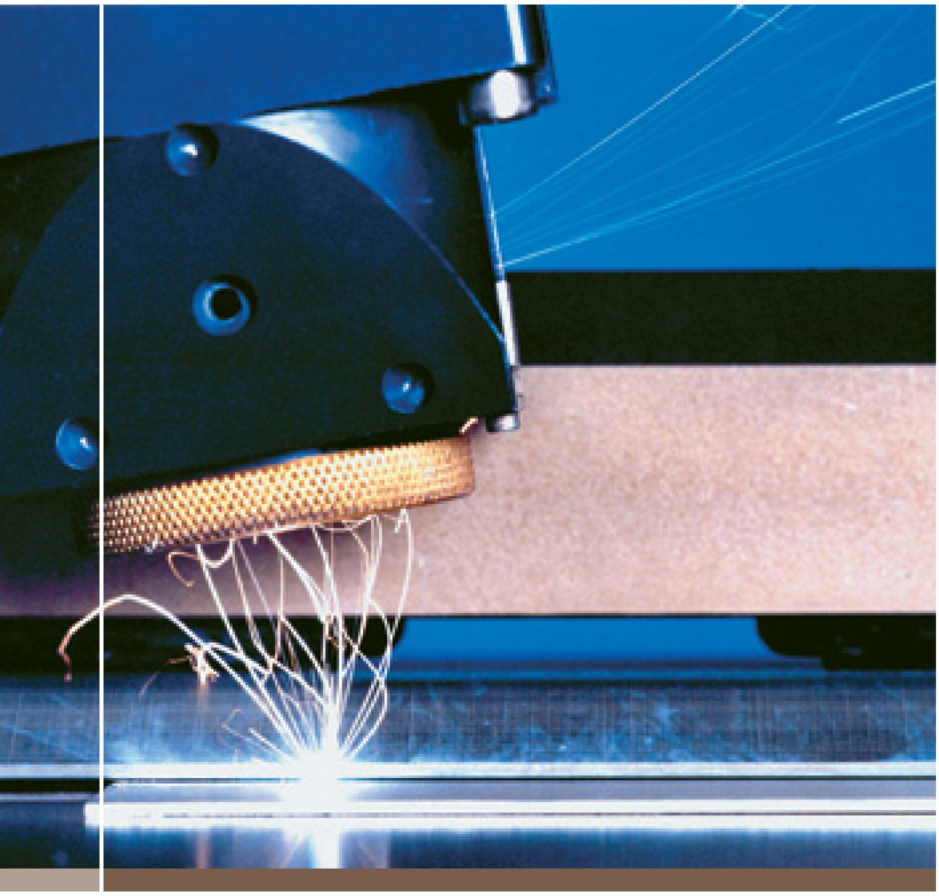
Research on lasers and laser applications

Since its invention and the first experimental demonstrations the laser has long overcome its initial image of being a solution for a yet unknown problem. In fact this technology has now reached an essential economical importance both as an independent industry as well as a key technology and mainspring for innovations in other industrial sectors. But also in science the laser has never lost its attractiveness and continues to open up new fundamental research opportunities ranging from microbiology and medicine over material processing and nano-science to fundamental research on light-matter interactions and quantum phenomena.



The research on lasers and their applications at the Universität Stuttgart is concentrated at the Institut für Strahlwerkzeuge (IFSW). It follows a holistic approach and spans the whole range from laser physics and laser development to laser applications and fundamental research on laser material processing. The aim is to generate essential innovation and competitive advantage in a wide field of manufacturing applications. For manufacturing purposes, the laser is indeed a universal tool as it covers all production processes defined by the German industry standard DIN 8580. That is to say: primary forming, deforming, separating, joining, coating, and altering material properties. All these laser applications in manufacturing have gained significant impulses with the improvements of the laser sources in the recent few years. And the actually most prominent and reputed laser worldwide, the thin-disc laser, is an invention of the IFSW. But also in the past, the IFSW has contributed key innovations for instance to the CO_2-lasers that are leading the global market today.

Still, this successful technology transfer would not have happened without a sound scientific but practical demonstration of where and how the laser technologies are superior to conventional manufacturing methods. This is why the holistic research approach with the merge of the newest laser sources with cutting-edge research on laser material processing was and is so important. Many of the most successful laser techniques in a wide range of manufacturing applications are a result of this approach. Among these are the solution of welding instability problems with double-focus techniques, an essential leap in precision with the invention of helical drilling with the development of a corresponding trepanning optics, the investigation and development of novel nozzles for laser material processing as well as fundamental research on the dynamics of light-matter interactions that led to a sound understanding of laser processing techniques.

All these research results have meanwhile found their way into widespread industrial implementations, and prove that the photonics research in Stuttgart indeed is at the leading edge of science and that the technology transfer to the innovative industry of the region is very efficient. This successful research environment shall be demonstrated with a few exemplary developments highlighted in the following.

1. The Thin-Disk Laser

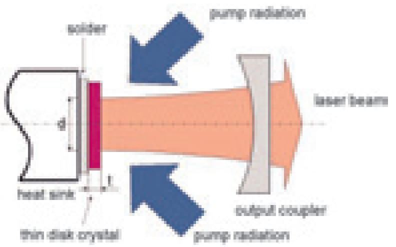
The thin-disk laser concept allows to build diode pumped solid state lasers with simultaneously highest output powers, highest efficiency and best beam quality. Nearly all operational modes of solid state lasers and laser amplifiers such as continuous wave, pulsed operation with pulse durations between femtoseconds and nanoseconds can be realised with this design and in most cases with clearly superior properties as compared to other laser concepts.

One of the outstanding features of the thin-disk laser is its excellent beam quality which results from the face cooling of the laser disk. **(01)** shows the principle of the thin-disk laser design. The laser crystal is shaped as a disk with a diameter of several mm (depending on the output power/ energy) and a thickness of 100 µm to 200 µm depending on the laser-active material, the concentration of the laser-active ions (the so-called doping level) in the thin-disk crystal and the excitation design (the so-called “pumping” of the laser material). The disk is coated to work as a highly reflective mirror on its back side for both the laser and the pump wavelengths and anti-reflection coated on the front side for both wavelengths. This disk is mounted with its backside on a water-cooled heat sink using indium-tin or gold-tin solder. This technique allows a very stiff fixation of the disk on the heat sink without deformation of the disk which acts as a backside-mirror of the laser resonator. To reduce the stress during the soldering process as much as possible the heat sink is made from a heat expansion matched material (Cu-W). The heat sink is water-cooled by impingement cooling using a multi-nozzle design inside the heat sink.

Due to this mounting and cooling technique the temperature gradients inside the laser crystal are mainly coaxial to the disk axis and the laser beam axis. Within the homogeneously pumped central area of the disk the temperature distribution is very uniform in radial direction. Therefore, these temperature gradients only slightly influence the laser beam propagating there and back through the disk. As compared to rod laser systems the thermally induced deformations and non-uniform refractive index changes (both causing lens effects and aspherical disturbances) are reduced by more than one order of magnitude in the thin-disk laser design. The stress induced birefringence is even more reduced and can be neglected for real laser systems. Additionally, due to the large surface-to-volume ratio the heat dissipation from the disk into the heat sink is very efficient thus allowing the operation at extremely high volume power densities in the disk (up to $1\ \mathrm{MW/cm^3}$ absorbed pump power density).

ZUSAMMENFASSUNG

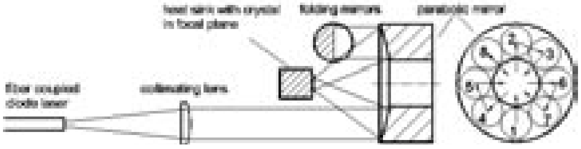
Dank seiner einmaligen Anwendungsvielfalt erfreut sich der Laser eines seit seiner Erfindung ungebrochenen und beispiellosen Siegeszuges in allen gesellschaftlichen, industriellen und wissenschaftlichen Bereichen. Das Institut für Strahlwerkzeuge (IFSW) verfolgt dabei einen ganzheitlichen Forschungsansatz der die Entwicklung neuer Laserstrahlquellen mit der Erforschung laserbasierter Materialbearbeitungsprozesse und der dafür benötigten Komponenten verbindet. Die Arbeit des IFSW wird hier anhand ausgewählter Beispiele aus den drei genannten Themenkreisen illustriert. Aus dem Bereich der Laserentwicklung wird das am IFSW erfundene und heute bereits sehr erfolgreich industriell umgesetzte Scheibenlaserkonzept vorgestellt. Die Forschung auf dem Gebiet der Materialbearbeitung mit Laserstrahlen hat wesentlich zum industriellen Erfolg des Scheibenlasers beigetragen und wird anhand der Erkenntnisse z.B. beim Bohren oder beim Schweißen illustriert. Dass es für den erfolgreichen Einsatz des Strahlwerkzeugs Laser mehr braucht als Laserstrahlen, Linsen und Spiegel zeigt der Bericht über aerodynamische Komponenten, welche einerseits zum Schutz der optischen Elemente eingesetzt werden und andererseits die für den Bearbeitungsprozess erforderlichen Druck- und Strömungsverhältnisse erzeugen.



01

The principle of the thin-disk laser design.

The disk can be pumped in a quasi-end-pumped scheme. In this case the pump beam hits the crystal under an oblique angle as shown in **(01)**. Depending on the thickness and the doping level of the crystal only a small fraction of the pump radiation is absorbed in the laser disk. Most of the incident pump power leaves the crystal after being reflected at the back side. By successive re-directing and imaging of this part of the pump power again onto the laser disk the overall absorption of the pumping beam can be increased. A very elegant way to increase the number of pump beam passes through the disk is shown in **(02)**. The radiation of the laser diodes for pumping the disk is first homogenized either by fibre coupling of the pump radiation or by focusing the pump radiation into a quartz-rod. The end of either the fibre or the quartz rod is the source of the pump radiation which is imaged onto the disk using the collimating lens and the parabolic mirror. In this way a very homogeneous pump profile with the appropriate power density in the disk can be achieved which is necessary for good beam quality. The unabsorbed part of the pump radiation is collimated again at the opposite side of the parabolic mirror. This beam is re-directed using two mirrors to another part of the parabolic mirror where the pump beam is focused again onto the disk, this time from another direction. This re-imaging procedure can be repeated until all the (virtual) positions of the parabolic mirror have been used. At the end the pump beam is re-directed back to the source thereby doubling the number of pump beam passes through the disk. In this way up to 32 passes of the pump radiation through the disk have been realized and more than 90 percent of the pump power is absorbed in the disk.



02

Pumping design for the thin-disk laser with 16 pump beam passes.

Using multiple pump beam passes through the disk results in a thinner disk and/or a lower doping concentration thus reducing the thermal effects like thermally induced lenses and stress in the disk. Another advantage is that the effective pump power density is increased (nearly 10 times for 16 pump beam passes) so that on the one hand the demands to the power density (beam quality) of the pump diodes are reduced and on the other hand also quasi-three-level laser materials (e.g. Ytterbium doped) can be used with this design.

When operating the disk in this set-up the output power or energy can easily be scaled just by increasing the pump spot diameter keeping the pump power density constant. Also, there is no need to increase the brightness of the pump laser diodes.

Very high laser output power can be achieved from one single disk by increasing the pump spot diameter while keeping the pump power density constant. The slope efficiency and the optical efficiency are nearly independent of the pump spot diameter. To date more than 4 kW power has been demonstrated from one single disk (Trumpf Laser). The high efficiency of the thin-disk laser results also in a very high electrical efficiency of the total laser system which is higher than 25 percent for industrial lasers with 4 kW output power and a beam propagation factor M^2 of less than 20.

An alternative way to scale the output power is the use of several disks in one resonator. More than 6.5 kW laser power has been demonstrated so far using 2 and 4 disks in one resonator (Trumpf Laser). Due to the moderate thermal effects in the disks the beam quality is nearly independent of the power and is at least 3 times better (for commercially available thin disk lasers) than that of rod lasers with the same output power.

Depending on the demands from materials processing the high-power thin-disk lasers in the kW power range are operated with a beam propagation factor (beam quality) M^2 of about 20 that means that the focusability of the laser beam is 20 times inferior to the theoretical limit ($M^2 = 1$). But beyond this beam quality, the thin disk laser design offers the possibility to operate high power lasers also with the diffraction-limited beam quality ($M^2 = 1$) due to the moderate thermal effects and the small optical distortions in the disk. Using an appropriate resonator design it is possible to achieve high laser output power with high optical efficiency.

Simulations show that scaling of the output power of one single disk is only limited by amplified spontaneous emission (ASE) if the pump spot diameter becomes larger and larger. Fortunately, the optical gain of lowly doped Yb:YAG is rather small so that ASE will occur only at very high pump power levels. For a 9 at. percent doped disk with a thickness of 200 µm the power limit occurs at a pumping power beyond 50 kW so that much more than 20 kW laser power can be extracted in cw-operation from one single disk.

This power level (20 kW) can be increased much more by further increasing the pump spot diameter. The limitation set by ASE can then be overcome by using a disk with an un-doped cap on top of the disk thus reducing the average radial gain by the square of the ratio between un-doped and doped material.

The simulations also show that the laser power level for diffraction-limited mode operation can be increased to the same power level as for multi-mode operation. The reason for this behaviour is that the aspherical contribution to the residual thermal lens of the disk inside a top-hat pump profile is extremely small (less than 10 nm optical path difference) and independent of the pump spot diameter itself. The resulting phase step at the edge of the pumped region can be compensated for by using simple adaptive optics.

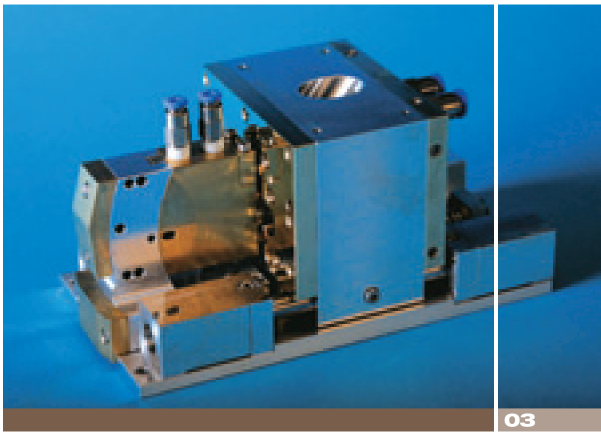
Besides the outstanding properties of the thin-disk laser design for cw-operation it is also well suited for pulsed laser systems especially if high average output power is required. Till today, pulsed thin-disk laser systems have been developed and demonstrated for the ns, ps, and fs pulse duration ranges (10^{-9}, 10^{-12}, and 10^{-15} seconds, respectively). All systems show an excellent beam quality and high efficiency.

Scaling the pulsed energy of one single disk is limited more severely by ASE than in the case of cw-operation since the gain under low repetition rate conditions is much higher as compared to the cw-operation of a disk. Nevertheless, using an un-doped cap on top of the disk will result in achievable pulse energy levels far beyond 10 J from only one single disk. This energy can be further increased by using multiple disks in one resonator.

Up to now several companies already offer thin disk lasers on the market for different applications. These lasers are covering the power range from several watts up to several kW for materials processing. **(03)** shows a thin disk module for the power range up to 500 W.

Using thin disk lasers for materials processing will considerably increase the process efficiency for many applications. Due to the good beam quality of thin disk lasers deep penetration welding becomes possible also for thin materials as well as remote welding at high power. In summary, the increase of laser and process efficiency will result in substantial cost reduction of laser manufacturing.

In future, new materials will be investigated with the goal to increase the power, the energy and the beam quality even further. Laser output powers of much more than 10 kW and energies of more than several J will be possible. New materials will open new markets for new wavelengths and with the semiconductor thin disk lasers customized lasers for specific markets will become feasible.



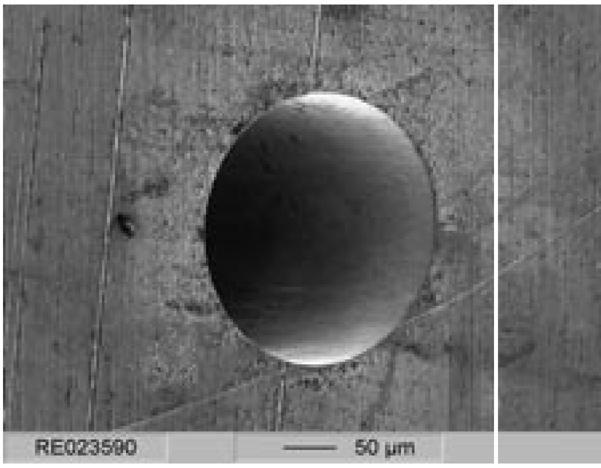
03

Thin-disk laser module for up to 500 W laser power.

2. Understanding Laser Material Processing

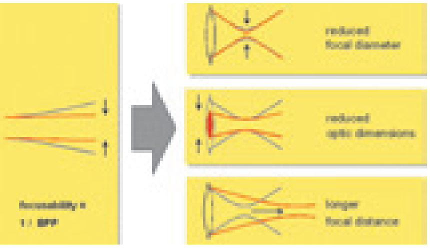
As stated in the introduction, strong synergetic effects result from simultaneous but linked developments and research in the fields of laser systems and their applications. The basic understanding of photonic production processes in one hand allows defining the direction of laser development. Early tests of newly developed systems on the other hand offer the chance to investigate, prove and demonstrate their potential and thus open new markets.

A recent example lies in the field of micro machining **(04)**. Whereas the majority of research groups propagated the recipe to increase accuracy by reducing the pulse duration down to the femtosecond region (1 fs = 10^{-15} s), fundamental theoretical investigations and experimental findings at the IFSW showed, that pulses shorter than 1 ps (= 10^{-12} s) do not offer further advantages for the processing of metals and that the highest precision can be reached with 10 ps long pulses. This conclusion superseded the development of complicated and expensive laser systems.



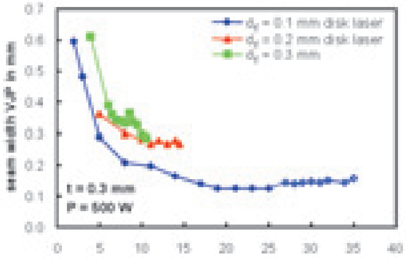
04

Hole produced in 1 mm thick steel with an experimental picosecond laser developed at the IFSW.



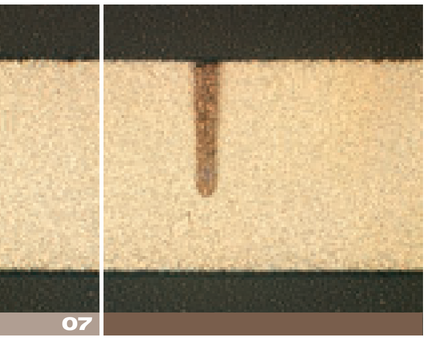
05

Benefits of improved focusability: reduced focal diameter (top), reduced optics dimensions (middle) or extended working distance (bottom).



06

Welding performance of a thin-disk laser (focus diameters 0.2 and 0.1 mm) compared to a conventional system (focus diameter 0.3 mm), both operated at 500 W, when applied to steel sheets of 0.3 mm thickness.



07

Cross sections through a 2.5 mm deep weld seam in steel achieved with a 3 kW thin-disk laser at a velocity of 9 m/min.

One of the first findings of the research at the IFSW was that an ideal laser for welding should offer high efficiency, a short wavelength (1 µm) and good focusability.

Both conventional laser systems used for welding, CO_2 lasers and lamp pumped Nd:YAG systems, could not meet all requirements. CO_2-lasers offered the advantages of high efficiency, low cost and strong focusability. Nd:YAG lasers, on the other hand, convinced production engineers by their short wavelength allowing beam conduct through flexible glass fibres.

The search for a laser concept able to fulfil all of the above requirements led to the invention of the disk laser. Industrial lasers based on this concept now combine the advantages of the conventional work horses.

With the thin-disk laser or generally with a laser of equal focusability such as the fiber laser, one can achieve either a significant reduction of the focus diameter by using the same focal length or an even stronger reduction of the dimensions of the focusing optics when maintaining the focal diameter **(05)**. In the latter way, accessibility is improved, integration in the handling device is facilitated and the dynamics of the system is improved due to the smaller moving mass. A third option to benefit from stronger focusability is to extend the distance between optics an workpiece which enables highly productive techniques such as remote welding which uses rapid beam deflection to eliminate non-productive times. In this case, the working volume accessible with scanner optics scales with the third power of the focusability. The remote welding is presently introduced in car body manufacturing and allows to substitute resistance spot welding to a large extent.

In addition to the advantages for system layout described above, higher focusability allows to overcome current limitations of the welding process. **(06)** demonstrates this in the case of welding thin sheets with low power. The maximum welding speed for full penetration is 35 m/min with a focus diameter of 0.1 mm of a disk laser which is three times faster as compared to the attainable speed with a larger focus diameter of 0.3 mm obtained from a conventional laser.

In welding of thicker materials the disk laser enables extremely slim weld cross sections **(07)** which so far could only be achieved with electron beams. In this way heat distortions can be minimized in welding of precise workpieces such as transmission components.

3. Gas-dynamical Components for Laser Material Processing

In order to ensure efficient processes with high-quality outcome, not only the laser process itself but also the environment of the process needs to be controlled and optimised. The result of laser material processing is very much influenced by the composition of shielding gases, pressure and gas flow circumstances.

These specific gas-dynamical conditions required to attain the desired results are usually limited to a small volume around the interaction region of the laser beam with the workpiece. In most cases this is accomplished very efficiently and effectively with appropriately designed gas nozzles.

The gases control requirements, however, are as diverse as the many different laser applications themselves. Additionally, gas-dynamical components often are also used to prevent the contamination of the expensive and sensitive optical elements. Especially the focusing optics and optical sensors close to the interaction zone are very vulnerable to damage caused by smoke and droplets generated by the highly dynamic laser-matter interaction. The degradation and the subsequent destruction of these optical components can again be prevented by appropriate gas cross-jets which are generated by specifically dedicated nozzles to deflect both smoke and droplets. The challenge in the combined use of shielding gas and cross-jets lies in the potential aero dynamical interaction of the different gas flows. In particular one must prevent that the cross-jet which protects the optical components draws the shielding gases off the workpiece.

To date a large variety of gas-dynamical components have been and still are being investigated and optimised for a wide variety of different laser material processing applications at the IFSW. As an illustration of the corresponding work, three interesting concepts shall be highlighted in the following: gas nozzles for high-power cutting with CO_2 lasers, a cross-jet nozzle for the protection of optical components and a gas-dynamical device to reduce the ambient pressure in the interaction zone to improve the rate of ablation with ultrashort laser pulses.

In the field of laser cutting the development of nozzles concentrates on the applications with inert gases as they require particularly high pressures and high flow velocities to efficiently remove the melt out of the gap. Compared to this task, the requirements for oxygen-assisted cutting are much less demanding. Due to the immediate required momentum interaction of the gas with the melt, the nozzle is usually very close to the workpiece surface which means that the laser beam has to be directed collinearly with the nozzle axis and focused through the nozzle opening onto the workpiece.

It is known since many years that the commonly used conical or conical-cylindrical nozzles cannot transfer high pressures over larger distances in the generated free jets. This is due to a gas-dynamic shock wave caused by the sudden deceleration of the gas in the jet impinging the workpiece. These shock waves get more pronounced the higher the velocity of the gas is that hits the workpiece surface. The gas velocity at the exit of conical nozzles is equal to the speed of sound and it significantly increases within a few millimetres of distance from the nozzle. Therefore the impact pressure on the workpiece is significantly reduced by the shock losses with increasing distance from the nozzle.

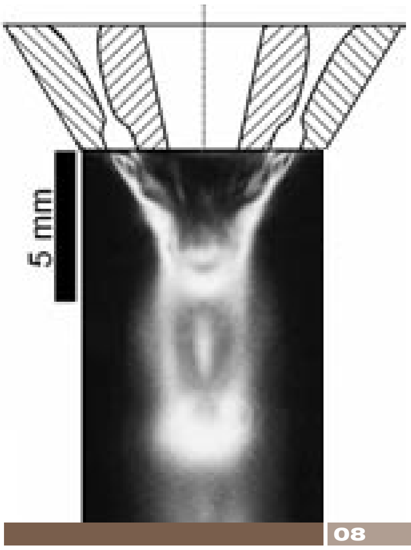
At distances larger than the diameter of the nozzle further shocks arise that get more and more pronounced with increasing gas pressure in the nozzle. Those shocks can be completely avoided by using specially shaped nozzles, the so-called Laval-nozzles. Simultaneously, the shocks mentioned first are limited in strength. The advantage of the Laval-nozzle therefore is the constant impact pressure on the workpiece over much larger distances in the free jet. However, due to the high gas consumption of Laval-nozzles, the use of conical nozzles is still favoured where short distances to the workpiece are possible and the investigations to optimise the according gas dynamics is still an important part of the implementation of laser cutting applications.

Novel gas nozzle designs are also required for the cases where no transmitting optical windows or lenses can be used in the focusing optics due to the high laser powers that have become available more recently. In this case the inner gas pressure cannot be built up between the focusing lens or a window and the nozzle opening. To solve this problem ring-shaped nozzles and the combination of several nozzles were successfully investigated in the past few years. With the combination of two Laval-nozzles, for instance, the two jets can be merged to form one single jet that propagates collinearly with the laser beam. The inherent asymmetry of this implementation can be avoided by the use of a ring-shaped Laval-nozzle as shown in **(08)**.

All optimisations and new developments of nozzles for laser cutting require a sound understanding and detailed investigations of the gas-dynamics and the melt flow in the cutting gap. Experimentally this is investigated with appropriately scaled models **(09)** and interferometric methods or, especially more recently, with direct observation with high-speed camera equipment.

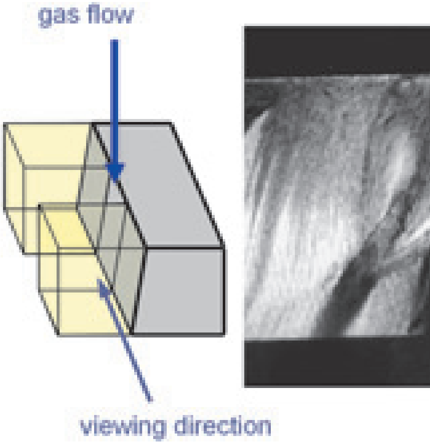
The same applies to the investigation and the development of cross-jets for the protection of the optical components particularly in laser welding applications **(10)**. It was shown that an efficient deflection of droplets requires the cross-jet to be placed as closely as possible to the workpiece surface. The gas velocity should be as high as possible to ensure the strongest possible deflection angles. This required the development of a special gas-dynamic nozzle that on the one hand provides the desired droplet deflection but on the other hand avoids the shielding gases form being drawn off the workpiese surface.

Another interesting gas-dynamical component was derived from very early investigations of aerodynamic windows that were



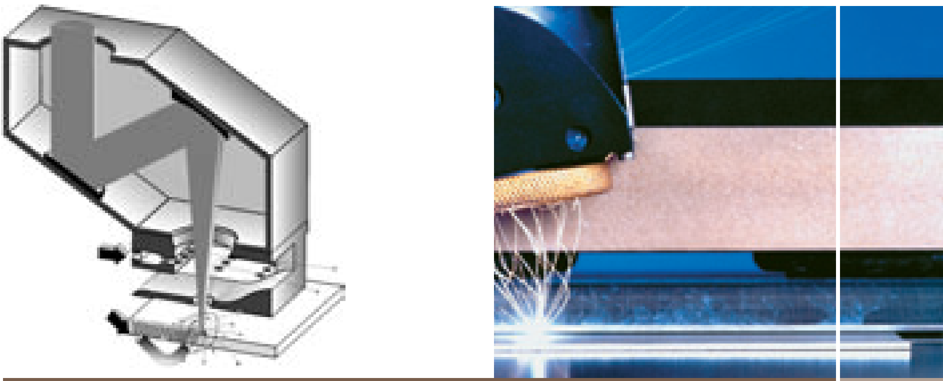
08

Schlieren picture of the gas jet produced by a ring-shaped Laval-nozzle with a gas pressure of 1 MPa and a gas flow of 350 bar×lt/min.



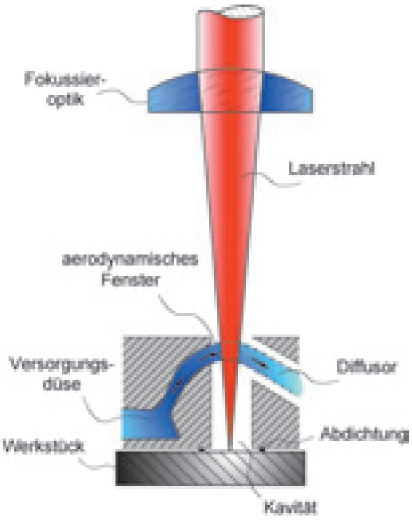
09

Experimental simulation of the melt flow in a cutting gap reproduced with optically transparent walls. A mixture of soot in petroleum is used to simulate the liquid melt flow.



10

Left: set-up with the cross-jet (top arrow) nozzle which avoids the disturbance of the shielding atmosphere (bottom arrow). Right: deflection of the spilling by the cross-jet.



11

Aerodynamic window to increase the rate of ablation with ultra-short laser pulses.

used to seal high-power CO_2 lasers. The knowledge on this technology now is exploited to reduce the ambient pressure to enhance the rate of ablation with ultra-short laser pulses. It has been shown that a reduction of the ambient pressure from approximately 1 bar to 0.1 bar can increase the ablation rate by at least one order of magnitude. The advantage of using an aerodynamic window as shown in **(11)** lies in the small evacuated volume just at the place where it is needed rather than evacuating larger chambers that house the whole workpiece.

4. Conclusions and Outlook

Summarising the past 20 years of laser research at the IFSW it can be concluded that one of the outstanding strengths is indeed the holistic research approach. Only by mastering every single aspect from the generation of laser beams to the fundamentals of the highly complex laser-matter interaction processes including the influence of the gas-dynamic environment at the interaction zone it is possible to successfully transfer novel and innovative technologies from academia to industry and generate the economic and societal benefits that we have seen so far.

This is an experience that will also be valid for the future. The holistic approach will be perpetuated although the research topic naturally will change. Once the thin-disk laser will have exceeded the 10 kW level the scientific interest will gradually shift from power scaling to shaping of custom mode properties. As the usual linearly or circularly polarised diffraction limited Gaussian modes not always – if not rarely – are the most suitable beams for given applications, the generation of modes with unconventional polarisation and/or intensity distributions will offer further potential of innovations. These all the more if the mode properties can be changed online during laser operation. On the other hand, the emergence of multi-kW lasers with nearly diffraction limited custom modes will create the necessity to develop novel optical fibres that allow to transmit the laser power without deteriorating the customised beam properties.

As in the past, it will be the research on laser applications that will point the direction of the laser research by assessing which of the above visions can be exploited in practice. Additionally, due to the fast and widespread implementation of the laser especially in manufacturing, there is a natural need for an improved quality assurance of laser machining processes. As this can only be achieved with a sound fundamental understanding of the highly dynamic laser machining processes the research on the laser-matter interaction, the complete numerical simulation of all relevant processes and the development of novel and better diagnostic tools is currently being reinforced with significant efforts. •

Peter Berger
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SUMMARY

Thanks to its unparalleled versatile applicability the laser enjoys an ever increasing popularity in all societal, industrial and scientific fields. The Institut für Strahlwerkzeuge (IFSW) contributes to this success by following a holistic research approach that links the development of novel laser sources with the investigations on laser material processing and on the thereto required components. The efforts of the IFSW are illustrated with selected examples from these three research areas. The thin-disk laser concept that was invented at the IFSW has already successfully been transferred to industry. The industrial success of the thin-disk laser was significantly stimulated by the research on the applications as illustrated with knowledge gained from investigations on drilling or welding. That the successful application of lasers involves more than light, lenses and mirrors is seen from the examples given on aerodynamic components that are being developed both to protect the expensive optics and to provide the ideal environment for optimised machining processes.

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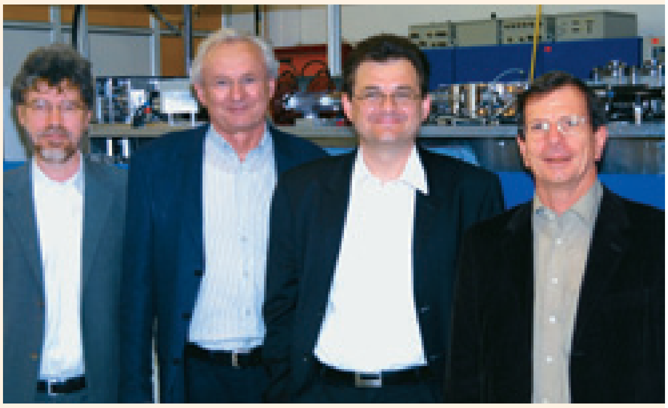

From left to right: Dipl.-Ing. Peter Berger, *Prof. Dr. rer. nat. habil.* Friedrich Dausinger, *Prof. Dr. phil. nat. habil.* Thomas Graf, *Dr. rer. nat.* Adolf Giesen.

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studied physics at Bonn University, and received his Ph.D. degree in 1982. From 1982 to 1986 he was with DLR (former DFVLR, the German Aerospace Establishment), where he was responsible for resonators, optics and discharge technology in the CO_2-laser developing group. Since 1986 at the Institut für Strahlwerkzeuge (IFSW) of the Universität Stuttgart. Head of the department for laser development and laser optics, working on diode pumped solid state lasers (thin disk laser) and on characterization of laser beams and of optical components used with lasers.

THOMAS GRAF

was born in Lugano, Switzerland, in 1966. He received the physics M.Sc. degree in 1993 and the Ph.D. degree in 1996 from the University of Bern, Switzerland. As a post-doctoral research associate he was engaged in research on high-power solid-state lasers with high beam quality, beam-shaping for diode-laser bars, and thermodynamics of optical systems at the University of Bern until 1997. He then joined the University of Strathclyde in Glasgow, Scotland (UK) where he was engaged in research on non-linear optics and passively mode-locked multi-Watt all-solid-state lasers. In April 1999 he was appointed head of the High-Power Lasers and Material Science Group at the Laser Department of the Institute of Applied Physics, University of Bern (Switzerland) where he was awarded the venia docendi in 2001 and where he was nominated assistant professor in April 2002. In June 2004 he was appointed as university professor and director of the Institut für Strahlwerkzeuge (IFSW) at the Universität Stuttgart. He is currently interested in high-power all-solid-state laser systems, laser beam shaping and laser applications in manufacturing.

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