High average power laser drivers for particle acceleration

EAAC, Elba, September 2019

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Outline

- Current laser technology for particle acceleration
- New requirements from applications
- Technology selection
- Laser developments for 100 Hz operation

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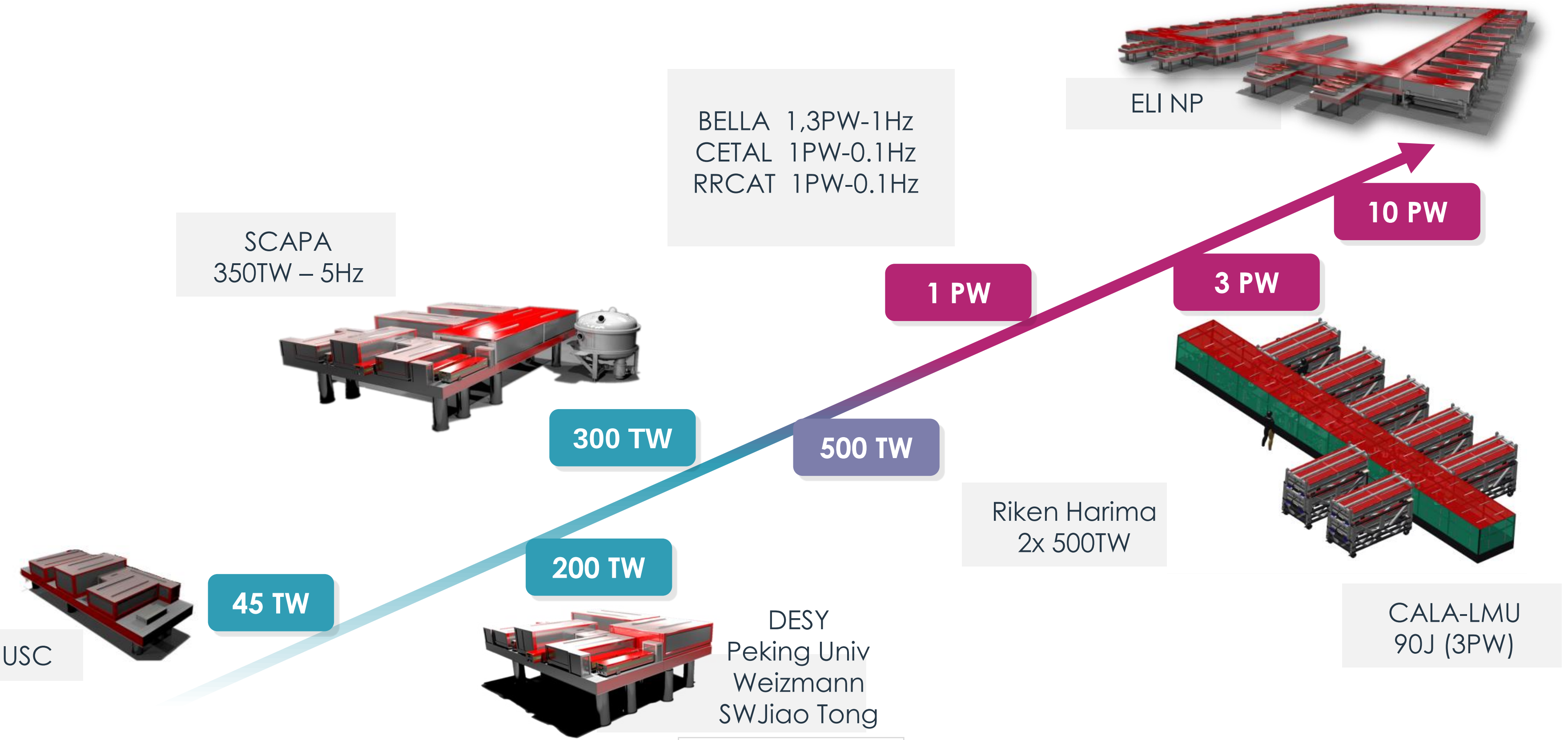
Current ultra high peak power lasers: from TW to > 10 PW



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BELLA: First PetaWatt Laser working at 1 Hz.

Has accelerated Electrons up to 7.8 GeV
A. Gonsalves talk tomorrow

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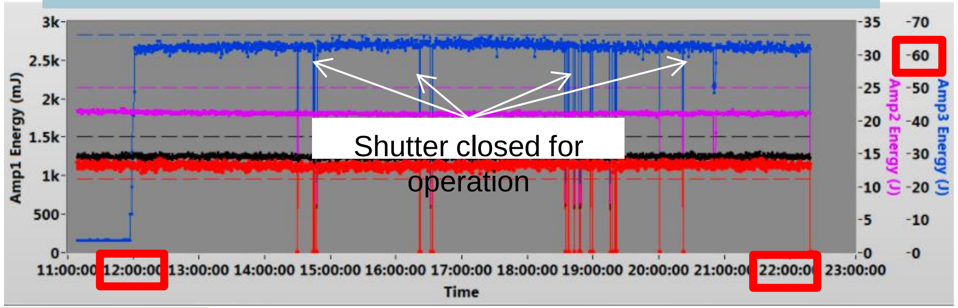
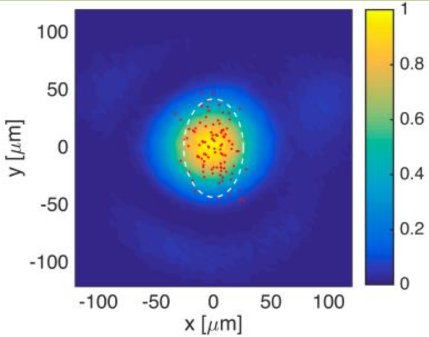
BELLA Laser Results

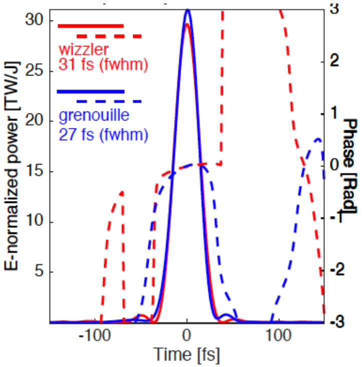
Final amplifier: Stable 62J, >10 hours operation



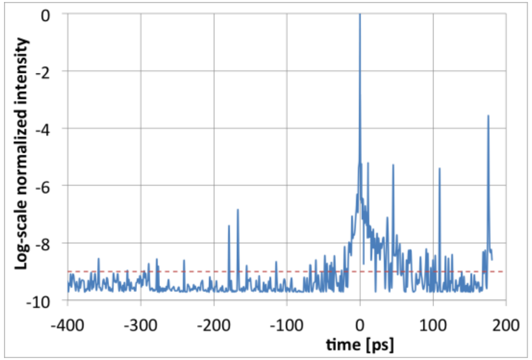
High quality spatial profile
Low pointing jitter



High quality temporal profile



High temporal contrast



49 [J on target] x 25 [TW/J] = 1.2 PW

* K. Nakamura et al., IEEE QE **53** (2017).

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Needs are now for high average power

Large projects ….

- EUPRAXIA: up to 100 J @ 20-100 Hz
- DoE roadmap for future colliders: 1st step is k-BELLA: 3 J – 30 fs @ 1 kHz
- KALDERA @ DESY: 3 J – 30 fs @ 1 kHz

….But also "smaller" lasers for industrial & medical applications

- Good example is X-Ray radiography source based on laser-plasma acceleration of electrons plus Bremstrahlung : typical laser required is 0.5 J – 50 fs with a repetition rate of 100 Hz or more → achievable with existing technologies
- There are other applications which will require higher peak and average powers
  - Proton therapy
  - Production of medical isotopes
  - etc…

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Potential technologies (1/2)

Ti:Sapphire

- Indirect CPA
- Large quantum defect → Significant thermal effects
- Short pulse capability: down to 15-20 fs
- Reasonable efficiency if using DPSS pumps
- High industrial maturity of TiSa amplifiers and FPSS/DPSS pump lasers (COTS)

OPCPA

- Indirect amplification: requires pump lasers
- No energy storage → weak thermal effects
- Very short pulse capability: down to 8-10 fs
- Lower amplication efficiency than TiSa: 15-20% extraction efficiency vs 40-50%
- Low industrial maturity for Joule class solutions. Complex pump lasers

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Potential technologies (2/2)

Direct CPA

- Nd:Glass, Yb doped hosts, Tm doped hosts
- Potential higher efficiencies (direct amplification)
- No ultrashort pulse capability:
  - 150 fs for Nd:Glass
  - 500 fs for Yb:YAG
  - To be checked for Tm:YLF : 60 fs ?
- No short term solution for pulse shortening through SPM at Joule input
- Except Flashlamp pumped Nd:Glass & Yb:YAG, very low industrial maturity

Thales choice for high peak power (> 10 TW) and high average power (> 100 W) generation in 100 Hz – 1 kHz range is Titanium Sapphire

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Thales approach for 100s Hz laser development

TW class systems

- Thales has a strong experience in 100Hz laser systems

Thales state-of-the-art

ALLS : 3TW, 30fs, 100Hz

Fully operational for more than 10 years

What can be done

10 TW, 100s Hz

Safe operations in amplifiers and compressor

Middle, long term

> 100 TW, 100s Hz

Issues to overcome :

- High energy pump laser
- Thermal management of the amplifier
- Compressor @ high average power

New pump laser – THEIA: > 700 mJ green @ 100 Hz & 200 Hz

THEIA

Power is coming

Specifications

Version	IR	Green	UV
Wavelength (nm)	1064	532	355
Repetition rate (Hz)		Up to 200	
Energy per pulse (mJ)	1000	700	500
Pulse to pulse energy stability (% rms)		< 1.0	
Typical pulse width (ns)		10	

Physical characteristics

Power supply	20.9 x 22 x 31.1 in	65 x 60 x 80 cm
Cooling unit	14.6 x 17.4 x 28.4 in	37 x 44 x 72 cm
Laser Head	63 x 11.3 x 7.4 in	160 x 29 x 19 cm

Utilities and environment requirements

Voltage	230 VAC ± 5% Single phase
Frequency	50 – 60 Hz
Water flow	> 2.7 gal/mn > 10 L/min
Static pressure	43.5 – 72 psi 3 – 5 bars
Temperature	15 – 17°C

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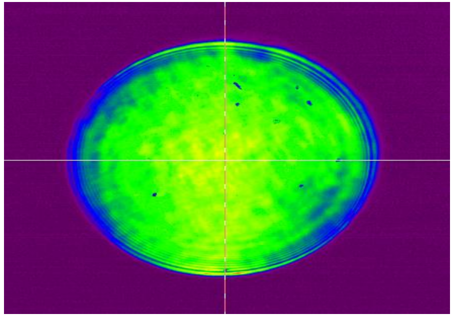
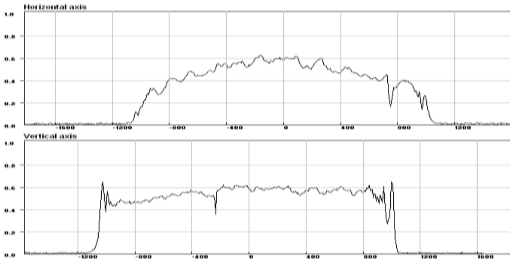
1064 nm Results

	100 Hz	200 Hz
Pulse duration FWHM	9 ns	12 ns
Energy (linearly polarized)	> 1.3 J	1.3J
Depolarization	< 6%	< 8 %
Energy stability	0.5 % rms	0.5 % rms



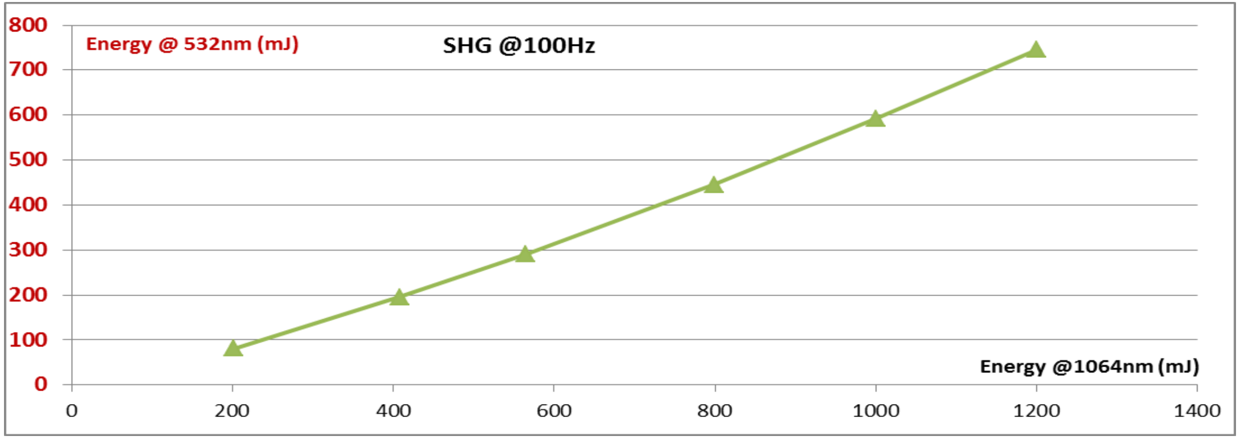


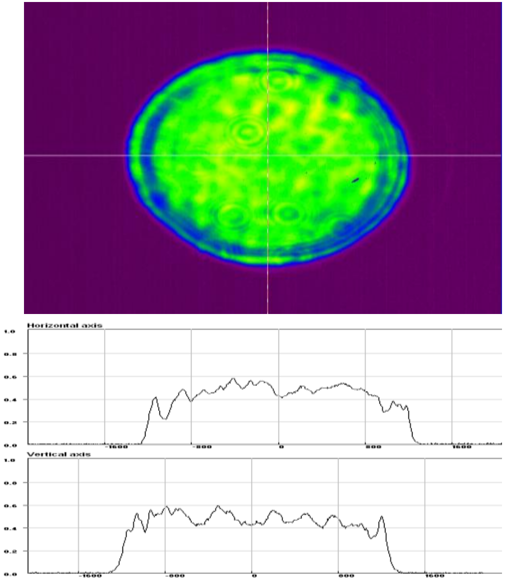
profile @ 200Hz

532 nm results @ 100Hz

- 780mJ @532nm
- ~7.5ns FWHM
- SHG efficiency : 65%
- Shot to shot energy stability : < 0,5% rms

  Recent results: **< 1% peak-to-valley !**





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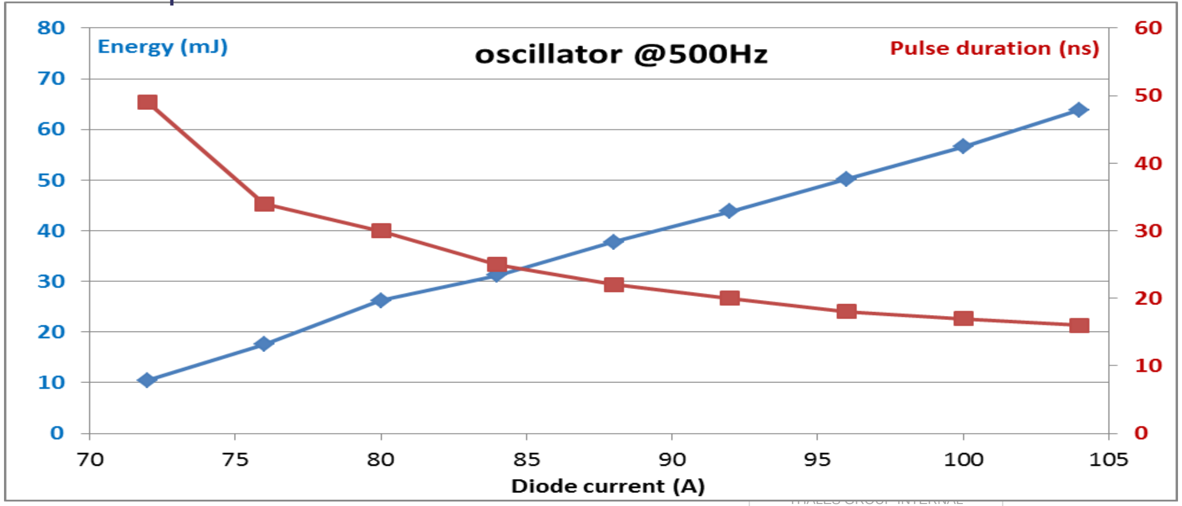
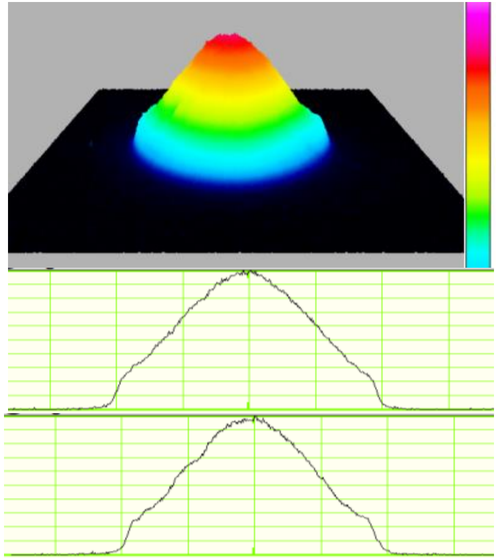
500 Hz Laser results: oscillator

Target specs : 0.7J @500Hz, 532 nm, M² 15-25

500 Hz Oscillator Results

- >60mJ @1064nm
- M² = 13
- ~15ns FWHM
- Depolarization <3%





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Amplification at high average power in Ti:Sa

- Thermal effects are strong in TiSa due the large quantum defects and material parameters (CTE & dn/dT) which lead to strong lensing
- Cryogenic amplifiers are a possible solution. They are now working for years in scientific 1 kHz-10 kHz commercial TiSa systems. Up to 1 kW cryostats are now commercially available
- But solution is not so well suited for compact and easy-to-use systems designed to be used by non laser experts
- What is helping for higher energies at 100 Hz is the larger spot size which leads for a lower heat density at the same average power.
- Our approach is based on “thick” TiSa disks (2 mm < t < 6 mm) compared to long bulk crystals (t > 15 mm). (Thin disks stand for t < 1 mm).
- This approach has been initially investigated by ELI-ALPS group

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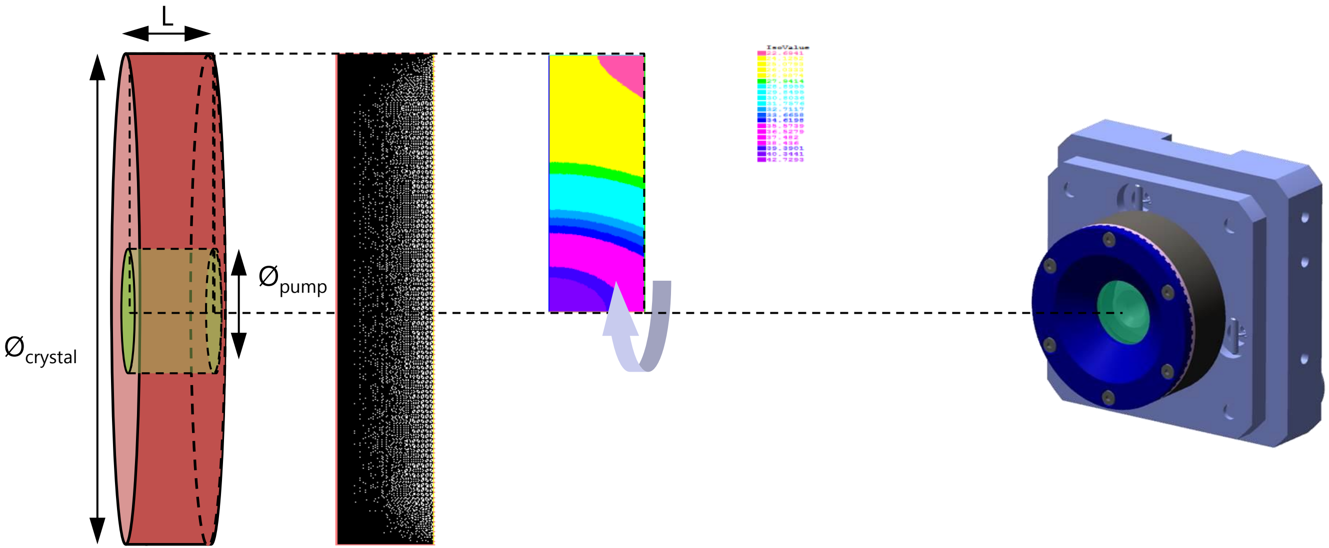
Latest development at High average power

Thick disk Amplifier : thermal simulation and mechanical design

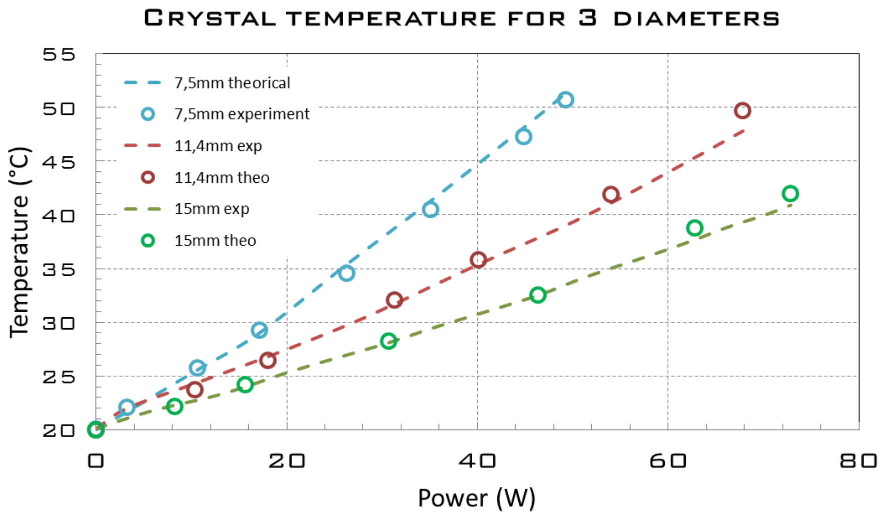


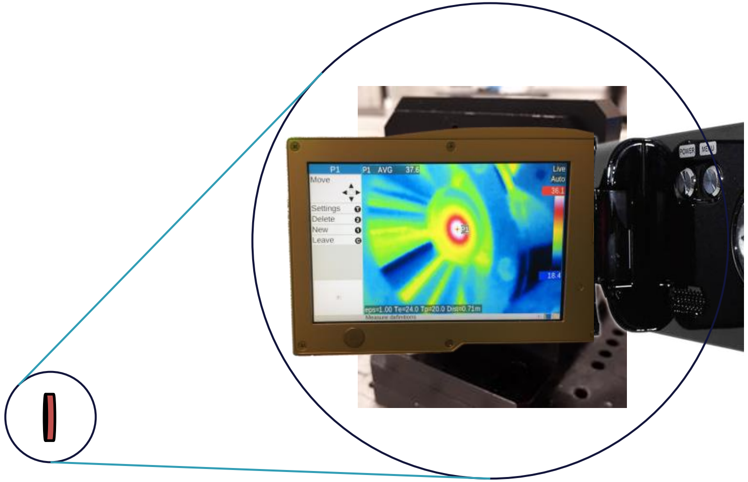
Crystal meshing

Finit element computation with rotational symmetry

Latest development at High average power

Thick disk Amplifier : thermal simulation and mechanical design





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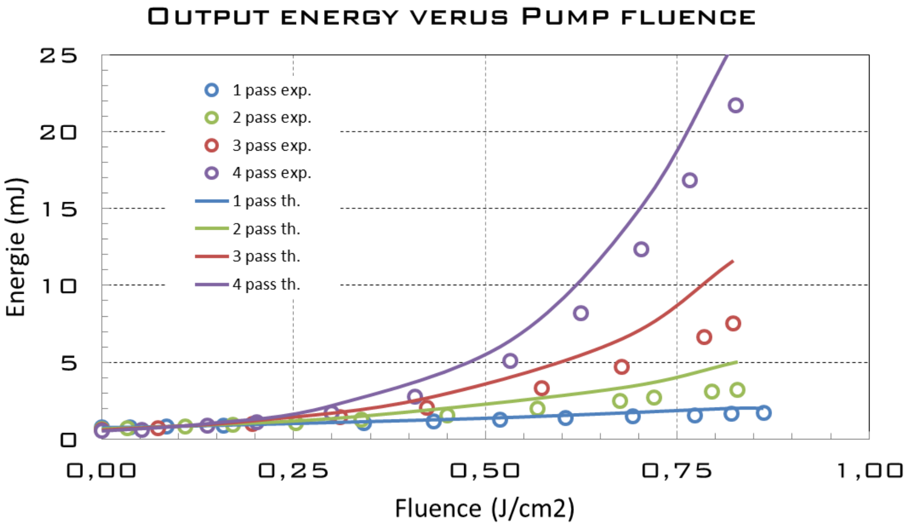
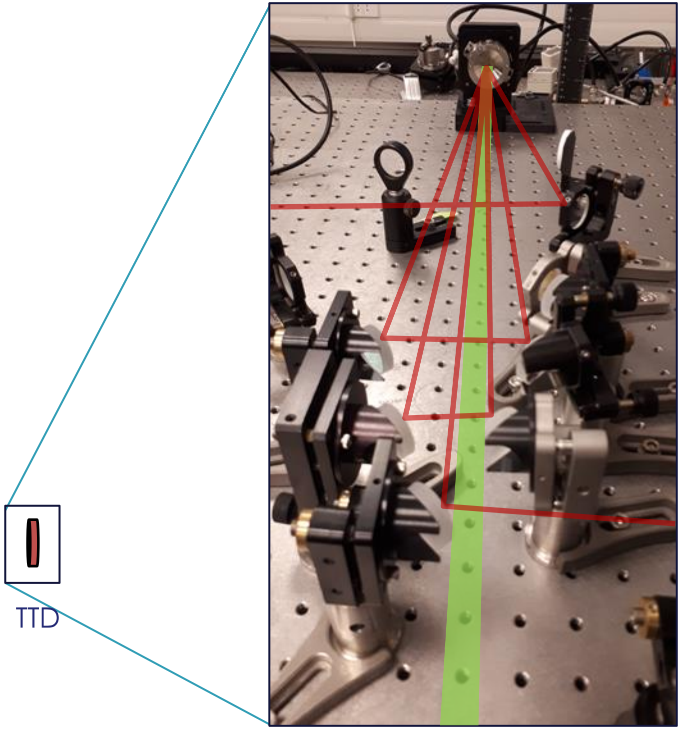
Latest development at High average power

Thick disk Amplifier : Amplification simulation and small signal experiment





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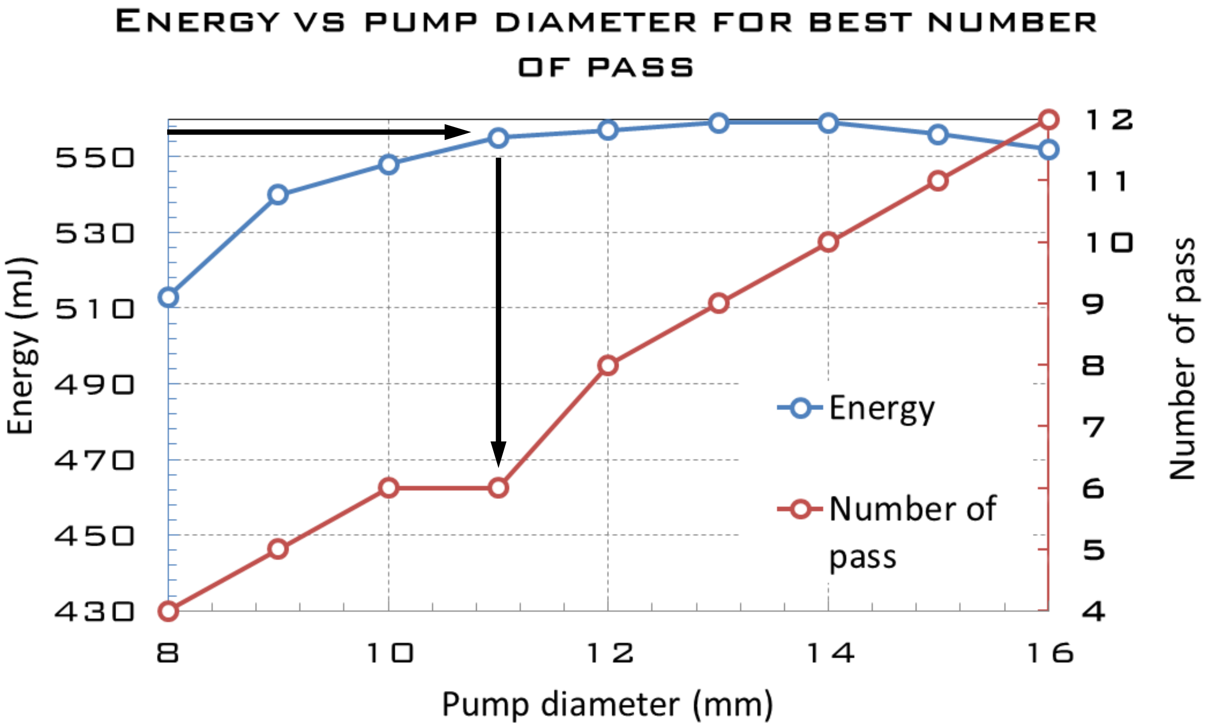
Latest development at High average power

Thick disk Amplifier : 550mJ @ 100Hz



Input energy	1,5 mJ
Pump energy	1,4 J
Repetition rate	100 Hz
Output energy	550 mJ
Compressor efficiency	90%
Compressed Energy at 50fs	500 mJ

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High average power compression

Some groups have pointed out the deleterious effects of heat absorption by gold gratings at significant average power levels

- S. Fourmaux (Opt. Exp, 178, 2009)
- V. Leroux (Opt. Exp, 13061, 2018)
- R. Clady (App Phys B, 2018, 124, 5)

Possible solutions are the following (either take one or combine them)

- Active cooling of the gratings (LLNL approach: D. Alessi, https://www.osti.gov/biblio/1333397)
- Enlarge laser beam and grating size to reduce average power densities and fluences on gratings (but compactness and cost issues as well as not very scalable)
- Use alternative gratings
  - MLD gratings : but limited bandwidth + LIDT issues ? Work on design (see Alessi on ArXiv 1811.03091)
  - "Hybrid gratings" (MLD + back metal layer): but absorption still too high ?

It is important to have means to characterize gratings under high average power and test also LDT

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Conclusions

- TW / PW lasers (up to 10 PW now available)do well for particle acceleration and have produced impressive science so far
- But current technologies are limited for the next challenges in science and also to be used in industry & medicine
- Ti:Sa remains technology of choice and with significant improvements should be used up to kW level
- Thales has developed new diode-pumped high rep rate (100-500 Hz) ns lasers for TiSa pumping
- There are also ongoing developments for next gen TiSa amplifiers
- Compression at high average power could remain a potential bottleneck. Some effort from the community are required.