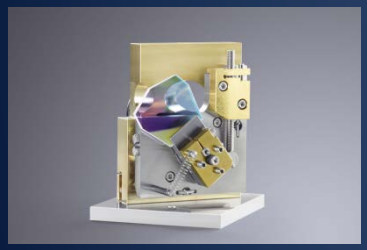
TRUMPF Scientific Lasers GmbH + Co. KG

High Average Power & High Energy Ultrafast Thin-Disk Amplifiers

2017 Source Workshop





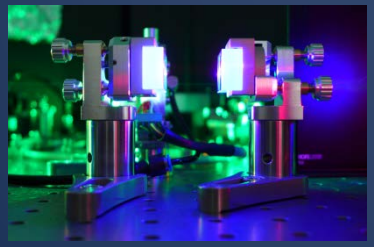
Tom Metzger
TRUMPF Scientific Lasers

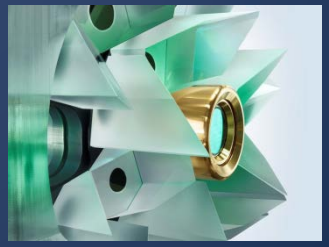
Dublin, 06.11.2017

Content

1. TRUMPF Scientific Lasers
2. Motivation
3. Thin-Disk Laser Technology
4. Regenerative Thin-Disk Amplifiers
5. Multipass Thin-Disk Amplifiers
6. Short Wavelength (XUV – Soft X-Ray)
7. Summary

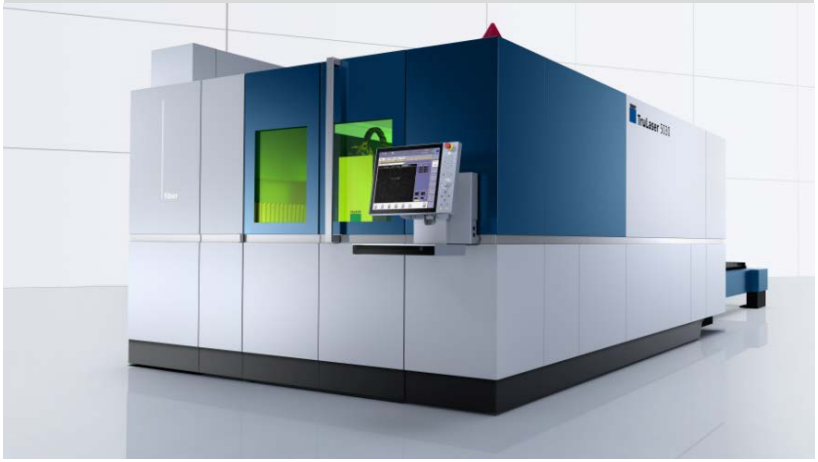
1. TRUMPF SCIENTIFIC LASERS

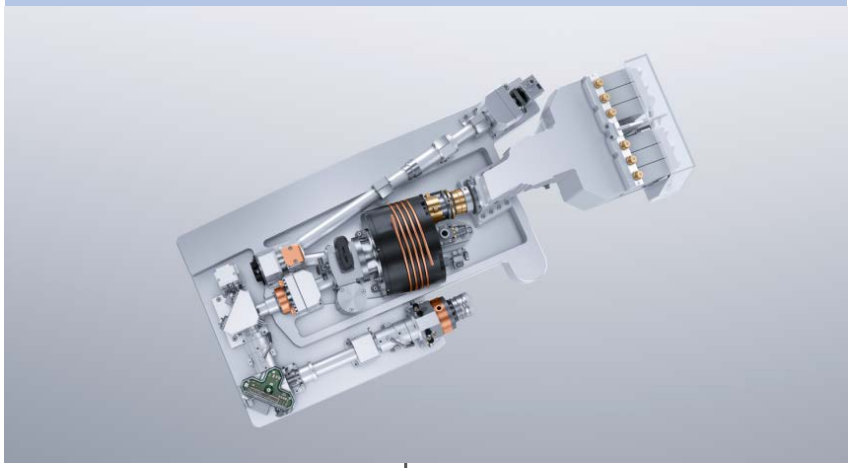


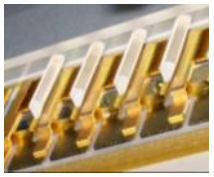
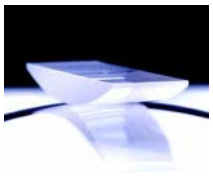

The Business Divisions of the TRUMPF Group

Machine Tools



Laser Technology / Electronics



TRUMPF Laser- und Systemtechnik GmbH, Ditzingen	TRUMPF Lasersystems for Semiconductor Manufacturing GmbH, Ditzingen	TRUMPF Laser GmbH + Co. KG, Schramberg	TRUMPF Laser Marking Systems AG, Grüsch, CH	TRUMPF Photonics, Princeton, USA	SPI Lasers, Southampton, UK	TRUMPF Scientific Lasers GmbH + Co. KG, München	Ingeneric GmbH, Aachen
							

TRUMPF Scientific Lasers

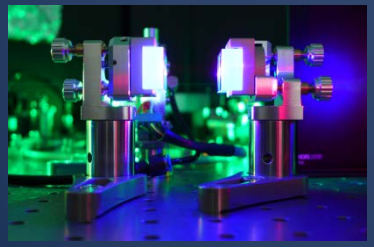
Introduction

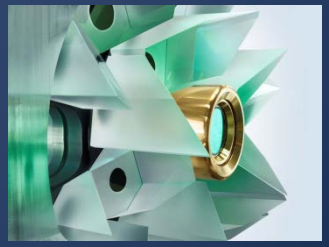
- Joint Venture between the TRUMPF Group and Prof. Ferenc Krausz founded in May 2012

- Strong benefits due to TRUMPF network:
  - Extensive expertise in thin-disk technology
  - High-quality product engineering and highest reliability
  - Worldwide service and spare part availability
- Strong cross link into the scientific community especially by Professor F. Krausz

- Product Portfolio:
  Picosecond amplifiers (mJ – J; 100W – 1kW)
  OPCPAs (µJ – mJ; <100W)

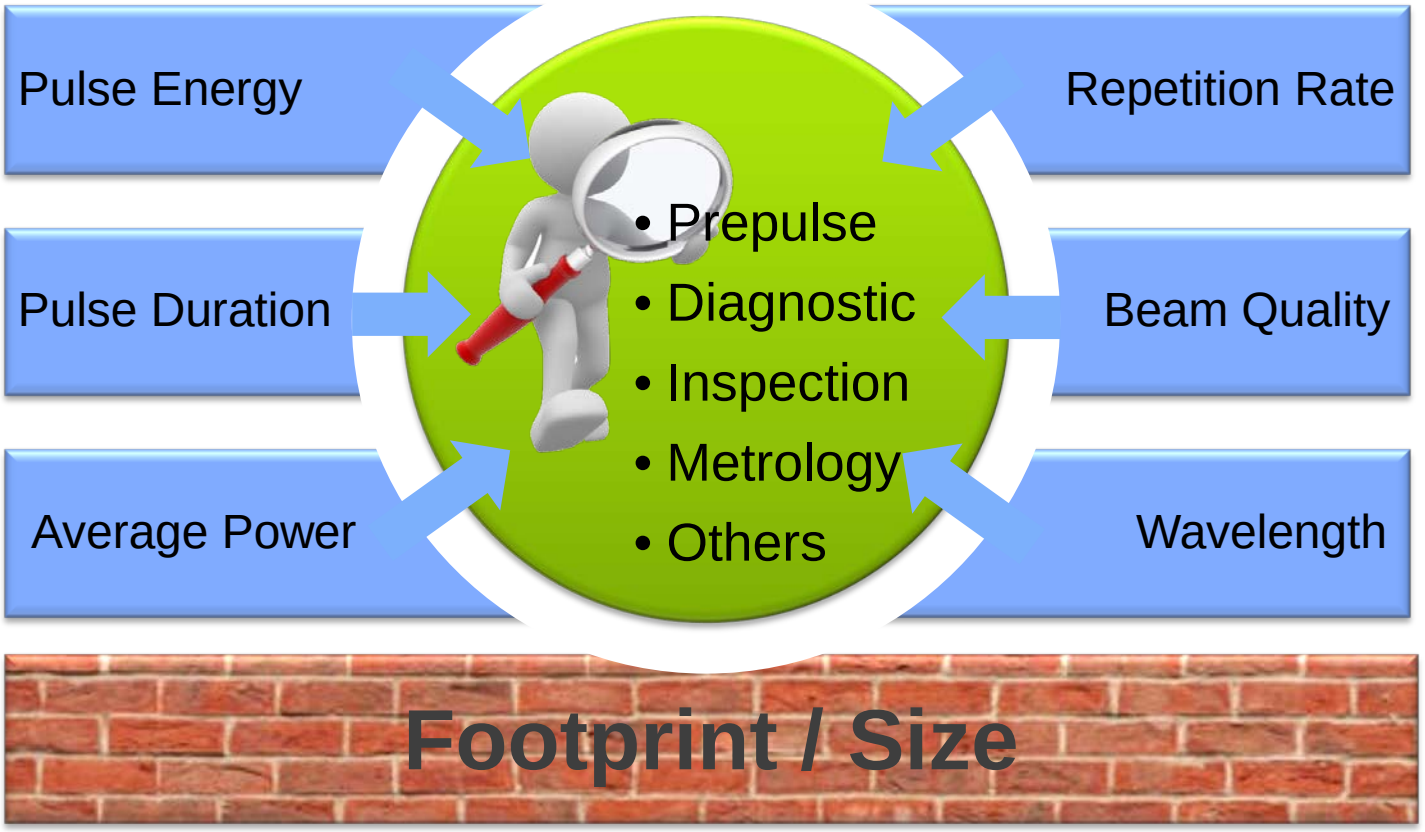
2. MOTIVATION



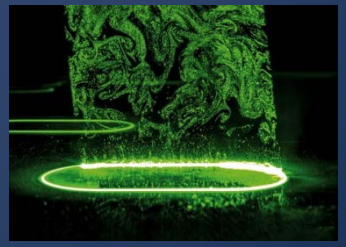
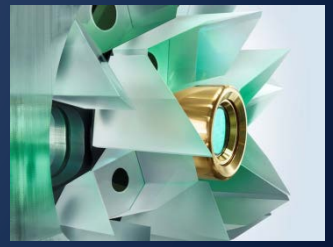

Motivation

Which laser parameters/light sources are required?



3. THIN-DISK LASER TECHNOLOGY

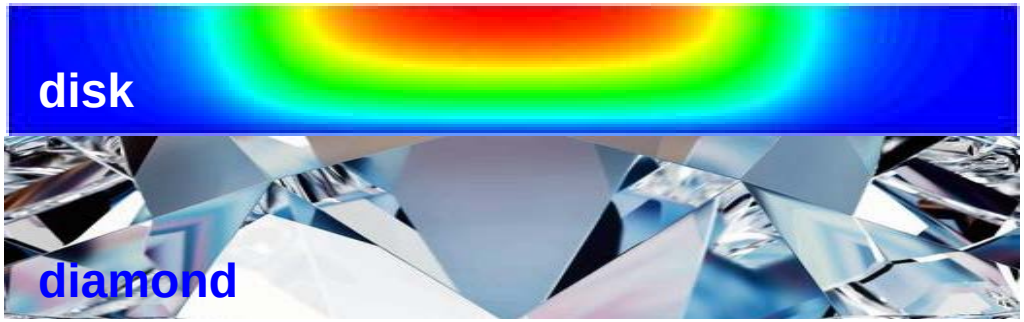


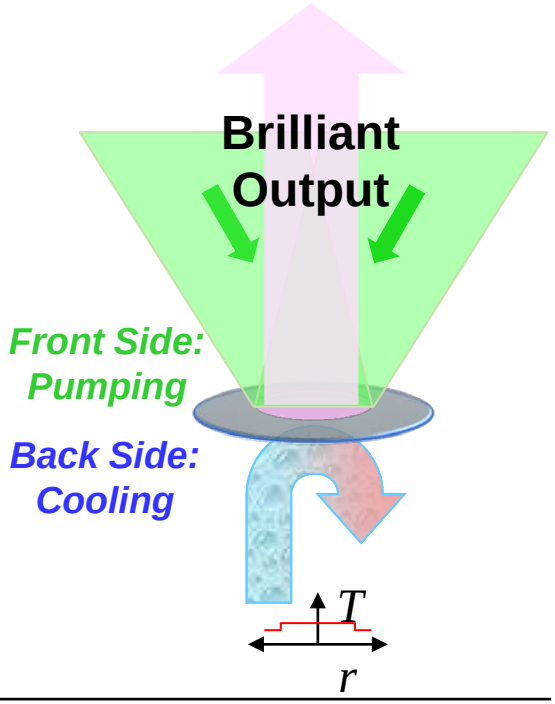




Disk Laser Principles (Prof. Giesen 1994)

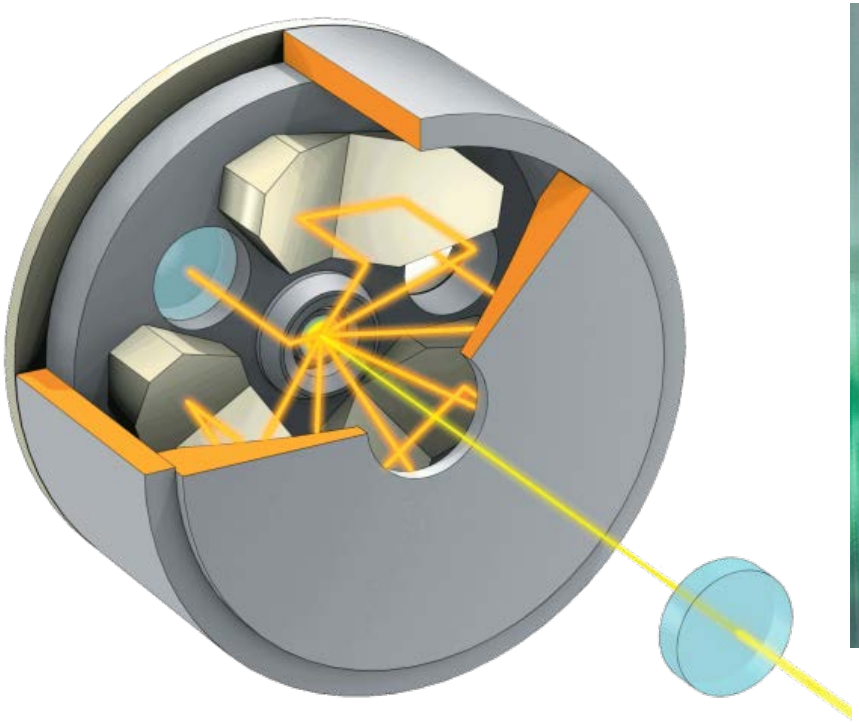
Diameter of pumped area >> disk thickness

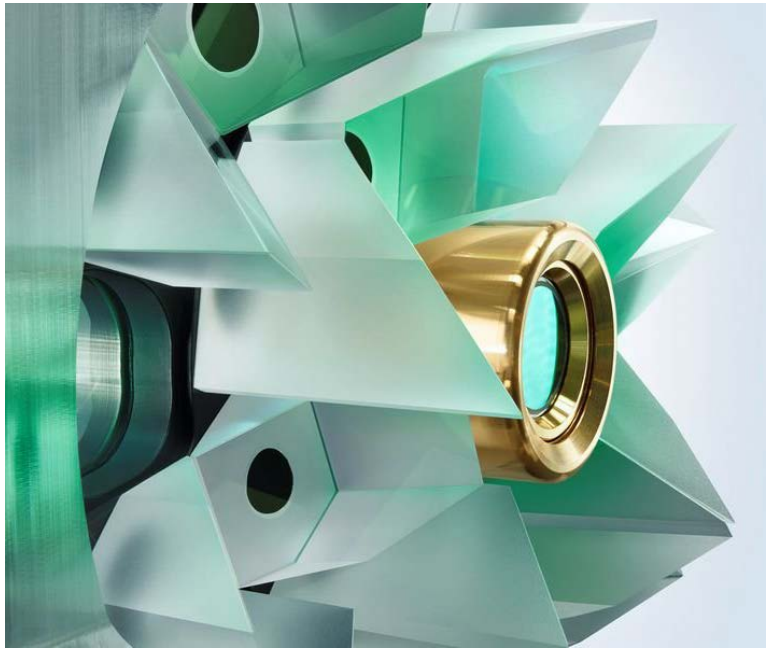
+ uniaxial heat flux: Low thermal lensing → High brightness
+ Low brightness constraints for pump diodes
+ High gain saturation: Insensitive to back reflections
+ Scalability by increase of beam cross section
+ Negligible nonlinearities at high peak powers



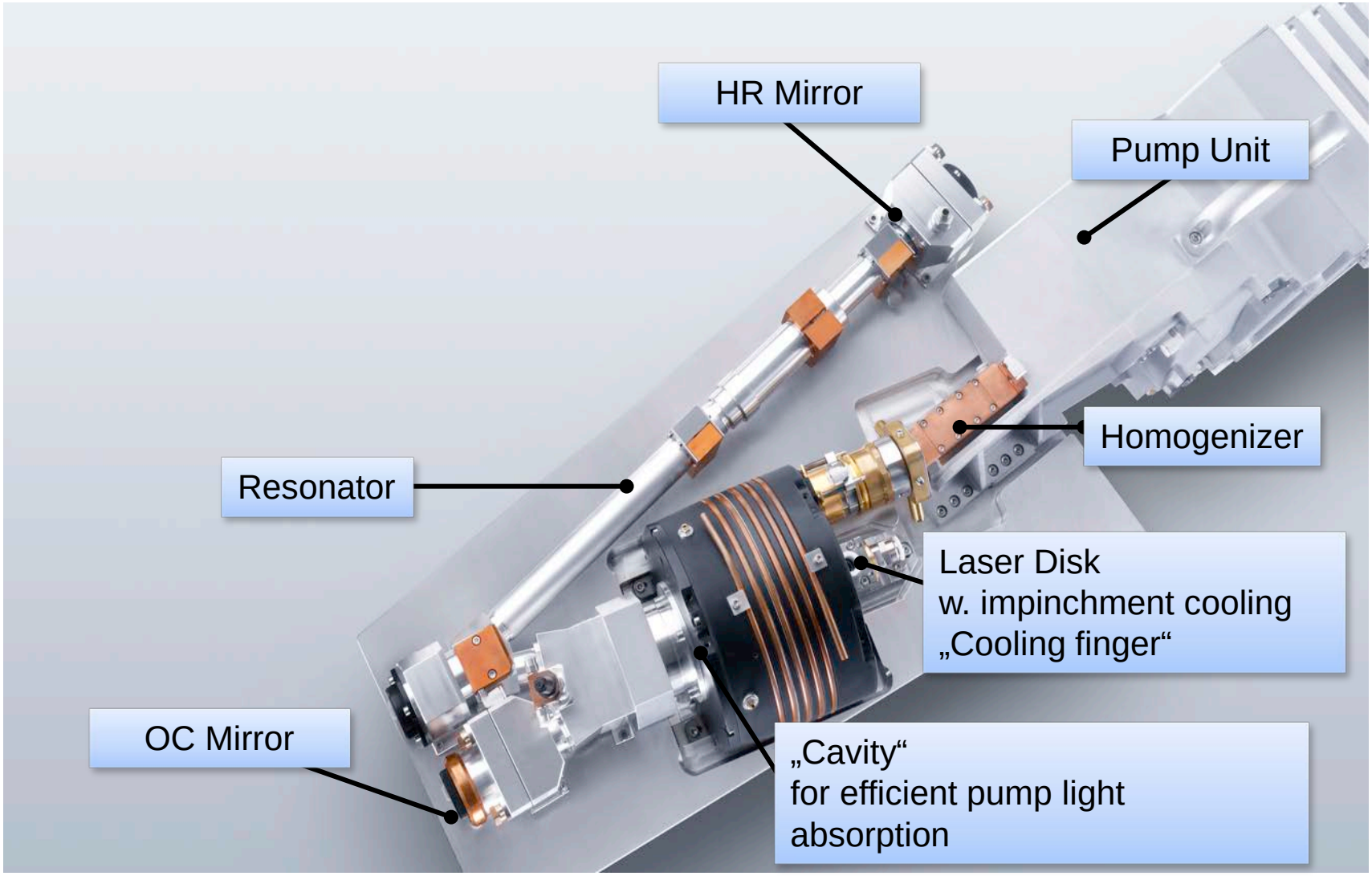


Disk Laser Principle (Yb:YAG, 1030nm)



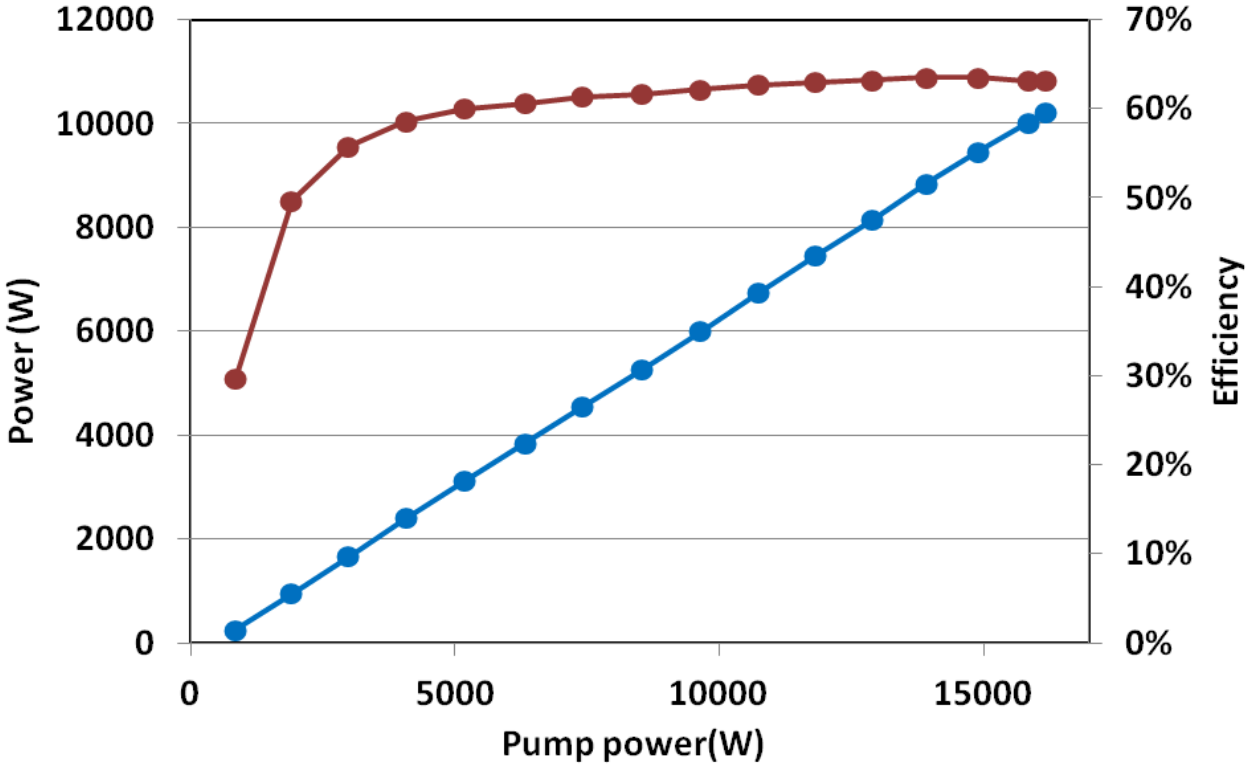


Optical Setup of cw Thin-Disk Laser (>10kW, Yb:YAG, 1030 nm)

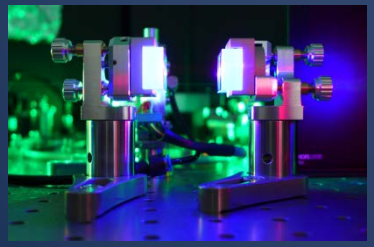


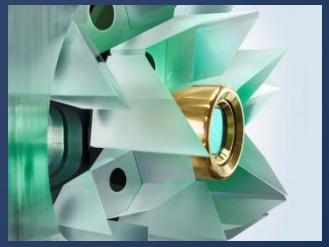
Record Performance: 10 kW per Disk & 62 % Optical Efficiency

→ There are no barriers to scale power/disk beyond current power levels



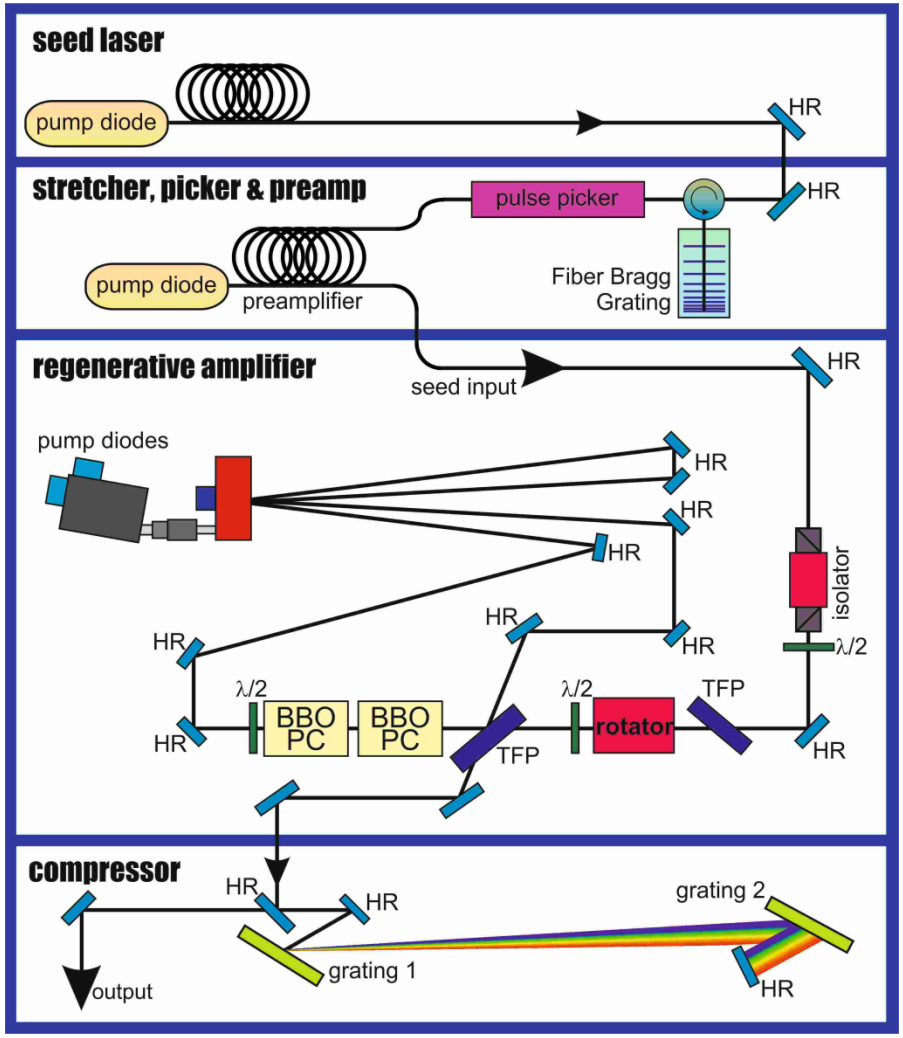
4. REGENERATIVE THIN-DISK AMPLIFIERS

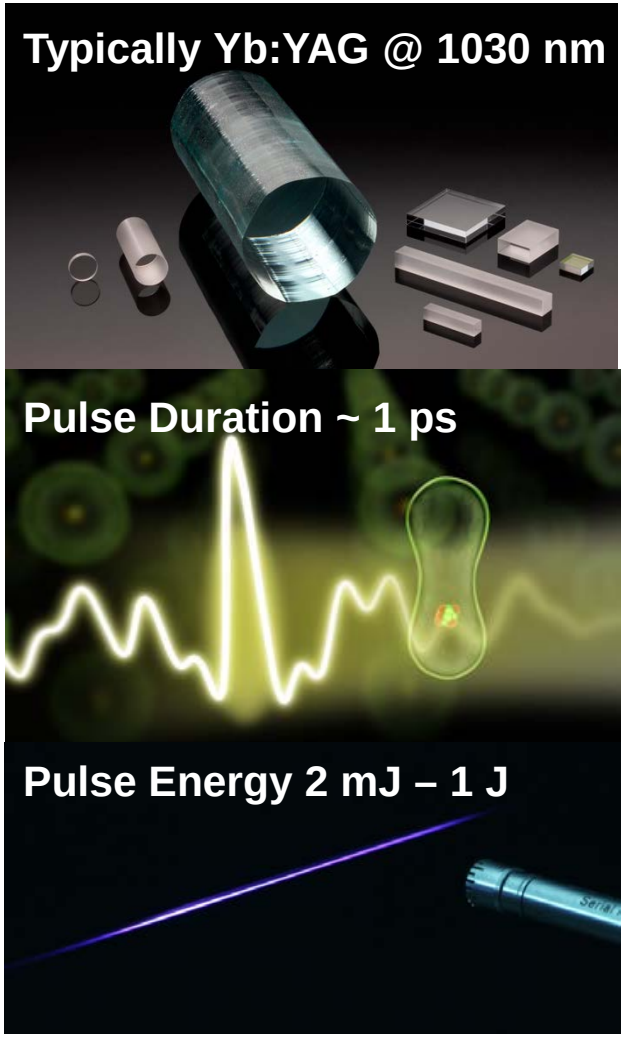






Typical Ultrafast Amplifier Schematic

Regenerative thin-disk amplifier (1030 nm; 1 ps)





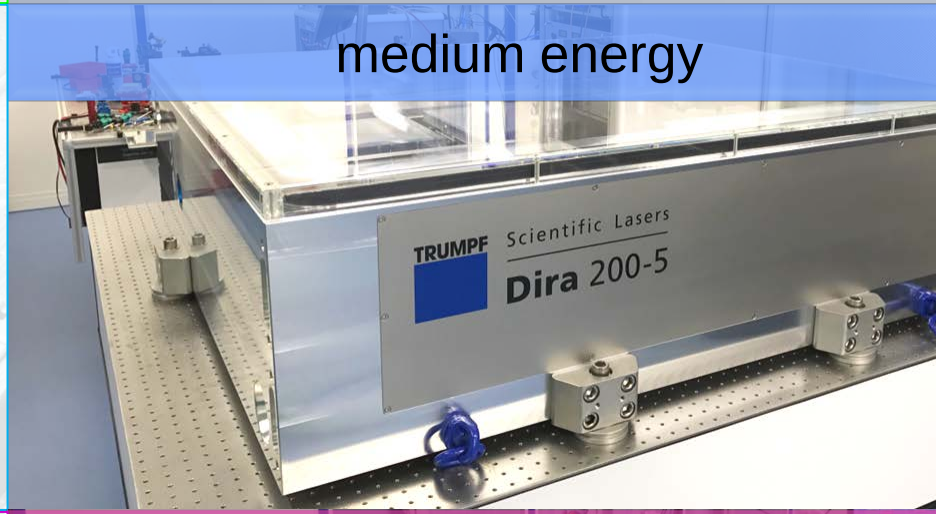
Overview of <2ps Regens

- **≤ 2mJ**
- ≤ 200W
- ≥ 100kHz

low energy

- **≤ 50mJ**
- ≤ 200W
- 5-100kHz

medium energy

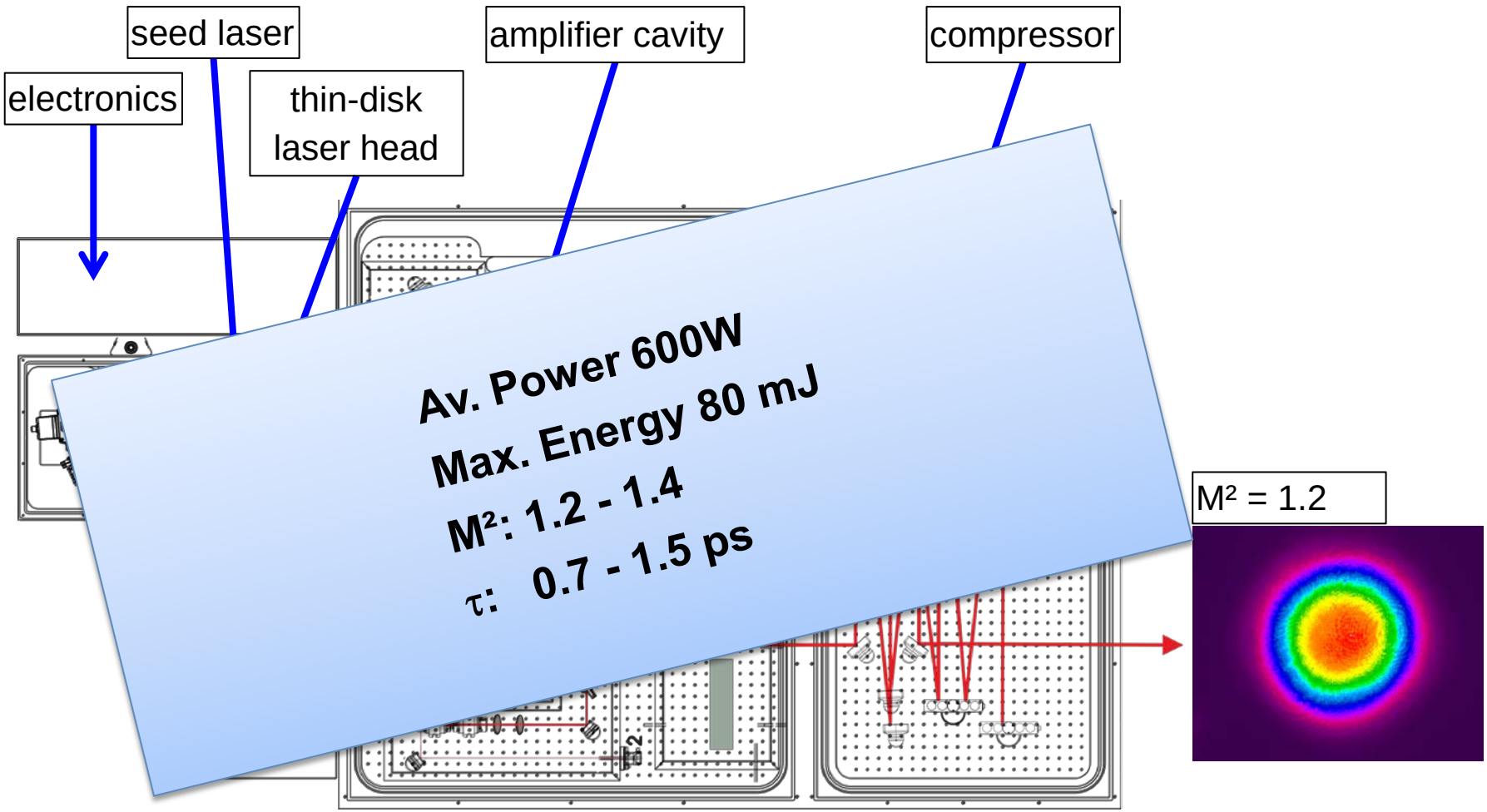


- **≤ 200mJ**
- ≤ 750W
- 5-100kHz

High energy & high average power

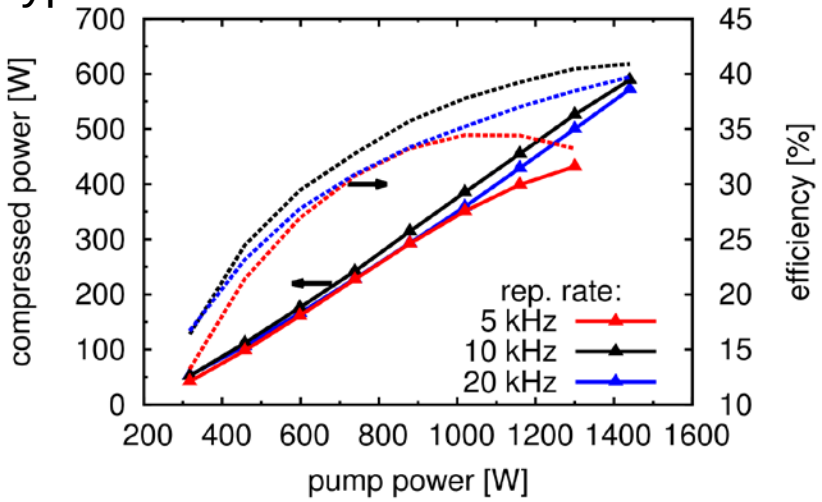
- *1 J (1kW; 1 kHz) development*

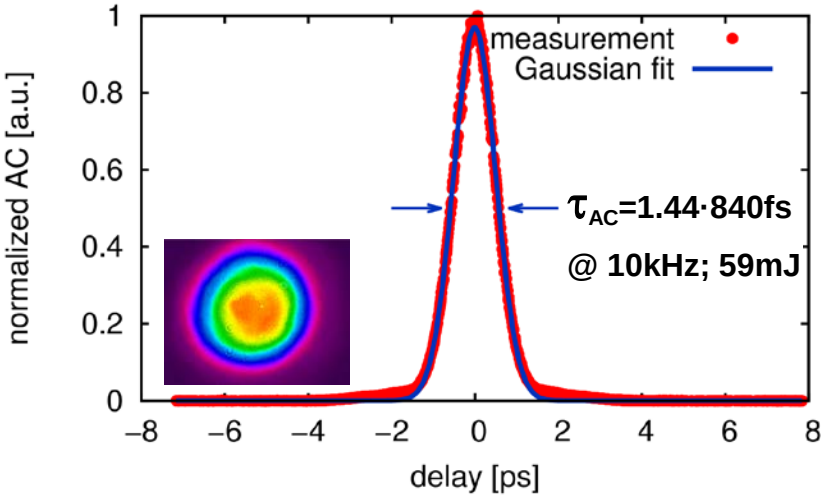
High Power Regenerative Amplifier (500W; few kHz)



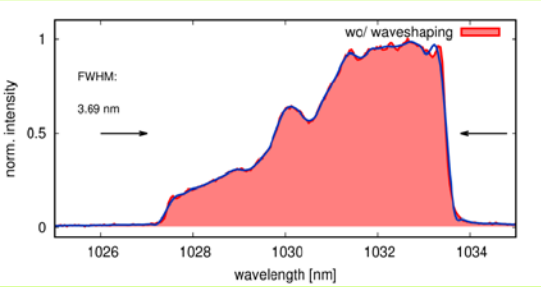
High Power Regenerative Amplifier (600W @ 8-200 kHz; <900fs)

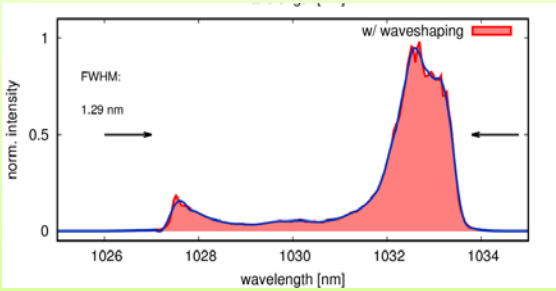
Typical Performance

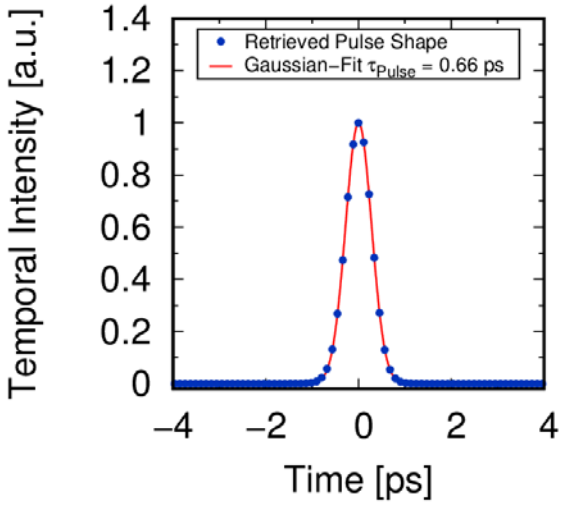




Spectral shaping for precompensating gain narrowing:
Pulse duration can be **reduced**: from **1.2 ps** to **< 700fs**

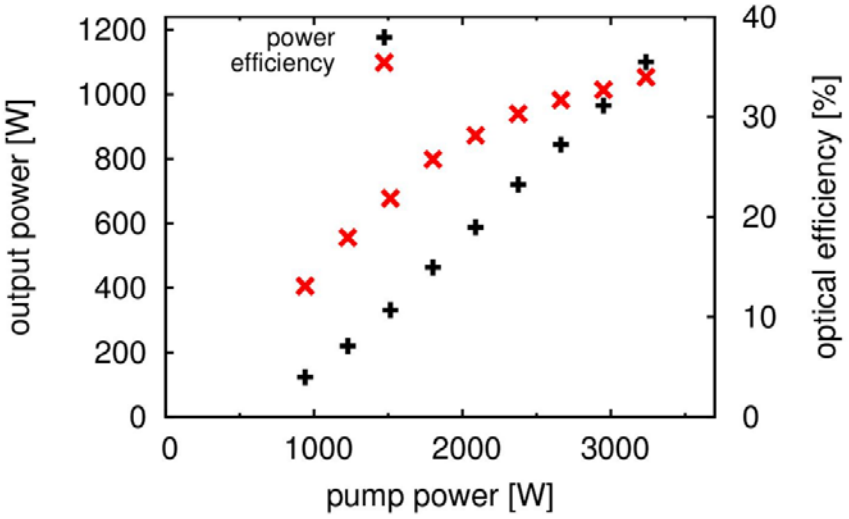


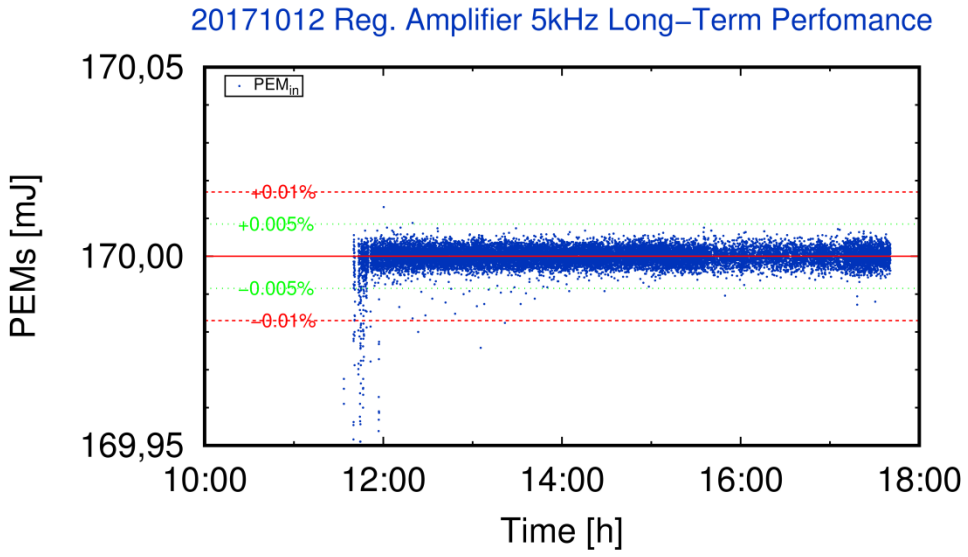




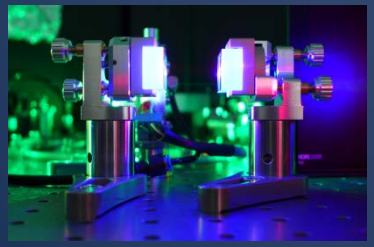
Further Scaling to >1kW (200mJ; 5kHz; 1ps; M² = 1.5)

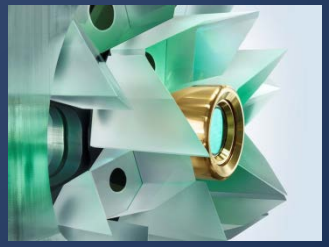
- M. Schultze, C. Wandt, S. Klingebiel, C. Teisset, M. Häfner, R. Bessing, T. Herzig, S. Prinz, S. Stark, K. Michel, and T. Metzger, "Toward Kilowatt-Level Ultrafast Regenerative Thin-Disk Amplifiers," in Lasers Congress 2016 (ASSL, LSC, LAC), OSA Technical Digest (online) (Optical Society of America, 2016), paper ATu4A.4.
- T. Nubbemeyer, M. Kaumanns, M. Ueffing, M. Gorjan, A. Alismail, H. Fattahi, J. Brons, O. Pronin, H. Barros, Z. Major, T. Metzger, D. Sutter, and F. Krausz, "1kW, 200mJ picosecond thin-disk laser system," Opt. Lett. **42**, 1381-1384 (2017).





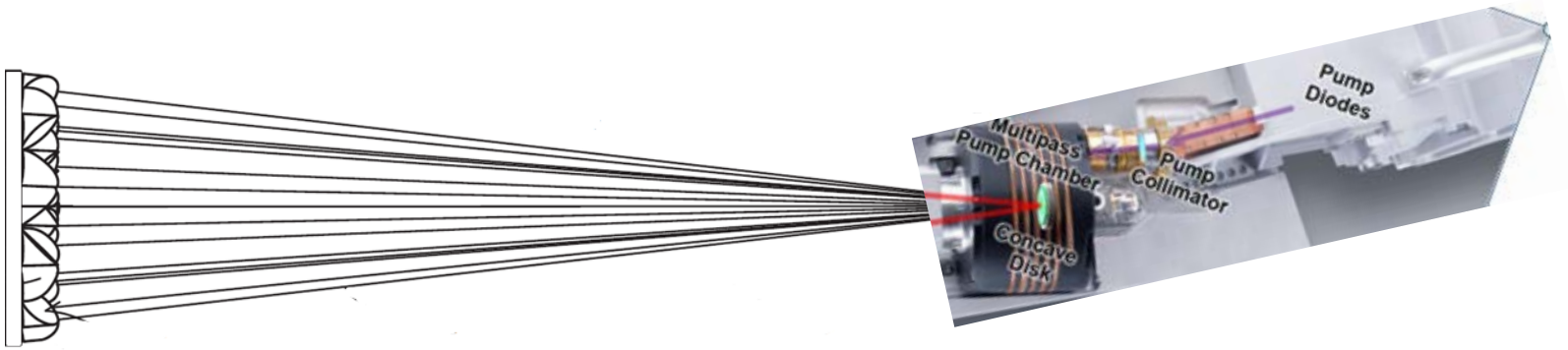
5. MULTIPASS THIN-DISK AMPLIFIERS

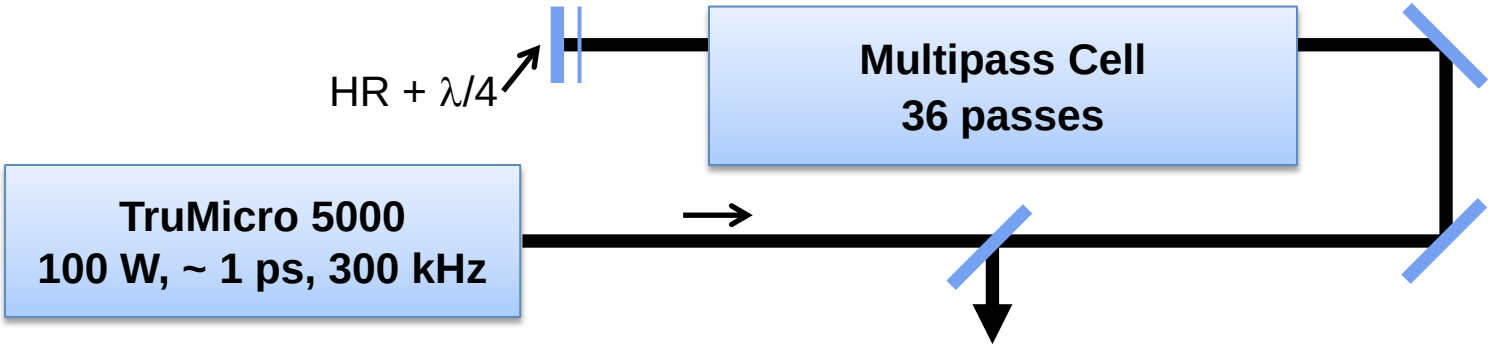






Power Scaling: Multipass

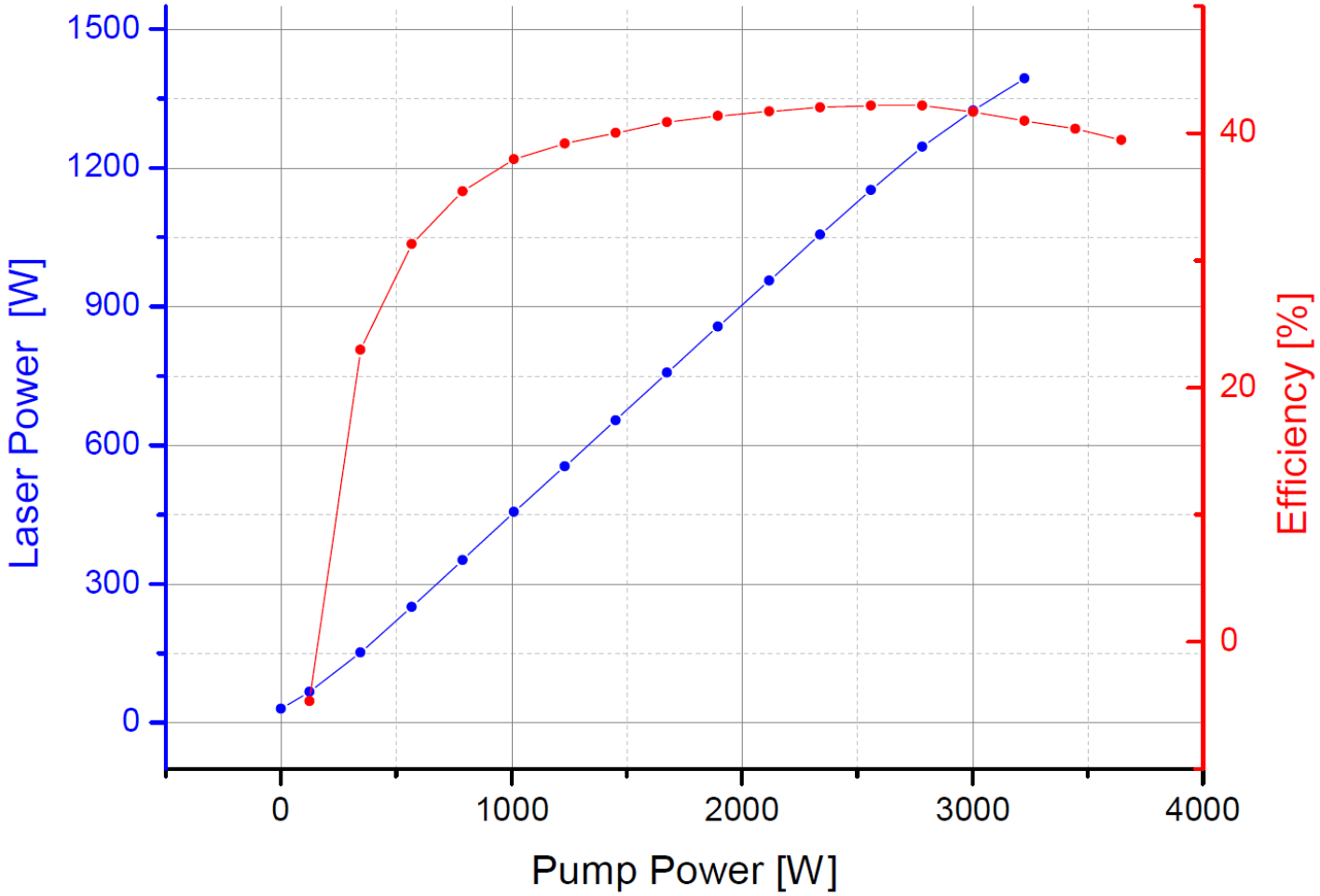
1st test results to demonstrate the potential of multipass amplifiers





Multipass: Ultrafast amplification

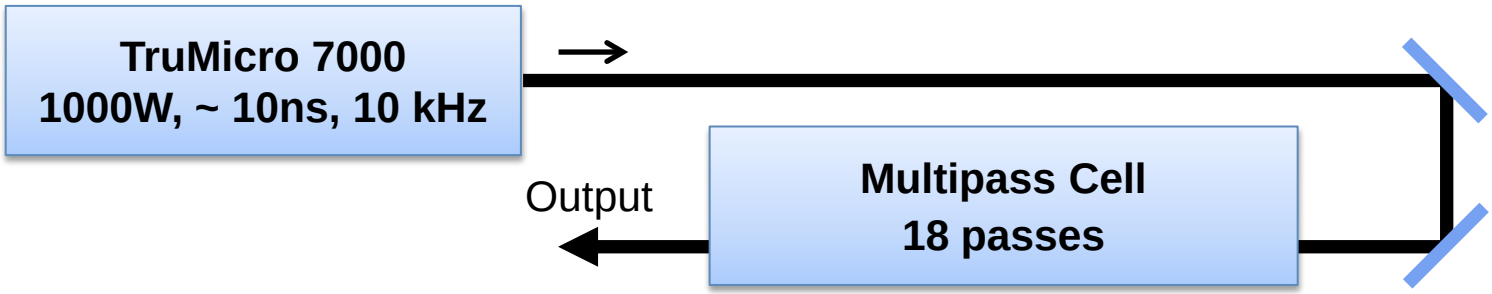
300 kHz, 1 ps, 36 disk passes, no CPA



- 1400 W output power @ 100 W of seed power, 1 ps pulse length

Power Scaling: Multipass

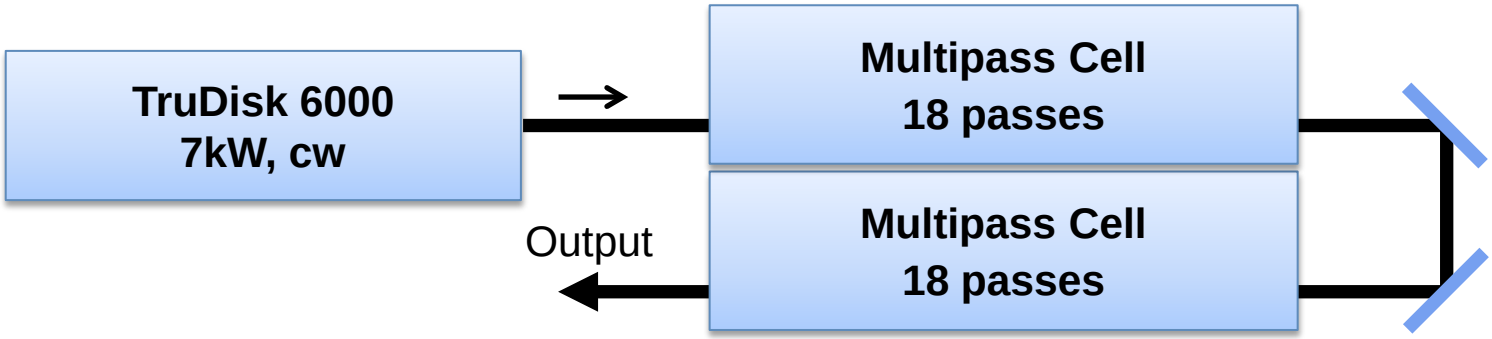
Seeding with 1kW of average power



- **3 kW output power @ 10kHz**
  - **Pulse duration ~10 ns**
  - **Beam quality M² ~ 11**

Power Scaling: Multipass

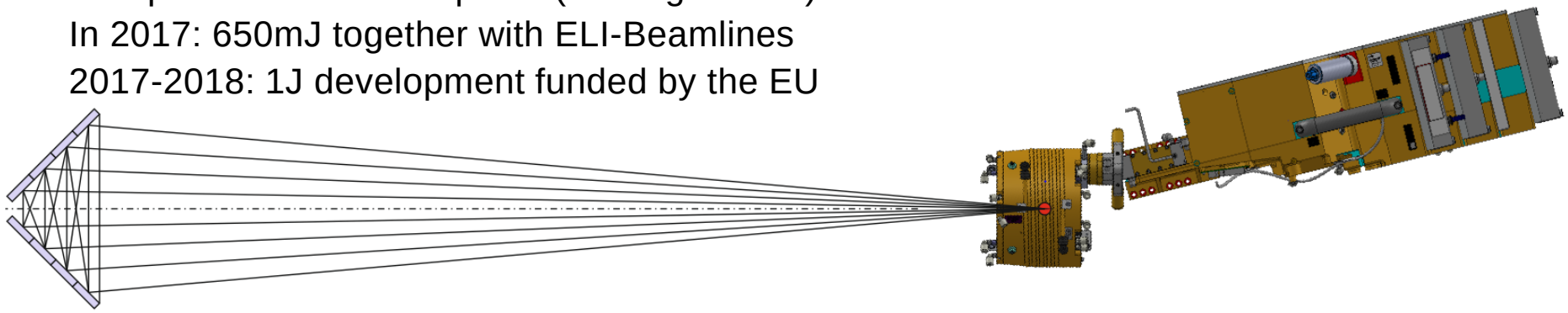
Seeding with 7kW (two single pass multipass cells)

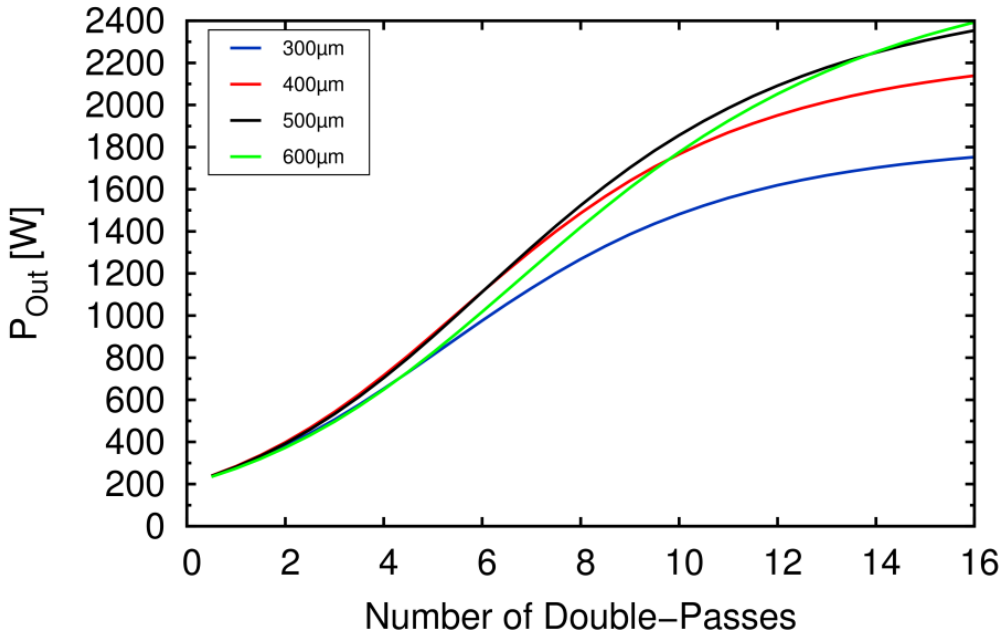


20 kW output power in cw
Multimode

Further Scaling to > 1J @ 1kHz (Development)

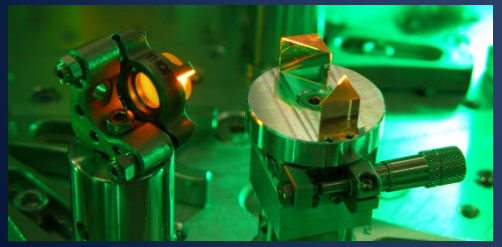
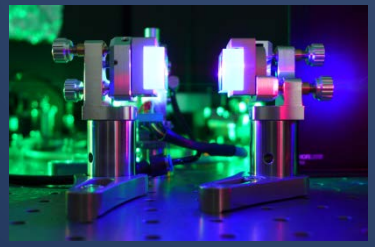
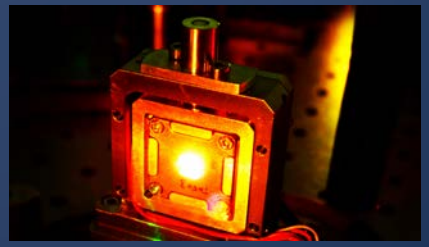
Multipass Thin-Disk Amplifier (coming soon!!!)
In 2017: 650mJ together with ELI-Beamlines
2017-2018: 1J development funded by the EU





- 20 mm disk diameter
- 20 kW of pump power
- 8 kW average pump power (40% duty cycle)
- 220 mJ seed laser
- 8 – 10 passes expected

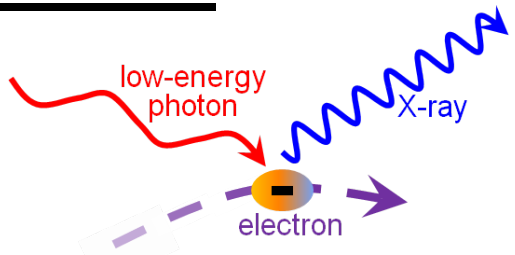
6. SHORT WAVELENGTH (EUV – SOFT X-RAY)


Examples Feasable with the TRUMPF Laser Sources

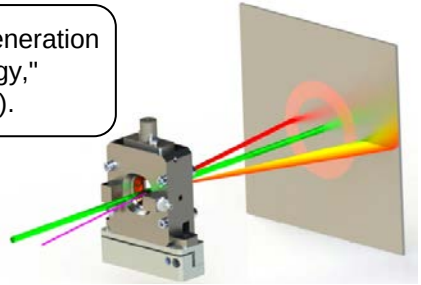
- Inverse Compton Scattering (X-Ray Generation)

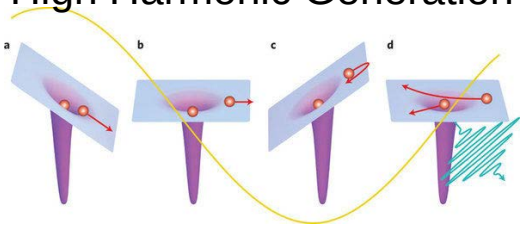
Graves et al., “Compact x-ray source based on burst-mode inverse Compton scattering at 100 kHz,” Phys. Rev. ST Accel. Beams **17**, 120701 (2014).



- Optical Parametric Chirped Pulse Amplification + High Harmonic Generation

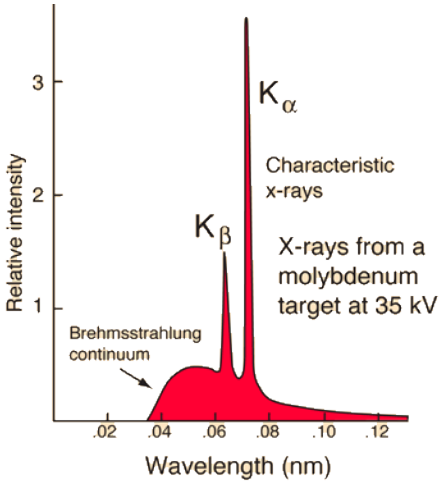
Fattahi et al., "Third-generation femtosecond technology," Optica **1**, 45-63 (2014).





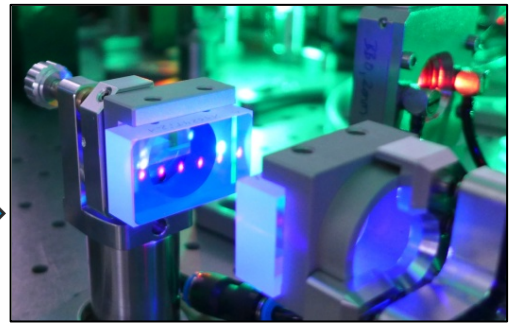
- X-ray emission from laser-target interactions

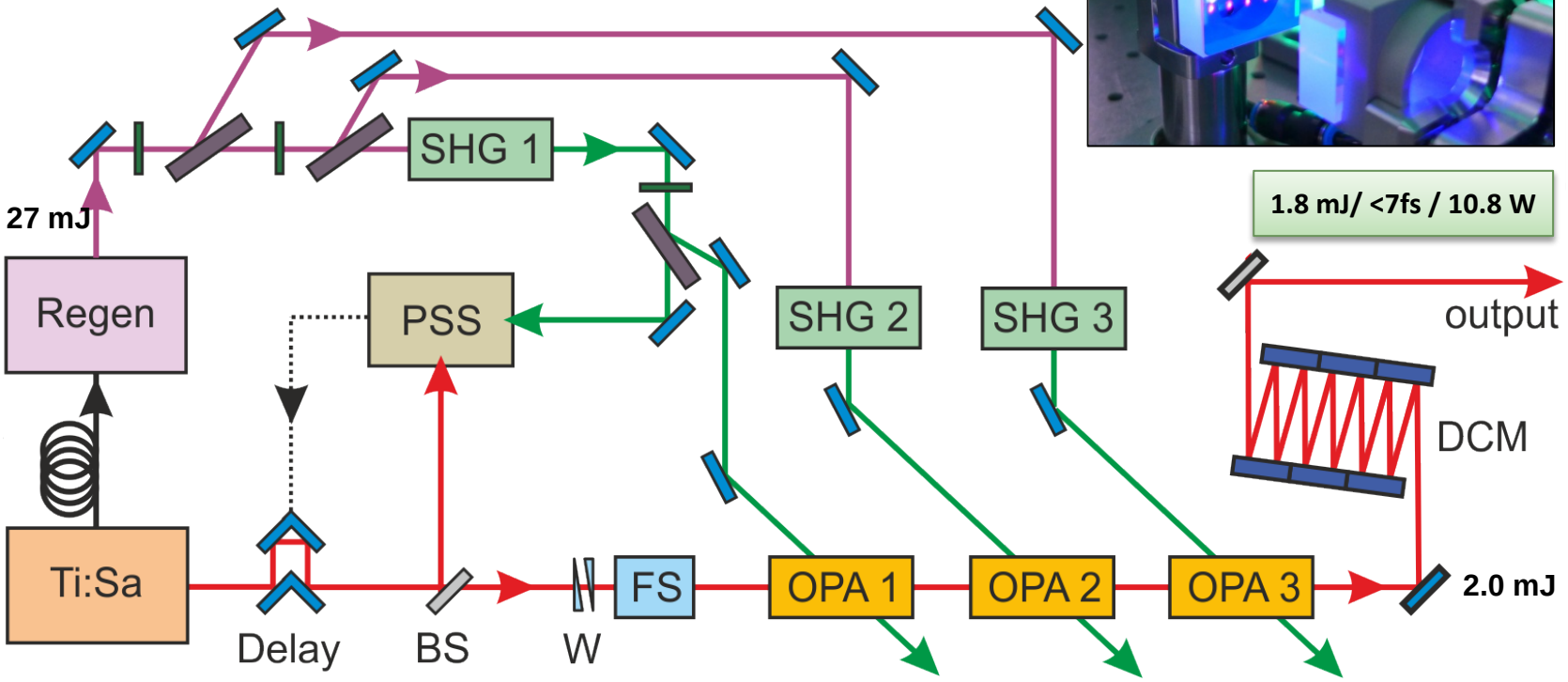
J. Yu, Z. Jiang, J.C. Kieffer, A. Krol, “Emission in high intensity femtosecond laser–target interaction. Phys Plasmas **6**, 1318 (1999).



TRUMPF Scientific Test OPA

Scheme

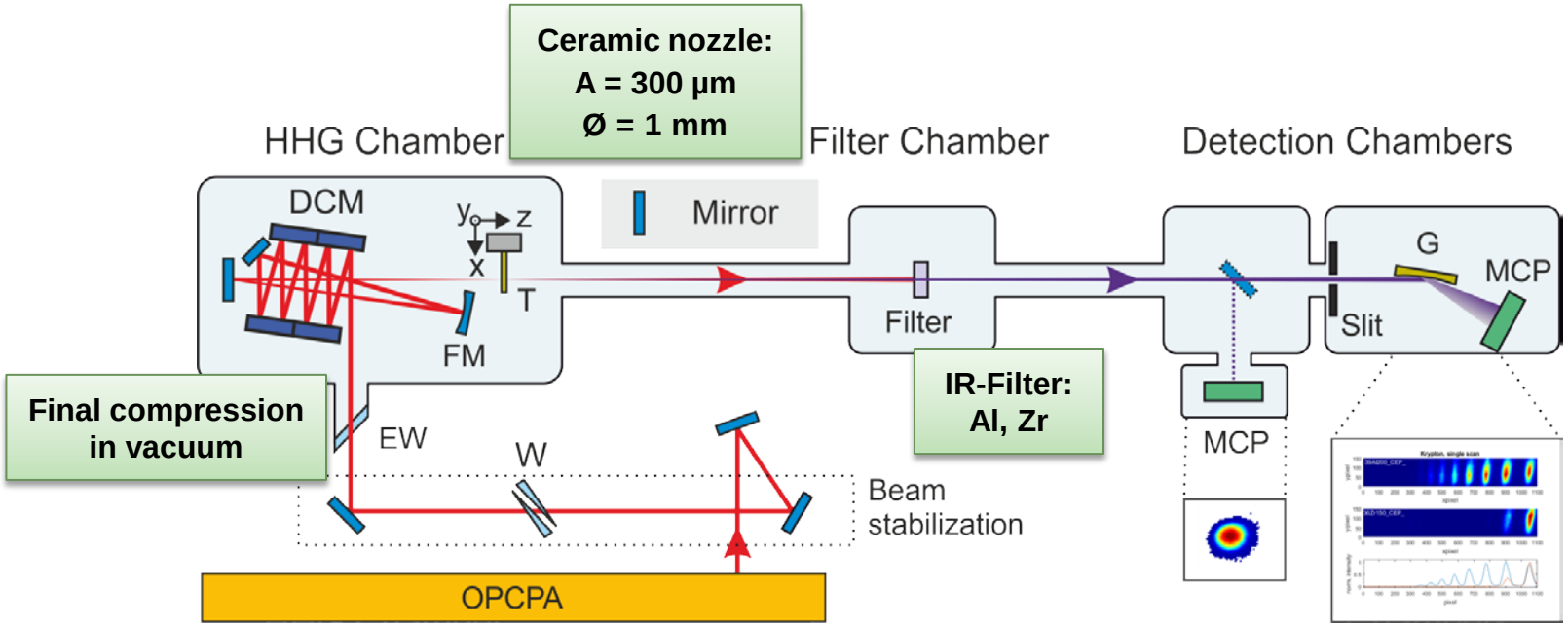




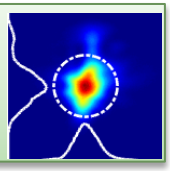
- S. Prinz et al. " Thin-disk pumped optical parametric chirped pulse amplifier delivering CEP-stable multi-mJ few-cycle pulses at 6 kHz," submitted to Optics Express 2017.
- S. Prinz et al. "Multi-mJ CEP-stable few-cycle pulses at 6 kHz from a thin-disk pumped OPCPA used for high-harmonic generation," Ultrafast Optics Conference 2017

High Harmonic Generation

Setup

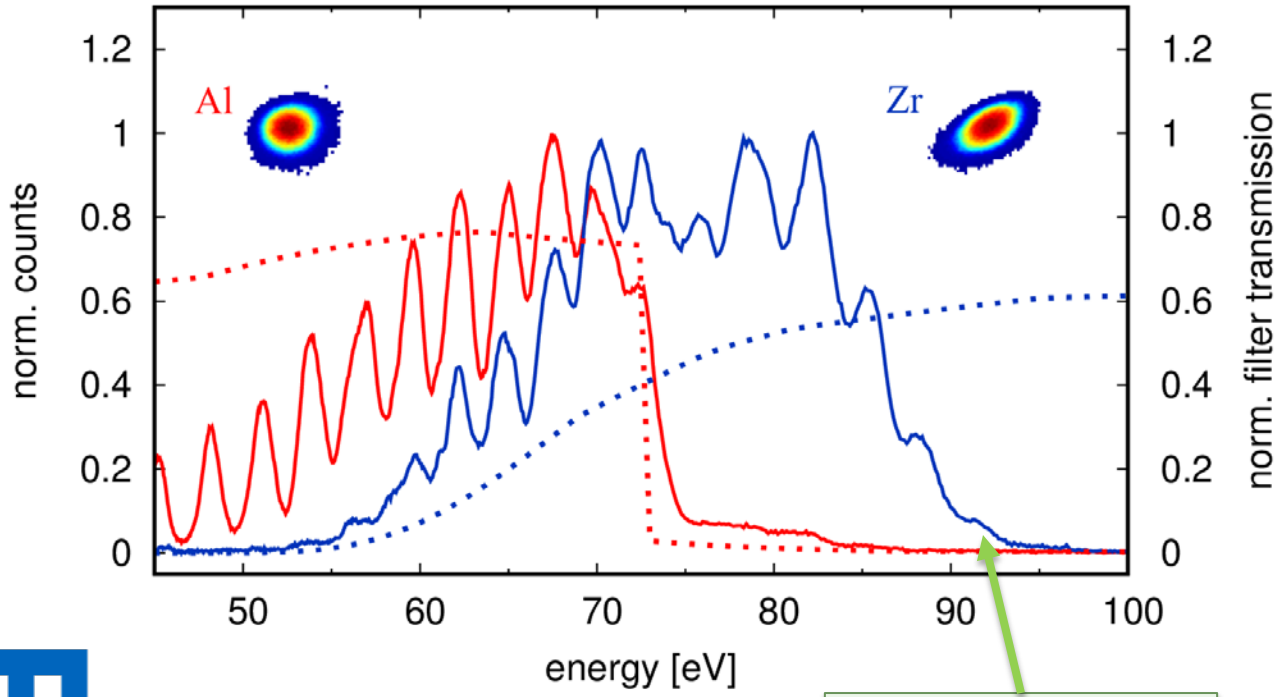


On target:
0.87 mJ, d ≈ 100µm
→ I ≈ 500 TW/cm²



High Harmonic Generation & experiments at TU München

Neon, p ≈ 100 mbar

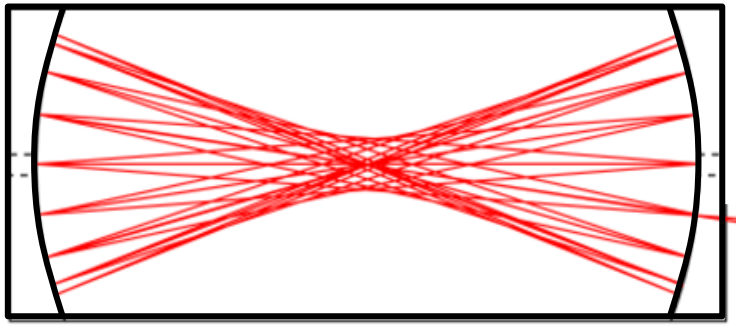


Technische Universität München

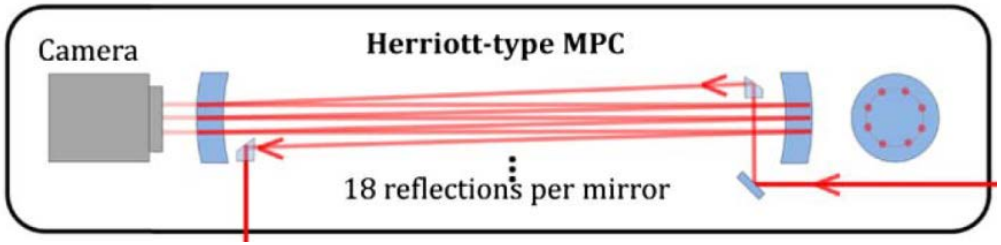
Prof. Reinhard Kienberger

Nonlinear Pulse Compression of ~1ps output of thin-disk lasers

Spectral broadening via SPM in a Herriott-Cell

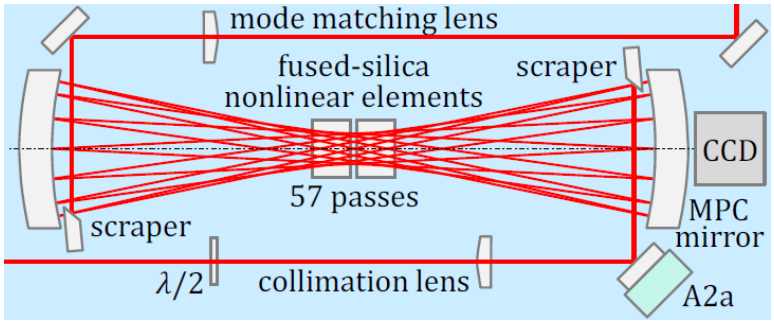


Idea:
Consecutively foci inside a gas filled cell to increase nonlinearities & to broaden the spectrum via self phase modulation (SPM). Final compression with chirped mirrors or gratings



Opt. Lett. 41, 4511 (2016)

0.9ps → 170fs
375W, 10MHz, 37.5µJ



Opt. Expr. 25, 20502 (2017)

0.9ps → 115fs
300W, 40MHz, 7.5µJ

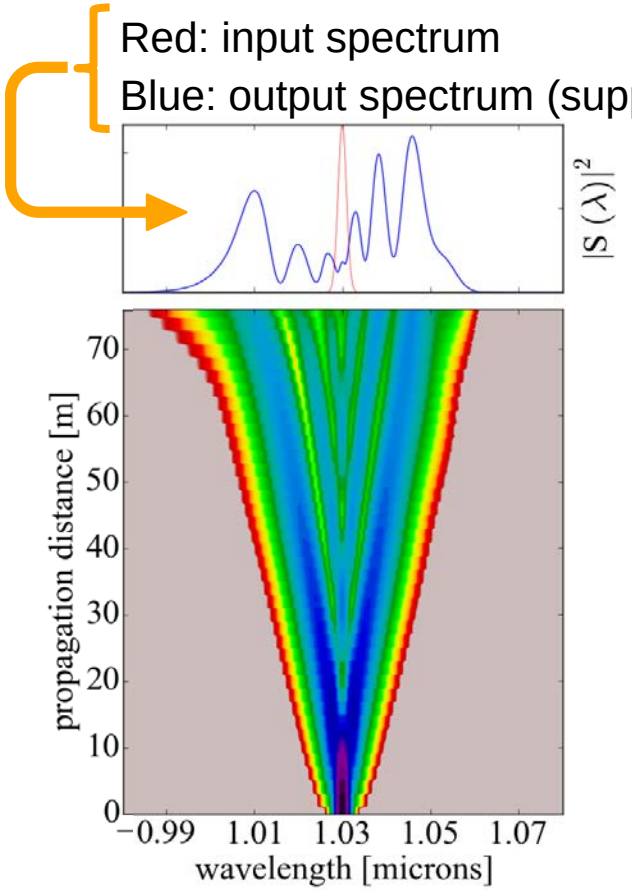
Nonlin Pulse Compression (TRUMPF Scientific Simulation)

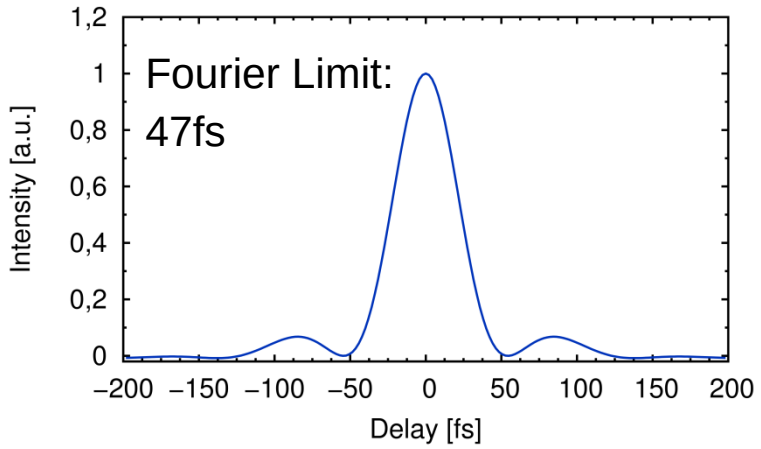
Example: simulation for 500µJ and 30 RTs

Gas cell @ 20 bars

Mirror Separation 2.0m
Mirror Curvature 1.4m
Max/Min beam waist 1.7mm /0.23mm

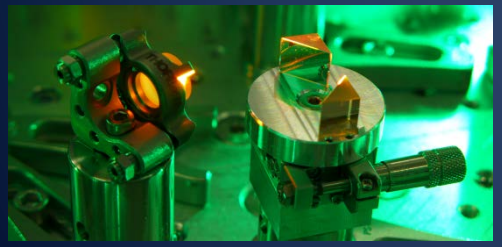
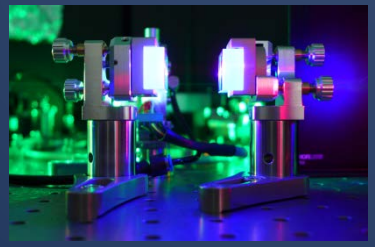
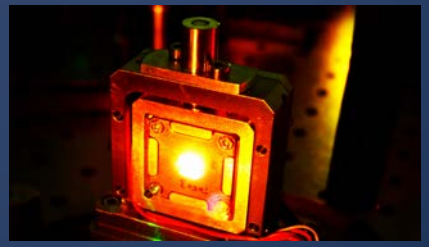
Red: input spectrum
Blue: output spectrum (supports <50fs)





2kW, 500µJ and ~50fs seem realistic

7. SUMMARY

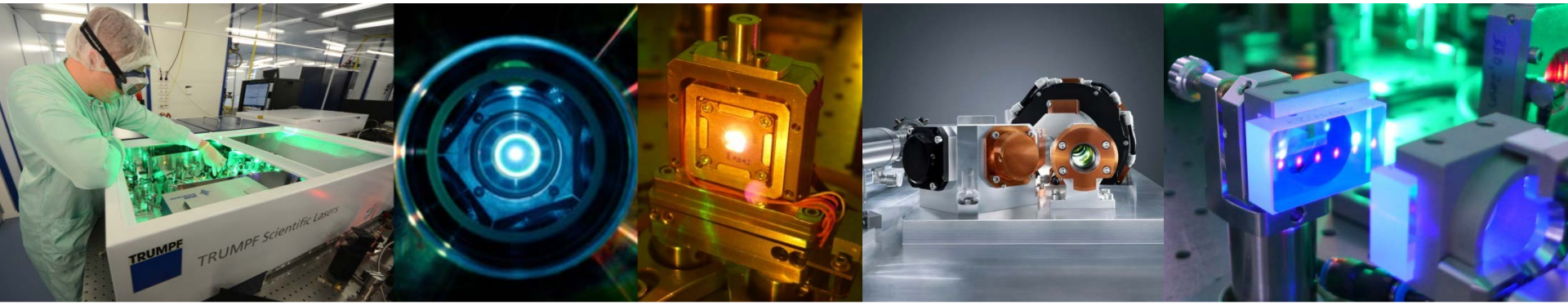

Summary

Power ≤ 1000W
Energy 1 - 200 mJ
M^2: 1.2 - 1.4
τ: 0.7 - 1.5 ps

- Regen. amplifier: **200 mJ; 1kHz (standard)**
  500W ; 6-100 kHz (standard)
  1kW; 5-100 kHz (completed)

- Multipass amplifier: **multi-kW possible & available (incl. nonlin. compression for HHG)**

- HHG, XUV, X-ray: **<30fs, >2kW are feasible for HHG generation**
  10^{17}–10^{18} W/cm² are available with our sources – Soft X-Ray/K-alpha
  OPCPAs with few mJ are available (100W seem feasible)



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