Thin-Disc-Based Driver

Jochen Speiser

German Aerospace Center (DLR)
Institute of Technical Physics
Solid State Lasers and Nonlinear Optics

German Aerospace Center

- Research Institution
- Space Agency
- Project Management Agency

6700 employees across 29 research institutes and facilities at

- 13 sites.

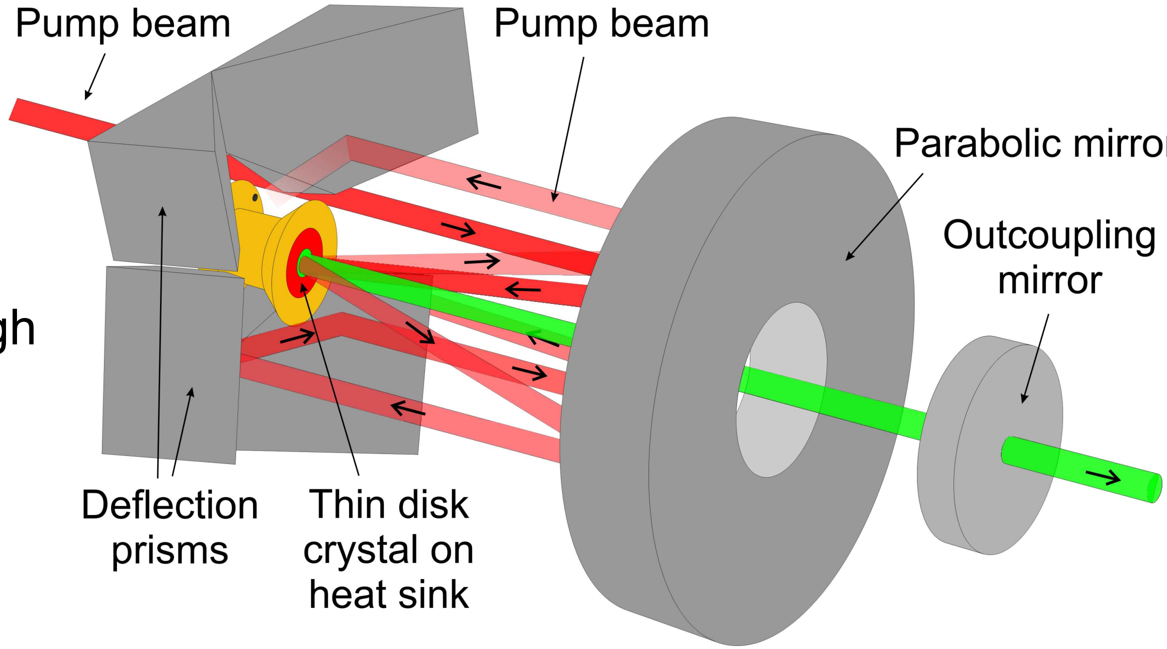
Offices in Brussels, Paris and Washington.

The **Institute of Technical Physics** works in selected fields of optics and photonics. The activities comprise investigations for aerospace as well as contributions to security and defense related topics.

1993 Invention of Thin Disk laser,
together with University of Stuttgart (IFSW)

Thin Disk laser concept

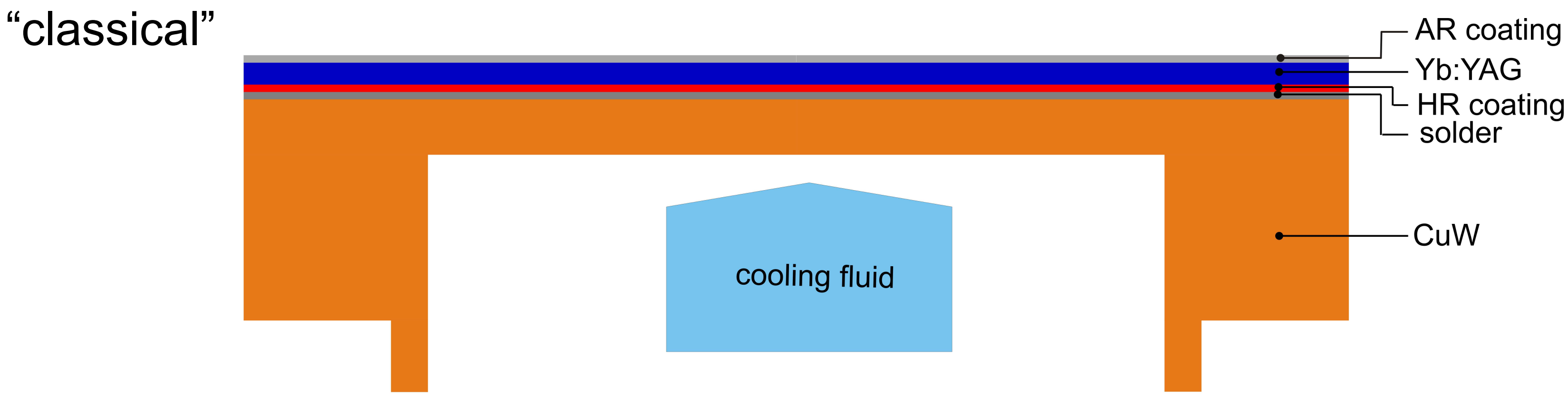
- Efficient cooling
- Heat flow parallel to laser beam
- Minimized thermal lens
- Low reabsorption
- High output power and high efficiency simultaneously
- variety of active materials
- thickness 0.1 – 1 mm
- disk diameter 5 – 45 mm

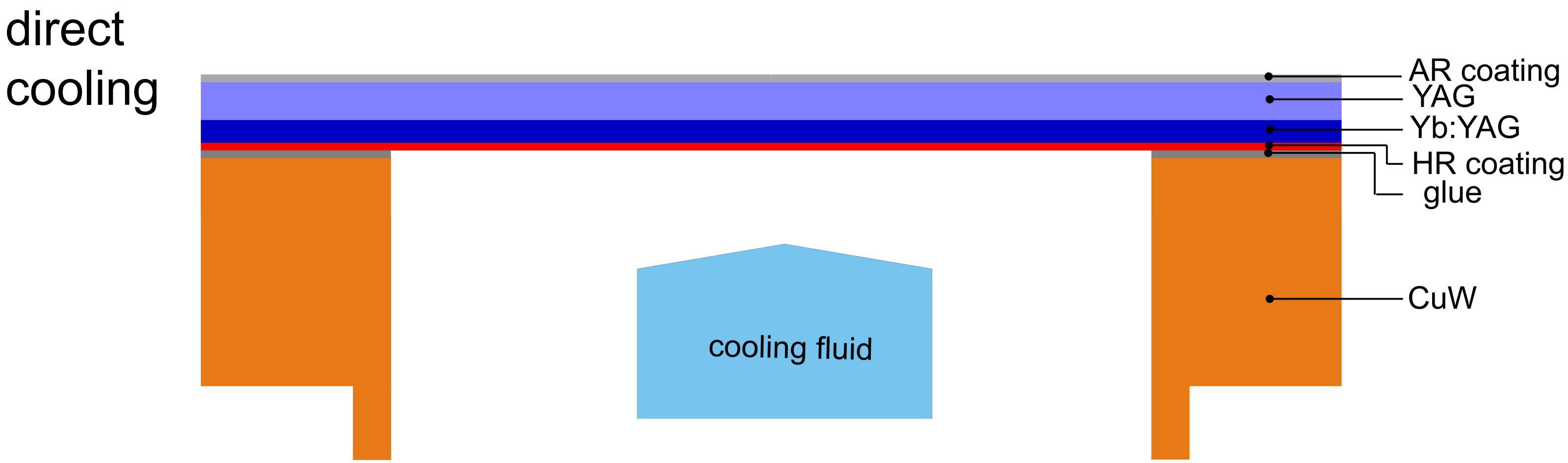


With 1 parabolic mirror and 5 plane mirrors 16 – 32 pump beam passes realized

=> Decoupling of pump absorption and laser reabsorption significantly increases performance of quasi-3-level materials like Yb:YAG

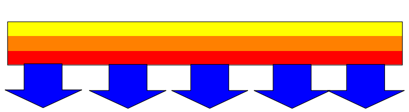
Thin disk laser mounting design





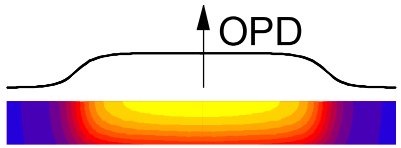
Advantages of the thin disk laser design

Large surface to volume ratio



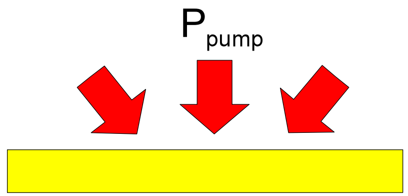
Efficient cooling

Axial heat flow, thin disk



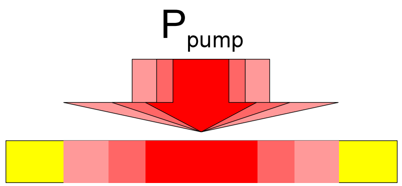
Small thermal lens

Multiple pump beam passes



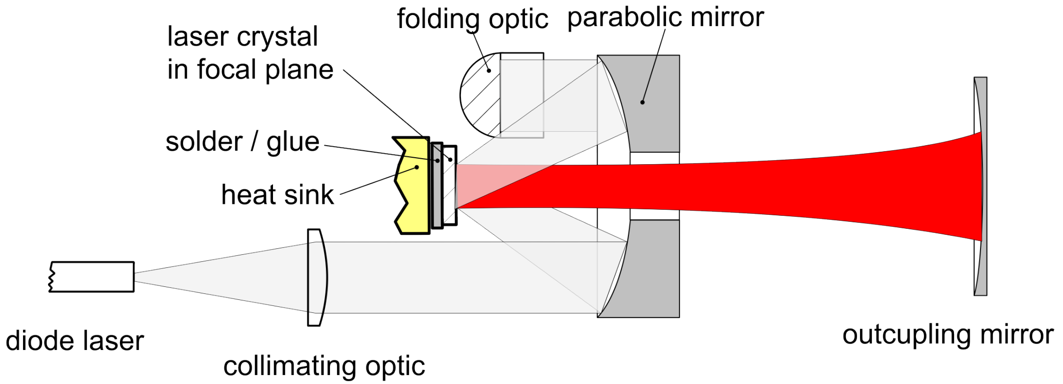
High pump power density,
good pump light absorption
low absorption of laser light

Laser action independent of pumped diameter



Power scalability

Why thin disk?



- Efficient cooling
- Power / **energy scaling by scaling of pump spot area** (power / **energy densities** and temperatures **constant**)
- 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
- High efficiency, good beam quality
- High pulse energies at high average power

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

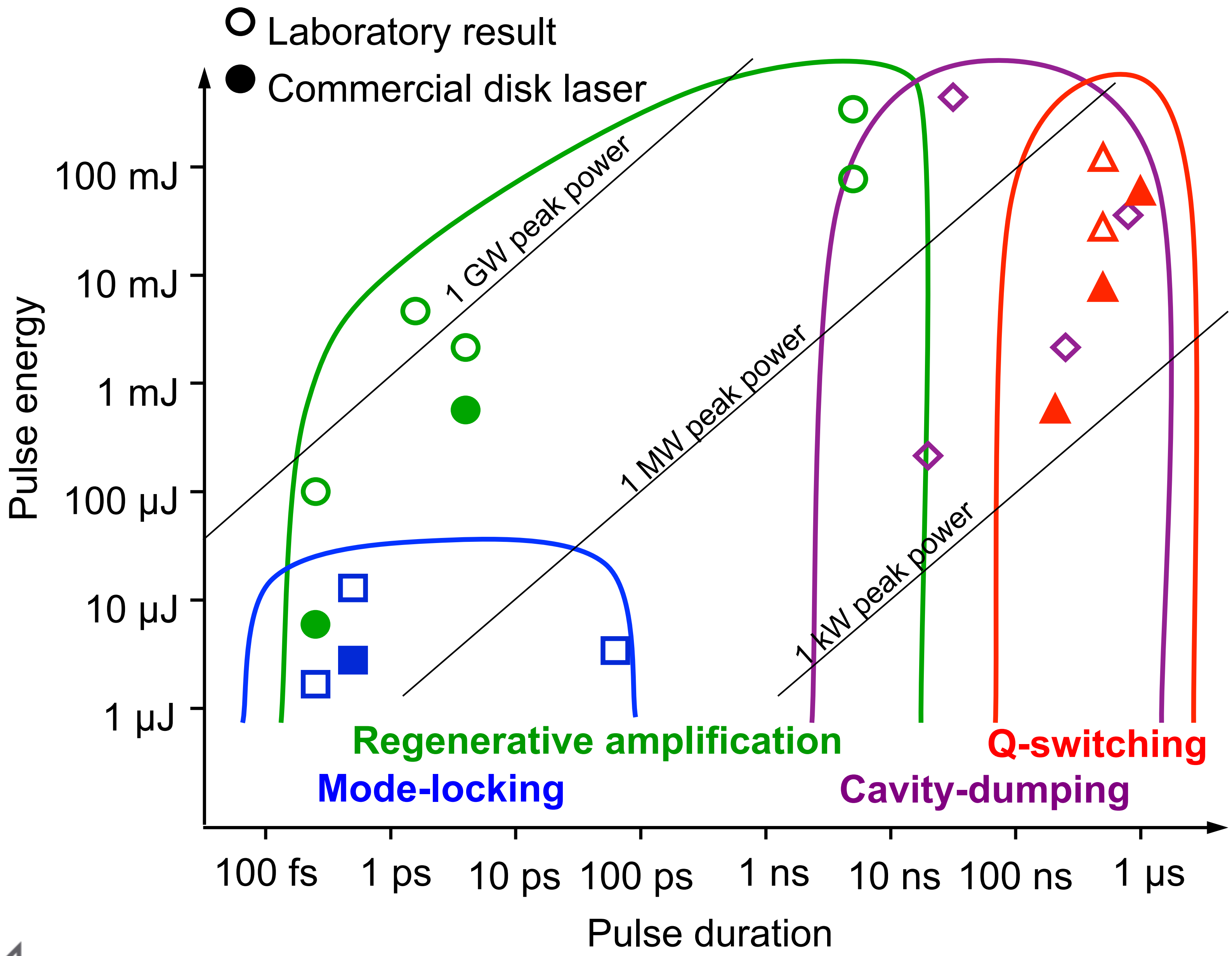
State of the art

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

Laboratory 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”, but no TEM_{00}
  (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)


Laboratory result
Commercial disk laser
Pulse energy
100 mJ
10 mJ
1 mJ
100 µJ
10 µJ
1 µJ
1 GW peak power
1 MW peak power
1 kW peak power
Regenerative amplification
Mode-locking
Q-switching
Cavity-dumping
100 fs
1 ps
10 ps
100 ps
1 ns
10 ns
100 ns
1 µs
Pulse duration

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), now ~ 500 mJ reached

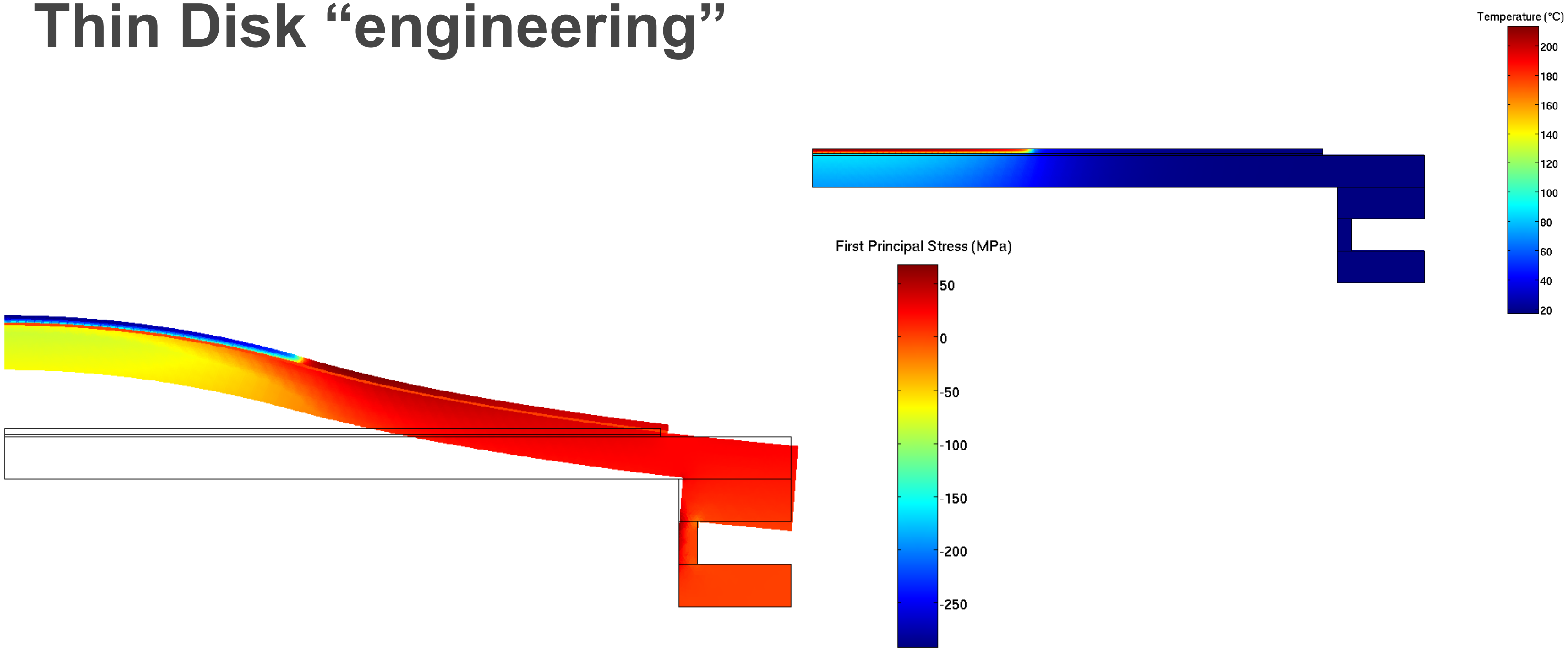
MPQ Garching

- 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

Thin Disk "engineering"



Thermal & mechanical modeling

- e.g. optimization of cooling design
- stress compensation by heat sink
- thermal lens

Numerical modeling – gain, extractable energy

$$\dot{N}_2 = Q - \frac{N_2}{\tau}$$ equation of motion

$$Q = \frac{E_p \lambda_p}{2\pi\hbar c_{vac}} \frac{\left(1 - \exp\left(-\alpha h M_p\right)\right)}{h}$$ pump source

with $\alpha = \sigma_{abs}(T) N_0 - \sigma_{abs}(T)\left(1 + f_{em}(T)\right) N_2$ absorption coefficient

$$g = h\left(\sigma_{em,laser}\left(1 + f_{abs,laser}\right) N_2 - \sigma_{em,laser} f_{abs,laser} N_0\right)$$ gain

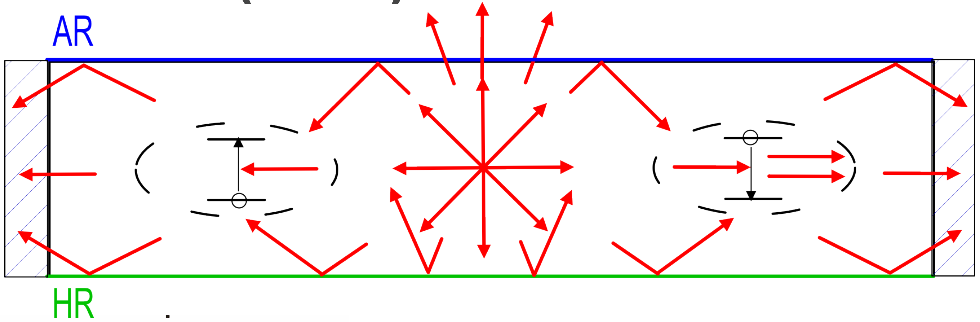
$$H_{extractable} = \frac{2\pi\hbar c_{vac}}{\lambda_{laser}} h\left(\left(1 + f_{abs,laser}\right) N_2 - f_{abs,laser} N_0\right)$$ extractable energy

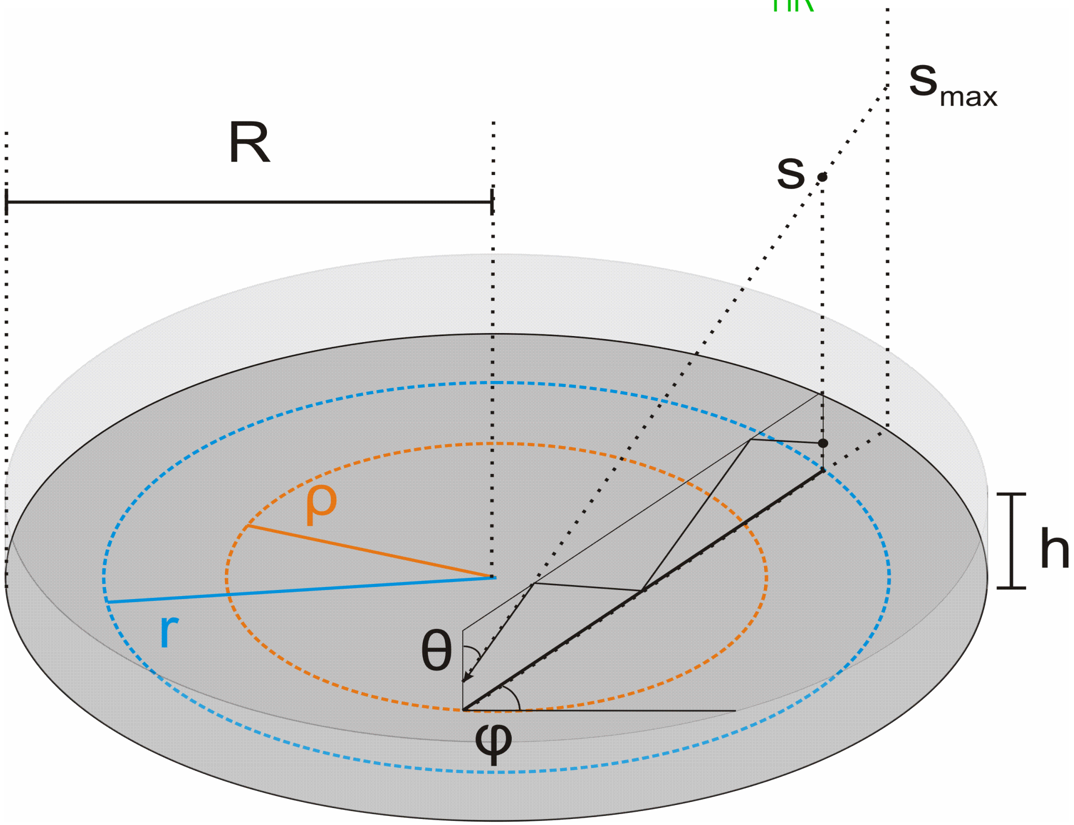
Formulas account for bleaching and quasi-3-level structure!

Amplified spontaneous emission (ASE)

"analytical ray tracing"

$$\dot{N}_2 = W_{pump} + W_{laser} - \frac{N_2}{\tau} + W_{ASE}$$





Irradiation by amplified spontaneous emission

$$\dot{N}_2 = Q - \frac{N_2}{\tau} - \int\int \gamma_\lambda \Phi_{\lambda,\Omega} d\lambda d\Omega$$

Modified equation of motion

$$d\Phi_\lambda(\vec{s}) = \beta_\lambda \frac{N_2(\vec{s})}{\tau} \frac{1}{4\pi s^2} g_\lambda(\vec{s}) dV$$

Photon flux density from a volume element at position $\vec{s}$

$$g_\lambda(\vec{s}) = \exp\left(\int_0^s \gamma_\lambda(\tilde{s}\hat{s}) d\tilde{s} \right)$$

amplification

with $\gamma_\lambda = \sigma_{em}(\lambda,T)(1 + f_{abs}(\lambda,T))N_2 - \sigma_{em}(\lambda,T) f_{abs}(\lambda,T) N_0$

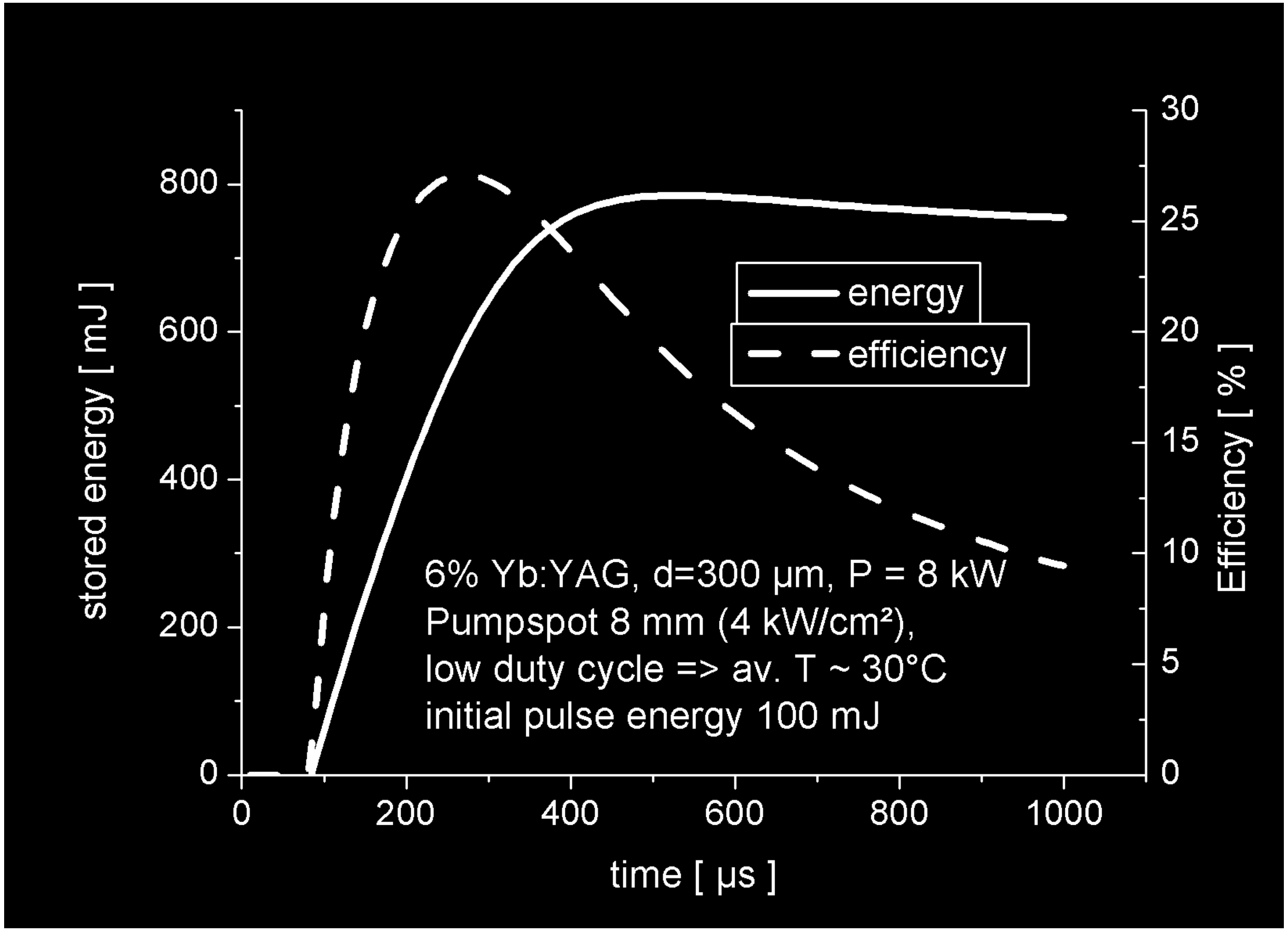
$$\Phi_{\lambda,\Omega} = \int_0^{s_{max}} d\Phi_\lambda(\vec{s})$$

Photon flux density from direction $\hat{s}$

Transformed to spherical coordinates:

$$\Phi_\lambda(\varphi,\vartheta) = \sin\vartheta d\vartheta d\varphi \frac{\beta_\lambda}{4\pi\tau} \int_0^{s_{max}} N_2(s,\varphi,\vartheta) g_\lambda(s,\varphi,\vartheta) ds$$

Calculation Multipass

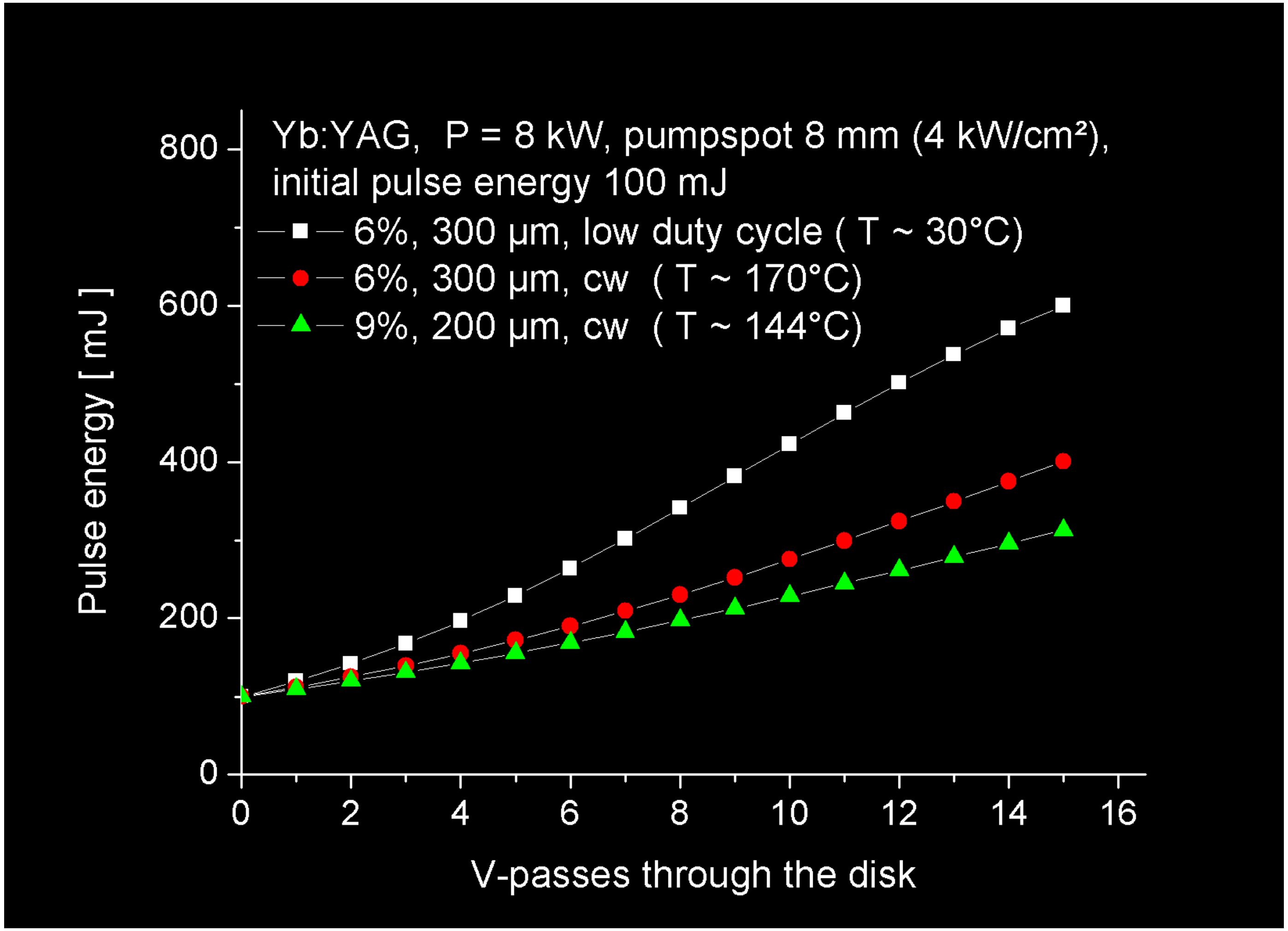


Time resolved model

- 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

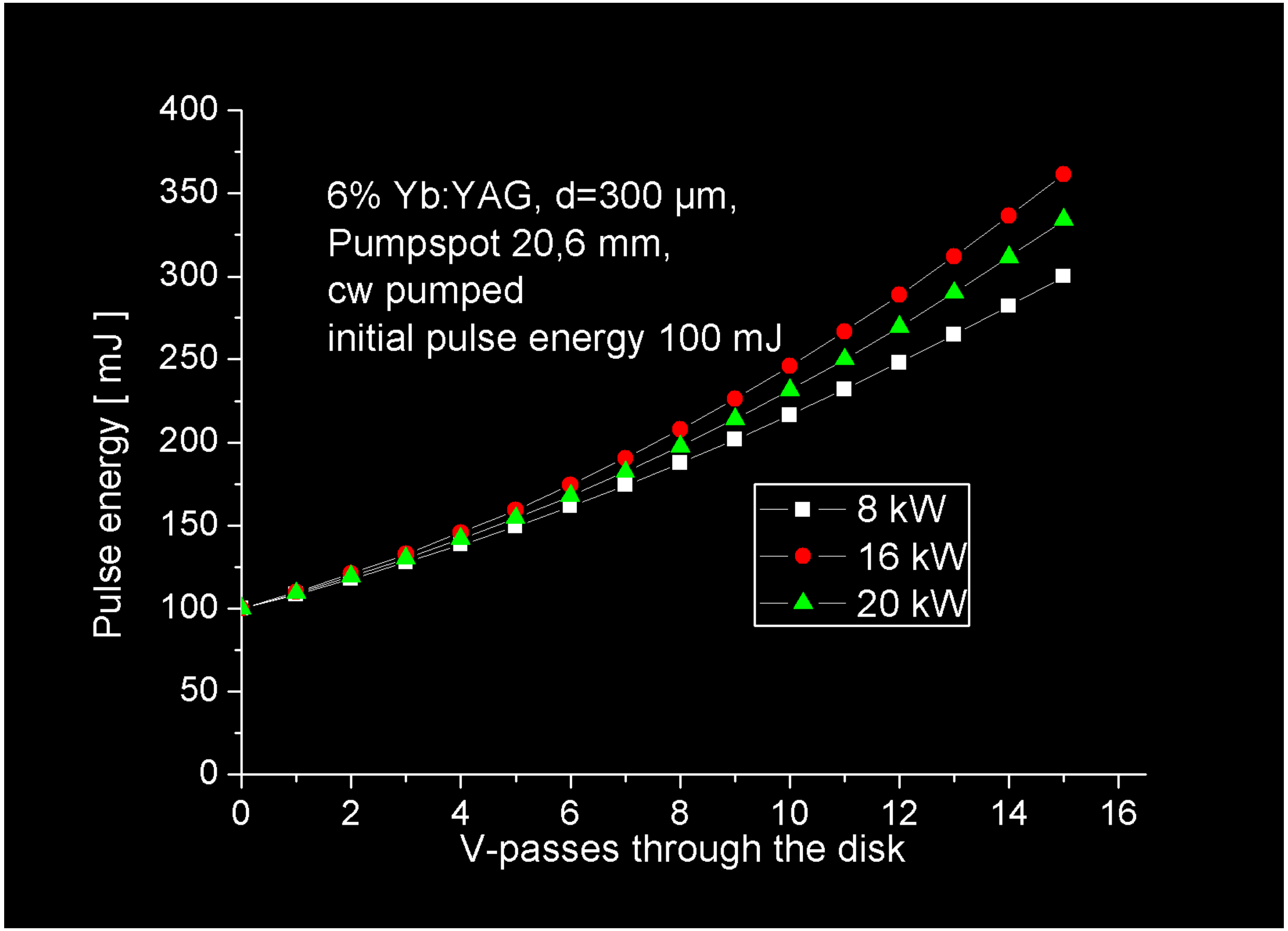
Calculation Multipass



Energy extraction based on *Lowdermilk, Murray, J. App. Phys. 51(6), 2436 (1980)*, initial pulse energy 100 mJ

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

Calculation Multipass



Increase 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

Scaling limits

Analytical considerations

- D. Kouznetsov et. al. *Surface loss limit of the power scaling of a thin-disk laser*, J. Opt. Soc. Am. B **23**, 1074 (2006)

$$\dot{N}_2 = W_{pump} + W_{laser} - \frac{N_2}{\tau}\exp\left(\frac{2R}{h}g\right) \qquad \tau_{ASE} = \tau\exp\left(-\frac{2R}{h}g\right)$$

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

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

- D. Kouznetsov, J. -F. Bisson, *Role of undoped cap in the scaling of thin-disk lasers*, J. Opt. Soc. Am. B **25**, 338 (2008)

$$\dot{N}_2 = W_{pump} + W_{laser} - \frac{N_2}{\tau}\left(1 + \frac{h}{2R}\exp\left(\frac{2R}{h}g\right)\right)$$

Scaling limits

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

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

- 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

J. Speiser, *Scaling of Thin Disk Lasers - Influence of Amplified Spontaneous Emission,* JOSA B **26** (2009)

Possible next stages based on space debris ranging laser concept

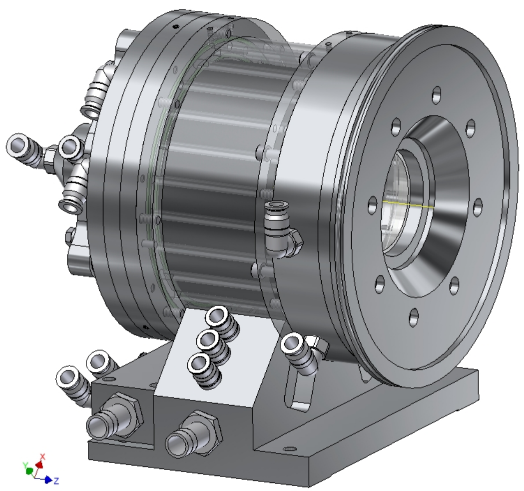
regenerative amplifier → 300 mJ, 1kHz → multipass amplifier → 2J, 1kHz → multipass amplifier → 4J, 1kHz

2 thin disk laser heads, 2 x 16 kW pump power 22 V-passes through each disk	2 thin disk laser heads, 2 x 16 kW pump power 8 V-passes through each disk

higher repetition rates:

- adapt the number of amplification passes

- add some additional mutipass moduls



new design for high-power Disk module

> 30 kW pump power, suitable for vacuum

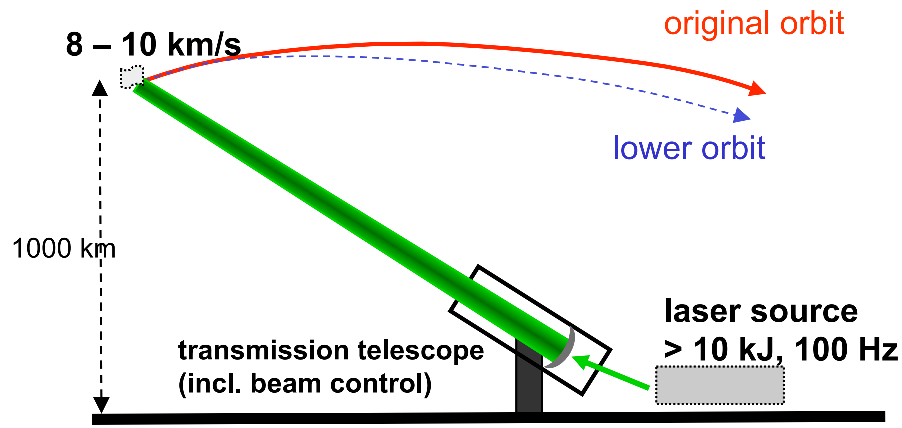
Development of DLR-TP and industrial partner

Pulsed Thin Disk MOPA with high energy (1 J – kJ) and high average power (1 kW – 100 kW)

master oscillator → regenerative amplifier → multipass amplifier → • • • multipass amplifier →

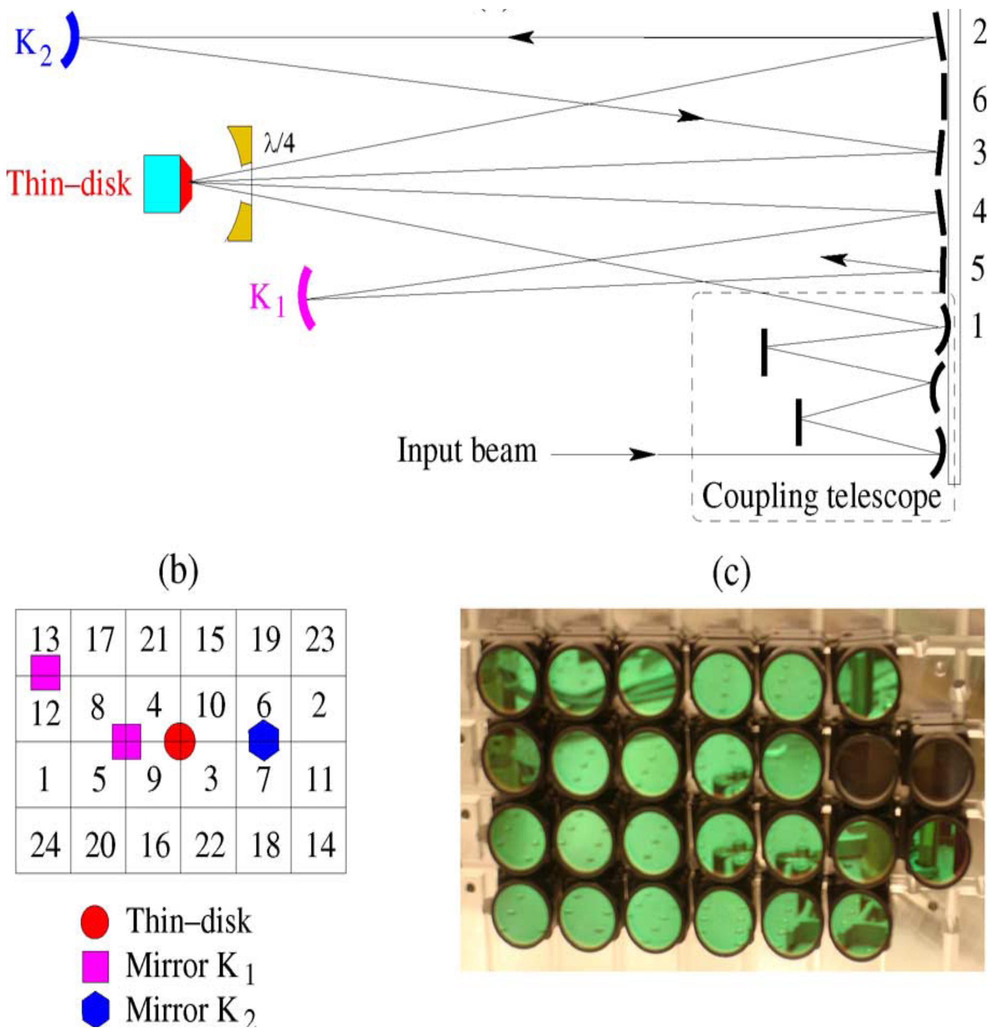
- Based on competence in high power cw Thin Disk lasers

- Application: Laser for ranging of space debris and
- De-Orbiting of space debris (longterm)



- **ORION draft: Clearing near-Earth space debris in two years using a 30-kW repetitively-pulsed laser**

"Established" technique for multipass

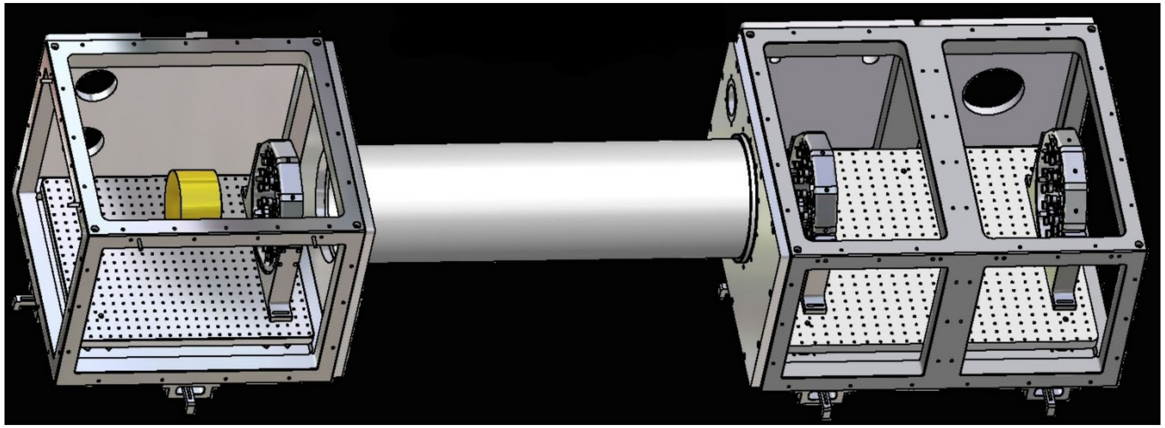


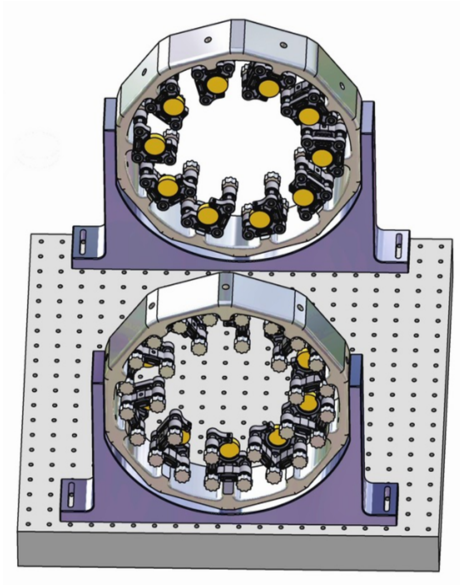
A. Antognini et al,

Thin-Disk Yb:YAG Oscillator-Amplifier Laser, ASE, and Effective Yb:YAG Lifetime

IEEE JQE, vol. 45, no. 8, (2009)

"Rotational" multipass
using relay-imaging





LMU
LUDWIG-
MAXIMILIANS-
UNIVERSITÄT
MÜNCHEN

“Technical” limitations

Pulse duration

- Gain spectra of Yb:YAG only suitable for few ps
- Promising, already tested*) alternative: $Yb:Lu_2O_3$
  ~ 300 fs, high power oscillator
- With some limitations: Yb:CaF
- other materials …

Damage threshold of coating

- Actually used coatings ~ 1 J/cm^2 for ~ ns pulse durations
- Increasing size of active area: limited by ASE effects
- > 10 J/cm^2 possible, Thin Disk requirements to be tested
- Alternative: coherent coupling of several Thin Disk amplifier chains

*) Südmeyer et al “High-power ultrafast thin-disc laser oscillators and their potential for sub-100-femtosecond pulse generation,” Applied Physics B, 97 (2): 281-295, 2009

Outlook

- **High energy Thin Disk laser**
  ~ 5 - 10 J based on actual technology (coating, disk diameter)
  scaling towards 100 J feasible
- **Pulse duration**
  Depends on suitable laser materials
- **Repetition rate**
  10 kHz and more possible with additional amplifier stages
- **Lower repetition rate / duty cycle (< 100 Hz)**
  More design flexibility (e.g. thickness) for ASE reduction
  Scaling much simpler
- **Further energy scaling**
  (Coherent) coupling of several amplifier chains
  ~ kJ possible

Numerical modeling
Equation of motion of excitation

$$\dot{N}_2 = Q - \frac{N_2}{\tau}$$ equation of motion

$$Q = \frac{E_p \lambda_p}{2\pi\hbar c_{vac}} \frac{\left(1 - \exp\left(-\alpha h M_p\right)\right)}{h}$$ pump source

with $$\alpha = \sigma_{abs}(T) N_0 - \sigma_{abs}(T)\left(1 + f_{em}(T)\right) N_2$$ absorption coefficient

$\sigma_{abs}(T)$	absorption cross section at pump wavelength
$f_{em}(T)$	ratio of emission to absorption cross section
N_0	density of active ions
h	crystal thickness
M_p	number of pump beam passes

Formulas account for bleaching and quasi-3-level structure!

Numerical modeling
Gain and extractable energy

calculate **gain**

$$g = h\left(\sigma_{em,laser}\left(1 + f_{abs,laser}\right)N_2 - \sigma_{em,laser} f_{abs,laser} N_0\right)$$

or extractable **energy** density per area

$$H_{extractable} = \frac{2\pi\hbar c_{vac}}{\lambda_{laser}} h\left(\left(1 + f_{abs,laser}\right)N_2 - f_{abs,laser} N_0\right)$$

with

$\sigma_{em,laser}$	emission cross section at laser wavelength (temperature-dependent)
$f_{abs,laser}$	ratio of absorption to emission cross section (temperature-dependent)

Extracable Energy

Table 4. Results of energy optimization

thermal loading parameter C [W/mm]	10	10	10	10
absorption with 24 passes [%]	80	80	80	20
single pass absorption $1-t$ [%]	6.49	6.49	6.49	0.93
internal losses β [%]	0.25	1	4	1
opt. double pass gain $2g$ [%]	0.39	1.42	5.24	1.32
reduced lifetime τ_{ASE} [μs]	722	627	482	634
max. ASE amp. $\exp(2\xi g)$	337	107	38	114
opt. doping concentr. N_0 [%]	0.23	0.36	1.04	0.03
optimized thickness h [mm]	3.43	2.23	0.89	5.48
optimized radius R [mm]	5118	734	61.5	1964
pump power P [MW]	300	9.48	0.17	111
extractable energy Q_{ex} [J]	6457	398	8.3	2172