

# Development of kW-level picosecond thin-disk pre-pulse laser for high-power EUV sources

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## Source Workshop 2017

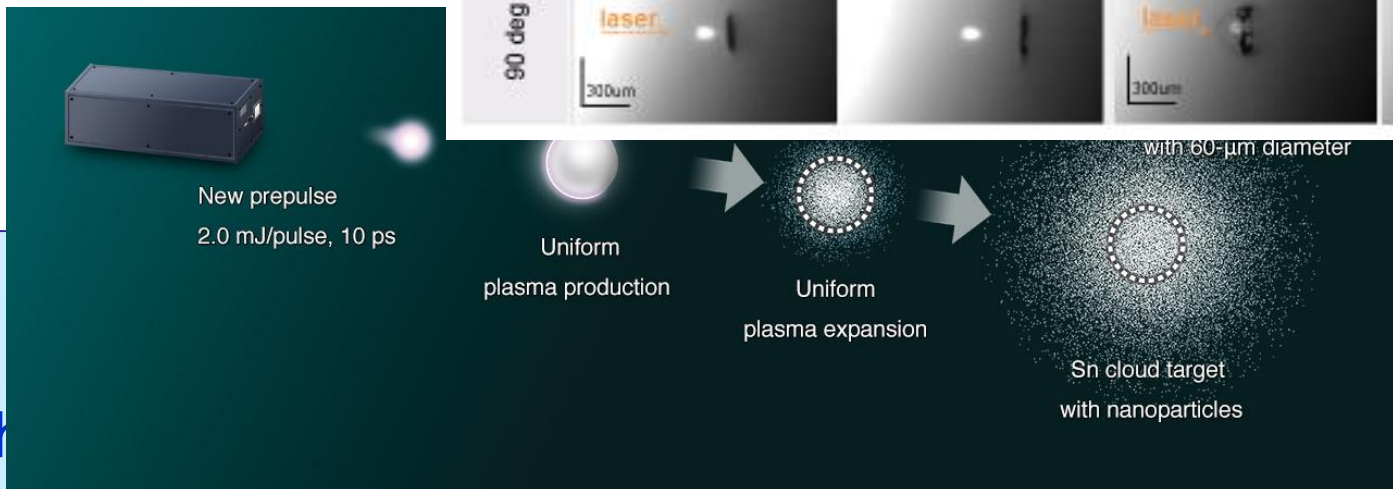
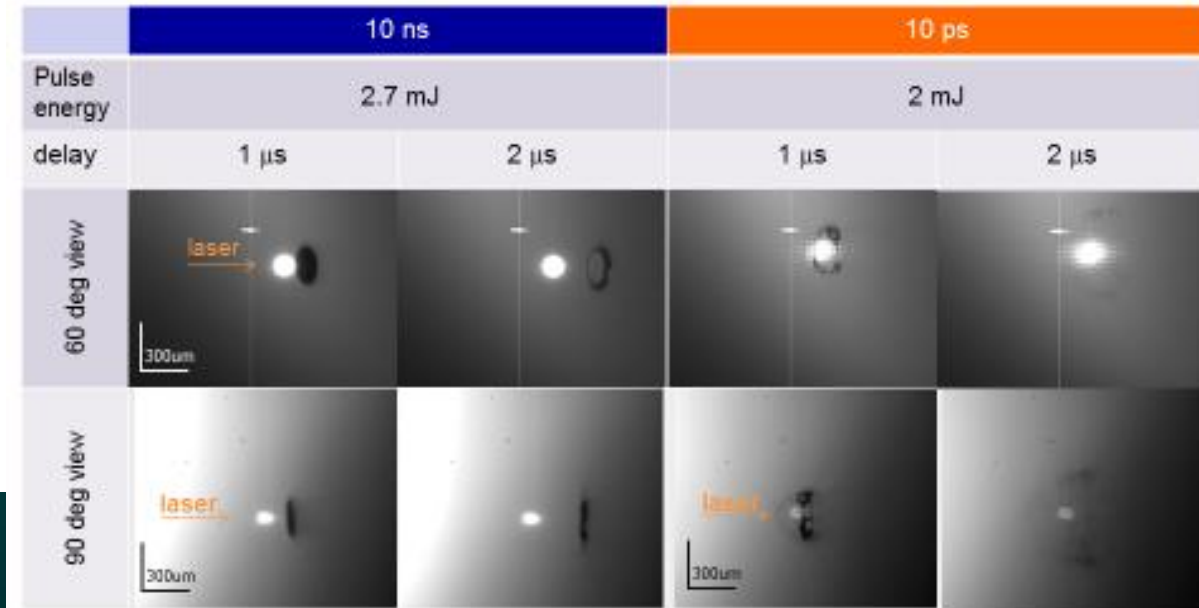
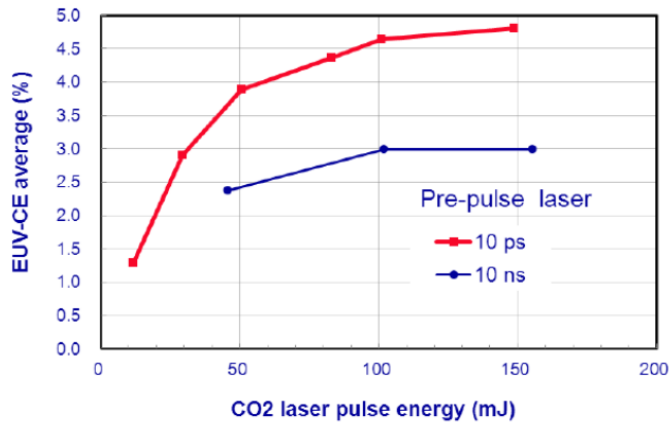
Dublin, 6<sup>th</sup> – 8<sup>th</sup> November 2017

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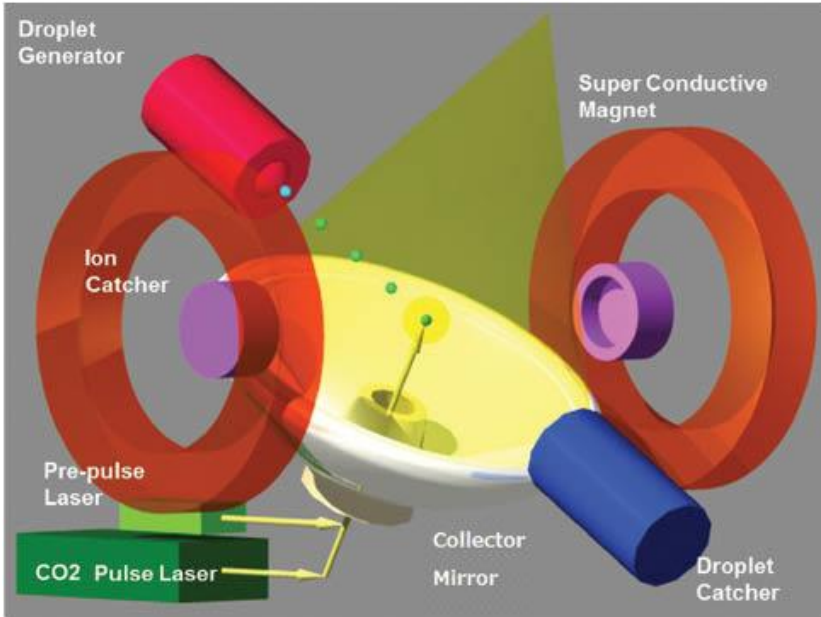
- Solid-state pre-pulse lasers for EUV lithography
- HiLASE thin-disk research programme
- High-repetition-rate picosecond laser system PERLA C
  - System design of the laser source
  - 0.45-kW ring regenerative amplifier
  - VIS-UV-DUV frequency conversion
- Summary

# EUV generation from Sn plasma with a pre-pulse

CO2 pulse energy vs. EUV-CE

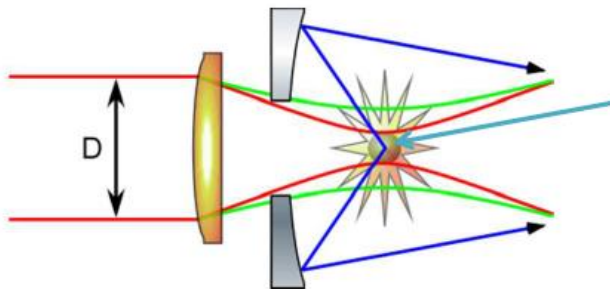


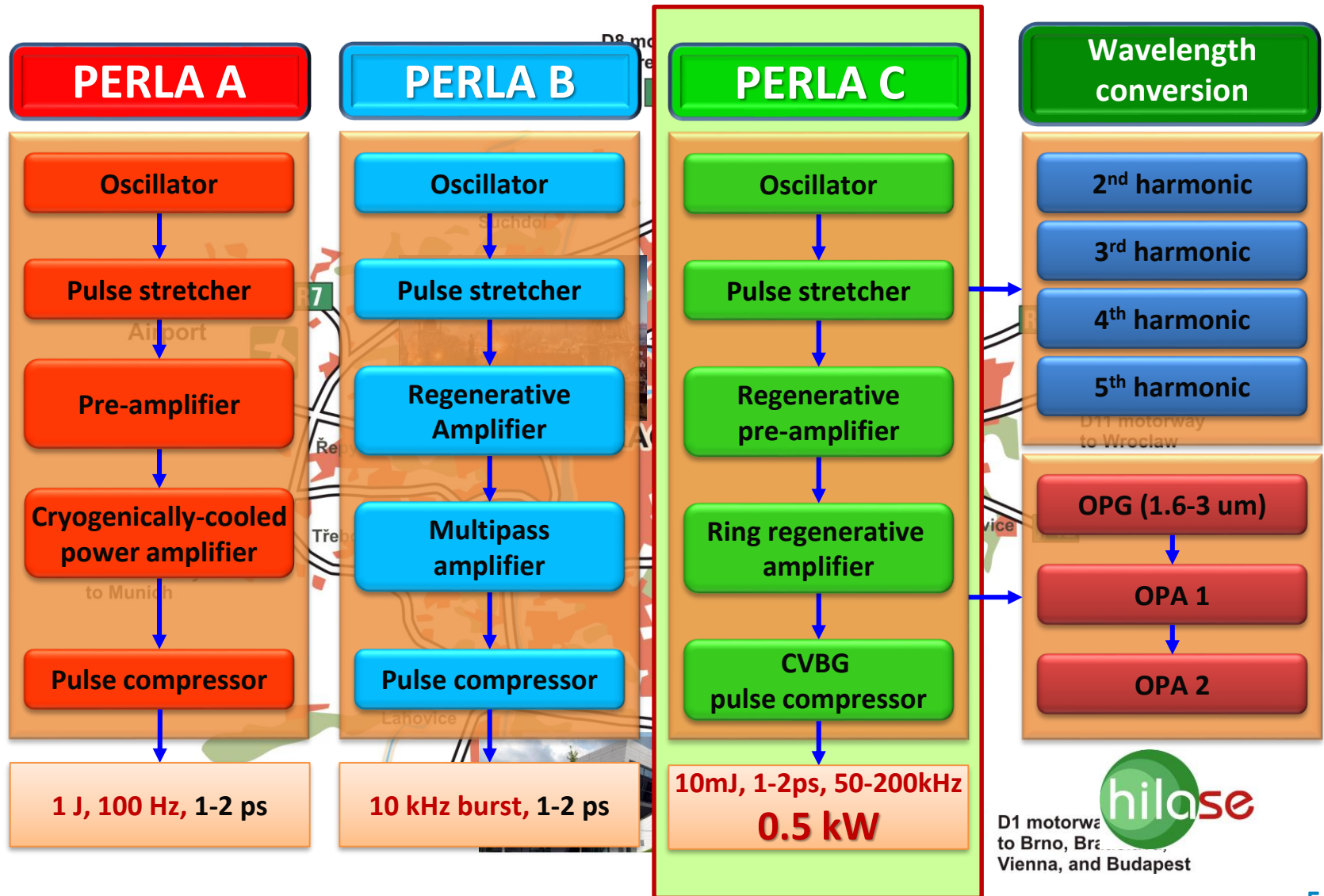
and full Sn atoms exhaust



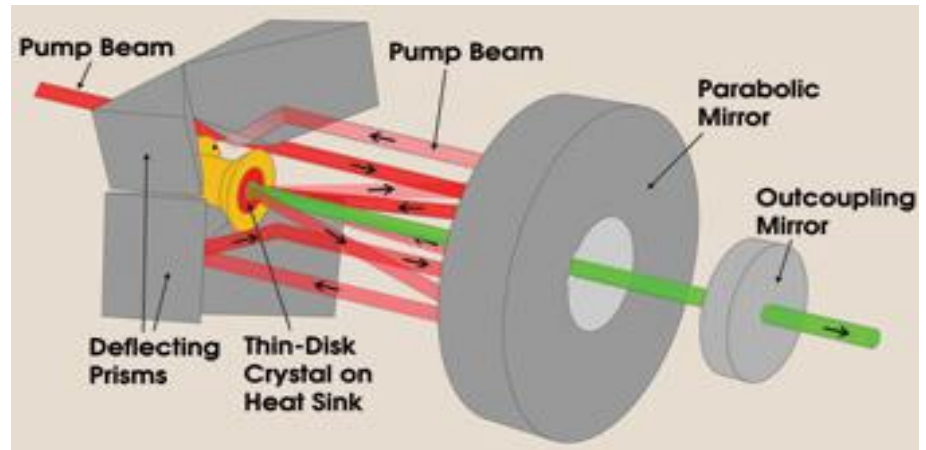
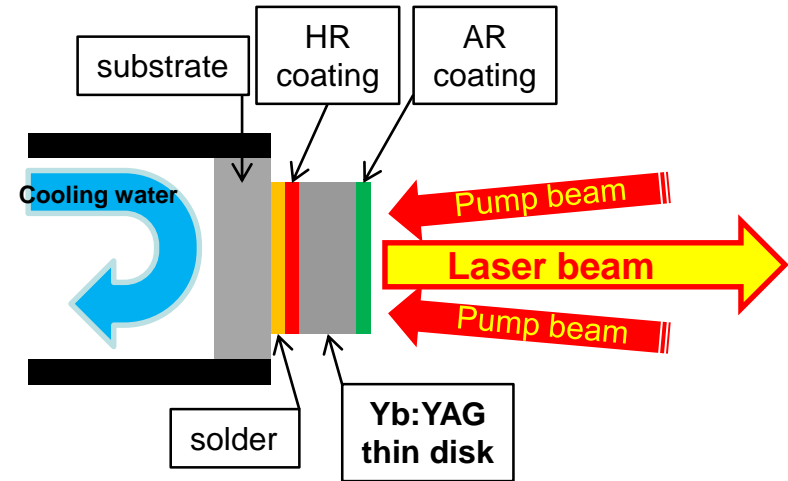
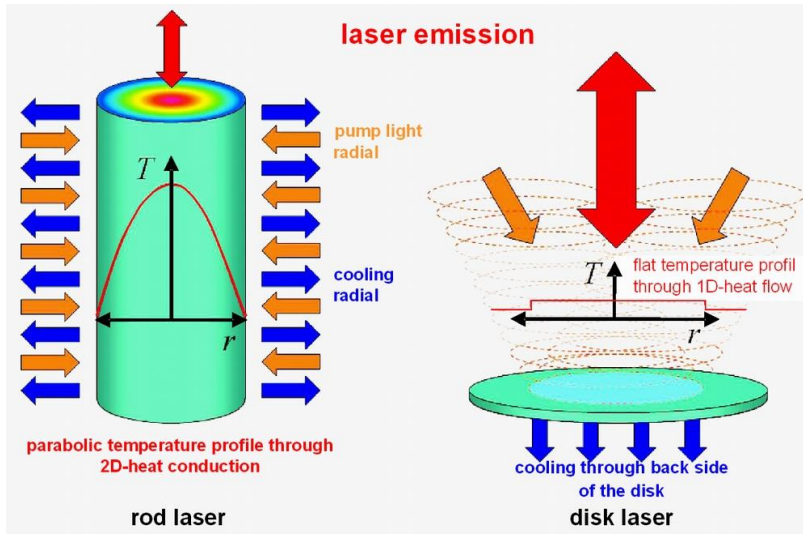
## Prepulse laser requirements

- Good beam quality ( $M^2 < 2$ )
- High repetition rate (100 kHz)
- High average power (100 W – 1 kW)
- Short pulse length (several ps)
- Wavelength 1  $\mu\text{m}$





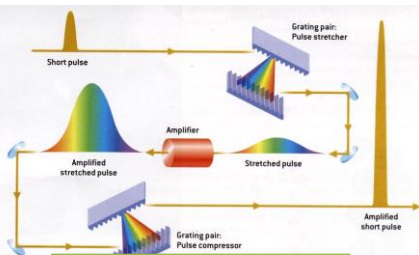
# Thin disk geometry for high power lasers



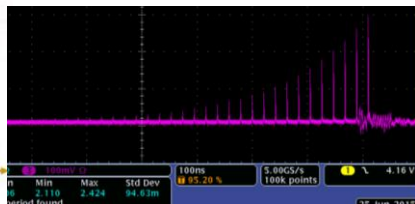
## Thin disk pros and cons:

- + Efficient cooling
- + Low thermal lensing
- + Axial heat flow
- + Low nonlinearities (B-integral, SPM)
- + High gain saturation
- Low single pass gain

# Elementary Technologies for Thin Disk Laser



CPA technology

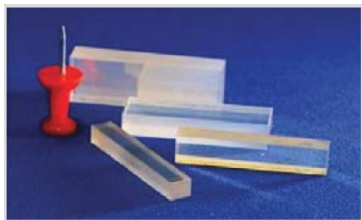
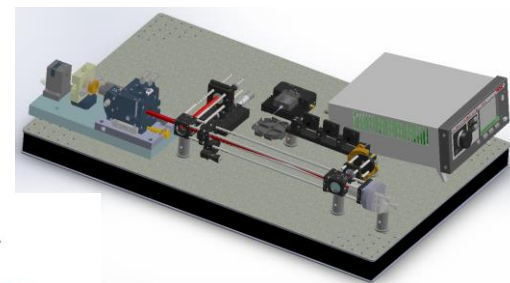


Ring regen

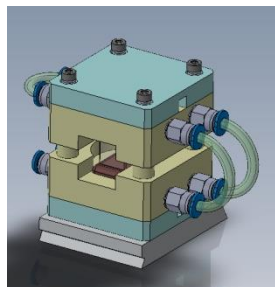
A4-size sub-ps fiber oscillator



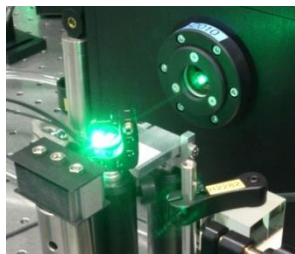
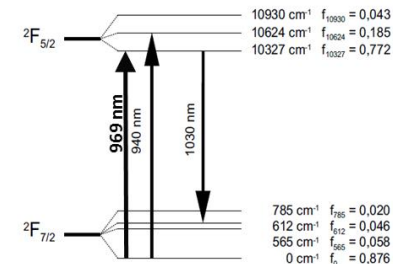
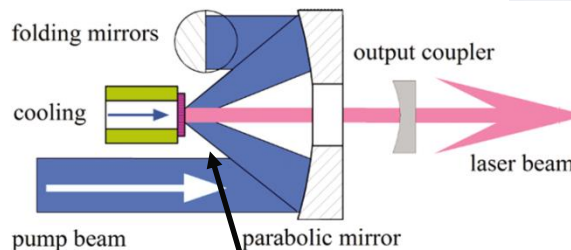
Precise disk curvature measurement



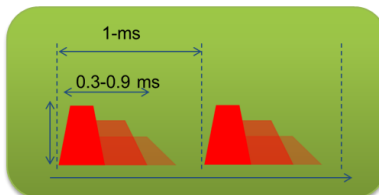
Bulk grating (CVBG) compressor



Large size fast BBO Pockels cell



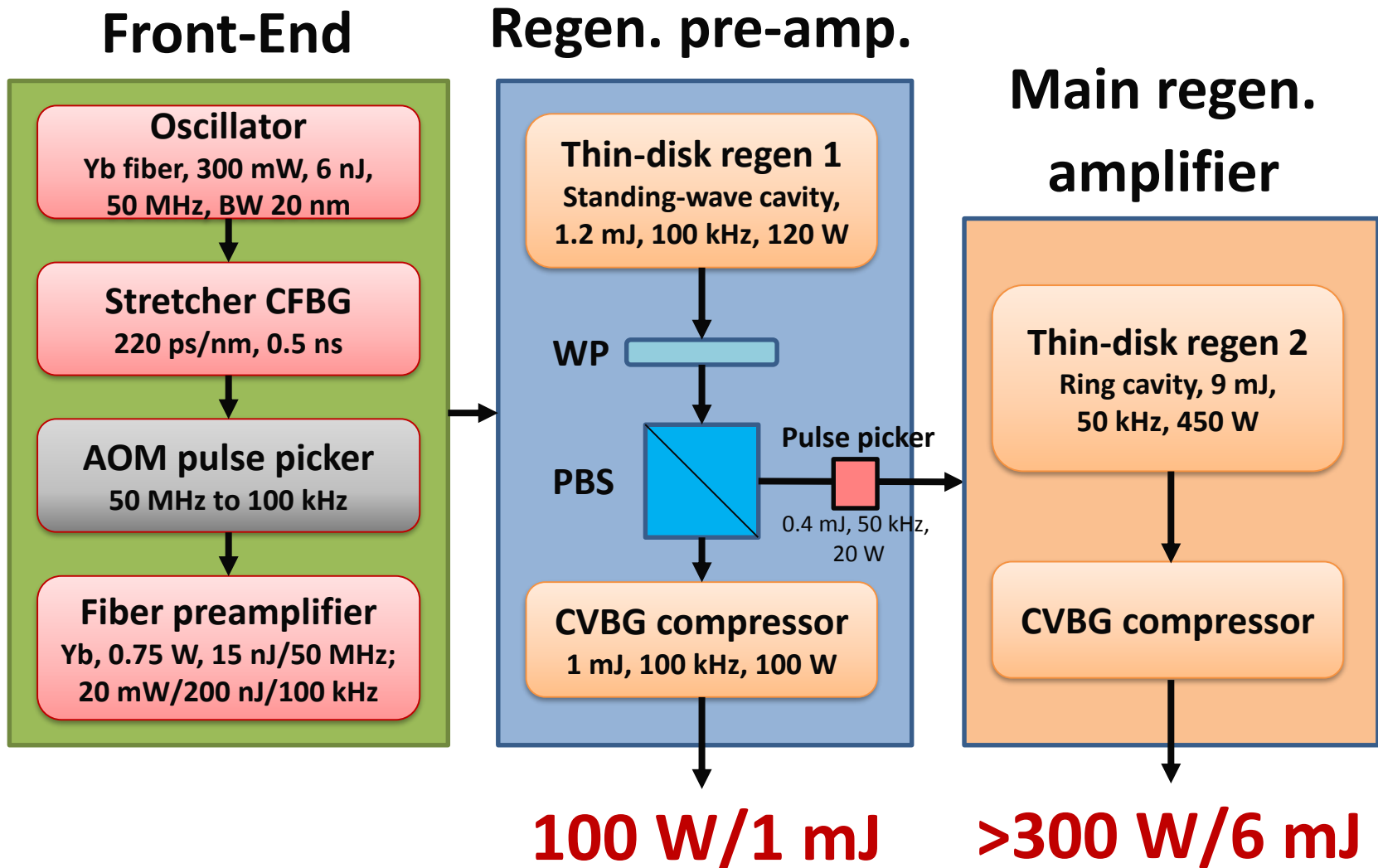
Wavelength conversion



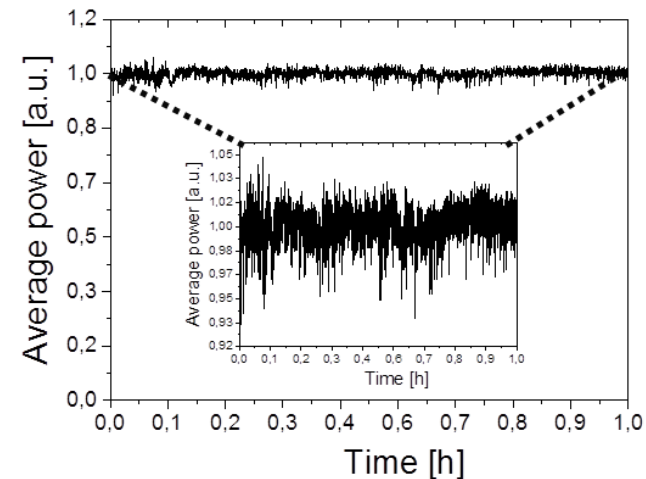
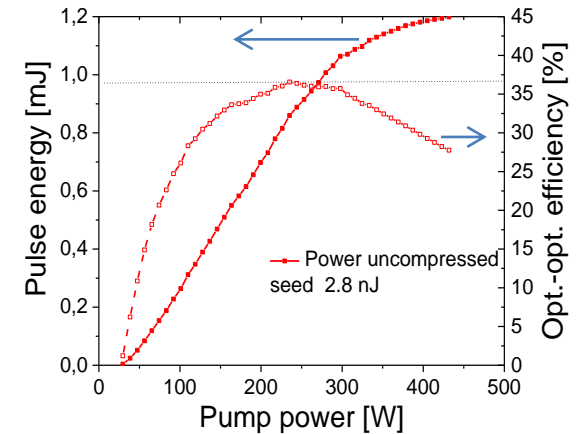
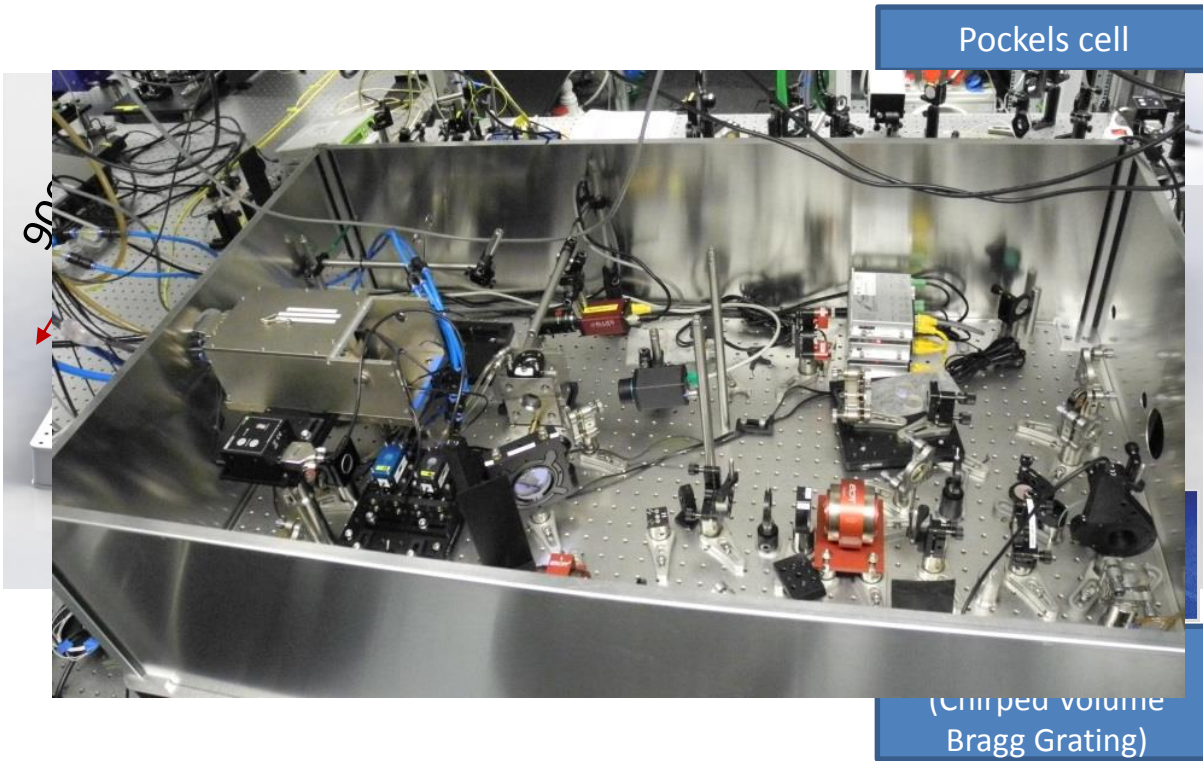
Pulsed pumping

Diamond-bonded disk

Zero-phonon-line (ZPL) Pumping (Yb:YAG)

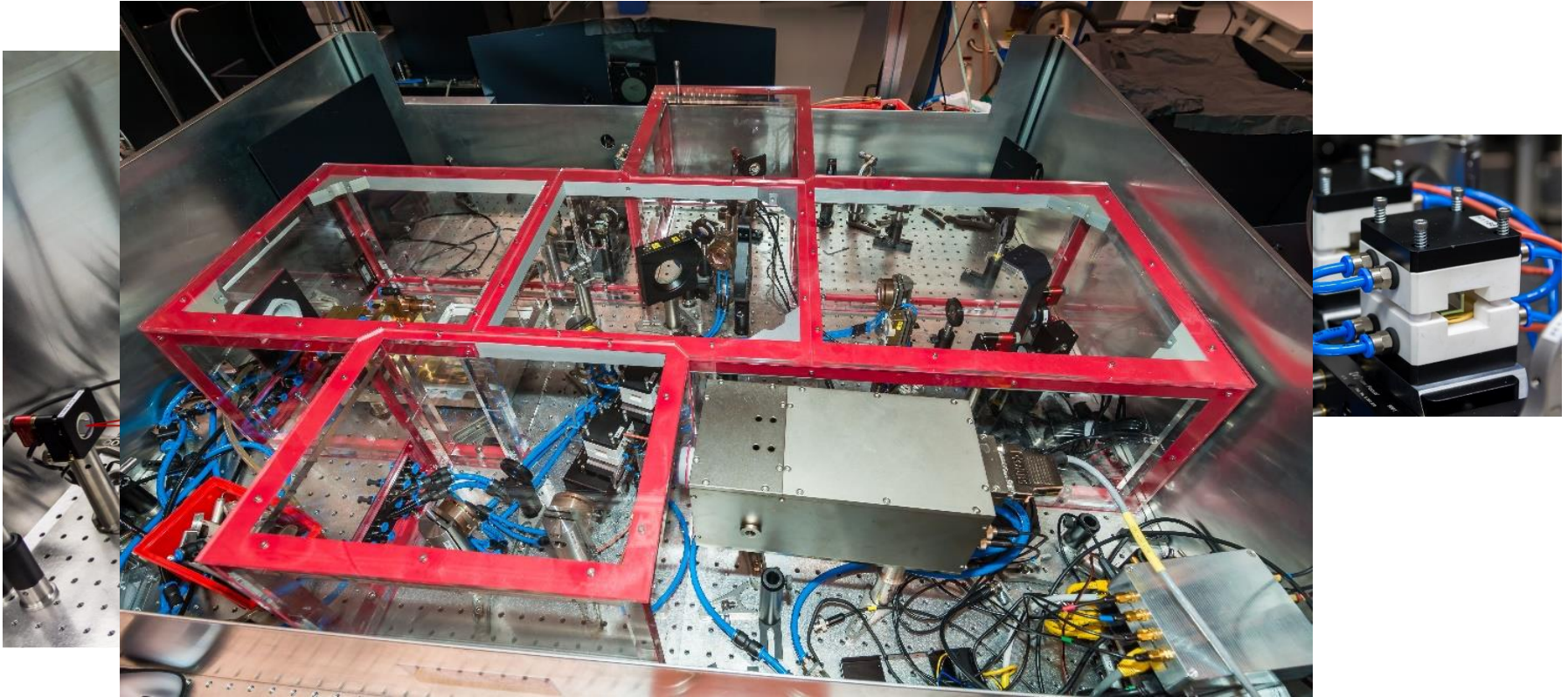


# 100-W, 100-kHz regenerative pre-amplifier

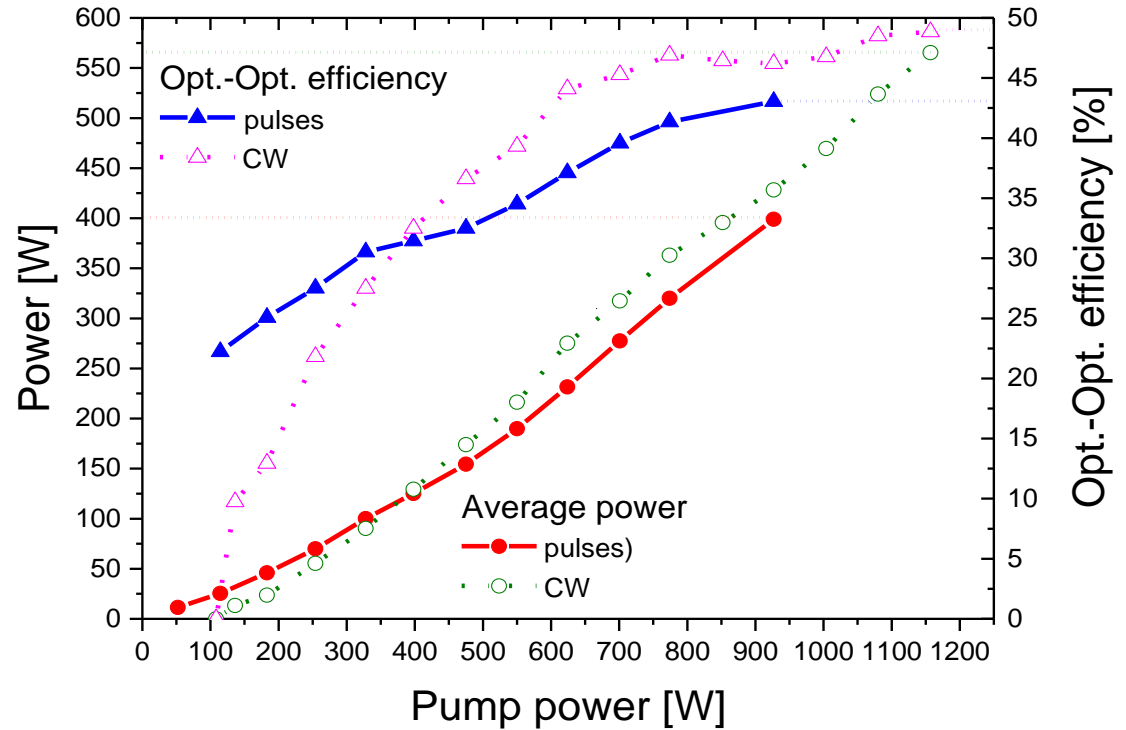
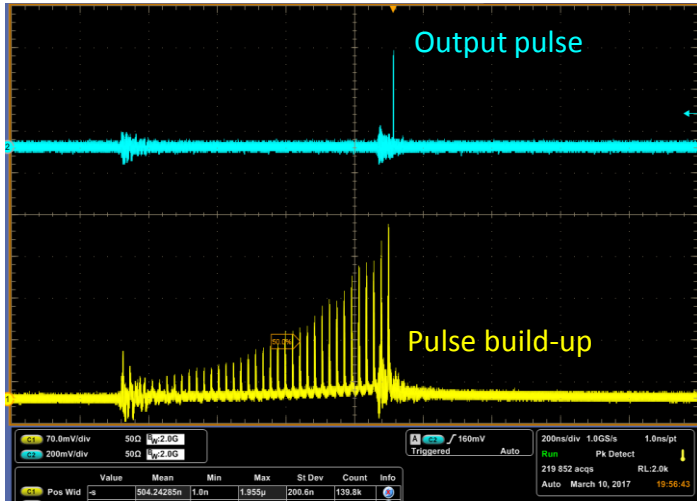


- Small-scale (0.9 x 1.2 m<sup>2</sup>) regen with Yb:YAG disk
- Linear cavity with 8x8x25mm BBO Pockels cell
- 120 W output power
- CVBG compressor
  - compressed pulses with 1 mJ energy

- Output energy fluctuation RMS 1.5%
- Fundamental spatial mode ( $M^2 < 1.3$ )
- Driving laser for HG and OPA



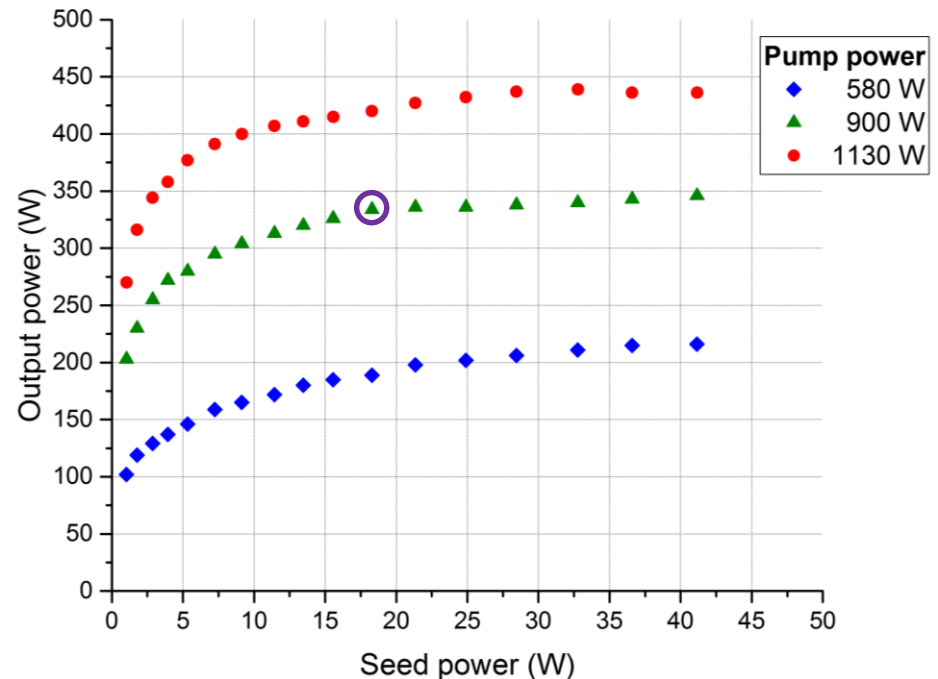
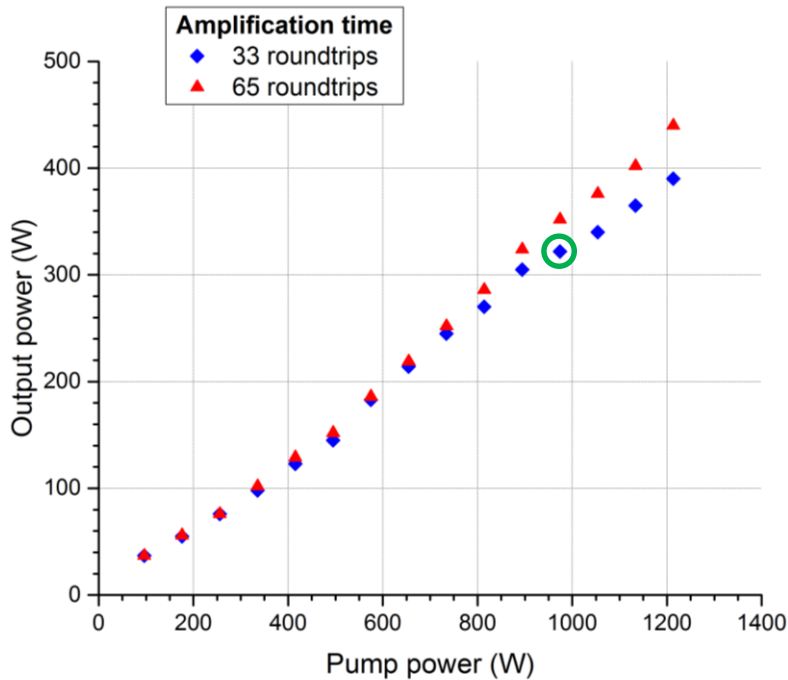
- Single diamond-bonded Yb:YAG thin disk
- Zero-phonon-line pumping (969 nm)
- 6.5 m long ring cavity, large mode diameter
- Compact size ( $1.2 \times 0.8 \text{ m}^2$  footprint)
- Tunable repetition rate: 50-500 kHz

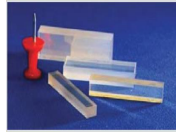


- Repetition rate 100 kHz (initial tests)
- Seed pulse energy 0.2 mJ, output energy 4 mJ
- 35 roundtrips (0.7  $\mu$ s, low gain due to high repetition rate)
- High efficiency > 43% in pulsed mode
- Output power was heat-limited (disk temperature)

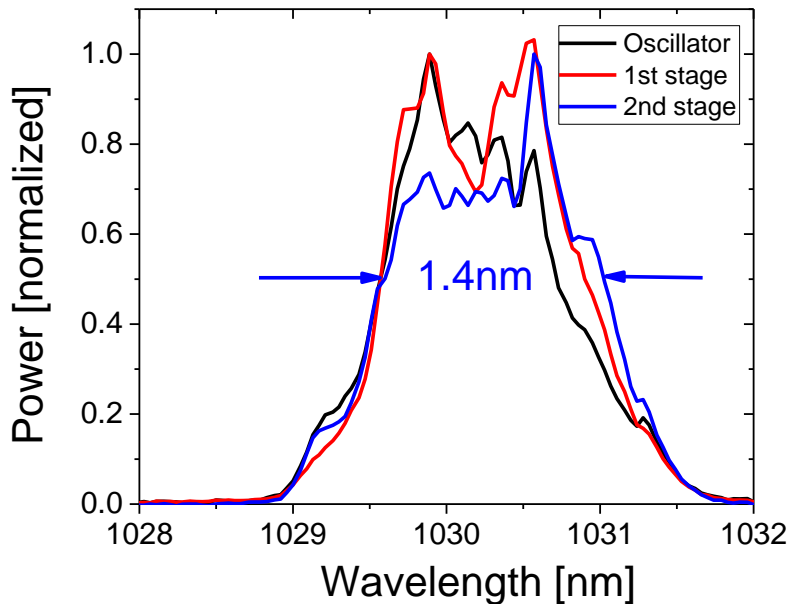
# PERLA C laser system output

- Repetition rate changed for an application requiring higher pulse energy
- Laser optimized for long-term stable operation (longest non-stop run over 10 hours) at 330 W output level
- Excellent far-field beam profile (before and after compressor)
- By increasing pump power, seed power and amplification time, output power was raised to 450 W (9 mJ pulse energy)

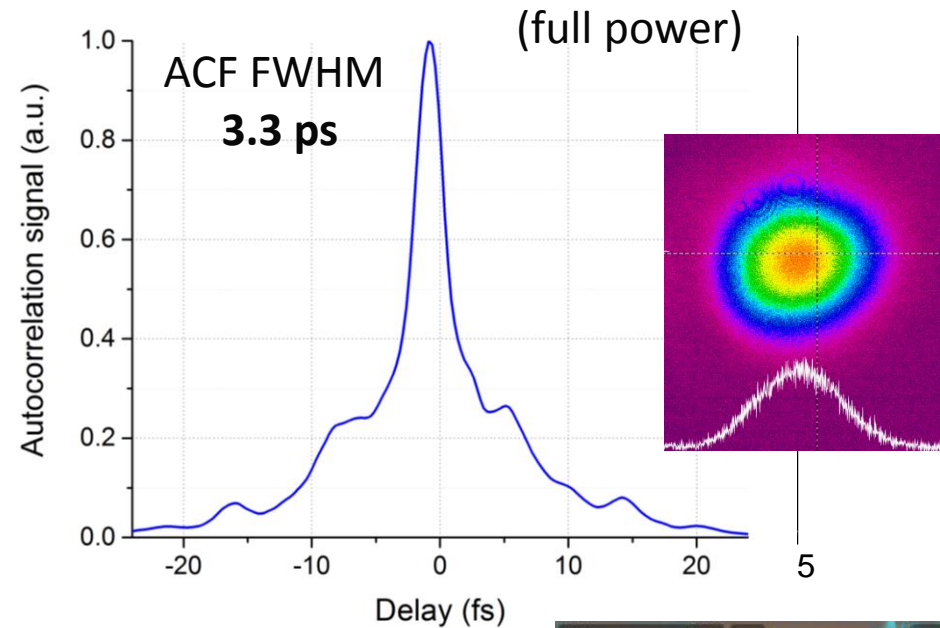




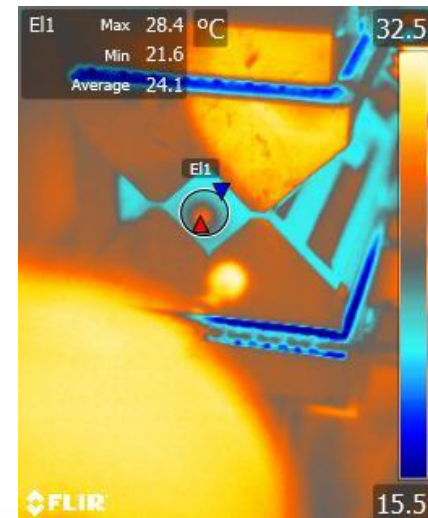
Pulse spectrum



Intensity autocorrelation

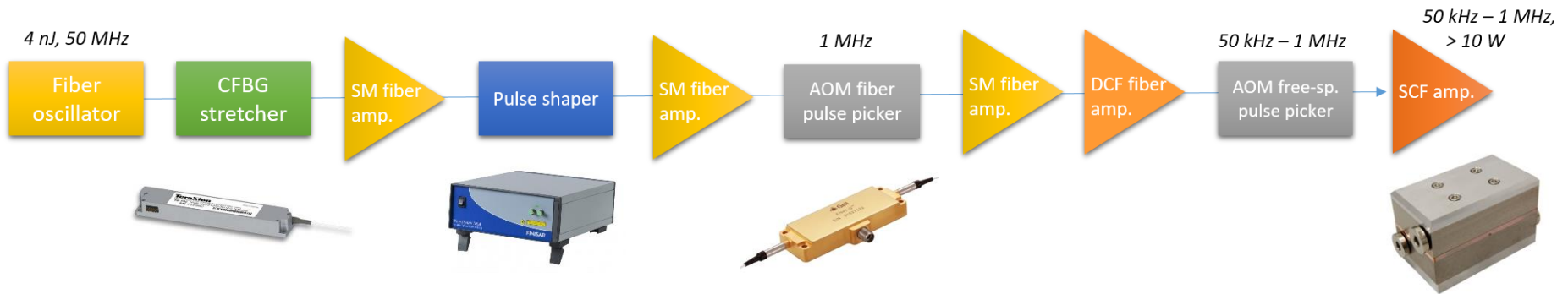


- Intensity autocorrelation  $\text{sech}^2$  fit 1.3 ps (FWHM recalculated)
- Pulse bandwidth limit 0.8 ps ( $\text{sech}^2$ )
- Pulse shape degrades at higher power levels (approx. > 150W)
  - central peak FWHM corresponds to 2.1 ps  $\text{sech}^2$  pulse
- For optimization of the pulse shape we plan to modulate the seed spectrum and phase

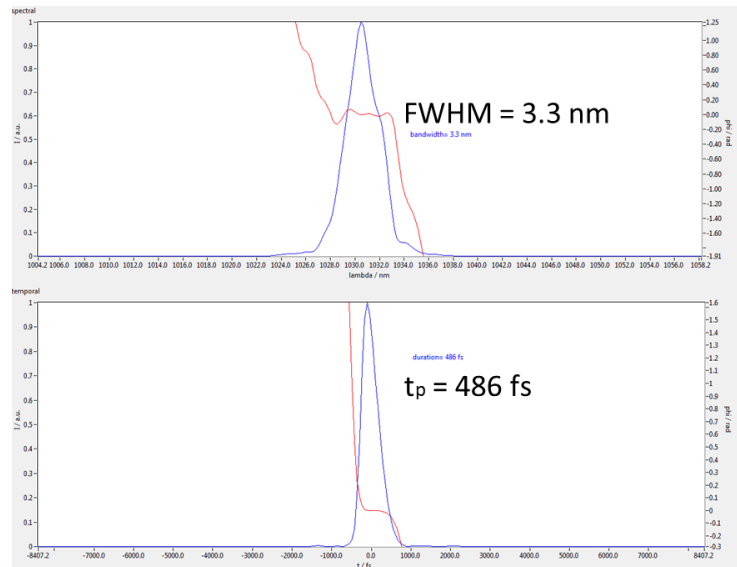
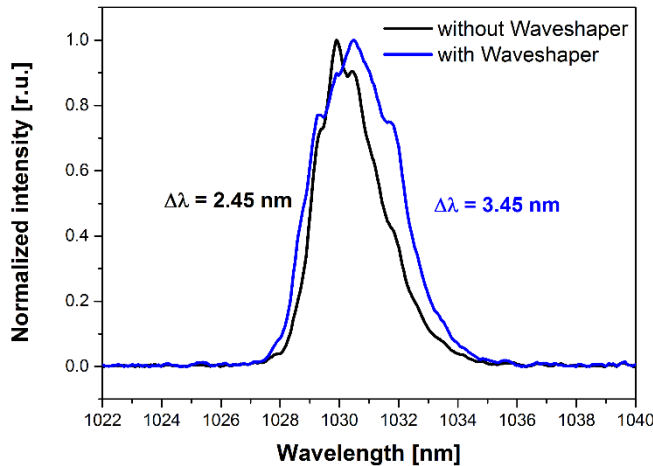


# Front-end upgrade and pulse-shaping

- New fiber front-end and single-crystal-fiber preamplifier is in preparation
- Variable repetition rate, improved pulse compression thanks to oscillator spectrum shaping
- Possibility for pulse-shape optimization

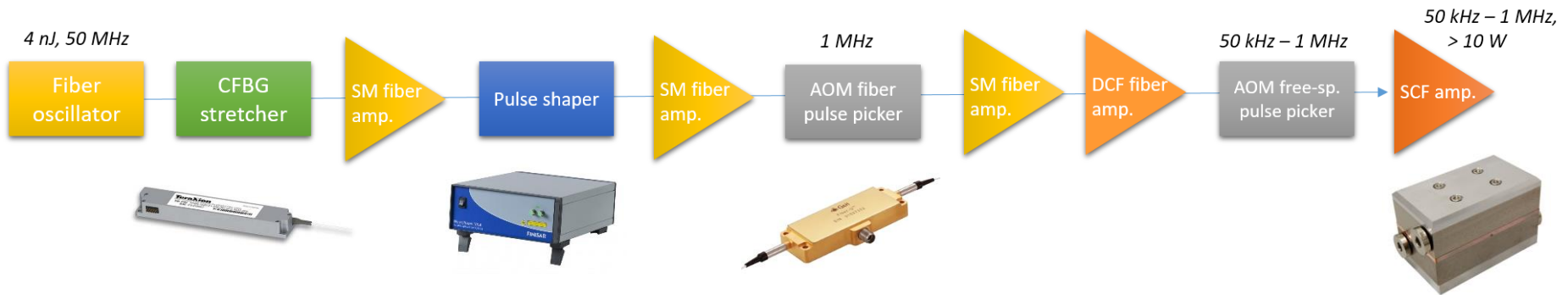


## Pulse-shaping with small-scale Yb:YAG regen:

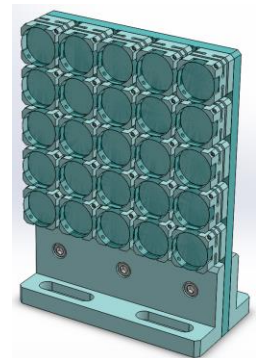
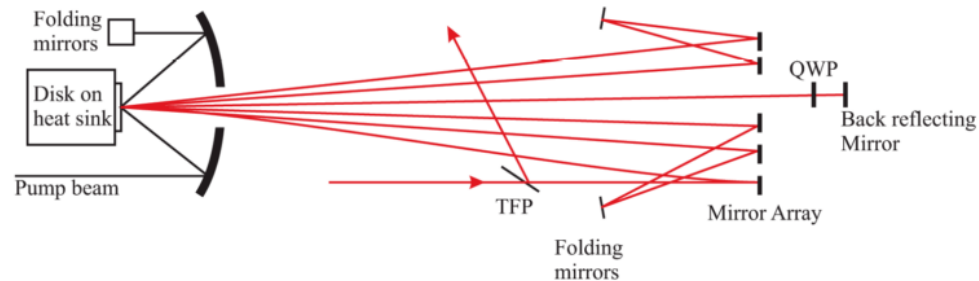
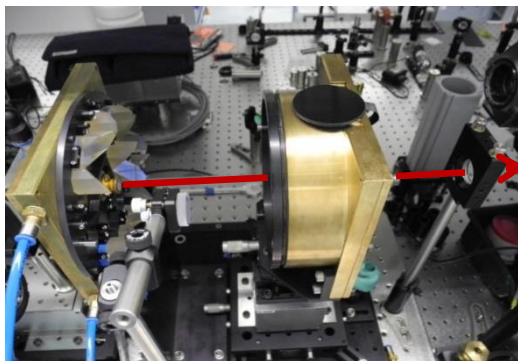


# Front-end upgrade and pulse-shaping

- New fiber front-end and single-crystal-fiber preamplifier is in preparation
- Variable repetition rate, improved pulse compression thanks to oscillator spectrum shaping
- Possibility for LPP EUV pre-pulse-shape optimization

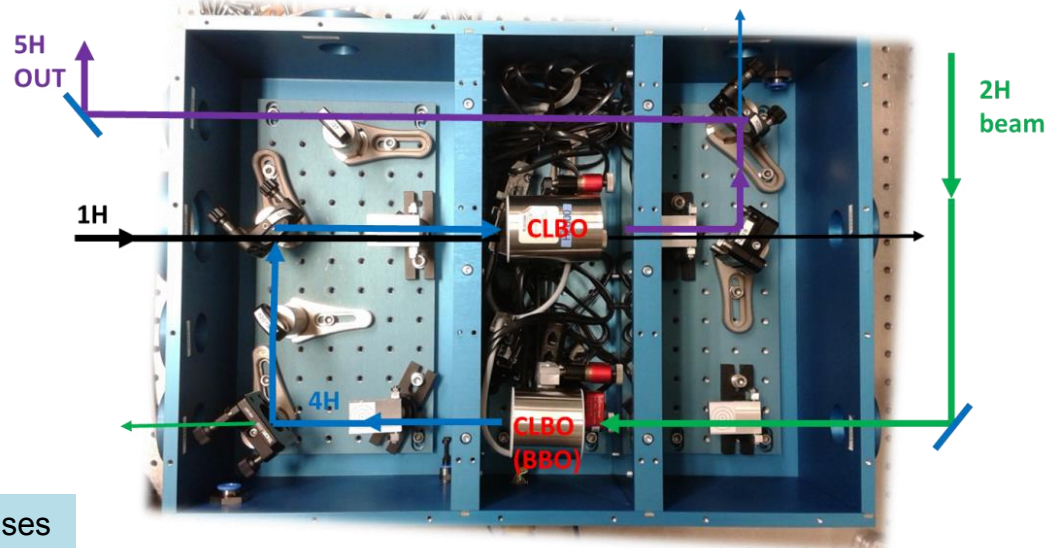
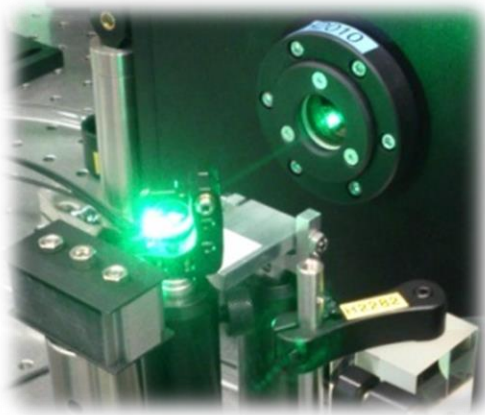
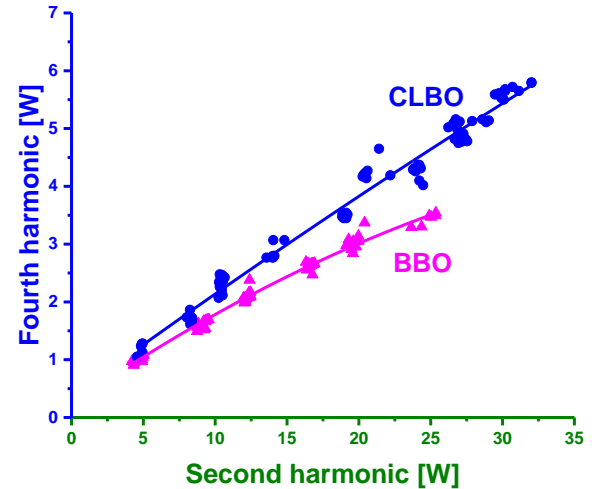


- Final booster multipass amplifying stage is planned
- 24-pass scheme to achieve > 1 kW average output power after compression (300 W seed, 3 kW pumping)



## Short wavelength PERLA C extension:

- Fundamental wavelength 1030 nm
- Picosecond pulses < 1 ps
- UV-B laser – glass cutting (solar cells, electronics)
  - 257.5 nm >6 W (world record)
  - 205 nm >0.8 W
- Visible laser – Cu welding (automotive), etc.
  - 515 nm >35 W
- Especially 4<sup>th</sup> harmonics is attractive for LPP EUV
  - Much lower ablation threshold compared to 1  $\mu$ m



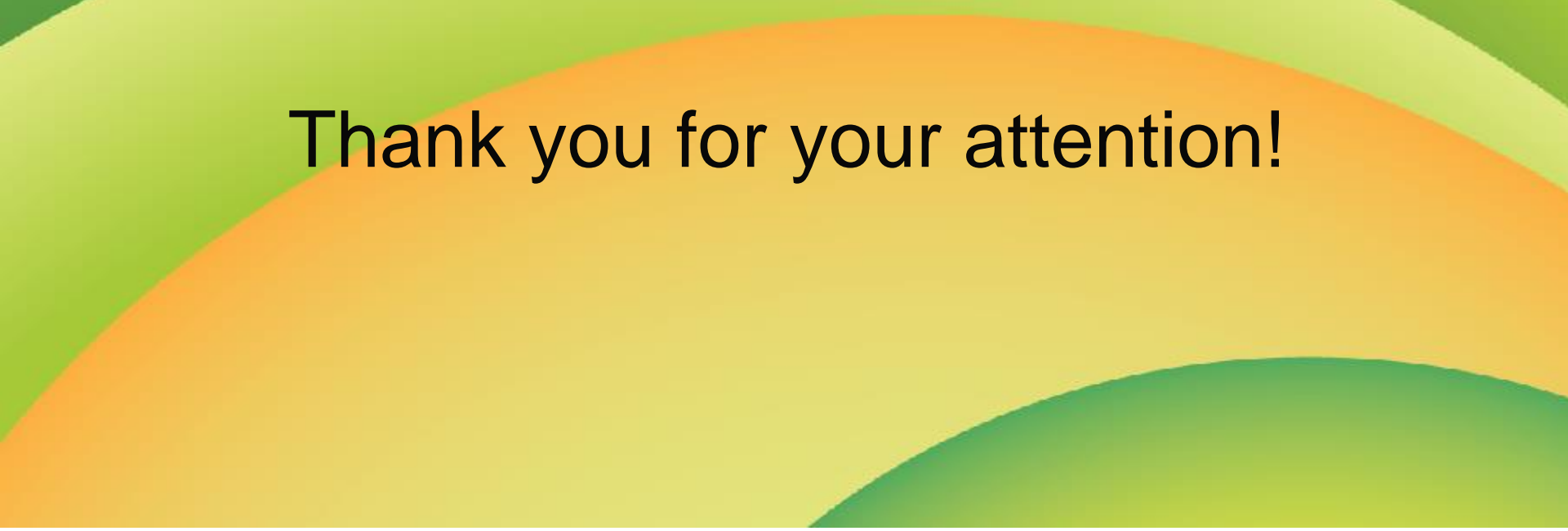
O.Novak et.al. "Picosecond green and deep ultraviolet pulses generated by a high-power 100 kHz thin-disk laser" Opt. Lett. Vol.41, No.22, 5210-5213,(2016).

- PERLA C picosecond laser system demonstrated
  - Output pulse energy 9 mJ at 50 kHz repetition rate
  - Perla C is excellent thin-disk pre-pulse platform for Sn LPP source
  - Nearly diffraction limited beam, compression <2ps
  - Efficient DUV generation (257 nm and 205 nm) – also attractive for LPP EUV lithography
- Further development plans
  - New fiber front-end with pulse-shaping feature
  - Final kilowatt amplifying stage
    - multipass amplifier and high-power compressor



*Save the date!*

**2018 Source Workshop**  
*November 5-7, 2018*  
**HiLase, Prague, Czech Republic**



**Thank you for your attention!**

**Acknowledgement:**

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