DELIVERABLE 1.9

APPOLO PUBLIC REPORT Y3

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INTRODUCTION

The APPOLO project has established 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 (preferable SMEs: for integration, lasers, beam control and guiding, software, etc.) in order 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 accumulating knowledge and infrastructure and promoting 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 7 new assessment experiments and developing the standardised procedures for the assessment service which can be provided for new project partners and customers beyond.

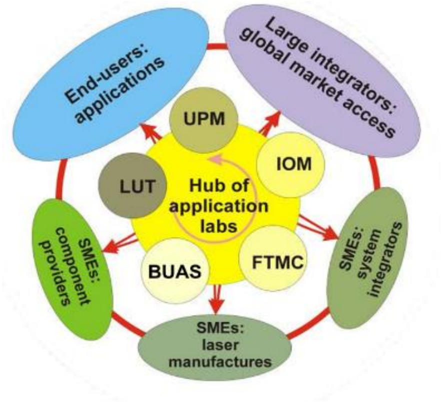
Particular objectives for the Y3 period were:

- Integration of new lasers, polygon scanner with on-line monitoring tools into laser system for thin film scribing assessment and validation with the integrated system of the scribing performance in CIGS solar cells;
- Selection of the optimised approaches for the P2 and P3 scribing for industrial technologies according to requirements of end user;
- Development of the handling procedures for perovskite-based solar cells in laser scribing experiments and transfer of the knowledge from CIGS scribing to that new material;
- Optimisation of high-performance laser texturing technologies for printing and embossing rolls with stitching the processed areas and integration of advanced lasers and scanners;
- Surface texturing of metallic moulds by lasers and validation of the replicated polymer surfaces;
- Assessment of the laser-based selective metallization of 3D-shaped polymers for MID and validation of the technologies for devices in automotive and sensing applications;
- Validation and implementation of laser-based metallization by LIFT on full-size solar cells;
- The start of new assessment experiments, selected after the Open call procedures, with a research partner from APPOLO HUB and 14 new industrial partners.

In the third year, RTD activities in three workpackages WP5, WP6 and WP7, have been finished.

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.

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 machineries.

APPOLO Objectives

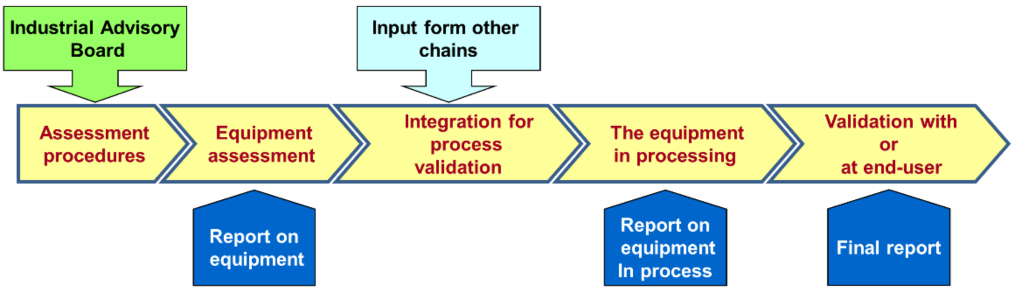
Establish and coordinate connections between

- 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 customization 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 in **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

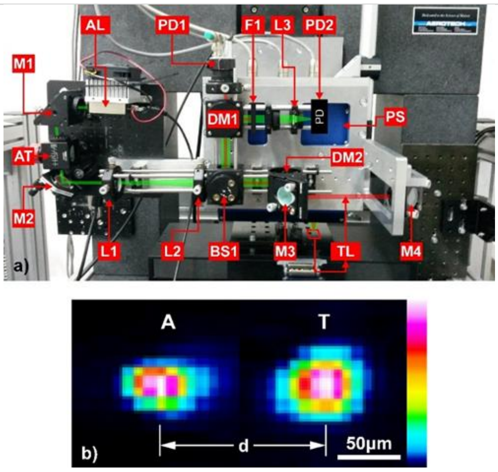
Validation of the scribing performance in CIGS solar cells with the integrated laser system

Partners: FTMC, LUT, EKSPLA, NST, AMSYS, ELAS, FLISOM, EMPA, ABENGOA

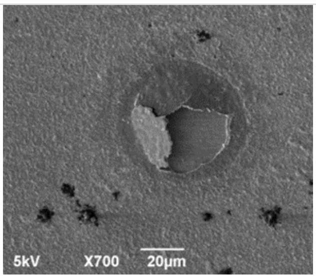
Integration of new lasers, polygon scanner with on-line monitoring tools into laser system for thin film scribing assessment and validation with the integrated system of the scribing performance in CIGS solar cells was performed in WP2 at FTMC.

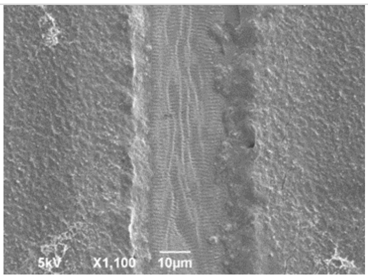
ELAS has finished upgrading its DuoMaster laser processing system by changing the main optical path. They finalised installation of its embedded Roll-to-Roll unit to the DuoMaster laser system at FTMC for validation of the laser scribing processes of CIGS solar cells on flexible polymer foils.
The used web width for PET was 150 mm, for Kapton - 250 mm. Flat working field for laser processing on the web is 300x300mm. The web could be moved into both directions: forth and back. Adjustable film tension and constant speed can be maintained during the laser process and in the stop mode. The incremental encoder is linked to the roll which is the nearest to the laser working field. The additional output of the encoder can be used for laser pulse synchronisation and beam position correction.

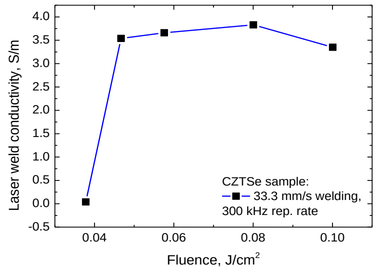
The on-line monitoring tools from LUT and AMSYS were validated in laser scribing experiments at FTMC enabling control of the process with a scanning speed of above 1 m/s and recognise defects in the ablation trench less than 50 µm at the scan speed of 50 m/s through optics of the polygon scanner LSE170.
The laser scribing of the CIGS samples without front contact (P2) was performed using pulse energy of 12.2 µJ and varying the number of scans per scribe. The best P2 scribe was got when 50 scans were applied. The average reflected the signal from such scribe was about 1 V. When the number of scans was increased further, the damage of polyimide layer took place and the signal drop was observed. These results show that it is possible to monitor online how the P2 scribe is being produced at the speed corresponding to the real processing conditions.



Fundamental harmonics of the 1.34 µm picosecond laser from Ekspla was utilised in the P2 and P3 processes in CIGS and CZTSe thin-film solar cells. The investigation was mainly focused on the P2 laser welding. Additionally, the laser-induced P3 lift-off process by exposing a molybdenum layer was investigated in thin-film CIGS solar cells deposited on flexible stainless steel substrates. In the case of CZTSe absorber, the P2 results were very promising. At the optimal laser processing conditions, a significant increase in the interconnect conductivity was achieved. By reducing scanning speed and increasing laser irradiation dose resulted in the conductivity increase to up to 3.83 S/m. Further increase of irradiation dose could lead to further increase of the P2 interconnect conductivity.







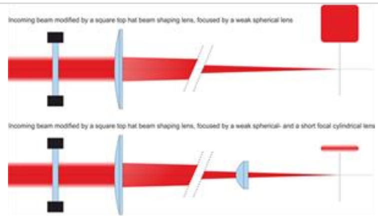
Combining of high-performance laser scribing with on-line monitoring tools makes it feasible optimisation of new laser processes development

Validation of high-throughput thin-film scribing processes

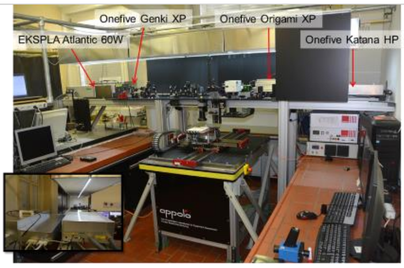
Partners: BUAS, ONEFIVE, EMPA, FLISOM

In APPOLO WP2, the assessment of optimized high-throughput scribing processes for the industrial patterning of CIGS solar cells and suitable tailored laser systems are in the focus. A strong cluster of laser provider (Onefive), end-user of scribing processes (Flisom), R&D sample and thin-film knowledge provider (EMPA) and APPOLO application lab (BUAS) was formed. The common goal is the elaboration of the assessment experiments and standards for laser-scribing processes and laser equipment. The phenomenon of heat accumulation occurs also for ultrashort pulses and depends mainly on the time available for thermal relaxation between two consecutive pulses. Based on this property, the scaling approach followed at the BUAS application lab seeks to maximize time spans available for said thermal relaxation by increasing the area processed per pulse.

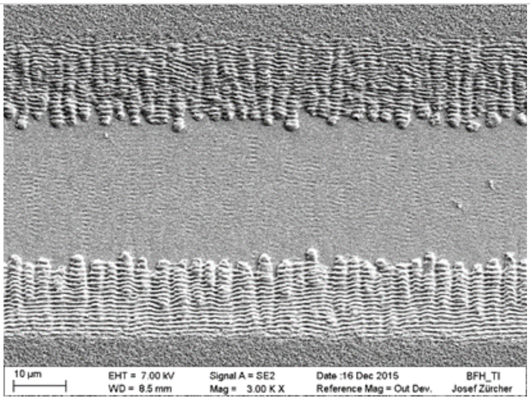
By increasing the spot size and the laser pulse energy the area processed per pulse can be increased using only one beam path. If the focal spot size is increased only in direction of scribing, a linear focus results. An additional optical Gaussian to top hat beam profile converter is used which produces a homogenous intensity distribution in direction of the line.



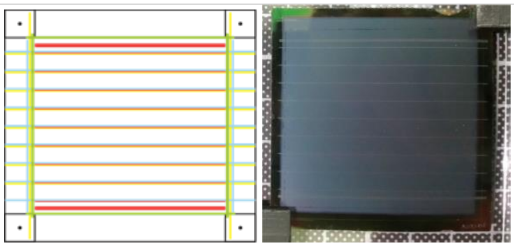
The lab scale scribing machine available at BUAS application lab is a highly versatile setup consisting of an industrial grade direct drive motion system and an optics platform. The latter provides a 4.2 x 0.6 m^2 optical experimentation area with laminar flow boxes installed for dust protection. The machine has been significantly expanded. The vision feature allows automated mapping of a large sample area and automated defect recognition.



Several types of validation experiments were made using APPOLO laser sources and reference lasers. High throughput scribing processes developed in the frame of APPOLO were validated against the BUAS reference processes. All validation scribing experiments shown here were made on samples produced at EMPA. The layer stack Mo/Cu(In,Ga)Se_2/CdS/ZnO was grown on float glass substrates of 50 x 50 mm^2 size. All presented scribing processes lead to very good results, complete or nearly complete exposure of the back contact, regular and smooth scribe borders and no cracks in the CIGS outside the processed area. Most important, there is no damage and no thinning of the back contact layer observed for the high-throughput processes.



Electrical performance of modules, processed using the optimized APPOLO high throughput P2 scribing process at 1720 mm/s and 325 mm/s, was comparable to the performance of the reference sample processed with a round focal spot at 90 mm/s. All three have shown conversion efficiency around 14 percent after annealing and without anti reflection coating.



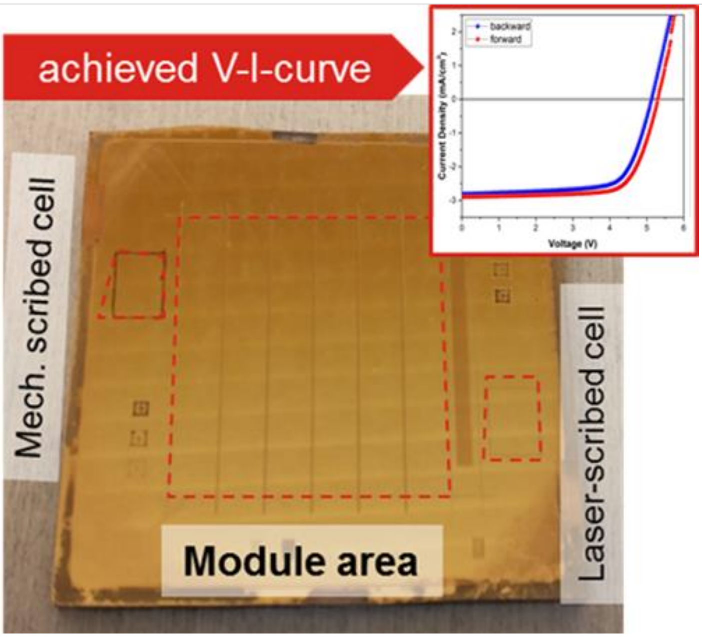
In the following, the final phase of the APPOLO assessment is the high through-put scribing processes and Onefive optimized laser sources. A series of assessment experiments are conducted at the facilities of industrial end-user Flisom. A tight collaboration between Flisom, BUAS, EMPA and Onefive makes it possible to assess the optimized scribing laser source in combination with optimized high-throughput scribing processes on industrially produced CIGS grown on flexible substrate at Flisom. Several series of functional modules on flexible substrate are produced and compared directly with Flisom's own reference modules.

Handling procedures for perovskite-based solar cells in laser scribing experiments and the first full-laser-scribed perovskite solar cell

Partners: IOM, UPM, EMPA, ABENGOA

Due to the modification of the WP3 objectives the work was concentrated on perovskite photovoltaic that is currently a hot topic in the PV community. Perovskite-based devices do not only allow potential low-cost and simple manufacturing of solar modules but the technology can also be added to already existing PV concepts like c-Si and CIGS in tandem configuration to increase the efficiency without substantially increasing the production complexity. In order to allow fast implementation of the technology a reliable and fast monolithic interconnection concept needs to be developed. In a first step the consortium in WP3 concentrated on understanding the mechanisms of the laser-scribing processes of the various layers in the particular perovskite device architecture; studies of the performance of the laser scribing with standard and ultrashort laser sources were performed. The studies of the surface morphology of the laser scribes in dependence on the laser scribing parameters result in the discovery of the material removal mechanism that can be laser ablation or a laser delamination process. The fundamental parameters for ultrashort laser pulses with ps length are the irradiation direction, film or rear side, and the laser wavelength that determine the mechanism.

Within this task a protocol for sample handling and shipping was developed that ensures minimized degradation of the samples to guarantee reproducible results. Making use of this protocol, the electrical properties of laser scribes have been studied also considering the final functionality of the scribes. For the separation scribe lines P1 and P3 the insulation resistance in dependence on the laser scribing parameters has been studied and optimized. In both cases specific procedures have been developed to achieve reproducible results. For the connecting scribe P2 the contact resistance in dependence on the laser-scribing process and design parameters, e.g. the scribe width, was studied to enabling further optimization.



Photograph of all-laser scribed perovskite solar module on glass substrate. With a voltage of ~ 6 V and an efficiency of > 10% a state-of-the-art result was achieved.

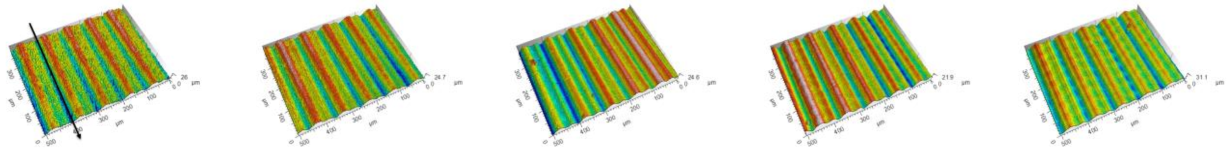
As first proof of concept perovskite mini-modules on glass substrate were fabricated and tested by using specific device architecture and large-area deposition methods developed at EMPA and applying the adapted laser scribing techniques.

The perovskite mini-modules were fully characterized including the morphology of the scribes, the characteristics of the interconnection area and the photovoltaic properties of the mini-modules. Further results have been obtained by additionally defining single reference solar cells both by laser and mechanical scribing. The currently achieved module efficiencies that are exceeding 10% and are almost comparable to their small-sized reference cells confirm the high quality of the ps-laser-scribing processes. The obtained results are the basis for minimizing serial resistance and dead area losses of the interconnection area for further module efficiency improvements.

Optimisation of high-performance laser texturing technologies for printing and embossing rolls

Partners: BUAS, IOM, LUMENTUM, NST, DG, SWG

Laser texturing of steel was investigated in WP4 with average powers exceeding 100 W. The optimum point for the repetition rate of 10 MHz was around 60 W. The heat accumulation can be reduced by reducing the overlap and enlarging the marking speed. The surface quality becomes better with decreasing overlap i.e. higher marking speed because the heat accumulation will also be decreased. However, for the overlaps of 25% and 12.5%, the single pulses become visible implying that the interlaced mode should be used to get a flat surface.



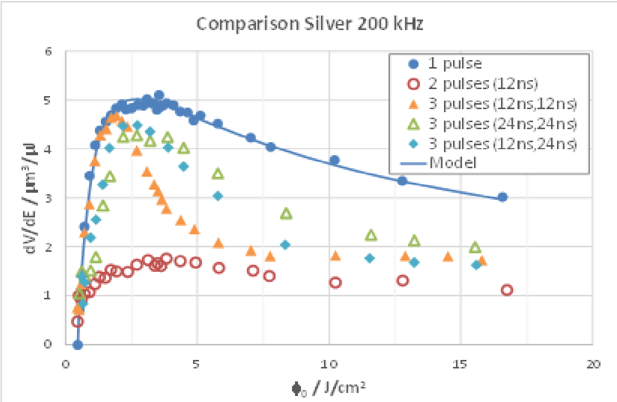
Surfaces topographies at the optimum point at a repetition rate of 10 MHz and an average power of about 60 W for different overlaps of 85%, 75%, 50%, 25% and 12.5% (from left to right).

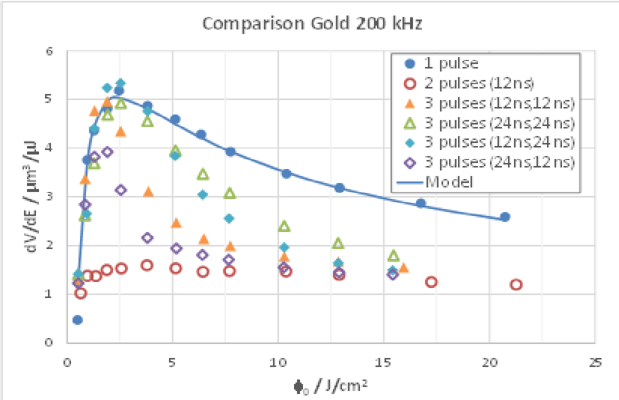
It was shown that the ablation process is, in principal, scalable up into the several 100 W regime, but it is limited by:

- **Plasma shielding** which occurs for copper and brass at the repetition rates of several MHz and increases for higher repetition rates. The effect becomes stronger as higher removed mass per pulse at the optimum point is.
- **Heat accumulation** which leads to bumpy surfaces. This effect becomes stronger if lower the heat conductivity or thermal diffusivity of the material is.

3-Pulse burst efficiency

In previous experiments, an increase of the specific removal rate for a three-pulse burst and copper was observed. A hypothesis concerning plasma shielding and change in the reflectivity of the surface due to its molten state was made. To foster this hypothesis, additional experiments with varying energy per pulse in the burst, other materials (gold and silver) and calorimetric measurements were performed and compared with previous results on copper and steel.

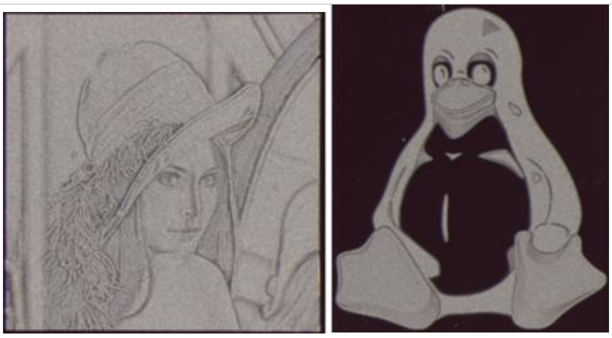




The behaviour of the second pulse can be explained by plasma shielding but for the increase in efficiency of the third pulse in case of copper, silver and gold alternative explanations have to be found. In APPOLO project, we can conclude that it is possible to achieve high specific removal rates with the three-pulse burst which can reduce the demands concerning the repetition rate by a factor of three.

Work on flat surfaces and stitching

The synchronised galvoscanner allows to combining two images. After the successful alignment of the two coordination system, the marking strategy in the intersection region is crucial for seamless stitching. The stitching strategies are already shown. In the last step, the best strategy was transferred to the setup including the synchronised galvoscanner and a linear axis. With a light microscope, almost no influence on the surface quality and optical effect can be found using the described strategy.



Two laser engraved pictures stitched form segments

Soft-touch surfaces on 3D curved automotive interior parts

Partners: LIGHTMOTIF, CRF

This work in WP5 is based on a technology previously developed by Lightmotif that enables laser ablation of micro- and nanoscale features on 3D curved moulds by ultrashort pulsed lasers. Lightmotif and CRF cooperate with the goal to obtain a method that enables the production of polymer parts for car interiors with added functionality due to a micro- and nano-textured surface, achieved by a textured mould. The surfaces should show a soft-touch effect that results from a largely reduced contact area of skin and polymer part. Besides the haptic properties of the surface other relevant aspects like aesthetic properties of the textures should be optimised.

The objective for the third year was to validate the manufacturing process of real automotive parts with soft-touch surfaces. For this purpose, a mould insert for a real automotive part was selected: a 'glovebox' element of a Fiat Grande Punto dashboard.

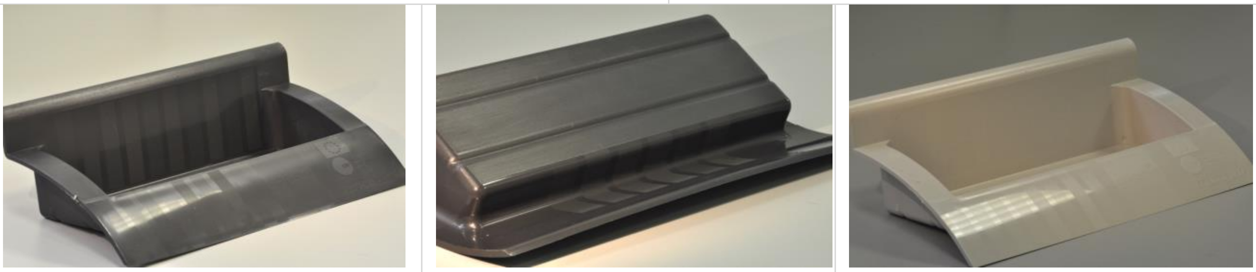
Besides serving for validation and demonstration, the injection moulded parts were also used to assess the influence of the texture angle on the release properties of the textured parts out of the mould.

Interior of the Fiat Grande Punto.

Lightmotif applied four earlier optimised textures in different curved areas to the three mould inserts. The textures were applied under varying angles of inclination, which can help to release the pillar textures out of the mould surface.

The three textured inserts.

Engraved logos on the mould surface.



Injection moulded parts.

Analysis of the injection moulded parts showed that the release of parts moulded was not limited by damage during the demoulding process. The analysis of the functional (soft-touch) properties showed very similar results on these 3D curved parts as compared to the earlier tested flat parts.

HOW TO EXPLOIT?

Utilisation of picosecond lasers in texturing of moulds for automotive interior parts offers freedom of designs. This new technology enables texturing of surfaces with features at the micro and nanoscale. Such surfaces can exhibit functional properties like superhydrophobicity, anti-glare, soft-touch and others.

This method is more environmentally friendly compared to traditional mould texturing by etching method as using of hazardous acids is avoided during the process. Using of laser micro-texturing allows mimicking etched surfaces, for example like the leather imitation textures, but it also allows to incorporate new functional properties by laser applied functional surface textures.

Lightmotif develops and sells 5-axis laser machining systems for mould texturing and micromachining on 3D curved surfaces.

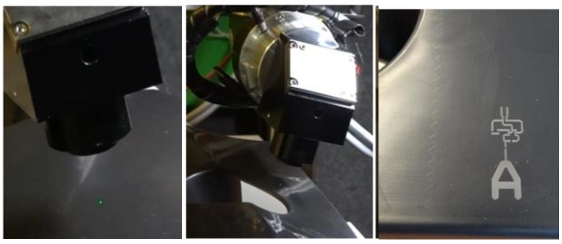
Laser-based selective metallization of 3D-shaped polymers

Partners: FTMC, EKSPLA, ELAS, AMSYS, CRF, BIOAGE

The objective of WP6 was to develop reliable schemes for direct writing of 3D wiring by laser radiation. The main aim was to perform surface processing of standard plastics instead of using highly specialized material which are expensive. We achieved all the targets, manufacturing demonstrators in the two main sectors as automotive and sensor.

Laser machine for real 3D patterning

The ADILAW processing head was adapted to the actual process conditions by creating the laser beam delivery path adjustment routine. The evaluation experiments were performed by making laser written patterns on the 3D curved automotive interior part. Productivity parameters were measured, tilting accuracy tests of the ADILAW occupied by FTS were performed.

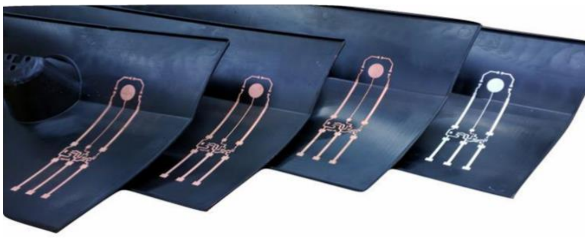


The patterning process by using ADILAW processing head

Two new technologies for laser-based selective metallization of polymers for moulded interconnect devices were developed in APPOLO which are applicable for carbon-doped and pure polymers used in car industry.

Method	LDS	LDS	SSAIL
	standard on market	**APPOLO carbon**	**APPOLO pure**
Equipment	ns-laser	ns-laser	ps-laser
Equipment depreciation, €/hour)	9.50	9.50	**15.00**
Plastic	PC/ABS for MID (metalo-organic additives	PC/ABS + 2% (by mass) MWCNT	PC/ABS
Approximate cost of plastic, €/kg	2	2	2
Approximate cost of additive to plastic, €/kg	**6**	1.4	**0**
Estimate of the cost of plating solution €/l	0.55	0.55	0.55
Chemical activation solution, €/l	0	0	**0.22**
Cost of chemical process, €/100 cm^2	0.11	0.11	**0.154**
Cost of laser processing, €/100 cm^2	0.17575	0.17575	**0.2775**
Processing expenses for a glove box cover, €	**3.25**	**1.45**	**0.93**

CRF selected the glove box cover of the Fiat 500 as a demonstrator for the integration of electronics. This specific component was first implemented on the USA version of the car and from July 2015, it is also included in the new facelift version for the European market. The main aim is to substitute the traditional manual opening system with a touch sensitive electronics that automatically opens the glove box when the user touches the sensitive area. All samples were electroless plated firstly with copper.



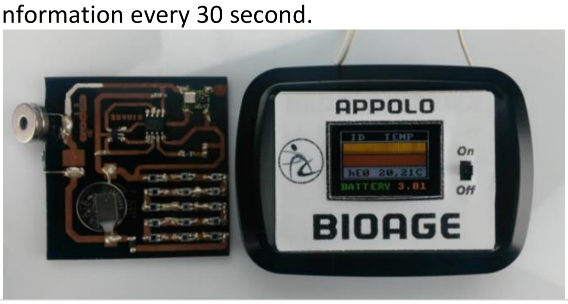
Glove box cover samples coated with copper and copper + silver.

Demo for automotive sector

All the components for glove box cover were assembled using a silver bi-component conductive glue based on silver paste. In particular, the connections were stuck before with a normal tape to the plastic substrate.

Demo for environmental sensors

The temperature sensor with miniaturized shape, volume and weight. The microcontroller acquires the data of the IC temperature chip and send the information every 30 second.



Laser-based metallization of full-size solar cells by LIFT

Partners: UPM, MONDRAGON ASSEMBLY, ABENGOA

The laser-induced forward transfer (LIFT) process is a technique to transfer locally different materials and in different sizes onto a number of different substrates. The laser beam is focused in the donor substrate/ribbon interface. During the pulse duration, the laser energy is deposited within the laser spot size into the interface, evaporating a little amount of the material and generating the expansion of the remaining material, accelerating the non-evaporated part of the metal film towards the acceptor substrate.

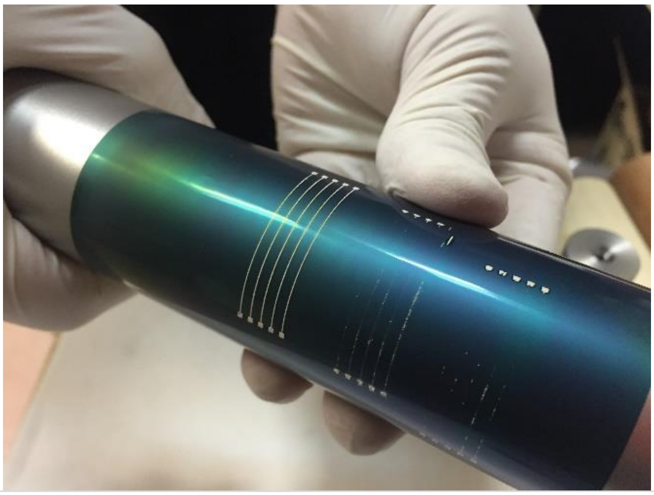
Main objective of WP7 was to design and develop reliable schemes for direct writing of flex electronics and photovoltaics in planar geometry using laser sources. In this third year of APPOLO project, the main results accomplished in the Work Package 7 are summarized.

It has been proved that laser curing and sintering of silver paste lines printed using LIFT can be achieved at different laser powers and scanning speeds, but there is a small parametric window for obtaining the desired properties (increased electrical conductivity and good mechanical adhesion), making it a very sensitive process.

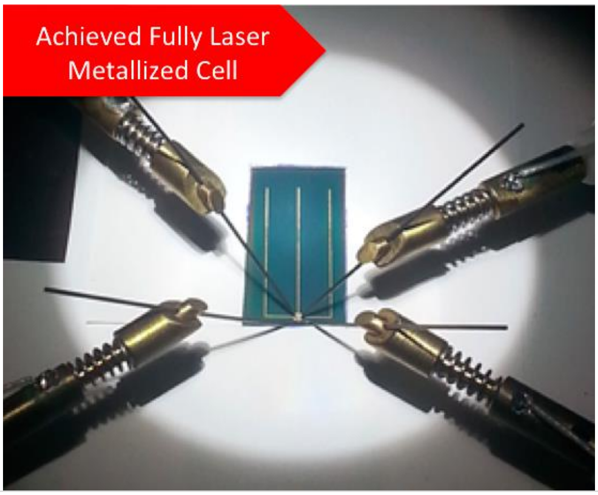
It has been proved that the selective laser curing and sintering can be combined with other laser direct writing printing techniques and be implemented in future photovoltaic industrial applications for developing an all-laser based metallization process. And it has been shown that can be used as a low temperature process due to its capability to produce local heat suitable for the process but leaving the rest of the cell almost at room temperature.

As a proof of concept, the full metallization of a CIGS solar cell on steel flex substrate with fingers and busses deposited by the proposed LIFT technology has been performed and a working solar cell has been obtained. The method used for LIFT printing of silver lines has overcome one of its main problems for industrialization, as is the printing of long lines.

As a result of the work done in WP7 Mondragon Assembly has developed a flexible industrial machine tool for adhesives/pastes dispensing, as well as for curing/sintering processes.



Metal fingers bended using a test cylinder with radius ¾".



CIGS solar cell Current-Voltage characterization with solar simulator.

Real-time monitoring and control techniques for laser processing

Partners: LUT

The use of ultrafast lasers provides many new possibilities for microscale processing applications due to their ability for virtually thermal ablation and high peak power. One particularly useful application is a thin film laser scribing, which can be used for example in solar panel manufacturing in order to improve the efficiency of solar cells. Processing speed in laser scribing applications can reach as high as several meters per second, in combination with high quality requirements. Defects in the scribing line, resulting from disturbances in the process, will greatly affect the quality of the end product. Presently, there is a demand for research in the fields of process monitoring and quality control. LUT having huge experience in monitoring laser macro-processing processes is testing sensitivity and lateral resolution of the techniques to be applied with ultra-short pulse lasers, possessing not so much high average power but working at high pulse repetition rate.

Real-time online monitoring of laser scribing of CIGS solar cells using photodiodes: The goal was to develop and evaluate a method for monitoring the laser scribing process in real time using photodiodes to detect defects in the process. Set of photodetectors were tested with 20 W nanosecond fiber laser working at repetition rate up to 1 MHz. Sensitivity all the techniques was tested and limitations of the techniques were evaluated.

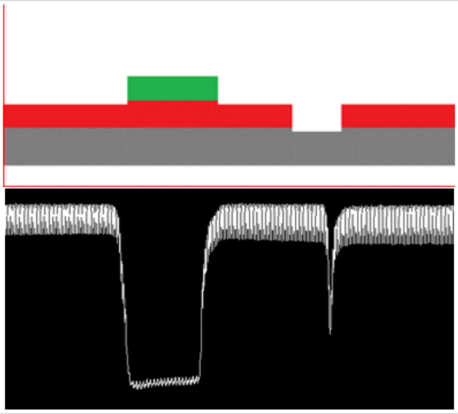
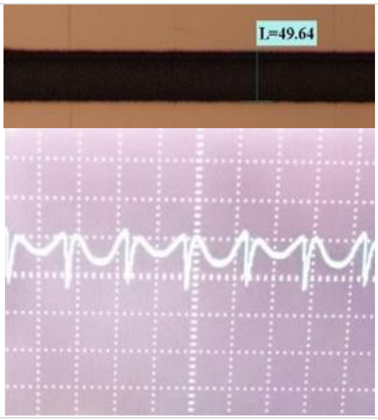


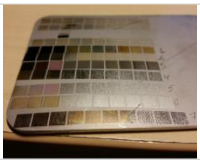
Diagram of test surface. Green: intact surface, red: second layer, grey: base layer and reflected light intensity curve when going over test scribed surface.



Micro image of the line on CIGS, along with the corresponding oscilloscope measurements.

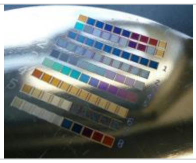
Real-time monitoring of laser colour marking utilizing nanosecond pulsed laser: LUT applied the same real-time monitoring and adaptive control methods developed to control the process of scribing CIGS, to do real-time monitoring of laser colour marking utilizing nanosecond pulsed laser. It was possible to generate different colours on metal surfaces with laser pulses. It is based on an oxidation process and thin film effect following it. The thickness of the oxide layer generated by the laser pulses defines how light is reflected off the surface and therefore generates different colours. The quality and uniformity of the colour and the shade depends on the laser parameters such as pulse duration, repetition rate, laser power, marking speed, line spacing and the focal spot diameter.

Stainless steel, Power 10-20 W, Speed 50-1500 mm/s.

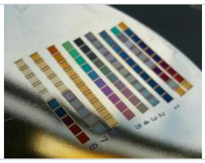


Stainless steel, Frequency 50-1000 kHz, Speed 100-1000 mm/s.

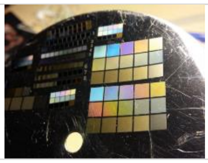
Stainless steel, Pulse duration: 4-200 ns.



Chromium, Power 15-20 W, Speed 100-500 mm/s, τ = 4, 100 ns.

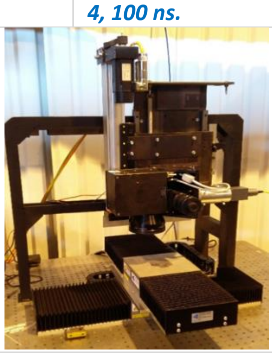


Chromium, Power 15-20 W, Speed 100-500 mm/s, τ = 4, 100 ns.



Chromium, Power 15-20 W, Speed 100-500 mm/s, τ = 4, 100 ns.

Development of a real-time simulation platform based on industrial automation process of CIGS laser scribing: First real-time online simulator for CIGS manufacturing based on real-process has been developed. This automation system is developed based on the real-process in the industry. The necessity of developing such simulator was to have same process methodology for real-time monitoring. The simulator integrated with the real-time control system of the pulsed laser and the scanner head. Also, the developed monitoring systems which were developed in APPOLO project are integrated to the simulator. In this way, adaptive real-time control of the CIGS thin film scribing based on real industrial process came possible.



New assessment experiments selected after the Open call procedures started in the third year of APPOLO project. The most progressed experiment is

LADRUM: Laser patterning of DRUM-moulds for large-area nano-imprinted polymer films

Partners: SCANLAB, NANOTYPOS,IOM

Bio-mimicking is one approach to developing technical solutions of micro- and nanotechnologies by using and adapting solutions of the nature that were optimised within billions of years. One of the most inspiriting details is the lotus leave effect providing water repellent and self-cleaning capabilities by combining a micro-/nanopatterned surface within the chemically unique material. However, for industrial applications, surfaces providing such qualifications must be inexpensive and applicable to free-form product surfaces. High volume and large area replication technologies such as roll-to-roll ultraviolet light assisted nanoimprint lithography (R2R-UV-NIL) are capable of the fabrication of hierarchical micro-/nanopatterns for tailored functional materials combining the required surface properties for applications.

A first design of the self-cleaning patterns was developed from the knowledge of photolithographically structured nickel shims considering the larger size of the laser spot for direct writing of such pattern. For writing different dimensions of the lotus leave-like surfaces, a process was designed making use of the fundamental and the third harmonics of a ps-laser in combination with beam splitting enabling both high-speed patterning and different pattern sizes. Both line and dot patterns were developed to check two selected opportunities of the primary pattern design.

Due to the limited knowledge on replication of laser-patterned nickel surfaces, some preliminary studies are performed to show the principal capabilities of replication of laser-patterned substrates. These experiments were performed on plane substrates wherein different dimple arrays were laser-machined. These test samples were utilised for UV-NIL to get replicated patterns onto thin polymer foils for measuring the finally aimed water repellent capabilities.

Photograph of a machined sleeve with decorative patterns.

For testing, the whole process from sleeve fabrication to the final replication by UV-NIL sleeves with preliminary patterns was machined. Basically, two different types of application-relevant surface patterns have been fabricated on nickel sleeves: dimple arrays with the hole diameters of 30 µm and an aspect ratio of approximately 1 and diffractive LIPPS pattern for decorative applications.

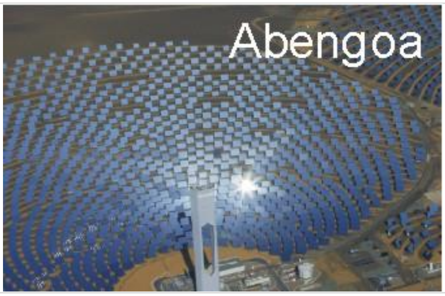
To allow the final test for the verification of the R2R UV-NIL process with laser-written master copies, all needed machines must enable to handle the same cylinders. To enable a low weight of the cylinders for shipping, the sleeve concept was utilised to realise the patterned cylinders; hence the very thin sleeves must slide on a rigid cylinder that is regularly a pressure cylinder.

The machining parameters have been adapted to the new UV-NIL materials and the different sizes of the cylinders.

With the first sleeves, a successful R2R UV-NIL process was developed. It was found that the demoulding is the most challenging step during UV-NIL. To fulfil all requirements for the targeted application, all the manufacturing processes parameters must be synchronised and optimised. Therefore, several materials were tested in order to obtain the suitable physical and chemical parameters (surface energy, hardness, curing speed and viscosity) for the successful replication of the structures and to achieve a high throughput processing.

Application areas of APPOLO technologies

Photovoltaics

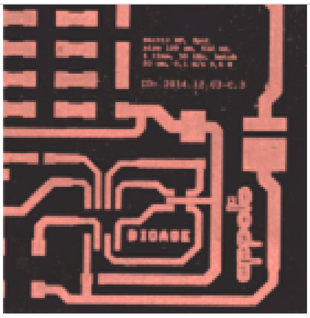


Jewellery

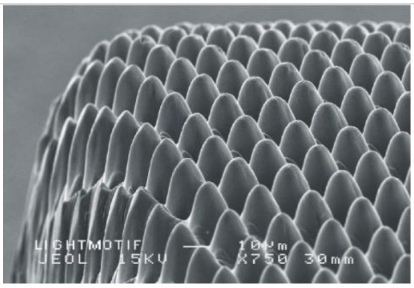
Printing and embossing

Automotive

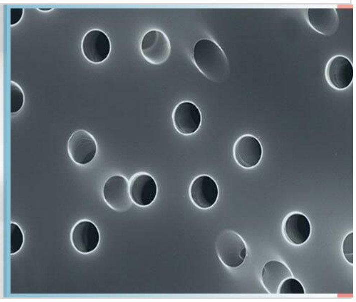
Electronics



Machinery



Bio-medicine



SUMMARY

APPOLO project is filling the gap between lasers producers, system integrators and end-users. APPOLO HUB – network of laser application laboratories deals with this issue working as knowledge transfer organisation providing laser process validation services. During APPOLO project validation of laser processes for thin film photovoltaics, printing/embossing and automotive applications are being developed.

The APPOLO HUB network model was established during Y3. 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.

The on-line monitoring tools from LUT and AMSYS were validated in laser scribing experiments at FTMC enabling control of the process with a scanning speed of above 1 m/s and recognise defects in the ablation trench at the scan speed of 50 m/s through optics of the polygon scanner LSE170. ELAS has finished upgrading their laser processing system and finalised integration of an embedded Roll-to-Roll unit to the DuoMaster laser system at FTMC for validation of the laser scribing processes of CIGS solar cells on flexible polymer foils. A set of optimised high throughput scribing processes with the scribing velocities higher than 1 m/s has been developed by BUAS and Flisom and validated on functional modules produced by EMPA.

The focus of WP3 was moved from CIGS to perovskite thin-film absorbers. This promising material drives the developments of recent boosting photovoltaic market. Based on this knowledge a mini-module design including an adapted fabrication process for the realisation of all laser-scribed perovskite mini-modules was developed by the collaboration of IOM with EMPA. To ensure a safe and low-damage handling of the samples to get reliable results regarding the laser scribing a common protocol of best practice for handling, processing and storage of these perovskite samples was developed and implemented.

In laser texturing, it was shown that for copper and brass a power scale-up into the 300 W regime with 3 ps pulses is possible and the removal rate in the range of 1 mm^3/s can be achieved. For steel, the heat accumulation is limiting the power scale up, and alternative approaches have to be developed to deal with 100 W average power or more.

A 3D mould texturing method was assessed and optimised for applications on automotive interior components, with the goal to obtain soft-touch effects by the micro/ nano-textured surfaces. The visual appearance of the surfaces was improved step-by-step and finally resulted in a perfectly homogeneous surface texture. For automotive applications, further optimisation is needed, however, the developments within APPOLO resulted in the technology that already is gaining acceptance by the industry.

All targets of WP6 were achieved, manufacturing demonstrators in two main sectors as automotive and sensor. The comparative cost analysis shows clear benefits of the technologies developed in APPOLO during the assessment of lasers for selective electroless metallization. The notable better performance was found in the new SSAIL technology, where polymers without additives are used, but only picosecond lasers can give the required polymer surface excitation.

As a proof of concept, the full metallization of a CIGS solar cell on steel flex substrate with fingers and busses deposited by the Laser Induced Forward Techniques (LIFT) technology has been performed and its electrical properties have been measured. The assessment has shown the possibility of metallizing a CIGS solar cell using LIFT and obtaining a working solar cell.

WP11 covered all activities in 7 new equipment assessment experiments. Due to the late legal accession of new partners, start on those new experiments was not smooth and equal.

In the **FAST experiment**, an improved scanning system of SCANLAB is 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 higher scanning speed with faster laser gating control should help to manage heat accumulation leading to surface melting.

The **PONT** experiment aims at evaluating the performances of a resonant near-infrared ablation in the spectral range of 1500-2000 nm. The laser technology is considered to perform holes in polymer films and thin layer shaped devices using two new sub-nanosecond laser sources with tuneable wavelength. Initial experiments with available laser sources in mid-IR evident the need of ultrashort (ps, fs) pulses to avoid extensive heating of the material.

Within the **LADRUM** experiment, the whole process of the pattern design, the fabrication steps and the techniques for characterization were developed and implemented. A uniform platform was chosen and applied to a specific sleeve design for that the laser patterning equipment as well as the roll-to-roll ultraviolet light assisted nanoimprint lithography (R2R UV-NIL) machine has been adapted. First sleeves have been machined for the development of a R2R process for thin foils, and the seamless replication using the laser-patterned sleeves has been shown.

Identification of the laser process requirements resulting from the existing industrial applications was done in the **NEW-DELI** experiment and based on the industrial process requirements, the delivery system specification have been identified. A first alpha sample has been realised by OPI and tested at own facilities with a nanosecond laser source. A detailed analysis was performed, and a new version of the cable (beta sample) was designed and realised, which assessment will be carried out in the following months.

FASTGALVO started with a delay, and an adaption of the project plan was done. In preparation of the planned experiments, the configurations of the scanner systems to be delivered were discussed with the partners. SCANLAB also analyses alternative scanner system configurations with higher scan speed.

The main objective of the **DECOUL-Cr** experiment is to study the use of pulsed laser sources to induce changes in chromium-coated parts. Two different laser sources have been applied, and different effects were observed on the marked areas of MAIER chromium-coated plates. The surface finishing utilising LIPSS offers a new interesting aesthetic that could be applied over chrome parts.

Laser developments at SISMA are ongoing in the **SUN-JEL** experiment. At the same time, FTMC started metal ablation experiments on samples provided by SISMA using a laser with close parameters, available in the laboratory. The procedures for a new laser assessment in metal ablation are prepared based on the experimental results.

Dissemination activities show good results, mainly due to the partners' strong representation of APPOLO at many international events promoting 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://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.

Further steps were taken to collect all IP and exploit it accordingly strategically. Five applications for patents are submitted to the date. 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.