PROJECT FINAL REPORT

Grant Agreement number: 314410

Project acronym: HALO

Project title: High power Adaptable Laser beams for materials prOcessing

Funding Scheme: Collaborative Project (STReP)

Period covered: **from** 01-Sep-2012 **to** 30-Apr-2016

Name, title and organisation of the scientific representative of the project's coordinator[1]**:**

Tom Legg; Project manager; Gooch and Housego (Torquay)

Tel: +44 1803 407 846

Fax: +44 1803 407 796

E-mail: tlegg@goochandhousego.com

Project website[2] **address:** www.halo-project.eu

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement .

[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

Contents

4.1 Final publishable summary report

Executive summary

HALO has been developing technology for the next generation of adaptable materials processing lasers. It brings together large laser manufacturers with key European component suppliers, academic and research organisations and end users of industrial laser systems. The project tackled a wide range of laser technology for processing several important materials, including sheet metal, ceramics and glass. Work has included the simulation of cutting processes, development of new components, experiments with novel laser configurations and the establishment of new processing techniques.

Due to the nature of the subject matter, the HALO results are rather technical and most of this report, and much of the dissemination material, is aimed at readers with a reasonable understanding of industrial lasers and their applications. However, it should be clear to all readers that the project has been very successful in improving a wide range of laser technology for the benefit of European industry. It targeted three areas of materials processing, which require very different types of lasers and cutting techniques.

Of course, the cutting of thick (>1 cm) pieces of stainless steel requires very high power lasers, which are usually “continuous wave” (CW) in other words use a steady high power laser beam. Cutting glass with lasers is very effective, but CW lasers cause cracking and other imperfections, so usually extremely short pulse lasers are used. Each pulse vaporises tiny quantities of glass in a miniscule fraction of a second, on a time-scale so short that thermal effects, which cause most of the damage mechanisms, do not play a significant role, resulting in greatly reduced cracking and high quality cut edges. The third application is liquid micro-jet laser cutting, in which a pulsed laser beam is shone along a very fine water jet, which greatly assists the cooling of the workpiece and offers extremely high cut edge quality for very hard materials, such as sapphire.

HALO has used adaptable beam technology, for instance using new beam shapes or multi-spot beams, to establish the new state-of-the-art in all three of these selected application areas. This has been achieved by using sophisticated simulations and careful observations of physical cutting processes to design completely new components and identify novel process characteristics.

The key advances include:

- Novel components for adaptable beams
    - Capillary tapers to generate a ring-shaped pump beam
    - The first reported isolators to maintain radial and azimuthal polarisation
    - Acousto-optic modulator to select laser mode shape
    - In-cavity acousto-optic Q-switch
    - Segmented waveplates to generate tailored polarisation multi-kW beams
    - S-waveplates to generate radial polarisation using nano-gratings
- Novel 2 µm laser design which can select and combine LG modes

- 20 W CW output power and Q-switched variant
- Trials performed demonstrating transparent polymer cutting

- Meta-models developed for metal, glass and liquid-jet cutting
  - New beam characteristics defined for optimised processes
  - HALO IT-tool with convenient GUI for user-friendly application
  - Reduced dross and roughness using standard optics in steel cutting
  - Reduced micro-cracking ps-pulse glass cutting process defined and validated
  - Higher damage threshold nozzle design identified for liquid jet cutting (LJC)
  - Reduced splashing regime for LJC proposed and validated
- Improved understanding of metal cutting using high-speed videography
  - Data implemented in meta-model with HALO IT-tool
- Improved glass cutting processes with ultra-short pulsed lasers using novel beam shapes and multi-spot beam patterns
  - Solved problem of rear-side damage for selected cutting regimes
  - Reduced micro-cracking and improved cut quality
  - Increased cutting speeds setting new state-of-the-art
- Identified optimised polarisation for sheet metal cutting
  - “Shell” pattern polarisation distribution calculated and realised experimentally
  - Dross significantly improved and cut edge quality improved
  - Production feed rate doubled setting new state-of-the-art
- LJC process for sapphire identified
  - Patent applied for on progressive cutting process strategy
  - New state-of-the-art defined for edge quality.

Project context and objectives

www.halo-project.eu

Materials processing is by far the highest value application of lasers, and Europe is a power-base for this technology. In particular, laser machines for cutting with CW lasers in the multi-kW range together with precision cutting using pulsed laser systems have the largest market share of laser systems worldwide. The underlying HALO objective was to help to develop the next generation of materials processing lasers for cutting applications, which will have adaptable beams actively optimised for specific processes.

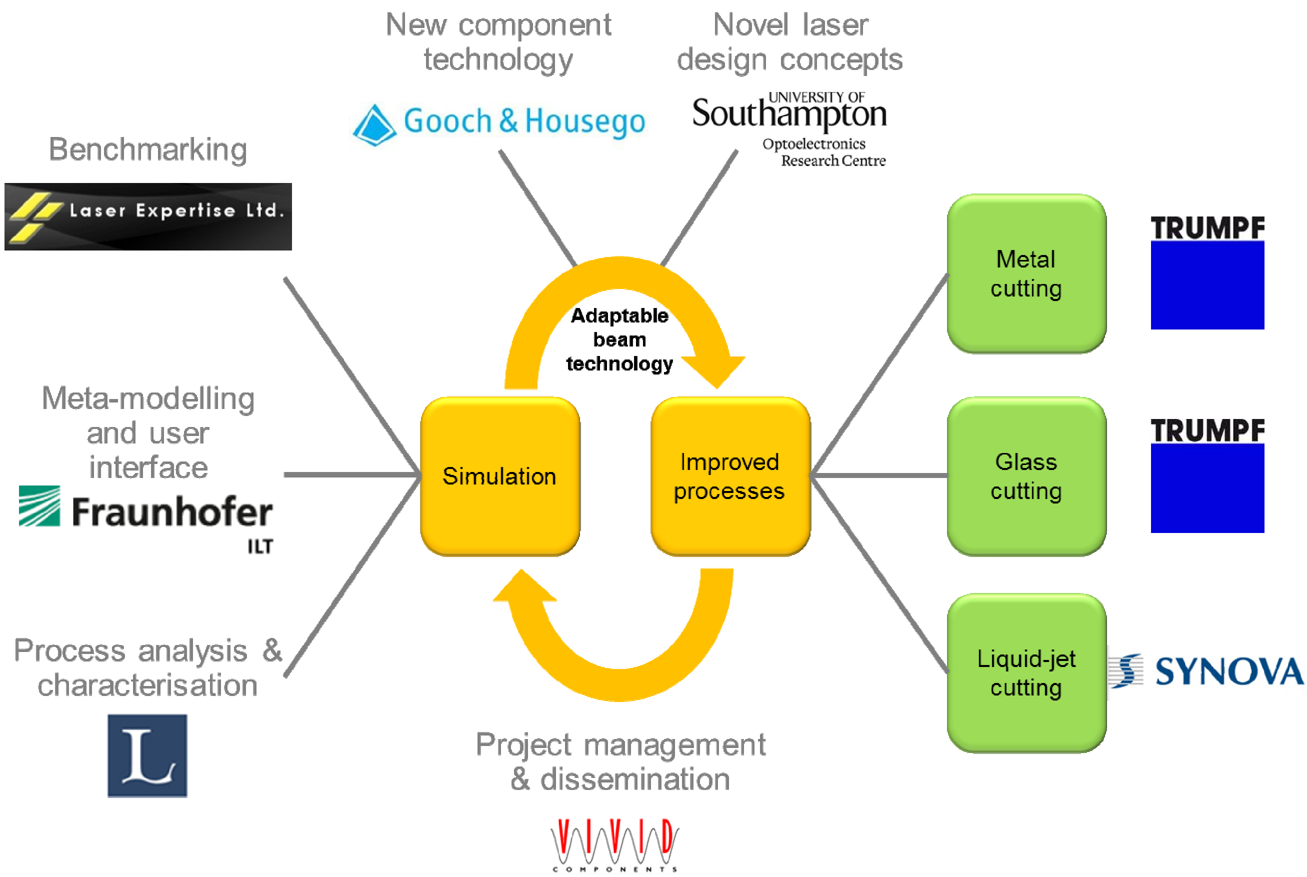


Figure 1: Schematic of the HALO project

Figure 1 shows an overview of how the work in the project was carried out. Three applications were selected: metal cutting (in fact, cutting of stainless steel with CW lasers), glass cutting (using ps-pulse lasers) and liquid-jet cutting (using pulsed lasers guided by water jet). Building on existing simulation tools, enhanced with a benchmarking exercise and new analysis and characterisation of the cutting processes, a so-called meta-model could be built and developed for the cutting processes. By exploring the many-dimensional parameter space in these meta-models, these simulations suggested new parameters and beam characteristics which could lead to improved processes. These beam profiles and process details were implemented experimentally, which sometimes entailed the fabrication of new components. Analysis of the modified processes provided further information which could be used to improve the meta-model, which in turn could be used to suggest further optimisation. In this iterative way, simulation and experiment went hand-in-hand, with academic and industrial partners working together in an effective collaborative team.

Preliminary investigations had already suggested that beams with novel polarisations and beam profiles, including “doughnut” or hollow beam profiles, and multi-spot laser beam patterns were potentially very interesting. In addition some novel laser designs had the potential to select a Gaussian or doughnut mode, or even a mixture of the two. These designs could be implemented at wavelengths in the 2 µm region, allowing the processing of plastic materials. These innovations required several technological advances:

- Components tailored for adaptable beams and new beam shapes
- New approaches to adaptable hollow beam sources at new wavelengths
- Techniques for beam shaping and forming
- Process optimisation for adaptable beam processing using IT-based meta-models
- Adaptable jet-assisted laser cutting.

Technical objectives

Components

Components required for adjustable beam lasers, including:

- Isolators suitable for adjustable beams and high power operation
- Hollow beam tapers for 2 µm rod laser
- MM pump combiners for 79x nm diodes for Tm-fibre laser pump sources
- Fused combiners 7:1 and 19:1
- High power AO modulators for Q-switching radially-polarised and azimuthally-polarised LG doughnut modes (as well as Gaussian TEM_{00} modes)

2 µm hybrid Ho:YAG laser with adaptable beam profile

A novel holmium-doped hybrid solid-state laser:

- High-power cladding-pumped 200 W Tm fibre laser pump source
- Low-loss fibre-based pump beam shaping and delivery scheme
    - Optimised to yield a ring-shaped or Gaussian-like intensity distribution
- High-power Ho:YAG laser at ~2.1 µm.
    - Laser output beam profiles include: annular Laguerre-Gaussian (LG_{01}) mode (with radial, azimuthal or linear polarisation), combination of the fundamental (TEM_{01}) and LG_{01} mode to yield a quasi-top-hat beam profile
- Theoretical modelling of fibre-laser-pumped Ho:YAG laser with adaptable output beams

Adapted laser beam cutting modelling

- Numerical tools for simulation of beam propagation, absorption and ablation (cutting) processes
- Optimisation of glass and sheet metal cutting using beam or pulse shaping
- Online-monitoring and offline characterisation techniques for the two cutting processes
- Simulation and optimisation of liquid-jet cutting processes with brittle materials.

Brittle material processing

- Establish a clear quantitative baseline for existing brittle material cutting technology in a meta-model
- Improve understanding of the interaction between ultra-short laser pulses and brittle materials
- Explore how spatial and temporal beam forming can improve the process
    - Eliminate material damage in the cutting of brittle materials
    - Increase fracture strength for 300 µm thick glass sheets.

Sheet metal cutting

- Establish a clear quantitative baseline for existing sheet metal cutting technology in a meta-model
- Understand the interactions during laser cutting of sheet metal
- Explore how spatial and temporal beam forming can improve the process
- Improve cutting quality and efficiency for 10 mm stainless steel:
    - Dross length
    - Ripple amplitude R_z

Liquid jet cutting

- Establish a clear quantitative baseline for existing liquid-jet cutting technology in a meta-model
- Understand the interaction between nozzle design and optical performance
- Explore how spatial and temporal beam forming can improve the process
- Enable liquid-jet cutting to cut delicate materials like glass and sapphire

Validation and benchmarking

- Bring models of laser cutting into operative application and design processes
- Validate quality of model predications through comparison with high speed videography
- Graphical user interface (GUI) for exploration of meta-models as a support tool in manufacturing industry.
- Benchmark and compare the new beam profile opportunities with state-of-the-art laser cutting
- Generate and evaluate experimental reference data for CO_2-laser cutting and 1 µm lasers

Demonstration

- End user testing in an industrial environment
    - Brittle material cutting
    - Sheet metal cutting
    - Liquid-jet cutting
- Quantified analysis of improved process quality in sheet metal cutting
    - Cut edge roughness
    - R_a value (root mean squared roughness)
    - R_z value (maximum perpendicular feature height)
    - Dross attachment
- Improved bending strength reduction for glass cutting.

Dissemination and exploitation
To disseminate the results of the project and encourage standardisation of the HALO technology, a range of activities were planned.

Dissemination activities

- Dissemination of project results to industry, the public and investment communities
    - Conference presentations
    - Peer-reviewed journal publications
    - Technology transfer workshop
    - Newsletters
- Public website with project presentation, video and information

HALO Industrial Group

- HALO Industrial Group (HIG)
- Identify novel applications for adaptable lasers in materials processing
- Establish commercial links to establish HALO technology.

In this summary, the key elements of the project are briefly reviewed and the objectives defined. Readers wishing to know more about the project are invited to contact the individuals identified for each technology area.

Please see the project website (www.halo-project.eu) for more details.

Main S&T results

HALO is a collaborative research project supported by the European Commission through its Seventh Framework Programme (FP7). Over its duration the project has been developing technology for the next generation of adaptable materials processing lasers. It brings together large laser manufacturers with key European component suppliers, academic and research organisations and end users of industrial laser systems. The project tackled a wide range of laser technology for processing several important materials, including sheet metal, ceramics and glass. Work has included the simulation of cutting processes, development of new components, experiments with novel laser configurations and the establishment of new processing techniques.

The key advances include:

- Novel components for adaptable beams
    - Capillary tapers to generate a ring-shaped pump beam
    - The first reported isolators to maintain radial and azimuthal polarisation
    - Acousto-optic modulator to select laser mode shape
    - In-cavity acousto-optic Q-switch
    - Segmented waveplates to generate tailored polarisation multi-kW beams
    - S-waveplates to generate radial polarisation using nano-gratings
- Novel 2 µm laser design which can select and combine LG modes
    - 20 W CW output power and Q-switched variant
    - Trials performed demonstrating transparent polymer cutting
- Meta-models developed for metal, glass and liquid-jet cutting
    - New beam characteristics defined for optimised processes
    - HALO IT-tool with convenient GUI for user-friendly application
    - Reduced dross and roughness using standard optics in steel cutting
    - Reduced micro-cracking ps-pulse glass cutting process defined and validated
    - Higher damage threshold nozzle design identified for liquid jet cutting (LJC)
    - Reduced splashing regime for LJC proposed and validated
- Improved understanding of metal cutting using high-speed videography
    - Data implemented in meta-model with HALO IT-tool
- Improved glass cutting processes with ultra-short pulsed lasers using novel beam shapes and multi-spot beam patterns
    - Solved problem of rear-side damage for selected cutting regimes
    - Reduced micro-cracking and improved cut quality
    - Increased cutting speeds setting new state-of-the-art
- Identified optimised polarisation for sheet metal cutting
    - “Shell” pattern polarisation distribution calculated and realised experimentally
    - Dross significantly improved and cut edge quality improved
    - Production feed rate doubled setting new state-of-the-art
- LJC process for sapphire identified
    - Patent applied for on progressive cutting process strategy
    - New state-of-the-art defined for edge quality.

Components

Capillary tapers

A set of 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 made by ORC (see below). 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 LG modes.

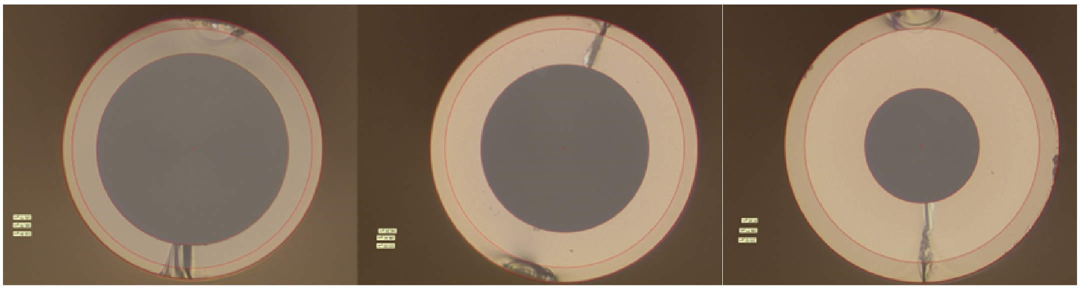


Figure 2: Cleaved capillary fibres with different aspect ratios

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. The consortium believes that this is the first time this has been demonstrated.

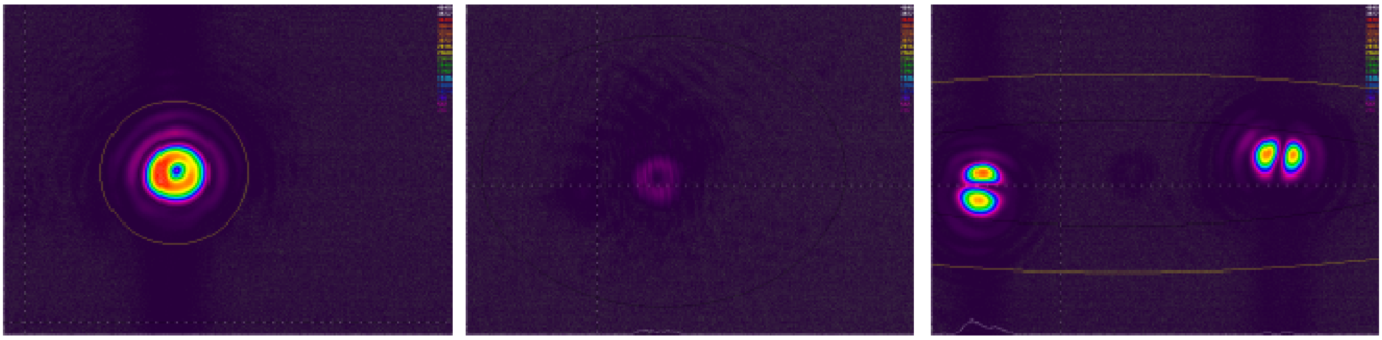


Figure 3: Left: Isolator input beam; Centre: Residual (unisolated beam). Right: Isolated beams showing decomposition of radially and azimuthally polarised LG01 modes into orthogonally polarised TEM_{10} and TEM_{01} modes.

➔ For more info contact Dr. Tom Legg; Gooch and Housego (Torquay) tlegg@goochandhousego.com

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 ORC Ho:YAG rod laser with either a standard multimode fibre or with a capillary fibre through one of the tapers described above. By using the AO switch to control the amount of power in each pump fibre, the user can choose between a TEM_{00}, a particular LG mode or a combination of both. This flexibility offers the opportunity to optimise the mode shape for the particular materials processing application of interest.

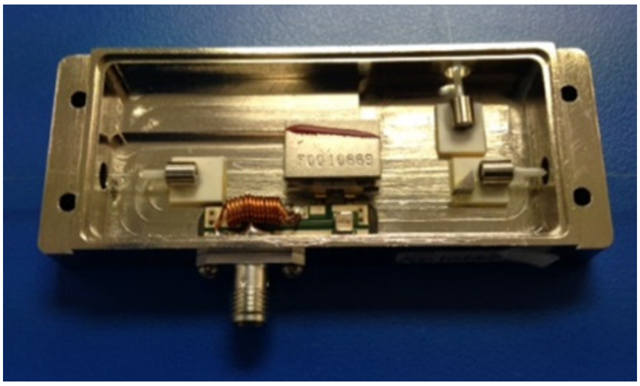


Figure 4: 3-port acousto-optic fibre switch

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.

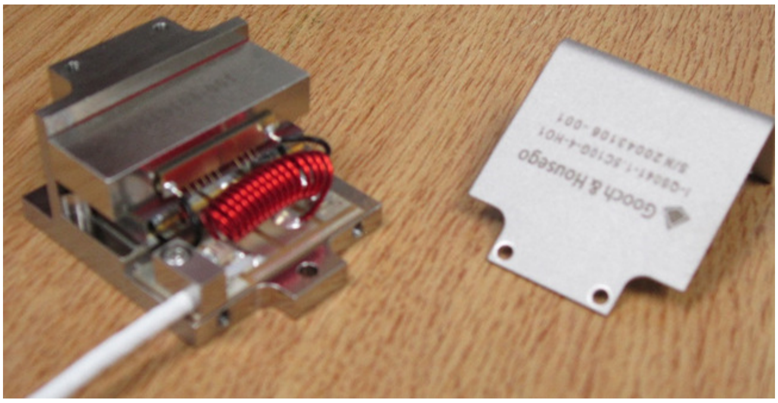


Figure 5: Polarisation independent, high power, Quartz AOM

➔ For more info contact Jon Ward; Gooch and Housego (UK) jward@goochandhousego.com

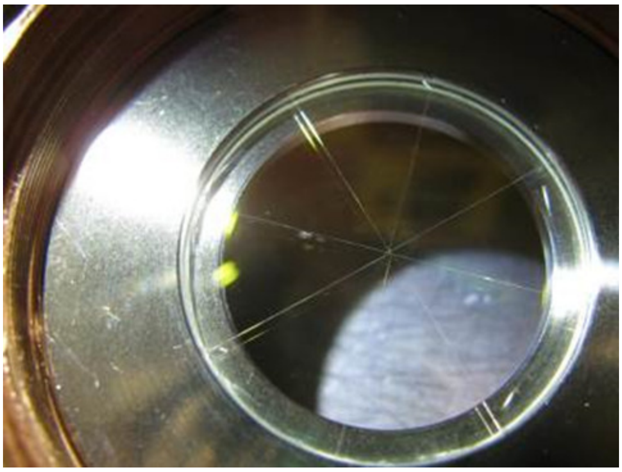


Figure 6: Segmented waveplates from G&H (UK)

Segmented waveplates

To manipulate the polarisation of a laser beam external to the laser cavity a series of segmented waveplates with a high laser induced damage threshold were developed, including radial ("dartboard") and striped ("shell") designs. 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 later).

More details may be found in: "Segmented Waveplate Polarisation Control for Laser Cutting," Peter E. MacKay, Tobias Häcker, and Tim Hesse, Opt. Fab. and Testing (2014) http://dx.doi.org/10.1364/OFT.2014.OTh4B.2

- ➔ For more info contact Dr. Peter MacKay; Gooch and Housego (UK) pmackay@goochandhousego.com

S-waveplates

The ORC has recently developed a continuously space-variant half-wave plate (S-waveplate) that allows a linearly-polarised laser beam in the two-micron wavelength band to be converted into a radially-polarised (or azimuthally-polarised) doughnut mode with both high efficiency and very high polarisation purity. The S-waveplate was fabricated using a femtosecond laser to write nano-structure gratings in a silica glass window. The grating structures induce birefringence with slow and fast axes aligned parallel and perpendicular to the grating direction respectively, allowing the construction of a two-dimensional array of microscopic half-wave plates aligned in a manner designed to produce the required position-dependent polarisation rotation.

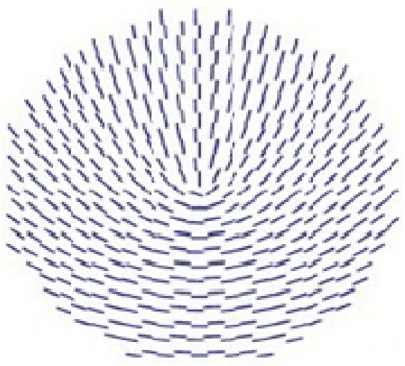


Figure 7: A schematic showing the orientation of nano-gratings in the ORC S-waveplate.

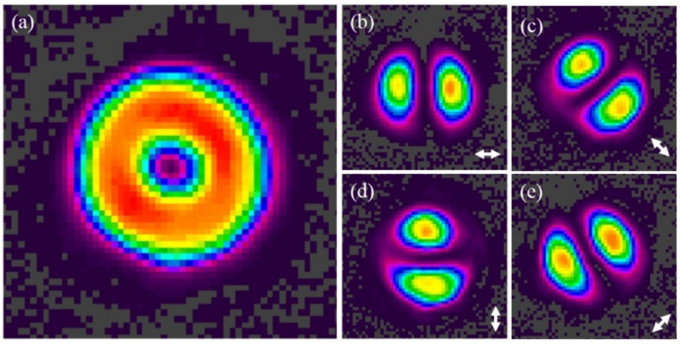


Figure 8: Intensity profile of radially polarised beam (a) without and (b-e) with an analyser polariser.

The S-waveplate was tested with a tunable thulium fibre laser yielding a doughnut-shaped radially-polarised (or azimuthally-polarised) beam with a polarisation extinction ratio (PER) of 18 dB and with a very low scattering loss of only 7%. The beam propagation factor (M^2) was measured to be ~2.15 and hence in close agreement with the theory. Optimisation of the S-waveplate design and fabrication procedure is expected to yield further improvements in performance in terms of loss, power handling and polarisation purity.

- ➔ For more info contact Prof. Andy Clarkson; Southampton ORC wac@orc.soton.ac.uk

Novel laser designs

A novel radially-polarised solid state laser has been 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.

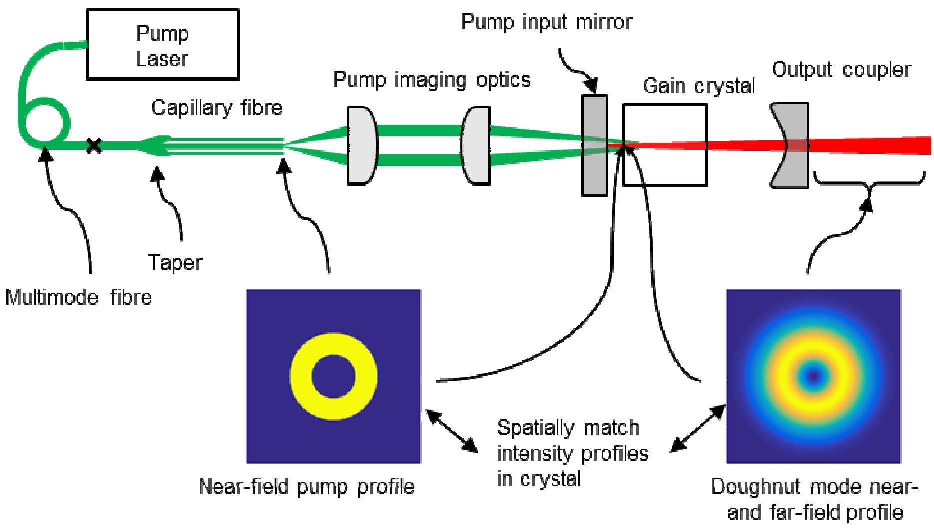


Figure 9: Schematic of ORC hybrid laser design

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.

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.

Selected conferences and publications

"Direct generation of radially-polarized output from an Yb-doped fiber laser," D. Lin, J. M. O. Daniel, M. Gecevičius, M. Beresna, P. G. Kazansky, W. A. Clarkson; *CLEO 2014*, OSA Technical Digest, paper JW2A.22 http://dx.doi.org/10.1364/CLEO_AT.2014.JW2A.22

"Simple Technique for High-Order Ring-Mode Selection within Solid-State Lasers," A. C. Butler, R. Uren, D. Lin, J. R. Hayes, and W. A. Clarkson; *CLEO Europe 2015* Paper CA 7-5

"Donut beam generation in a hybrid fiber laser pumped Ho:YAG laser," A. C. Butler, P. C. Shardlow, R. T. Uren, W. A. Clarkson; *Photonics West 2016* Paper 9726-61

"Cladding-pumped ytterbium-doped fiber laser with radially polarized output," Di Lin, J. M. O. Daniel, M. Gecevičius, M. Beresna, P. G. Kazansky, and W. A. Clarkson; Optics Letters **39**, p. 5359-5361 (2014) http://dx.doi.org/10.1364/OL.39.005359

"Polarization-dependent transverse mode selection in an Yb-doped fiber laser," D. Lin & W.A. Clarkson; Optics Lett. **40**, p. 498-501 (2015) http://dx.doi.org/10.1364/OL.40.000498

➔ For more info contact Prof. Andy Clarkson; Southampton ORC wac@orc.soton.ac.uk

Meta-modelling

Meta-modelling enables the derivation of rules for the design of optical components to enable high quality laser cutting. In HALO, meta-modelling was used throughout the project to improve sheet metal cutting, brittle material cutting and liquid jet cutting.

As an example of the method, one potential route for improving metal cutting which was investigated was the use of elliptical beams. As is well-known from recent publications, the most prominent measure to improve cut quality is to increase the angle of incidence of the laser radiation at the cutting front. A straight-forward design rule for an appropriate optical component is to choose an elliptical beam instead of a circular one, in order to increase the angle of inclination while maintaining a small kerf width. However, simple application of this plausible rule fails, since its applicability is restricted to a bounded region of parameter settings. In HALO, tailored meta-modelling approaches were developed and applied to accomplish the request for determination of applicability regions for successful design thinking.

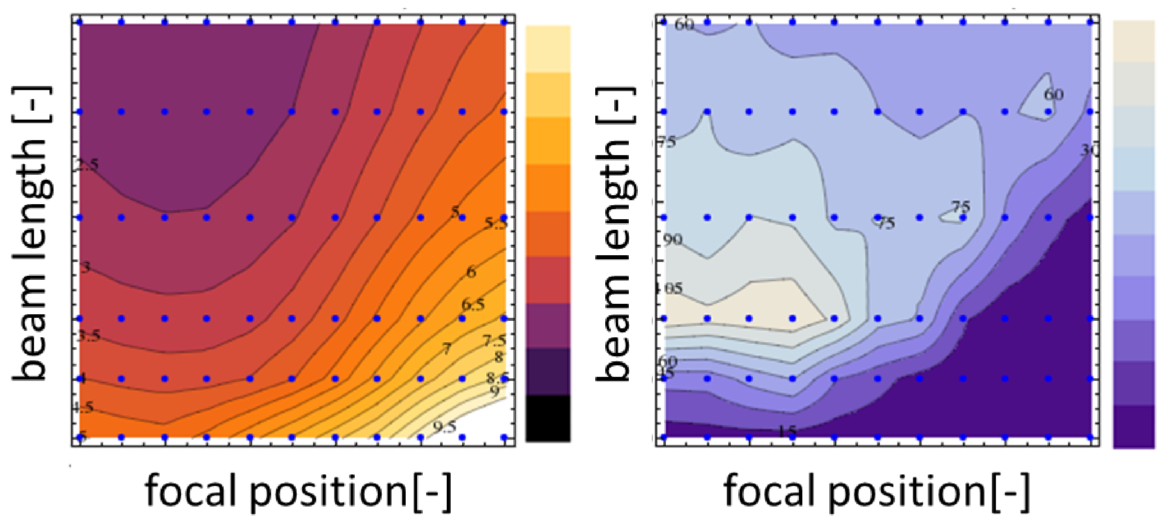


Figure 10: Inclination (left, 0-10°) of the cutting front and roughness (right, 0-150 µm) of the resulting cut surface as functions of beam length at focus parallel to the cutting direction and its focal position. By visual exploration of the Process Maps generated by the Meta-Model of sheet metal cutting the concept of elliptical beam shaping is refined.

HALO design thinking has four steps: “understand,” “observe,” “concept,” and “iterative design.” Understanding is achieved by going beyond identification of interaction chains and describing them by mathematical models. Observation beyond experimental evidence is improved by comprehensive numerical simulations including high-dimensional process maps. Concept generation is based on visual exploration of process maps and iterative design by experimental testing.

The region for successful application of the design rule of elliptical beam shaping is an example of additional relevant information extracted with the meta-modelling approach. By visual exploration of the process maps generated by the meta-model of sheet metal cutting, the general concept of elliptical beam shaping is refined, namely, the monotone relation between front inclination and roughness is not general, but holds only within a bounded region of parameter combinations (Figure 10).

Selected conferences and publications

“Metamodeling of Laser Cutting,” U. Eppelt & T. Al-Khawli; *ICNAAM 2014* AIP Conf. Proc. **1648**, 01000 http://dx.doi.org/10.1063/1.4912302

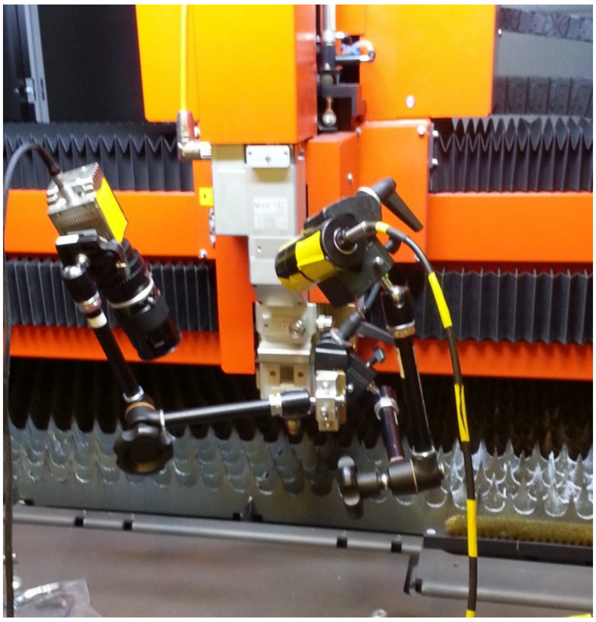
“Meta-Modelling Techniques Towards Virtual Production Intelligence ,” Wolfgang Schulz and Toufik Al Khawli; Advances in Production Technology; part of the series “Lecture Notes in Production Engineering” p. 69-84 (2014) http://dx.doi.org/10.1007/978-3-319-12304-2_6

“Sensitivity Analysis of Laser Cutting Based on Metamodeling Approach,” Toufik Al Khawli, Urs Eppelt and Wolfgang Schulz; Handbook of Research on Computational Simulation and Modeling in Engineering, ch. 20, p. 618-639 (2015) http://dx.doi.org/10.4018/978-1-4666-8823-0.ch020

➔ For more info contact Prof. Wolfgang Schulz; Fraunhofer ILT
wolfgang.schulz@ilt.fraunhofer.de

High speed imaging and analysis

One important HALO task performed at Luleå University of Technology (LTU) was to develop and apply a high speed imaging (HSI) methodology for the validation of the simulations and meta-models that have been developed by Fraunhofer ILT. This includes HSI of drop ejection, dross formation and cutting front melt where different analysis methods are applied, particularly for understanding of dynamic phenomena.



A series of cutting experiments including HSI to capture the cutting front melt behaviour under industrial state-of-the-art conditions was performed on site at a workshop and demo centre. A typical experiment, shown in Figure 11, is the cutting of 6 mm and 10 mm stainless steel using a 1 µm fibre laser at powers between 2 kW and 4 kW, with cutting speed up to 4 m/min and nitrogen as the cutting gas. The melt behaviour on the cutting front was monitored with laser-illuminated HSI equipment mounted perpendicular to the cutting front. The images were taken by a Photron SA1 (San Diego, California) high-speed camera, at 4000 to 6500 frames per second. A fibre-guided pulsed diode laser (Cavitar, peak power 500 W) with a wavelength of 808 nm was used to illuminate the cutting front.

Figure 11: The experimental set-up of the HSI camera and illumination laser, before alignment, in the laser cutting workstation.

Figure 12 shows an example of the results: a time series with 1.5 ms interval between each image, from one of the cutting experiments that was performed. In this case the sample thickness was 6 mm, and three focal positions were evaluated. The key objective was to capture the relations between the focal positions and the cutting front melt behaviour.

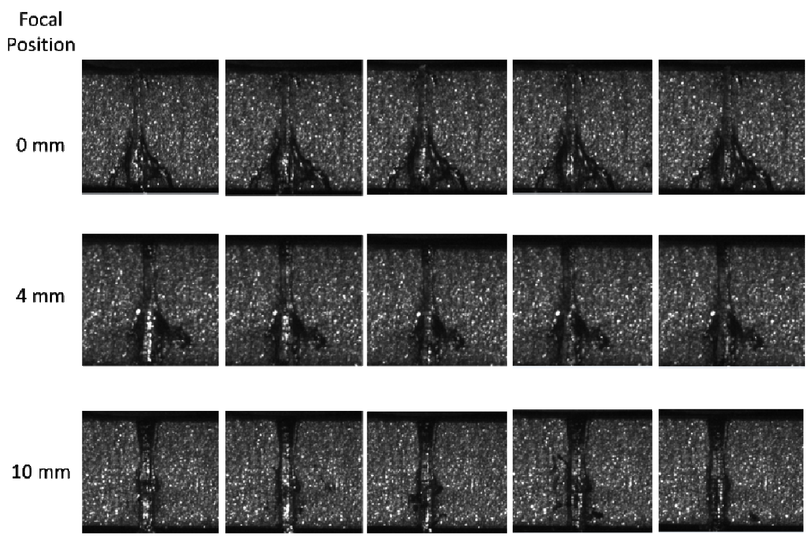


Figure 12: Time series with 1.5 ms interval for three different focal positions

Selected conferences and publications

"Measuring the Melt Flow on the Laser Cut Front," Jetro Pocorni Dirk Petring, John Powell, Eckard Deichsel, Alexander F.H. Kaplan; Physics Procedia **78**, p. 99-109 (2015) http://dx.doi.org/10.1016/j.phpro.2015.11.022

"Analyzing and Post-modelling the High Speed Images of a Wavy Laser Induced Boiling Front," R.S. Mattia, A.F.H. Kaplan; Physics Procedia **78**, p. 192-201 (2015) http://dx.doi.org/10.1016/j.phpro.2015.11.043

"Local flashing events at the keyhole front in laser welding," Alexander F.H. Kaplan; Optics and Lasers in Engineering **68**, p. 35-41 (2015) http://dx.doi.org/10.1016/j.optlaseng.2014.12.019

"The Effect of Laser Type and Power on the Efficiency of Industrial Cutting of Mild and Stainless Steels," Jetro Pocorni, Dirk Petring, John Powell, Eckard Deichsel and Alexander F. H. Kaplan; J. Manuf. Sci. Eng **138**, p. 031012 (2015) http://dx.doi.org/10.1115/1.4031190

➔ For more info please contact: Torbjörn Ilar; Luleå University of Technology Torbjorn.Ilar@ltu.se

The HALO IT-tool

The use of the meta-modelling in HALO was very successful, but it is difficult for the user to visualise and keep track of all the different variables and their potential effects. Consequently an IT-tool with a user-friendly GUI was developed within the project. This included a range of different software code modules (partly with embedded data), namely a laser cutting model, a parameter meta-model, a cutting database, cut front streak images and a cut quality optimisation 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 the 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. Figure 13 shows the main GUI and its optimisation tool.

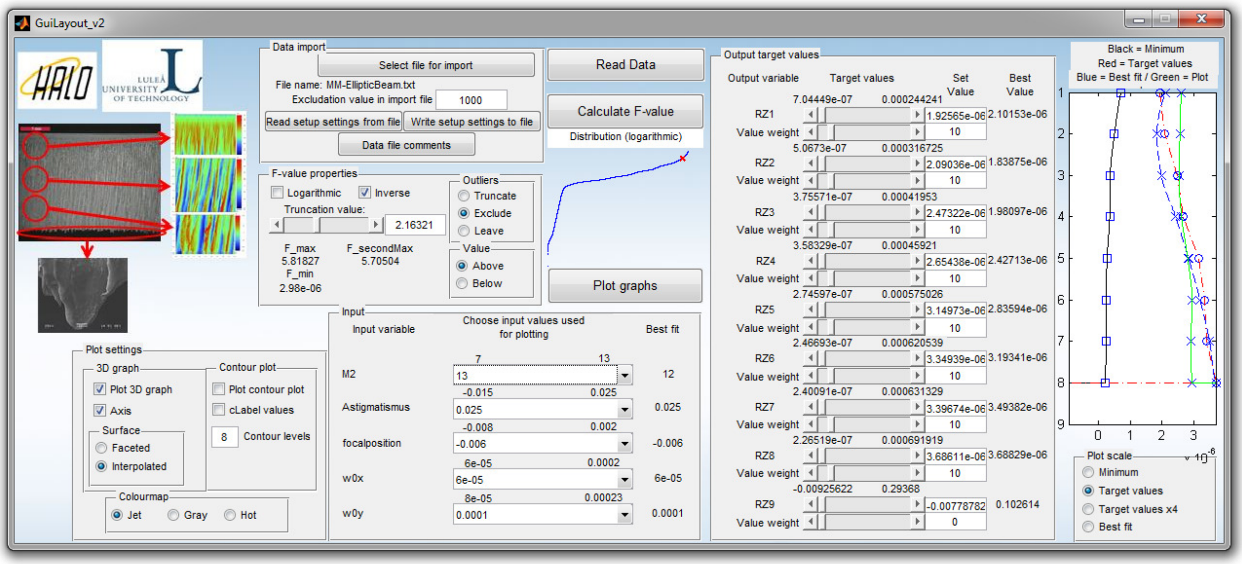
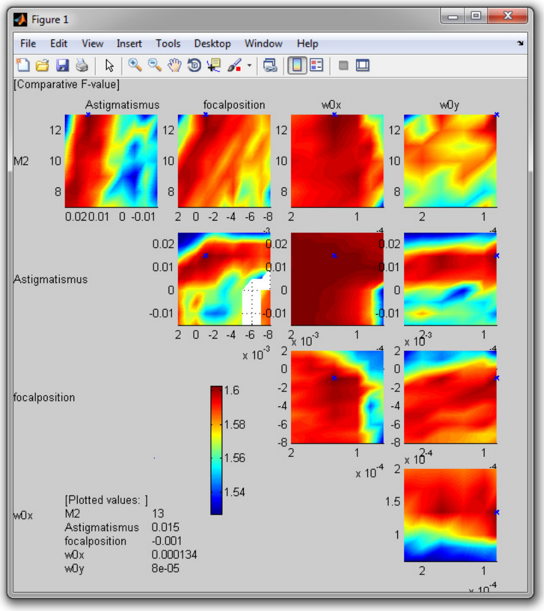


Figure 13: Screenshot of the main GUI of the HALO IT-tool, including the optimisation tool.

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/

The screenshot (Figure 14) 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.

Figure 14: Example of optimisation results (roughness variation across part of the parameter space) from the physical model for a specific laser cutting case and system

Selected conferences and publications

"Basic imaging and modelling analysis of the processing front in laser remote fusion cutting," Ramiz S. Matti, Alexander F.H. Kaplan; LIM 2015 Session We_A31_2; Paper 4

"Analysis of laser remote fusion cutting based on a mathematical model," R. S. Matti, T. Ilar and A. F. H. Kaplan; J. Appl. Phys. **114**, 233107 (Dec-2013) http://dx.doi.org/10.1063/1.4849895

➔ For more info please contact: Torbjörn Ilar; Luleå University of Technology Torbjorn.Ilar@ltu.se

Glass cutting

Conventional methods for brittle material cutting, e.g. mechanical scribing and breaking or etching, lead micro-cracks and require post-processing to achieve good edge quality. Moreover, the market trend is towards thinner, more stable glass where mechanical methods will reach their limits. Cutting with ultra-short pulsed lasers has huge potential. However there are several process techniques using ultra-short pulsed lasers for glass separation.

During HALO, novel techniques to cut display glass have been developed, for example the processing of transparent materials with ultra-short pulsed lasers by tailored absorption. Non-linear absorption enables a variety of different methods for laser processing of transparent materials. Absorption inside the volume offers high potential but may cause damage if not properly controlled. Applying ultra-short pulses reduces the fluence necessary for non-linear absorption. Beam shaping provides additional parameters to control processing.

2D-cutting of glass used in display technology illustrates the relevance for industrial laser processing by inscription of (elongated) modification for cleaving and/or selective laser etching of glass and sapphire in sheet geometry (Figure 15).

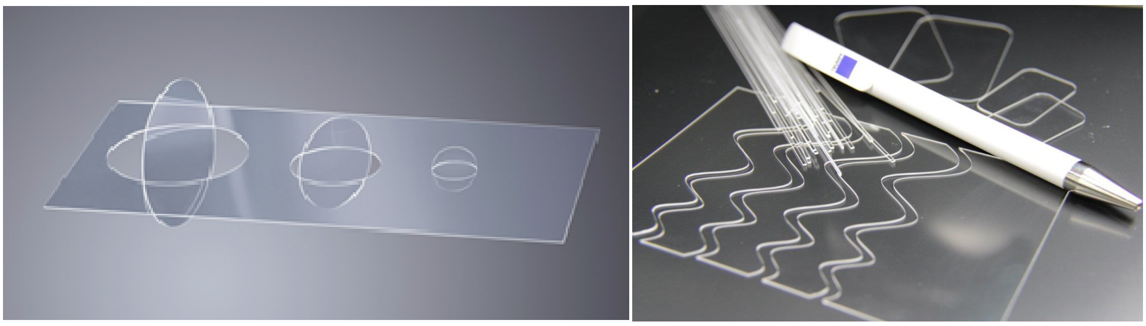


Figure 15: High speed glass cutting by modification.

The different glass cutting methods are illustrated in summary in Figure 16. Specially thin and hardened glass in particular can be cut by means of material modification. Ultra-short laser pulses modify a narrow area along the desired cutting line. This modification intrinsically weakens the glass, which breaks in a controlled manner and with mirror-like smoothness at the desired location with precision to one hundredth of a millimetre with almost zero cutting gap.

The focusing optics for highly dynamic cutting distributes the intensity of the laser light along the beam axis – the length of the focus is extended. In just one pass, depending on the pulse energy, the laser pulses modify the complete inner separation planes of a glass sheet, 700 µm thick, for example. With the high-power lasers in the TruMicro Series from TRUMPF cutting speeds of up to 1 m/s can be achieved using this “modification cut.”

In comparison with this only 5 mm/s may be achieved by laser cutting of 0.7 mm glass sheets by an ablation process. But the process is more flexible in geometries with radii and particularly for inner contours than with the modification cut. For the modification cut internal or external induced stress is needed to cleave the sample. Furthermore the ablation process has the advantage that it can be transferred to other non-transparent materials. This has been shown in the trials during HALO.

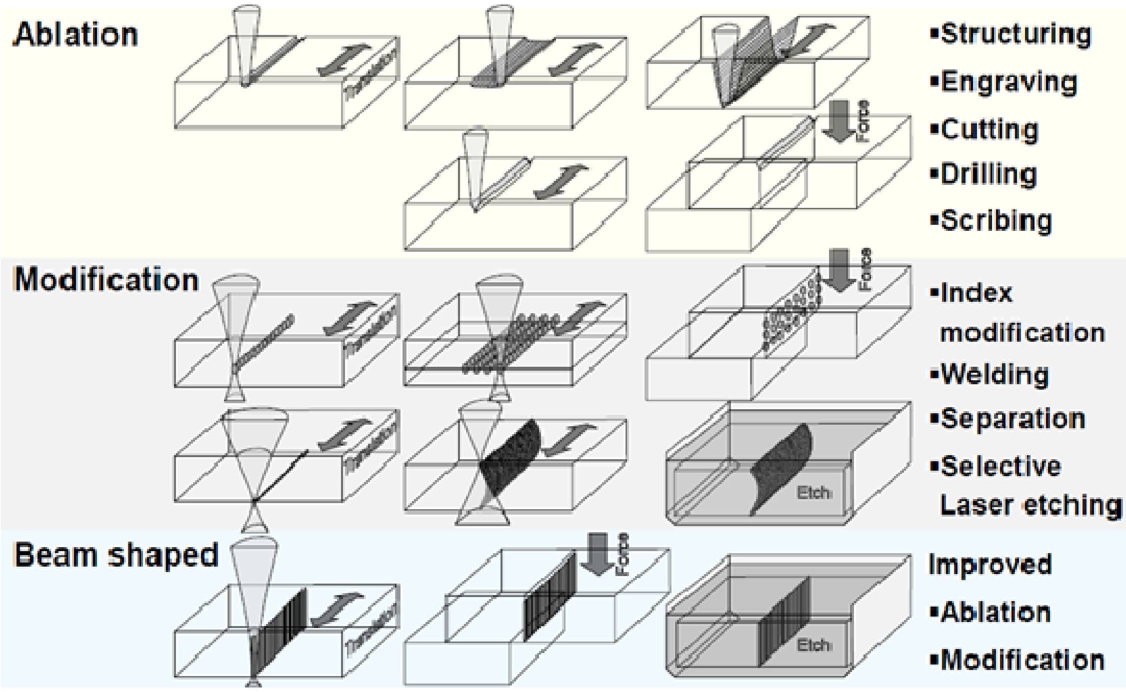


Figure 16: Schematic of different glass cutting methods

In conclusion TRUMPF is confident that both processes are necessary: the ablation cut and the modification cut, in order to have solutions for all industrial requests as conventional methods are increasingly squeezed out of the market.

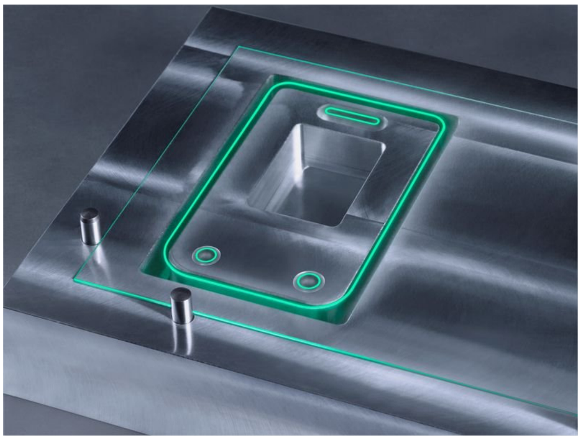
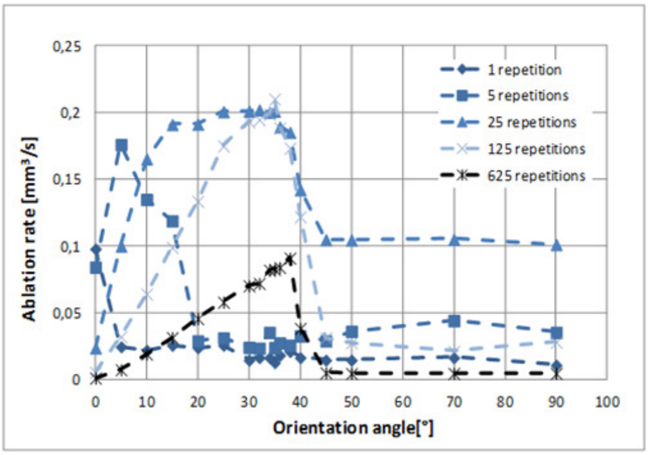


Figure 17: Laser cutting of a mobile display.

In the HALO project TRUMPF investigated the influence of beam shape and pulse duration on the cutting speed and quality of alumina-silicate 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 minimise 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 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 (Figure 18). 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.

Figure 18: Ablation rate of process with line arrangement at different angles relative to the feed rate direction.

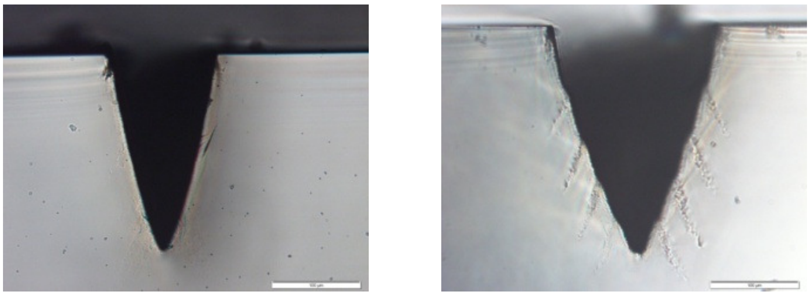


Figure 19: Cross- section of two ablation samples
Left: at an orientation angle of 20° showing excellent quality.
Right: at an orientation angle of 35° showing material damage.

The polygon arrangement (Figure 21) proved that it is possible to use the best of both configurations by a 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 DOE showed that multi-spot arrangements show a quantitative advantage, i.e. improved energy specific volume.

Figure 20: Graph showing the energy specific volume of processes with and without optimised multi-spot arrangement at different pulse overlaps.

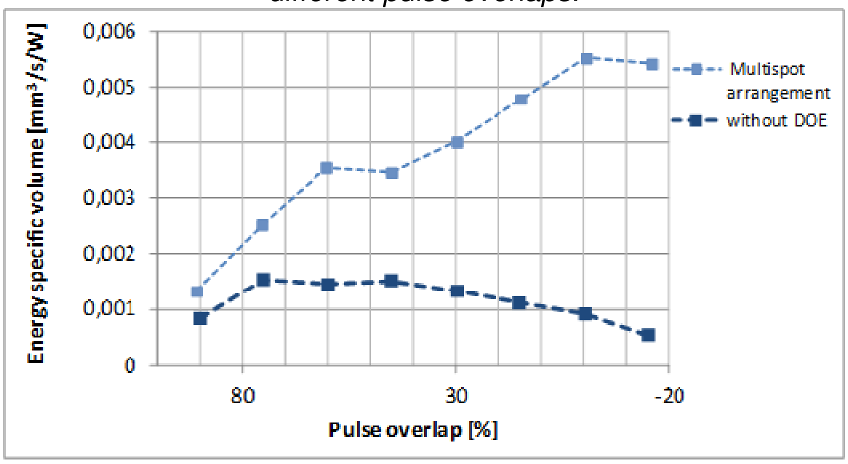
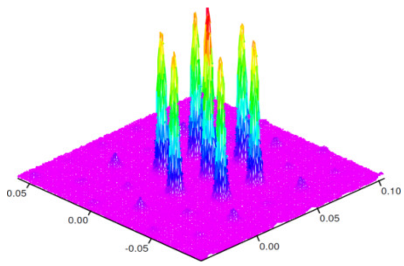


Figure 21: Intensity distribution of a polygon multi-spot arrangement.



Selected conferences and publications

"Picosecond laser ablation on transparent materials," Simone Russ; Christof Siebert; Urs Eppelt ; Claudia Hartmann ; Birgit Faißt ; Wolfgang Schulz Proc. SPIE Vol. **8608** (86080E) (2013) http://dx.doi.org/10.1117/12.2001991

"Comparison of different processes for separation of glass and crystals using ultra short pulsed lasers," M. Kumkar; L. Bauer; S. Russ; M. Wendel; J. Kleiner; D. Grossmann; K. Bergner; S. Nolte; Proc. SPIE **8972**, 897214 (2014) http://dx.doi.org/10.1117/12.2044187

"Influence of pulse duration on the glass cutting process," L. Bauer, U. Keller, S. Russ, M. Kumkar, B. Faißt, R. Weber, T. Graf; LIM 2015 Session Tu_A32_3; Paper 5 (2015)

"Ultrafast laser ablation of transparent materials," Lara Bauer; Simone Russ; Myriam Kaiser; Malte Kumkar; Birgit Faißt; Rudolf Weber; Thomas Graf; Proc. SPIE **9735**, 97350X http://dx.doi.org/10.1117/12.2212449

- ➔ For more information please contact: Lara Bauer; TRUMPF Laser
  Lara.Bauer@de.TRUMPF.com

Metal cutting

During the HALO project, in the sheet metal cutting sub-project, work was focused on investigating the impact of various configurations of beam, including elliptical beams, radial polarisation and tailored laser beam polarisation. The most successful was the tailored polarisation, as expected from the simulations. 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 Figure 22.

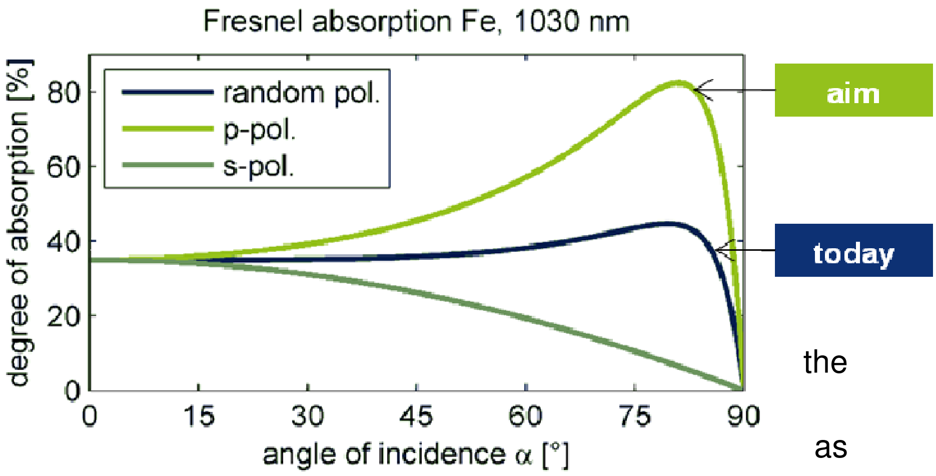


Figure 22: Absorption diagram for solid state lasers

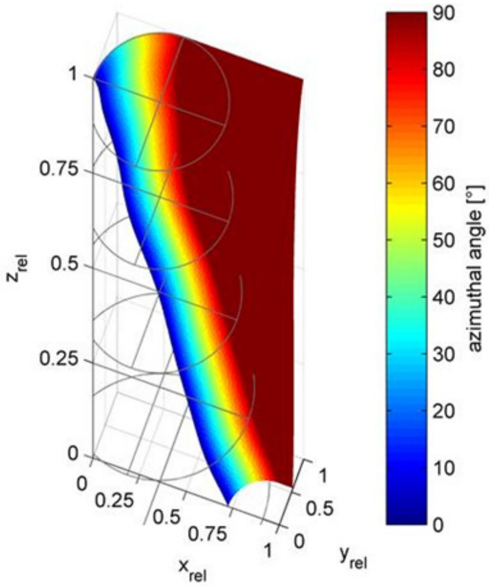


Figure 23: 3D model of cutting kerf

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.

Figure 23 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.

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 (see

Figure ***6***). To investigate the impact of the optimised polarisation, cutting experiments in 15 mm stainless steel were performed, with excellent results (Figure 24):

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

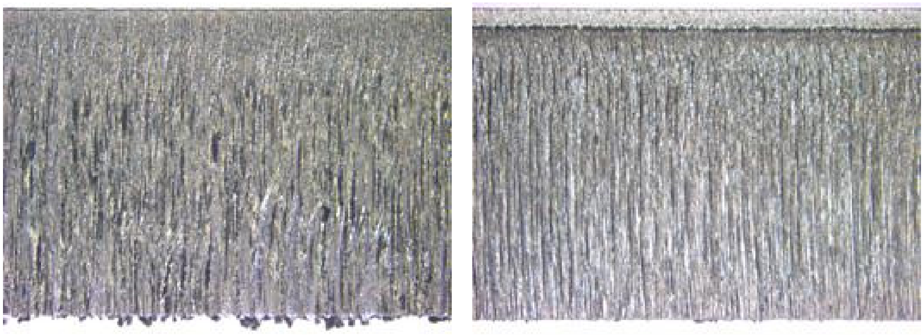


Figure 24: Cutting results in 15 mm stainless steel.
Left: State-of-the-art with random polarisation showing dross at the bottom of the workpiece and rough surface finish
Right: optimised polarisation showing no dross, improved surface quality: and performed at twice the feed rate!

➔ For more info please contact: Tobias Häcker; TRUMPF Werkzeugmaschinen tobias.haecker@de.trumpf.com

Liquid-jet cutting

During the HALO 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.

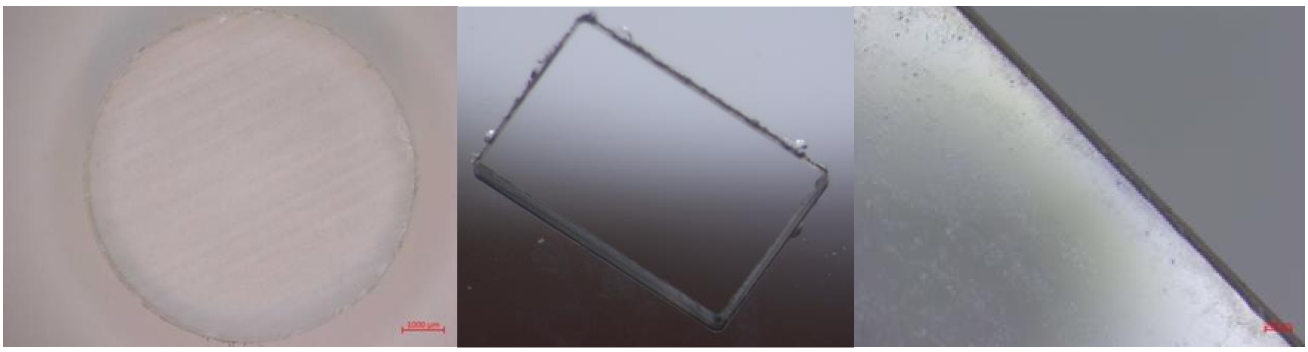


Figure 25: Samples of sapphire cut by water-guided jet

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.

Further details may be found in “Laser Microjet© Cutting of up to 3 mm Thick Sapphire,” Bernold Richerzhagen, Yury Kuzminykh, Patrik Hoffmann, Annika Richmann; *ICALEO 2014* ISBN: 9781940168029 (p. 148).

- ➔ For more information please contact: Helgi Diehl; Synova
  hdiehl@synova.ch

Impact

Impact of the project for HALO partners

The full name of the HALO project is, “High power Adaptable Laser beams for materials prOcessing.” HALO has made major advances in this field and has delivered a wide range of component technology for its partners.

Impact for academic partners

Spin-out potential

The academic partners have a strong track record of exploiting IP both in terms of licensing to users and in the formation of spin-out companies from the universities.

ORC

In the Southampton area alone, there is a cluster of more than ten companies engaged in photonics with their roots in the ORC. These companies play a major role in the regional and national economy. The spin-out companies continue to maintain strong links with the universities, sponsoring research and Ph.D. students, providing a route through to the marketplace for new ideas, applications and technology.

If this is appropriate for technology relating to the HALO novel laser designs (ORC), then this would be welcomed and encouraged by the consortium. Where appropriate, knowledge generated from HALO will be used to improve under-graduate lecture material, as well as potentially future post-graduate projects to continue promising aspects of the research. Currently there are no specific plans for spin-out companies, however, the HALO laser designs have significant commercial potential, and this may be reviewed in the light of enquiries in the coming months.

ILT

One to two spin-outs per year have been generated on average by Fraunhofer ILT since its foundation in 1985. This led to innovative laser manufacturers (e.g. Laserline), laser system suppliers (e.g. CLEAN Lasersysteme), laser engineering companies (e.g. S&F Systemtechnik) and laser head suppliers (e.g. Laserfact) playing international key roles in their specific markets. Therefore, it is self-evident that also the HALO outcomes already motivated an intense discussion at Fraunhofer ILT about founding a related spin-out. The main objective is the commercialisation of customised simulation and IT tools using the achieved meta-modelling experience from HALO.

LTU

For LTU there are two aspects which are regarded as having high potential for commercialisation:

a) new laser system optics to tailor the laser beam to a (cutting) process

b) the HALO IT-optimisation software tool, possibly interacting with a meta-model and/or a database.

The commercialisation potential for a) and b) in the form of spin-off companies is regarded as relatively high, but as often experienced it depends on whether a few individuals are willing to take make an entrepreneurial career and take initiative here, e.g. Ph.Ds. from the project (two LTU-students will achieve their doctorates based on HALO in 2017). The participating research group is in close and regular contact with 'LTU Business AB', the LTU unit supporting commercialisation of results and transfer to industry or initiation of start-ups, who will be informed about the project outcomes with commercialisation potential.

Ongoing research

ORC

The research results relating to the novel lasers sources developed at the ORC have been the subject of numerous journal and conference papers, including two invited papers at leading international conferences. This has helped ORC to maintain its position as one of the leading research groups in the field of lasers and laser technology. Moreover, the project has allowed ORC to make preliminary studies in a new research area (i.e. laser processing of materials) aided by the numerous interactions with HALO project partners, who have considerable expertise in this area.

The project has facilitated the training of post-doctoral research fellows and research students in various aspects of laser technology. One of the research students has successfully completed his Ph.D. studies and is now working on a project in a related area, and one of the research fellows has recently taken up employment at a UK company working on high power lasers.

ILT

The high-speed video diagnostics and streak imaging method developed in HALO will continue to be used in order to identify and understand beam parameter influence and rules for achieving improved cutting quality. The technique and the related equipment of Fraunhofer ILT has been successfully demonstrated during HALO for oxide-free cutting of stainless steel with circular beam and random polarisation. Based on the achieved knowledge quality, features such as roughness and dross could be improved by a factor of two. Manufacturers and end-users of fibre lasers for cutting of metals further look for better edge quality due to the strong global market competition. Related customer projects making use of HALO’s process diagnostics method have been started already.

On the same route, the evaluation technique to predict quality indicators from CALCut cutting process simulations is meanwhile successfully used in customer projects. After related publications by Fraunhofer ILT, industrial customers placed orders for this service as a key part of well-endowed RTD projects. The technique becomes increasingly recognised and is used to minimise time of cutting process development by virtual parameter screening and optics adaptation.

Also the work on meta-modelling and its utilisation for comprehensive data management could successfully be transferred into first industrial projects for various laser applications. Further funding, including Horizon 2020, for initialising innovative business cases will be applied for.

Furthermore, mentioned achievements and resulting academic progress are also conveyed in projects and lectures of the laser chairs of RWTH Aachen University (LLT, NLD, TOS) being associated with Fraunhofer ILT. Projects such as the Cluster of Excellence "Integrative Production Technology for High-Wage Countries" and the recently started Photonics Cluster at the new Aachen Campus benefit from and contribute to a continuing exploitation of HALO outputs.

LTU

The successful results from HALO are of high value for other ongoing and planned research projects at LTU. The EU-FP7-project TailorWeld, tailoring laser beams for welding has strong mutual synergies, and also has an accompanying IT-Tool, although of a different type and with other objectives. For the ongoing research in remote fusion cutting part of the new knowledge on laser cutting is of direct benefit. The findings from the high speed imaging and streak photography are already applied in a series of other laser research projects. Summarising, much valuable research substance on laser cutting and on the analysis methods was generated in HALO that is in different manners valuable for various other LTU-projects, usually in larger academic and industrial cooperation.

Other commercialisation opportunities

ORC

The results generated by HALO have attracted a great deal of interest from the laser and laser-user community. ORC is currently in discussion with interested parties to identify funding opportunities to take the work forward and explore routes to commercialisation.

ILT

Most commercialisation opportunities result from the significant system-supplier and end-user benefits generated by the improved cutting processes and optical systems on the routes described already above in sections "Spin-out potential" and "Ongoing research".

LTU

Regarding (a), the laser system optics, relevant companies will continue to be informed about the possibilities, particularly one system manufacturer in Sweden which must remain confidential at this time. For (b), the IT-tool, in combination with other IT-tools generated recently, a dialogue with corresponding IT-companies as well as with Swedish laser users (mainly cutting job-shops) has been initiated and will be continued.

Impact for industrial partners

The industrial partners are all extremely well placed to exploit the outputs from the project using existing infrastructure and commercial routes. The HIG has helped to identify potential new applications and customers, which will provide clear, focused commercial exploitation routes.

G&H

HALO has been an extremely positive project for G&H, and has enhanced its relationship with important a key laser manufacturer (TRUMPF) and machine fabricator (Synova). In particular the close collaboration and co-development of the segmented waveplates has been a highly valuable experience.

HALO has not led to specific new products because it is still in the research and development domain. Nevertheless, several notable advances towards products have been made, which are expected to be exploited in future development work as the market matures:

- 3-port acousto-optic switch – The G&H (Torquay) business development unit is currently assessing opportunities for other applications and potential to introduce a 3-port variant of the Fibre-QTM AOM as a standard product.
- Capillary tapers – These components are very interesting, but there is unlikely to be a large market in the short term. However know-how for working with fibres with air-guiding features and fusion rig developments implemented during HALO are being applied to new novel components for fibre lasers using photonic crystal fibre.
- Multi-segment waveplates: The development work with TRU-W on the segmented waveplates included both a dart-board design, parallel striped, and shell pattern waveplates. The resulting component was capable of handling the necessary optical power (4 kW) for steel cutting. This involved the exploration of a number of bonding techniques, and has led to a new design approach which is expected to find use in various complex multi-segment optics in future.

TRU-W

In HALO it was shown that adapting polarisation is a worthwhile field of action. Striped polarisation is the most profitable option, but also more difficult to implement into a cutting machine than radial polarisation since it is not rotationally symmetric.

TRU-L

The HALO achievements help TRU-L to get competitive advantages by beam guidance, beam shaping and pulse shaping (especially pulse duration) by scaling throughput of laser processing and meeting quality requirements. For example it was shown in HALO that tight focusing avoids sub-surface damage and scales the throughput by increasing the number of spots by factor of seven. As discussed above, flexibility in shape and geometry is key for the display industry.

Synova

HALO has helped Synova to increase its understanding of its core process, including the simulation of fluid flow and splashing, mechanisms of nozzle damage and improved nozzle design. In addition it has led to the identification of processes to cut sapphire: something which was simply not possible at the start of the project.

LEL

Laser Expertise has learned a great deal about the future of laser cutting as a result of the HALO project. Apart from the excellent international networking opportunities offered by the project, the members of the consortium have generated some important advances in the field. The firm will be using its improved technical knowledge when considering future investments. As well as laser cutting, Laser Expertise offers a consultancy service to the laser applications industry, and the contacts and knowledge gained as part of the HALO project will help to optimise industrial growth in this area.

HALO events

During the course of the project, HALO participated in a range of public events to disseminate the project results. The following lists summarise the key events.

Conferences (22 events; 39 presentations)

- *LASE 2013; part of Photonics West 2013 (05-07 Feb-2013; San Francisco, USA)*
  - "Single-frequency Nd:YAG laser with LG01 mode output"
    - Lin, Di , Daniel, J.M.O. and Clarkson, W.A (ORC)
  - "Picosecond laser ablation on transparent materials"
    - Simone Russ; Christof Siebert; Urs Eppelt ; Claudia Hartmann ; Birgit Faißt ; Wolfgang Schulz (TRU-L & ILT)
    - Proc. SPIE Vol. 8608 (86080E)
    - http://dx.doi.org/10.1117/12.2001991
- *CLEO/Europe-IQEC 2013 (13-16 May-2013; Munich, Germany)*
  - "Controlling the handedness of directly excited Laguerre Gaussian modes in a solid-state laser"
    - Paper CA-10.2
    - D. Lin, J.M.O. Daniel, and W.A. Clarkson (ORC)
- *NOLAMP 2013 (26-28 Aug-2013; Gothenburg, Sweden)*
  - LTU hosted the 14th Nordic Laser Materials Processing Conference
  - "Measuring the State-of-the-Art in Laser Cut Quality"
    - J.K. Pocorni, J. Powell, T. Ilar, A. Schwarz and A.F.H. Kaplan (LTU & LEL)
  - "Modelling the cutting geometry for laser remote fusion cutting of metals"
    - Matti, R.S., T. Ilar and A. F. H. Kaplan (LTU & LEL)
- *"Laserbearbeitung von Glaswerkstoffen" (26-Nov-2013; Hannover, Germany)*
  - Workshop on laser processing of glass at Laser Zentrum Hannover (LZH)
  - Lisa Bauer (TRU-L) presented HALO work on glass cutting using picosecond lasers
- *ALU Workshop (03-Dec-2013; Cambridge, UK)*
  - Association of Laser Users Workshop on: "Power beam delivery and manipulation"
  - HALO tabletop
  - Peter MacKay and Tom Legg (G&H)
- *LASE 2014; part of Photonics West 2014 (01-06 Feb-2014; San Francisco, USA)*
  - "Comparison of different processes for separation of glass and crystals using ultra short pulsed lasers"
    - M. Kumkar; L. Bauer; S. Russ; M. Wendel; J. Kleiner; D. Grossmann; K. Bergner; S. Nolte (TRU-L)
    - Proc. SPIE **8972**, 897214 (2014)
    - http://dx.doi.org/10.1117/12.2044187
- *CLEO 2014 (08-13 Jun-2014; San Jose, USA)*
  - Conference on Lasers and Electro-Optics (CLEO 2014)
  - "Direct generation of radially-polarized output from an Yb-doped fiber laser"
    - D. Lin, J. M. O. Daniel, M. Gecevičius, M. Beresna, P. G. Kazansky, W. A. Clarkson (ORC)
    - CLEO: 2014, OSA Technical Digest, paper JW2A.22
    - http://dx.doi.org/10.1364/CLEO_AT.2014.JW2A.22

- *Optical Fabrication and Testing (22-26 Jun-2014; Hawaii, USA)*
    - “Segmented Waveplate Polarisation Control for Laser Cutting”
        - Peter E. MacKay (G&H), Tobias Häcker, and Tim Hesse (ILT)
        - http://dx.doi.org/10.1364/OFT.2014.OTh4B.2
- *SLT14-Stuttgart Laser Technology Forum 2014 (25-Jun-2014; Stuttgart, Germany)*
    - “Simulation of Glass Cutting” [Invited]
        - W. Schulz (ILT)
    - Analysing the influence of pulse duration on the glass cutting process
        - L. Bauer (TRU-L)
- *67th IIW Annual Assembly (13-18 Jul-2014; Seoul, South Korea)*
    - “Interaction of the beam with the wavy keyhole front in laser welding”
        - A.F.H. Kaplan (LTU)
        - CONF-2014-84
- *Europhoton 2014 (24-29 Aug-2014; Neuchatel, Switzerland)*
    - 6th EPS-QEOD Europhoton Conference
    - "Efficient conversion to radial polarization in the two-micron band using a continuously space-variant half-waveplate”
        - Lin, D, Shardlow, P., Beresna, M., Kazansky, P.G. and Clarkson, W.A. (ORC)
        - Paper WeD-T2-O-06
    - “High power radially-polarized Yb-doped fiber laser”
        - Lin, Di , Daniel, J., Gecevičius, M., Beresna, M., Kazansky, P.G. and Clarkson, W.A. (ORC)
        - Paper ThA-T2-O-05
    - “Spectrally-tailored thulium-doped fibre amplified spontaneous emission source at two-microns”
        - Poster TuP-T1-P-24
        - A. Billaud, P.C. Shardlow, J.M.O. Daniel, W.A. Clarkson (ORC)
- *ICNAAM 2014 (22-28 Sep-2014; Rhodes, Greece)*
    - 12th Int. Conf. of Numerical Analysis and Applied Mathematics
    - “Metamodeling of Laser Cutting”
        - U. Eppelt & T. Al-Khawli (ILT)
        - AIP Conf. Proc. **1648**, 01000
        - http://dx.doi.org/10.1063/1.4912302
- *ICALEO 2014 (19-23 Oct-2014; San Diego, USA)*
    - International Congress on Applications of Lasers & Electro-Optics 2014
    - “Differences in Cutting Efficiency Between CO_2 and Fiber Lasers when Cutting Mild and Stainless Steels”
        - Jetro Pocorni, Dirk Petring, John Powell, Eckard Deichsel, Alexander F.H. Kaplan (LTU, LEL & ILT)
        - ISBN: 9781940168029 (p. 905)
    - “Laser Microjet© Cutting of up to 3 mm Thick Sapphire”
        - Bernold Richerzhagen, Yury Kuzminykh, Patrik Hoffmann, Annika Richmann (Synova)
        - ISBN: 9781940168029 (p. 148)
    - “Absorption peaks depending on topology of the keyhole and wavelength”
        - Alexander F.H. Kaplan and Ramiz S. Matti (LTU)
        - ISBN: 9781940168029 (p. 1907)
        - Journal version also published in J. Laser Applications **27**, p. S29012 (See below.)

- *CLEO 2015 (10-15 May-2015; San Jose, USA)*
    - Conference on Lasers and Electro-Optics (CLEO)
    - “Cladding-pumped Yb-doped fiber laser with vortex output beam”
        - D. Lin, W. A. Clarkson (ORC)
        - http://dx.doi.org/10.1364/CLEO_SI.2015.STh4L.1
- *CLEO Europe 2015 (21-25 Jun-2015; Munich, Germany)*
    - European Conference on Lasers and Electro-optics 2015
    - “Simple Technique for High-Order Ring-Mode Selection within Solid-State Lasers”
        - A. C. Butler, R. Uren, D. Lin, J. R. Hayes, and W. A. Clarkson (ORC)
        - Paper CA 7-5
    - “Tm-doped fibre laser with radially-polarized output beam at 2 µm”
        - D. Lin, P. Shardlow, M. Beresna, P. G. Kazansky, and W. A. Clarkson (ORC)
        - Paper CJ P-10
    - “High Power Spectrally-Tailorable Thulium-Doped Fibre Amplified Spontaneous Emission Source”
        - A. Billaud, P. C. Shardlow, A. Butler, D. Jain, J. Sahu, and W. A. Clarkson (ORC)
        - Paper CJ P-30
- *LIM 2015 (21-25 Jun-2015; Munich, Germany)*
    - Lasers in Manufacturing Conference 2015
    - “Influence of pulse duration on the glass cutting process”
        - L. Bauer, U. Keller, S. Russ, M. Kumkar, B. Faißt, R. Weber, T. Graf (TRU-L)
        - Session Tu_A32_3; Paper 5
    - “Basic imaging and modelling analysis of the processing front in laser remote fusion cutting”
        - Ramiz .S. Matti, Alexander F.H. Kaplan (LTU)
        - Session We_A31_2; Paper 4
- *NOLAMP 2015 (25-27 Aug-2015; Lapeenranta, Finland)*
    - Conference on Nordic Laser Materials Processing 2015
    - “Measuring the melt flow on the laser cut front"
        - Jetro Pocorni (LTU)
    - “Analyzing and post-modelling the high speed images of a wavy laser- induced boiling front”
        - Ramiz Matti (LTU)
- *ICNAAM 2015 (23-29 Sep-2015; Rhodes, Greece)*
    - 13th International Conference of Numerical Analysis and Applied Mathematics
    - “An integrated approach for the knowledge extraction in computer simulation models with a multidimensional parameter space”
        - Wolfgang Schulz (ILT)
- *OSA Advanced Solid-State Lasers Conference (04-09 Oct-2015; Berlin, Germany)*
    - “Cladding-pumped radially-polarized fiber Lasers”
        - W. A. Clarkson, D. Lin, , M. Beresna, P. G. Kazansky, P. Shardlow (ORC)
        - Paper AW2A.4 (Invited Paper)
- *Fraunhofer IWS Laser Symposium 2016 (23-24 Feb-2016; Dresden, Germany)*
    - “Meta-Modelling towards virtual production engineering”
        - Wolfgang Schultz (ILT)

- *Photonics West 2016 (14-18 Feb-2016 San Francisco, USA)*
    - "Ultrafast laser ablation of transparent materials"
        - Lara Bauer; Simone Russ; Myriam Kaiser; Malte Kumkar; Birgit Faißt; Rudolf Weber; Thomas Graf (TRU-L)
        - Proc. SPIE **9735**, 97350X
        - http://dx.doi.org/10.1117/12.2212449
    - "Donut beam generation in a hybrid fiber laser pumped Ho:YAH laser"
        - A. C. Butler, P. C. Shardlow, R. T. Uren, W. A. Clarkson (ORC)
        - Paper 9726-61
- *AKL 2016 (29-Apr-16; Aachen, Germany)*
    - "Adaptable Lasers for Cutting Sheet Metal, Glass and Silicon: Project Overview - Simulation and Meta-Modelling"
        - Wolfgang Schulz (ILT)
    - "Novel Adaptable Laser Designs"
        - Andy Clarkson (ORC)
    - "Cutting Brittle Material: Cutting Phenomena and Multi-Spot Techniques"
        - Lara Bauer (TRU-L)
    - "Cutting Brittle Material: 3D Ablation with Liquid-Jet Guided Laser in 5-axis CNC Machines"
        - Bernold Richerzhagen (Synova)
    - "Cutting Sheet Metal: Adapted Polarization Beam Shaping for High-Quality Cutting"
        - Tobias Häcker (TRU-W)
    - "Cutting Sheet Metal: High-Speed Imaging Analysis of Laser Beam Cutting"
        - Alexander Kaplan (LTU)

Planned

- *CLEO 2016 (05-10 Jun-2016; San Jose, USA)*
    - Conference on Lasers and Electro-Optics
    - "High Power Fiber Lasers with Radially Polarized Output Beams"
        - W. Andrew Clarkson; Di Lin; Martynas Beresna; Peter G. Kazansky; Peter C. Shardlow (ORC)
        - Paper SM4Q.1 [Invited]
    - "Reduced thermal lensing in an end-pumped Nd:YVO4 laser using a ring-shaped pump beam"
        - D. Lin; W. A. Clarkson (ORC)
        - Paper SM3M.5
    - "Handedness of Laguerre-Gaussian LG01 Mode in a Unidirectional Ring Laser"
        - Robin T. Uren; W. Andrew Clarkson (ORC)
        - Paper STu1M.6
- *HPLS&A 2016 (05-09 Sep-2016; Gmunden, Austria)*
    - International Symposium on High Power Laser Systems and Applications
    - "Status and prospects in 2D laser cutting"
        - T. Hesse and T. Häcker (TRU-L)
- *LANE 2016 (19-22 Sep-2016; Fuerth, Germany)*
    - 9th Int. Conf. on Photonic Technologies
    - "Imaging of the dynamic melt movement induced by a pulsed laser"
        - R.S.M. Samarjy & A.F.H. Kaplan (LTU)

- *ICALEO 2016 (16-20 Oct-2016; San Diego, USA)*
    - International Congress on Applications of Lasers & Electro-Optics 2016
    - "Investigation of the piercing process in laser cutting of stainless steel"
        - Jetro Pocorni, John Powell, Jan Frostevarg, Alexander F.H. Kaplan (LEL & LTU).

Trade shows and exhibitions (13 events)

- *Photonics West 2013 (05-07 Feb-2013; San Francisco, USA)*
    - G&H & TRU-L both had exhibition booths
- *Laser World of Photonics (13-16 May-2013; Munich, Germany)*
    - Both G&H and TRUMPF had booths at this event
    - ILT (Wolfgang Schultz) gave a presentation on HALO topics during the "Lasers and laser systems for Production" congress, which was entitled, "Towards high-quality laser cutting of glass: Simulation and diagnosis of ultra-short pulse ablation"
    - ILT (Thomas Molitor) also gave a presentation on "Process diagnosis with high speed camera"
    - In addition HALO was included in the presentation shown on the ILT-stand at the Munich fair entitled "Newest achievements from ILT."
- *NOLAMP 2013 (26-Jun-2016; Gothenburg, Sweden)*
    - 14th Nordic Laser Materials Processing Conference
    - HALO had a tabletop at this event
- *ICT 2013 "Create, Connect, Grow" (Vilnius, Lithuania; 06-09 Nov-2013)*
    - Bruce Napier (Vivid) attended and represented HALO. This included a pop-up banner and leaflets (on the related FP7 project ISLA booth)
- *Photonics West 2014 (01-06 Feb-2014; San Francisco, USA)*
    - G&H & TRU-L both had exhibition booths
- *FiSC/ International Laser Symposium 2014 (27-28 Feb-2014; Dresden, Germany)*
    - HALO had a joint booth with the ISLA project
    - Bruce Napier (Vivid) and Gary Stevens (G&H)
- *Photonics Europe (14-16 Apr-2014; Brussels, Belgium)*
    - HALO had a booth in the "Innovation Village" at this event
    - Bruce Napier (Vivid), Toby Woodbridge and Mia Swain (G&H)
- *AKL 2014 (07-09 May-2014; Aachen, Germany)*
    - HALO banners at ILT booth
- *LASYS (24-Jun-2014; Stuttgart, Germany)*
    - TRU-L exhibition stand with HALO leaflets
- *ICALEO 2014 (19-23 Oct-2014; San Diego, USA)*
    - International Congress on Applications of Lasers & Electro-Optics
    - HALO partners TRU-L and Synova had booths at this large international event
- *Fraunhofer IWS Laser Symposium 2016 (23-24 Feb-2016; Dresden, Germany)*
    - HALO booth; Bruce Napier (Vivid) and Wolfgang Schultz (ILT)
- *Photonics Europe 2016 (03-07 Apr-2016; Brussels, Belgium)*
    - HALO booth; Bruce Napier (Vivid)
- *AKL 2016 (29-Apr-16; Aachen, Germany)*
    - Booth at "Laser Technik Live; Bruce Napier (Vivid) and Peter MacKay (G&H)

Other presentations (Twelve events)

- *Factories of the Future Impact Workshop (11-Mar-2013, Brussels, Belgium)*
    - Bruce Napier presentation on HALO (Vivid)
- *International Institute of Welding annual meeting (11-Sep-2013; Essen, Germany)*
    - Dirk Petring (ILT) presentation on HALO to the IIW
- *Factories of the Future Impact Workshop (24-Mar-2014, Brussels, Belgium)*
    - Tom Legg presentation on HALO (G&H)
- *SCHOTT Expert Panel (18-Jun-2014; Mainz, Germany)*
    - Laser Processing of Glass – Practical Aspects and Simulation
    - [Invited] "Simulation and Diagnosis of ultra-short pulse ablation," W. Schulz (ILT).
- *LASYS (24-Jun-2014; Stuttgart, Germany)*
    - Wolfgang Schulz part of Expert Forum on "Lasers in Action"
- *CEOI Space Technology Showcase (13-Nov-2014; London, UK)*
    - Peter MacKay (G&H) presentation on HALO Hyper Bond components
- *Factories of the Future Impact Workshop (29-Apr-2015, Brussels, Belgium)*
    - Tom Legg presentation on HALO (G&H)
- *World of Photonics (25-Jun-2015; Munich, Germany)*
    - "Prof. Wolfgang Schulz (ILT) presentation “HALO–Real Time Adjustment of Laserbeam Properties for Optimum Process Results”
        - Part of “European Research on Laser Based Technologies” Forum"
    - Live demonstration of meta-modelling at ILT booth
- *AILU Annual Job Shop Meeting (14-Oct-2015; Worcester, UK)*
    - John Powell (LEL) presentation on adaptable beams
- *Mittweider Lasertagung 2015 (19-20 Nov-2015; Mittweider, Germany)*
    - “Meta-Modelling and Visualization of multi-dimensional Data”
    - Wolfgang Schultz (ILT)
- *84th Meeting of the Japanese Laser Processing Society (19-Jan-2016; Nagoya, Japan)*
    - "Virtual laser cutting simulation for real process parameter optimization"
    - Plenary address: Dirk Petring (ILT)
- *Photonics Europe 2016 (03-07 Apr-2016; Brussels, Belgium)*
    - HALO presentation; Bruce Napier (Vivid)
    - Part of the workshop “Advanced Manufacturing and Photonics for Production”

Journal papers

In addition to the conference papers and posters listed above, the following fourteen journal papers were published arising from HALO work during the project:

- Rapid, electronically controllable transverse mode selection in a multimode fiber laser
    - J. M. O. Daniel and W. A. Clarkson (ORC)
    - Optics Express, **21**, pp. 29442-29448 (Dec-2013)
    - http://dx.doi.org/10.1364/OE.21.029442
- Analysis of laser remote fusion cutting based on a mathematical model
    - R. S. Matti, T. Ilar and A. F. H. Kaplan (LTU)
    - J. Appl. Phys. **114**, 233107 (Dec-2013)
    - http://dx.doi.org/10.1063/1.4849895
- Meta-Modelling Techniques Towards Virtual Production Intelligence

- Wolfgang Schulz , Toufik Al Khawli (ILT)
- Advances in Production Technology; part of the series "Lecture Notes in Production Engineering" p. 69-84 (2014)
- http://dx.doi.org/10.1007/978-3-319-12304-2_6

- Analysis of moving surface structures at a laser-induced boiling front
  - R.S. Matti and A.F.H. Kaplan (LTU)
  - Applied Surface Science **317** p. 560-567 (2014)
  - http://dx.doi.org/10.1016/j.apsusc.2014.08.190
- Cladding-pumped ytterbium-doped fiber laser with radially polarized output
  - Di Lin, J. M. O. Daniel, M. Gecevičius, M. Beresna, P. G. Kazansky, and W. A. Clarkson (ORC)
  - Optics Letters, **39**, p. 5359-5361 (2014)
  - http://dx.doi.org/10.1364/OL.39.005359
- Controlling the handedness of directly excited Laguerre–Gaussian modes in a solid-state laser
  - Di Lin, J. M. O. Daniel, and W. A. Clarkson (ORC)
  - Optics Letters **39**, p. 3903-3906 (2014)
  - http://dx.doi.org/10.1364/OL.39.003903
- Measuring the Melt Flow on the Laser Cut Front
  - Jetro Pocorni Dirk Petring, John Powell, Eckard Deichsel, Alexander F.H. Kaplan (LTU & LEL)
  - Physics Procedia **78**, p. 99-109 (2015)
  - http://dx.doi.org/10.1016/j.phpro.2015.11.022
- Polarization-dependent transverse mode selection in an Yb-doped fiber laser
  - D. Lin and W.A. Clarkson (ORC)
  - Optics Letters, **40**, p. 498-501 (2015)
  - http://dx.doi.org/10.1364/OL.40.000498
- Analyzing and Post-modelling the High Speed Images of a Wavy Laser Induced Boiling Front
  - R.S. Mattia, A.F.H. Kaplan (LTU)
  - Physics Procedia **78**, p. 192-201 (2015)
  - http://dx.doi.org/10.1016/j.phpro.2015.11.043
- Absorption peaks depending on topology of the keyhole front and wavelength
  - Alexander F.H. Kaplan and Ramiz S. Matti (LTU)
  - J. Laser Applications **27**, p. S29012 (2015).
  - http://dx.doi.org/10.2351/1.4906469
- Local flashing events at the keyhole front in laser welding
  - Alexander F.H. Kaplan (LTU)
  - Optics and Lasers in Engineering **68**, p. 35-41 (2015).
  - http://dx.doi.org/10.1016/j.optlaseng.2014.12.019
- The Effect of Laser Type and Power on the Efficiency of Industrial Cutting of Mild and Stainless Steels
  - Jetro Pocorni, Dirk Petring, John Powell, Eckard Deichsel and Alexander F. H. Kaplan (LTU & LEL)
  - J. Manuf. Sci. Eng **138**, p. 031012 (2015)
  - http://dx.doi.org/10.1115/1.4031190
- Sensitivity Analysis of Laser Cutting Based on Metamodeling Approach
  - Toufik Al Khawli, Urs Eppelt and Wolfgang Schulz (ILT)
  - Handbook of Research on Computational Simulation and Modeling in Engineering, ch. 20, p. 618-639 (2015)

  - http://dx.doi.org/10.4018/978-1-4666-8823-0.ch020
- Post-modelling of images from a laser-induced wavy boiling front
  - R.S. Mattia, A.F.H. Kaplan (LTU)
  - Applied Surface Science **357**, p. 2277–2284
  - http://dx.doi.org/10.1016/j.apsusc.2015.09.226

Planned (Five papers)

- Transient interaction of a boiling melt with a pulsed Nd:YAG-laser
  - R.S.M. Samarjy (LTU)
  - Optics and Lasers in Engineering: in press 2016
- Imaging of the dynamic melt movement induced by a pulsed laser
  - R.S.M. Samarjy (LTU)
  - Physics Procedia: in press 2016
- Fibre laser cutting stainless steel:fluid dynamics and cut front morphology
  - Jetro Pocorni (LTU)
  - Optics and Laser Technology: submitted Mar-2016
- Investigation of the piercing process in laser cutting of stainless steel
  - Jetro Pocorni (LTU)
  - Journal of Laser Applications: submitted May-2016
- Numerical simulation of laser ablation driven melt waves
  - Jetro Pocorni (LTU)
  - Journal of Applied Physics: planned submission Jul-2016

Other publications

- optics.org (06-Dec-2012)
  - "Gooch & Housego announces the start of work on the HALO project"
- Electro-optics (09-Jan-2013)
  - "HALO project rings in the manufacturing changes"
- Laser Systems Europe; Spring 2013 (printed magazine); Issue 18 p. 6 (01-Mar-2013)
  - "HALO project rings in the manufacturing changes"
- Laser Focus World article (12-May-2015)
  - “HALO project results: Optimized beam profiles for laser machining”
- Fraunhofer ILT press release (12-May-2015)
  - “Searching for the perfect laser beam"
- "The Laser User" AILU magazine Issue 76, p. 17 (01-Jun-2015)
  - "Observations on the cutting efficiency of lasers,"
- Laser Systems Europe (Summer 2015; p. 7) (15-Jun-2015)
  - "HALO project to offer higher quality laser cutting"
- Blech p. 58-61 (Jun-2015)
  - “Der perfekte Laserstrahl”
  - Trade magazine for German sheet metal processing

HALO workshop

A workshop was held on FRI 29-Apr-2016 at the Eurogress (Aachen, Germany) to present the results of the HALO project as part of the AKL 2016 conference and exhibition. This workshop consisted of a set of six technical presentations from the HALO consortium summarising the outcomes from the project, to an expert audience from the laser processing industry.

The attendance was 80-100 people throughout the session, which surpassed expectations.

The slides from the workshop have been made available to the attendees of AKL 2016

[For confidentiality reasons, these are not publically available.]

The agenda was as follows:

08:30 - 08:50	Adaptable Lasers for Cutting Sheet Metal, Glass and Silicon: Project Overview - Simulation and Meta-Modelling *Prof. Wolfgang Schulz, Fraunhofer ILT, Aachen (D)*
08:50 - 09:00	Adaptable Lasers for Cutting Sheet Metal, Glass and Silicon: Novel Adaptable Laser Designs *Prof. Andy Clarkson, ORC - University of Southampton, Southampton (UK)*
09:00 - 09:15	Cutting Brittle Material: Cutting Phenomena and Multi-Spot Techniques *Lara Bauer, TRUMPF Laser GmbH, Schramberg (D)*
09:15 - 09:30	Cutting Brittle Material: 3D Ablation with Liquid-Jet Guided Laser in 5-axis CNC Machines *Dr. Bernold Richerzhagen, SYNOVA S.A., Ecublens (CH)*
09:30 - 09:50	Cutting Sheet Metal: Adapted Polarization Beam Shaping for High-Quality Cutting *Dr. Tobias Häcker, TRUMPF Werkzeugmaschinen GmbH + Co. KG, Ditzingen (D)*
09:50 - 10:00	Cutting Sheet Metal: High-Speed Imaging Analysis of Laser Beam Cutting *Prof. Alexander Kaplan, LTU, Lulea (SE)*

Further information

Please visit the HALO website for further information: www.halo-project.eu

This will be updated with new developments following the project, including new products and further information on related publications and conference presentations.

The website includes presentation and other background material, including:

Project intro video	http://youtu.be/yJjext-HS2U
Project update video	http://youtu.be/K92-dc-xHUg
Project newsletters 1-6	http://halo-project.eu/documents/newsletters/
A list of publications:	http://halo-project.eu/documents/publications/

4.2 Use and dissemination of foreground

A1: List of all scientific (peer reviewed) publications

No.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers (if available)	Is/Will open access provided to this publication?
1	Rapid, electronically controllable transverse mode selection in a multimode fiber laser	J. M. O. Daniel	Optics Express	Vol. 21, Issue 24	Optical Society of America	USA	2013	29442-29448	http://dx.doi.org/10.1364/OE.21.029442	Yes
2	Analysis of laser remote fusion cutting based on a mathematical model	R. S. Matti	Journal of Applied Physics	Vol. 114	AIP Publishing	Online	2013	233107 (1-9)	http://dx.doi.org/10.1063/1.4849895	Yes
3	Controlling the handedness of directly excited Laguerre–Gaussian modes in a solid-state l	Di Lin	Optics Letters	Vol. 39	Optical Society of America	USA	2014	3903-3906	http://dx.doi.org/10.1364/OL.39.003903	Yes
4	Cladding-pumped ytterbium-doped fiber laser with radially polarized output	Di Lin	Optics Letters	Vol. 39	Optical Society of America	USA	2014	5359-5361	http://dx.doi.org/10.1364/OL.39.005359	Yes
5	Analysis of moving surface structures at a laser-induced boiling front	R.S. Matti	Applied Surface Science	Vol. 317	Elsevier	USA	2014	560-567	http://dx.doi.org/10.1016/j.apsusc.2014.08.190	Yes
6	Meta-Modelling Techniques Towards Virtual Production Intelligence	W Schultz	Lecture Notes in Production Enginee	2015	Springer	Switzerland	2015	69-84	http://dx.doi.org/10.1007/978-3-319-12304-2_6	Yes
7	Sensitivity Analysis of Laser Cutting based on Metamodeling Approach	T Khawli	Handbook of Research on Computational Simulation and Modeling in Engineering	Ch. 20	IGI Global	USA	2015	618-639	http://dx.doi.org/10.4018/978-1-4666-8823-0.ch020	Yes
8	The Effect of Laser Type and Power on the Efficiency of Industrial Cutting of Mild and Stainless Steels	Jetro Pocorni	J. Manuf. Sci. Eng	Vol. 138	American Soc. Of Mech. Eng.	USA	2015	031012 (6 page	http://dx.doi.org/10.1115/1.4031190	Yes
9	Polarization-dependent transverse mode selection in an Yb-doped fiber laser	D. Lin	Optics Letters	Vol. 40	Optical Society of America	USA	2015	498-501	http://dx.doi.org/10.1364/OL.40.000498	Yes
10	Local flashing events at the keyhole front in laser welding	Alexander F.H.	Optics and Lasers in Engineering	Vol. 68	Elsevier	USA	2015	35-41	http://dx.doi.org/10.1016/j.optlaseng.2014.12.019	Yes
11	Absorption peaks depending on topology of the keyhole front and wavelength	Alexander F.H.	J. Laser Applications	Vol. 27	AIP Publishing	Online	2015	S29012	http://dx.doi.org/10.2351/1.4906469	Yes
12	Measuring the Melt Flow on the Laser Cut Front	Jetro Pocornia	Physics Procedia	Vol. 78	Elsevier	USA	2015	99-109	http://dx.doi.org/10.1016/j.phpro.2015.11.022	Yes
13	Analyzing and Post-modelling the High Speed Images of a Wavy Laser Induced Boiling Front	R.S. Mattia	Physics Procedia	Vol. 78	Elsevier	USA	2015	192-201	http://dx.doi.org/10.1016/j.phpro.2015.11.043	Yes
14	Post-modelling of images from a laser-induced wavy boiling front	R.S. Mattia	Applied Surface Science	Vol. 357	Elsevier	USA	2015	2277-2284	http://dx.doi.org/10.1016/j.apsusc.2015.09.226	Yes
15	Fibre laser cutting stainless steel:fluid dynamics and cut front morphology	Jetro Pocorni	Optics and Laser Technology	Submitted Mar-2016	Elsevier	USA	N/A	N/A	N/A	Yes
16	Investigation of the piercing process in laser cutting of stainless steel	Jetro Pocorni	Journal of Laser Applications	Submitted May-2016	AIP Publishing	Online	N/A	N/A	N/A	Yes
17	Numerical simulation of laser ablation driven melt waves	Jetro Pocorni	Journal of Applied Physics	To be submitted Jul-2016	AIP Publishing	Online	N/A	N/A	N/A	Yes
18	Transient interaction of a boiling melt with a pulsed Nd:YAG-laser	R.S.M. Samarjy	Optics and Lasers in Engineering	In press 2016	Elsevier	USA	N/A	N/A	N/A	Yes
19	Imaging of the dynamic melt movement induced by a pulsed laser	R.S.M. Samarjy	Physics Procedia	In press 2016	Elsevier	USA	N/A	N/A	N/A	Yes

A2: List of all dissemination activities

No.	Type of activities	Main leader	Title	Date	Place	Type of audience	Countries addressed
1	Other	Vivid	D9.2 HALO project presentation	28-Nov-12	N/A	All	Worldwide
2	Other	Vivid	D9.3 Project fact sheet	30-Nov-12	N/A	All	Worldwide
3	Press release	G&H	D9.1 HALO project start press release	06-Dec-12	N/A	Scientific & industry	Worldwide
4	Magazine	G&H	optics.org article; "Gooch & Housego announces the start of work on the HALO project"; http://optics.org/press/1765	06-Dec-12	Online	Scientific & industry	Worldwide
5	Magazine	G&H	Electro-optics article; "HALO project rings in the manufacturing changes"	09-Jan-13	N/A	Scientific & industry	Worldwide
6	Exhibition	G&H	Photonics West 2013 (booth & representation)	05-Feb-13	San Francisco, USA	Scientific & industry	Worldwide
7	Exhibition	TRU-L	Photonics West 2013 (booth & representation)	05-Feb-13	San Francisco, USA	Scientific & industry	Worldwide
8	Conference	ORC	Photonics West 2013 ORC paper D. Lin, J. M. O. Daniel, W. A. Clarkson, "Single-frequency Nd:YAG laser with LG01 mode	05-Feb-13	San Francisco, USA	Scientific & industry	Worldwide

			output," LASE 2013 (Photonics West), paper 8599-51.				
9	Conference	ILT	Photonics West 2013 TRU-L/ILT paper Simone Russ ; Christof Siebert ; Urs Eppelt ; Claudia Hartmann ; Birgit Faißt ; Wolfgang Schulz "Picosecond laser ablation on transparent materials“ Proc. SPIE Vol. 8608 (86080E) doi:10.1117/12.2001991.	05-Feb-13	San Francisco, USA	Scientific & industry	Worldwide
10	Magazine	G&H	Article in Laser Systems Europe; Spring 2013 (printed magazine) Issue 18 p. 6 "HALO project rings in the manufacturing changes"	01-Mar-13	N/A	Scientific & industry	Worldwide
11	Video	Vivid	D9.4 Project intro video	04-Mar-13	Online	All	Worldwide
12	Workshop	Vivid	Factories of the Future Impact Workshop	11-Mar-13	Brussels, Belgium	Scientific & industry	Europe
13	Exhibition	G&H	Laser World of Photonics 2013 (booth & representation)	13-May-13	Munich, Germany	Scientific & industry	Worldwide
14	Exhibition	TRU-L	Laser World of Photonics 2013 (booth & representation)	13-May-13	Munich, Germany	Scientific & industry	Worldwide

15	Exhibition	ILT	Laser World of Photonics 2013 (booth & representation, including HALO in "Newest achievements from ILT" presentation)	13-May-13	Munich, Germany	Scientific & industry	Worldwide
16	Conference	ORC	CLEO/Europe-IQEC 2013, paper CA-10.2 D. Lin, J.M.O. Daniel, and W.A. Clarkson, Controlling the handedness of directly excited Laguerre Gaussian modes in a solid-state laser	13-May-13	Munich, Germany	Scientific & industry	Worldwide
17	Conference	ILT	Laser World of Photonics 2013, ILT Presentation in "Lasers and laser systems for Production" congress "Towards high-quality laser cutting of glass: Simulation and Diagnosis of ultra-short pulse ablation"	13-May-13	Munich, Germany	Scientific & industry	Worldwide
18	Conference	ILT	Laser World of Photonics 2013, ILT "Process Diagnosis with High Speed Camera"	13-May-13	Munich, Germany	Scientific & industry	Worldwide
19	Flyers	Vivid	2000 HALO double-sided glossy A5 flyers: copies sent to	14-May-13	N/A	All	Worldwide

			all partners.				
20	Other	Vivid	D9.6 Project newsletter 1	22-May-13	Online	Scientific & industry	Worldwide
21	Other	ILT	Wolfgang Schulz and Lisa Bürgermeister teaching award (RWTH), especially lecture and exercise "Modelling, Model Reduction and Simulation in Laser Processing" (which included HALO work)	11-Jun-13	Aachen, Germany	Scientific & industry	Germany
22	Conference	ILT	14th Nordic Laser Materials Processing Conference NOLAMP 14 (tabletop)	26-Aug-13	Gothenburg, Sweden	Scientific & industry	Nordic
23	Conference	ILT	14th Nordic Laser Materials Processing Conference NOLAMP 14; ILT paper, "Measuring the State-of-the-Art in Laser Cut Quality"	26-Aug-13	Gothenburg, Sweden	Scientific & industry	Nordic
24	Conference	LTU	14th Nordic Laser Materials Processing Conference NOLAMP 14 LTU paper Matti, R.S., T. Ilar and A. F. H. Kaplan Modelling the cutting geometry for laser remote fusion cutting	26-Aug-13	Gothenburg, Sweden	Scientific & industry	Nordic

			of metals				
25	Presentation	ILT	HALO presentation at International Institute of Welding annual meeting	11-Sep-13	Essen, Germany	Scientific & industry	Worldwide
26	Other	Vivid	Newsletter 2 sent to RSS list & online	25-Oct-13	N/A	Scientific & industry	Worldwide
27	Exhibition	Vivid	ICT 2013 "Create, Connect, Grow" HALO pop-up banner and leaflets distributed (ISLA booth)	06-Nov-13	Vilnius, Lithuania	Scientific & industry	Europe
28	Workshop	TRU-L	Workshop “Laserbearbeitung von Glaswerkstoffen”; TRU-L presented HALO work on glass cutting using picosecond lasers	26-Nov-13	Hannover, Germany	Scientific & industry	Germany
29	Workshop	G&H	Power beam delivery and manipulation workshop; HALO tabletop	03-Dec-13	Cambridge, UK	Scientific & industry	UK
30	Other	Vivid	Updated HALO_VIV_013_C_WP9 D9.2 Project presentation	28-Jan-14	Online	Scientific & industry	Worldwide
31	Exhibition	G&H	Photonics West 2014; booth &	04-Feb-14	San Francisco, USA	Scientific	Worldwide

			flyers			& industry	
32	Exhibition	TRU-L	Photonics West 2014; booth & flyers	04-Feb-14	San Francisco, USA	Scientific & industry	Worldwide
33	Conference	TRU-L	TRU paper at Photonics West 2014 Frontiers in Ultrafast Optics: Biomedical, Scientific, and Industrial Applications XIV; Glass and Thin Film Processing: Paper 8972-40 "Comparison of different processes for separation of glass and crystals using ultra short pulsed lasers"	04-Feb-14	San Francisco, USA	Scientific & industry	Worldwide
34	Exhibition	Vivid	FiSC/ International Laser Symposium 2014 (joint tabletop with ISLA project)	27-Feb-14	Dresden, Germany	Scientific & industry	Worldwide
35	Newsletter	Vivid	Newsletter 3 (D9.12) sent to distribution list and put online	07-Mar-14	N/A	Scientific & industry	Worldwide
36	Workshop	G&H	Presentation at FoF Impact Workshop	24-Mar-14	Brussels, Belgium	Scientific & industry	Europe
37	Conference	Vivid	Photonics Europe 2014; tabletop exhibition space	14-Apr-14	Brussels, Belgium	Scientific & industry	Europe
38	Conference	ILT	ILT presentation at AKL 2014 International Laser Technology	07-May-14	Aachen, Germany	Scientific & industry	Worldwide

			Congress				
39	Conference	ORC	Conference on Lasers and Electro-Optics (CLEO) "Direct generation of radially-polarized output from an Yb-doped fiber laser" D. Lin, J. M. O. Daniel, M. Gecevičius, M. Beresna, P. G. Kazansky, W. A. Clarkson,	08-16 Jun-2014	San Jose, USA	Scientific & industry	Worldwide
40	Workshop	ILT	SCHOTT Expert Panel Laser Processing of Glass – Practical Aspects and Simulation 6 experts were invited, including Wolfgang Schulz (ILT)	18-Jun-14	Mainz, Germany	Scientific & industry	Europe
41	Workshop	ILT	SCHOTT Expert Panel Laser Processing of Glass – Practical Aspects and Simulation Invited talk: "Simulation and Diagnosis of ultra-short pulse ablation," W. Schulz (ILT).	18-Jun-14	Mainz, Germany	Scientific & industry	Europe
42	Conference	G&H	Optical Fabrication and Testing (OF&T) [Part of the OSA Classical Optics Congress 2014.] Peter MacKay: invited to give	22-Jun-14	Hawaii, USA	Scientific & industry	Worldwide

			extended presentation (30 min) on "Segmented Waveplate Polarisation Control for Laser Cutting"				
43	Exhibition	TRU-L	LASYS International Trade Fair for Laser Material Processing-Exhibition stand	24-Jun-14	Stuttgart, Germany	Scientific & industry	Worldwide
44	Exhibition	ILT	LASYS International Trade Fair for Laser Material Processing-Wolfgang Schulz part of Expert Forum on "Lasers in Action"	24-Jun-14	Stuttgart, Germany	Scientific & industry	Worldwide
45	Conference	TRU-L	Stuttgart Laser Technology Forum 2014 (SLT14) TRU-L presentation "Analysing the influence of pulse duration on the glass cutting process"	24-Jun-14	Stuttgart, Germany	Scientific & industry	Worldwide
46	Conference	ILT	Stuttgart Laser Technology Forum 2014 (SLT14) Invited talk: "Simulation of Glass Cutting"; W. Schulz ILT	24-Jun-14	Stuttgart, Germany	Scientific & industry	Worldwide
47	Conference	LTU	IIW Congress 2014 LTU paper: Kaplan, A. F. H. Interaction of the beam with the wavy keyhole front in laser welding	13-Jul-14	Seoul, S. Korea	Scientific & industry	Worldwide

48	Conference	ORC	Europhoton 2014 6th EPS-QEOD Europhoton Conference Efficient conversion to radial polarization in the two-micron band using a continuously space-variant half-waveplate Paper WeD-T2-O-06	24-Aug-14	Neuchatel, Switzerland	Scientific & industry	Worldwide
49	Conference	ORC	Europhoton 2014 6th EPS-QEOD Europhoton Conference High power radially-polarized Yb-doped fiber laser Paper ThA-T2-O-05	24-Aug-14	Neuchatel, Switzerland	Scientific & industry	Worldwide
50	Conference	ILT	Metamodeling of Laser Cutting U. Eppelt, T. Al-Khawli. ICNAAM - 12th International Conference of Numerical Analysis and Applied Mathematics	22-Sep-14	Rhodes, Greece	Scientific & industry	Worldwide
51	Conference	ILT	ICALEO 2014; International Congress on Applications of Lasers & Electro-Optics "Differences in cutting efficiency between CO2 and fiber lasers when cutting mild and stainless steels," covering work from LTU, Laser	19-Oct-14	San Diego, USA	Scientific & industry	Worldwide

			Expertise and Fraunhofer ILT.				
52	Conference	LTU	ICALEO 2014; International Congress on Applications of Lasers & Electro-Optics LTU paper Kaplan, A. F. H and R. S. Matti Absorption peaks depending on topology of the keyhole and wavelength	19-Oct-14	San Diego, USA	Scientific & industry	Worldwide
53	Conference	Synova	ICALEO 2014; International Congress on Applications of Lasers & Electro-Optics "Laser Microjet© cutting of up to 3 mm thick sapphire"	19-Oct-14	San Diego, USA	Scientific & industry	Worldwide
54	Conference	LTU	ICALEO 2014 2nd Place Winner Student Paper Award Contest	19-Oct-15	San Diego, USA	Scientific & industry	Worldwide
55	Workshop	G&H	CEOI Space Technology Showcase Peter MacKay presentation on HALO Hyper Bond components	13-Nov-14	London, UK	Scientific & industry	Europe
56	Video	Vivid	Second video (D9.15) online	26-Jan-15	Online	Scientific	Worldwide

						& industry	
57	Workshop	G&H	Impact of the Factories of the Future PPP Workshop	29-Apr-15	Brussels, Belgium	Scientific & industry	Europe
58	Press article	ILT	Laser Focus World article HALO project results: Optimized beam profiles for laser machining	12-May-15	Online	Scientific & industry	Worldwide
59	Press release	ILT	"Searching for the perfect laser beam" Fraunhofer ILT press release	12-May-15	Online	Scientific & industry	Worldwide
60	Conference	ORC	Conference on Lasers and Electro-Optics (CLEO) "Cladding-pumped Yb-doped fiber laser with vortex output beam," D. Lin, W. A. Clarkson	10-15 May-2015	San Jose, USA	Scientific & industry	Worldwide
61	Press	LEL	Article in "The Laser User" AILU magazine "Observations on the cutting efficiency of lasers," Issue 76, p. 17 (Spring 2015)	01-Jun-15	N/A	Industry	UK
62	Press	ILT	Article on HALO in Laser Systems Europe (Summer 2015; p. 7) "HALO project to offer higher quality laser cutting"	15-Jun-15	Online	Industry	Europe

63	Conference	ILT	Prof. Wolfgang Schulz (ILT) presentation "HALO–Real Time Adjustment of Laserbeam Properties for Optimum Process Results" Part of "European Research on Laser Based Technologies" Forum	25-29 Jun-2015	Munich, Germany	Scientific & industry	Worldwide
64	Exhibition	ILT	Live demo of metamodelling GUI at Laser WoP	25-29 Jun-2015	Munich, Germany	Scientific & industry	Worldwide
65	Conference	ORC	CLEO Europe paper: part of Photonics Congress Simple Technique for High-Order Ring-Mode Selection within Solid-State Laser Resonators; CA-7.5 MON	25-29 Jun-2015	Munich, Germany	Scientific & industry	Worldwide
66	Conference	ORC	CLEO Europe poster: part of Photonics Congress Tm-doped fibre laser with radially-polarized output beam at 2 um; CJ P.10	25-29 Jun-2015	Munich, Germany	Scientific & industry	Worldwide
67	Conference	ORC	CLEO Europe poster: part of Photonics Congress High Power Spectrally-Tailorable Thulium-Doped Fibre Amplified Spontaneous Emission Source; CJ P.30	25-29 Jun-2015	Munich, Germany	Scientific & industry	Worldwide

68	Conference	TRU-L	"Influence of Pulse Duration on the Glass Cutting Process" Accepted at LiM2015 http://www.wlt.de/lim/ Lasers in Manufacturing: part of Photonics Congress	25-29 Jun-2015	Munich, Germany	Scientific & industry	Worldwide
69	Conference	LTU	Lasers in Manufacturing (LiM); part of Laser World of Photonics Matti, R. S. and A. F. H. Kaplan Basic imaging and modelling analysis of the processing front in laser remote fusion cutting,	25-29 Jun-2015	Munich, Germany	Scientific & industry	Worldwide
70	Conference	LTU	Jetro Pocorni paper NOLAMP 2015 Measuring the melt flow on the laser cut front	25-27 Aug-2015	Lapeenranta, Finland	Scientific & industry	Nordic
71	Conference	LTU	Ramiz Matti paper NOLAMP 2015 Analyzing and post-modelling the high speed images of a wavy laser- induced boiling front	25-27 Aug-2015	Lapeenranta, Finland	Scientific & industry	Nordic
72	Conference	ILT	ICNAAM 2015; Wolfgang Schulz "An integrated approach for the knowledge extraction in	23-29 Sep-2015	Rhodes, Greece	Scientific & industry	Worldwide

			computer simulation models with a multidimensional parameter space”				
73	Conference	ORC	Advanced Solid-State Lasers conference “Cladding-pumped radially-polarized fiber Lasers” W. A. Clarkson, D. Lin, , M. Beresna, P. G. Kazansky, P. Shardlow Paper AW2A.4 (Invited Paper).	04-09 Oct-2015	Berlin, Germany	Scientific & industry	Worldwide
74	Workshop	LEL	John Powell presentation on adaptable beams AILU Annual Job Shop Meeting	14-Oct-15	Worcester, UK	Industry	UK
75	Press	Vivid	Article in "Blech" Trade magazine for German sheet metal processing; p. 58-61 (Jun-2015) Der perfekte Laserstrahl	05-Nov-15	Online	Industry	D
76	Conference	ILT	Mittweider Lasertagung 2015 „Meta-Modelling and Visualization of multi-dimensional Data” „Meta-Modellierung und Darstellung Höherdimensionaler Daten“	19-20 Nov-2015	Mittweida, Germany	Scientific & industry	Worldwide

77	Conference	ILT	Plenary address (Dirk Petring) 84th Meeting of the Japanese Laser Processing Society "Virtual laser cutting simulation for real process parameter optimization"	19-Jan-16	Nagoya, Japan	Scientific & industry	Japan
78	Exhibition	Vivid	Fraunhofer IWS Laser Symposium 2016 HALO booth	23-24 Feb-2016	Dresden, Germany	Scientific & industry	Worldwide
79	Conference	ILT	Fraunhofer IWS Laser Symposium “Meta-Modelling towards virtual production engineering” “Meta-Modellierung als Werkzeug für die virtuelle Produktion”	23-24 Feb-2016	Dresden, Germany	Scientific & industry	Worldwide
80	Conference	ORC	LASE conference at Photonics West 2016 “Donut beam generation in a hybrid fiber laser pumped Ho:YAH laser” A. C. Butler, P. C. Shardlow, R. T. Uren, W. A. Clarkson Paper 9726-61	13-18 Feb-2016	San Francisco, USA	Scientific & industry	Worldwide

81	Conference	TRU-L	Paper presented at PW2016 Ultrafast laser ablation on transparent materials Lara Bauer ; Simone Russ ; Myriam Kaiser ; Malte Kumkar ; Birgit Faißt ; Rudolf Weber ; Thomas Graf Proc. SPIE 9735, 97350X (doi:10.1117/12.2212449)	13-18 Feb-2016	San Francisco, USA	Scientific & industry	Worldwide
82	Conference	Vivid	Presentation at SPIE Photonics Europe 2016 Part of "Advanced Manufacturing and Photonics for Production"	05-Apr-16	Brussels, Belgium	Scientific & industry	Worldwide
83	Exhibition	Vivid	Booth at SPIE Photonics Europe 2016 Part of "Photonics Innovation Village"	05-Apr-16	Brussels, Belgium	Scientific & industry	Worldwide
84	Exhibition	Vivid	AKL 2016 HALO booth at "Laser Technik Live" exhibition	29-Apr-16	Aachen, Germany	Scientific & industry	Worldwide
85	Conference	ILT	AKL 2016- HALO session Adaptable Lasers for Cutting Sheet Metal, Glass and Silicon: Project Overview - Simulation and Meta-Modelling	29-Apr-16	Aachen, Germany	Scientific & industry	Worldwide

86	Conference	ORC	AKL 2016- HALO session Novel Adaptable Laser Designs	29-Apr-16	Aachen, Germany	Scientific & industry	Worldwide
87	Conference	TRU-L	AKL 2016- HALO session Cutting Brittle Material: Cutting Phenomena and Multi-Spot Techniques	29-Apr-16	Aachen, Germany	Scientific & industry	Worldwide
88	Conference	Synova	AKL 2016- HALO session Cutting Brittle Material: 3D Ablation with Liquid-Jet Guided Laser in 5-axis CNC Machines	29-Apr-16	Aachen, Germany	Scientific & industry	Worldwide
89	Conference	TRU-W	AKL 2016- HALO session Cutting Sheet Metal: Adapted Polarization Beam Shaping for High-Quality Cutting	29-Apr-16	Aachen, Germany	Scientific & industry	Worldwide
90	Conference	LTU	AKL 2016- HALO session Cutting Sheet Metal: High-Speed Imaging Analysis of Laser Beam Cutting	29-Apr-16	Aachen, Germany	Scientific & industry	Worldwide
91	Conference	ORC	Conference on Lasers and Electro-Optics (CLEO:2016) “Reduced thermal lensing in an end-pumped Nd:YVO4 laser using a ring-shaped pump beam” D. Lin; W. A. Clarkson	05-10 Jun-2016	San Jose, USA	Scientific & industry	Worldwide

			Paper SM3M.5				
92	Conference	ORC	Conference on Lasers and Electro-Optics (CLEO:2016) "High Power Fiber Lasers with Radially Polarized Output Beams" W. Andrew Clarkson; Di Lin; Martynas Beresna; Peter G. Kazansky; Peter C. Shardlow Paper SM4Q.1 (Invited Paper).	05-10 Jun-2016	San Jose, USA	Scientific & industry	Worldwide
93	Conference	ORC	Conference on Lasers and Electro-Optics (CLEO:2016) "Handedness of Laguerre-Gaussian LG01 Mode in a Unidirectional Ring Laser" Robin T. Uren; W. Andrew Clarkson Paper STu1M.6.	05-10 Jun-2016	San Jose, USA	Scientific & industry	Worldwide
94	Conference	TRU-W	T. Hesse, T. Häcker. Status and prospects in 2D laser cutting International Symposium on High Power Laser Systems and Applications	05-09 Sep-2016	Gmunden, Austria	Scientific & industry	Worldwide

95	Conference	LTU	LANE 2016 (9th Int. Conf. on Photonic Technologies) Imaging of the dynamic melt movement induced by a pulsed laser R.S.M. Samarjy & A.F.H. Kaplan	19-22 Sep-2016	Fuerth, Germany	Scientific & industry	Worldwide
96	Conference	LTU	ICALEO 2016 Investigation of the piercing process in laser cutting of stainless steel Jetro Pocorni, John Powell, Jan Frostevarg, Alexander F.H. Kaplan	16-20 Oct-2016	San Diego, USA	Scientific & industry	Worldwide