Deliverable 1.2: Process and System Specifications

Dissemination Level: Public (PU)

<u>Owner</u>

Name: William Scalbert

Lead Beneficiary: Element Six

Phone: +353 (0) 87 700 8216

E-mail: william.scalbert @e6.com

<u>Context</u>

Author(s): W. Scalbert (E6); M.Lustfeld (Bosch); N. Dury (C4L)

Work Package: WP1

Task: T1.2 Process and System Specification

<u>Document Status</u>

Version: 1.0

Last modified: 06/03/17

Status: Final

Approved by: Marwan Abdou-Ahmed

Date Approved: 14/03/17

Declaration: Any work or result described therein is genuinely a result of the Hiperdias project. Any other source will be properly referenced where and when relevant

Table of Contents

1. Version History 3
2. Scope 4
3. Bosch 5
4. Class 4 Laser AG 9
5. Element Six Ltd 15
   5.1. Laser specifications 15
6. Summary and Discussion 22

1. Version History

Version	Summary of Change	Written By	Approver	Date
0.1	First draft	W. Scalbert		05.12.2016
0.2	Bosch perspective (Section 3)	M. Lustfeld	A. Ametowobla	24.01.2017
0.3	Second draft	W. Scalbert	A. White Head	31.01.2017
0.4	C4L Perspective	N. Dury		03.02.2017
0.5	Marwan’s correction	M. Abdou Ahmed		12.02.2017
0.6	C4L corrections	N. Dury		13.02.17
0.7	E6 corrections	W. Scalbert		14.02.2017
0.8	Bosch corrections	M. Lustfeld		15.02.17
0.9	E6 corrections	W. Scalbert		05.03.2017
1.0	First issue		M. Abdou-Ahmed	06/03/17

2. Scope

The deliverable D1.2 intends to review the specifications stated in deliverable D1.1 by the three end-users (Bosch, Class 4 Laser and Element Six) at the beginning of the project.

As these specifications will condition the future upcoming developments of the end-users' process (WP2), and of the laser and system (WP3-7) by the other partners, the three end-users will support their required specifications by data proving the necessity of such specifications toward the achievement of their process requirements. Development progress from WP2 and WP7 will highlight some relations between the end-users' specifications and requirements. In the light of these analyses, some requirements will be agreed, discussed, confronted or even modified if already proven unrealistic.

Therefore, the specifications will finally be established: Laser source specifications will be reviewed in a first part, followed by the optics and system technology specifications in a second part.

3. Bosch

The 3D silicon processing machine to be developed in HIPERDIAS is supposed to serve as an example of a device to be used in mass manufacturing of high-precision products such as sensors and Microelectromechanical systems (MEMS). As such, it has to meet strict requirements:

- Requirements concerning the process: High productivity at very high precision. These criteria are tracked by key performance indicators (KPI's) as introduced in D1.1 and further evaluated with experimental data in D1.3. A short overview is given in section 3.1. The components decisive for whether or not the challenging KPI values can be attained are the laser source and the beam delivery system. These are further discussed in sections 3.2 and 3.3.
- Requirements concerning the machinery: Systems to be implemented in mass production need to comply with a set of challenging and diverse requirements. They need to ensure a safe operation environment for any staff in contact with the systems, compatibility with the laser process and with all the manufacturing systems in its proximity, very high reliability, fast discharge and reloading of samples, and implementation of a quality control system. These requirements are discussed in section 3.4 – 3.7.

This deliverable presents a mostly qualitative overview of process and system requirements. Quantitative assessments of the process parameters, in particular with regard to reaching the KPI's are provided in deliverable D1.3. Further in-depth experimental evaluations will be discussed in deliverable 2.1 (process development).

3.1 Process requirements

Table 1: Overview of the KPI's to be attained (see also deliverable D1.1)

Key Performance Indicator	Unit	Target Value
average ablation rate	mm^3/s	≥1
peak ablation rate	mm^3/s	≥3
shape deviation	µm	≤10 (waviness)
surface roughness	µm	≤1
thickness of surface damage	µm	≤1
Surface defects (e.g. pores, holes > 1 µm diam.)	$1/mm^2$	None
edge radius (minimum achievable)	µm	as small as possible
edge-steepness (maximum achievable)	degree	≥ 70

A model geometry has been defined covering relevant geometry features and machining challenges that will have to be met in the industrial environment (**Table 1**, for details of the model geometry see deliverables D1.1 and D1.3). Both laser source and beam delivery system have been attributed for in this geometry. Regarding the laser source, the test geometry features a high total ablation volume, inclined planes, through holes, and sharp corner edges. Its sizing is typical of industrial geometries with dimensions of up to several mm in all directions. An inclined plane serves to track shape deviation with respect to the inclination angle, symmetry (left / right) and edge-steepness. The through-holes mainly require high ablation rates so to remove the material until complete penetration of the wafer as quickly as possible. Additionally, the geometry allows evaluation of the beam deflection system since a high number of corners / edges is required to be implemented with a high geometrical accuracy. This in turn requires highly precise positioning and fast switching of the laser beam.

3.2 Laser source development

As most promising laser technique for high-resolution material machining, Ultra-Short Pulsed (USP) lasers (pulse duration of few picoseconds and shorter) were considered as laser beam source. Such systems are considered ideal when it comes to controlling the energy deposition and respective surficial and subsurficial (several µm beneath the surface) modifications of a material such as Si. The goal in these applications is to tailor the surface characteristics to serve a particular purpose by controlling the energy delivery from the laser source towards the various degrees of freedom of the illuminated material.

Laser-matter interaction with such pulsed lasers triggers a variety of time-scale dependent processes influenced by the applied conditions (i.e. fluence, pulse duration, number of pulses, etc). Owing to the intrinsic properties of focused ultra-short laser pulses, they are more flexible and more accurate than any other machining method when micrometre precision is required as in the case of 3D-silicon microprocessing. Previous studies determined a maximum achievable average intrinsic ablation rate for silicon during ultrafast laser ablation in the range of 1 – 3 mm^3/kJ of input laser energy. Thus, in the final stage, the targeted laser power of 1000W is fully required to reach the targeted average ablation rate of 1 mm^3/s.

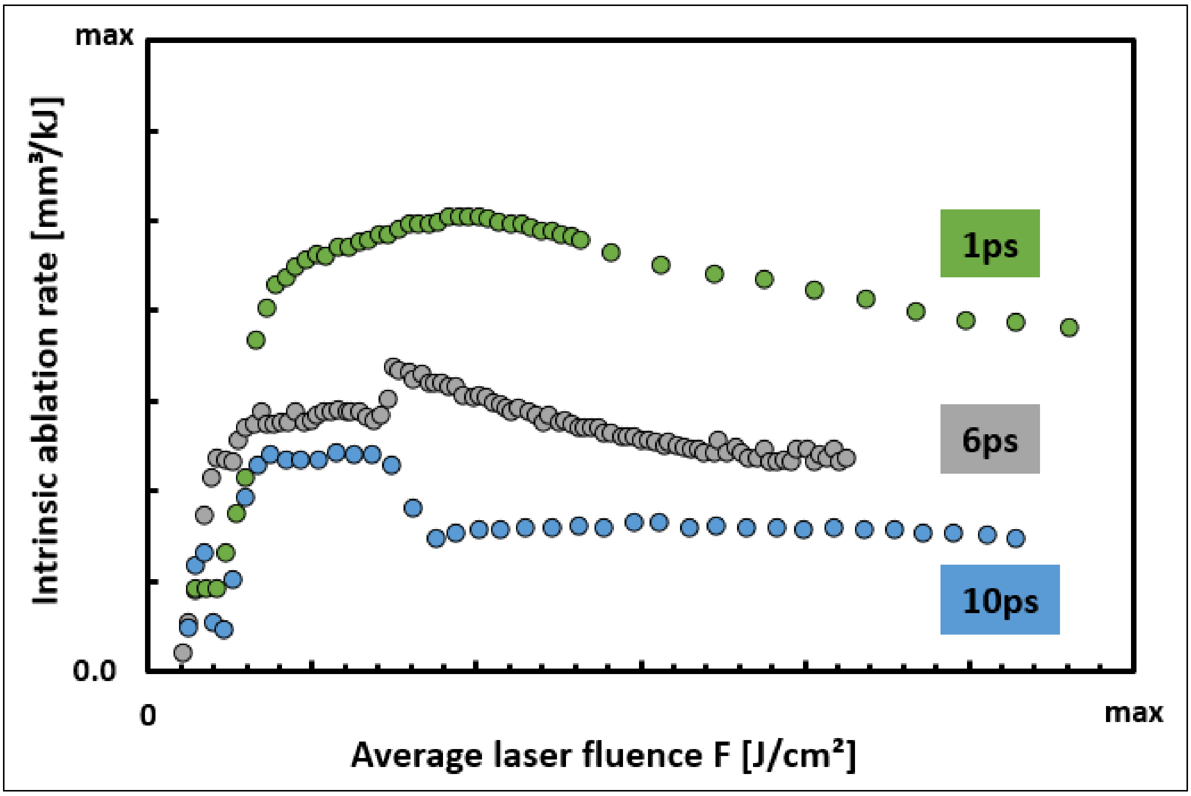


Figure 1: Intrinsic ablation rate as a function of average laser fluence for different pulse durations

A thorough experimental analysis documented in D1.3 focused on how the different laser parameters affect the average ablation rate and quality of the obtained surface. Three different laser sources with average power of 40 W or 50 W each, near IR wavelength (1030 nm to 1064 nm), and different pulse duration (1 ps, 6 ps, 10 ps) were investigated. For the experimental investigations, the average laser power of all sources was varied between minimum and maximum power in up to 50 steps. Thereby, at a given laser focal spot size, the average laser fluence on the material was varied between 0 and the maximum attainable value at full power. Both intrinsic ablation rate and surface roughness were determined for all fluence values as exemplarily shown in Figure 1.

These results show that the ablation rate increases with decreasing values of pulse duration. In all cases the ablation rate reaches an optimum value at a relatively low fluence, in agreement with literature data regarding to metal processing[1]. Thus, optimum performance would be achieved using a laser source with a short pulse duration focused to relatively low fluence values. However, regarding to surface quality (i.e. roughness, waviness, etc.) such a clear correlation has not yet been established. The specific condition of the silicon surface after 3D processing rather is influenced by a number of process parameters, mainly pulse duration and fluence, and optimum conditions are found for varying combinations of these influential parameters. Generally, regarding laser pulse duration, there appears to be a trade-off between productivity (high productivity at low pulse duration) and quality (high-quality at longer pulse duration) with the optimum parameter combination yet to be determined within WP 2.1.

Additional experiments were carried out with a laser source operating in burst mode. This implies that instead of single pulses, a set of several pulses (at least two) are being emitted in a very short time frame (≤ 100 ns). The emission frequency of these bursts can be varied in the same range as pulses in single-pulse mode (hundreds of kHz). Experiments performed with a 10 ps laser indicate a strong impact of the burst mode on the ablation rate, which depends both on the number of pulses per burst and the intraburst distance. Exact relations are yet to be examined within WP 2.1. Although, the burst mode seems to significantly increase the overall ablation rate.

Taking all of the mentioned parameter variations into account, the target intrinsic ablation rates of 3 mm^3/kJ (peak) and 1 mm^3/kJ (average) appear to be attainable, reaching the productivity KPI's for the 1000 W source pursued within HIPERDIAS. As scanner technology is a limiting factor for high pulse repetition rates, requiring fast scanning velocities, the maximum laser power should be available at pulse repetition frequencies of ≤ 2000 kHz. Thus, high maximum pulse energies of ≥ 0.5 mJ are required. The laser wavelength is assumed to be in the 1030 nm regime. However, as also frequency doubled and tripled radiation are being investigated within WP2.1, the implementation of frequency conversion should at least be considered.

3.4 Beam delivery, scanning and control

The optical path of the laser machining station naturally is required to handle the very high laser power without damage to optical elements and without influence of laser power variations on the phase front distribution. Thus, low absorption coatings need to be implemented on lenses and mirrors. All components have to be suitable for pulse durations down to 1 ps at a pulse energy of 0.5 mJ regarding the damage threshold and dispersion. According to experience this implies the

[1] Neuenschwander, Beat, et al. "Optimization of the volume ablation rate for metals at different laser pulse-durations from ps to fs." *SPIE LASE*. International Society for Optics and Photonics, 2012.

requirement of high-quality fused silica for all transmitting optical elements (e.g. lenses, protective glass) and high-quality coatings for all transmitting and reflecting optical elements (e.g. polarization optics, mirrors).

The beam deflection system (most probably galvanometer scanner) is required to provide very high dynamics and a high positioning accuracy, at least delivering state-of-the-art performance of the best scanner systems currently available on the market. To handle the high average power, the beam should exhibit a large diameter (e.g. >10 mm). All apertures must be larger than twice the beam passing the aperture to avoid diffraction. Using a large focal length of the focusing device (e.g. 500 mm) may prove beneficial to achieve highest scanning dynamics with large incoming beam sizes.

Tight specifications on product geometry accuracy will presumably require synchronization of laser performance (pulse energy, pulse repetition frequency) with scanner dynamics, in order to avoid the formation of trenches during acceleration and deceleration of the scanning mirrors. Thus, fast and flexible triggering (ideal: pulse on demand) and fast power variation are necessary.

3.5 Safety

In order to handle the high ablated volumes at maximum laser power, a sufficiently powerful suction system is required to avoid detrimental effects from fumes and residues both to the operating staff and to the product. Further, care has to be taken regarding possible hazards due to the explosiveness of silicon dust. It is known that material processing with high-power ultrafast lasers emits soft X-ray radiation. Thus, proper protection has to be taken into account. Further definition of laser safety and x-ray shielding requirements should be done when optimum processing parameters e.g. laser pulse energy, pulse duration, and spot size have been determined.

3.6 Sample fixation and movement

In order to allow for the processing of typical substrates, a sample fixation should be designed which is capable of handling and securely clamping 200 mm silicon wafer. In order to easily access different positions on the work piece and to allow for a quick adjustment of the focal position, a xyz axis system with a state-of-the-art NC control should be incorporated into the laser processing machine.

3.7 Further requirements

The laser processing machine should be equipped with an in-situ camera system to monitor the ablation process. A further increase of efficiency and user friendliness will be achieved by providing a quick manual axis movement control (e.g. a “hand-wheel”). The HMI of the machine should allow both for quick manual set up of laser programs as well as batch programming for larger parameter variations, including the movement of the axis system (e.g. set up of automatic focus search). Furthermore, the machine should fulfil the common requirements regarding laser and electrical safety. These issues are discussed in more details within the scope of WP6.

4. Class 4 Laser AG

The fine cutting processing machine develop within HIPERDIAS shall be the base for a new laser production machine that will serve the watch industry, but is also intended to profit to other markets in need of very high qualitative fine cut of metallic and non-metallic elements with a high throughput as the medical industry for instance (in perspective with today technologies). This new processing system should enable to use the full advantage of laser technology (flexibility, absence of tooling, no contact process…) while competing with the quality level of traditional machining (milling, etching), and this at an industrial production pace especially on functional parts.
This process also requires highly precise positioning, high repeatability, a high frequency and energy of the laser as well as a fast switching of the beam.

The geometries chosen cover a broad range of geometrical features and machining challenges, such as high accuracy, small features, functional surfaces, through holes, a relative high thickness…

- Requirements concerning the process: Very high precision and high qualitative surface quality. These criteria are tracked by key performance indicators (KPI's) which have been introduced in D1.1 and further evaluated in D1.3. An overview is given in section 4.1. Whether or not the challenging KPI values can be attained depend on the laser source and the motion and beam delivery system. These aspects are further discussed in sections 4.2 and 4.3.

- Requirements concerning the laser: previous trials and studies gave an overview in which range the laser parameters should be. These aspects are discussed in section 4.4.

- Requirements concerning the machinery: The developed system should be with manual loading and unloading, as the loading requirement vary a lot from part to part. This system can be a Class 4 safety level (work with goggles required) or a class 1 (no goggles required) if working in Class 4 level, the goggles will be provided by C4L. The system must be able to run in an industrial environment. It needs to ensure a safe operation environment for any staff in contact with the systems, very high reliability, and implementation of an optical quality control system. These requirements are discussed in section 4.5 – 4.7.

4.1 Process requirements

The geometries chosen cover a broad range of geometrical features and machining challenges, such as high accuracy, small features, functional surfaces, through holes…

This also requires highly precise positioning, high repeatability, a high frequency and energy of the laser as well as a fast switching of the beam.

Table 2 shows a summary of target geometry and process key performance indicators required for productive industrial production and meeting end-user-quality requirements of the C4L demonstrator applications.

Table 2: Overview of the KPI's to be attained (see also deliverable D1.3)

Key Performance Indicator	Unit	current process value
Parts thickness	mm	0.1 – 0.3
Part dimensions	mm	Gear diameter: 5-10 Watch arm length: ca.20
Material covered	Brass, stainless steel, one non-metallic material to be defined	
General dimensions tolerances	µm	From ± 5 to ± 20
Specific dimensions tolerances	µm	+-2
Smallest holes	µm	From 50 to 100
Maximal side steepness (taper)	Related to the tolerances ; 1° when not specified otherwise	
Average cutting speed (relative to shape and thickness)	mm/min	≥300
Shape deviation	µm	+- 2
Surface roughness (non-functional)	µm	0.4 (N5)
Surface roughness (functional)	µm	0.1 (N3)

4.2 Laser source development

An Ultra-Short Pulsed (USP) laser source (sub-picosecond pulse duration) is considered. Experiment have shown the significant improvement when using such source for fine cutting and micromachining of watch components. Element that could not be manufactured with laser – if at all, are now made possible. Such systems are considered ideal when it comes to controlling the energy deposition and respective surficial and subsurficial modifications of a material such as metals, ceramics or organic materials.

The laser should be able to work on an equally base with the three different kind of optics mentioned in section 4.4.

As CNC and scanner technology are a limiting factor for high pulse repetition rates, requiring fast scanning velocities, the maximum power should be available at pulse repetition frequencies of ≤ 2000 kHz. Thus, high maximum pulse energies of ≥150µJ and ≤500 µJ are required. The energy vs. repetition rate curves of the laser will need to be discussed with the laser manufacturer along WP3.2 and WP2.1.

Within its activity, C4L, test laser of different average power (5W, 10W, 20W and 40W) within the pulse range of 290fs up to 10ps. Within the near IR wavelength (1030 nm to 1064 nm).

Pulse energy over 150µJ could be required for the thicker parts. These data will be refined within WP2.1.

This enables C4L to define an optimum focal spot size, (15-25µm), and pulse duration (300fs – 900fs). It could be confirmed that the ablation rate increases with decreasing values of pulse duration. Due to the material concerned, the range bellow 500fs is preferred.

Another important parameter is the overlap which results from the frequency and speed, either from the trepanation optic and motion system, or from the scanning optic. The optimal overlap will be further established within WP 2.1. Past experiences demonstrate that a low overlap limiting the local heating and pulse saturation effect allows a better quality.

Pulse energy and pulse duration are the most two important parameters for a qualitative cutting process and their range will be refined all along WP2.1. A tuneable pulse duration is a most valuable advantage to be able to address the desired range of materials.

Figure 2: Intrinsic ablation rate as a function of pulse duration[2]

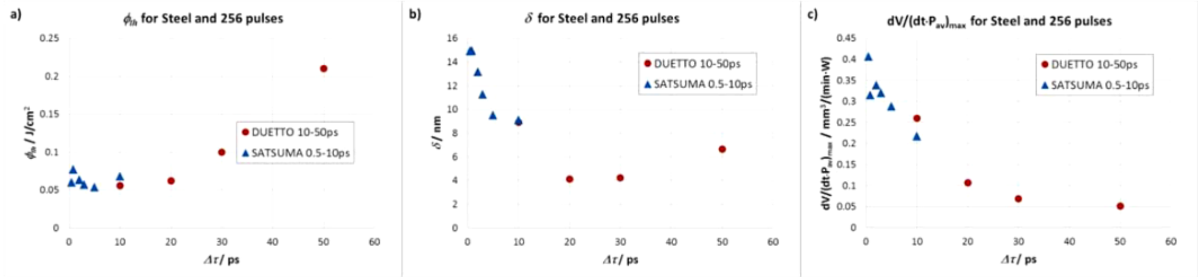


Fig. 5. (a) Threshold fluence (b) energy penetration depth and (c) deduced maximum removal rate (5) for steel 1.4301 and 256 pulses as a function of the pulse duration between 500fs and 50ps. One series of experiments were performed with an adapted DUETTO ps-system and the second series with a SATSUMA fs system; please refer to [34,35] for further experimental details.

Figure 3: Intrinsic ablation rate as a function of average laser fluence at 540fs[3]

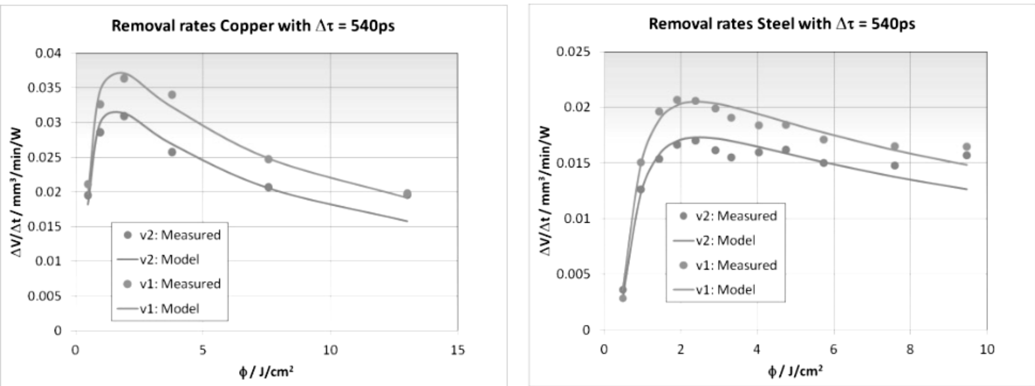


Fig. 2. Deduced removal rates from the machined squares and the corresponding model function from the least square fits for copper (left) and stainless steel (right) for a pulse duration of 540 ps.

[2] Neuenschwander, Beat, et al. " Surface structuring with ultra-short laser pulses: Basics, limitations and needs for high throughput" 8th International Conference on Photonic Technologies LANE, 2014

[3] Neuenschwander, Beat, et al. "From fs to sub-ns: Dependence of the material removal rate on the pulse duration for metals" Lasers in Manufacturing Conference, 2013

4.4 Beam delivery, scanning and control

The optical system of the laser system naturally is required to handle the very high laser power without damage to optical elements and without influence of laser power variations on the beam quality and focus position (e.g. due to thermal lensing). Thus, low absorption coatings and lenses / mirrors need to be implemented.

This implies low absorption coatings on lenses and mirrors. All components have to be suitable for pulse durations bellow 1ps down to 300fs at a pulse energy of 500 µJ regarding the damage threshold and dispersion.

Several beam delivery systems will be tested according to the cutting strategy implemented:

- Rotation optic (also known as trepanning optic)
- Galvanometer scanner (Intelliscan from Scanlab for instance)
- Direct beam cutting optic (From C4L)

The laser and the system have to enable the use of these three beams delivery.

The galvanometer scanner is required to provide very high dynamics and a high positioning accuracy. To handle the high average power, the beam should exhibit a large diameter (e.g. >10 mm). 80 to 160mm focal distance would enable to cover the required spot sizes along with the required field sizes.

4.5 Safety

In order to handle the high ablated volumes at maximum laser power, a sufficiently powerful suction system is required to avoid detrimental effects from fumes and residues both to the operating staff and to the product.

4.6 Sample fixation and movement

In order to allow for the processing of typical substrate of different thicknesses, a sample fixation should be designed which is capable of handling thin plates of metal without mechanical damages or deformation.

A xyz axis system with a state-of-the-art NC control should be incorporated into the laser processing machine along with a proper vision system to position the part rightly.

4.7 Further requirements

In order to enable efficient process development, the laser process machine should be equipped with an in-situ camera system to position and inspect the laser processed area (off axis also possible as long as the axes accuracy allow respecting the parts requirement).

The HMI of the machine should allow both for quick manual set up of laser programs, as well as batch programming for larger parameter variations, including the movement of the axis system (e.g. set up of automatic focus search and part position recognition).

4.8 Summary Tables

The following values are those typically used with the benchmarking system. They do not enables to combine a good quality with an industrial speed and pace.

Table 3: Typical parameter needed for fine cutting with the current benchmarking system

Laser specification	Symbol	Unit	Value	Remark
Wavelength	λ	nm	1030	
Pulse duration	τp	fs	290- 500	Tuneable pulse duration to fit different materials properties
Repetition rate MAX	frep	kHz	1000	5 µJ @ 1000kHz
Average power MAX	Pmax	W	5	
Pulse energy MAX	Emax	µJ	85	@max. 60kHz
Beam quality factor	M^2	–	1.1	
Focus radius (x)	dfx	µm	15-30	
Focus radius (y)	dfy	µm	15-30	
Focal length	F	µm	80-160	

Table 4: Summary of current processes specifications and KPI Status

Key Performance Indicator	Unit	current process value	KPI Status
Part thickness	mm	0.1 – 0.3	
Part dimensions	mm	Gear diameter: 5-10 Watch arm length: ca. 20	
Material covered	**<u>Metal</u>**, ceramic, sapphire, carbon		
General dimensions tolerances	µm	From ± 5 to ± 20	
Specific dimensions tolerances	µm	+- 5	
Smallest holes	µm	From 50 to 100	
Maximal side steepness (taper)	°	0 to 10	
Average cutting speed (relative to shape and thickness)	mm/min	USP laser: ≤50 Fibre laser ≥300mm/min	
Surface roughness (non-functional)	µm	0.6	
Surface roughness (functional)	µm	0.3	
Surface roughness values indicated are measured after washing and post treatment. The goal of the new process will also be to reduce this post processing			

Table 5: required Laser specifications summary

KPI	Benchmark Laser Performances	C4L Specifications for the HIPERDIAS Laser
Average power	5W	200W
Pulse Length	230-20,000 fs	Tuneable around 500 fs (range to be discussed)
Frequency	60KHz-1MHz	100KHz-2MHz
Pulse energy	Max 85µJ	200µJ – higher to be disccussed
Wavelength	1030 nm	1030 nm
Beam quality	TEM 00 – 1.1	TEM 00 – 1.1
Output Beam diameter (before BE)	5mm	Approx. 5mm

5. Element Six Ltd

At this stage of the project, only material removal rate and surface roughness from the Element Six end-user requirements, and redefined in details as KPI1 and KPI5 in deliverable D1.3, were studied (table 1): the relationship between surface roughness/material removal rate of diamond material and Laser average power, pulse length and overlap will be presented in the following paragraphs. As described in deliverable D1.3 regarding measurement methods of KPI1 and KPI5, 3x3mm squares were ablated; the Laser ablation was realized with a femtosecond Laser (5W, 1030 nm, 230fs-10ps, 60kHz-2MHz); and then the ablated squares were only measured by 3D laser scanning for these preliminary studies concerning WP1. More sophisticated measures of KPI5 as long as KPI6, KPI8 and KPI9 will be pursed in WP2 and their results will be available in D2.3.

These preliminary studies will lead to a refinement of the Element Six specifications of the Laser to be developed within HIPERDIAS.

Table 1: KPI studied in deliverable D1.2 in relation to Laser and system specifications

<table>
<tr><th colspan="2">Benchmarking product</th><th colspan="2">Description</th></tr>
<tr><td colspan="2">PCD Syndite</td><td></td><td><u>Dimensions</u>
Diameter = 70 mm
Overall thickness = 1.6 mm
PCD layer thickness = 0.5 mm

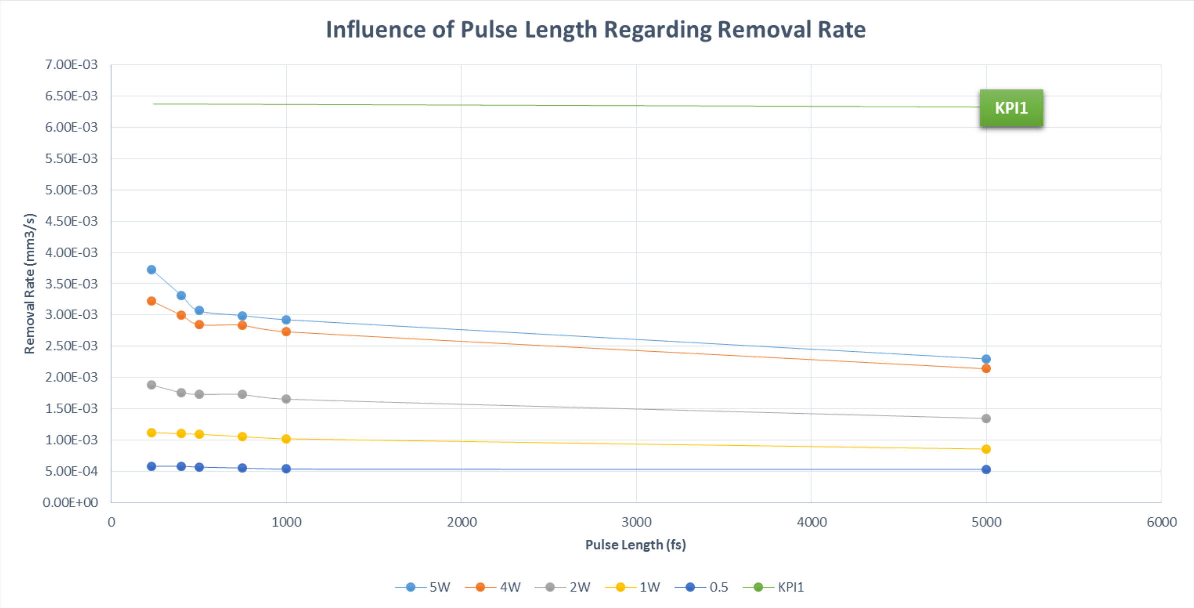
<u>Material</u>
Two layers: PCD layer (alloy of polycrystalline diamond and cobalt) and WC layer</td></tr>
<tr><th>No</th><th>KPI</th><th>KPI Values for success</th><th>Validation Status</th></tr>
<tr><td rowspan="3">1</td><td rowspan="3">Material Removal Rate</td><td>Expected : > 0.150 mm^3/s per disc</td><td></td></tr>
<tr><td>Validated : > 0.075 mm^3/s per disc</td><td></td></tr>
<tr><td>Non validated : < 0.007mm^3/s per disc</td><td></td></tr>
<tr><td rowspan="3">5</td><td rowspan="3">Surface Roughness</td><td>Expected : Sa < 0.010 µm, Sz < 0.12 µm (1)</td><td></td></tr>
<tr><td>Validated : Ra < 0.100 µm (2)</td><td></td></tr>
<tr><td>Non validated : Ra > 0.100 µm</td><td></td></tr>
</table>

(1) *Results confirmed to be independent from direction of measurement to ensure true mirror optical finish*
(2) *Under condition of mechanical polishing time as defined in D1.3.*

5.1. Laser specifications

5.1.1. Ultra-short Pulses

The potential need of using pulses in the picosecond range has been mentioned in deliverable D1.1; higher pulse lengths were considered to possibly increase the material removal rate (KP1). So, in this deliverable D1.3, various pulse lengths were tested at different average power to measure diamond removal rate evolution and finally confirm or not the need of picosecond pulses on the HIPERDIAS Laser (graphic 1). These tests were done at fixed frequency and overlap in distance between beam spot centres. Influence of the overlap on process performances has been studied to optimize process for these following tests (cf. section 5.2.2.).

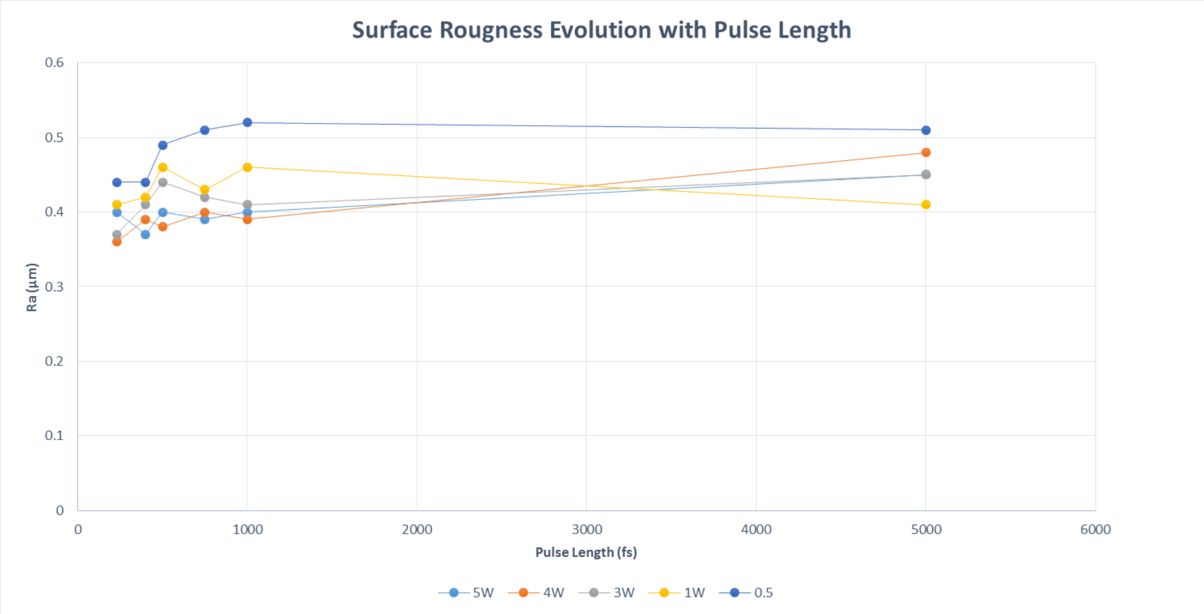


Graphic 1: Removal rate as a function of pulse length for different average powers

This study clearly reveals an increase of the material removal rate when the pulse length decreases. This observation correlates with previous studies about the influence of picosecond pulses length on the ablation rate of non-metallic materials[1]. And these results show that this phenomenon extends down to femtosecond pulses. So, in order to achieve KPI1, ultra-short pulses in the femtosecond order below 1 picosecond are required. The shortest pulses are preferable to ensure highest chances of success to reach KPI1.

The evolution of the diamond surface roughness (KPI5) with the pulse length has also been analysed to validate the need of ultra-short pulses to achieve a smoother surface finish (graphic 2).

[1]Beat Neuenschwander, Beat Jäggi, Marc Schmid, Urs Hunziker, Beat Luescher, Carmine Nocera, *Processing of Industrially Relevant Non Metals with Laser Pulses in the Range between 10ps and 50ps,* Paper (M103).



Graphic 2: Sa as a function of pulse length for different average powers

The surface roughness does not significantly reduce along the reduction of pulse length, although a slight decrease of the roughness is still measurable even with the 3D laser scanning. Similar studies highlighted the same small effect of pulse length on surface roughness for non-metals in the picosecond range[1].

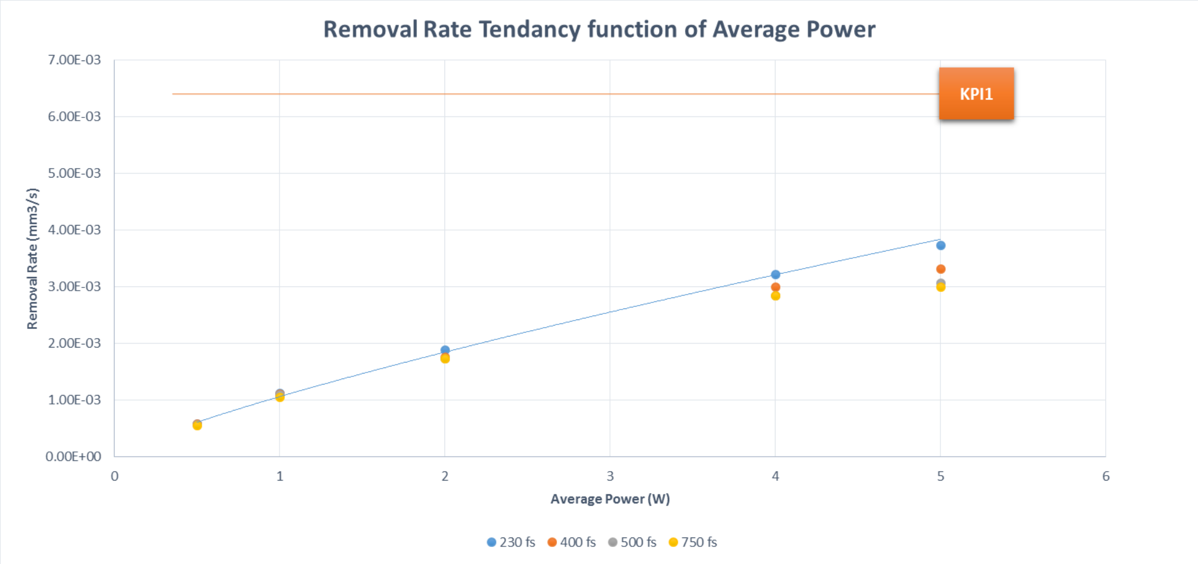
In conclusion, considering only KPI1 and KPI5, shortest pulse length achievable by Laser manufacturer partners is required for highest productivity as long as best surface finish. Sub-picosecond pulses are a minimum required as efficiency and quality of the ablation process drops above 1 picosecond. And requirement for picoseconds pulses is no longer part of the specifications as previously assumed in deliverable D1.1.

5.1.2. High Average Power

The KP1 line displayed on graphic 1 represents the minimum objective in terms of removal rate that the HIPERDIAS project must achieve. And a 10 times higher removal rate is at least expected for the project to be successful as stated in deliverable D1.3:

- Material removal rate = 0.075 mm^3/s

An increase of the material removal rate KPI1 is demonstrated when average power increases (graphic 1), but the behaviour of diamond material relative to a high increase of average power has still to be studied when higher average power will be available: so some forecasts have been estimated as the high average power Laser source is not available yet (graphic 3).



Graphic 3: Removal rate as a function of average power for different pulse length

With the average power available from the current femtosecond source, the ablation process seems to follow a trend between 0 to 5W according to experimental results (best fit was calculated at 230 fs, results at lower pulse length were less accurate). So a very approximately tendency has been done without considering any material interaction changes which could occur with a raise of the average power up to 200 W, 200 W being the initial average power agreed with partners and specified for the diamond ablation process in deliverable D1.1. The process is assumed to remain a cold ablation process at high average power (cf. section 5.2.2). At 200 W, the Laser ablation is highly unlikely to become a “hot” ablation process considering the shortness of femtosecond pulses compared to the frequency set during the trials. At least, the tendency shows that the KP1 line can be reached with femtosecond pulses at a 200 W average power. However, a 0.075 mm^3/s removal rate will be challenging to meet: the removal rate model at 230 fs indicates that this value is barely met at 200 W.

Lowest pulses available on the 200 W Laser version were mentioned to be around 600 fs during project reviews with partners. **T**herefore 200 W average power will be a minimum required. And, as already presumed in deliverable D1.1, testing the 1000 W Laser is then still considered as an option if KPI1 is not achieved along progress of the project.

5.1.3. Pulse burst mode

The lowest pulse length will probably be around 600 fs as claimed by the partners and the study at 5 W shows the Laser ablation of the diamond material is a cold ablation process and might likely remain cold at 200 W. In these conditions, highest expectations for KPI1 (> 0.150 mm^3/s) could potentially be challenging to achieve according to previous forecasts. One option to increase the material removal rate and perfectly ensure meeting highest expected KPI1 at 200W and 600 fs is to generate thermal effects in the diamond material during the ablation process. Thermal effects can be created by the use of pulse burst function to induce heat into the diamond material.

In conclusion, the availability of a pulse burst function is a new requirement. The impact of pulse bursts must be investigated in WP2.

5.1.4. Summary Table

As standing now with the femtosecond Laser source used in the Class 4 Laser facilities, none of Element Six KPI1 and KPI5 can be reached even though pulse length were ultra-short (230 fs).

Table 2: Status of KPI1 and KPI5

No	KPI	Current Laser Performances	Current Validation Status
1	Material removal rate	0.0035 mm^3/s	
5	Surface Roughness	0.36 µm	

So Laser specifications have been updated as followed:

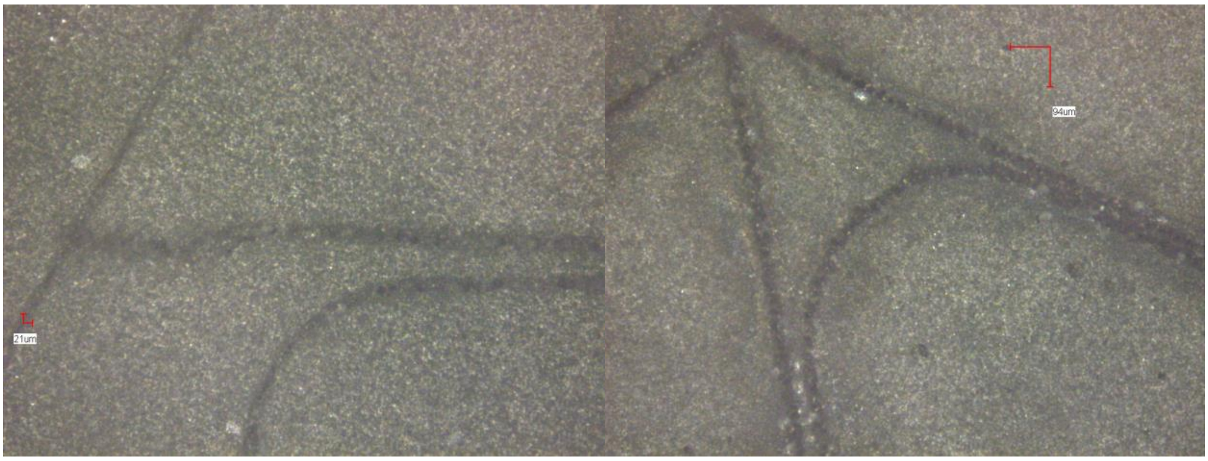
Table 3: Laser specifications summary

KPI	Current Laser Performances	E6 Specifications for HIPERDIAS Laser
Power	5W	> 200W 500/1000 W
Pulse Length	230 fs	< 1000 fs
Frequency	60KHz-1MHz	60KHz-2MHz Pulse burst (multi pulses mode)
Wavelength	1030 nm	1030 nm

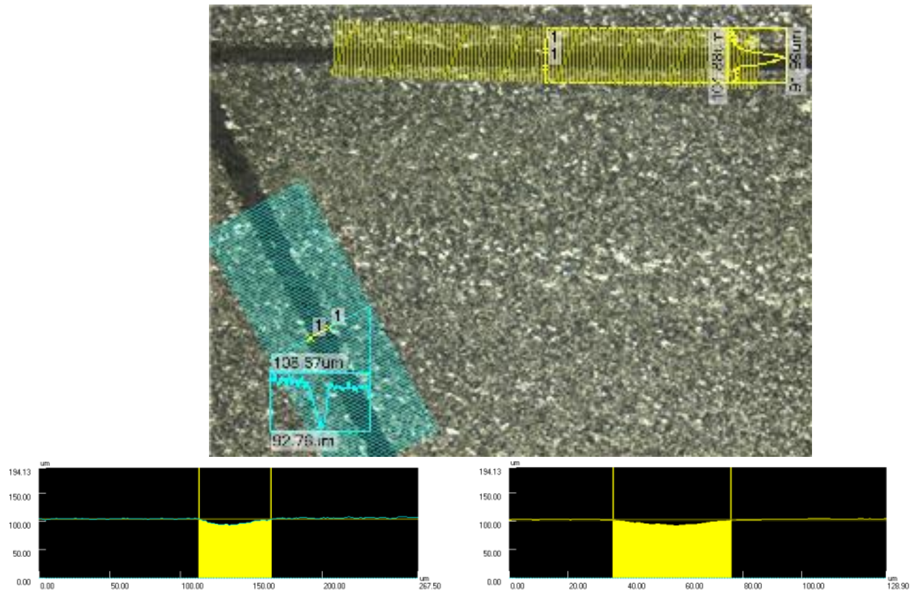
5.2. Optics and systems technology

5.2.1. Polarization

In parallel to the project of HIPERDIAS, some studies on diamond material revealed the high influence of polarization on Laser processing of diamond material. Some very typical effects of linear polarization were visible during some Laser processing of diamond material (picture 1). But the main effect of linear polarization concerning the HIPERDIAS project was the difference of cutting kerf width depending on the machining direction (picture 2): the components of the polarization beam interact differently with diamond material as their amplitude is different.



Picture 1: Linear Laser cutting kerf before (left) and after (right) set up of λ/4 plate



Picture 2: Laser cutting kerf width variation depending on cutting direction: 40 µm in X direction (left) up to 50 µm with a Y component (right)

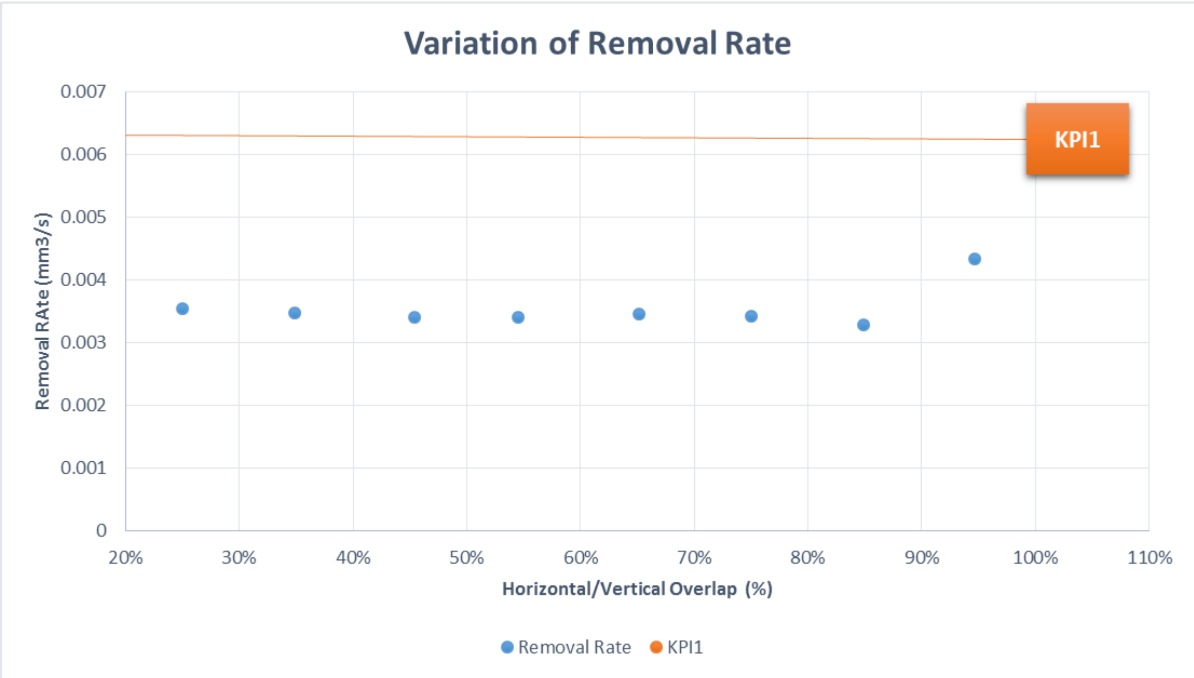
An optical mirror finish is desired on the diamond surface (KPI5), the surface has to reflect light through specular reflection without any diffusion reflection. In order to achieve such a finish, the surface must be extremely smooth and completely uniform as stated in deliverable D1.3: surface roughness must be low and no machining direction can be visible otherwise no specular reflection can occur. The conclusion from observing the effect of a linear polarization on the diamond material is that a circular polarization is necessary to Laser-ablate diamond surface up to a mirror finish. A circular polarized the beam has same interactions with the material in every direction reducing the marks of machining directions and allow to get a uniform machining across all direction of the surface of the diamond material.

The 5W femtosecond Laser source emitting a linear polarized beam, a λ/4 plate has immediately been set up on the beam pass to work with a circular polarization instead of a linear polarization for all the preliminary tests. Measure of the kerf width shows a big improvement of the kerf size in X and Y directions (38 µm and 33 µm) and confirms the laser beam is close to be polarized circularly.

So the Laser beam is required to have a circular polarization. Polarizing optics must be implemented on the beam path of the high power Laser beam to ensure circular polarization of the Laser beam onto the work piece.

5.2.2. Overlap

The objective of testing various overlap distances is to determine the overlap percentage which would give the highest performances. This optimized overlap will be then fixed for all the next tests (detailed in previous paragraphs).



Graphic 4: Removal rate as a function of pulse length for different average powers

The material removal rate (KPI1) remains constant for overlap between 25% up to 85%. When the overlap reaches an extreme value of 95%, the ablation rate rises. Overlapping the pulses between 25% and 85% has no effect on the ablation process. This behaviour for small up to high overlaps demonstrates that the Laser ablation of diamond is indeed a cold ablation process when femtosecond pulses are used, as stated in literature publications*. However, a thermal effects occur when diamond material is hit by spots close to fully recover one after another: heat accumulates on same spot of material as spot are overcrossing each other. The heat generation favours the process of ablation leading to an increase of material removal rate. Important degradation of the diamond surface at 95% overlapping attests of a heat accumulation in the material compared to lower overlapping percentages.

The Laser ablation is a cold ablation process with no heat accumulation when scanning overlapping spots until an extreme limit. Therefore, under certain conditions, the scanning strategy can possibly generate heat into the diamond even with femtosecond pulses. This support the assumption of the possible impact of pulse burst function regarding KPI1 (cf. section 5.1.3.).

6. Summary and Discussion

After preliminary studies carried out in the frame of WP1, specifications of the Laser source and its system have been updated and refined by the end-users:

- Power average

Bosch ultimately fully requires 1,000W of average power to meet their KPIs. Element Six absolutely requests a minimum of 200 W average power to reach the starting range of success of their KPI. And Element Six demands towards partners to have the possibility to run some trials on the 1,000 W Laser version. Class 4 Laser also expects a 200 W of average power.

- Pulse length

All end-users agree on the need of the availability of a tuneable pulse length in the picosecond range or below to adjust it to the optimal ablation rate/surface roughness ratio of their process.
However, in terms of achievement of their diamond removal rate only, Element Six would like to get the shortest possible pulse length that the Laser manufacturer partners can achieve on the 200 W Laser source. Pulse length would be satisfactory below the previously discussed 600 fs and the partner Amplitude Systemes acknowledged that 400 fs will be reachable on the 200 W Laser. Class 4 Laser requires a window between 400 fs and 900 fs in adherence with Amplitude Systemes qualifications while Bosch specified the need of pulse duration in the picosecond range or below on the 1,000 W Laser source.

- Frequency (Repetition Rate)

A maximal frequency in the MHz range is needed by all end-users to achieve a fast cutting of watch parts, and high ablation rate of Silicon and Diamond materials.

- Burst Mode

A pulse burst mode is a specification from Bosch and Element Six to allow optional methods of increasing the material removal rate of their process and reach highest possible value for their respectively defined KPI1 (two pulses burst at least).

- Frequency Conversion

Only Bosch specified the possibility to tune wavelength of the Laser source by frequency conversion (second harmonic generation at least).

- Beam Quality

Beam quality is an important factor for Class 4 Laser as an end-user developing a fine cutting process. A high beam quality is desired from Class 4 Laser prospective to allow them smoothest finish on cutting edges of their watch parts: TEM 00 (M2 <1.1)