PHOTONICS PUBLIC PRIVATE PARTNERSHIP

WP 2 Process Development

Dr.-Ing. 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

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

- Agenda:
    - Task 2.1: Fundamentals Si Processing
    - Task 2.2: Fundamentals Fine Cutting of Metals
    - Task 2.3: Fundamentals Diamond Ablation
    - Task 2.4: Upscaling

Partners involved:

BOSCH

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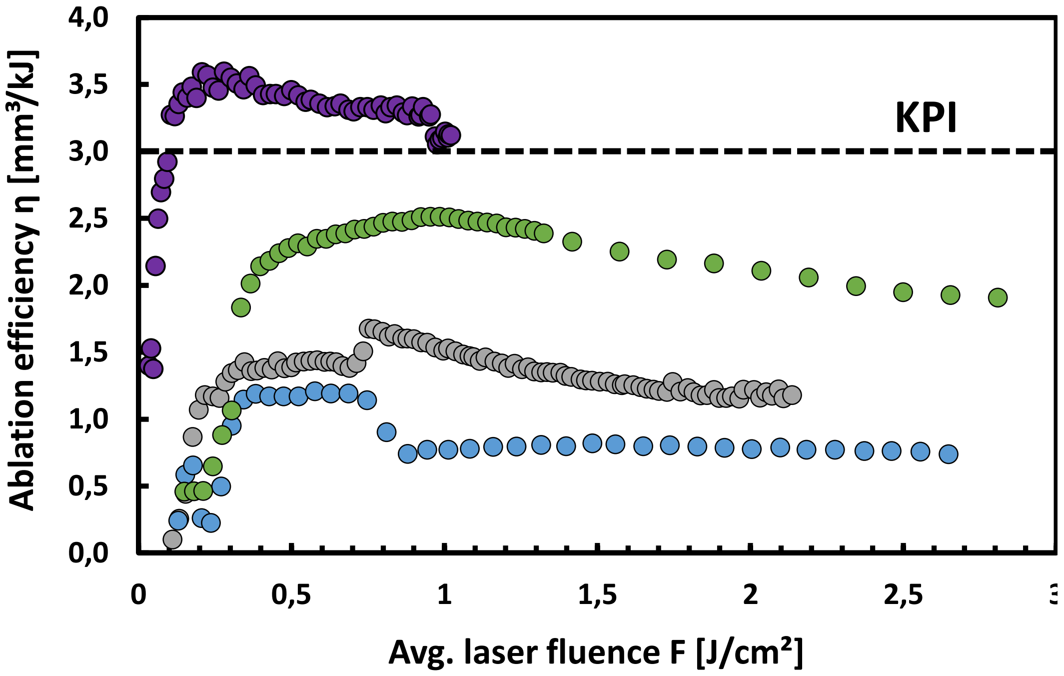
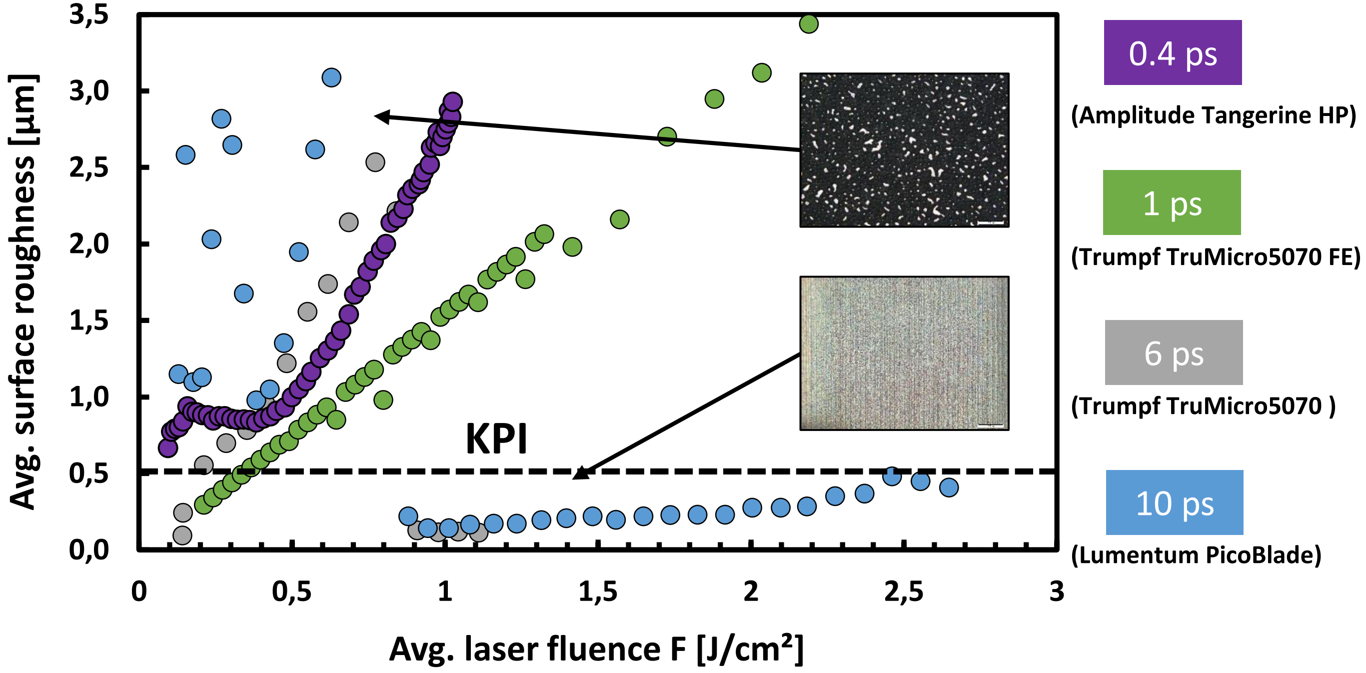
Task 2.1: Fundamental process development 3D Si processing





- Decisive KPI's (s. WP1): ***ablation efficiency**** and ***surface roughness***
- Parameters w/ highest impact: Avg. laser fluence and laser pulse duration
- Shift between ablation regimes observed for long pulse duration (> 1 ps): Jump in ablation efficiency, substantial decrease of surface roughness
- ***Critical: trade-off between surface quality and productivity***

* Also referred as "energy specific ablation rate"

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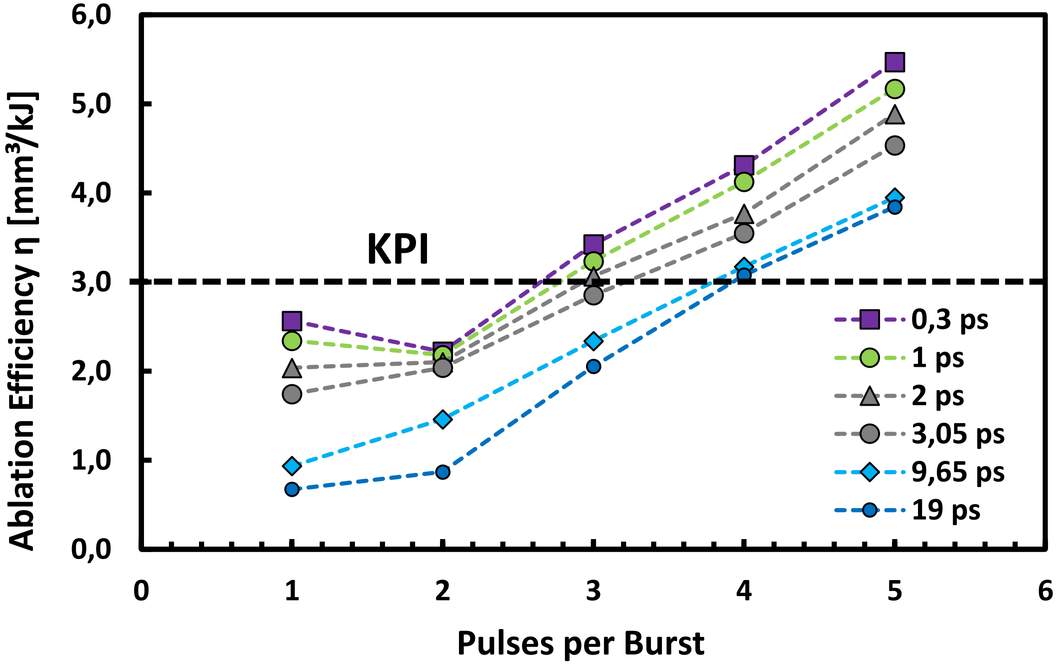
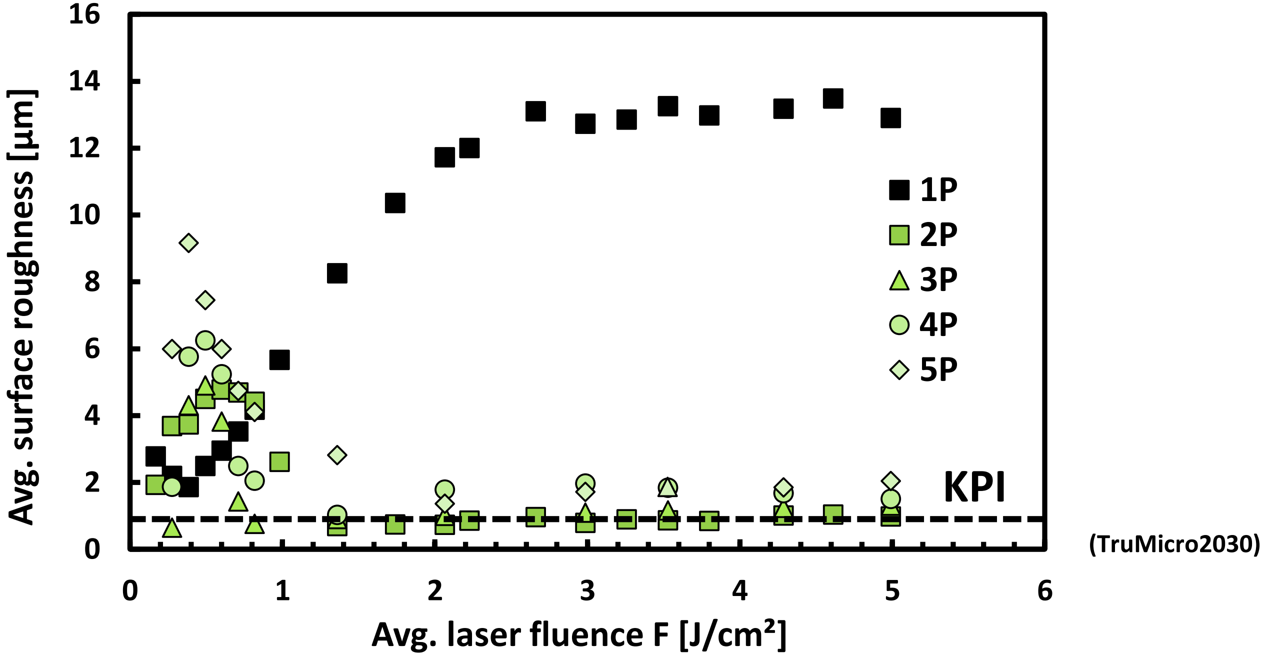
Task 2.1: Vital Parameter: Burst Mode





- Access to high quality regime at short pulse durations enabled! → ***Tradeoff manageable***
- ***Unexpected result:*** Ablation efficiency can be increased with more pulses per burst

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

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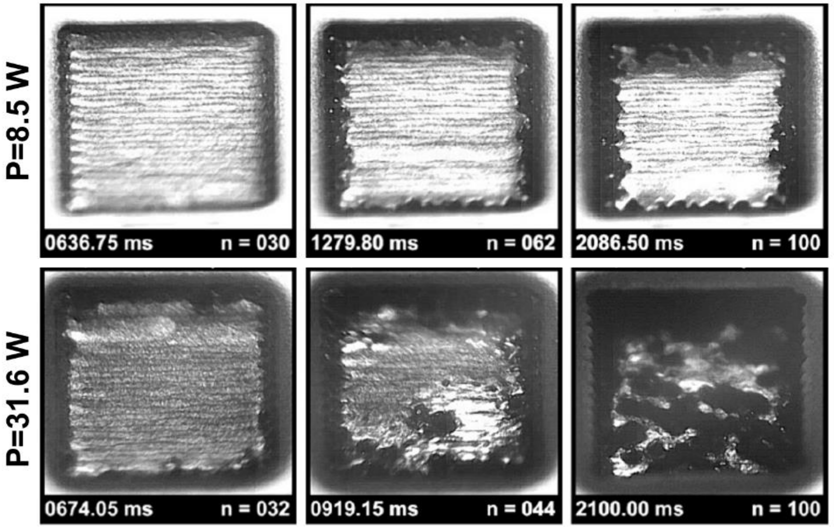
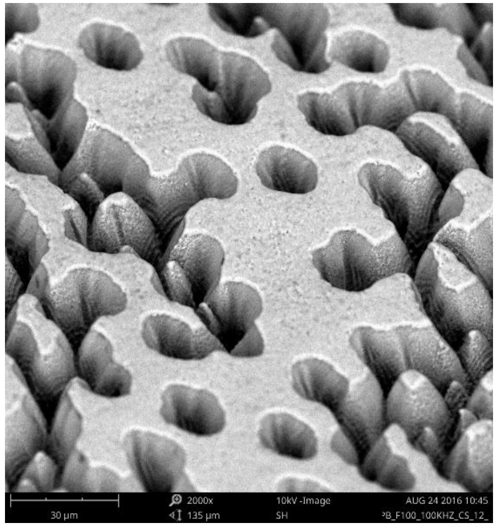
Task 2.1: Surface Condition

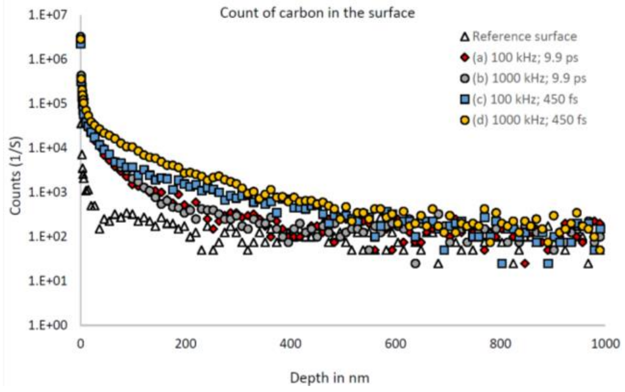
Deterioration of surface:

- High-Speed imaging, SEM analysis
- ***Heat accumulation*** leads to surface deterioration

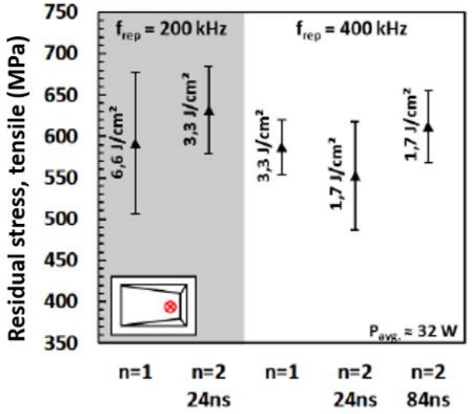




Depth of damage layer (smooth surface) < 1 µm evaluated using SIMS*



Raman spectroscopy reveals high tensile residual stress in surface layer



* Secondary Ion Mass Spectroscopy

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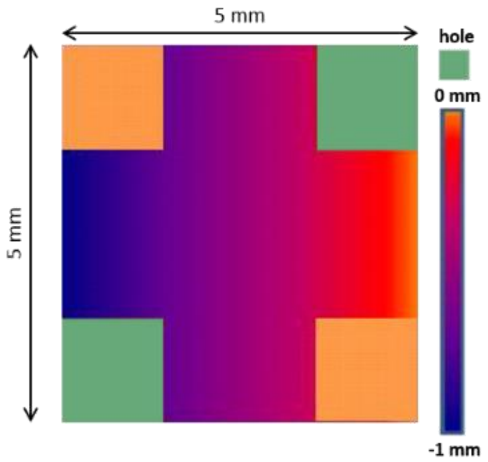
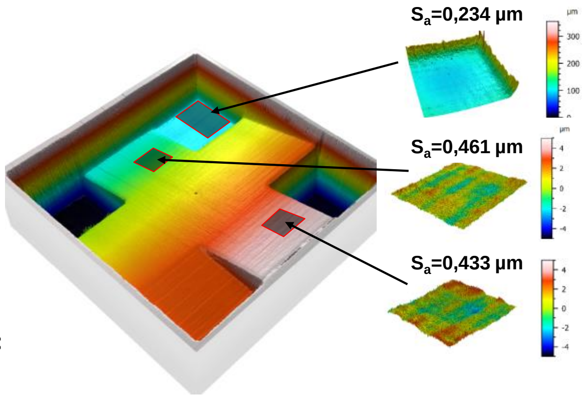
Task 2.1: Status of BOSCH Key Performance Indicators

Test structure

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





Bosch contribution including material from:
[D. Brinkmeier, Master's thesis]
[A. Hoppmann, Master's thesis]
[Y. Kasinathan, Master's thesis]
[B. Giese, Bachelor's thesis]
(performed @ Bosch Renningen)

KPI evaluation

Type	Unit	Target	Status M2017
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	12.2
Average surface roughness Ra	µm	≤1	0.5
Surface damage thickness	µm	≤1	less than Ra
Surface defects > 1 µm	1/mm²	none	0.05
Min. edge radius	µm	≤ 200	60
Max. edge-steepness	degree	≥ 70	82

→ Upscaling (T2.4)

- Results achieved: All KPIs w/i specifications, except for absolute ablation rate
- Translation of requirements into machine parameters → Discussion & comittment of Partners
- **Productivity/quality trade-off managed by using burst mode**

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Partners involved:

BOSCH

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Task 2.2: Process limits fine cutting of metals

- Objectives:

  Fundamental process development

  Investigate ablation mechanism

  Influence of processing parameters

  Generate input for upscaling

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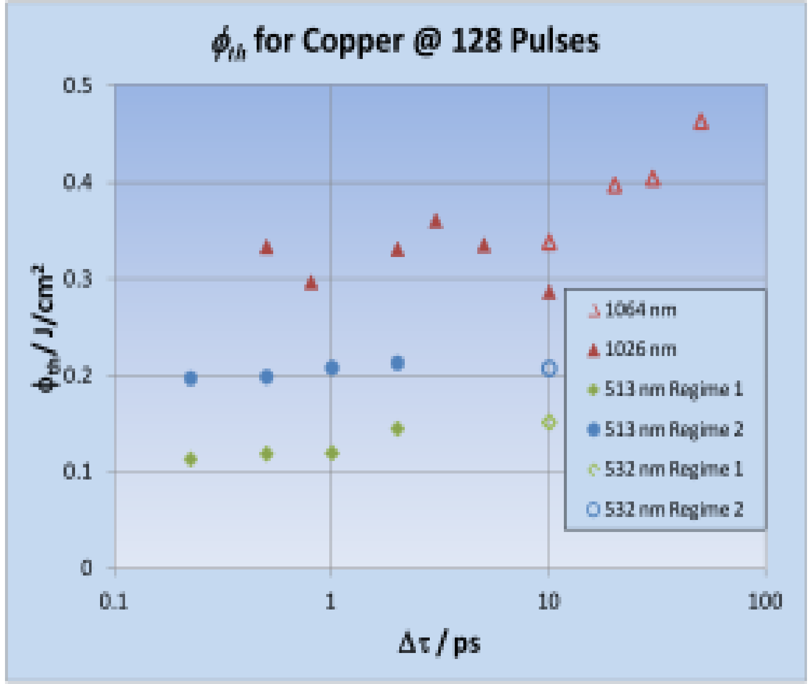
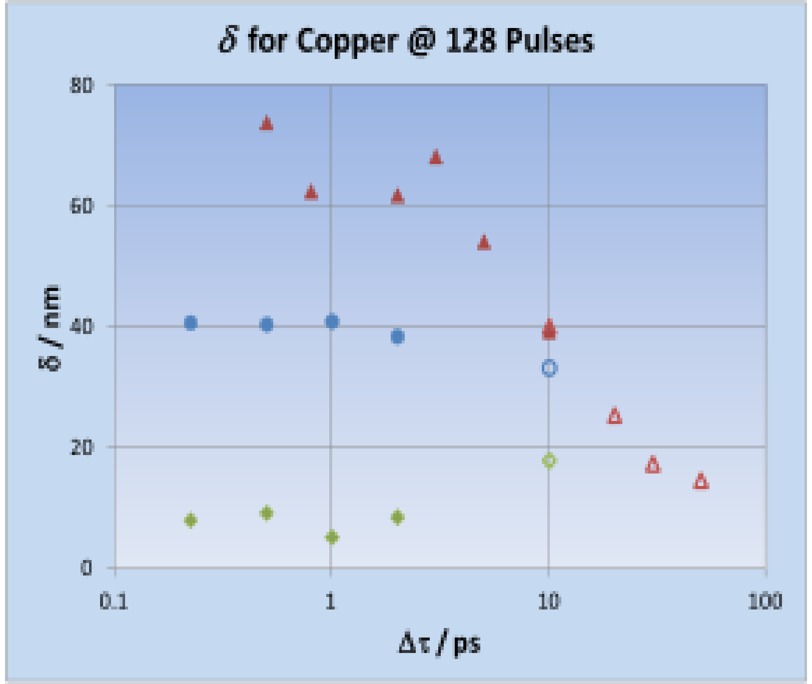
Task 2.2: Process limits fine cutting of metals

- Literature review: **summary**





Results form Neuenschwander et al. demonstrating an unchanged threshold fluence below 10ps, and an increasing energy penetration depth below 10ps pulse duration.

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  - **Investigate ablation mechanism**
  - **Influence of processing parameters**
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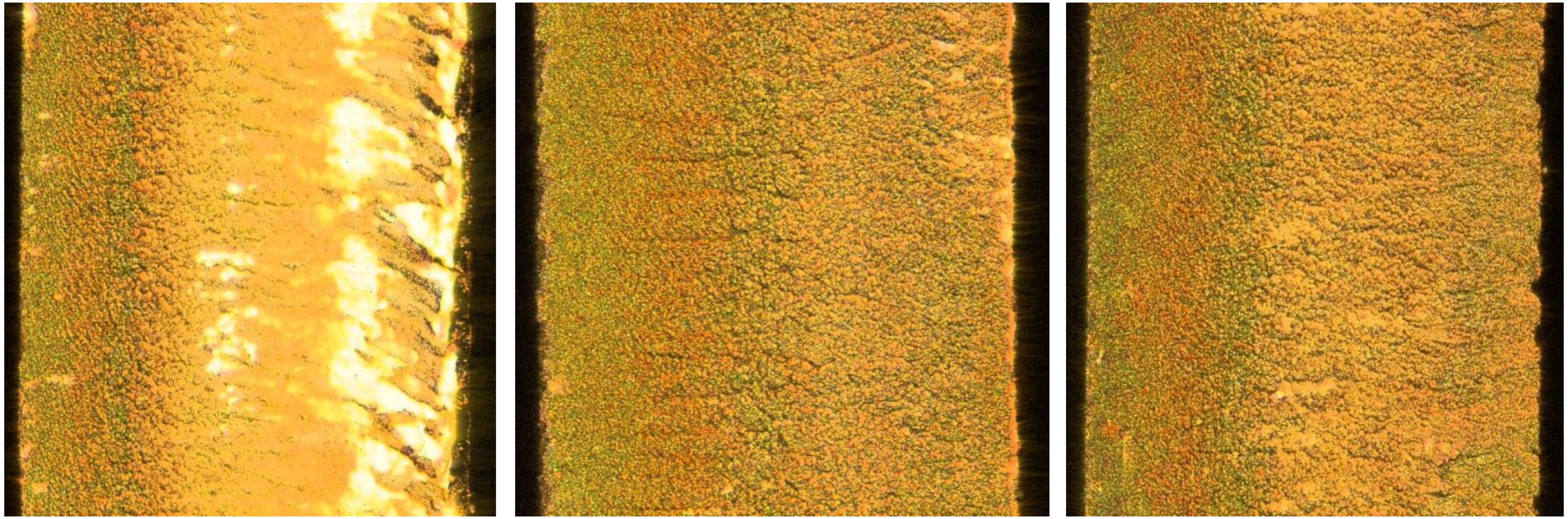
Task 2.2: Process limits fine cutting of metals

- Improvement in surface quality with increasing pulse energy: Brass



Images of the cut surfaces for varying pulse energy. (From L-R) 35µJ, 65µJ, 83µJ. Keyence VK-8710K Laser scanning microscope, 20x objective.

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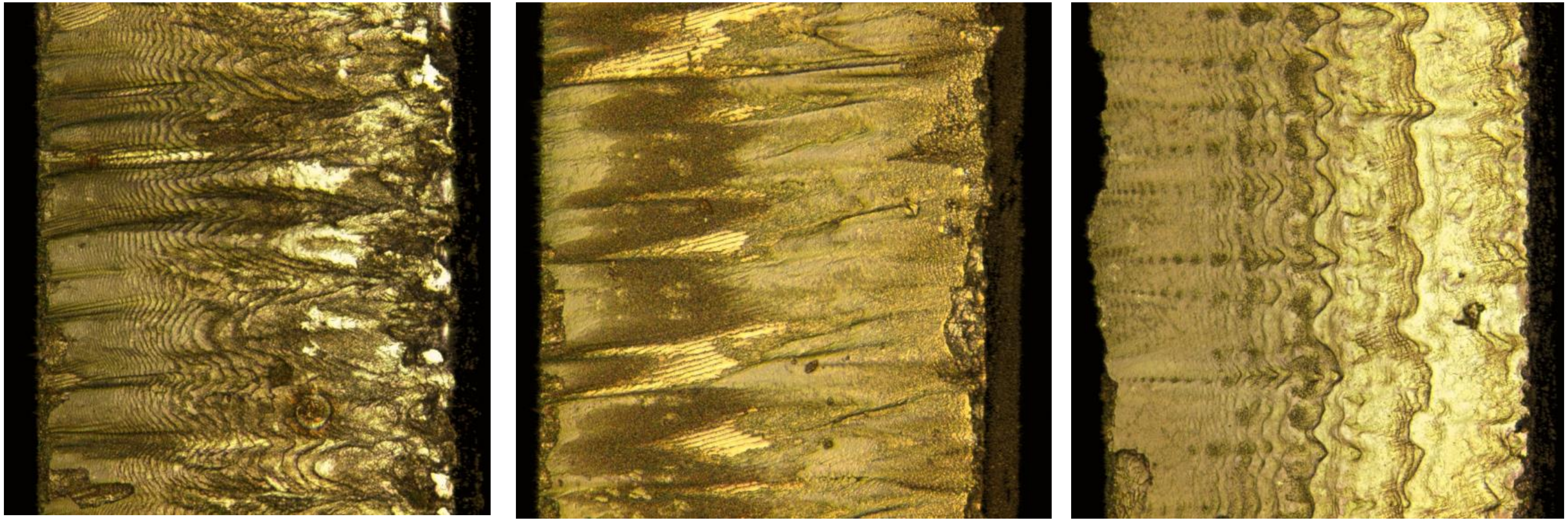
Task 2.2: Process limits fine cutting of metals

- Improvement in surface quality with increasing pulse energy: Steel



Images of the cut surfaces for varying pulse energy. (From L-R) 35 µJ, 65 µJ, 83 µJ. Keyence VK-8710K Laser scanning microscope, 20x objective.

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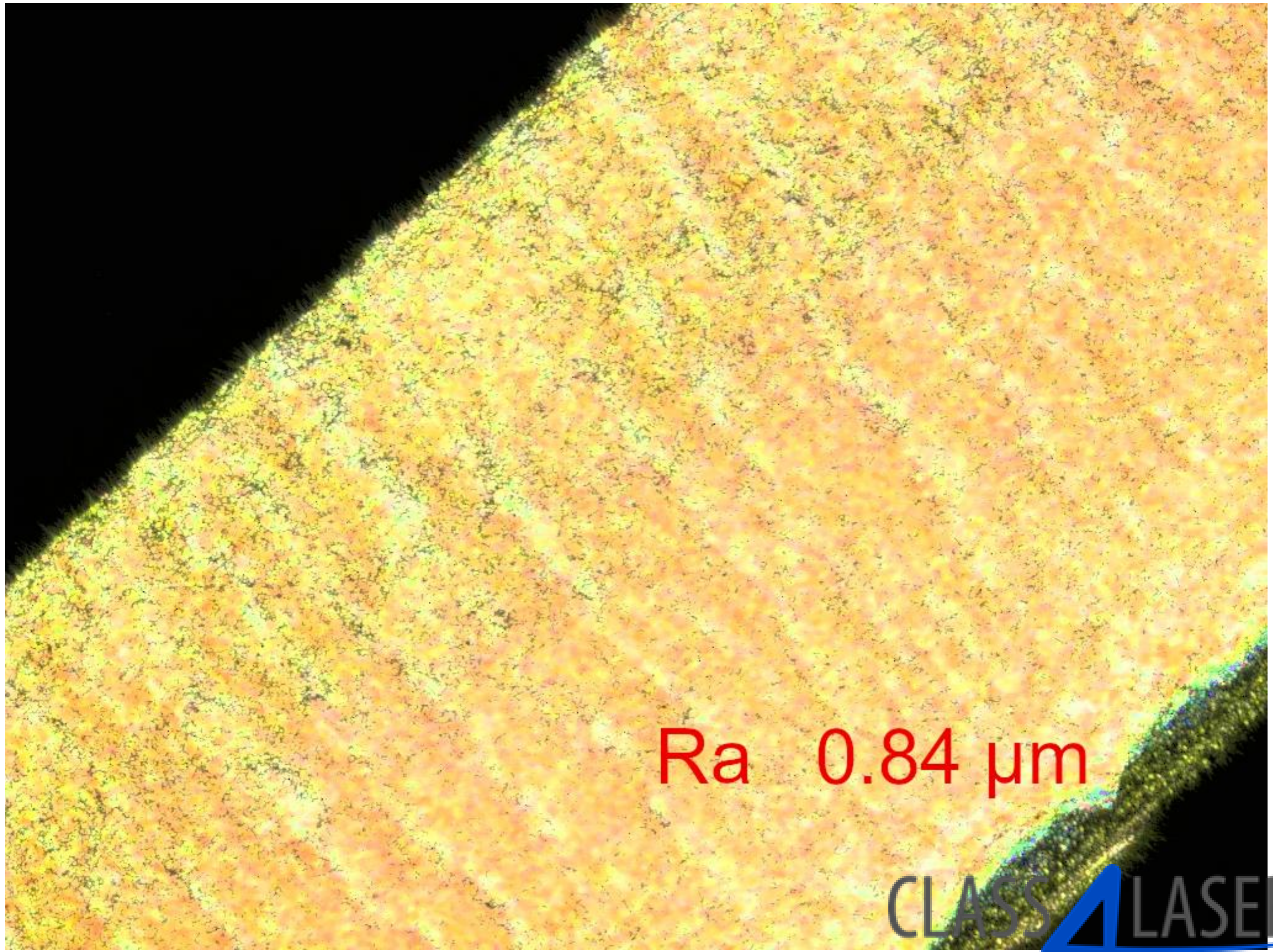
MS26 High quality fine cutting of metal with low average power



Images of the cut surface. Keyence VK-8710K Laser scanning microscope, 50x objective

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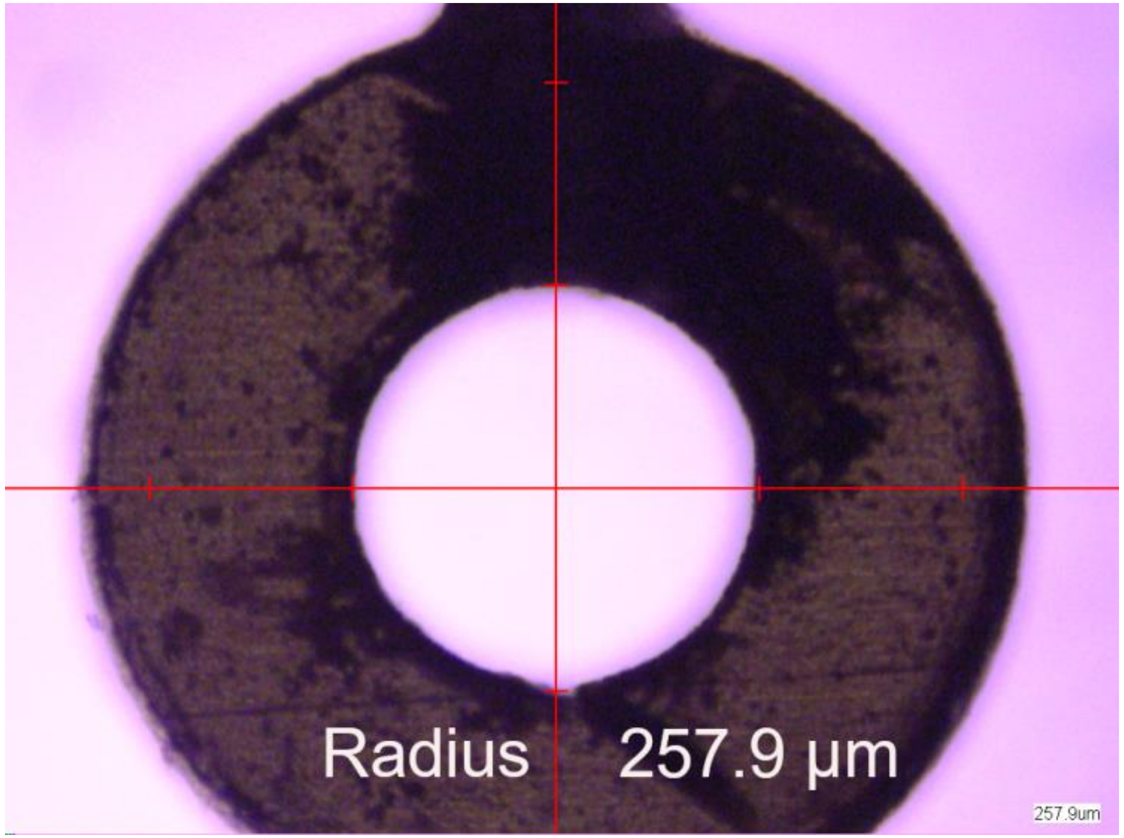
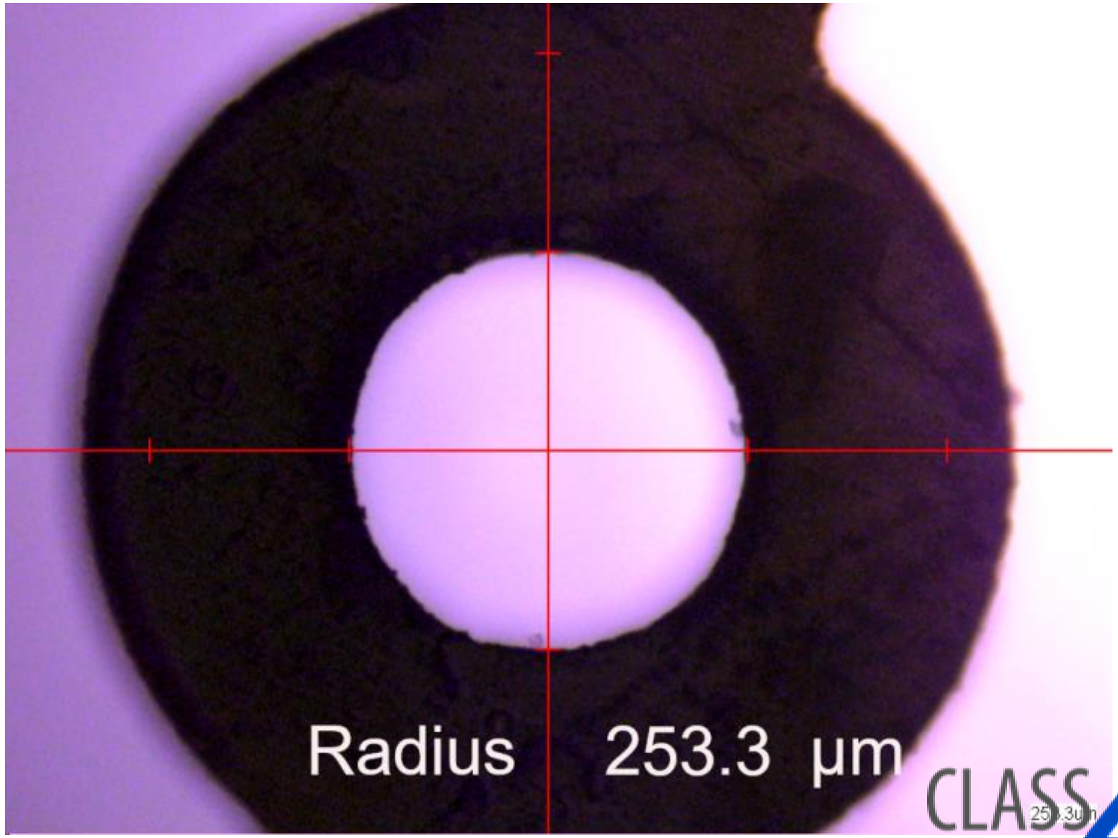
MS26 High quality fine cutting of metal with low average power





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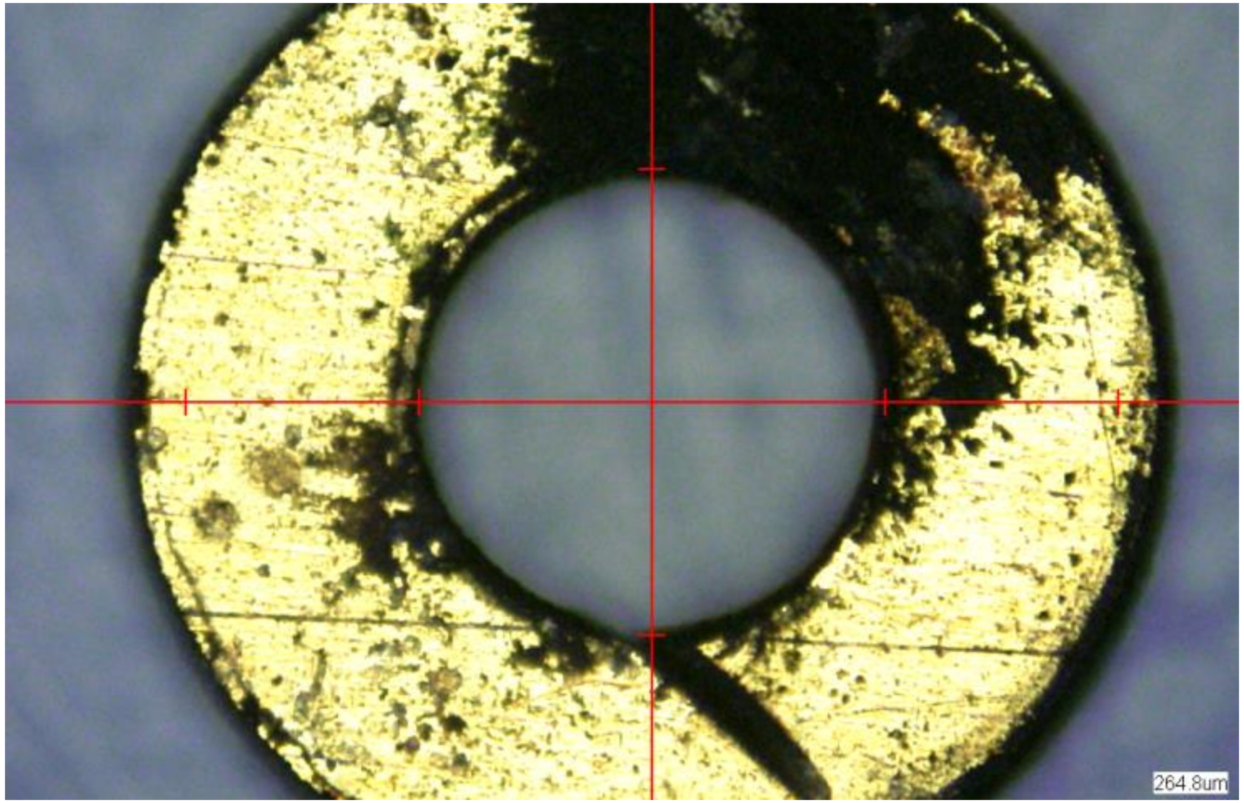

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MS26 High quality fine cutting of metal with low average power

No.	KPI	Values	Status
2	Surface roughness (functional/non-functional)	Expected : $R_a \leq 0.1$ µm / 0.4 µm	
		Validated : $R_a < 1$ µm / 1 µm	✓
		Not validated : $R_a \geq 1$ µm	
3	Shape deviation	Expected : < ± 2 µm	
		Validated : < ± 5 µm	✓
		Not validated : > ± 5 µm	
4	Taper	Expected : 0˚	
		Validated : Within dimension tolerances	✓
		Not validated : Above dimension tolerances	
5	Colouration	Expected : None	
		Validated : Washable surface oxidation	✓
		Not validated : Persistent surface oxidation	
6	Untying of part	Expected : Fall down in US-bath	✓
		Validated : Fall down in US-bath with separation cut	
		Not validated : Mechanical removal	

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Task 2.3: Fundamental process development diamond ablation

- Status
  - T2.3 — Complete ✓
  - D2.3 confidential version — Document submitted ✓
  - D2.3 public version — Document submitted ✓

Work presented at the PhotonicWest 2018

William Scalbert, David Tanner, Fathima Laffir, Ronald Holtz, "Development of high power laser ablation process for polycrystalline diamond polishing: Part 1. Fundamental understanding of PCD ultra-short pulsed laser ablation,"Proc. SPIE 10525, High-Power Laser Materials Processing: Applications, Diagnostics, and Systems VII, 105250N (15 February 2018); doi:10.1117/12.2290197

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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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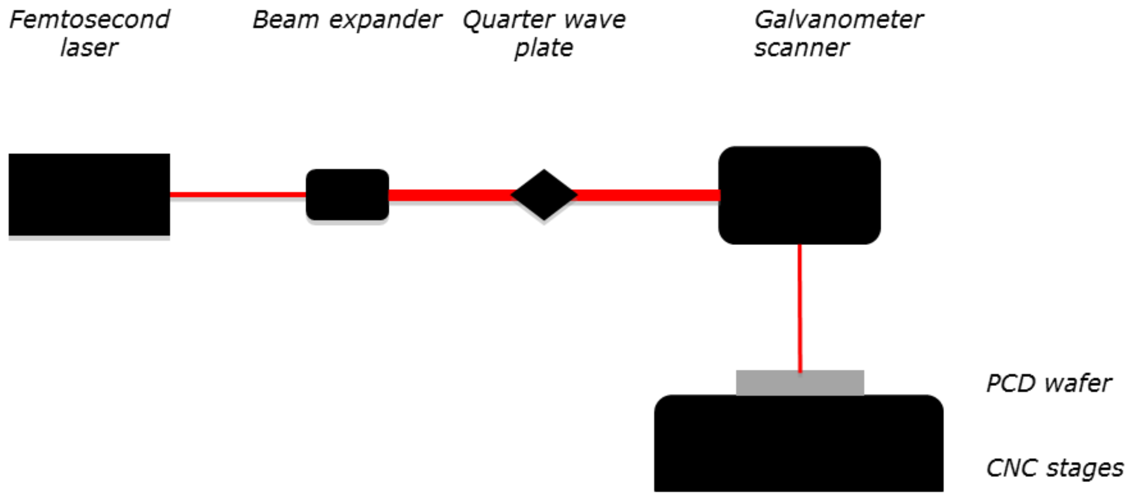
Task 2.3: Fundamental process development diamond ablation

- 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	Circular
M^2	< 1.2

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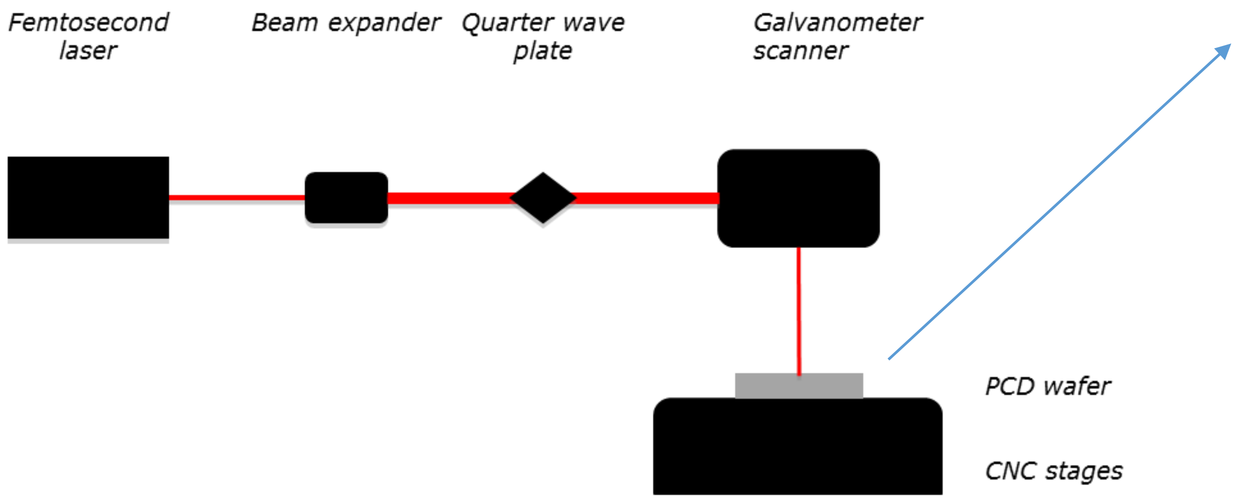
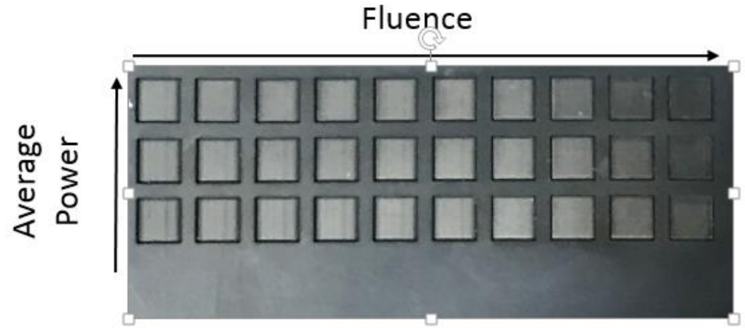


Measurement by scanning laser microscopy of :
- Ablated volume for removal rate calculation
- Surface roughness



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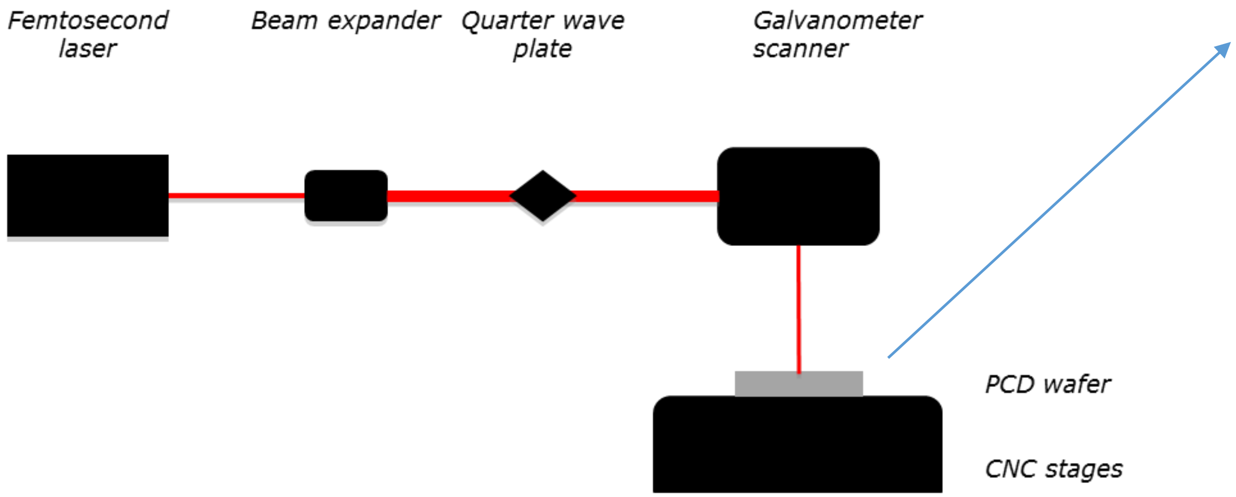
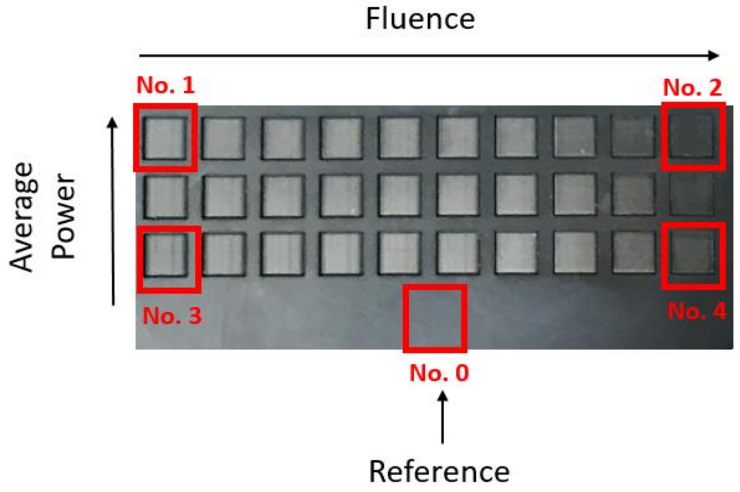


Physicochemical characterisation by Raman spectroscopy :
– Carbon structure



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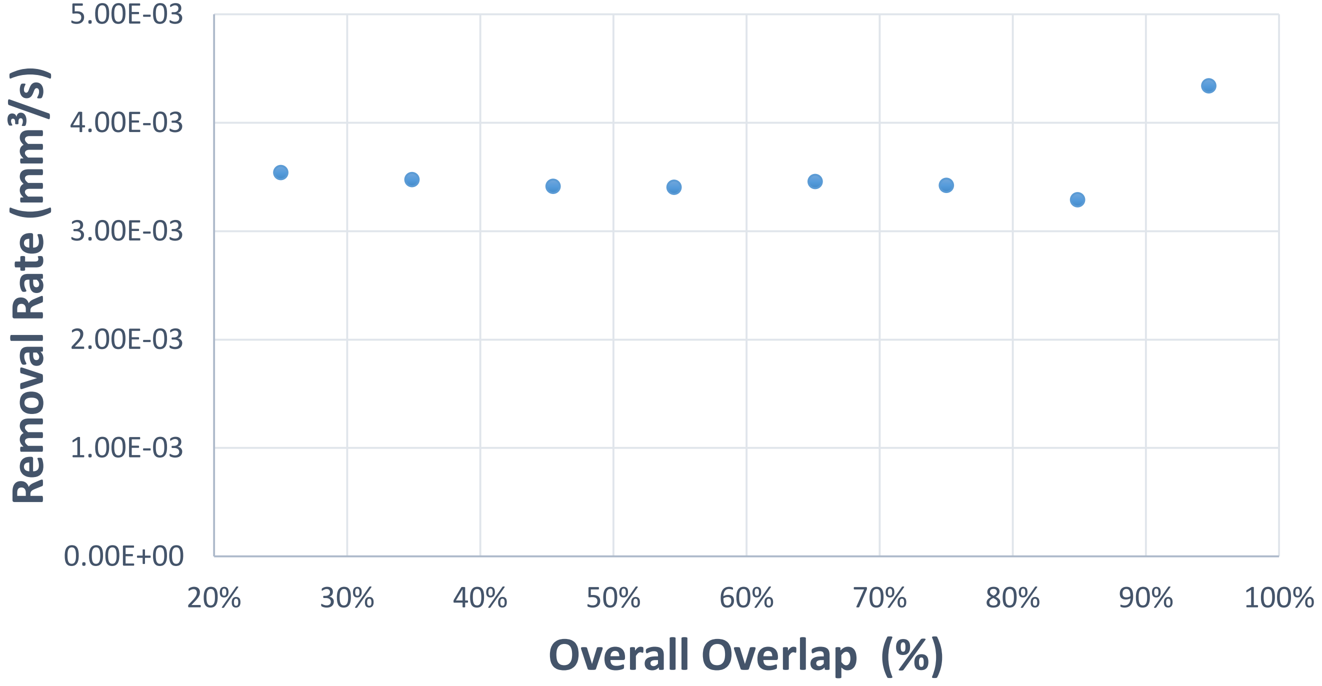
Task 2.3: Fundamental process development diamond ablation

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



Over 95% overlap :
- Increase of ablation rate

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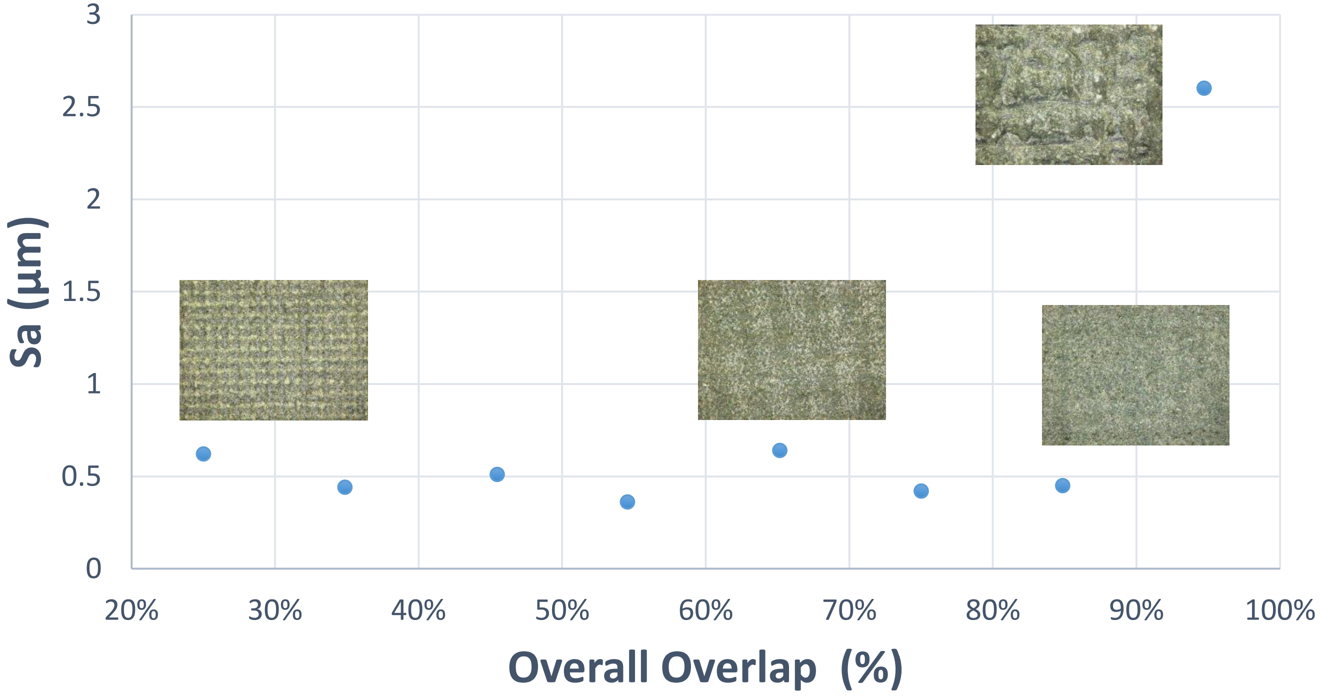
Task 2.3: Fundamental process development diamond ablation

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



Over 95% overlap :
- Increase of ablation rate
- 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

  - Measurements of the ablation rate variation with fluence

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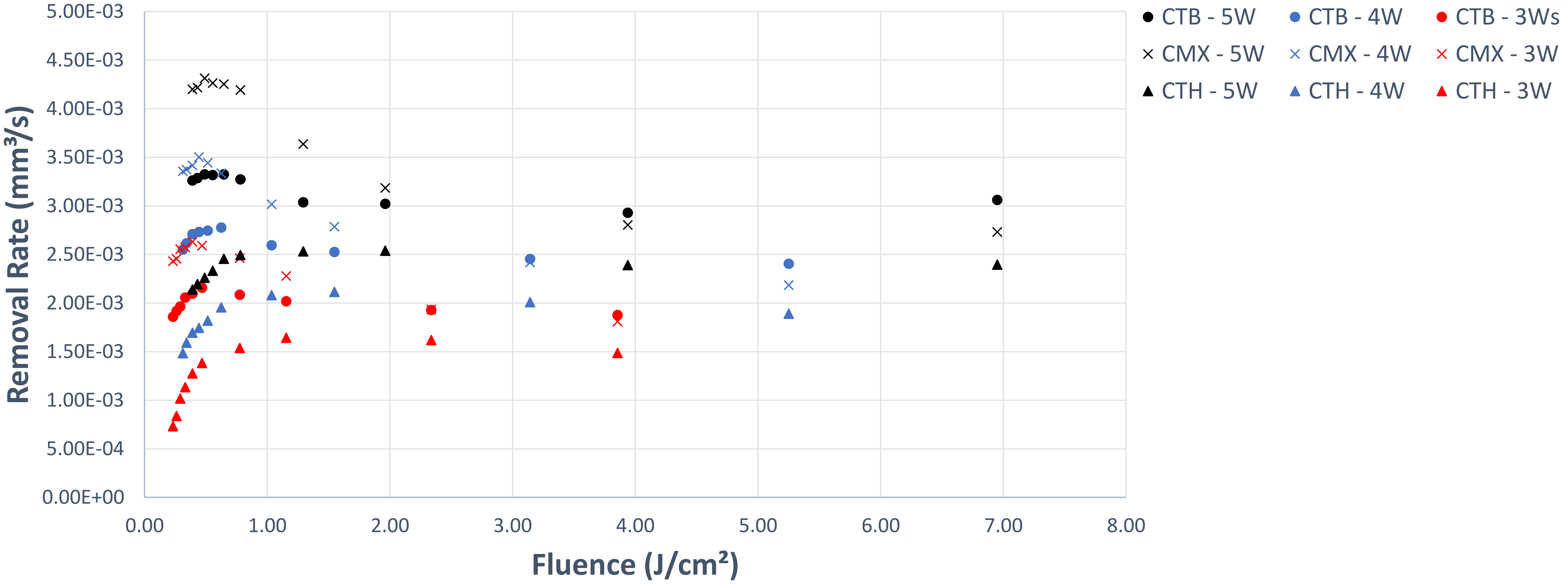
Task 2.3: Fundamental process development diamond ablation



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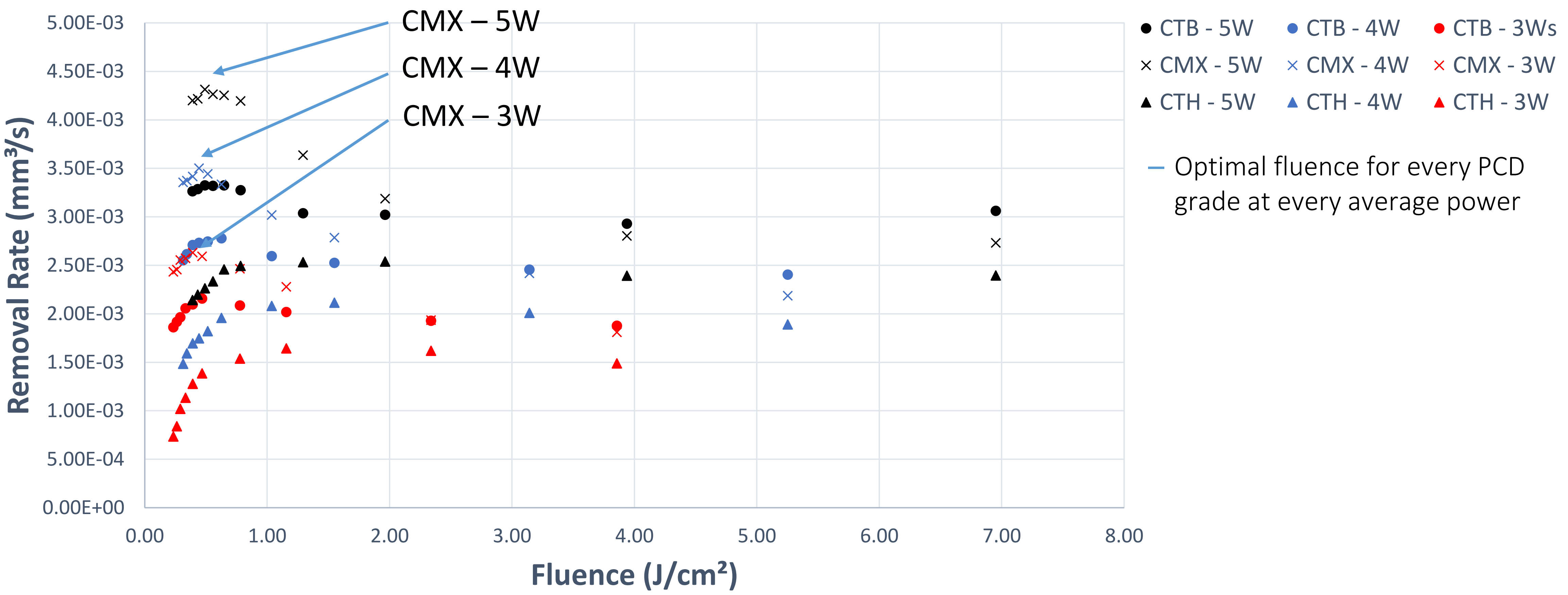

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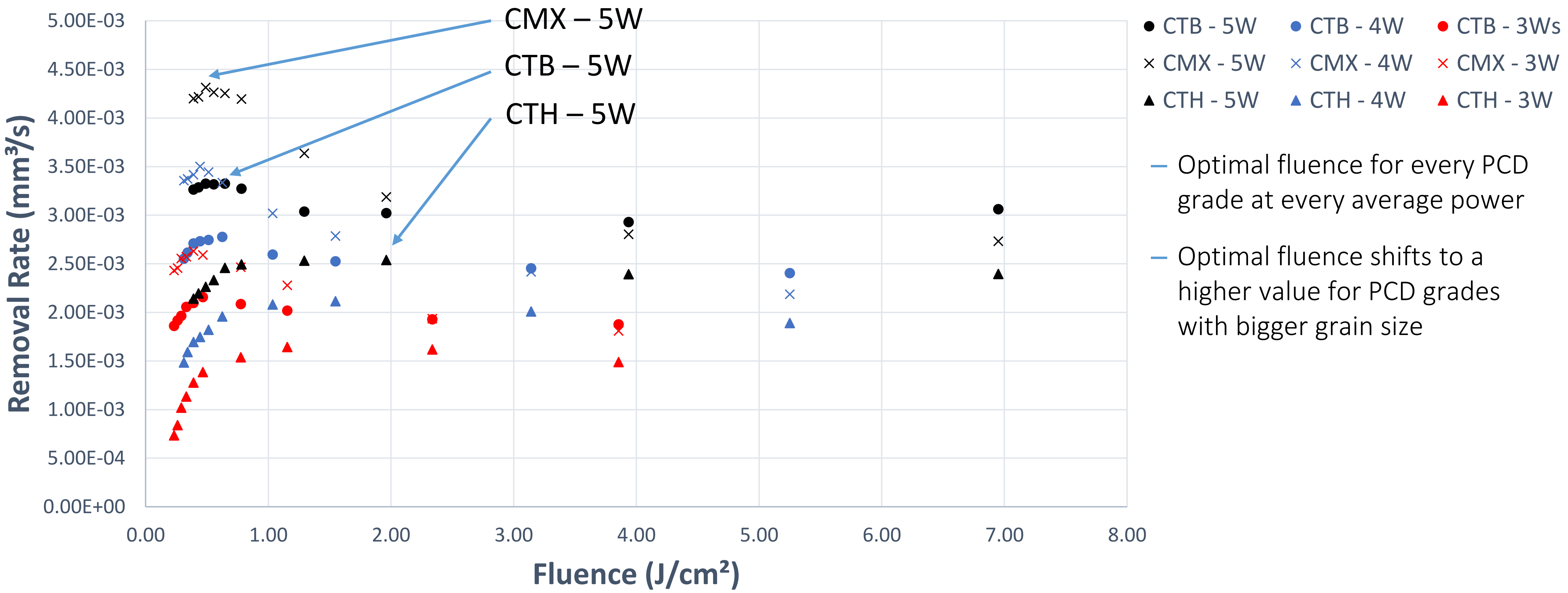
Task 2.3: Fundamental process development diamond ablation



- 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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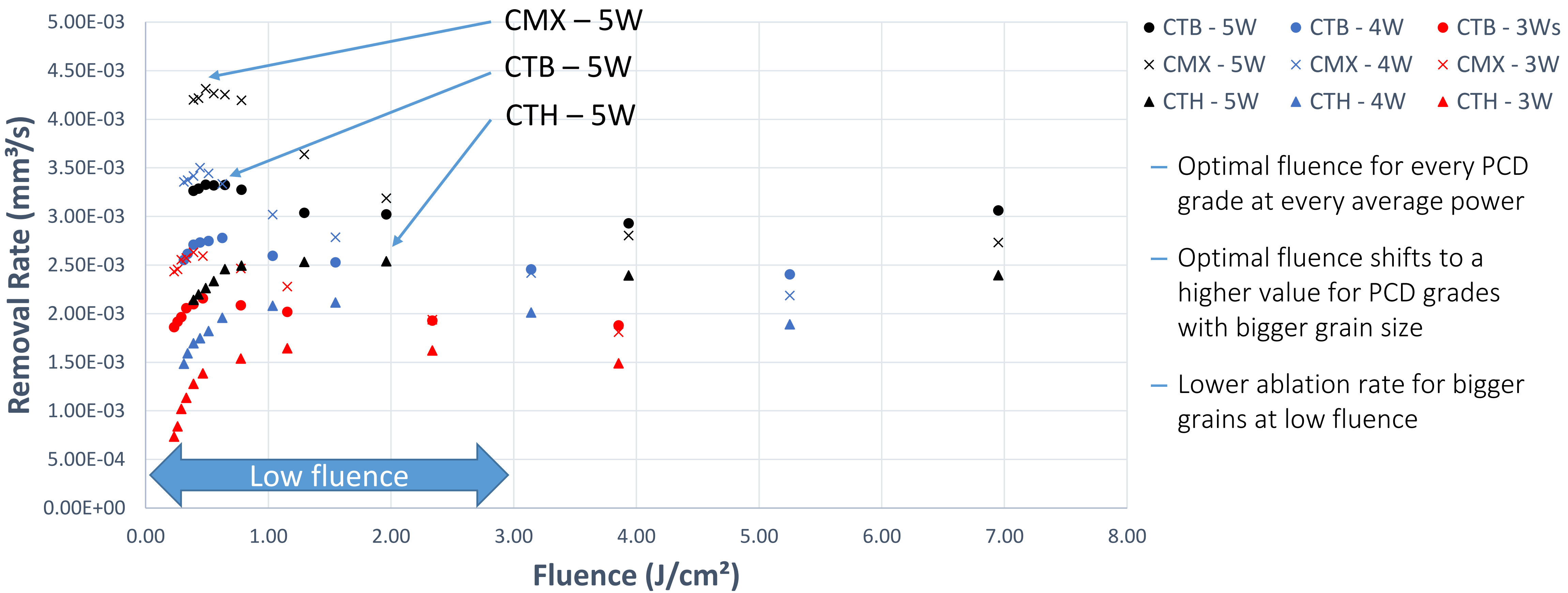
Task 2.3: Fundamental process development diamond ablation



- 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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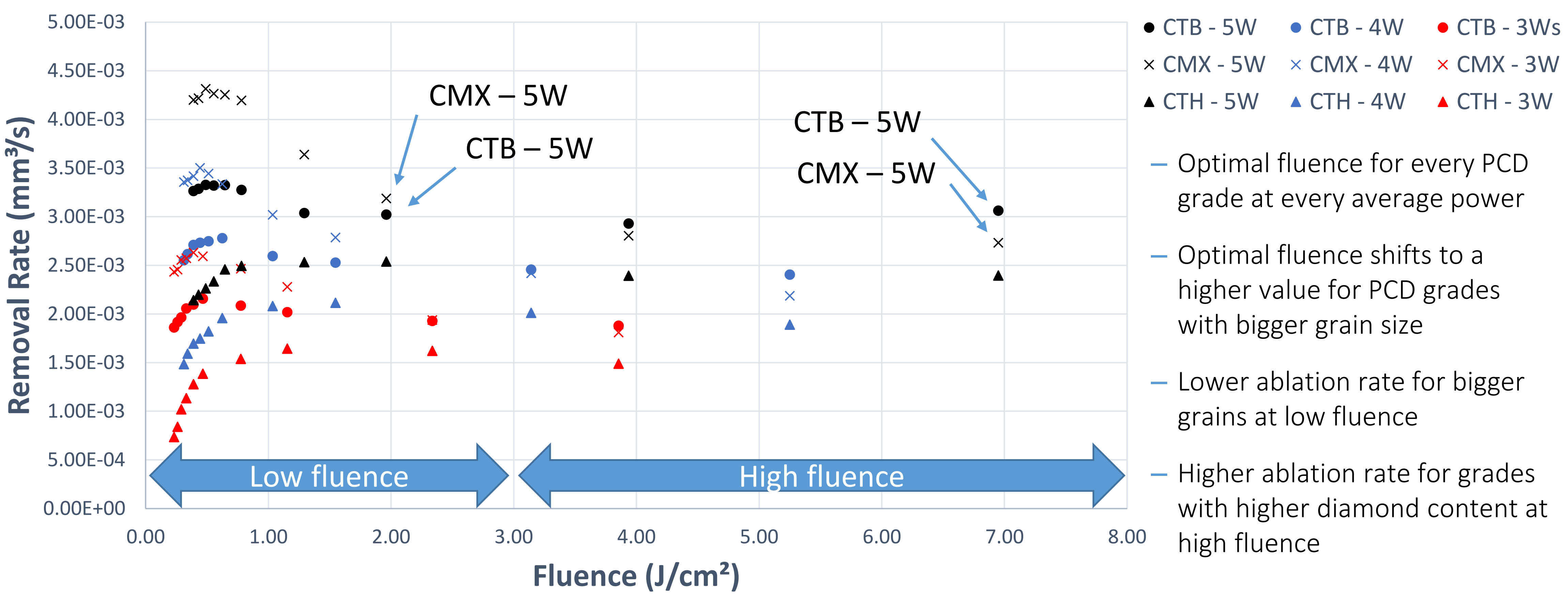

- Optimal fluence for every PCD grade at every average power
- Optimal fluence shifts to a higher value for PCD grades with bigger grain size
- Lower ablation rate for bigger grains at low fluence
- Higher ablation rate for grades with higher diamond content at high fluence

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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 10 µm
    - Optimal fluence expected between 0.5 J/cm^2 and 1 J/cm^2 for processing at high power
    - High power laser over 100 µJ pulse energy
    - Fluence over 1 J/cm^2 with 100 µJ and spot of 10 µm
    - 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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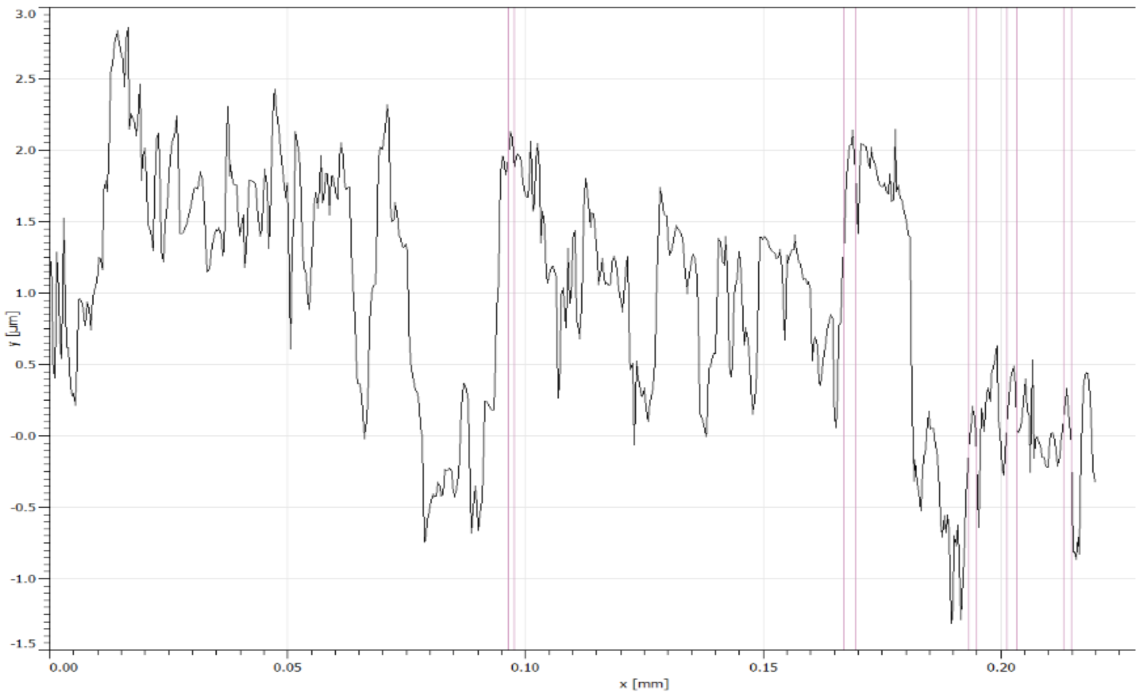
Task 2.3: Fundamental process development diamond ablation

- 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

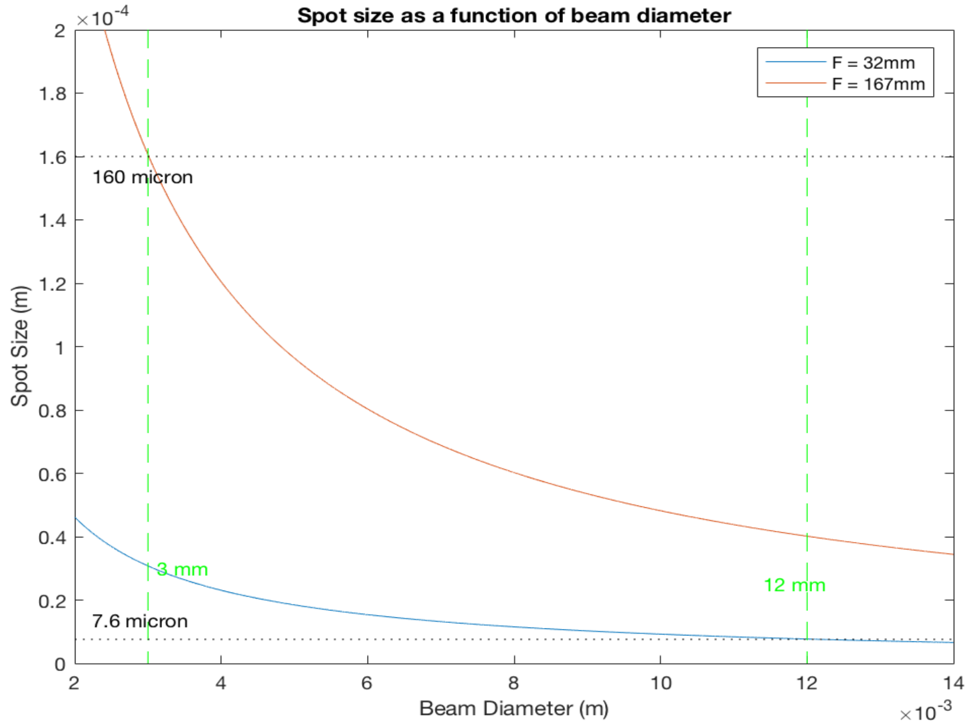
- Process Optimization and Limitation in Spot Size
  - Limitation in spot size and speed
    - Minimum can only reach 7.6µm.

    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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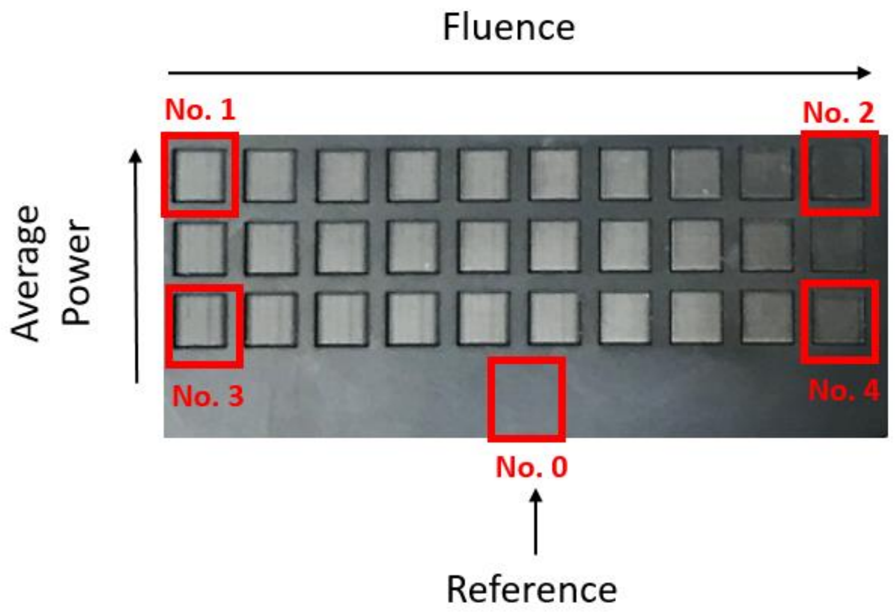
Task 2.3: Fundamental process development diamond ablation

- 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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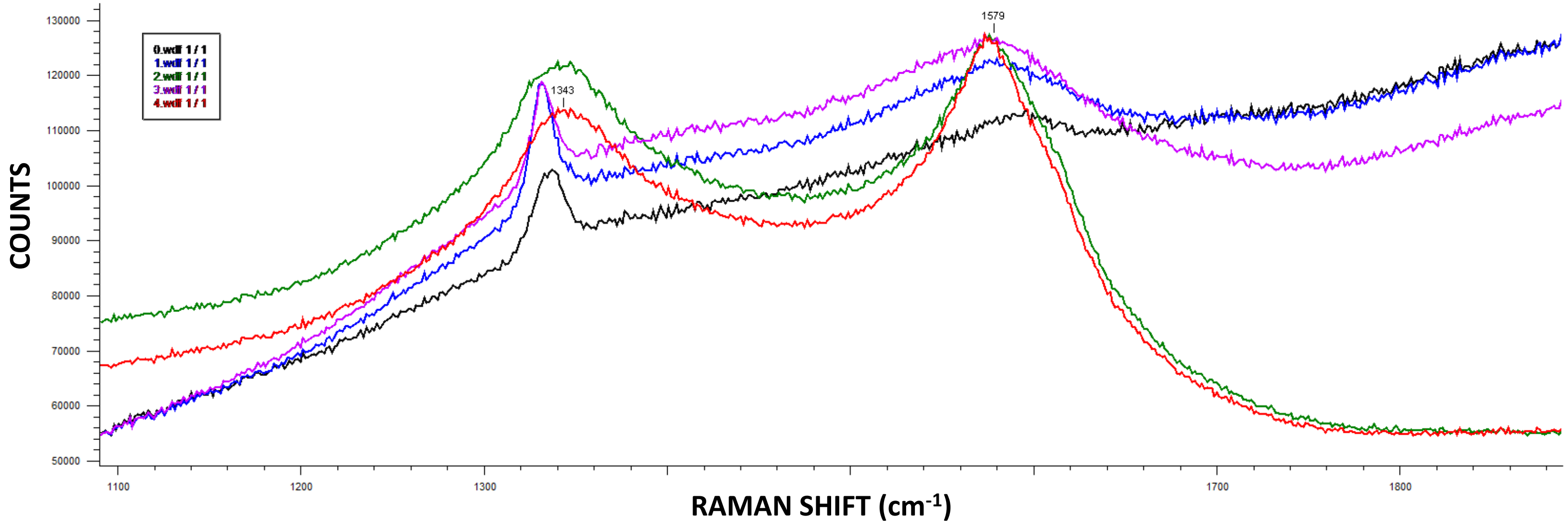
Task 2.3: Fundamental process development diamond ablation

- 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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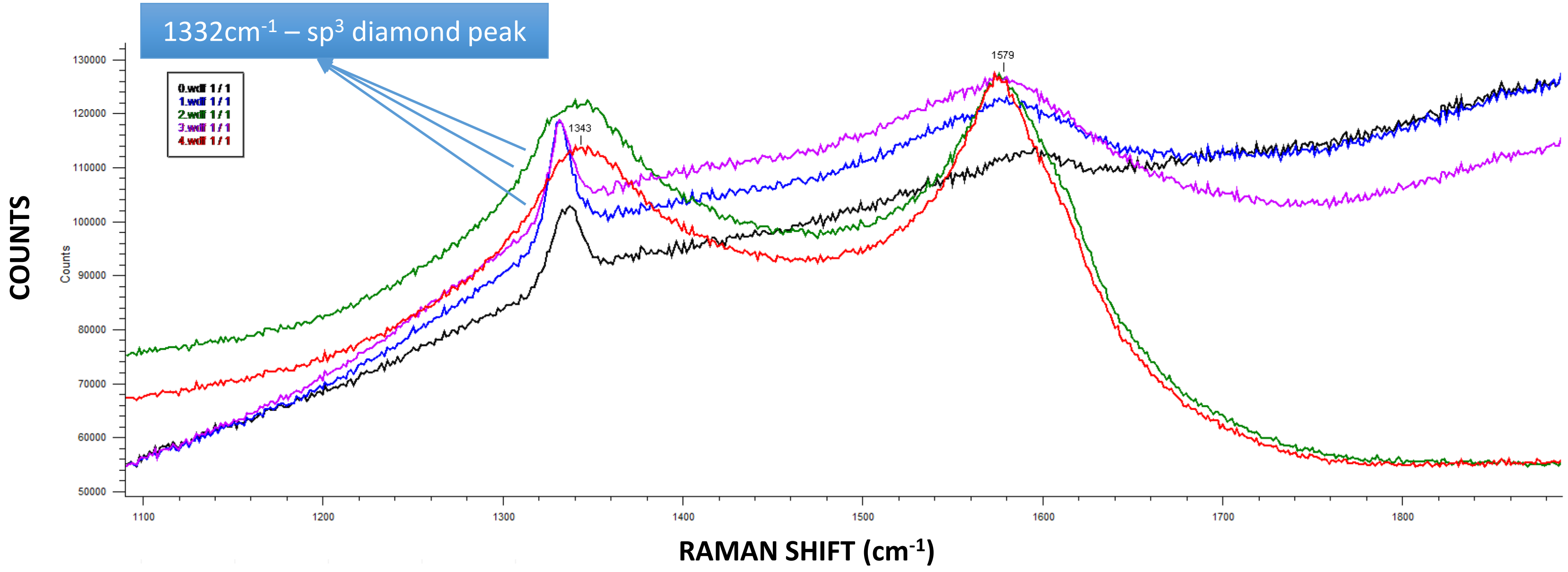
Task 2.3: Fundamental process development diamond ablation

- 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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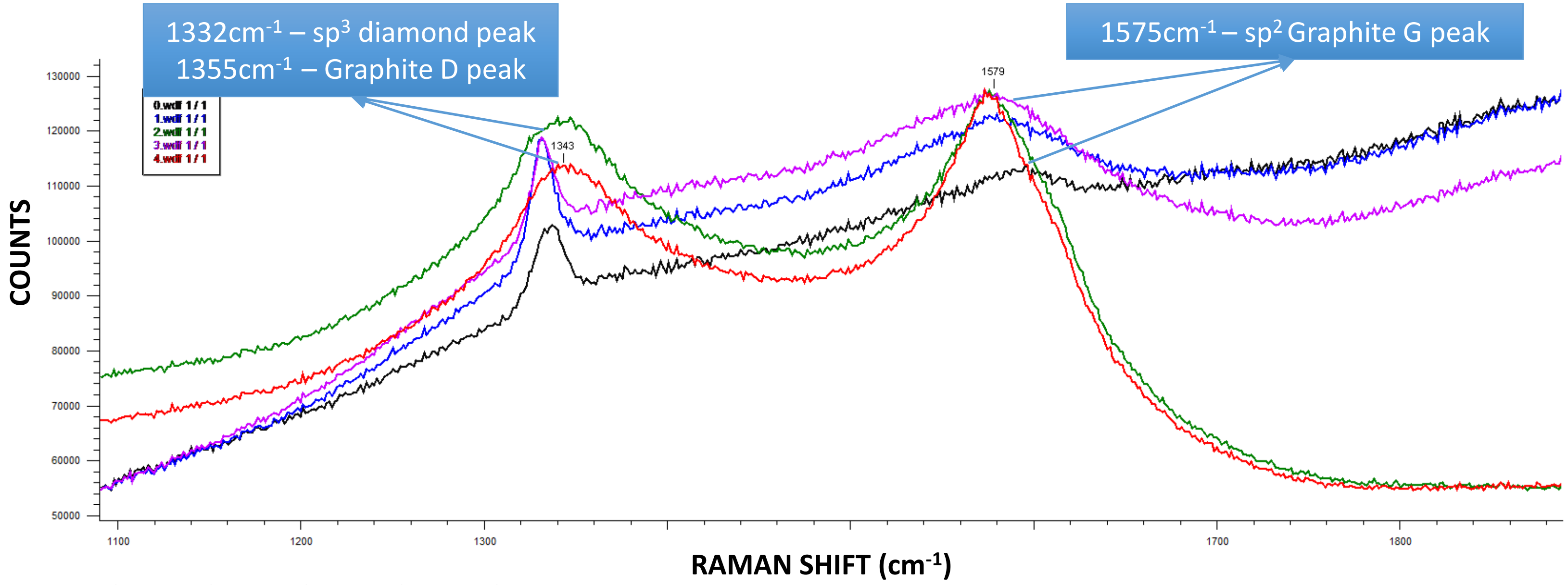

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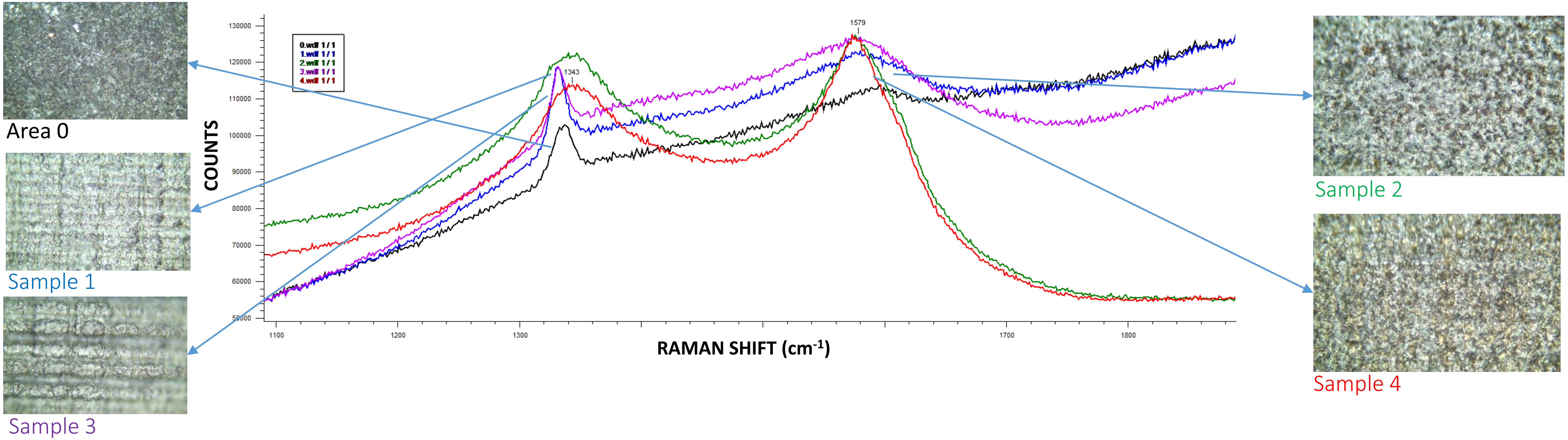

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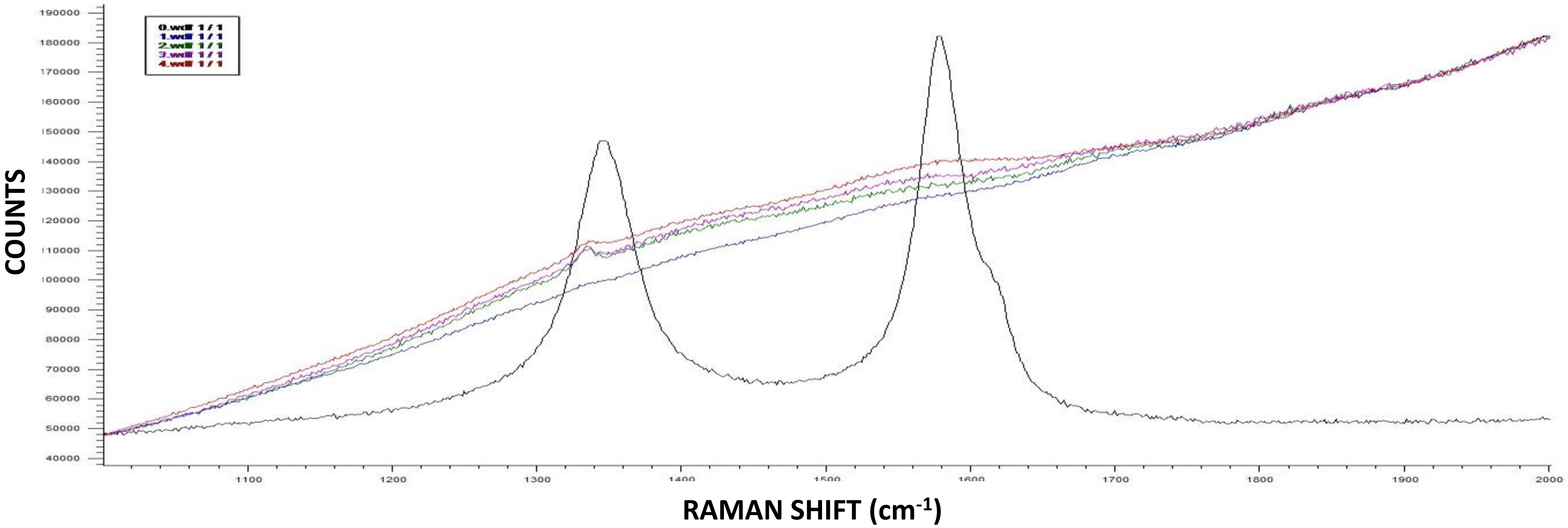

CTB010

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
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

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Task 2.3: Fundamental process development diamond ablation

- Conclusion

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Polarization	Circular	Circular	Circular

**Due to optical limitations

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Work Package 2

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

- Agenda:
  - Task 2.1: Fundamentals Si Processing
  - Task 2.2: Fundamentals Fine Cutting of Metals
  - Task 2.3: Fundamentals Diamond Ablation
  - **Task 2.4: Upscaling**

Partners involved:

BOSCH

lasea LASER ENGINEERING APPLICATIONS

CLASS 4 LASER See the light

elementsix™ a De Beers Group Company

IFSW

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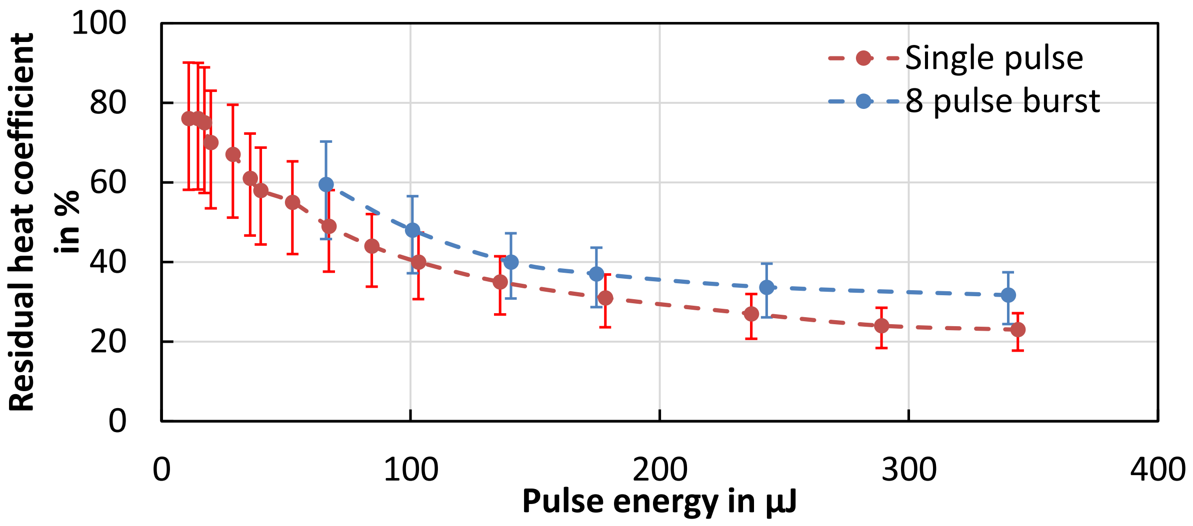
Task 2.4: Upscaling of applications for high throughput - Si Processing

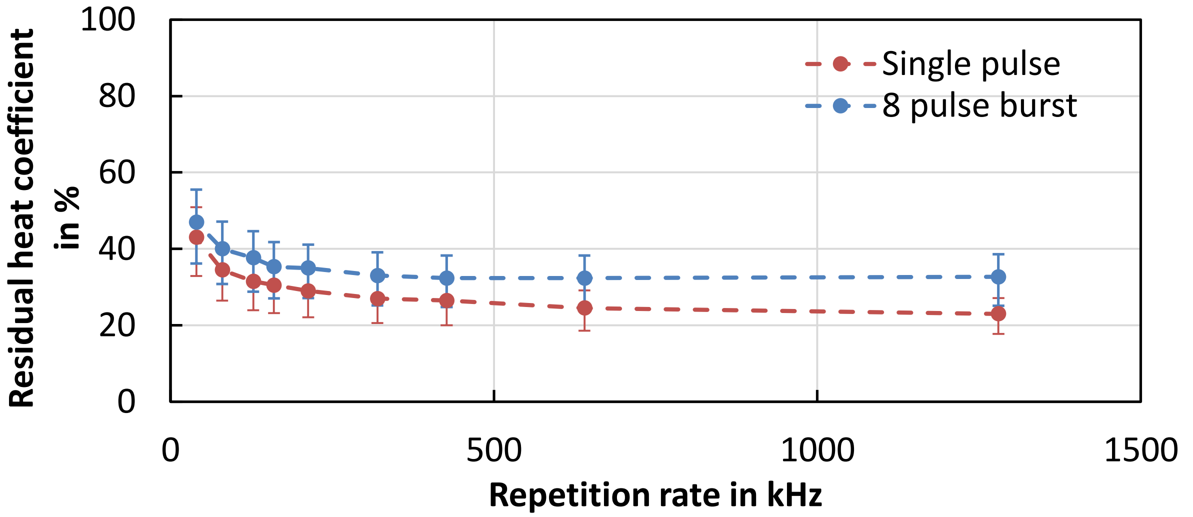
Heat accumulation – residual heat

- Calorimetric measurement of the residual heat
- Residual heat coefficient:

$$\eta_{resP} = \frac{E_{res}}{E_{P,total}}$$

➡ **More heat generated using burst mode**





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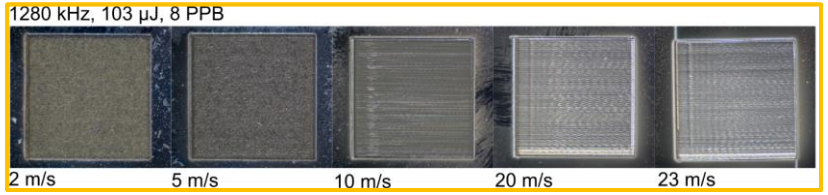
Task 2.4: Upscaling of applications for high throughput

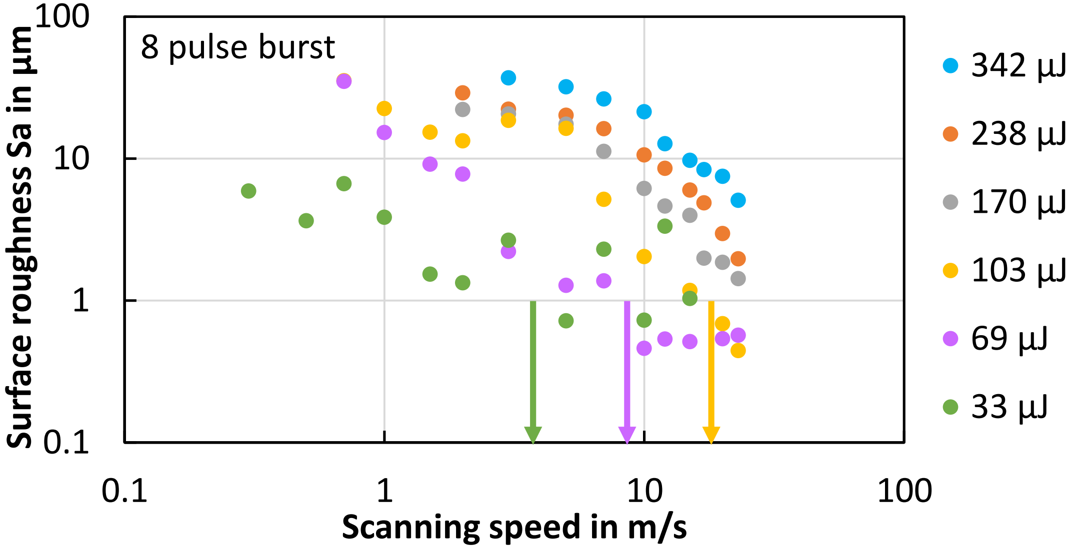
Heat accumulation between subsequent pulses – critical scanning speed

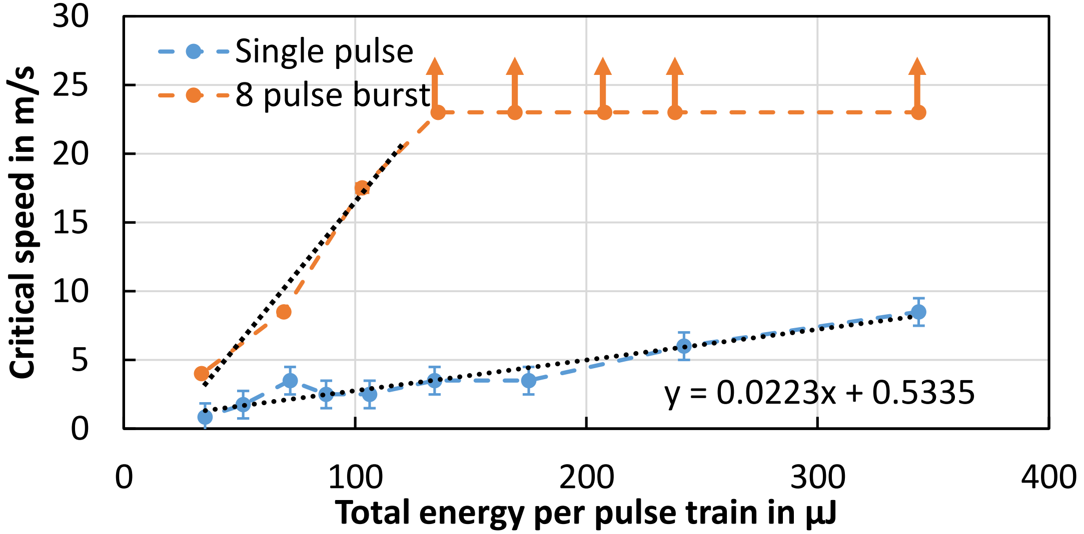
- Ablation of 5 mm x 5 mm squares with different speeds, pulse energies and repetition rates



- Evaluation of critical speed for HAP at Sa = 1 µm

Processing at 1 kW @ 1.28 MHz (1 PPB): 18 m/s
Processing at 1 kW @ 1.28 MHz (8 PPB): 148 m/s





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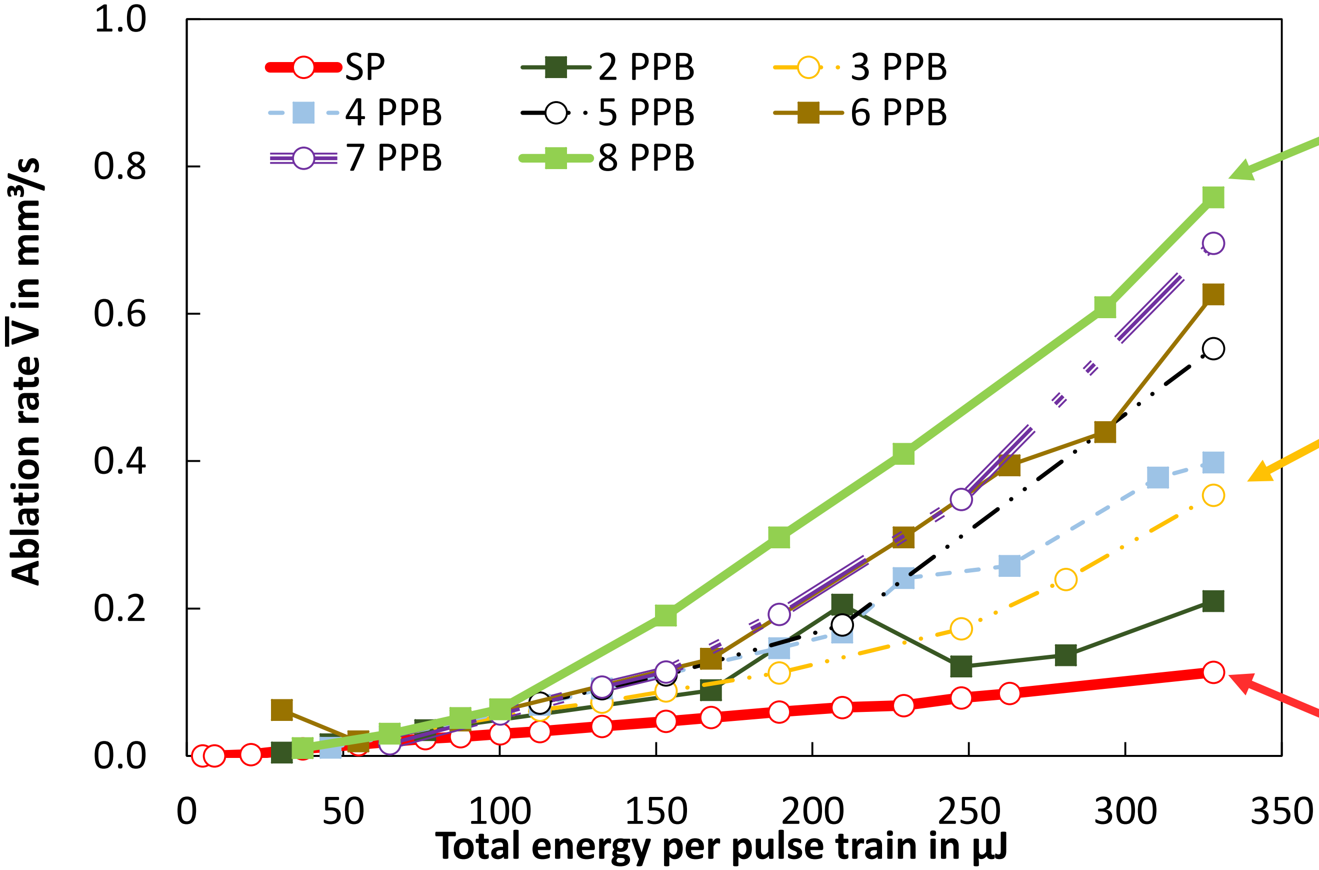
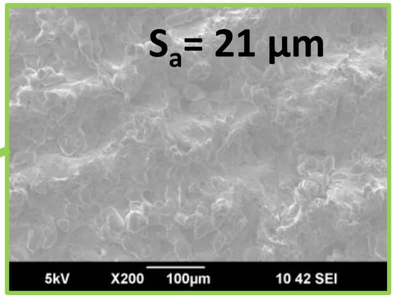
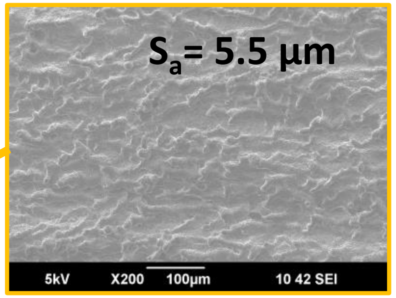
Task 2.4: Upscaling of applications for high throughput

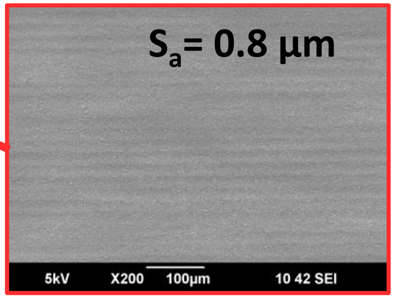
Ablation rate

- Ablation of 5 mm x 5 mm squares with different numbers of pulses per burst, pulse energies and repetition rates









➡ **More pulse energy leads to higher ablation rate**

➡ **Burst mode increases ablation rate significantly!**

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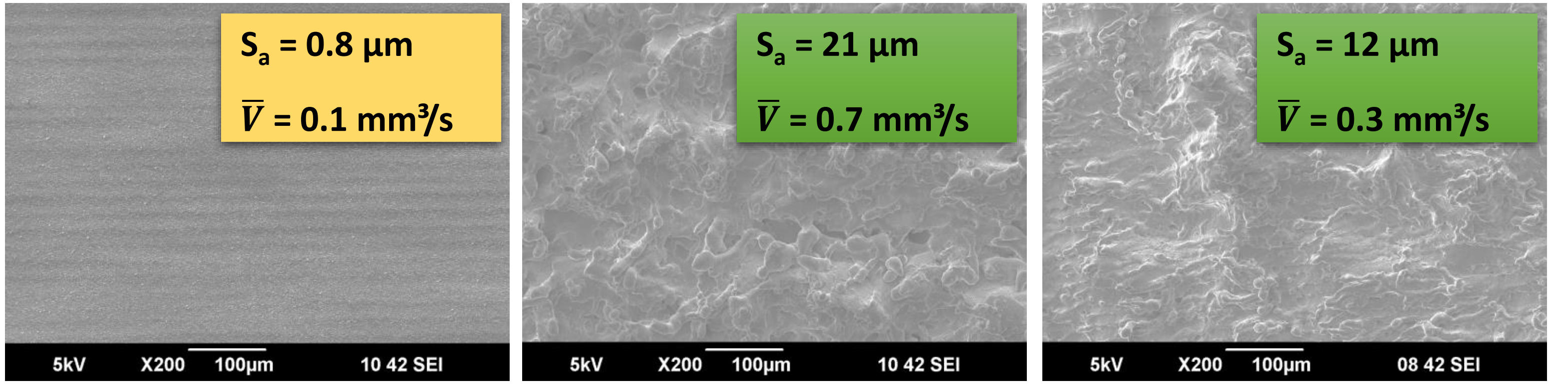
Task 2.4: Upscaling of applications for high throughput

Upscaling strategies

1. Use scanning speeds near the critical speed for the HAP effect → **no HA**
2. Use burst mode with high number of pulses per burst → **high ablation rate**
3. Reduce fluence to an optimum value by increasing the focused beam diameter
   → **good surface quality**

Outlook for further process improvement: Two-step processing.

Single pulses v_s= 9 m/s | 7 pulses per burst v_s= 9 m/s | 7 pulses per burst v_s= 15 m/s



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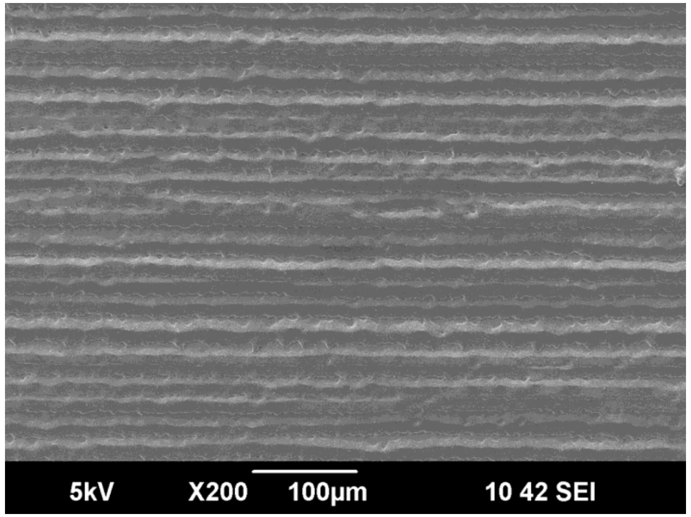
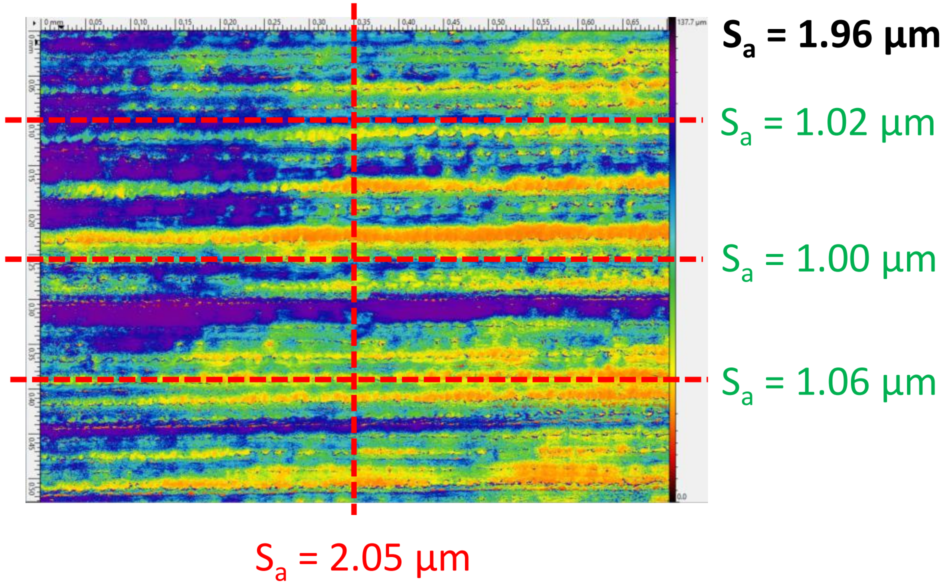
Task 2.4: Upscaling of applications for high throughput

Example of an optimized Si ablation process

Laser / process parameters	Value	Unit
Average laser power	430	W
Pulse duration	320	fs
Intraburst distance	25	ns
Number of pulses per burst	7	
Scan velocity	15	m/s
Hatching distance	20	µm
Repetition rate	1280	kHz
Spot diameter	150	µm
Pulse energy per burst	336	µJ
Pulse energy	48	µJ
Energy specific ablated volume	4,32	mm³/kJ
Ablation rate	0,63	mm³/s
Surface roughness S_a	1,96	µm





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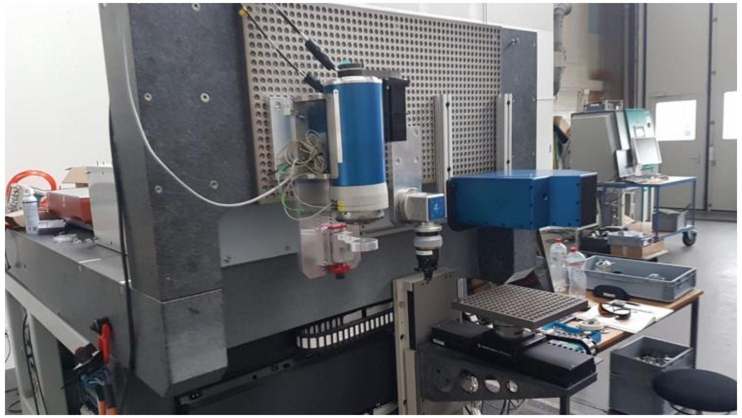
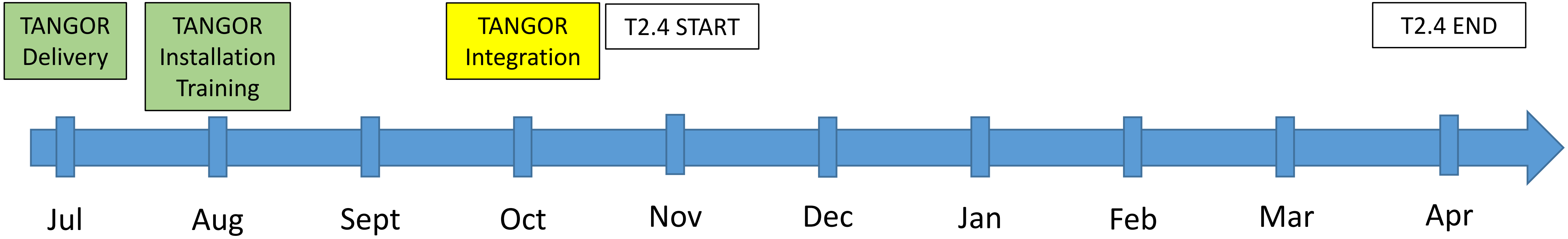
Task 2.4: Upscaling of applications for high throughput - Diamond ablation

- Pre-work
  - Agreement between AMP, C4L and E6 for installation of industrial laser Tangor 100W
  - Follow up installation and integration according to E6 specifications
- Schedule of T2.4 for E6





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WP 2 - Deliverables

Deliverable	Title	Due	Status	Comment
D2.1	Process limits 3D Si processing	M24 (01.2018)	Submitted	
D2.2	Process limits fine cutting of metal	M24 (01.2018)	Submitted	
D2.3	Process limits diamond processing	M24 (01.2018)	Submitted	
D2.4	Processing strategies for high power 3D Si processing	M30 (07.2018)	Submitted	Finalized M31.
D2.5	Processing strategies for high power fine cutting of metal	M30 (07.2018)	Delayed	Planned for M39
D2.6	Processing strategies for high power diamond processing	M30 (07.2018)	Delayed	Planned for M39

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WP 2 - Milestones

Mile stone	Title	Due	Status	Comment
MS25	High quality 3D Si processing with low average power	M24 (01.2018)	Achieved	
MS26	High quality fine cutting of metal with low average power	M24 (01.2018)	Achieved	
MS27	High quality diamond processing with low average power	M24 (01.2018)	Achieved	
MS38	High quality 3D Si processing with high average power	M30 (07.2018)	Not achieved	Phase 1 (M22-M32): 450 W Phase 2 (later): 1000 W
MS39	High quality fine cutting of metal with high average power	M30 (07.2018)	Not achieved	Planned for M39
MS40	High quality diamond processing with high average power	M30 (07.2018)	Not achieved	Planned for M39

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