History, principles and prospects of thin-disk lasers

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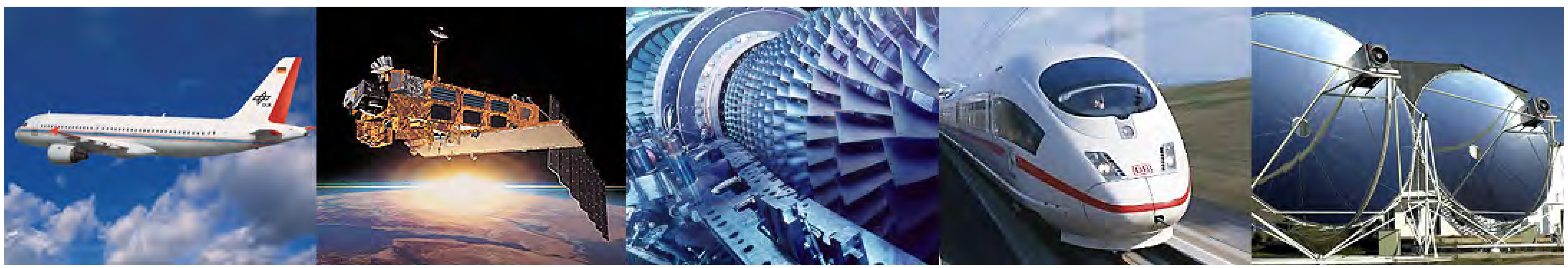


- Research Institution
- Space Agency
- Project Management Agency

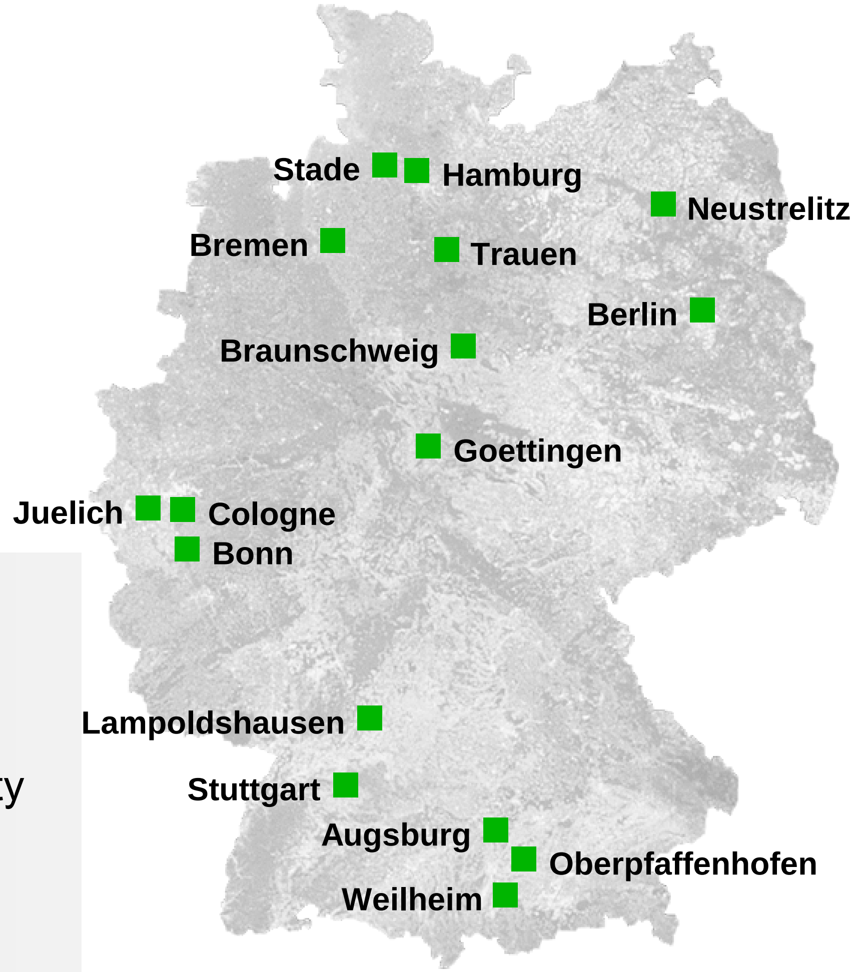
Locations and employees

Approx. 8000 employees across 33 institutes and facilities at

- 16 sites.

Offices in Brussels, Paris,

Tokyo and Washington.



The **Institute of Technical Physics** works in selected fields of optics, lasers and laser systems. 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)

Outline

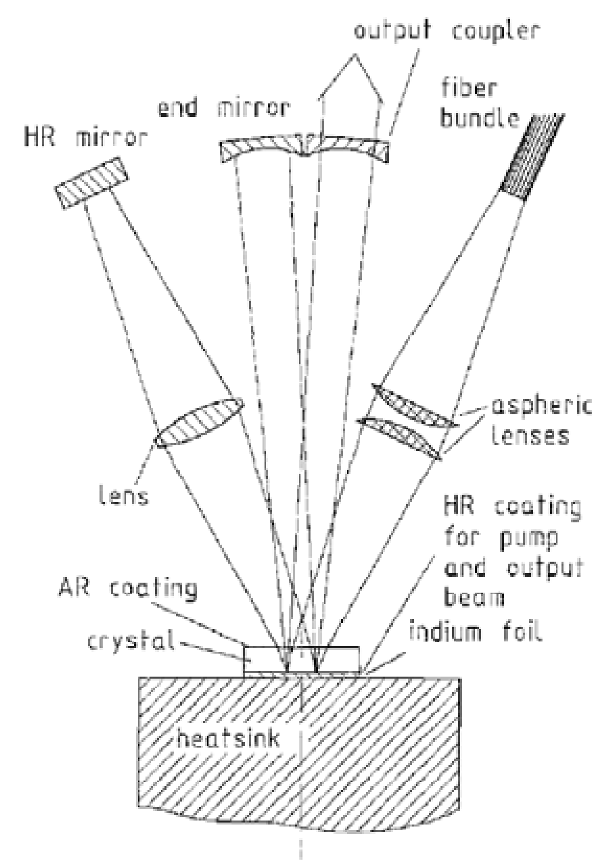
- Thin Disk laser concept & historical development
- Technical realization and scaling (mostly cw)
- Pulsed Thin Disk lasers
- High energy / high power concepts
- Thin disk modeling / challenges
- Scaling limits
- Speculative trends

Thin Disk laser concept

- Yb:YAG – small quantum defect, long lifetime, broad absorption, but thermal population of lower laser level
- Challenge: Efficient heat removal at high power densities to operate Yb:YAG without cryo-cooling
- Solution: thin layer of active material, one face cooled

Thin Disk Laser

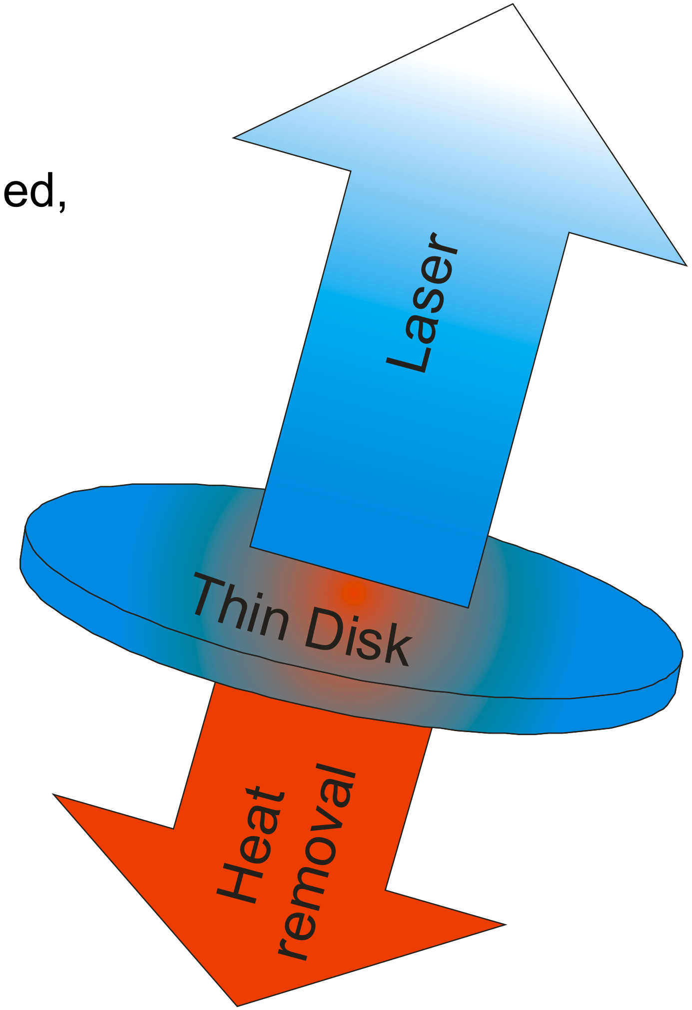
- A. Giesen et al., *Scalable Concept for Diode-Pumped High-Power Solid-State Lasers*, Appl. Physics B **58** (1994), p. 365



9% Yb:YAG, 300 µm thick, 0.95 mm pump spot diameter – 2 W output power

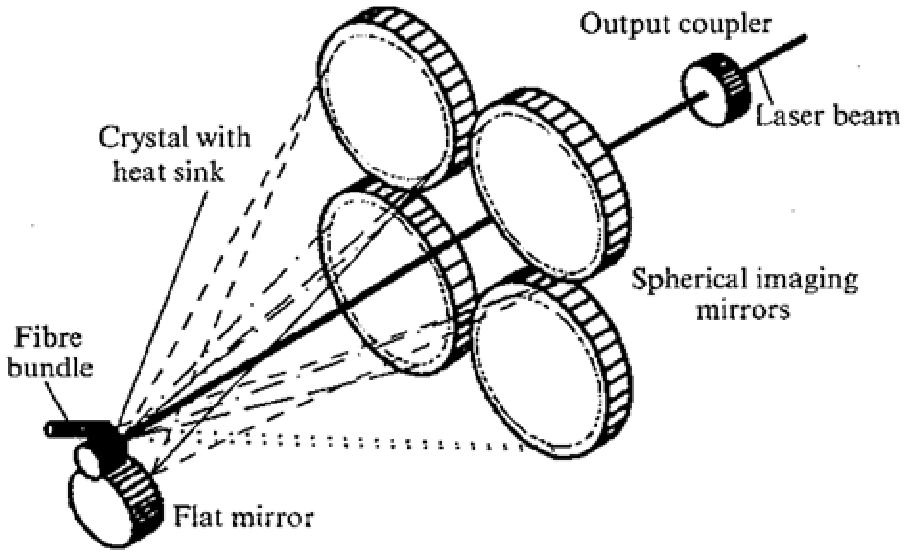
Thin Disk laser concept

- 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)
- Moderate intensities



Thin Disk laser concept

- High-doped material less preferable, “thin” disk
- Small pump absorption in single pass – re-use not absorbed pump power (multiple passes)
- Benefit: Decoupling of pump absorption and laser reabsorption
- More passes: higher efficiency – similar efficiency with 16 passes and 15°C cooling temperature as 8 passes with -25°C *

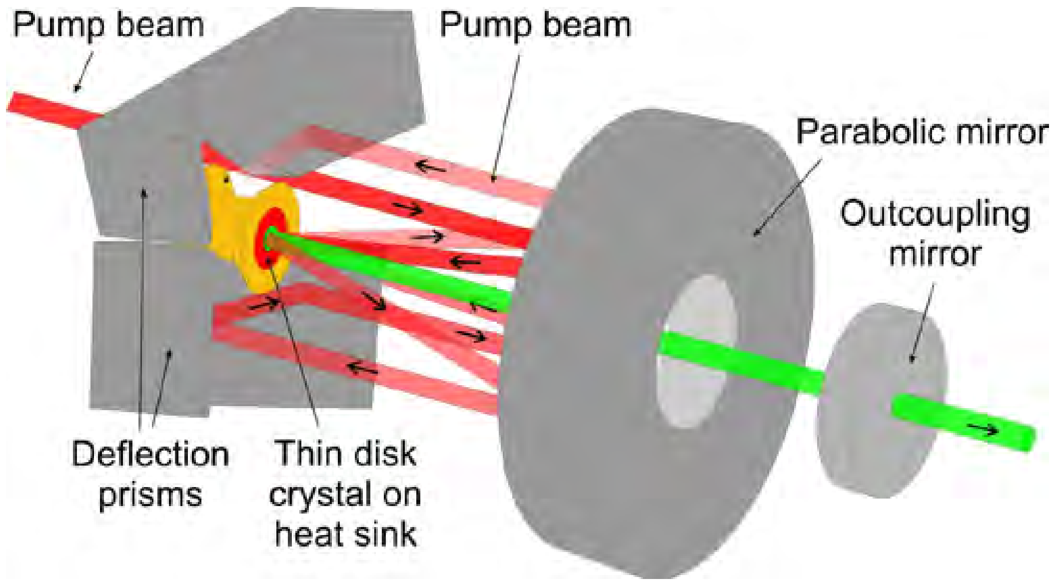


“historical” 8 pass pump setup (IFSW, Univ. Stuttgart)

* Contag et al., *Theoretical modeling and experimental investigations of the diode-pumped thin-disc Yb:YAG laser*, Quantum Electronics **29** (1999), No. 8, p. 697.

Thin Disk laser concept

- Simple setup to re-use not absorbed pump power
- With 1 parabolic mirror and 5 plane mirrors 16 – 32 pump beam passes realized
- Relay-imaging to keep beam divergence constant



courtesy Institute of Laser Physics, University of Hamburg

- 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 – early developments

- M. Karszewski et al., *100 W TEM_{00} Operation of Yb:YAG Thin Disc Laser with High Efficiency*, Advanced Solid State Lasers, Optical Society of America, (1998)
- C. Stewen, et al., *A 1-kW CW thin disc laser*, IEEE JSTQE **6** (2000)

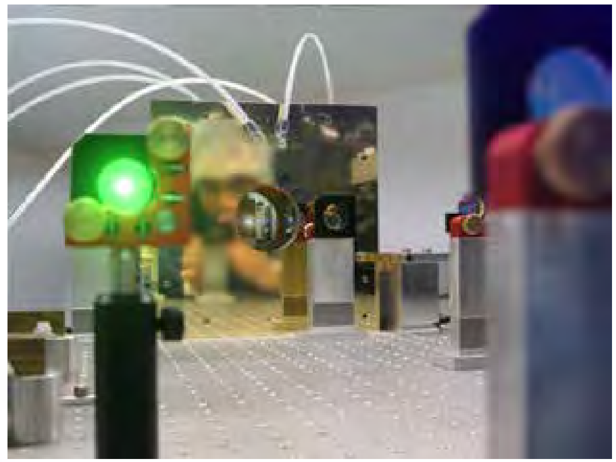
First commercial products

- 10 W Nd:YVO thin disk laser in 1997 (Jenoptik)
- 1 kW Yb:YAG thin disk laser in 2001 (Trumpf)

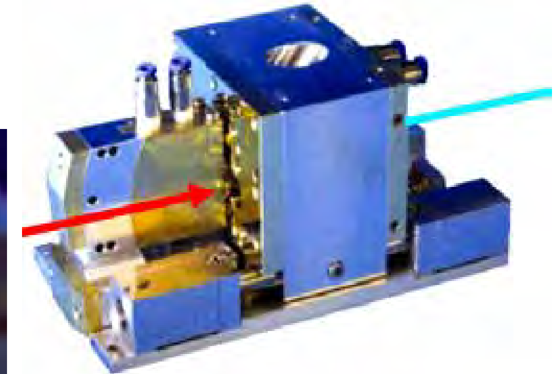
Development mostly driven by industrial material processing

Thin Disk laser – technical realization

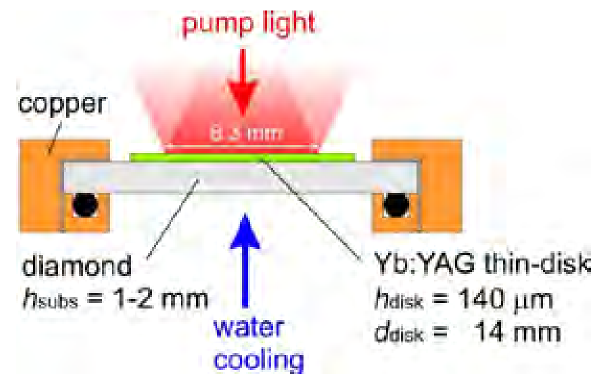
medium power disk (> 500 W)



medium power Thin Disk pump module in operation



low power Thin Disk pump module



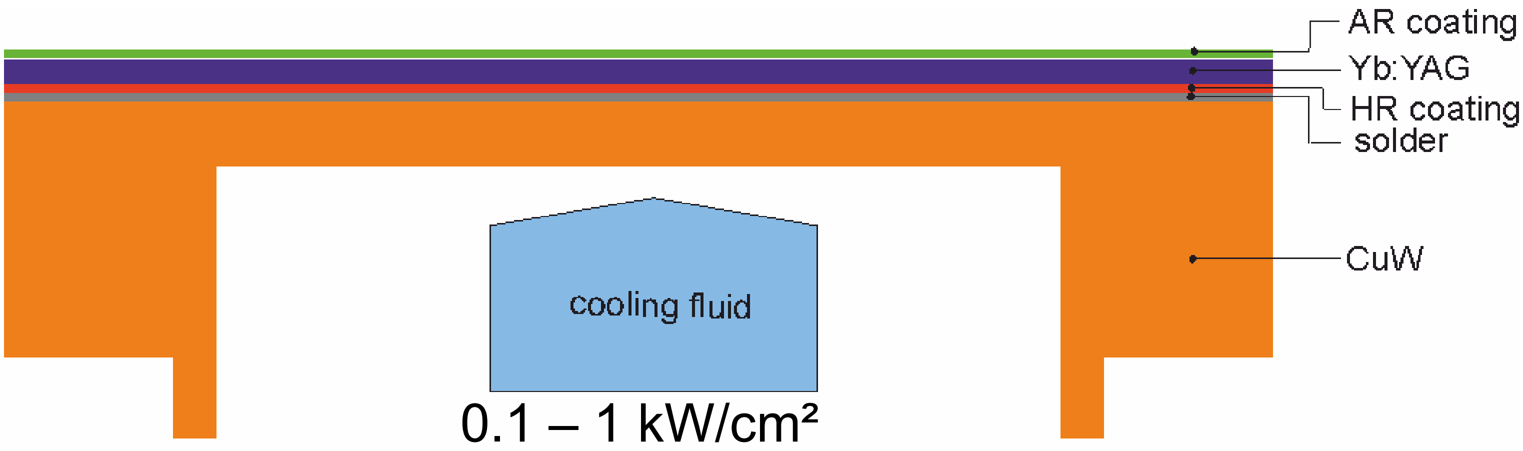
new design for high-power Disk module

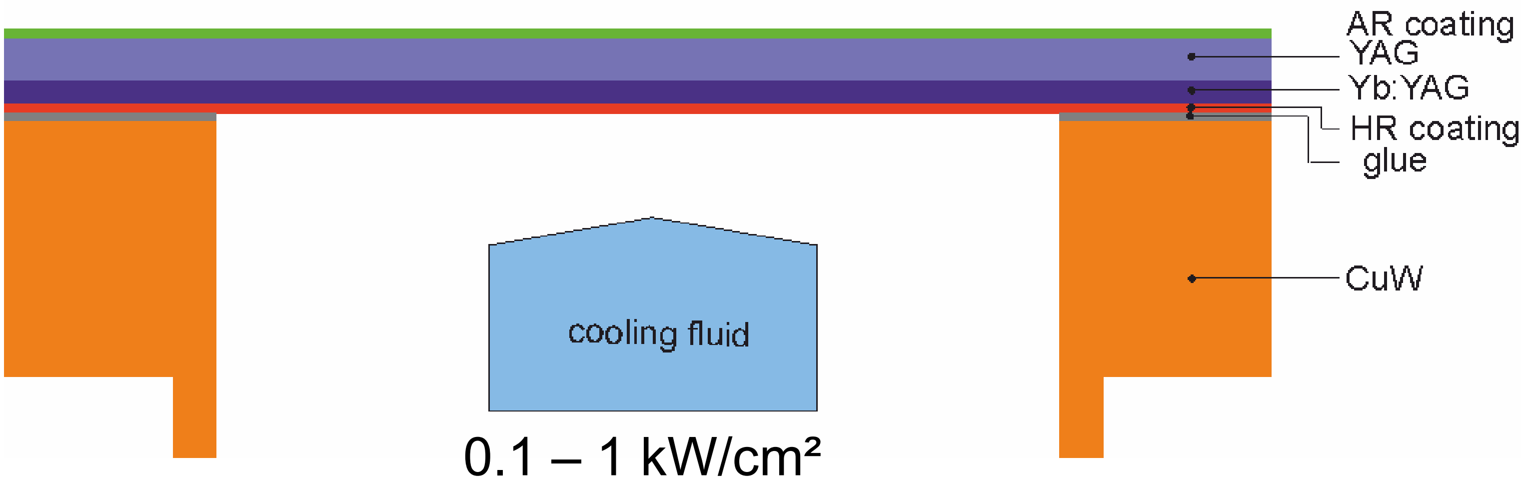
> 30 kW pump power, suitable for vacuum

Development of DLR-TP and industrial partner (Dausinger + Giesen GmbH)

Thin Disk engineering

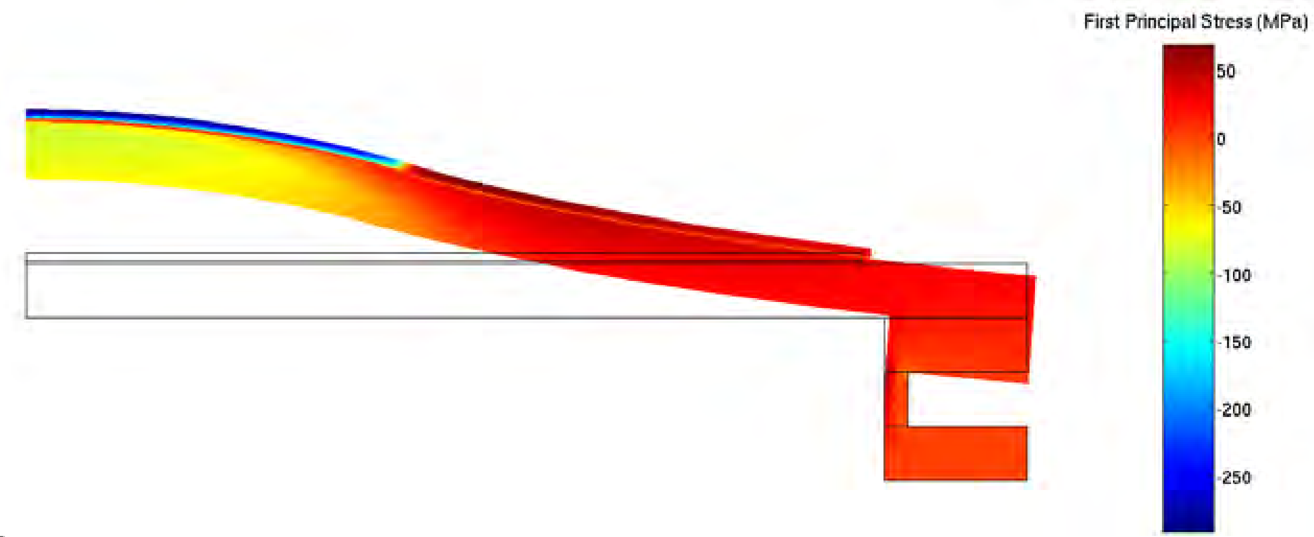
“classical” or directly cooled composite disk?





Thin Disk engineering
Thermo-mechanical modeling with commercial FEM

- e.g. optimization of cooling design
- stress compensation by heat sink
- thermal lens – deformation, thermal expansion, change of refractive index



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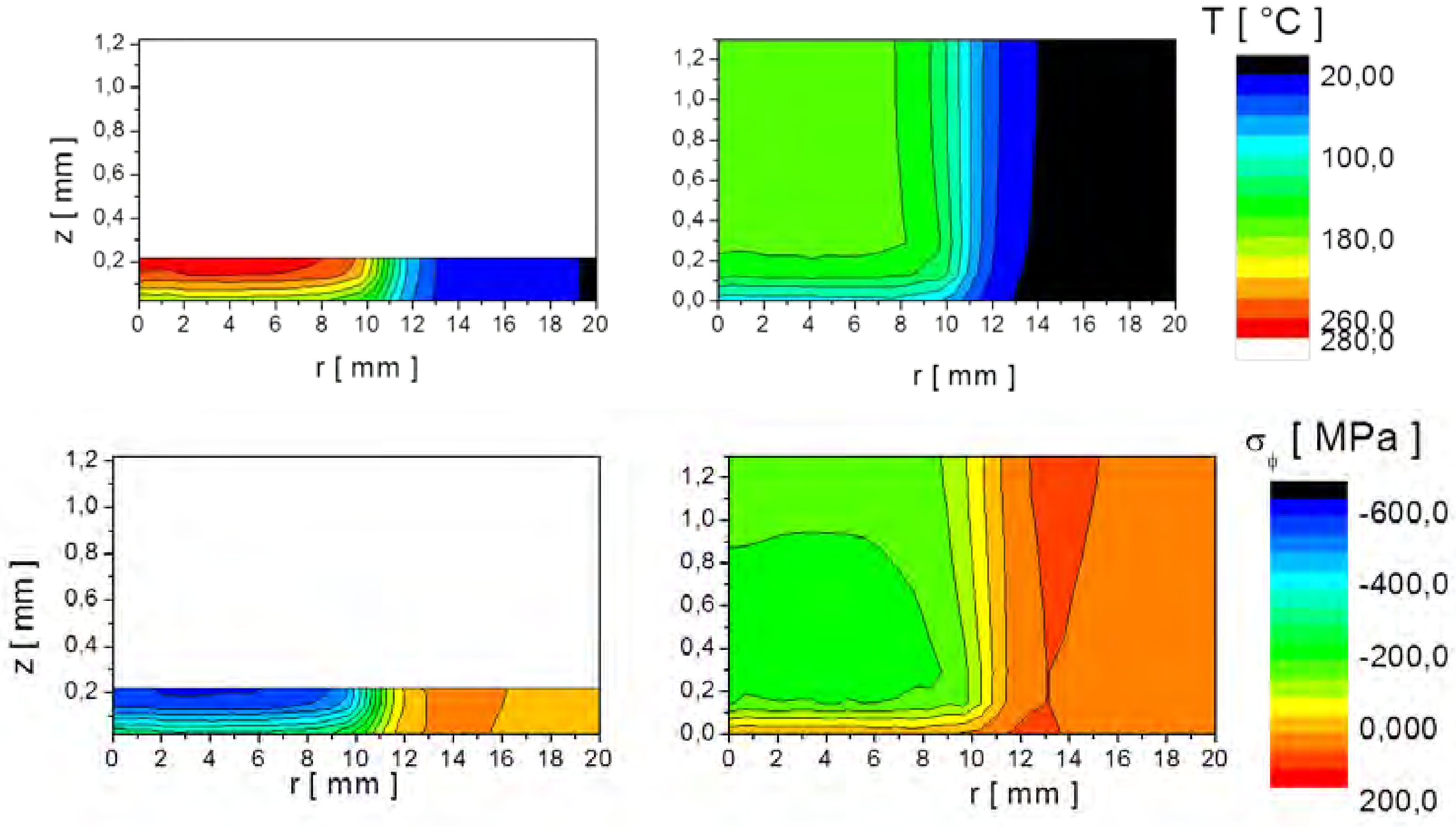
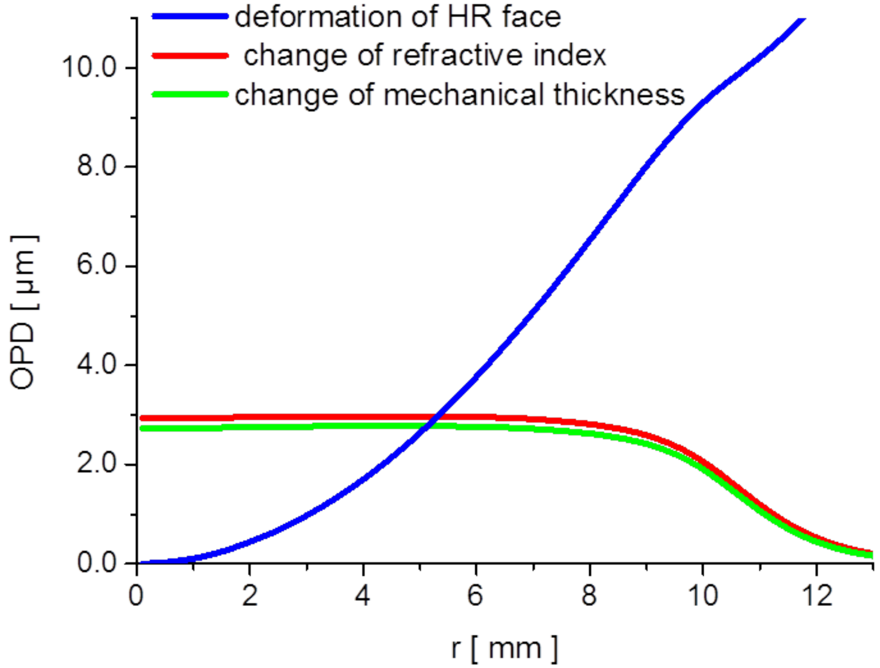
Temperature and azimuthal stress
pump power 25 kW, laser output power 14 kW



DLR

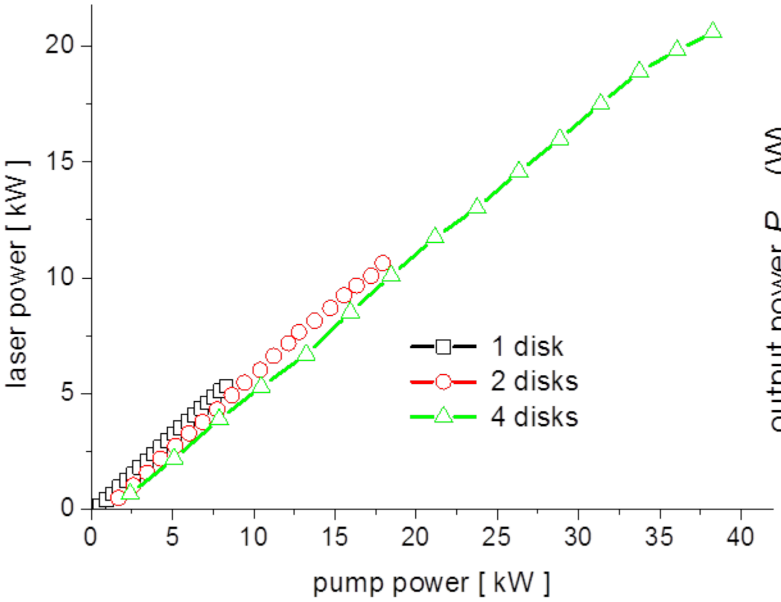
Thermally induced phase distortions

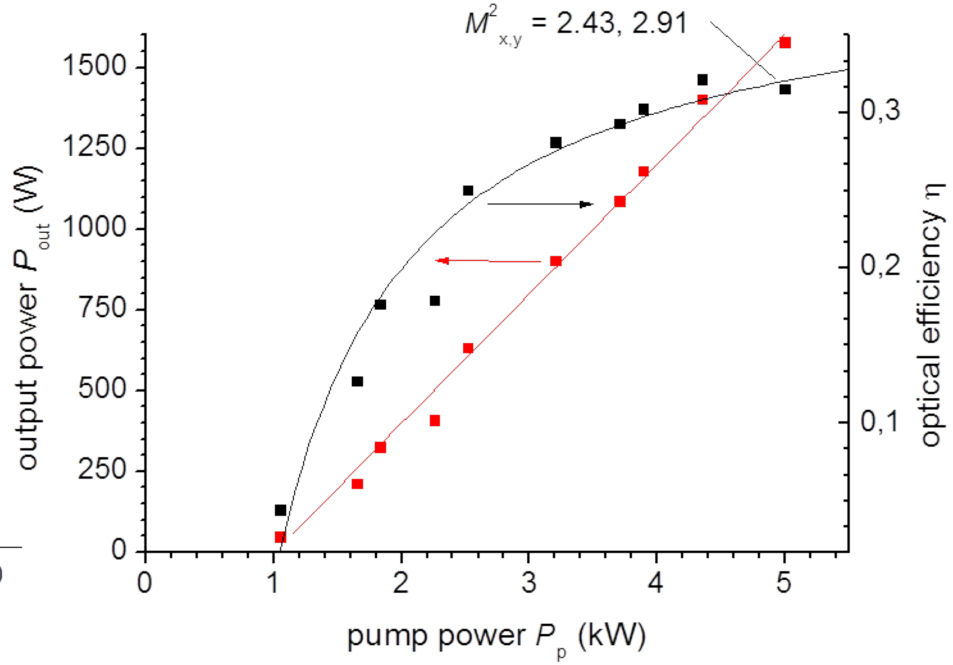
$$OPD(r) = 2\left[\int_0^h \left[n_0 + \boxed{\frac{\partial n}{\partial T}\cdot\left(T(r,z) - T_0\right)} + \Delta n_s(r,z) - 1\right]\cdot \boxed{\left[1+\varepsilon_z(r,z)\right]} dz - \boxed{z_0(r)}\right]$$



- 9% Yb:YAG,
- crystal thickness 180 µm,
- disk diameter 40 mm,
- 24 pump passes,
- pump spot
- diameter 22 mm,
- cooling fluid temperature 15°C, directly water cooled
- 25 kW pump power

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 relay neutral gain modules* (4 disks) in V-shaped resonator, including one adaptive mirror

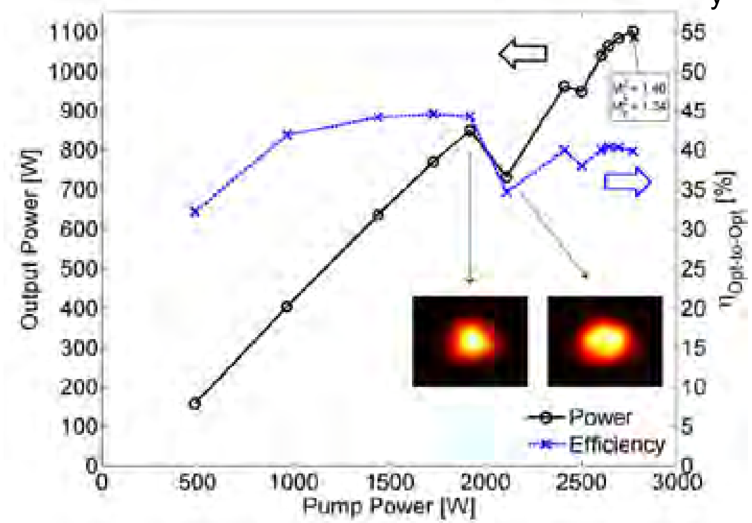
* J. Mende et. al., *Concept of Neutral Gain Modules for Power Scaling of Thin-Disc Lasers*, Applied Physics B, 97 (2), 2009

Thin-disk laser in nearly fundamental mode operation

$M^2_x = 1.40$
$M^2_y = 1.34$

~ 1.1 kW output power with M² < 1.4

Yuan Han Peng et al.,
1.1 kW Near Fundamental Mode Yb:YAG Thin Disk Laser,
Opt. Lett. **38** (2013), pp. 1709-1711



~ 4 kW output power with M² < 1.4

S. Schad et al., *Near fundamental mode high-power thin-disk laser*
Solid State Lasers XXIII: Technology and Devices **8959** (2014)

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 (typical)

- Mode-locked oscillator, 50 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)

Thin Disk laser – other materials
(not exhaustive)

Host Material	
YAG / LuAG	Yb^{3+}, Nd^{3+}, Tm^{3+}, Ho^{3+}
YVO_4	Yb^{3+}, Nd^{3+}
Sc_2O_3	Yb^{3+}
Lu_2O_3	Yb^{3+} , Tm^{3+}
$KY(WO_4)_2)$	Yb^{3+}
$KGd(WO_4)_2)$	Yb^{3+}
$NaGd(WO_4)_2$	Yb^{3+}
$LaSc_3(BO_3)_4$	Yb^{3+}
$Ca_4YO(BO_3)_3$	Yb^{3+}
$GdVO_4$	Nd^{3+}
ZnSe	Cr^{2+}

Neodymium

- R. Koch et al., *Near diffraction limited diode pumped thin disk Nd:YVO4 lase*r LASERS IN MATERIAL PROCESSING (1997)
- A. Giesen et al, *Diode-pumped Nd:YAG thin disc laser*, Conference on Lasers and Electro-Optics CLEO ’99 (1999)

Neodymium on quasi-three-level transition

- J. Gao et al., *Nd:YVO_4 thin disk laser with 5.8 watts output power at 914 nm*, OSA Trends in Optics and Photonics (TOPS) Vol. 73 (2002)
- J. Gao et al., *25-W Diode-Pumped Continuous-Wave Quasi-Three-Level Nd:YAG Thin Disk Laser*, Advanced Solid-State Photonics Technical Digest (2005) TuB34

Thin disk suitable for Nd on quasi-three-level transition

DLR

Thin Disk laser – other materials
(not exhaustive)

Host Material	
YAG / LuAG	Yb^{3+}, Nd^{3+}, Tm^{3+}, Ho^{3+}
YVO_4	Yb^{3+}, Nd^{3+}
Sc_2O_3	Yb^{3+}
Lu_2O_3	Yb^{3+} , Tm^{3+}
$KY(WO_4)_2)$	Yb^{3+}
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$NaGd(WO_4)_2$	Yb^{3+}
$LaSc_3(BO_3)_4$	Yb^{3+}
$Ca_4YO(BO_3)_3$	Yb^{3+}
$GdVO_4$	Nd^{3+}
ZnSe	Cr^{2+}

Sesquioxides

- M. Larionov et al., *Thin disk laser operation and spectroscopic characterization of Yb-doped Sesquioxides*, Trends in Optics and Photonics Vol. 50 (2001), WC4
- T. 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
- C. Kraenkel et al., *Yb-doped sesquioxide thin disk lasers exceeding 300 W of output power in continuous-wave operation*, CLEO/QELS (2010)

$Yb:Lu_2O_3$ – high thermal conductivity
crystal growing challenging – ceramics?

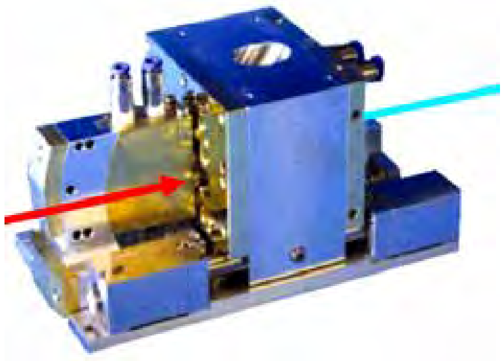
Thin Disk laser – other materials
(not exhaustive)

Host Material	
YAG / LuAG	Yb^{3+}, Nd^{3+}, Tm^{3+}, Ho^{3+}
YVO_4	Yb^{3+}, Nd^{3+}
Sc_2O_3	Yb^{3+}
Lu_2O_3	Yb^{3+} , Tm^{3+}
$KY(WO_4)_2)$	Yb^{3+}
$KGd(WO_4)_2)$	Yb^{3+}
$NaGd(WO_4)_2$	Yb^{3+}
$LaSc_3(BO_3)_4$	Yb^{3+}
$Ca_4YO(BO_3)_3$	Yb^{3+}
$GdVO_4$	Nd^{3+}
ZnSe	Cr^{2+}

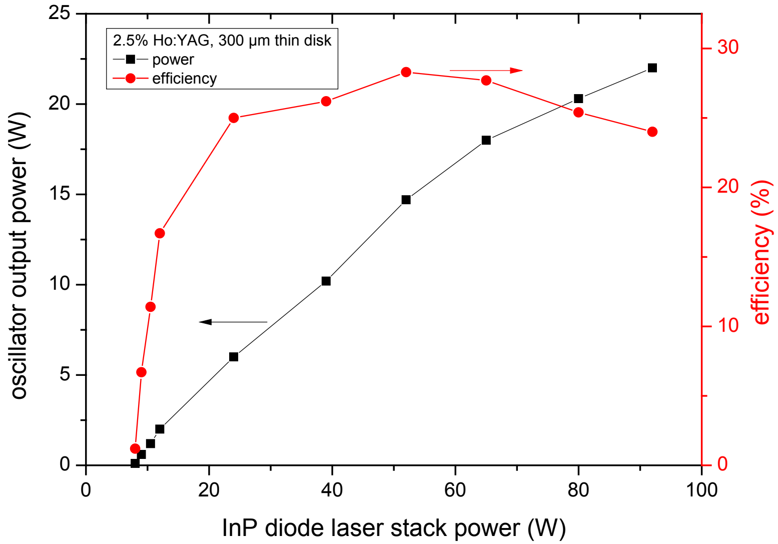
2 µm wavelength range

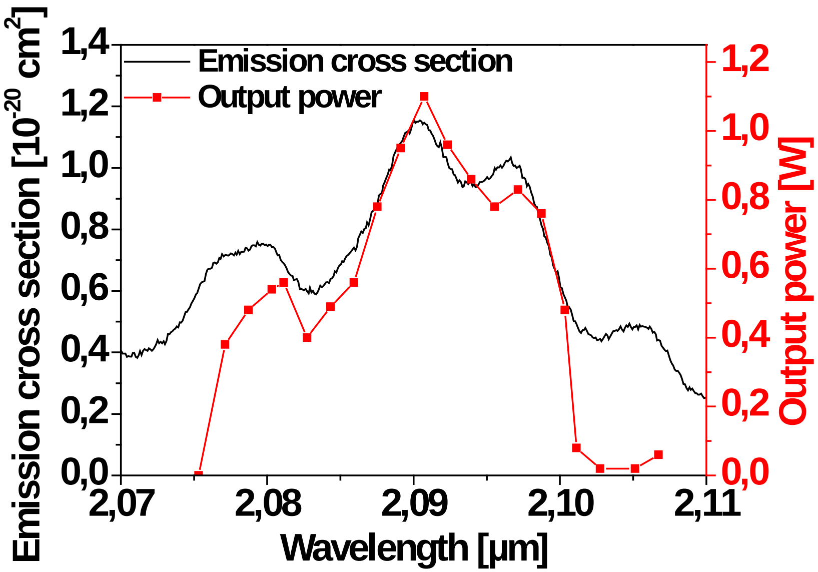
- A. Diening, et al., *High power Tm:YAG thin-disc laser*, OSA Technical Digest Series, Conference on Lasers and Electro Optics, CLEO'*98*. (1998), CWF46.
- M. Schellhorn, *Performance of a Ho:YAG thin-disc laser pumped by a diode-pumped 1.9 mum thulium laser*, Applied Physics B, vol. **85**, no.4 (2006) pp. 549-52.
- M. Schellhorn et al., *Diode-pumped Tm:Lu_2O_3 thin disk laser*, Advances in Optical Materials, Optical Society of America (2011) ATuB14
- G. Renz et al., *InP-Diode Laser Stack Pumped Ho:YAG or Cr:ZnSe Thin Disk Lasers*, Conference on Lasers and Electro-Optics Europe (2013)

Thin disk suitable for diode pumping Cr:ZnSe



New laser materials for the 2 – 3 µm wavelength range





Ho:YAG Thin Disk laser

- Pump source: fiber coupled InP diode stacks
- Laser output power only limited by available pump power
- More than 20 nm tuning range, suitable for Standoff / LIDAR applications

Pulsed thin disk lasers – early developments

Thin disk based regenerative amplifier (ps, 100 µJ, 1 kHz)

- C. Honninger et al., *Diode-pumped thin-disk Yb:YAG regenerative amplifier*, APPLIED PHYSICS B-LASERS AND OPTICS **65** (1997)

Mode locked thin disk laser (730 fs)

- J. Aus der Au et al., 16.2-W average power from a diode-pumped femtosecond Yb : YAG thin disk laser, OPTICS LETTERS **25** (2000)

Q-switched thin disk laser (~100 ns, ~ 5 mJ, 1 - 6 kHz)

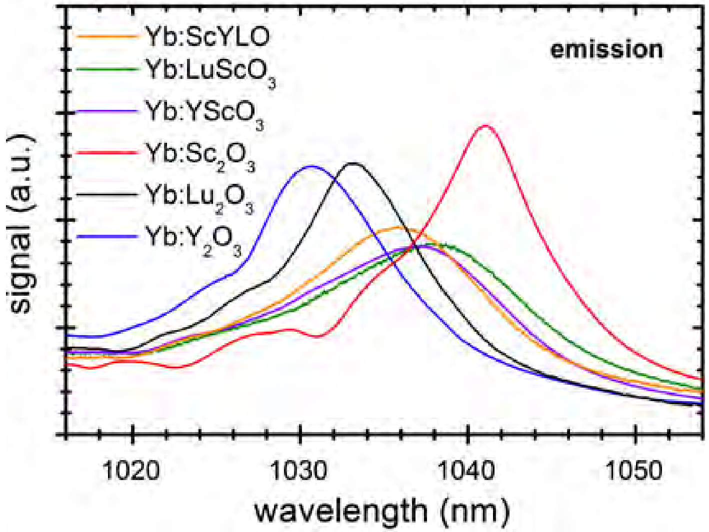
- I. Johannsen et al., *Q-switched Yb:YAG thin disk laser*, ADVANCED SOLID-STATE LASERS 2001, PROCEEDINGS, (2001)

Q-switched thin disk lasers: long pulse duration (100 ns - µs), low power systems (< 100 W) used for many applications, e.g. frequency doubled

Pulsed thin disk lasers – actual trends
(mostly driven by material processing)

Mode locked thin disk laser

- High average power (> 100 W)
  T. Südmeyer et al., *Power-Scaling of Femto-second Thin Disk Lasers,* Advanced Solid-State Photonics (2011)
  K. Beil et al., *Yb-doped mixed sesquioxides for ultrashort pulse generation in the thin disk laser setup*, Applied Physics B **113** (2013)



- Kerr lense modelocking (~ 300 fs)
  J. Brons et al., *120 W, 4 µJ from a purely Kerr-lens mode-locked Yb:YAG thin-disk oscillator*, Advanced Solid-State Lasers Congress, Optical Society of America (2013)

- Intracavity multipass for energy scaling
  J. Neuhaus et al., *Subpicosecond thin-disk laser oscillator with pulse energies of up to 25.9 microjoules by use of an active multipass geometry,* OPTICS EXPRESS **16** (2008)

high power e.g. for material processing

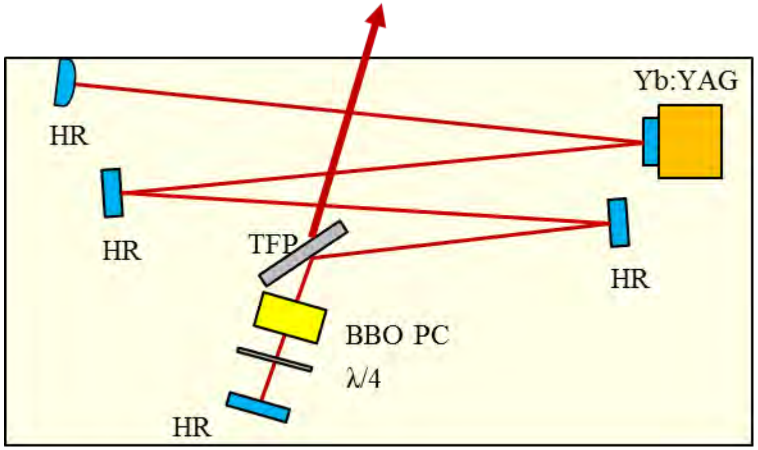
Pulsed thin disk lasers – actual trends
(mostly driven by material processing)

Thin disk based regenerative amplifiers

- High average power (> 100 W), low pulse energy
- sub-ps pulse duration for some applications – emerging competition with modelocked systems
- Several ps / mJ systems without CPA
- Sesquioxides due to scalability and broad emission spectrum

Cavity dumped operation

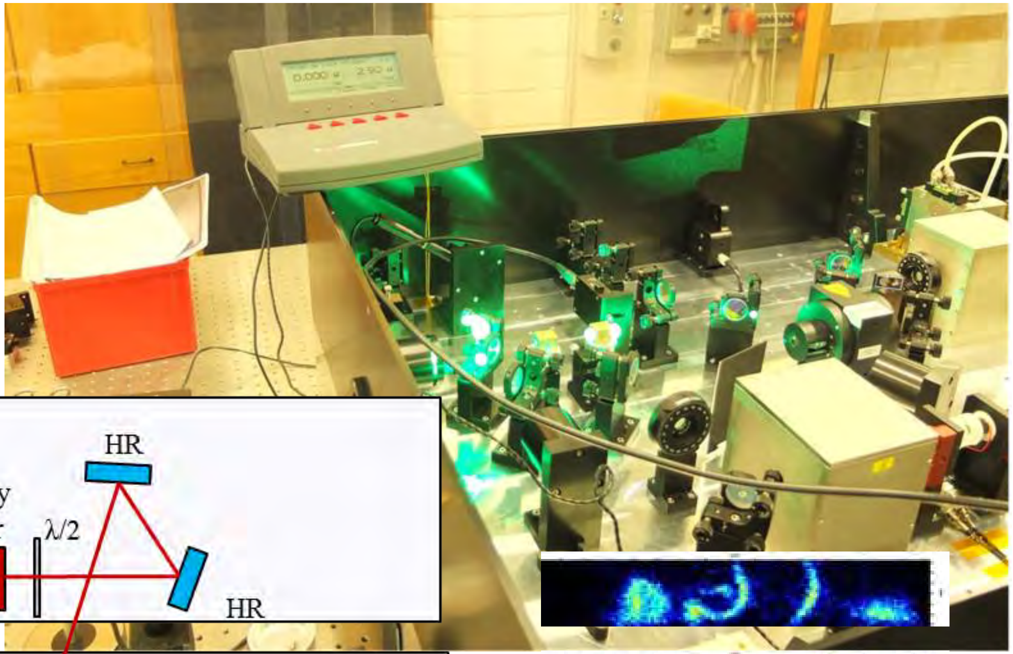
- Similar to regenerative amplifier, but no short pulse oscillator
- Pulse duration ~ 30 ns to ~ µs (> cavity length)
- up to 80 mJ, 750 W average power as commercial product

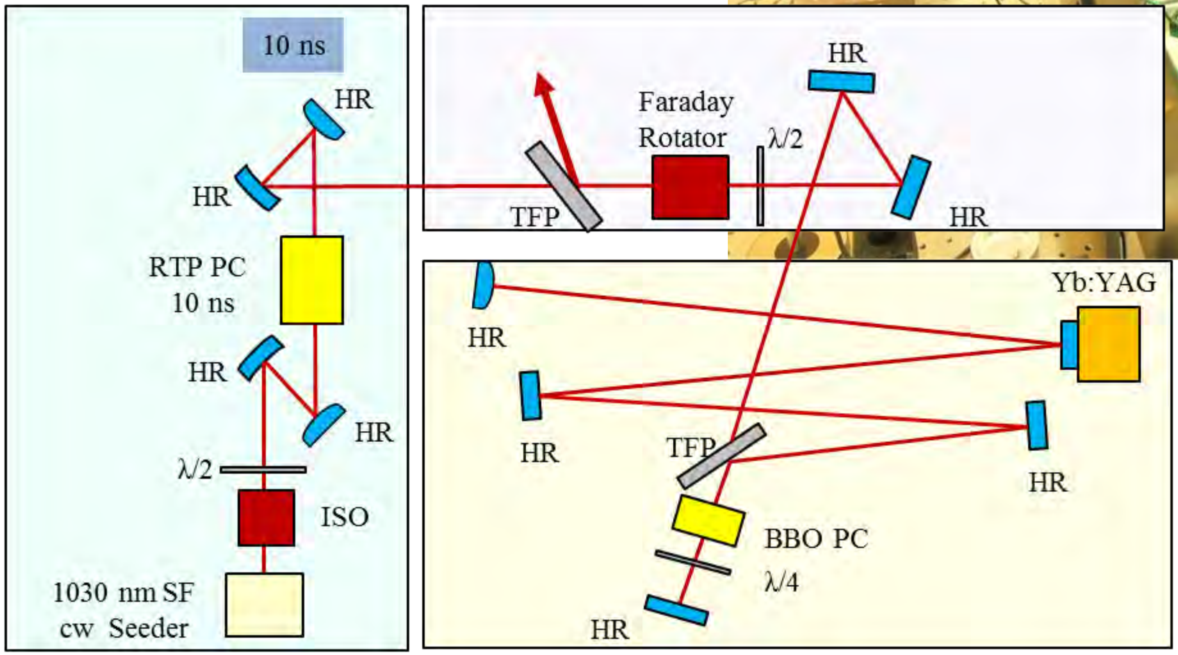


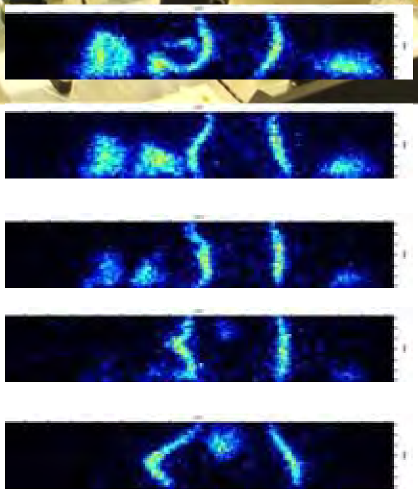
Regenerative thin disk amplifiers

Regenerative amplifier
(with single frequency seeding)

application:
THG for detection of CH_2O in combustion processes (LIF)





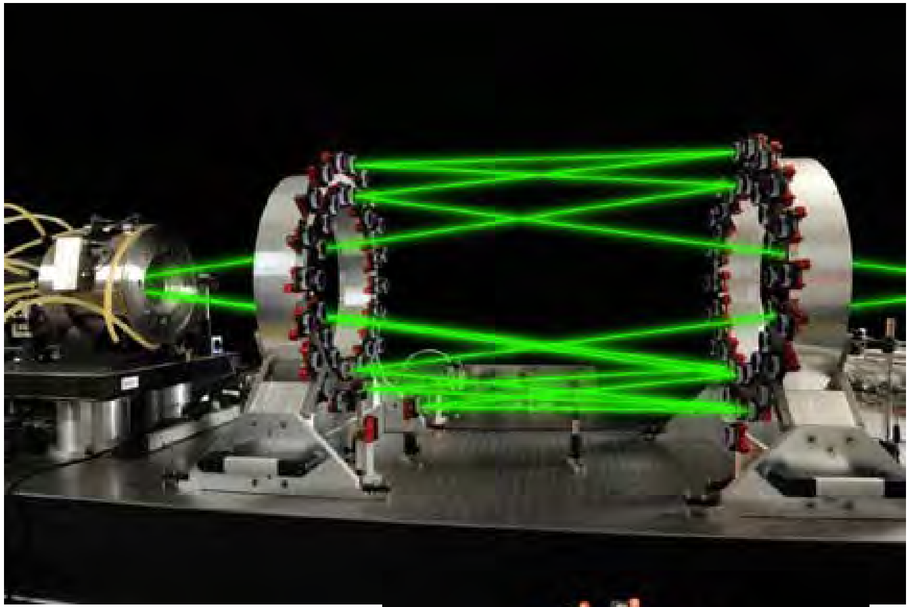


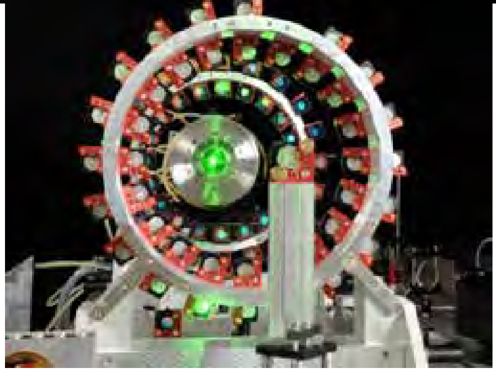
High energy pulsed thin disk concepts

- **High energy pulsed thin disk laser = thin disk amplifier**
- "typical" thin disk pulsed laser: (bulk, disk or fiber) oscillator + regenerative thin disk amplifier
  - up to 100 mJ @ 1 kHz / < 1 kW average power, high rep-rate
  - limited by the need for large aperture, low loss electro-optical switch
- higher pulse energies: geometrical multipass amplifier
  - increasing pump spot and disk size
  - large pump spot size + unsaturated gain: strong ASE

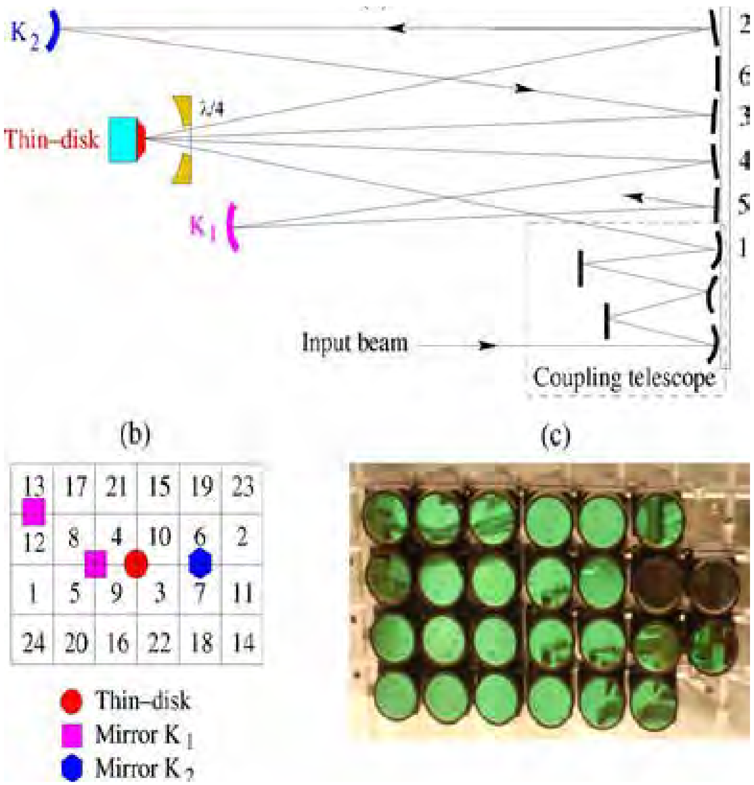
Thin-disk multipass amplifier

- Relay-Imaging multipass
- Control of phase distortions
- Internal focus
- Shown setup 20 passes





"planar", non-imaging multipass



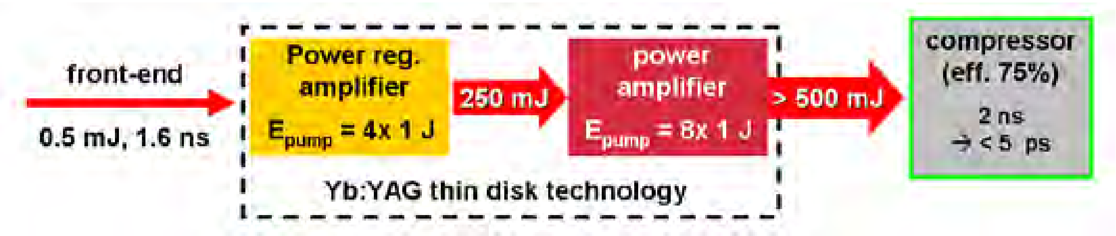
A. Antognini et al,
Thin-Disk Yb:YAG Oscillator-Amplifier Laser, ASE, and Effective Yb:YAG Lifetime
IEEE JQE, vol. 45, no. 8 (2009)

Modification:
J.-P. Negel et al., *1.1 kW average output power from a thin-disk multipass amplifier for ultrashort laser pulses*, Opt. Lett. **38** (2013)

- 80 passes, 800 kHz
- Amplification ~ 13

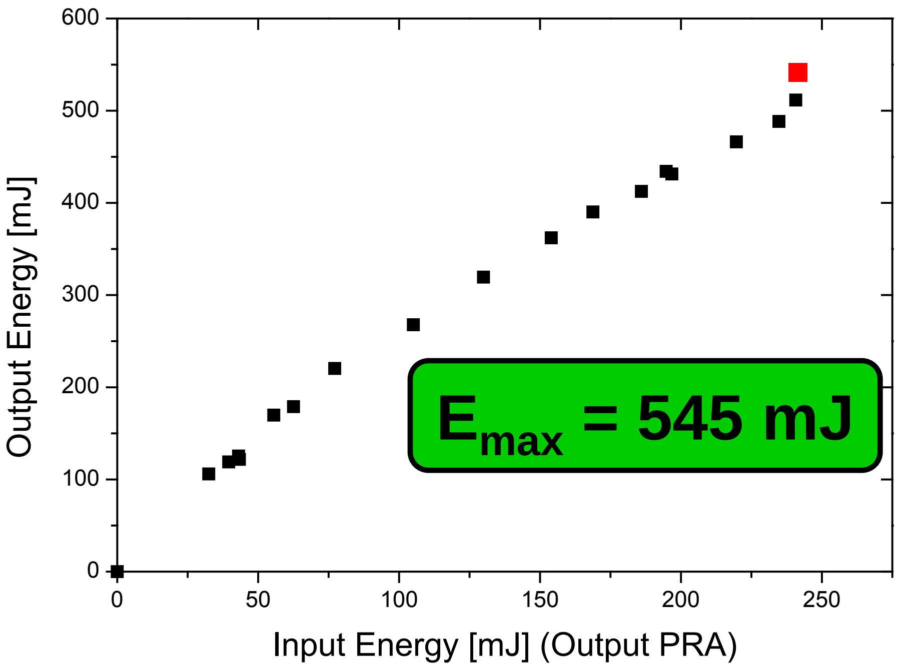
Multipass Amplifier – Results

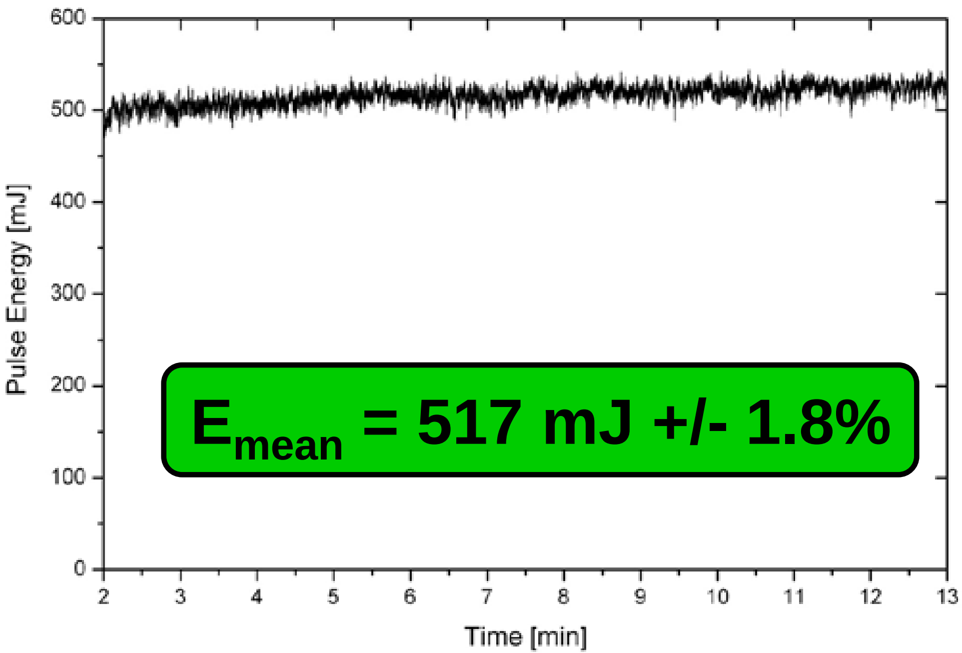
Thin Disk Amplifier Chain



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

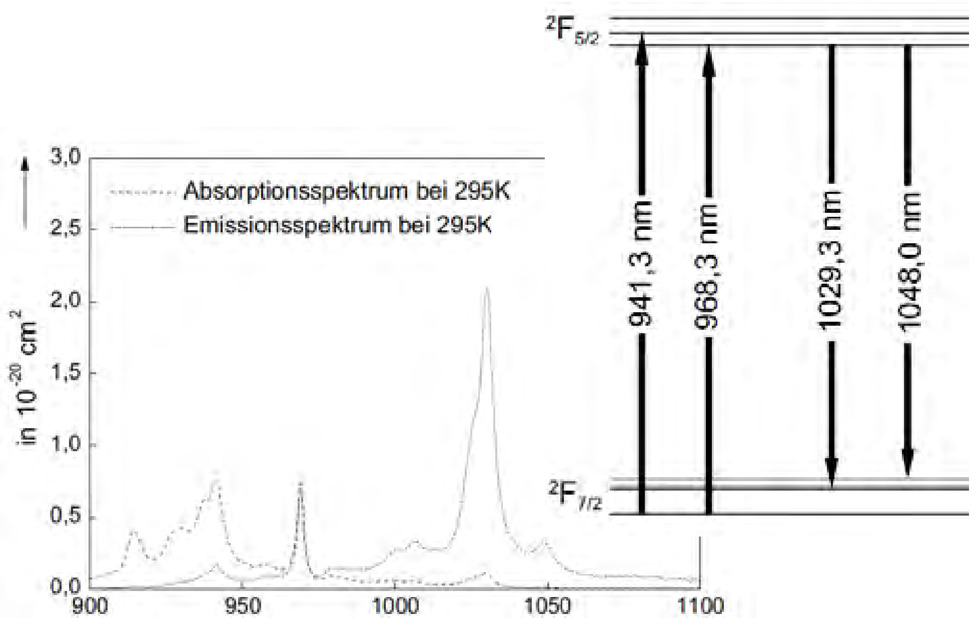
multipass output after 4 double passes – pump power 6 kW





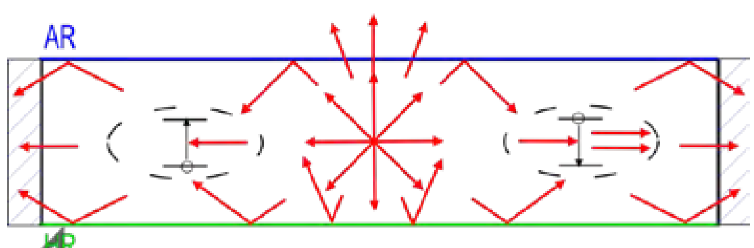
Design Challenges

- significant temperature-depender reabsorption
- operated at a comparable high inversion level
- strong coupling between pump absorption, laser amplification, inversion and temperature



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

$$\alpha_p = \sigma_{abs}(T)N_0 - \sigma_{abs}(T)(1+f_{em}(T))N_2$$

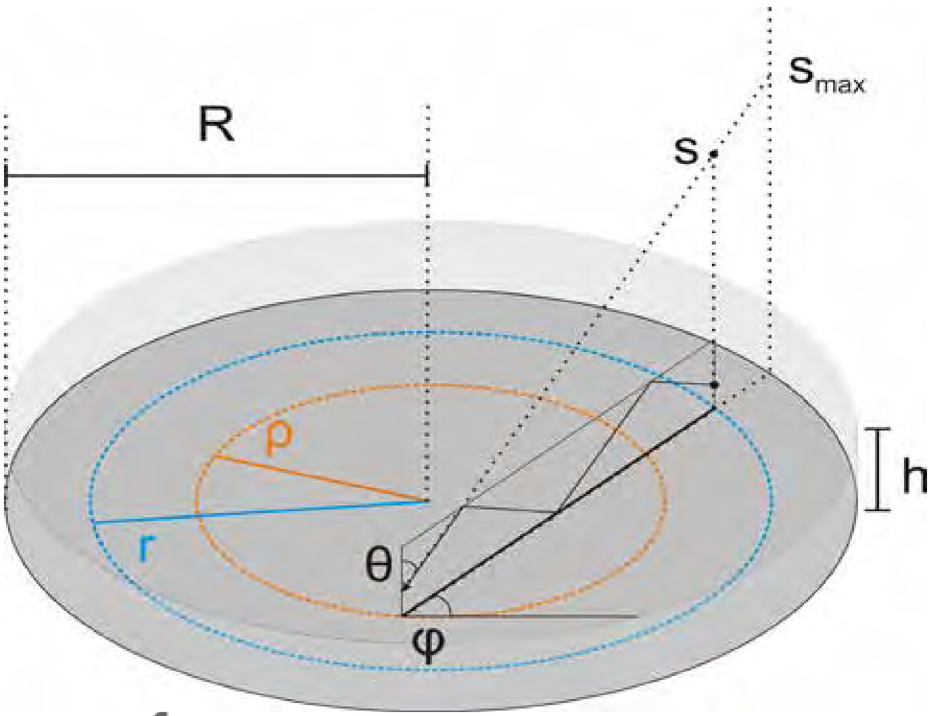


$$\dot{N}_2 = Q - \frac{N_2}{\tau} - \gamma_{laser}\Phi_r + W_{ASE}$$

Design Challenges
Amplified spontaneous emission (ASE)

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

can be integrated with a semi-implicit method
→ transient model

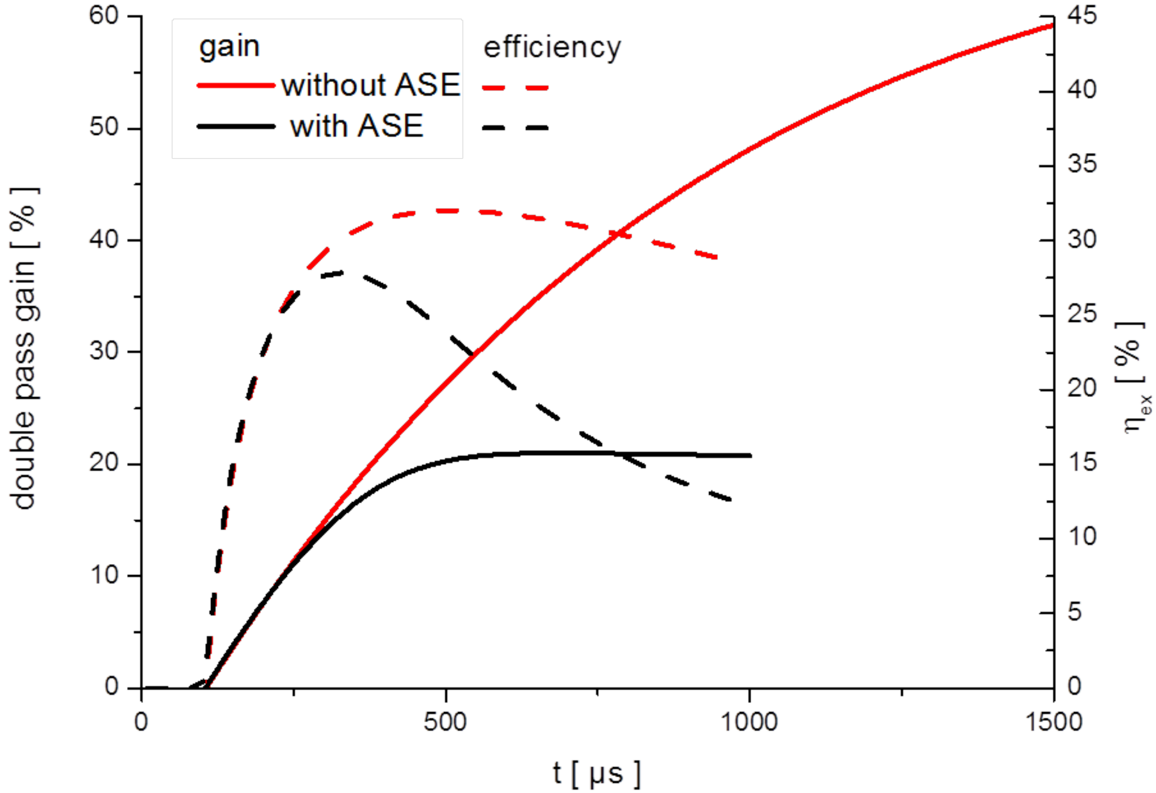


Photon flux density from a volume element at position $\vec{s}$

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

Requirement for model:
No back reflection from outer edges, e.g. by **absorbing cladding**

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



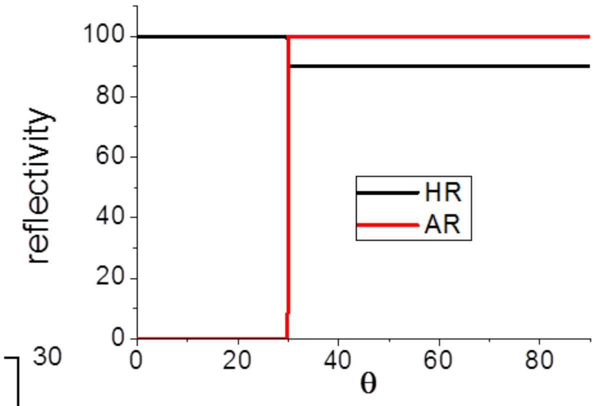
4.5% Yb:YAG, thickness 600 µm, pump power 16 kW, pump spot diameter 18.6 mm

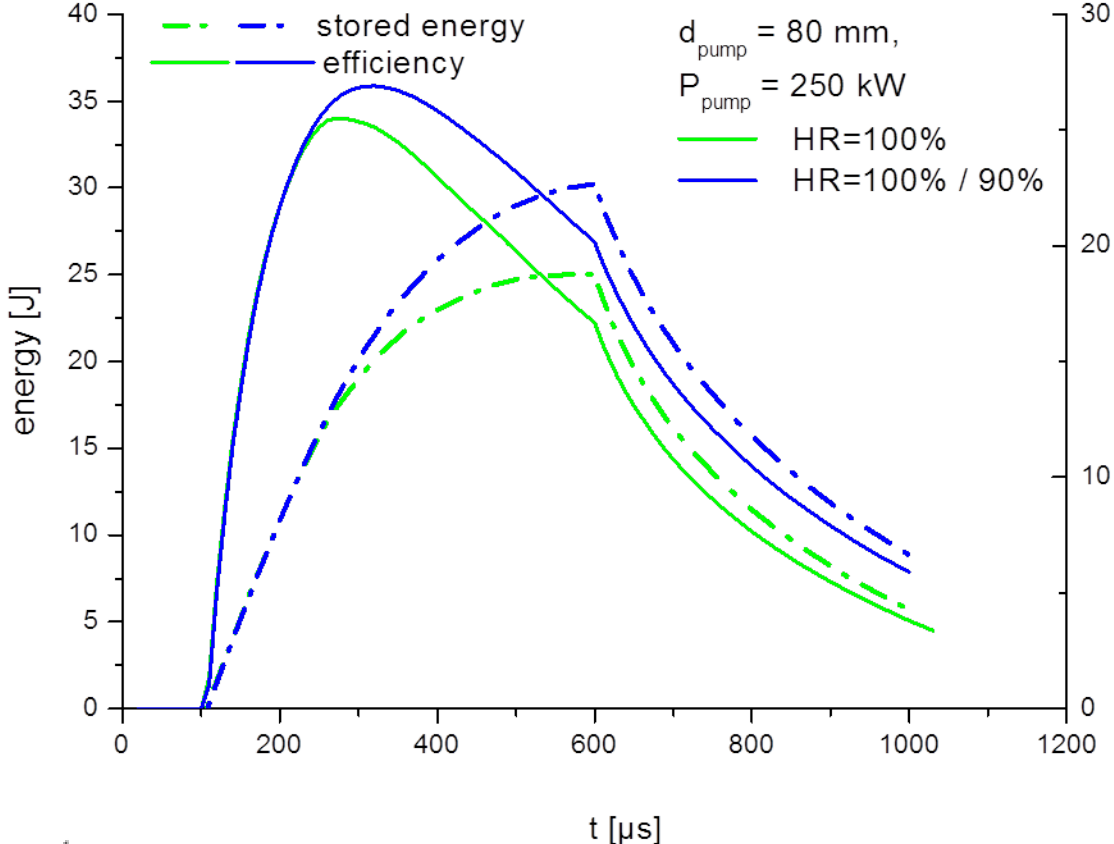
Transient model:

- 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

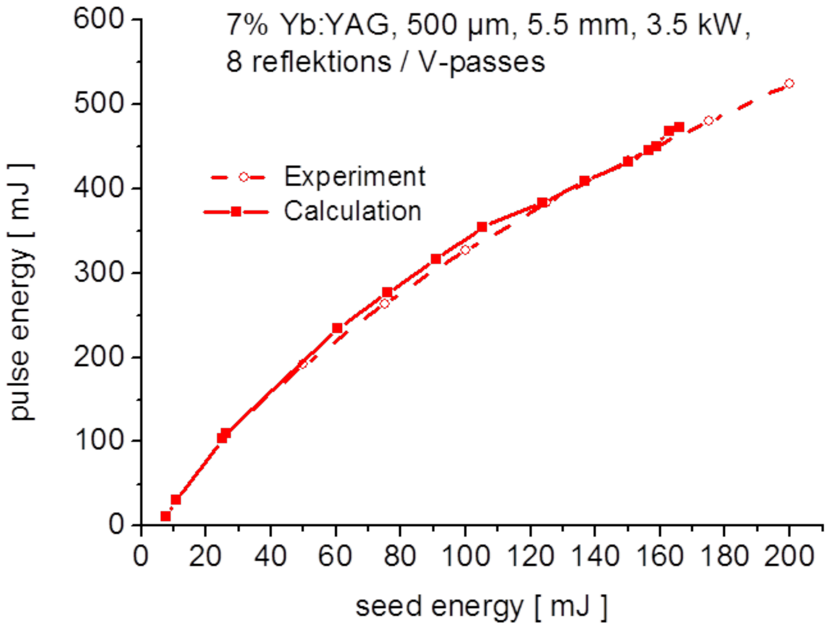
Scaling of the stored energy
influence of HR design





- 1.5% Yb:YAG
- 1800 µm thick
- ~ 5 kW/cm² pump power density
- 5% duty cycle
- ~ 10% heat generation
- average temperature 42° C

Geometrical Multipass amplifier
Numerical calculations & experimental results



Low duty cycle, low pump power
Comparison with results from
Max Born Institute

Model originally developed for:

- pulse amplification
- low repetition rate,
  esp. qcw pumping
- „thick disk“

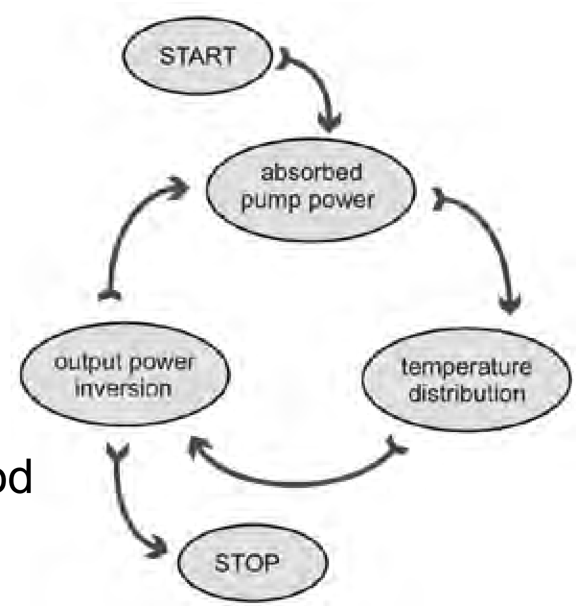
Consequences:

- max. iteration time = pump pulse
- Temperature no critical issue
- Absorption efficiency high

Design challenges
Modifications of numerical model

Established quasi-static model ***winray***:

- Raytracing for pump absorption (angular & spectral distribution)
- Temperature calculation with finite volume method
- (ASE calculations with Monte Carlo raytracing)
- Iterative solver
- Especially suitable for cw oscillators up to few kW



„equivalent“ model (disk dimensions, doping, pump spot, pump power …

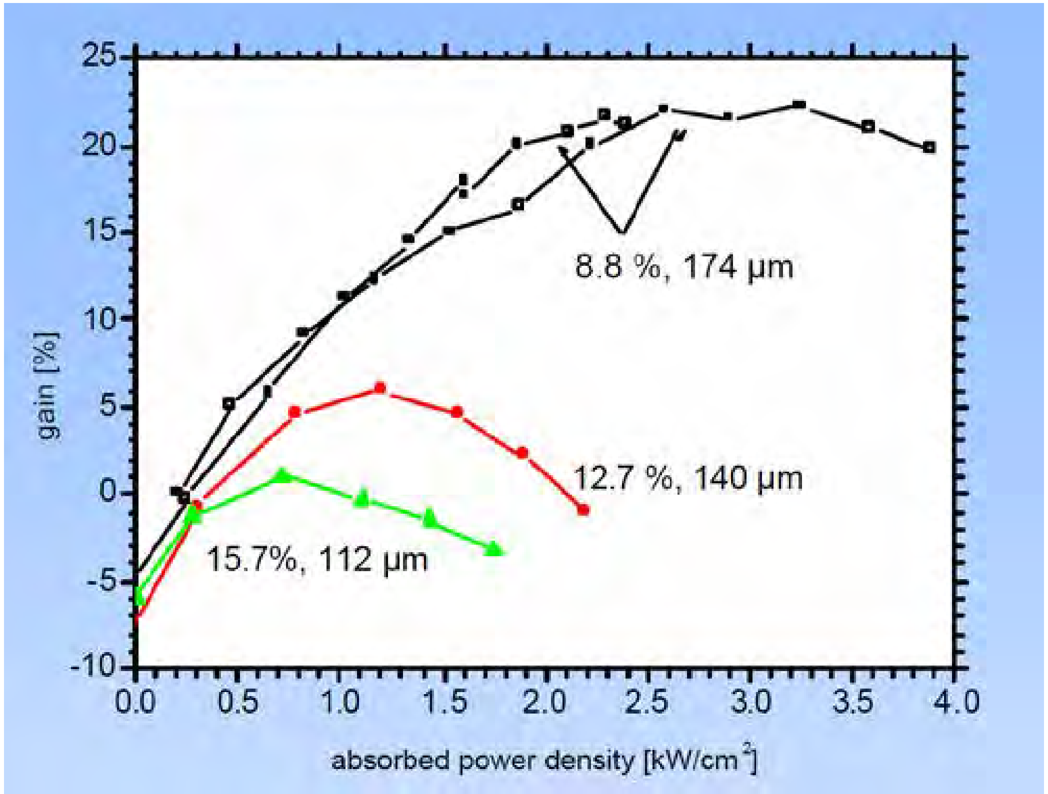
winray

temperature
absorption
efficiency

transient model with ASE (illumination)

DLR

Design challenges - Influence of doping concentration on achievable gain



M. Larionov et al., *Nonlinear Decay of the Excited State in Yb:YAG*, ASSP 2005, Vienna

- doping-dependent, non linear loss
- additional heat generation
- intrinsic effect?
- generation of charge transfer band?
- enhanced by impurities!

Modifications …

Upconversion-like effects in rate equation:

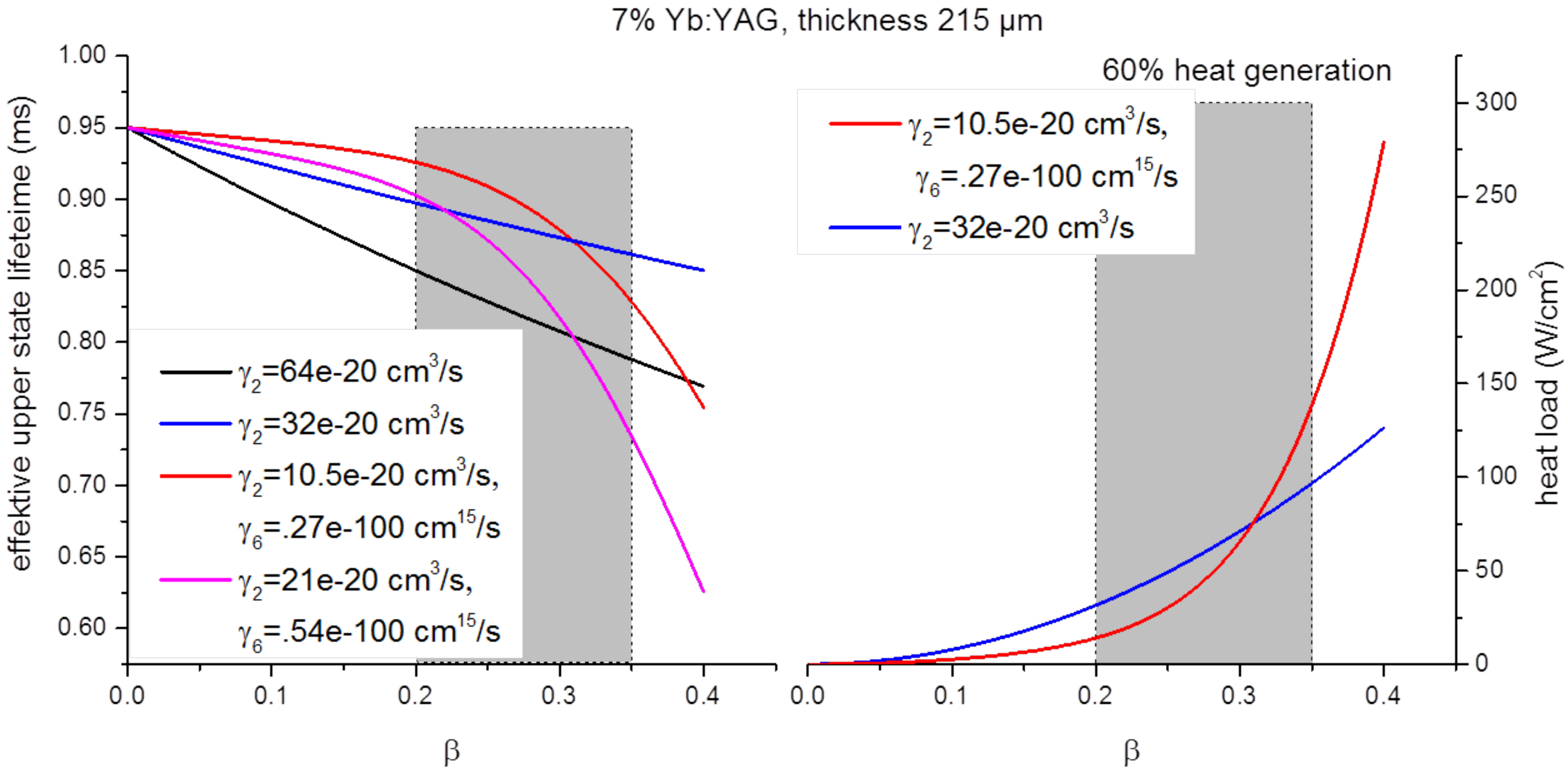
$$\dot{N}_2 = Q - S - \frac{N_2}{\tau} - \gamma_2 N_2^2 - \gamma_6 N_2^6 - \iint \gamma_\lambda \Phi_{\lambda,\Omega} d\lambda d\Omega$$

- „classical“ upconversion $\sim N_2{}^2$ (no upconversion in Yb:YAG)
- energy migration between ions $\sim N_2{}^6$
- Photoconductivity $\sim N_2{}^2$ ... $N_2{}^4$ according to publications
- some amount of heat generation

Most parameters uncertain, $\gamma_2 = 64 \cdot 10^{-20}$ $cm^3 s^{-1}$ fit to results from 2005

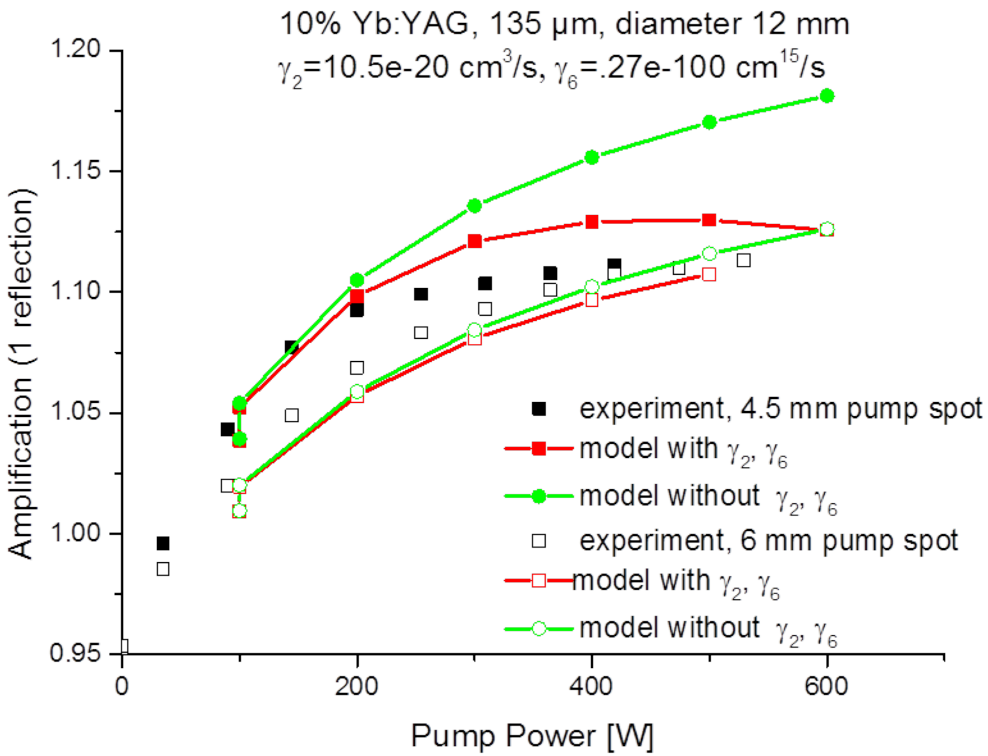
Additional temperature calculation steps necessary in model

Upconversion-like effects



Inversion parameter $\beta = {}^{N_2}/_{N_0}$

Double pass small signal gain experiments



Several different disks
16 pump passes
~ 1 W oscillator

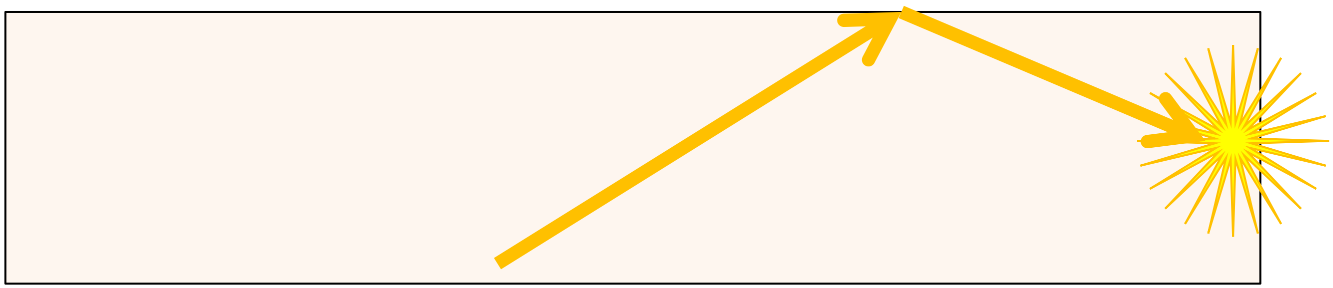
Pump spectra from experiment

absorption efficiencies and initial temperatures calculated with ***winray***

Additional temperature iterations

Amplification $G = \exp(2\gamma_{osc}h)$

Design challenges
What happens at the edge?



- Cylindrical rim of the disk is not perfectly transmitting / typically not polished / sometimes bevelled
- For a simple model: isotropic scattering of a fraction of the power reaching the rim
- Preserving the spectral distribution
- Fraction defined by parameter χ_{ref}
- Can be realized in the existing model as additional source of photons
- Time behaviour not exact: values of the step before are used

Modifications …
What happens at the edge?

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SOLID STATE AND LIQUID LASERS

Thin Disk Laser—Energy Scaling[1]

Jochen Speiser

Artificial spiking

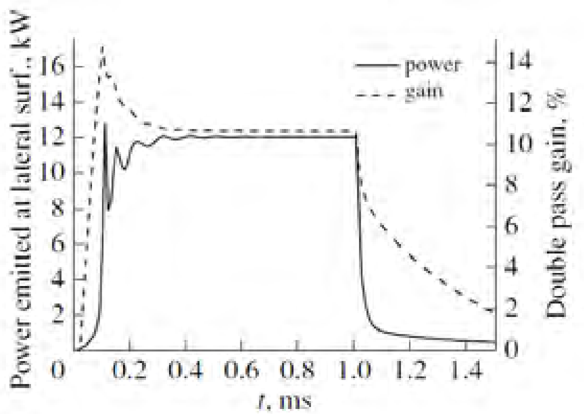


Fig. 10. Laterally emitted power and double pass gain. 4.5% Yb:YAG, thickness 300 µm, 16 kW pump power, 12.4 mm pump spot diameter.

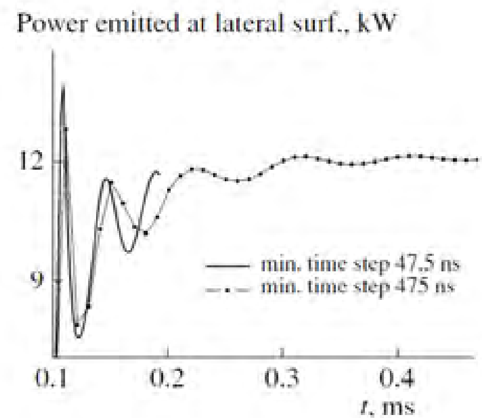
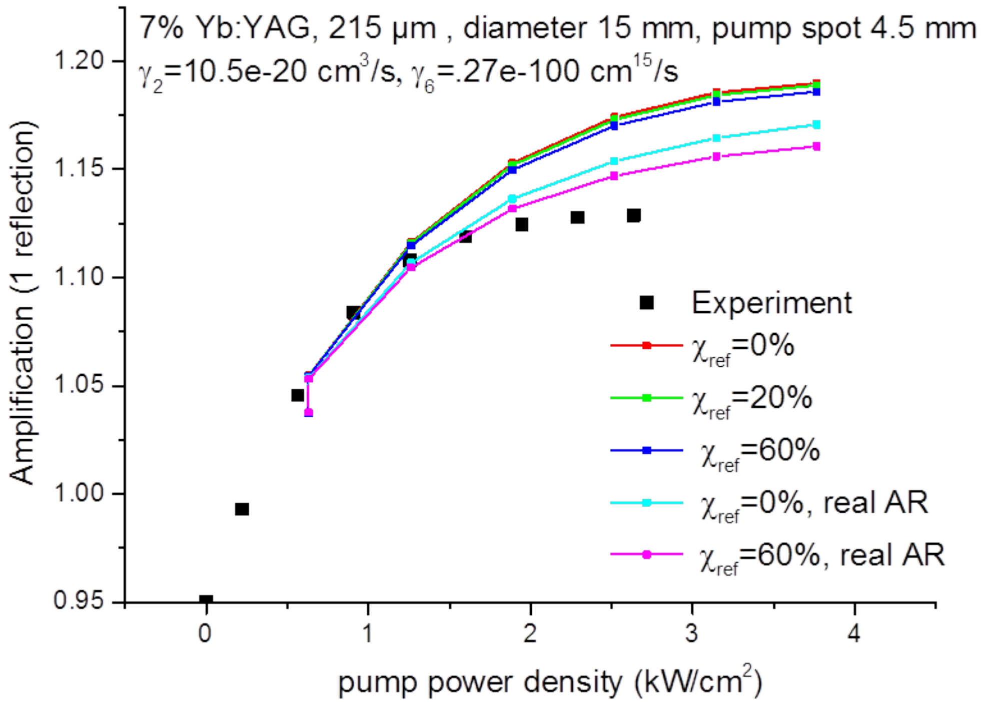


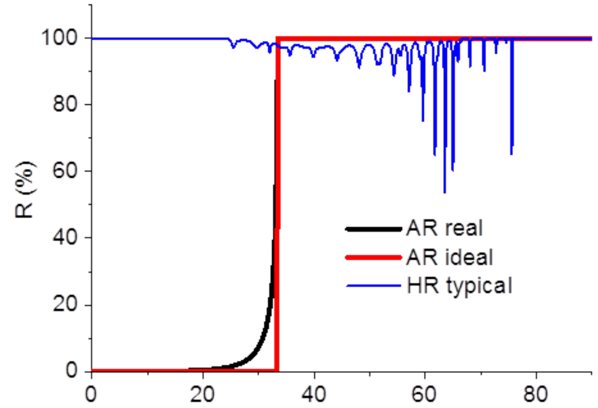
Fig. 11. Laterally emitted power. 4.5% Yb:YAG, thickness 300 µm, 16 kW pump power, 12.4 mm pump spot diameter.

Double pass small signal gain experiments

influence of backscattering at the edge

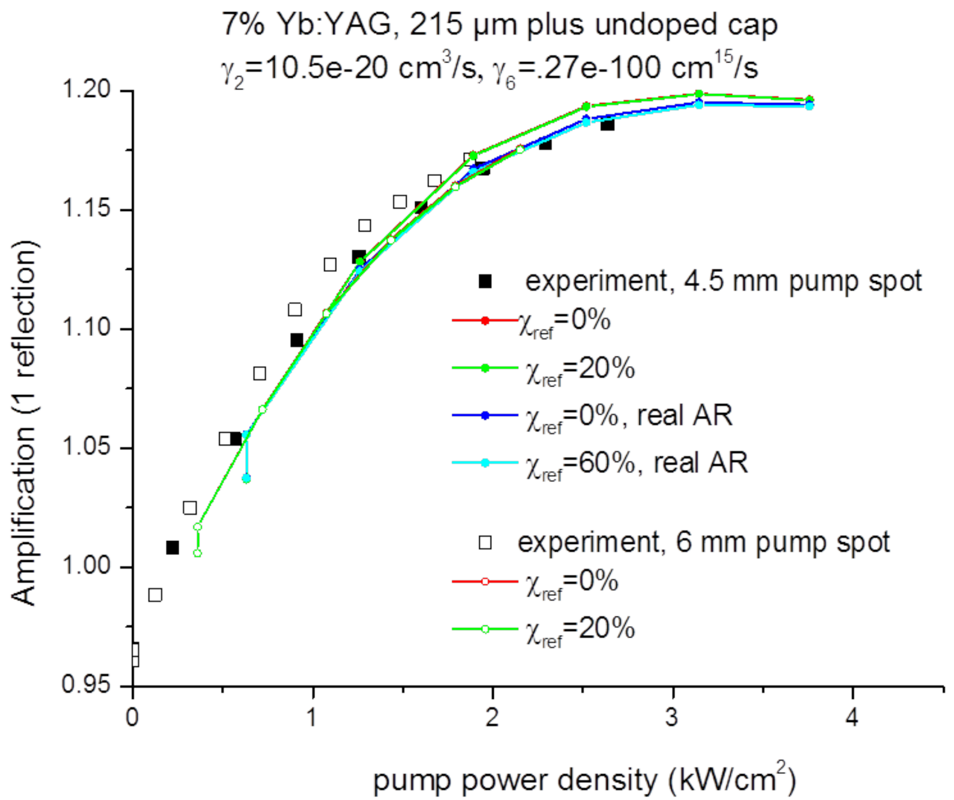
AR coating effects





- large unpumped area
- significant absorption
- low feedback from the edge
- Modified AR increases feedback?

Double pass small signal gain experiments
disk with ASE suppressing cap



Conclusions

- Challenges from cw pumping / cw amplification identified
- Material parameters uncertain
- “interference “ between ASE and “upconversion” – similar order of magnitude for moderate pump spots
- More sophisticated experiments necessary?

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}

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

- 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

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

- 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% (20 cm pump diameter)
- **400 J with L_{int}=1%** / 8 J with L_{int}=4%

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

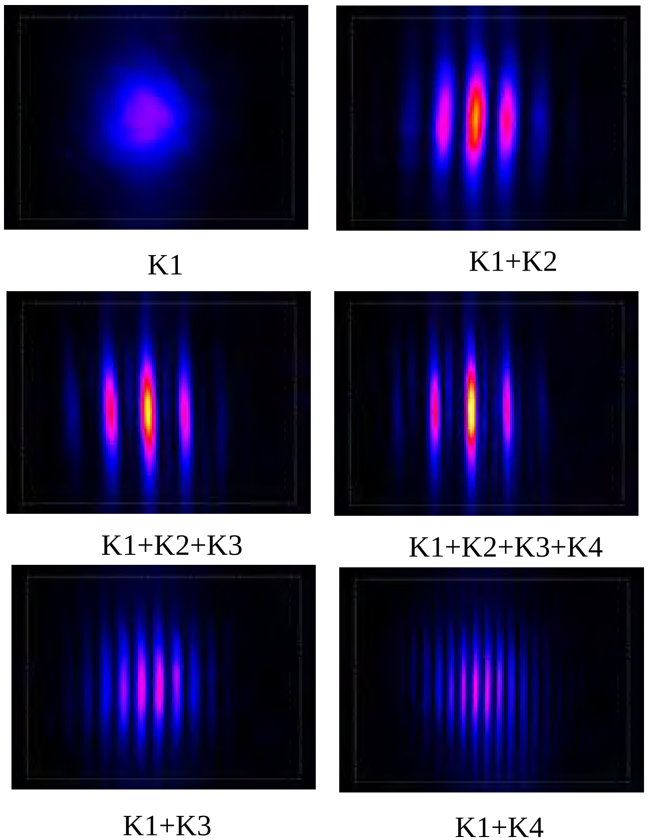
J. Speiser, *Scaling of Thin Disk Lasers - Influence of Amplified Spontaneous Emission,* JOSA B **26** (2009)

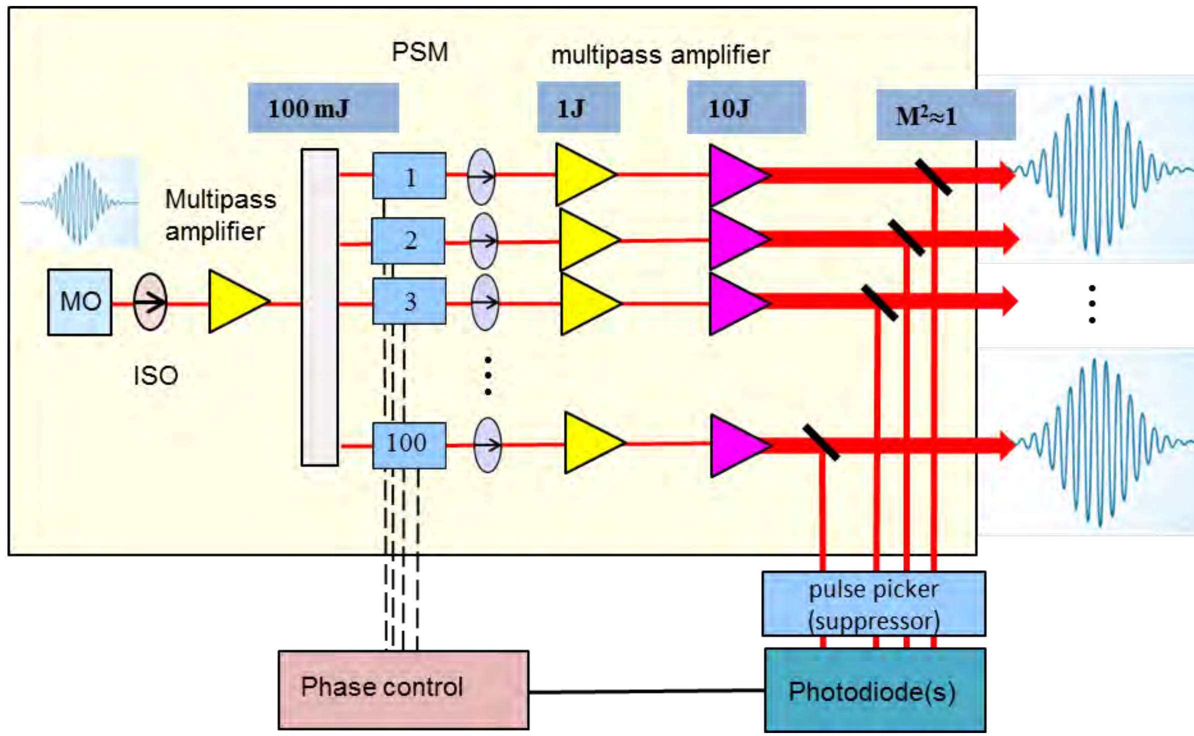
Future trends
(highly speculative)

- **Alternative mounting / bonding approaches**
- **Increased use of ceramic materials**
  - challenging materials
  - doping distribution
  - size less important
- **“thicker” disks – reduced duty cycle, > 10 J**
- **Further energy scaling**
  (Coherent) coupling of several amplifier chains
  ~ kJ possible

Coherent coupling of pulsed thin disk amplifiers

Coherent coupling
of fibre lasers





Laser concept for **Space Debris Removal**
(FP7 Poject CLEANSPACE)
goal 15 kJ, 50 Hz, 10 ns (~ 1500 amplifier chains)