# Beam Shaping for Industrial Laser Sources

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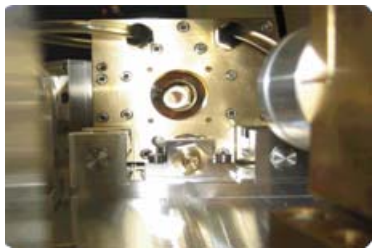

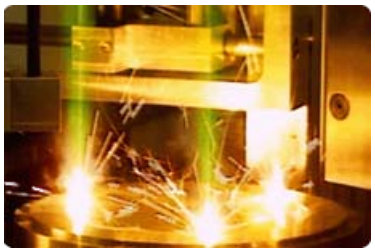

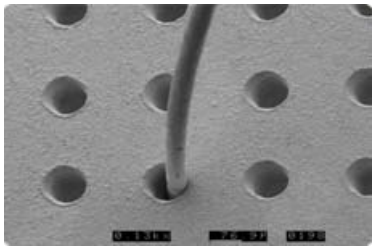

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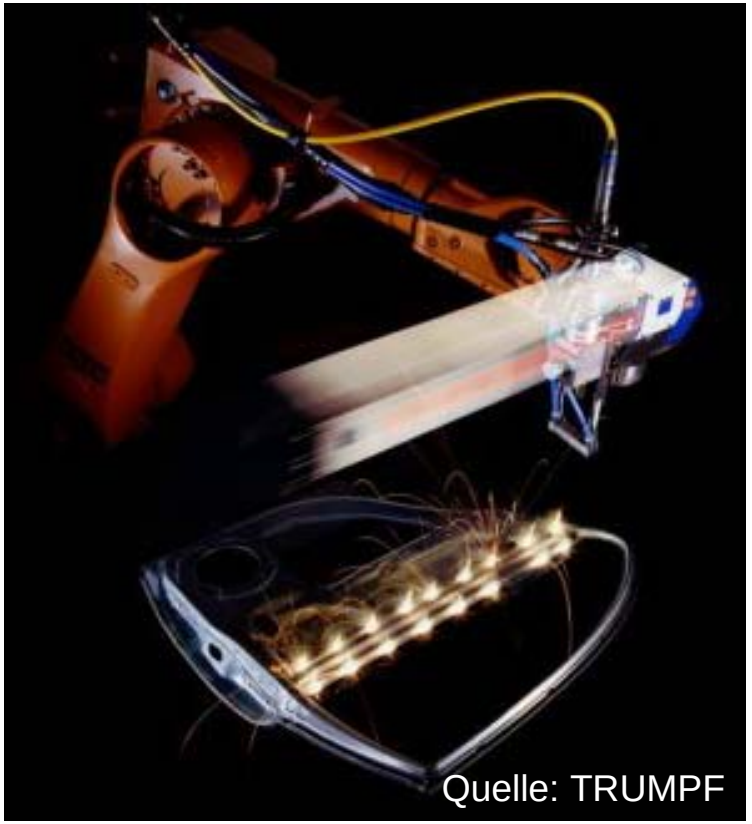
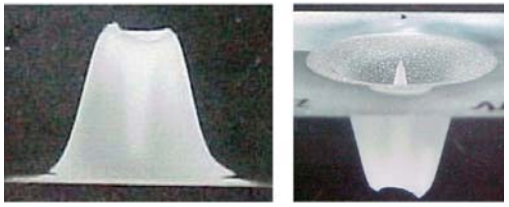
# Laser Development ↔Advanced Applications

- The ongoing advance on laser sources continuously opens up novel and prestigious applications.
- The improvement in beam quality made it possible to overcome past limitations (e.g. in welding) and opened the way to remote processing.
- A further improvement of the processes requires specific optimisations of the beam shapes (such as radial or azimuthal polarisations).
- In addition, the improved brightness and the shaped beam properties urgently require the development of novel fibre concepts for beam delivery.

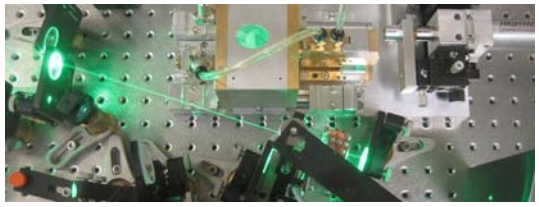


# Selected Topics for the SSOM Lecture on Beam Shaping

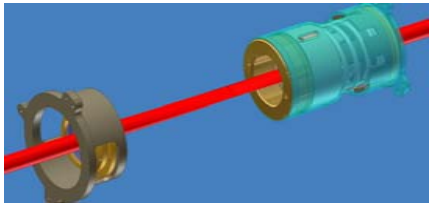
- Spatial Beam Shaping:
  Radial polarization to enhance process efficiency and quality



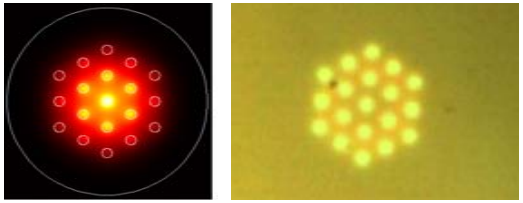
- Temporal Beam Shaping:
  Laser source with switchable short and ultrashort pulses for higher productivity



- Spatiotemporal Beam Shaping:
  A novel beam rotator for helical drilling to improve the process quality



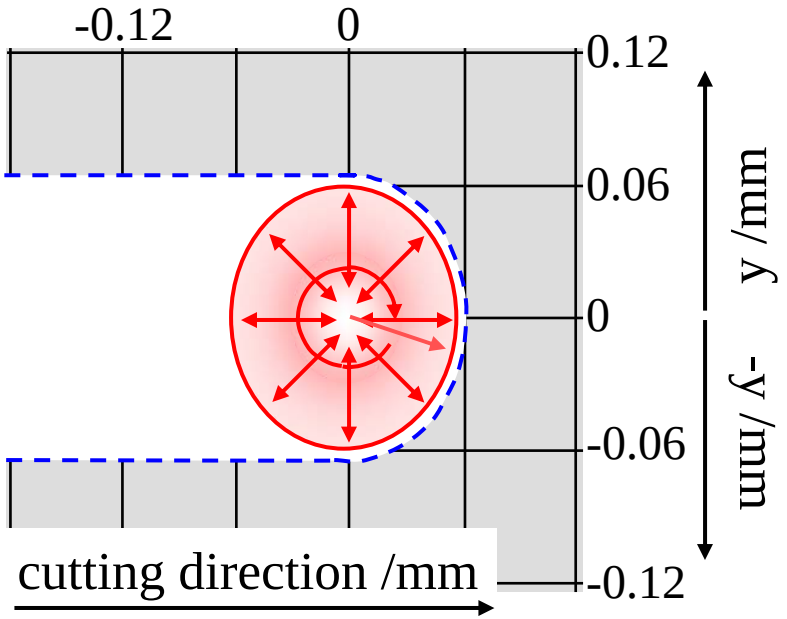
- Novel Fibers for High-Power Beam Delivery:
  Low-loss 19-core fiber for cw kW diffraction-limited radiation



# Radially Polarised Beams

## Example: cutting with radially polarised beams

- The beam is p-polarised everywhere in the kerf
- This leads to an enhanced absorption of the beam in the material
- Efficiency predicted to be improved by 1.5 to 2 times with respect to circular polarisation
  (V. G. Niziev and A. V. Nesterov, J. Phys. D: Appl. Phys. 32, 1455-1461, 1999)

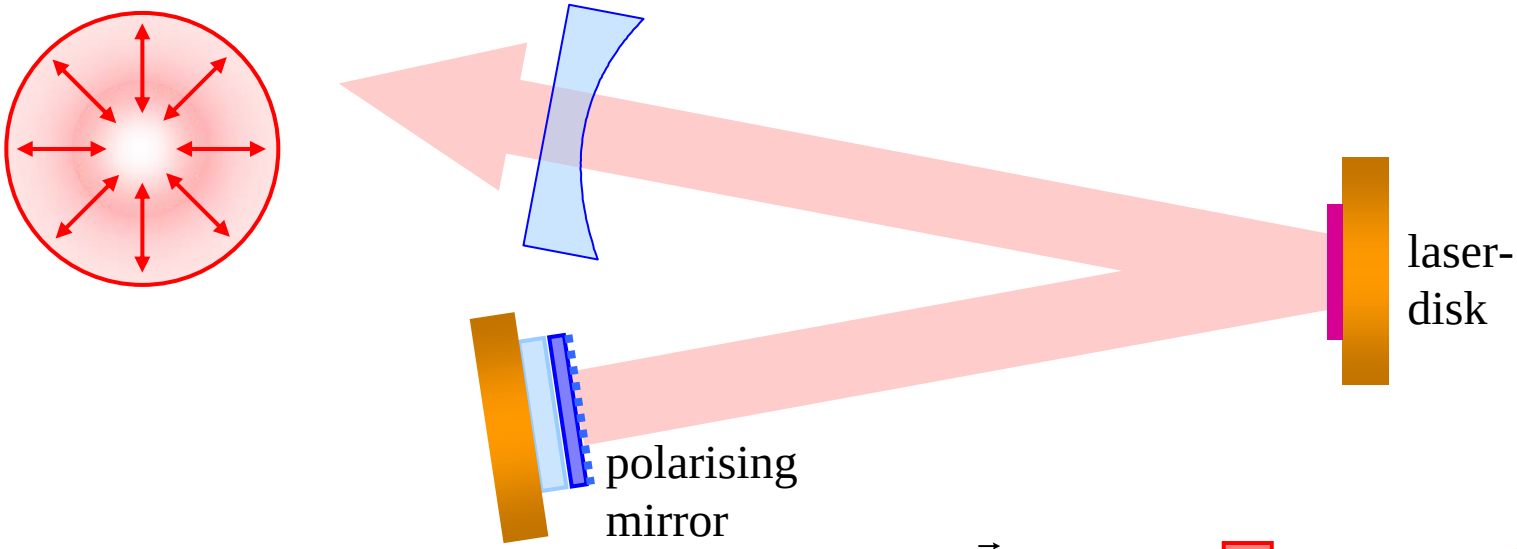


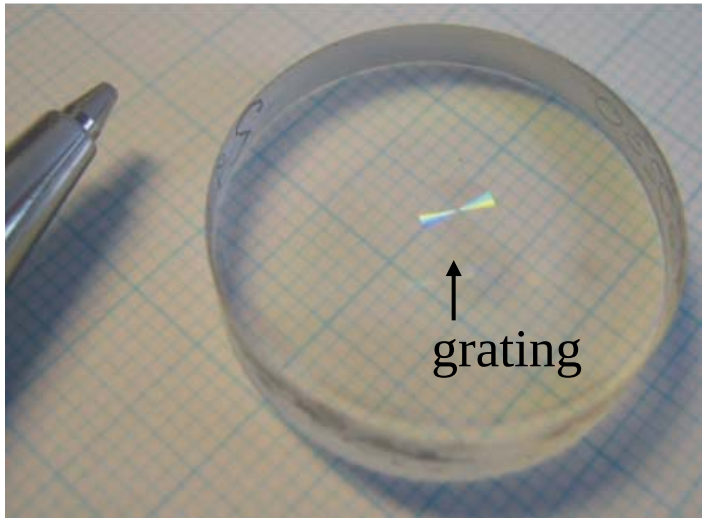

## First investigations of applications:

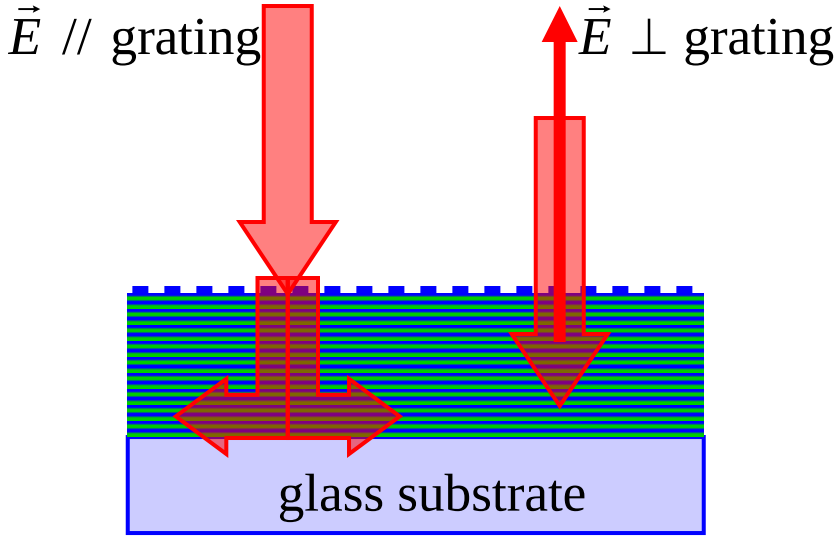
- Dr. Moser (LASAG) et al., “Exploiting Radial Polarisation in Material Processing”, SLT 2008
- Dr. Hammann (TRUMPF), “Laser Cutting with $CO_2$ Lasers – The Benchmark”, SLT 2008

# Shaping the Polarisation Distribution

- Proof of principle with rod lasers (up to 130 W) at University of Bern (Appl. Phys. B 80, 707-713, 2005)
- At IFSW: transfer of the technology to $CO_2$ and Yb:YAG thin-disk lasers

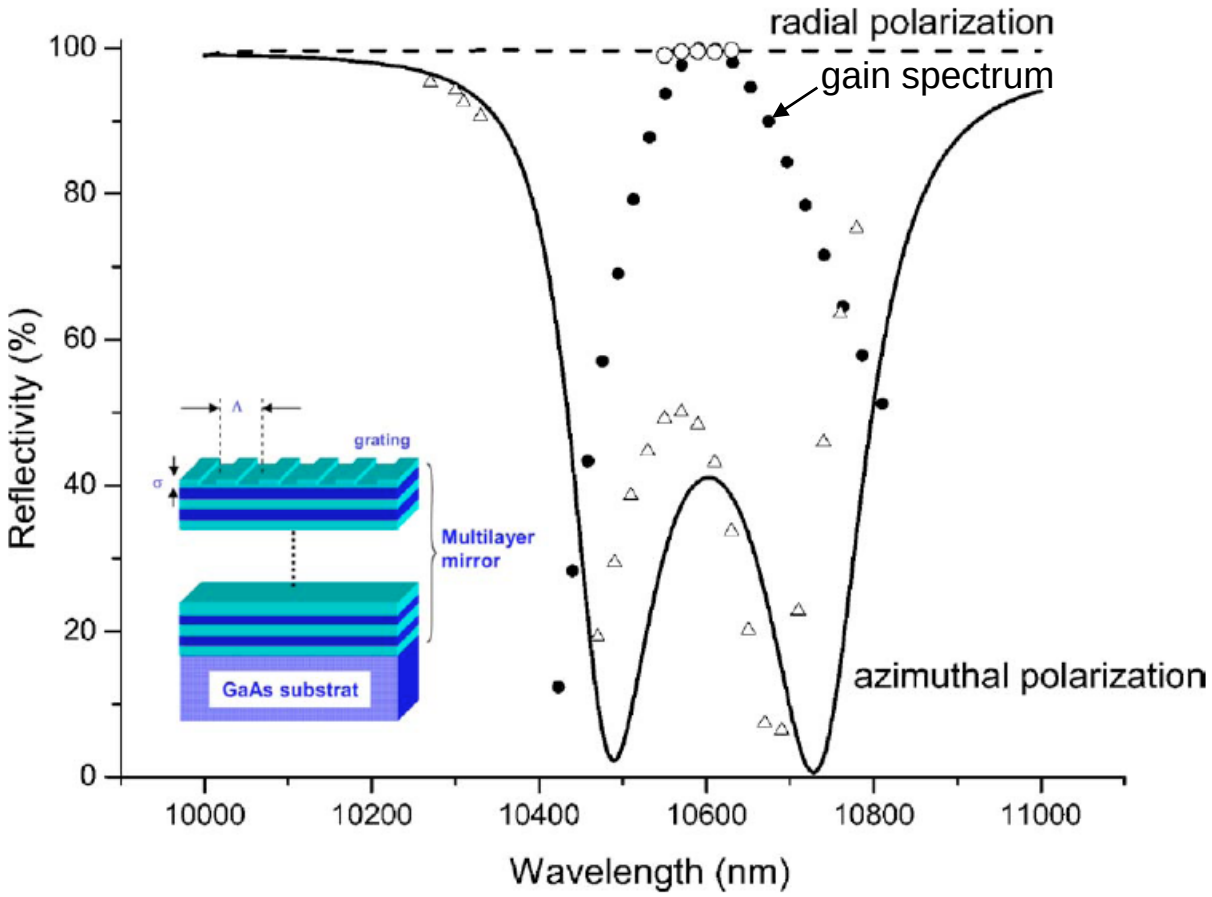


# 3 kW Radially Polarised $CO_2$ Laser (Opt. Lett. 32, 1824, 2007)

- Here we used a grating (etched in the top layer) to couple to two adjacent leaky wave-guide modes of the multilayer:



# 3 kW Radially Polarised $CO_2$ Laser (Opt. Lett. 32, 1824, 2007)

- 3 kW of radially polarised output power was demonstrated with a commercial $CO_2$ laser:

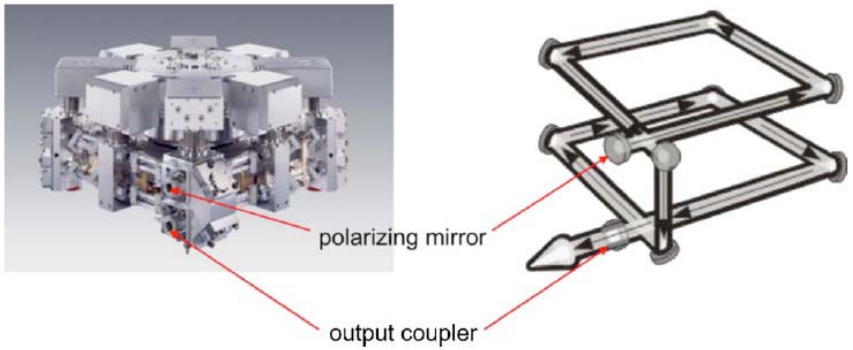



Fig. 3. (Color online) $CO_2$ laser resonator used for the generation of the radially polarized beam.

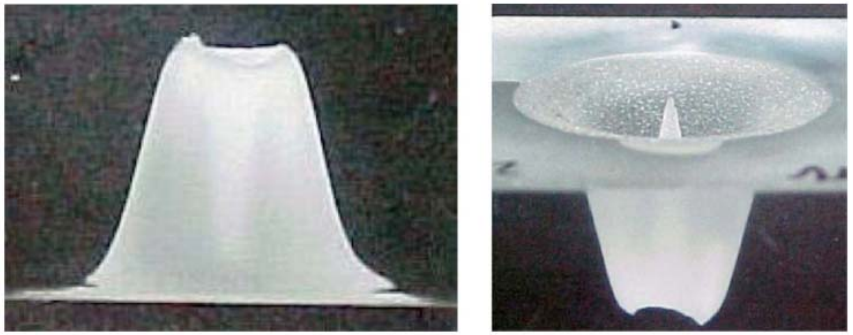


Fig. 4. (Color online) Burn-in of the doughnut $CO_2$ laser beam into a plexiglas cube.

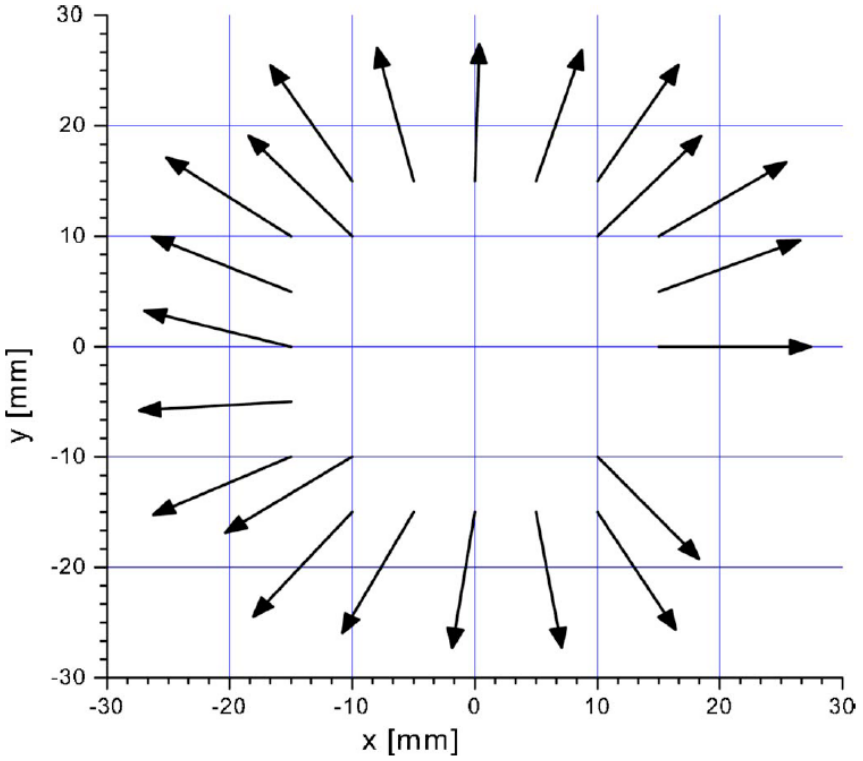
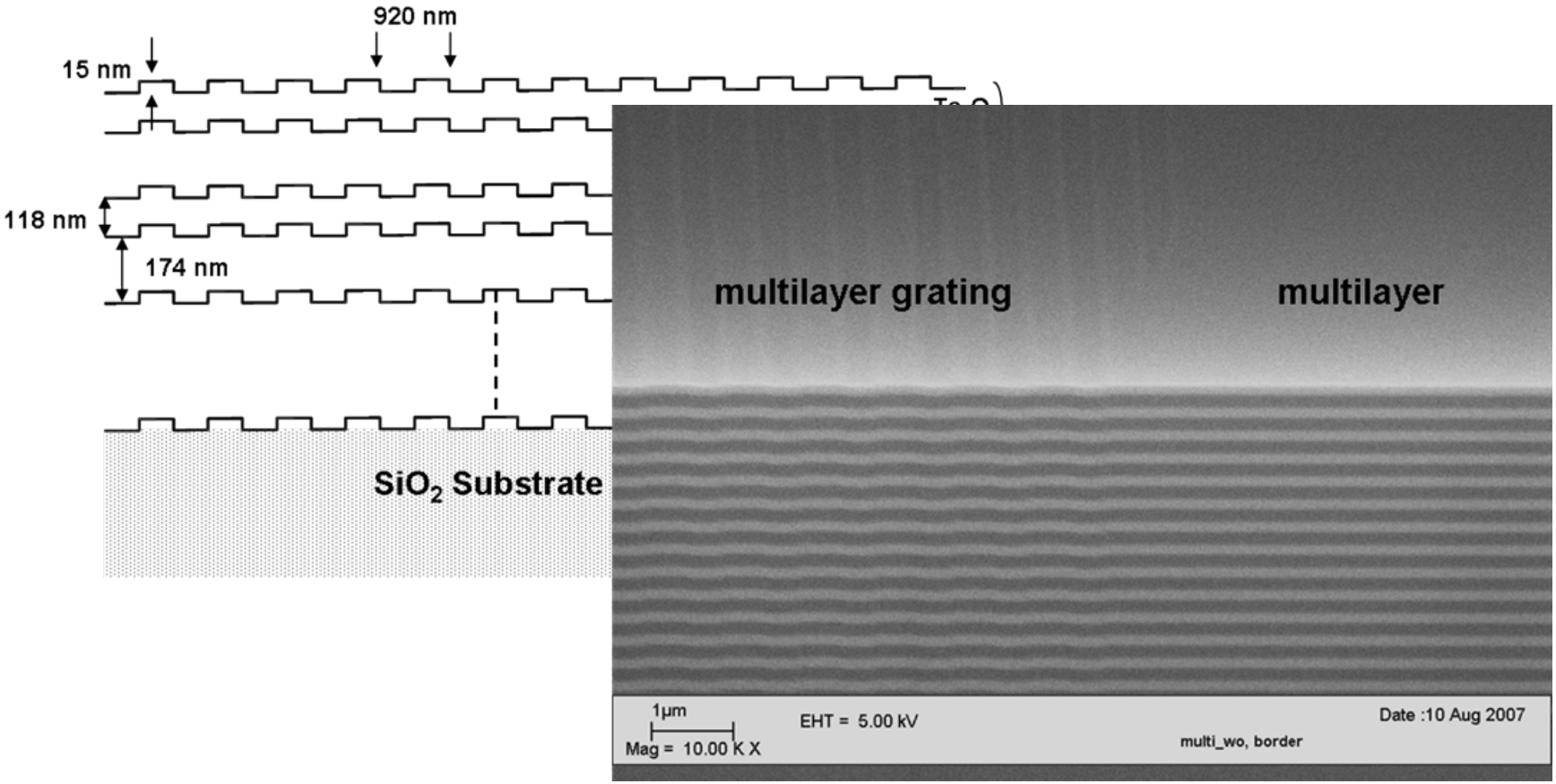



Fig. 5. (Color online) Measured polarization distribution over the beam cross section. The arrows show the polarization direction through the lasnix apparatus at different positions over the beam cross section.

# New Mirror Concept for Yb:YAG Thin-Disk Lasers

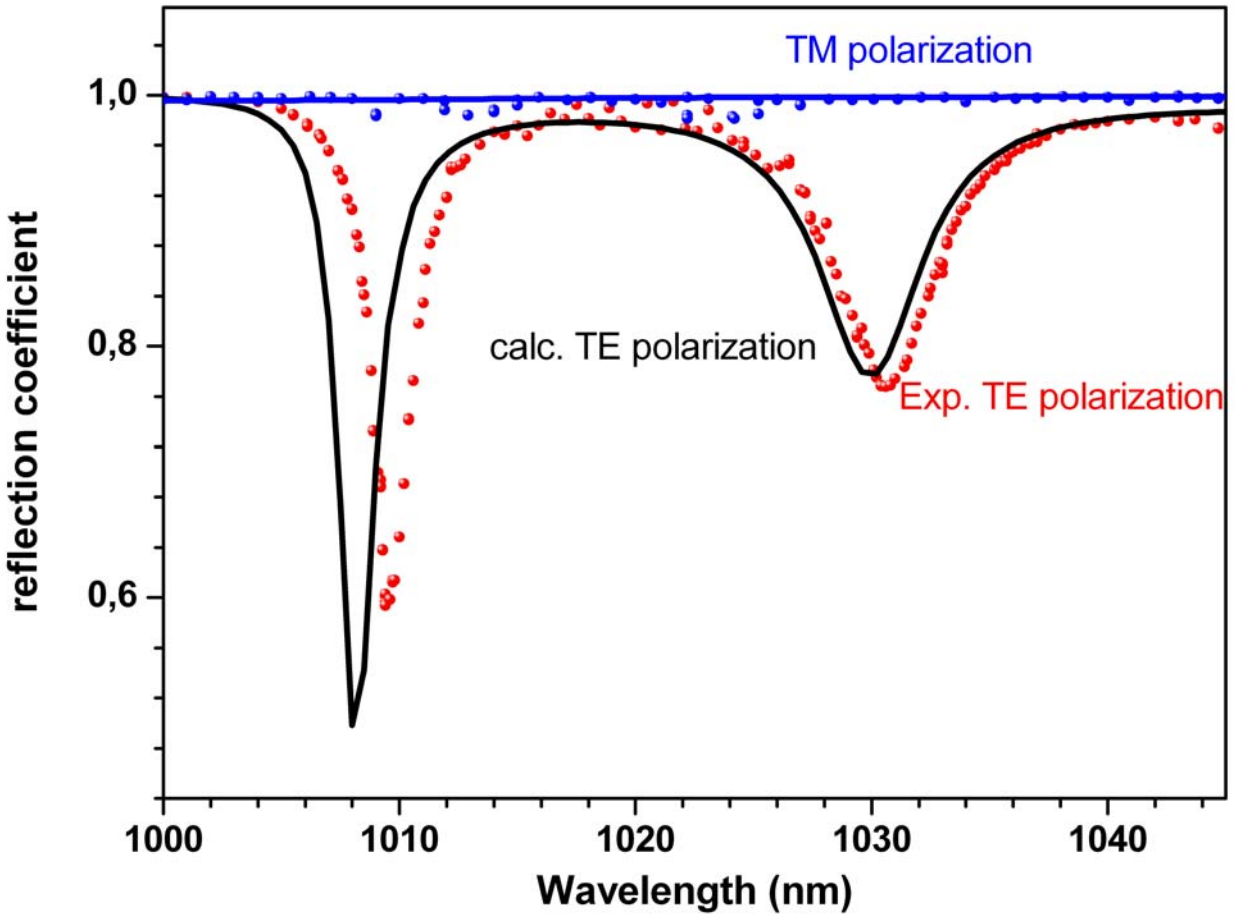
- Previous concept: grating in top layer of the HR mirror
- New design: grating etched into the substrate beneath the multilayer coating
  - ↳ shallower grating with less scattering loss
  - ↳ significantly broader spectral bandwidth
  - ↳ significantly broader manufacturing tolerances

  (Optics Letters 32, 3272-3274, November 2007)



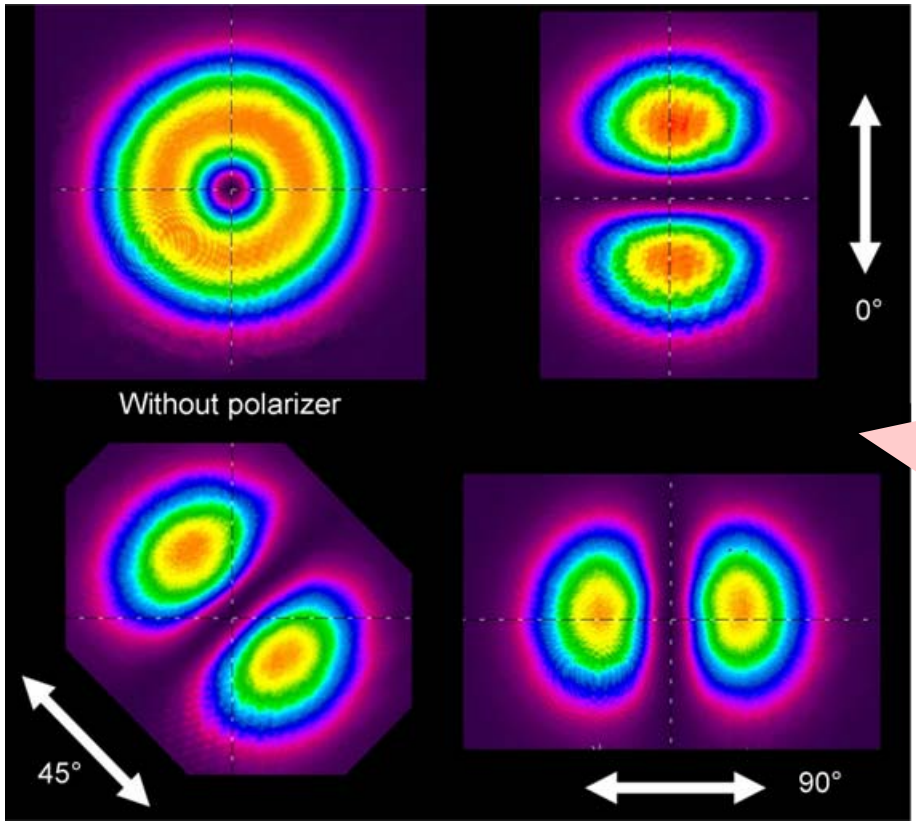
# Performance of the New Polarising Mirror

- Very good agreement between design values and measurements:

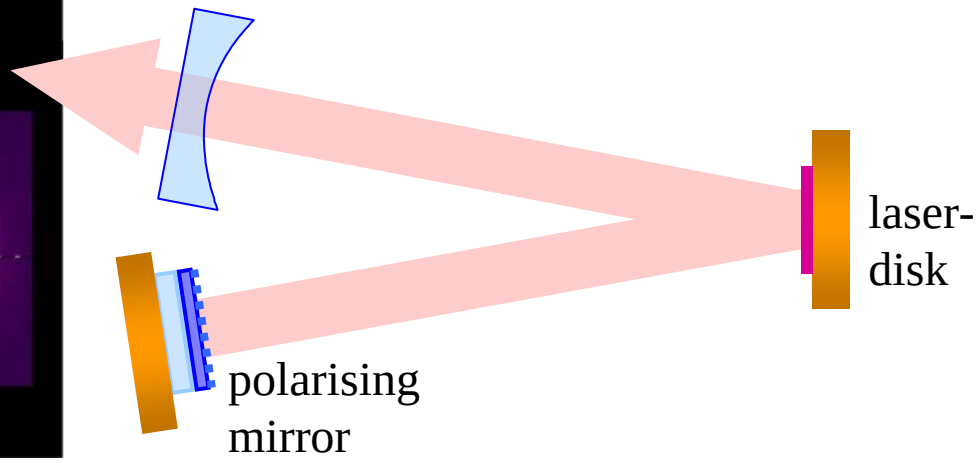


# The First Radially Polarised Thin-Disk Laser (low power)

- First demonstration of a radially polarised thin-disk laser at a moderate power of 10 W:



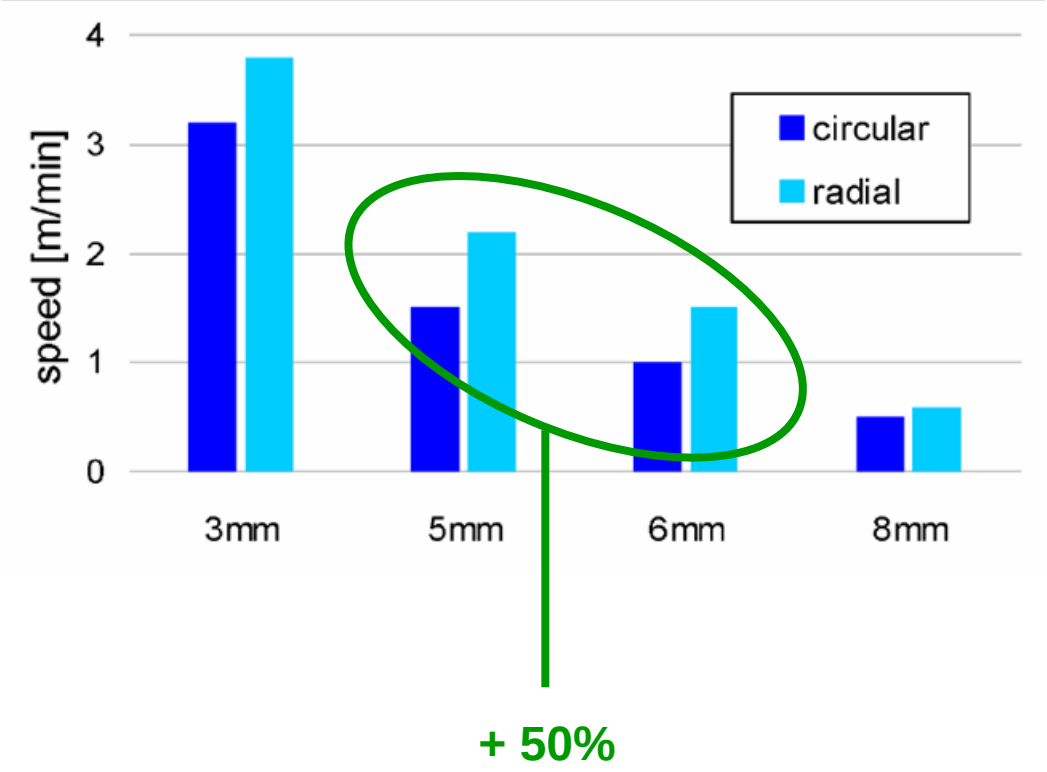

M. Abdou Ahmed, A. Voß, M. M. Vogel, and Th. Graf: Opt. Lett. 32 (13), 3272 (2007)

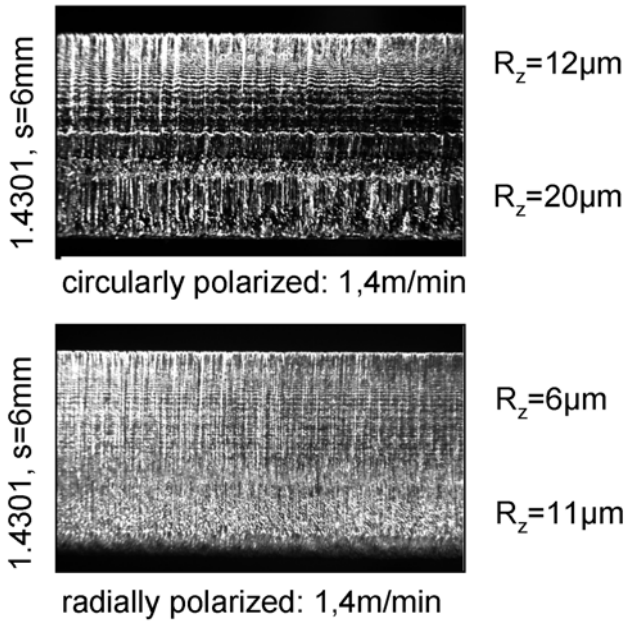



- Currently 220 W, higher powers to be demonstrated soon.

# First Experimental Results: Cutting with Radial Polarization

- First experimental investigations of cutting with a radially polarized $CO_2$ laser confirm the theoretical predictions based on the Fresnel absorption!
  M. Abdou Ahmed, A. Voß, M. M. Vogel, A. Austerschulte, J. Schulz, V. Metsch, T. Moser, and Th. Graf, SPIE Proceedings of the GCL-HPL Conference 2008, 15.-19. September 2008, Lisbon



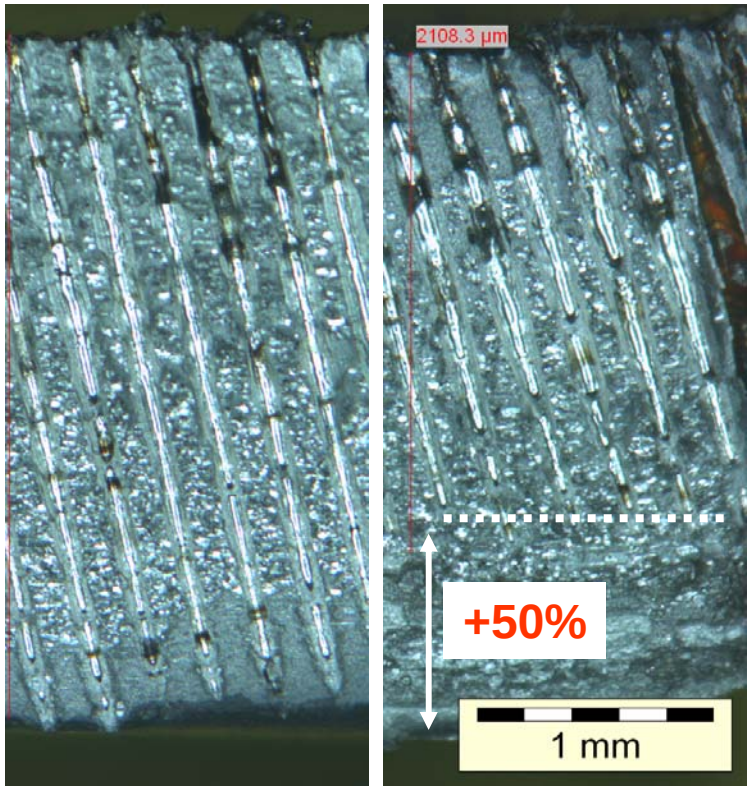
# First Experimental Results: Drilling

- First experimental investigations on drilling with a radially or azimuthally polarized Nd:YAG laser confirm the predictions based on the Fresnel absorption!
  M. Abdou Ahmed, A. Voß, M. M. Vogel, A. Austerschulte, J. Schulz, V. Metsch, T. Moser, and Th. Graf, SPIE Proceedings of the GCL-HPL Conference 2008, 15.-19. September 2008, Lisbon

- Material: Spring steel CK 101, 3.0 mm
  Pulse duration 0.11 ms
  Pulse energy 200 mJ,
  Repetition rate 45 Hz
  Process gas: air

**150 pulses:**

azimuthal | radial

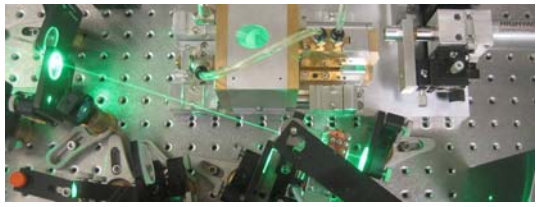


# Selected Topics for the SSOM Lecture on Beam Shaping

- Spatial Beam Shaping:
  Radial polarization to enhance process efficiency and quality



- Temporal Beam Shaping:
  Laser source with switchable short and ultrashort pulses for higher productivity



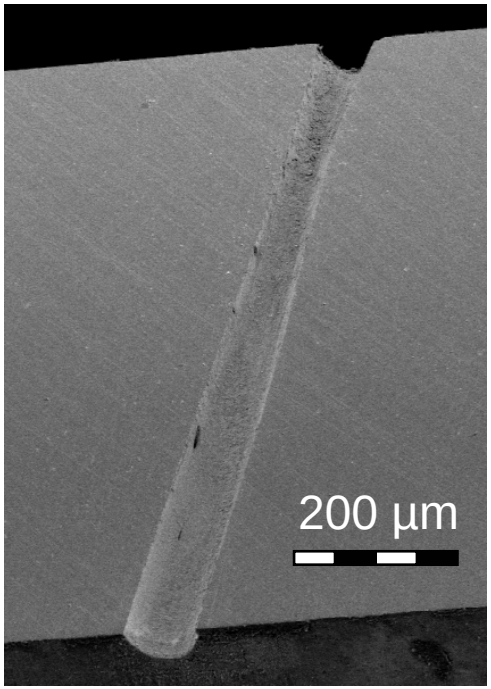
- Spatiotemporal Beam Shaping:
  A novel beam rotator for helical drilling to improve the process quality

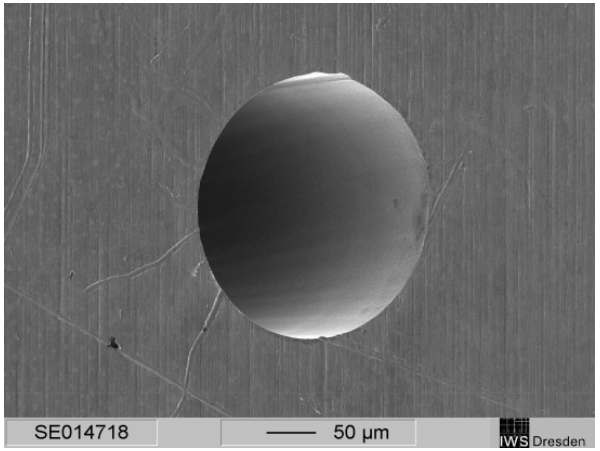


- Novel Fibers for High-Power Beam Delivery:
  Low-loss 19-core fiber for cw kW diffraction-limited radiation

# Productivity Enhancement for Micro Drilling

- Typical requirements for laser micro drilling: Ø ≤ 100 µm, z ≤ 1 mm
  high contour precision und quality without post processing

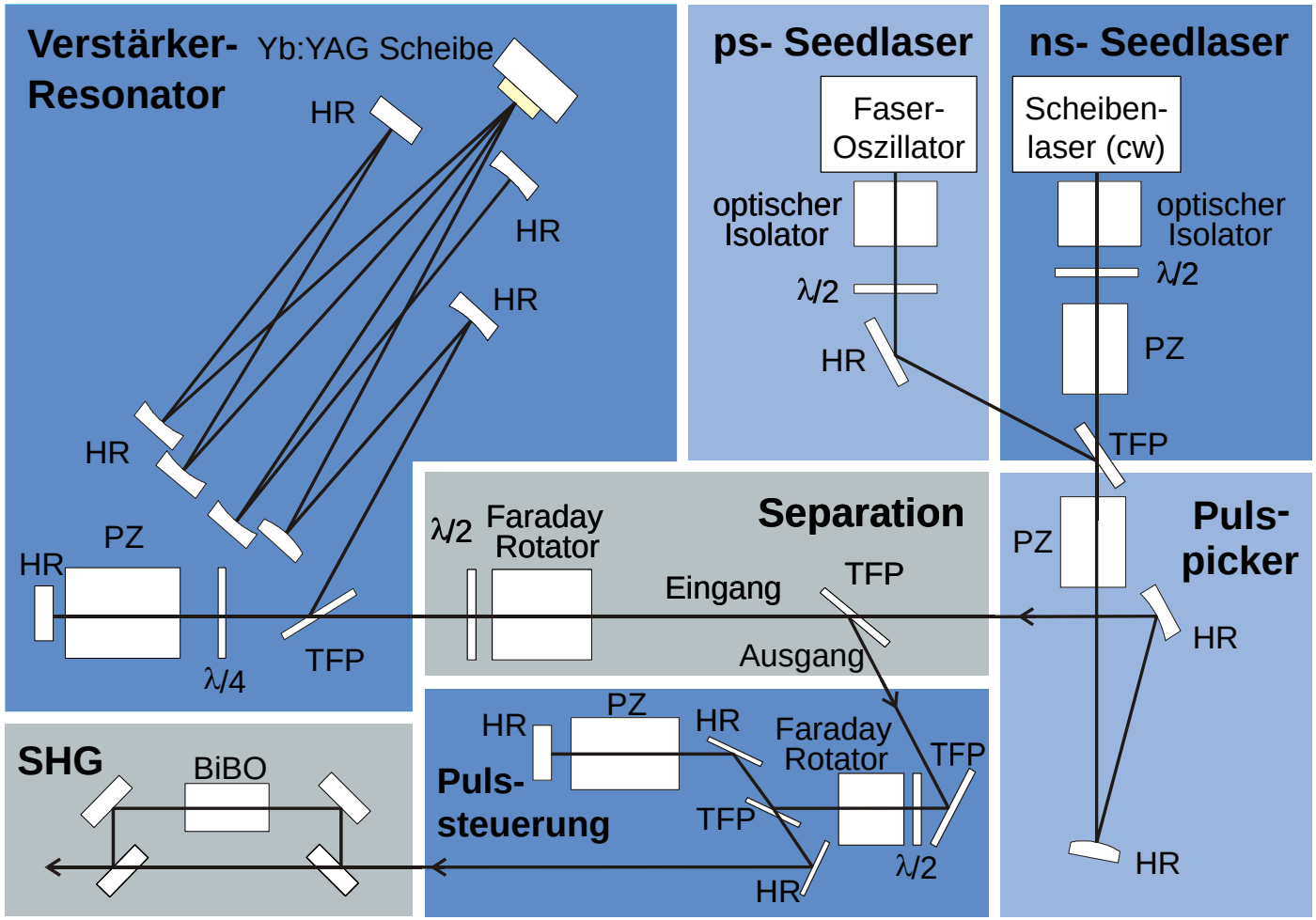



- Precision and quality can be attained with ps-pulses but the productivity had to be improved by three orders of magnitude to be profitable:
  a) increase of average power of the laser sources
  b) hybrid pulse operation (ns / ps pulses)
  c) processing strategies / system technology

# Laser Source for Productive Ablation Processes

- Regenerative Yb:YAG thin-disk amplifier with ps and ns seed laser and switchable frequency doubling

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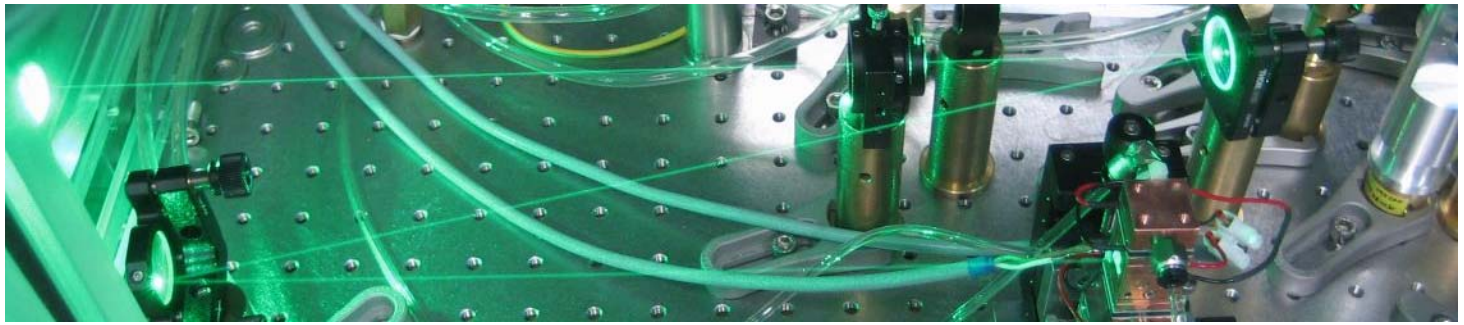
# Laser Source for Productive Ablation Processes

- Performance IR (1030 nm):
  pulse duration 5,5 ps or 15 ns, arbitrarily programmable sequences
  $M^2 \leq 1{,}3$
  repetition rate between 5 kHz and 200 kHz
  average power 62 W
  maximum pulse energy 2,3 mJ

- Performance green (515 nm):
  pulse duration 3,8 ps or ca. 15 ns, arbitrarily programmable sequences
  $M^2 \leq 1{,}7$
  repetition rate between 5 kHz and 200 kHz
  average power 28,8 W
  maximum pulse energy 1,1 mJ

- Outlook: average power scalable to >400 W



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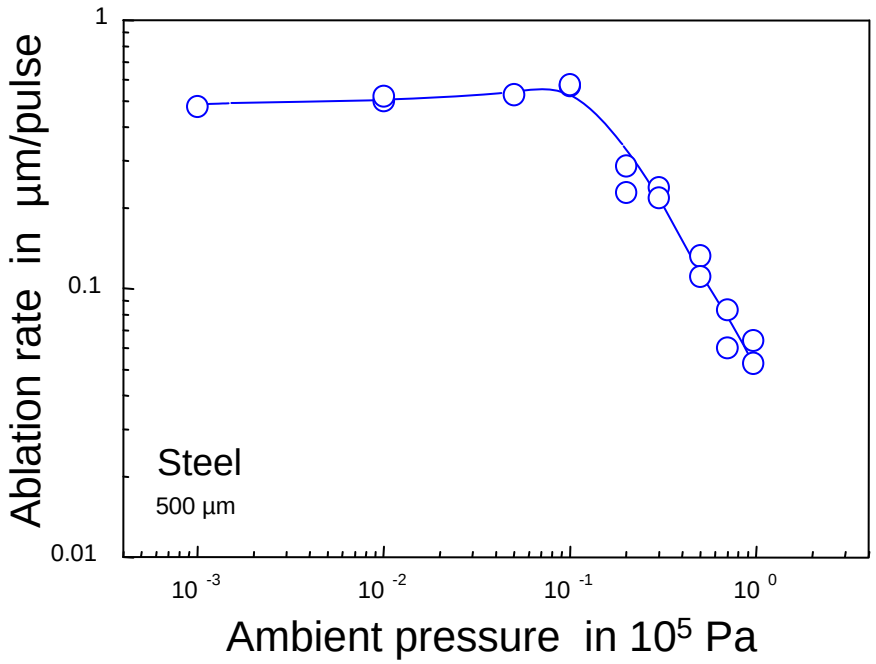
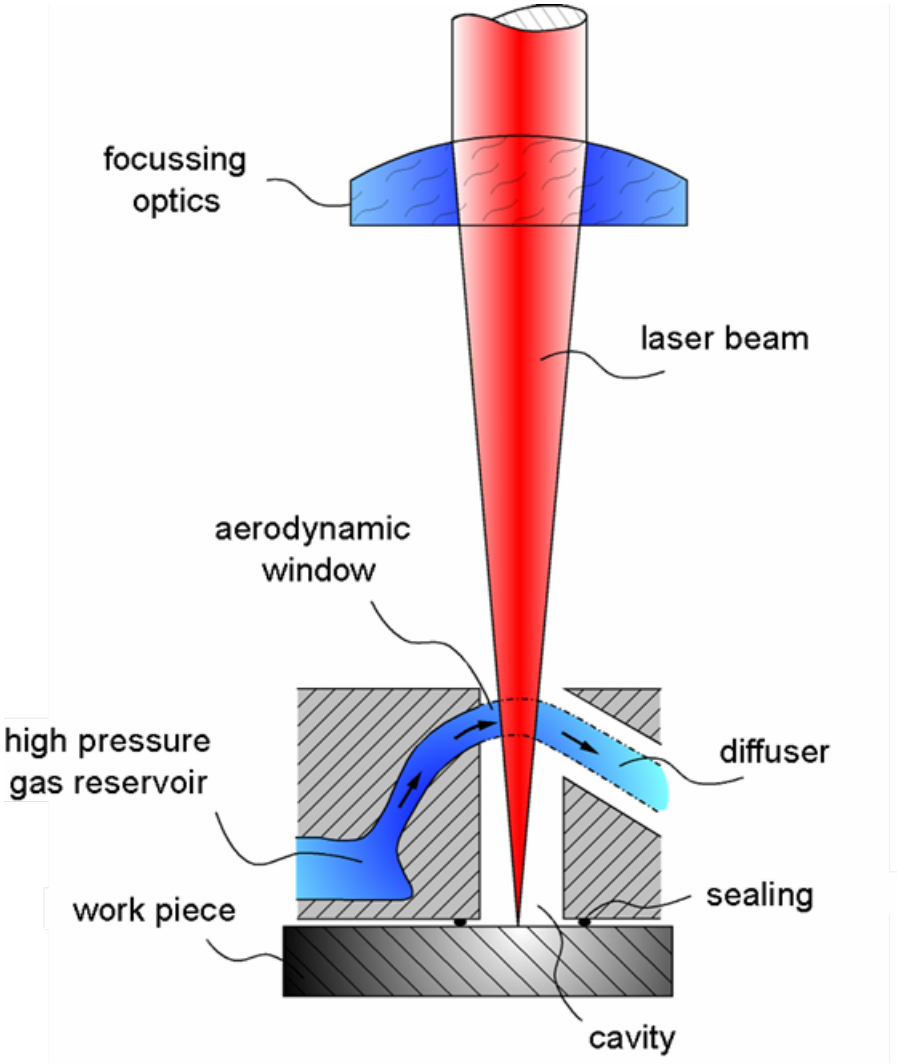
# Productivity Enhancement with Aerodynamic Techniques

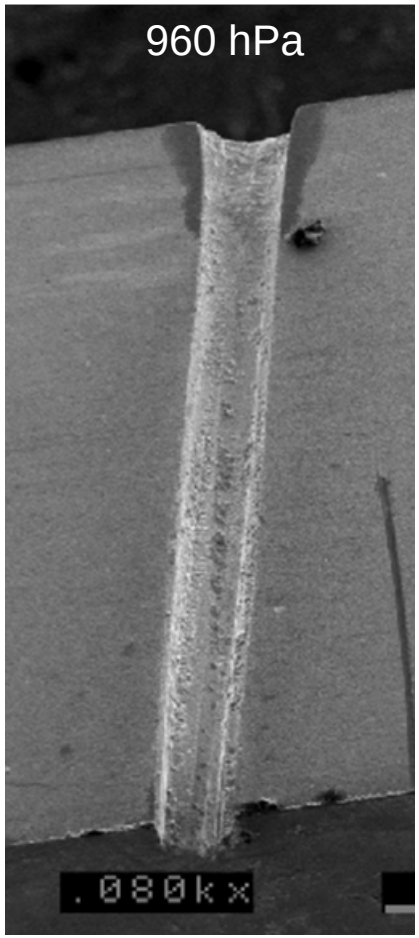
- Aerodynamic window to increase the ablation rate

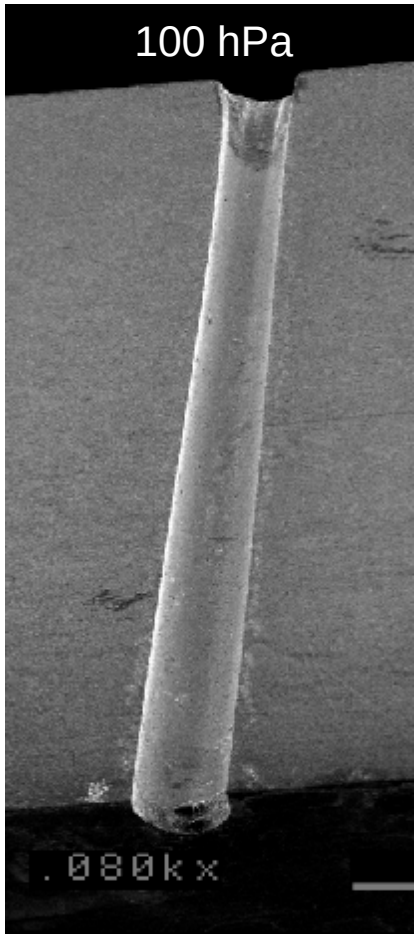


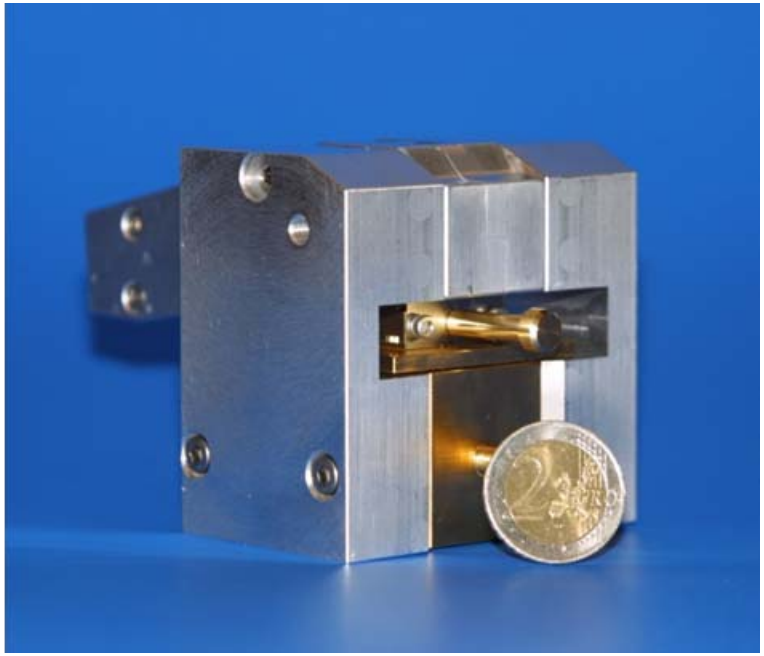



# Productivity Enhancement by Aerodynamic Technology

- Aerodynamic window to increase the ablation rate



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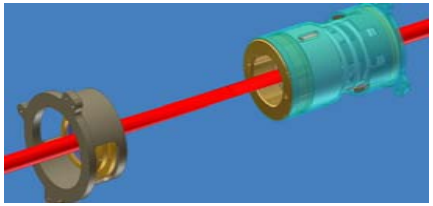
- Spatial Beam Shaping:
  Radial polarization to enhance process efficiency and quality



- Temporal Beam Shaping:
  Laser source with switchable short and ultrashort pulses for higher productivity



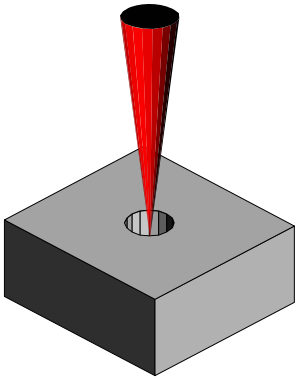
- Spatiotemporal Beam Shaping:
  A novel beam rotator for helical drilling to improve the process quality



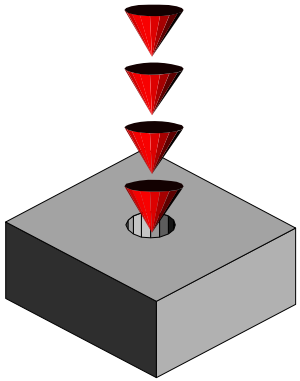
- Novel Fibers for High-Power Beam Delivery:
  Low-loss 19-core fiber for cw kW diffraction-limited radiation

# Processing Techniques for Drilling

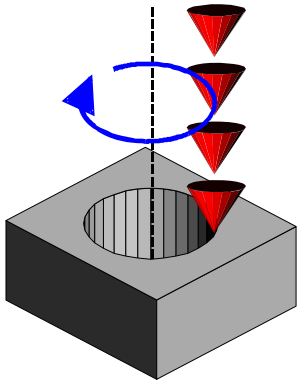
single pulse



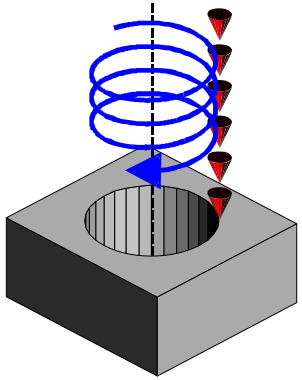
percussion



trepanning



**helical drilling**

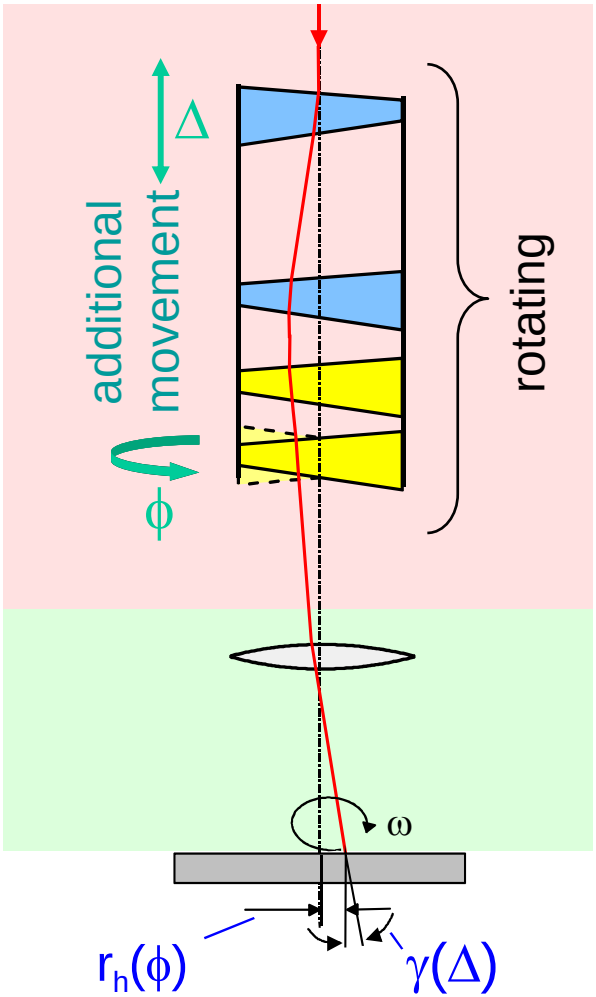


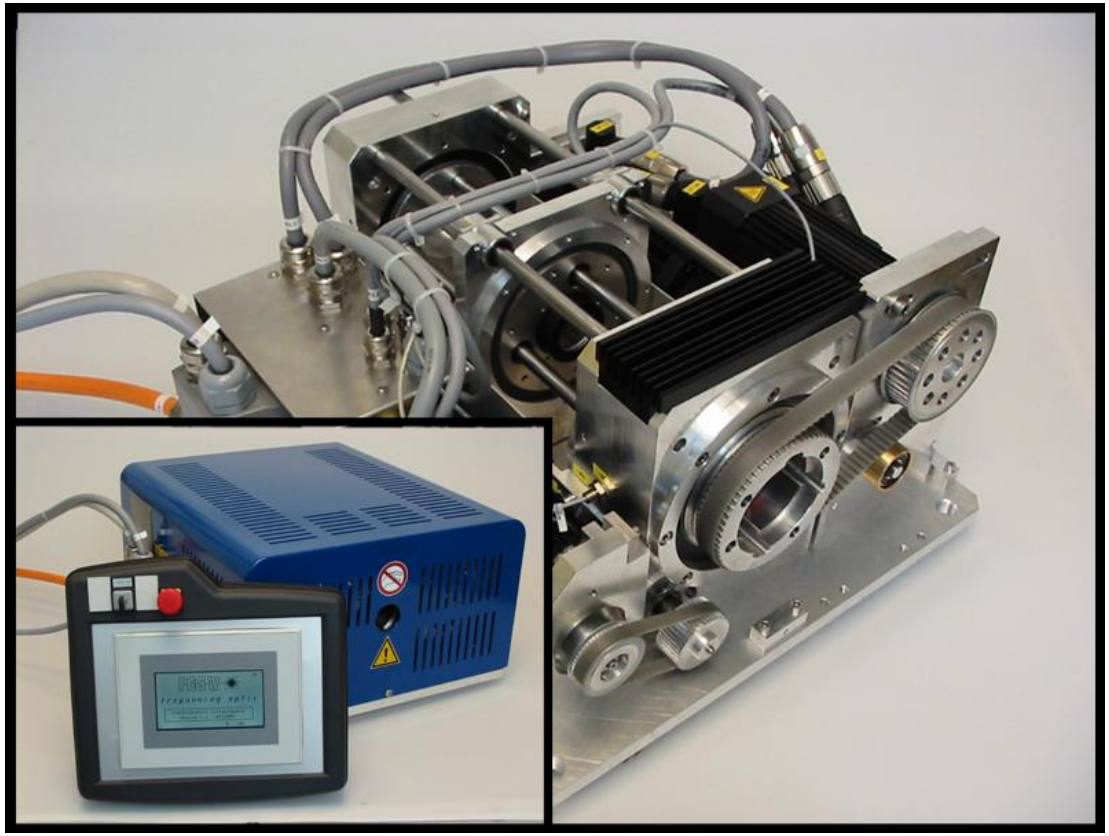
„chip“ volume

precision

# Helical Drilling Optics with Rotating Wedges

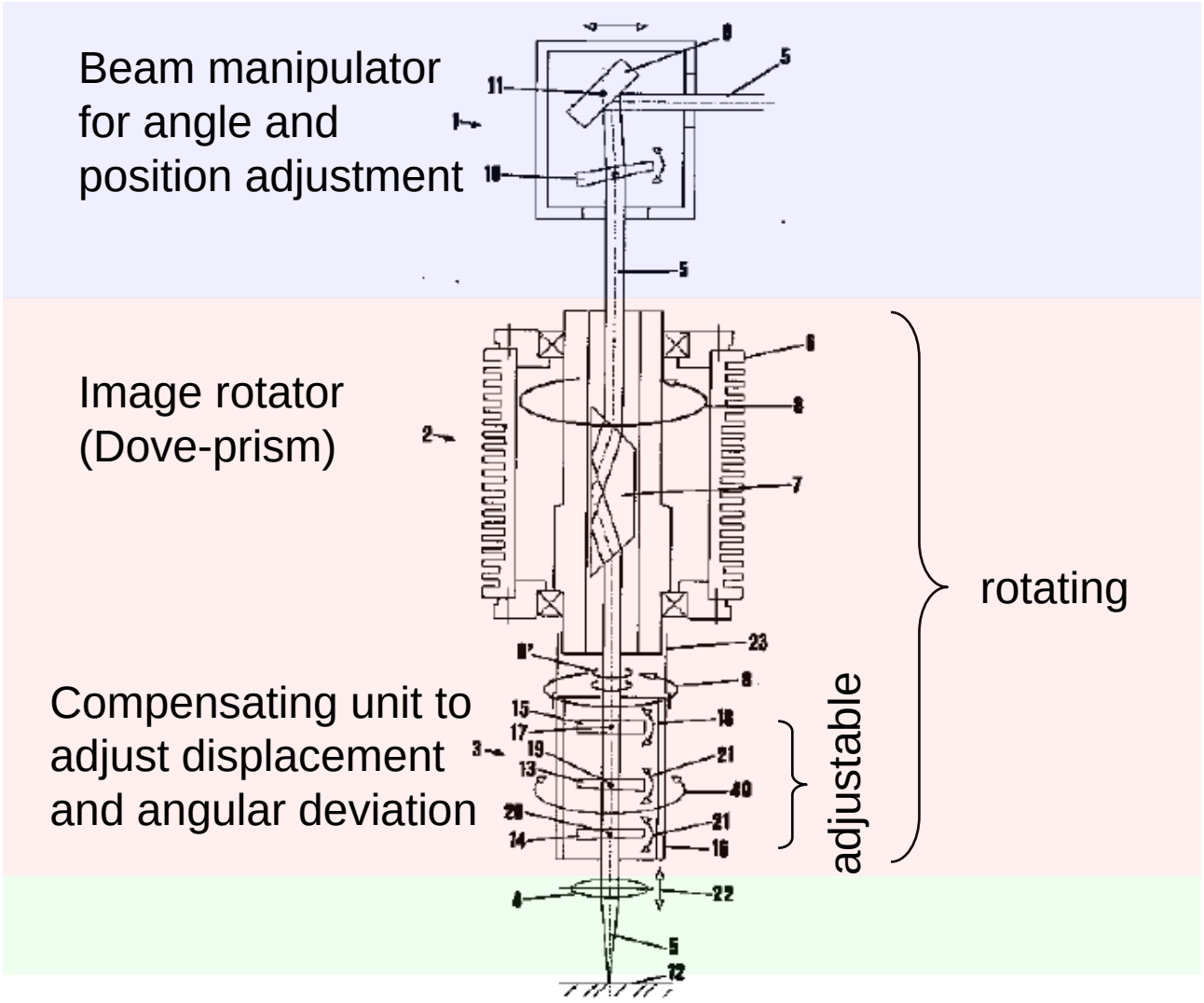
- During rotation the wedges are additionally moved and twisted to adjust the angle of incidence and the helix radius.



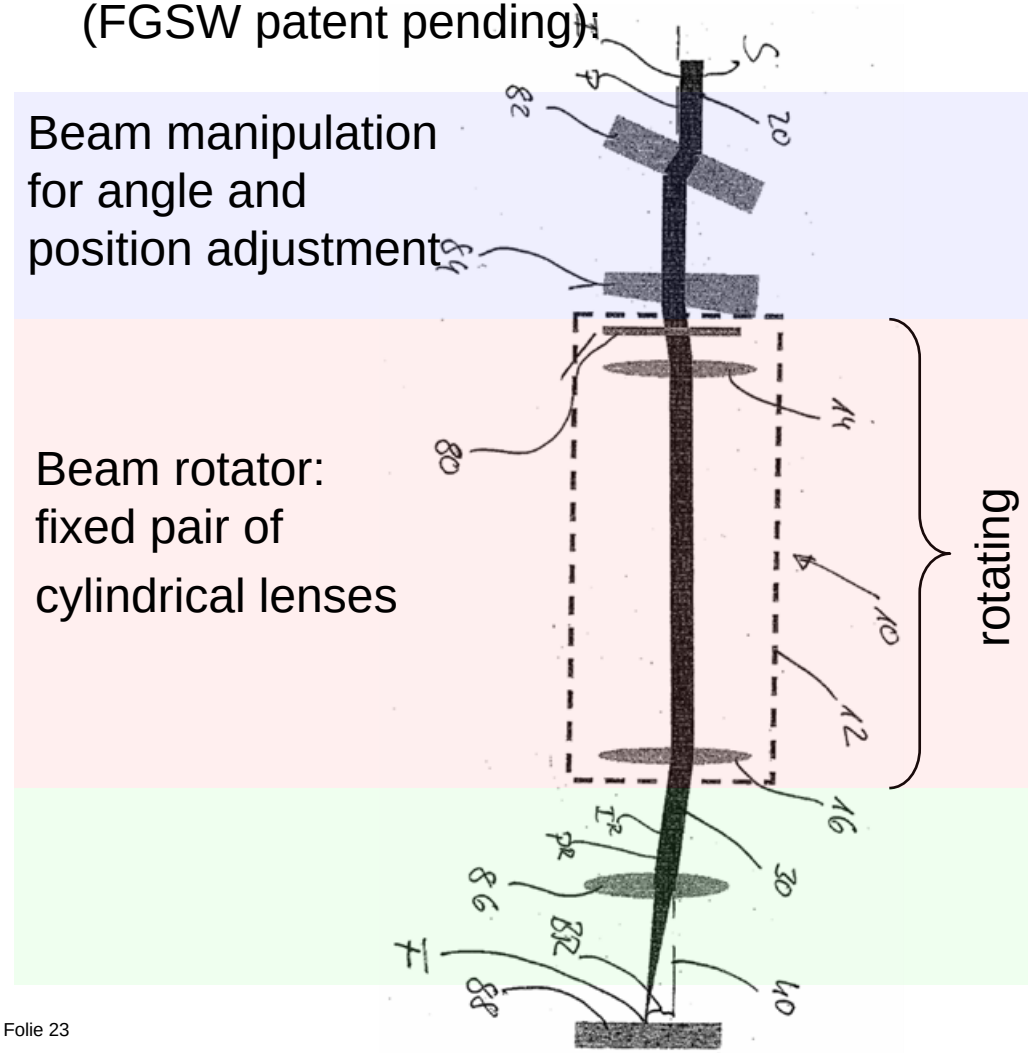
# Drilling Optics with Additional Image Rotation

- The drilling quality can be improved with an image rotation by an additional rotating Dove-prism. ILT Aachen (Patent WO 2007/000194 A1)



# New: Simple Helical Drilling Optics with Beam Rotation

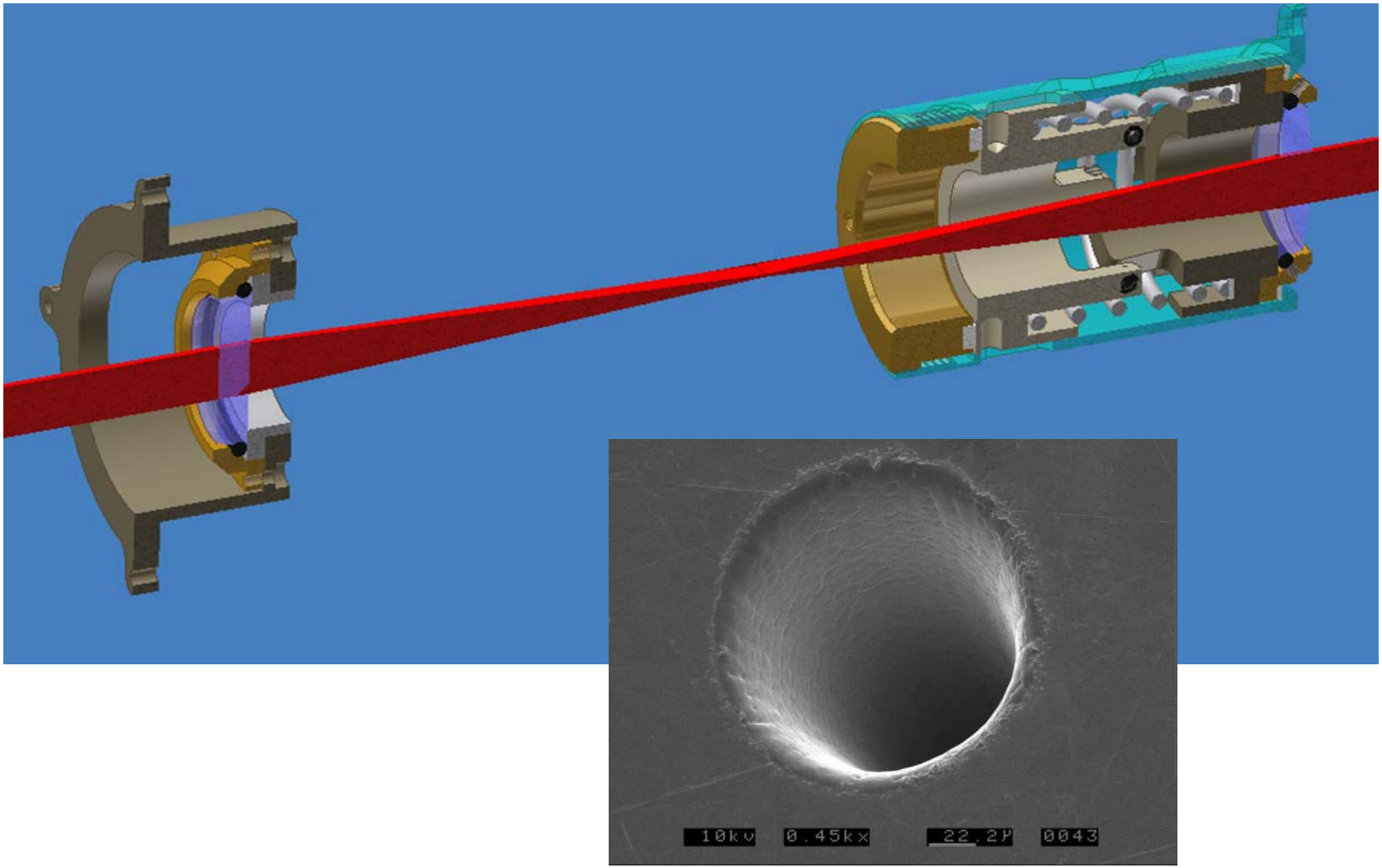
- Image rotation is not required: simple beam rotation is sufficient (rotation of intensity distribution)
- Beam rotation can simply be achieved with a rotating pair of cylindrical lenses! (FGSW patent pending):




- Simple design
- Short paths in glass (low dispersion for ultra-short pulses!)
- No impact on polarization by total reflection at Dove-prism
- Double rotation frequency of the beam

# New: Simple Helical Drilling Optics with Beam Rotation

- Successful drilling performance with experimental set-up
- First prototype to be presented at LASER 2009 in Munich.




($\tau$ = 160 ns, steel)

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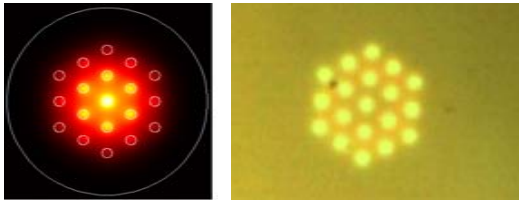


# Fibre Developments

**The commercial success of the thin-disk laser originates from**

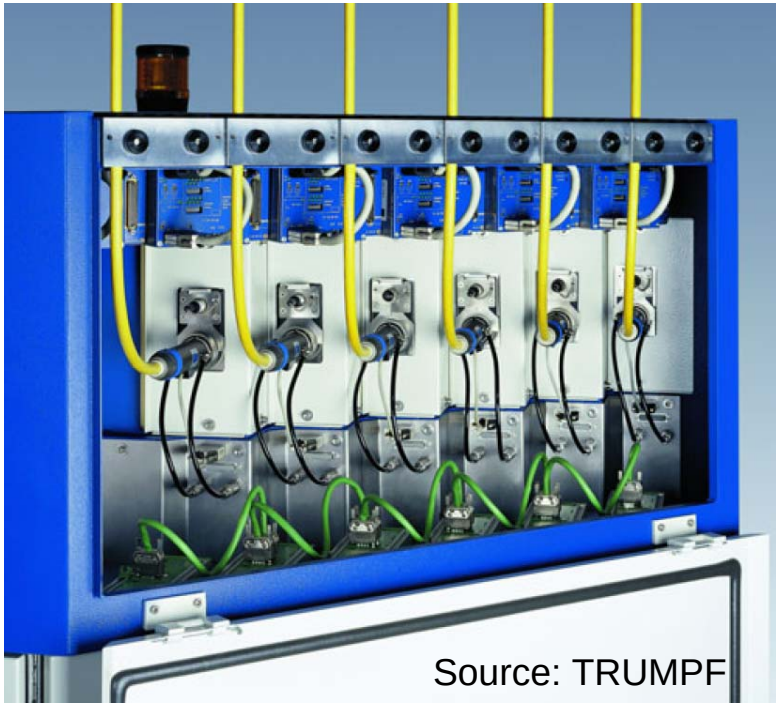
- The efficient, reliable and industry-proof devices on the market.
- The possibility to deliver the (yet multi-mode) beam over unrivalled long distances (> 100 m) in optical fibres.
- Very low sensitivity to back reflections.
- …

**Novel fibres are required soon:**

- With the foreseeable advances of the laser sources towards further increased brilliance and special beam properties completely novel fibre concepts have to be developed.

  ↳ Avoid non-linear phenomena and bending effects.

  ↳ Fibres for special beams such as with radial polarisation.



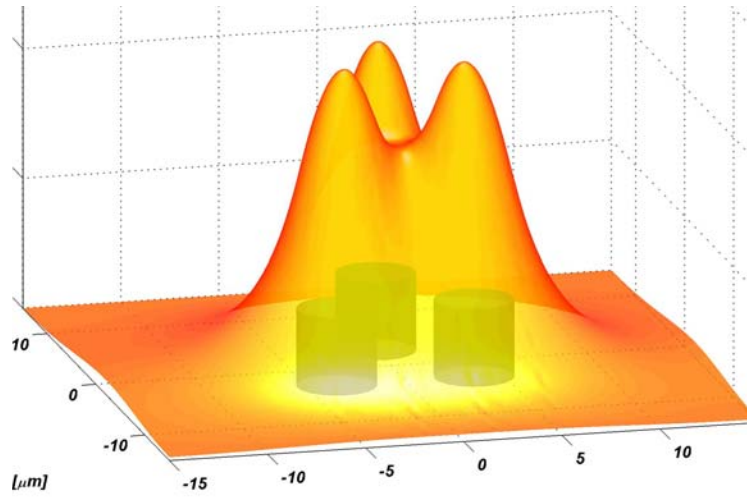
Source: TRUMPF

# Developments for Fiber-Optic Beam Delivery

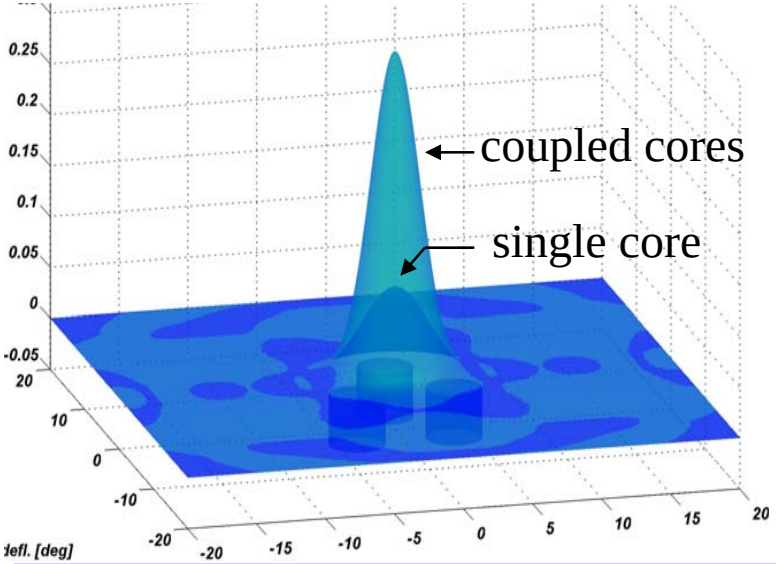
- The success with fiber lasers show, that high powers can be generated in fibers with almost diffraction limited quality.

- However, the same fiber structures are not suited for passive beam delivery
  - ↳ Bending effects that are exploited in lasers are detrimental in beam delivery
  - ↳ Nonlinear effects increase with fiber length (>100 m required for delivery!)

- One possible solution (among others) to these problems are evanescently coupled multiple-core fibers!

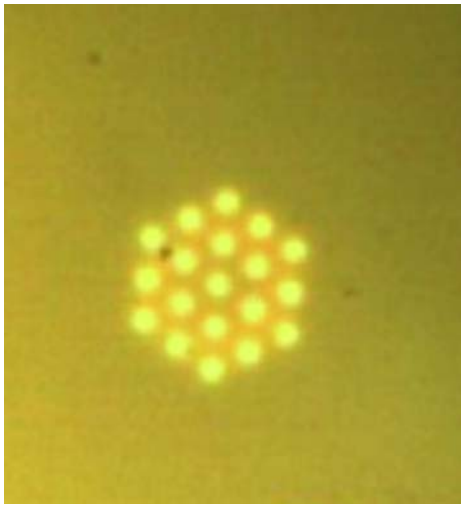



Field distribution in the fiber




Intensity distribution in the far field

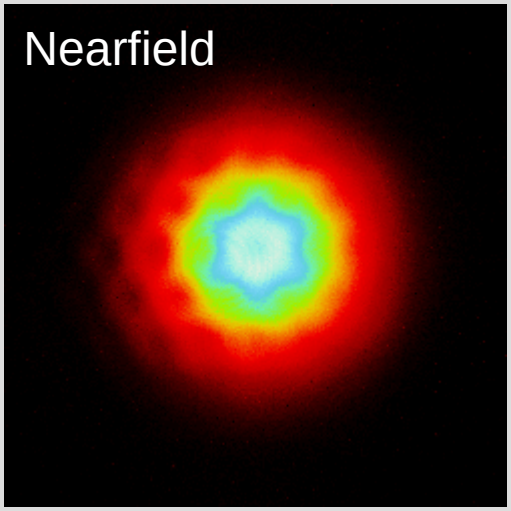
# A fundamental-mode 19-Core Fiber

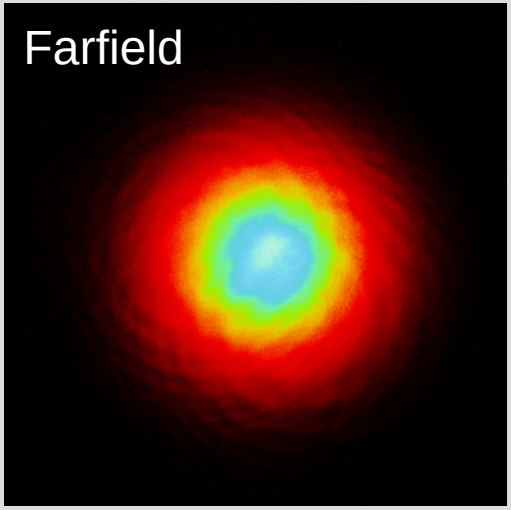


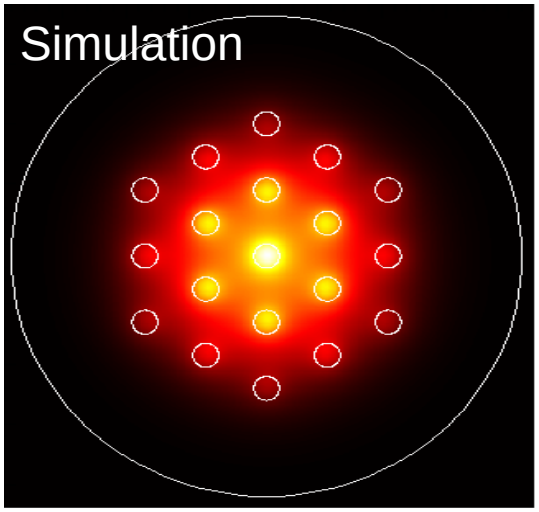
**19-core-singlemode-fiber**

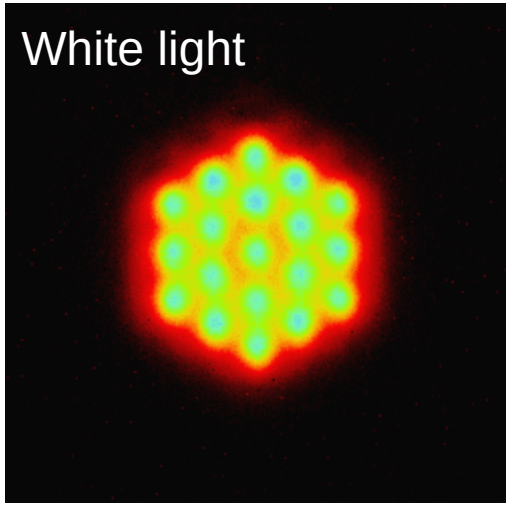
N.A. ~ 0,108
$n_{clad}$ = 1,45
$n_{core}$ = 1,454
Core-∅: 2 µm
Core to core distance: 5,5 µm
450 µm² effective area
truly single-mode

Measurement

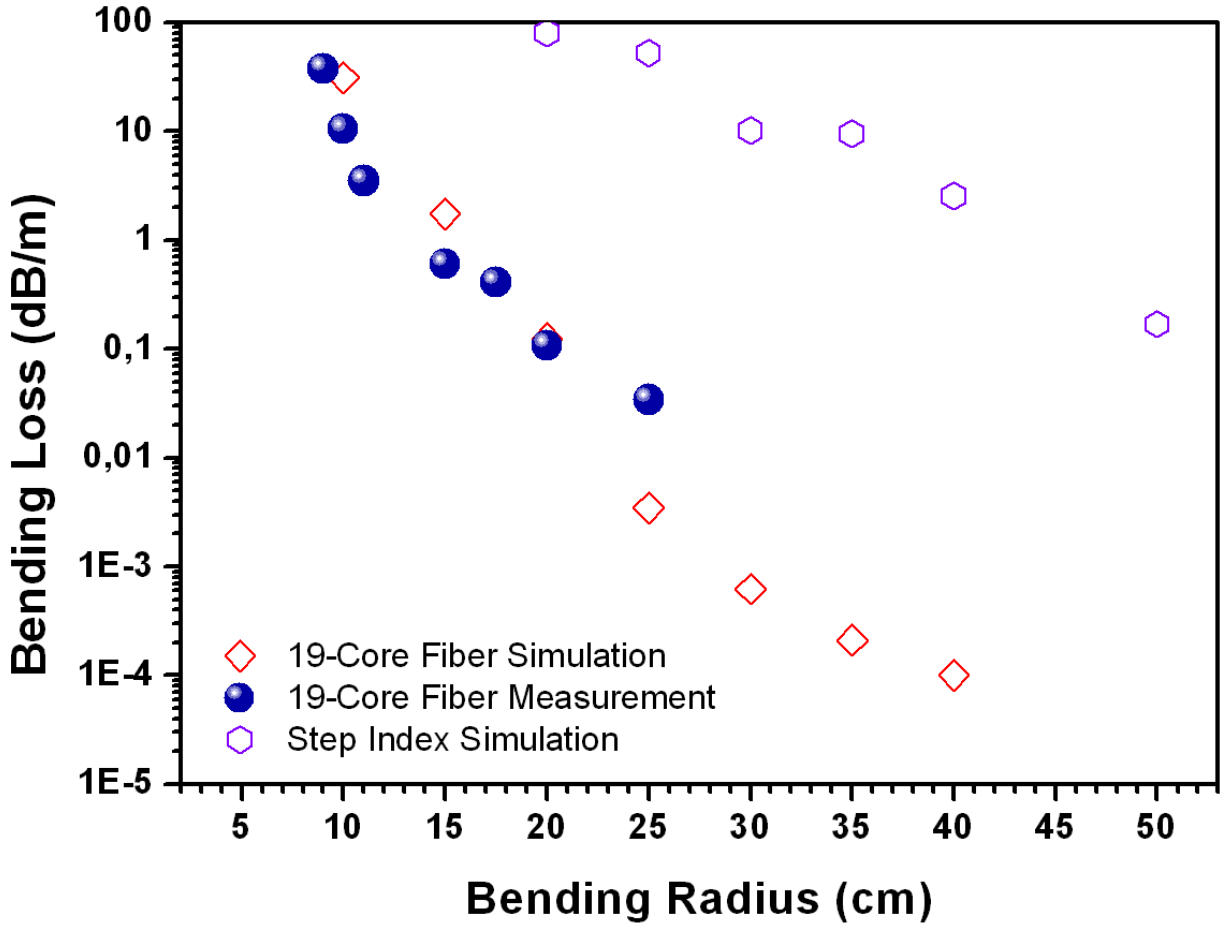


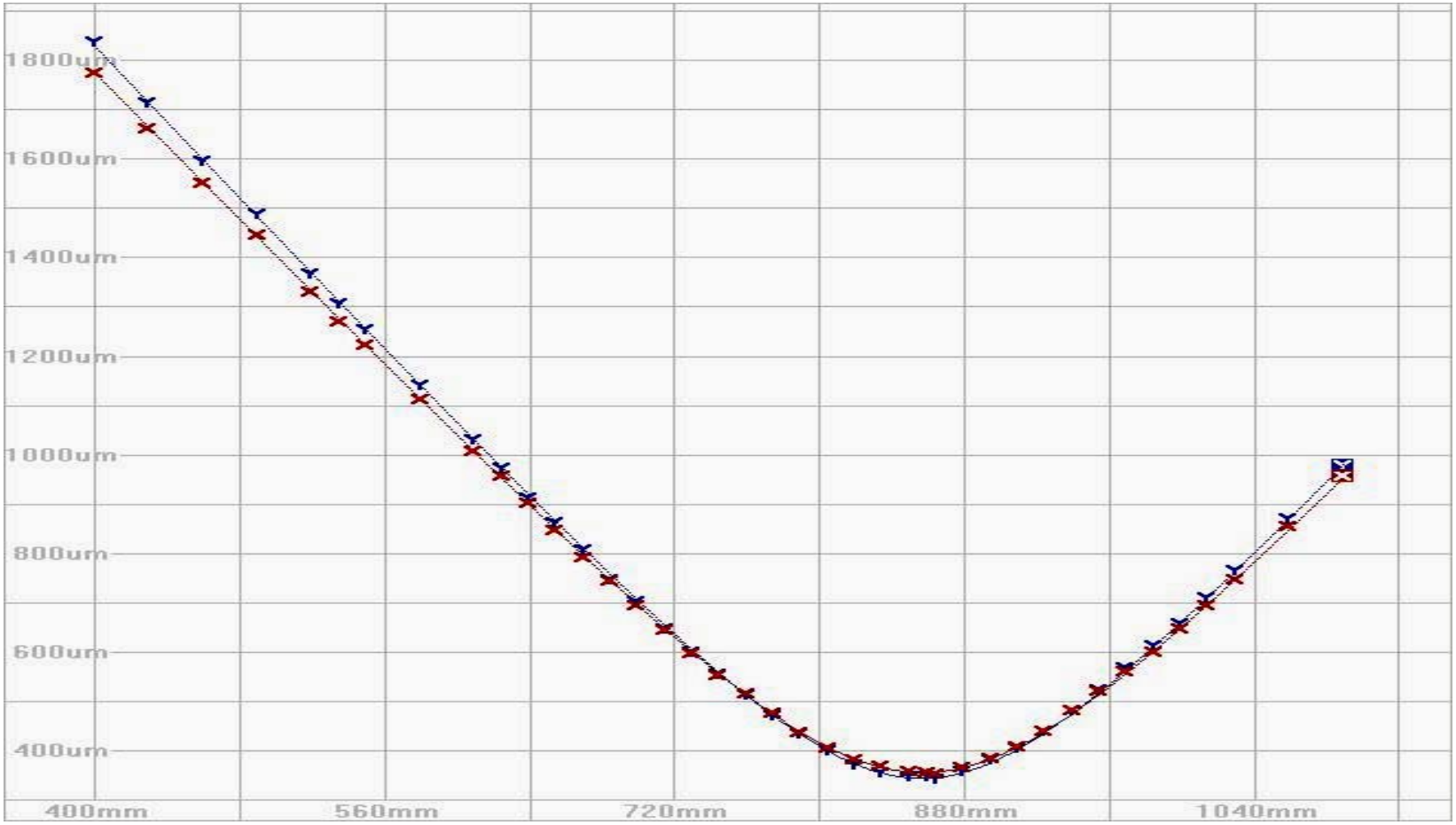



# A fundamental-mode 19-Core Fiber: Bending Sensitivity




- The bending-induced losses of the 19-core fibre are two orders of magnitude lower than those of a comparable step-index fibre!

# A fundamental-mode 19-Core Fiber: Beam Quality



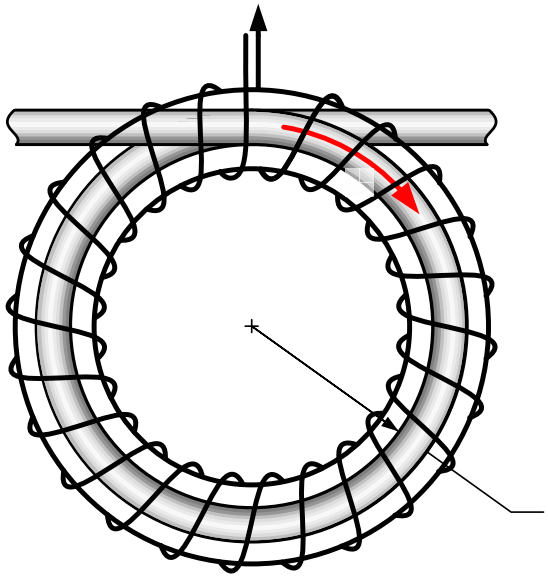

- $M^2 < 1.03$ for all measurements (different length, different bending radii)

# Fibre-integrated optical isolator

- **Goal:**
  Fully fibre-integrated isolator suitable for high-power beams in the kW range.

- **Concept:**
  Realisation of Faraday-rotation and polarizer directly in a silica glass fibre.

- Disclosure of the technical details will follow after patent application.



LANDESSTIFTUNG
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# Summary

- Spatial Beam Shaping
  - radial polarization to enhance process efficiency and quality
  ↳ new project RaPoS on cutting and welding (2009-2011)
- Temporal Beam Shaping
  - Laser source with switchable short and ultrashort pulses for higher productivity
  ↳ current laser developments for applications in photovoltaics
- Spatiotemporal Beam Shaping
  ↳ a novel beam rotator for helical drilling to improve the process quality
- Novel Fibers for High-Power Beam Delivery
  - low-loss 19-core fiber for cw kW diffraction-limited radiation
  ↳ project HOTFiber including Bragg-type fibers and fiber lasers (2008-2010)

- 8.-10. June 2010 in Stuttgart
- Together with SLT and LPM