High power Adaptable Laser beams for materials prOcessing

HALO project newsletter #6

June 2016

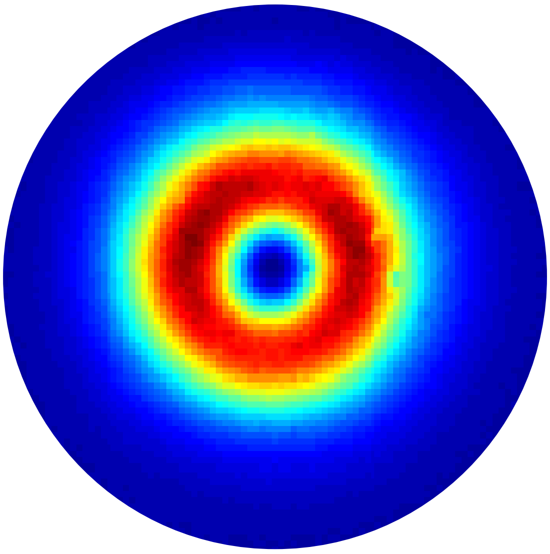
Welcome to the final HALO project newsletter!

The HALO project is now complete and we report here on the progress in the last part of the project. More information can be found on the project website (www.halo-project.eu), including an overview presentation, which was updated recently following the Photonics Europe event in Brussels (Apr-2016).

HALO had three industrial applications areas: stainless steel cutting using CW lasers, glass cutting with ps-pulsed lasers and sapphire cutting using ps-lasers guided by water jet (liquid-jet cutting). We are pleased to report that HALO has advanced the state-of-the-art in all three areas! This has been possible through experimentally validated simulations, and bespoke “made to measure” optical components defined by the modelling and verified through experiments. Work continues in all project areas so if you have questions or would like to know more, please get in touch!

In this newsletter:

- *G&H (Torquay) presents the results of its component development: the first reported isolators supporting LG modes and customised capillary fibres for novel laser development*
- *G&H (UK) reports on its AO modulators made during the project, and on segmented waveplates used to set a new record in steel cutting*
- *ORC has developed a new hybrid laser operating at 2 µm which has been used for polymer processing*
- *TRUMPF Laser has made dramatic improvements in the area of glass cutting using ps-pulse lasers, with higher speed and quality*



- *TRUMPF Werkzeugmaschinen has established the new state-of-the-art in stainless steel cutting using tailored polarisation beams to achieve record speed and quality with lower dross.*
- *Synova reports on a novel process which sets the new standard for high quality sapphire cutting*
- *Several HALO partners have worked together to produce the HALO IT-tool for optimisation of laser cutting*
- *A summary of the advances in metal cutting provided by simulation and components devised through HALO.*

HALO is supported by the European Commission through the Seventh Framework Programme (FP7), project number 314410.

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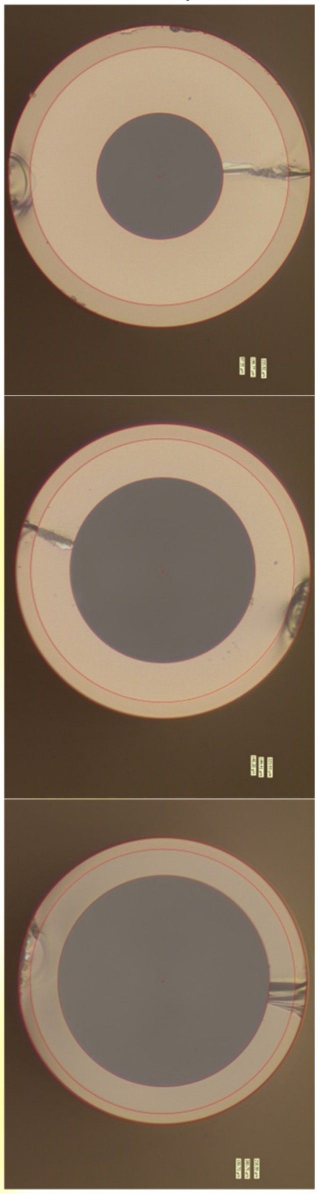
HALO components for adapted beams

Gooch & Housego

The development of components to operate with, and on, complex beam shapes and polarisations formed a large part of the HALO project. The novel laser designs and processes developed in HALO required components which were not available prior to the project. These included components to create adaptable lasers which emit various Laguerre-Gaussian ring modes, such as the hybrid laser developed by the ORC (see page 4), and components to be placed directly in the laser beam external to the laser cavity to produce novel polarisation states which were calculated to optimise the laser cutting process (see page 9).

The Ho:YAG rod laser with adaptable beam shapes developed by the ORC and demonstrated in HALO required several unique components. These were both active and passive components including a capillary fibre taper, a 3-port fibre coupled acousto-optic switch and a high power polarisation independent Q-switch designed for intra-cavity operation in the Ho:YAG laser.

Cleaved capillary fibres with different aspect ratios

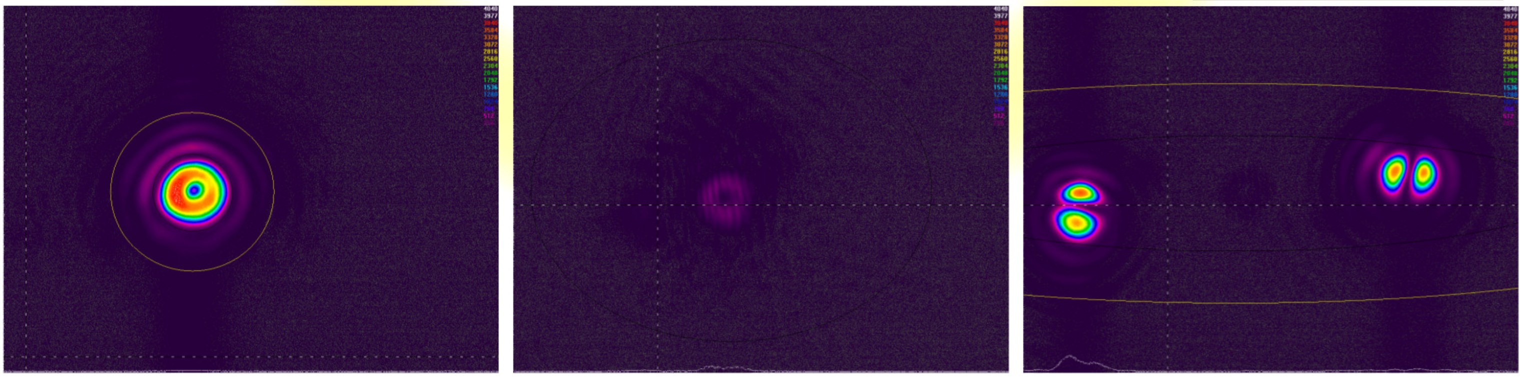


Capillary tapers

The capillary fibre tapers were used to produce a ring-shaped pump profile to spatially excite Laguerre-Gaussian ring modes in the end-pumped Ho:YAG rod laser. The capillary tapers connected a standard 105/125 µm multimode pump fibre to a fluorine clad capillary fibre with low loss. Tapers were made with several different aspect ratio capillary fibres ranging from 100/200/235 µm to 160/200/217 µm (air/silica/fluorine doped cladding) designed to excite different order Laguerre-Gaussian modes.

Optical isolator

A Faraday isolator designed to operate on and maintain radial and azimuthal polarisation in a Laguerre-Gaussian ring mode was demonstrated in HALO. An isolation of >22 dB with an insertion loss of <0.4dB was demonstrated. This is the first time to our knowledge that this has been demonstrated.



Left: Isolator input beam; Centre: Residual (unisolated beam). Right: Isolated beams showing decomposition of radially and azimuthally polarised LG_{01} modes into orthogonally polarised TEM_{10} and TEM_{01} modes.

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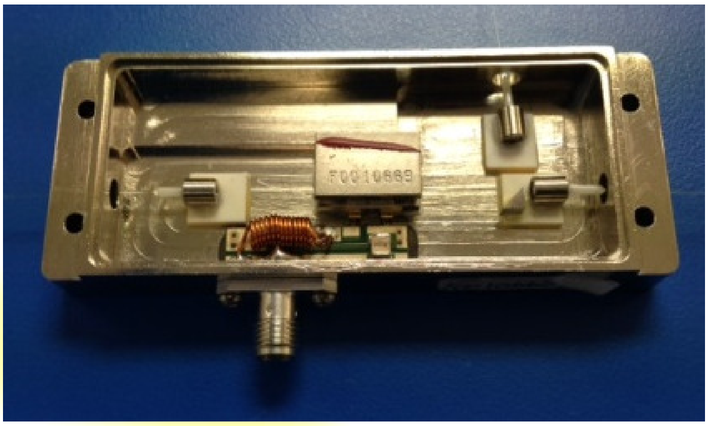
Gooch & Housego

3-port acousto-optic switch

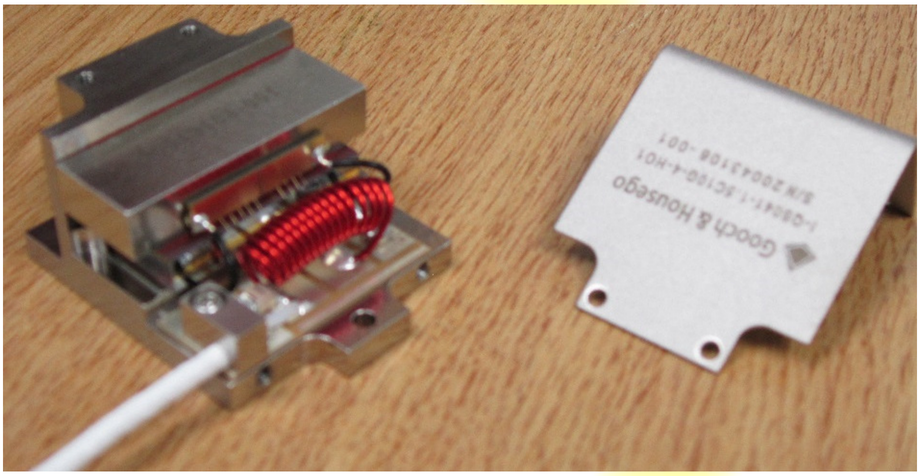
The 3-port acousto-optic switch with a single input fibre and two output fibres was designed for high power operation and used to selectively pump the Ho:YAG rod laser with either a standard multimode fibre or with a capillary fibre through one of the tapers described on page 2. By using the AO switch to control the amount of power in each pump fibre it should be possible to adaptably choose between the TEM_{00} mode, a particular LG mode or a combination of both. This flexibility allows the user to optimise the mode shape for the particular materials processing application of interest.



3-port acousto-optic fibre switch

Acousto-optic Q-switch

To Q-switch the Ho:YAG rod laser a high power polarisation independent acousto-optic (AO) Q-switch was developed by Gooch and Housego (UK). To enable high-power operation the AO modulator (AOM) used a quartz crystal as the AO interaction material. A novel design was developed to mitigate the natural birefringence of the quartz crystal.



Polarisation independent high power quartz AOM

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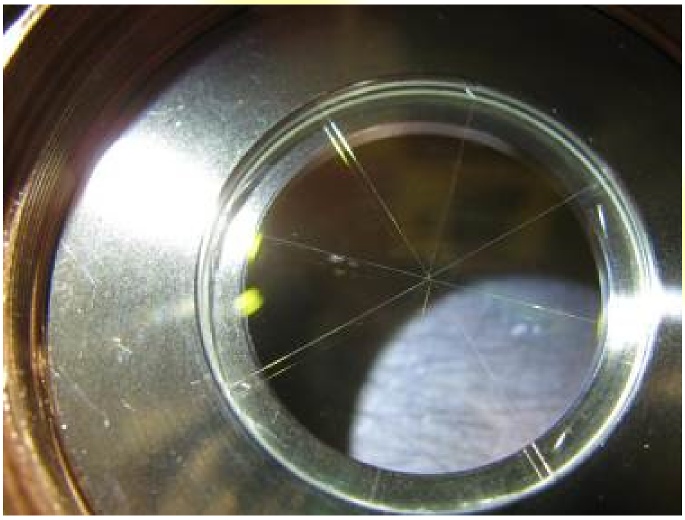

Segmented waveplates made at G&H (UK)

Segmented waveplates

To manipulate the polarisation of a laser beam external to the laser cavity a segmented waveplate with a high laser induced damage threshold was developed. These were used by TRUMPF to optimise the polarisation distribution at the cut front of a high power laser used for metal cutting achieving record breaking speeds for steel cutting with a 1 µm laser (see pages 6 and 9).

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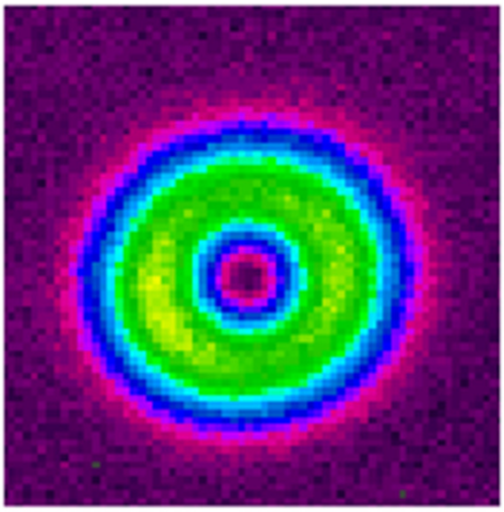
Processing of polymers with radially polarised 2 μm laser

University of Southampton
Optoelectronics Research Centre

Laser processing trials on polymer materials have commenced using a novel radially-polarised solid state laser developed at the ORC under the HALO project. The laser brings together fibre laser and bulk solid state laser technologies in the form of a hybrid fibre laser pumped bulk laser. In this scheme, the single-mode output beam from a cladding pumped Tm-doped silica fibre laser operating at 1.91 μm is re-formatted using a specially-designed passive fibre with an annular guide to produce an output beam with a doughnut-shaped near-field beam profile.



Radially-polarised output beam from hybrid Ho:YAG laser

This multimode ring-shaped beam is used to end pump a bulk solid-state laser based on Ho:YAG, which operates at ~2.1 μm. By carefully matching the transverse spatial profile of the pump and hence the inverted region with the intensity profile of the desired laser mode, a series of different doughnut laser modes can be selectively excited including a radially polarised doughnut mode and higher order Laguerre Gaussian doughnut modes.

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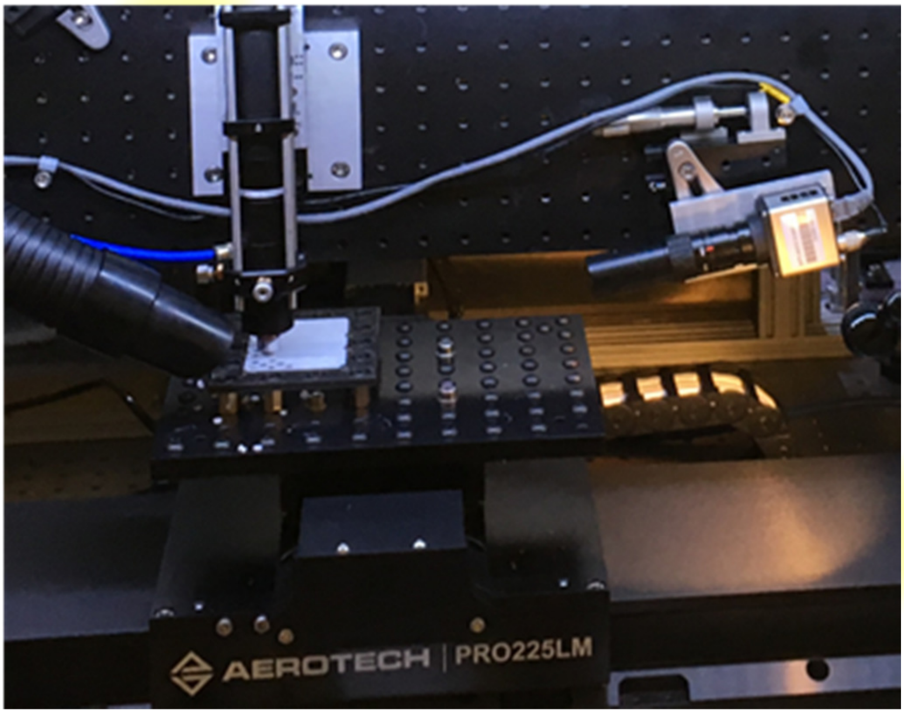


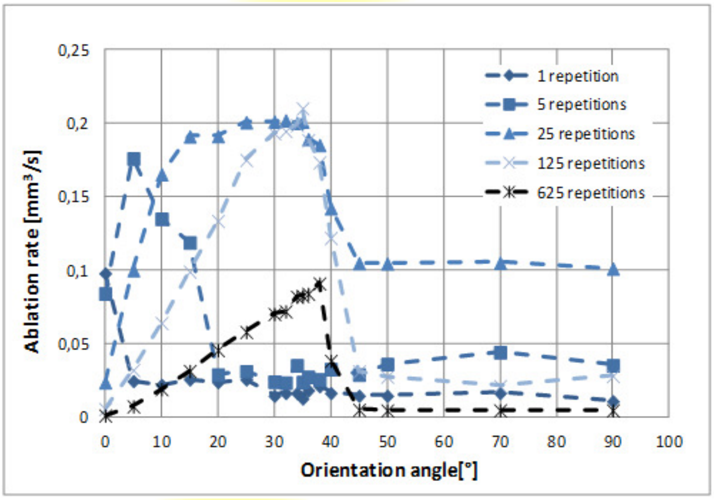
Laser machining set-up showing Ho:YAG laser cutting holes in polybutylene terephthalate

The slope efficiencies with respect to incident pump power are typically ~65% for all modes with output power up to 19 W, limited by available pump power. The advantages of radially polarised doughnut beams for metal cutting are well-known. The study (still underway at the time of writing) will seek to answer the question as to whether radially polarised (or azimuthally polarised) laser beams in the two micron band can benefit laser processing of different commonly used polymers. Particular attention will be directed towards transparent polymers which absorb strongly in the two micron wavelength band without the need of addition dopants: a major advantage over systems using 1 μm radiation.

Cutting of brittle materials

In this project TRUMPF investigated the influence of beam shape and pulse duration on the cutting speed and quality of aluminosilicate glass processed with ultrafast lasers. The high intensities of the ultra-short laser pulses initiate non-linear absorption. A steep temporal increase in the pulse intensity is required to minimize the amount of energy propagating through the material and causing damage at the rear side. This could be verified by single pulse ablation experiments. For pulse durations of 1 ps and 0.4 ps the ablation threshold fluences were lower than for 6 ps. The primary rear-side damage could be prevented with shorter pulse durations, however the process efficiency could not be enhanced.

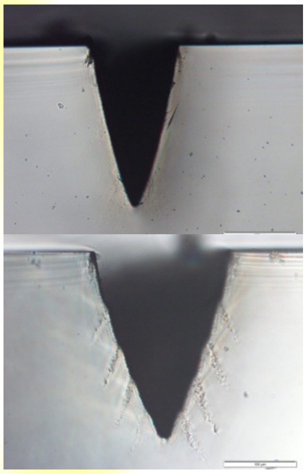
The analysis of multi-spot experiments showed that the ablation rate as well as the quality can be improved by using multi-spots (see figures below). By adjusting the angle of a linear multi-spot pattern to the scan direction, the optimum configurations regarding quality and process time were identified. However, the best orientation angle regarding quality generated a spatial line overlap and the best orientation angle regarding process time resulted in well separated lines.



Left: Ablation rate of process with line arrangement at different angles relative to the feed rate direction.

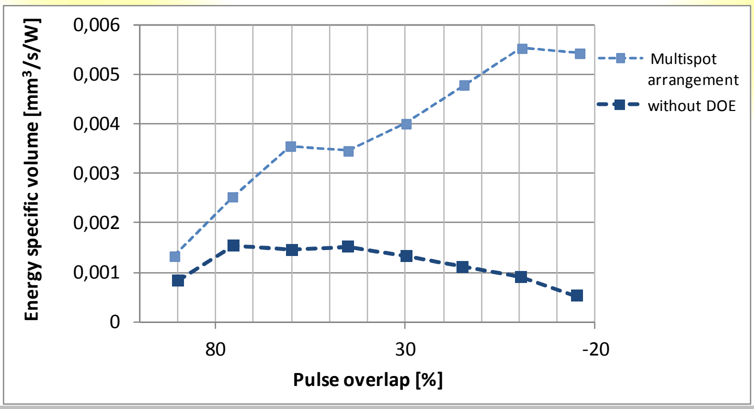
Right (upper) Cross- section of ablation sample at an orientation angle of 20° showing excellent quality.

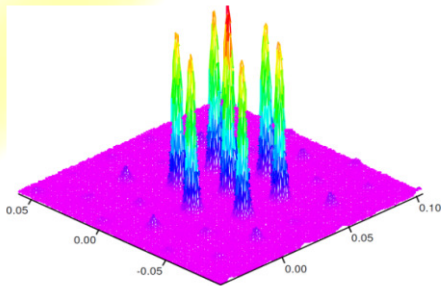
Right (lower) Cross- section of ablation sample at an orientation angle of 35° showing material damage.



The polygon arrangement (see below) proved that it is possible to use the best of both configurations by an approximated circular arrangement where the spots are well separated in the centre of the groove and overlap at the edge of the groove. A comparison of the energy specific volume of the process with and without the DOE showed that multi-spot arrangements show a quantitative advantage, i.e. improved energy specific volume.

Graph showing the energy specific volume of processes with and without optimised multi-spot arrangement at different pulse overlaps.





Intensity distribution of a polygon multi-spot arrangement.

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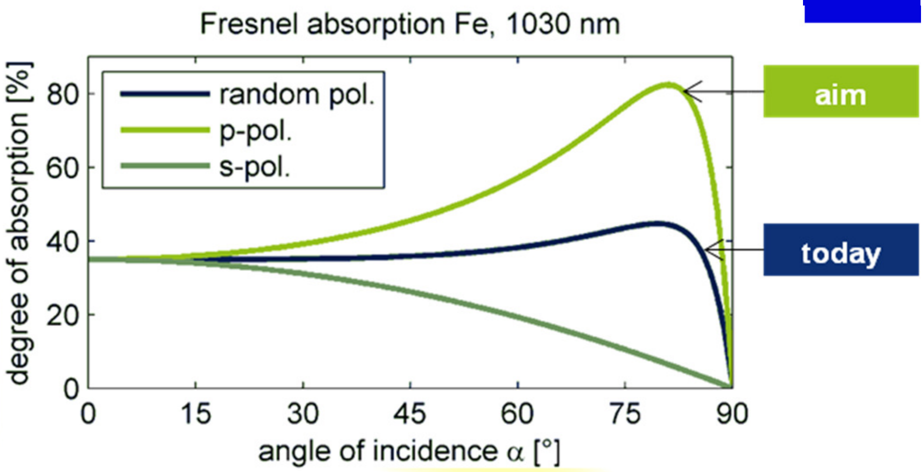
TRUMPF

Stainless steel cutting with adapted beams

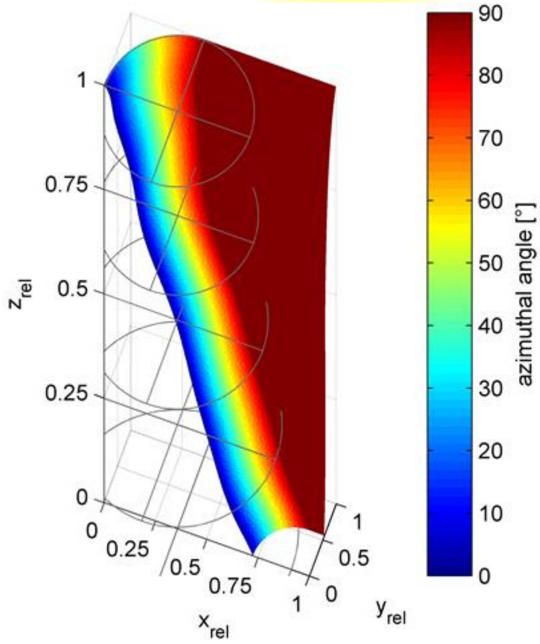
During the final HALO period, in the sheet metal cutting sub-project, work was focused on investigating the impact of a tailored laser beam polarisation.

Since current industrial solid state lasers are randomly polarised, an optimised polarisation distribution has the potential to drastically increase the absorption rate, as can be seen from the graph opposite.



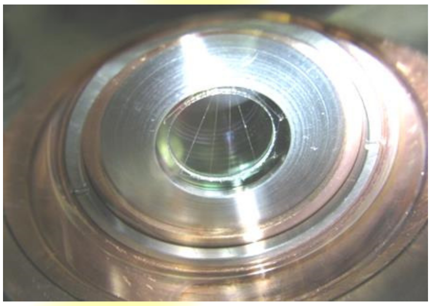
Absorption diagram for solid state lasers

Optimising the polarisation means to orientate the electric field of the incoming laser beam at every point of incidence towards the local cut front normal. Therefore, a detailed analysis of the cutting kerf geometry was necessary. The diagram on the left shows a 3D reconstruction of a cutting kerf in 15 mm stainless steel as it exists during the cutting process. Due to the inclination of the cut front, the optimal laser beam polarisation turns out to have a characteristic striped pattern.



3D model of cutting kerf

To realise the new polarisation distribution, so-called segmented waveplates were fabricated by Gooch and Housego (UK), in which each stripe of the electric field of an incoming linear polarised beam can be orientated individually.



5-segment waveplate manufactured by Gooch & Housego (UK).

To investigate the impact of the optimised polarisation, cutting experiments in 15 mm stainless steel were performed:

- *Quality* Dross is clearly reduced.
- *Productivity* Feed rate is doubled.

} See page 9.

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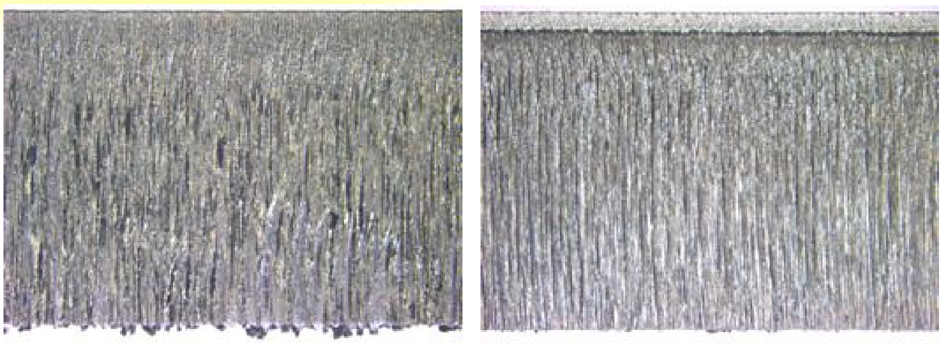
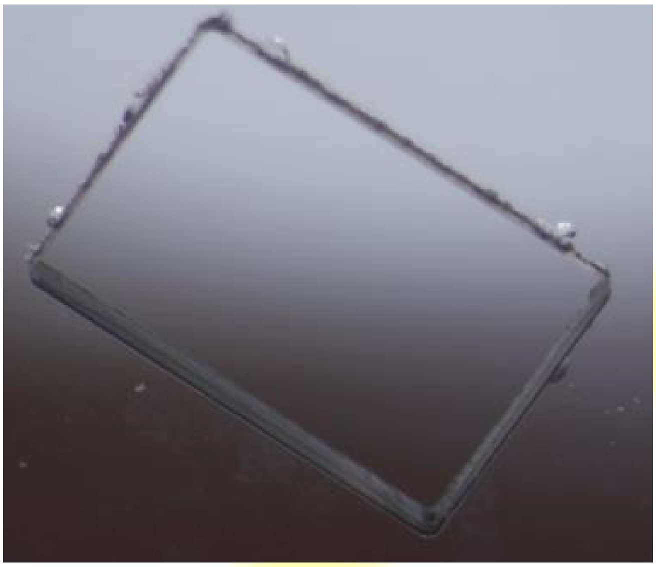
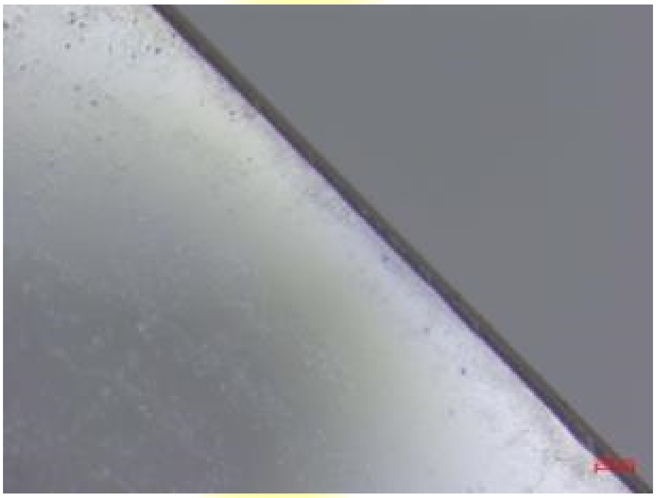


Cutting results in 15 mm stainless steel.

Left: State-of-the-art with random polarisation showing dross at the bottom of the workpiece and rough surface finish.

Right: optimised polarisation showing no dross with improved surface quality: and performed at twice the feed rate!.

Liquid jet cutting of sapphire


Samples of sapphire cut by water jet guided laser.

In the last period of this EC funded project, Synova has standardised one of the key components of its technology, i.e. the geometry of the nozzle, which is the core element that allows coupling of the focused laser light into the fibre-like laminar water jet. Through HALO, the preferential channel length has been defined to be as short as the manufacturing process allows and the manufactured nozzle is now much less susceptible to damage owing to the high power focused laser radiation and the high water pressure. The back surface of the nozzle has to demonstrate preferentially a spherical profile. Temporal jet stability has been increased when applying nozzles with sharp edge geometry.

Application of liquid jet technology to the novel laser processing of hard-to-machine materials, e.g. sapphire, has demonstrated promising results in terms of feasibility and speed. Moreover, the surface quality has been highly appreciated by customers; surface roughness values <500 nm have been achieved.

In relation to the material thickness, two different strategies for cutting sapphire have been identified. For structures with thickness <1 mm, the market acceptable cutting speed has been achieved by applying a single cut technique. In contrast, for sapphire samples >1 mm, a newly developed approach using parallel cuts has been applied. This technique allows an increase in the overall speed compared with a single line cut. However, the achieved speed in thick materials is still too low to compete with traditional mechanical machining.

Further improvement in the surface quality, in particular decreased chipping, has been achieved by means of so-called “progressive cutting”. For this recently developed process, Synova has filed a patent “Processing strategy” (application number 15002232.5). This process will be exploited internally to facilitate high quality sapphire processing and to win more customers for Synova technology in the coming years.

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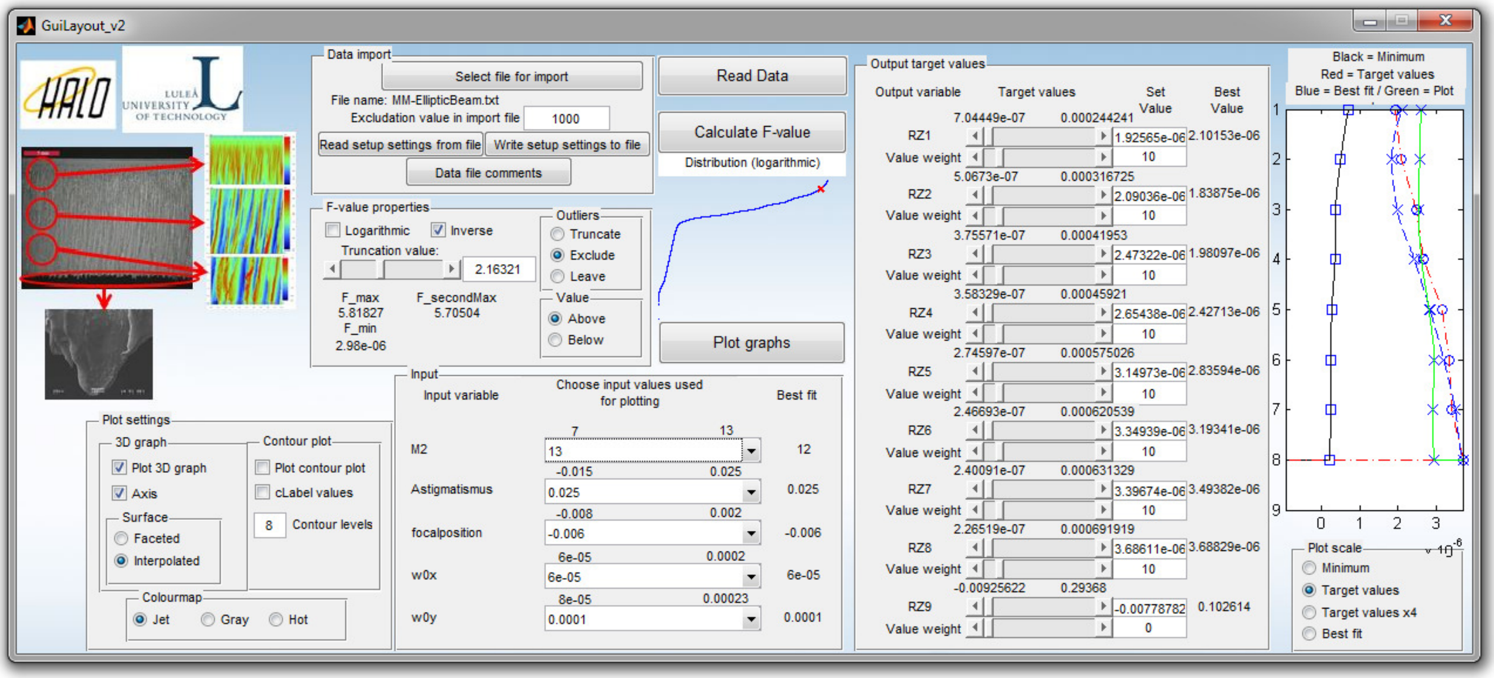
HALO meta-modelling and IT-tool for laser cutting

Different software code modules (partly with embedded data) were developed during the HALO project, namely a laser cutting model, a parameter meta-model, a cutting database, cut front streak images and a cut quality optimization tool. These models are integrated to a common IT-based planning and evaluation tool (the HALO IT-tool) in the form of an interactive procedure that enables the user, via a specially designed GUI, to communicate between the different modules, to transfer data and to operate the different modules simultaneously in a multi-tasking manner.

This work was conducted in close collaboration between three of the partners within the HALO project; Luleå University of Technology; Fraunhofer ILT and Laser Expertise.

The HALO IT-tool is tailored for experts with a certain background in laser cutting, who can apply the IT-tool for themselves but it also serves clients with less expertise who are untrained on the HALO IT-tool. Trained users can assist clients such as laser system or optical component manufacturers as well as companies (especially SMEs) applying laser cutting.

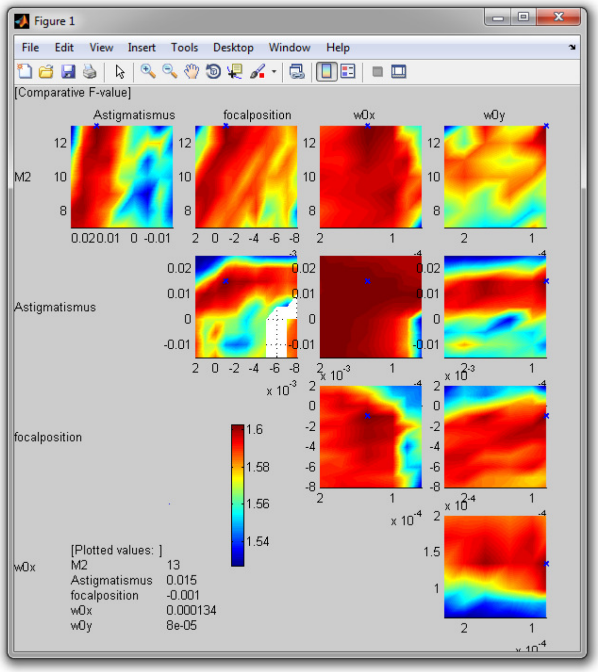
The screenshot below shows the main GUI and its optimization tool.



Screenshot of the main GUI of the HALO IT-tool, including the optimisation tool.

The IT-tool was tested and validated and it was shown to be highly suitable for the further improvement of laser cutting applications and laser cutting systems, e.g. to develop advanced focusing optics for laser beam shaping. The consortium also produced a user guide and a demo video clip to insure an efficient and fruitful user experience. The HALO IT-tool is ready for use, to support applications and developments in industry towards more effective laser optics and processes.

The user guide is also available on request, and a short video showing how the tool works is online at the HALO website: http://halo-project.eu/documents/further-technical-info/



Example of optimisation results (roughness variation across part of the parameter space) from the physical model for a specific laser cutting case and system

The screenshot (left) shows a typical calculation result: in this case, the variation of the derived target F-value over two parameters, plotted for several other parameter combinations, based on data exported from the physical process model that were further processed in the optimisation tool. The left half of the screen shows the GUI including choices for the output format, while in the right half the target and calculation values for cut surface roughness over depth are plotted, beside controllers to define the respective weighting per work piece depth.

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Laser cutting advances made in HALO

As part of the HALO project, cutting experts from both TRUMPF and Fraunhofer ILT (Aachen) have investigated a wide range of optical conditions to optimise cut speed and quality for solid state lasers, and compared the results with a benchmark study carried out at Laser Expertise. Both speed and quality have been improved in medium/thick section (>8 mm) stainless steel by using radial or striped polarisation instead of the traditional random polarisation.

For more information please contact:
Prof. John Powell Laser Expertise
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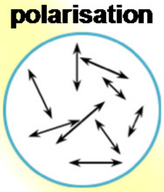
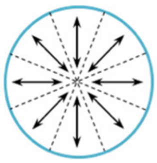
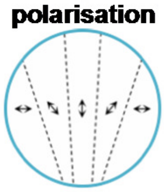
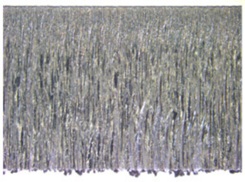
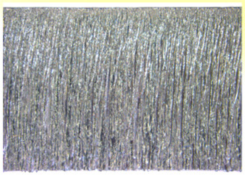
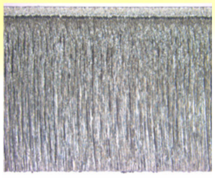
	Random polarisation	Radial polarisation	Striped polarisation
			
Production feed rate	100%	140%	240%
Dross	clearly visible	minimal dross	minimal dross
Cut edge			

Typical results are given in the figure opposite. This clearly demonstrates the cut quality and speed improvements possible if these new polarisation states are used for the cutting process. Radial and striped polarisers deliver the laser beam to the cut front in an optimised rather than randomised state and this leads to improved absorptivity. In the case of radial polarisation cutting speeds were improved by over 40% and dross (or burr) was reduced to trivial levels. The results are even more impressive for striped polarisation, which led to a speed increase of >140% also with a diminution in dross levels. The in-depth knowledge generated during HALO has also led to substantial improvements in cut quality for solid state laser cutting using standard random polarisation. In this case surface roughness and dross levels have both been improved by more than a factor of two.