# Recent Advances of High Power 1 µm Lasers

II-VI DEUTSCHLAND

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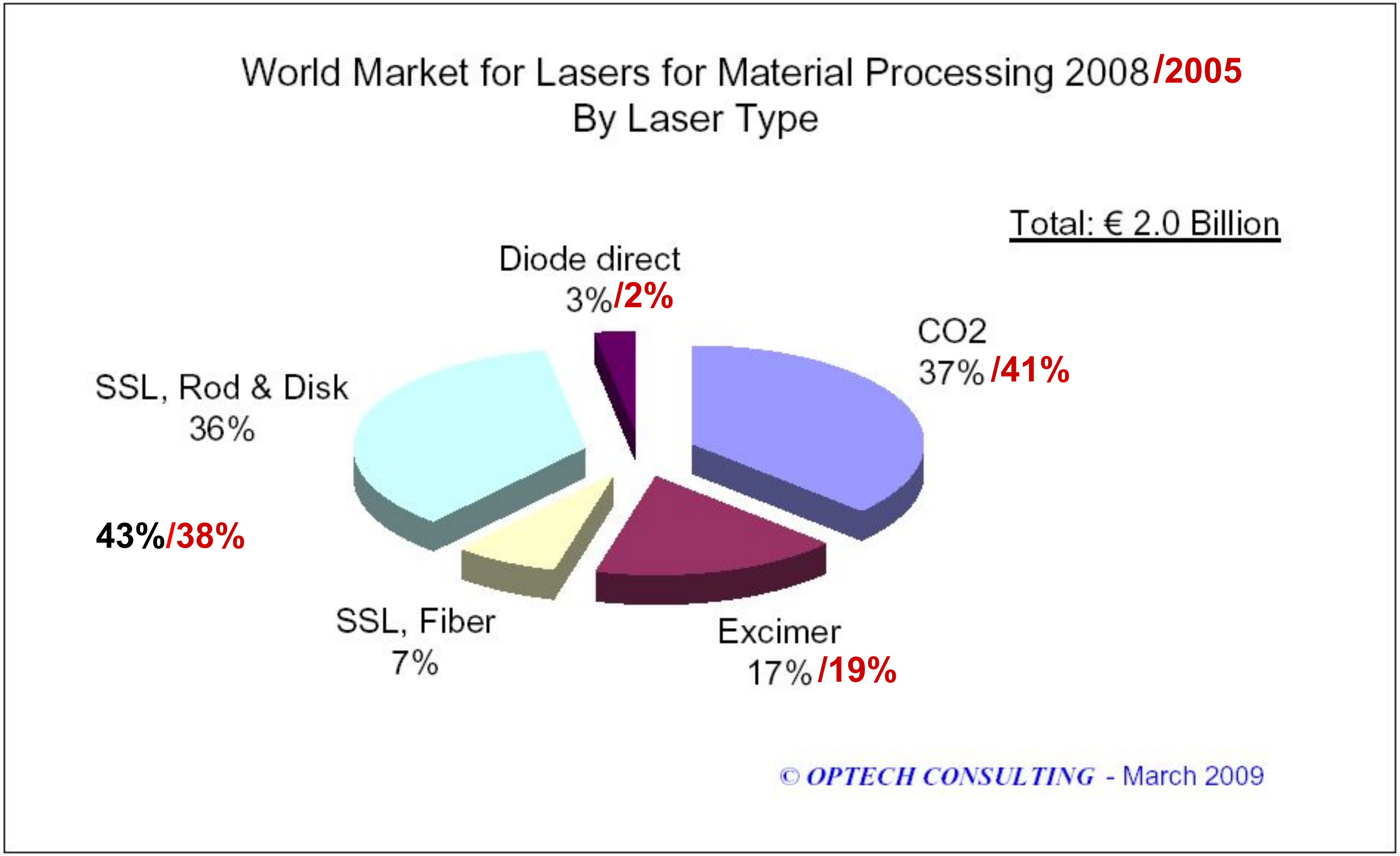
# Abstract

With the advent of reliable Yb:YAG disk lasers and Yb-doped fiber lasers the industry is now adopting these novel sources in their laser material processing systems. Not only superior beam quality and brightness in comparison to conventional technological high power lasers, but also the simplified handling via multi-kW-fibers open up new high performance industrial applications. Recent results underline the importance of 1 µm wavelength high power-lasers. The advantages and present limitations of 1 µm solid state lasers will be discussed.

# Introduction



World Market for Lasers for Material Processing 2008/2005
By Laser Type

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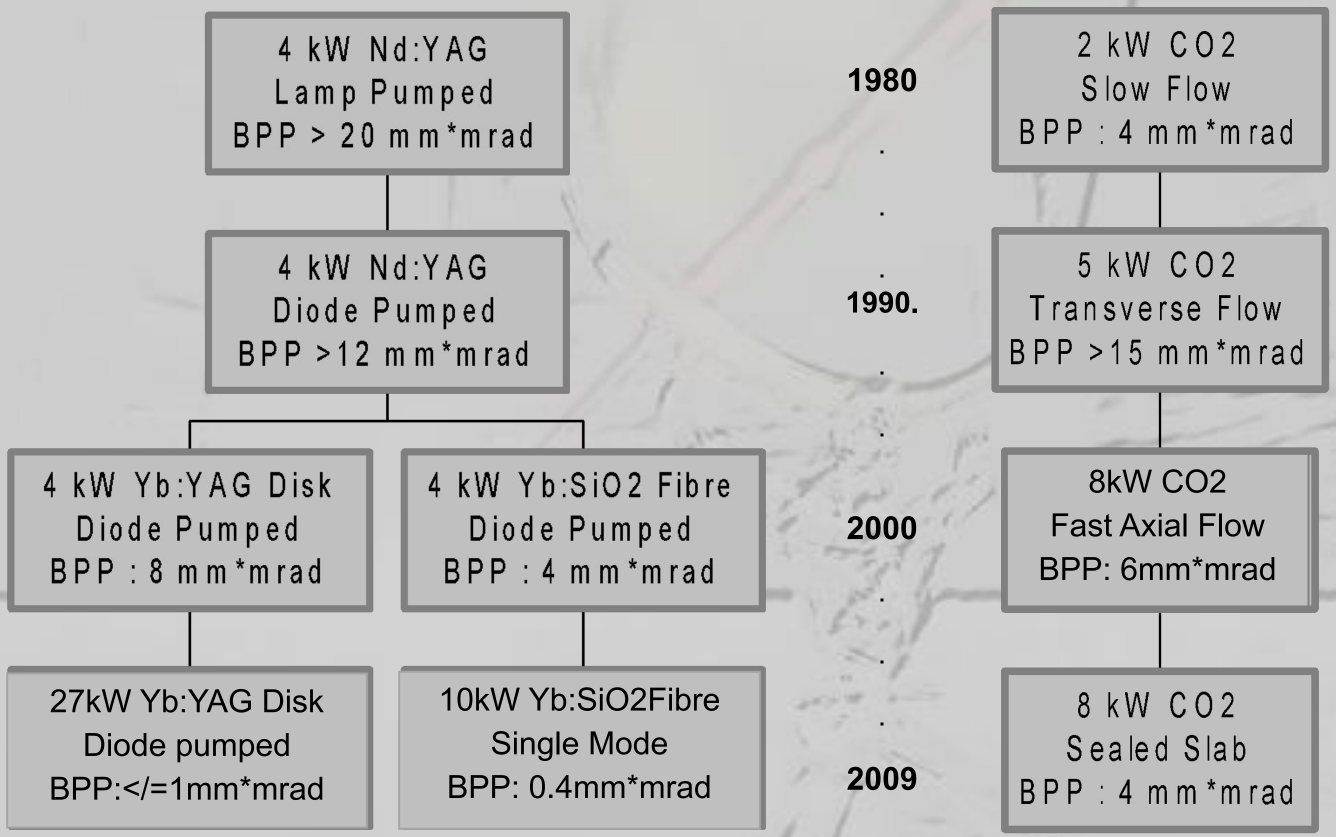
# Introduction

## Evolution of the Beam Parameter Product for Industrial High Power Lasers (2009)

Laser Wavelength: ≈ 1µm 10,6 µm
Diff. Lim. : 0,34mm mrad 3,7 mm mrad



4 kW Nd:YAG
Lamp Pumped
BPP > 20 mm*mrad

4 kW Nd:YAG
Diode Pumped
BPP >12 mm*mrad

4 kW Yb:YAG Disk
Diode Pumped
BPP : 8 mm*mrad

4 kW Yb:SiO2 Fibre
Diode Pumped
BPP : 4 mm*mrad

27kW Yb:YAG Disk
Diode pumped
BPP:</=1mm*mrad

10kW Yb:SiO2Fibre
Single Mode
BPP: 0.4mm*mrad

**1980**
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.
.
**1990.**
.
.
**2000**
.
.
.
**2009**

2 kW CO2
Slow Flow
BPP : 4 mm*mrad

5 kW CO2
Transverse Flow
BPP >15 mm*mrad

8kW CO2
Fast Axial Flow
BPP: 6mm*mrad

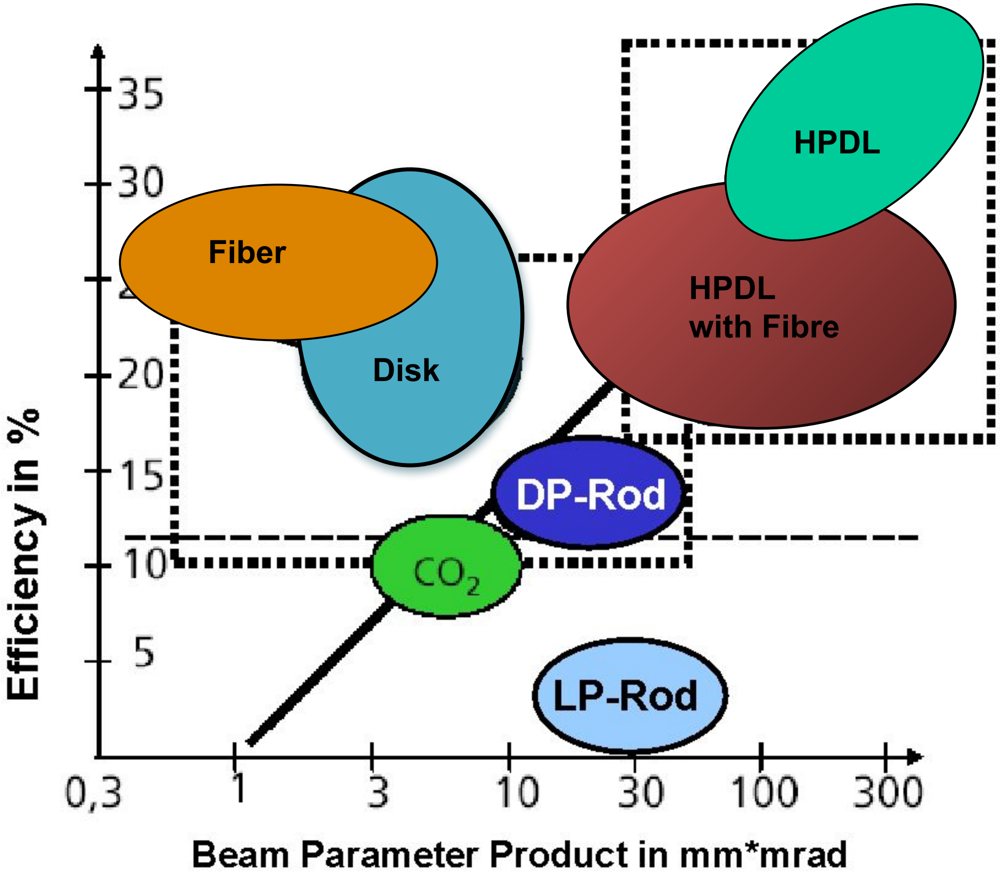
8 kW CO2
Sealed Slab
BPP : 4 mm*mrad

# Introduction

## Efficiencies and Beam Parameter Product of Industrial Laser Systems

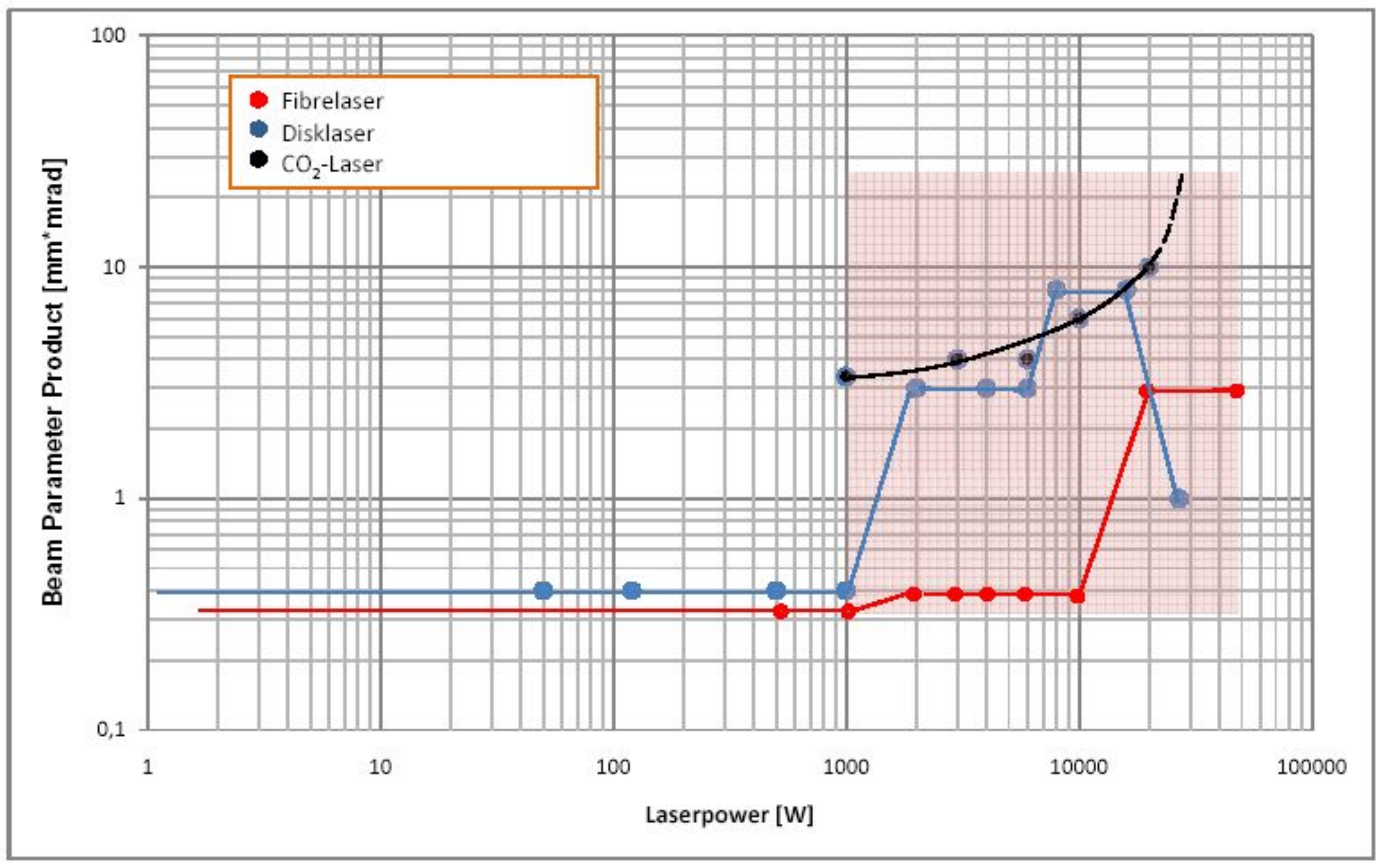
Disk and Fibre Laser show very high efficiency with low beam parameter product.

Diode Lasers show highest efficiencies with lowest operating cost.



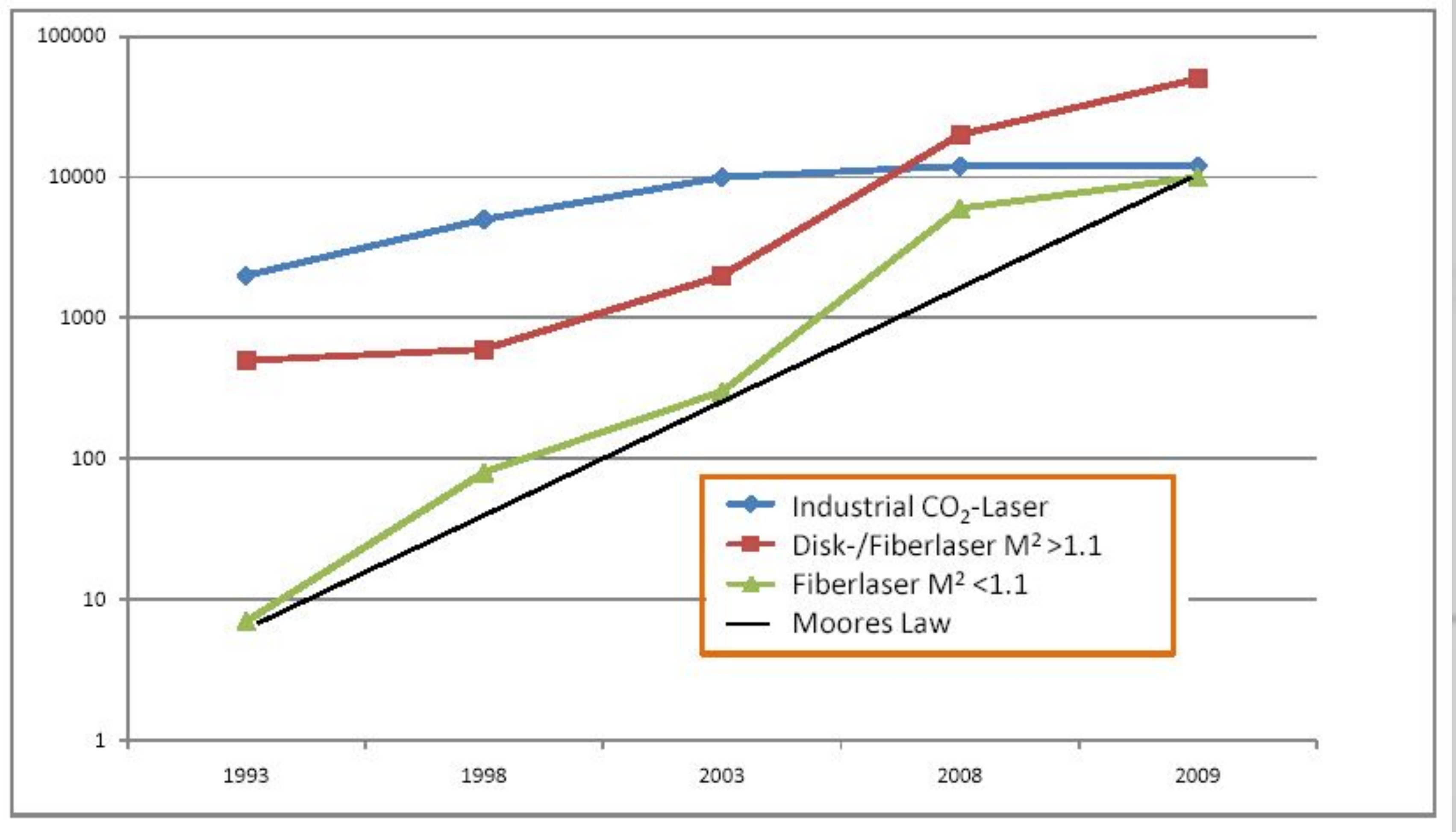
# Introduction

## Beam Quality of Fiber-/Disk-Laser vs $CO_2$-Laser



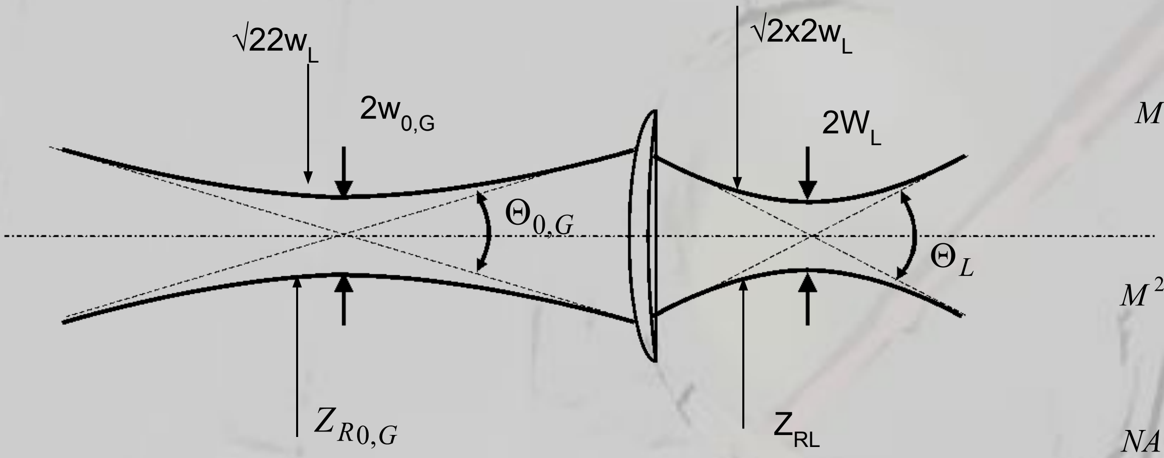
# Introduction

## Power Levels of DPSS-Lasers and Trend of MOOREs Law



# Beam Quality & Brilliance

## Caustic of Gaussian Laser Beam



$$M^2 = \frac{BPP_L}{BPP_G}$$

$$BPP_L = \left( \frac{\lambda_L}{\Pi} x1rad \right) xM^2$$

$$M^2 = NA * d_{fibre}$$

$$F = \frac{f}{D}$$

$$NA = \sin\alpha = \sqrt{n_1^2 - n_2^2}$$

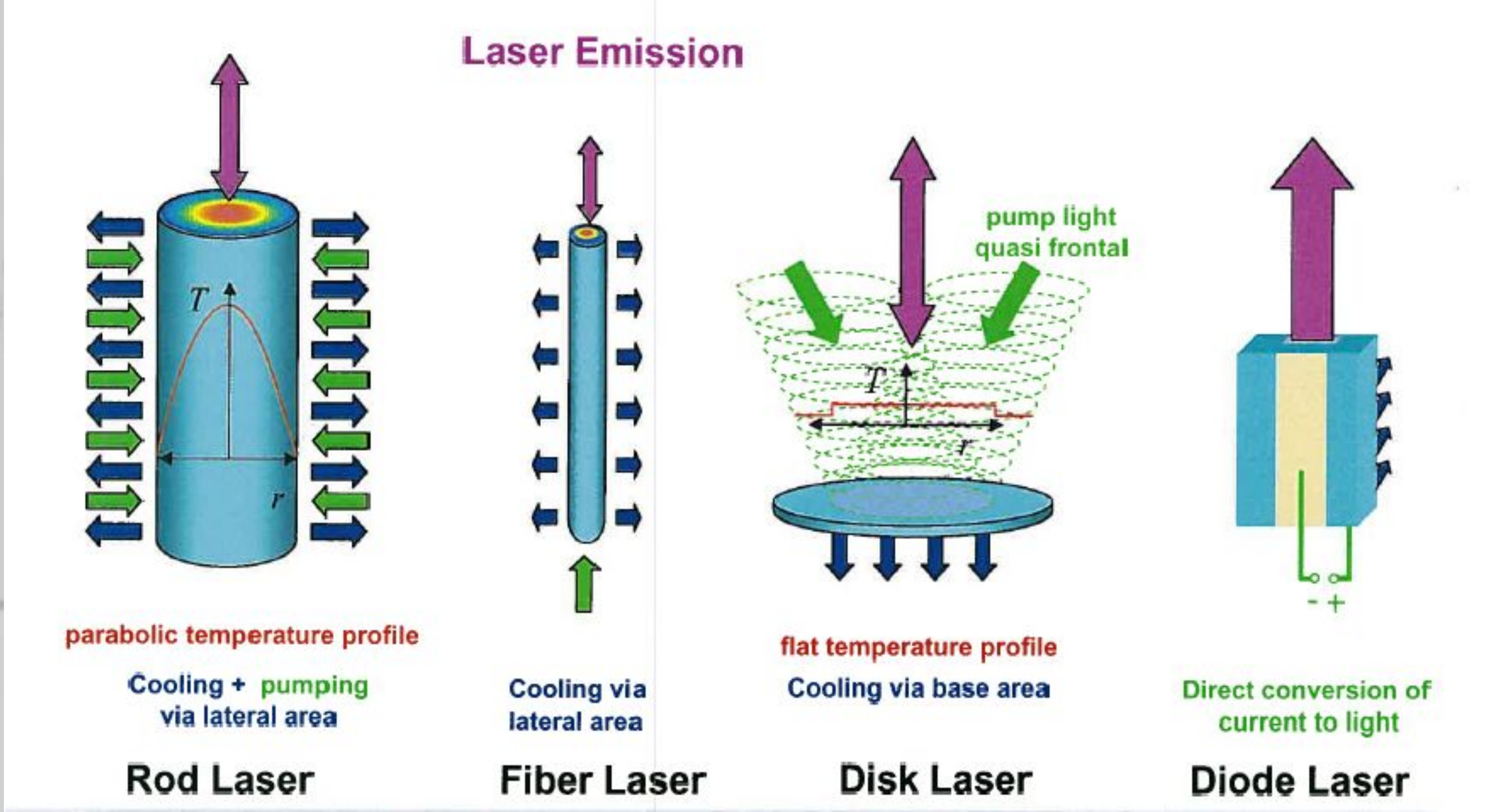
$$d_0 = \frac{4\lambda_L}{\pi} * M^2 * F + \frac{K * D^3}{f^2}$$

$$\boldsymbol{BPP = W_{0,G} * \frac{\Theta_{0,G}}{2} = W_L * \frac{\Theta_L}{2} = \frac{\lambda_L}{\pi} = const}$$

$$B \cong \frac{P_L}{M_x^2 * M_y^2 * \lambda_L^2} \cong \frac{P_L}{BPP^2 * \lambda_L^2} \left[ \frac{W}{m^2 rad} \right]$$

# Solid State 1µm Laser (SSL)

## Current Solid State Laser Concepts



parabolic temperature profile

Cooling + pumping via lateral area

**Rod Laser**

Cooling via lateral area

**Fiber Laser**

flat temperature profile

Cooling via base area

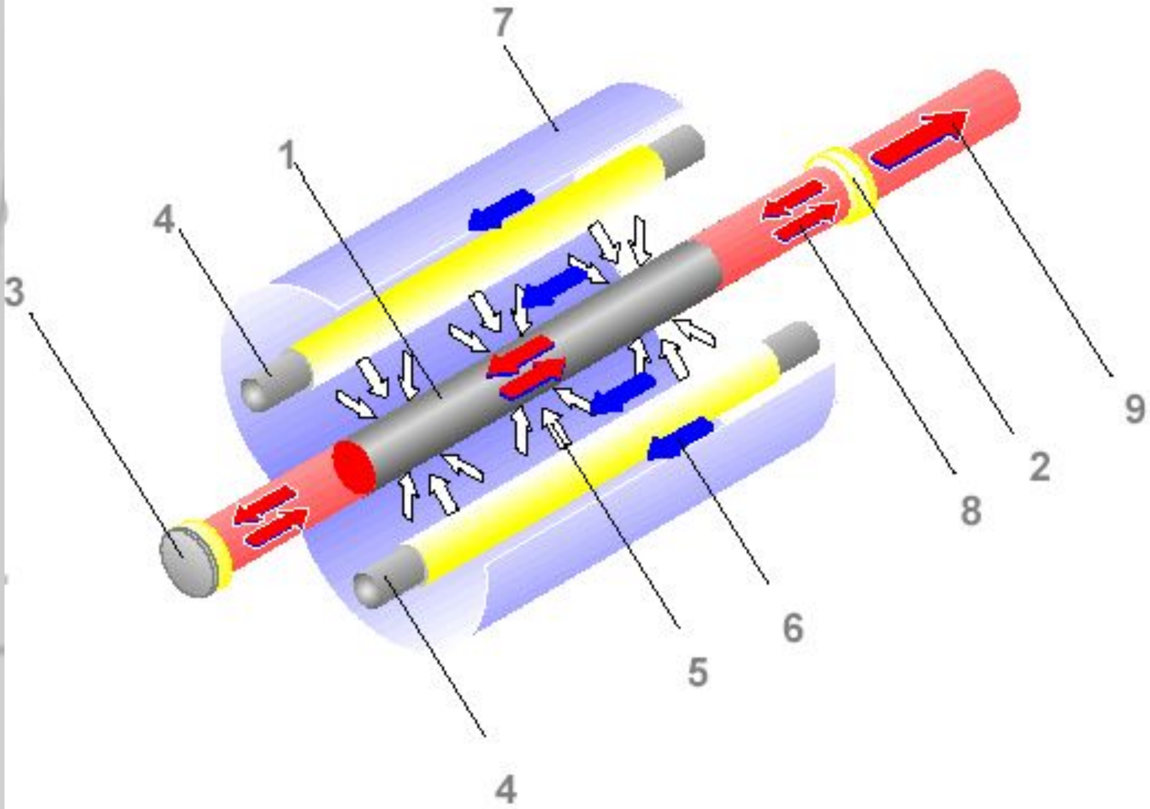
**Disk Laser**

Direct conversion of current to light

**Diode Laser**

# Nd:YAG Rod Laser

## Principle of a Lamp Pumped YAG-Laser



1. Nd:YAG-crystal
2. Output mirror
3. Rear mirror
4. Excitation by light
5. Pump light
6. Cooling water
7. Reflector
8. Stimulated emission
9. Laser beam

# Nd:YAG Rod Laser

## Limits of Rod Lasers, Mechanical Stress

Thermo-Mechanical Parameters limit the max. Thermal Load in a Laser Rod and the resulting max. Stress is Limited by Tensional Failure (Breakage) of the Laser Rod.

$$\frac{P_v}{l} = 8\pi \frac{K(1-\nu)}{\alpha E} \sigma_{\max}$$

W. Koechner „Solid-State Laser Engineering“, Springer, 1999

| with: | | |
|---|---|---|
| | $P_v$ | Dissipated Heat |
| | $l$ | Rod Length |
| | $K$ | Thermal Conductivity |
| | $\nu$ | Poisson Ratio |
| | $\alpha$ | Coefficient of Thermal Expansion |
| | $E$ | Coefficient of Elasticity |
| | $\sigma_{\max}$ | Max. Permitted Tensile Stress at Rod Surface |

The Resulting upper Limit of Dissipated Heat for YAG Material is then

$$\frac{P_v}{l} \approx 200 \frac{W}{cm},$$

independent of Rod-Diameter

# Nd:YAG Rod Laser

## Limits of Rod Lasers, Optical Properties

Parameters for Thermo-Optical Effects Result in the Formation of a Thermal Lens with Focal Length f:

$$f = \frac{KA}{P_v}\left(\underbrace{\frac{1}{2}\frac{dn}{dT}} + \underbrace{\alpha C_{r,\phi} n_0^3} + \underbrace{\frac{\alpha r_0 (n_0 - 1)}{l}}\right)^{-1}$$

W. Koechner „Solid-State Laser Engineering“, Springer, 1999

**Fraction of 70%:**
due to Index of Refraction Change with Temperature

**Fraction of 20%:**
due to Index of Refraction Change with Mechanical Stress

**Fraction of 10%:**
due to change of Optical Path Length by Variation of Rod Length

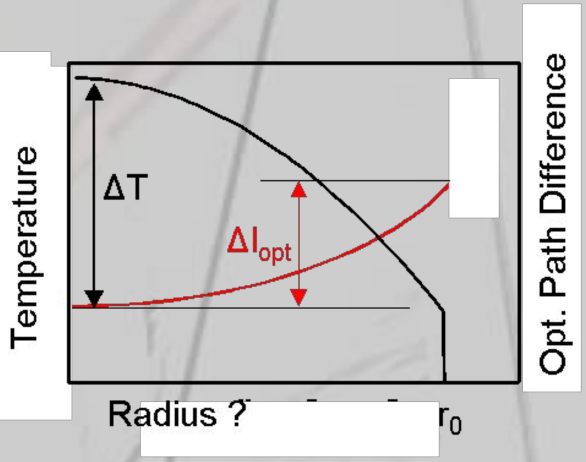
| | | | | |
|---|---|---|---|---|
| with: | K | Thermal Conductivity | $C_{r,\varphi}$ | photoelastic Coefficient |
| | A | Rod Cross-Section | $n_0$ | On-Axis Index of Refraction |
| | $P_v$ | Dissipated Heat | $r_0$ | Rod-Radius |
| | dn/dT | Index of Refraction Change with T | l | Rod-Length |
| | α | thermal Expansion | | |

Typical Focal Length (Order of Magnitude) for Rod Lasers with P = 1kW CW-Power:

$$\infty \geq f \geq 10cm$$

# Nd:YAG Rod Laser

## Limits of Rod Lasers, Focus-ability



Thermal Lens:

$$\infty \geq f \geq 10cm$$

Optical Path Difference between Axial- and Peripheral Rays :

$$50\mu m \leq \Delta l_{opt} \leq 100\mu m$$

Inhomogeneities of Pump-Intensity and Cooling Efficiency result in Degradation of Focusability $M^2$, if:

$$\Delta l_{opt,asph} \geq 0,1\lambda = 0,1\mu m$$

For Distortion free Lasing Homogeneity and also Temporal Stability of the Pump Beam Intensity have to be kept below 0.1%!!!

Focusability Decreases with Laser Power since these Conditions are increasingly difficult to reach!

# Nd:YAG Rod Laser

***Conclusion:***

- The maximum extractable volume power density is limited to $\leq 100\ \mathrm{Wcm}^{-3}$ (typically ≤1kW/rod and for slabs - depending on size - </= 10 kW/slab).

- The typical high BPP (20 to >50 mm*mrad) of multi-rod kW-class Nd:YAG-lasers and the even higher BPP (30 to >80 mm *mrad) for Nd:YAG slabs results in poor focusability

- The Wall Plug Efficiency of rod- and slab-lasers is very low (≤3% for lamp pumped lasers to approx.10% for Diode pumped systems)

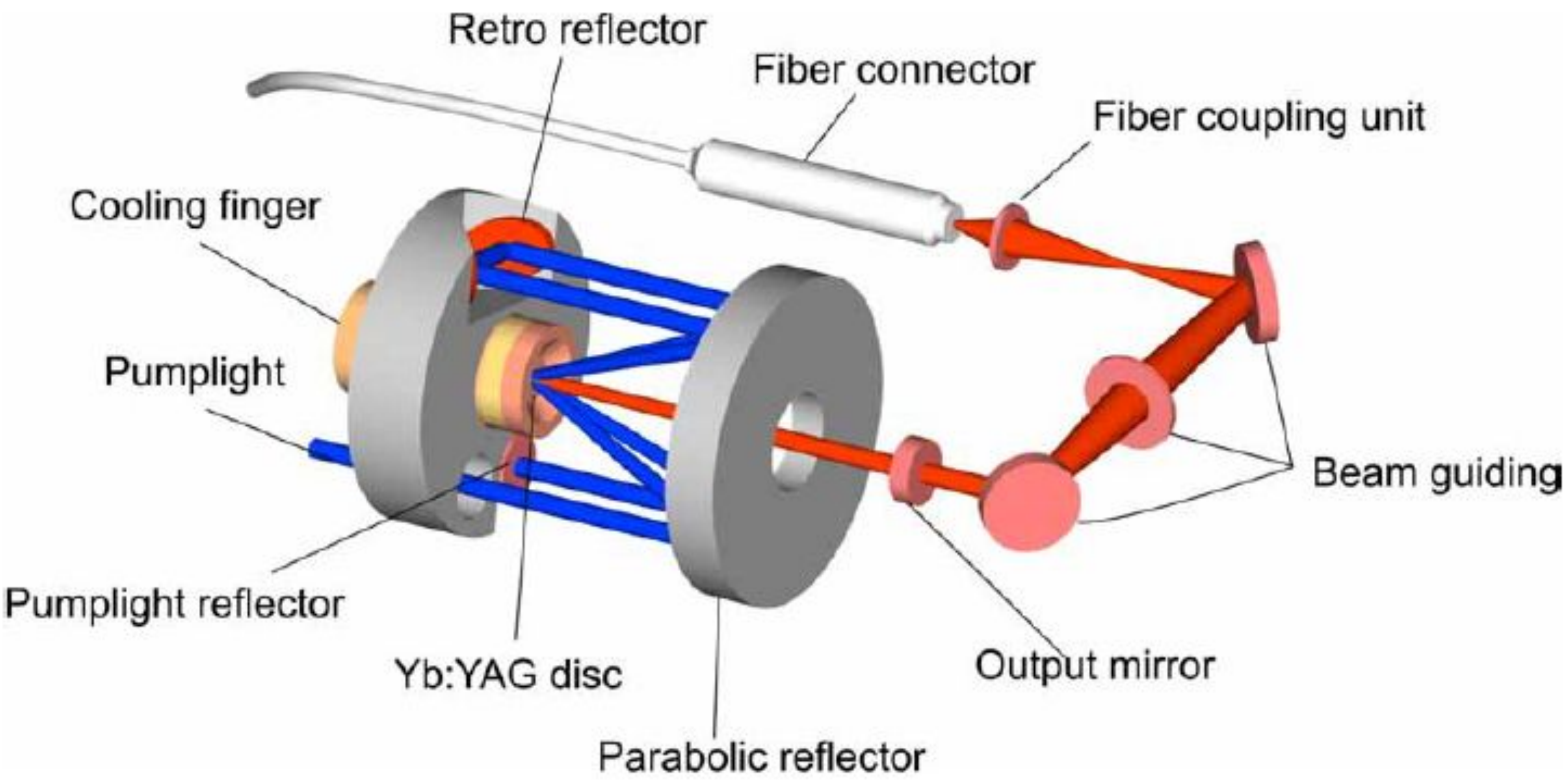
- Rod- and slab-lasers (lamp- or Diode-pumped) suffer from thermal problems due to radial temperature gradients ($\Delta T \approx 50$ K)

- The maximum dissipated heat in a laser rod is limited to ≈ 200 W/cm length and independent of the rod diameter

- Focusability decreases with increased laser power

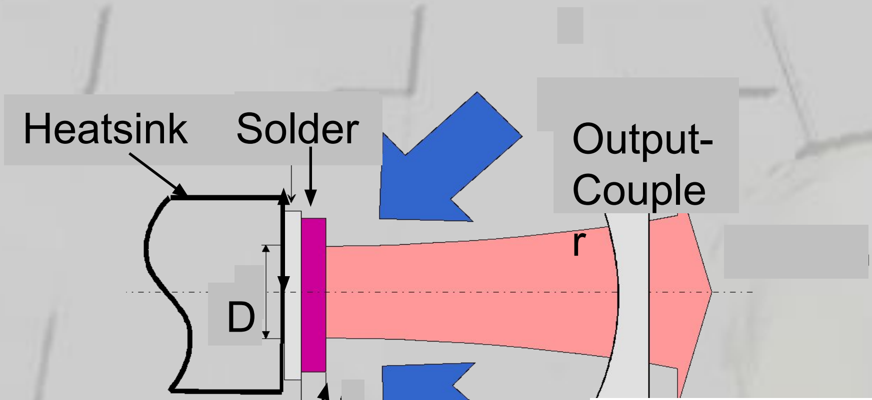
# Yb:YAG Disk Laser

## Disk laser, resonator configuration

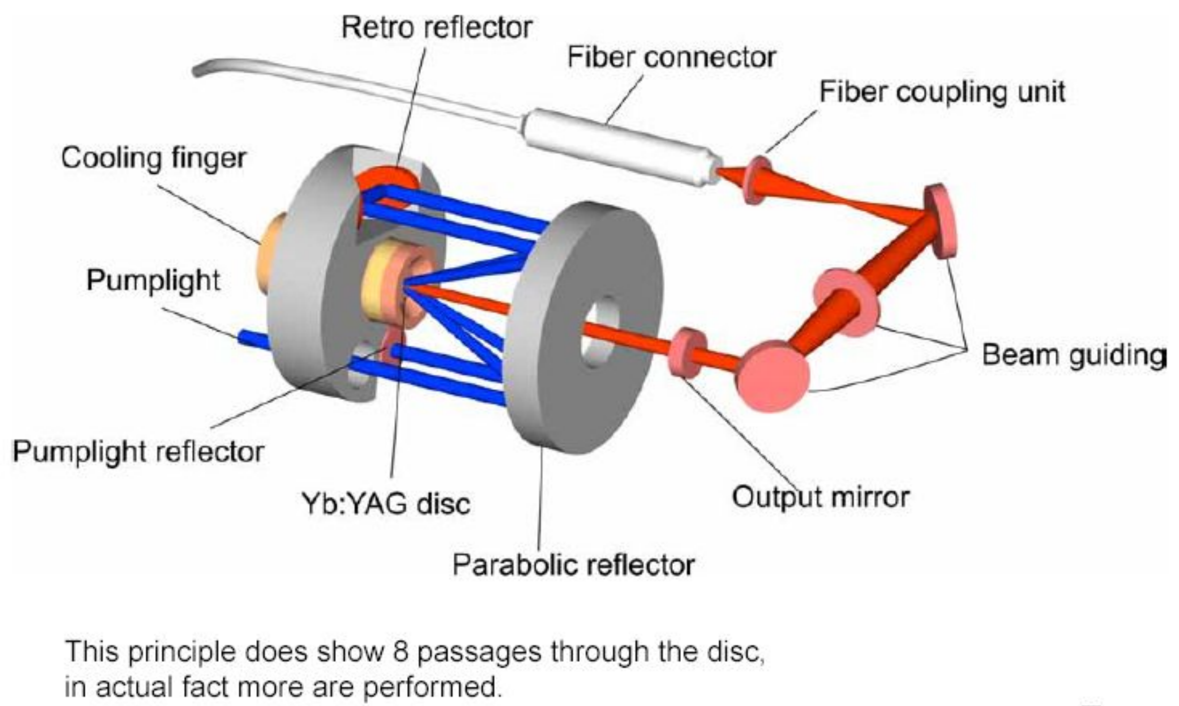


This principle does show 8 passages through the disc, in actual fact more are performed.

# Yb:YAG Disk Laser



Principle of Yb:YAG disk laser



This principle does show 8 passages through the disc, in actual fact more are performed.

# Yb:YAG Disk Laser

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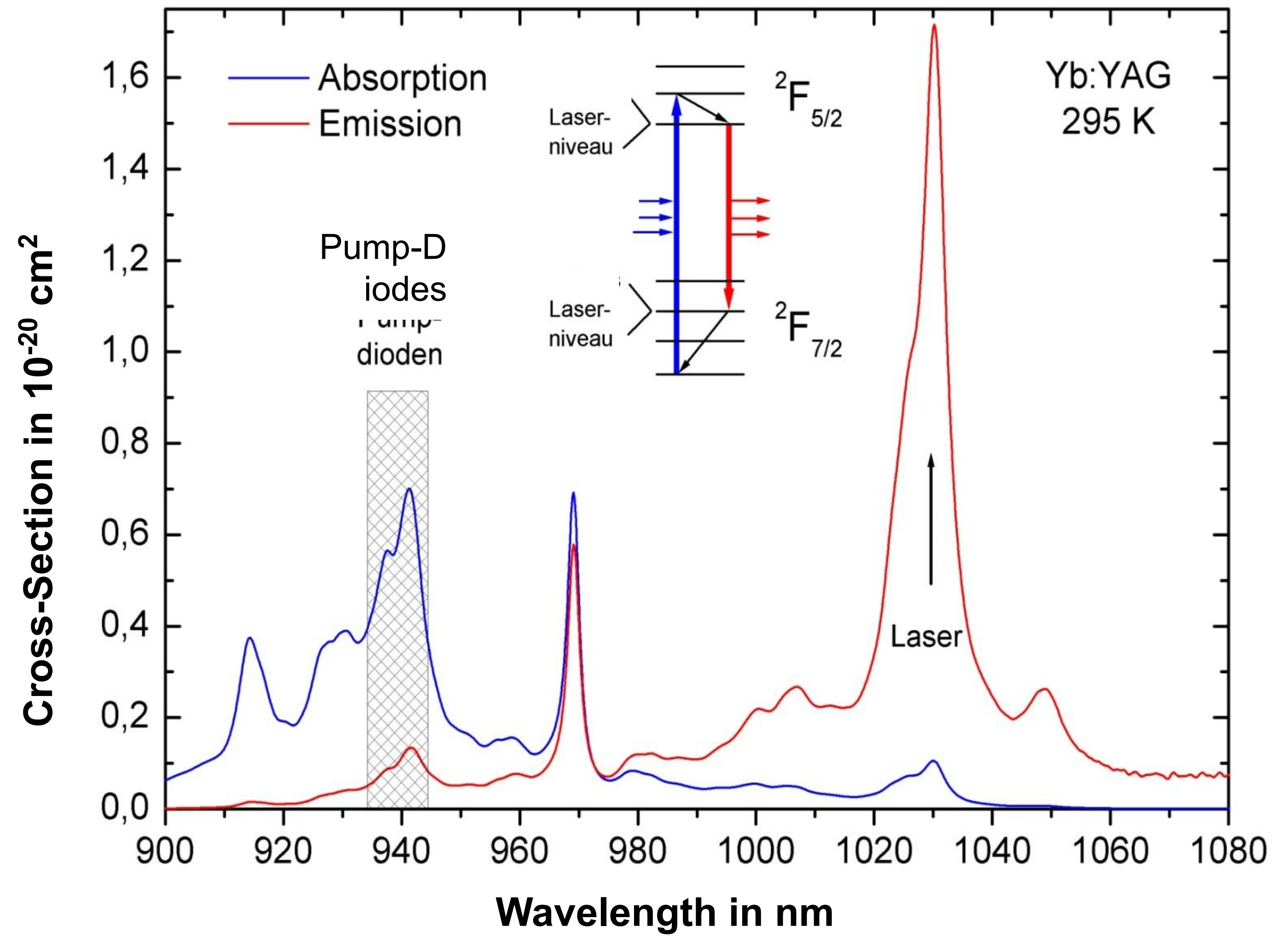
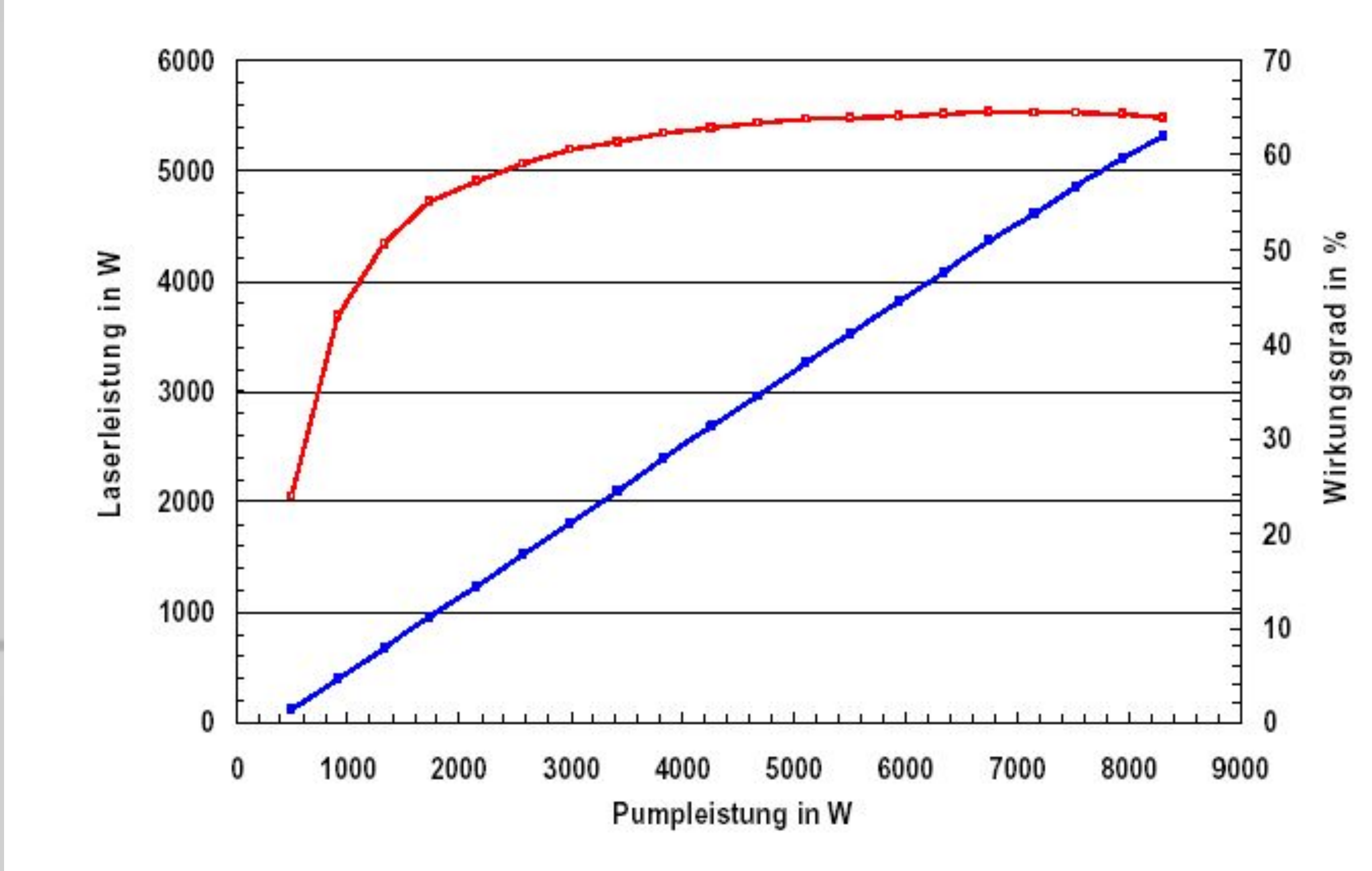
## Yb:YAG Disk Laser: Absorption-, Emission-Spectra



# Yb:YAG Disk Laser

## Pumping Efficiency of a Single Disk



# Yb:YAG Disk Laser

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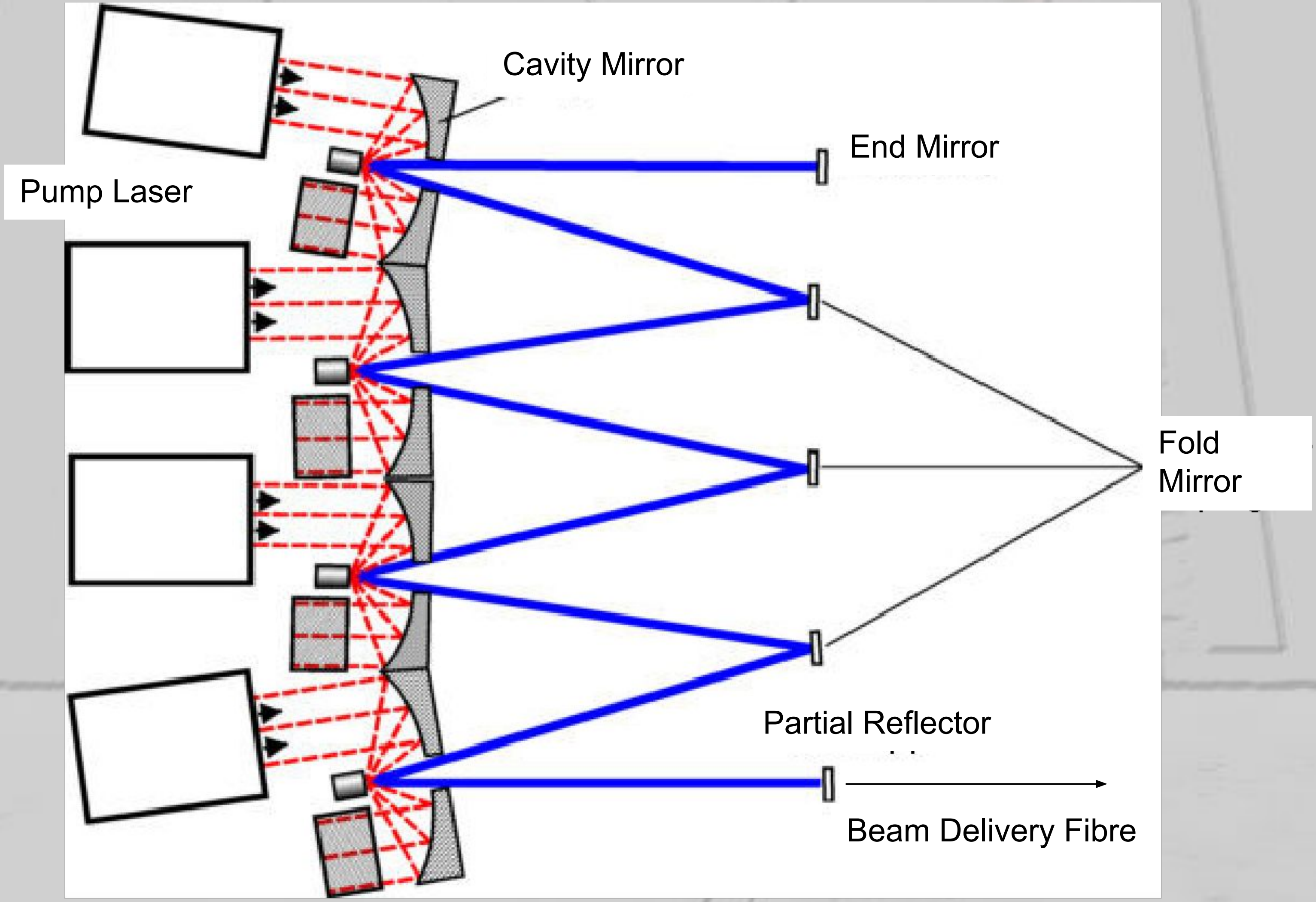
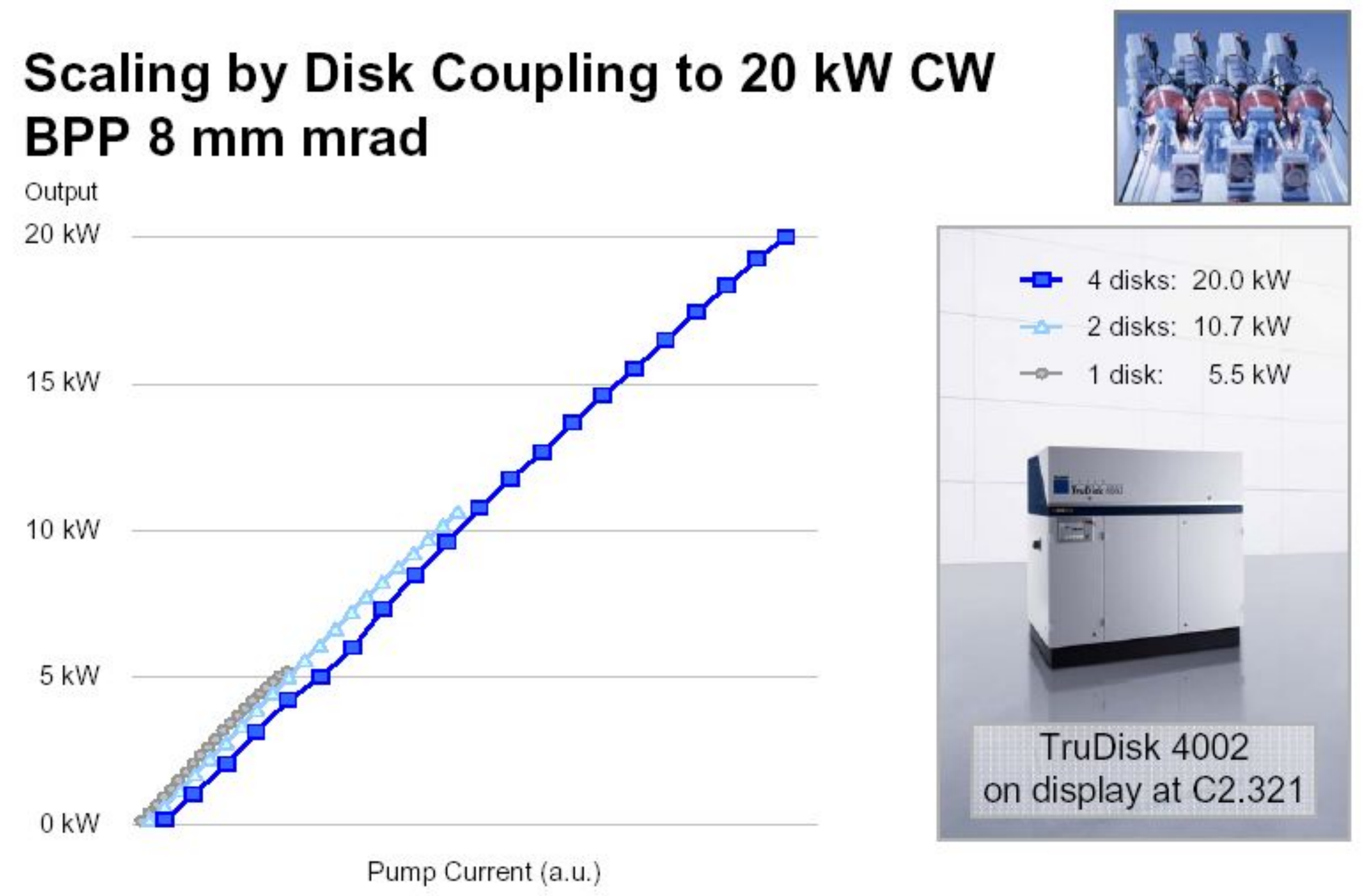
Cavity design for a multiple-disk laser



# Yb:YAG Disk Laser

## Output power scaling with number of disks

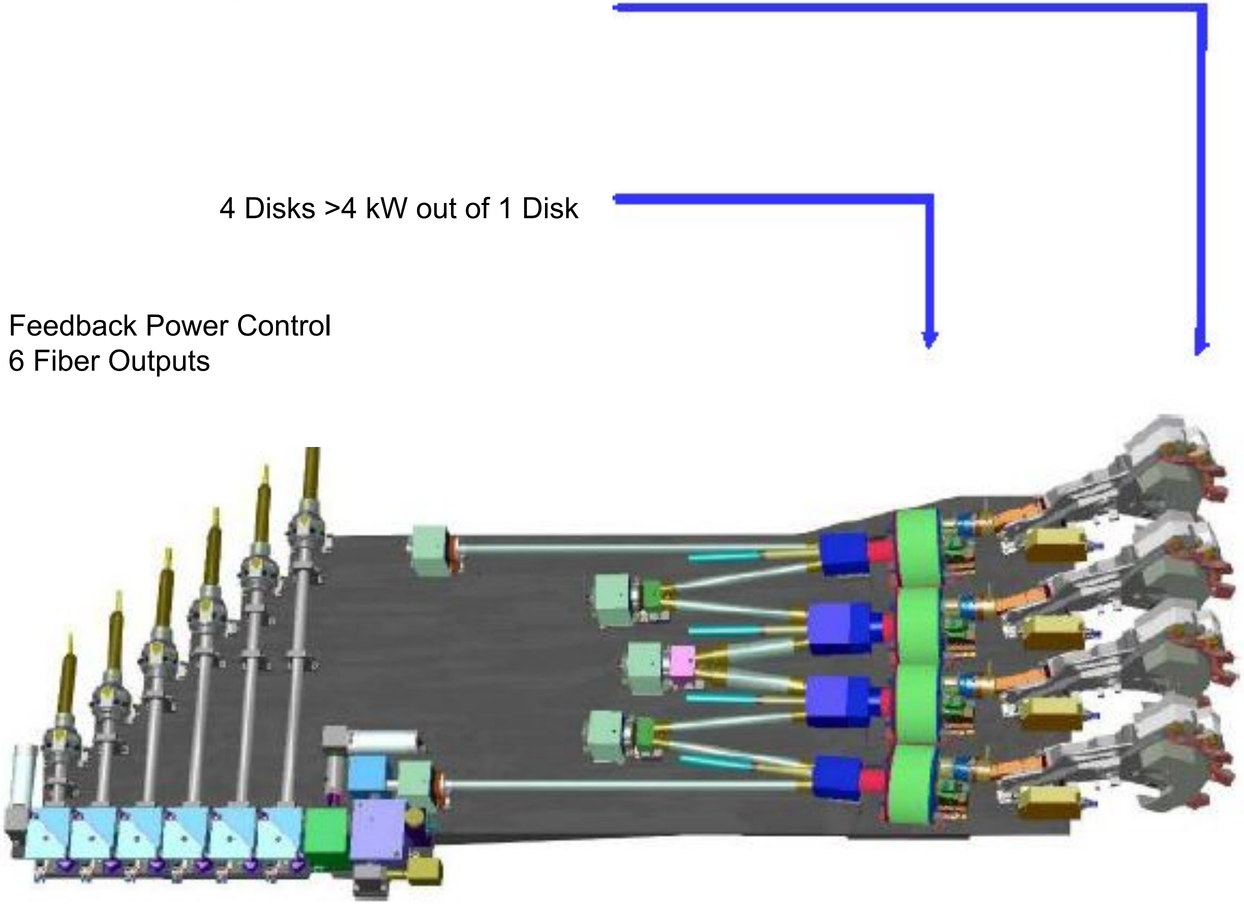


**Scaling by Disk Coupling to 20 kW CW**
**BPP 8 mm mrad**

TruDisk 4002
on display at C2.321

# Yb:YAG Disk Laser

## Configuration of an 16 kW disk laser



4 Pump modules with Diode bars

4 Disks >4 kW out of 1 Disk

Feedback Power Control
6 Fiber Outputs

# Yb:YAG Disk Laser

## Limits of Disk laser, resonator length restriction

Fundamental Mode Operation of a confocal resonator is defined by:

$$N_F = \frac{w_a^{\,2}}{\lambda L} \approx 1$$

$N_F$ Fresnel-number
$W_a$ beam radius at the disk
L resonator-length

For a max. achievable power density of 50 W/mm$^2$ at the disk the beam radius is:

$$w_a^{\,2} = \frac{P_L}{50\pi}\left[mm^2\right]$$

$P_L$ expected fundamental mode laser power

Consequently the resonator lenght as function of laser power is given by:

$$L \approx \frac{w_a^{\,2}}{\lambda} = 6{,}37\cdot 10^{-3}\,\frac{P_L}{\lambda}\left[mm\right]$$

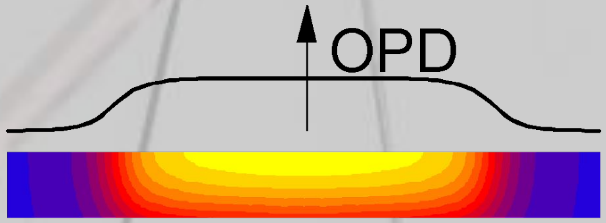
Resonator lenght scales with laser power and reaches 30 m at 5 kW laser power

That long resonators are mechanically and optically not very stable

# Yb:YAG Disk Laser

## Limits of Disk Lasers, phase distortion and optical path difference

The temperature gradient at the edge of the pump-spot results in a phase distortion since the index of refraction in hot Yb:YAG material is different to the cooled outer part of the disk.



Depending on the design the optical path difference is:

$$0{,}1\mu m \leq \Delta l \leq 1\mu m$$

This path difference reduces the efficiency of fundamental mode operation.

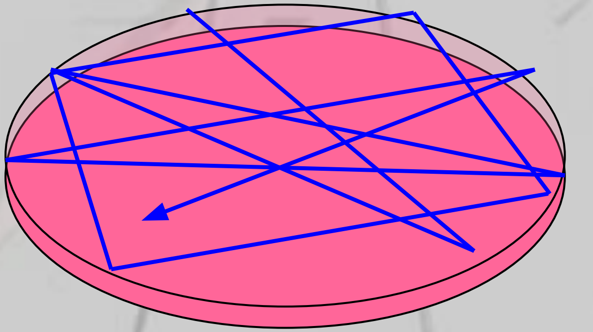
$$0{,}9 \geq \frac{\eta_G}{\eta_{MM}} \geq 0{,}5$$

$\frac{\eta_G}{\eta_{MM}}$ Ratio of $TEM_{00}$- to multi-mode-efficiency

An adaptive mirror in the disk cavity helps to compensate the phase distortion.

# Yb:YAG Disk Laser

## Limits of Disk-Lasers, amplified stimulated emission (ASE)



- Gain Reduction
- Lasing within the disk

Remedy possible by:

Disk diameter >> Pump spot diameter

Special edge shaping to supress volume reflexion

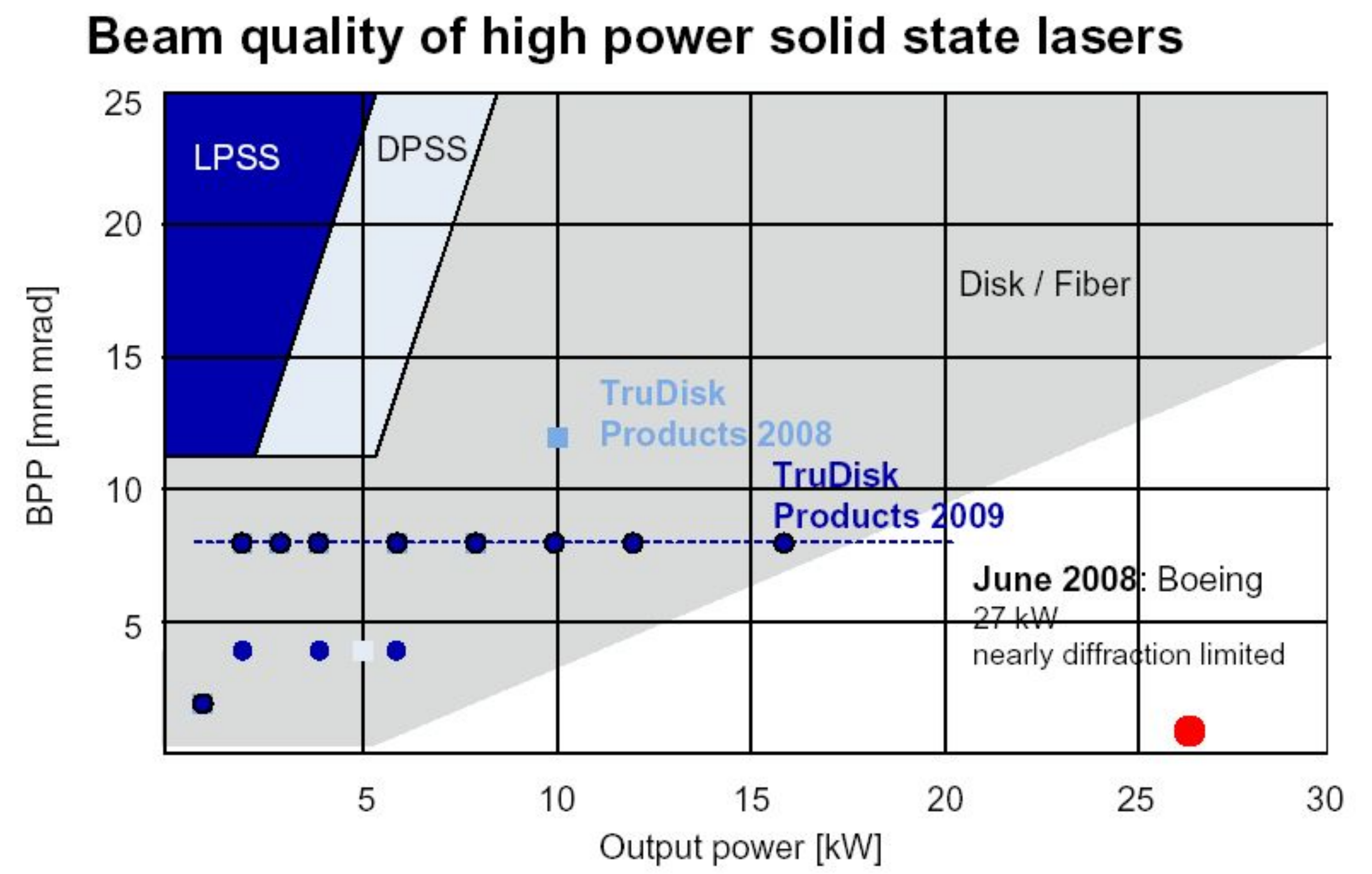
ASE limits the maximal power / disk to:

$30kW < P_L < 1MW$ depending on the design

The resulting maximal extractable power density per disk is therefor:

$$\frac{P_L}{A} \approx 10 \frac{kW}{cm^2}$$

# Yb:YAG Disk Laser



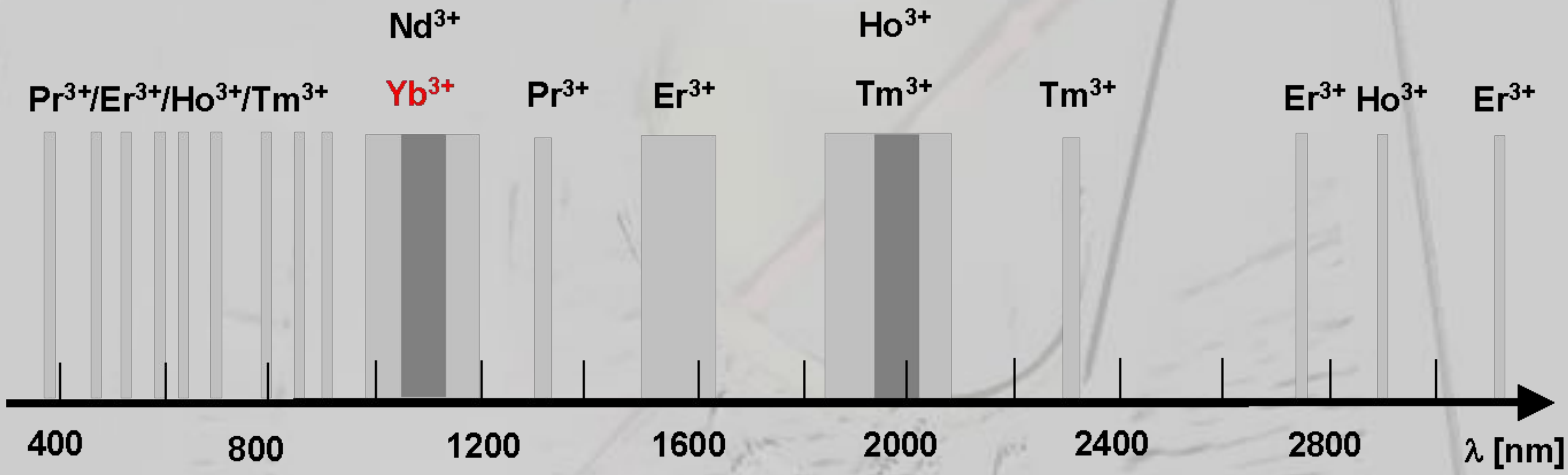
# Yb:YAG Disk Laser

***Conclusion:***

- The maximum extractable volume power density per disk ≈ 1 MW/cm$^3$ resulting in extractable power density of 10 kW/cm$^2$: …100 kW/disk possible
- The low BPP of industrial multi-disk kW-class laser results in good focusability
- High Wall Plug Efficiency (e.g. >/= 27% at the work piece)
- Conventional (folded) Resonator allows for tailoring of the BPP and very compact design (important features for material processing)
- Low resonator power-density (back-reflex insensitivity)
- Effective pumping (≈65% optical efficiency)

# Yb-Fiber Laser

## Emission Spectrum of Fiber Lasers

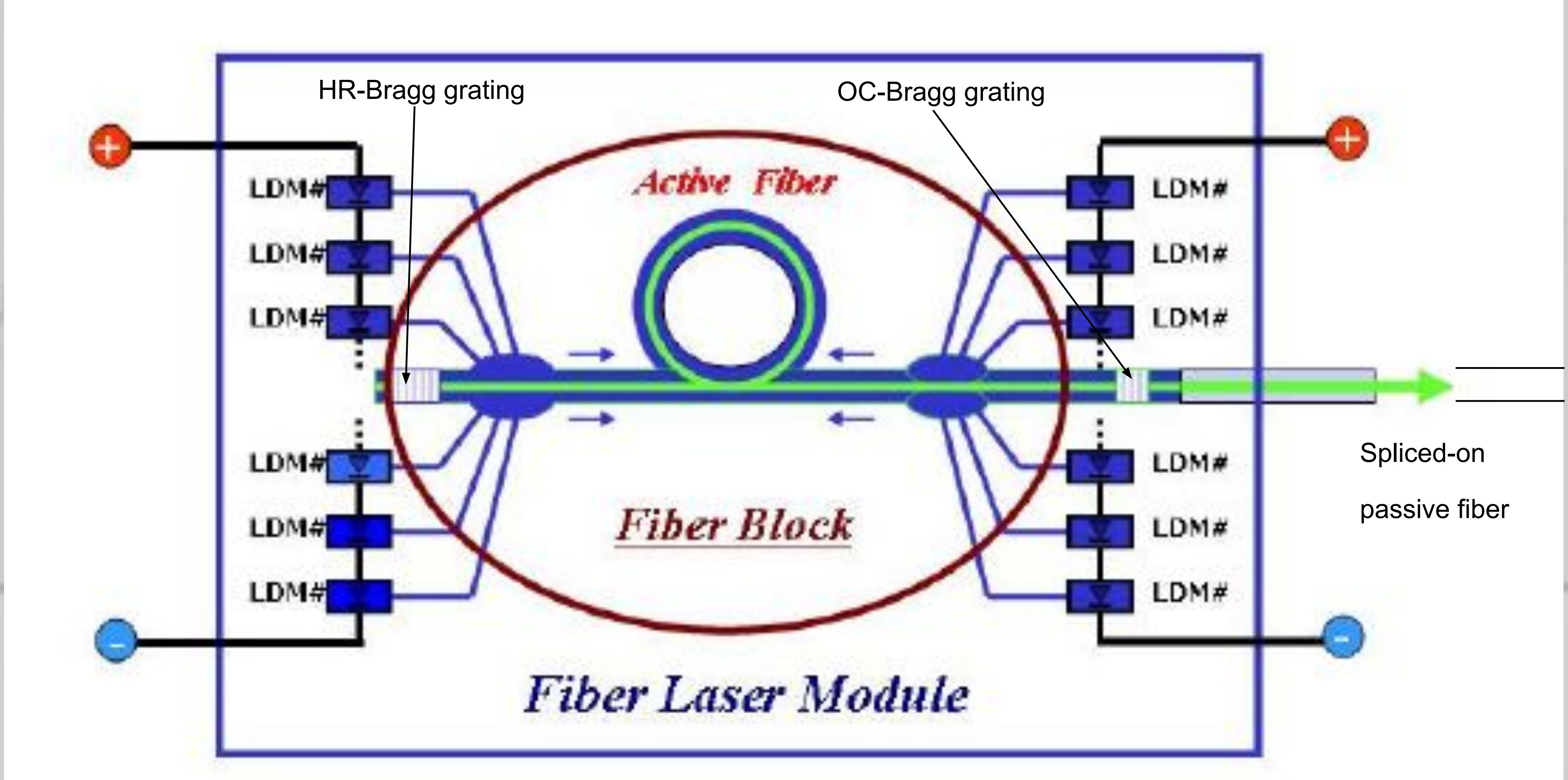


**first demonstration of a fiber laser: in the early sixties !**

E. Snitzer, “Neodymium glass laser,” Proc. of the Third International conference on Solid Lasers, Paris, page 999 (1963).
C.J. Koester and E.Snitzer, “Amplification in a fiber laser,” Appl. Opt. 3, 10, 1182 (1964).

# Yb-Fiber Laser

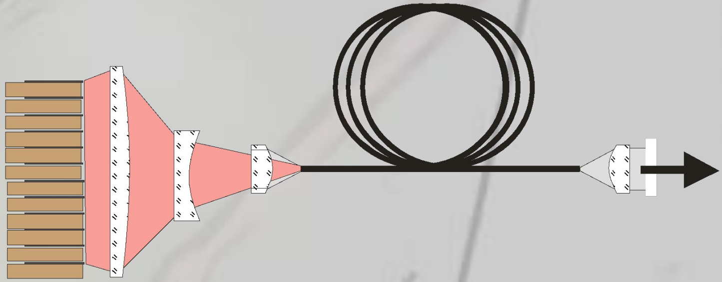
High power single emitter pumping



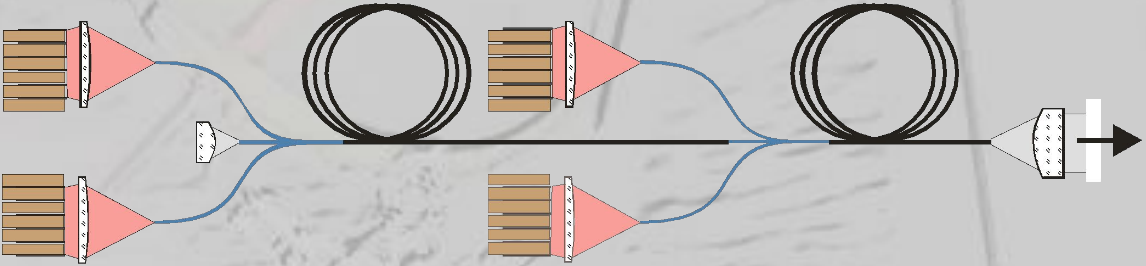
# Yb-Fiber Laser

## Pump Concepts for Fiber Laser

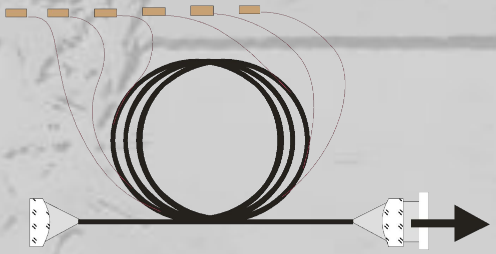
**End-on-Pumping by high power diode laser Stacks**



**Pumping by several small Stacks**



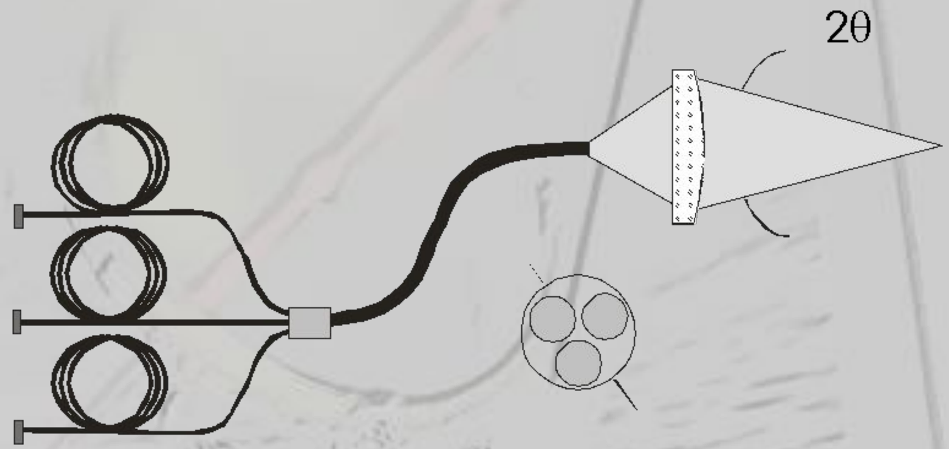
**Pumping by many individual Single Mode Emitters**



# Yb-Fiber Laser

## Scaling of output power by means of beam combination

- incoherent beam superposition
- total output power scales with number of modules
- max. theoretical beam quality scales with $P_0^{1/2}$
- real beam quality approximately
  2 - 5 times lower
  (due to losses)



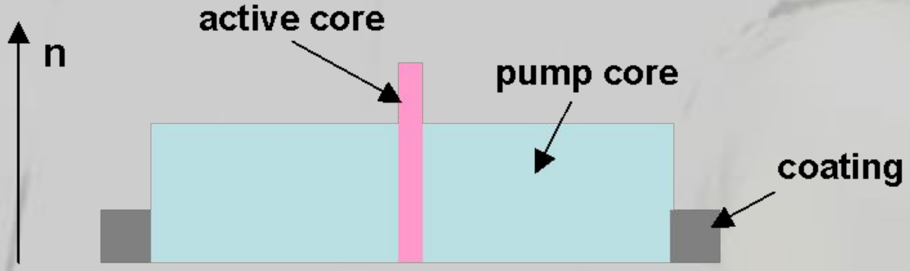
Beam quality : $Q = \theta \bullet w \propto \sqrt{P_{total}}$

Example : 60 modules, 100 W each = 6 kW

Max. beam quality = $8 * Q_0$

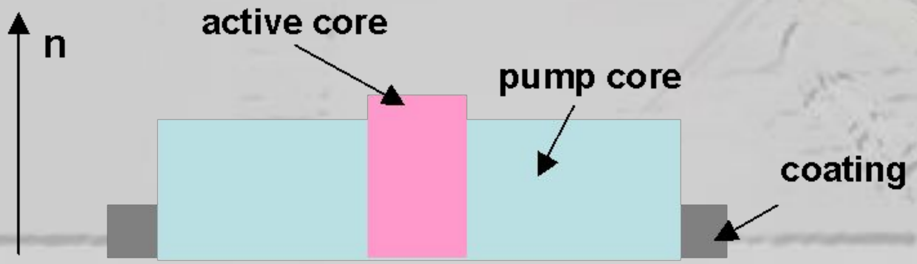
# Yb-Fiber Laser

## Low NA large mode area fiber design



core ∅ <10 µm
core NA = 0.1 – 0.2
absorption length > 20 m

**double-clad large-mode-area fiber**



core ∅ = 30 .. 40 µm
core NA = 0.06 .. 0.08
absorption length < 10 m

**increased mode-field diameter**
**reduced fiber length**

→ **reduced nonlinearity**

# Yb-Fiber Laser

## Limits of Fiber Lasers, power limitations for active fibers

1. **Available power per unit length of fibre**
   Heat loss within the core material,
   Thermal flux through inner and out cladding,
   Heat transfer by air or water

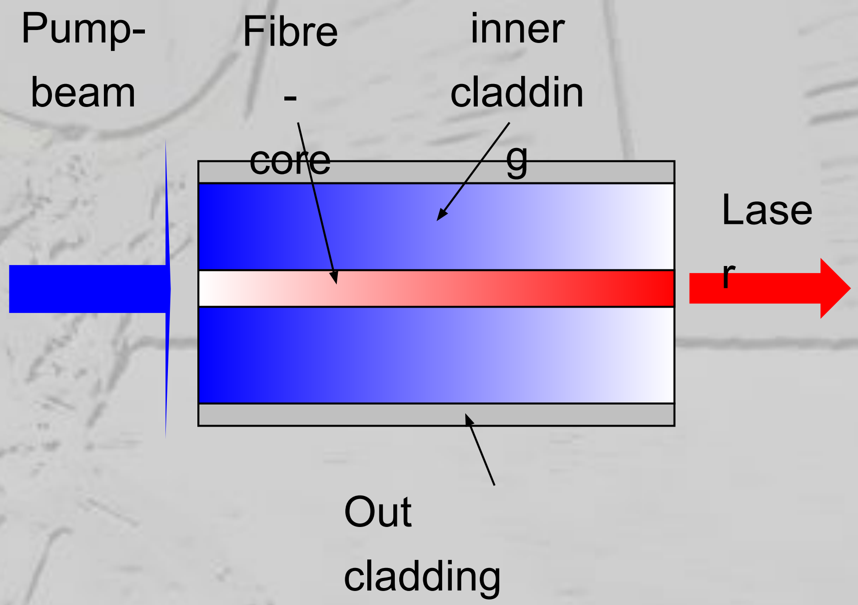
Temperature limits laser power per length unit

For water cooling this limit amounts to:

$$\frac{P_L}{l} \approx 1200 \frac{W}{m}$$

For a 40 µm diameter core
the max. extractable volume power density is therefor:

$$\frac{P_L}{V} \approx 1 \frac{MW}{cm^3}$$



# Yb-Fiber Laser

## Limits of Fiber Lasers,limiting effects of quartz damage threshold and SRS

**Power density of fibre core and -endfaces**

Damage threshhold of quartz: $E_{\max} \approx \frac{1GW}{cm^2}$

For a fibre core diameter of 40 µm results then:

$$P_{L,\max} \approx 9kW$$

Stimulated Raman Scattering SRS (non linear effect) limits the internal power:

Max. power limited by SRS:

$$P_{SRS} \approx 16 \cdot \frac{A_{eff}}{L_{eff} g_R}$$

| | |
|---|---|
| $P_{SRS}$ | max. power out of the fibre |
| $A_{eff}$ | effective area of the fibre core |
| $L_{eff}$ | effective fibre length |
| $g_R$ | Raman gain coefficient |

Power scaling possible by:
- increasing of the core diameter
- Shortening of fibre length

# Yb-Fiber Laser

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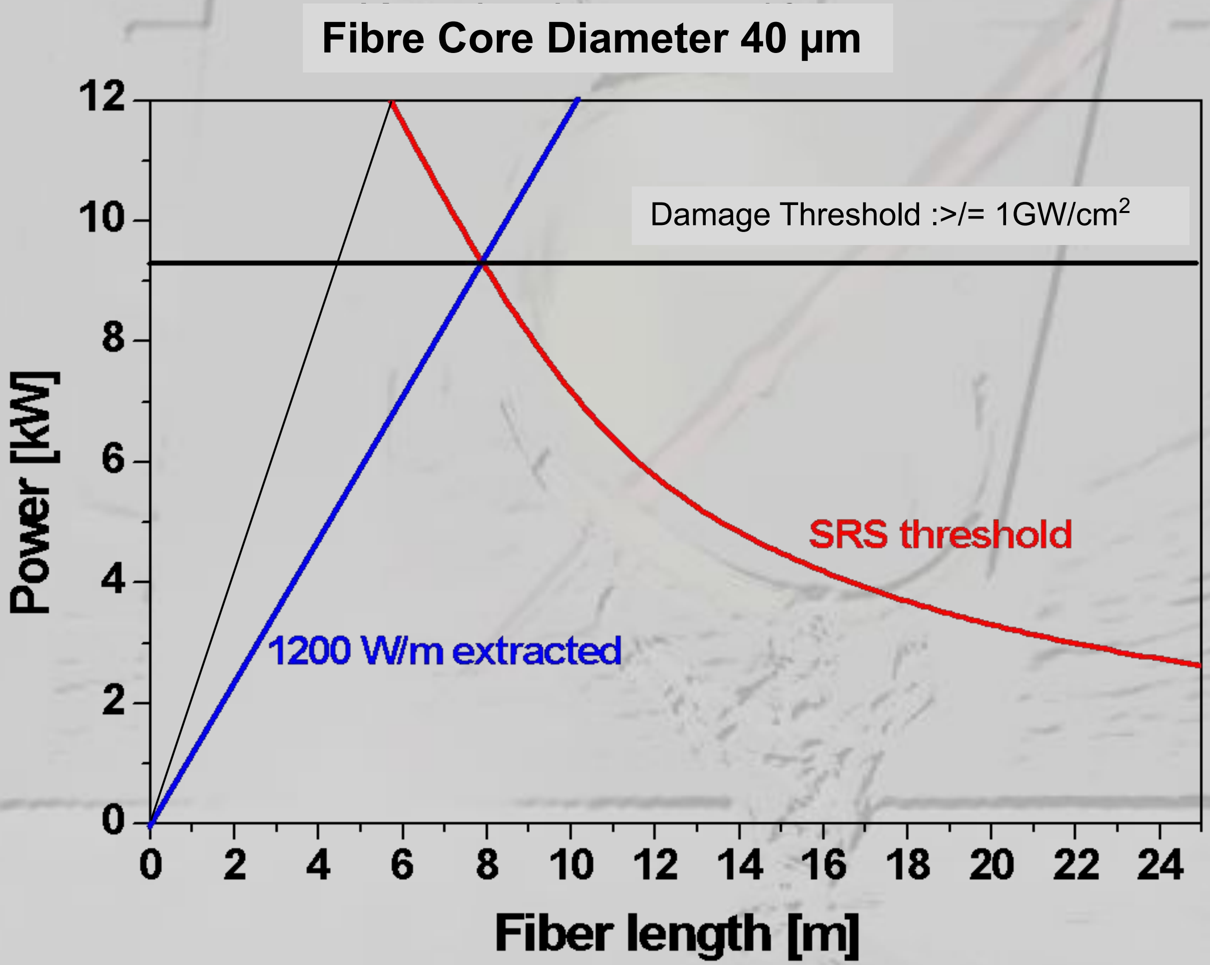
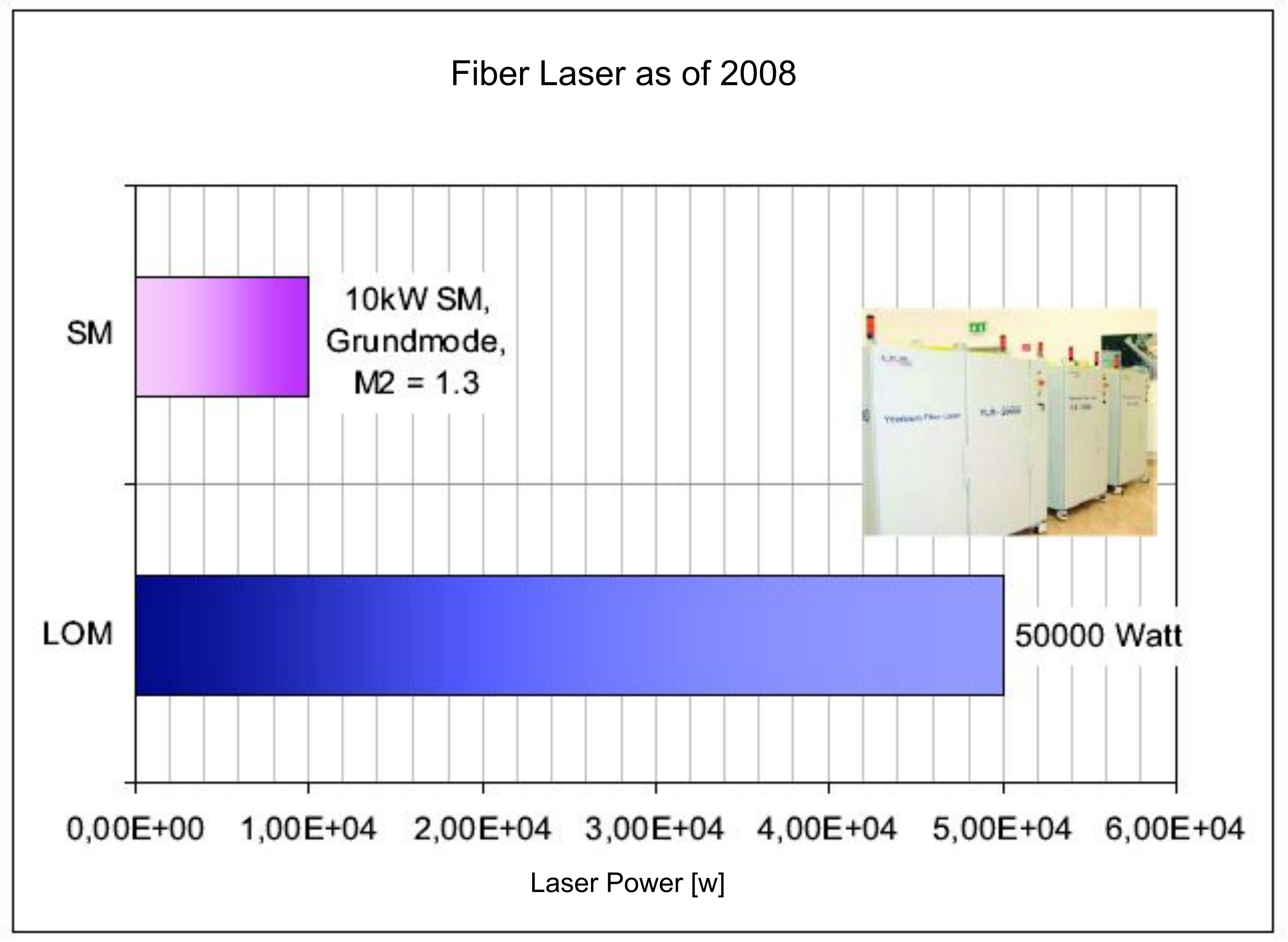
Limitations of fundamental mode fiber lasers with present technology



**10 kW fundamental mode fibre laser is possible**

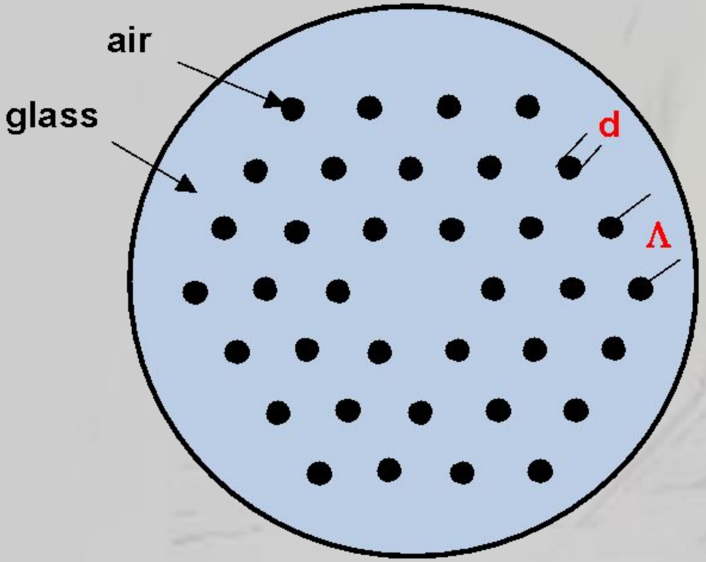
# Yb-Fiber Laser

## Beam quality and laser power of commercial fiber lasers

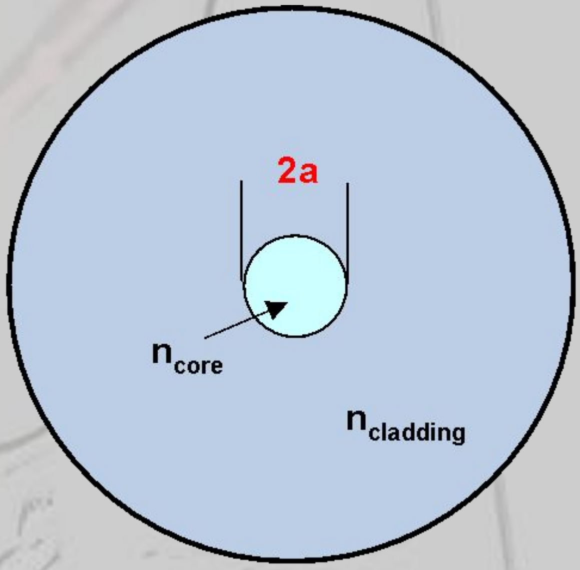


# Yb-Fiber Laser

## Design of large mode area fibers



microstructured fiber



step-index fiber

➔ $\Delta n \sim 1\cdot10^{-4}$

NA ~ 0.02

➔

➔ $\Delta n \sim 1\cdot10^{-3}$

NA ~ 0.06

# Yb-Fiber Laser

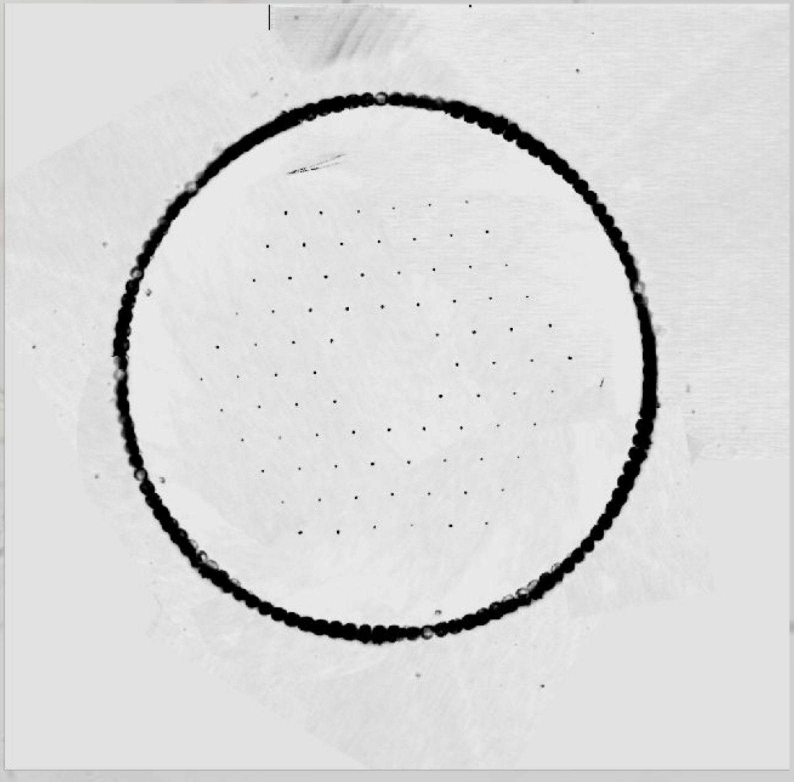
## Design of multi-kW photonic chrystal fiber

core diameter: 42 µm (~30 µm MFD)

laser core NA: ~0.03

pump core diameter: 500 µm

pump core NA: ~ 0.6



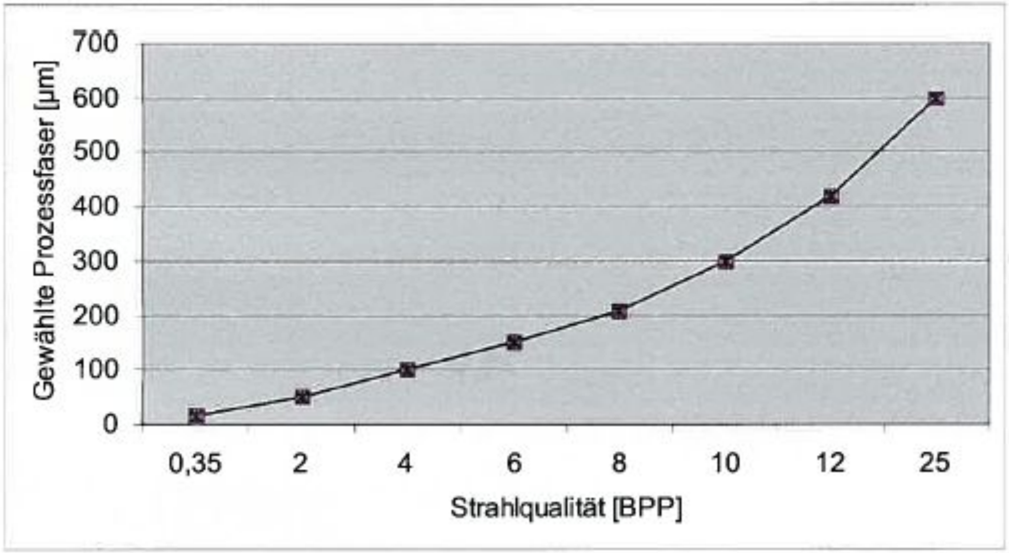
# Yb-Fiber Laser

***Conclusion:***

- The maximum extractable volume power-density may reach 1 MW/cm$^3$: …>/=10 kW/fiber with fundamental mode possible
- The very good low BPP of a multiple-fiber kW-class Yb-fiber laser results in very good focusability (depending on design: < 10 mm*mrad)
- The Wall Plug Efficiency of fiber lasers is very high (i.e. ≈ 30%)
- Power scaling by incoherent beam superposition
- With the availability of Large Mode Area (LMA) fibers multi-kW fundamental mode lasers offer highest beam quality and brilliance.

# Yb-Fiber Laser

## Beam Parameter Product vs Fibercore Diameter



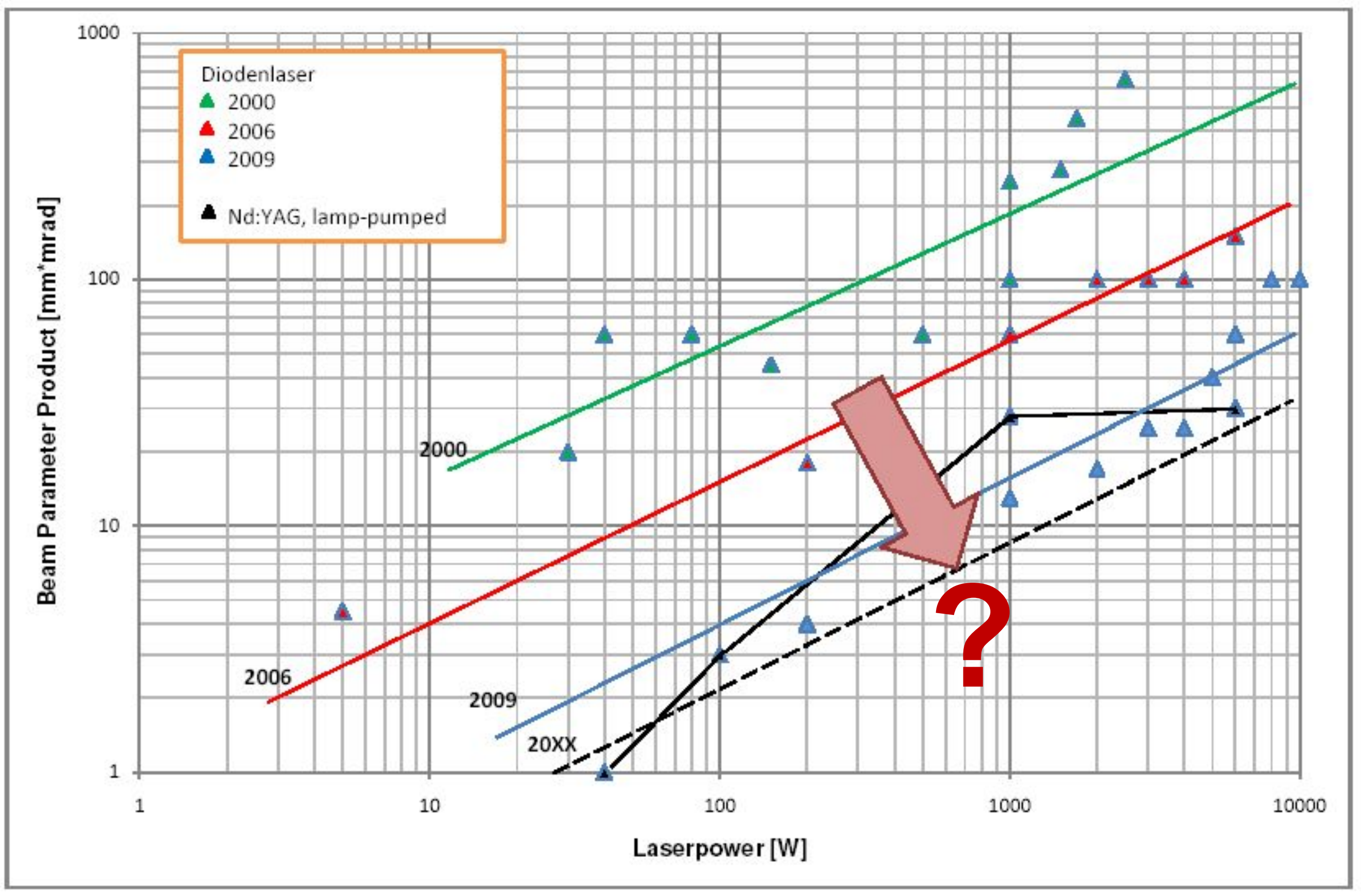
Beam Quality in dependence from Fiber Diameter

free accesseable Processfiber

$d_o$ = 15µm, BPP = 0,35 mm mrad
$d_o$ = 50µm, BPP = 2 mm mrad
$d_o$ = 100µm, BPP = 4 mm rad
$d_o$ = 150µm, BPP = 6 mm rad
$d_o$ = 200µm, BPP = 8 mm mrad
$d_o$ = 600µm, BPP = 25 mm mrad

# High Power Diode Laser

## Beam-quality of Diode Lasers



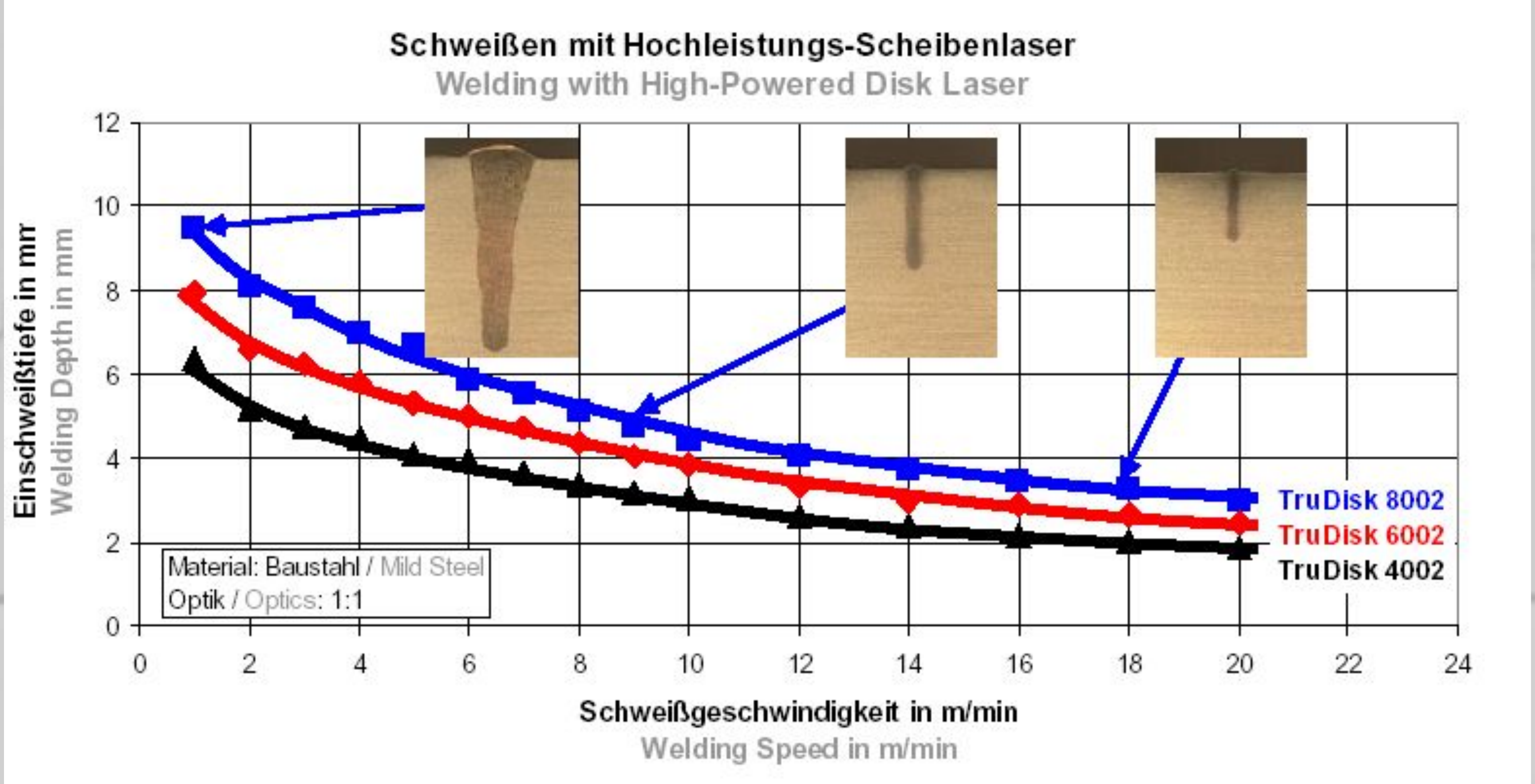
# High Power Diode Laser

***Conclusion:***

- High power diode lasers offer highest wallplug efficiency (e.g. 40-50%)
- The beam quality of multi-kW Diode lasers at present is comparable to lamp-pumped YAG-lasers
- Lifetime of Diodes, stacks and bars has increased considerably (>50.000h)
- Wavelength combining of several high power Diode modules possible
- Fiber Optic delivery is state of the art

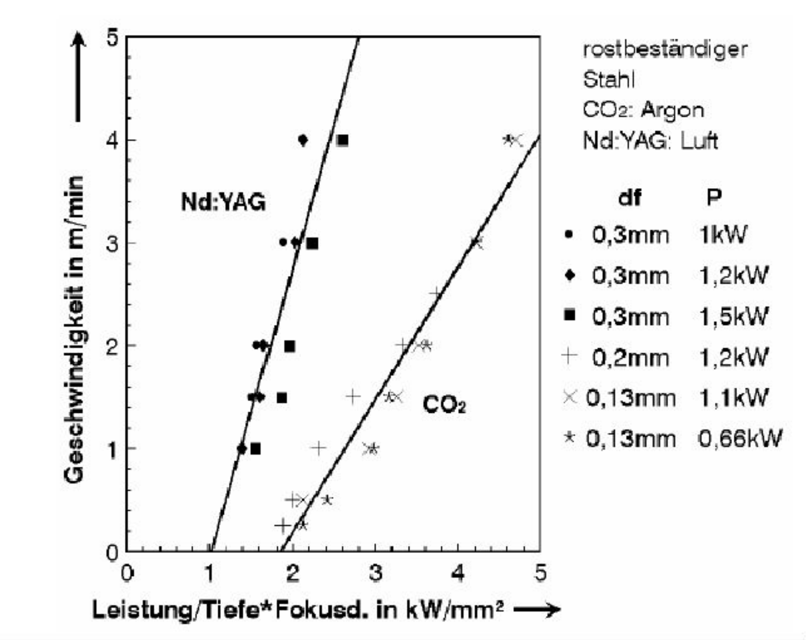
# Applications

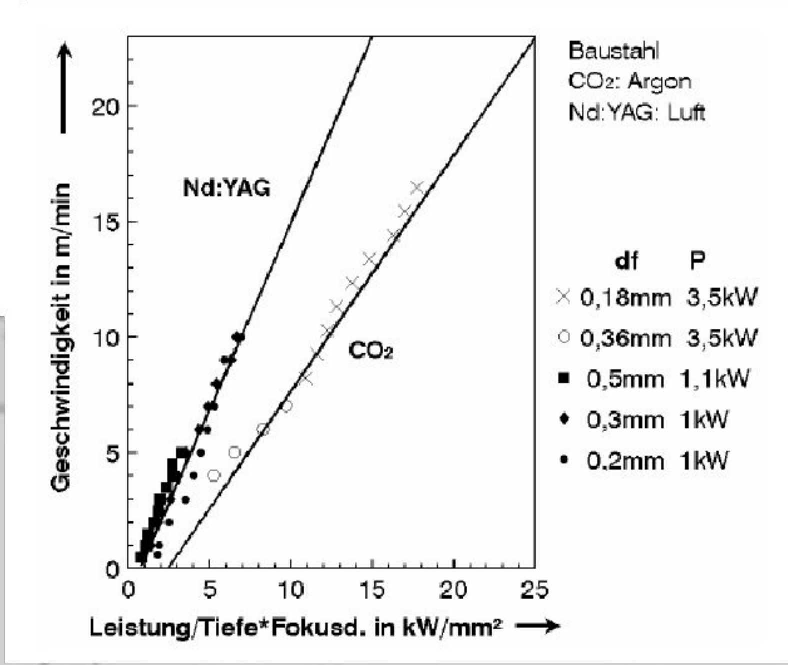
## Welding results with disk lasers



# Applications

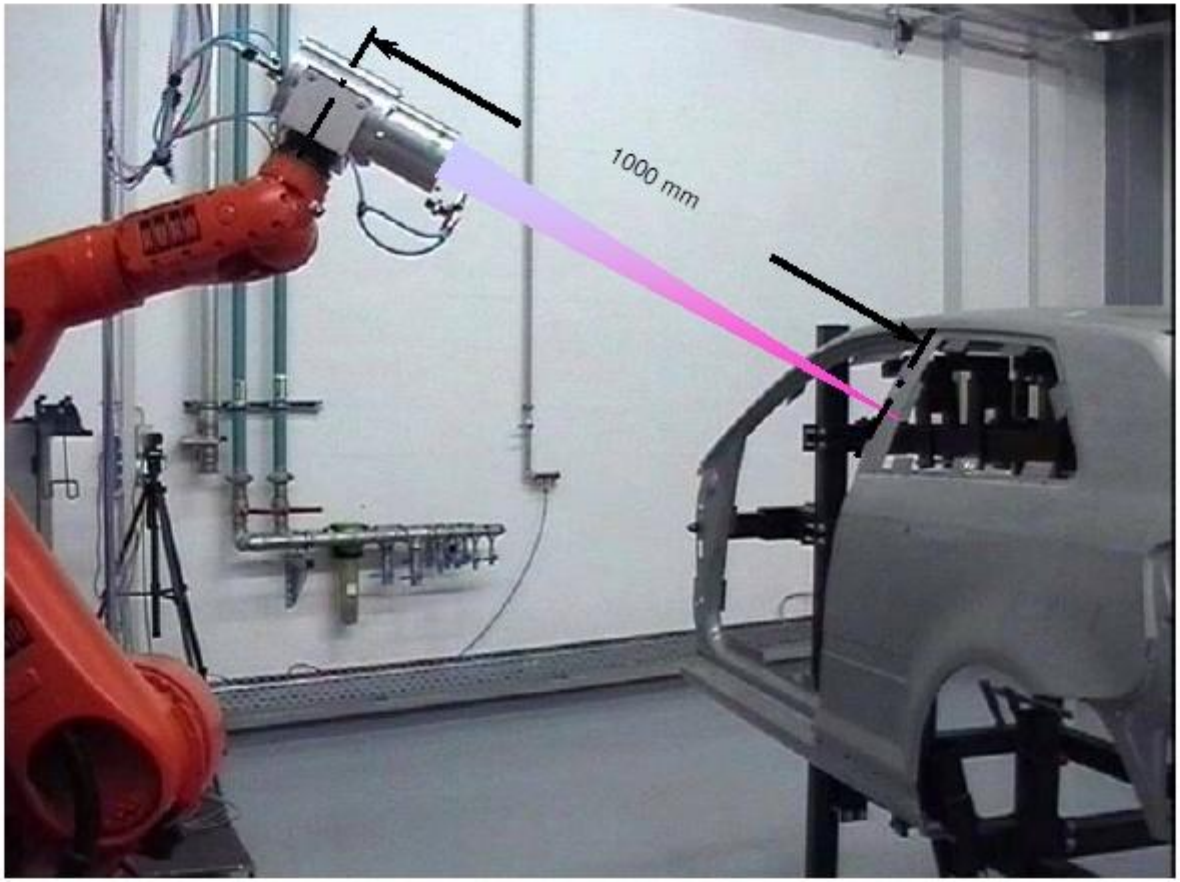
## Welding efficiency of $CO_2$- vs YAG-laser





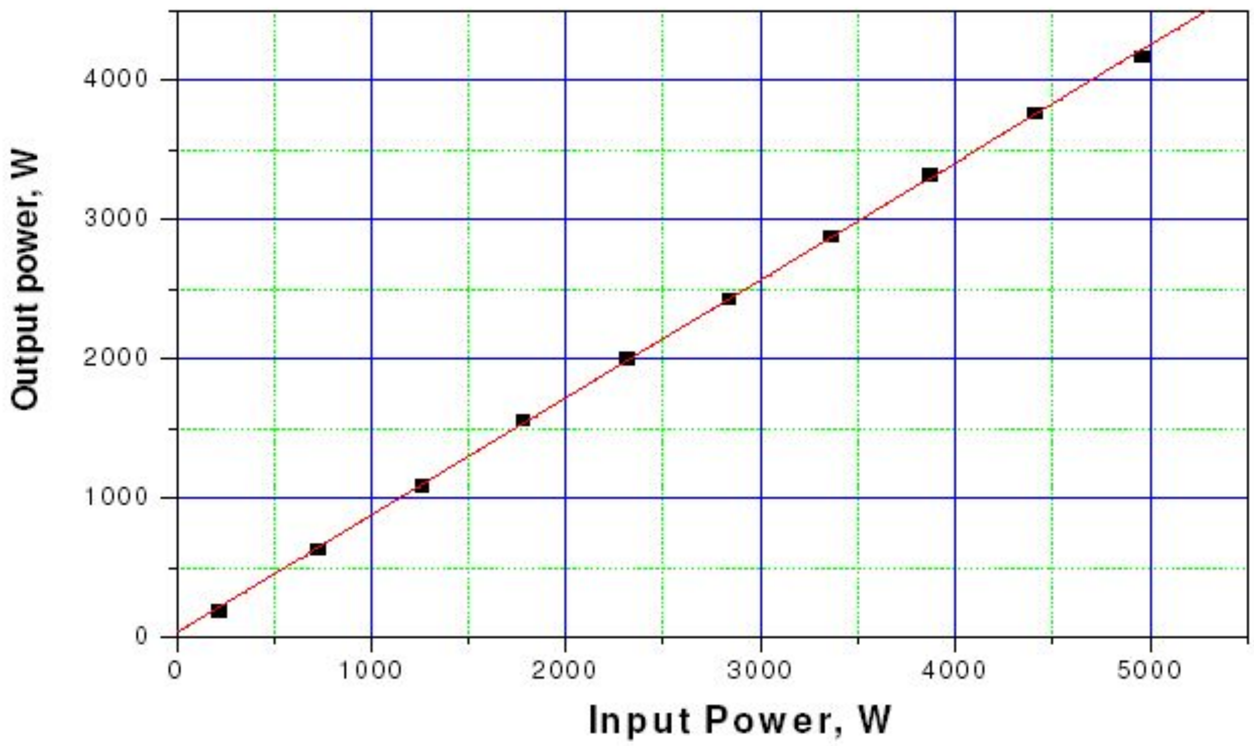
# Applications

## Remote Welding



High productive production of body in white

# Applications

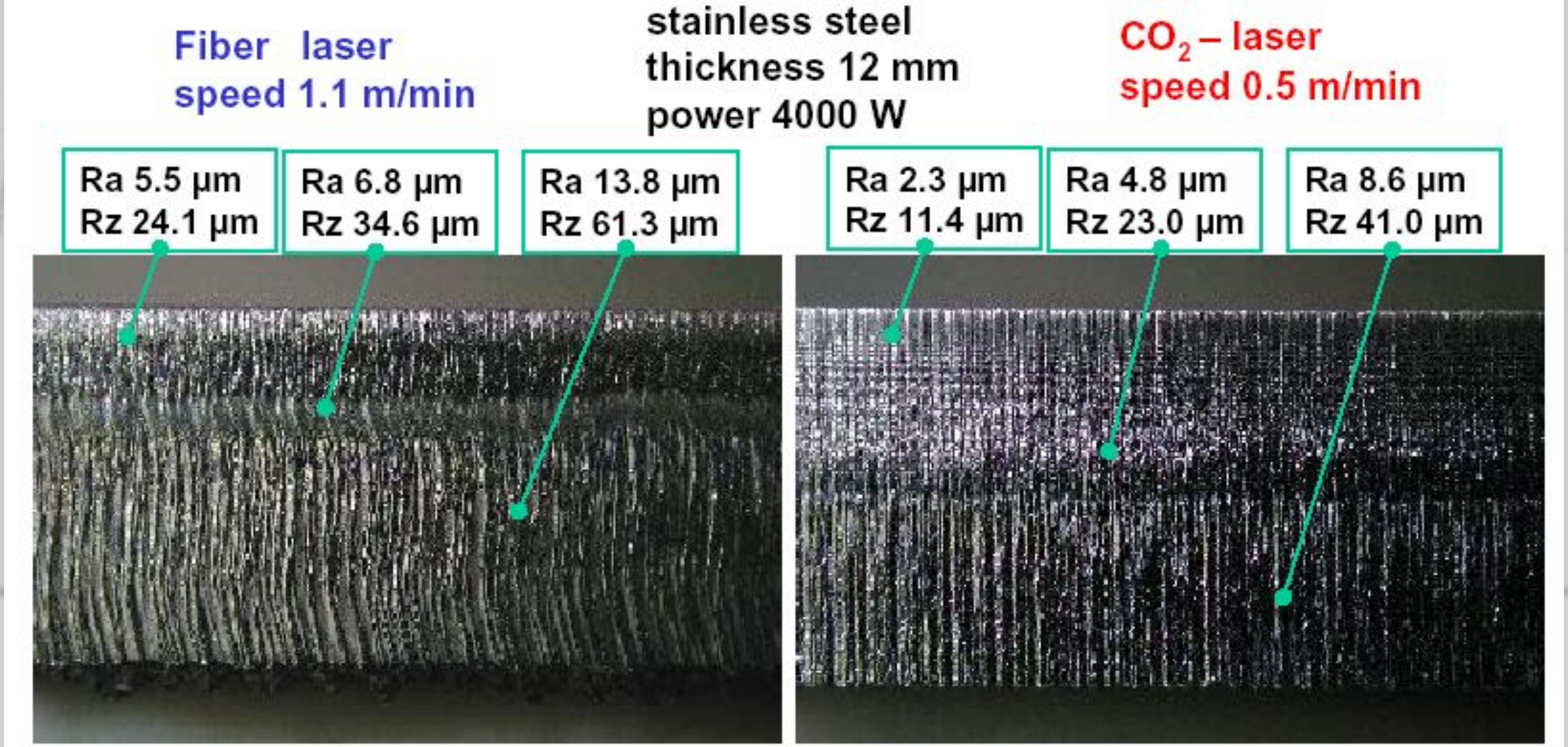


Transmission of 5kW power through 1km MM fiber

Output power after 1000 m of fiber MK-300 vs. input power
Average total loss 15.5 % +/- 0.5 %

# Applications

## Comparison of fiber- andCO2-laser cutting edge quality



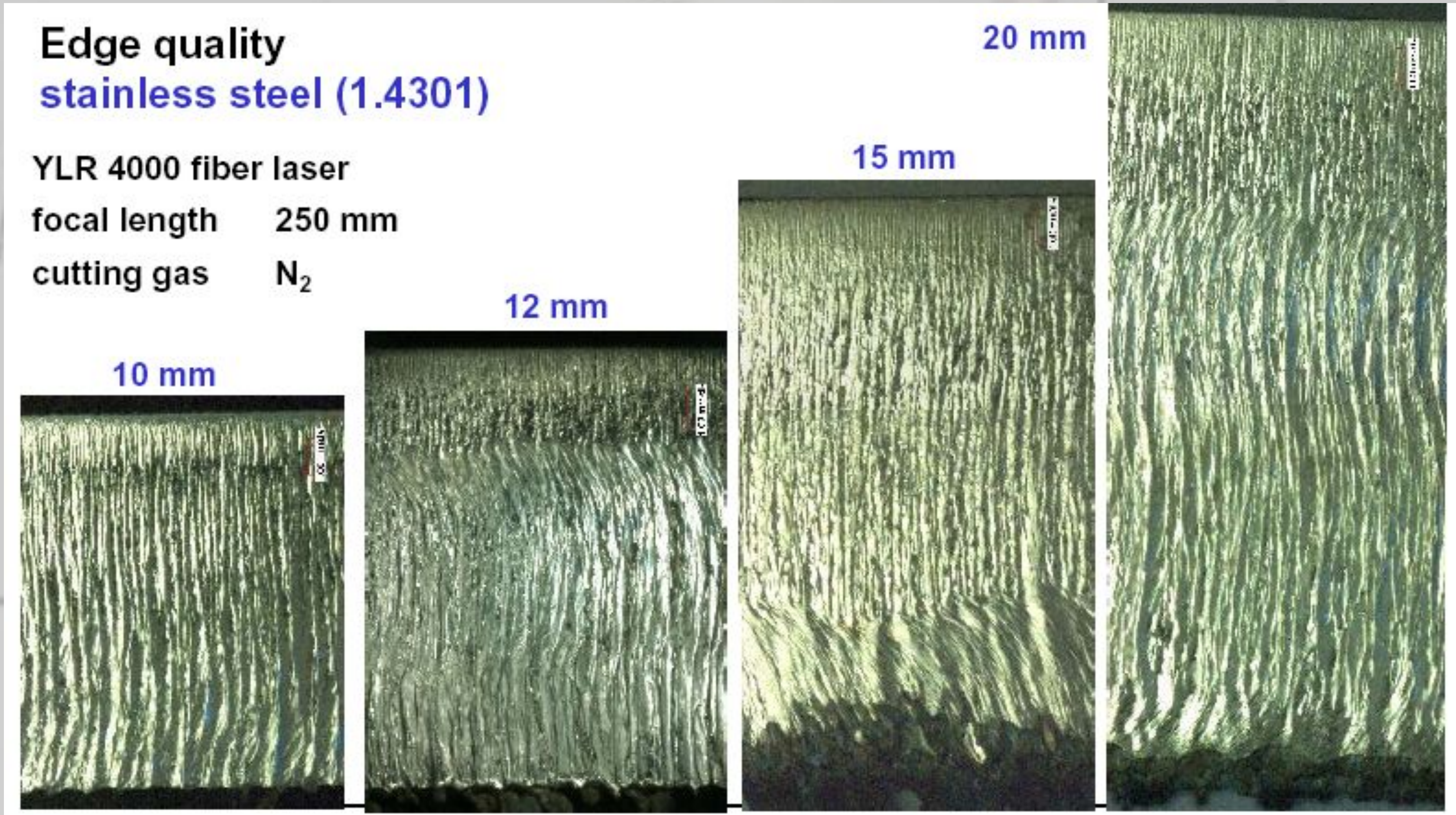
**Fiber laser**
**speed 1.1 m/min**

**stainless steel**
**thickness 12 mm**
**power 4000 W**

**$CO_2$ – laser**
**speed 0.5 m/min**

# Applications

## Fiber laser cutting quality for different thicknesses



**Edge quality**

**stainless steel (1.4301)**

**YLR 4000 fiber laser**

**focal length 250 mm**

**cutting gas $N_2$**

# Acknowledgements

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