8th of May 2014

Digital Photonic Production - Crosslinking of virtual Reality with the Reality of Laser Manufacturing

Univ.-Prof. Prof. h.c. Dr. Reinhart Poprawe, M.A.

AKL'14
INTERNATIONAL LASER TECHNOLOGY CONGRESS

RWTH Rheinisch-Westfälische Technische Hochschule Aachen
Lehrstuhl für Lasertechnik LLT

Fraunhofer ILT

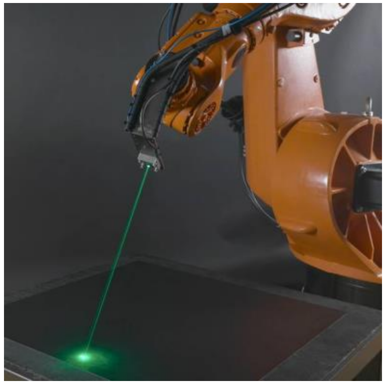
Contents

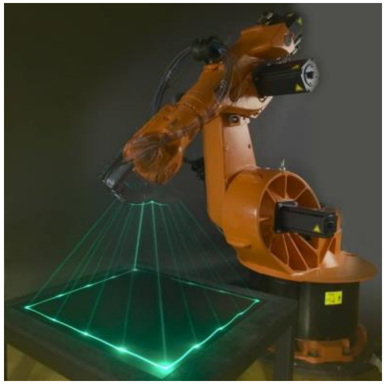
The Vision of Digital Photonic Production

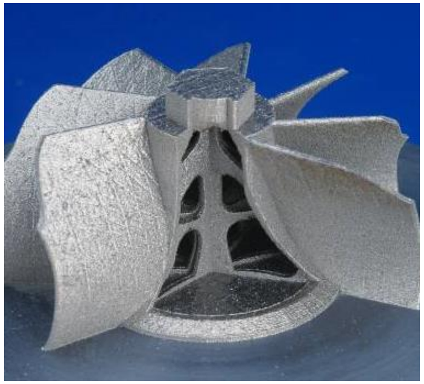
Digital Photonic Production –
"Bits to Photons to Atoms"

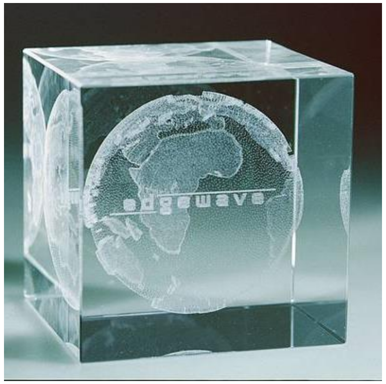
Using light as a tool means …

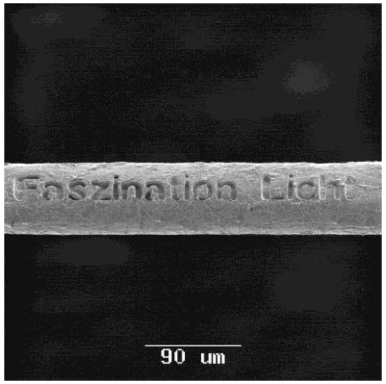
- highest intensity
- highest speed
- shortest interaction (precision)
- mass-less, force-less, no tools
- best controllability (CAD to product)



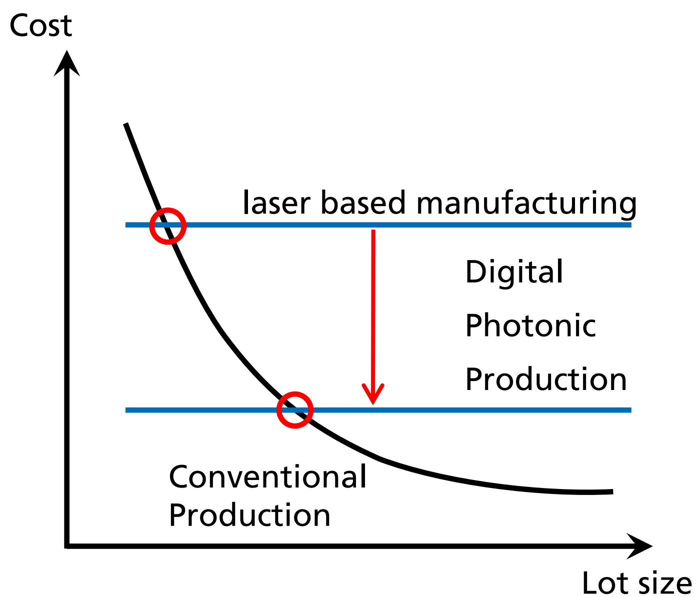


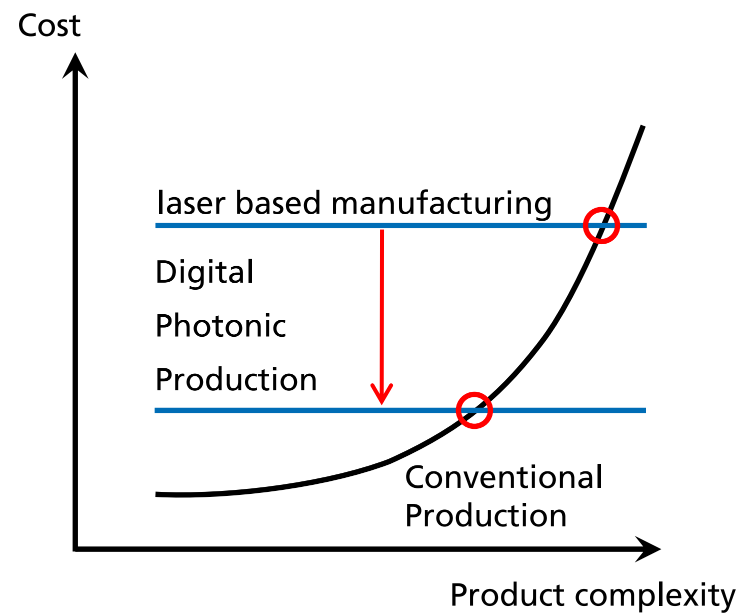


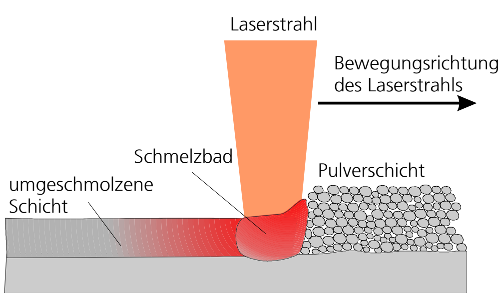




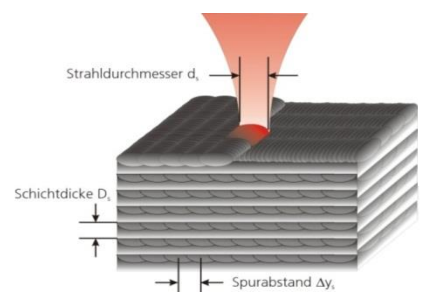
Digital Photonic Production – A new Industrial Revolution?!



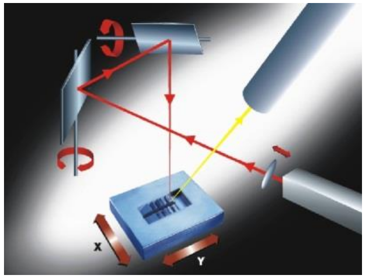




SLM 1-3 cm³ / min



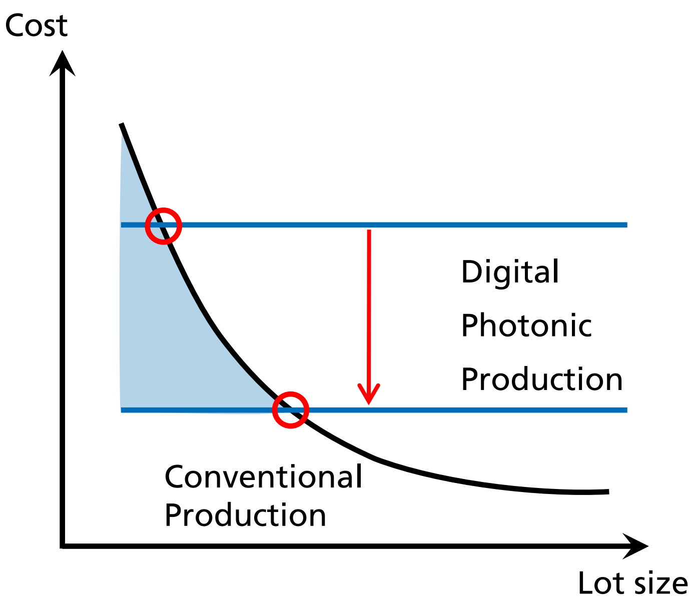
LMD 10-30 cm³ / min



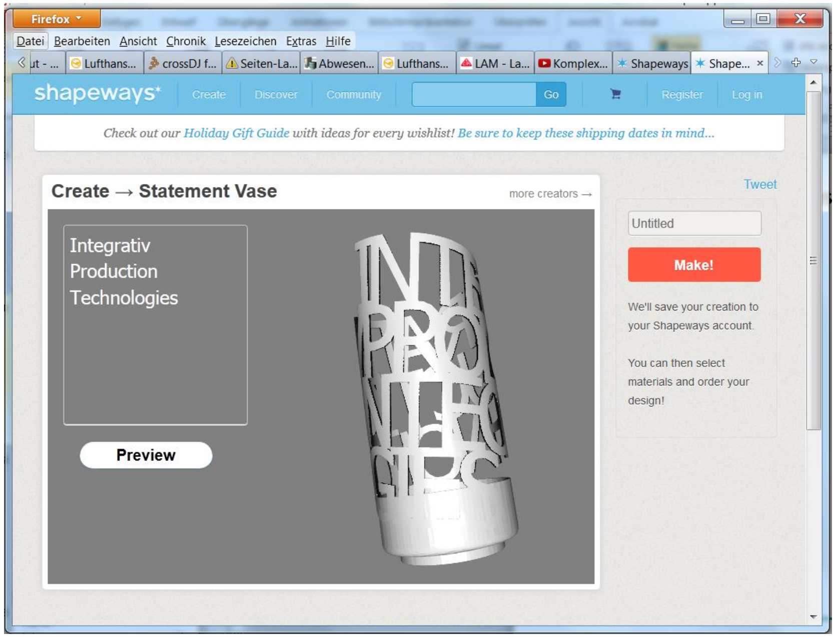
Ablation 0,2-0,5 cm³ / min

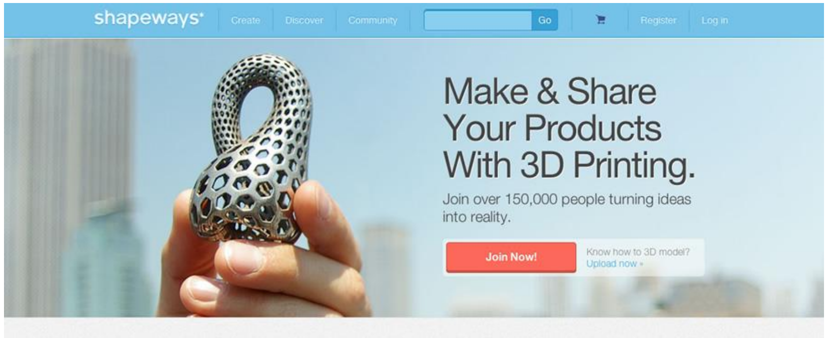
Digital Photonic Production

Individualisation for free

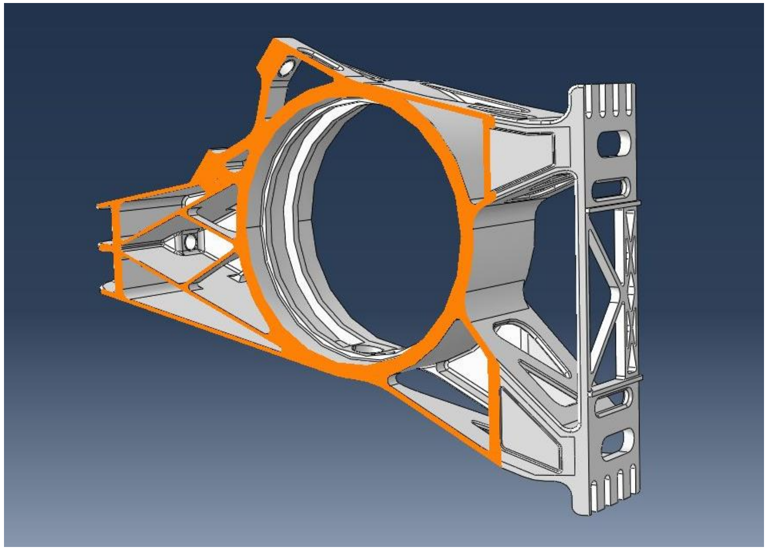


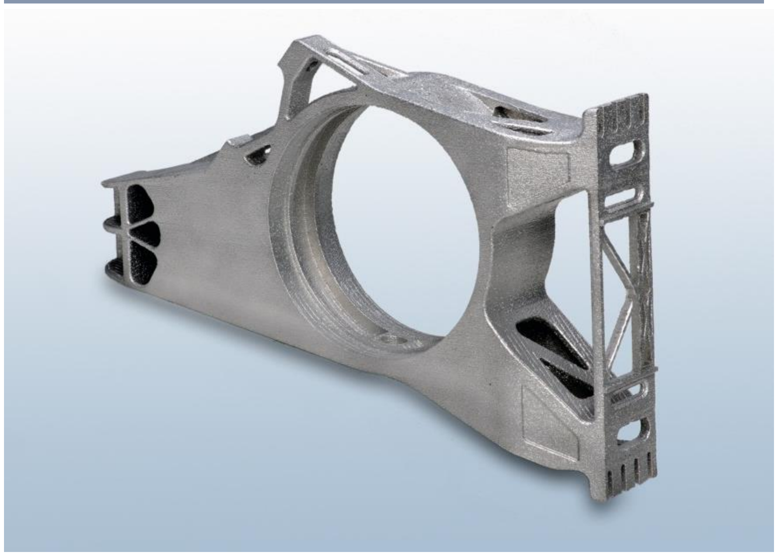
Innovative Business models



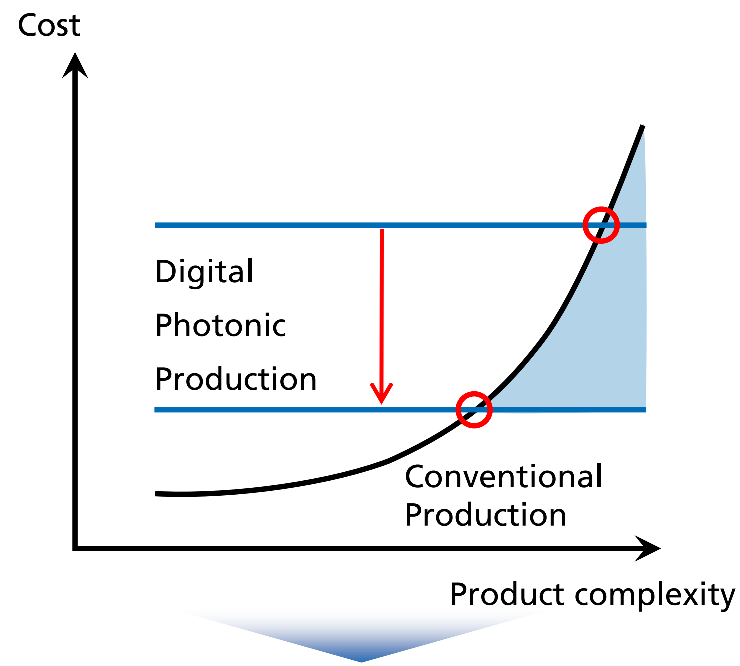


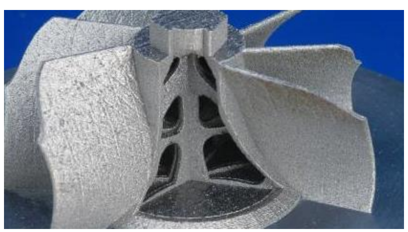
Digital Photonic Production





Complexity for free

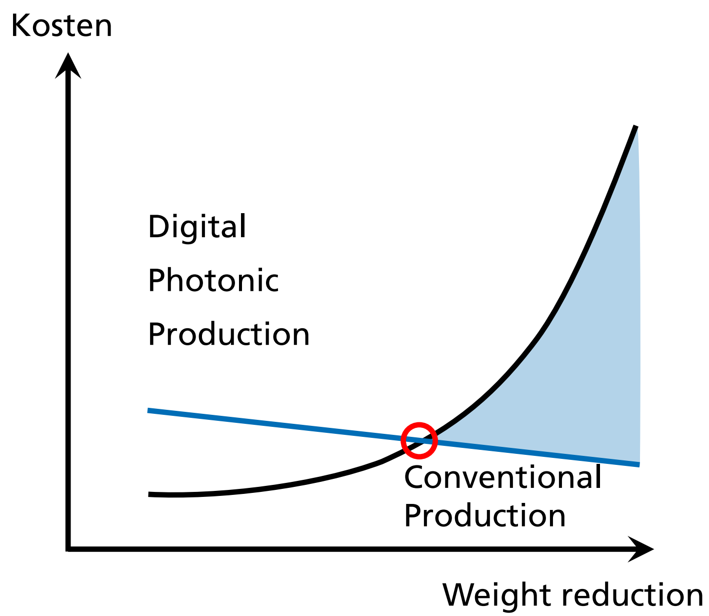




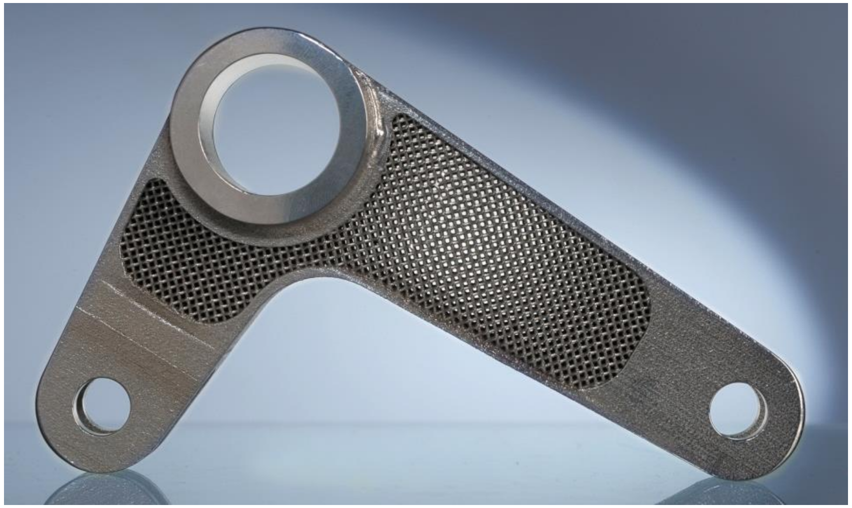
Innovative Products

Digital Photonic Production – Lightweight Construction

Less weight less cost

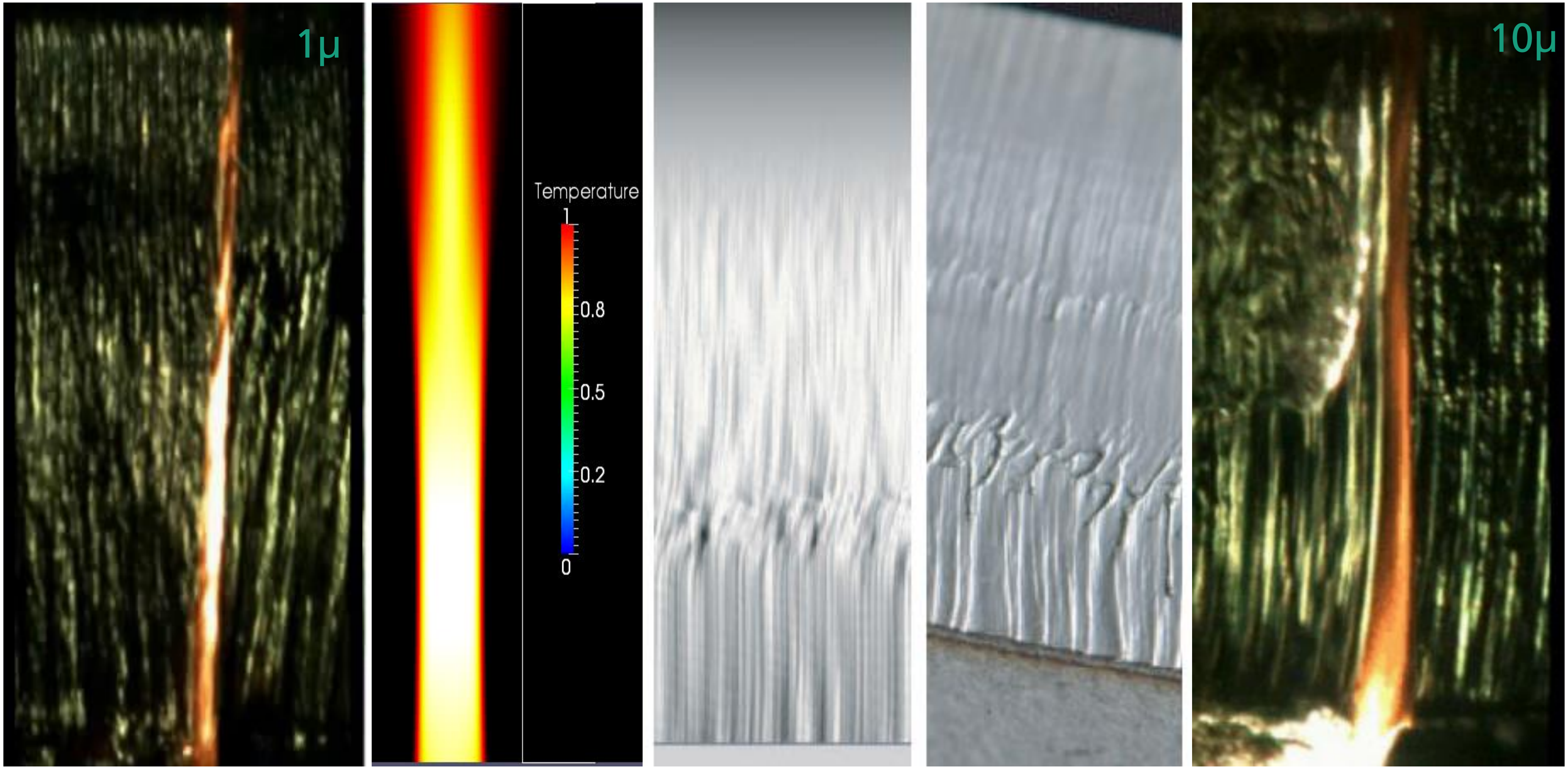


Coherent objectives



Simulation and Modelling

Simulation *QuCut* compared to experimental evidence

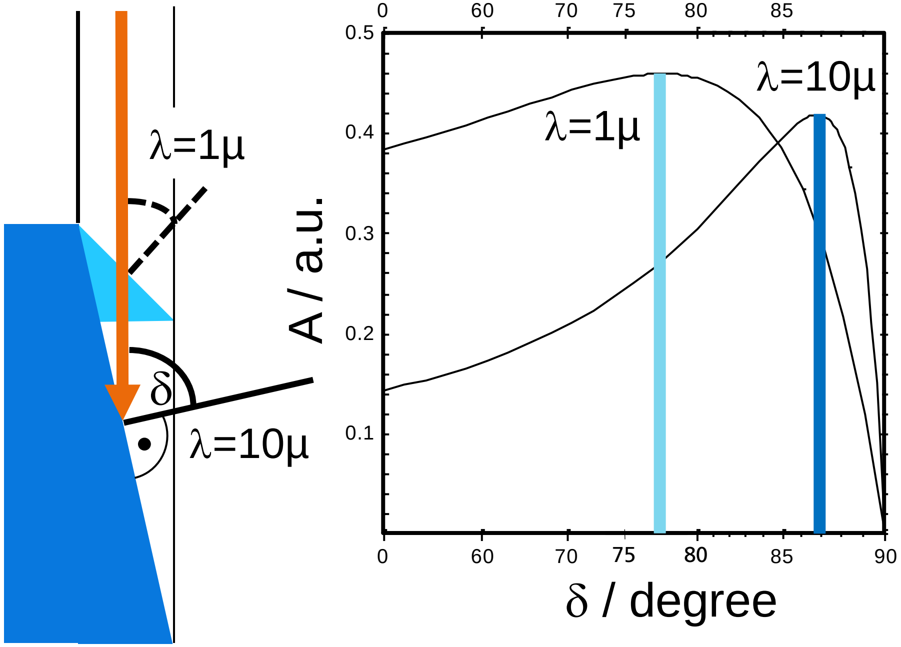


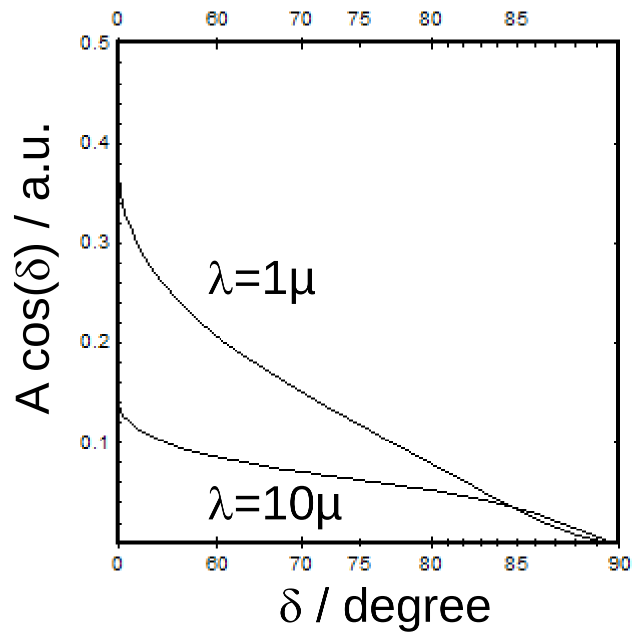
Exp | Sim *QuCut* | Sim *QuCut* | Exp | Exp

Fresnel Absorption for Steel at 2500 K (Circular / Random Polarisation)*

* Complex refractive index calculated by modified Drude approach (Petring 1994)

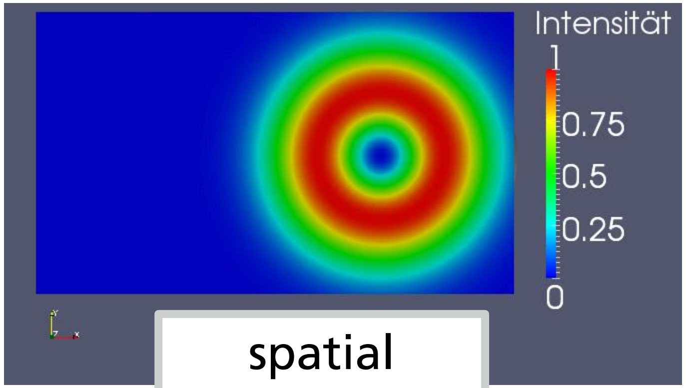
- Impact of Wavelength



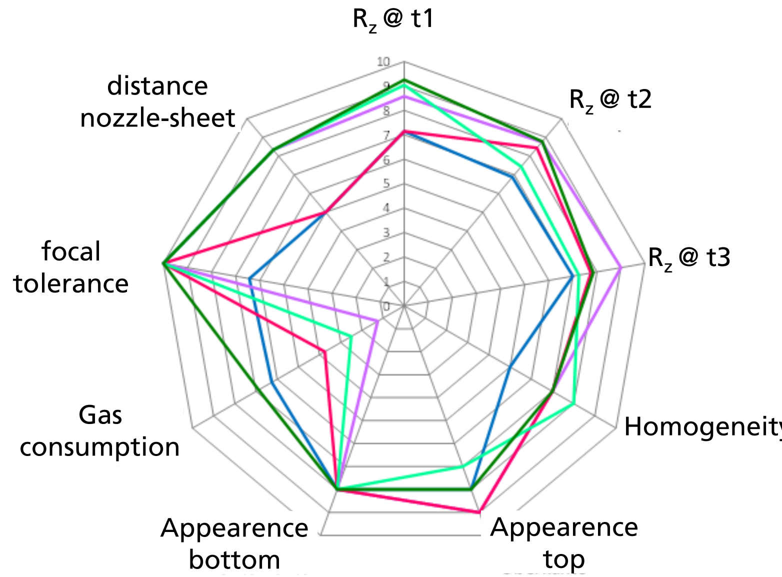


- A stroke of luck for CO_2 lasers at grazing incidence
- High aspect ratios and grazing incidence are counterproductive at 1µ.
- Higher sensitivity for perturbations at 1µ.

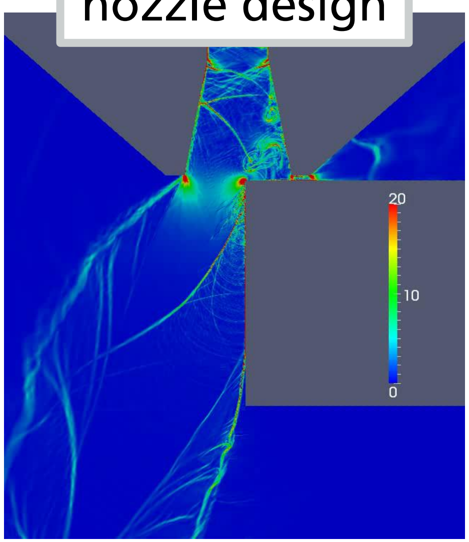
Simulation based design



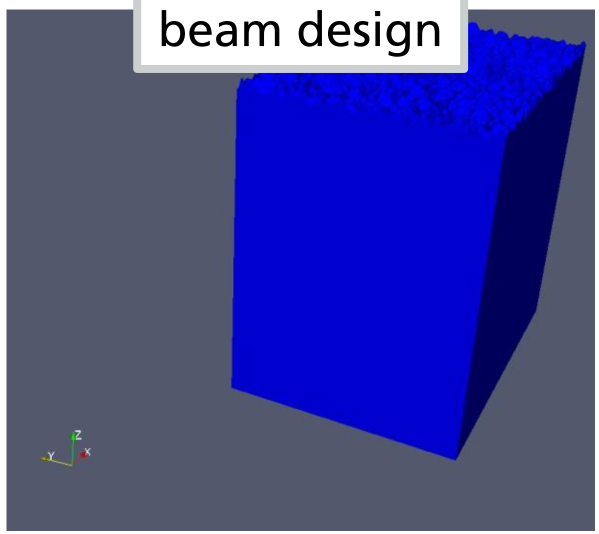
spatial beam design



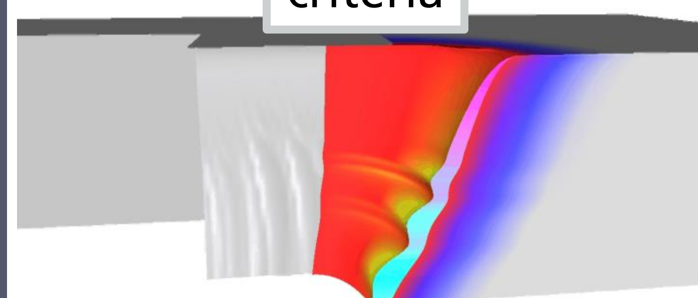
nozzle design



temporal beam design



criteria



“Laser-Metrology 4.0”

Laser analysis of liquid slags – a new first

- Motivation
- use of slag from metallurgical process route for
  - road construction
  - cement industry

  instead of waste disposal
- Solution
- inline chemical analysis of slag composition with laser spectroscopy
- measurement and assessment in slag bucket of truck (600 – 1300°C)
- measuring system for automated 24/7-operation

K. Pilz, Berg- und Hüttenmännische Monatshefte, vol. 157 (6-7), 250-257, 2012.

Laser analysis of liquid slags – in operation since 11/2013

view inside slag ladle with
hot BOF slag

slag transporter underneath
measuring cabinet

plasma on the slag surface
during measurement

AKL'14 INTERNATIONAL LASER TECHNOLOGY CONGRESS

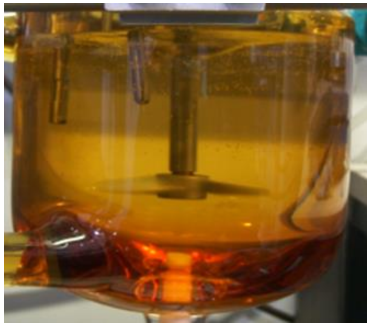
voestalpine

Fraunhofer ILT

Inline analysis of polymerization processes with laser light scattering

- dynamic light scattering (DLS) measures particle size distributions from Brownian particle movement, range: nm to µm
- probe developed by ILT/LLT enables inline measurements in turbulent reaction vessels
- particle growth measured during polymerization of microgels

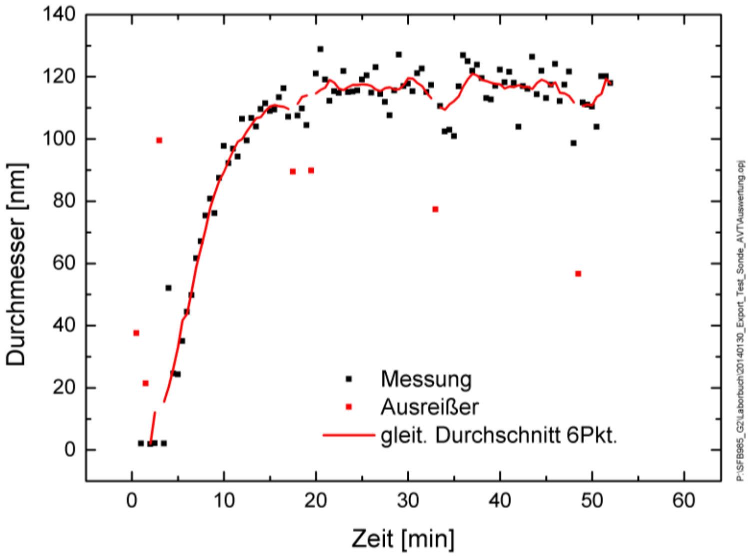
probe for inline DLS, ∅ 35 mm



start of reaction:
no particles; monomers in solution

end of reaction:

strong scattering due to microgel particles



measured particle growth during polymerization of a microgel

photos, left: AVT, RWTH Aachen

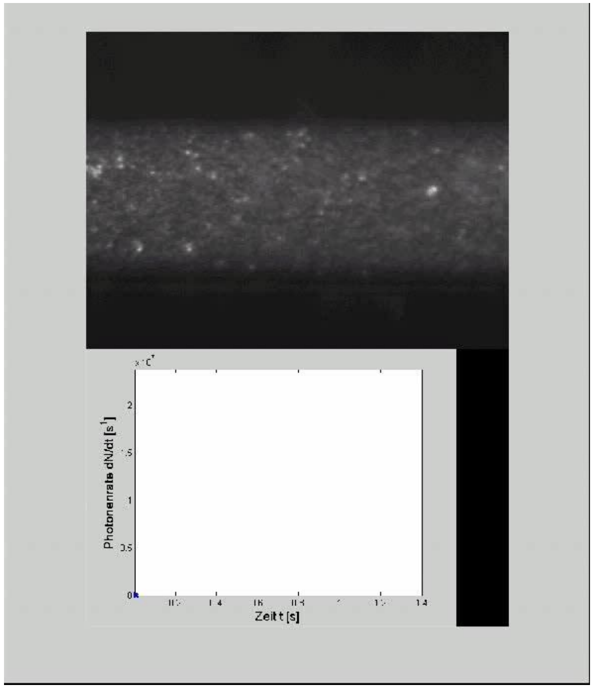
AKL'14 INTERNATIONAL LASER TECHNOLOGY CONGRESS

Fraunhofer ILT

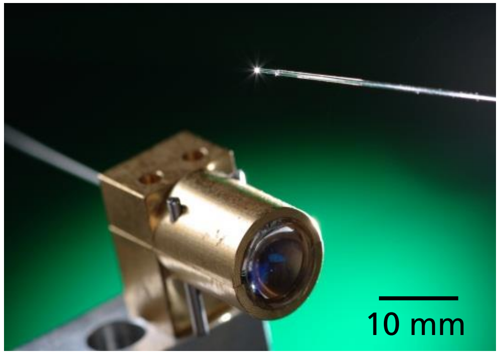
Single cell recognition in a microfluidic channel

- specific marking of cells in a purified blood sample with fluorescent marker molecules
- processing of the sample in a microfluidic device
- detection of single cells with a sensitive fluorescence sensor based on tailored light

fluorescence events

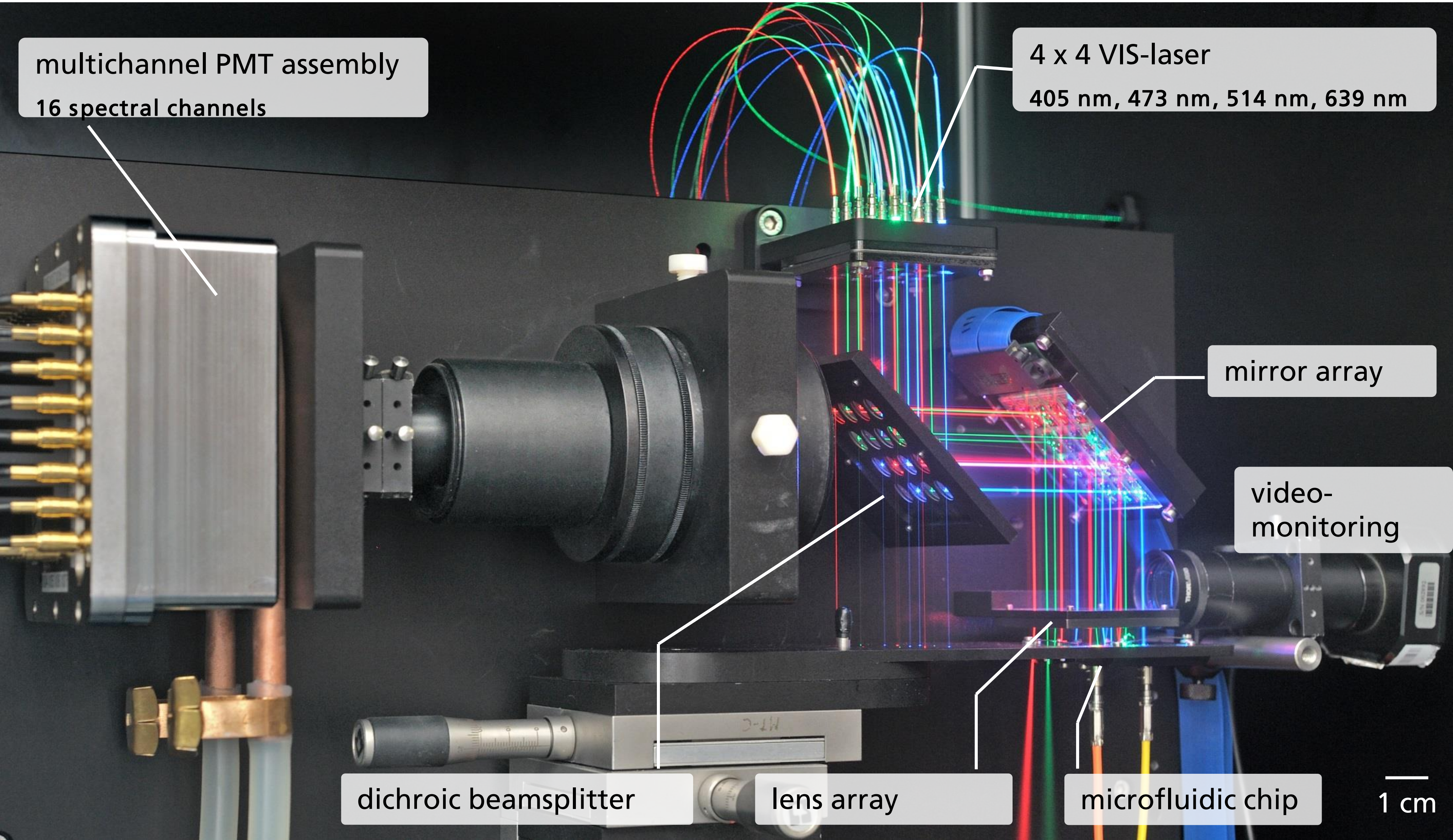


video



fiberoptic sensor

Tailored light for multi-species recognition in microfluidic devices - multichannel fluorescence sensor

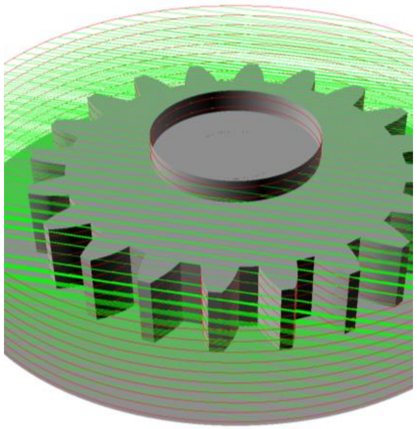


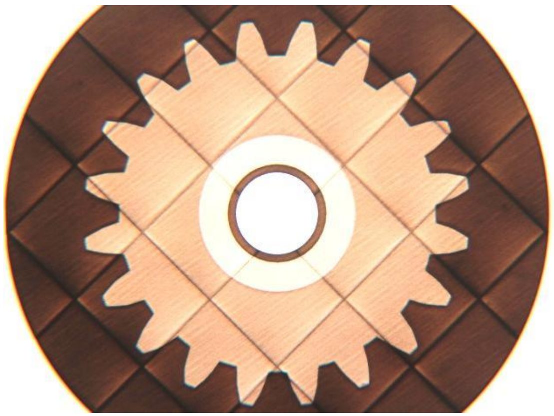
SLE, Ablation and Polishing (glass)

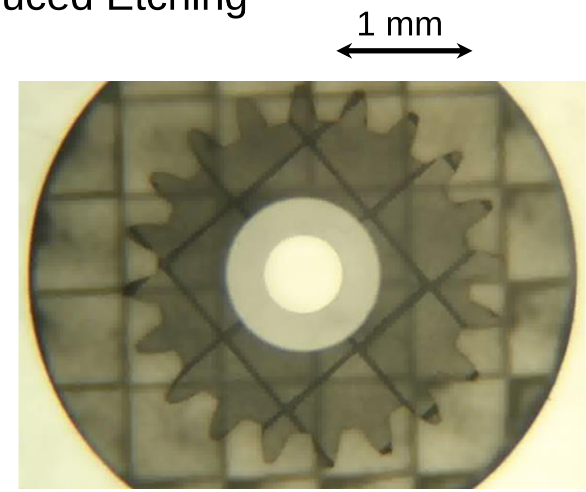
Digital Photonic Production with ISLE

fs laser radiation

ISLE: In-volume Selective Laser-induced Etching



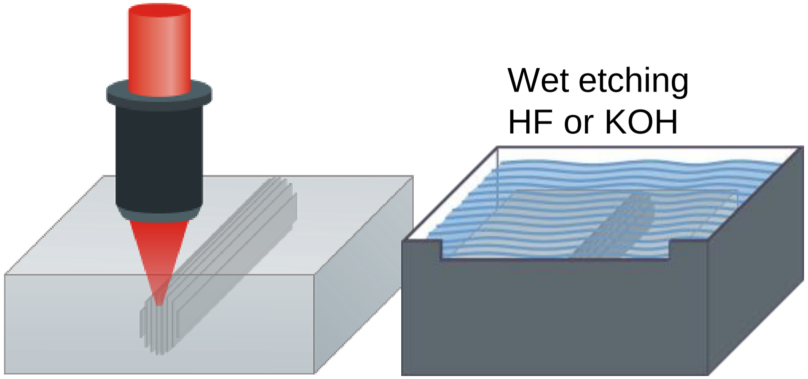


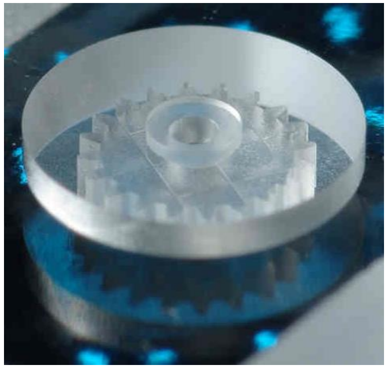


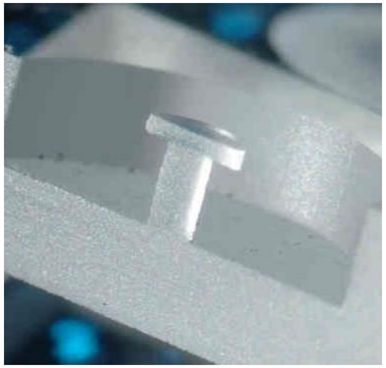
3D-CAD Model
in Layers

Selective Modification
by Laser Radiation

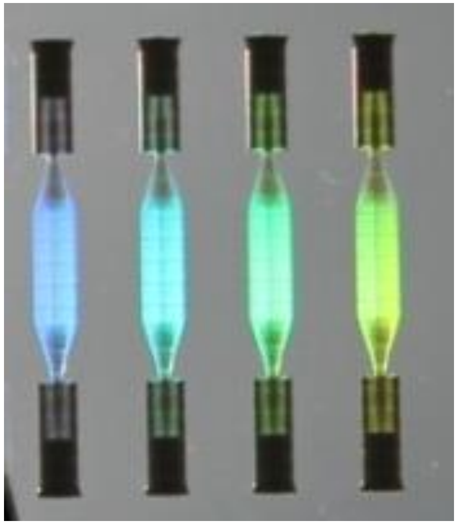
Removal of Modified Material
by Wet Chemical Etching



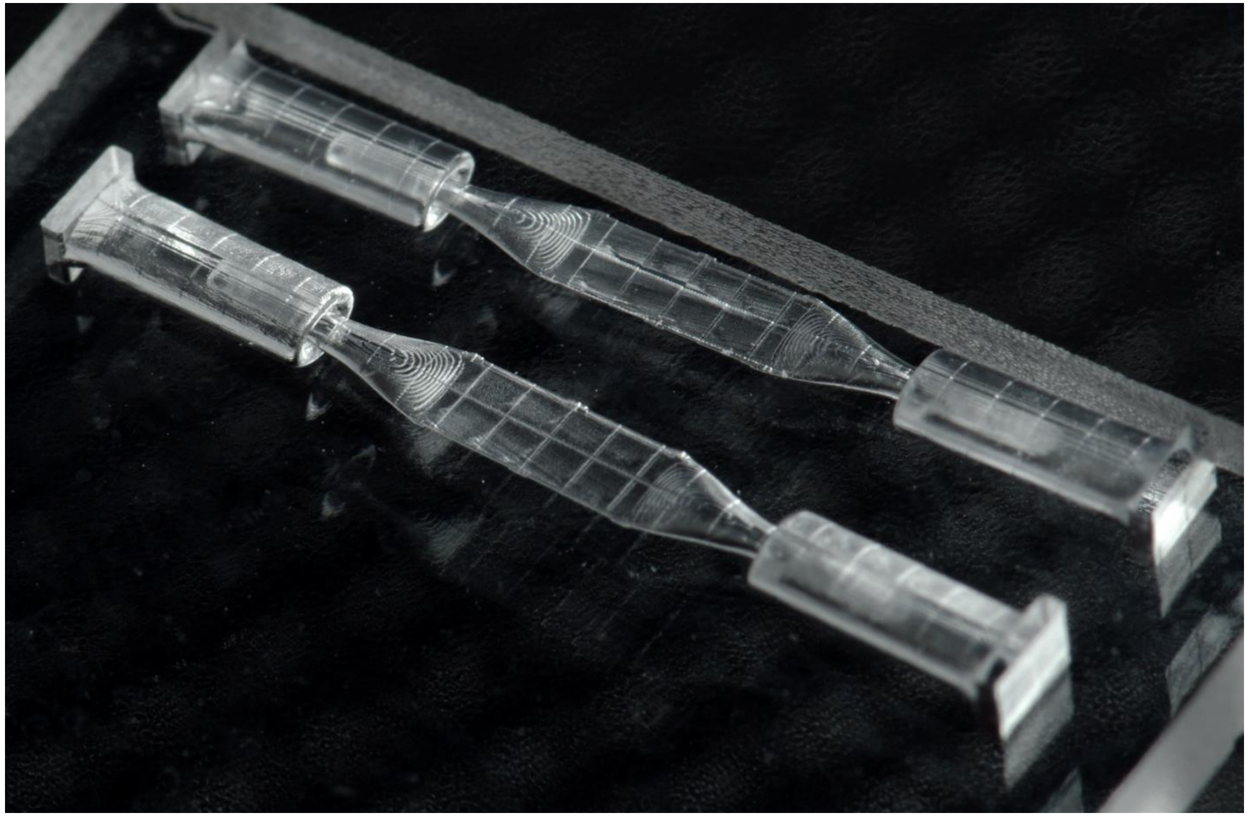




Digital Photonic Production: Resulting Microfluidics



Diffraction at modified lines before etching



- 3D microfluidic device after etching before separation
- Transparency is increased when filled with water (immersion)

Micro Holes Cut in Fused Silica

Holes cut in 1 mm fused silica e.g. for

- Optical Fiber placement
- Filtering applications
- Openings in casings
- Inlets for gases or fluids
- Electrical vias

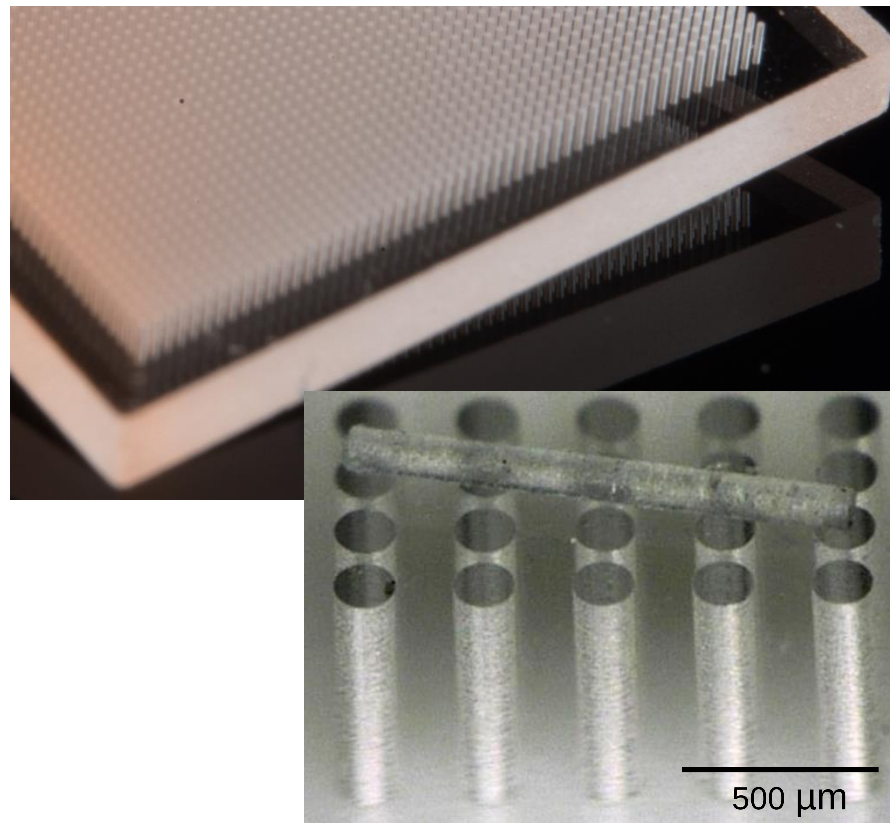
Min. hole diameter ~ 30 µm

Max. hole diameter ~ 1 mm

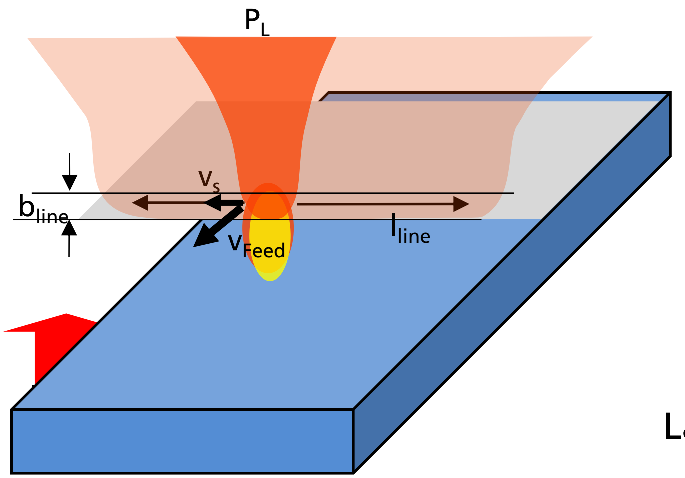
Max. hole length ~ 2 mm

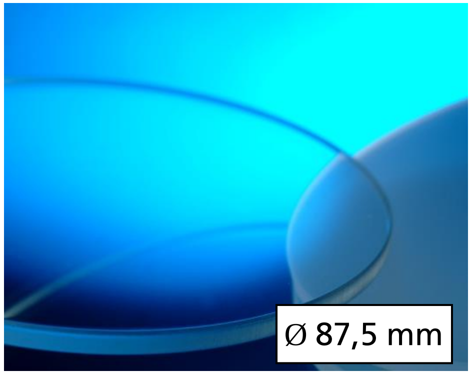
Max. hole taper ~ 20 µm

Precision ~ 2 µm

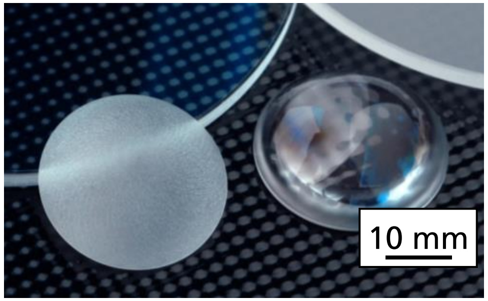


Laser polishing with CO_2 laser radiation





Laser polished fused silica and initial condition (grinded)



Initial condition (grinded) and laser polished BK7 optics

- Smoothing of the roughness through material flow without material removal
- Reducing the surface roughness
- No change of the surface geometry

- Process speed up to 1 cm²/s
- Rq = 4nm*, Wq = 10nm*, PV = 4µm
- Micro roughness Rq = 0,32 nm**
- Comparable results for optics

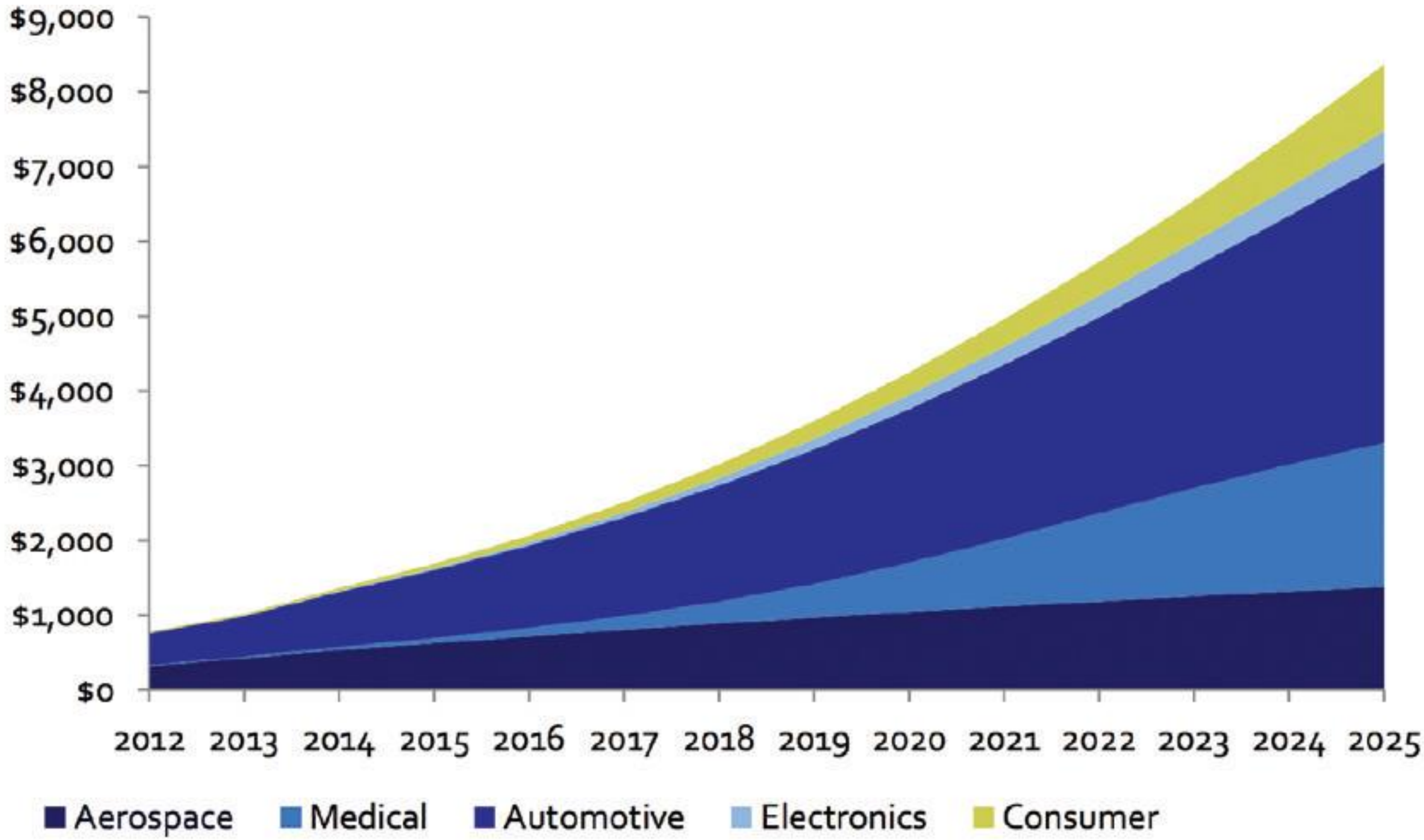
*DIN Standard 10110-8: Band width 2,5 – 800 µm for Rq, Band width 500 – 2500 µm for Wq, Rq measured on 1x1 mm² and Wq on 18x18 mm²

** Measured on 70 x 50 µm², Pixel distance 0,1 µm

Additive Manufacturing

LAM = SLM + LMD

3D-Printed Parts Market Size



Source Lux Research ©2013

Additive Manufacturing Systems Worldwide

Over 24 years (1988– 2012) total industrial AM systems **installed**

United States 38.0%, Japan 9.7%, Germany 9.4%, China 8.7%, United Kingdom 4.2%, France 3.2%

Additive Manufacturing System **Manufacturers:**
A Shifting Global Landscape

	US	EU	Japan	China
2003	**10**	7	7	3
2013	4	**16**	2	7

Two main suppliers of polymer 3D-Printing Systems in US (Stratasys. 3D-Systems),

All of the companies that manufacture **metal powder**-bed fusion AM systems are currently located outside the US: **7 in Europe and 2 in China.**

Source: BOS Phototonics 2014

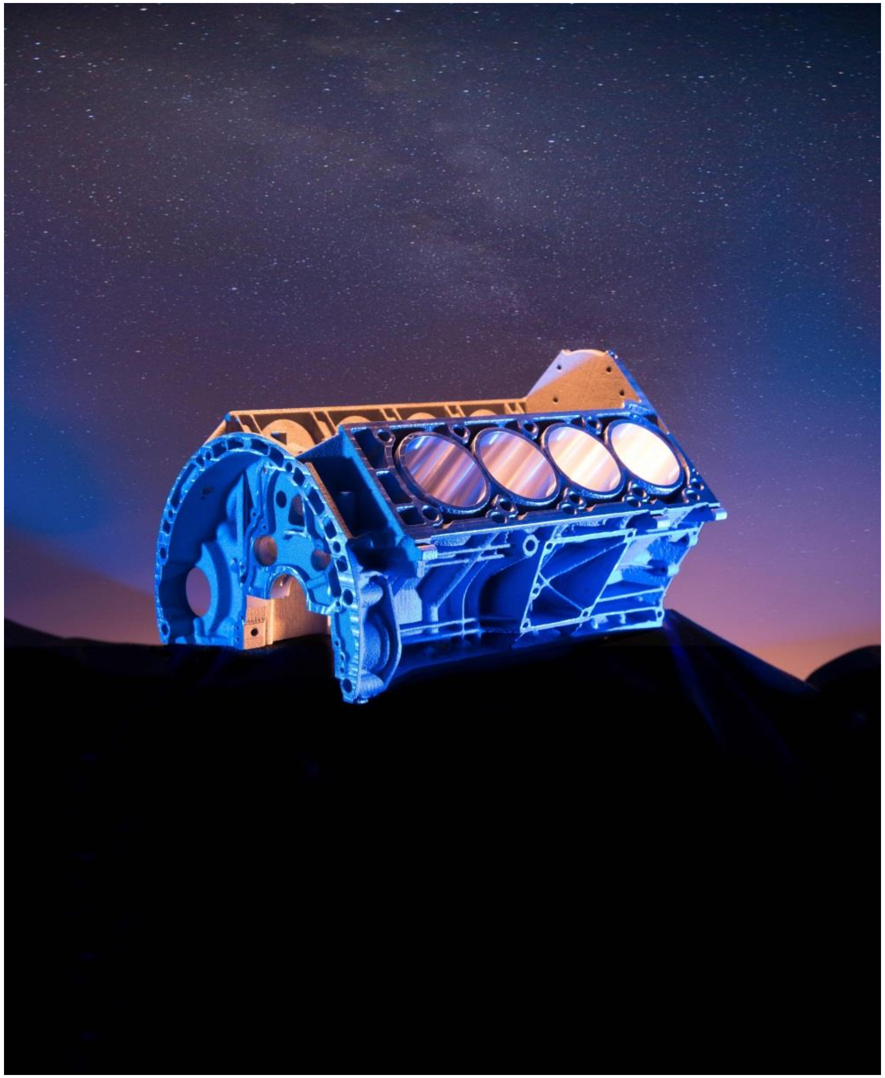
Worldwide first ILT Industrial Application: SLM – Dental Restaurations

- Application reconstruction of single teeth
- Process steps:
  - preparation
  - model
  - digitalization
  - design (CAD)
  - manufacturing (DLF)
  - control of model
  - ceramic cover
- Production start: Nov. 2002

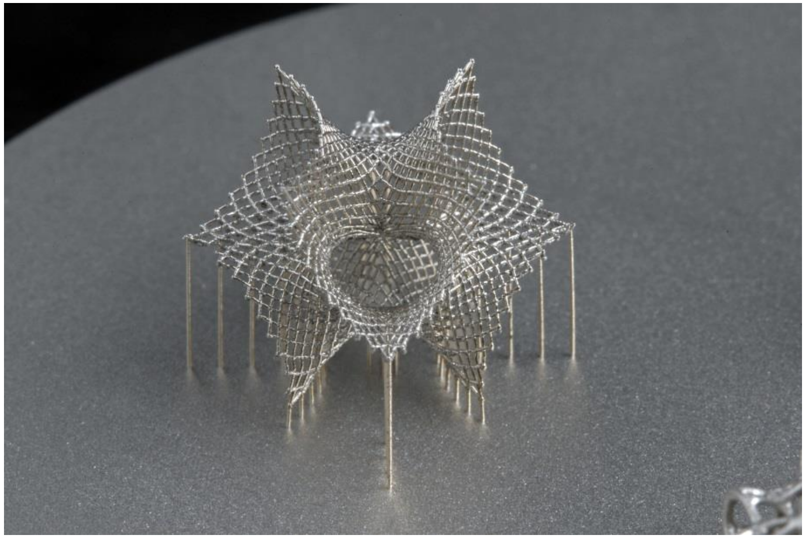
In cooperation with BEGOmedical AG

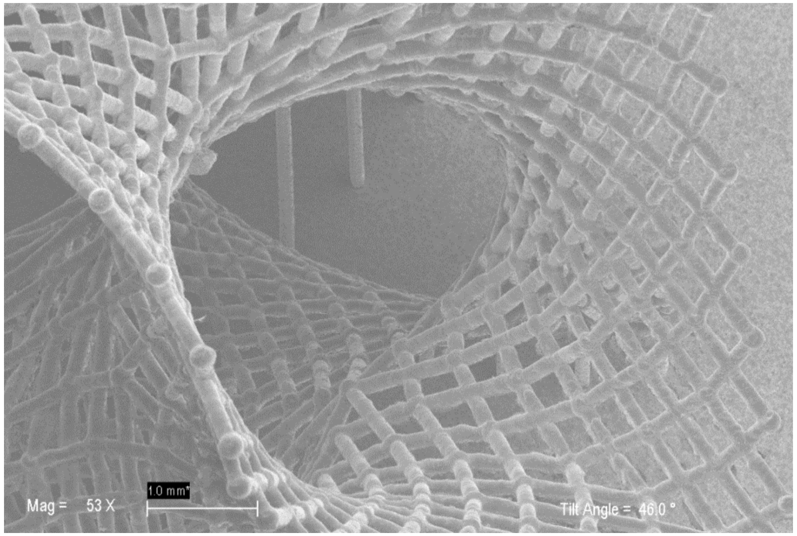
Laser Additive Manufacturing – Automotive Examples

- Motor Block Mock up
  1/3 original size
- Material: AlSi12
- 400W Laser, 4 days 19h
- Cast: app 3 months



Process
Micro-SLM





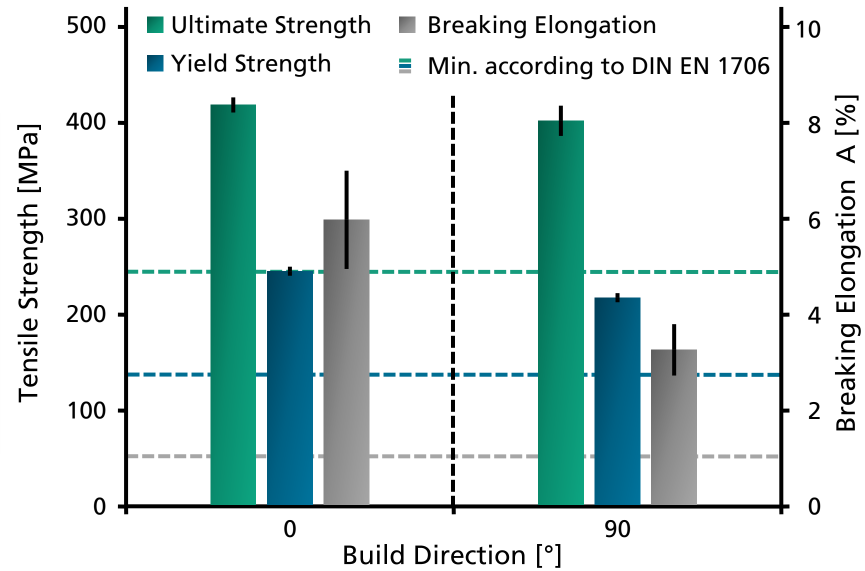
Material

Analysis of mechanical properties

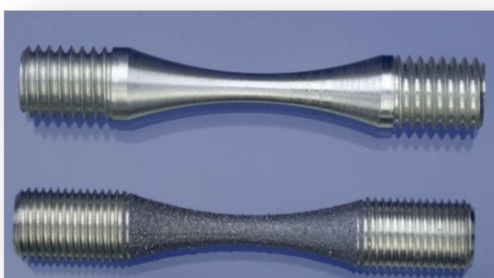
Static load

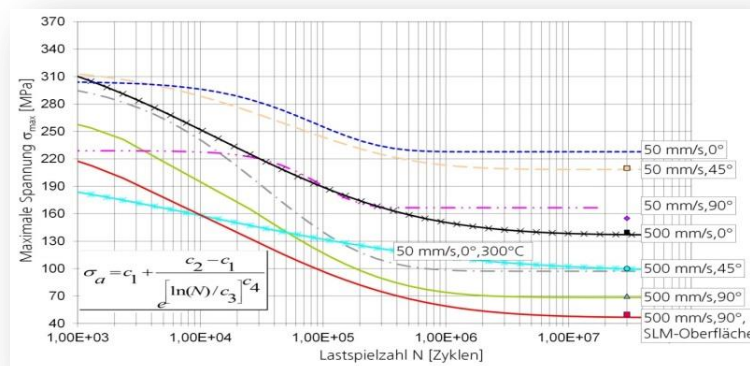
Liegend (0°)

Stehend (90°)

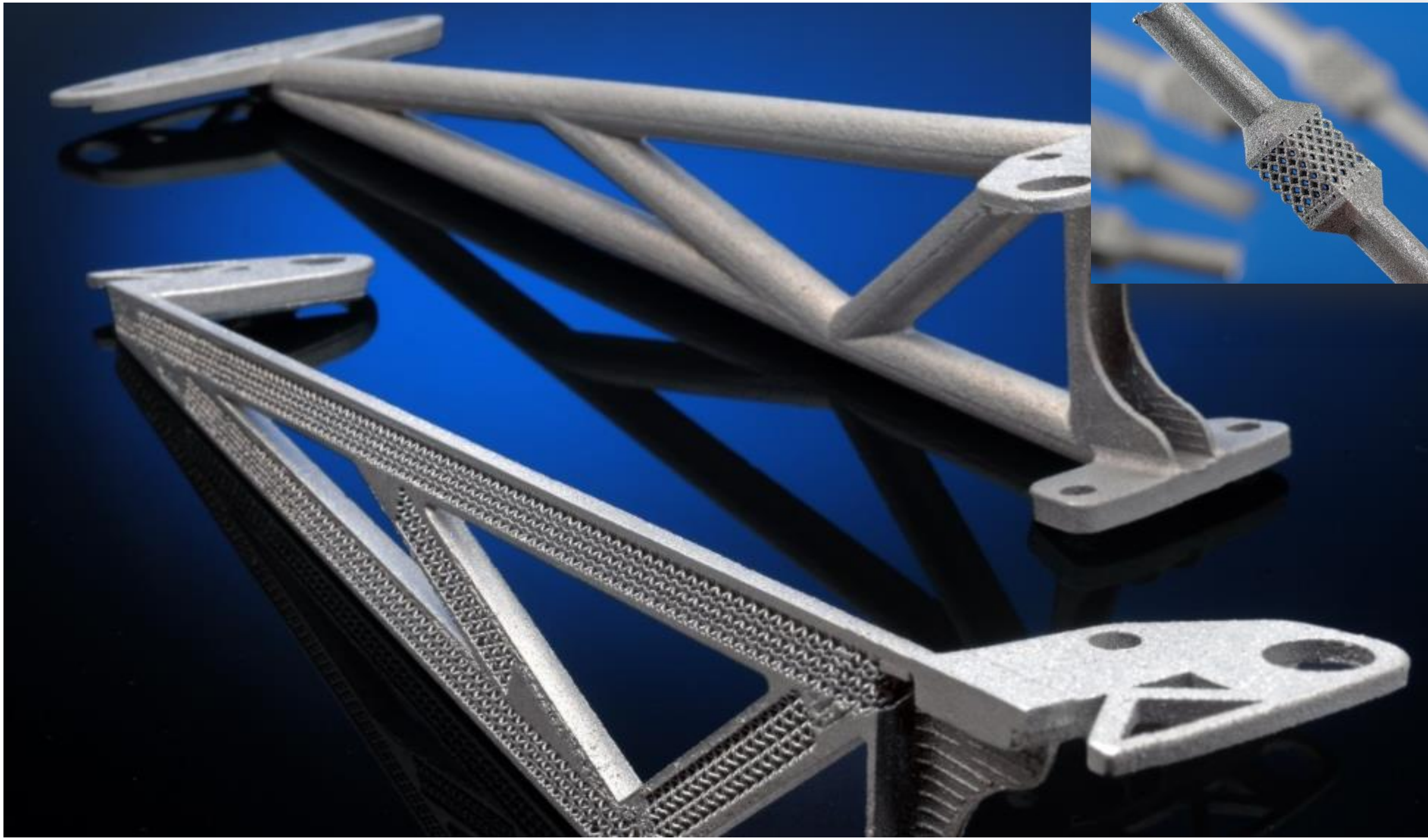


Dynamic load

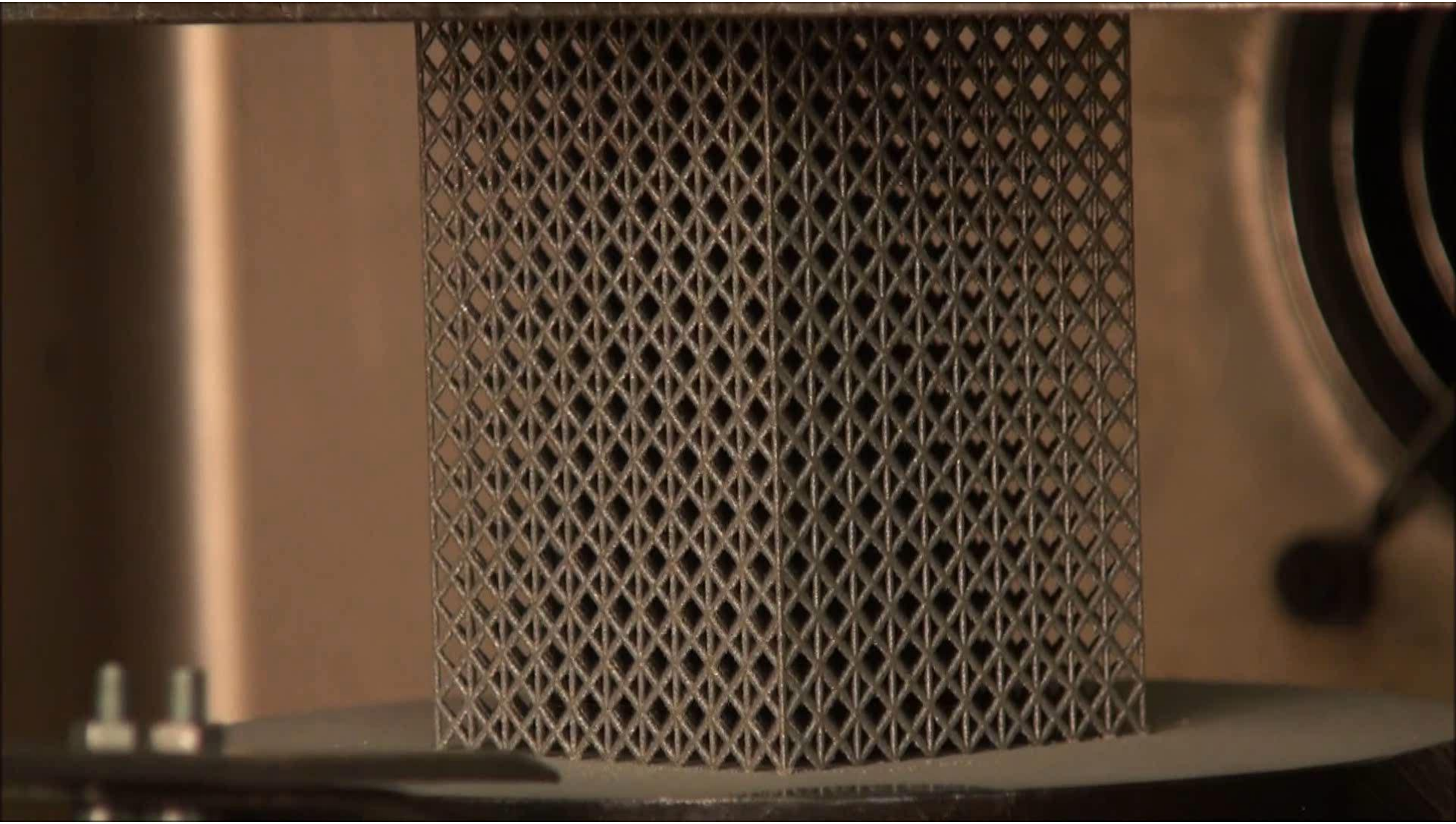




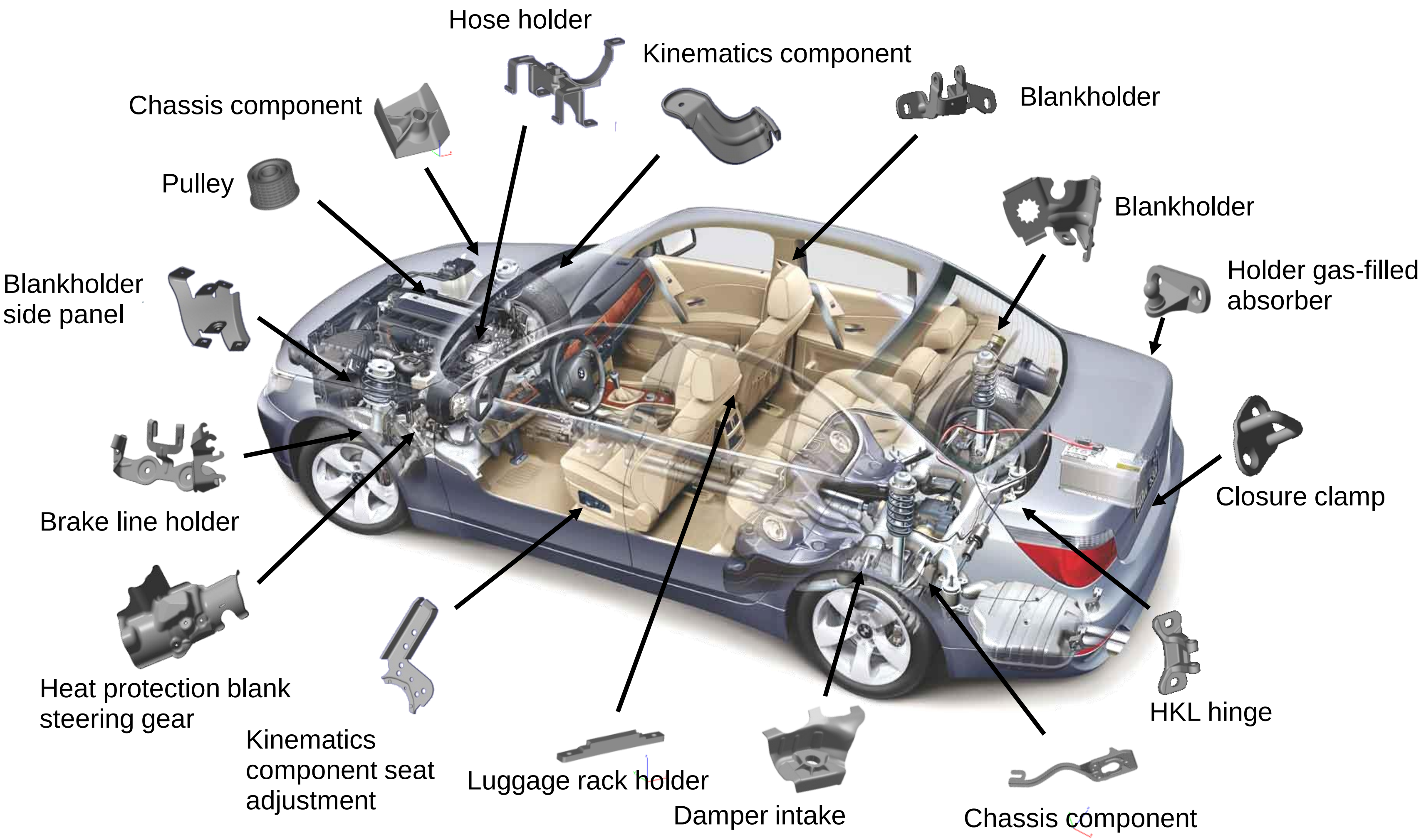
Light Weight Design



Tests of lattice structures

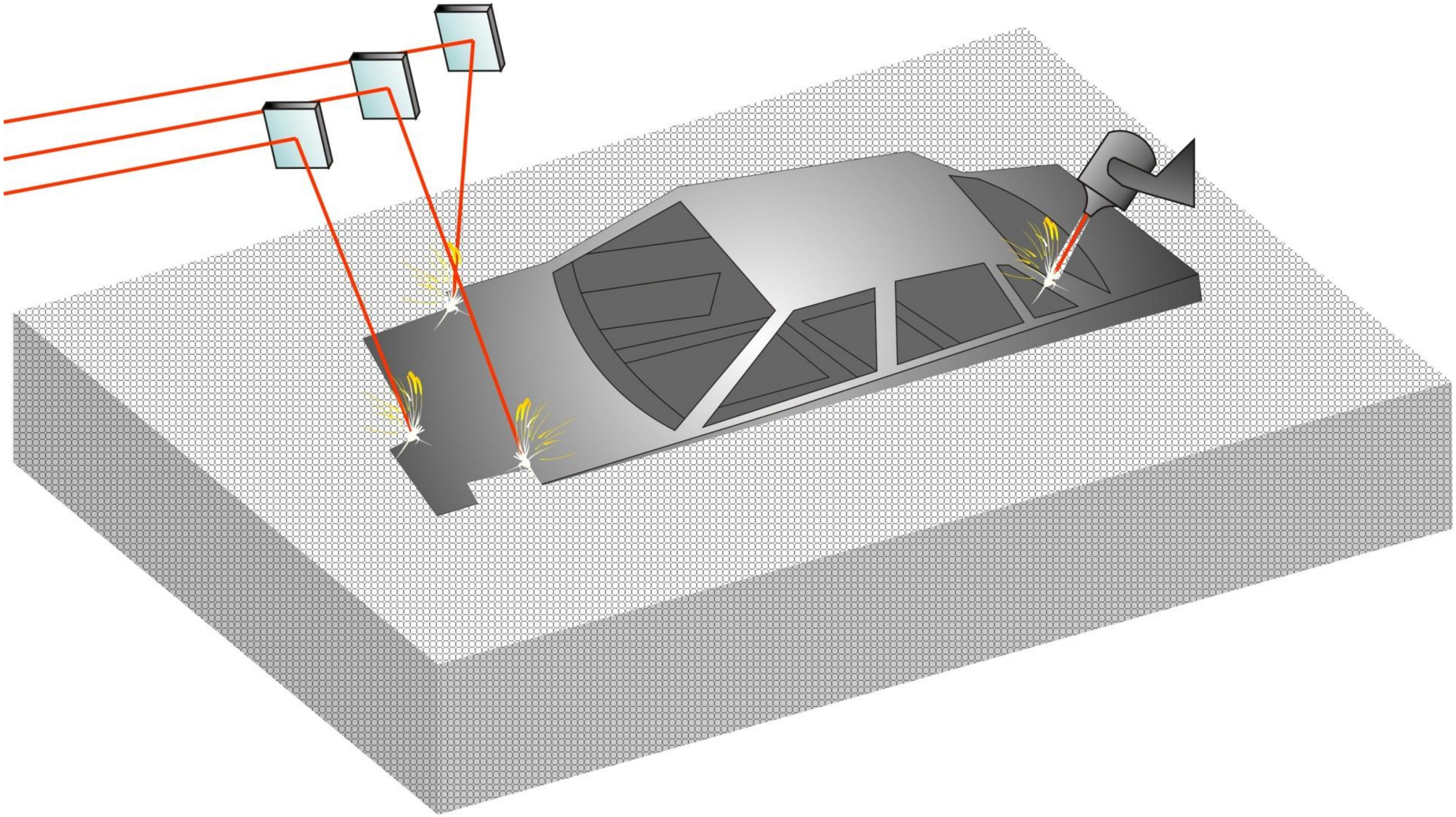


Laser Additive Manufacturing – Automotive Examples



Source: N. Skrynecki, Kundenorientierte Optimierung des generativen Strahlschmelzprozesses, 2010

Vision SLM 2030



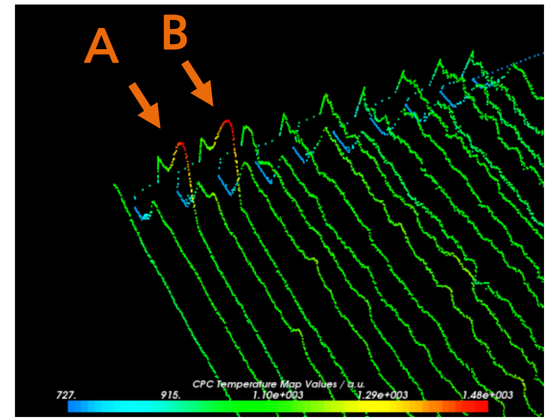
SLM

POP_1209_910911_5142

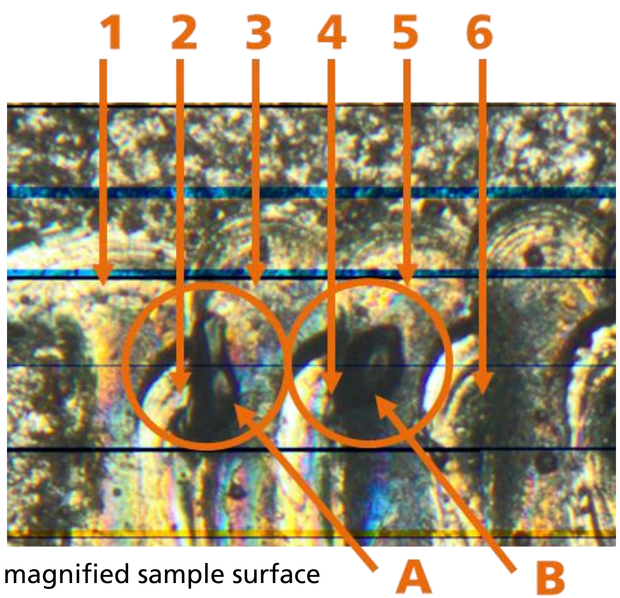
Process Monitoring in Selective Laser Melting (SLM)
Thermal Emission Map and Surface Modification

Detection of deviations in melting behaviour

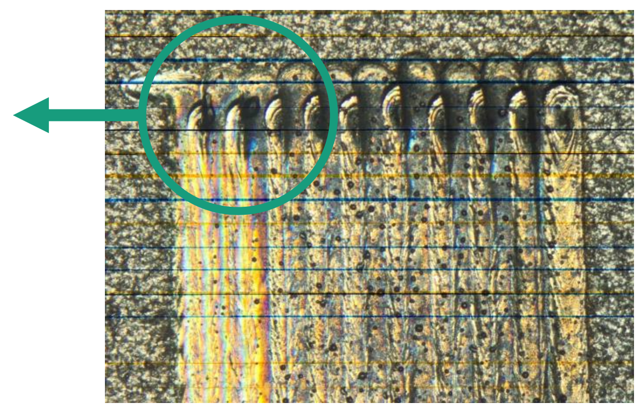
- Peak emission at start of track 3 and 5
- Surface defects at „A“ and „B“
- Tracks with even numbers end prematurely (scan direction upwards)



thermal emission map



magnified sample surface

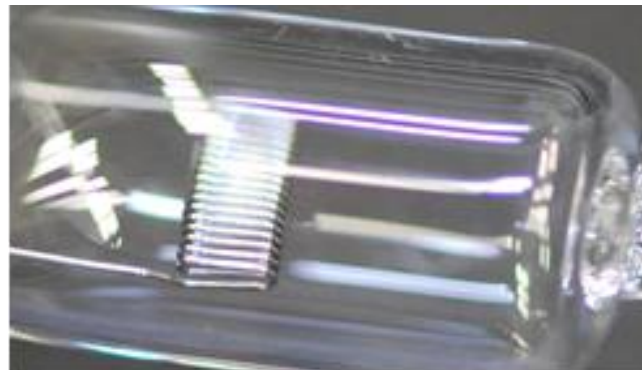


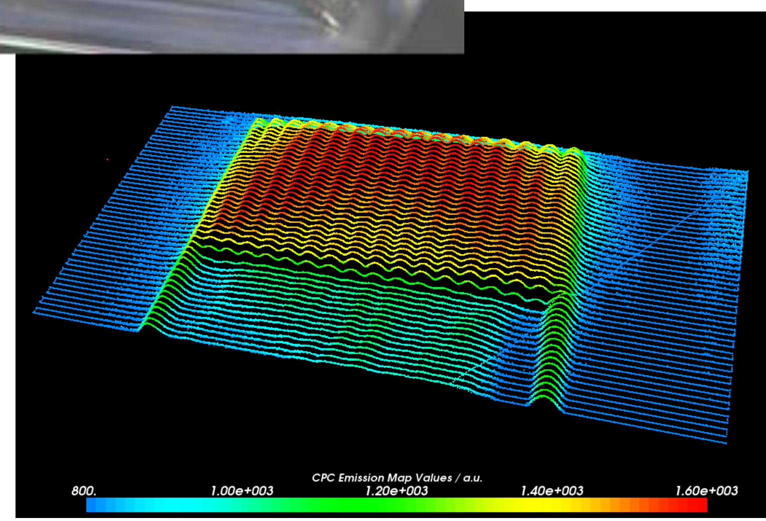
surface of the inconel 718 sample (200W, 400mm/s, 200µm)

Process Monitoring in Selective Laser Melting (SLM)

System – Verification Pyrometric Sensing

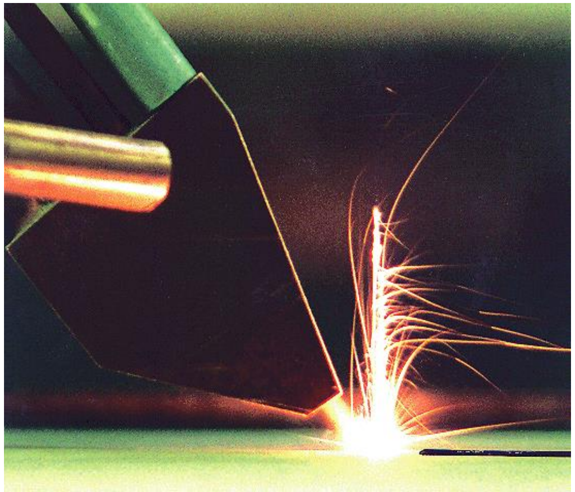
- Emission of the filament measured through glass
- Detector
  - Pyrometer 1.2µ..2µm
  - T_{95} 10µs
  - Resolution 12 bit
- Time resolution
  - Samplerate 100kHz
- Feedrate of scanning system
  - 250 mm/s



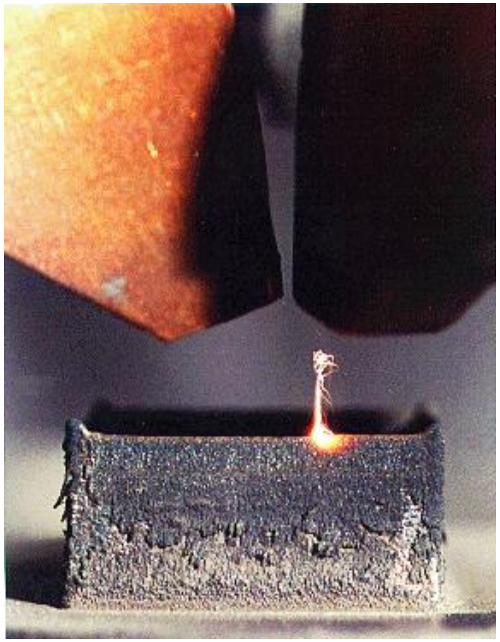


Laser Metal Deposition

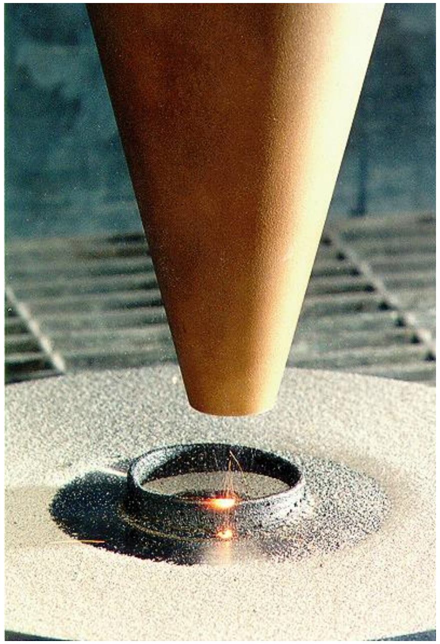
Laser Metal Deposition



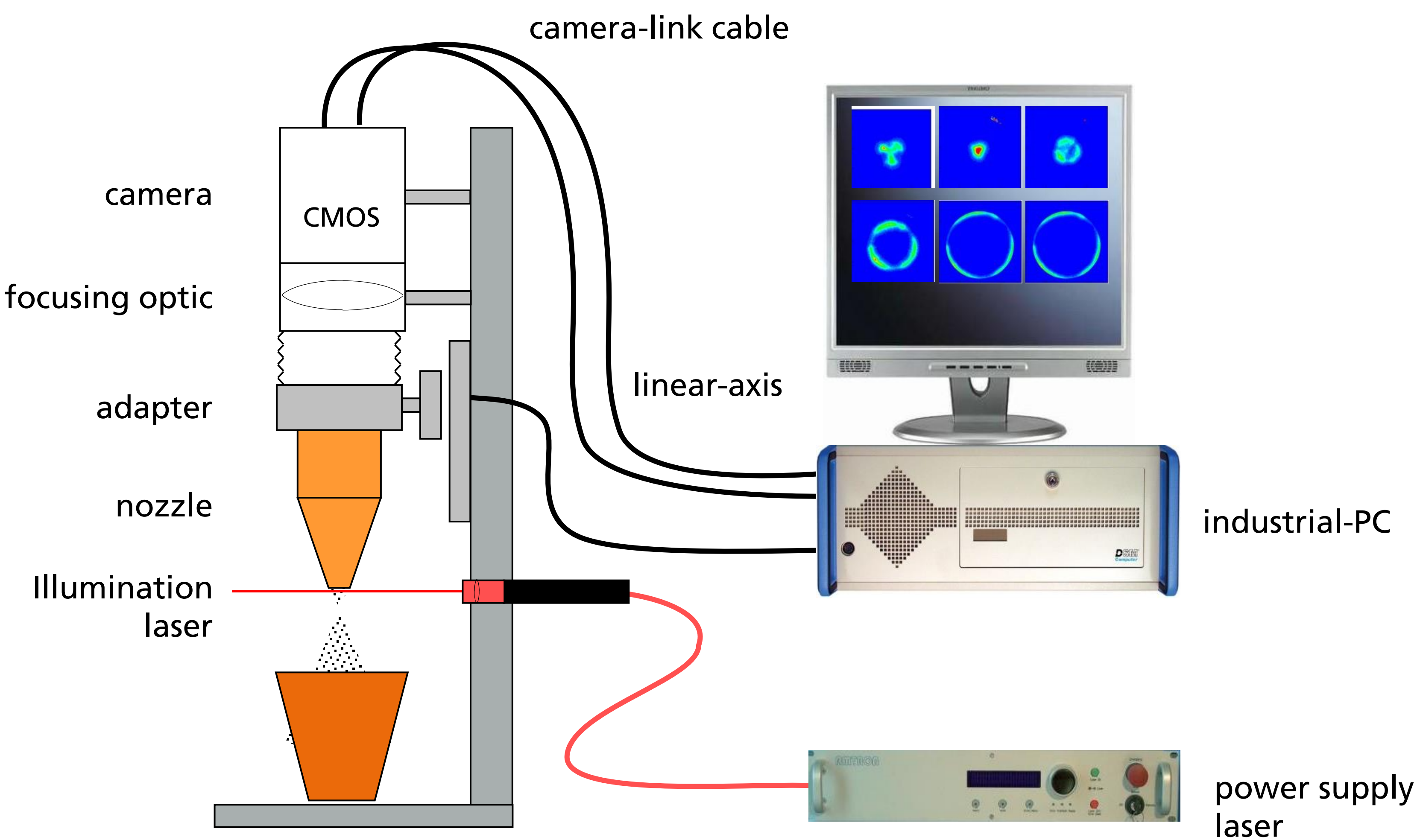
10 mm



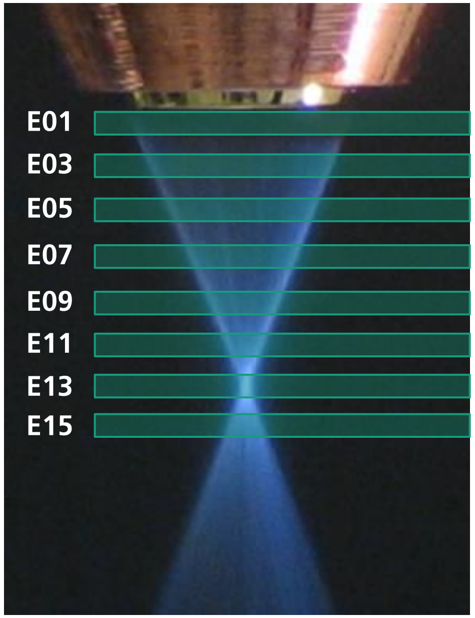
10 mm



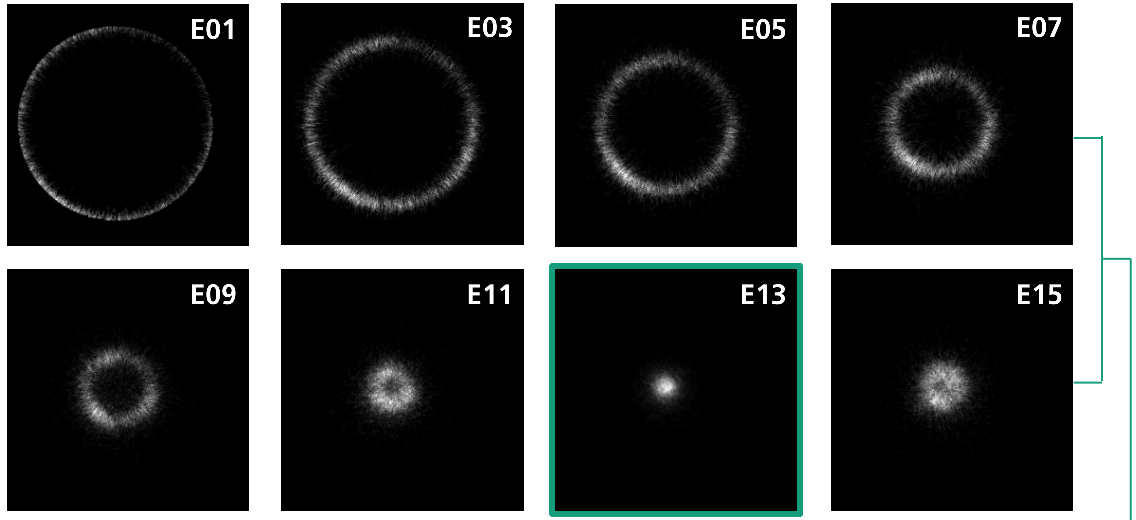
Experimental Setup for Powder Focus Measurement

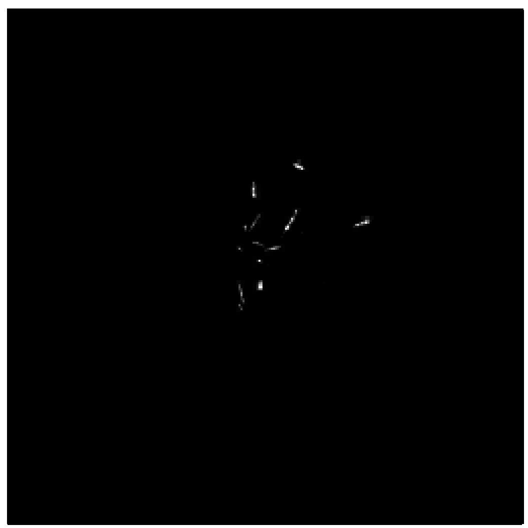


Videos of Powder-Gas-Jet



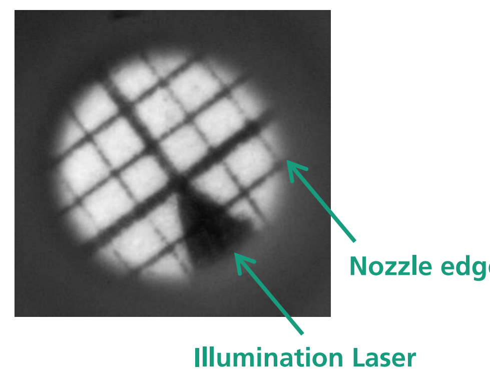
Powder-Gas-Jet





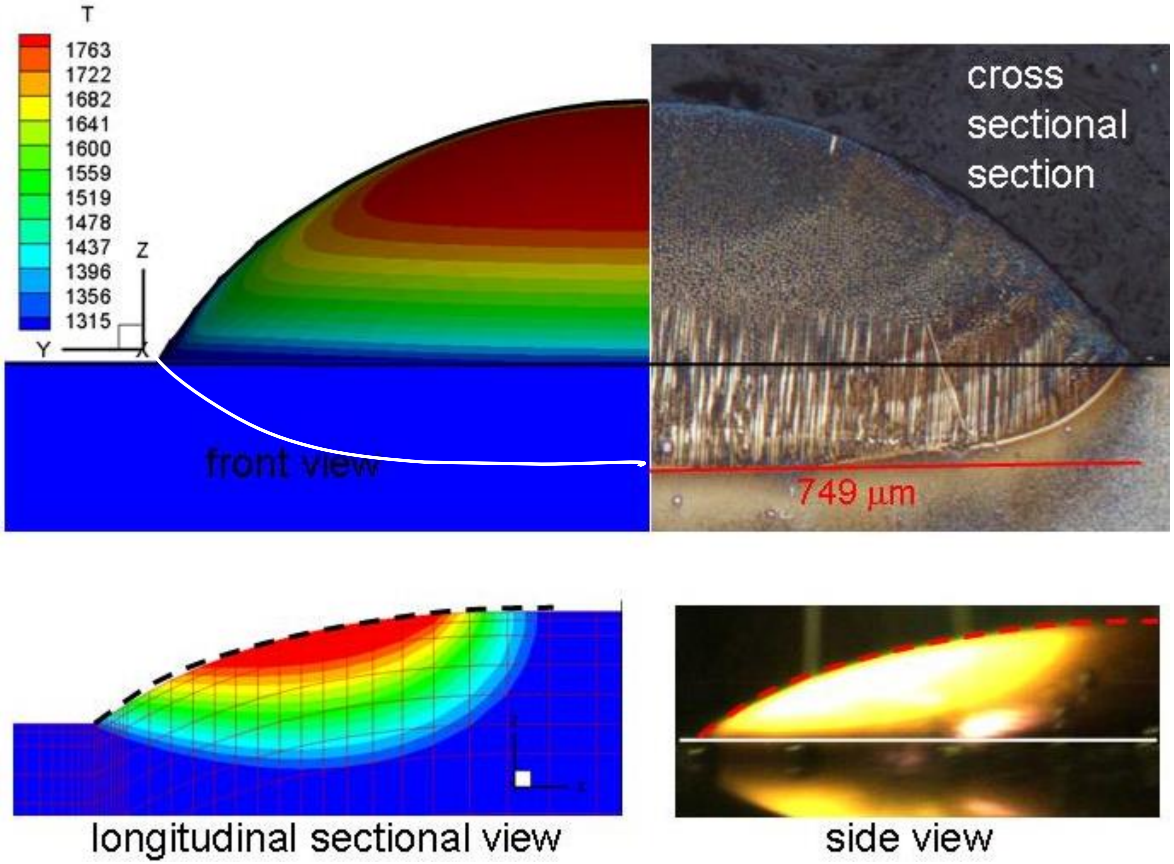
Summarized pictures

Coaxial nozzle
Powder: 20 – 60 µm
m_P 3%



Modelling LMD:
Comparison experimental and computed results

Melt pool surface in longitudinal (bottom) and cross (top) section of first track

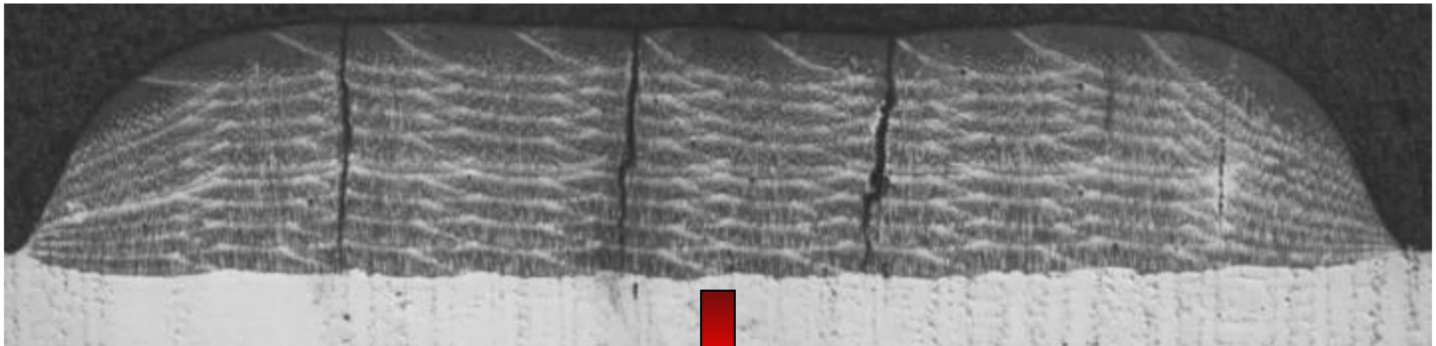


- good agreement of experimental and computed details of the geometry of the melt pool surface

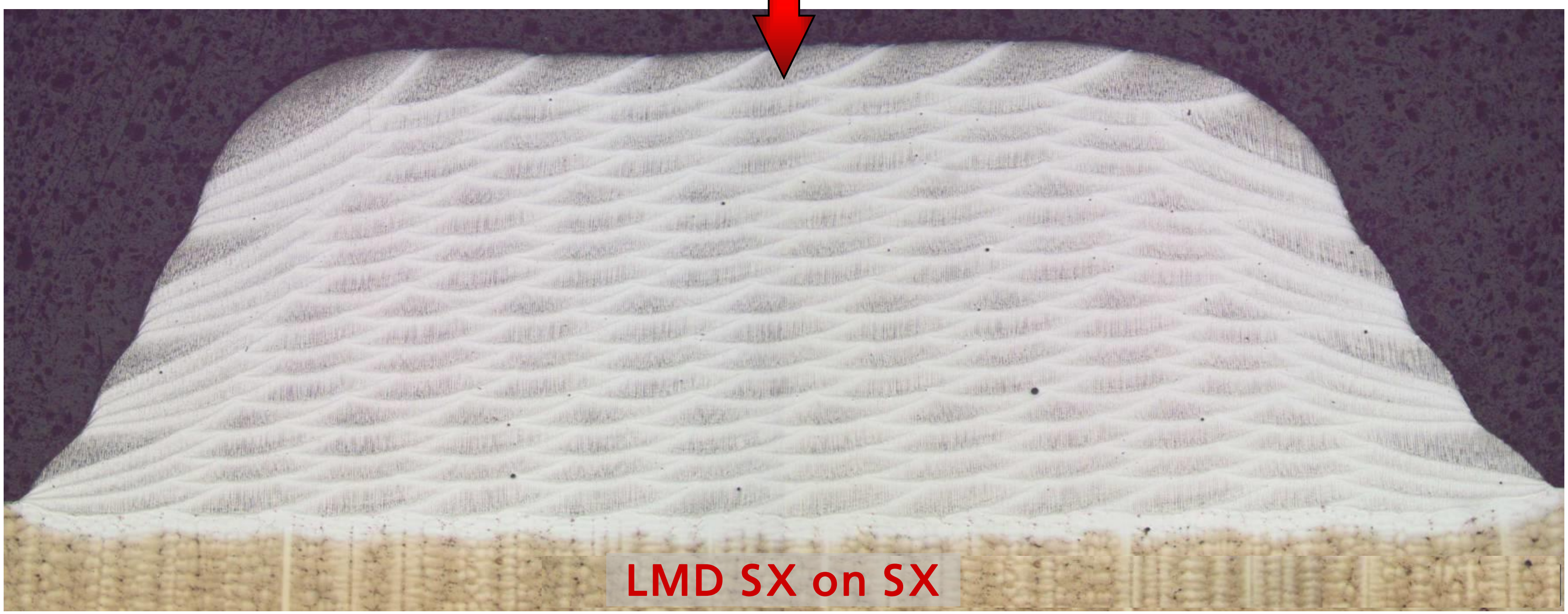
AKL'14 INTERNATIONAL LASER TECHNOLOGY CONGRESS

Fraunhofer ILT

Under development – epitaxial LMD repair SX on SX



result of process development: indication- free deposit



Wear protection of a forging die

Aim

Improving the wear performance with a **nano carbide reinforced layer** of typical forging steels

Result

- Increased mechanical propeties due to grain refinement ($d_{average}$ = 6 µm) and fine carbide precipitations
- Tests with a mock-up die show improvement
- Real forging tests are ongoing

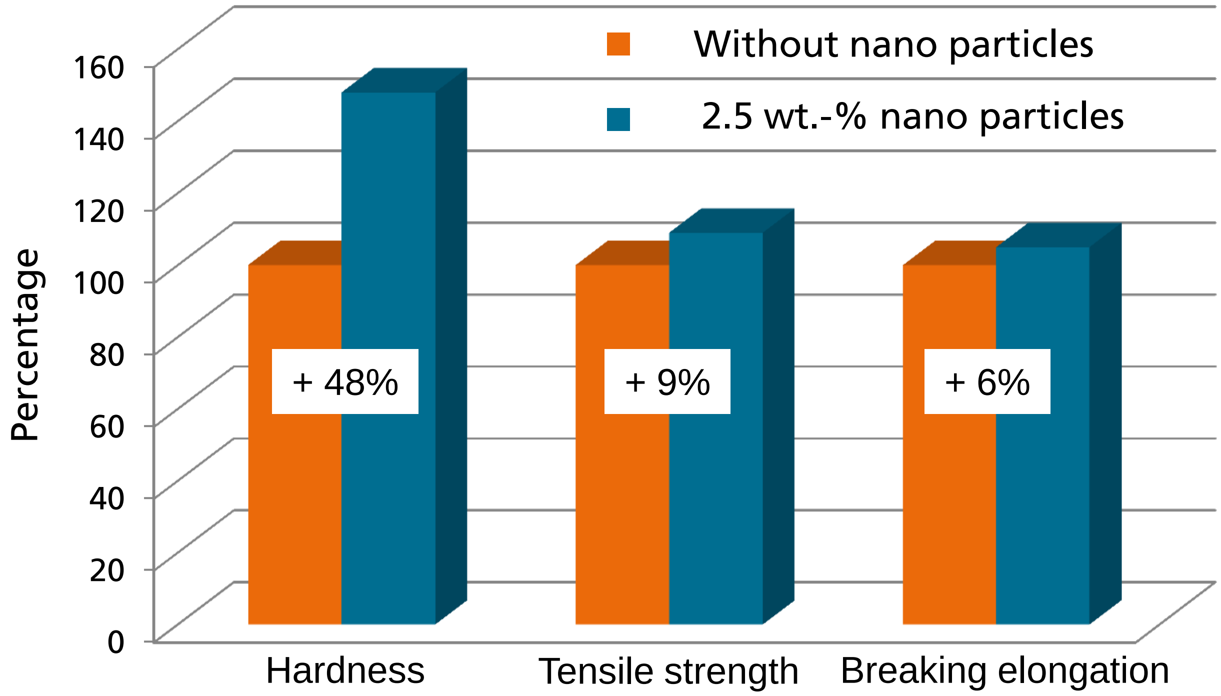

Worn forging die


Laser cladding process


Forging process

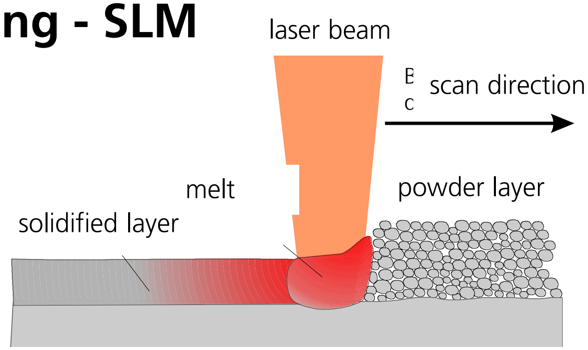
Effect of nano particles

- Small additions of nano particles (< 2.5 wt.-%) cause a wignificant increase of mechanical properties



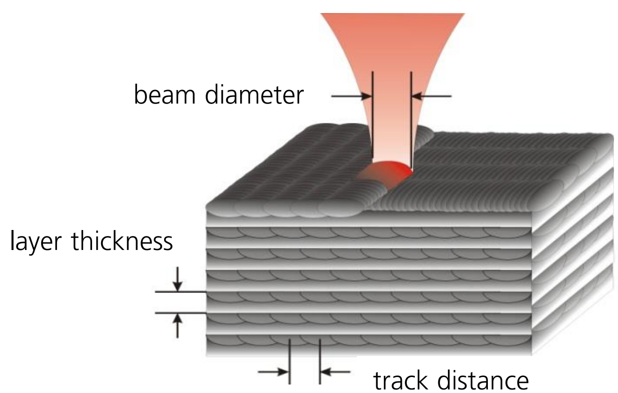
Additive Manufacturing by Lasers: Productivity

Selective Laser Melting - SLM



- Build up Rate
  1-3 cm³/min
  = app. 1kg/h steel
  = app. 300 g/h aluminium

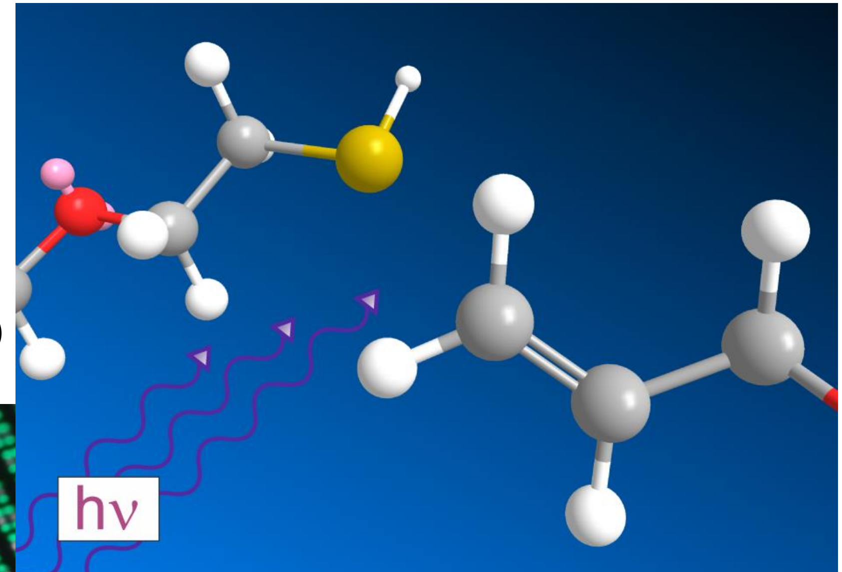
Laser Metal Deposition - LMD

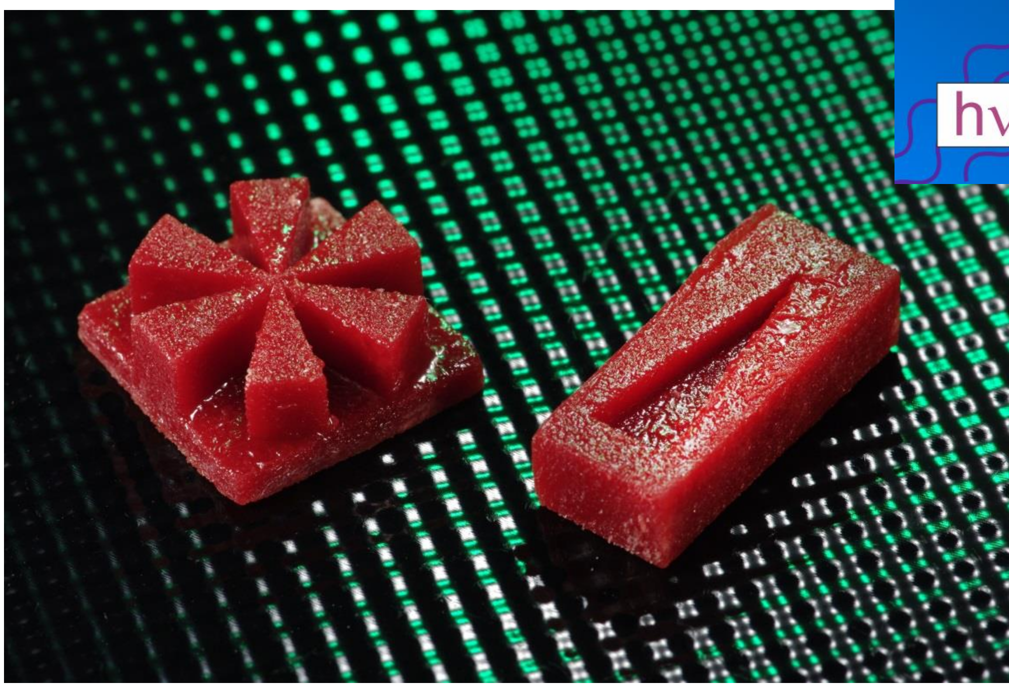


- Build up Rate
  10-30 cm³/min
  = app. 10 kg/h steel
  = app. 3 kg/h aluminium

Biocompatible Photopolymers

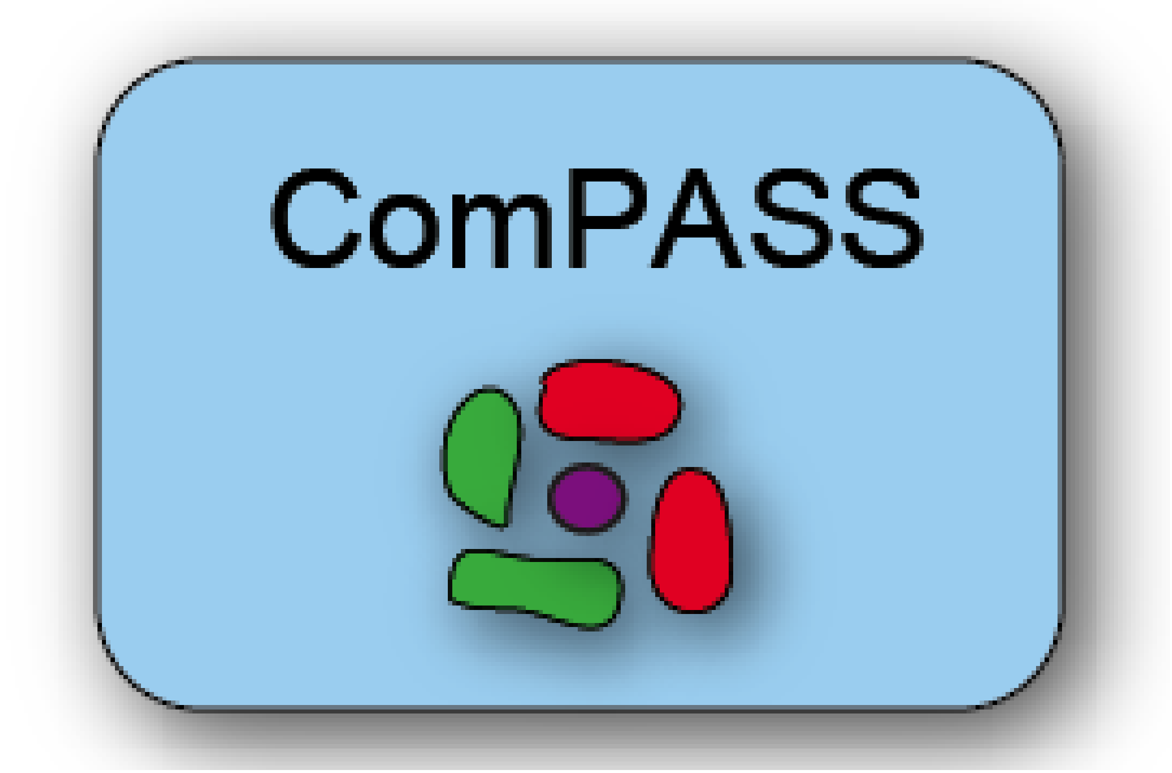
- Thiol-Ene Click-Chemistry
- Natural absorbers (beta carotene)
- Printing of high resolution objects
- Acrylate, Soft materials (Hydro Gels)



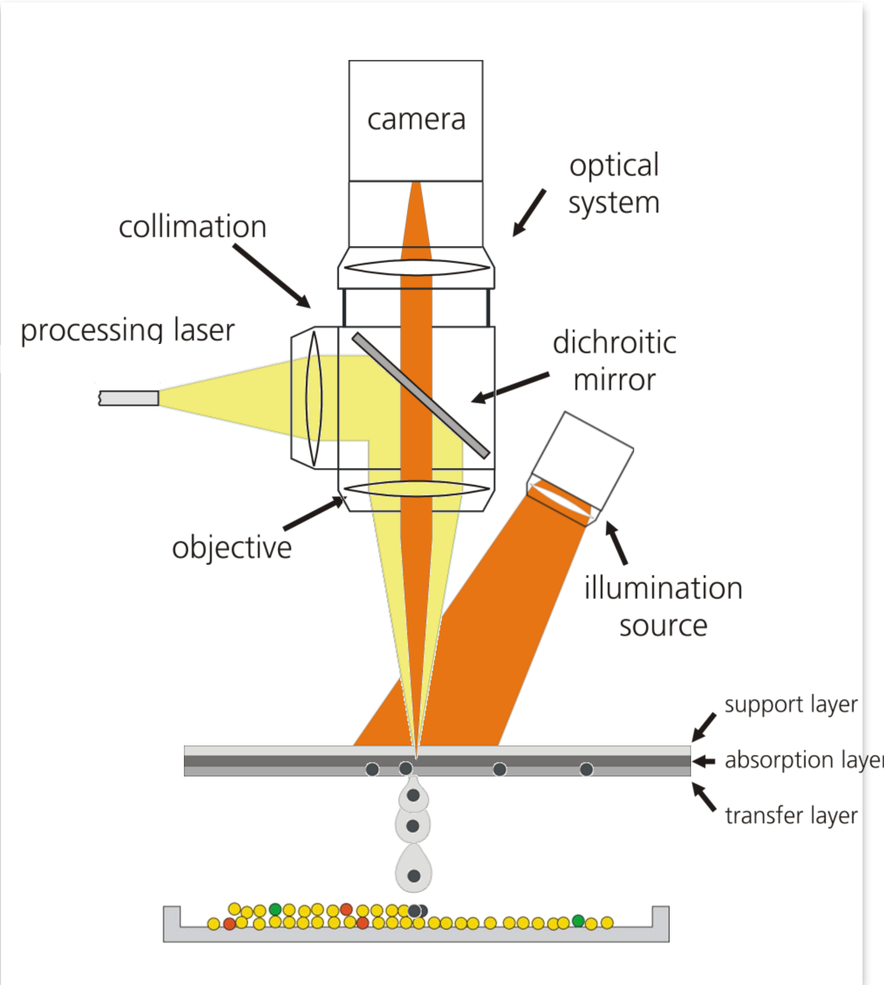


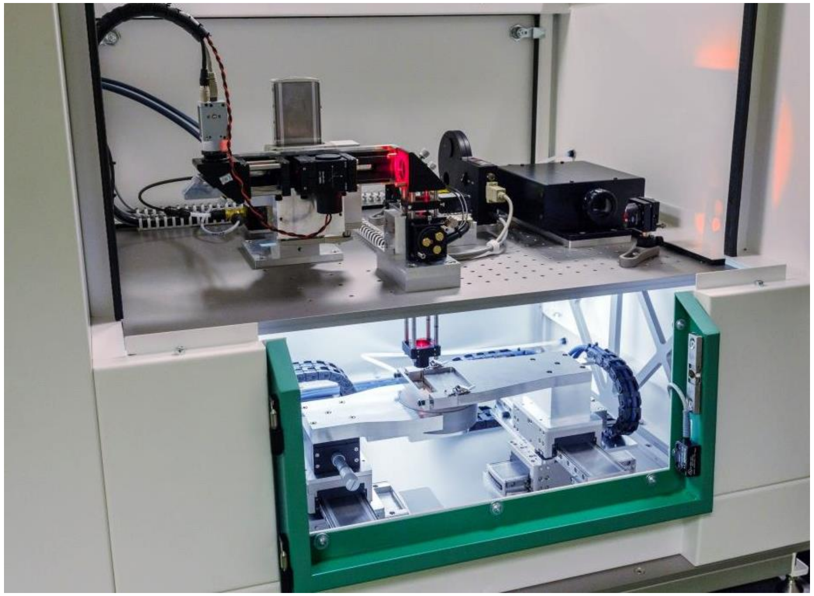
Organ printing cell by cell

Build up/ Research in a stem cell niche



LIFTSYS – Advanced MachineTool



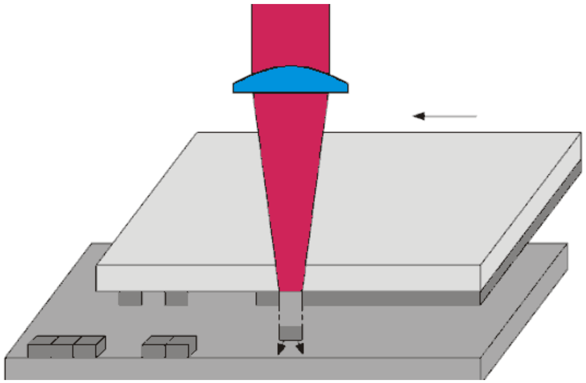


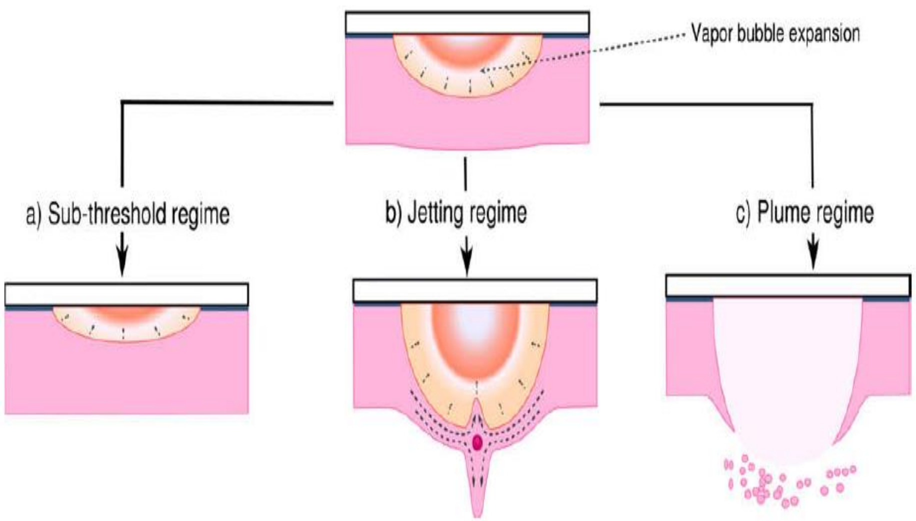
transfer layer:
- biomolecules and proteins
- living cells embedded in hydrogel

receiver layer:
- slides and wafers coated with hydrogel

image processing
- selection of transfer material
- placement of transfer materials on receiver

Laser Induced Forward Transfer (LIFT)





F. Guillemot *et al.*, Acta Biomaterialis 6, pp. 2494-2500, 2010

By a laser induced vapor bubble three regimes of the process can be identified:

- Sub-threshold regime
- Jetting regime
- Plume regime

Cell Transfer
LIFTSYS - Tool

Technical Data:

Size: 1080 x 850 x 800 mm^3

Interfaces:

Embedded PC, CNC kernel for PLC and GUI interaction, G-Code programming, 5 stages (X, Y, U, V and Z)

Laser parameters:

Type:	microchip laser
Wavelength:	355 nm, 1064 nm
Pulse width:	~1 ns
Max. Power:	25 µJ/pulse

Add-ons:

Motorized beam expander

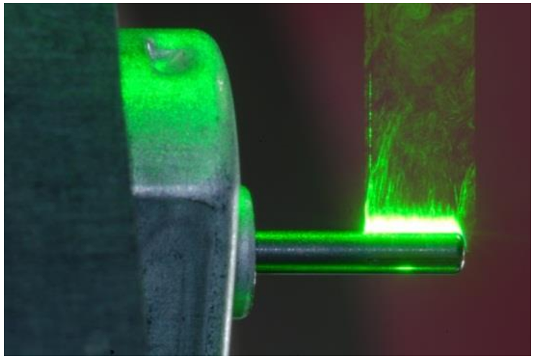
Attenuation

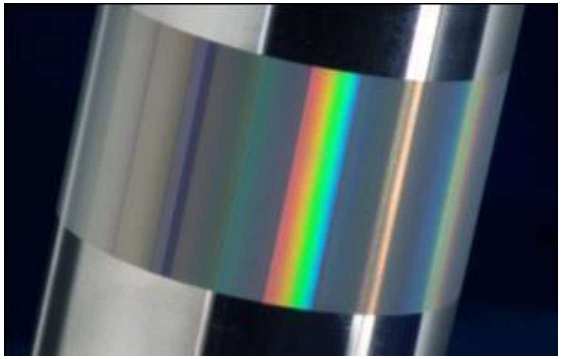
Coaxial camera system

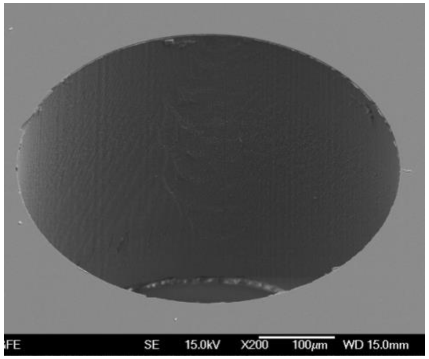
- Transfer materials:
  - Hydrogels
  - Cells
  - PDMS
  - Metals

Ultrafast

Ultrashort pulsed Lasers – A new tool for precision machining





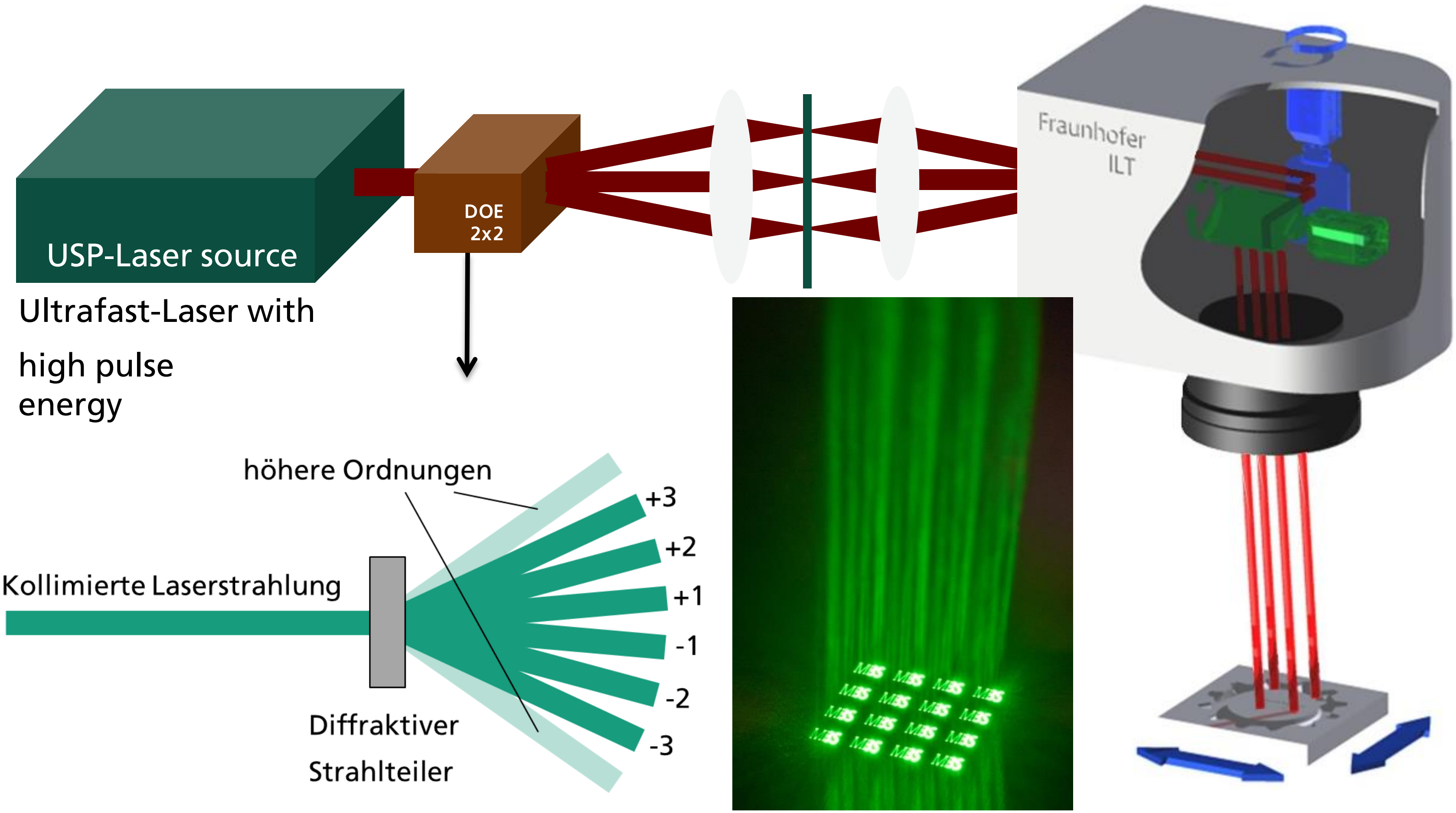


- **Flexible tool with no material dependance**
  - Wide bandgap materials (Glass, Sapphire, Diamond)
  - Semiconductors (Silicon, GaAs, SiC)
  - Metals (WC, Steel, Copper)
  - Polymers
  - Biological materials

- **High Accuracy**
  - Sub 100 nm precision in ablation depth
  - Material selective processing
  - In volume processing

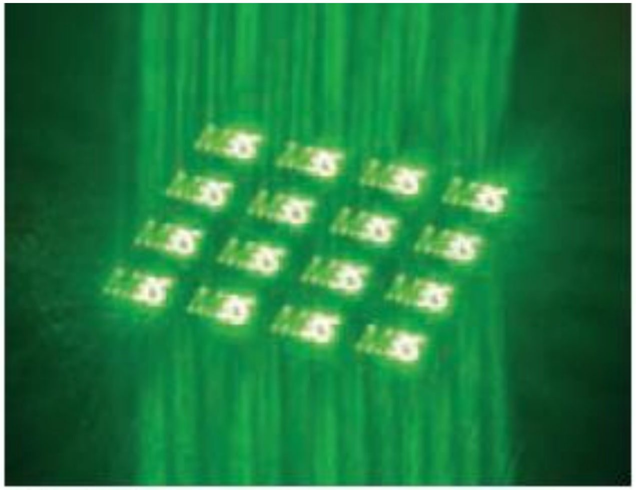
- **Tool independent processing**
  - Tool-free, wear-free and resource-efficient
  - Almost no lead-time (Digital Photonic Production)
  - Universal application (due to high variety of parameters)

Massive parallel processing using beam splitting by diffractive optical elements (DOE)

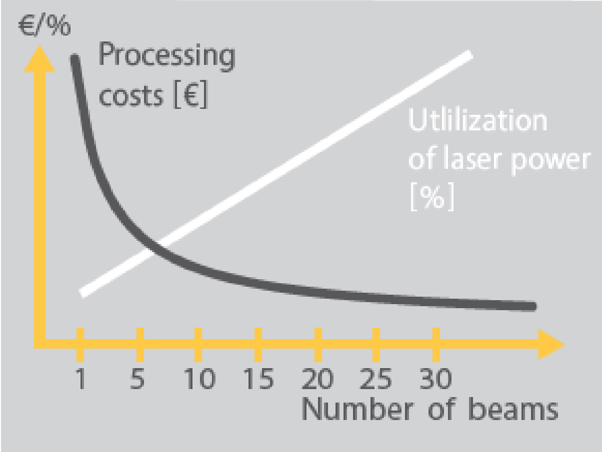


Massive parallel processing using beam splitting by diffractive optical elements (DOE)

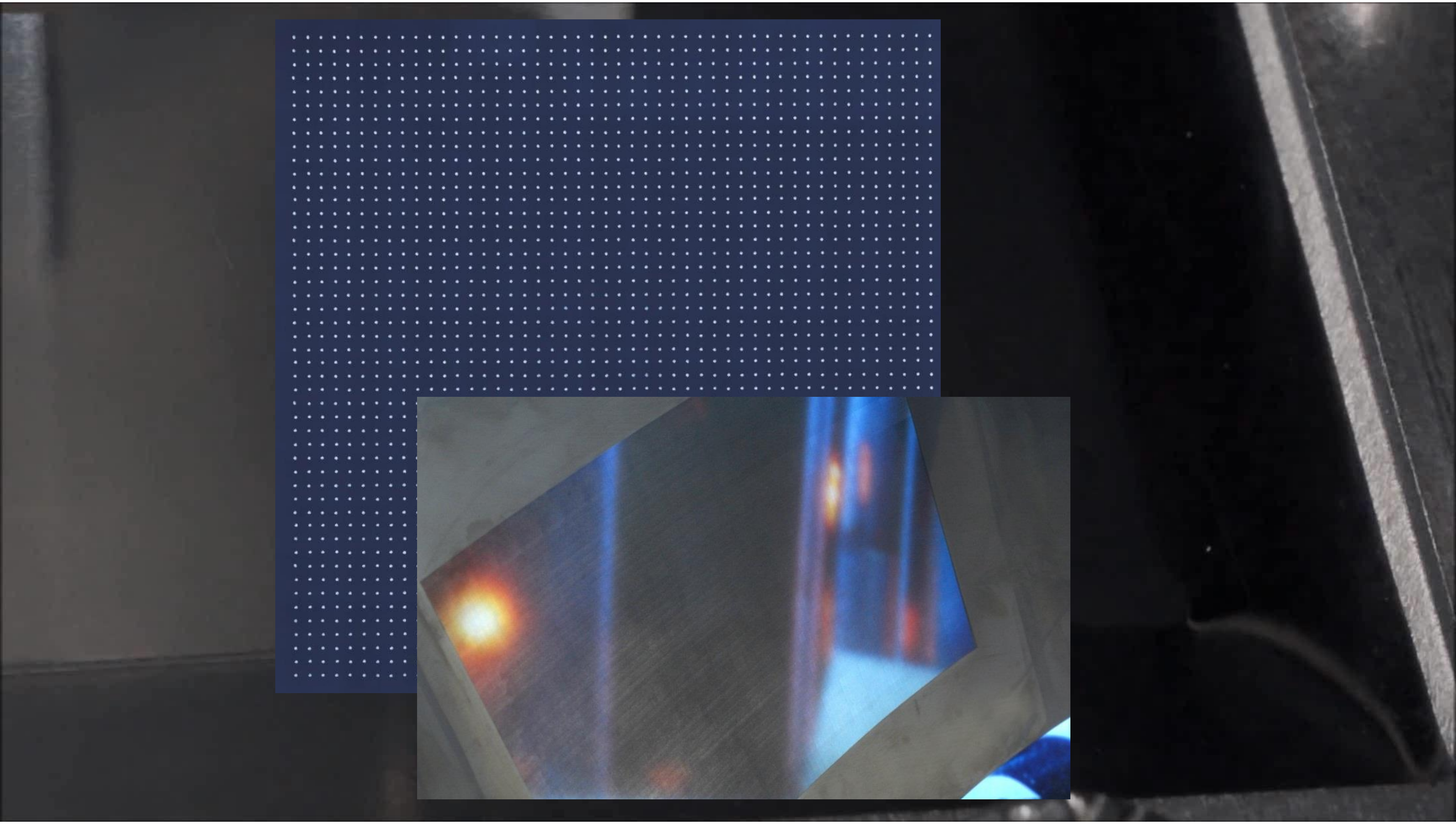
- Periodic pattern with n x m spots
- Movement of spot pattern with the scanner system
- Typical period of pattern: 0,3-2 mm
- Optical efficiency >70 %
- Spot uniformity > 93 %
- Semi-automated alignment
- Exchangeable beam splitter
- Masking of unwanted higher orders
- Masking of main orders to reduce number of spots (x and y direction)



Multi beam laser processing with 16 sub beams



Video: Parallel laser processing using 196 beams



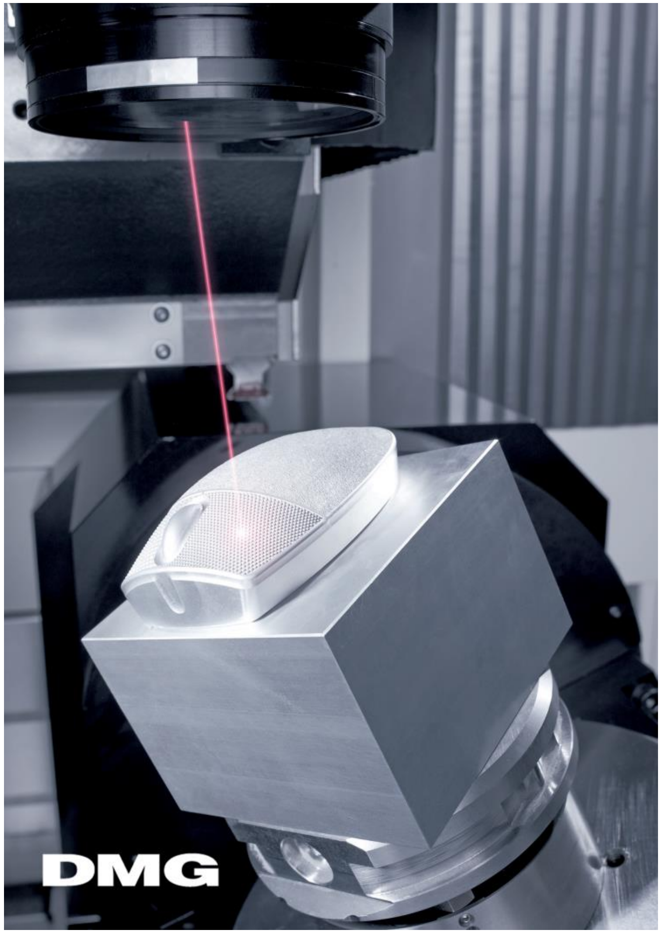
Photonics production:
Ultrafast Manufacturing using Ultrafast Lasers

Today:

- Typical ablation rates of e.g. Aluminum ca. 1 mm^3/min
- Limited by max. Laser power and Scanning speed

Future potential:

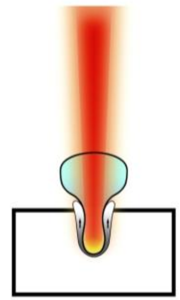
- Ablation rates of **>5 mm^3/sec**
- Use of fast deflection systems and >1 kW average Power
- Direct manufacturing of small components e.g. with specific surface features



Polymer-Metal Joints
Formability improvement

Polymer Metal Hybrid for Light Weight Design

Laser based process chain



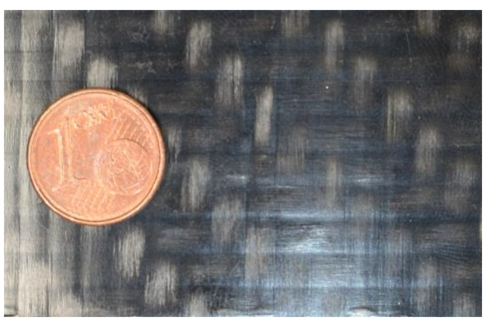
Metalic joining partner

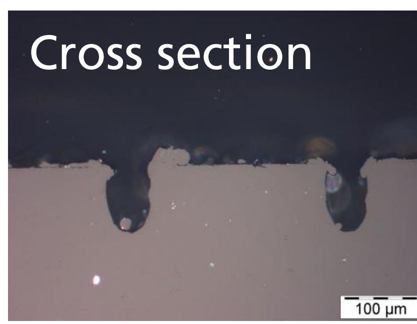
Surfcace treatment

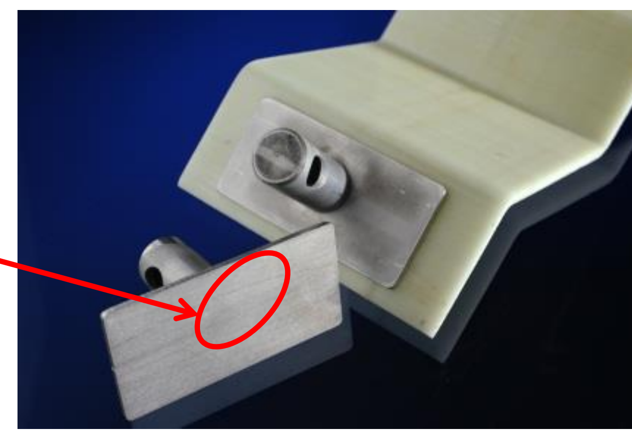
FRP

Joining partner

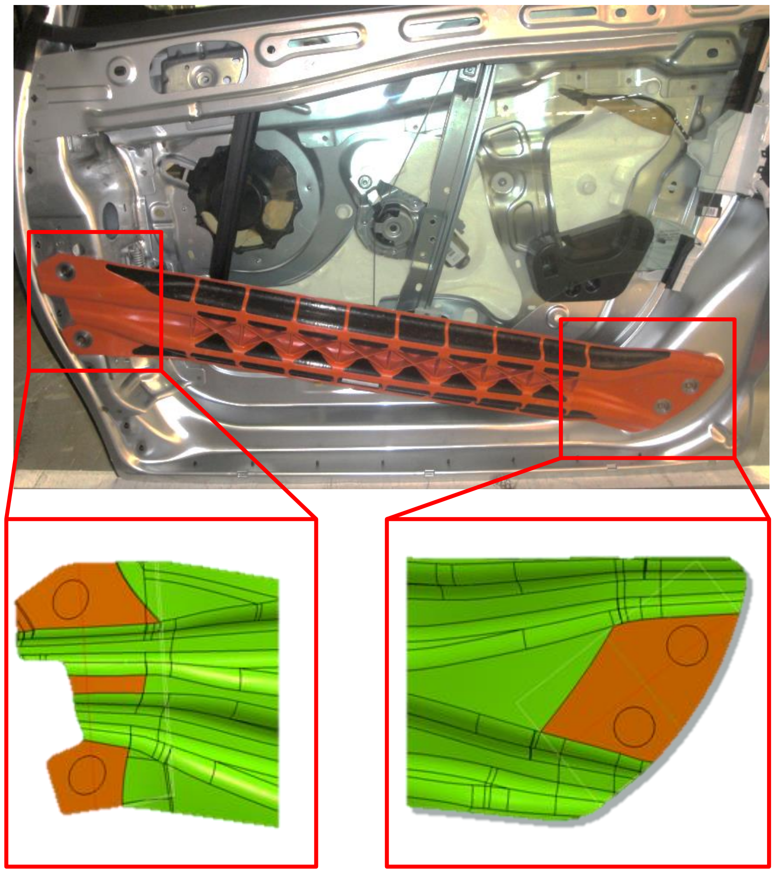
Thermal joining

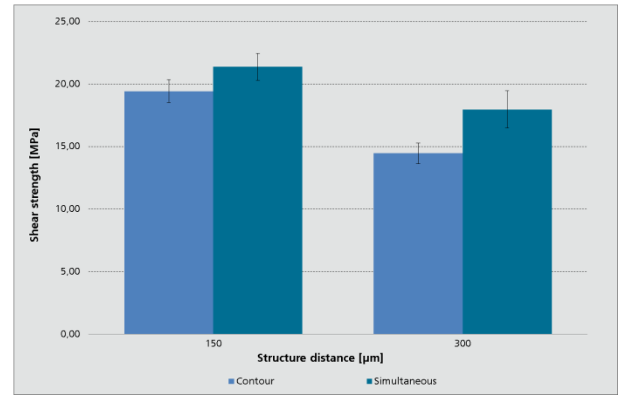






Perspective: Demonstrator in EU-Project PMJoin
Reinforcement element for car door (PSA)





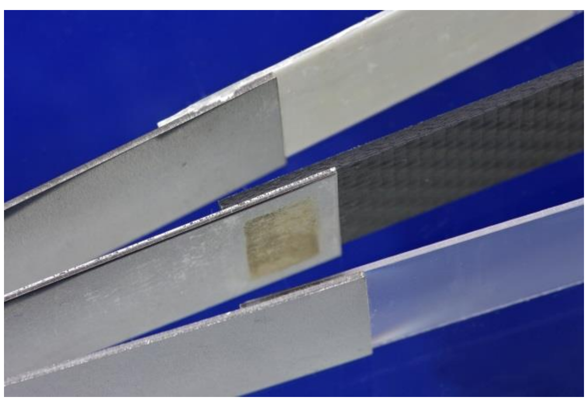
1 Determination of joining area and simulation of transferable tensile shear forces

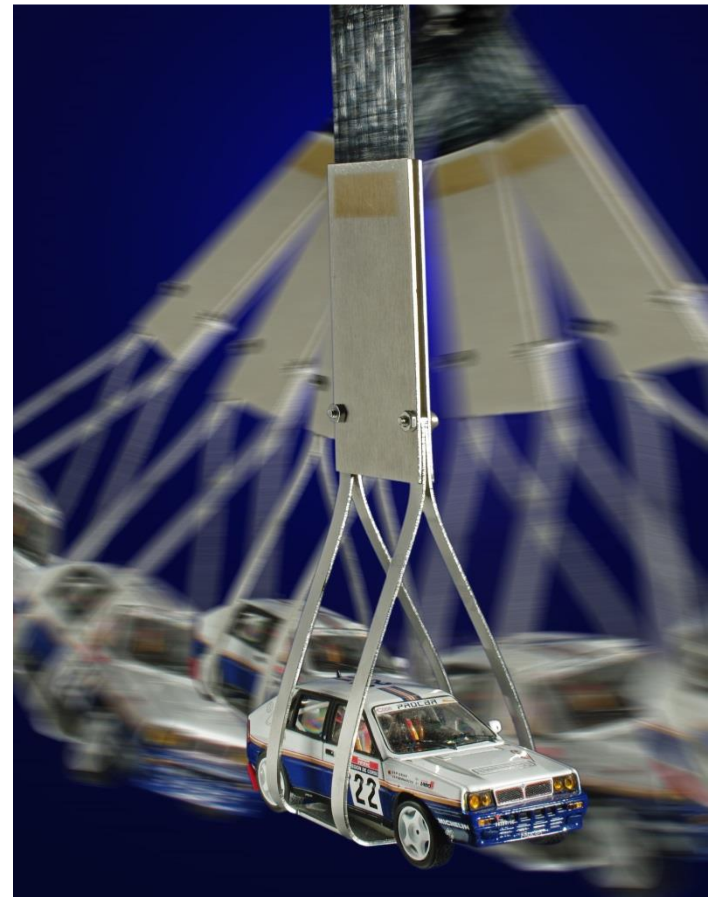
2 Determination of process window for material combination and necessary structure density

3 Structuring and joining of demonstrator and subsequent mechanical testing

Polymer Metal Hybrid for Light Weight Design
Applications in Automotive

- Laser microstructuring and laser joining
- Double sided connection
  - Sandwich: Metal-GFRP-Metal
- Joining area ~ 30 x 12 mm²
- Resulting shear force > 16kN
- Various materials possible



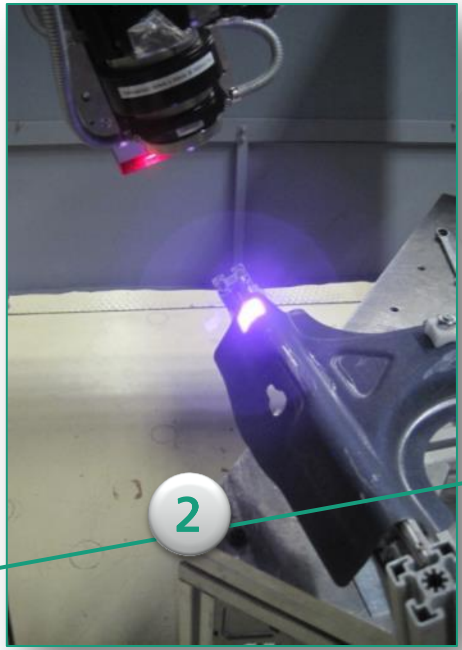


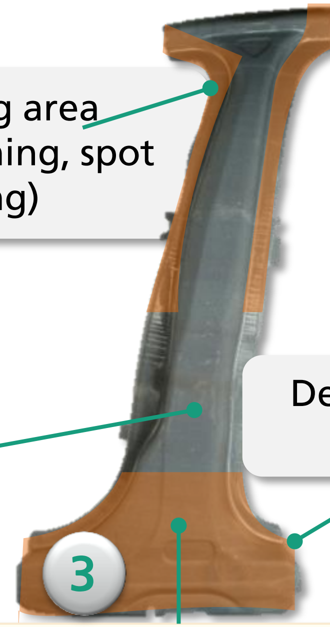
Laser Heat Treatment of Press Hardened Parts

Press hardened B-pillar
(hot formed at ca. 900 °C,
hardened during cooling inside
the tool)

Laser Heat Treatment (Softening)

High strength part with increased ductility in joining and crash areas





Joining area
(Clinching, spot
welding)

Deformation
zones

Material 22MnB5
Tensile strength ~ 1500MPa
Breaking elongation ~5%

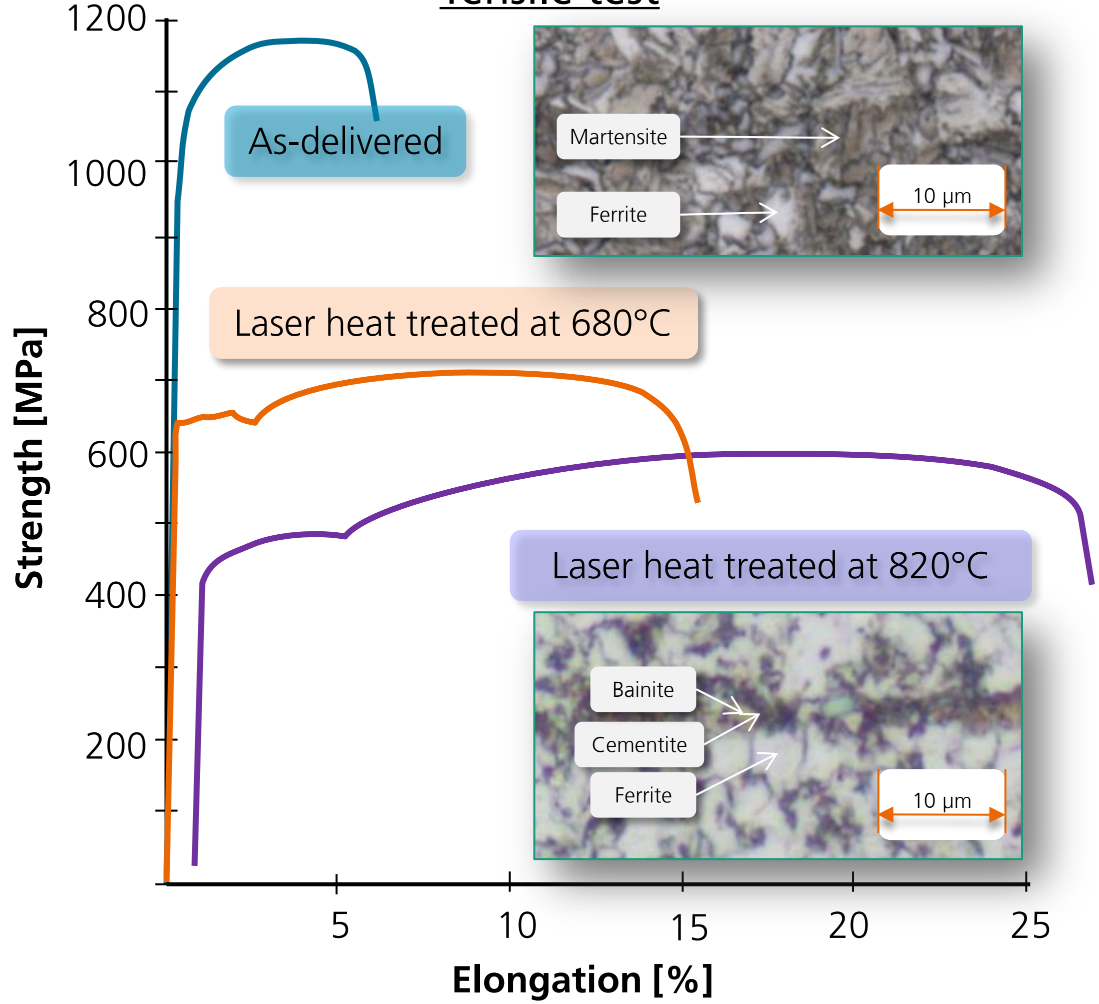
Material 22MnB5
Tensile strength ~600 MPa
Breaking elongation ~20%

Microstructure Transformation during Laser Softening

Example: „Docol 1200"

- As-delivered: Martensitic structure witrh high strength (1200 MPa), but low formability
(< 6% breaking elongation
- After laser heat treatment (softening): Microstructure mainly ferritic with low strength and increased formability (up to 27 % breaking elongation)

Tensile test



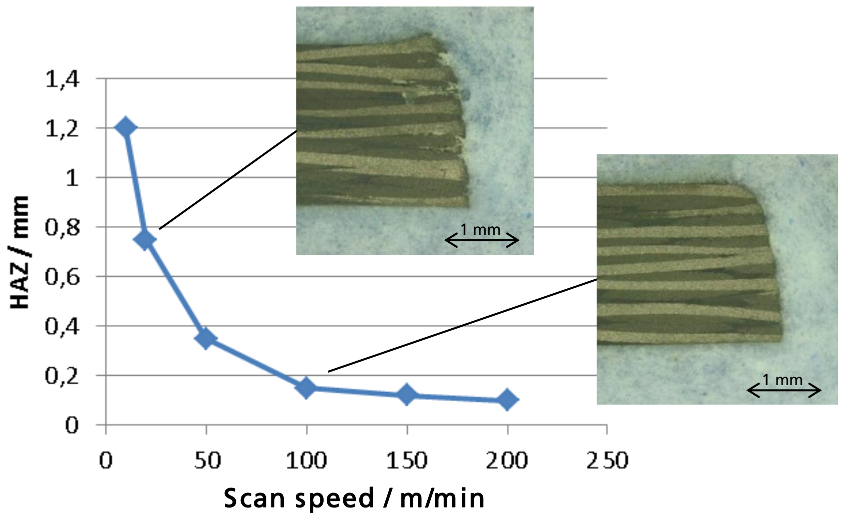
AKL'14 INTERNATIONAL LASER TECHNOLOGY CONGRESS

Fraunhofer ILT

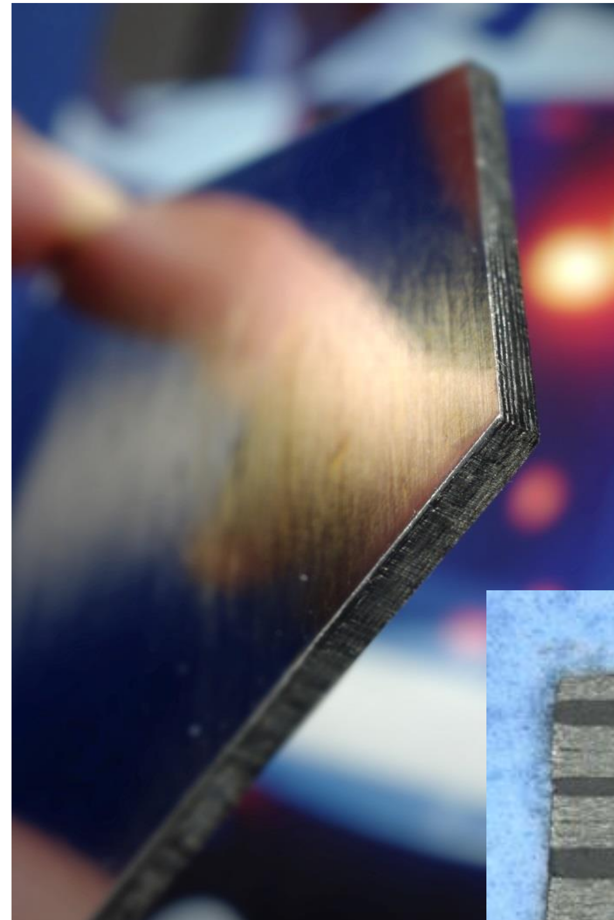
Cutting of Carbon Fibre Reinforced Polymers

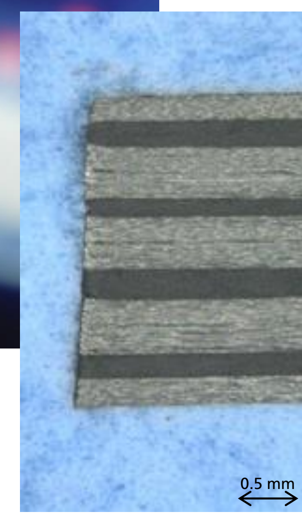
Cut edges with
low heat affected zones <100 µm by

- High processing speed
  -> Multi-pass ablation cutting
- High brightness lasers
  -> multi-kilowatt single mode fiber lasers
- Short pulsed / UKP lasers
  -> ps, fs-lasers or ns-CO_2-lasers



Width of heat affected zone vs scan speed for cutting with a ns-CO_2-laser (1.1 kW average power, ~200 kW peak power)





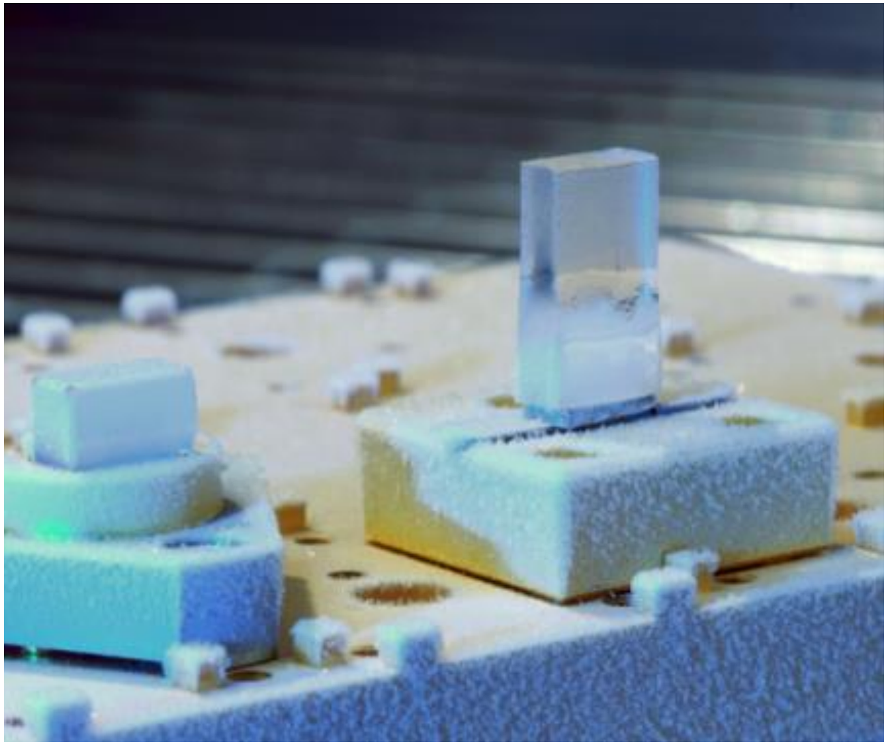
Cut edges and cross section of CFRP, 2.6 mm thickness, cut by a SM-fiber laser
(4 KW, 100 m/min, 7 passes)
leading to 12m/min cutting speed

New Lasers

Solder based Mounting Technology for Laser Optics

- High Precision by Active Alignment
- Multiple Re-Alignment Capability
- Thermo-mechanically Stable
- Mechanically Robust
- Very Compact

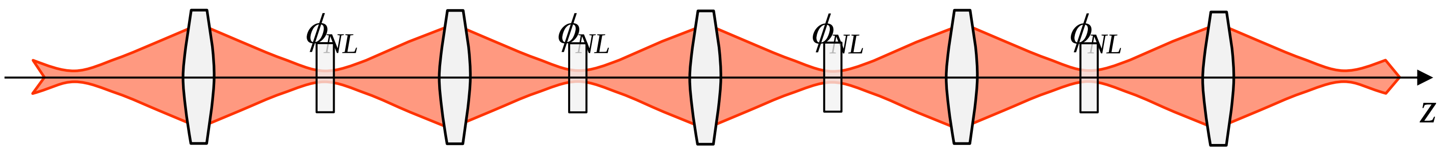
Parameter	Result
Max. Misalignment	10 µrad
Temperature Range	-30 °C bis +50 °C
Temperature Drift	< 0,5 µrad/K



- Benefit for Lasers and Laser Optics
  - Larger Temperature Range
  - Reduced Cooling Requirements
  - Enhanced Live Time of (UV) Lasers

Ultrafast Pulses by New Pulse Compression Concept

- Concept
  - External Unit for Spectral Broadening and Compression
  - Distributed Kerr Elements



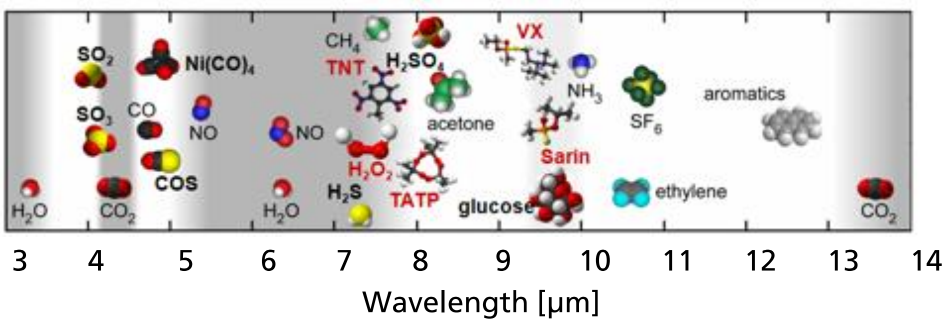
- Results

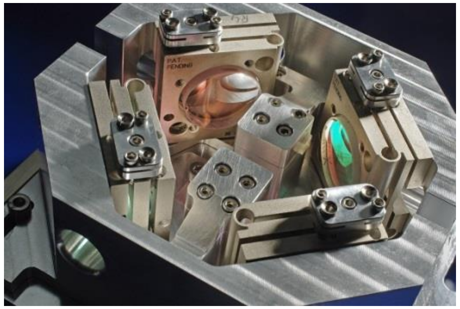
Pulse Duration	170 fs
Average Power	375 W @ 37,5 µJ
Beam Quality	M^2 = 1.3
Conversion efficiency 800 fs to 170 fs	91%

- Benefit and Outlook
  - Scalable to Multi kW Average Power and Multi mJ Pulse Energy
  - Pulse Compressor Concept allows for Efficiency up 98 %
  - High Throughput Materials Processing in the Regime of Strongly Nonlinear Absorption

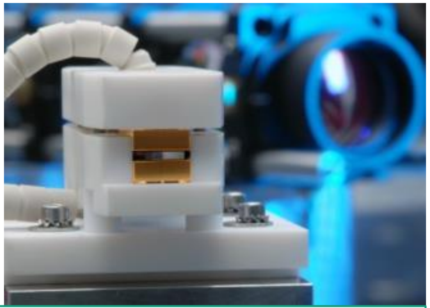
Parametric Generation of High Power Infrared Light

- Addressing the "Spectral Fingerprint Region" for
  - Processing of Organics / Plastics / Compounds
  - Measurement Applications





OPO

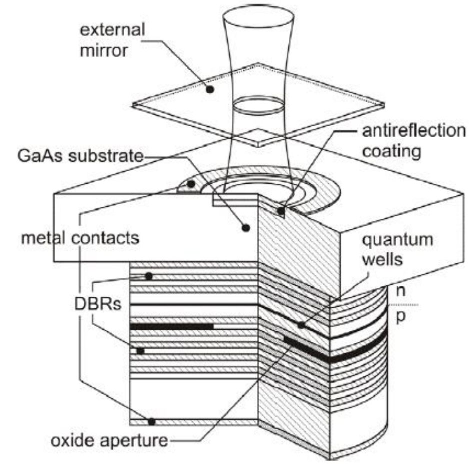


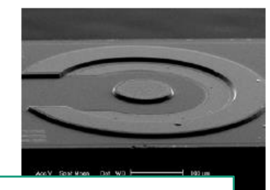
OPG

- Benefit for Applications
  - Ultra High Absorption
  - Very High Selectivity
- Implementation
  - OPO/OPG Converter for Commercial Solid State and Fiber Lasers

Vertical Emitters for High Power Applications

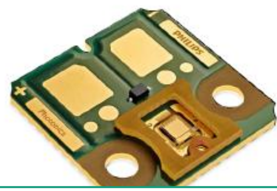
- Power Scaling of VCSEL
  - Multi kW Arrays available
  - e/o Efficiency Improvement to 50 % (Lab: 60%)
- But: Brightness orders of Magnitude below Edge Emitters



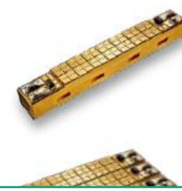


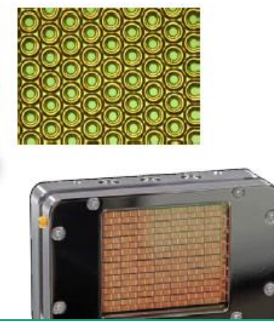
Datacom

Illumination



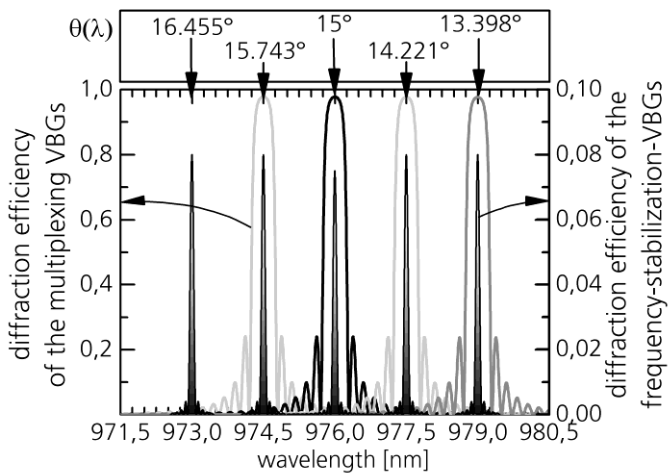
Material-Processing

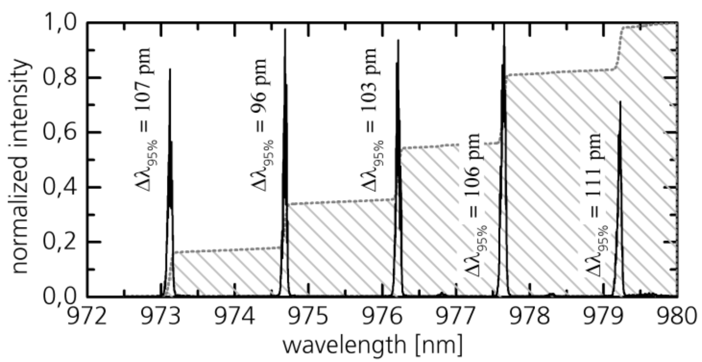


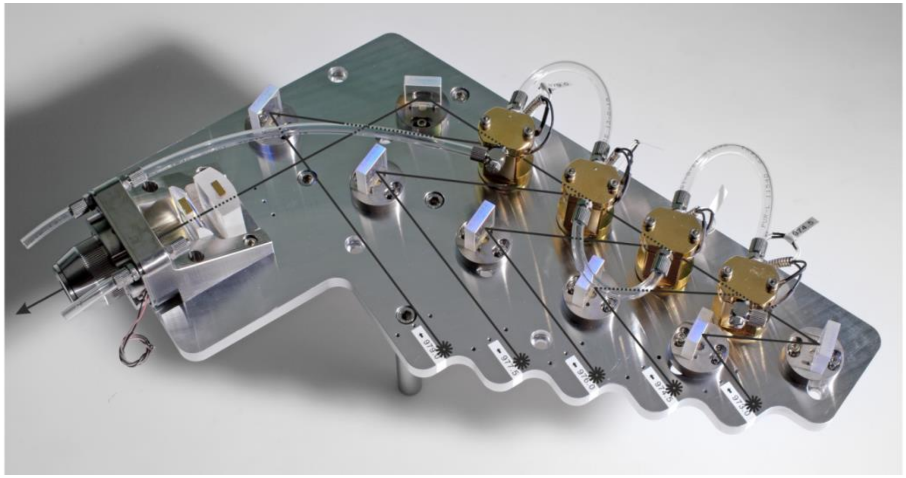


- Transfer of Modeling Results to an Improved Chip Design
  - 270% Brightness Improvement in 3 Years
  - e/o Efficiency at max. Brightness about 50% of the Low Brightness Devices now

High-Power Dense Wavelength Division Multiplexing of Diode-Laser Radiation







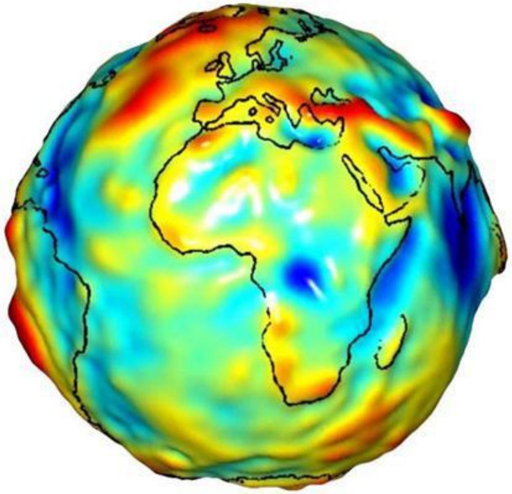
- Application
  - Brightness Scaling of Diode Lasers
  - Brightness Scaling of Fiber Lasers and Solid State Lasers

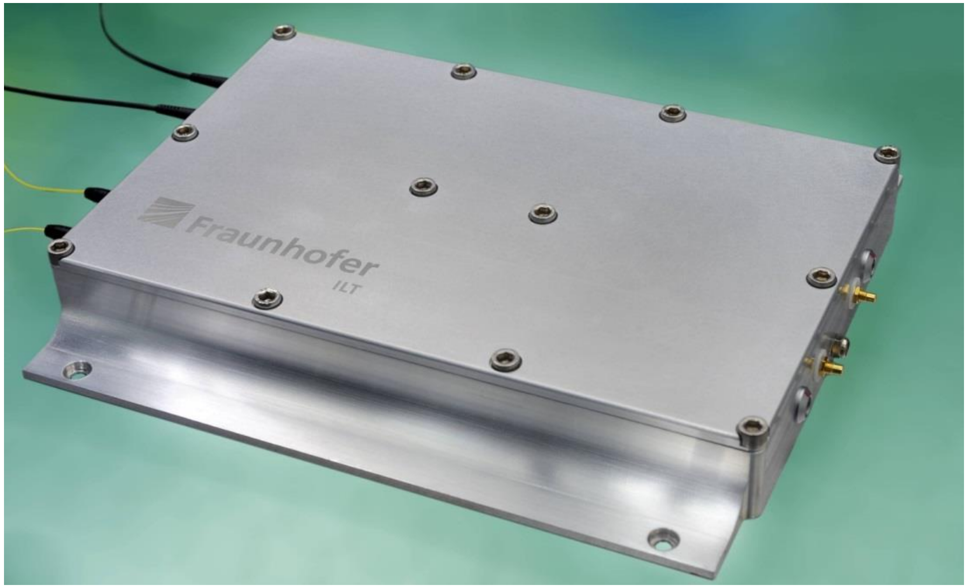
AKL'14 INTERNATIONAL LASER TECHNOLOGY CONGRESS

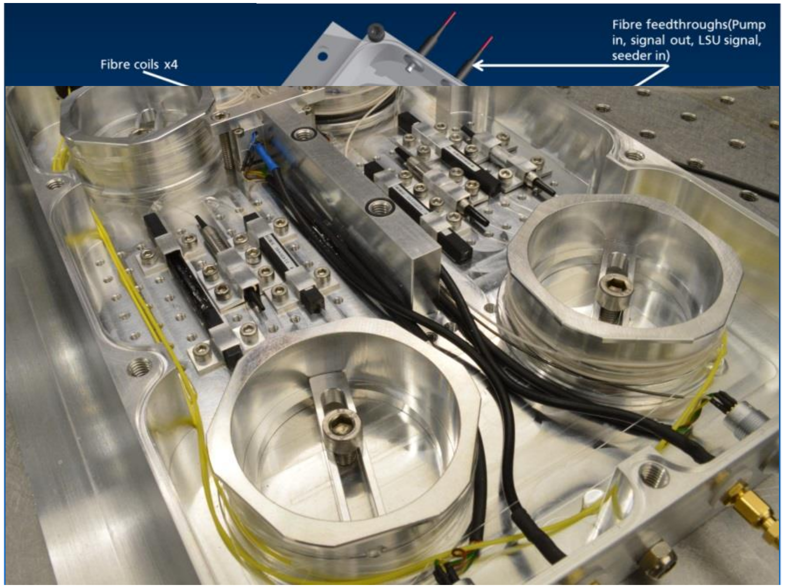
Fraunhofer ILT

Fiberlaser for Ultra Precision Interferometry

- Applications and Benefit
  - Precision Interferometry Over Very Large Distances (multi 100 km)
  - Precision Interferometry in Harsh Environment
  - Free Space Optical Communications Links





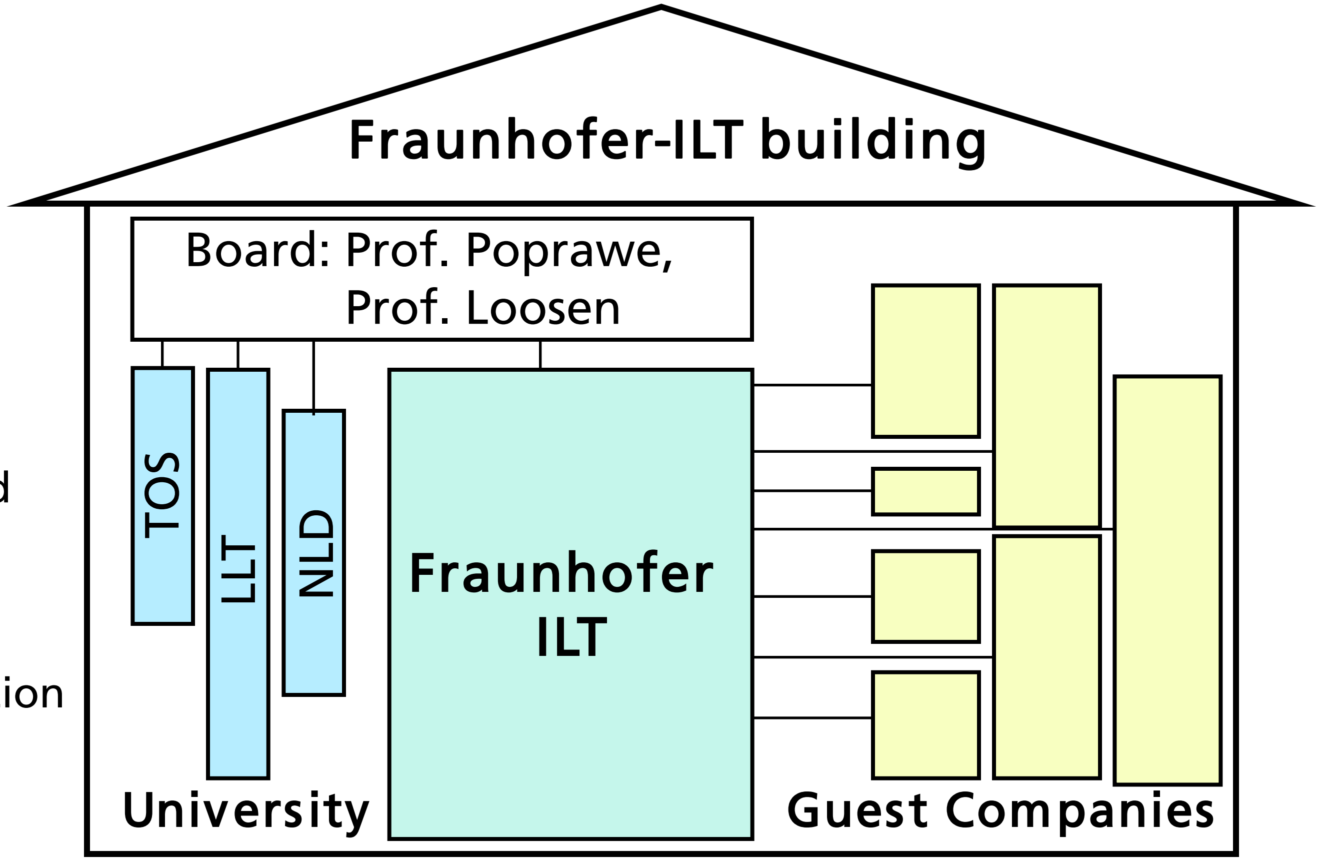


Lasers and Photonics in Aachen

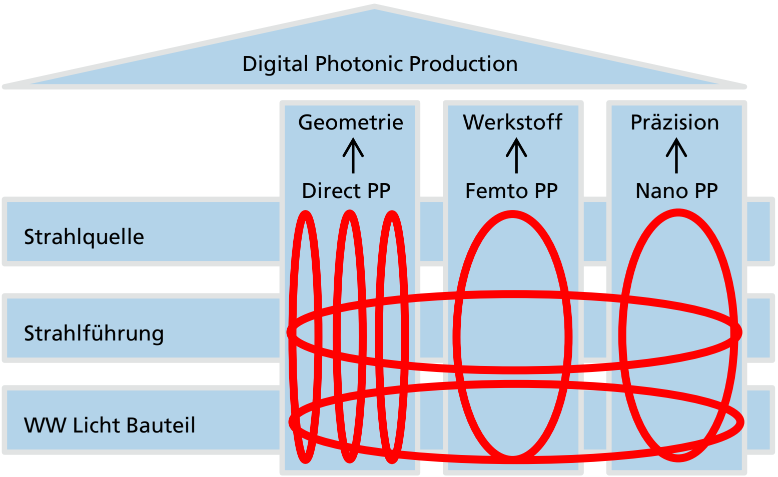
“OUTLOOK” Friday, May 9, 16:00

Fraunhofer/ILT – University – Guest Companies

- cooperating partners in the Fraunhofer-ILT building:
  - Fraunhofer-ILT
  - 3 university chairs
  - guest companies
- linkage Fraunhofer and University by common management
- linkage Fraunhofer – companies by cooperation contracts



1. „BMBF-Forschungscampus“ Digital Photonic Production



15 Jahre Laufzeit
2 Mio Förderung p.a.

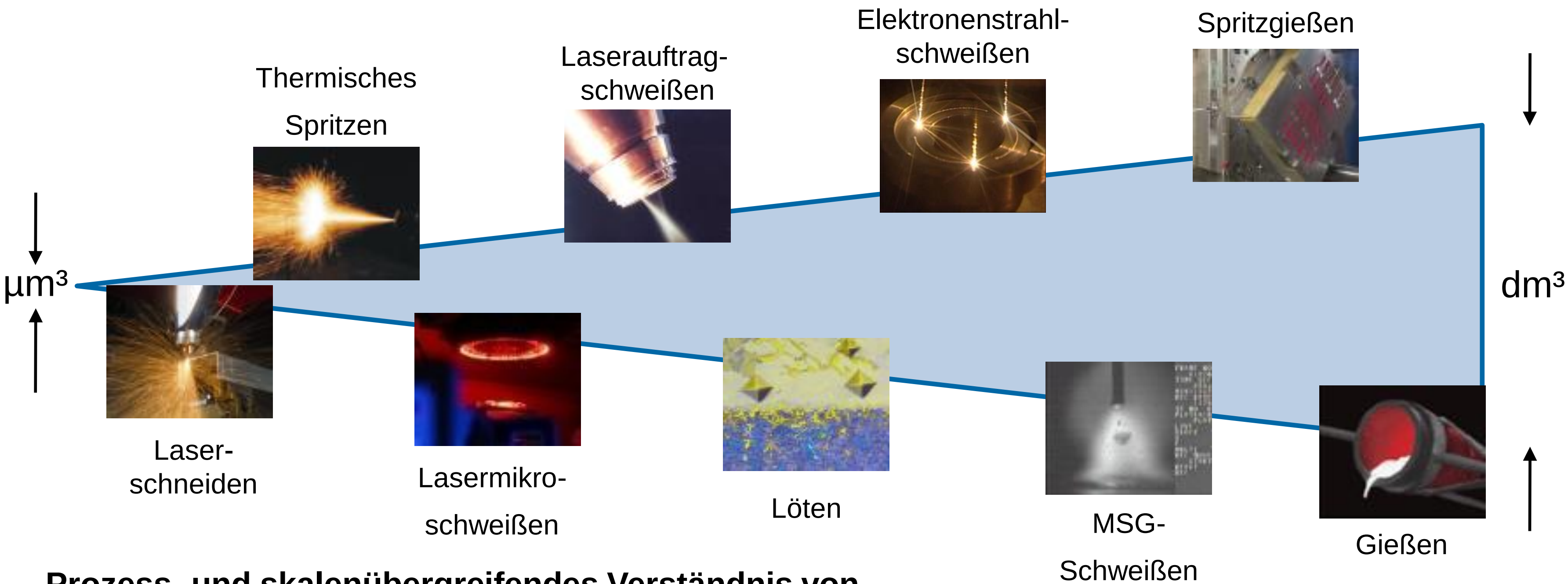
Förderprojekte erste Hauptphase

- Direct PP-1 – VCSEL-SLM
- Direct PP-2 – Advanced SLM Systems
- Direct PP-3 – SLM Turbine
- Femto Photonic Production
- Nano Photonic Production
- Strahlführungssysteme – MaGeoOptik
- Prozesskette – Digitales Datenmodell für photonische Prozessketten

2. Innovation Center „Digital Photonic Production“ Autumn 2015

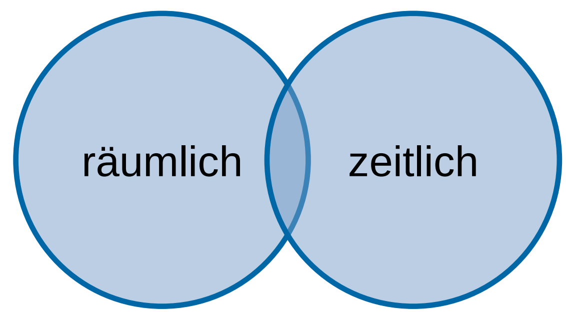
3. Research Center „Digital Photonic Production“ 91b Summer 2018

4. SFB "Precision Melt Engineering" SFB 1120 (May 2014)



Prozess- und skalenübergreifendes Verständnis von

- Schmelzeentstehung
- Schmelzedynamik
- Schmelzebeeinflussung
- Erstarrung unter externer Modulation des Wärmeentzugs



AKL'14 Sponsors

abariscan VERTICAL SOLUTIONS
AMPHOS
AdlOptica
Budenheim
Cambridge Technology
COHERENT
DILAS Industrial Laser Systems
edgewave
FISBA OPTIK
Herding FILTERTECHNIK reine Produktivität
H.I.B HYDAC INTERNATIONAL
II-VI HIGHYAG
IPG LASER
IXUN LASERTECHNIK GMBH
JENOPTIK
KKT chillers
LASER COMPONENTS
LASER World of PHOTONICS
LASER 2000
laserline
LEISTER
LIMO Lissotschenko Mikrooptik
Ocean Optics
OPHIR Photonics A Newport Corporation Brand
OPTOSKAND
OSRAM Opto Semiconductors
RIEDEL PRECISION IN COOLING
PHILIPS
PHOTON ENERGY
PRECITEC
PRIMES
reis REIS LASERTEC
rofin
SCANLAB innovators for industry
scansonic industrial production technology
Spectra-Physics. A Newport Corporation Brand
SPI Lasers
Time-Bandwidth
TOPAG Lasertechnik
TRUMPF
II-VI DEUTSCHLAND
II-VI LASER ENTERPRISE
ULT UMWELT-LUFTTECHNIK
WILEY-VCH
wolf PRODUKTIONSSYSTEME

Thank you very much for your Attention!