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APPLICATIONS

WP4: Laser Design and Optimization

Overview of latest developments and critical issues

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On behalf of WP4

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http://eupraxia-project.eu

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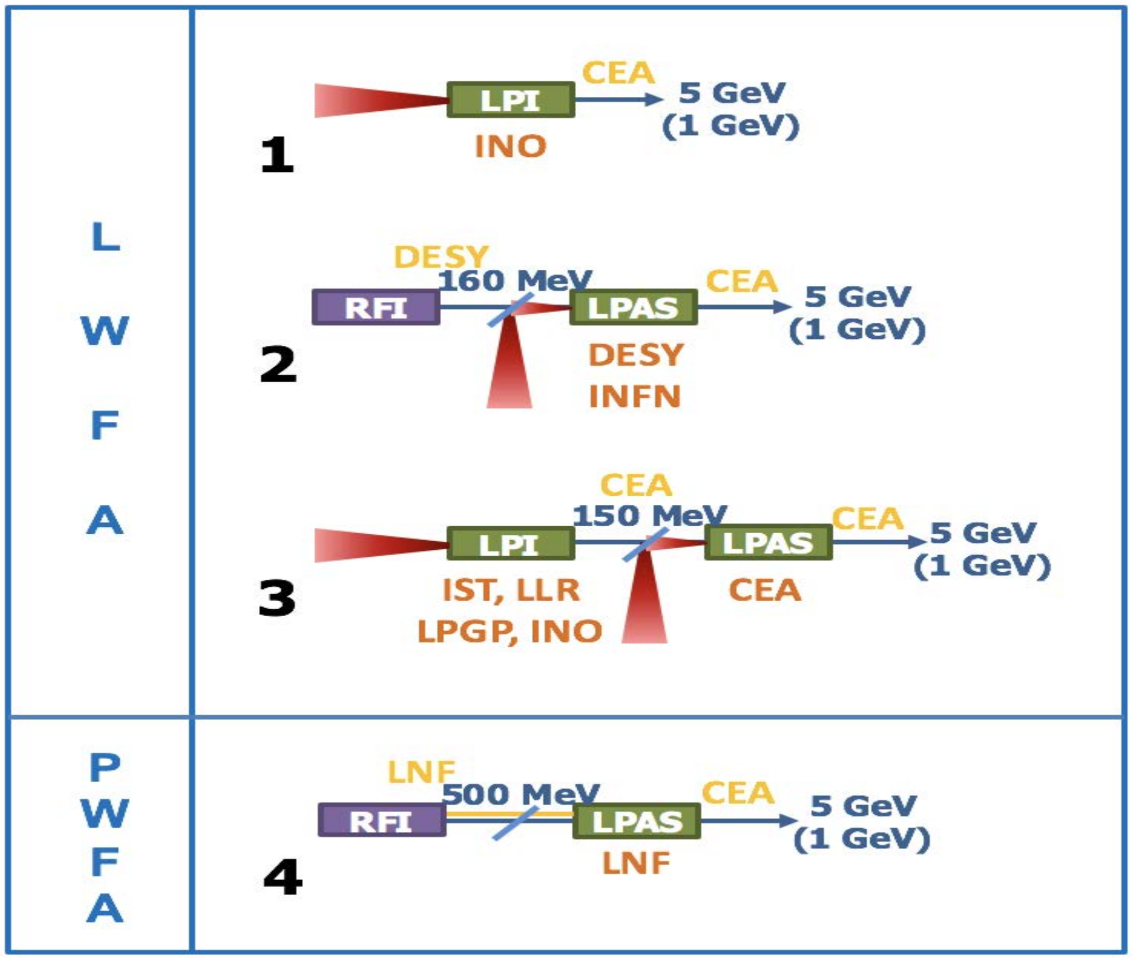
CONTENT

- EuPRAXIA laser requirements and strategy
- Baseline design
- Options
- Conclusions

EuPRAXIA Laser Layout

*Acceleration schemes (WP2), selected to provide a beam at **5 GeV** meeting FEL and HEPO requirements and a beam at **1 GeV** 'usable' for FEL and HEPO, as a 'commissioning' step.*



EuPRAXIA Laser Specifications

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Injector Laser 150 MeV – LASER 1

Laser 1 - Injector 150 MeV			
Parameter	**Label**	**P0**	**P1**
Wavelength (nm)	λ (nm)	800	800
Maximum energy on target (J)	Etarget	5	7
Maximum output energy (J)	Eout	8.8	12.5
Energy tuning resolution (% of targeted value)	dE	7	5
Total output energy (incl. Diagnostic beams)	Etot	7	10
Pulse length (FWHM) (fs)	τ	30	20
Repetition rate (Hz)	f	20	100
Requirement on energy stability (RMS) %	σ<E>	1	0.6

EuPRAXIA Laser Specifications

Horizon 2020

Injector Laser 1GeV – LASER 2

LPI/LPA - Injector 1 GeV			
Parameter	**Label**	**P0**	**P1**
Wavelength (nm)	λ (nm)	800	800
Maximum energy on target (J)	Etarget	15	30
Maximum output energy (J)	Eout	18.8	37.5
Energy tuning resolution (% of targeted value)	dE	7	5
Shortest pulse length (FWHM) (fs)	τ	30	20
Repetition rate (Hz)	f	20	100
Requirement on energy stability (RMS) %	σ<E>	1	0.6

EuPRAXIA Laser Specifications

Accelerator Laser 5GeV – LASER 3

LPA - Driver 5 GeV			
Parameter	**Label**	**P0**	**P1**
Wavelength (nm)	λ (nm)	800	800
Maximum energy on target (J)	Etarget	50	100
Maximum output energy (J)	Eout	62.5	125
Energy tuning resolution (% of targeted value)	dE	7	5
Shortest pulse length (FWHM) (fs)	T	60	50
Repetition rate (Hz)	f	20	100
Requirement on energy stability (RMS) %	σ<E>	1	0.6

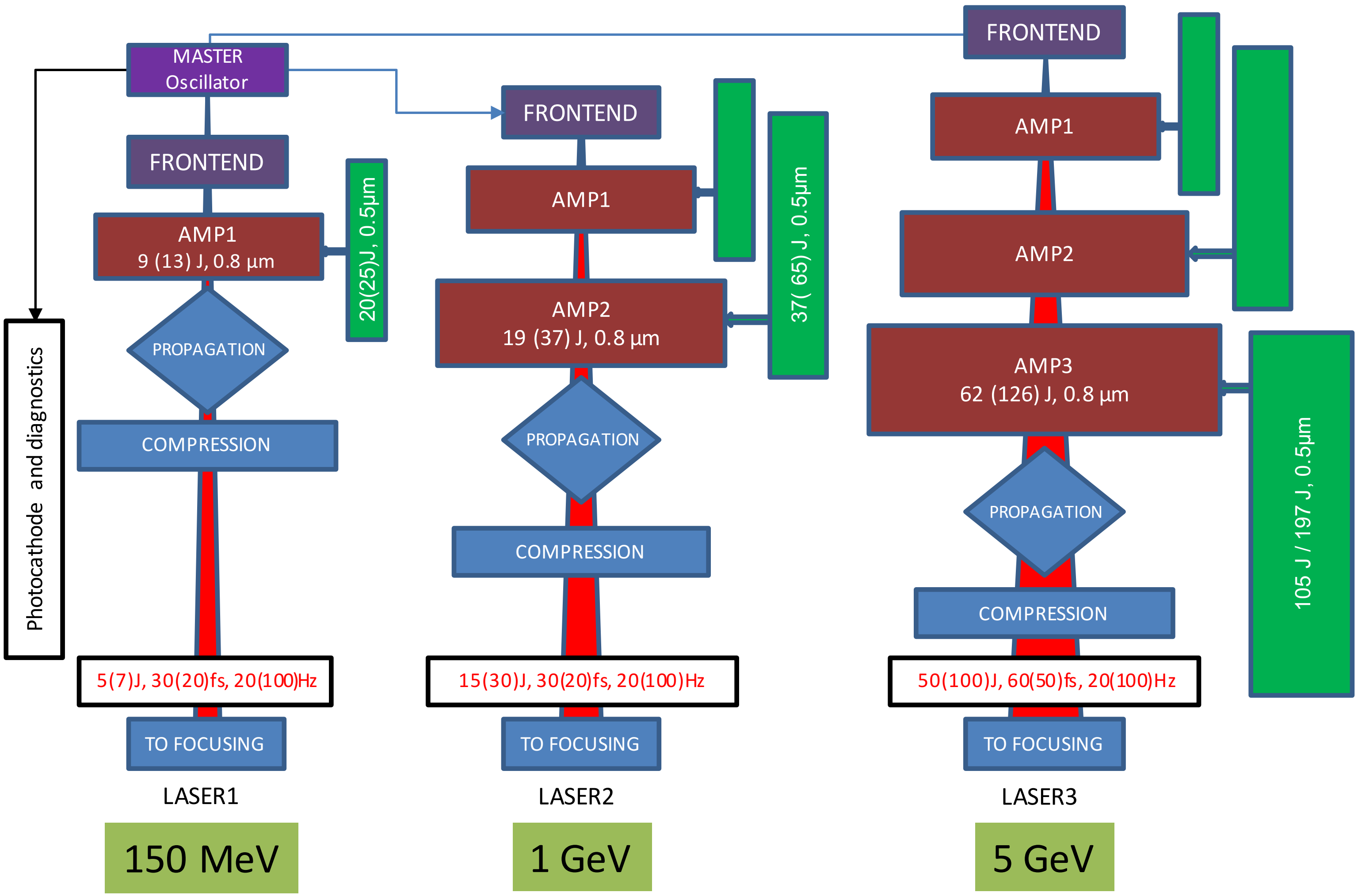
L.A.Gizzi et al., A viable laser driver for a user plasma accelerator., NIM-A, (2018).

LASER STRATEGY OVERVIEW

- **Originally driven by boundary conditions:**
  - Beyond state of the art;
  - Laser with unique (rep-rated) performance;
  - Industry to provide the laser;
  - High Technology Readiness Level;
  - Timescale of development (5 yrs)
- Involve leading industry and research labs;
- Reach consensus on baseline configuration;
- Down-select emerging technology components;
- Identify R&D for critical components;
- Develop full CDR of baseline;
- Evaluate investment and running costs.
- **Include options to account for:**
  - Evolutionary baseline configuration;
  - Higher efficiency, higher repetition rate.

Baseline configuration

Titanium-Sapphire system with diode-pumped pump lasers



L.A.Gizzi et al., A viable laser driver for a user plasma accelerator., NIM-A, (2018).

Amplifiers strategy

EuPRAXIA — Horizon 2020

• 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

G. Toci

DPSSL Pump lasers: needed <P>

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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 Pump 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**

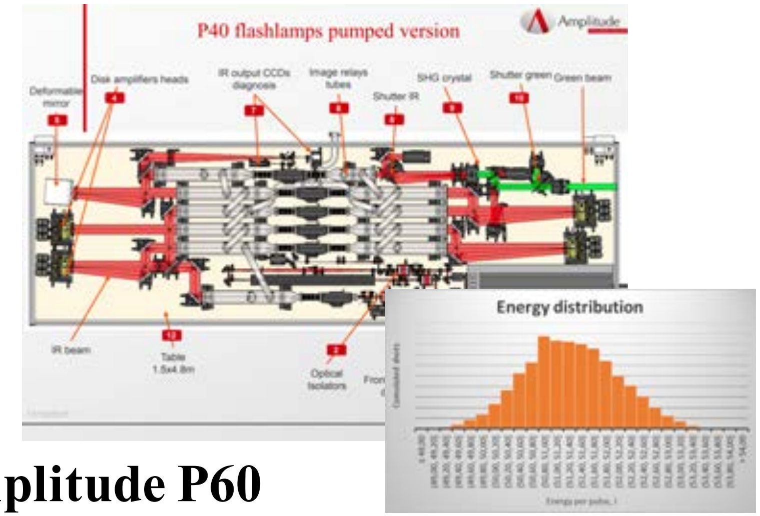
Total fundamental wavelength average pump power ranges from **3 kW** (20 Hz) to **30 kW** (100 Hz)

PUMP LASERS: STRATEGY

- Follow industrial developments of high average power pump lasers;
- Motivate DPSSL implementation on currently available industrial flash-lamp pumped systems for 10 Hz performance;
- Link to available effort in prototyping from research labs for enhanced performance (20 Hz);
- Attract new resources for high power diode developments for future 100 Hz upgrade.

Candidate pump energy sources

Promising developments based on diode pumping technology are in progress at EuPRAXIA industrial and research partners, progressively matching requirements



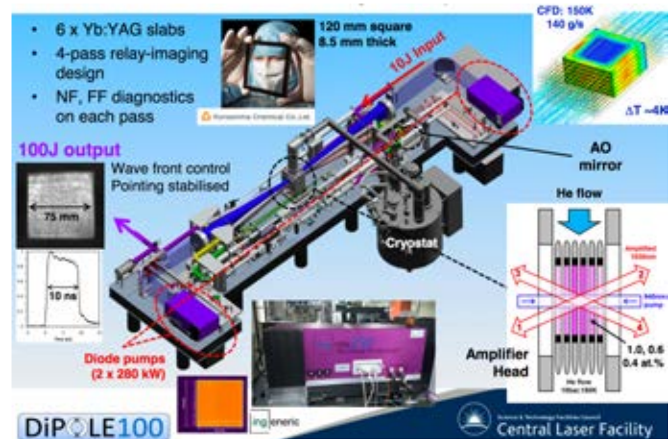
Amplitude P60

Flashlamp pumped Nd:YAG

Design: 60 J @ 10 Hz, 532 nm

<u>Conversion to DPSS fully designed</u>

- Expected rep. rate 50 Hz
- Cost of diode still an issue – currently 5x compared to flashlamps.
- Expected to decrease in 5-10 yrs.
- Maintenance free operation for 25-30 yrs.



DIPOLE[1] 100 @ CLF-STFC

DPSSL Yb:YAG, cryogenic He cooling

100 J @ 10 Hz, @515 nm

Planned developments: 10J @ 100 Hz

Established at 10 Hz

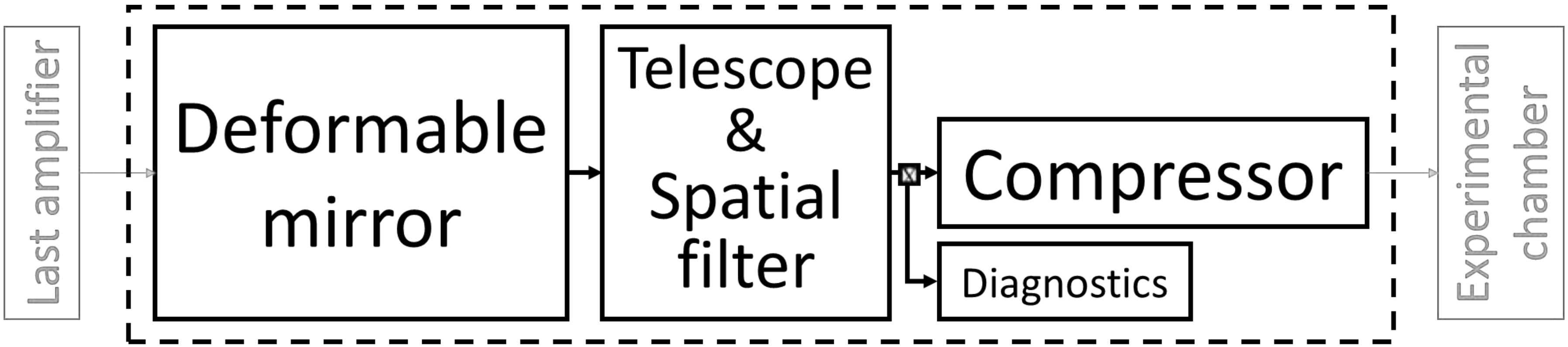
Route to 20 Hz pumping for EuPRAXIA:

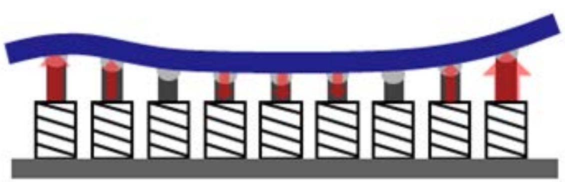
Angular multiplexing

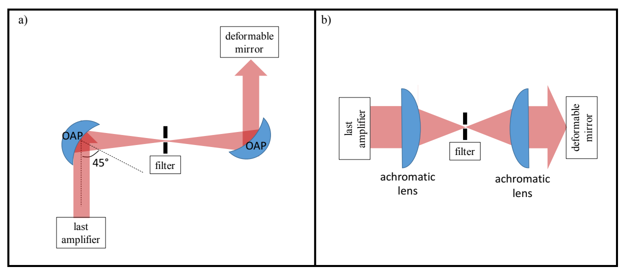
[1]P. Mason et al., Kilowatt average power 100J-level diode pumped solid state laser," Optica 4, 438-439 (2017)

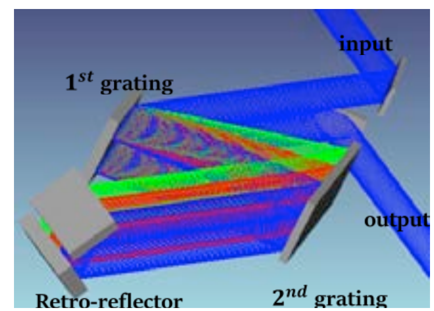
Transport to target

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









Different grating 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.

Pulse train for resonant wakefield

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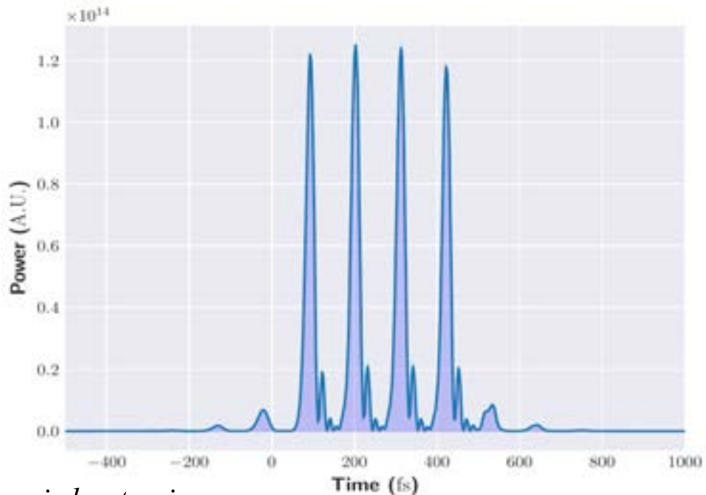
A (QUASI) LOSSLESS SCHEME

Motivation. Shortcomings of current proposed/employed schemes

- 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



Simulation carried out using the MIRO code

Quasi lossless Train gEneration by an early aMplitude dIvision (TEMPI) [2]
Splitting occurs very early in the laser chain. Effects due to pulse interference manageable

L. Labate

Test experiment in progress at CNR ILIL laboratory

Energy losses negligible as compared to the overall pump energy
Compact and simple setup

CNR INO
CONSIGLIO NAZIONALE DELLE RICERCHE
ISTITUTO NAZIONALE DI OTTICA

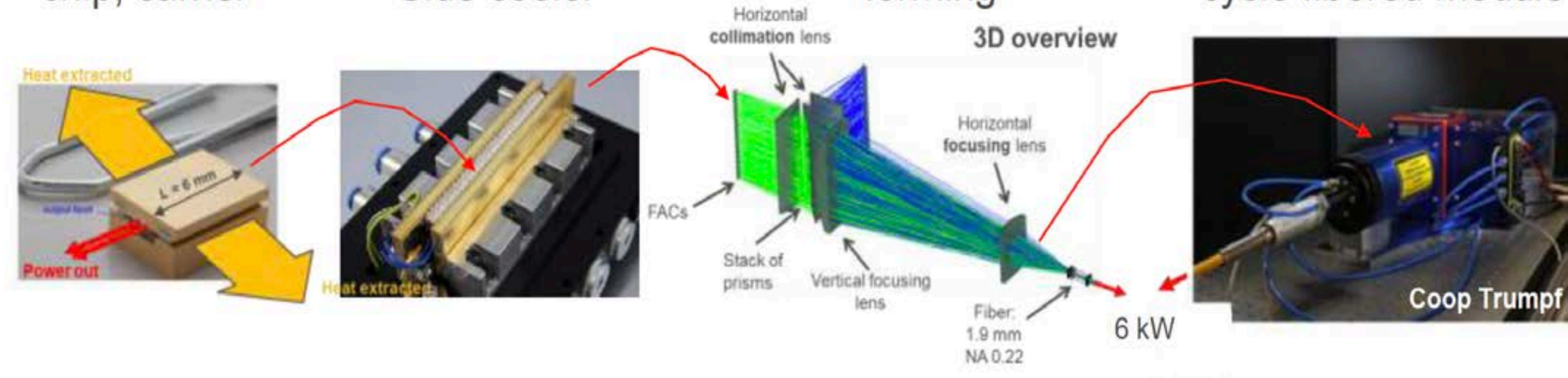
[1] B. Dromey *et al., Appl. Opt.* **46**, 5142 (2007)
[2] L. Labate, G. Toci, P. Tomassini, L.A. Gizzi, *submitted*

100 Hz pump laser

White paper 100 Hz pump trials to assist EuPRAXIA system design (STFC, LLNL, HZDR, FBH), supported by the Institute of Quantum Optics, Friedrich-Schiller-University, Jena in Germany

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

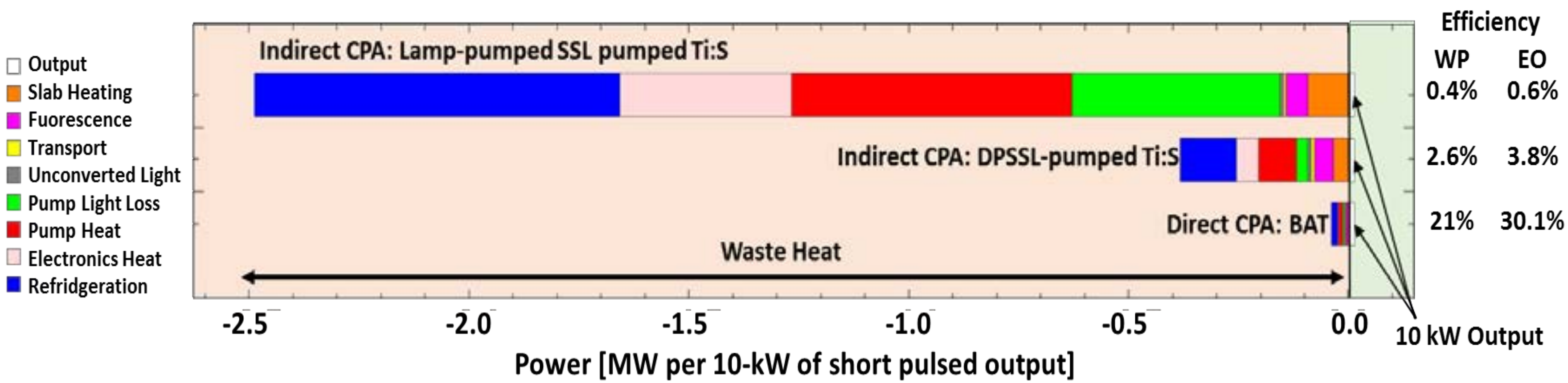
P. Crump

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

Higher efficiency

- Plasma accelerators will require high repetition lasers with high efficiency. Direct pumping of lasing medium with diodes is the solution.

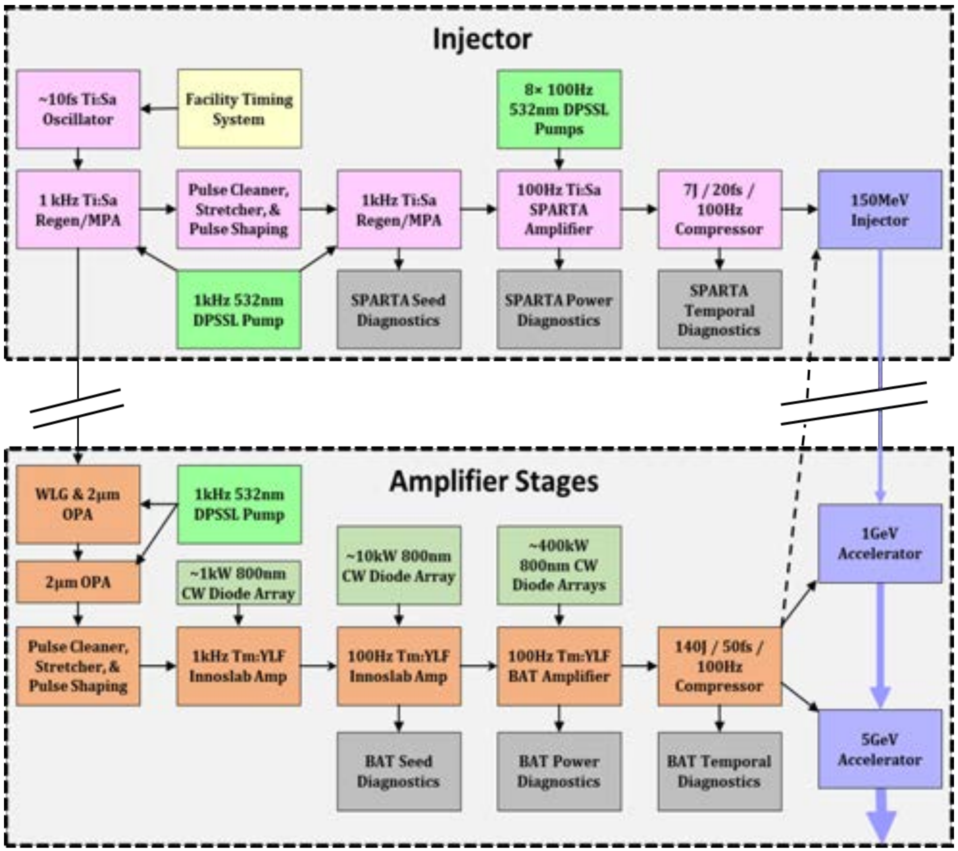
Direct CPA (required for >100Hz) - energy efficient.



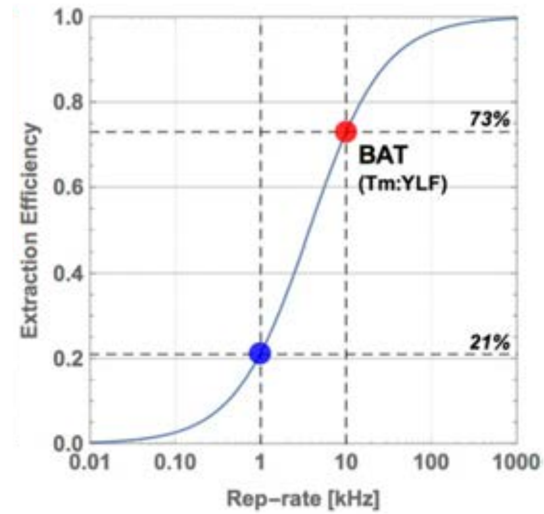
C. Siders et al., EAAC 2017

DIRECT CPA with Tm:YLF

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



Laser system designed to deliver 7J/30fs/230TW at 100Hz : average power of this system = 700W



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

(*) Lawrence Livermore National Laboratory

Baseline cost Estimate

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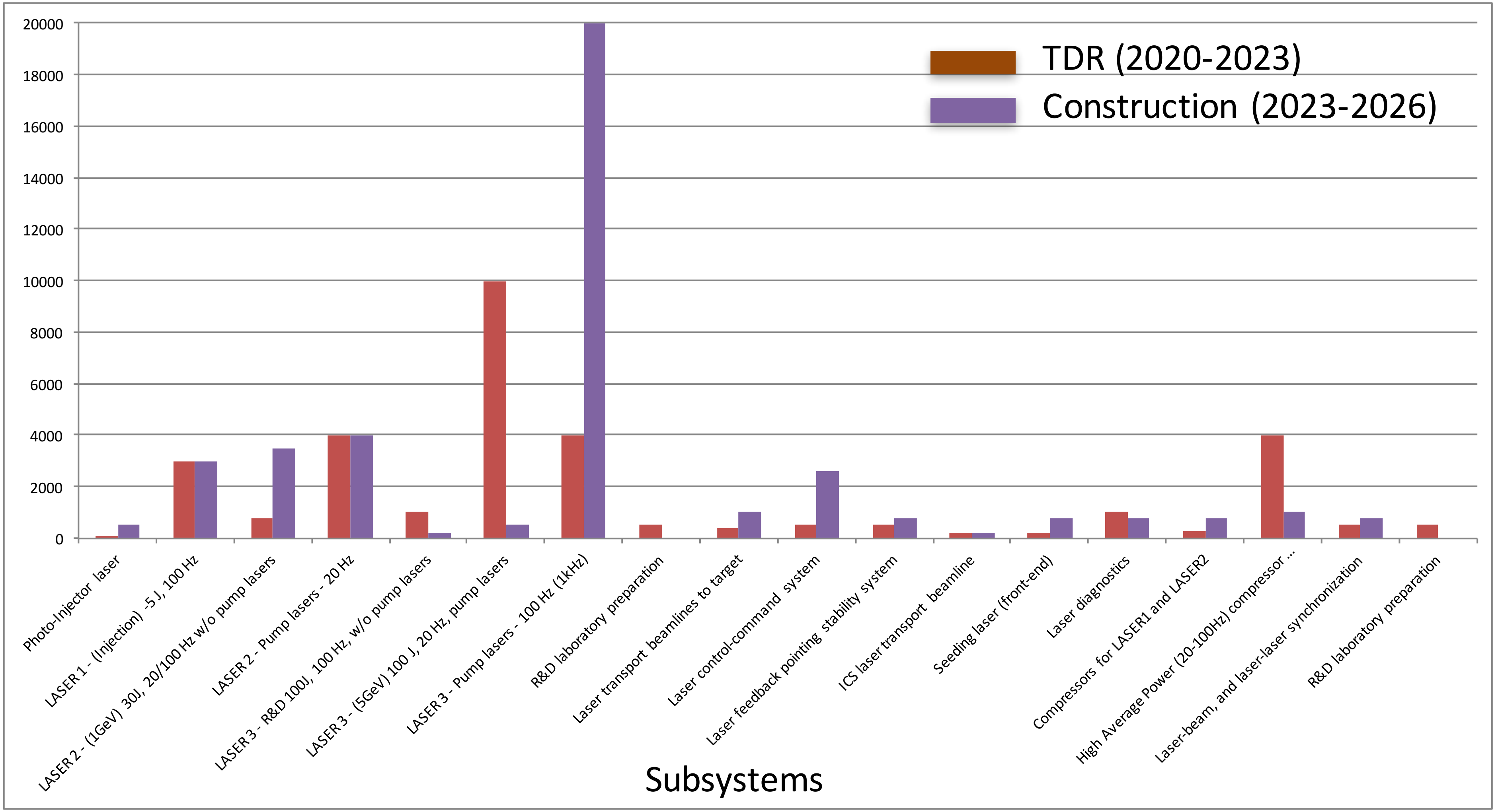
R&D and Investment



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Baseline cost Estimate

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subtopic	TDR/prototyping (e.g. 2020 - 2023)		Construction (e.g. 2023 - 2026)		Local facility used for R&D, proptotyping and tests	comment
	personnel (cumulative for 4 years) [FTE]	material (total) [k€]	personnel (cumulative for 4 years) [FTE]	material (total) [k€]	(name of facility)	
R&D (please specify in comments)						R&D is dedicated to finalize the technology considered for the technical design. During the R&D phase we consider construction of an entire chain (LASER3) prototype at 20 Hz. Construction phase will use prototype components to build the whole system - LASER1, LASER2, LASER3.
Photo-Injector laser	2	100	4	500	CNRS, Paris	Scale existing schemes
LASER 1 - (Injection) -5 J, 100 Hz	4	3000	8	3000	CNR-INO, Pisa	This will be based on industrial systems and will be developed with laser industry. The prototyping of LASER1 includes the front-end which will then be replicated for LASER2 and
LASER 2 - (1GeV) 30J, 20/100 Hz w/o pump lasers	8	800	8	3500	CNR-INO, Pisa	This will be developed in close collaboration with Laser Industry. Here most of the cost for the construction phase is dedicated to diode stacks
LASER 2 - Pump lasers - 20 Hz	4	4000	4	4000	FBH Berlin(?)	This involves industry and other institutes including , STFC, IOQ Jena, Here most of the cost for the construction phase is dedicated to diode stacks
LASER 3 - R&D 100J, 100 Hz, w/o pump lasers	8	1000	12	200	CNR-INO, Pisa	This will be developed in close collaboration with Laser Industry.
LASER 3 - (5GeV) 100 J, 20 Hz, pump lasers	8	10000	12	500	CNR-INO, Pisa	This will be developed in close collaboration with Laser Industry. Here most of the cost for the construction phase is dedicated to diode stacks
LASER 3 - Pump lasers - 100 Hz (1kHz)	16	4000	16	20000	FBH Berlin(?)	This involves industry and a collaboration including FBH, STFC, IOQ-JENA ... Here most of the cost for the construction phase is dedicated to diode stacks
R&D laboratory preparation	4	500	0	0	CNR-INO, Pisa	
Laser transport beamlines to target	6	400	8	1000	CNRS, Paris	
Laser control-command system	16	500	16	2600	CNRS, Paris	
Laser feedback pointing stability system	8	500	8	800	CNRS, Paris	This will be developed in collaboration with STFC and other applicable facilities
ICS laser transport beamline	4	200	8	200	CNR-INO, Pisa	ICS laser will be based on one of the three main beamlines, with custom management
Seeding laser (front-end)	8	200	4	800	CNR-INO, Pisa	
Laser diagnostics	8	1000	8	800	CNRS, Paris	Only final diagnostics : after compressor and at the focal plan : full aperture, near and far field, pulse duration, energy, contrast Spatio spectral
Compressors for LASER1 and LASER2	6	250	4	800	CNRS, Paris	
High Average Power (20-100Hz) compressor (Laser3)	12	4000	6	1000	CNRS, Paris	This will be developed in close collaboration with Laser Industry.
Laser-beam, and laser-laser synchronization	12	500	8	800	DESY, Hamburg	
R&D laboratory preparation	4	500	0	0	CNRS, Paris	
Partial Total	**134**	**30950**	**134**	**40500**		

Running costs* (diode lifetime)

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Eupraxia	Cost of ownership @ 20Hz				
50J @ 532nm @ 20Hz (300 days per year @ 20H a day - expected diodes kifetime = 5x10^9 shots e.g 12.5 years @ 20Hz)					
				per year	Per year/ watt
1	Recurrent costs			214 545,45 €	214,55 €
2	Diode replacement (12.5 years)			327 600,00 €	327,60 €
			Total		**542,15 €**

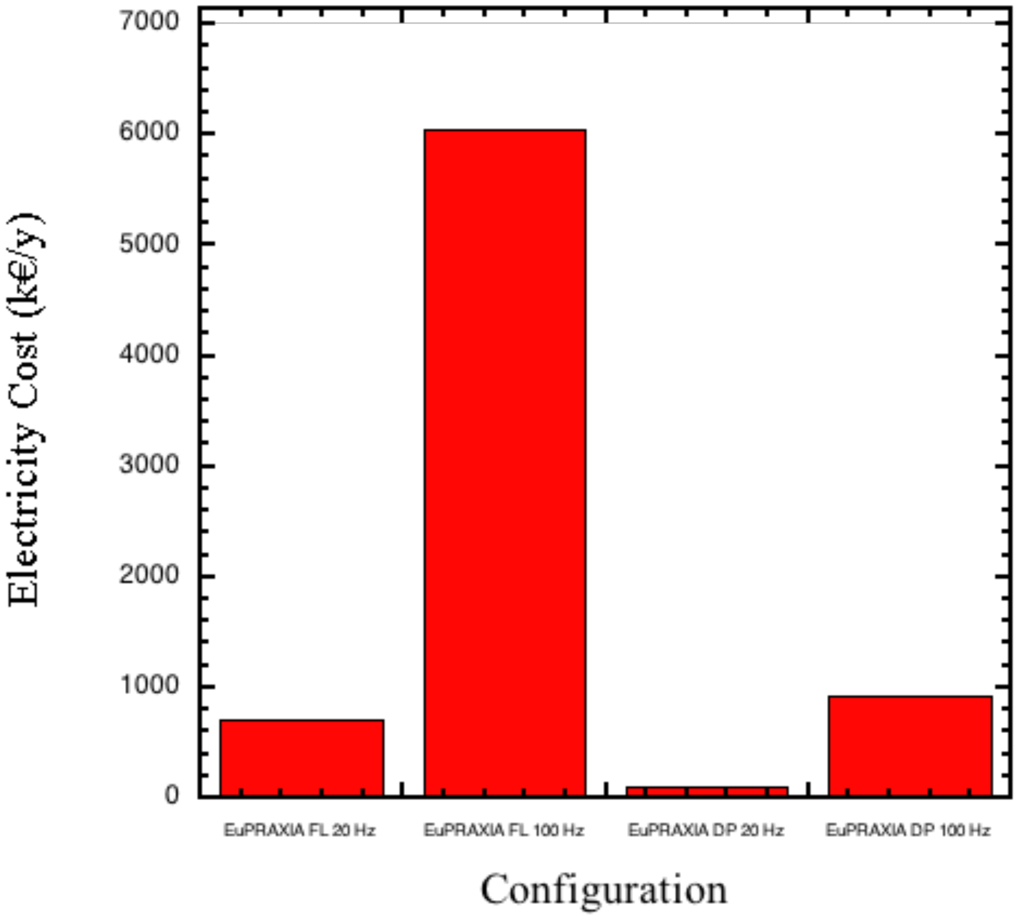
Eupraxia	Cost of ownership @ 50Hz				
50J @ 532nm @ 50Hz (300 days per year @ 20H a day - expected diodes kifetime = 5x10^9 shots e.g 5 years @ 50Hz)					
				per year	Per year/ watt
1	Recurrent costs			214 545,45 €	85,82 €
2	Diode replacement (5 years)			819 000,00 €	327,60 €
			Total		**413,42 €**

Eupraxia	Cost of ownership @ 100Hz				
50J @ 532nm @ 100Hz (300 days per year @ 20H a day - expected diodes kifetime = 5x10^9 shots e.g 2.5 year @ 100Hz)					
				per year	Per year/ watt
1	Recurrent costs			214 545,45 €	42,91 €
2	Diode replacement (2.5 year)			1 638 000,00 €	327,60 €
			Total		**370,51 €**

Evaluated for the Amplitude P60 System

Running cost Estimate

Scaling from efficiency of systems comparing
flashlamp pumped (0.4%),
indirect diode pumping (2.5%) 6.5X,
eventually evolving towards direct CPA (21%) 9,1X.



Configuration	Total pump power (kW)	Wall Plug Power (kW)	Electricity Cost (k€/y)
laser1 FL 20 Hz	0,384	96	58
laser2 FL 20 Hz	1,128	282	169
laser3 FL 20 Hz	3,228	807	484
laser1 FL 100 Hz	2,57	643	386
laser2 FL 100 Hz	9,09	2273	1364
laser3 FL 100 Hz	28,59	7148	4289
laser1 DP 20 Hz	0,384	15	9
laser2 DP 20 Hz	1,128	43	26
laser3 DP 20 Hz	3,228	124	74
laser1 DP 100 Hz	2,57	99	59
laser2 DP 100 Hz	9,09	350	210
laser3 DP 100 Hz	28,59	1100	660
FULL System FL 20 Hz	4,740	1185	711
FULL System FL 100 Hz	40,25	10063	6038
FULL System DP 20 Hz	4,740	182	109
FULL System DP 100 Hz	40,25	1548	929

Reduction of electricity running costs due to higher diode efficiency

Summary on developments

- Prototyping of Ti:Sa amplifiers
- Addressing 100 Hz pump lasers developments
- Thermal management of compressor gratings
- Stability (pointing & more) and active control
- Driver pulse temporal shaping (multi-pulse)
- Synchronization
- Construction
- Integration Issues
- …

Seed funding planned by internal collaboration.
De-risking R&D phase expected prior to TDR.

Cluster approach

Cluster on laser technology (EuP-LASTECH):

R&D on laser drivers, prototyping, tests, construction of final hardware …

Institutes: key WP4 participants and associated labs

TDR development issues

- **Amplifier configuration ($$):**
  - Build a test amplifier to test Thermal load, Cooling;
- **Pumping technology ($$$):**
  - Scaled 100 Hz rep rep. rate, high energy pumping;
- **Grating technology ($$)**
  - Run high average power illumination tests at existing facilities, to make assessments on LIDT, Thermal load, Cooling. Lifetime;
- **Pointing stability ($)**
  - Build tools and run tests at existing facilities; define route for active stabilization;
- **Temporal and Spatial Shaping ($)**
  - Develop efficient pulse train, temporal contrast, AO control and measurements.

SUMMARY

- Delivering a solid baseline concept at 20 Hz with evolutionary Ti:Sa;
  - Major recent progress of *diode pumping* technology matches 20 Hz operation requirements, with frequency doubled DPSSL based pumping units;
  - Backup option with *flashlamp pumping* still available (*pros*: affordable investments and cheaper running costs – cons: dead end in terms of rep-rate and less attractive for technology developments.
- Design phase ongoing: preliminary 20 Hz design going technical;
- Evolution towards 100 Hz repetition rate tackling open issues:
  - Pump laser technology including diode developments
  - Amplifier design and thermal management
  - Transport and compression thermal model and criticalities;
- Significant development activities and funding needed to solve standing technical issues for forthcoming TDR phase => **EuP-LASTECH**


Discussion and questions?