High Power Thin Disk Lasers

Dr. Adolf Giesen

German Aerospace Center
Institute of Technical Physics

Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Research Topics - Institute of Technical Physics

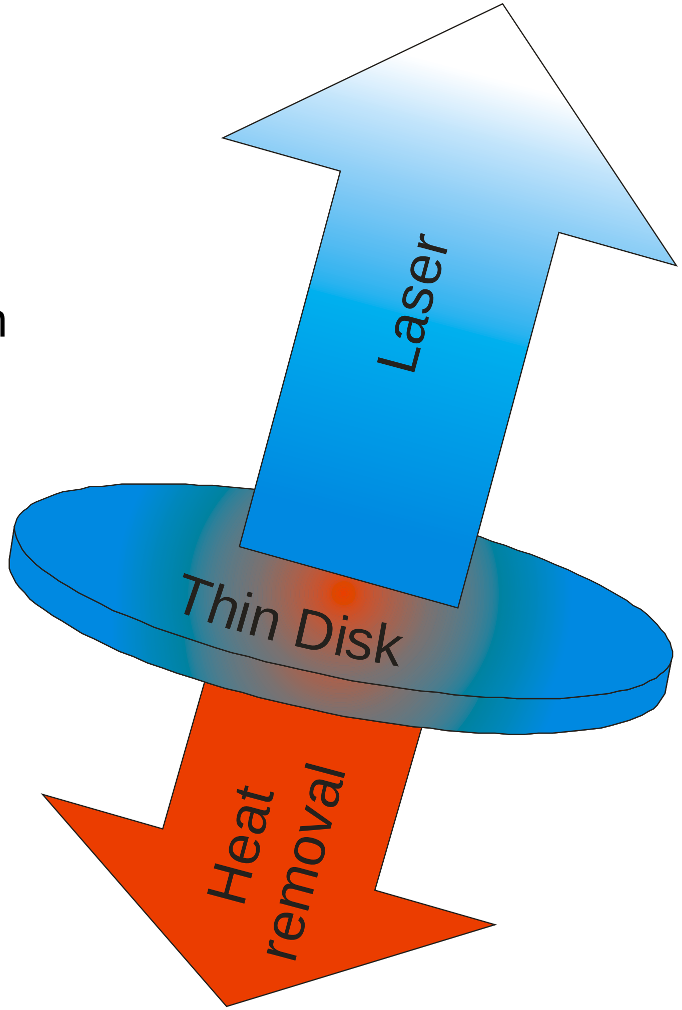
	Laser sources and nonlinear optics Speiser	Beam control and optical diagnostics Riede	Atm. propagation and target effects Handke	Studies and Concepts Eckel
„Stand off“ Detection Handke	Pulse laser NLO	(Receiver) Optics	Trials, spectroscopy, data processing	System studies, risk reduction
Long range laser effector Speiser	High power laser	Beam control	Propagation and target effects	Scenarios, system studies
Laser propulsion Eckel	(Pulse) Laser	Transmitter optics beam control	Target effects	Mission studies, system concepts
Opt. reconnaissance (space situational awareness) Riede	Pulse laser	Telescope, beam control	Atmospheric data, trials	Threat analysis, system studies

Outline

- Thin Disk laser concept
- State of the art (commercial & laboratory)
- Pulsed Thin Disk lasers – influence of ASE
- Power scalability & high brightness
- High power laser design
- Eye-safe Thin Disk laser
- Scaling limits
- Summary

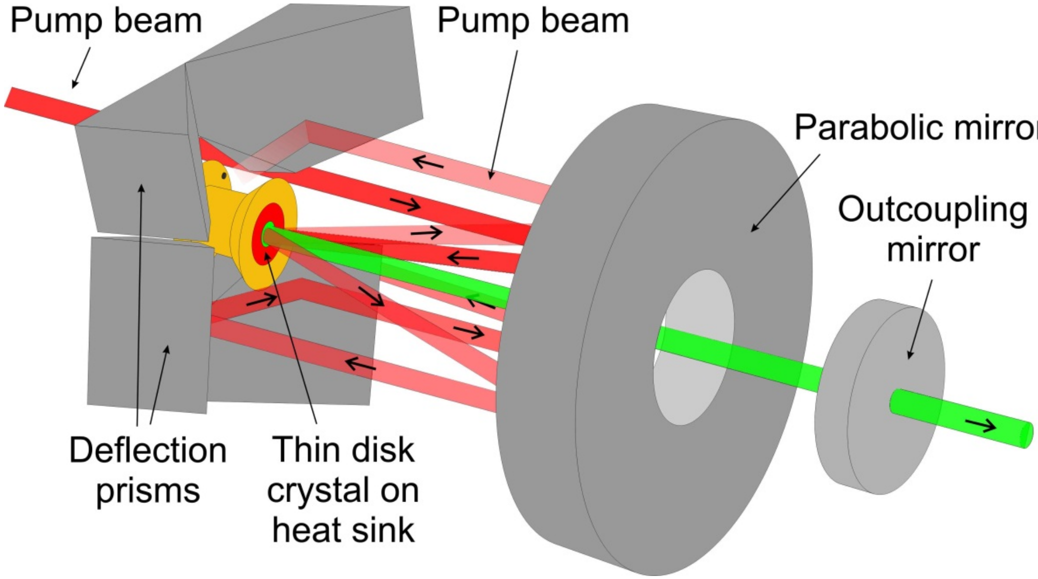
Thin Disk laser concept

- Core idea: thin active material, one face cooled, used as active mirror
- thickness 0.1 – 1 mm, diameter 5 – 45 mm
- Heat flow parallel to laser beam
- Minimized thermal lens
- High output power and high efficiency simultaneously
- Power / energy scaling
  by scaling of pump spot area
  (power / energy densities and temperatures constant)
- variety of active materials



Thin Disk laser concept

- Small pump absorption in single pass
- Simple setup to re-use not absorbed pump power
- With 1 parabolic mirror and 5 plane mirrors 16 – 32 (44) pump beam passes realized

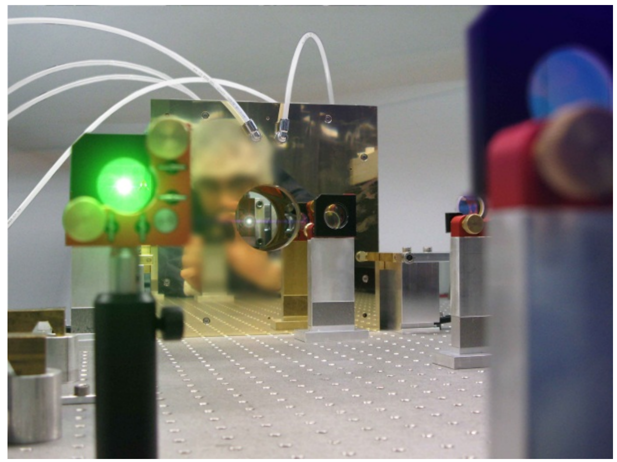


- Pump source brightness requirements: constant for power scaling (~80 kW cm^{-2} sr^{-1} for 5 kW/cm^2 with 24 pump passes)* **=> low costs**
- Decoupling of pump absorption and laser reabsorption significantly increases performance of quasi-3-level materials like Yb:YAG

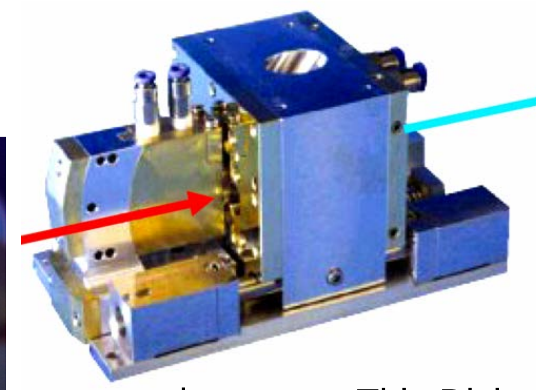
* S. Erhard, *Pumpoptiken und Resonatoren f. den Scheibenlaser*, PhD Thesis, 2002

Thin Disk laser – technical realization

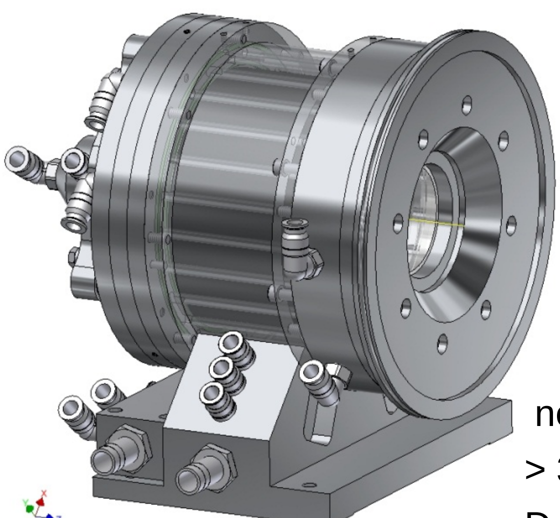
medium power disk (> 500 W)



medium power Thin Disk
pump module in operation



low power Thin Disk
pump module



new design for high-power Disk module
> 30 kW pump power, suitable for vacuum
Development of DLR-TP and industrial partner (D+G)

State of the art - Commercial systems

High power, multimode

- 1 kW, 1 disk, 2 mm mrad (M^2 ~ 6)
- 4 kW – 16 kW, 1 – 4 disks, < 8 mm mrad (M^2 ~ 24)

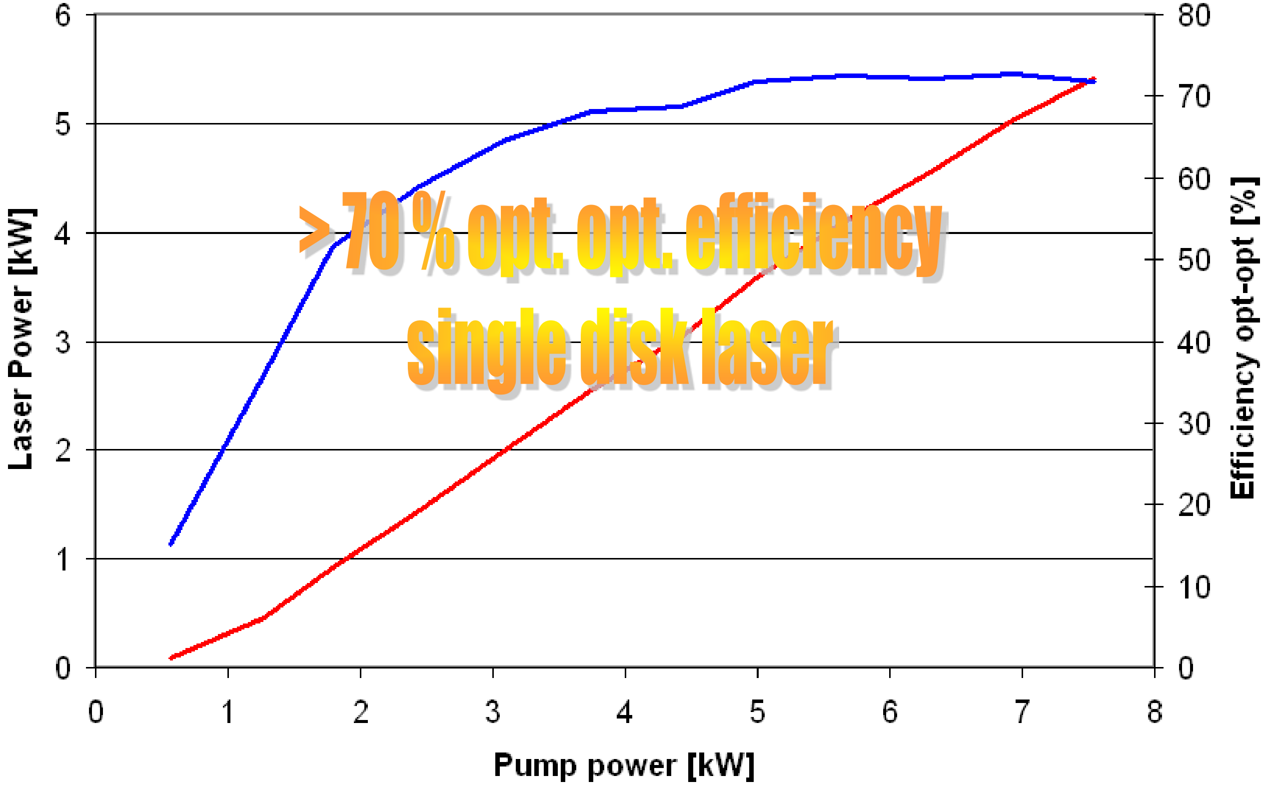
Pulsed

- Mode-locked oscillator, 80 W average power, 800 fs
- Regenerative amplifier, 40 µJ, 100 kHz, 400 fs
- Cavity dumped, 750 W average power, 80 mJ, 30 ns

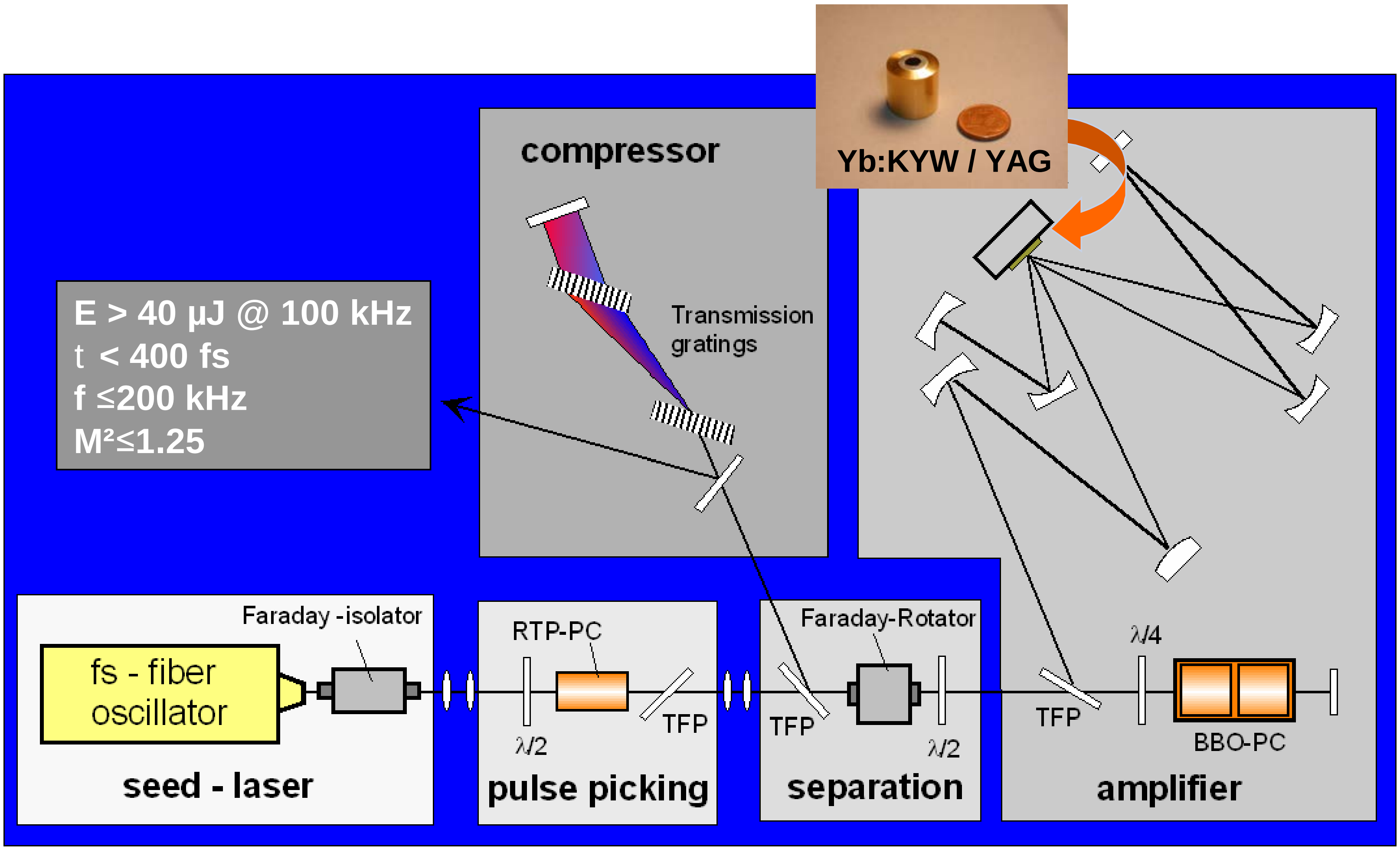
Small systems

- 3 W @ 532 nm, 105.7 mm x 62 mm x 24 mm
  (without DC power supply)

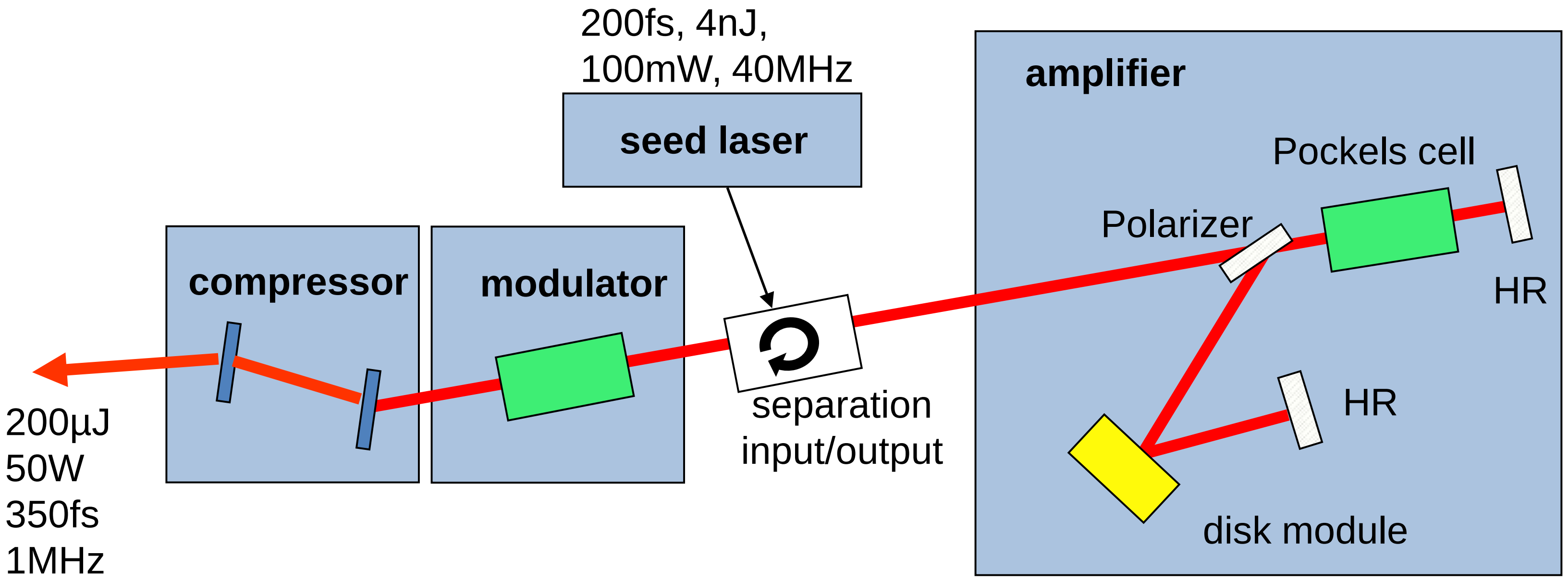
Enhanced efficiency with 44-pass pump cavity



JenLas® D2.fs
regenerative thin disk laser



VaryDisk



Different pulse durations out of one resonator
No further alignment for applications

a product of Dausinger + Giesen GmbH

State of the art – Lab results

- 500 W, $M^2 < 1.1$

  (A. Killi et. al. „The broad applicability of the Disk Laser principle – from CW to ps“, in *Solid State Lasers XVIII: Technology and Devices*, Proc. SPIE Vol 7193 (SPIE 2009))

- 27 kW, about 10 disks in an unstable resonator – “excellent beam quality”

  (P. Avizonis et. al. “PHYSICS OF HIGH PERFORMANCE Yb:YAG THIN DISK LASERS”, CLEO 2009)

- 380 mJ, 8 ns, 88 W average power, $M^2 < 1.3$

  (A. Killi et. al. „The broad applicability of the Disk Laser principle – from CW to ps“, in *Solid State Lasers XVIII: Technology and Devices*, Proc. SPIE Vol 7193 (SPIE 2009))

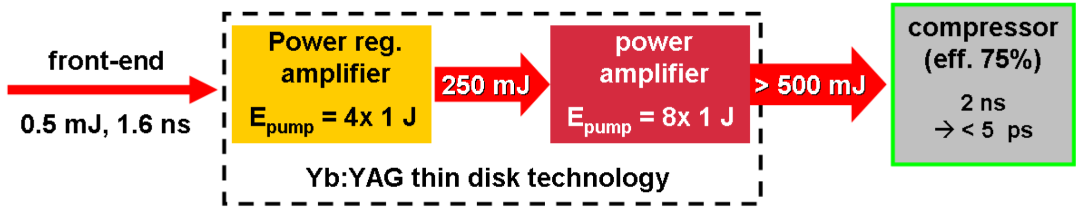
- CPA-System with 188 mJ, 100 Hz, $M^2 < 1.1$, compressible < 2 ps, amplification to ~ 300 mJ demonstrated

  (J. Tümmler et. al. “High Repetition Rate Diode Pumped CPA Thin Disk Laser of the Joule Class”, CLEO Europe 2009)

Multipass Amplifier – Results

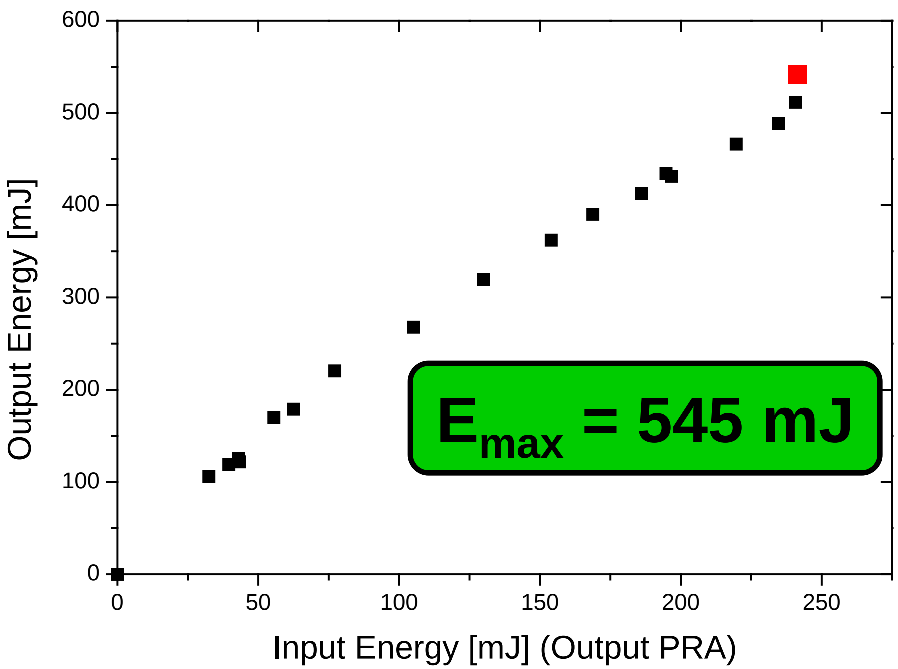
Max-Born-Institut

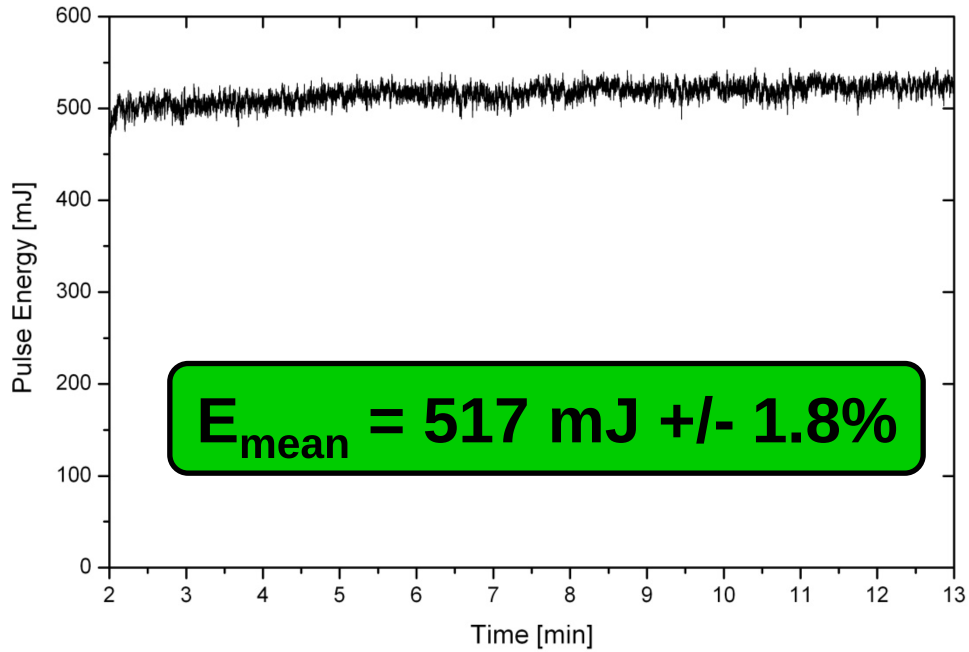
Thin Disk Amplifier Chain



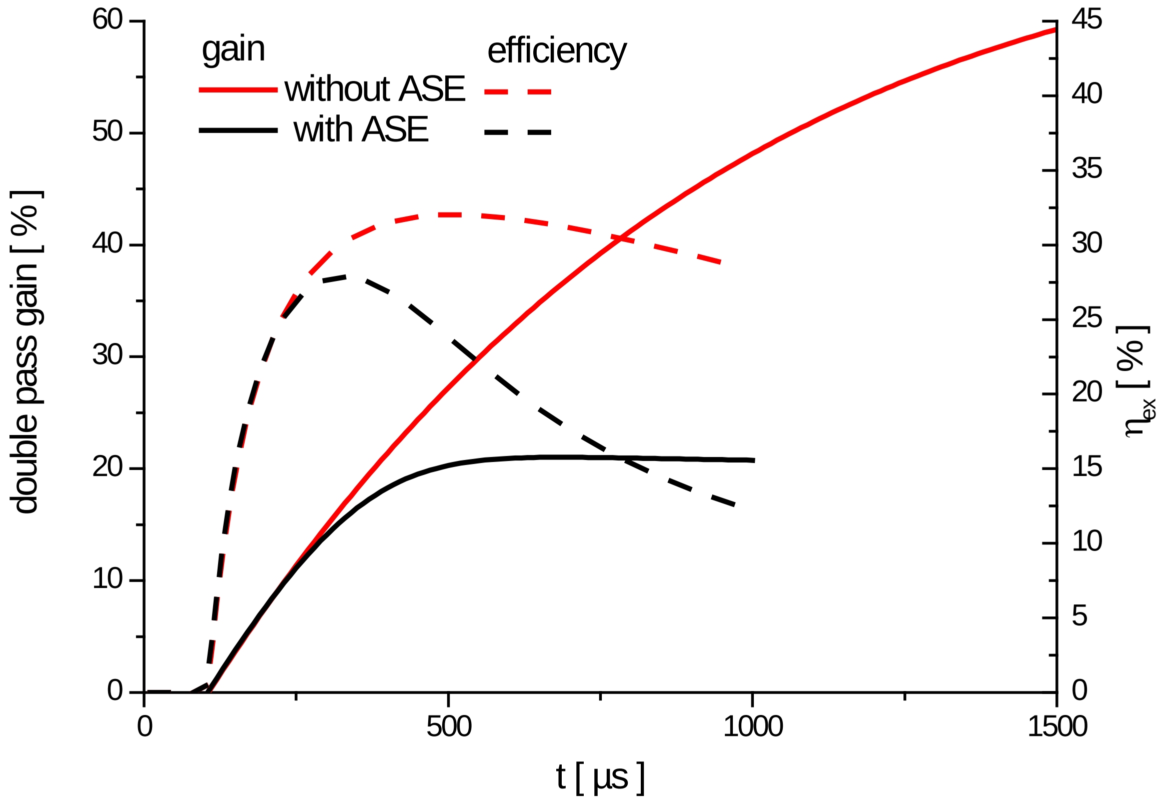
Disk parameter:
- diameter: 17 mm
- thickness: 500 µm
- doping level: 7%

multipass output after 4 double passes – pump power 6 kW





Amplified spontaneous emission (ASE)
results of time resolver numerical model



4.5% Yb:YAG, thickness 600 µm, pump power 16 kW, pump spot radius 9.8 mm

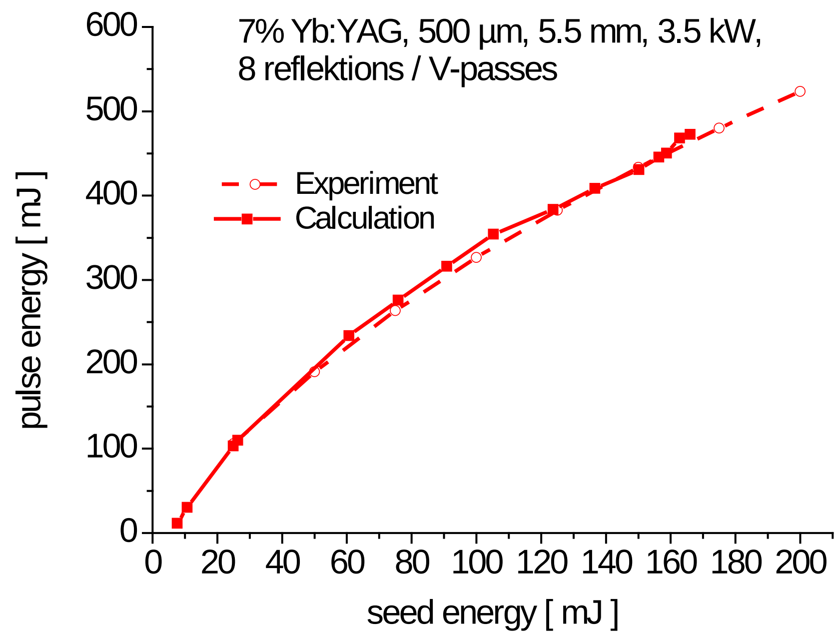
Time resolved model:

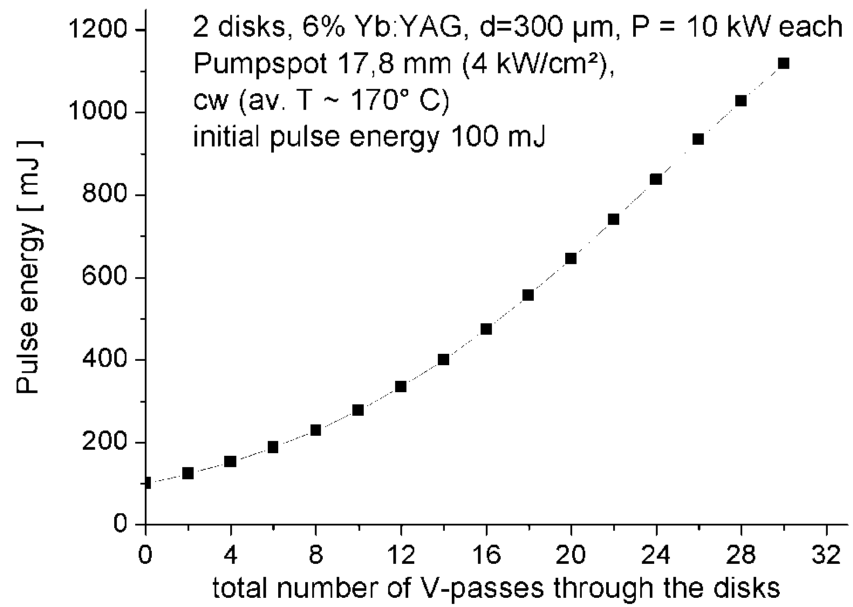
- spatial pump absorption
- spatial inversion
- ASE in the disk
- average temperature
- calculations with 1 ms pump pulse, 10% heat generation
- here: 10% duty cycle

=> Calculate gain / max. stored energy / efficiency

Geomtrical Multipass amplifier

Numerical calculations & experimental results





Low duty cycle, low pump power

Comparison with actual results from Max Born Institute

high duty cycle, high pump power

Possible concept for multipass amplifier

Actual high energy / high peak power projects

Max Born Institute

- Yb:YAG Thin Disk CPA system (regenerative amplifier + several multipass stages), goal: 1 J, 5 ps, 100 Hz (1,6 J before compressor, ns), **550 mJ reached**

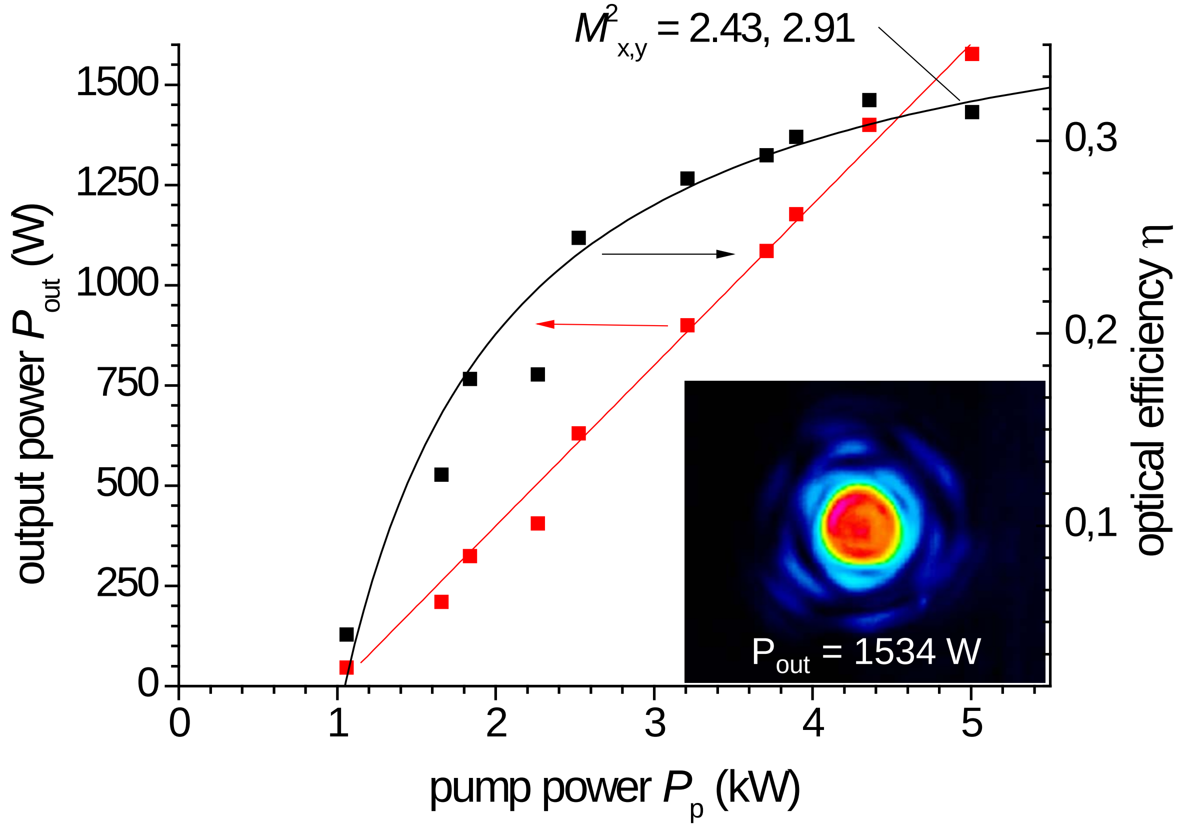
MPQ Garching

- Yb:YAG Thin Disk CPA system (regenerative amplifier), **28 mJ, 3 kHz, 1.6 ps running**
- extension with multipass amplifier stages planned (up to 10 J discussed)

DLR-TP

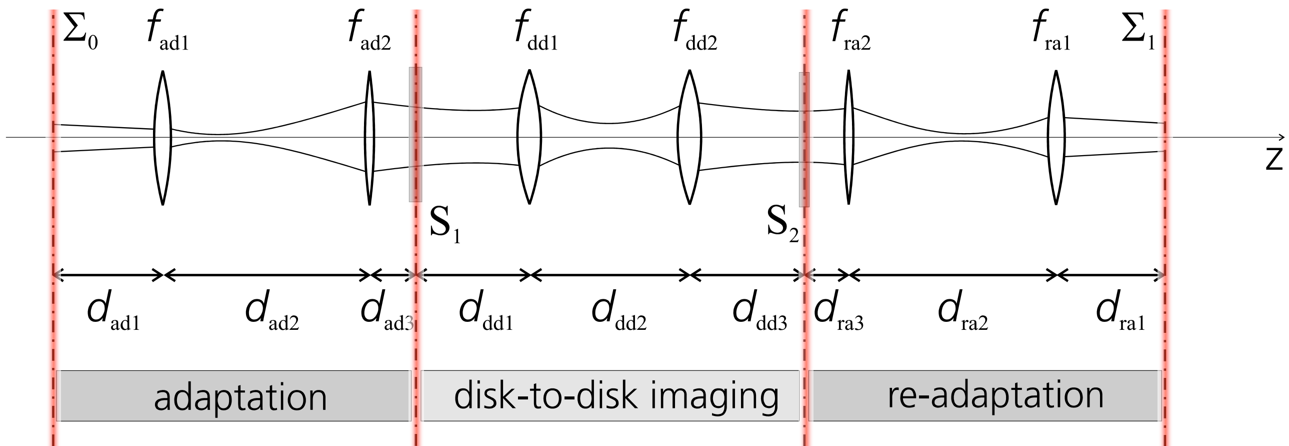
- Yb:YAG Thin Disk system (regenerative amplifier + 1 multipass stage), goal: 1 J, 100 ps – 10 ns, 1 kHz for laser ranging of space debris

High-Brightness Oscillator using Neutral Gain Modules
V-shaped resonator with 2 Relay NGMs and AO

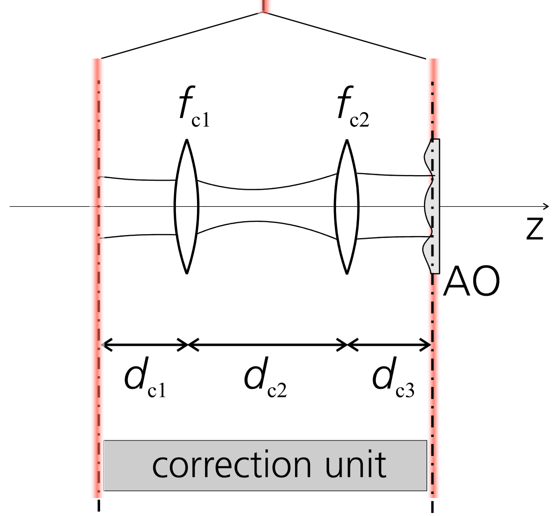


Concept of Neutral Gain Modules

Relay NGM with optional OPD compensation



-·-·- conjugated planes



$$\Sigma_0 \mapsto S_1 \mapsto \ldots$$

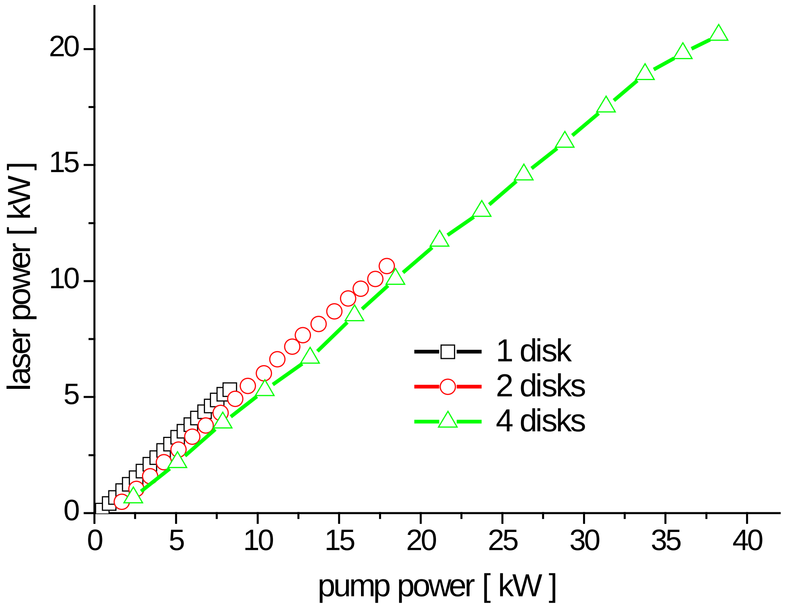
$$\mapsto S_j \mapsto S_k \mapsto \ldots$$

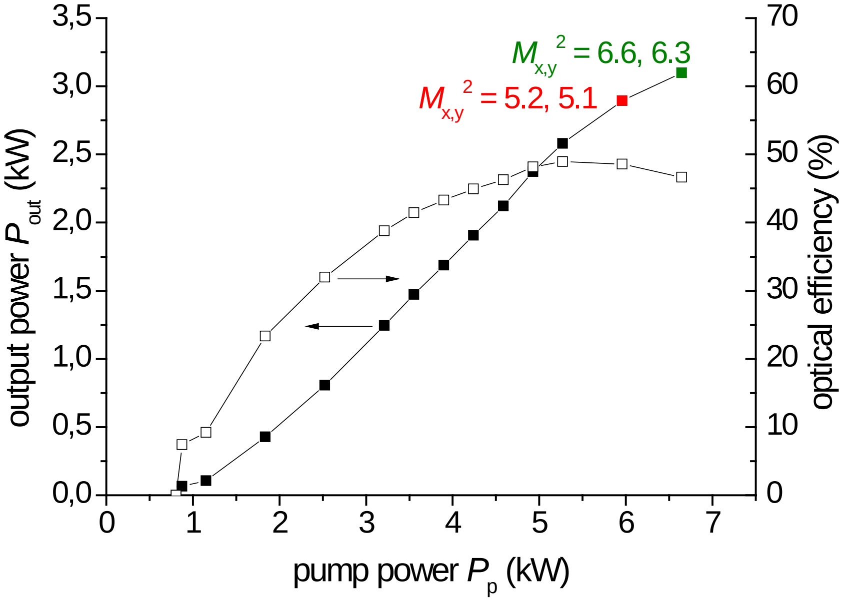
$$\mapsto \mathrm{AO} \mapsto \ldots \mapsto \Sigma_1$$

$$M_{D_{tot}} = \begin{pmatrix} 1 & 0 \\ -D_{tot} & 1 \end{pmatrix}$$

$$M_{corr} = M_{D_{tot}}^{-1} = \begin{pmatrix} 1 & 0 \\ +D_{tot} & 1 \end{pmatrix}$$

Power scalability & Brightness





5.3 kW out of one disk /
20 kW with four disks

extracted volume power density > 600 kW/cm³

Courtesy TRUMPF Laser Schramberg

Two confocal neutral gain modules* (4 disks) in V-shaped resonator

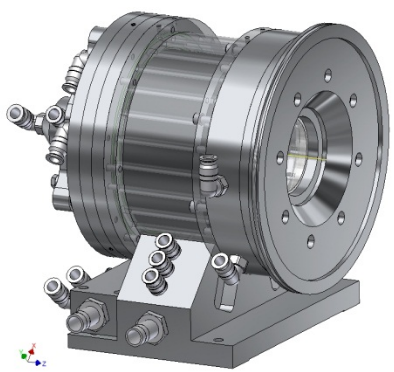
3 kW laser power, M² ≈ 6.5

* J. Mende et. al., *Concept of Neutral Gain Modules for Power Scaling of Thin-Disc Lasers,* Applied Physics B, 97 (2), 2009

3-stage MOPA for 10 kW

master oscillator → $14\%\ I_{sat}$ → multipass amplifier → $33\%\ I_{sat}$ → multipass amplifier → $52\%\ I_{sat}$ → multipass amplifier →

master oscillator	multipass amplifier	multipass amplifier	multipass amplifier
Stable resonator	6 kW pump power	6 kW pump power	6 kW pump power
6 kW pump power	11.3 mm pump diam.	11.3 mm pump diam.	11.3 mm pump diam.
2 kW output power	20 passes	8 passes	6 passes
	5 kW output power	7.5 kW output power	10 kW output power



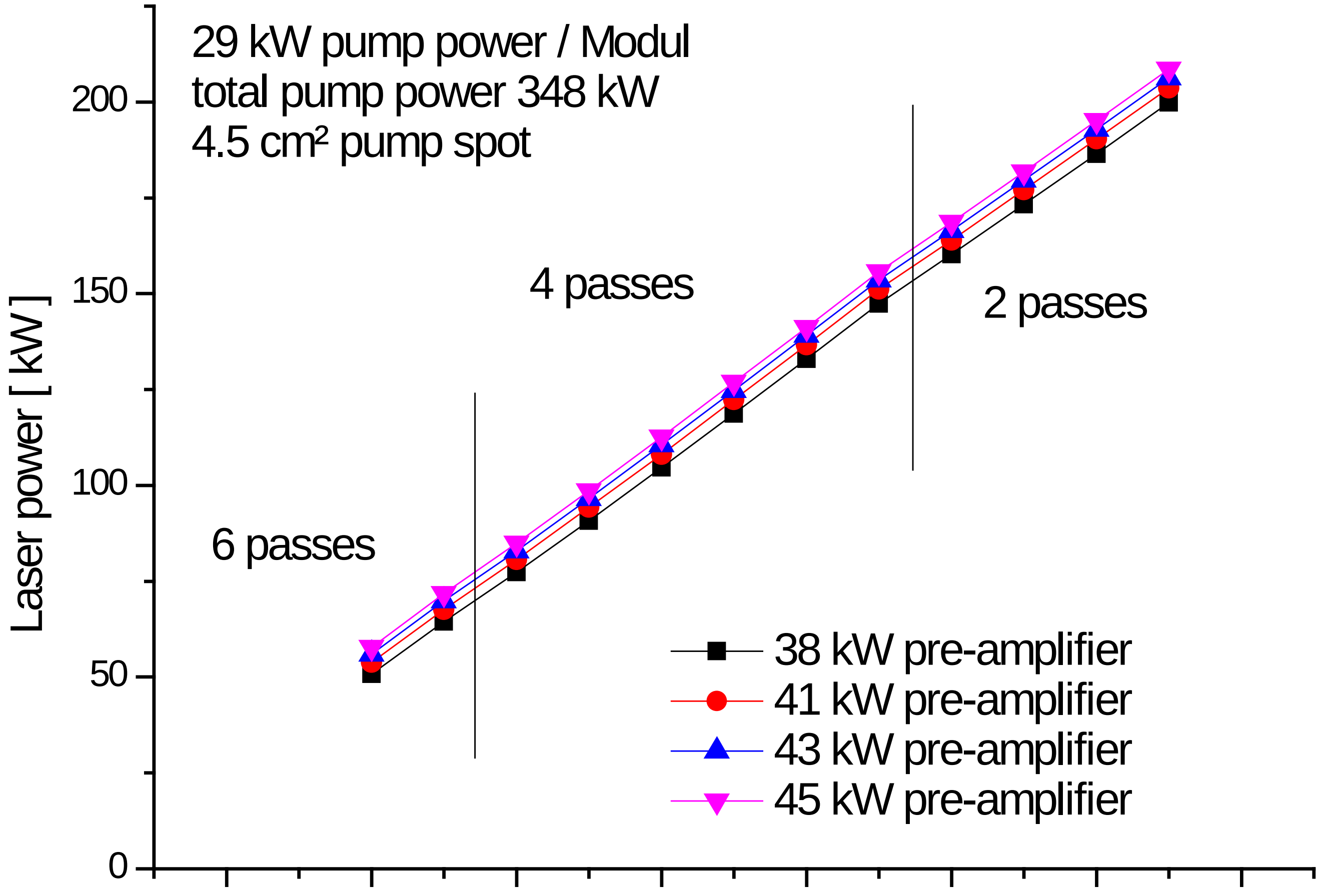
Pump spot diameter, pump power and power densities similar to actual commercially used systems!

new design for high-power Disk module
30 kW pump power, suitable for vacuum
Development of DLR-TP and industrial partner (D+G)

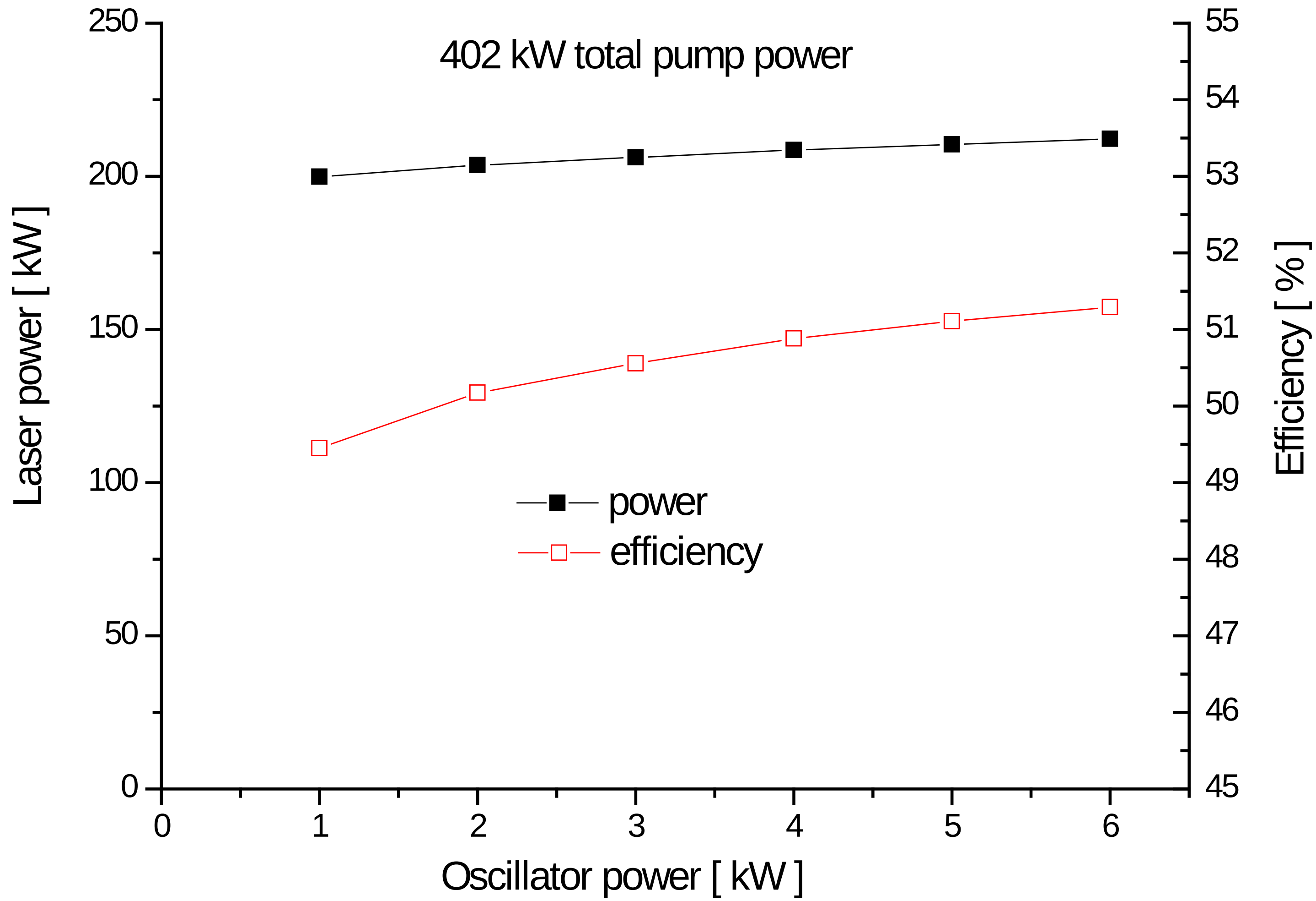
MOPA for 200 kW

- Low power oscillator (~ 2-3 kW laser power)
- Pre-Amplifier with pump & beam size adaption
  - 1 low-power amplifier (~ 6 kW pump power) with high number of multipasses
  - 3 mid power amplifiers with high number of multipasses
- 12 stage Power Amplifier with constant beam size & low number of multipasses

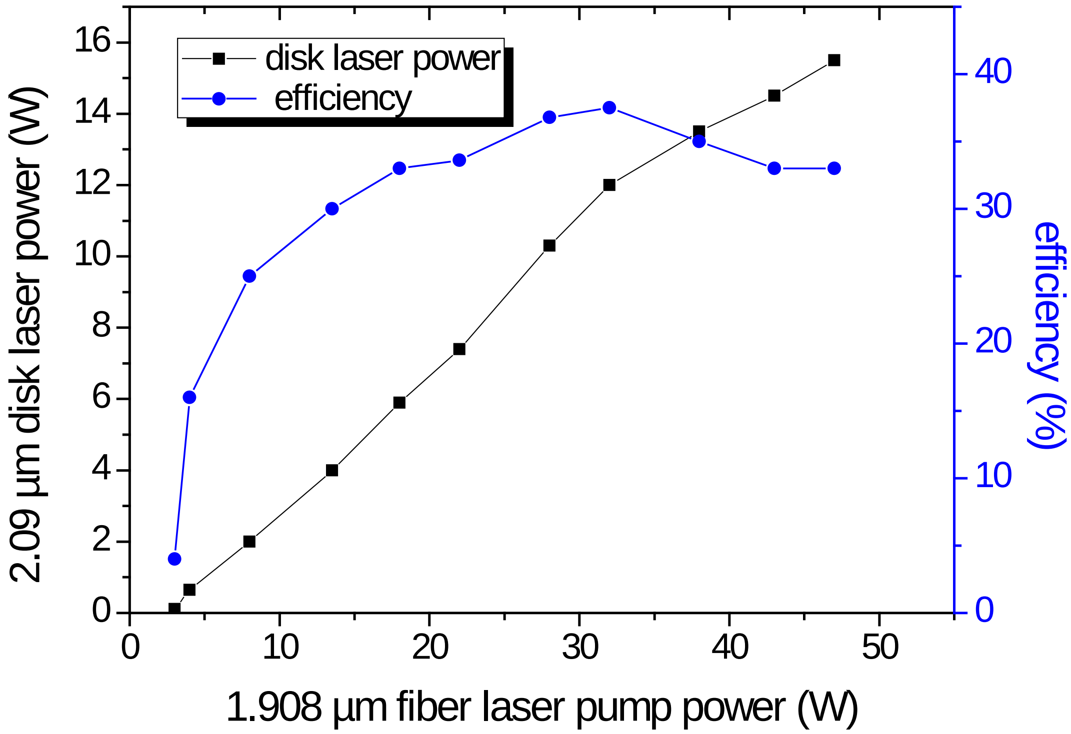
Power amplifier



Preamp + Power amplifier

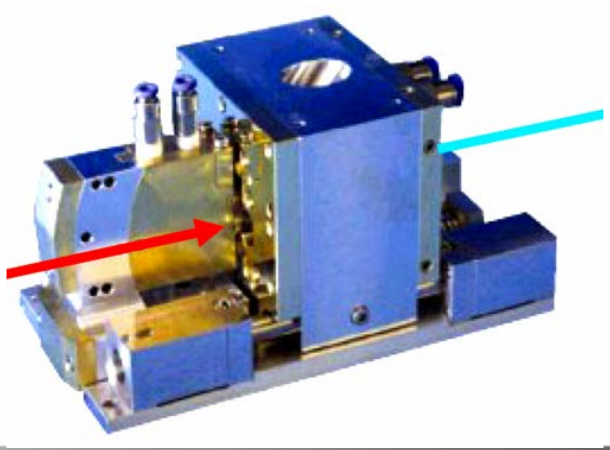


New laser materials for the 2 – 3 µm wavelength range

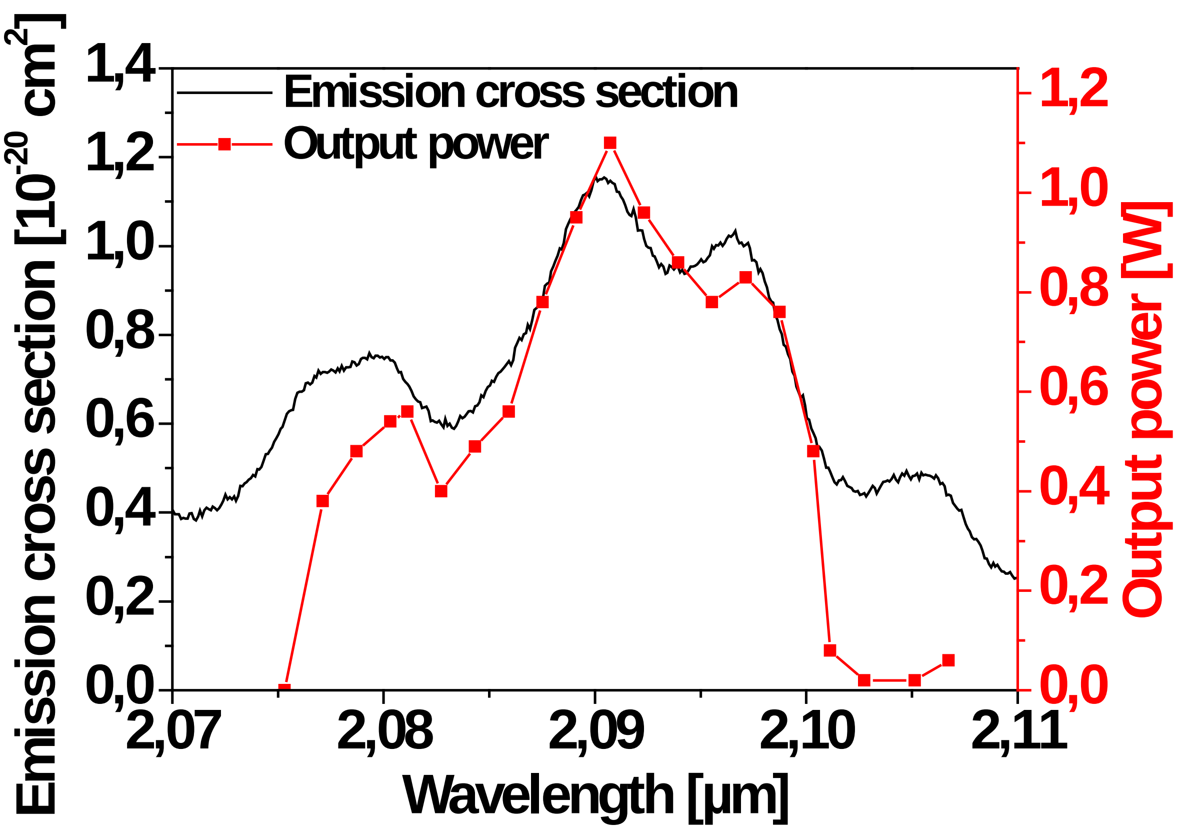


Ho:YAG Thin Disk laser

- Pump source
  50 W Tm-fiberlaser
- Laser output power only limited by available pump power



New laser materials for the 2 – 3 µm wavelength range



Ho:YAG Thin Disk laser

- First low-power experiments
- More than 20 nm tuning range
- Suitable for Standoff / LIDAR applications
- High power operation possible

Scaling limits

- Use "analytical ray tracing" with some simplifications / idealizations and some rough estimations

$$\tau_{ASE} \sim \tau \frac{r_p}{h} \exp\left(-\frac{2r_p}{h} g \right)$$

- Scaling strongly influenced by "thermal load parameter" / "thermal shock parameter" C_{th} and internal loss L_{int}

$$P_{out,\max} \sim {C_{th}}^{2} \cdot {L_{\text{int}}}^{-3}$$

- 570 kW with L_{int}=1%, 22 MW with L_{int}=0.25%, efficiency about 10%

- **1 MW with L_{int}=0.25%, efficiency about 50%**
- **400 J with L_{int}=1%**

- Would benefit from materials with higher thermal conductivity and less heat generation (like $Yb:Lu_2O_3$) or reduced duty cycle

D. Kouznetsov et. al. *Surface loss limit of the power scaling of a thin-disk laser*, J. Opt. Soc. Am. B 23, 1074 (2006)
J. Speiser, *Scaling of Thin Disk Lasers - Influence of Amplified Spontaneous Emission,* JOSA B **26** (2009)

Outlook

- **High power Thin Disk lasers**
  several 100 kW based on actual technology (coating, disk diameter) feasible with good beam quality and high efficiency
- **High energy Thin Disk lasers**
  ~ 5 - 10 J based on actual technology (coating, disk diameter) under construction, scaling towards 100 J feasible
- **Eye-safe Thin Disk lasers**
  High power operation possible
- **Pulse duration**
  nearly arbitrary with MOPA (limited by round-trip time of first amplifier; sub-ps need suitable laser materials)
- **Further energy scaling**
  (Coherent) coupling of several amplifier chains
  ~ kJ possible