DELIVERABLES 1.10

APPOLO PUBLIC REPORT Y4

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INTRODUCTION

The APPOLO project is establishing and coordinates connections between the end-users, which have demand on laser technologies for (micro)fabrication, knowledge accumulated in the laser application laboratories of research institutes and universities and the laser equipment manufacturers to facilitate faster validation of the process feasibility and adaptation or customization of the technology (equipment) for manufacturing conditions. The core of the consortium consists of laser application laboratories around Europe which are connected to a virtual APPOLO HUB, accumulates their knowledge and infrastructure and promotes the easy-to-access environment for development and validation of laser-based technologies. The APPOLO project cover activities on technical, technological and economical assessment of new equipment supplied by project partners in 8 complex assessment value chains and preparation of standardised procedures for the assessment service which can be provided for new project partners and customers beyond.

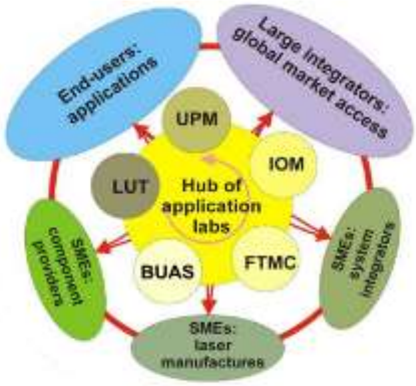
During the first half of the APPOLO project implementation, the consortium has established clear outlines for assessment procedures and templates. Using these procedures, partners validate new equipment by assessing them according to APPOLO HUB specified parameters. These assessments allowed partners to present their finding to customers and, therefore, gained feedback how to implement assessment procedures for the desired application successfully. The dissemination activities include training on assessment procedures, exchange of knowledge of successful assessment experiments.

RTD work in the last year of the project was concentrated on seven new experiments selected after an open call. Some activities from the initial part of the project were also continued to finalise assessment procedures delayed due to late delivery of equipment. The new laser, advanced galvoscanners, fibre delivery for ultrashort pulse lasers were validated for applications in machinery, tooling, nanoimprint lithography, precise processing of metals and polymers.

Two websites for the APPOLO project are running with a permanent update of information: www.appolo-fp7.eu for all project related activities and dissemination and http://www.appolohub.eu/ for APPOLO HUB as a single access point to consolidated infrastructure and expertise of the laser application laboratories, involved in the project. Core partners of APPOLO project have prepared and tested routes for sustainable operation of APPOLO HUB after end of the project, providing service in validation and development of laser-based technologies for new customers./

Goal of APPOLO

to exploit distributed knowledge, existing at



- academic application labs,
- equipment manufacturers,
- system integrators,
- end-users

and to enable the development of industrial laser processing for innovative products, technologies and machinery.

APPOLO Objectives

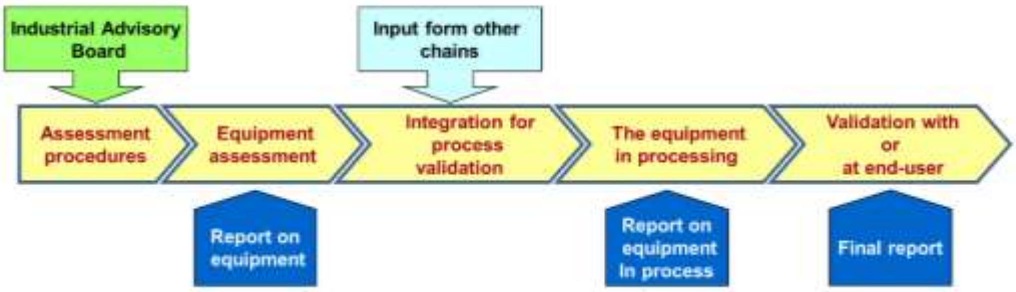
Establish and coordinate connections between

- the **end-users**, which have demand on laser technologies for (micro)fabrication;
- knowledge accumulated in the **application laboratories** of research institutes and universities;
- the laser **equipment manufacturers** (preferable SMEs: for integration, lasers, beam control and guiding, software, etc.)

Facilitate faster validation of the process feasibility, adaptation or customisation of the technology & equipment for manufacturing conditions, including:

- reliability of the components;
- their interaction;
- assessment of the dedicated production processes;
- process speed, quality and repeatability;
- socio-economic issues.

15 Complex Assessment Value Chains



APPOLO HUB (www.appolohub.eu) is a network of laser application laboratories providing laser micromachining assessment services for industry partners. HUB is performing the testing activities at one of **6 laser application laboratories,** located in Switzerland, Spain, Germany, Netherlands, Finland and Lithuania.

APPOLO HUB offers service to assess and verify novel laser manufacturing technologies for industrial use.

- **Assessment of laser equipment**: We assess new lasers, scanners, beam guiding equipment and laser workstations to verify how they meet customer requirements.
- **Laser processing verification**: We offer service to define the optimal laser equipment for your samples and products with ns, ps and fs lasers.
- **Laser micromachining Ownership Costs & Benefits**: Information about costs and alternatives for ultra-short pulse laser processing: analysis and limits of laser processing parameters; process flow analysis; cost-of-ownership estimations including maintenance requirements & lifetime.

We are part of I4MS

Performance of fibre laser process for industrial application

Partners: BUAS (Switzerland), ONEFIVE (Switzerland), EMPA (Switzerland), FLISOM (Switzerland)

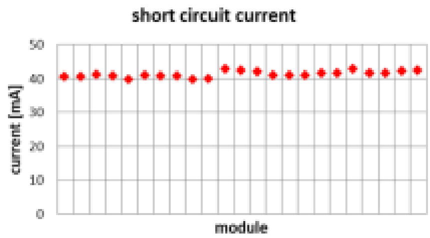
In third assessment stage, APPOLO WP2 experiments were moved to reflect the situation and environmental conditions of the industrial production process as much as possible. For the present assessment case of laser scribing of thin-film solar cells on a flexible substrate, this involves that the optical scribing unit should work reliably without the need for human intervention during the experimental period. Scribing process parameters determined during preliminary experiments were not re-adjusted at least within one production batch. Production of thin-film samples should be done on a production line or at least a pilot line. Scribing must be done at industrially relevant throughput. Performance of the scribing processes developed in APPOLO was directly compared to industrial reference samples produced using existing production processes. Sample characterisation has been done according to quality measurement standards of the end-user.

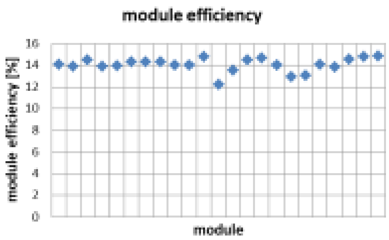
step	place	description
1	Flisom	Deposition of back contact in roll-to-roll process
2	Flisom	P1 scribing of functional module pattern (Onefive laser)
3	Flisom	Growing of CIGS absorber layer in roll-to-roll process Cutting out and framing of functional modules Deposition of CdS and intrinsic ZnO (EMPA)
4	BUAS	P2 scribing on APPOLO scribing machine
5	EMPA	Deposition of ZnO:Al front contact
6	Flisom or BUAS	P3 scribing of front contact pattern
7	Flisom or EMPA	Electrical characterization of functional modules

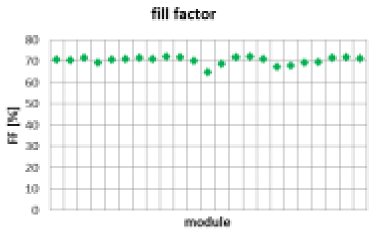
Workflow used in APPOLO assessment experiments

Production of samples for APPOLO assessment experiments was integrated into regular batch production on Flisom's pilot line. In order to work as closely as possible to the production conditions and to guarantee the validity of the experimental results, reference batch production runs were selected for APPOLO experiments. The typical roll was several hundred meters long and 600 mm wide. Every five to ten meters of the roll, Flisom inserted a quality assessment section where different electrical, photoelectrical, and geometrical characteristics of the thin-film stacks are measured and evaluated.

Three production runs were selected for APPOLO assessment, with samples which passed Flisom's first level quality assessment and intra-roll variation was within acceptable limits for production. From these three rolls, a total of 24 samples (8 per roll) were processed using APPOLO parameters for the testing variability of results. Electrical characterisation of 24 samples from three different production batches (rolls) has shown the low variability of results.







Results:

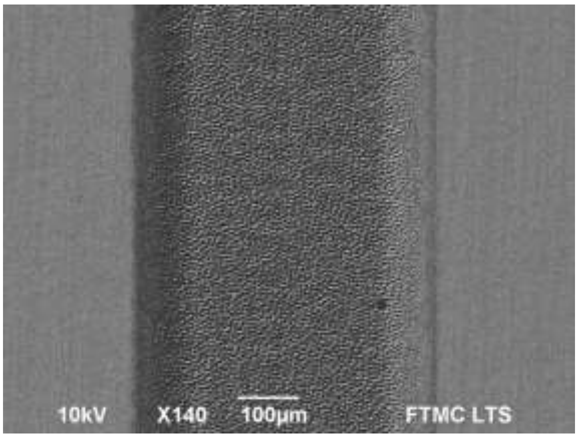
- The efficiency of 15 percent was reached on industrial samples using standard APPOLO patterning without lowering the scribe-separation.
- A comprehensive series of assessment experiments have been conducted on Flisom's pilot line and partially on APPOLO scribing machine.
- Suitability of APPOLO processes for the industrial production of CIGS thin-film solar cells has been demonstrated.

Scribing performance of the system with polygon scanner

Partners: FTMC (Lithuania), LUT (Finland), EKSPLA (Lithuania), NST (Belgium), AMSYS (Israel), ELAS (Lithuania), FLISOM (Switzerland), EMPA (Switzerland)

Laser microprocessing of metals

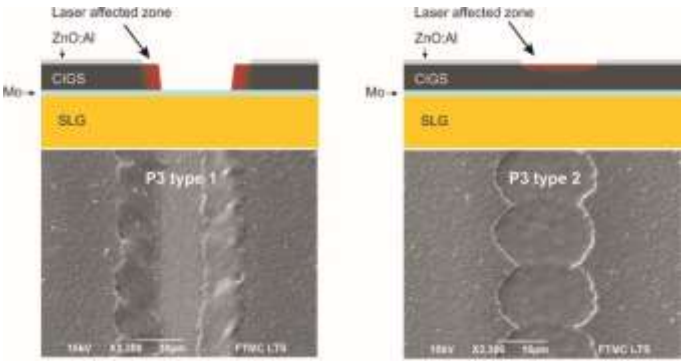
The NST LSE 300 polygon scanner was validated in the case of groove formation in steel foil for APPOLO Hub customer process. The challenge was to obtain high material removal rate and quality without laser-induced thermal stress to the 150 µm thick foil. Corresponding material removal rate and specific ablation efficiency were obtained of 0.055 mm^3/s and 0.075 $mm^3/min/W$, respectively. The thermal stress to the thin foil was minimal, no foil deformations were observed. The groove parameters fully match customer specifications. High process throughput and long scan-line option make an NST LSE 300 polygon scanner an outstanding tool for this kind of processing.



SEM image of the laser processed groove

The investigated CIGS scribing regimes.

In the frames of the APPOLO project, different scribing approaches were investigated for CIGS module structuring. The P3 “type 1” regime involved direct laser ablation of the TCO and absorber material to expose the molybdenum back-contact. In this case, high pulse overlap regime is required. Therefore, there is a large chance of heat accumulation during the scribing. However, these issues are less critical in the case of P2 scribing (interconnect formation). For this, the P3 process parameters can be easily adapted for the P2 scribing. The P3 “type 2” involved removal of the front-contact only. That is a low pulse overlap regime, and laser-induced thermal effects can be reduced.



Laser scribing process types investigated in the APPOLO project.

After process validation procedures we conclude, that the P3 “type 2” scribing process (TCO lift-off) is the only available solution in the case of CIGS cell separation purposes. The green (532 nm wavelength) picosecond laser is optimal for such task. P3 “type 2” is a fast process, and low power picosecond lasers (<1 W@100 kHz) can fully meet process throughput requirements for a 1 m wide CIGS deposition line. Such laser parameters also apply in the case of the P1 process. In the case of the P2 process, higher power picosecond laser is needed, since a high pulse overlap is needed to remove the CIGS layer entirely. In this case, the laser should operate at power >6.5 W@1000 kHz at 1064 nm wavelength.

Overall, with three separate scribing machine approach for each P1, P2 and P3 scribe, the laser process can add an additional cost of 3.413 €/module or 0.031 €/Wp with a total investment about 1.1 M€ for 15 MW/year line capacity.

Laser-scribing of P2 for Perovskite PV for optimal interconnection fabrication

Partners: IOM (Germany), UPM (Spain), EMPA (Switzerland), FLISOM (Switzerland)

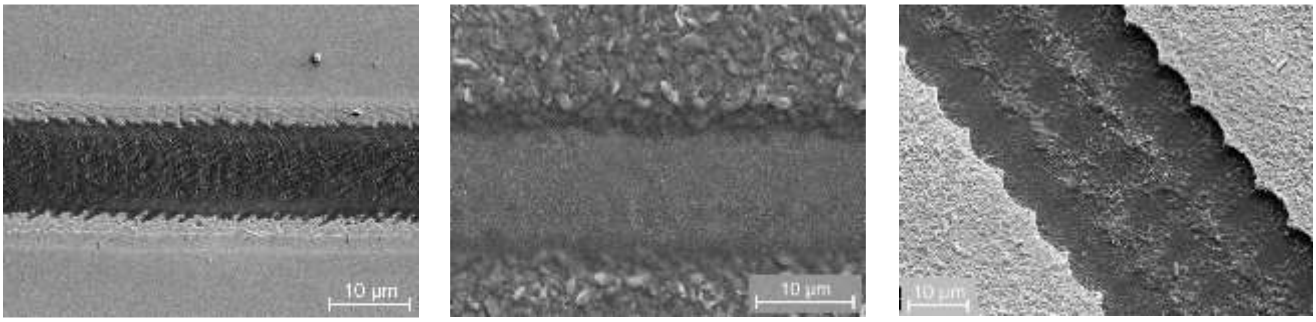
The activities of WP3 were restructured due to the extension of the work to laser scribing of perovskite films as a new exciting absorber material for thin film photovoltaics. The workplan was reorganised, and a new end-user (FLISOM) was incorporated.

The main work done is based on one future vision related to the activities of the end-user, which is currently focused on the fabrication of flexible thin film CIGS solar modules, to combine CIGS and perovskite solar technology for R2R tandem module fabrication. This approach can significantly increase the efficiency of solar modules, which is the fundamental parameter in being competitive with silicon PV at least for applications that require flexible solar modules.

One crucial part of the work concentrated on the optimisation of the thin film stack for perovskite solar cells including the development of the suited fabrication technologies of the particular films for a semi-transparent solar cell design. Therefore, the usually used gold back contact was replaced by a TCO layer to achieve the transparency of the solar cell up to the band gap of the absorber. In particular, the deposition techniques were adapted to avoid damage to the absorber within the TCO deposition process. Furthermore, additional materials suitable for a transparent conductive layer were chosen and optimised.

The laser-based scribing process of the perovskite film was studied in more detail to gain the understanding of the laser-photon perovskite-film interaction process in relation to the best characteristics of the laser scribing for the integrated interconnection process of modules fabrication. Two ablation mechanisms have been observed in general: the standard laser ablation due to fast evaporation/decomposition of the material and a lift-off process due to laser-driven interface phenomena. Both processes were observed for the studied laser irradiation directions – film and substrate side irradiation – and for the examined laser sources. Low laser threshold fluences for patterning were found for photon energies above the band gap or ultrashort laser pulses. For those laser processing conditions, a selective scribing can be achieved without damaging the substrate including deposited films (TCO).

For the module fabrication process, the TCO patterning was also studied. The scribing of the TCO film on the glass substrate with ps- laser has been optimised and transferred to plastic substrates. Both UV and well as IR ps laser pulses can be considered for scribing of the TCO at the substrate. The patterning of the improved TCO films deposited on the perovskite film for the semi-transparent solar cell configuration was managed by using UV-ps laser pulses taking into account that the TCO film has a much higher threshold for scribing than the perovskite film.



P1 P2 P2

SEM images of the three scribes required for integrated interconnection P1, P2, and P3 with ps-laser UV pulses.

These ps-laser scribing processes were successfully applied for performing integrated interconnection of perovskite solar cells on glass and flexible substrates consisting of six cells. The expected higher efficiencies of tandem modules enable savings of the total cost of PV systems due to the reduced area of the installations.

Combination of polygon scanner and linear/rotation axes performance

Partners: BUAS (Switzerland), IOM (Germany), LUMENTUM (Switzerland), NST (Belgium), DG (Switzerland), SWG (Germany)

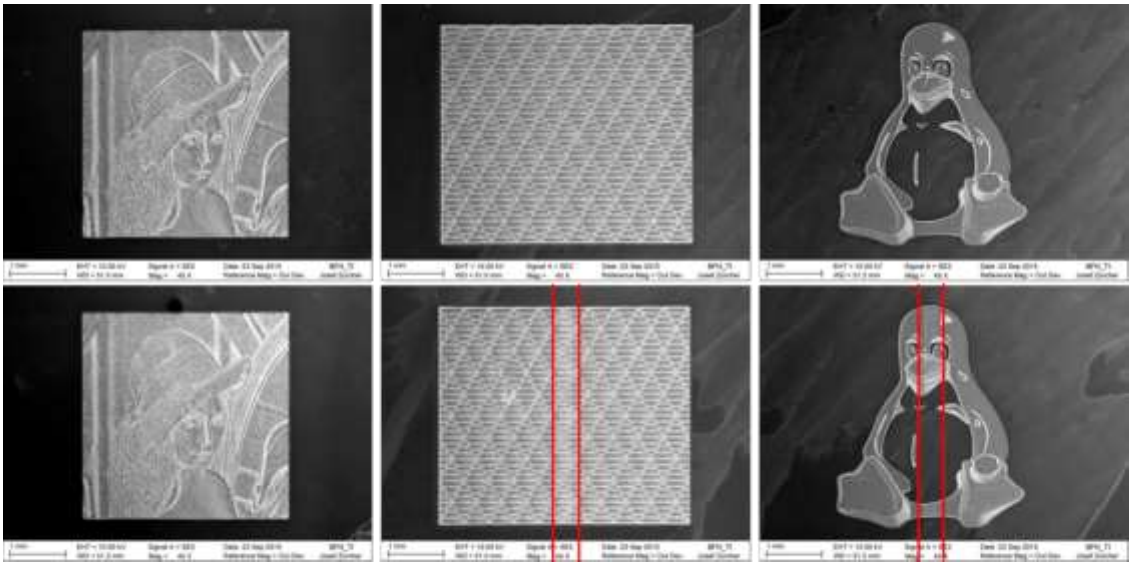
The combination of the high power laser fs-laser system (900 fs, 80 W) from Lumentum with the standard LSE-170 line scanner from Next Scan Technologies and a rotatory axis was performed for fast and precise surface texturing on rolls.

First, the strongly astigmatic beam from the laser system had to be transformed to a stigmatic one; then an existing mechanical set-up was entirely reworked by Daetwyler Graphics and BUAS so that the polygon line scanner and the rotating drum carrying the sleeves could be built in. Third, the control software was adapted, and all the three devices are operating fully synchronised to each other. The specified position accuracy of the LSE-170 line scanner of ±5 µm and the repeatability of <3 µm were confirmed. The accuracy was also kept if the machine was stopped between to marking processes.

Left: base cylinder; middle; copper sleeve; right: mounted sleeve and base cylinder in the setup

Combination of a synchronised Galvoscanner with linear axes to extend the working area

A new measuring device to determine the differences between the coordinate system of the scanner and the axes system was developed and tested. It allows a position accuracy of about 10% of the spot size and the correction of the length and angle errors between the two coordinate systems. With this set-up, four different stitching strategies and their influence on visual effects at the intersection between two working fields were investigated. It finally depends on the shape/surface of the 3D-structure if the intersection region can be observed or not. Even in the case when it can be observed, it was not possible to measure any height difference in the intersection region. To avoid this effect, the position and shape of the intersection line have to be aligned with the image whenever this is possible.



SEM images for three different 3D-structures; upper row: non-stitched images; lower row: stitched images.

FAST: Breakthrough solutions in laser patterning for reduced friction

Partners: Scanlab GmbH (Germany), SKF B.V. (Netherlands) and Lightmotif B.V. (Netherlands)

The goal of the FAST project was to assess how recent galvoscanning system improvements could be used to improve the speed and/or quality of high-definition laser surface texturing processes. A fast gating mode and a faster / small aperture scan head were tested for an application where mould inserts needed to have a micro-pillar texture. SKF, end-user of this project, uses the mould inserts for the production of seals. The texture is used to change the properties and appearance of the seal.

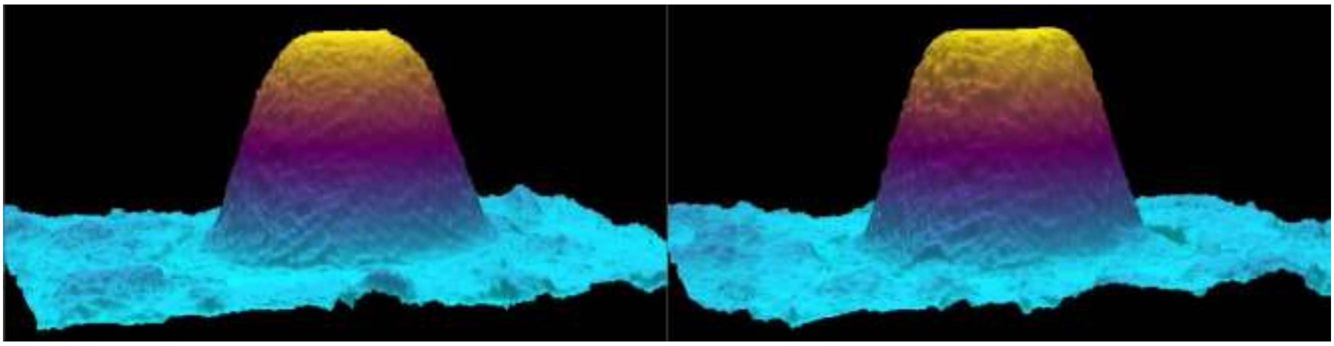
Achieving faster laser micro-milling processes means having to use a higher average laser power, which in turn generally requires one to use high scan speeds to avoid heat accumulation, which can have a negative effect on the surface quality or cause excessive melt, causing the definition of the texture to suffer.

Surface texturing on a double-curved surface means the processing of the target surface needs to be split into small tiles, which can result in a low duty cycle when the scanner is spending a significant amount of time is on jumps and run-ins. A small aperture scan head with smaller / lighter scan mirrors can be used to reduce the time needed for run-ins / re-positioning.

A high definition texture will often have many small features that. A fast process for making such textures requires a complex gating pattern where the laser needs to be rapidly and accurately toggled on and off, especially for high scan speeds. Ideally, the scan system control hardware should support laser output modulation at full speed that the laser hardware can handle (> 2 MHz).

Fast pixel mode for SCANLAB RTC5

A faster pixel output mode for the SCANLAB RTC5 control board was integrated and tested using scan speed of up to 6 m/s. This fast pixel mode allows scanning of straight lines while modulating / gating the laser at the full rate that the laser hardware is capable of (> 2 MHz). A hatch pattern stroke with many small line segments can be scanned in a single pass at high speeds without loss of texture definition.



Two images of about 40 µm diameter pillars made with the exact same process (2 m/s scan speed), executed with a standard / 308 kHz pixel clock (left) and using the fast pixel mode (right).

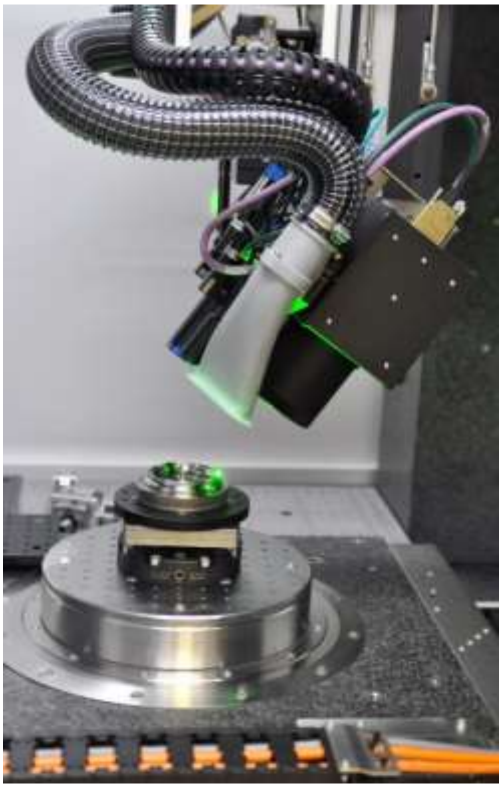
Small aperture scan head with digital encoders

The intelliSCANse® 10 is SCANLAB's smallest aperture scan head which features the digital encoder technology required for highly accurate laser micromachining. Compared to the intelliSCANde® 14 mm the tracking error / time lag is almost twice as small (0.11 ms vs 0.21 ms). Both scanners were tested, and the results confirm that for the same high accuracy the time spent on re-positioning (jumps) and accelerating (run-ins) can be halved when using the smaller aperture.

Mould inserts

Mould inserts for a bearing seal mould were textured using the improved scan system. The process used a relatively high scan speed (2 m/s) to avoid heat accumulation. Thanks to the fast and accurate gating the texture's small features still have a high definition. The fast dynamics of the small 10 mm aperture scan head enable a relatively high duty cycle when processing small tiles (70–90 %).

Photograph of a textured mould insert, where a pillar texture was applied to a conical ring around the circumference.

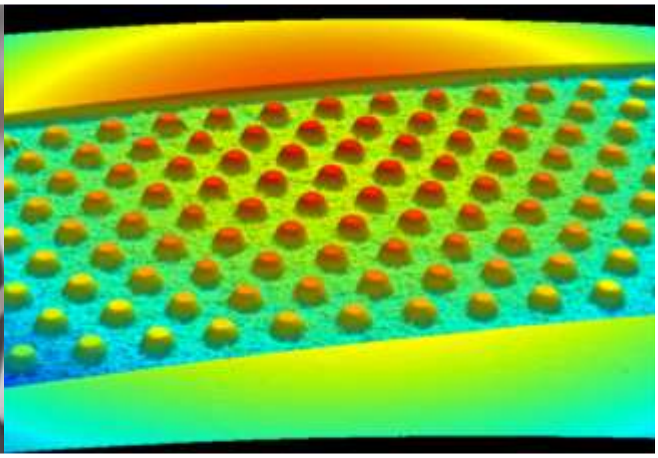


5-axis machine of Lightmotif during texturing on a mould insert.

Demonstrators

The developed technology was used to machine different pillar patterns in rings on balls made of stainless steel and cemented carbide, to be used for dissemination of the results. The picture shows a measurement of the texture on a steel demonstrator ball.

Different pillar patterns were applied in rings to this demonstrator



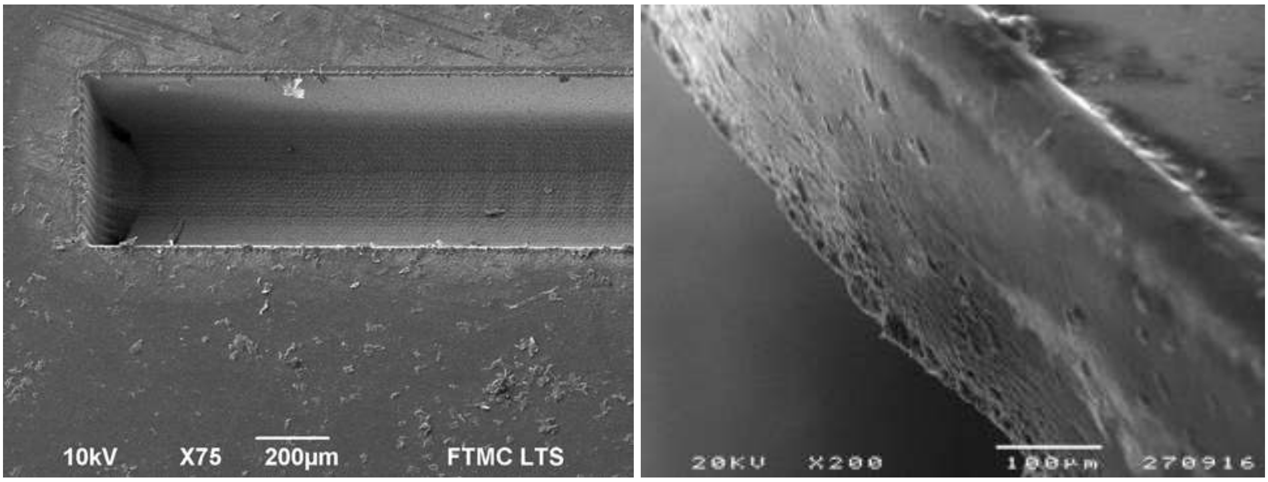
3D profile of a pillar texture on one of the demonstrator balls.

PONT: Breakthrough solutions in resonance NIR laser texturing of polymers

Partners: Laserspec SPRL (Belgium), OSAI Automation System SPA (Italy), it4ip SA (Belgium) and FTMC (Lithuania)

The main project goal was to evaluate the performance of resonant photo-ablation of polymer films in the near infrared pulses. Every polymer has its own unique infrared absorption spectrum that serves as its “molecular fingerprint”. The ability to access many mid-IR wavelengths in this molecular fingerprint region is therefore necessary in order to resonantly excite different polymers. Therefore, tuneable OPO (optical parametric oscillator) based lasers offer possibilities to apply them in Resonant IR (RIR) ablation of polymers.
The key to RIR ablation is that the excitation is resonant with a vibrational mode of the polymer target. Typical optical penetration depths of resonant IR light are much larger than penetration depths at UV wavelengths, and the corresponding volumetric energy density is much less. The criterion of resonant excitation is necessary in order to achieve successful material ablation.

With lasers available in PONT experiment, RIR was tested in the overtone range of polymer vibrational modes of 1.5-1.8 µm. A comparison test was performed with ablation using UV laser sources.
No evidence of the laser-induced polymer resonant ablation was observed in investigated IR region. The resonant ablation effects were negligible in the multi-pulse ablation regimes. Processing at this wavelength induced high thermal damage of samples (large heat affected zone, unstable melting of the material). To do significant damage to a sample by a single scan, it was required to use low scanning speed and high overlap (99.3%). At higher scanning speed thermal damage was lower, however, at such regime only irregular subsurface modifications were observed. A clean cut was not achieved even using higher scanning speed and multiple-scan technique.
Possibly IR ablation was triggered by surface defect absorption, while bulk absorption was the very weak for investigated materials. In the case of UV (355 nm wavelength) laser ablation, the results were auspicious. Nanosecond UV pulses showed potential for membrane cutting applications. However, only picosecond UV pulses showed precise processing quality in the case of polymer structuring.

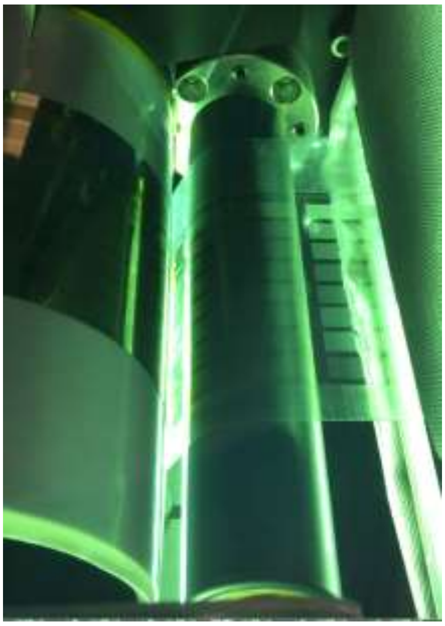


SEM image of the groove profile (left) and cut edge (right). Both machined with machined with optimal UV laser.

LADRUM: Breakthrough solutions in laser patterning of drum-moulds for large-area nano-imprinted polymer films

Partners: Scanlab AG (Germany), Nanotypos (Greece) and IOM (Germany)

High throughput manufacturing requires continuous lithography processes capable of reproducing micro and/or nanoscale structures with high precision and without any discontinuities. Alternative lithography techniques tribute to the development of novel materials giving rise to added functionalities and properties. Despite the progress of manufacturing processes made, it still remains a bottleneck to realise large area flexible surfaces at low cost and without discontinuities.

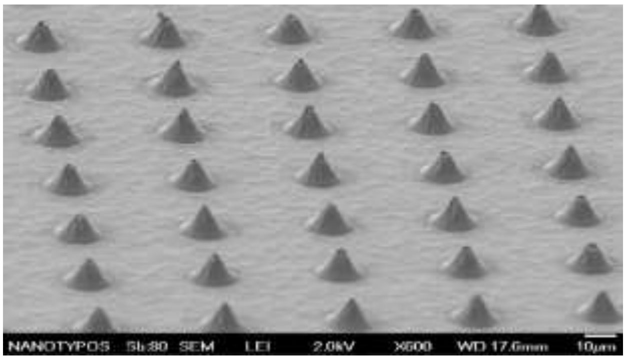


R2R UVNIL embossing process

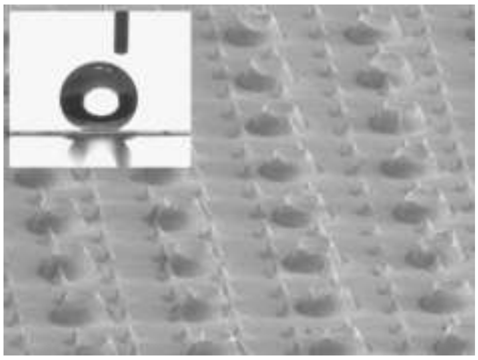
Within LADRUM project we have established the manufacturing chain to realise large area micro/nanopatterned films with tailored surface properties. In particular, hierarchical features have been realised by ultrashort pulse laser sources with high power in combination with fast scanning technologies. Direct engraving of tailored three-dimensional features into a nickel cylindrical drum/mould have been exploited and transferred in a continuous mode into a commercial UV curable resist material. The Nickel drum mould was in the form of a sleeve (no-discontinuities) and has been treated and engraved with high precision within a machining tool capable of processing multiple laser machining wavelength while state of the art beam splitting and accurate scanning tools were used to avoid discontinuous boundary issues and low thermal impact.

With the aim to obtain super-hydrophobic surfaces, particular designs and structures ranging from sub-1 µm up to 100 µm were examined. Partner ***Nanotypos*** performed a roll-to-roll ultraviolet light assisted nanoimprint lithography (R2R UV-NIL) to replicate at the high rate our textured nickel surfaces produced at ***IOM***.

Throughout our experiments, the emphasis was given to generate 3D topographies which tend to have the best performance according to our theoretical calculations. All processing parameters were optimised to have a robust replication technology starting from the laser processing values up to the final R2R embossing step. Based on our experiments, hierarchical topographies which combine two level features, resulted in having the best water repelling values hence water contact angle values of 158°.



5 µm base diameter micro-pyramid structures



Combination of 5 µm & 30 µm (diameter) structures presenting WCA of 158o

NEW-DELI: Breakthrough solutions in fibre-based delivery system for pulsed laser beams

Partners: OPI Photonics SRL (Italy), IRIS SRL (Italy) and BUAS (Switzerland)

The goal of the NEW-DELI's solution was to be the key enabling factor effective and efficient processing technologies for tailoring the surface quality properties of Additive Manufacturing parts by laser ablation and surface-structuring. Because of this, the sectors of applications have been identified in the aerospace, automotive and Medtech ones, and materials to be treated in Aluminium alloys, Titanium alloys and Steel. Moreover, scribing processes on thin film photovoltaic modules have been identified as further possible fields of application of NEW-DELI, showing the application of the delivery system also for those processing cases where there is a need for short-pulse beams for material treatments.
So far, the delivery of these ultra-short pulses has been through free-space systems, an approach that poses many limitations to machine designers. Very recently, however, innovative fibre based delivery solutions have been reported exploiting a new type of speciality fibre able to route high peak power pulses with minimal distortion and, especially, no fibre damage. OPI has prototyped an industrial grade cable system based on the fibres mentioned above. BUAS has validated the cable performance, and IRIS owns processes and machines for the cable testing in a real industrial environment focusing on advanced laser-based manufacturing processing.

The delivery cable for ultra-short pulses enables, first, the possibility to detach the laser source and power supply from the processing area providing much more design flexibility for processing machine builders and integrators. Second, it enables wide working area given the possibility to move the processing head (e.g. on a gantry system). And finally, the developed innovative cable open the possibility to equip a robot with micromachining capability thanks to the fibre based delivery, thus enabling new dynamic processing for the micro-machining field and all the applications where high energy and/or high peak laser power is required.

Robot material processing through the ultra-short pulse fibre delivery system.

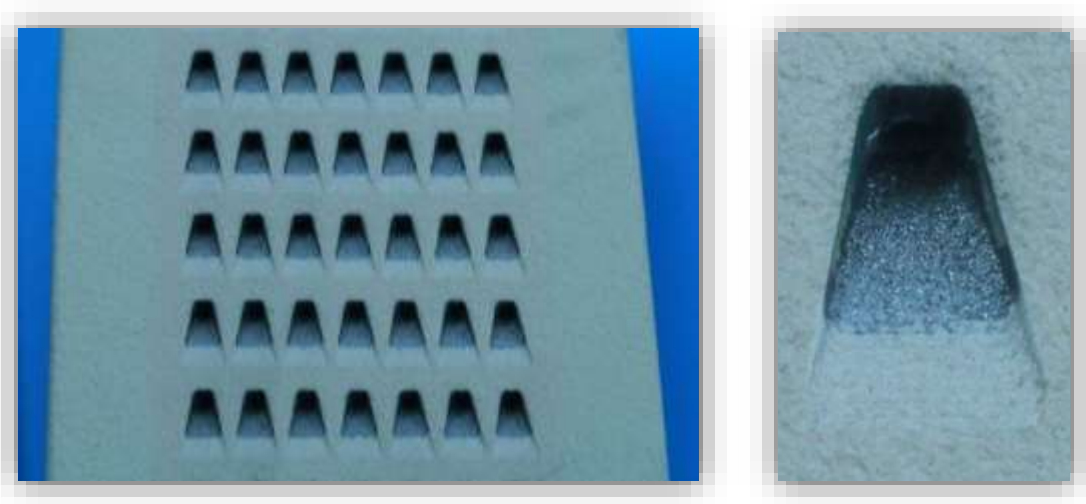
This USP delivery cable system is targeting as a key application the Additive Manufacturing sector, where the fibre transport of high-energy, ultra-short, pulses (for surface finishing by cold ablation) in parallel with high-power, high-brightness, CW light delivery (for powder sintering) are required to enable new features in next generation of processing machines. In such application, the processing head has to move in a wide working area thus the fibre delivery (already existing for continuous beams) is absolutely necessary for the pulsed laser processing. The developed solution is thus the only possible one (unless the pulse width is so long that traditional fibre can be used, but this excludes all the ultra-short pulse processing).

FastGALVO: Breakthrough solutions in ultra-fast galvoscanners for laser micromachining

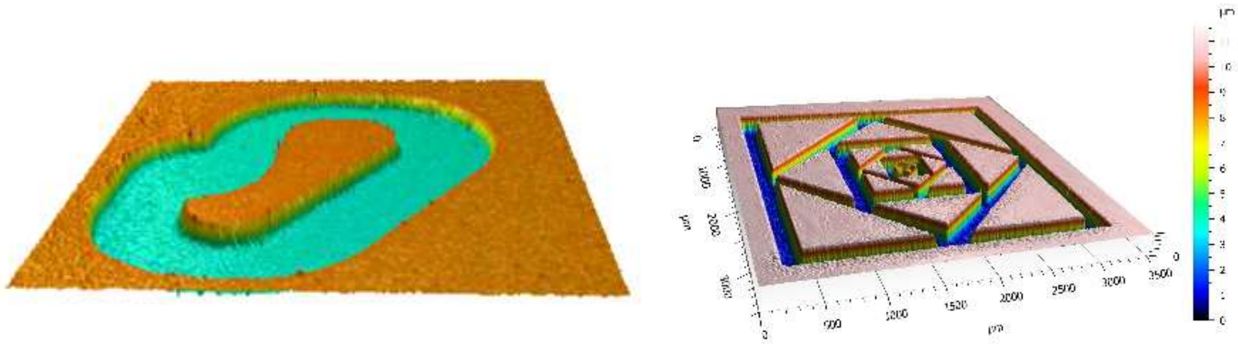
Partners: Scanlab GmbH (Germany), Robert Bosch GmbH (Germany), GE Power (Switzerland) and BUAS (Switzerland)

The general goal of the experiment was to assess the newest generation of Scanlab's intelliSCAN$_{SE}$ and excelliSCAN galvoscanners for laser micromachining with ultrashort pulses at high average powers in typical micromachining applications.

Within the already running APPOLO project, only the adaption of the existing slower intelliSCAN$_{DE}$ system with a maximum speed of about 10 m/s with a 160 mm objective, was originally planned. In the meantime, Scanlab has developed two new and much faster scanner systems, the intelliSCAN$_{SE}$ and the excelliSCAN, as well as the new improved control board RTC6. Both scanner systems are very interesting for surface texturing and micromachining applications within the APPOLO project. The possibility to use the highest acceleration independent of the marking speed makes these systems very interesting for machining small surfaces and structures. Its potential to reduce machining time was explored in real industrial applications and fully synchronised mode.



Cooling hole reproduction in a hard coating film with high-power ps-lasers enabled by the APPOLO project



Laser-machined small structures: Left: swirl chamber for injection nozzle machined using the new exelliSCAN technology, Right: complex structure machined using an intelliSCAN$_{SE}$ scanner and the synchronised scanning solution from BUAS.

All performed experiments clearly showed that the newly developed scanner technology allows to take benefit of increased acceleration values and marking speeds in all applications. Significant reduction in the overall machining time has been observed at maintained or even improved machining quality. For some applications, this scanner technology even allowed to use the laser system up to its limits. Therefore, it is very well suited for most micro-machining applications with minimal machining times.

DECOUL-Cr: Breakthrough solutions in ultrafast laser equipment for decorative finishing in automotive chrome plated parts

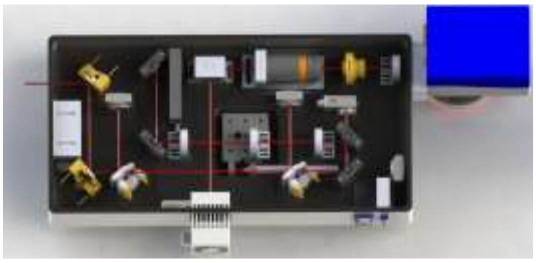
Partners: Lasing (Spain), Maier (Spain), UPM (Spain)

The goal of the DECOUL-Cr was to improve the quality of unique decorative chrome plated parts for the automotive industry using advanced laser technologies and design a complete solution to be integrated into factory line.

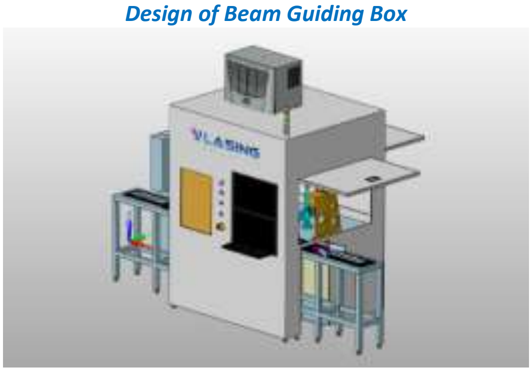
There were two different business sectors involved in the experiments, 1) Special Automotive Parts decoration from End User side (Parts manufacturer) and 2) Development of advanced laser systems from Integrator side. Precision laser applications are very complex due to the number of variables that are involved, making critical to control them for real manufacturing lines. Significant thermal changes produced mainly in all industrial environments creates essential problems that need to be controlled and resolved at real time as internal misalignments between laser sources and processing heads, laser power losses, 3D errors due mechanical drifts, making necessary to find new solutions capable of minimising these effects.

LASING designed a new concept of Analytical & Control tool named BGB (Beam Guide Box) that integrates all the optical and mechanical components that ensure an advanced and repeatable laser processing. The BGB can be installed in front of any laser, CW or pulsed with emission ranges from 1064 nm to 320 nm and technically provides the following specifications:

1) Continuous analysis of laser beam path obtaining beam pointing and beam profile data.
2) Automatic beam path correction using two sets of CCD´s sensor and Piezo mountings.
3) Motorized beam size expansion from 1x to 4x.
4) Automated energy control using polarisation optics.
5) Continuous energy and 2D beam analysis.
6) Fast and precise divergence adjustment to perform 3D or fast 2.5D processing.
7) Fast pulse counting electronics capable of detecting one pulse missing during the laser processing.
8) 2D Galvanometer head with F-theta or Telecentric lens.



Design of Beam Guiding Box



Conceptual design of complete solution integrating BGB unit.

Automotive exterior parts marked with different process parameters and different designs.

A comprehensive assessment of picosecond equipment for decorative marking of chromed part for the automotive industry has been done. A laser parametric window using ps-laser sources emitting at 532 nm has been established in such a way that all the specifications needed for marking the targeted chromed parts have been fulfilled.

SUN-JELL: Breakthrough solutions in laser marking for jewellery

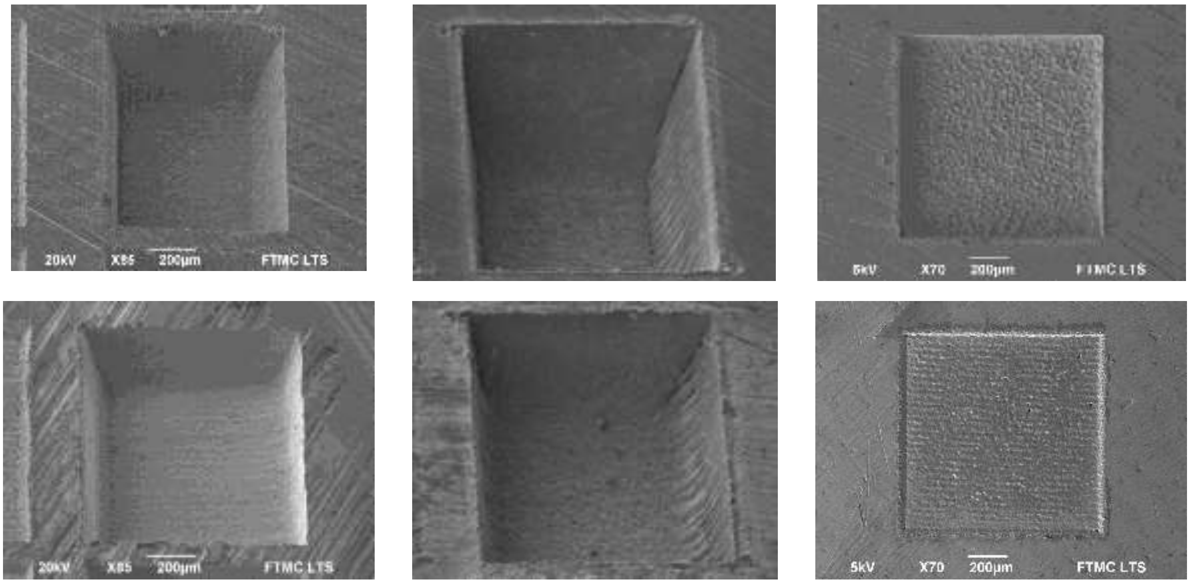
Partners: SISMA SPA (Italy), LAC SPA (Italy), FTMC (Lithuania)

THE SUN-JELL laser prototype was validated in FTMC and SISMA tests facilities. SUN-JELL laser prototype provided comparable processing quality to other laser sources – nanosecond Baltic HP and sub-nanosecond Atlantic HE. Burr effect reduction was the main goal of the SUN-JELL project. However, even at sub-nanosecond regime burr formation was observed. In order to prevent such effects, water-assisted ablation was proposed. During tests, water assist helped to prevent surface oxidation and debris formation near the processing area. Also, there is a potential to increase the ablation rates applying water assist technique. However, depending on the process parameters and material, ablated surface roughness could be altered compared to ablation in the air. The FTMC and SISMA logos were successfully engraved with optimised laser processing parameters. The maximum material removal rates of 0.03 mm^3/s were obtained keeping optimal ablation quality in brass.

Baltic HP | *SUN-JELL* | *Atlantic HE*

Water assist

Air

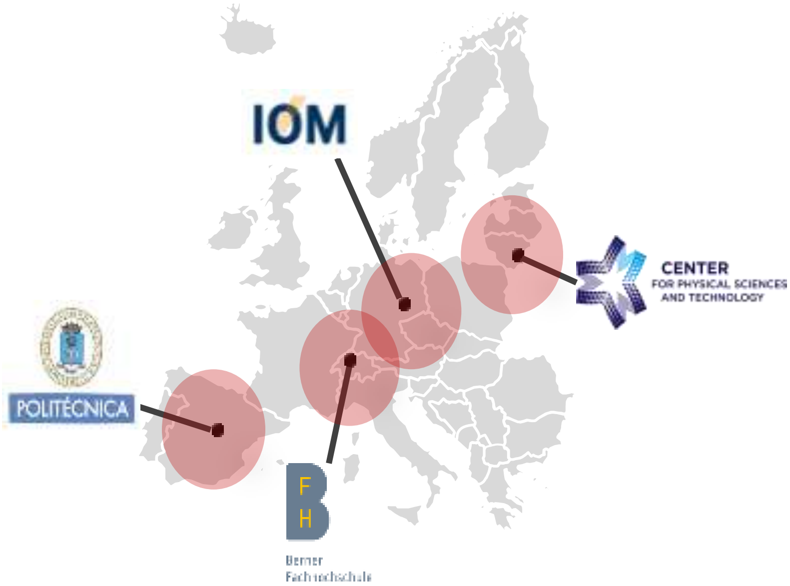


9.1 W, 100 kHz, 1000 mm/s, 10 µm hatch, 100 loops. | *12 W, 100 kHz, 1000 mm/s, 10 µm hatch, 100 loops* | *0.08 W, 1 kHz, 10 mm/s, 10 µm hatch, 50 loops*

SEM and optical images of laser engraved symbols in the brass sample. The "FTMC" letter dimensions in 1.4 x 5mm. R3, 5.6 W, 100 kHz, 10 µm hatch, 100 loops, water assist (left), Pattern engraved into silver with 10 kHz (top) and 30 kHz (bottom) repetition rates (right).

APPOLO HUB – laser technology validation service beyond the APPOLO project

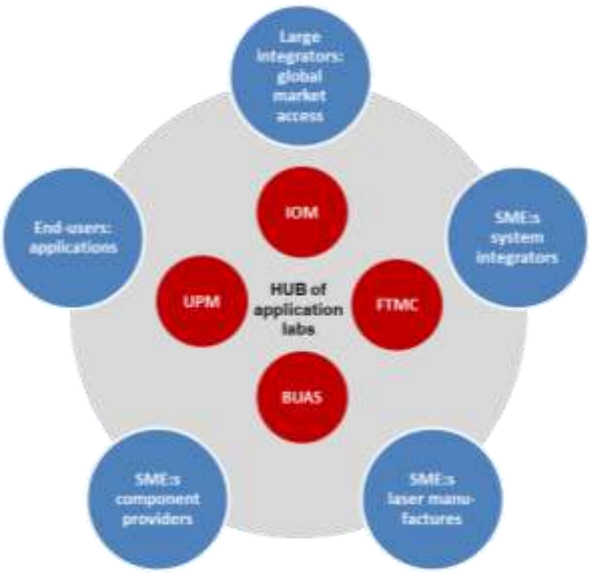
APPOLO HUB (www.appolohub.eu) is a network of laser application laboratories providing laser micromachining assessment services for industry partners. The HUB is performing the testing activities at four different laser application laboratories, located in Switzerland, Spain, Germany, and Lithuania.



The HUB is envisioned to become a centre for technology transfer to the manufacturing industry, which utilises laser micromachining technologies. The main rationale for the APPOLO HUB is to make it easier for customers (mainly end-users) to access assessment services and to evaluate their quality and trustworthiness as well as to give assessment labs easier access to new customers. A key objective is the development of a trusted brand name which reliably communicates the trust that is needed for the assessment experiments itself as well as the positive thematic and emotional associations with the leading-edge laser application.

APPOLO HUB offers services to assess and verify novel laser manufacturing technologies for industrial use, as follow:

- **Assessment of laser equipment:** We assess new lasers, scanners, beam guiding equipment and laser workstations to verify how they meet customer requirements.
- **Laser processing verification:** We offer service to define the optimal laser equipment for your samples and products with ns, ps and fs lasers.
- **Laser micromachining Ownership Costs & Benefits:** Information about costs and alternatives for ultra-short pulse laser processing: analysis and limits of laser processing parameters; process flow analysis; cost-of-ownership estimations including maintenance requirements & lifetime.



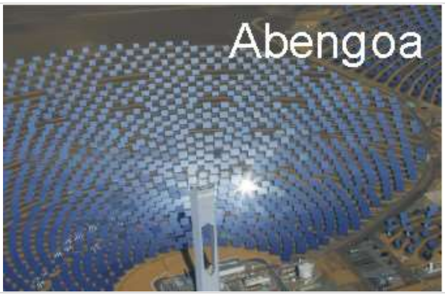
Two types of target groups have been identified and defined as APPOLO HUB customers:

- System integrators;
- End-users (both experienced as well as inexperienced ones).

The **system integrators** are highly important to the HUB. Looking for additional expertise in the field of laser micro-manufacturing, they are primarily expected to utilise consulting services, services for testing of equipment and process development.

Application areas of APPOLO technologies

Photovoltaics



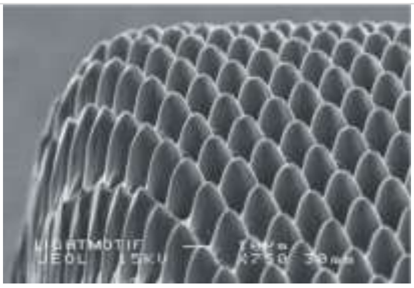
Jewellery

Printing and embossing

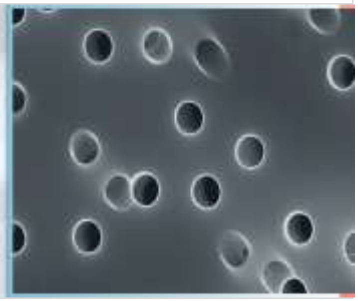
Automotive

Electronics

Machinery



Bio-medicine



SUMMARY

APPOLO project finished its activity trying to fill the gap between lasers producers, system integrators and end-users. During APPOLO project validation of laser processes for thin film photovoltaics, printing/embossing and automotive applications are being developed.

APPOLO HUB – network of laser application laboratories is working as knowledge transfer organisation providing laser process validation services. The HUB is aimed to make a research-oriented network, where industrial partners will come to test, assess and implement novel laser solutions for their markets. The HUB members actively promote their activities as to showcase their achievements in laser processing solutions. The output of the assessment made possible industry demonstrations of laser applications in their particular field. The APPOLO HUB role, therefore, is to assess these applications in the research framework, allowing all industrial partners to develop successful applications for manufacturing use. Routs for sustainable operation on the APPOLO HUB were agreed between key partners in the consortium and APPOLO HUB Agreement was signed with regular – laser application laboratories and associate partners as intermediates to end-users.

WP2 finally was finished with nearly all goals reached. During the implementation period, significant delays were accumulated in particular tasks due to unavailability of the scheduled equipment for assessment. The LSE300 polygon delivered by NST was thoroughly validated by FTMC in metal ablation and thin-film scribing, showing excellent performance in both types of processing. For validation of on-line monitoring techniques developed by LUT, they were tested in a colour marking of metals and additive manufacturing by selective laser melting paving the way for exploitation the project results.

A set of optimised high throughput scribing processes with the scribing velocities higher than 1 m/s has been developed by BUAS and validated on R&D samples and functional modules on the float glass substrate produced by EMPA. A small batch of functional modules was produced in cooperation with FLISOM to test the in-process performance of the fibre delivered scribing laser. The fibre-delivered ultrashort pulses can be used for thin-film solar cell scribing including the high-throughput P2 process employing specifically tailored spot profiles. It was shown that optimised scribing processes developed in APPOLO are ready to be implemented in industrial scribing machines.

WP3 was finalised with a renewed goal on perovskite thin film solar cells with manufacturing the first all-laser-scribed mini-modules. It was shown, that perovskites films can be ablated at very low fluences by almost any ultra-short pulse laser system. The main thin film removal mechanisms are laser ablation and thin film delamination lift-off. Material modifications can be found only for ns-laser sources due to the decomposition of the perovskites to PbI_2.

For the application of the laser scribing to mini-modules fabrication a solar cell design was developed that will allow finally semi-transparent modules developments. Both the front and the back electrode made by TCO films. This design, however, is much more challenging for all-laser scribed integrated module fabrication. All-laser scribed integrated-interconnected mini-modules were fabricated on rigid and flexible substrates, meaning glass and plastics. The fabricated modules were fully characterised by electrical measurements proving a champion module efficiency of 10.7 %. The potential application of perovskites is flexible tandem solar modules with a CIGS bottom module. The expected higher efficiencies of tandem modules enable savings of the total cost of PV systems due to the reduced area of the installations.

Activities in **WP4** were affected by many delays in delivery of equipment during the whole project period. Limited average power of LUMENTUM laser and remaining issues with LSE170HNA polygon did not allow to reach the final goals as planned. However, the results of the engraving and embossing tests utilising laser-textured sleeves show high-quality surface structures, which cannot be reached by conventional methods. The details of fine structures are precisely reproduced without missing elements down to the resolution of 1000 l/cm. Due to the significantly improved depth resolution without observable steps, the developed technology and set-up should

be tested in the field of optical embossing structures as, e.g. Fresnel lenses or lenticular. With an additional improvement in the resolution, even applications in the security filed could be targeted.

The replication process was easy to perform because of the surface properties of the ps-laser engraved copper structure shows the good release of the foils or silicone mass without destruction of the foil, unwanted residuals or failures. However, the speed of the engraving still needs to be improved to obtain more attractive values for industrial use. Utilised a higher average power laser and all benefits of improved polygon scanner, the machining time could be reduced by a factor of 4.5.

WP11 covered all activities in 7 new equipment assessment experiments. Disturbance with the late start of the new experiments continued all the time. Nevertheless, most of them reached the final goals.

In the **FAST experiment**, an improved scanning system of SCANLAB was assessed by LM, and new processes are developed for the fabrication of functional surface textures that SKF wants to use to reduce friction in their products. The fast pixel mode was implemented by SCANLAB allowing control of laser operation at a synchronised repetition rate up to 3.2 MHz. The precise laser patterning speed was increased up to 2 m/s with a high material removal rate and applied in surface texturing of moulds. The processing time for a demonstrator insert with a total volume to be removed of 11.5 mm^3 was around 30 minutes when using a process with an average laser power of 5 W.

The **PONT** experiment aimed at evaluating the performances of a resonant near-infrared ablation in the spectral range of 1500-2000 nm. The laser technology was considered to drill holes in polymer films. The Resonant IR laser ablation was tested utilising sub-ns and ps- OPO laser systems delivered by LASERSPEC. Extended study at FTMC and OSAI provided a comparison of the Resonant IR and UV laser ablation of polymers, in particular toward requirements of the end user IT4IP. The RIR approach leads to significant thermal impact to the material, and the ablation threshold is tens time higher compared with that of UV (355 nm) radiation. The experiments confirmed necessity to use ultrashort (ps, fs) laser pulses, preferable to UV, to avoid excessive heating of the remaining polymer during the processing.

Within the **LADRUM** experiment, the whole process of the pattern design, fabrication steps and techniques for characterisation were developed and implemented for roll-to-roll UV nanoimprint lithography (R2R-UV-NIL). Many efforts was put in laser fabrication of hierarchical structures on drums combing patterning with 1064 and 355 nm radiation at IOM and validating their replications. The selected patterns were successfully transferred on seamless nickel sleeve. A fabrication chain for the fabrication of micro/nano-textured web materials comprising of laser direct surface texturing and UV-NIL replication allows high throughput large area patterning of flexible web materials without a seam and with high precision. The goal of producing functional films with tailored wetting properties was demonstrated by NANOTYPOS featuring surfaces with water contact angle values of up to 158°.

A fibre delivery of pulsed laser radiation using Kagome type fibre was prepared by OPI and validated in the **NEW-DELI** experiment by BUAS and IRIS. Performance and stability were tested at BUAS with fibre lasers from ONEFIVE. Real testing of the fibre delivery was performed in experiments on laser scribing of thin-film solar cells with picosecond lasers. NEW-DELI cable has been tested at 10 ns with 20 kW peak power; 150 ns 1 mJ pulses and 10 ps 300 mJ pulses. M2 factor smaller than 1.2 has resulted in a coupling efficiency of around 85-90%. No fibre damage has occurred when operating with ultrashort lasers.

The **FASTGalvo** experiment combined the developments of SCANLAB and BUAS to ramp speed of laser processing utilising galvoscanners. Precise processing of small features is now feasible at a speed of 15 m/s utilising a new excelliSCAN scanner, RTC6 control board and advanced control from BUAS. The performed experiments showed that the newly developed scanner technology allows to take benefit of increased acceleration values and marking speeds in all applications. Significant reduction in the overall machining time has been observed at maintained or even improved machining quality. For some applications, this scanner technology even allowed to use the laser system up to its limits. Therefore, it is very well suited for most micro-machining applications with minimal machining times. Bidirectional scanning, as well as the adaption of the scan line length to the bitmap proposed by BUAS, should be implemented. The technologies were validated by BOSCH in the fabrication of small structures and reopening holes for cooling by GE.

The main objective of the **DECOUL-Cr** experiment was to study the use of pulsed laser sources to induce changes in chromium-coated parts. Two different laser sources have been applied by UPM, and different effects were observed on the marked areas of MAIER chromium-coated plates. The surface finishing utilising LIPSS offers a new exciting aesthetic that could be applied to chrome parts. A comprehensive assessment of picosecond laser equipment for decorative marking of the chromed part has been done. The experiment reached its final goal providing a validated technology for automotive industry. At the same time, LASING developed the whole laser processing system implementing the technology ready to be integrated into a manufacturing line.

A modified sub-nanosecond high pulse energy laser from SISMA was investigated at FTMC and validated in the deep engraving of metals for jewellery in the **SUN-JELL** experiment. Delays in delivery and discovered problems with laser performance did not allow to reach the final goal. However, the performance of a new laser was tested in the SISMA laser machine as well. Use of sub-nanosecond pulses in the delicate marking of metals have shown promising results to continue. A water-assisted laser ablation helped to prevent surface oxidation and debris formation. The materials ablation rates reached 0.005-0.021 mm^3/s, while surface roughness was below 2 µm at a laser power level of 12 W. The SUN-JELL laser source was integrated into a SISMA laser machine, and their performance was validated in deep engraving stainless steel, brass and gold for the end user LAC.

Dissemination activities show good results, mainly due to the strong partners' representation of the APPOLO project at many international events promoting the project results and the APPOLO HUB idea. Two new issues of the APPOLO newsletter and a brochure were prepared and distributed. The dissemination activities were coordinated with the I4MS initiative. Two websites are running for the project: www.appolo-fp7.eu for all project related activities and dissemination and http://appolohub.appolo-fp7.eu/ for APPOLO HUB as a single access point to consolidated infrastructure and expertise of the laser application laboratories, involved in the project. Amount of public information was significantly enlarged on the website.

Further steps were taken to collect all IP and exploit it accordingly strategically. Twelve applications for patents are submitted or are in the process of submitting out of 37 innovations in total generated in different workpackages. Partners expect to be able to generate sales of € 76M over the next five years with these innovations, generating at least 66 additional jobs with this. Long discussions led to a HUB sustainability strategy promising to keep the APPOLO HUB in place as both a cooperation and a marketing & sales tool and Cooperation agreement was signed among regular partners.