EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

EuPRAXIA


ESFRI
ROADMAP 2021

6th European Advanced Accelerator Concepts Workshop
17–23 Sept 2023
Hotel Hermitage, La Biodola Bay, Isola d'Elba, Italy

EuPRAXIA laser requirements and current conceptual design issues

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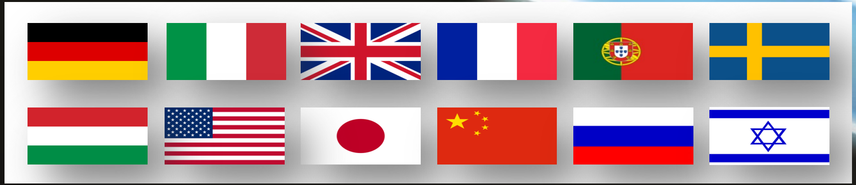

http://eupraxia-project.eu

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

Outline

- EuPRAXIA laser requirements
- Overall layout
- Thermal management options
- Modelling
- Pump lasers
- Summary

ESFRI

The EuPRAXIA Project

ESFRI 2021

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

ESFRI

New RIs for Roadmap 2021 announced

Strategy Report on Research Infrastructures

ROADMAP 2021

EuPRAXIA

CONCEPTUAL DESIGN REPORT

EuPRAXIA

European Plasma Research Accelerator with eXcellence In Applications

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

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The EuPRAXIA project

- The EuPRAXIA project aims at the construction of an **innovative compact electron accelerator** using laser- and electron-beam-driven plasma wakefield acceleration;

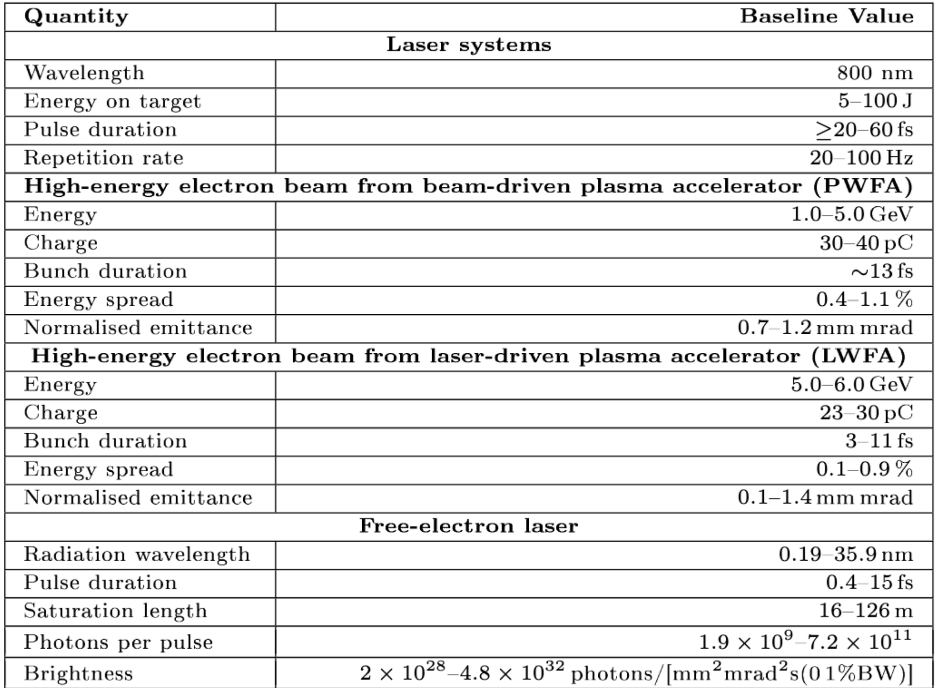
- EuPRAXIA foresees the implementation of a **laser wakefield accelerator** (LWFA) at the 1-5 GeV target energy and a repetition rate of 20-100 Hz, requiring the most advanced and robust ultrashort pulse laser technologies available to date;

- The **Design Study project** was carried out initially by 16 laboratories and universities from 5 EU member states within the European Union's Horizon 2020 programme;

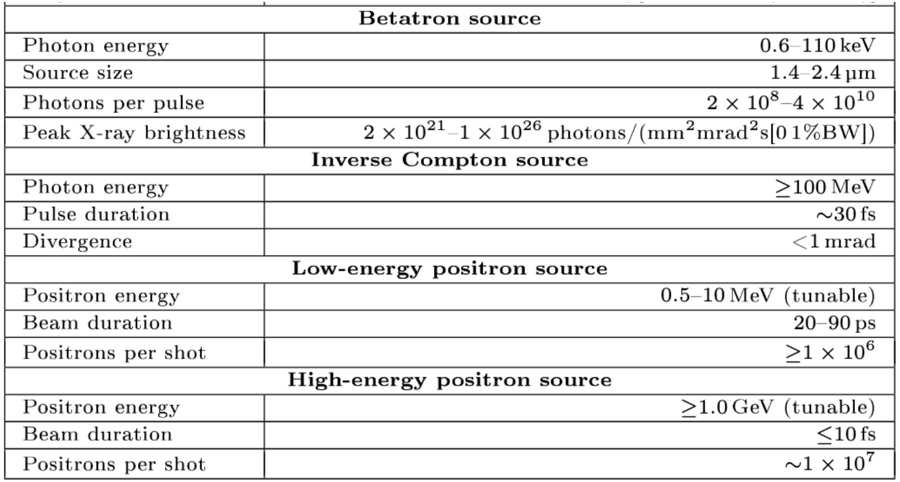
- A **Conceptual Design Study** has addressed the development of a ultrashort pulse laser system (pulse durations in the range of tens of fs) and energies up to 100 joules, yielding a PW scale peak power, targeting a repetition rate of up to 100 Hz, a performance never achieved so far

- EuPRAXIA was included in the **ESFRI Roadmap (2021)** and a **Preparatory Phase project** is ongoing.

The EuPRAXIA project: main specs



Quantity	Baseline Value
Laser systems	
Wavelength	800 nm
Energy on target	5–100 J
Pulse duration	≥20–60 fs
Repetition rate	20–100 Hz
High-energy electron beam from beam-driven plasma accelerator (PWFA)	
Energy	1.0–5.0 GeV
Charge	30–40 pC
Bunch duration	∼13 fs
Energy spread	0.4–1.1 %
Normalised emittance	0.7–1.2 mm mrad
High-energy electron beam from laser-driven plasma accelerator (LWFA)	
Energy	5.0–6.0 GeV
Charge	23–30 pC
Bunch duration	3–11 fs
Energy spread	0.1–0.9 %
Normalised emittance	0.1–1.4 mm mrad
Free-electron laser	
Radiation wavelength	0.19–35.9 nm
Pulse duration	0.4–15 fs
Saturation length	16–126 m
Photons per pulse	1.9×10^{9}–7.2×10^{11}
Brightness	2×10^{28}–4.8×10^{32} photons/[mm^{2}mrad^{2}s(0 1%BW)]



Betatron source	
Photon energy	0.6–110 keV
Source size	1.4–2.4 µm
Photons per pulse	2×10^{8}–4×10^{10}
Peak X-ray brightness	2×10^{21}–1×10^{26} photons/(mm^{2}mrad^{2}s[0 1%BW])
Inverse Compton source	
Photon energy	≥100 MeV
Pulse duration	∼30 fs
Divergence	<1 mrad
Low-energy positron source	
Positron energy	0.5–10 MeV (tunable)
Beam duration	20–90 ps
Positrons per shot	$\geq 1 \times 10^{6}$
High-energy positron source	
Positron energy	≥1.0 GeV (tunable)
Beam duration	≤10 fs
Positrons per shot	$\sim 1 \times 10^{7}$

RATIONALE OF LASER DRIVER DESIGN STUDY

ESFRI 2021

- In the EuPRAXIA project, **several alternative technological approaches were considered** and down-selected, to provide the required laser driver performances.
- We based the design on **Chirped Pulse Amplification (CPA) in Ti:Sapphire**, pumped by all-solid state green lasers (i.e. diode pumped, frequency doubled Yb or Nd lasers)
- **Thermal management** related to the handling of high pump average power was the most complex aspect in the design, requiring out-of-the-box thinking and original solutions
- **Optimization of energy extraction** was also an issue, aimed to reduce pump energy requirements and waste heat production.

Three laser systems envisaged, to drive three stages:
- Laser Plasma Injector at 150 MeV (LPI 150MeV)
- Laser Plasma Injector/Accelerator at 1 GeV (LPI 1GeV)
- Laser Plasma Accelerator at 5 GeV (LPA 5GeV)

For each system, two levels of performances considered:
P0: low energy, 20 Hz rep rate
P1: high energy, 100 Hz rep rate

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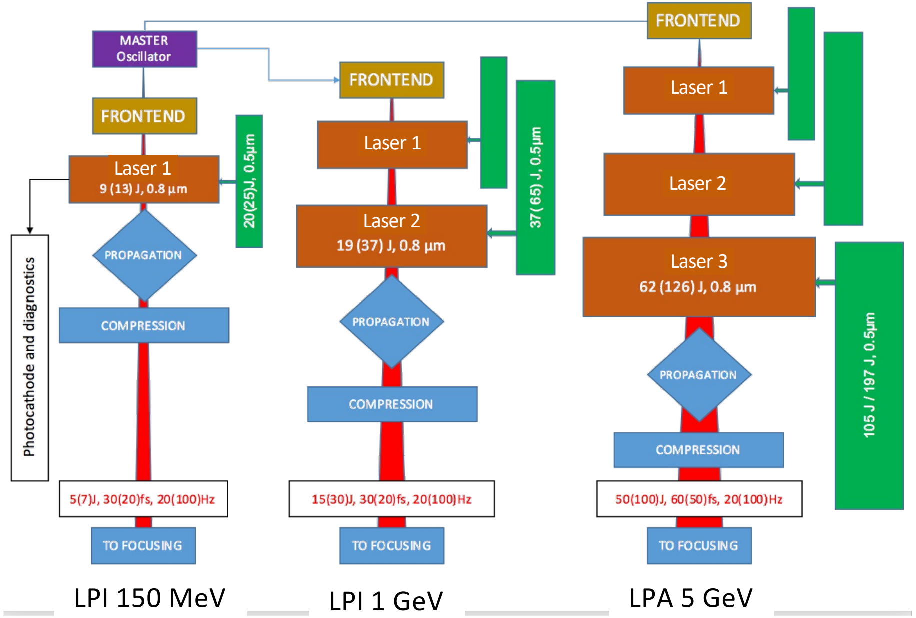
GENERAL ARCHITECTURE



Modularity of amplification stages:

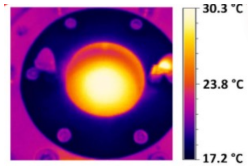
LPI 150 MeV ⇒ Laser1
LPI 1 GeV ⇒ Laser1 + Laser2
LPA 5 GeV ⇒ Laser1 + Laser2 + Laser3

- adjustments on pulse duration/bandwidth
- Synchronization: common master oscillator
- Pulse duration/wavelength tailoring : separate front end
- Scalability: possibility to upgrade from P0 to P1 performance levels without a major changes

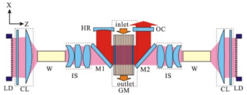
Underpinning EuPRAXIA Laser development

High repetition rate (100 Hz) will speed up R&D of pending issues for Ti:Sa laser TDR

THERMAL MANAGEMENT OF POWER AMPLIFIERS



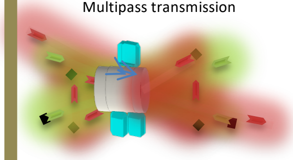
WATER/GAS COOLING



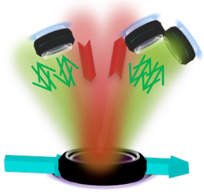
Prototyping needed

AMPLIFIER GEOMETRY TRANSMISSION VS. REFLECTION

Multipass transmission

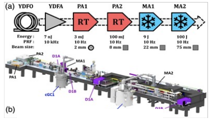


Multipass reflection

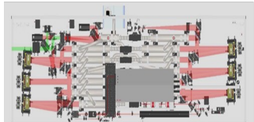


Prototyping needed

DPSSL PUMP SOURCES TECHNOLOGY



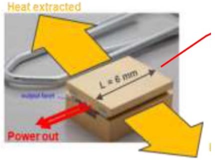
DiPOLE 100 (STCF)



P-60 technology (Amplitude)

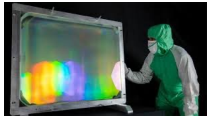
Currently no solution for full system specs (P1): development

DIODE LASERS EFFICIENCY, BRIGHTNESS AND LIFETIME



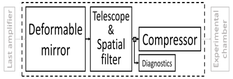
Needs development

COMPRESSOR AND TRANSPORT: THERMAL AND MECHANICAL

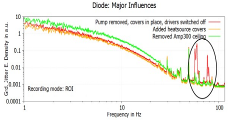


Gold -> MD, MLD, MMLD

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



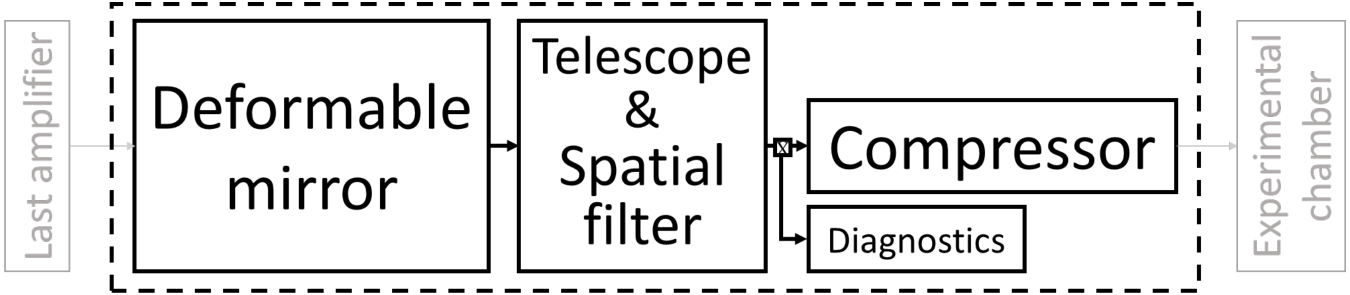
Deformable mirror
Telescope & Spatial filter
Compressor
Diagnostics

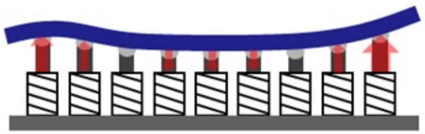


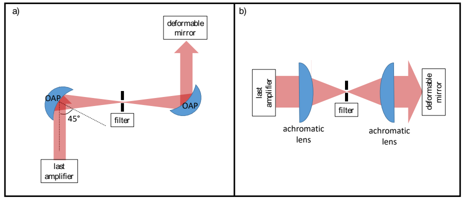
Main challenges: large optics, mechanical stability, beam quality control, pointing stability

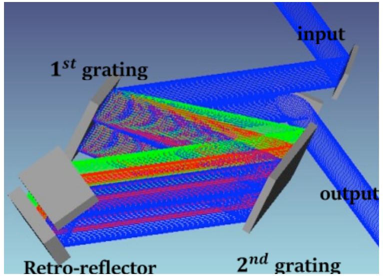
Transport to target

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







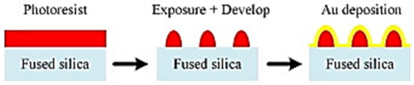


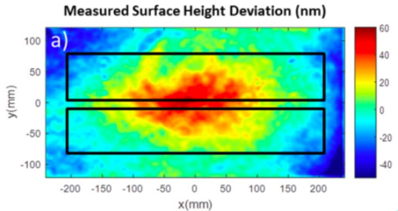
Compressor: grating technology

Different technologies under evaluation to address main issues with higher repetition rate. Strategy includes **reduction** of the thermal load at high average power, **cooling** of residual heat and **control** of thermal effects on compression quality.

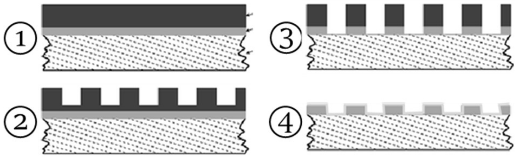
Lawrence Livermore National Laboratory

Gold Coated Grating Cooling (BK7 and ULE substrates)
for allowing higher thermal load

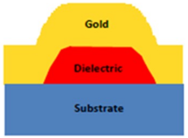




Gold Coated Grating without epoxy resin (Photoresist-Free)
for lower thermal stress



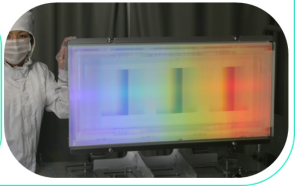
MD Gratings
Metal Dielectric
Gratings



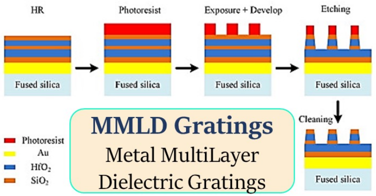
Plymouth Grating Laboratory

MLD gratings
MultiLayer
Dielectric
Gratings.

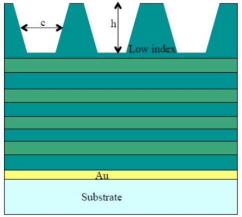
The biggest one is
91*cm x* 42*cm* large



THALES SAFRAN HORIBA JOBIN YVON Cilex Apollon INSTITUT FRESNEL

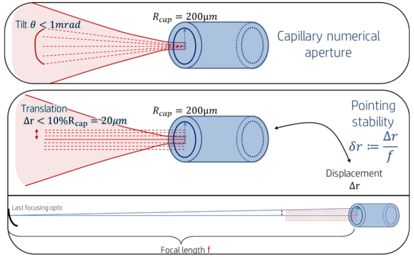


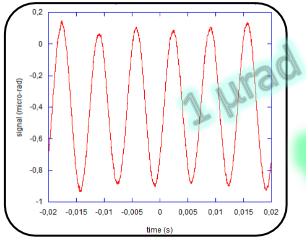
MMLD Gratings
Metal MultiLayer
Dielectric Gratings

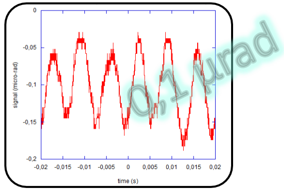


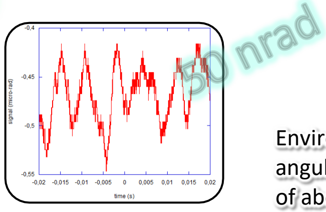
Beam Pointing Stability

Eupraxia requirements for beam pointing stability are extremely demanding. 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

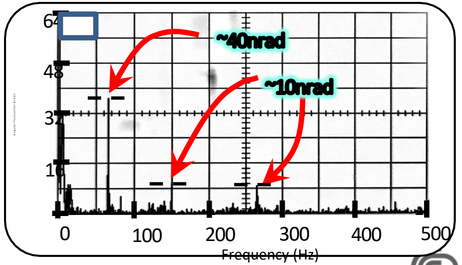
Environmental angular noise of about 30 nano-rad

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.



AMPLIFICATION CHAIN: REQUIREMENTS

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

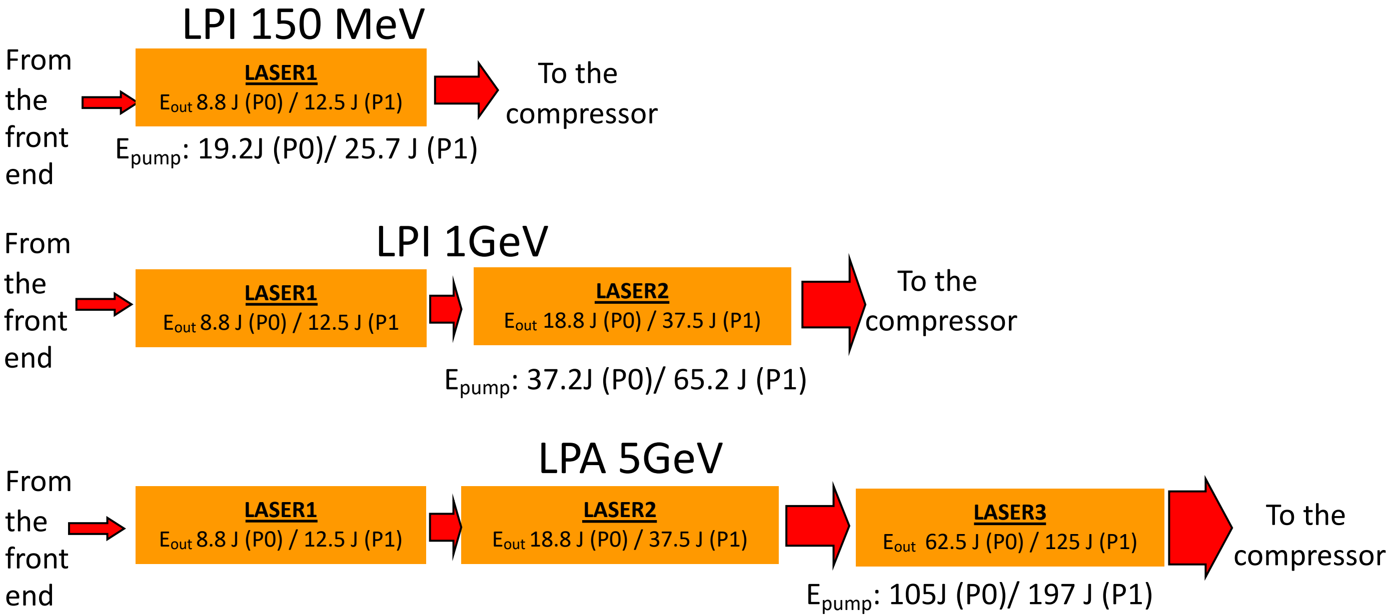
Maximum output energy: (Energy on Target)/(Compressor Efficiency)

Compressor efficiency assumed **80%**

Seed energy: 1.5 J

AMPLIFIERS MODULAR ARCHITECTURE

Foreseen I/O energy and pump requirements



LPI 150 MeV

From the front end → **LASER1** E_{out} 8.8 J (P0) / 12.5 J (P1) → To the compressor

E_{pump}: 19.2J (P0)/ 25.7 J (P1)

LPI 1GeV

From the front end → **LASER1** E_{out} 8.8 J (P0) / 12.5 J (P1 → **LASER2** E_{out} 18.8 J (P0) / 37.5 J (P1) → To the compressor

E_{pump}: 37.2J (P0)/ 65.2 J (P1)

LPA 5GeV

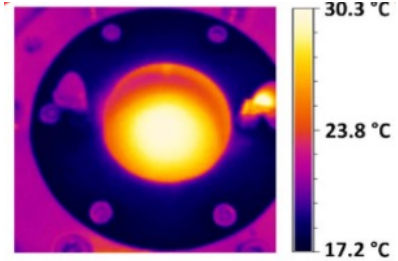
From the front end → **LASER1** E_{out} 8.8 J (P0) / 12.5 J (P1) → **LASER2** E_{out} 18.8 J (P0) / 37.5 J (P1) → **LASER3** E_{out} 62.5 J (P0) / 125 J (P1) → To the compressor

E_{pump}: 105J (P0)/ 197 J (P1)

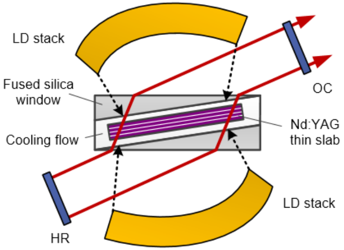
Three main modules: LASER1, LASER2, LASER3
LASER1: stand-alone for LPI 150 MeV
LASER2: output stage for LPI 1 GeV, second stage for LPA 5GeV
LASER3: high energy stage for LPA 5GeV
Two levels of performance : P0 and P1

THERMAL MANAGEMENT

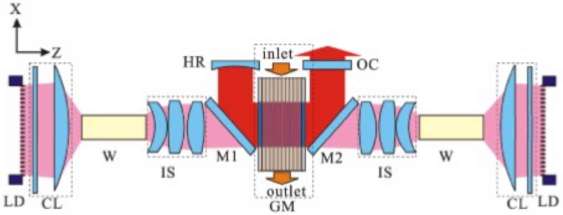
Expanding knowledge base for water cooled with "through" propagation: some examples



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 3 kW Nd:YAG laser, 20 kW CW pump power, D_2O (After X. Fu *et al.* , Opt. Express, **22**, 18421 (2014)



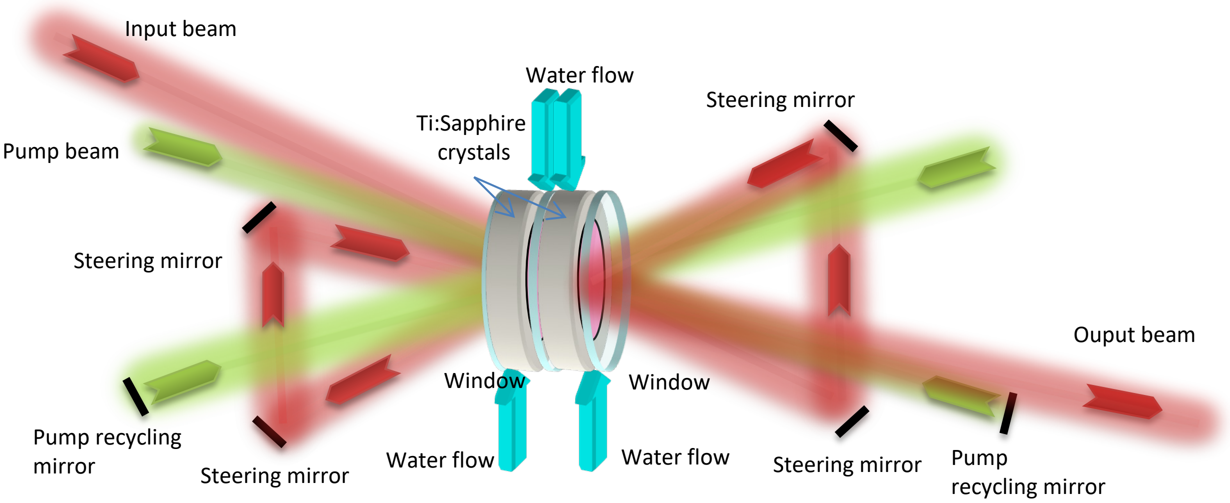
Fluid (Siloxane) cooled Nd:YLF laser, 5 kW CW pump power (After Z. Ye *et al.* , Opt. Express, **24**, 1758 (2016)

AMPLIFICATION MODULES: CONCEPTUAL LAYOUT

Two possible solutions envisaged, determined by thermal management considerations

Common features:
- gas cooling found to be insufficient at the given power density
- face cooling of gain elements by water flow (longitudinal cooling)
- gain volume split in some sub-elements to increase cooling surface
- multi-step pumping for parasitic laser management

1 – Multipass amplification scheme in transmission



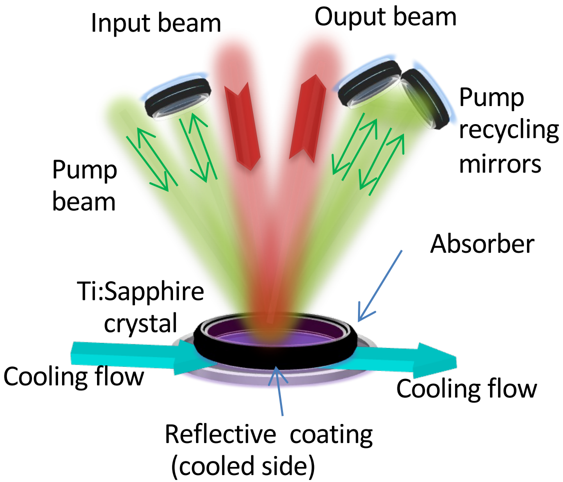
Double side, double pass pumping
Crystal split in 2 elements, face cooled by water flow, to increase cooling surface
Multipass amplification (4 to 6 depending on stages)
Absorption layer on crystal sides for parasitic lasing suppression

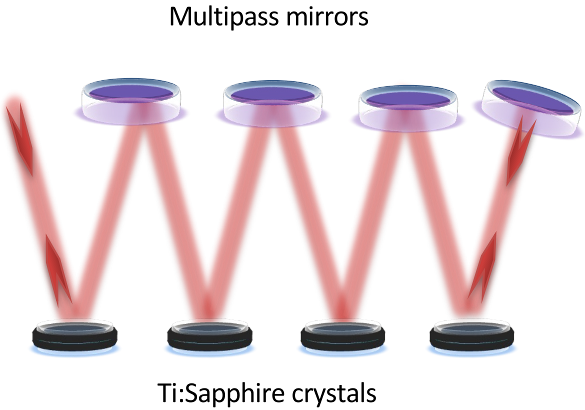
AMPLIFICATION MODULES: CONCEPTUAL LAYOUT

Two possible solutions envisaged, determined by thermal management considerations

Common features:
- **face cooling** of gain elements by water flow (longitudinal coling)
- **gain volume split** in some sub-elements to increase cooling surface
- **multi-step pumping** for parasitic laser management

2 – Multipass amplification scheme in reflection ("Active mirror")



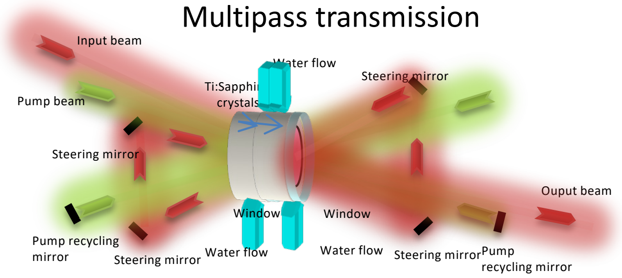


- Multi-pass pumping scheme to ensure effective pump absorption
- Overall pump energy equally divided among the 4 elements
- Overall gain length split in 4 elements, water cooled on the back side
- Multiple reflections required to obtain efficient energy extraction
- Absorption layer on crystal sides for parasitic lasing suppression

CRITICAL DESIGN CROSSROAD

Which geometry is better?

Multipass transmission



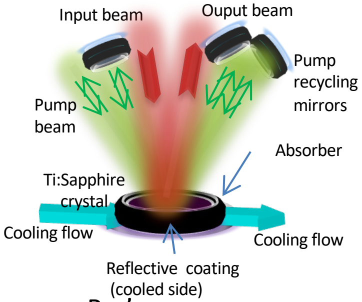
Pro's

- Simpler scheme (up to 2 sub-crystals, single pump path)
- Broader cooling surface available
- Less sensitive to mechanical vibrations
- Less sensitive to parasitic reflections (contrast issues)

Con's

- **Aberrations from fluid turbulences**
- **Very critical design of the fluid ducts**

Multipass reflection



Pro's

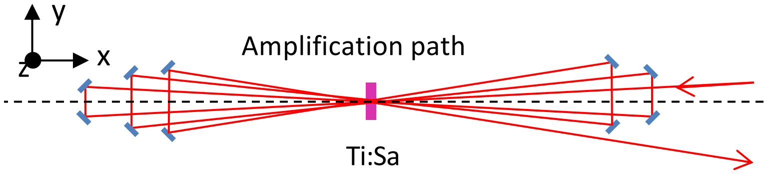
- **No aberration from cooling fluid**
- Modularity

Con's

- Less cooling capability
- More complex set-up (up to 3 units required , pump splitting)
- More sensitive to mechanical vibrations
- Possible issues from parasitic reflections (pulse contrast)

Both schemes equally studied in the preliminary design: equivalent perfomances from simulations
Critical aspects (i.e. optical aberrations from cooling fluid) beyond numerical simulations capabilities
Dedicated experimental development (i.e. realization and testing of small scale pilot devices) is required to address this design choice

EXAMPLE OF LAYOUT FOR TRANSMISSION AMPLIFIERS

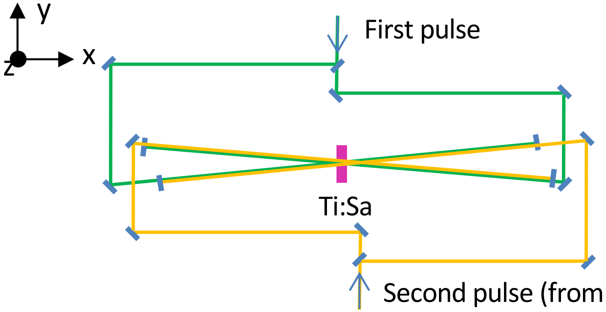


6 passes configuration, bow-tie geometry

Angle between passes	~ n x 1.2° (n=1,2,3)
Footprint length:	~ 4 mt (Laser 1)
	~ 5 mt (Laser 2)
	~ 8 mt (Laser 3)

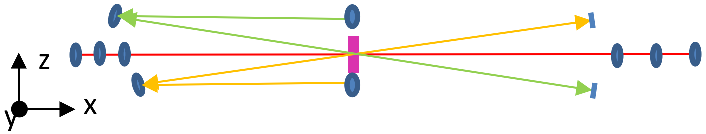
(to avoid beam superimposition)

Pumping path (single pump source, split in 2 pulses)



Each pump pulses passes twice through the crystals
Pumping from both sides to reduce peak fluence and parasitic lasing

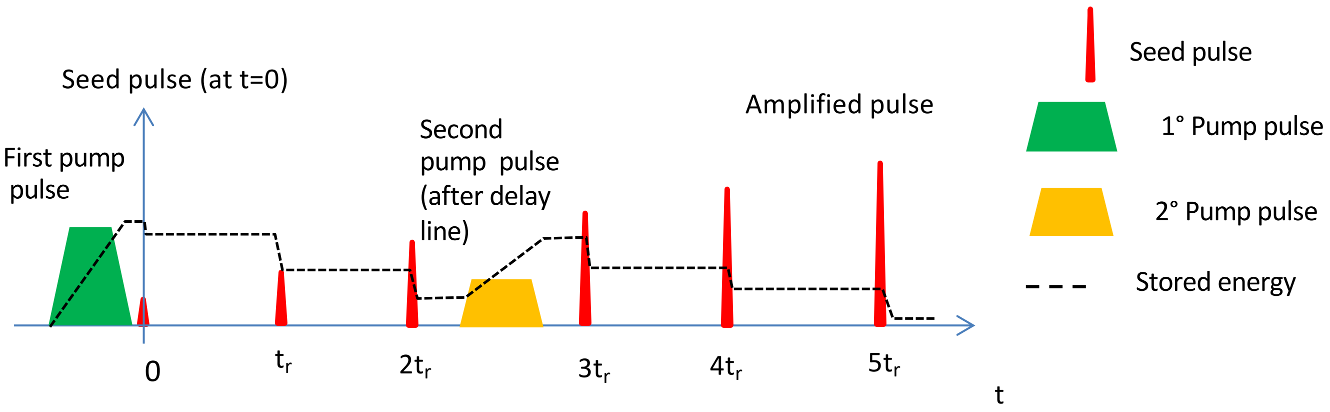
Extraction During Puming (EDP) implementation
The pump pulse must be split before of the injection; one of the pulses goes through a delay line to implement the EDP



Off-plane angular multiplexing of the pump beams to have more pump “gates” available

Pump angular multiplexing: 2 pumping “gates” required for each pump laser

PUMP TIMING AND EDP ENERGY RIPARTITION

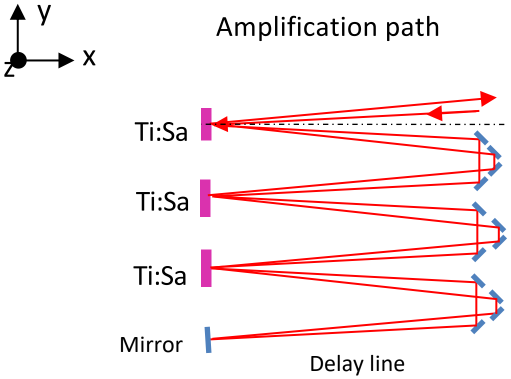


Pump pulse absorption time ~10 ns
t_r: pulse round trip time between passes
(12 ns, 15 ns, 18 ns respectively for Laser 1, Laser2 and Laser3

The delay line of the second pump pulse has to to provide the proper delay between the two pulses.

EXAMPLE OF LAYOUT FOR REFLECTION AMPLIFIERS

Amplification path



3 disks, 2 double passes configuration

Half angle between passes ~ 1.2°-2.4 °

Footprint length: ~ 3 mt (Laser 1)

~ 5 mt (Laser 2)

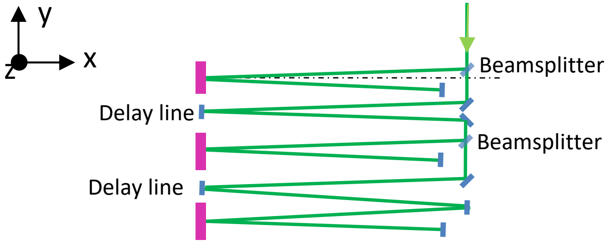
~ 8 mt (Laser 3)

(to avoid beam superimposition)

Footprint width < 1.5 m

Straightforward extension to 4 disks

Pumping path (single pump source)

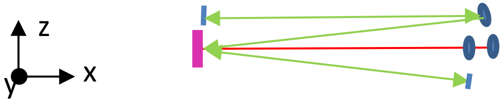


Pump pulse energy is distributed among the disks by beamsplitters (or waveplates+polarizers)

Each pump pulse passes twice through the crystals

EDP implementation

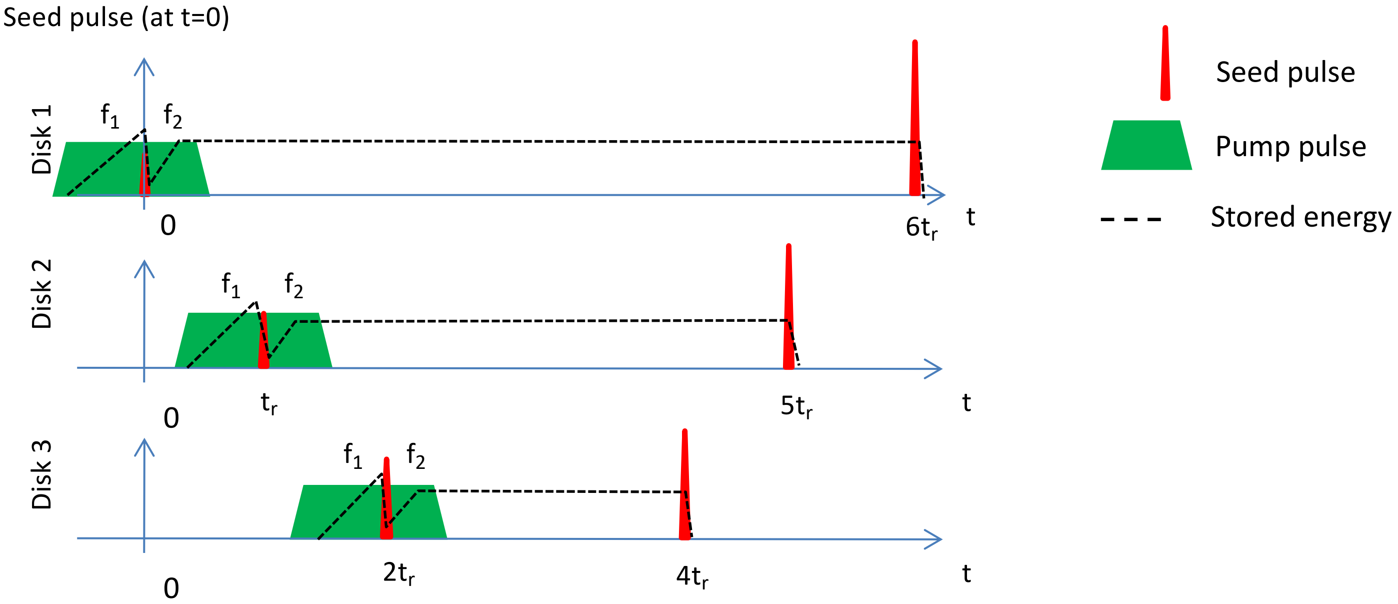
The arrival of the pump pulse is synchronized with the arrival of the amplified pulse by means of fixed delay lines (equal path length) . Energy repartition between the passes is achieved by fine tuning of the delay



Off-plane pump injection to avoid beam path occlusions

One injection “gate“ for each pump source

PUMP TIMING AND EDP ENERGY RIPARTITION



t_r: pulse round trip time between passes
(12 ns, 15 ns, 18 ns respectively for Laser 1, Laser2 and Laser3

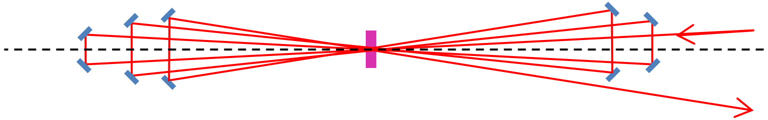
The delay lines of the pump between the disk ensures **synchronization of pump arrival** with the seed pulse. Fraction f_1 of pump pulse energy is available for 1° pass amplification, fraction f_2 for the 2° pass. The ratio f_1/f_2 can be adjusted by finely tuning the delay between the pump and the seed pulse

NUMERICAL SIMULATION OF AMPLIFICATION MODULES

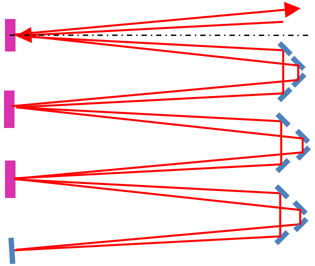
The amplification stages were numerically simulated (MIRO - CEA)
The code allows for the simulation of amplification of ultrashort pulses, accounting for GVD, nonlinear effects, spectral narrowing effects and so on

The different amplification stages were extensively analyzed in the different architectures (transmission vs reflection scheme)

Simulations for the two architectures implemented:
- same overall gain length, number of passes
- same doping level
- same overall pump energy
- same beam cross section



vs.



We obtained:
- Very similar energy extraction performance for the two schemes
- Very similar sensitivity of output energy vs seed, pump energy

Results are summarized in the following slides

AMPLIFICATION MODULES: AMP 1

Crystal clear aperture ∅ (cm)	6 cm	Crystal thickness (cm, overall)	1.2
Doping level (%Wt.)	0.075	Absorption coefficient (cm-1)	1.2

Performance level P0

Pump energy (J)	19.2	Pump beam diameter (cm, FWHM)	5.0
Pump fluence at crystal surfaces (J/cm^2)	0.76	Absorbed pump energy (%)	94%
Seed pulse energy (J)	1.5	Seed beam diameter (cm, FWHM)	4.7
Output energy	8.9	Extraction efficiency	38.7%
Output beam diameter (cm FWHM)	4.5	Output beam peak fluence (J/cm2)	0.55
EDP scheme	65% 1st pass, 35% 4th pass	Max G_T	~ 15 (before the 4th pass)
S_{pump} ($\Delta E_{out}/\Delta E_{pump}$)	0.53	S_{seed} ($\Delta E_{out}/\Delta E_{seed}$)	2.4

Performance level P1

Pump energy (J)	25.7	Pump beam diameter (cm, FWHM)	5.0
Pump fluence at crystal surfaces (J/cm2)	1.01	Absorbed pump energy (%)	94%
Seed pulse energy (J)	1.5	Seed beam diameter (cm, FWHM)	4.7
Output energy (J)	12.7	Extraction efficiency	43.6%
Output beam diameter (cm FWHM)	4.6	Output beam peak fluence (J/cm^2)	0.765
EDP scheme	65% 1st pass, 35% 4th pass	Max G_T	~ 30 (before the 4th pass)
S_{pump} ($\Delta E_{out}/\Delta E_{pump}$)	0.58	S_{seed} ($\Delta E_{out}/\Delta E_{seed}$)	2.67

6 passes amplification scheme

AMPLIFICATION MODULES: AMP 2

Crystal clear aperture ∅ (cm)	10	Crystal thickness (cm, overall)	2.0
Doping level (%Wt.)	0.05	Absorption coefficient (cm-1)	0.79

Performance level P0

Pump energy (J)	37.2	Pump beam diameter (cm, FWHM)	9.0
Pump fluence at crystal surfaces (J/cm^2)	0.425	Absorbed pump energy (%)	96%
Seed pulse energy (J)	6.25	Seed beam diameter (cm, FWHM)	8.0
Output energy (J)	19.1	Extraction efficiency	35.0%
Output beam diameter (cm FWHM)	8.0	Output beam peak fluence (J/cm^2)	0.38
EDP scheme	60% 1st pass, 40% 3rd pass	Max G_T	~ 6 (before the 3rd pass)
S_{pump} ($\Delta E_{out}/\Delta E_{pump}$)	0.45	S_{seed} ($\Delta E_{out}/\Delta E_{seed}$)	1.8

Performance level P1

Pump energy (J)	65.2	Pump beam diameter (cm, FWHM)	9.0
Pump fluence at crystal surfaces (J/cm^2)	0.75	Absorbed pump energy (%)	96%
Seed pulse energy (J)	8.75	Seed beam diameter (cm, FWHM)	8.0
Output energy (J)	37.5	Extraction efficiency	44.1%
Output beam diameter (cm FWHM)	8.3	Output beam peak fluence (J/cm^2)	0.72
EDP scheme	60% 1st pass, 40% 3rd pass	Max G_T	~ 14 (before the 3rd pass)
S_{pump} ($\Delta E_{out}/\Delta E_{pump}$)	0.53	S_{seed} ($\Delta E_{out}/\Delta E_{seed}$)	1.49

6 passes amplification scheme

AMPLIFICATION MODULES: AMP 3

Crystal clear aperture ∅ (cm)	16 cm	Crystal thickness (cm, overall)	3.2
Doping level (%Wt.)	0.03	Absorption coefficient (cm-1)	0.47

Performance level P0 (6 passes)

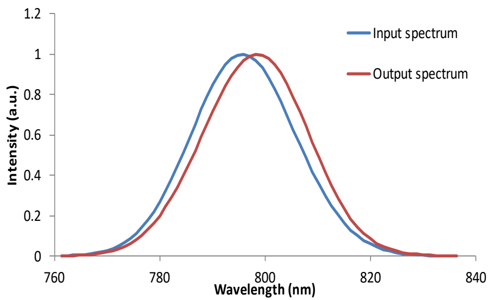
Pump energy (J)	105	Pump beam diameter (cm, FWHM)	14.0
Pump fluence at crystal surfaces (J/cm^2)	0.51	Absorbed pump energy (%)	96%
Seed pulse energy (J)	18.8	Seed beam diameter (cm, FWHM)	12.8
Output energy (J)	62.4	Extraction efficiency	41.5%
Output beam diameter (cm FWHM)	12.8	Output beam peak fluence (J/cm^2)	0.49
EDP scheme	65% 1st pass, 35% 3rd pass	Max G_T	~ 18 (before the 1st pass)
S_{pump} ($\Delta E_{out}/\Delta E_{pump}$)	0.53	S_{seed} ($\Delta E_{out}/\Delta E_{seed}$)	1.64

Performance level P1 (4 passes)

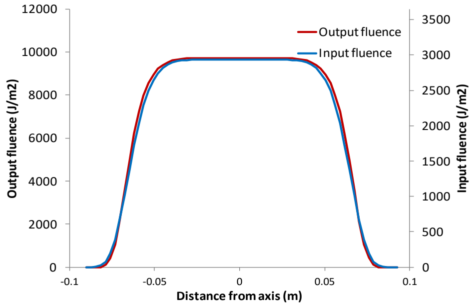
Pump energy (J)	197	Pump beam diameter (cm, FWHM)	14.0
Pump fluence at crystal surfaces (J/cm^2)	0.95	Absorbed pump energy	96%
Seed pulse energy (J)	37.5	Seed beam diameter (cm, FWHM)	12.8
Output energy (J)	126.0	Extraction efficiency	44.9%
Output beam diameter (cm FWHM)	13.0	Output beam peak fluence (J/cm^2)	1.08
EDP scheme	65% 1st pass, 35% 3rd pass	Max G_T	~ 20 (before the 3rd pass)
S_{pump} ($\Delta E_{out}/\Delta E_{pump}$)	0.54	S_{seed} ($\Delta E_{out}/\Delta E_{seed}$)	1.4

EXAMPLES OF SIMULATION RESULTS

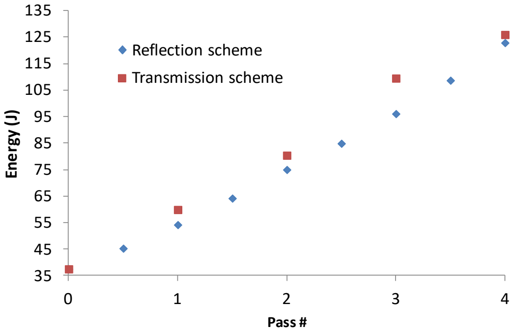
Input/output spectrum (AMP3, P1)



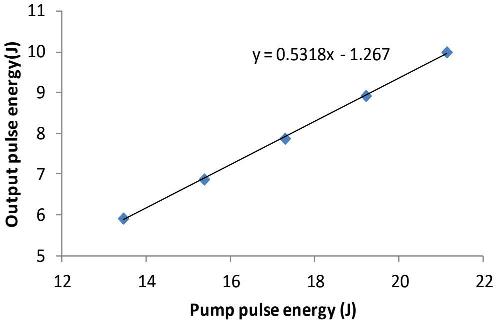
Input/output beam profile (AMP3, P1)



Output energy vs. number of passes (AMP3, P1, transmission / reflection schemes)



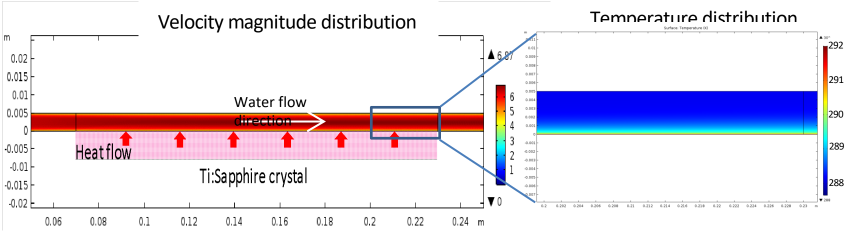
Output energy vs. pump pulse energy (AMP1, P0)



FLUID-DYNAMICS SIMULATIONS

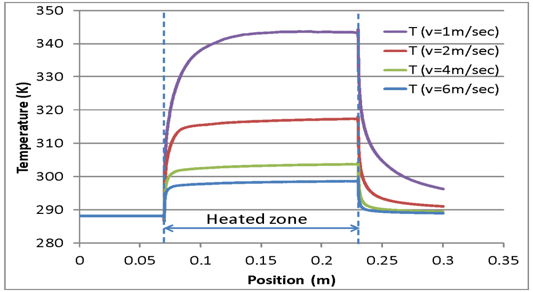
Water cooling of disk amplifiers: modelling physics

- Simulation software: COMSOL multiphysics (ver. 4.2 and 5.2)
- Finite Element Analysis approach
- Numerical solution of the Navier-Stokes equations for mass and energy transport
- Low Reynolds k-ε solution method
- Thermal coupling with boundary layer at the channel walls (heated Ti:Sa crystal)
- Time-averaged simulation (i.e. time-dependent turbulences not modelled)

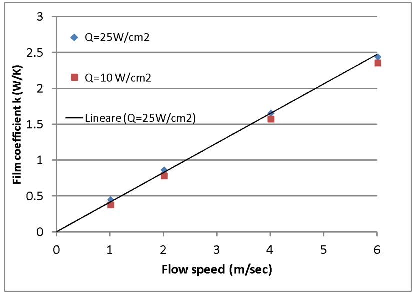


Example:

- channel thickness 5 mm, flat channel walls
- inlet flow speed 6 m/sec,
- heat input 25 W/cm^2 (AMP3 at P1 performance level)
- heated length 160 mm (AMP3 pump beam ∅);
- temperature dependence of water properties
- water input temperature 15 °C
- mesh ~ 128000 elements



Temperature of Ti:Sa surface at different inlet flow speed
Water inlet temperature 15°C (288.15 K)
Heat input 25 W/cm2, Channel heigth 5 mm



Effective film coefficient (heat exchange coefficient between water and heated wall for different flow speed and heat input levels

THERMOMECHANICAL SIMULATIONS

Temperature distribution

Temperature distribution for AMP3 transmission disk (left, 1.6 cm thickness) and AMP3 reflection disk (right 1.3 cm thickness) at P1 pump level

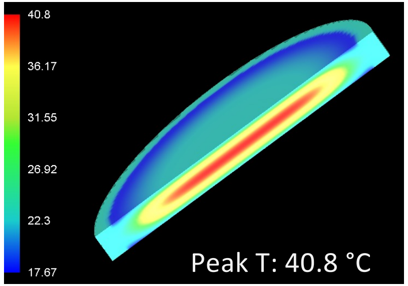
Deformation distribution

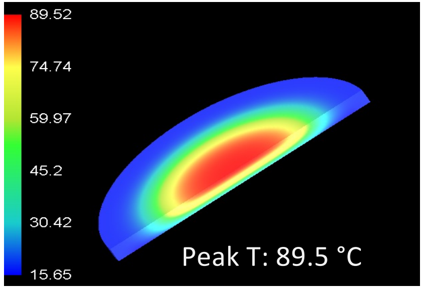
Axial displacement distribution (mm) for AMP3 transmission disk (left, 1.6 cm thickness) and AMP3 reflection disk (right 0.8 cm thickness) at P1 pump level

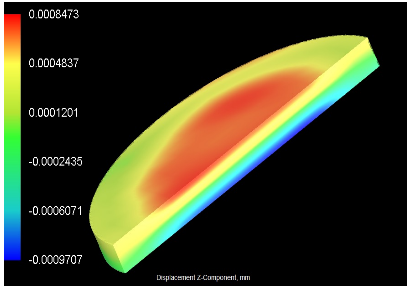
Optical path difference (OPD)

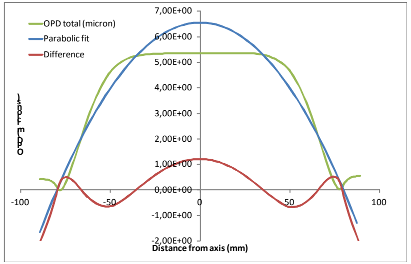
OPD in microns resulting from thermal expansion and thermooptic effect. Parabolic fit and higher order aberrations also shown. Left: AMP3 transmission disk; right AMP3 reflection disk at P1 pump level

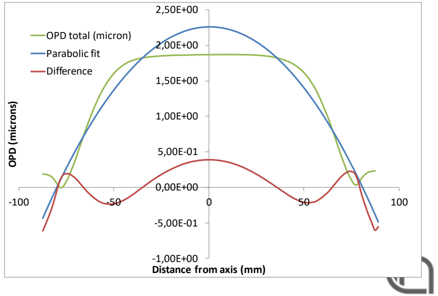
Modelling: Finite Element Analysis (FEA)







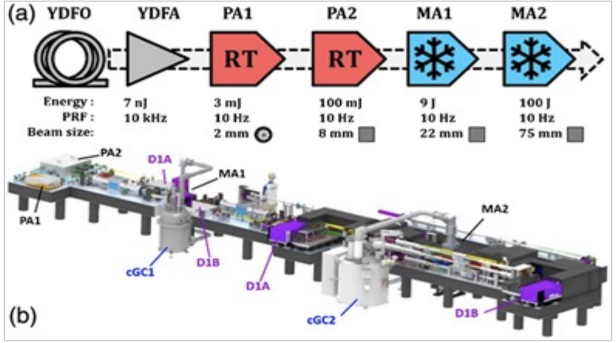




Phase modification requires Adaptive Optics compensation

PUMP SOURCES TECHNOLOGIES

DiPOLE 100 (STCF)

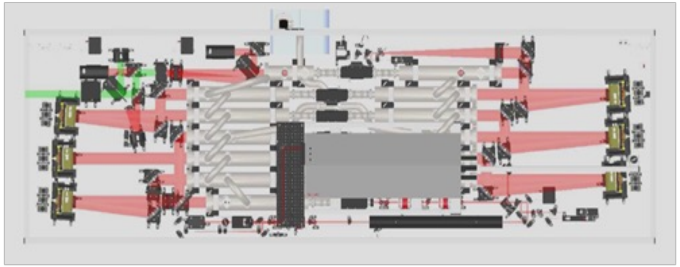


Cryogenically operated Yb:YAG, diode pumped
100J @1030 nm , 10 Hz demonstrated
Energy stabilty 1% RMS (few hours of operation)
60 J SHG @ 515 nm, 10 Hz expected

Possible upgrades include:

- IR Output energy 150 J
- **SHG output > 100 J**
- **PRF 100 Hz @ 10 J**

P-60 technology (Amplitude)



Nd:YAG Disk Amplifier Heads (DAH), liquid cooled.
Current design: flashlamp pumping
Scalable design (n. of DAH units): P20, P30…

Design specificatons (6 DAH):
~80 J @ 1064 nm, 10 Hz
60 J @ 532 nm, 10 Hz

Possible developments
- Diode pumping
- **50 Hz rep rate**

DIMENSIONING OF PUMP SOURCES ARRAYS

P0 performance level

Issue: *P0 operation regime has a pulse repetition rate of 20 Hz.*
The two available pump sources have a repetition rate of only 10 Hz.

To circumvent this problem (until higher rep rate devices are developed) we considered to use two (or two sets) of pump sources and shot them interleaved, so that repetition rate of the pump pulses arriving to the amplifiers id effectively doubled.

Issue: *Pump energies higher than about 60 J (as needed by the AMP3 module) require more than a single pump source.*

This calls for specific arrangements to multiplex the input from several pump units to the amplification crystals.

P1 performance level

Issue: *P1 operation regime considers a pulse repetition rate of 100 Hz, along with higher energies than P0. Currently no solutions for pump sources are available to meet these requirements.*

Speculatively, we have considered the availability of a system similar to Amplitude P60 but operating at 50 Hz (conversion to diode laser pumping of the flashlamp pumped P60) with the same output energy of 60 J/pulse in the green.

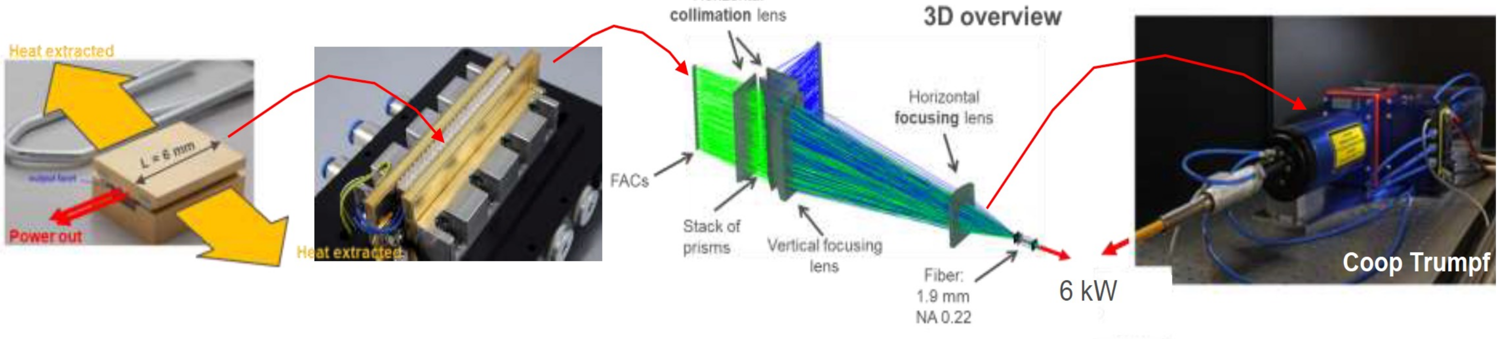
Again, reaching 100 Hz requires the time interleaving of a pair of twin sources. This analysis did not include the DiPOLE 100 system, as no developments are currently planned toward a high energy, high rep rate system.

Diode laser developments

ESFRI 2021

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



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

MAIN OUTPUTS OF THE EUPRAXIA DESIGN STUDY

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

The end

ESFRI

New RIs for Roadmap 2021 announced

Strategy Report on Research Infrastructures

ROADMAP **2021**

CONCEPTUAL DESIGN REPORT

EuPRAXIA

European Plasma Research Accelerator with eXcellence In Applications

Thank you!