Cryogenically Cooled Laser Amplifiers

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HEC-DPSSL, Lake Tahoe, Sept. 12th – Sept. 14th
Outline

Introduction:
- Why cryogenic cooling?
- Yb:CaF$_2$ @ cryogenic temperatures
- Burst mode?

Burst Mode Laser system:
- General layout
- Frontend
- Amplifiers

Conclusion
Why cryogenic cooling?

In case of Yb$^{3+}$ doped media cryogenic cooling yields (typically):

- Higher efficiency
- Higher gain

Why?
Lower laser levels are thermally depopulated!

Yb:CaF$_2$ @ 300K

- $n = 1.4$ + low $n^2$
- Lifetime 1.9ms
- Broad emission and absorption bands
- Good thermal conductivity
- Not birefringent
- Large size available

- Low emission cross sections
- High saturation fluence (74J/cm$^2$)
- Strong reabsorption @ laser wavelength
Yb:CaF$_2$ @ 100K

- Higher $\sigma_e$ @ 1030 nm
- Bandwidth nearly maintained but structured
- Absorption around 940 nm nearly unaffected
- Reabsorption @ 1030 nm negligible
- BUT: still not high gain material still moderate saturation fluence (approx. 40 J/cm$^2$)

Further Improvement is achieved for mechanical properties in case of cryogenic cooling:
e.g. higher thermal conductivity (x4 for undoped material between 300 and 100 K!)
Cryogenic cooling improves the amplification properties, but there are still challenges to face for efficient operation:

1. Yb:CaF$_2$ is still rather a low gain material

2. The saturation fluence is still high compared to LIDT values for Pulses in the nanosecond range

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- e.g. higher thermal conductivity (x4 for undoped material between 300 and 100 K!)
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- e.g. higher thermal conductivity (x4 for undoped material between 300 and 100 K!)

Advanced multipass imaging schemes

Other pulse modes
Burst mode

Amplification of multiple pulses within one amplification cycle

- Fluence for single pulse stays low → reduced LIDT issue
- Total extraction fluence of burst is high → efficient extraction

<table>
<thead>
<tr>
<th>burst parameters for our system</th>
</tr>
</thead>
<tbody>
<tr>
<td>reprise within burst $\tau_1$</td>
</tr>
<tr>
<td>reprise of bursts $\tau_2$</td>
</tr>
<tr>
<td>pulses per burst</td>
</tr>
<tr>
<td>burst length $\tau_3$</td>
</tr>
<tr>
<td>length of single pulse</td>
</tr>
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</table>

- Laser
- Pump

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What is offered by bursts?

- **diode pumped high energy fs lasers**
  - gain saturation of broadband materials is typically well above LIDT in CPA Yb-doped systems
  - limited efficiency
  - rather low average power

- **diode pumped high power fs lasers**
  - very high average power, but rather low peak power
  - good efficiency

- **fs - burst mode amplifier**
  - LIDT for bursts is way higher even at lower stretching
  - good efficiency possible
  - medium average power
  - medium peak power
Applications

- Interaction with particle beams from accelerators
  - Matched pulse mode
  - Higher energy as CW pumped

- FHe bursts applications

- Other
  - Materials processing
  - Combustion diagnostics
  - Plasma diagnostics
  - ...

- Dose and energy sensitive experiments
  - X-ray source
  - Electron acceleration
  - HHG
  - Spectroscopy
Frontend amplitude satzuma + pulse compression

Stretcher

S0
50W CW diode pumped

S1 (cryogenic)
2.5 kW Diode pumped

Pulse Picker

S2 (cryogenic)
16kW Diode pumped

Experiment

Implementation in progress
Installed + running
under development

1MHz, 1W, 150fs

1MHz, 200ps

1MHz, 10W

1MHz, 1W, 150fs

x mJ bursts

mJ range, e.g. ns pulse

up to 200 mJ, 10Hz

achieved >300 mJ, 0.5Hz

up to 5J, 10Hz

Alternative Frontend

1MHz, 5W, 200ps

1MHz, 10W

1MHz, 10W
Burst laser system

- Frontend amplitude
  satzuma + pulse compression

- Stretcher
  1MHz, 1W, 150fs
  1MHz, 200ps

- S0
  50W CW diode pumped
  1MHz, 10W

- S1 (cryogenic)
  2.5 kW Diode pumped
  1MHz, 1W, 150fs
  up to 200 mJ, 10Hz
  achieved >300 mJ, 0.5Hz

- S2 (cryogenic)
  16kW Diode pumped
  up to 5J, 10Hz
  x mJ bursts

- Pulse Picker

- Experiment

- alternative Frontend
  mJ range, e.g ns pulse

- Implementation in progress
  Installed + running
  under development
Amplitude Satsuma generates 300 fs, 1 MHz, 1 W

- Stretched to ca. 50 ps

- BME Pockels-cell cuts out bursts of 500 pulses, 1Mhz

- Burst reprise 10 Hz
## Burst laser system

<table>
<thead>
<tr>
<th></th>
<th>S0</th>
<th>S1</th>
<th>S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>10W, 0.1-1MHz</td>
<td>200mJ, 10Hz</td>
<td>up to 5J, 10Hz</td>
</tr>
<tr>
<td>pump</td>
<td>50W CW fiber coupled (105µm)</td>
<td>2.5 kW laser diode stack (ms pulses)</td>
<td>17 kW laser diode module (ms pulses, homogenized)</td>
</tr>
<tr>
<td>cooling</td>
<td>water</td>
<td>LN2</td>
<td>LN2</td>
</tr>
<tr>
<td>special</td>
<td>average power booster for fs</td>
<td>high gain multi pass</td>
<td>high energy +efficiency very compact</td>
</tr>
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<td></td>
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<td>relay imaging</td>
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</tbody>
</table>
S0 – CW amplifier

**Frontend**
- amplitude
- satsuma + pulse compression

**S0**
- 50W CW diode pumped

**Stretcher**
- 1MHz, 200ps

**S1 (cryogenic)**
- 2.5 kW Diode pumped
- 1MHz, 1W, 150fs

**S2 (cryogenic)**
- 16kW Diode pumped
- up to 200 mJ, 10Hz
- up to 5J, 10Hz

**Pulse Picker**
- x mJ bursts

**Compression**
- 1MHz, 10W

**Experiment**

**Alternative Frontend**
- mj range, e.g. ns pulse

**Implementation in progress**
- Installed + running
- under development
- 4f imaging scheme, copropagating pump and extraction beam
- Heat splitted on two or more Yb:CaF$_2$ crystals in the image planes
- Pumped with 50W fiber coupled laser diode
S0 – CW amplifier
S0 – CW amplifier

Commissioning soon!
Frontend amplitude satsuma + pulse compression

1MHz, 1W, 150fs

S1 (cryogenic) 2.5 kW Diode pumped

mJ range, e.g. ns pulse

up to 200 mJ, 10Hz

S2 (cryogenic) 16kW Diode pumped

x mJ bursts

Pulse Picker

1MHz, 200ps

S0 50W CW diode pumped

1MHz, 200ps

1MHz, 10W

Compression

Experiment

1MHz, 1W, 150fs

Implementation in progress

Installed + running

under development
Amplifier S1 - setup

- Doublerelay imaging: two nested relay systems
- 24 passes @ 2mm beam diameter

2.5 kW
940 nm

2.5m
3m
Amplifier S1 - setup

Imaging setup for amplifier S1

pump setup

LN2 cryostat (modified Janis ST500UC), 3W @80K

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Amplifier S1 - results

Input:
Burst of 500 pulses
150μJ total
1Mhz burst internal
Burst starts 1.5ms after pump

Amplifier:
24 passes
2.5 kW / 2 ms
Reprate 0.5 Hz
Gain up to 2000
Extraction efficiency of more than 10% @ cryogenic temperature!

Amplifier S1 - results
Amplifier S1 - results

- Gain narrowing low
- Good beam profile
Frontend amplitude amplification with satsuma and pulse compression.

Stretcher:
- 1 MHz, 1 W, 150 fs
- 1 MHz, 200 ps

S0 (50 W CW diode pumped)

S1 (cryogenic, 2.5 kW diode pumped):
- 1 MHz, 1 W, 150 fs
- 1 MHz, 200 ps
- mj range, e.g., ns pulse
- x mj bursts up to 200 mj, 10 Hz

S2 (cryogenic, 16 kW diode pumped):
- 1 MHz, 30 W
- x mj bursts up to 5 J, 10 Hz

Pulse Picker

Compression

Experiment

Implementation in progress
- Installed + running
- under development

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Amplifier S2 - setup

- Again two nested relay systems
- 16 passes through the material
- Adaptive mirror can be applied
- Very compact, whole amplifier fits in vacuum tube
- 1 cm beam diameter
- Designed for up to 5J output
Amplifier S2 - setup

Commissioning soon!
We are constructing an all diode pumped burst mode laser system:

- Based on Yb:CaF$_2$
- Burst mode allows higher extraction fluencies and efficiency
- CPA system
- Designed for 5 J / burst + 10 Hz

**Status:**

**Frontend:** ready, producing bursts of **500 pulses, 1MHz, 300fs**

**S0:** CW – pumped preamp, on table, commissioning soon

**S1:** cryogenic cooled, achieved **gain > 2000, > 300 mJ** with good beam profile, **FWHM bandwidth about 4.5 nm**, ready

**S2:** cryogenic cooled, on table commissioning soon
Thank you for your attention!

Work supported by:

HZDR

HELMHOLTZ GEMEINSCHAFT

Helmholtz-Institut Jena
thermal model predicts about 40 K temperature shift starting from cryo-head
• crystal under high vacuum enviroment (10-7 mbar achieved)
Yb:CaF2 as laser medium for broadband amplification
- down to 100 fs possible
- very long lifetime (1.9 ms)
- good thermal conductivity
- especially @ cryogenic temperature

amplification of bursts (up to several 100 pulses)
- higher fluence extractable without damage
- higher efficiency possible

as vacuum enviroment is employed for cooling, we can also put the whole amplifier into vacuum:
- less problems with air disturbances
- focus planes dont need seperate vacuum tubes, window passes are spared