Ultrafast Lasers with Radial and Azimuthal Polarizations for High-efficiency Micro-machining Applications

The Ultrafast_RAZipol project has received funding from the European Community's Seventh Framework Programme under Grant Agreement No. 619237

RAZipol

Beneficiaries – Call Topic Objective ICT-2013.3.2 Photonics iii) Laser for Industrial processing

Universität Stuttgart

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UNIVERSITÄT STUTTGART
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STUTTGART LASER TECHNOLOGIES

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Class 4 Laser Professionals AG

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GSI SLV Mecklenburg-Vorpommern

cnrs

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next scan technology

GFH GmbH

KITE INNOVATION EUROPE

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SEVENTH FRAMEWORK PROGRAMME

Project aims

- **Primary objectives:**
  - Highly flexible high-power ultrafast laser source (objective 1) with average output power of 500 W1 at High Repetition Rates (20-40 MHz) and 200W2 at Low Repetition Rates (0.2-1 MHz)
  - Cost-efficient solutions for a broad range of applications (objective 2)
  - Optimization of demanding high-volume applications regarding efficiency as well as quality (objective 3)

- **Two target applications:**
  1. Fast, large-area structuring, of Lab-on-a-Chip wafers
  2. Precision trepanning drilling of high-aspect ratio holes

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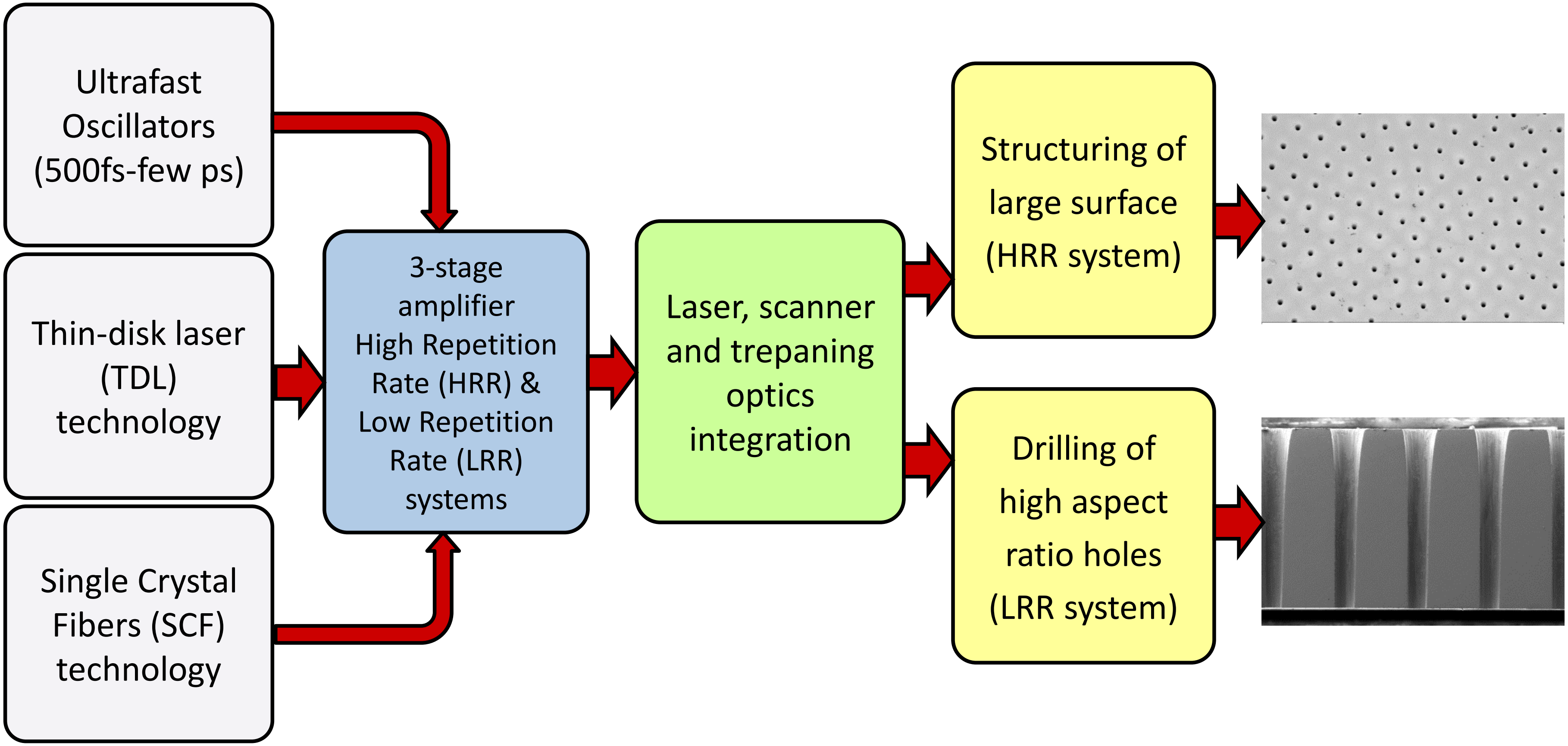
Overview project structure



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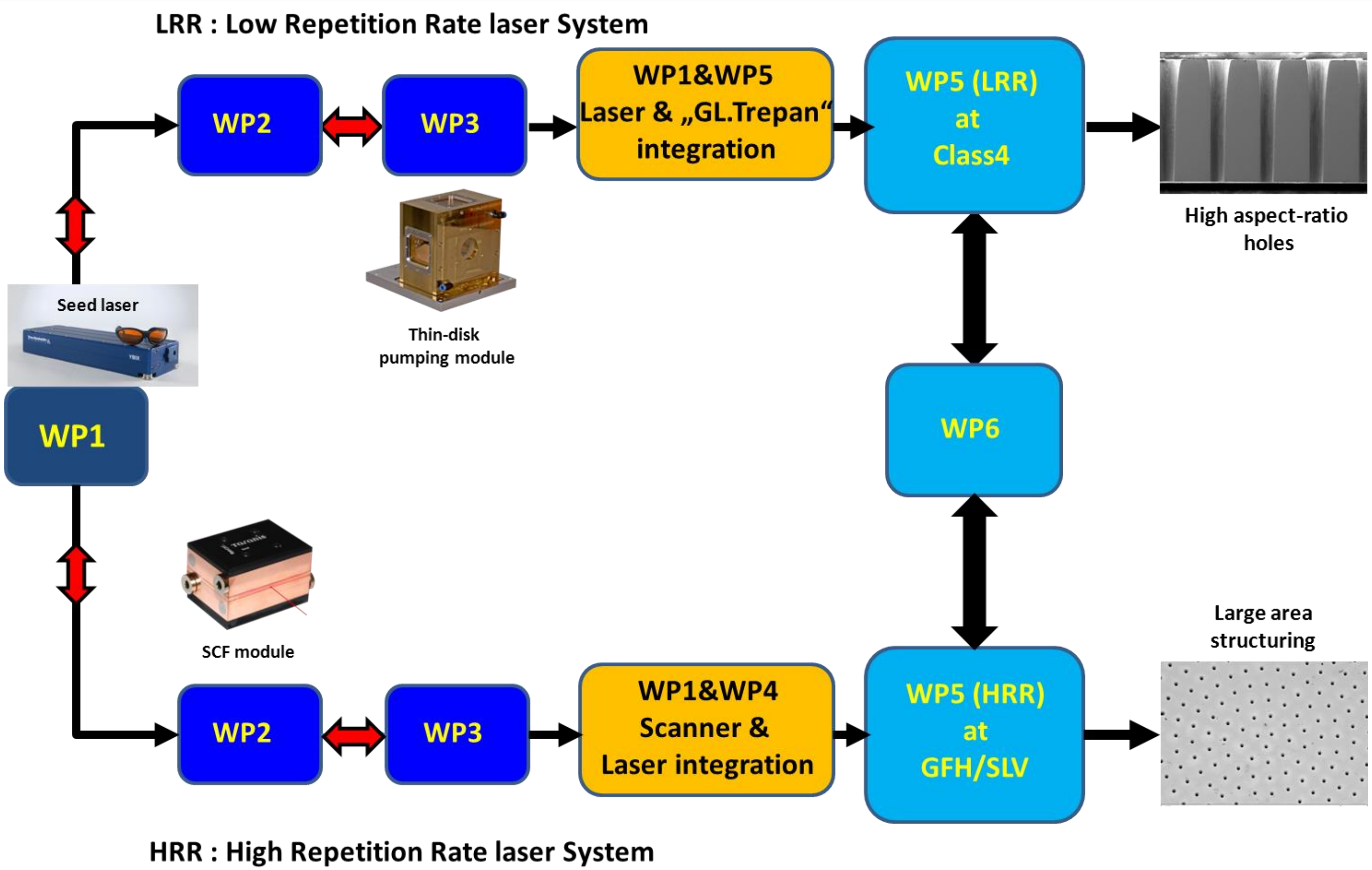
SEVENTH FRAMEWORK PROGRAMME

Overview work package structure



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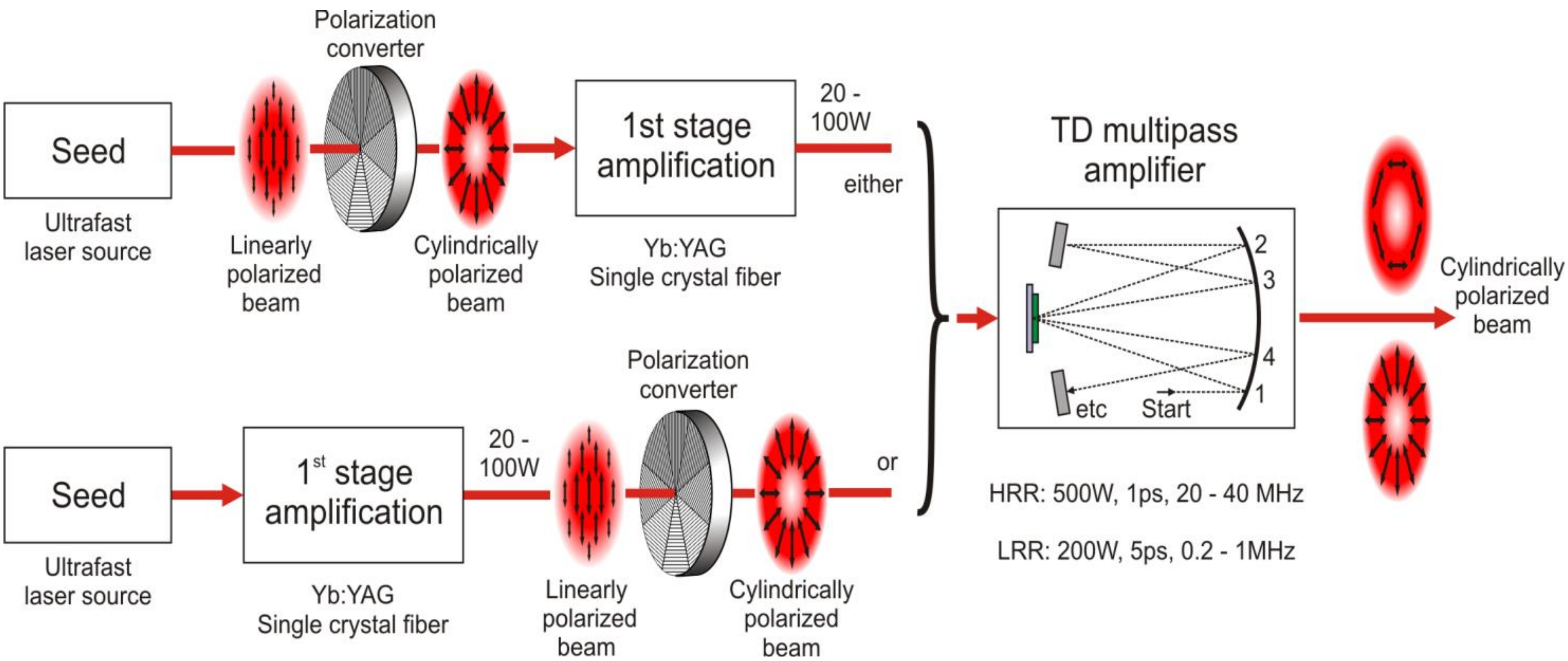
Project concept



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Key Laser and Application Parameters

Application	Key Laser Parameters	Key Application Parameters
Large area fast scanning for surface structuring (HRR)	MOPA with radially/azimuthally polarized beams having 500 W average power, at repetition rates in the 20-40 MHz range generating pulse energies (12.5 - 25 µJ) and pulse duration of 1 ps	Scan field full telecentric up to 8" wafer size (borosilicate/silicon). Structuring (texturing and patterning),
Trepanning drilling of deep, high aspect ratio holes (LRR)	MOPA with radially/azimuthally polarized beams having 200 W average power, at repetition rates 0.2-1 MHz generating high pulse energies (0.2-1 mJ) at pulse duration of 5 ps	Entrance diameter (<50 µm), Exit diameter (<50 µm) , material thickness (2 mm), aspect ratio (40:1), surface roughness of hole

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SEVENTH FRAMEWORK PROGRAMME

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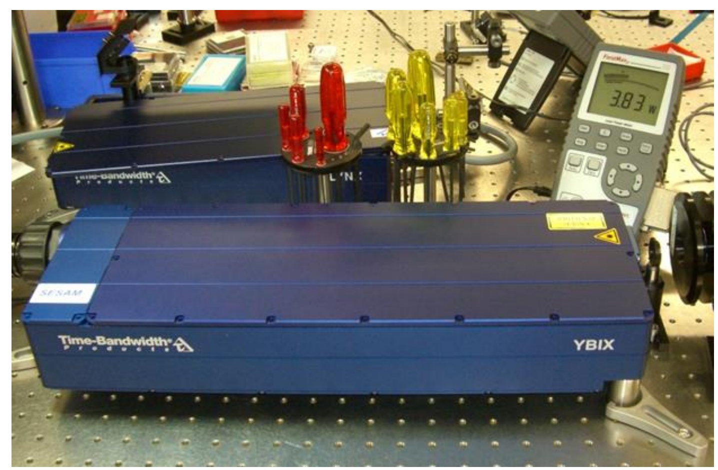
The Oscillator (WP1) Lumentum

- WP1 objectives
  - High repetition rate (HRR) oscillator: P_{out} = 3W, Rep. rate: 20-40MHz, pulse duration: 500fs
  - Low repetition rate (LRR) oscillator: P_{out} = 3W, Rep. rate =20-40MHz, pulse duration: 3-5ps + pulse picker for rep. rate: 0.2-1MHz, Tuning range: 5-10 nm.
- The design is based on Lumentum's industrial femtosecond laser platform YBIX, typically operating at a repetition rate near 80 MHz and a pulse energy of 35 nJ



The laser power supply and the oscillator

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The Oscillator (WP1) Lumentum

Output Parameters	HRR System	LRR System
Pulse energy	137 nJ	94 nJ
Pulse duration	350 fs	7 ps
Central wavelength	1030 nm	1030.2 nm
Pulse repetition rate	20 MHz	500 MHz
Average power	2.9 W	47 mW

- For the LRR system, it was later decided to operate the laser at 200 kHz to reach 1 mJ pulse energy from the final amplifier
- The industrial grade laser has an excellent beam quality with M2<1.1 in both x and y, beam roundness >0.8 and power fluctuations <1.5% rms

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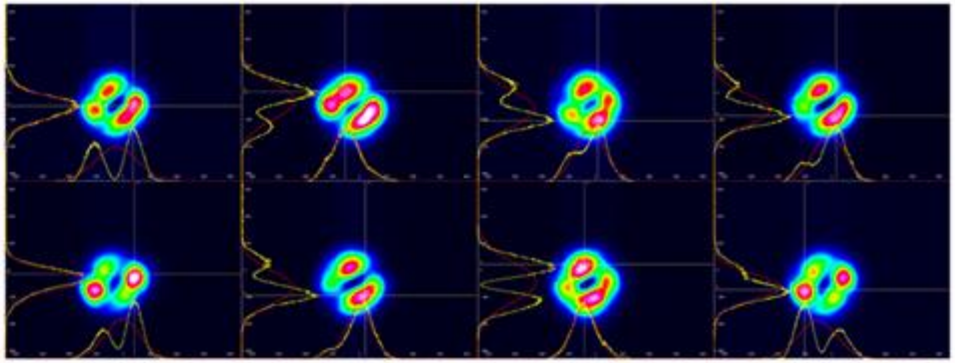
The Oscillator (WP1) Lumentum

- A GWOC was used to generate a radially polarised beam direct from the seed oscillator
- Due to a temporally unstable transversal laser mode profile resulting from the GWOC, modelocking experiments could not be performed with the bulk geometry used by LUMEN
  - this instability may be due to the preferential polarization state in which the cavity lases
  - This could be related to thermal or mechanical stress in the gain crystal. Similar experiments in the thin-disk configuration were conducted at USTUTT, where the superior thermal management properties of the thin-disk enabled a stable passively modelocked, radially polarized output



Sequence of beam profiles recorded with a frame rate of 3 fps with the GWOC

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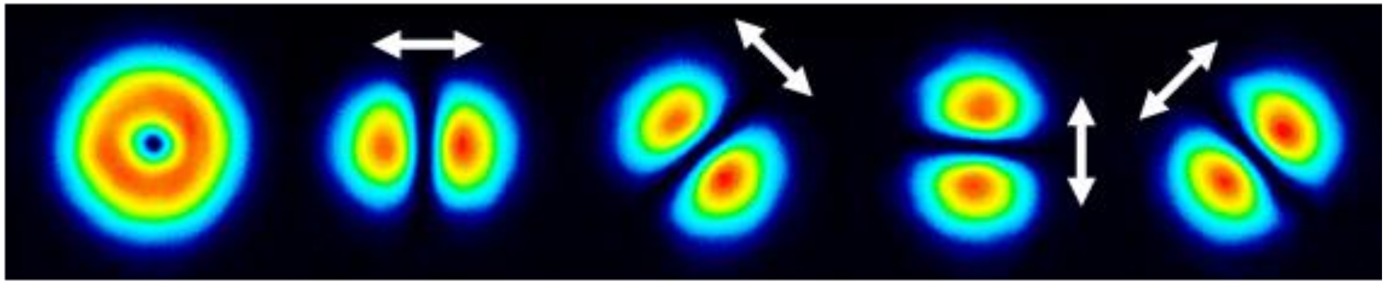
The Oscillator (WP1) Lumentum

- USTUTT was able to obtain a radially polarized thin-disk modelocked oscillator with an output power exceeding 13 W and at pulse duration of 907 fs with a GWOC produced in the same batch.
  - The strong advantages of the thin-disk compared to the bulk configuration are the much better thermal properties related to the one-dimensional heat-flow in the thin-disk



Recorded intensity distribution of the radially polarized mode without and with polarization analyzer at different transmission axis

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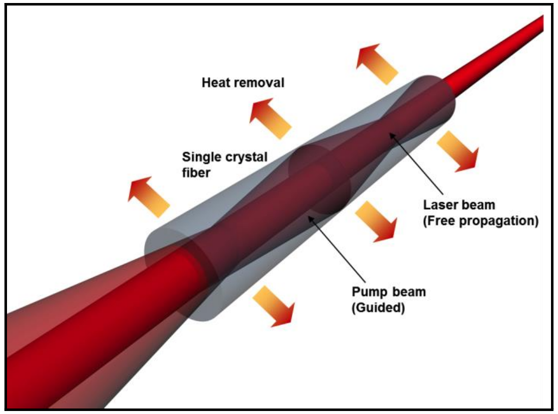
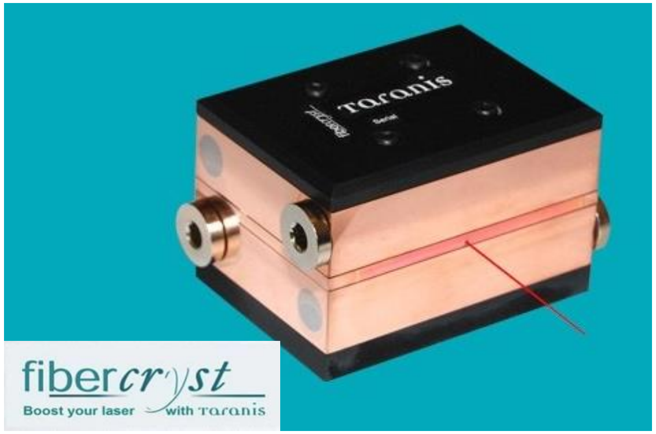
Single Crystal Fiber Amplifier (WP2) - CNRS

- WP2 Objectives:
  - High repetition rate (HRR) system: P_{out} = 70W (100W), Rep. rate: 20-40MHz, pulse duration: 1ps
  - Low repetition rate (LRR) system: P_{out} = 35W (70W) , Rep. rate: 0.2-1MHz, pulse duration: 5ps
- The concept of single crystal fibre amplifier (SCF) has been developed and patented by CNRS and FIBERCRYST



Concept of the Single Crystal Fiber (SCF)



Single Crystal Fiber (SCF) amplifier module

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Single Crystal Fiber Amplifier (WP2) - CNRS

- The goal was to use a SCF to directly amplify femtosecond pulses in a passive master oscillator power amplifier (MOPA) scheme to achieve high energy and high average power pulses with radial and azimuthal polarizations without any stretching and recompression of the pulses
  - I.e., without the use of chirped pulse amplification (CPA)
- The seed oscillator provides 360 fs pulses at a repetition rate of 20 MHz with an average power of 1.5 W and a spectral width of 3.45 nm FWHM centered at a wavelength of 1031 nm
- The SCF operates in double-pass configuration and is pumped by a high-brightness diode delivering 120 W of power at a wavelength of 940 nm through a fiber with a core diameter of 200 µm and a NA of 0.22
- The pump fiber output is imaged to a spot diameter of 400 µm a few mm inside the SCF which had a diameter of 1 mm
- After the oscillator being optically isolated, a half wave plate and a polarizer are used to control the incident signal power
- A dichroic mirror which is transmitting the pump beam (at 940 nm) is used to reflect the signal (at 1031 nm) into the SCF
- The double-pass of the beam is realized by a quarter-wave-plate placed after the SCF in order to obtain a 90° rotation of the polarization between the first and the second pass
- A polarizer separates the output from the input beam after the second pass

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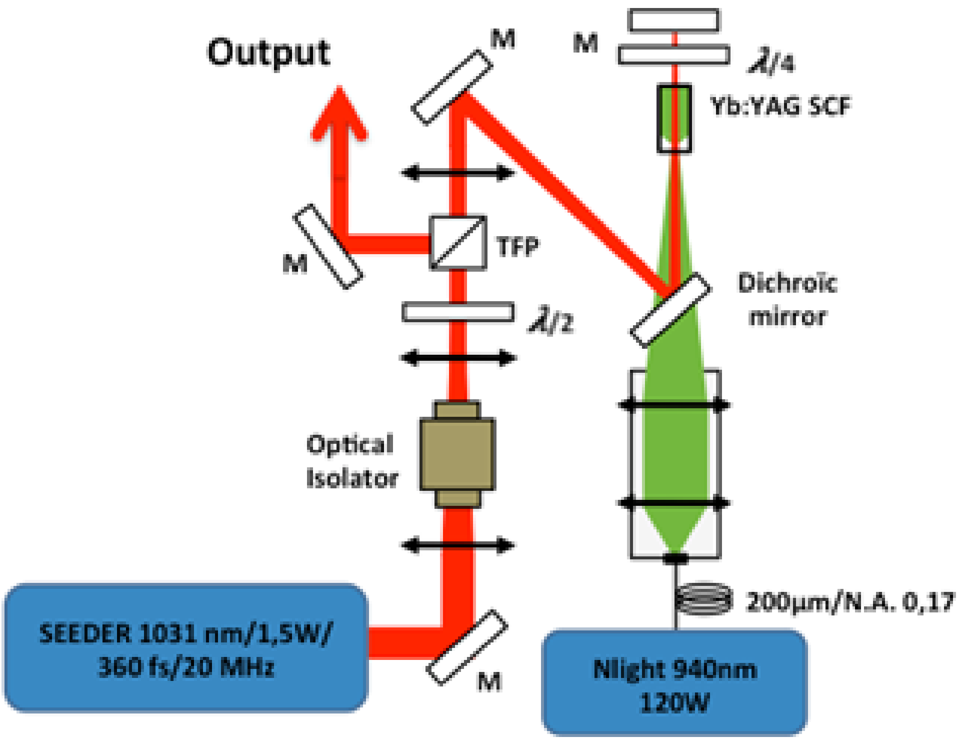
Single Crystal Fiber Amplifier (WP2) - CNRS



Configuration of the double-pass SCF preamplifier (TFP : Thin Film Polarizer)

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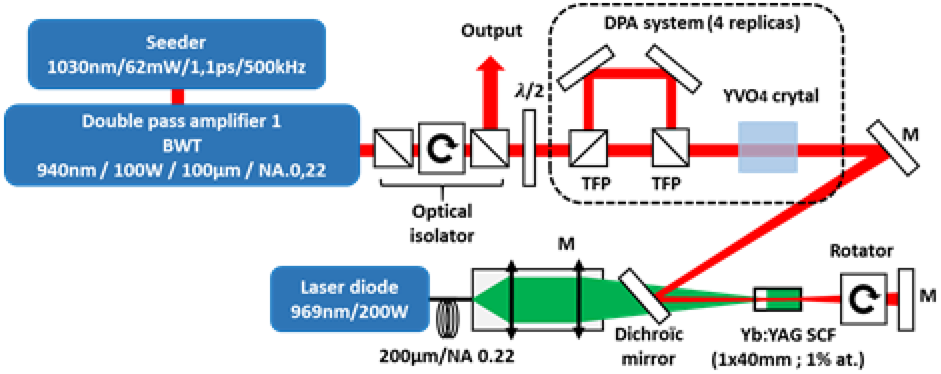
Single Crystal Fiber Amplifier (WP2) - CNRS

- The second SCF amplifier operates in double-pass configuration and uses Divided Pulse Amplification
- The SCF is pumped at 969 nm using a wavelength stabilized laser diode delivering 185 W
- To distribute the thermal load along the SCF and maintain the beam quality during amplification, the doping concentration is also reduced to 1%
- The input power seeded into the second amplifier stage is 4.7 W, corresponding to a peak power of around 1 MW (@ 500 kHz and 9 ps pulse)



Experimental setup of the second amplifier stage

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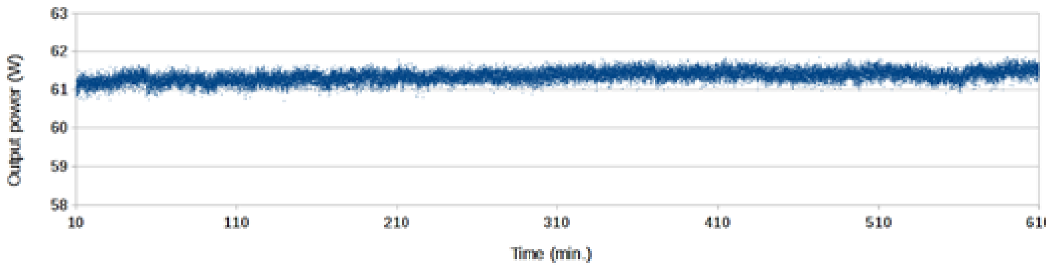
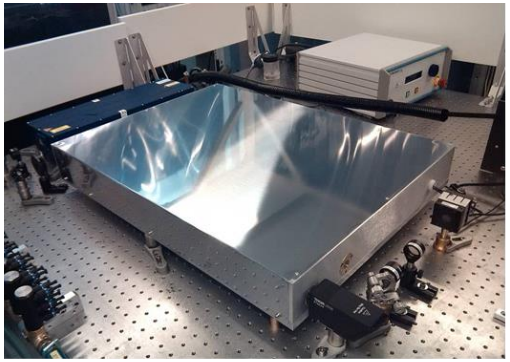
Single Crystal Fiber Amplifier (WP2) - CNRS

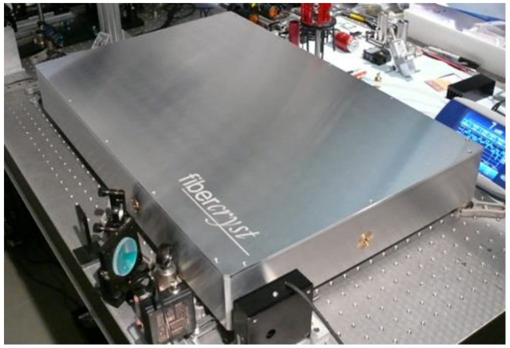
- The HRR integrated system contains three SCF amplification stages in a 740x550 mm footprint
  - The typical output power of the system is 60 W at 20 MHz, with pulses of 680 fs
  - The stability of the system output was measured to be as good as 0.2% RMS over 10 hours
  - Long-term measurement of output power of the HRR integrated amplifier:





Integrated version of the HRR SCF amplifier

- The LRR integrated system contains two SCF amplifiers and an integrated version of the DPA setup, in a 710x460 mm footprint.
  - In nominal operation the amplifier delivers an output power of 47 W at the repetition rate of 500 kHz, leading to a pulse energy of 94 µJ



Integrated version of the LRR SCF amplifier

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Thin-disk Multipass Amplifier (WP3) - USTUTT

- WP3 objectives:
  - High repetition rate (HRR) system: P_{out} = 500W, Rep. rate: 20-40MHz, pulse duration: 1ps
  - Low repetition rate (LRR) system: P_{out} = 200W, Rep. rate: 0.2-1MHz, pulse duration: 5ps
- The multipass amplifier uses a mirror array of 60 individually adjustable mirrors and is operated in a single pass configuration due to the cylindrical (radial/azimuthal) polarization
- A Yb:YAG thin-disk was mounted on a diamond heat sink and is used as amplifier medium
- The disk is pumped at 969 nm wavelength (with stabilized laser diode provided by DILAS) by a multi-pass cavity with 24 passes
- The pumped spot has a diameter of approximately 5 mm

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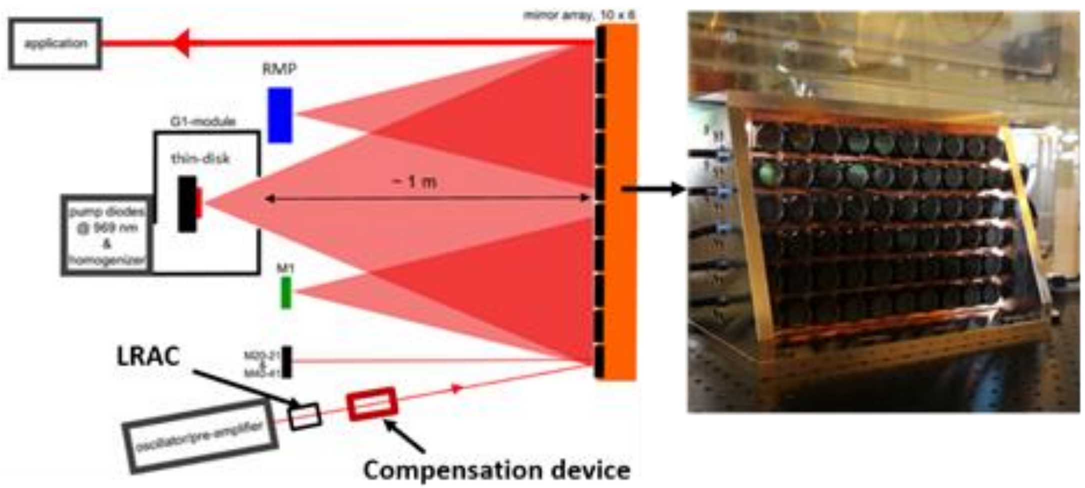
Thin-disk Multipass Amplifier (WP3) - USTUTT



Schematic representation of the thin-disk multipass amplifier (left). A Photograph of the mirror array (with 60-mirrors) is shown on the right side

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Thin-disk Multipass Amplifier (WP3) - USTUTT

- The main results obtained on the High Repetition Rate System are summarized below:

	Configuration 1 (20 MHz)		Configuration 2 (10 MHz, including AMOs)	
	Seed	**TD-MPA**	**Seed**	**TD-MPA**
Output Power (W)	75	580	40	416
Repetition rate (MHz)	20	20	10	10
Pulse duration (fs)	727	782	670	716
Pulse energy (µJ)	3,45	29	4	41,5
Beam qualitiy factor (M^2)	<1,3	<2,3	<1,3	2,3
Optical efficiency (%)	n.m.	48	n.m.	45
Polarization	Linear	radial/azimuthal	linear	radial/azimuthal
DOP (%)	n.m.	>95	n.m.	>95

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Thin-disk Multipass Amplifier (WP3) - USTUTT

- The design for the TD-multipass amplifier for the LRR-system is similar to the HRR
  - The LRR has a smaller pump spot diameter of around 4.7 mm
  - 3 different seed lasers were used for the demonstration of more than 200W of output power at a pulse energy approaching 1 mJ
  - The results are summarized in the following table:

	Configuration 1 (500kHz, ps pulses)		Configuration 2 (200 kHz, ps pulses)		Configuration 3 (200 kHz, fs pulses)	
	Seed	**TD-MPA**	**Seed**	**TD-MPA**	**Seed**	**TD-MPA**
Output Power (W)	44	265	36	210	40	235
Repetition rate (kHz)	500	500	200	200	200	200
Pulse duration (ps)	5,3	5,3	8,2	7,8	805	888
Pulse energy (µJ)	3,45	530	180	1050	200	1175
Beam qualitiy factor (M^2)	<1,3	<2,3	<1,3	<2,3	<1,3	<2,3
Optical efficiency (%)	n.m.	29	n.m.	30	n.m.	27
Polarization	Linear	radial/azimuthal	linear	radial/azimuthal	linear	radial/azimuthal
DOP (%)	n.m.	>95	n.m.	>95	n.m.	>95

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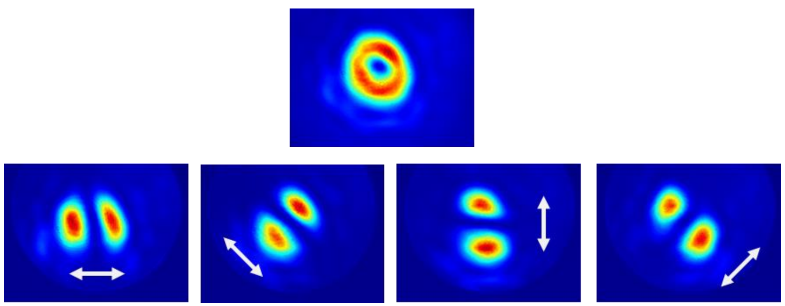
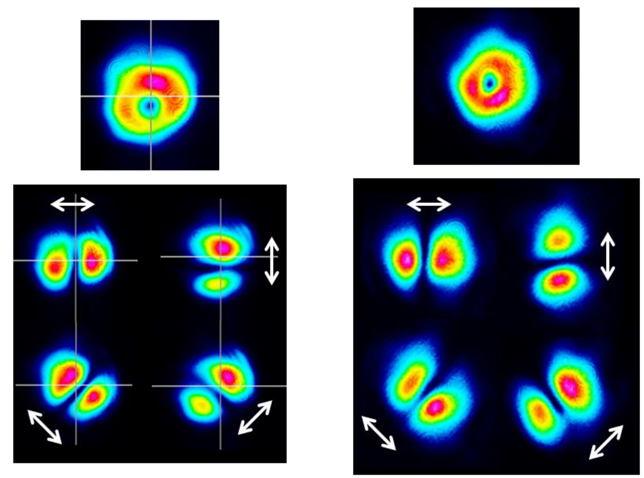
Thin-disk Multipass Amplifier (WP3) - USTUTT

➢ HRR system



Beam profile of converted seed beam (top) and its polarization analysis (bottom). The white arrows indicate the transmission axis of the polarizer

➢ LRR System



Output beam profile of the amplified beams (top) and their polarization analysis (bottom) at maximum output power for both configuration 1 (left) and 3 (right). The white arrows indicate the transmission axis of the linear polarizer

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Laser and Scanner Integration (WP4) - NSTBVBA

- WP4 objectives:
  - 200 mm polygon scanners with up to 300m/s scanning speed
  - Trepanning optics
- A polygon scanner with 170 mm scan line length, and focused spot size of 25 µm has been developed, and integrated in the GFH laser micro machining center
- Spot scan speeds can be set from 25 to 100 m/sec
- Using a 20 MHZ rep-rate laser the scanner can be operated at highest moving speed (100 m/s) at a 5 µm spot pitch
  - This is equivalent to an 80% spot overlap writing process
- Modulator concepts have been developed, and implemented in the 500W/20MHz rep-rate laser built in this project.
- Scanner and laser operation has been successfully demonstrated at 150W average laser

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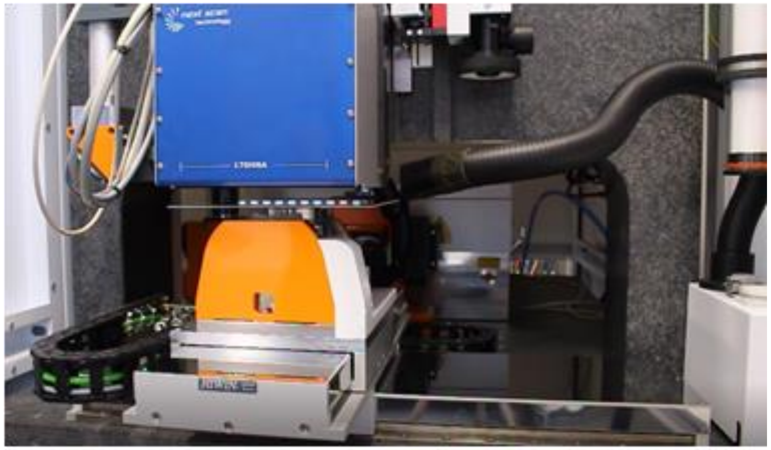
Laser and Scanner Integration (WP4) - NSTBVBA

- For the intended demonstrator in this project, 150W laser was sufficient
  - More testing is needed to verify operation and thermal stability of the scanner at higher average power
- The newly developed scanner will be commercially available from Q4/2017



LSE170HNA-RP integrated in GFH laser machining center

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Machine Setup, Laser and Optics Integration (WP5) - GFH

- WP5 objectives:
  - Set up of machining base; definition of interfaces and communication between the machine control and the developed units; integrate laser, optics and scanner in machining system for evaluation and proof of concept
  - Provision of demonstrator platform for the high repetition rate applications

Example of machined sample substrate

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Machine Setup, Laser and Optics Integration (WP5) - GFH

- The two lasers developed within this project have either a very high repetition rate of 20MHz with pulse energies above 25µJ or high pulse energies up to 1mJ with decent pulse repetition rates of 200kHz
  - In the first case, the pulse energy is sufficient for the single pulse ablation of thin films on flat substrates but the high repetition rate overstrains most galvo systems on the market
  - The high pulse energy in the second version of the laser will help to drill high precision spinneret holes or fuel injection holes in a very competitive drill time
- The task in this work package was to overcome the current shortcomings and utilize the developed laser systems in demonstration machines for defined applications
- The beam size out of the high repetition rate laser was expanded by a 2x beam expander telescope to reach the defined 11mm scanner input beam diameter necessary for the desired focal spot of 25µm diameter with a radially or azimuthally polarized beam being focused by a focal length optic of 170mm in the polygon scanner.
- The control of the bitmap machining is mastered by the polygon controller from Nextscan. In order to scribe 2D-patterns, a CNC axis needs to transport the substrate synchronized to the scan speed and desired line distance. In order to achieve this, the Y axis was used and the CNC control extended to allow the NST controller to trigger the transport

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Machine Setup, Laser and Optics Integration (WP5) - GFH

- The GUI of the machining system was also upgraded with an interface handling the communication with the polygon scanner and laser
- An Ethernet communication with TCP/IP protocol is used for the bitmap transfer and a USB interface with a serial line protocol is used for status display
  - The bitmap size is in this setup limited to 4MB
- The developed HRR laser can emit more than 500W with up to 20MHz pulses
  - In order to allow the modulation of the pulses by the polygon head, the application trials are done at 10MHz
  - The laser was operated at a defined power level of 320W
  - On 100nm Pt, with 4.2µJ the following spot sizes were achieved:

Polarisation	Spot size achieved
Linear	22.8µm
Radial	31.9µm
Azimuthal	32.5µm

  - The scan speed of 100mm/s results in 3.75mm/s axial feed rate. The ablation rate could be considerably increased to > 600mm²/s.

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Machine Setup, Laser and Optics Integration (WP5) - GFH

- The tests have verified that the necessary system functions for the HRR applications are in operation:
  - The beam modulation concept works.
  - The system sustains the power levels so far tested, and the beam stability is sufficient for the application trials.
  - The transport axis´ movement is synchronous to the polygon operation.
  - The optical resolution and the pulse energy achieved is sufficient for the application.
  - A planar ablation rate exceeding 600mm^2 / s can be achieved with such a high repetition rate system using a high speed polygon scanner.

HRR laser layout on optical table next to machining system

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Application Development (WP6) – C4L

- WP6 objectives:
  - To develop the laser processes for 2 applications, related to the 2 lasers that have been developed within Razipol:
    - High repetition rate, low energy
    - High energy, low repetition rate
  - Perform benchmark process development on existing laser sources (5, 25 and 50W)
  - Define the required specifications of the news lasers as precisely as possible as well as the optic path specification in relation with the different polarization to evaluate: circular, radial, azimuthal.
  - To validate the polarization effect to the process efficiency of the different application fields and the optimization of the process

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Application Development (WP6) – C4L

- Main results HRR System
  - The optimized process parameters resulted in good structure qualities with high ablation rates

Polarisation	Radial
Rep Rate	10.5 MHz
Pulse energy on workpiece	4.2 µJ
Scanning speed	100 m/s
Scan resolution	9 µm
Focus diameter	32 µm
Spot overlap	72%
Ablation rate	≈ 630 mm^2/s

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Application Development (WP6) – C4L

- Main results LRR system
- The following limitations are still under investigation:
  - Polarisation state after the drilling optic to compare the polarization states on a more reliable base
  - Drilling with cleaned beam (diaphragm) for a perfectly circular beam for all polarization states in order to get smaller holes
- The laser shows its ability to run steadily and provide reliable result at high power (up to 195 W)
- Due to the specificity of the drilling optic, only 120W could be brought to the work piece, due to losses within the optic
  - Nevertheless the upscale ability could be demonstrated

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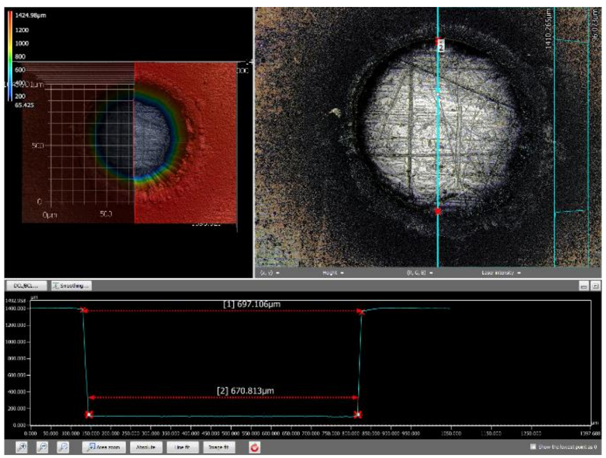
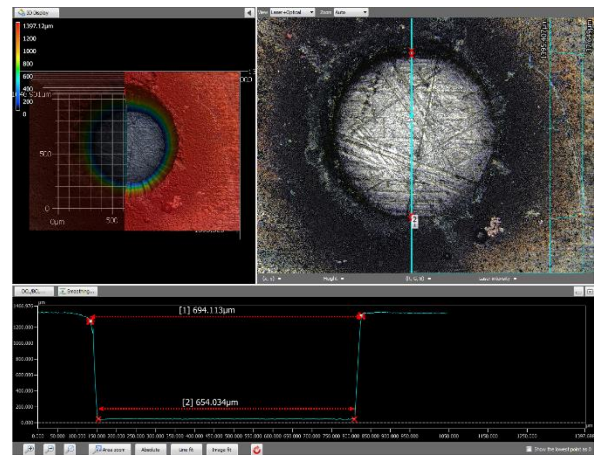
Application Development (WP6) – C4L

- Drilling diameters @117W and 160W



Azimutal: 0.68mm – 0.66mm (entrance – exit)



Radial: 0.7mm – 0.67mm

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Demonstration (WP7) – SLV

- WP7 objectives:
  - Deployment of developed process know-how from WP5 and WP6 in the manufacturing of final application samples for surface structuring using optimized process parameters and integrated laser and scanner system (HRR, low pulse energy)

Figure 1: HRR laser system (left) and GFH machine (right)

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Demonstration (WP7) – SLV

- After preliminary testing process development and optimization for patterning thin metallic layers (lab-on-a-chip) were performed using different types of metallic coatings on 6” wafers
  - results showed a high efficiency of the RAZipol technology compared to conventional methods as well as the benchmark application
  - Compared to the benchmark application, a **78 times faster** structuring process was achieved at high patterning qualities, which resulted in a significant reduction of the process costs

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Demonstration (WP7) – SLV

- There were **nearly no power losses measured by using the radial/azimuthal polarization converter**
  - However, a polygon scanner based power loss of about 36 % was measured.

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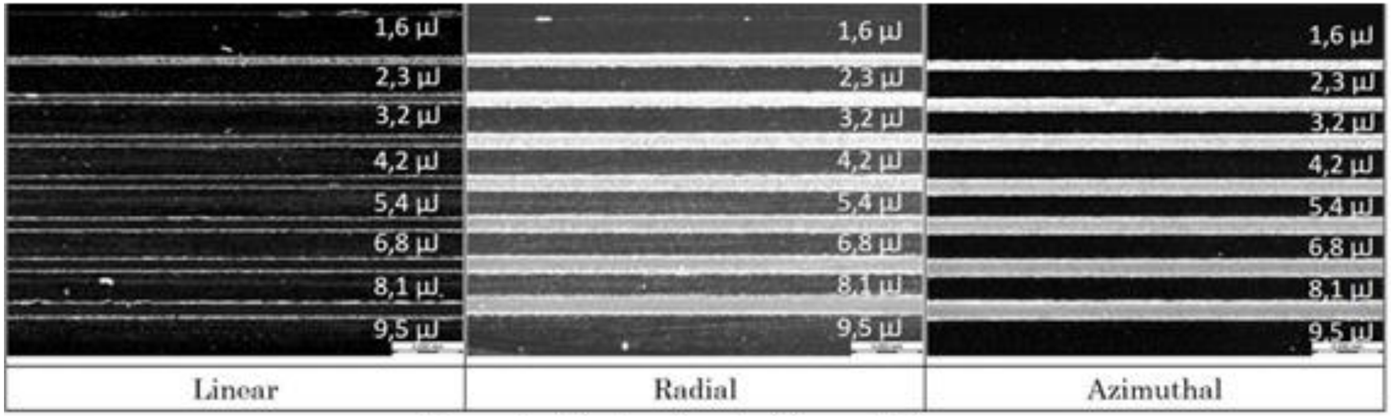
Demonstration (WP7) – SLV

- Material-specific ablation thresholds were determined by increasing the pulse energy by the help of the λ/2-waveplate stepwise
  - For these tests, single lines with a scan resolution of 9 µm were used. Furthermore, the influence of the polarization type was investigated



Ablation thresholds on platinum

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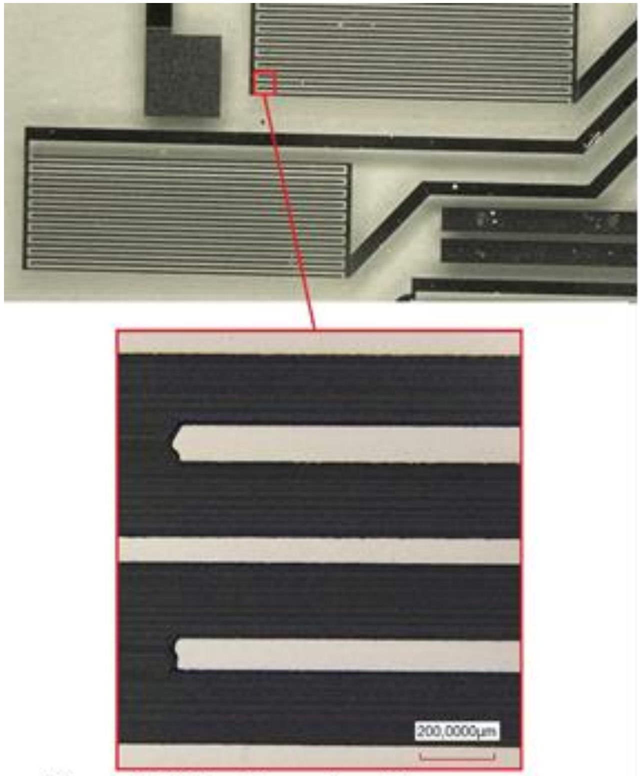
Demonstration (WP7) – SLV

- Following process optimisation, the patterning results show a good quality with sharp edges and without damage to the glass carrier material at a high ablation rate of about 378 cm^2 per second
- The image to the right shows the patterning results of a LOC glass wafer section, which was platinum coated with layer a thickness of about 100 nm



HRR patterned resistance sensor on platinum LOC

The Ultrafast_RAZipol project has received funding from the European Community's Seventh Framework Programme under Grant Agreement No. 619237

Demonstration (WP7) – SLV

- Patterning large wafers with the HRR system using radial or azimuthal polarization enabled a 78 times faster processing time, compared to the benchmark application
- A 50 % higher ablation rate was achieved using radial or azimuthal instead of linear polarization
- With a typical area per chip of 16 mm^2, per hour about 18 chips can be produced with the benchmark laser, while about 1400 chips per hour can be theoretically produced with the RAZipol HRR system
  - Taking into account, that several positioning steps have to be done during the processing, a realistic value of 600 chips per hour can be estimated
- Especially for prototype manufacturing, the HRR system offers significant benefits

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