Scaling of ps-kHz-pulses to multi-kW levels using thin-disk technology and synchronization to ERL for the Romanian System

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ELI TDR-CDR (white paper-EU)

• ELI Vision – GM, WS, JC,
  – International Landscape - European Leadership
  – Science and Society – EQUAL balance
  – Stimulus – industrial opportunities
  – Community growth – integrated proposal
  – User facility

• ELI Science – NL, GM, GK
  – Detailed at an appropriate level
  – Applications

• ELI Technology – JC, BR, GS, DU
  – Site non specific
  – Development requirements – TRL

• Implementation strategy – GK, BR, GS, VZ, MD, WS
  – Costs – time – risks
  – Risk – Phased – Darwinian – time seperability
  – Nodes – European national programmes
  – Specs-table
  – People – LLE – FP8
  – ERIC – Governance ?
Photon momentum $\mathbf{p} = h \cdot \mathbf{k}$

Seed $\mathbf{k}_3$

Pump $\mathbf{k}_2$

Idler $\mathbf{k}_1$

difference frequency generation (DFG)
wave mixing:

$\mathbf{k}_3 = \mathbf{k}_2 - \mathbf{k}_1$

Optical parametric amplifier (OPA)

Optical parametric amplifier (OPA)

Optical axis

pump

signal

idler

nonlinear optical crystal

$\alpha$

$\Theta$

$\mathbf{n}$: Wellenvektor

Photon momentum $\mathbf{p} = \mathbf{n} \cdot \mathbf{k}$
OPCPA design

- Large aperture DKDP crystals
- Total pump energy: 20 J @ 515 nm
- 1D modelling with saturation (pump depletion)
- no dispersion included

<table>
<thead>
<tr>
<th>stage</th>
<th>pump energy</th>
<th>ampl. signal energy</th>
<th>crystal length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5 mJ</td>
<td>500 µJ</td>
<td>3.8 mm</td>
</tr>
<tr>
<td>2</td>
<td>20 mJ</td>
<td>3.5 mJ</td>
<td>3.8 mm</td>
</tr>
<tr>
<td>3</td>
<td>200 mJ</td>
<td>40 mJ</td>
<td>3.5 mm</td>
</tr>
<tr>
<td>4</td>
<td>1 J</td>
<td>169 mJ</td>
<td>3.0 mm</td>
</tr>
<tr>
<td>5</td>
<td>3 J</td>
<td>722 mJ</td>
<td>2.8 mm</td>
</tr>
<tr>
<td>6</td>
<td>5 J</td>
<td>1.7 J</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>7</td>
<td>5 J</td>
<td>2.8 J</td>
<td>1.7 mm</td>
</tr>
<tr>
<td>8</td>
<td>5 J</td>
<td>3.8 J</td>
<td>1.5 mm</td>
</tr>
</tbody>
</table>

- Verify design with more sophisticated calculations:
  - "pseudo 3D": 2D with cylindrical symmetry
  - take into account dispersion by split-step method
  - effect on saturation on beam profile

Zs. Major et al., Review of Laser Engineering, 37, 431 (2009)

E. Zeremskis et al., Optics Comm. 203, 435 (2002)
A. Dubietis et al., JOSAB 15, 1135 (1998)
Advantages of the thin disk lasers:

- small thermal lens allows high beam quality
- effective cooling allows high pump densities (0.8 MW/cm³)
- energy and power scaling via area of the disk
- extremely high pulse energies possible via large aperture
- low nonlinearities (SPM) through thin amplifier medium

Yb:YAG as gain material (1030 nm):

- very high quantum efficiency (91%) – low heat generation
- high absorption bandwidth (10 nm) – low requirements at the pump diodes (940 nm)
- no upconversion / excited state absorption
- high heat conduction and stress resistance of YAG
- long life time of the upper laser level (~1 ms)
- high emission bandwidth (~6 nm) – short pulses possible
Principle of thin disk laser

Cooling finger with nozzle
Carrier: (Cu, diamond)
AR
HR

Yb:YAG disk
cooling water

Disk parameter
thickness: 100 - 900 µm
diameter: 10 - 35 mm

- effective cooling
- small thermal lens
- high pump power density 10 J/cm²
- power/energy scalability \( \approx (d)^2 \)
- moderate gain

courtesy of Trumpf Laser GmbH
Front-end – where it all starts from

OPA Seed- & Pumplaser optical synchronised

GDD = 10^8 fs²

\( \Delta \lambda = 4 \text{ nm} @ \lambda_{\text{signal}} = 1030 \text{ nm} \)

\( \tau_{\text{stretch}} = 730 \text{ ps} \)

40 dB Verstärkung 1pJ \( \rightarrow \) 1nJ

Yb:YAG-disk amplifier
150 round trips
35 mJ; 3.0 kHz; 210 ps
>100 W average power

GDD = -10^8 fs²; \( \Delta \lambda = 1 \text{ nm} \)

25 mJ puls energy @ 3.0 kHz

\( \tau_{\text{compressed}} = 1.6 \text{ ps} \rightarrow 150 \text{ W} \)
Prototype (Yb:YAG; 1030 nm):

- Size: 1m x 2m
- Average power: 75 W
- Repetition rate: 1-10 kHz
- Pulse duration: 1.6 ps
- Max. pulse energy: 25 mJ @ 3 kHz
- Optical efficiency: 34 %
- Pulse- to Puls- stability: < 0.7 %
- Long-term stability (9h): ± 0.6 %

System can probably be extended to 50-100 mJ at 1kHz (longer pulses, increased beam diameter on disk)

Beam quality $M^2 < 1.1$

$M^2 = \frac{\lambda}{\pi \omega_f \Theta_f}$
Energy scaling via disk based amplifiers

- scaling factor: 1 → 10
- pump spot Ø: 3 mm → 9.5 mm
- pump power: 300 W → 3 kW
- pulse energy: 30 mJ → 300 mJ
- gain: 1,2 @ 0.3 kW → 1,2
- required V-passes through disk: 80 regen → 13 multi pass
- 5 J OPA @ 1 kHz
- 25 J @ 515 nm
- 5 x 10 J @ 1030 nm
- 500 kW pump diodes
- 100 mm Ø disk
- large disk head (100 kW pump light)

courtesy of: Trumpf Laser GmbH
Available thin disk amplifier heads

500 W diode pump power
Ø few mm; energy few mJ

5 kW diode pump power
Ø 8 mm; energy: 500 mJ

12 kW diode pump power
Ø 35 mm; Estimated Energy: 2-3 J

5 J OPA @ 1 kHz
25 J @ 515 nm
5 x 10 J @ 1030 nm
500 kW pump diodes
100 mm Ø disk
large disk head
(100 kW pump light)
Yb:YAG thin-disk amplifier currently under construction at the MPQ

- Multi pass under construction
- 4.7kW diode pump light
- Pump spot Ø ~10mm
- Based on a Trumpf thin disk
- Up to 20 V-passes through the disk
- Expected pulse energy: > 150mJ (3kHz)
- Expected completion end of 2010
High-repetition-rate chirped-pulse-amplification thin-disk laser system with joule-level pulse energy

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We are reporting on the development of a disk-pumped chirped-pulse-amplification (CPA) laser system based on Yb:YAG thin-disk technology with a repetition rate of 100 Hz and output pulse energy in the joule range. The focus lies with the first results of the preamplifier—a regenerative amplifier (RA) and a multipass amplifier (MP). The system consists of a front end including the CPA stretcher followed by an amplifier chain based on Yb:YAG thin-disk amplifiers and the CPA compressor. It is developed in the frame of our x-ray laser (XRL) program and fulfills all requirements for pumping a plasma-based XRL in grazing incidence pumping geometry. Of course it can also be used for other interesting applications. With the RA pulse energies of more than 165 mJ can be realized. At a repetition rate of 100 Hz a stability of 0.8% (1σ) over a period of more than 45 min has been measured. The optical-to-optical efficiency is 14%. The following MP amplifier can increase the pulse energy to more than 300 mJ. A nearly bandwidth-limited recompression to less than 2 ps could be demonstrated. © 2009 Optical Society of America

OCIS codes: 140.3538, 140.3480, 140.3580.

Fig. 1. Scheme of the thin-disk laser system.

Fig. 5. Scheme of the MP. Input and output pulse energies are experimental values.
The challenge with thin disk amplifiers: ASE

 ASE
- caused by total reflection between AR & HR coating
- supported by extreme high pump power densities
  1MW/cm² (10kW/cm²)
- the thinner the disk the higher the ASE
- the larger the disk diameter the higher the ASE

ASE: possible work around

- **thin disk**: high doping concentration
  - strong ASE (high pump power density)
  - good cooling (cool disk)

- **thick disk**: low doping concentration
  + low ASE (reduced pump power density)
  - bad cooling (hot disk)

- **bonded disk**: high doping on undoped cap
  + low ASE
  + good cooling (cool disk)

- careful calculation of the amplifier required; bonded or even ceramic disks required, are there other tricks??

Calculations for the multipass amplifier

Time resolved model:
- spatial pump absorption
- spatial inversion
- ASE in the disk
- average temperature
- calculations with 1 ms pump pulse, 10% heat generation
- here: 10% duty cycle

=> Calculate max. stored energy

6% Yb:YAG, d=300 μm, P = 8 kW
Pumpspot 8 mm (4 kW/cm²),
low duty cycle => av. T ~ 30°C
initial pulse energy 100 mJ

Courtesy of Jochen Speiser
Energy extraction based on:

- initial pulse energy 100 mJ
- higher duty cycle leads to higher temperature and less extractable energy
- reducing disk thickness increases ASE influence

Calculation: influence of duty cycle / disk thickness

Yb:YAG, $P = 8 \text{ kW}$, pumpspot 8 mm (4 kW/cm²), initial pulse energy 100 mJ
- ▬ 6%, 300 μm, low duty cycle (T ~ 30°C)
- 🔴 6%, 300 μm, cw (T ~ 170°C)
- △ 9%, 200 μm, cw (T ~ 144°C)

V-passes through the disk

Pulse energy [mJ]

0 200 400 600 800
0 2 4 6 8 10 12 14 16

Courtesy of Jochen Speiser
Calculation: influence of the pump spot size & pump power

Gain: pump power & pump spot size
- reduced gain, less efficient extraction with 8 kW
- at higher pump powers: higher temperature and stronger influence of ASE due to increased radial gain
- “scaling limit” reached between 16 kW and 20 kW for this disk thickness

6% Yb:YAG, d=300 μm, Pumpspot 20,6 mm, cw pumped
initial pulse energy 100 mJ

Pulse energy [mJ] vs. V-passes through the disk

8 kW, 16 kW, 20 kW

Courtesy of Jochen Speiser
Possible work-around:

- combine 2 disks in 1 multipass amplifier
- reduced pump spot diameter reduces ASE

2 disks, total pump power 20kW sufficient to reach 1 J with less than 15 reflections at each disk

Further evaluation: higher efficiency with two amplifier stages for 100 mJ -> 1 J

2 disks, 6% Yb:YAG, d=300 μm, P = 10 kW each
Pumpspot 17.8 mm (4 kW/cm²), cw (av. T ~ 170°C)
initial pulse energy 100 mJ
Calculation: single or double disk amplifier

1 or 2 disks
6% Yb:YAG, d=300 μm, P = 8 kW
Pumpsot 16 mm (4 kW/cm²),
low duty cycle => av. T ~ 30°C
initial pulse energy 100 mJ
Synchronization on subps- and fs- scale

Ps: using the rf-masterclock of the LINAC and stabilizing and locking both oscillators to each other

Electron Bunch Timing with Femtosecond Precision in a Superconducting Free-Electron Laser

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FIG. 1 (color online). Schematic of the free-electron laser FLASH with the locations of the two bunch arrival-time monitors (BAM1, BAM2) and the two bunch compression monitors (BCM2, BCM3). ACC1-ACC6: accelerating modules, BC1 and BC2: bunch compressors.
FIG. 2 (color online). Operation principle of the electron bunch arrival-time measurement using an electro-optic modulator (EOM).

The key component of the BAM is a novel electro-optic detection scheme. The beam-induced bipolar signal from a pickup electrode with more than 10 GHz bandwidth is utilized to modulate the amplitude of the laser pulse train by means of a commercial Mach-Zehnder type electro-optic modulator (EOM). The principle of the arrival-time
Diode pump sources for thin disk lasers

- 13 kW fiber coupled
  - cw / pulsed (80µs rise time)
  - 15 Euro/Watt

- 10 kW cw / 12 kW pulsed, free beam
  - (80µs rise time)
  - 13.5 Euro/Watt

- Work on >25 kW multiple fibers
  - Euro/Watt ??

- Work on 50 kW fiber bundle
  - 20 Euro/Watt ??

- Do it yourself: unlimited terrible dangerous 100kW free beam
WP 7A last week

1. OPCPA front-end (DPSSL ps pump up to Joule level) Ro, Hu, Cz

2. Ti:sa (back-up) (DPSSL) Ro
Conclusions

Current thin disk technology: ~ 2 Joule possible, Ro

Numerical Modeling for Disk Amplifiers

Large disks / bonding technology required, Hu

Powerful laser diodes required > 50 kW, Hu

Large laser head needs to be developed, Hu

Synchronization possible on sub-ps level and fs-level conceivable to ERL, Ro
Thanks!