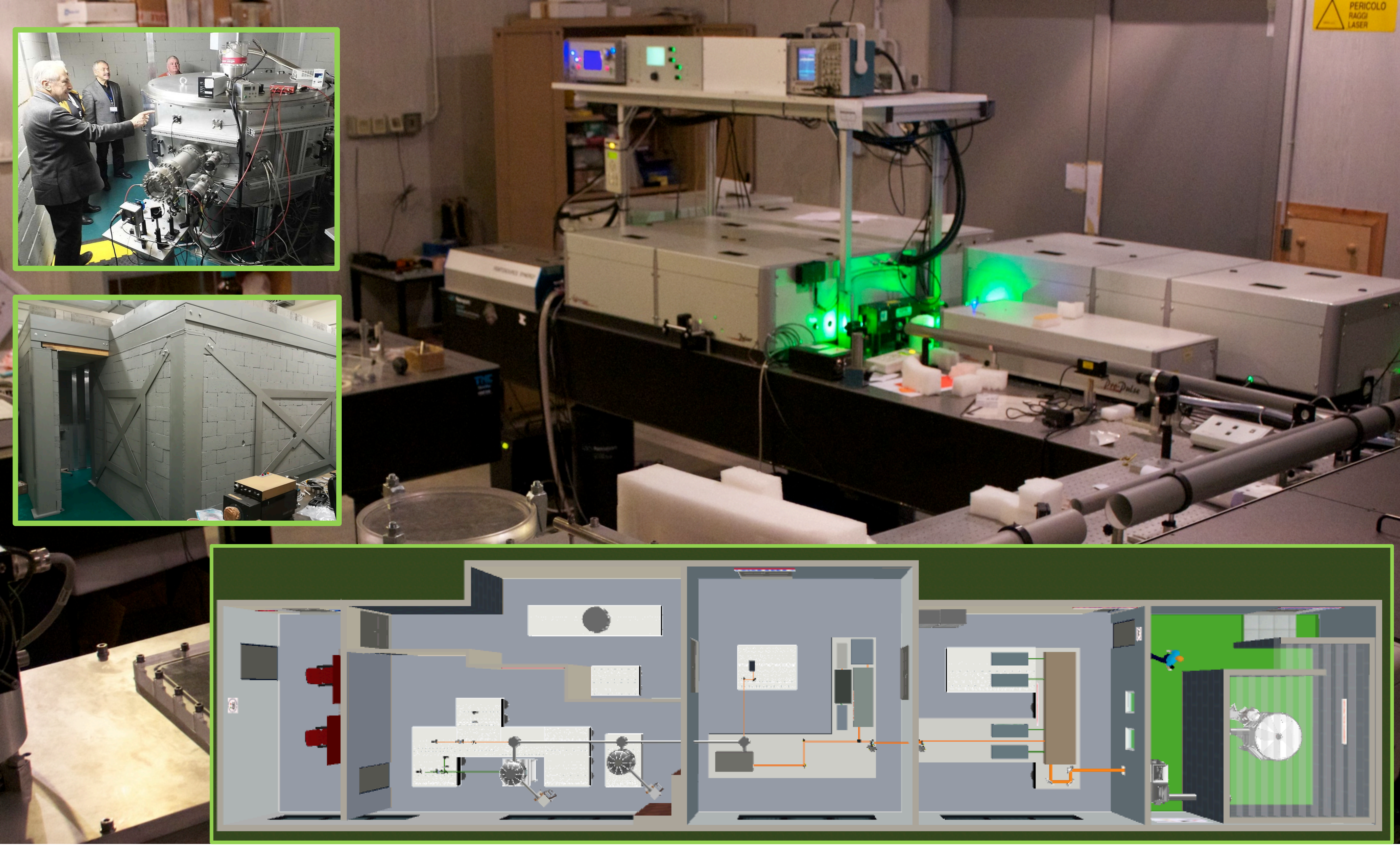
On behalf of the EuPRAXIA Laser Design WP4

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.

Consiglio Nazionale delle Ricerche

Area della Ricerca di Pisa



Laboratorio di Irraggiamento con Laser Intensi

Istituto Nazionale di Ottica – Consiglio Nazionale delle Ricerche

CNR INO
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ISTITUTO NAZIONALE DI OTTICA

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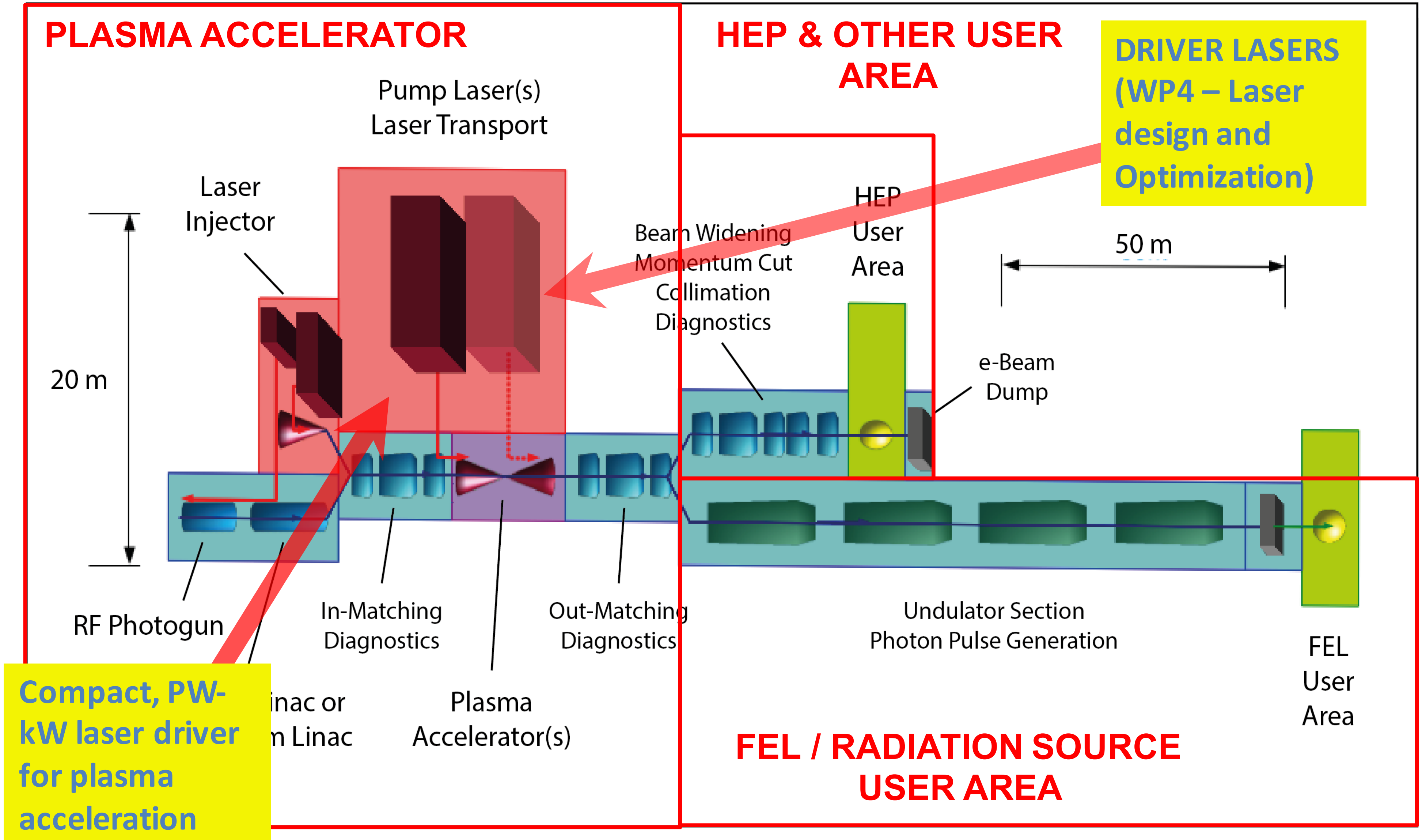
industries (green)
laboratories (blue)
shaded — major contributors/collaborators

CONTENT

- Introduction to EuPRAXIA
- Strategy for a PW-kW laser for EuPRAXIA
- Main EuPRAXIA laser features
- Preliminary laser design
  - Main industrial components
- Needed key industrial developments
- Conclusions

EuPRAXIA LAYOUT



EuPRAXIA Objectives

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

1. Address **quality**. Show **plasma accelerator technology is usable**:
   - Incorporate established accelerator technology for optimal quality
   - Combine expertise from accelerator, laser labs, industry, international partners
   - Develop new technical solutions and a few use cases
2. Show **benefit in size and cost** versus established RF technology:
   - Proposed solutions must offer a significant benefit, e.g. fitting constrained spaces (small labs, hospitals) and/or must be less effective.
   - Cost benefits must include low operational costs (turn-key, industrial lasers at high repetition rate, cost-effective RF components, ...): small team, remote OP, ...

*Note: EuPRAXIA will initially be **low wall-plug power efficiency***

- *Efforts with **industry and laser institutes** to improve rep. rate & efficiency (incorporate all viable laser technologies with higher efficiency)*

Addressing Quality

Application to FEL requires low (total) energy spread (<1%) and low emittance (<1mm mrad)

1. Improve **technical components and approaches in plasma accelerator** concepts producing already GeV class beams:
   - Improved laser technology
   - Feedbacks
   - New and old concepts for solutions in one stage all plasma facility

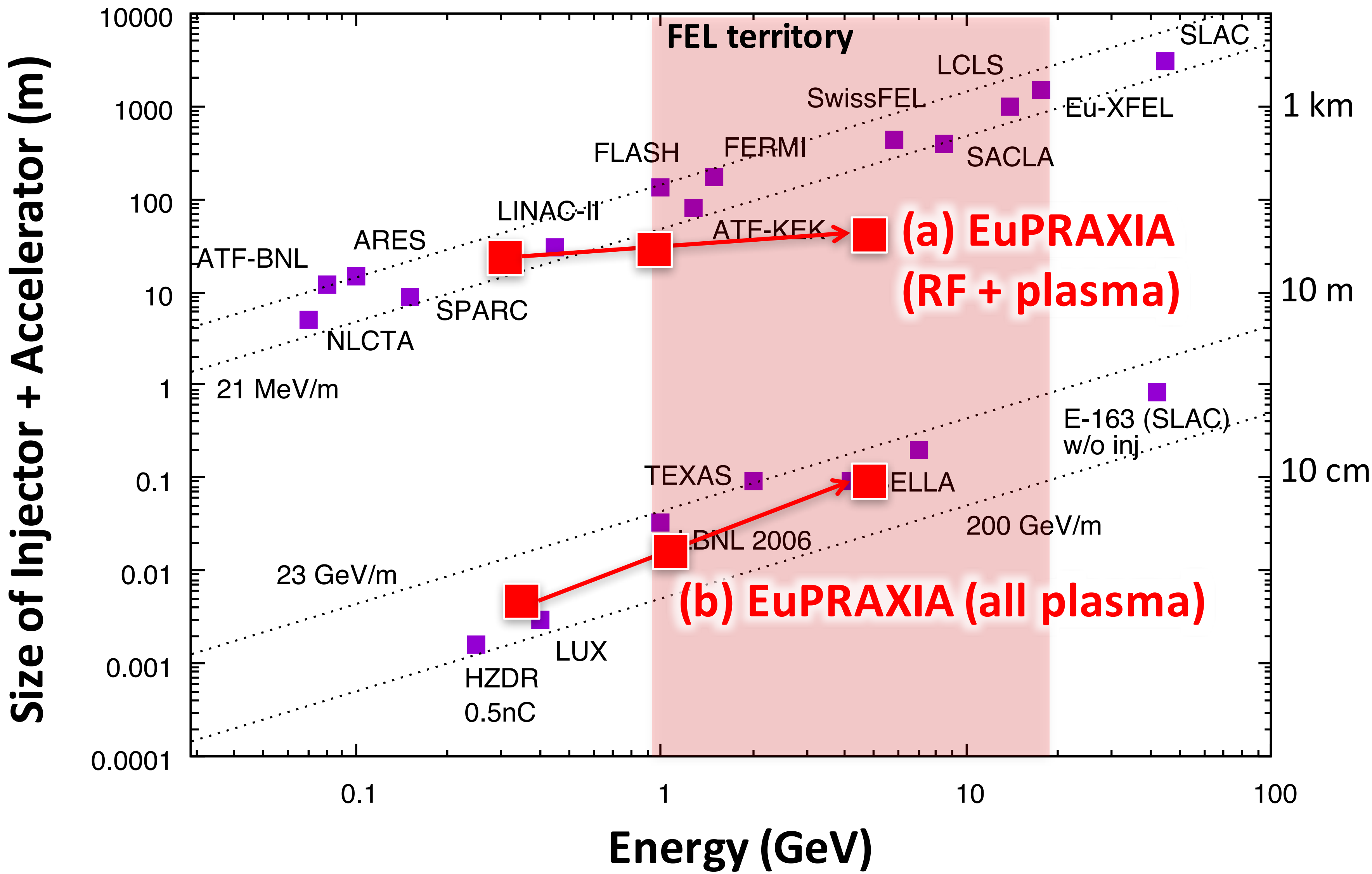
2. Start with a **high quality beam from a small RF injector** and boost it to high energy:
   - Starting point quality is assured (start with FEL quality beam)
   - Solve new issues, e.g. timing: new solutions needed
   - Fully stageable → path to high energy

Project timeline

09.2014	Proposal submission
07.2015	Approval
11.2015	**<u>Start of EuPRAXIA project</u>**
11.2016	First common study version of EuPRAXIA design
11.2017	**<u>Mid-term</u>**
08.2019	Application to **<u>ESFRI roadmap</u>** for 2020 update
10.2019	Final **<u>conceptual design report</u>** and end design study
2020+	*Construction decision*
> 2021 – 2025	*Construction*
> 2025 – 2035	*Operation*

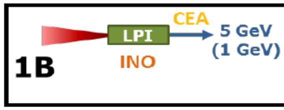
Short time scale: EuPRAXIA Laser design based on technology with high TRL
Guideline: exploring extension of existing concepts and prototypes

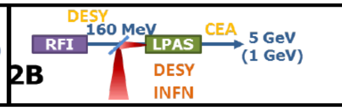
EuPRAXIA Development Paths
towards high quality electron beams

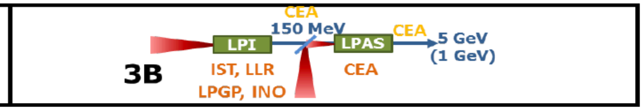


Schemes under consideration (WP2)

Horizon 2020







Final Energy			150 MeV	1Gev / 5 Gev
1 GeV	CNR-INO (P.Tomassini) DL: 0.9x8 J, 30 fs, 45 µm IL (2nd Harm.): 0.01 J, 38 fs, 3.5 µm delay 40 fs	DESY (E.Svystun & A.F. Pousa) 101 J 100 fs 54.4 µm INFN (Andrea Rossi) 6.4 J 110 fs 35 µm	IST-ID L. Silva & J. Vieira 0.45 J 28 fs 8.4 µm CNRS-LLR (A. Beck) 10.5 J 28 fs 40 µm CNRS-LPGP (G. Maynard) 0.47 J 20 fs 16 µm CNR-INO (P.Tomassini)* DL: 0.7x4-0.3x8 J, 25 fs, 27 µm IL (3omega): 0.02 J, 30 fs, 4.2 µm delay 47 - 49 fs; *N2-Ar	CEA (X. Li & P. Nghiem) Quasi - linear: 15J, 1080 fs, 55 µm Bubble:
5 GeV	CNR-INO (P.Tomassini) DL: 2.2x8 J, 50 fs, 60 µm IL (3rd Harm.): 0.02 J, 60 fs, 3.5 µm delay 102 fs	DESY (E.Svystun & A.F. Pousa) 45.6 J 70 fs 50 µm INFN (Andrea rossi) 25.6 J 110 fs 70 µm		CEA (X. Li & P. Nghiem) Quasi - linear: 53J, 130 fs, 55 µm Bubble: 75 J, 108 fs, 48 µm

energy (J)
duration (fs) FWHM
waist (µm)

150 Mev
1GeV
5GeV

nothing proposed for the 4B

Large BW (≈30 fs) required for injector/1GeV stage. May be relaxed (≈50 fs) for 5GeV stage.
Not compatible with many available direct CPA schemes (Nd, Yb).
MULTI-PULSE drivers attracting increasing attention.

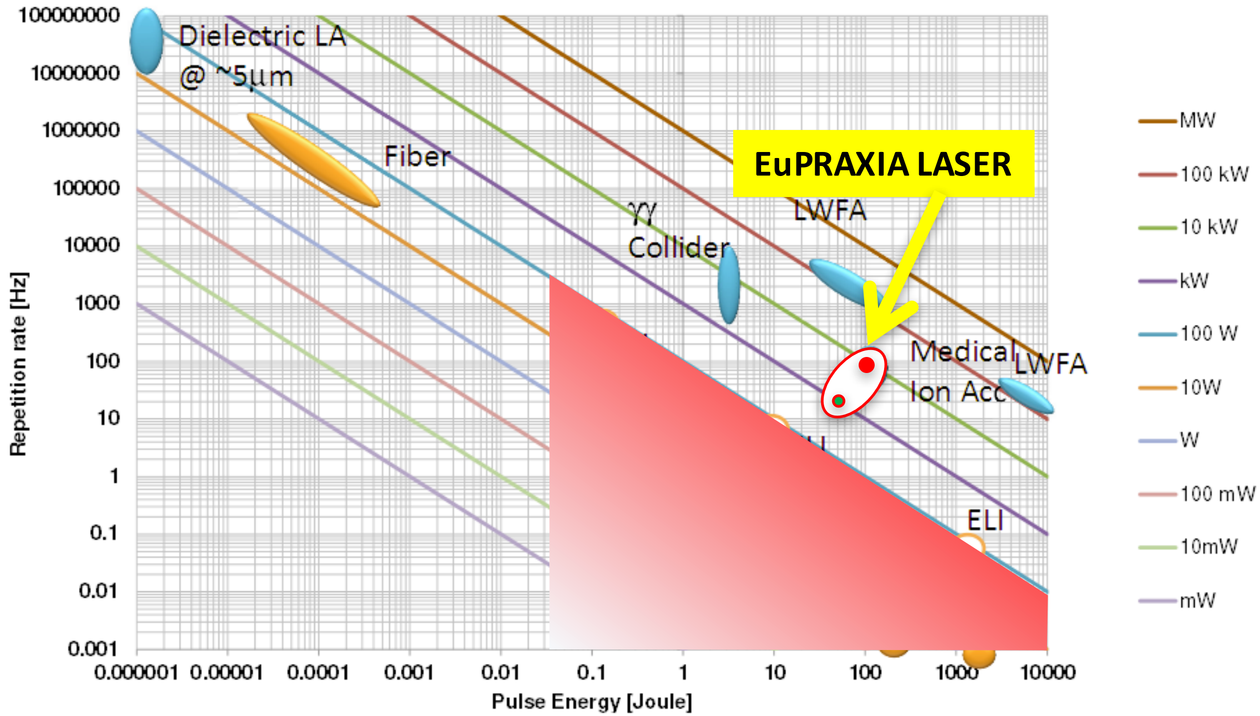
KEY FEATURES OF EUPRAXIA LASER

Horizon 2020

- Short pulse PW-kW laser technology (CPA, diode pumping);
- High repetition rate to allow user operation while enabling active stabilization via feedback loops;
  - Minimum 20 Hz, but exploring 100 Hz option
- Average power ranging from 1kW to 10 kW;
- Extraordinary performances of beam transport, focusing, diagnostics with the reliability of an industrial system.
- Pump lasers, TiSa crystal management and compressor gratings at 100 Hz need funding and demonstrators prior to final TDR – collaboration ready to start.

EuPRAXIA LASER: A STEP FORWARD

A PW-class system, with **demanding high average power**
(>1 **kW,** ideally 10 kW**)**



The EuPRAXIA **PW-kW** laser is, by all means, a unique system.

Programmes worldwide (e.g. kBELLA, LBNL, US) are exploring similar concepts.

EU can build on current leadership in PW laser technology to keep the pace.

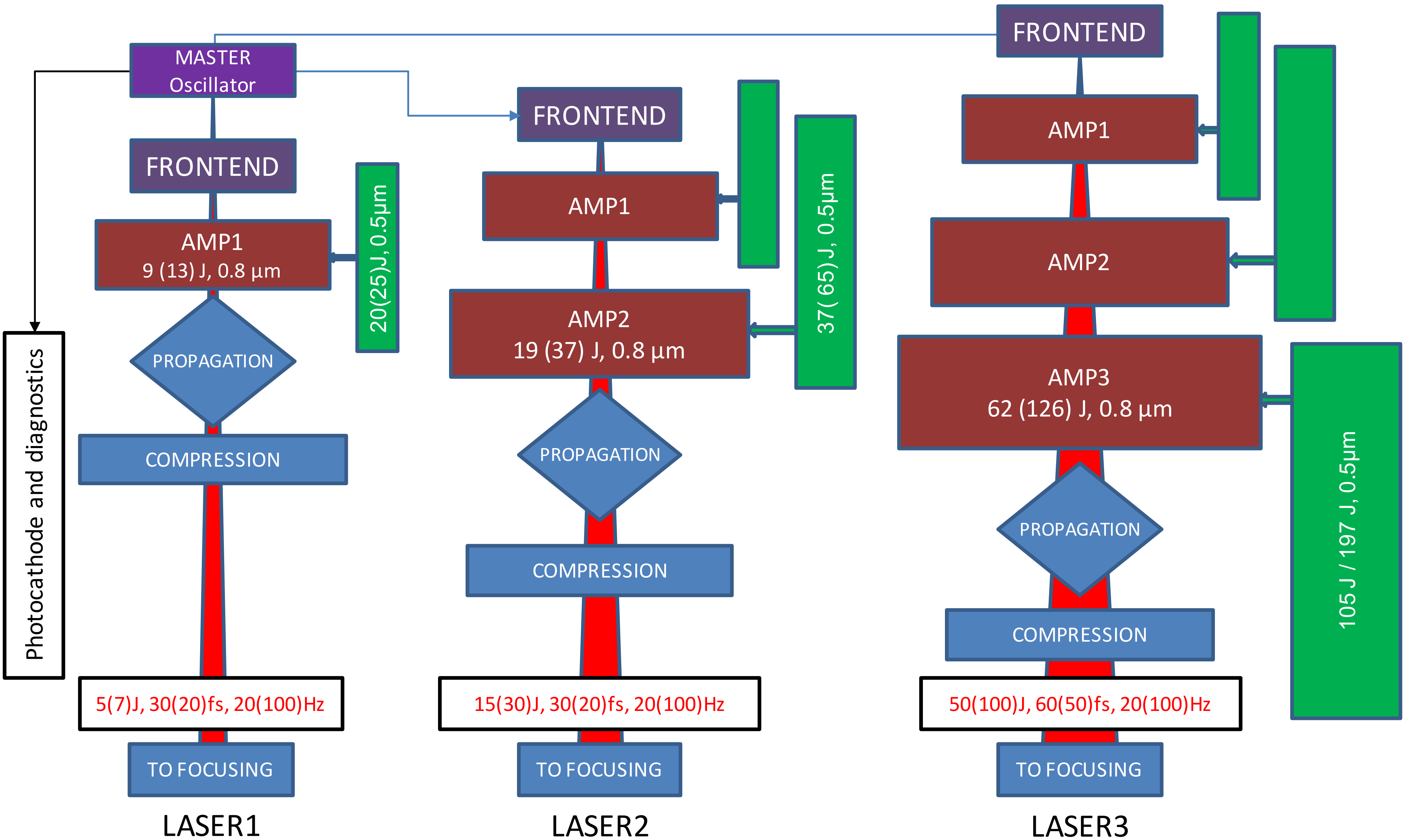
LASER: STRATEGY 1/2

- **EuPRAXIA requires up to tens of kW** average laser power with PW peak power and up to 100 Hz repetition rate;
- **Consensus** reached in the EuPRAXIA laser community is that Ti:Sa technology pumped by diode-pumped solid state (DPSSL) lasers provides a relatively safe ground, with major European industrial endeavour in place;
- **Recent developments** match our requirements, with DPSSL prototypes pump lasers offering kW performances with potential scalability to 10s of kW at the required wavelength of 0.5 μm;
- At the same time, **other technologies are developing** aiming at higher rep. rates, higher average power levels and even more efficient configurations.

LASER: STRATEGY 2/2

- **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 if EuPRAXIA evolves towards lower energy per pulse >10 kHz;
- **Direct Chirped Pulse Amplification** with lasing media pumped directly by diodes is ideal for higher efficiency and higher rep-rate (see also M4.2 milestone report of April 2017)
- **Direct CPA concepts explored** in benchmarking phase and bottlenecks emerged concerning the minimum achievable pulse duration and scaling;
- **More recently**, motivated by kBELLA project (LBNL, US) and also by EuPRAXIA, new concepts are emerging in this scenario (LLNL), now entering design and prototyping for intermediate average power levels;
- **Consideration is given** to such schemes in view of significant ongoing developments for possible complementary combinations.

EuPRAXIA LASER (Ti:Sa)



Summary Tables

LASER 1 - Injector 150 MeV

Parameter	Label	P0	P1
Wavelength (nm)	$\lambda_{1\,(nm)}$	800	800
Maximum energy on target (J)	E_{target}	5	7
Maximum output energy (J)	E_{out}	8.8	12.5
Energy tuning resolution (% of targeted value)	dE	7	5
Total output energy (incl. Diagnostic beams)	E_{tot}	7	10
Pulse length (FWHM) (fs)	τ_1	30	20
Repetition rate (Hz)	f_1	20	100
Requirement on energy stability (RMS) %	$\sigma_{<E>}$	1	0.6

LASER 2 - Injector 1 GeV

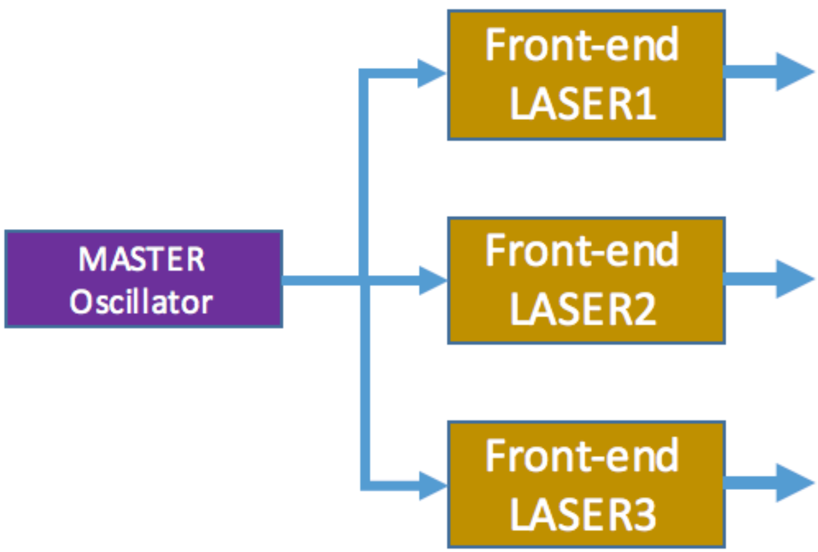
Parameter	Label	P0	P1
Wavelength (nm)	$\lambda_{2\,(nm)}$	800	800
Maximum energy on target (J)	E_{target}	15	30
Maximum output energy (J)	E_{out}	18.8	37.5
Energy tuning resolution (% of targeted value)	dE	7	5
Shortest pulse length (FWHM) (fs)	τ_2	30	20
Repetition rate (Hz)	f_2	20	100
Requirement on energy stability (RMS) %	$\sigma_{<E>}$	1	0.6

LASER 3 - Driver 5 GeV

Parameter	Label	P0	P1
Wavelength (nm)	$\lambda_{2\,(nm)}$	800	800
Maximum energy on target (J) *	E_{target}	50	100
Maximum output energy (J)	E_{out}	62.5	125
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
Requirement on energy stability (RMS) %	$\sigma_{<E>}$	1	0.6

FRONT-END

Each laser beamline required independent spectral amplitude/phase control that is carried out in the front-end: EuPRAXIA required three independent front-end sections seeded by the same laser oscillator independently as per the requirements of the seeding of each of the three amplification chains

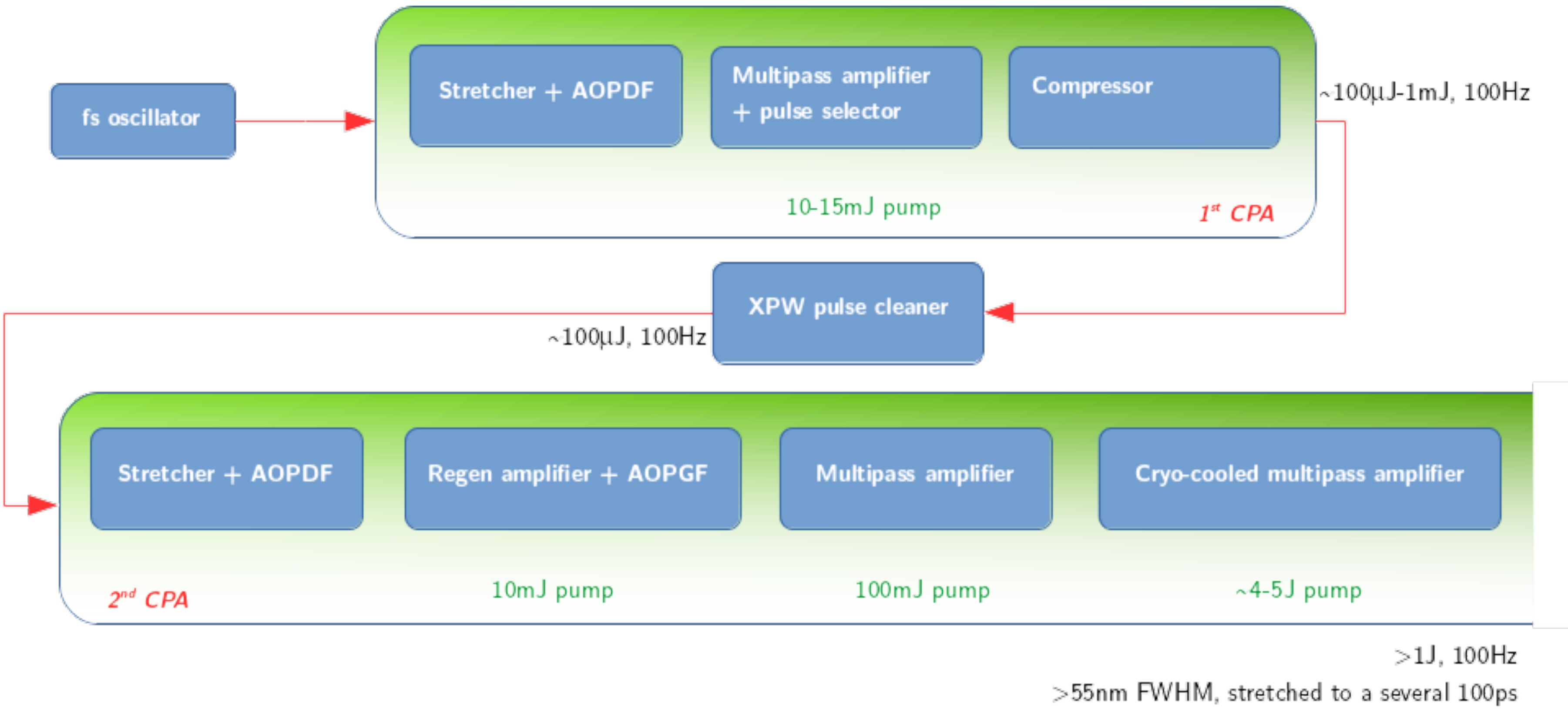


- Overall synchronization: single master oscillator, broadband
- Independent adjustment of spectral amplitude for each amplification chain: separate front –ends, with the same architecture
- Pulse energy 1.0-1.5 J
- Stretched pulse duration ~ 500 ps
- Main requirement: high pre-pulse contrast

Each of these front-end will deliver stretched pulses with ~1J energy to the subsequent amplification stages

Main Front-end components

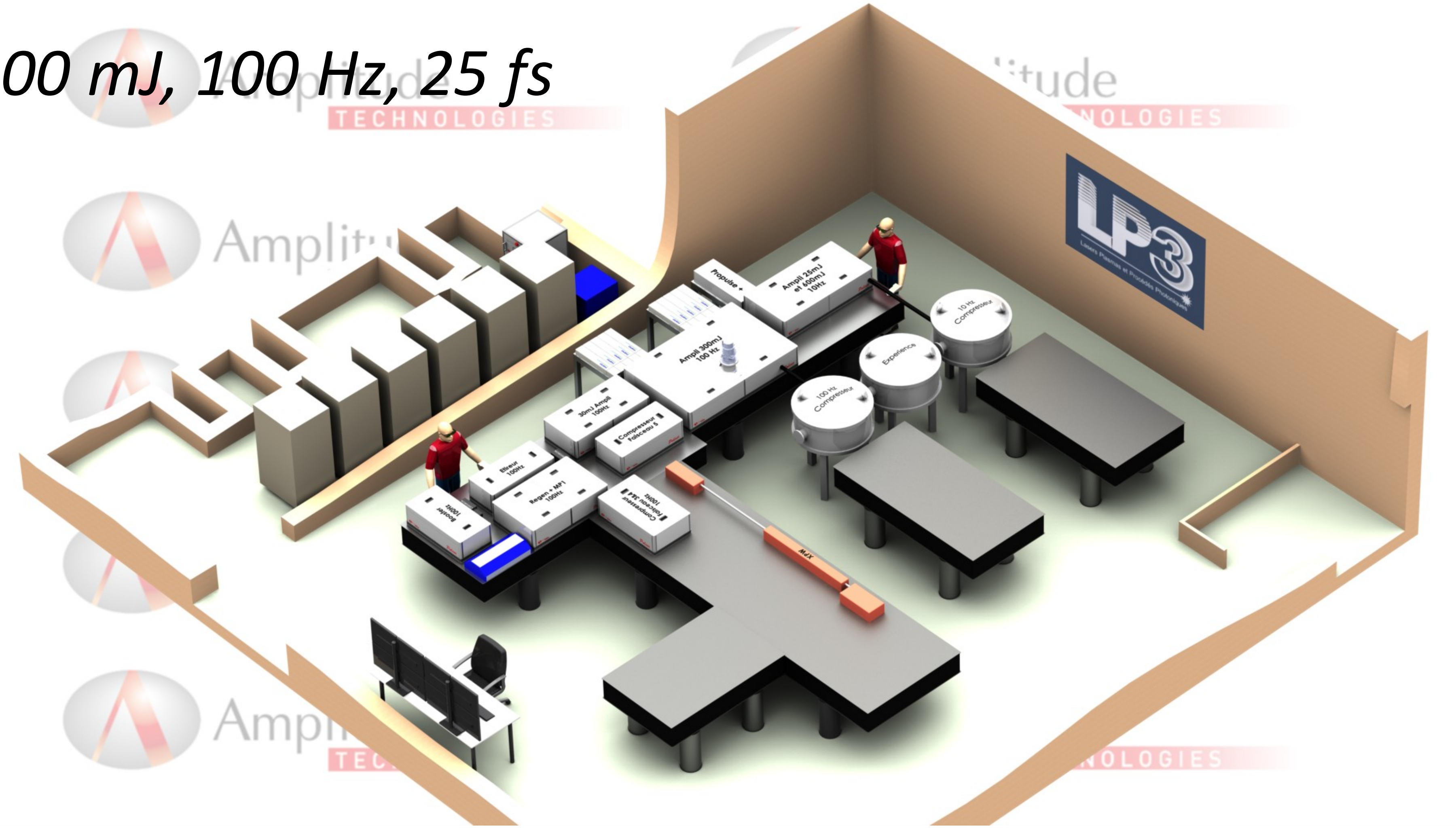
State of the art components to ensure pulse energy for the main amplifiers with large bandwidth (short pulse duration), control of spectral phase, high contrast …



Starting from existing industrial systems at 100 Hz

INDUSTRIAL SUBSYSTEMS: an example

300 mJ, 100 Hz, 25 fs



Amplifiers strategy

Design guidelines

- Modularity: possibility to use the same amplification stages in the different laser chains
- Scalability: possibility to upgrade from P0 to P1 performance level, “simply” by increasing pump energy and rep rate (conservative design at P0)
- **High extraction efficiency (esp. at P1) to reduce pump energy requirements**
- **Thermal management issues**

Methodology

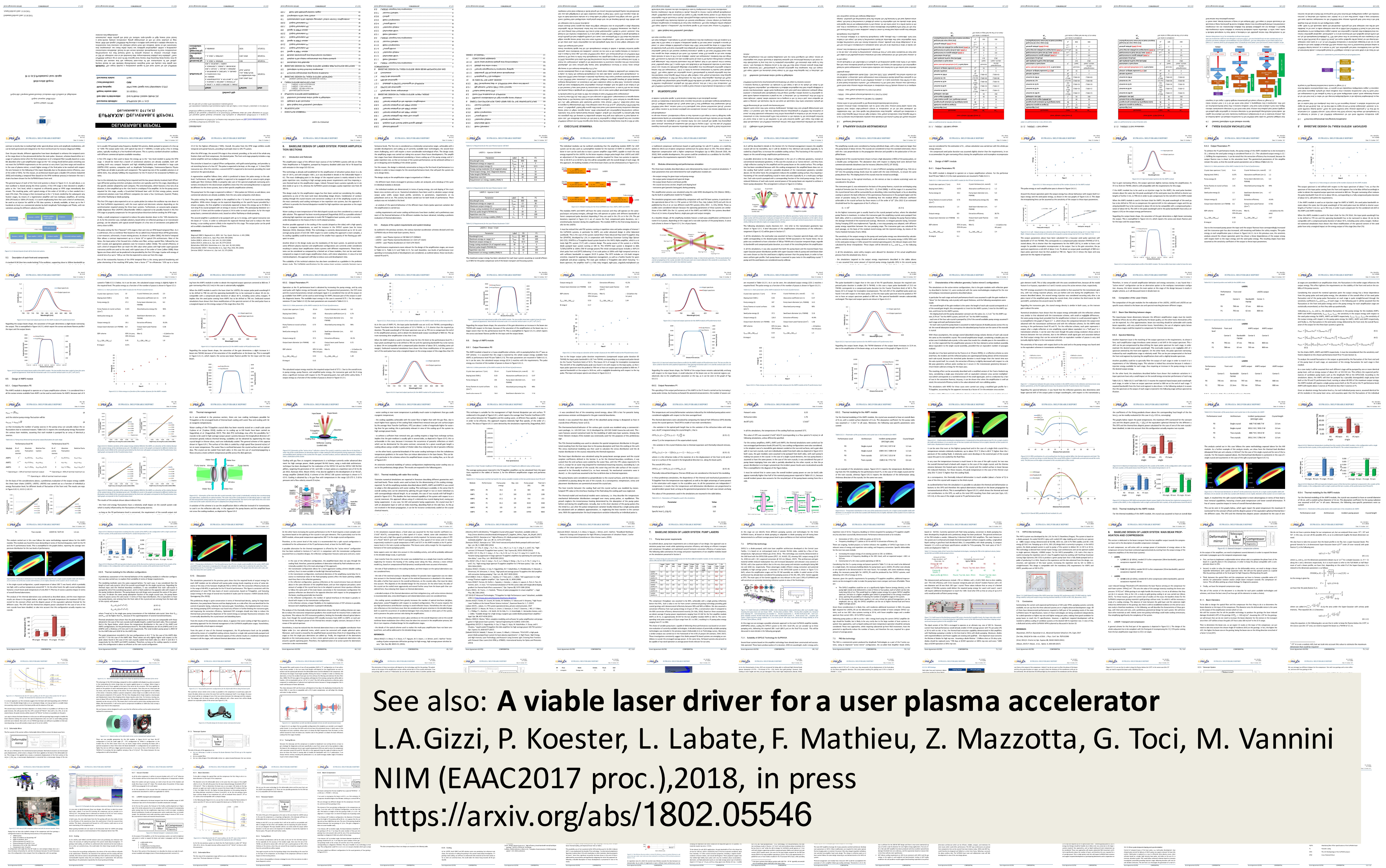
- Evaluation of the amplification parameters (energy, spectrum, beam size, stability, parasitic lasing) with numerical simulations (MIRO - CEA);
-Validation of modelling with existing systems up to multi-J level;
- Preliminary thermomechanical evaluation by means of FEA simulations (LAS-CAD);

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

EuPRAXIA Report on preliminary Laser design

Horizon 2020



See also: **A viable laser driver for a user plasma accelerator**

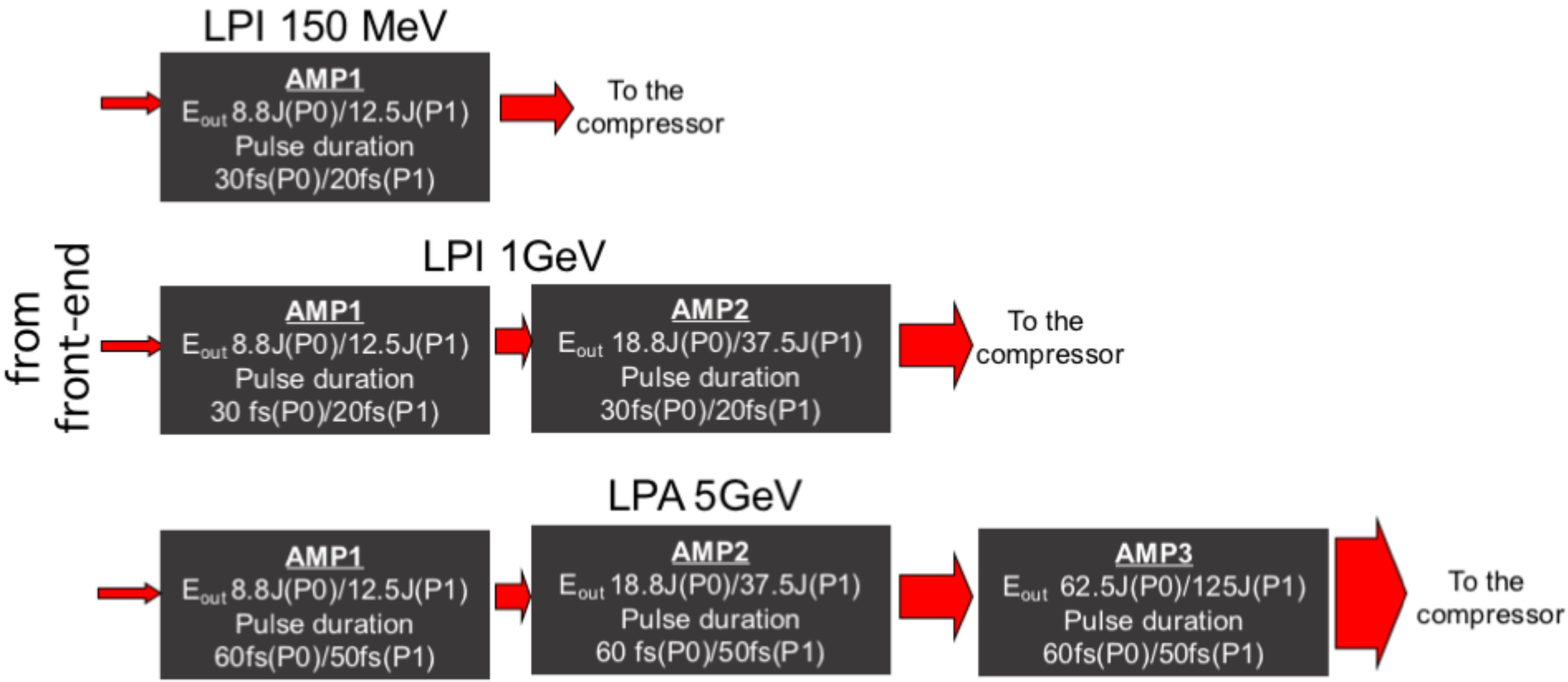
L.A.Gizzi, P. Koester, L. Labate, F. Mathieu, Z. Mazzotta, G. Toci, M. Vannini

NIM (EAAC2017 proc.),2018, in press

https://arxiv.org/abs/1802.05546

Beams and amplifier stages

Amplifiers' performances modelled to size components and confirm basic estimates



Power amplifiers: needed <P>

Horizon 2020

Power amplifiers require high average power pump lasers

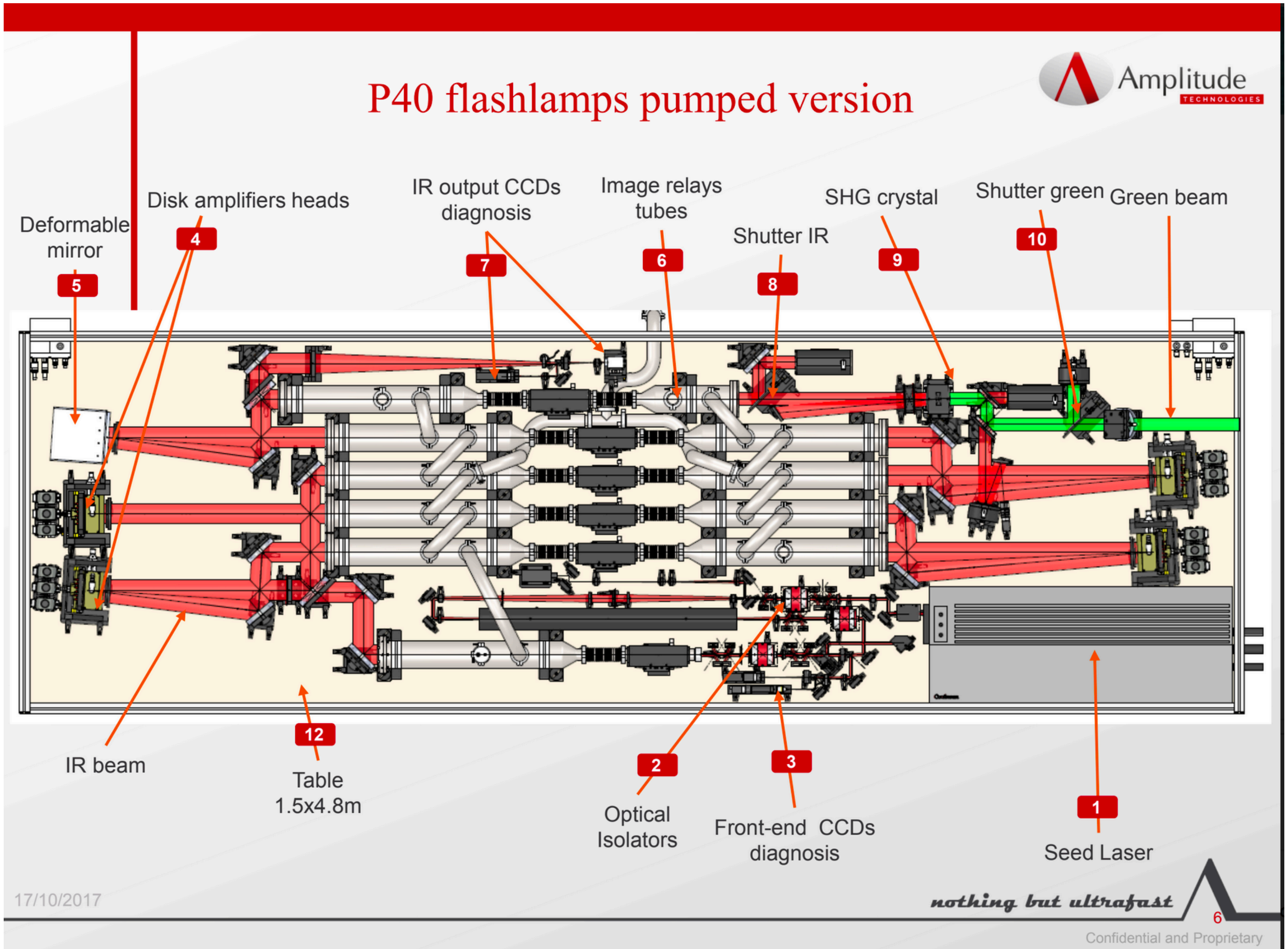
	Target E (J)	Out E (J)	PRF (Hz)	Seed E (J)	Design Out E (J)	0.5µm Pulse E (J)	Extr. Eff. (%)	<P> (532 nm) (kW)	Thermal Load (kW)	IR Pulse E (J)	<P> (1µm) (kW)
LASER1 (AMP1) P0	7,0	8,8	20	1,5	8,9	19,2	39	0,4	0,2	27,4	0,5
LASER1 (AMP1) P1	10,0	12,5	100	1,5	12,7	25,7	44	2,6	1,3	36,7	3,7
LASER2 (AMP2) P0	15,0	18,8	20	6,3	19,1	37,2	35	0,7	0,4	53,1	1,1
LASER2 (AMP2) P1	30,0	37,5	100	8,8	37,5	65,2	44	6,5	3,3	93,1	9,3
LASER3 (AMP3) P0	50,0	62,5	20	18,8	62,4	105,0	42	2,1	1,1	150,0	3,0
LASER3 (AMP3) P1	100,0	125,0	100	37,5	126,0	197,0	45	19,7	9,9	281,4	28,1

Total fundamental wavelength average power estimates ranges from **5 kW** (20 Kz) to **40 kW** (100 Hz)

INDUSTRIAL SUBSYSTEMS: PUMP LASERS

Horizon 2020

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

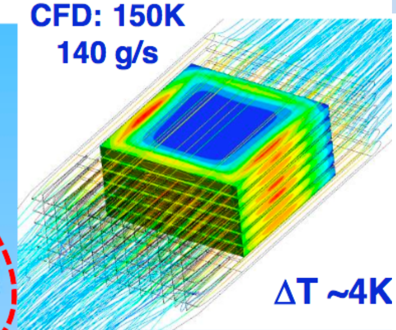


Flashlamp pumped Nd:YAG/
DPSSL possible
80 J output energy demonstrated @ **10 Hz**, 1064 nm
60 J SHG energy @ 532 nm : design target (**40 J** demonstrated)

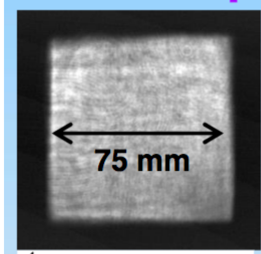
- Cost of diode still an issue – currently 5x total (including operational) costs compared to flashlamps.
- Expected to decrease in 5-10 yrs.
- Maintenance free operation for 25-30 yrs.

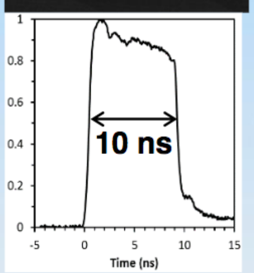
DiPOLE 100

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

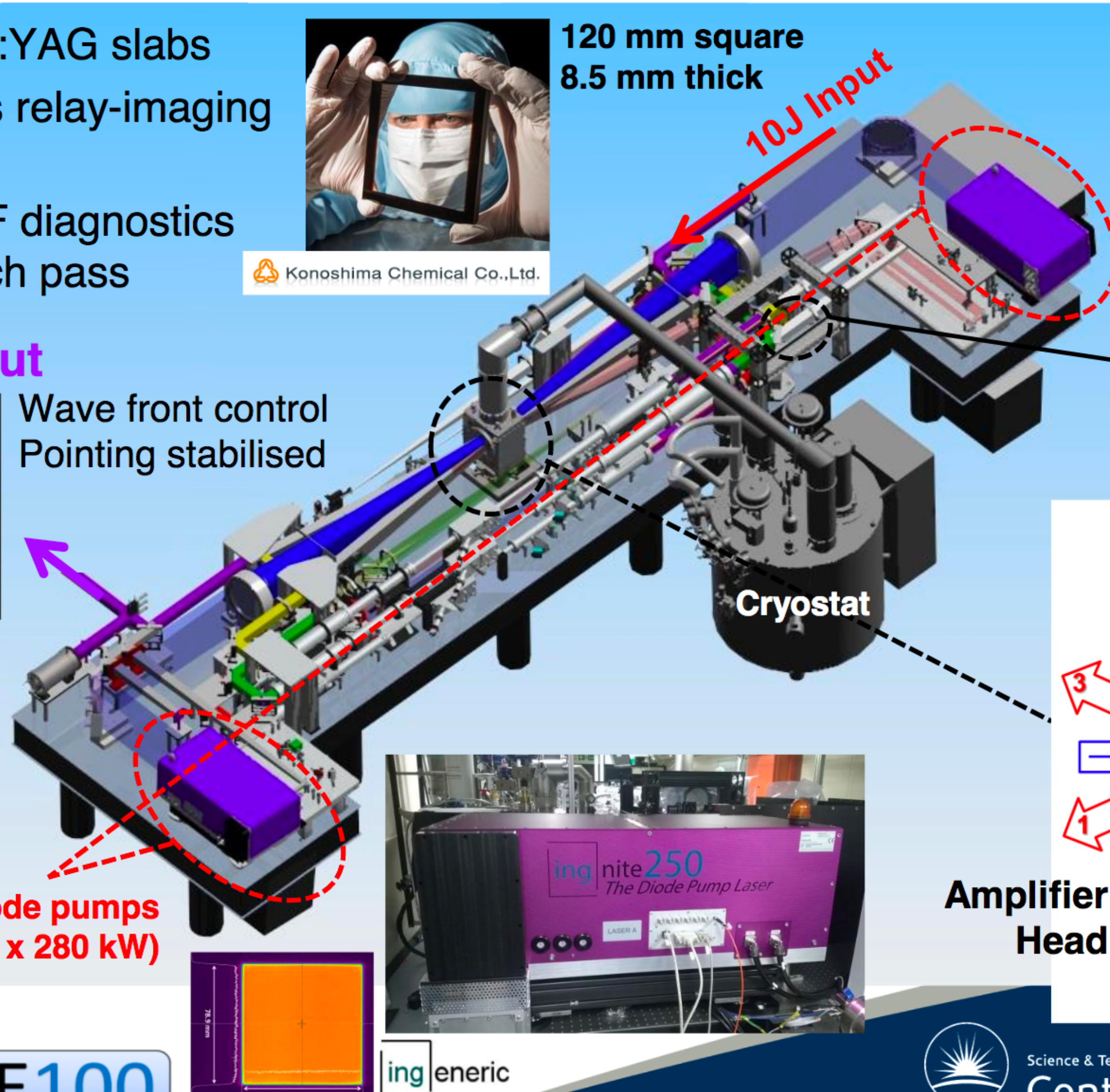


100J output

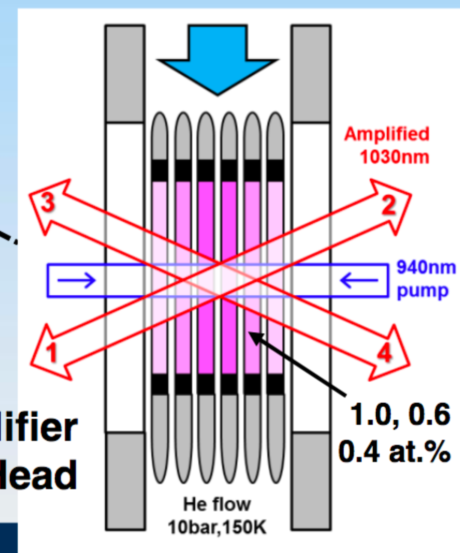




Wave front control
Pointing stabilised



He flow



Amplifier Head

ingeneric

DiPOLE100

Science & Technology Facilities Council
Central Laser Facility

SCENARIO FOR BASELINE (MANDATORY)

Parameter	L1	L2	L3
Pulse rate (Hz)	**20 (100)**	**20 (100)**	**20 (100)**
Wavelength	**515**	**515**	**515**
Energy (J)	19 (26)	37 (65)	105 (200)
Power (kW)	0.4 (2.6)	0.7 (6.5)	2.1 (20)
Conversion	70%	70%	70%
Wavelength	**1030**	**1030**	**1030**
Energy (J)	27 (37)	53 (93)	150 (280)
Power (kW)	0.5 (3.7)	1.1 (9.3)	3.0 (28)
Extraction	25%	25%	25%
Diode	**940**	**940**	**940**
Power (kW)	2.0 (15)	4.4 (37)	12 (112)

DiPOLE

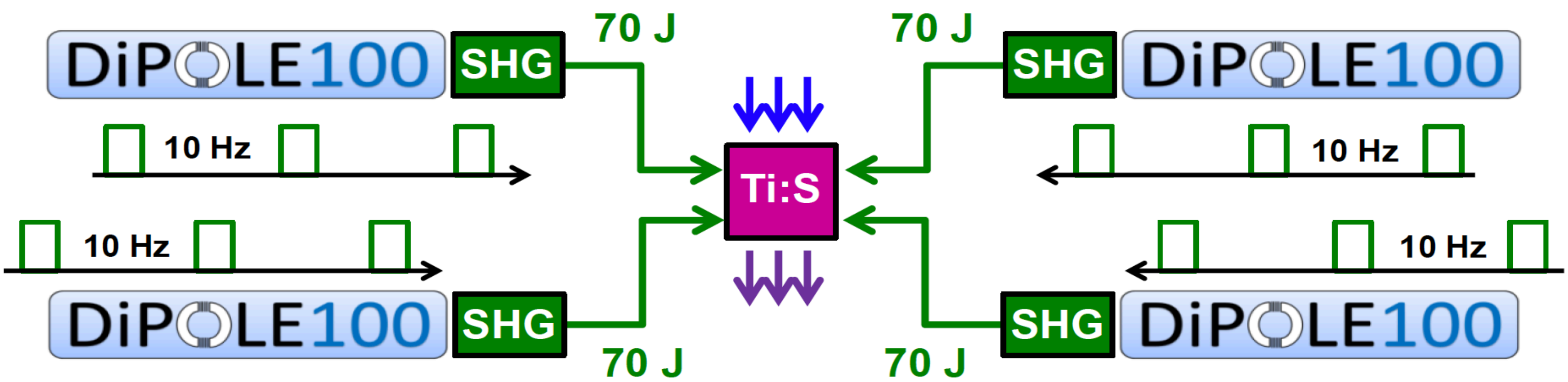
Building blocks exist (or available in near future) for **Baseline performance**

P. Mason, M. Divoký, K. Ertel, J. Pilar, T. Butcher, M. Hanuš, S. Banerjee, J. Phillips, J. Smith, M. D. Vido, A. Lucianetti, C. Hernandez-Gomez, C. Edwards, T. Mocek, J. Collier, Kilowatt average power 100j-level diode pumped solid state laser, Optica 4 (4) (2017) 438–439

EXISTING off-the-shelf Technology

- L3 Baseline: 105 J @ **515 nm**, 20 Hz
  - Interleave 4 x DiPOLE100 @ 10 Hz

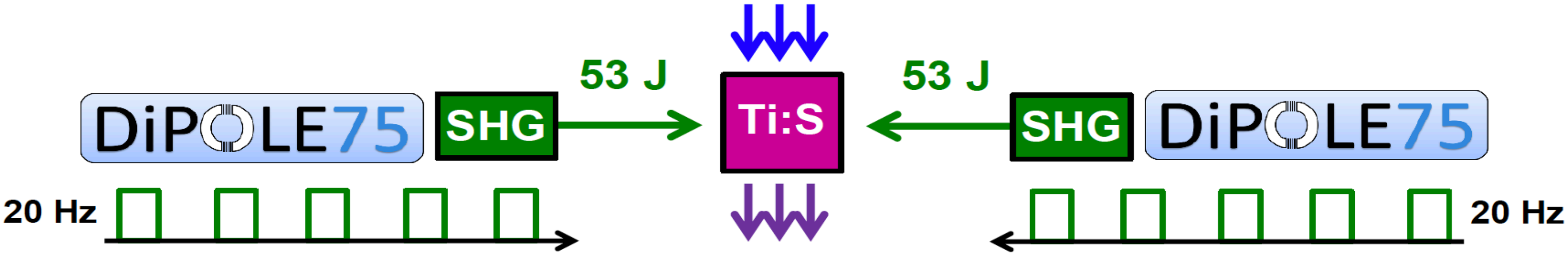
- 140 J @ **515 nm**, 20 Hz



PLANNED TECHNOLOGY

- L3 Baseline: 105 J @ **515 nm**, 20 Hz
  - DiPOLE150 @ 10 Hz (4.1 kW thermal load)
  - 2 x DiPOLE75 @ 20 Hz

- 105 J @ **515 nm**, 20 Hz



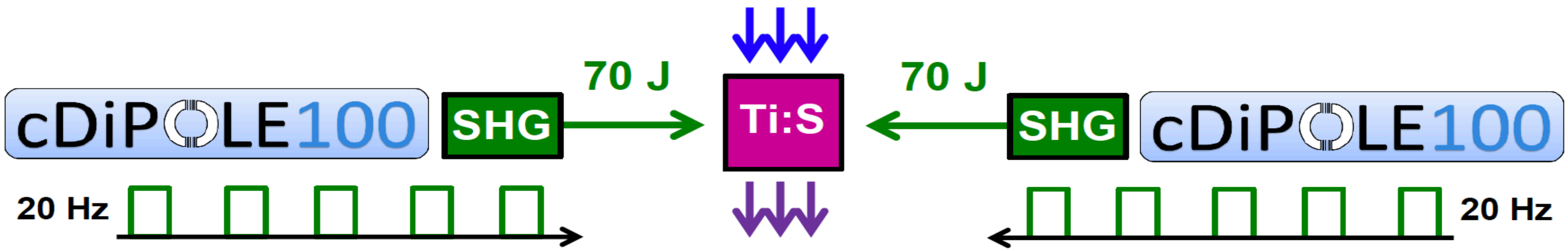
MODERATE R&D INVESTMENTS

Horizon 2020

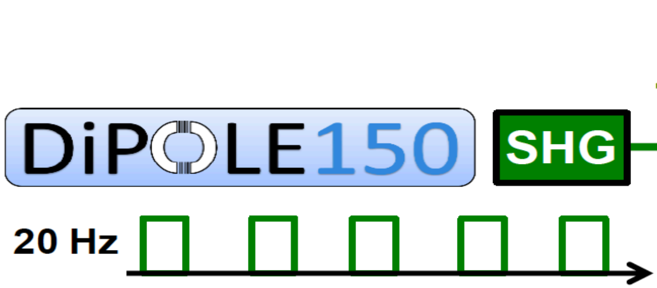
- L3 Baseline: 105 J @ **515 nm**, 20 Hz
  - Operate @ higher fluence ⇒ reduce aperture
  - Higher gain ⇒ fewer amplifier stages
  - Relax beam quality ⇒ higher thermal load (P_{avg}, PRF)
  - 2 x compact-DiPOLE100 @ 20 Hz (5.5 kW load)

Compact

Simpler & more affordable



<u>or</u> 1 x DiPOLE150 @ 20 Hz (8 kW load)

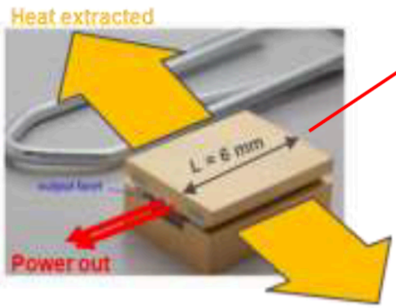


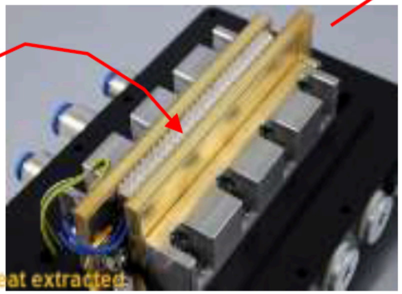
100 Hz pump laser

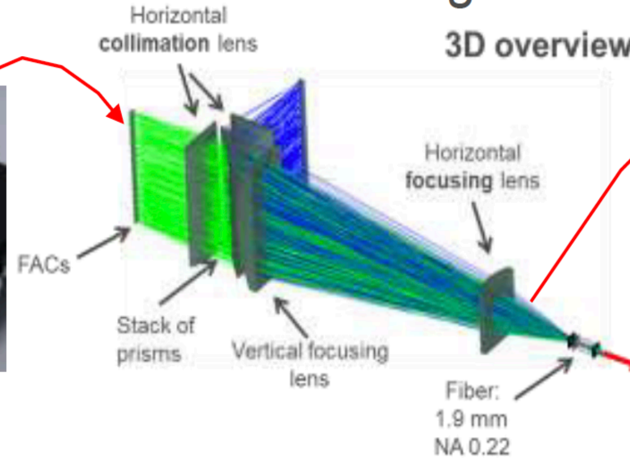
Horizon 2020

FBH brilliant high duty cycle pump: small-series prototype

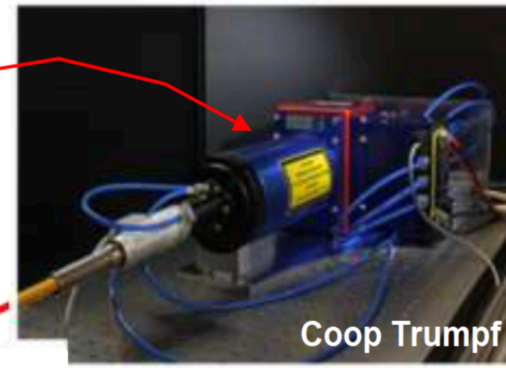
Novel chip, carrier → Novel passive Side cooler → Custom beam forming → Brilliant, high duty cycle fibered module







6 kW



130W from 1.2mm
Peak: ~ 245 W
60% efficiency
2x brighter than bars

1…20% DC
1…100ms
Passive cooling

6 kW 60% efficiency
M^2 ~ 300 x 300

1.4 MW/cm^2-sr
50% efficiency
M^2 ~ 700

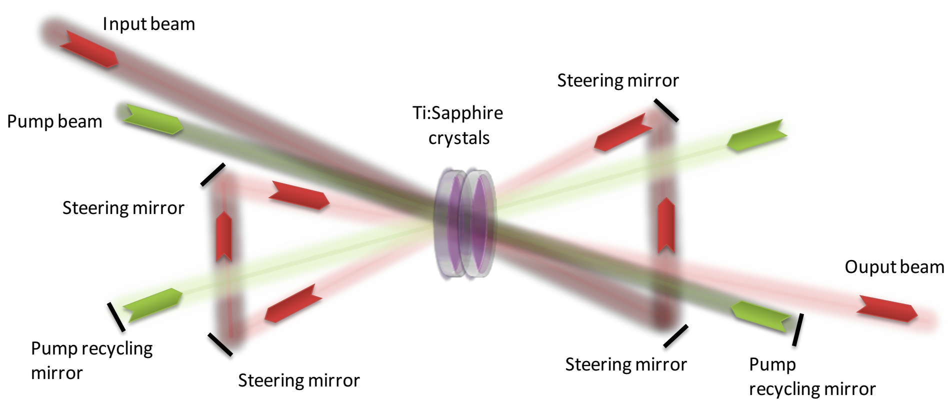
6 units delivered to Max Born Institut, Berlin; 2 in build

Leibniz Ferdinand Braun Institut

Thermal management

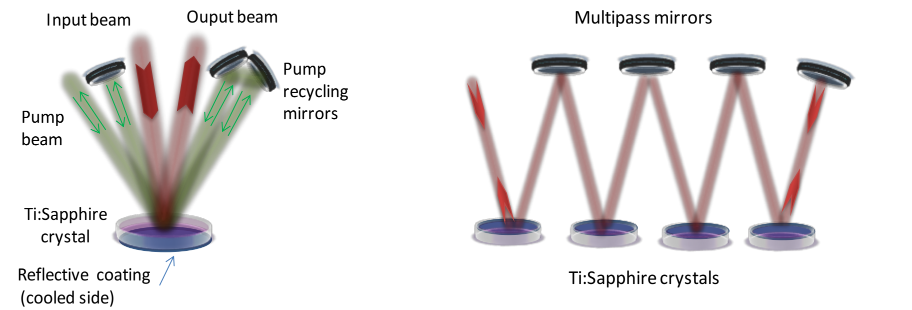
Transmission vs. "active mirror" configuration is currently being evaluated to account for thermal management

Transmission geometry

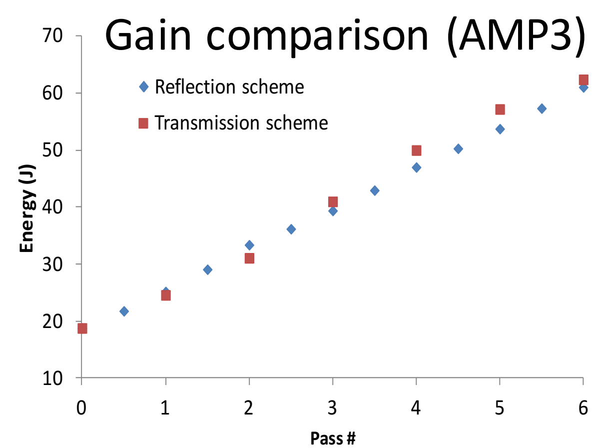


Pro: More efficient (double-side) cooling and reduced complexity;
Con: propagation through flowing cooling liquid

"Active mirror" geometry



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

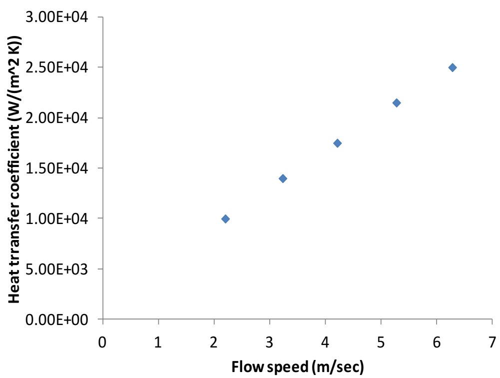


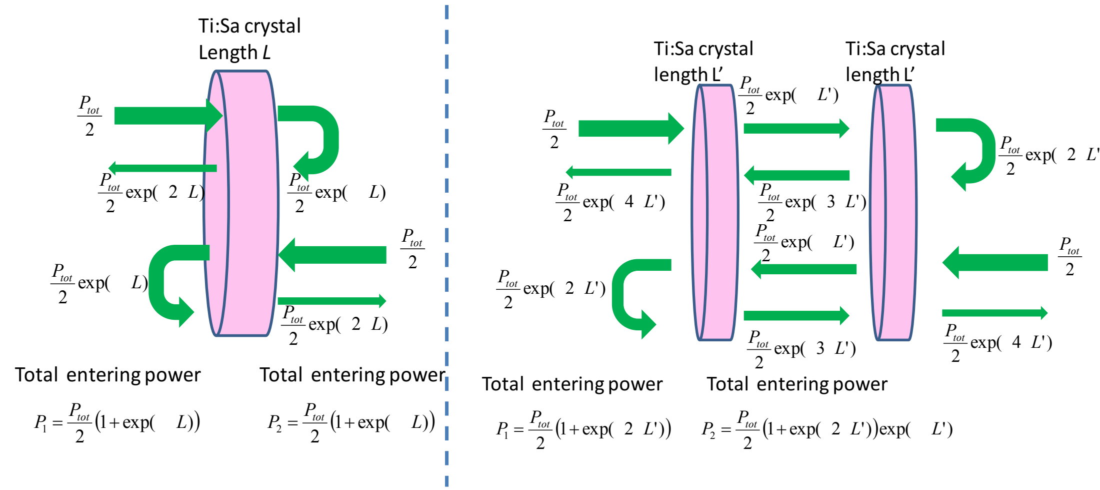
*) Water cooled Ti:Sa amplifier ("Active Mirror" configuration) under development at ELI-HU (After V. Cvhykov *et al.*, Opt. Lett, **41,** 3017, 2016)
) Fluid (D_2O) cooled Nd:YAG laser, 20 kW CW pump power, D_2O (After X. Fu *et al.*, Opt. Express, **22, 18421 (2014)
***) Fluid (Siloxane) cooled Nd:YLF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

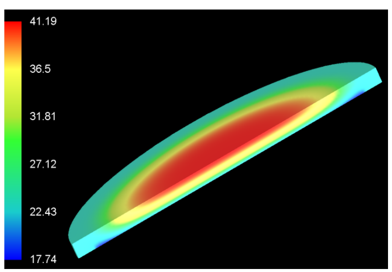
Thermal modelling

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

Water cooling



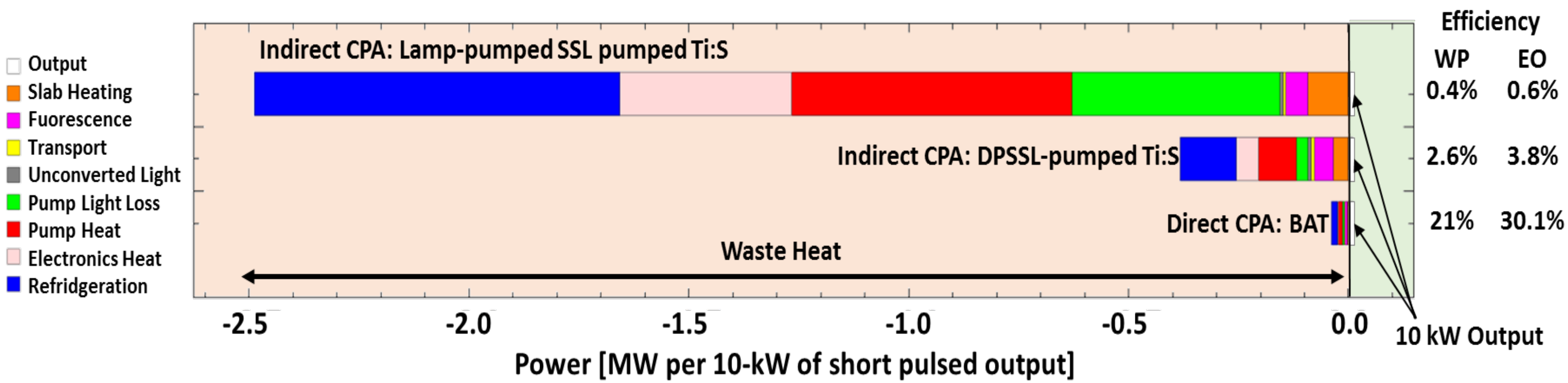




Both cooling schemes are capable of reducing the transverse temperature gradients to manageable values.

DIRECT CPA

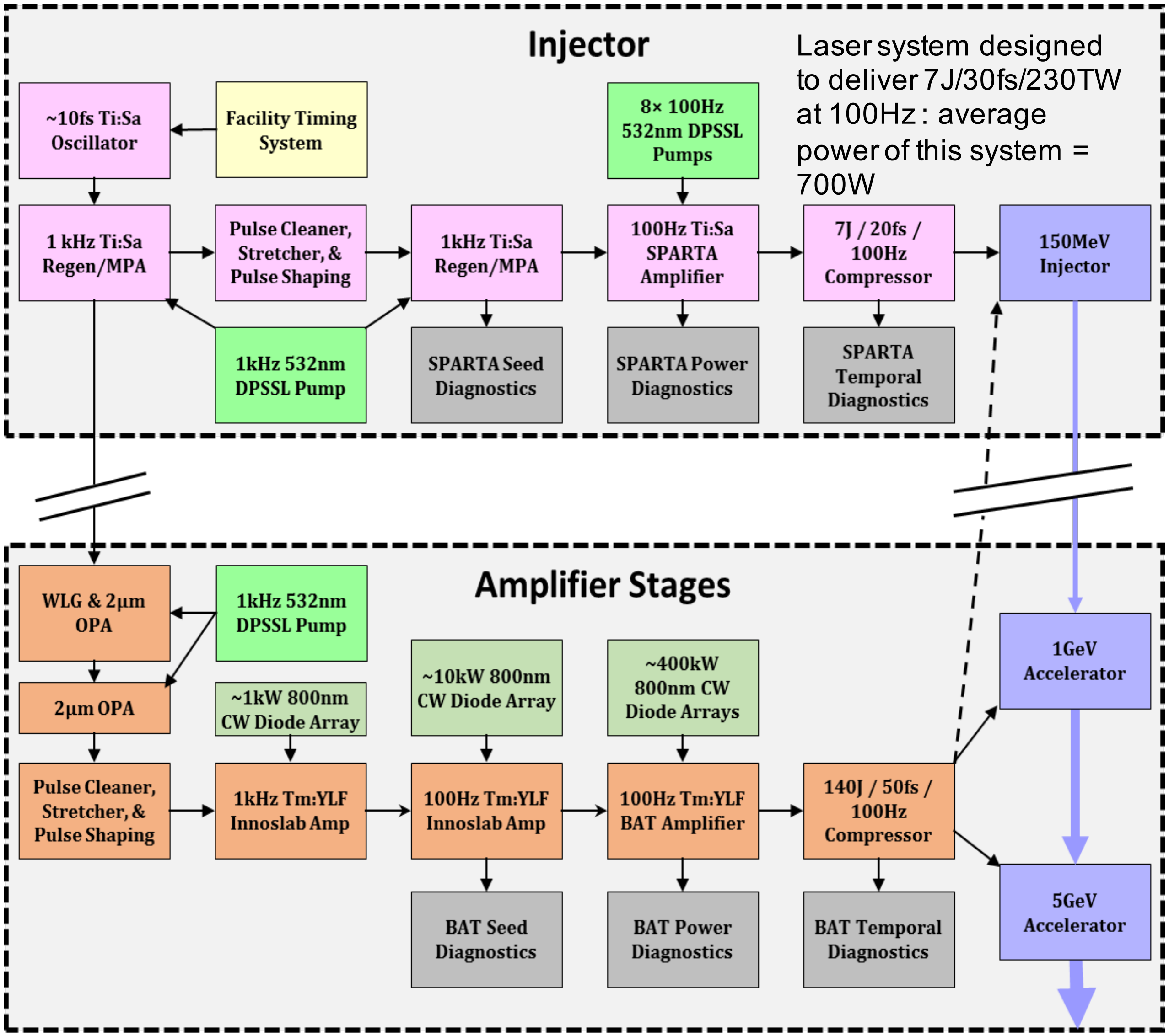
Direct CPA (required for >100Hz) - energy efficient.

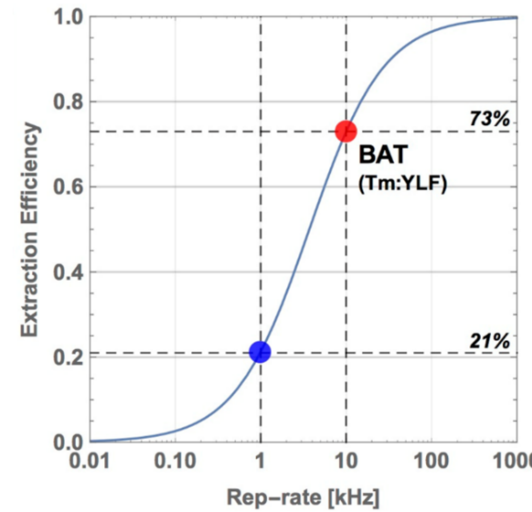


C. Siders et al., EAAC 2017

DIRECT CPA with Tm:YLF

Tm:YLF: Big-Aperture-Thulium Laser (BAT*)



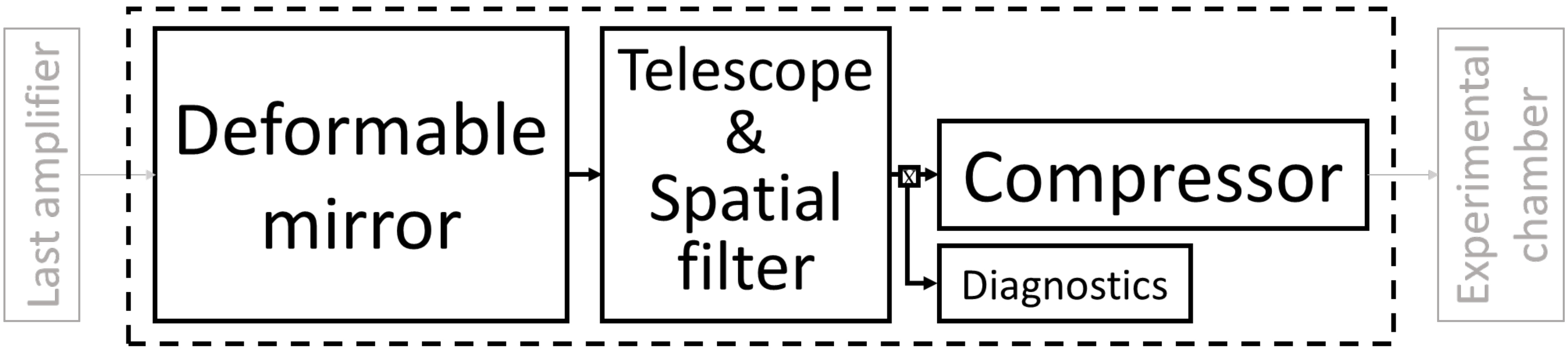


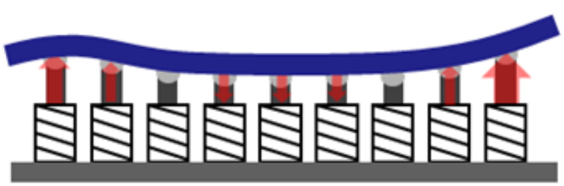
- Central wavelength at 1.9 μm,
- Pulse duration potentially as short as 50 fs
- WPE very high for >10 kHz (<5% at 100 Hz)

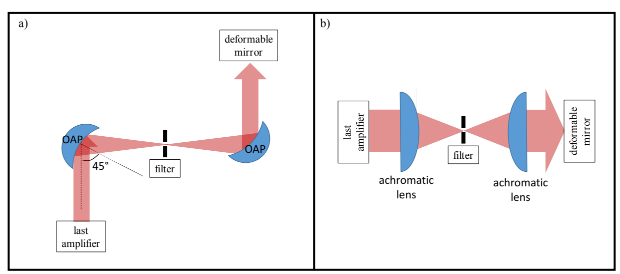
(*) Lawrence Livermore National Laboratory

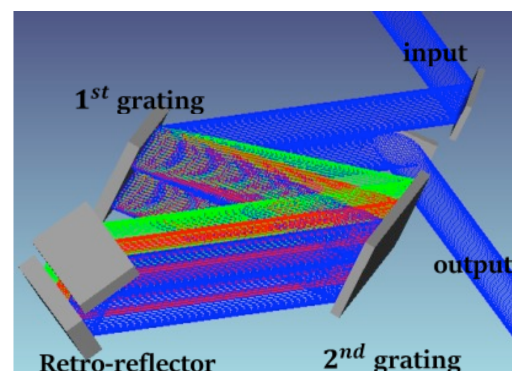
TRANSPORT TO TARGET

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





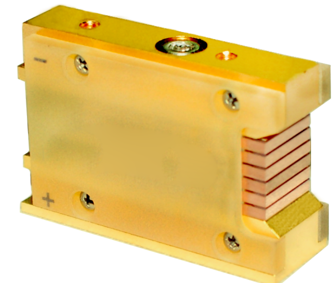


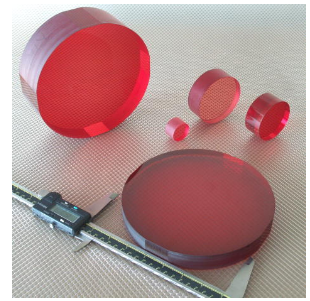


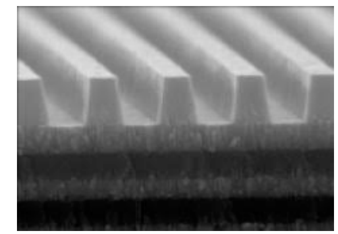
Open issues

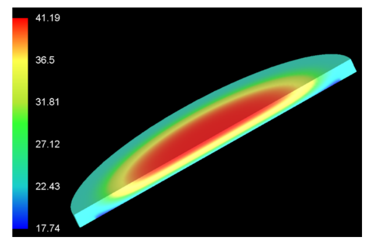
EuPRAXIA laser relies on industrial development in:

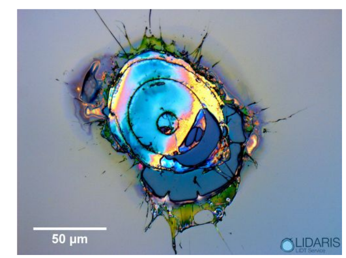
- Pumping technology: diode (direct or indirect) pumping;
- Gain media: material should be industrially available at laser quality, scalable in size and capable of supporting large bandwidth and efficient cooling;
- Grating technology to improve for higher damage threshold and smaller beam size
- Optics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

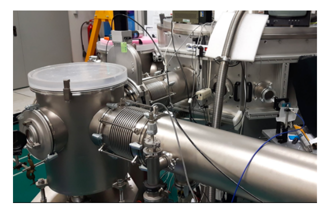












Major R&D and technology transfer to embed in final systems

EuPRAXIA

LABs AND INDUSTRY

Horizon 2020

A wide collaboration is ready to be involved to tackle open issues

Amplitude TECHNOLOGIES

THALES

VCS vacuum components & systems

SAFRAN

VACUUM FAB MOTION CONTROL & OPTICS

HORIBA JOBIN YVON

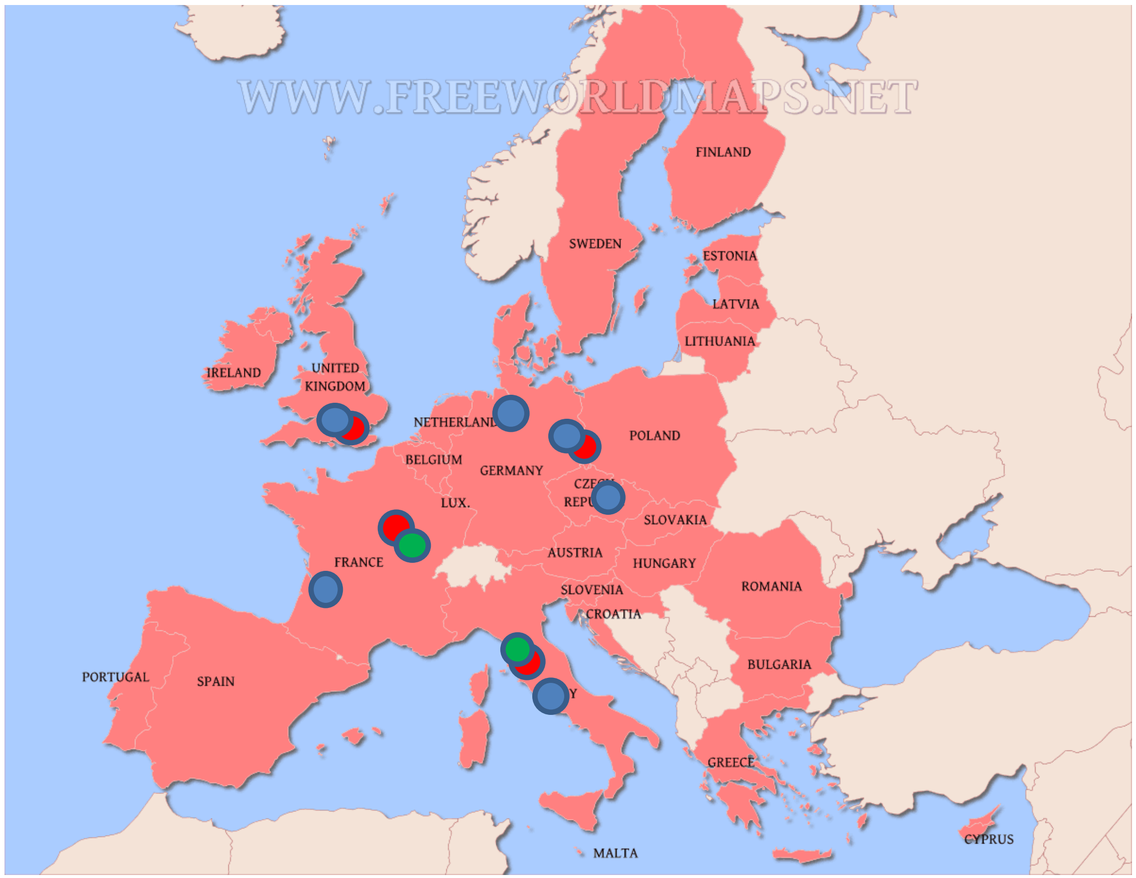
ISP SYSTEM

TRUMPF

imagine optic™

DYNAMIC OPTICS

and many more



Consiglio Nazionale delle Ricerche

cnrs centre national de la recherche scientifique

Science & Technology Facilities Council

INFN Istituto Nazionale di Fisica Nucleare

Lawrence Livermore Natl. Lab

FBH Leibniz Ferdinand Braun Institut

SUMMARY

- EuPRAXIA aiming at high quality plasma acceleration;
- PW-kW laser system driver, beyond current state-of-the-art ;
- Design phase ongoing: preliminary Ti:Sa design with existing pump-lasers (P60 with DPSSL, DiPOLE …);
- Also considering evolution towards higher repetition rate with more efficient (direct CPA) and more scalable architectures (e.g. Tm:YLF).
- Significant development/demonstrators needed to solve standing issues in pumps, thermal management of Ti:Sa, compressor gratings, beam pointing.

EuPRAXIA

Consortium

Horizon 2020

16 Participants

DESY
INFN
Consiglio Nazionale delle Ricerche
cnrs
University of Strathclyde Glasgow
IST-ID Associação do Instituto Superior Técnico para a Investigação e Desenvolvimento
Science & Technology Facilities Council
SOLEIL SYNCHROTRON
MANCHESTER 1824 The University of Manchester
UNIVERSITY OF LIVERPOOL
ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development
cea
SAPIENZA UNIVERSITÀ DI ROMA
UH Universität Hamburg
Imperial College London
UNIVERSITY OF OXFORD

22 Associated Partners

(as of October 2016)

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清華大學 Tsinghua University
HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF
LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
wigner
KPSI Kansai Photon Science Institute JAEA
大阪大学 OSAKA UNIVERSITY
RIKEN
Stony Brook University CASE
CERN
LUND UNIVERSITY
BERKELEY LAB
UCLA
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ОБЪЕДИНЕННЫЙ ИНСТИТУТ
ИЯФ ПАН
JÜLICH FORSCHUNGSZENTRUM