WP 2 Process Development

Christian Freitag, University of Stuttgart

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 687880

Work Package 2

Partners involved:

BOSCH
lasea – LASER ENGINEERING APPLICATIONS
CLASS4LASER – See the light
elementsix – a De Beers Group Company
IFSW

- HIPERDIAS application areas:
  - 3D Silicon processing
  - Fine cutting of metals
  - Diamond ablation

- Agenda:
  - Task 2.1: Fundamentals Si Processing - Update from Bosch
  - Task 2.2: Fundamentals Fine Cutting of Metals - Update from C4L
  - Task 2.3: Fundamentals Diamond Ablation – Update from E6
  - Task 2.4: Upscaling – Update from USTUTT

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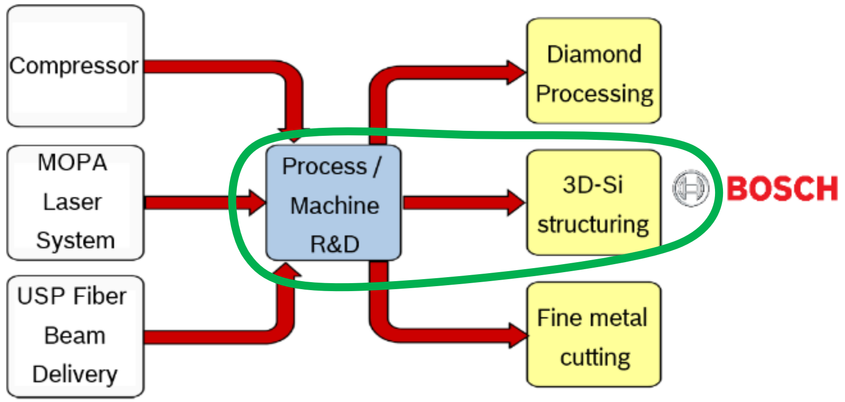
HIPERDIAS – BOSCH Objectives

- Overall: physical root-cause analysis ultrashort pulse laser ablation of Si
- WP1: Define characteristic requirements (KPIs)
- WP2.1:
  Test structure and process evaluation on medium-power systems (≅ 50 W)
- Process optimization & parameter robustness
  incl.: target specifications HIPERDIAS high-power system
  (Integration meeting in 05/17 w/ Amplitude, LASEA, USTUTT)
- **WP2.4, WP7:** Support process upscaling: Start as soon as IFSW 500 W laser system available



WP	H1/16	H2/16	H1/17	H2/17	H1/18	H2/18
WP1	Definition and evaluation of KPIs					
WP2.1		Fundamental Process Development & Definition of System Specifications (medium-power lasers up to ≅ 50 W)				
WP2.4, WP7					Support upscaling to 1 kW system	

completed — completed — to start asap

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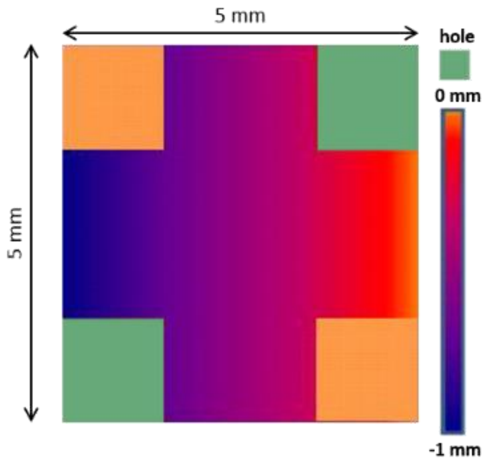
WP 2.1 – BOSCH Key Performance Indicators

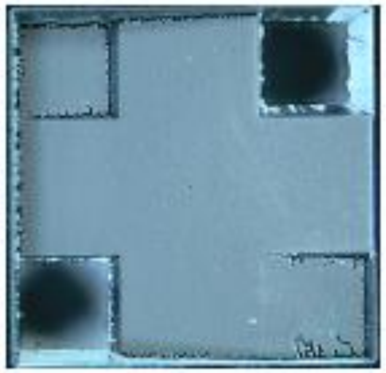
Test structure

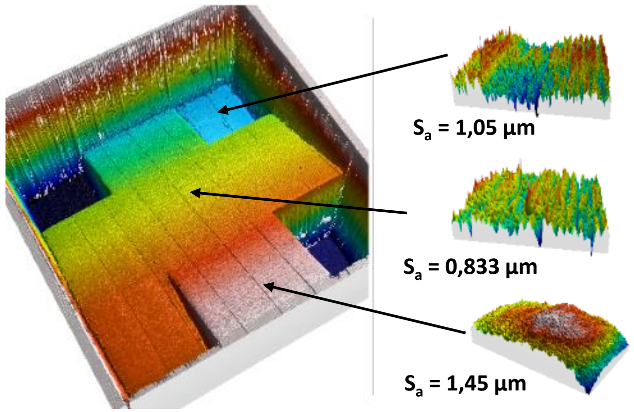
- Features typical of potential applications:
- Ablated volume: 12 mm³
- Chamfer
- Steep walls
- Tight radius



KPI evaluation

Type	Unit	Target	Current Status
Average ablation rate	mm³/s	≥1	0.05
Peak ablation rate	mm³/s	≥3	0.1
Average ablation rate (specific)	mm³/kJ	≥1	3.1
Peak ablation rate (specific)	mm³/kJ	≥3	5.5
Shape deviation	µm	≤10	<10
Average surface roughness Ra	µm	≤1	<0.5
Surface damage thickness	µm	≤1	<1
Surface defects > 1 µm	1/mm²	none	None
Min. edge radius	µm	≤ 200	60
Max. edge-steepness	degree	≥ 70	80





- Results achieved: All KPIs w/i specifications, except for absolute ablation rate
- Critical: trade-off between surface quality (roughness) and productivity (ablation rate)
- **Productivity/quality trade-off managed by using burst mode**

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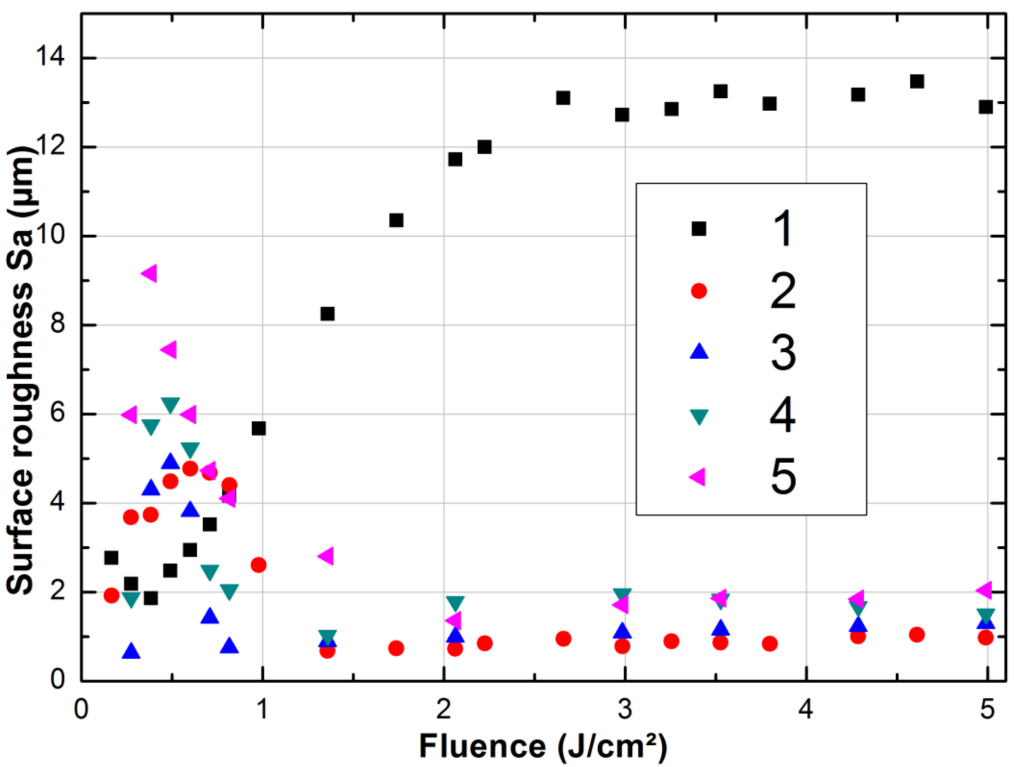
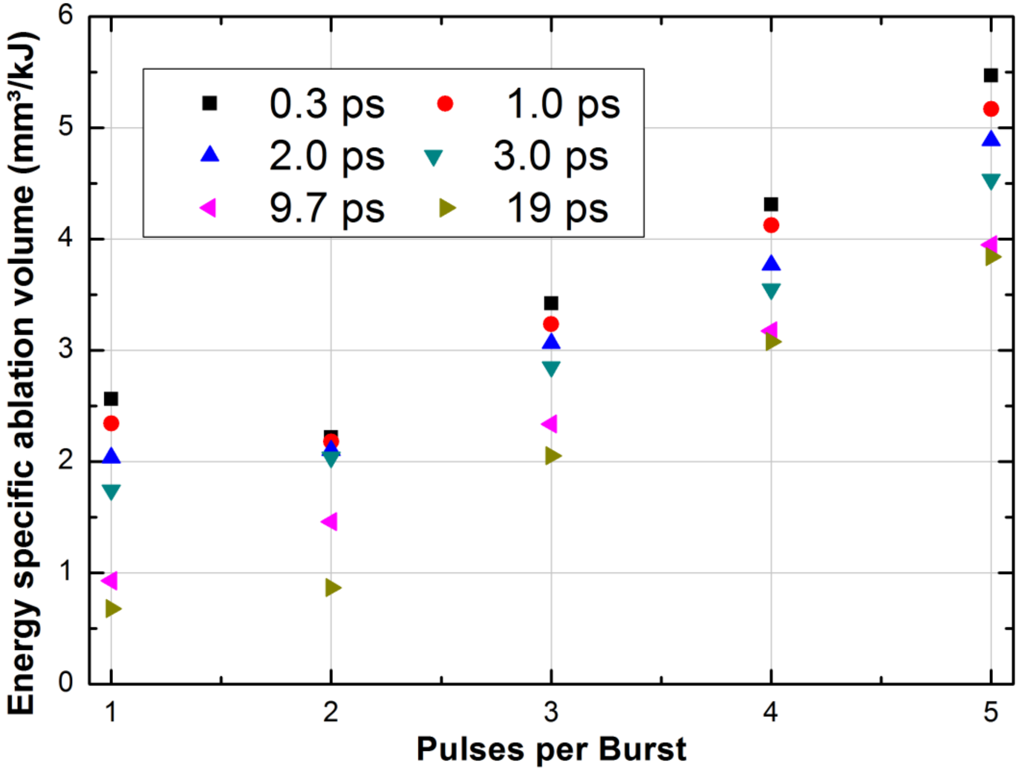
WP 2.1 –Ablation in Burst Mode





„Sweet spot“ identified w/ 5-pulse bursts, 0.3 ps pulse duration and 2 J/cm² fluence

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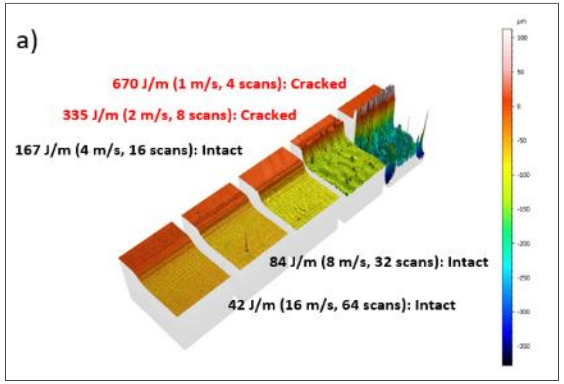
WP 2.1 – Summary

Single-pulse vs. burst-mode ablation

	single-pulse	2-pulse burst	5-pulse burst
pulse duration to access regime II	> 3 ps	0.3 ps (or less)	0.3 ps (or less)
roughness Ra	≫ 1µm (0.3ps)	1 µm	1 µm
ablation rate	2.5 mm³/kJ	2 mm³/kJ	5.5 mm³/kJ

Outlook: Upscaling to 500 W (1000 W)

- 1st trials w/ 670 W source at USTUTT (2016)
- High scan speed required
- Wafer failure if heat removal insufficient



- System specs defined on integration planning meeting (05/17 at USTUTT)
- Upscaling to start @ USTUTT as soon as laser system available → important challenge:
  Adapt scanning strategy and heat removal to avoid surface deterioration and catastrophic heat accumulation

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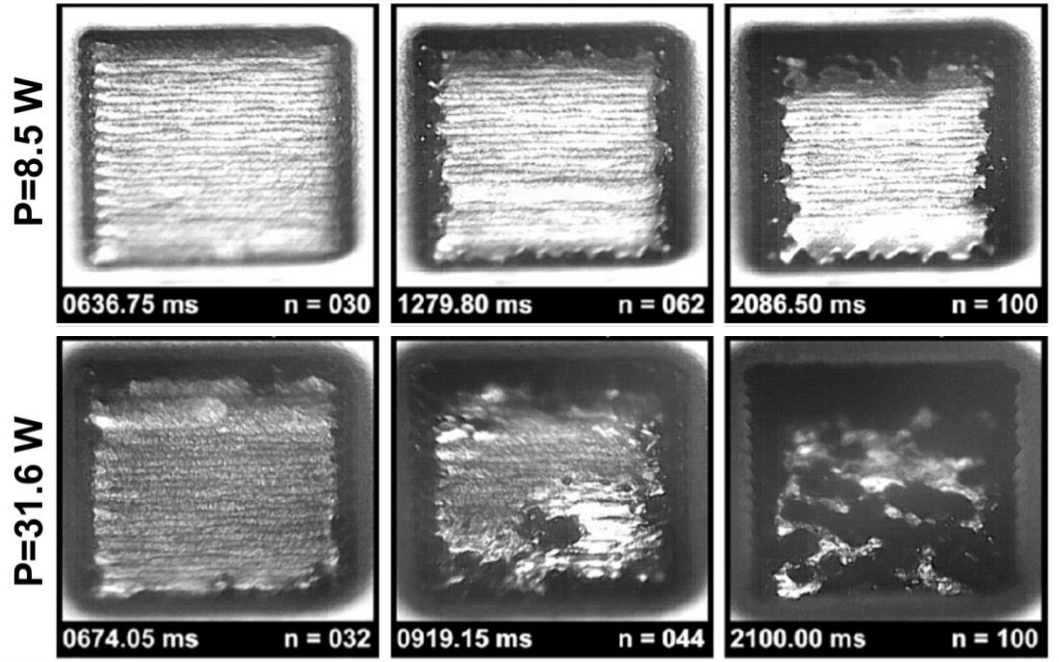
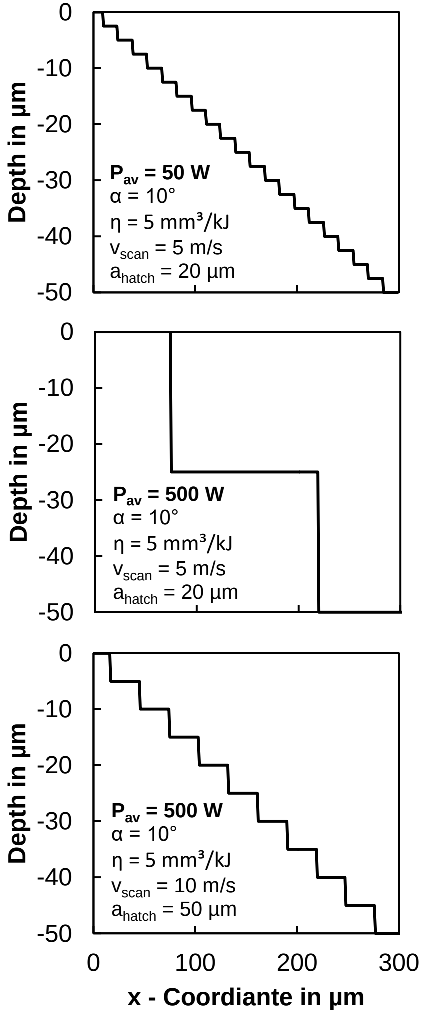
WP 2.4 – Outlook: Challenges



[D. Brinkmeier, Master's thesis]

+ Challenge: Does **higher ablation depth per overscan** interfere with precision requirements?

Geometric impact of parameters on chamfer morphology (example)



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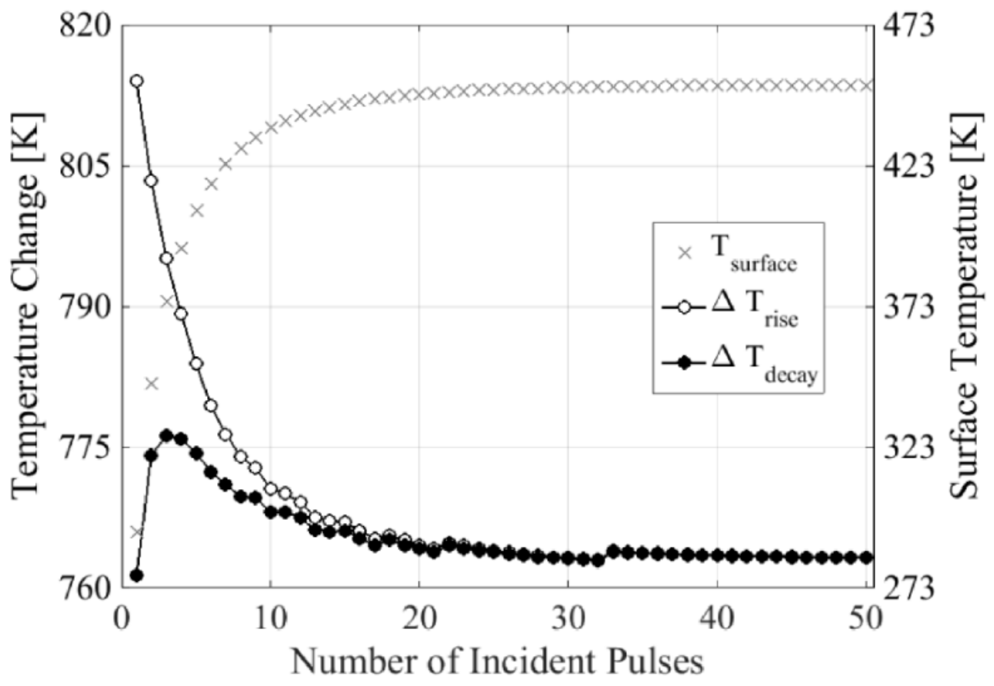
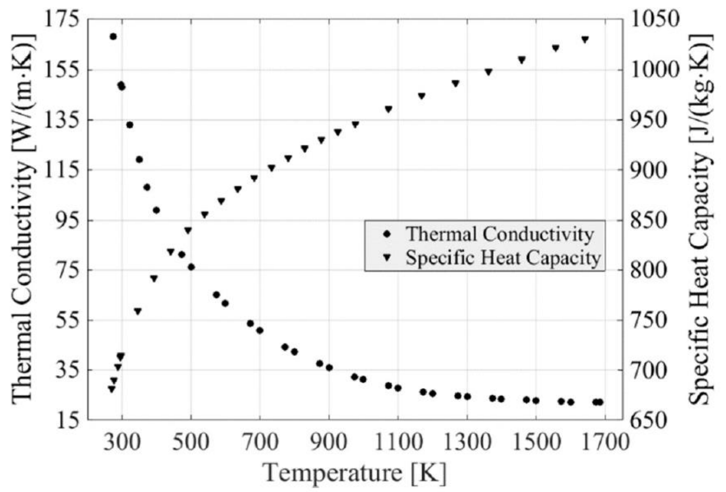
WP 2.4 – Outlook: Challenge: Heat Accumulation

Surface temperature change of wafer due to incident laser pulses

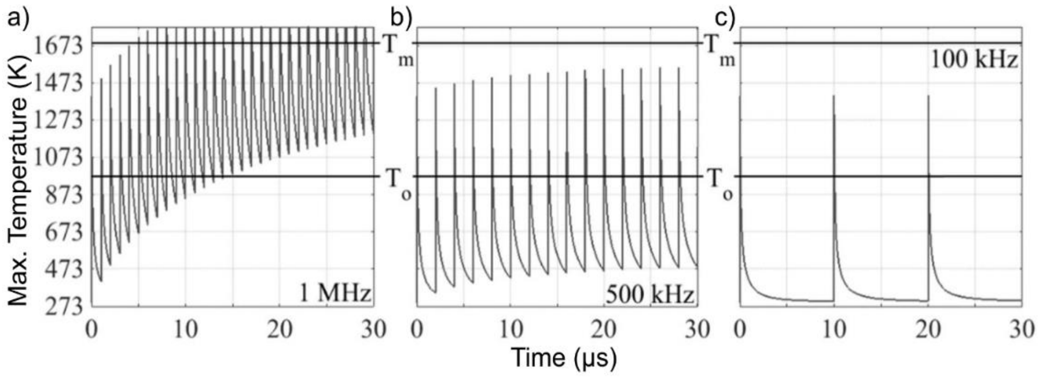


Taylor, L. L., *et al. Optical Materials Express* **6**:2745

Si material constants as a function of temperature



Evolution of wafer surface temperature during Si ablation at different repetition rates



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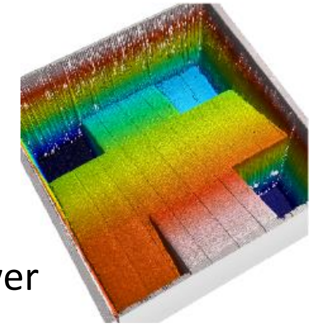
Bosch Contribution – Current Status

Milestone M2.1 (M24): **done**



"High quality 3D Si processing with low average power"

- KPIs achieved w/ low average power
- Optimum parameter set communicated to laser and system development partners

Deliverable D2.1 (M24): **done**

- *„Process limits 3D Si processing"*

Deliverable D2.4 (M30):

- Upscaling Si ablation
- Work to be started asap

HIPERDIAS

Deliverable 2.1: Process limits 3D Si processing

Dissemination Level: Confidential (CO)

Owner

Name:	Martin Lustfeld
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Context

Author(s):	M. Lustfeld, G. Kunz, M. Ametowobla (Bosch); J.A. Ramos de Campos, D. Bruneel (LASEA)
Work Package:	WP2
Task:	Task 2.1: Fundamental process development 3D Si processing

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Work Package 2

Partners involved:

BOSCH
lasea LASER ENGINEERING APPLICATIONS
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- HIPERDIAS application areas:
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Description of Work

- **Task 2.2** *Fundamental process development fine cutting of metals* (C4L;USTUTT)
  - Understand process parameters, low power system.
  - Serves as input for upscaling
  - **Completed**. Deliverable 2.2 – M24 *(01.2018)*
- **Task 2.3** *Fundamental process development diamond ablation* (E6; C4L)
  - Support role for E6, facilitate experimentation.
  - **Completed**. Deliverable 2.3 – M24 *(01.2018)*
- **Task 2.4** *Upscaling of applications for high throughput* (USTUTT; C4L,BOSCH,LASEA)
  - Achieve KPI's
  - **Incomplete.** Deliverable 2.5 – M30, Deliverable 2.6 – M30 *(07.2018)*

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WP 2 – Deliverables

Deliverable	Tille	Due Date	Status	Update
D2.1	**D2.1** Process limits 3D Si processing	M24 (01.2018)	✓	
D2.2	**D2.2** Process limits fine cutting of metal	M24 (01.2018	✓	
D2.3	**D2.3** Process limits diamond processing	M24 (01.2018	✓	
D2.4	**D2.4** Processing strategies for high power 3D Si processing	M30 (07.2018)		
D2.5	**D2.5** Processing strategies for high power fine cutting of metal	M30 (07.2018)	✗	M36 (01.2019)
D2.6	**D2.6** Processing strategies for high power diamond processing	M30 (07.2018)	✗	M36 (01.2019

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Deliverable 2.2 – Set up

Laser Source: Carbide (Light Conversion)

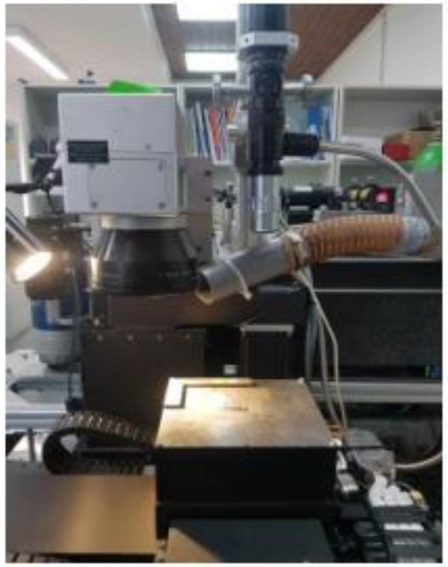
Wavelength	1030nm
Average power	5 W
Max. pulse energy	83 µJ
Max. frequency	1 MHz
Pulse duration	230 fs to 20 ps

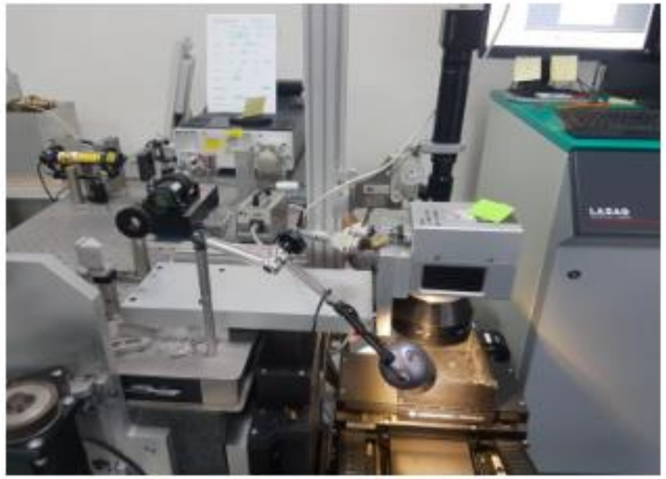
Beam deflection : Scancube III 14 (Scanlab)

Operation	Galvonometer
Marking speed	2500 mm.s^{-1}
Scan field	70mm^2 (100mm telecentric)

Axis : PRO165LM (Aerotech)

Axis	X,Y,Z
Repeatability	< 1µm
Accuracy	**2 µm**
Max speed	2000 mm.s^{-1}





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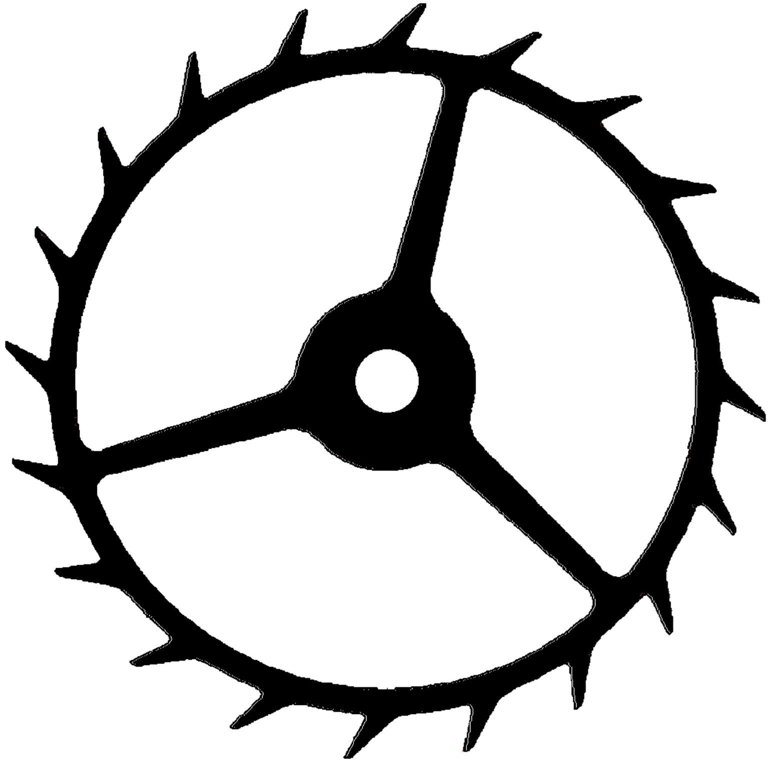
Deliverable 2.2 – Material

Brass : MS63 (Allmeson GmbH)

Cu:Zn	63:37
Thickness	0.2 mm
Geometry	Variable
Density	8.5g.cm^{-3}
Melting Point	920˚C

Steel : 1.4310 (Deutsche Edelstahlwerke)

Contents	Fe, Cr, Ni, Mn, Mo, N, C, P, S, Si
Thickness	0.2 mm
Density	7.9 g.cm^{-3}
Melting Point	1420 ˚C
Geometry	Variable
Characteristics	Good mechanical, high tensile s trength suitable



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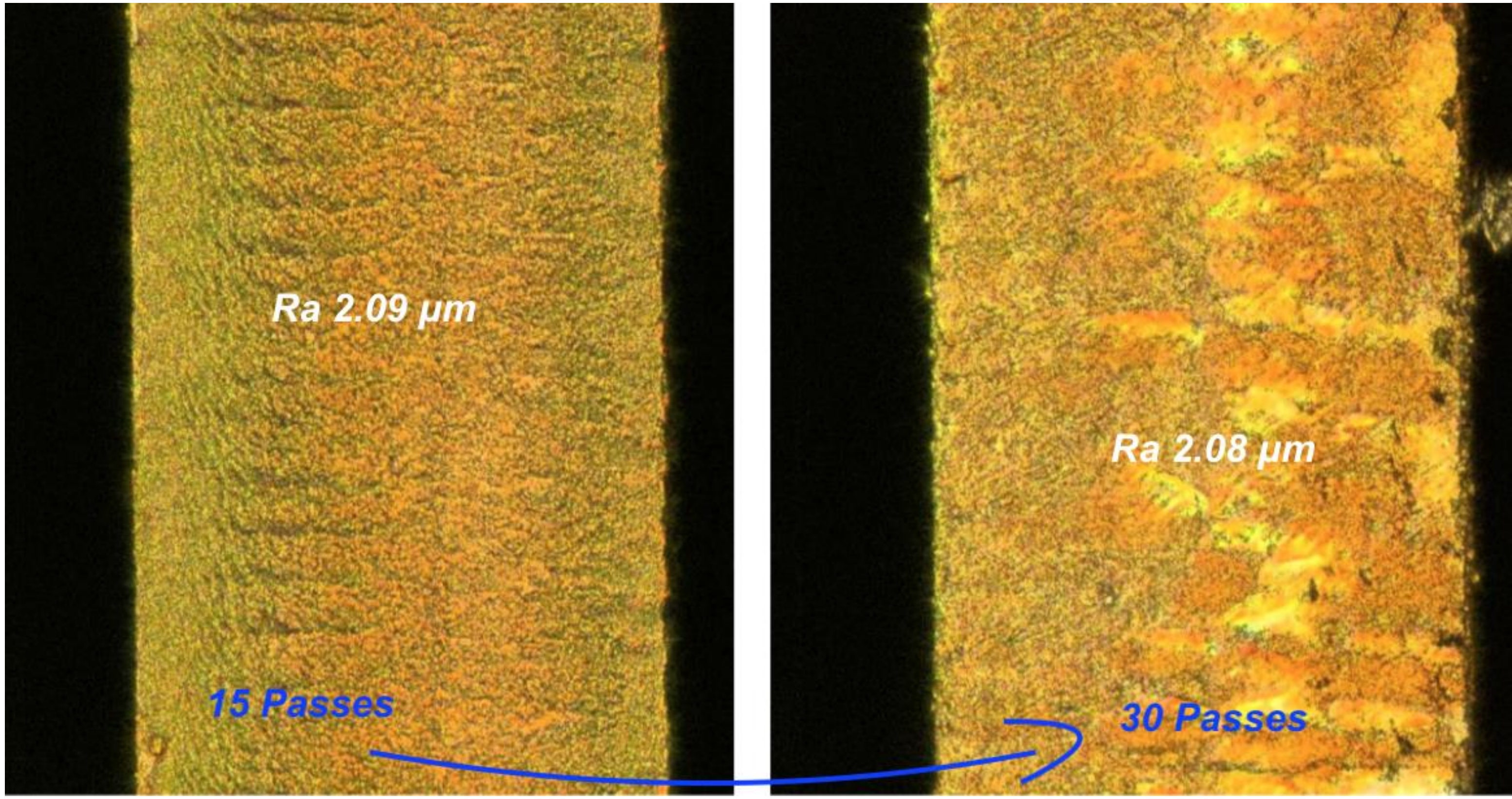
Deliverable 2.2 – Conclusions



- Visual inspection must be used, equal consideration.
- Recalibration for 120W system trials

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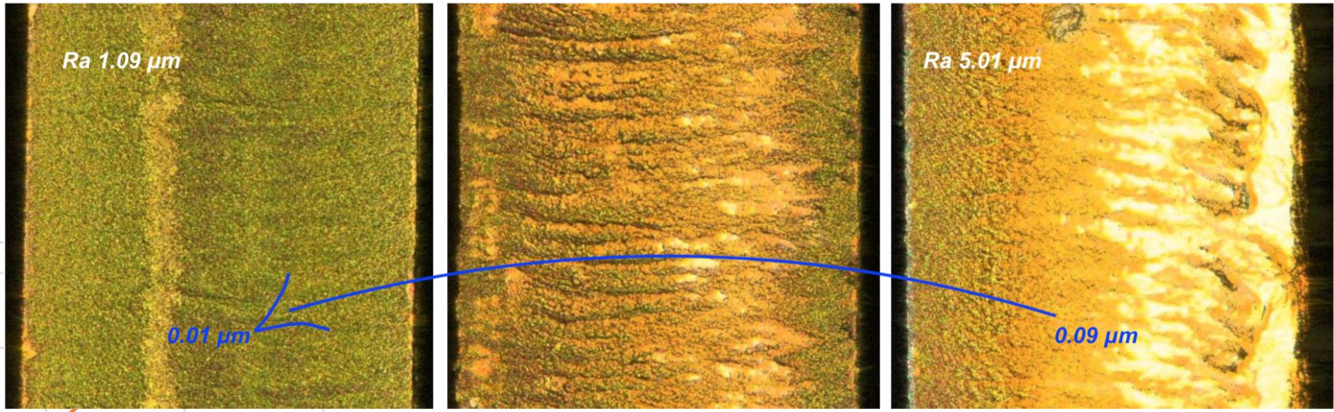
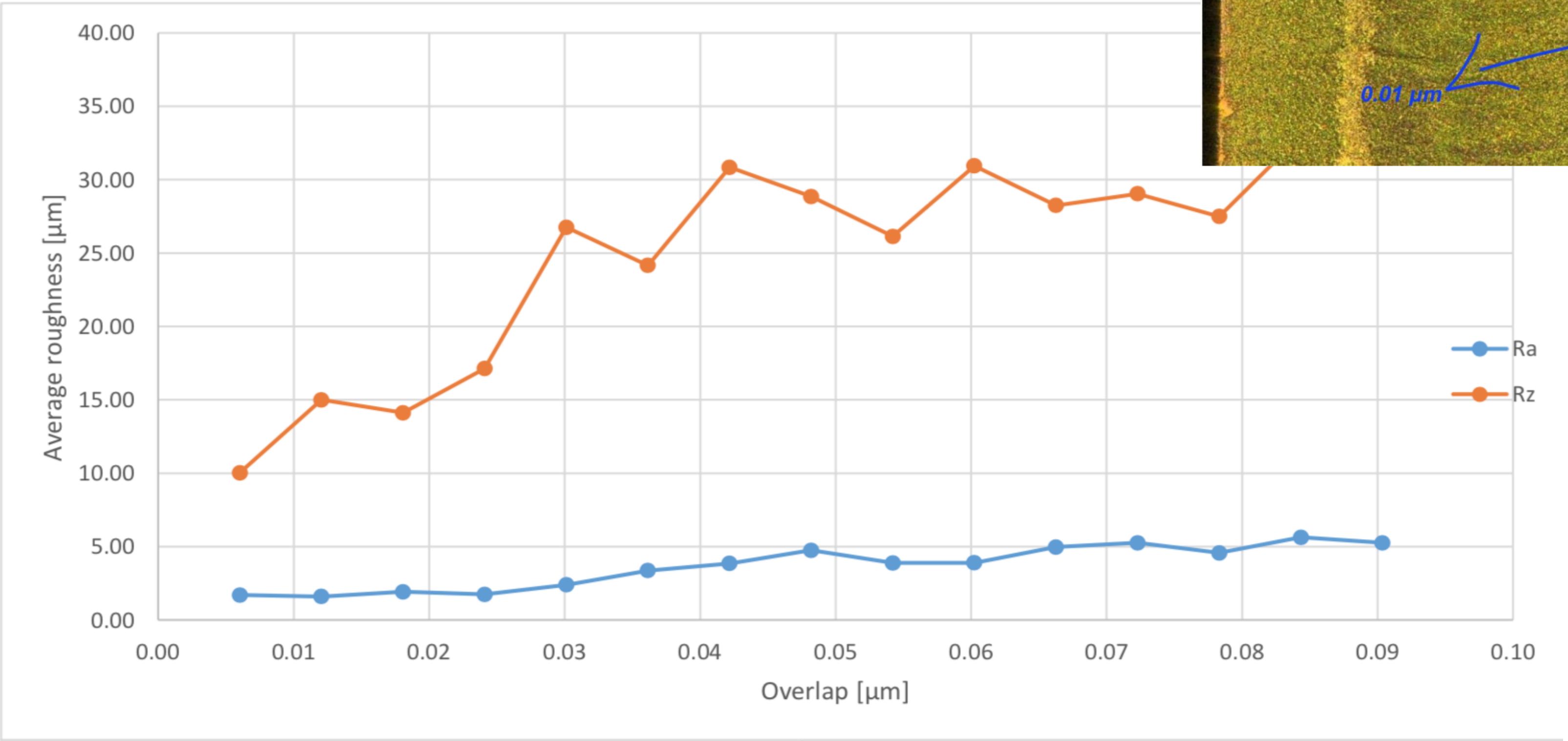
Deliverable 2.2 – Conclusions





- Overlap minimized
- Slow speeds 6 – 90 mm.min^{-1}
- 30.12 µJ, 166kHz

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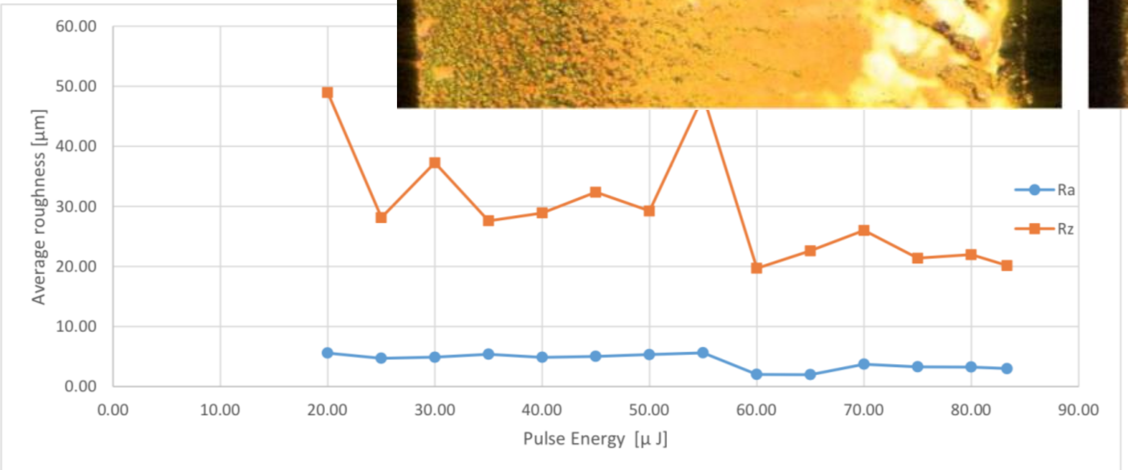
Deliverable 2.2 – Conclusions



- More pulse energy
- 37.5 mm/min
- 0.09 µm Overlap

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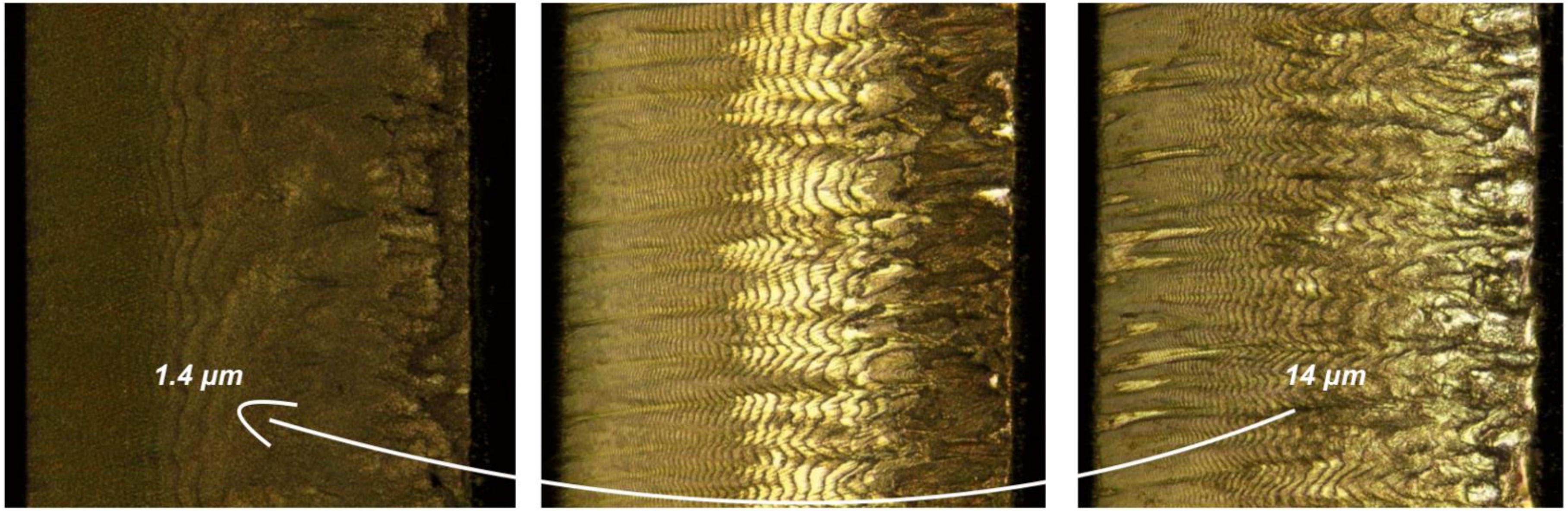
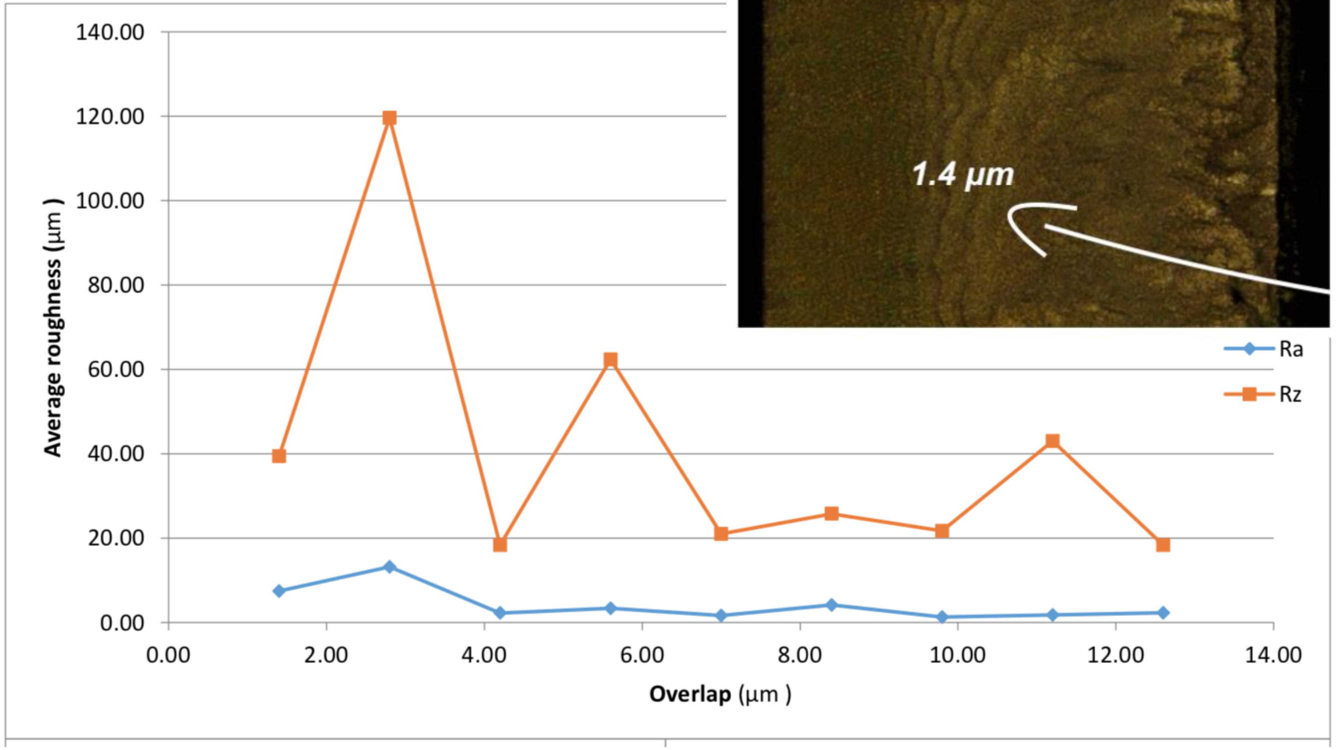
Deliverable 2.2 – Conclusions





- 70 μJ
- 400fs
- 71 kHz
- 33 mm.min^{-1}

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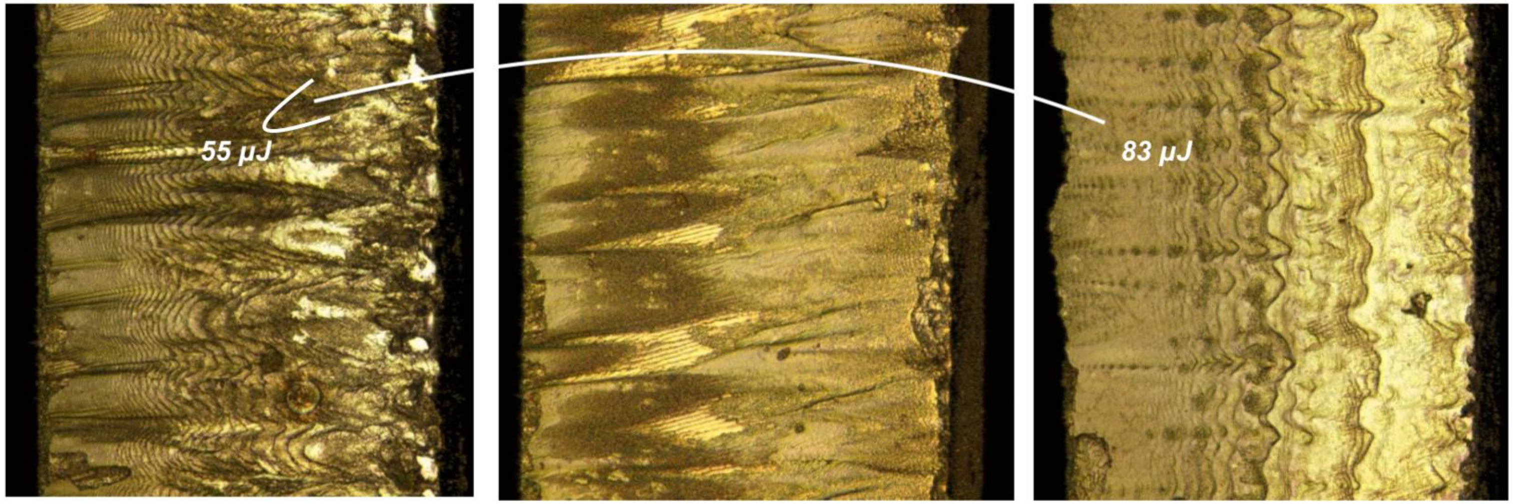
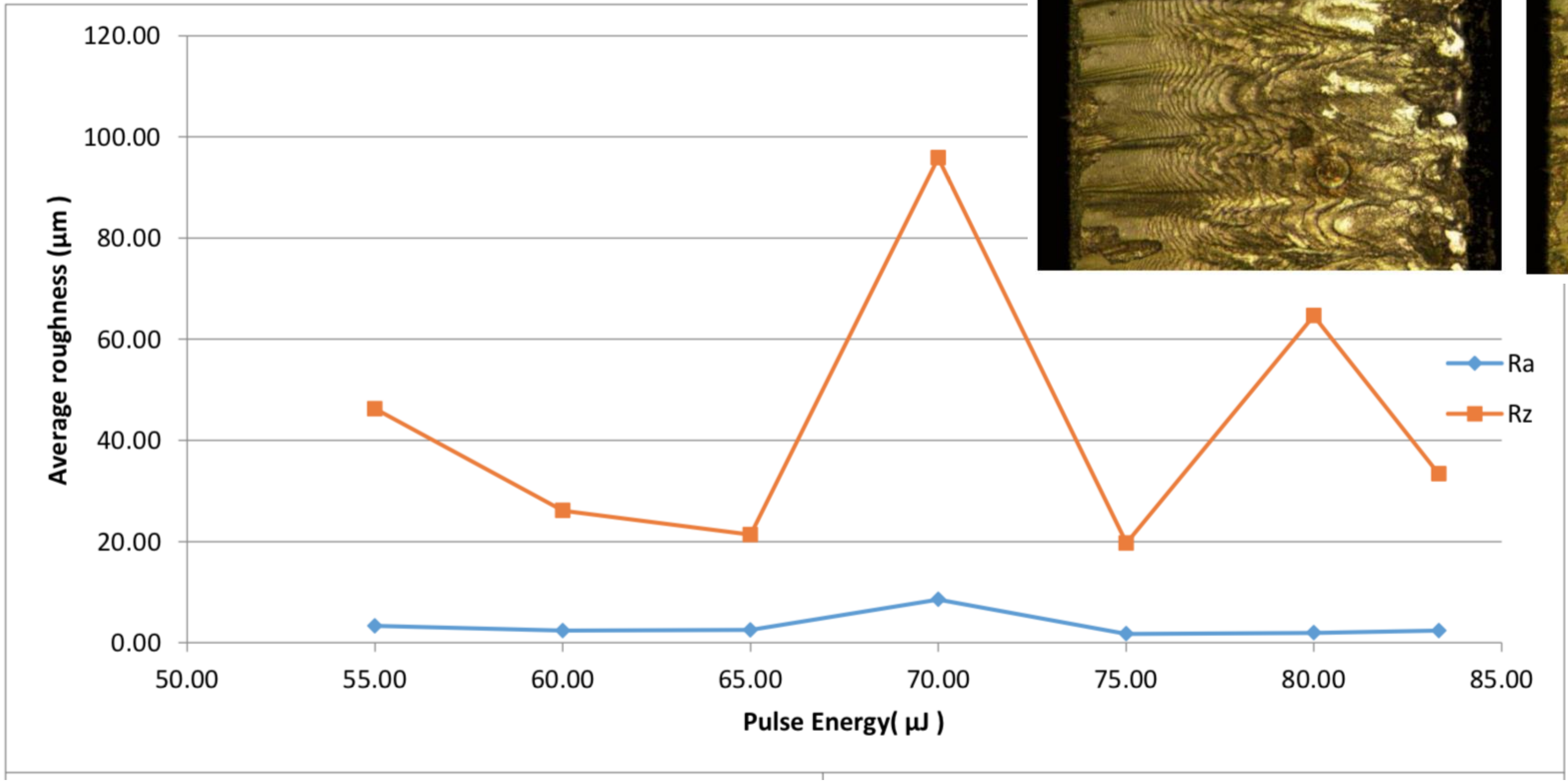
Deliverable 2.2 – Conclusions





- 400 fs
- 60 kHz
- 8.33 µm Overlap
- 23 - 43 mm.min^{-1}

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WP 2 Plan of experimentation

2 Step process

2 Months – Primary processing (fundamental process development)

3 Months – Applied processing

1 Month – Buffer

No.	KPI	Values	Validation status
1	**Cutting speed**	Expected : ≥ 400 mm/min	
		Validated : ≥ 300 mm /min	
		Not validated : < 300 mm/min	
2	**Post Processing/Cleaning**	Expected : Washing	
		Validated : Vibratory grinding (electro-polishing for some parts only)	
		Not validated : Additional work/cost	
3	**Production Cost** *In €, for 1 watch arm 0.15mm thick – 20mm long – batch of 1000*	Expected : ≤ 0.4	
		Validated : ≤ 0.45	
		Non validated : > 0.45	
4	**Surface roughness (functional/non-functional)**	Validated : ≥ 300 mm /min	
		Not validated : < 300 mm/min	
		Not validated : R_a ≥ 1 µm	
5	**Shape deviation**	Expected : < ± 2 µm	
		Validated : < ± 5 µm	
		Not validated : > ± 5 µm	
6	**Taper**	Expected : 0°	
		Validated : Within dimension tolerances	
		Not validated : Above dimension tolerances	
7	**Colouration**	Expected : None	
		Validated : Washable surface oxidation	
		Not validated : Persistent surface oxidation	
8	**Untying of part**	Expected : Fall down in US-bath	
		Validated : Fall down in US-bath with separation cut	
		Not validated : Mechanical removal	

Fundamental

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WP 2 *Process development*

Task	M23	M24	M25	M26	M27	M28	M29	M30	M31	M32	M33	M34
Fundamental developmetn (5W)		**D2.2**										
Laser arrival						***May (Mid)***		**July (Mid)**				
Upscaled applications												
Fundamental processing (120W)										**Sep (Mid)**		
Applied Processing (120W)										**Sep (Mid)**		**→ Jan (Mid)**
4 beam path processing								**July (Late)**				

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Partners involved:

BOSCH

lasea
LASER ENGINEERING APPLICATIONS

CLASS4LASER
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Task 2.3: Fundamental process development diamond ablation

- Status
  - T2.3 — Complete ✔
  - D2.3 confidential version — Document complete ✔
  - D2.3 public version — Awaiting for approval from engineering manager ✔

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Task 2.3: Fundamental process development diamond ablation

- Experimental set up
  - Three Element Six PCD grades tested

PCD Grade Name	Average Grain Size (µm)	Diamond Content (wt %)	Cobalt Content (wt%)
CMX850	1	80	20
CTB010	12	90	10
CTM025	30	90	10

  - Grades presenting highest variation in diamond grain size and diamond content

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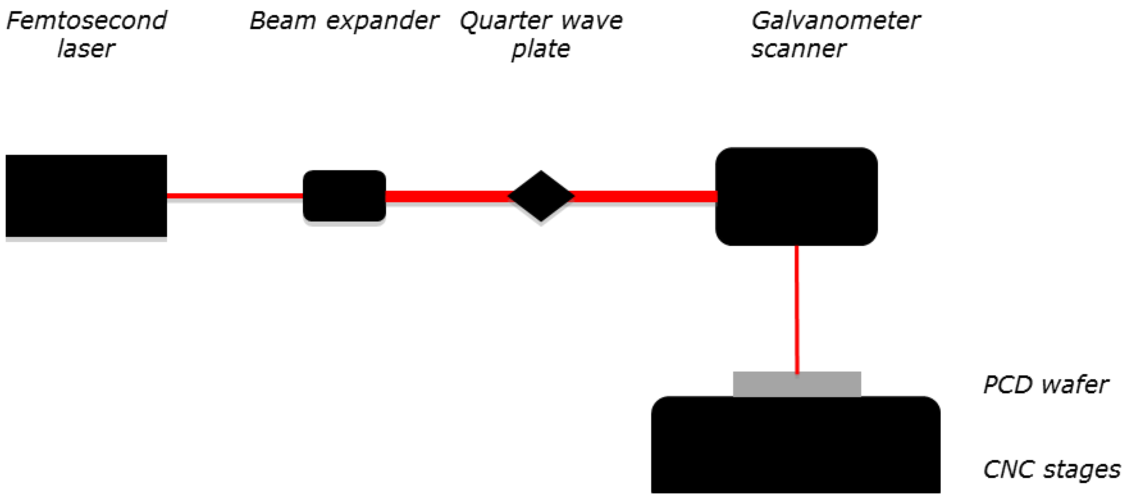
Task 2.3: Fundamental process development diamond ablation

- Experimental set up
  - Ablation trials with low power ultra-short pulsed laser



Characteristics of the femtosecond laser used in T2.3:

Wavelength	1030nm
Pulse length	230fs – 10ps
Maximum average power	5W
Frequency	60kHz – 1MHz
Polarization	Linear
M^2	< 1.2

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Task 2.3: Fundamental process development diamond ablation

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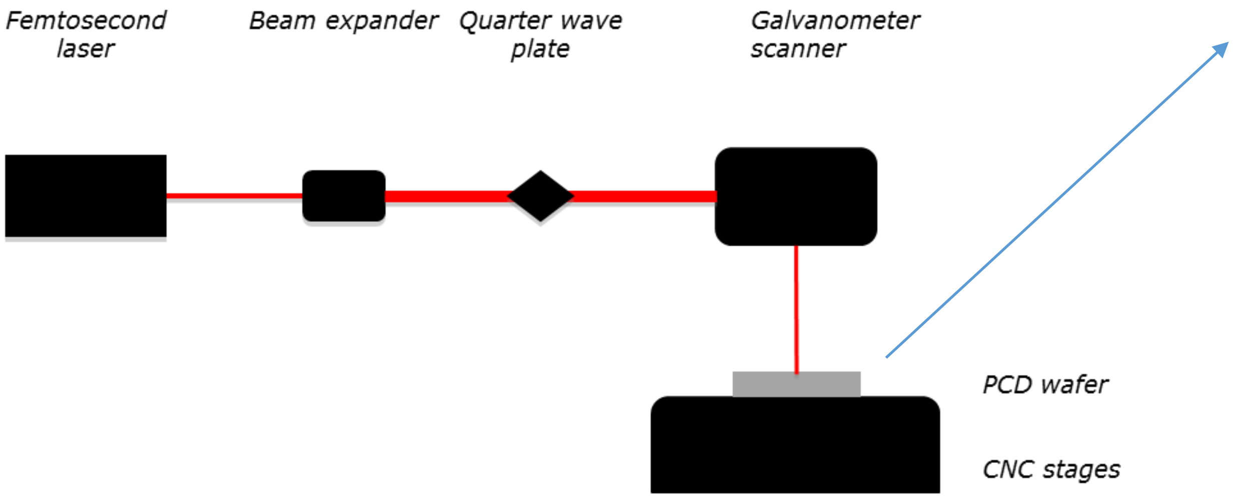
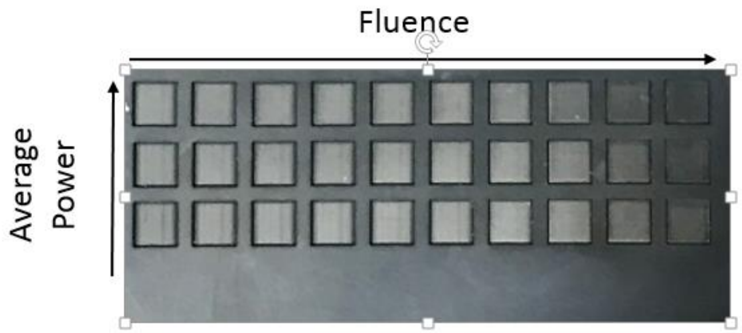
  - Ablation trials with low power ultra-short pulsed laser



Measurement by scanning laser microscopy of :
- Ablated volume for removal rate calculation
- Surface roughness



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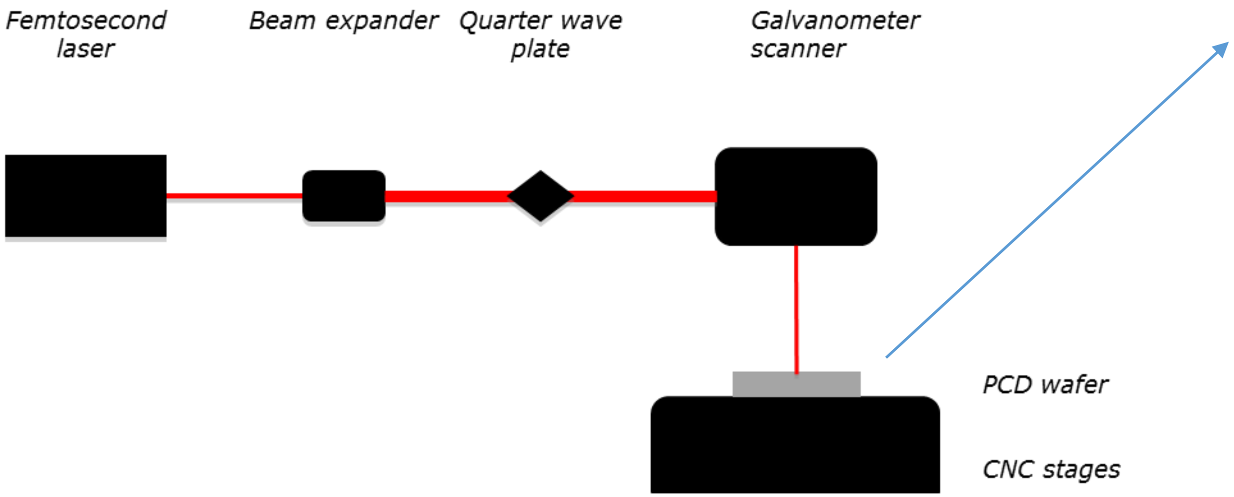
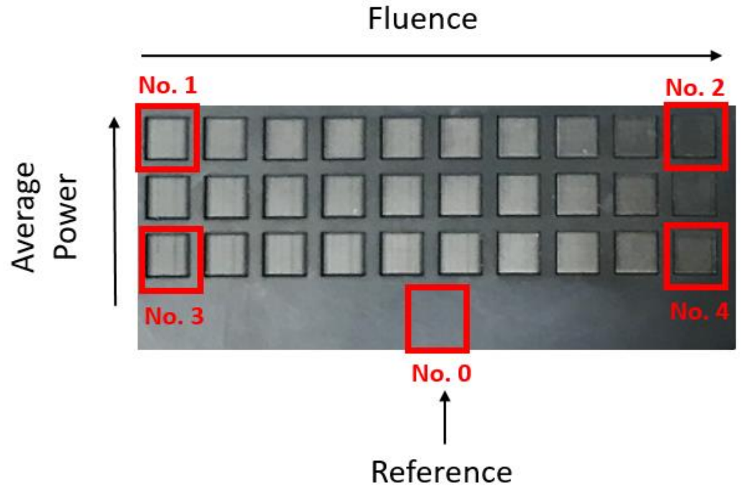


Physicochemical characterisation by Raman spectroscopy :

- Carbon structure



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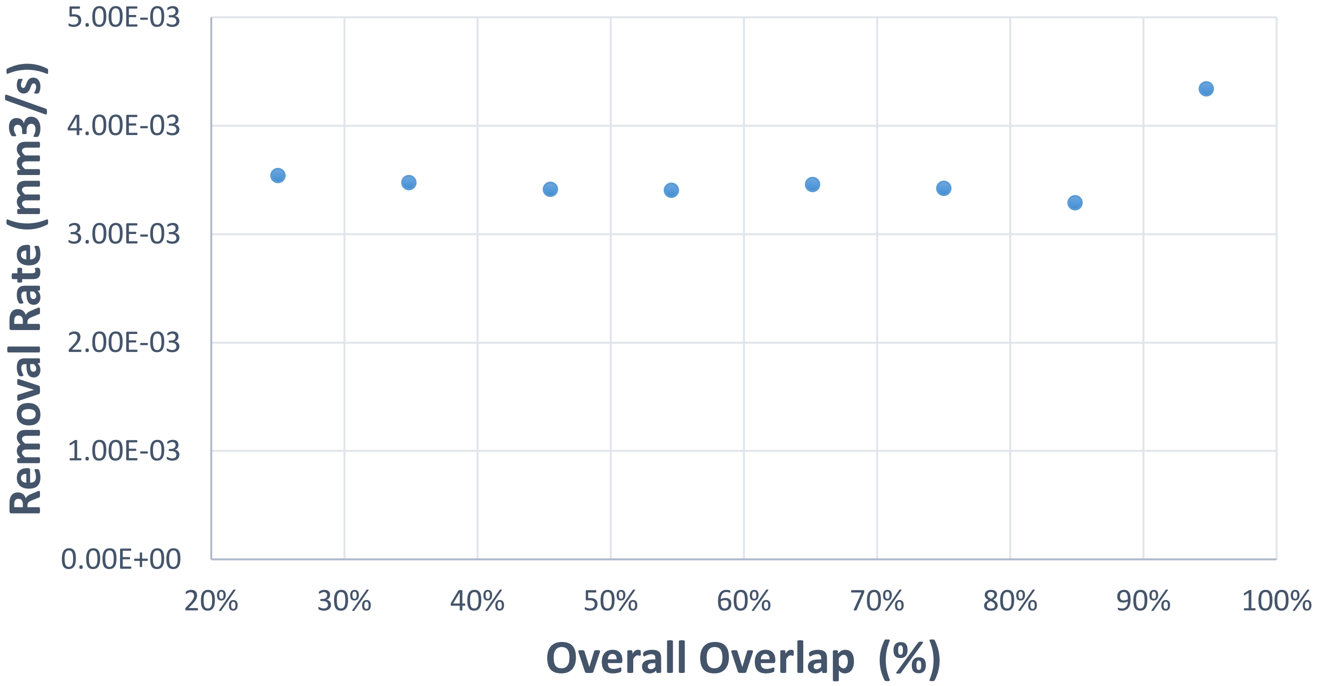
Task 2.3: Fundamental process development diamond ablation

- Influence of Heat Accumulation
  - Increase of ablation rate with heat accumulation



Over 95% overlap :
- Increase of ablation rate

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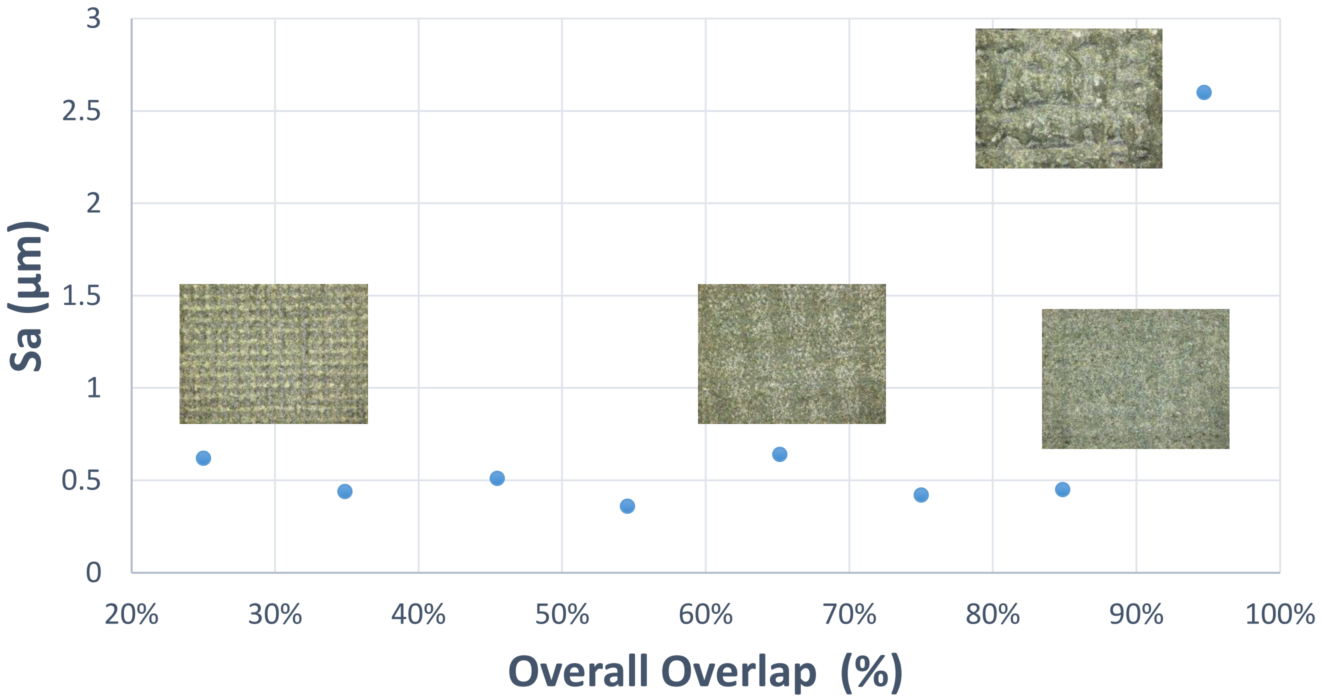

Over 95% overlap :
- Increase of ablation rate
- Surface critically damaged

HEAT ACCUMULATION EFFECT

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Task 2.3: Fundamental process development diamond ablation

- Variation of Ablation Rate with PCD grades
  - PCD grades

PCD Grade Name	Average Grain Size (µm)	Diamond Content (wt %)	Cobalt Content (wt%)
CMX850	1	80	20
CTB010	12	90	10
CTM025	30	90	10

  - Measurement of the ablation rate variation with fluence

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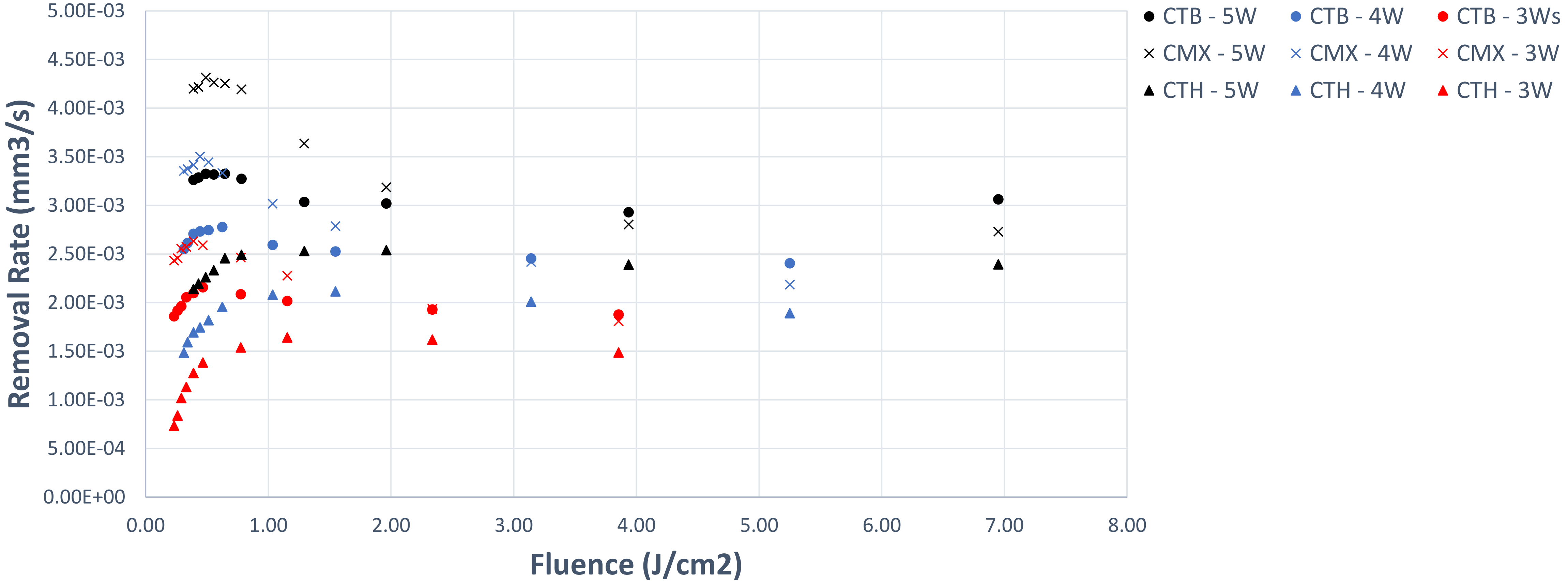

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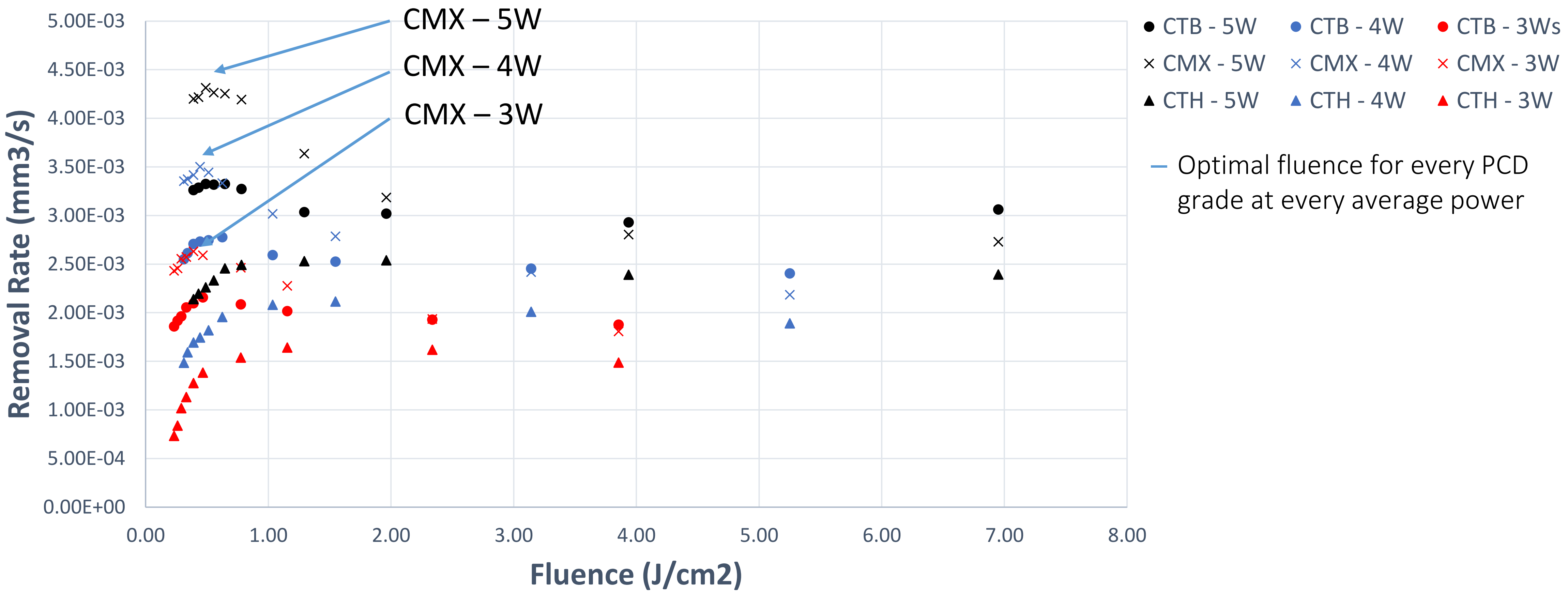
Task 2.3: Fundamental process development diamond ablation



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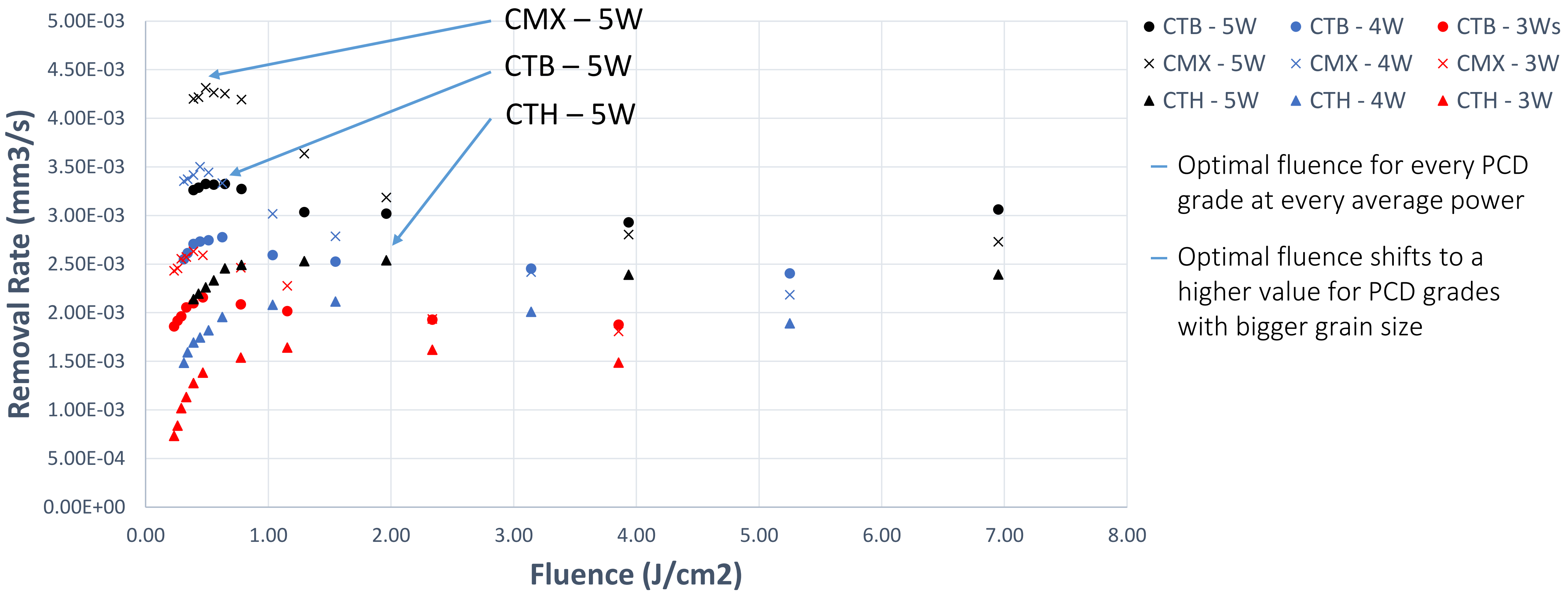
Task 2.3: Fundamental process development diamond ablation



- Optimal fluence for every PCD grade at every average power
- Optimal fluence shifts to a higher value for PCD grades with bigger grain size

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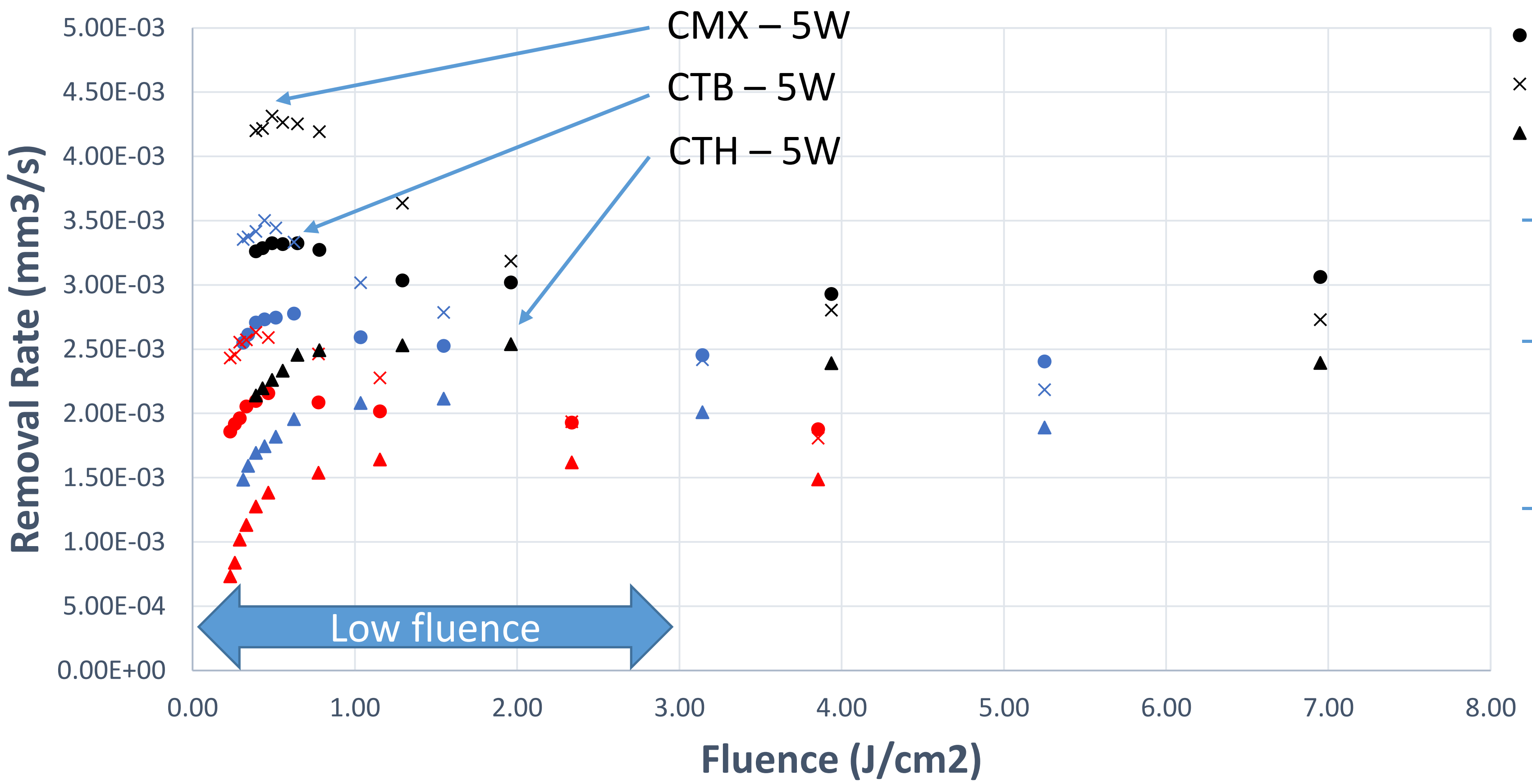
Task 2.3: Fundamental process development diamond ablation



- Optimal fluence for every PCD grade at every average power
- Optimal fluence shifts to a higher value for PCD grades with bigger grain size
- Lower ablation rate for bigger grains at low fluence

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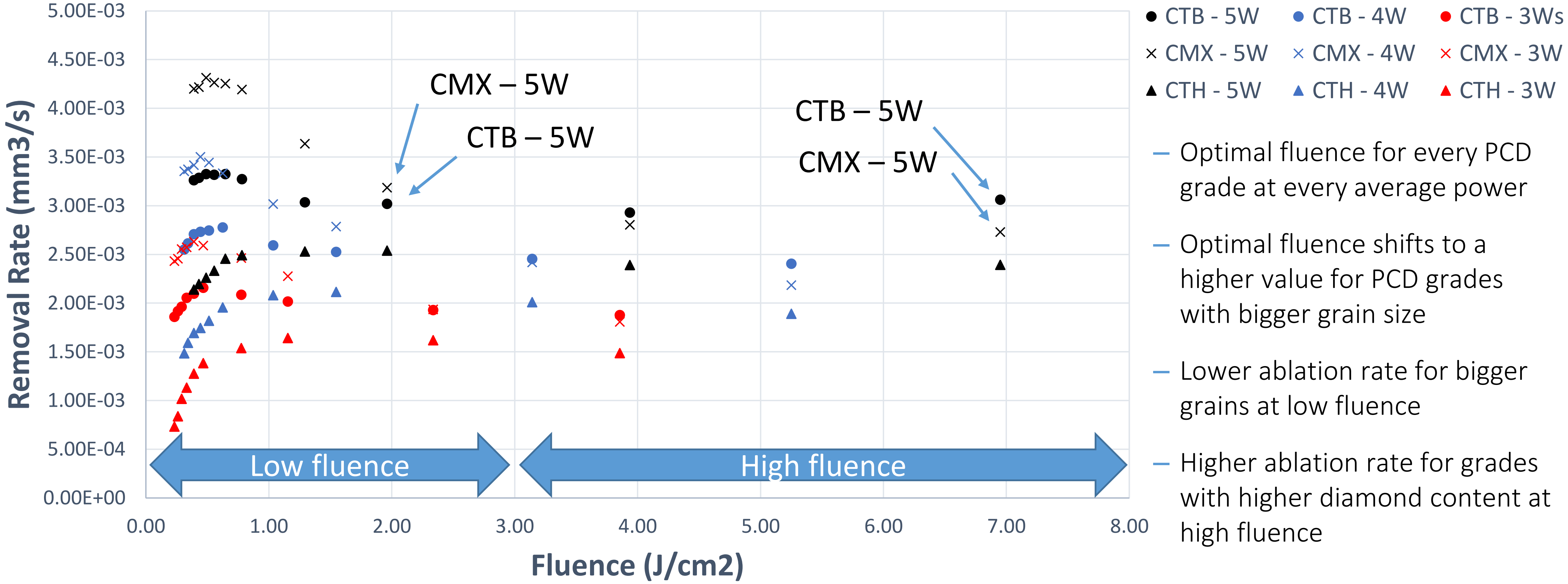
Task 2.3: Fundamental process development diamond ablation



- Optimal fluence for every PCD grade at every average power
- Optimal fluence shifts to a higher value for PCD grades with bigger grain size
- Lower ablation rate for bigger grains at low fluence
- Higher ablation rate for grades with higher diamond content at high fluence

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Task 2.3: Fundamental process development diamond ablation

- Process Optimization and Limitation in Spot Size
  - Two steps processing
    - Polishing to be achieved with spot size below 10µm
    - Optimal fluence expected between 0.5J/cm^{-2} and 1J/cm^{-2} for processing at high power
    - High power laser over 100µJ pulse energy
    - Fluence over 1J/cm^{-2} with 100µJ and spot of 10µm
    - So two processing steps required:

    1. Smoothing step will be performed with large spot size at high pulse energy/high average power
    2. Finishing step will be performed with small spot at low pulse energy/low average power

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Task 2.3: Fundamental process development diamond ablation

- Process Optimization and Limitation in Spot Size
  - Maximum spot size

$$d = 2\sqrt{\frac{E}{\pi F}}$$

Average power: P = 200W
Frequency: f = 2MHz
Pulse energy: E = 100µJ

Optimal fluence: F =	**0.49J/cm^{-2}**	**1J/cm^{-2}**	**2J/cm^{-2}**
Spot diameter: d =	**160µm** **Maximal spot size**	112µm	80µm

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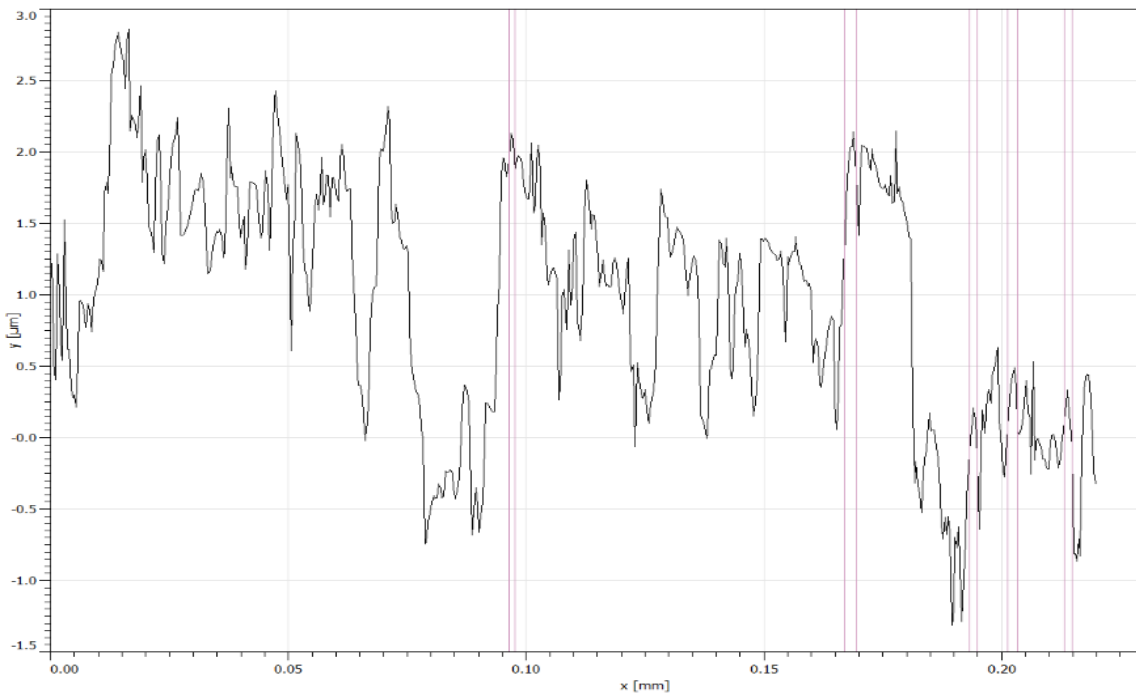
Task 2.3: Fundamental process development diamond ablation

- Process Optimization and Limitation in Spot Size
  - Minimum spot size
    - Topography of lapped PCD wafer
    - Peak with an average width of 1µm
    - Optimal minimum spot size 1µm
    - Not corresponding to final ablated surface prior to laser-polishing



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Task 2.3: Fundamental process development diamond ablation

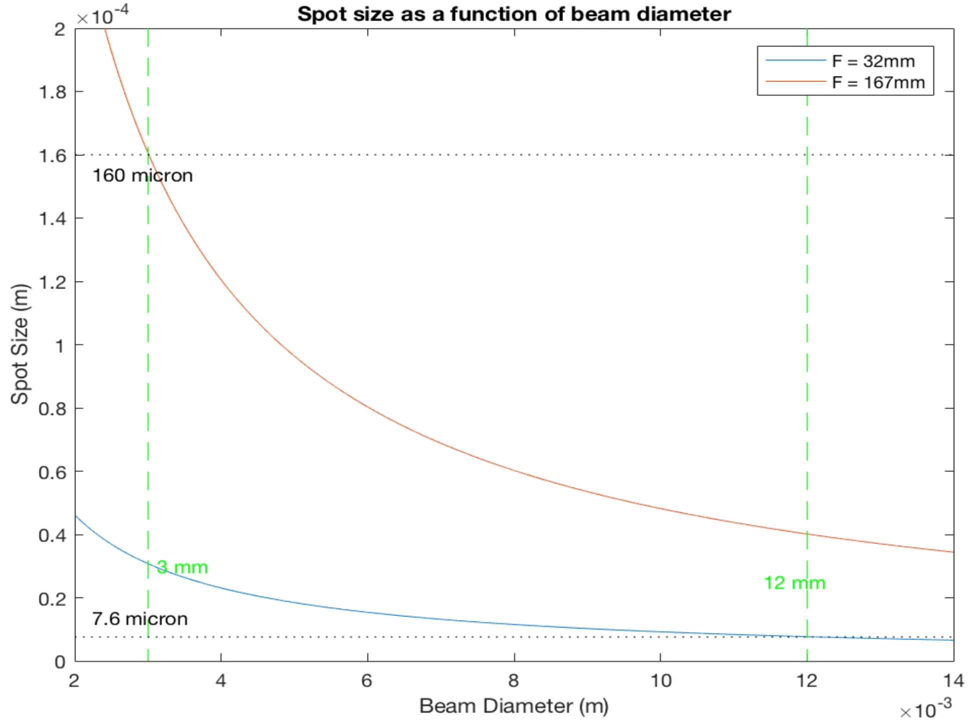
- Process Optimization and Limitation in Spot Size
  - Limitation in spot size and speed
    - Minimum can only reach 7.6µm.

    Not critical as topography after ablation at high power is yet unknown.

    The goal was to determine smallest spot achievable on this system.

    - Maximum reaches 160µm.

    Match the requirement of spot diameter to work close to the optimal fluence at high pulse energy



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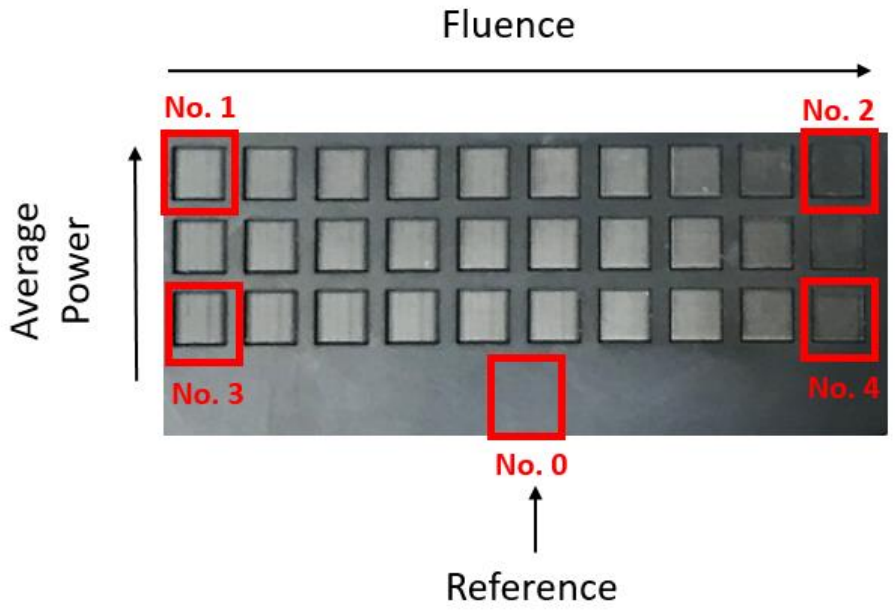
Task 2.3: Fundamental process development diamond ablation

- Graphitization of Diamond under Ultra-Short Pulsed Ablation
  - Raman spectroscopy analyses



Area 0	Reference point (initial surface)	Lapped surface for CMX850* EDM ground surface for CTB010*
Sample 1	High power – Low fluence	5W – 0.39 J/cm^{-2}
Sample 2	High power – High fluence	5W – 6.95J/cm^{-2}
Sample 3	Low power – Low fluence	3W – 0.23J/cm^{-2}
Sample 4	Low power – High fluence	3W – 3.86J/cm^{-2}

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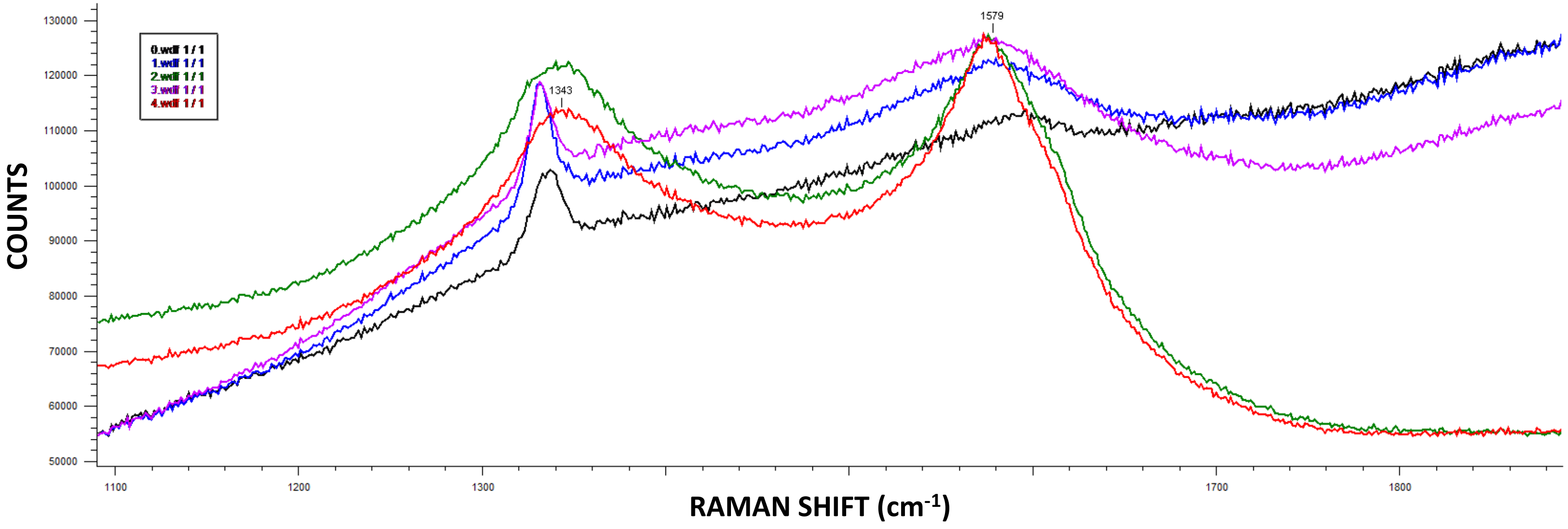
Task 2.3: Fundamental process development diamond ablation

- Graphitization of Diamond under Ultra-Short Pulsed Ablation
  - SEM/Raman Spectrometer Measurements



CMX850

1µm grain size,

80% wt diamond content

Area 0	Initial surface
Sample 1	5W – low fluence
Sample 2	5W – high fluence
Sample 3	3W – low fluence
Sample 4	3W – high fluence

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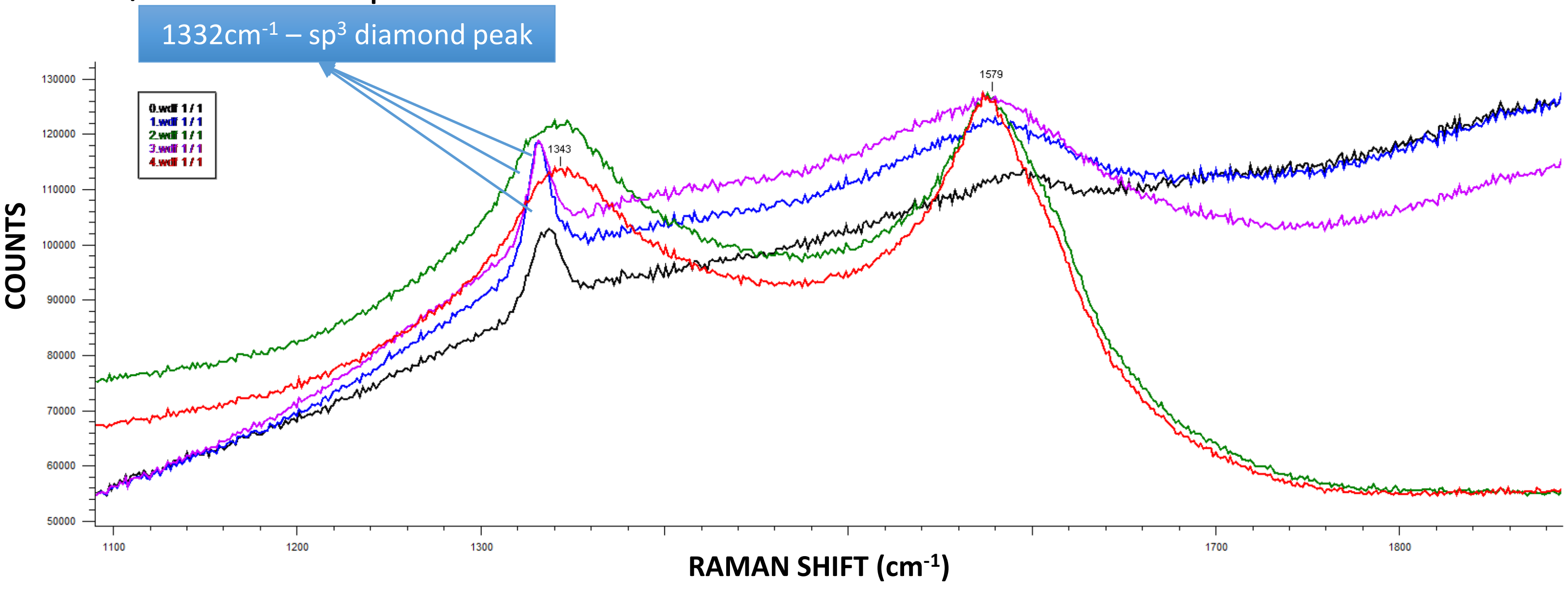
Task 2.3: Fundamental process development diamond ablation

- Graphitization of Diamond under Ultra-Short Pulsed Ablation
  - SEM/Raman Spectrometer Measurements



CMX850

1µm grain size,

80% wt diamond content

Area 0	Initial surface
Sample 1	5W – low fluence
Sample 2	5W – high fluence
Sample 3	3W – low fluence
Sample 4	3W – high fluence

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Task 2.3: Fundamental process development diamond ablation

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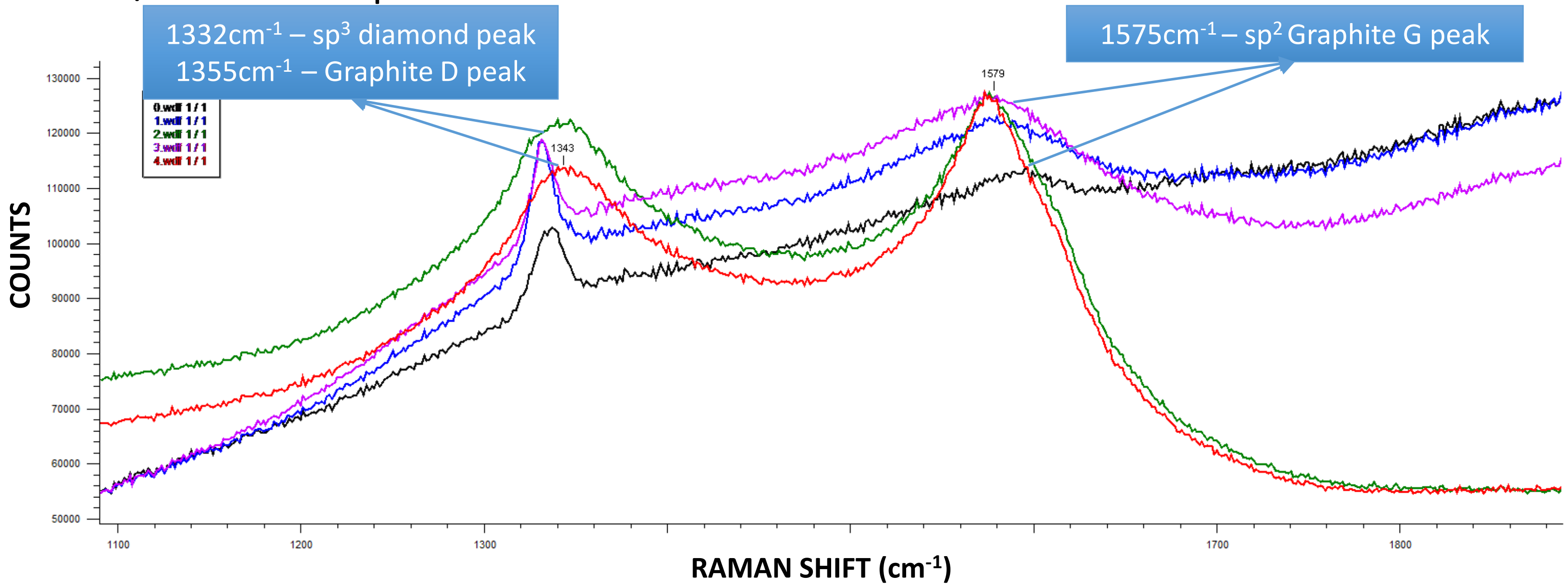

CMX850

1µm grain size,

80% wt diamond content

Area 0 Initial surface

Sample 1 5W – low fluence

Sample 2 5W – high fluence

Sample 3 3W – low fluence

Sample 4 3W – high fluence

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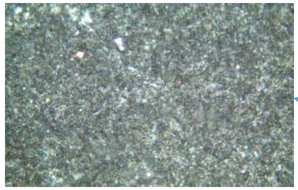
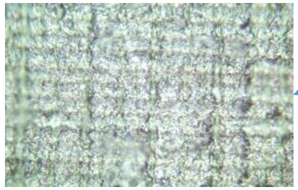
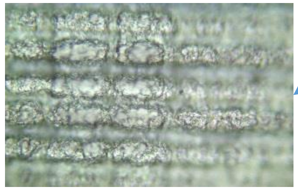
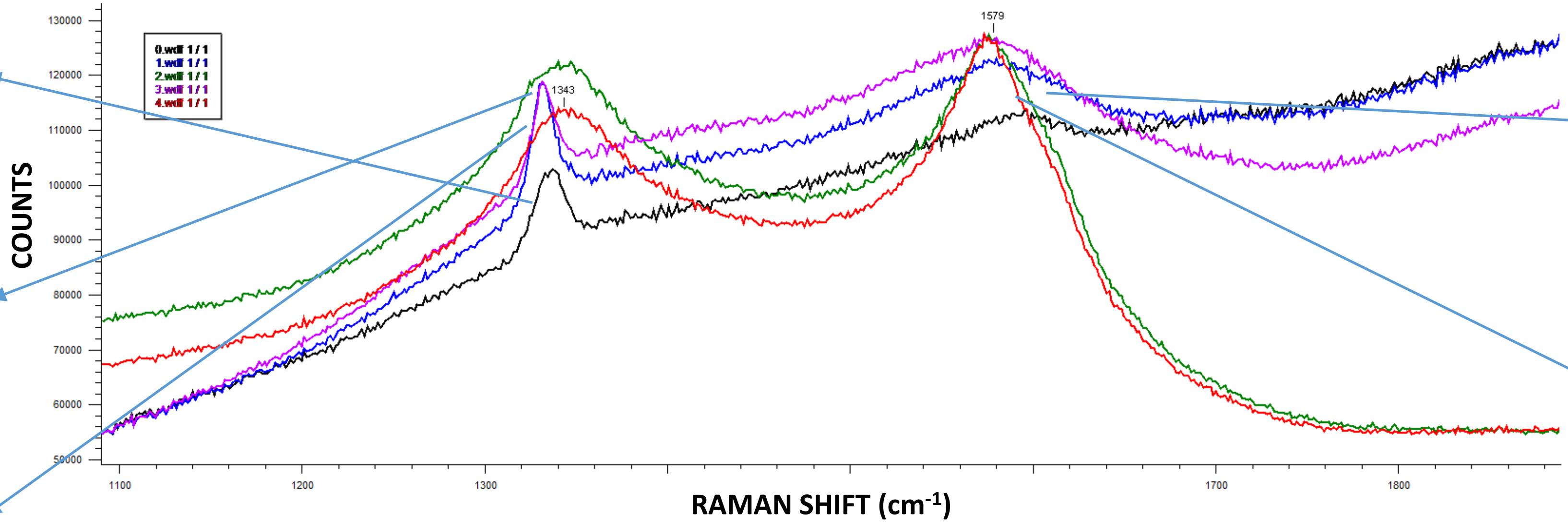
Task 2.3: Fundamental process development diamond ablation

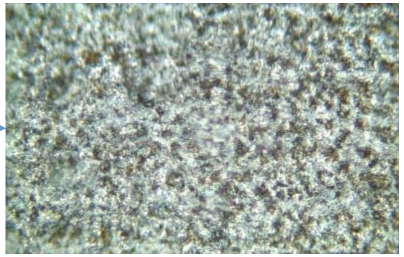
- Graphitization of Diamond under Ultra-Short Pulsed Ablation
  - SEM/Raman Spectrometer Measurements

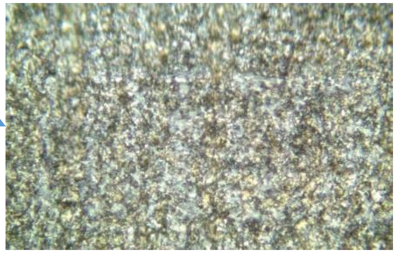

Area 0


Sample 1


Sample 3




Sample 2


Sample 4

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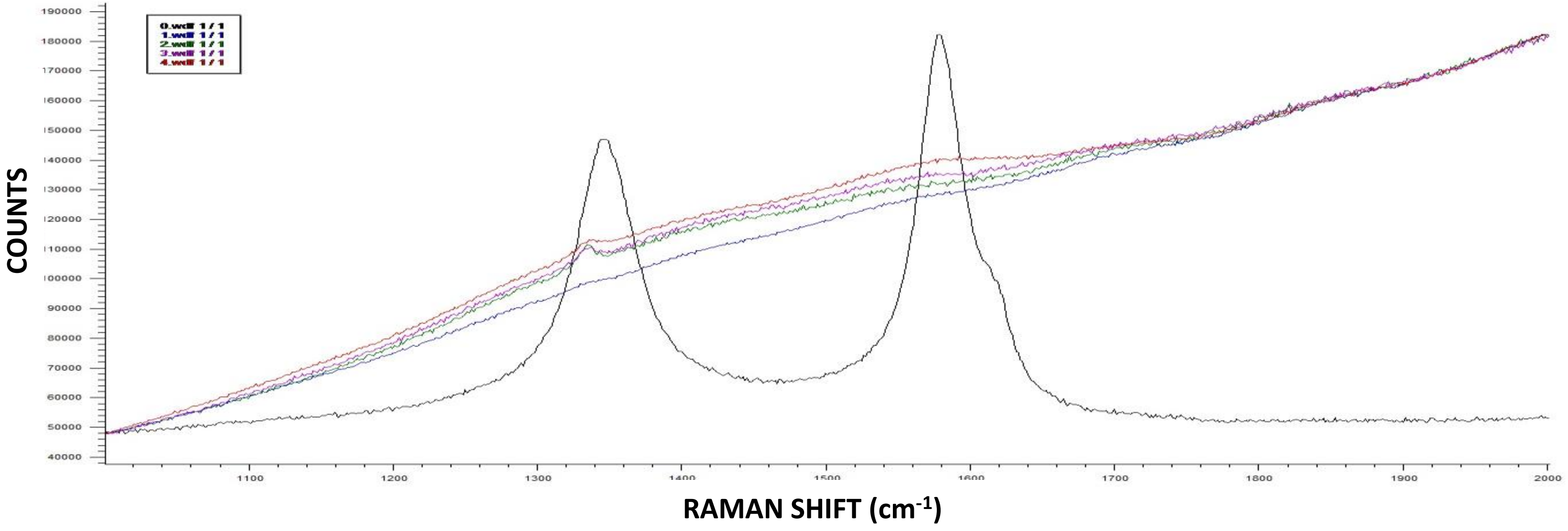
Task 2.3: Fundamental process development diamond ablation

- Graphitization of Diamond under Ultra-Short Pulsed Ablation
  - SEM/Raman Spectrometer Measurements



CTB010

12µm grain size,

90% wt diamond content

Area 0	Initial surface
Sample 1	5W – low fluence
Sample 2	5W – high fluence
Sample 3	3W – low fluence
Sample 4	3W – high fluence

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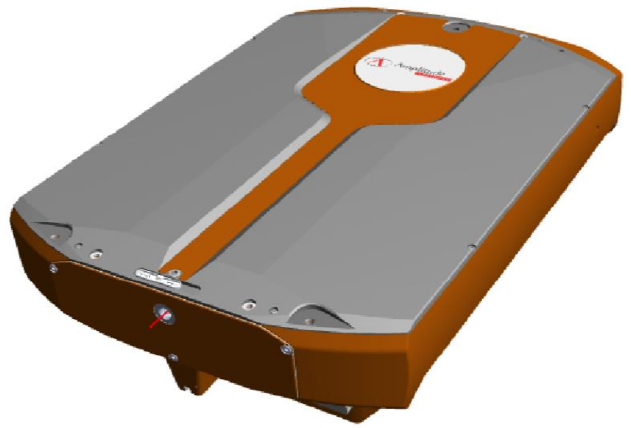
Task 2.3: Fundamental process development diamond ablation

- Conclusion

Parameters	Current Performances	E6 Specifications	Specification agreed with partners
Wavelength	1030nm	1030nm	1030nm (GREEN??)
Power	5W	200W	100W*
Pulse duration	230fs – 10ps	< 500 fs – 10ps	400fs – 10ps
Frequency	60kHz-1MHz	<2MHz	<2MHz
M^2	1.2	1.2	<1.3
Pulse burst	None	Pulse burst	Multi pulses burst??
Maximum scanning speed	3000mm/s	<3000mm/s	3000mm/s
Spot diameter	20µm	2µm – 160µm	7.6µm - 160µm
Polarization	Circular	Circular	Circular

- *Agreement on delivery of industrial TANGOR laser with average power of 100W
- **Installation : 14th of May**



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Task 2.4: Upscaling of applications for high throughput

- Status
  - Task not started – To start by mid of June ✖
    - Delibery of 100W TANGOR – 1st week of May
    - Installation scheduled on 14th of Mays
  - D2.4 not started ✖

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Work Package 2

Partners involved:

BOSCH
lasea LASER ENGINEERING APPLICATIONS
CLASS4LASER See the light
elementsix a De Beers Group Company
IFSW

- HIPERDIAS application areas:
  - 3D Silicon processing
  - Fine cutting of metals
  - Diamond ablation

- Agenda:
  - Task 2.1: Fundamentals Si Processing - Update from Bosch
  - Task 2.2: Fundamentals Fine Cutting of Metals - Update from C4L
  - Task 2.3: Fundamentals Diamond Ablation – Update from E6
  - Task 2.4: Upscaling – Update from USTUTT

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Task 2.4: Upscaling (500 W)

- Schedule:
  - This week: Characterization of the amplified laser
  - Next week: Connecting laser to Lasea station and testing
  - Week beginning 07.05.: Start of experiments
- Goal (1000 W):

Key Performance Indicator	Symbol	Unit	Target Value	BOSCH
KPI #1: average ablation rate	$\bar{V}$	mm³/s	**≥1**	**0,0574 (P_{av} = 20 W)**
KPI #2: peak ablation rate	$\dot{V}_{max}$	mm³/s	**≥3**	–
KPI #3: shape deviation	δ_S	µm	**≤10 (waviness)**	<10
KPI #4: average surface roughness	S_a	µm	**≤1**	<0,5
KPI #5: thickness of surface damage	$l_{d,sd}$	µm	**≤1**	<1
KPI #6: Surface defects > 1 µm	–	1/mm²	**none**	none
KPI #7: min. achievable edge radius	r_e	µm	**≤ 200**	60
KPI #8: max. edge-steepness	α_e	degree	**≥ 70**	80

→ 1.435 mm³/s @ 500W

2.87 mm³/s @ 1000W (linear scaling)

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Task 2.4: Upscaling (500 W)

IFSW

- Strategy:
  - Use parameters from D2.1 (Bosch) as a starting point

Laser / Process Parameters	Symbol	Unit	Value	IFSW
Average power	P_{av}	W	20	
Pulse duration	τ	fs	320	300
Intraburst distance	τ_{burst}	ns	20	25
Burst number	n_{burst}	-	5	Max. 5
Scan velocity	v	m/s	0,655	
Hatch distance	a_{hatch}	µm	13,1	
Pulse repetition rate	f_{rep}	kHz	80	Max. 1.28 MHz
Spot diameter	d_{spot}	µm	71,25	TBD
Pulse energy per burst	E_{burst}	µJ	250	
Pulse energy	E_{pulse}	µJ	50	390 µJ

Number of pulses per spot:
8,7
Hatch overlap:
18%
Burst available up to **5 pulses** (with declining pulse energy)
Pulse repetition rate **1.28 MHz** (adjustable)
D2.1: Energy specific ablation volume **constant for high fluences @ 300 fs**

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Task 2.4: Upscaling (500 W)

- Strategy:
  - Investigate heat accumulation effects in detail
    - Calorimetric measurement of $\eta_A \cdot \eta_{resP}$
    - Simulation of heat accumulation
    - Heat accumulation between pulses → v_{crit} / $N_{P,crit}$
    - Heat accumulation between overscans → $N_{OS,crit}$
  - Influence of system specific parameters on energy specific ablation volume
    - Fluence (spot size)
    - Number of burst pulses
    - Pulse repetition rate
  - Controlled ablation with OCT
    - Reach required shape accuracy by controlled depth progress
    - Two step process possible: Fast ablation followed by accuracy improvement.

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