Institution: University of Hull	
Unit of Assessment: 9 - Physics	
Title of case study: Laser and process development for manufacturing applications	
Period when the underpinning research was undertaken: January 2000 to present	

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Dr Howard V Snelling	Lecturer	June 2001 – present
Prof Peter E Dyer	Emeritus Professor	1978 – 2010, then emeritus

Period when the claimed impact occurred: 2013 - ongoing

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

By taking a functional physics approach whereby the generation of knowledge of laser physics and light-matter interactions is applied to problems identified by industrial partners, we have enabled the launch of a new laser system, generated novel laser-based processes and diagnostics, and produced a high-quality workforce that supports the UK laser industry. Specifically, our research partnership with Luxinar Ltd has enabled the launch of their ultrashort pulse, high average power, laser and it has taken them into new markets - helping them maintain a specialised workforce of 160 and a turnover of £40m. Working with The Welding Institute, we have contributed to the reduction of the need for digital displays that use the rare element indium (identified as an "at risk" material by the EU). Equally, by developing fume sampling techniques for laser processes, we have increased the capability of BOFA Ltd to address workplace safety. Lastly, we have generated a talent-pipeline that transitions alumni of the group into laser-based industries, which supports the UK National Strategy for Laser-based Manufacturing. Our longstanding cooperation with laser companies in our region also underpins the UK's capacity in this key industry in the North East of England.

2. Underpinning research

The Hull Laser Group (HLG) has a long history and built its first laser in 1965. At that time, the research emphasis focused on the early development of laser devices and the Hull group accumulated a series of key breakthroughs - including the world record for the generation of the shortest laser wavelength. Laser manufacturing companies spun out of these early research activities and the university began a sustained relationship with industrial partners in this field. The activities of the group shifted to encompass laser applications by the mid-1980s whereby the applied physics expertise of the Hull academics was focussed on understanding the interaction of light with materials. Our three current research areas that underpin the impact case are: (2.1) non-linear processes with ultra-short laser pulses, (2.2) laser irradiance regimes for glass processing, and (2.3) non-reciprocity in laser irradiation of polymers.

2.1 Non-linear processes with ultra-short laser pulses

Innovations in laser design have continued throughout the group's history and our focus has evolved from predominantly gas laser research to solid state sources [1]. The sub nanosecond nature of this solid-state laser naturally lead to studies of even shorter pulse interactions in the femtosecond regime [2]. Utilising non-linear, two-photon, absorption allowed laser light to couple with normally transparent materials. In the case of reference [2], this was a cancer treatment drug and greater penetration into the tumour could be achieved using this novel process. Utilising this mechanism in other transparent materials also generates laser-induced absorption and dielectric breakdown. In this way, crack free machining of "difficult" glasses was achieved [3].

2.2 Laser irradiance regimes for glass processing

Increased use of chemically toughened glasses in displays (e.g., “Gorilla glass” in tablets and mobile phones) together with a need for ever more complex geometries (e.g., display formats and holes for sensors) is challenging traditional glass machining techniques. Earlier pioneering work from Hull Laser Group laid out the principles of laser-induced cracking in glasses. Utilising this knowledge in the current REF period, we have shown that ultrashort pulses can avoid micro crazing and produce defect free features [3]. Surface forming poses a further problem if optical quality finishes are required. We have studied the effect of high laser intensities in producing colour centres in glass and the concomitant change in chemical reactivity. Utilising a hybrid laser-chemical procedure, we have enabled surface figuring suitable for novel, Laplacian, optical elements [4].

2.3 Non-reciprocity in laser irradiation of polymers

Many digital displays rely upon indium tin oxide, but the use of indium represents a risk factor for steady supply due to its scarcity. The display and photovoltaic industries can be made more resilient to this risk by developing indium-free alternatives. The current candidate materials require heat treatment to increase their conductivity, but this then precludes the use of temperature sensitive substrates such as polymers for flexible electronics and low-cost photovoltaics. However, rapid laser heating on timescales shorter than the rate of decomposition allows the survival of these materials at higher temperatures. Using our understanding of laser-polymer interactions [5] we have developed a laser-based process that localises the heating in space and time to enable the use of plastic substrates in devices [6].

3. References to the research

1. S Pearce, C L M Ireland, **P E Dyer**, Solid-state Raman laser generating <1 ns, multi-kilohertz pulses at 1096 nm, Optics Communications, 260, 680-686 (2006), doi:10.1016/j.optcom.2005.11.033

2. M Atif, **P E Dyer**, T A Paget, **H V Snelling**, M R Stringer, Two-photon excitation studies of m-THPC photosensitizer and photodynamic activity in an epithelial cell line, Photodiagnosis and Photodynamic Therapy, 4, 106-111 (2007), doi:10.1016/j.pdpdt.2006.10.004

3. D M Karnakis, M R H Knowles, K T Alty, M Schlaf, **H V Snelling**, Comparison of glass processing using high repetition femtosecond (800nm) and UV (255nm) nanosecond pulsed lasers, Progress in Biomedical Optics and Imaging - Proceedings of SPIE, 5718, art. no. 32, pp. 216-227 (2005), doi: 10.1117/12.588194

4. A A Serkov and **H V Snelling**, Enhanced chemical etch rate of borosilicate glass via spatially resolved laser-generated color centers, J. Phys. D: Appl. Phys. 53, 135306 (2020), doi: 10.1088/1361-6463/ab6515

5. A L Marchant, **H V Snelling**, Reciprocity in long pulse duration laser interactions with polymers, J.Phys D: Applied Physics, 45, 215402 (2012), doi:10.1088/0022-3727/45/21/215402

6. A A Serkov, **H V Snelling**, S Heusing, and T Martins Amaral, Laser sintering of gravure printed indium tin oxide films on polyethylene terephthalate for flexible electronics, Nature: Scientific Reports 9:1773 (2019), doi: 10.1038/s41598-018-38043-y

Dr Snelling has been awarded research grants that total £936,895 as PI in the last five years, and an additional £557,547as CI (totalling **£1,494,442**). The majority of this work has involved industrial collaborations. The list below displays grants relevant to the impact described here.

- Leverhulme Trust, Laplacian Magic Windows, RPG-2016-181, Sept 2016–Feb 2019, **H V Snelling** (PI), M V Berry (Bristol) & D Jesson (Cardiff), £123,828.
- Luxinar Ltd., High precision picosecond laser machining centre, April 2016–June 2020, **H V Snelling** (PI), £120,000.
- EPSRC–CIM-Laser, Scoping studies for new laser interaction regimes, EP/K030884/1, April 2016-Oct 2016, **H V Snelling** (PI), **P E Dyer** & J Lee (Luxinar Ltd), £45,336.
- EU-H2020, Indium free innovative technology, INFINITY 641927, Dec 2014 – April 2018 **H V Snelling** (PI) & C D Walton, £515,896.

- Purex International Ltd., Small scale electrostatic precipitator, Sept 2011–Sept 2012, **H V Snelling** (PI), £20,322.
- Purex International Ltd., Fume from laser cutting of CFRP, Oct 2010–Sept 2013, **H V Snelling** (PI), £8,784.
- KTP–Innovate UK, Fume analysis, August 2009–Feb 2012, H V Snelling (Knowledge based Supervisor) & S M Kelly, £146,360.
- EPSRC–IeMRC, Laser Patterning of Thin-Films, Sept 2005–June 2006, **H V Snelling** (PI), £20,377.

4. Details of the impact

The research impact in this REF period has (4.1) enabled the launch of a new laser system, (4.2) generated novel laser-based processes and diagnostics, and (4.3) produced a high-quality workforce that supports the regional and wider UK laser industry. This research impact helps laser companies to remain financially viable in a harsh, competitive market, and, in time, to develop their market share and proliferation. Our impact is also manifest through the development and retention of long-term research-relationships with high profile companies that specialise in laser-based technologies and their applications.

4.1 New product launch for Luxinar Ltd.

Our research and development work with Luxinar Ltd emerges from longstanding relationships and collaboration with the company and its core employees through their evolution from Laser Applications Ltd, to Lumonics, to Coherent (Hull), and to Rofin-Sinar [A]. This relationship has spanned 40 years of laser development and our more recent laser-material interaction research. It enabled Luxinar to maintain and grow its market share in a very competitive industry. The benefits of this collaboration led to the construction of a joint University of Hull / Luxinar Laser Applications Laboratory in January 2017 (with investment of around £350,000, including £120,000 and the loan of a £140,000 laser from Luxinar, and £50,000 from the University). This development allowed Luxinar to move beyond gas laser manufacturing to produce a portfolio of solid-sate ultrashort pulse lasers. These lasers offer higher pulse repetition rates, at shorter pulse durations and higher average power than is currently available in a system suitable for industrial deployment. Specifically, the collaboration has facilitated the development of the new LXR100 product [B], launched in February 2020. The digital display industry is a major target for the applications of this laser. By modelling the laser interaction with glass, the University was able to define the required specifications for this laser as part of its design process. This ensured that the research and development investment of Luxinar was focussed successfully on developing a device with the correct characteristics to succeed in a specific, target market.

The technology and innovation director at Luxinar explains [A]:

> *"Luxinar has invested £3.4m, with the aim to recoup our investment by 2023. The collaboration with Hull aided both the generation of the required specification whilst contributing technical know-how and insights into the development process."*

Furthermore, the University/Luxinar Joint Applications Laboratory now provides the capability for the company to optimise the software control to fulfil specific customer requirements in real world scenarios. This is essential in a competitive market and Luxinar's continued success supports its £40m turnover and 160 highly-skilled employees. Luxinar's director agrees:

> *"…the ability to collaborate with the laser group at the University of Hull has complimented and enhanced our technical capability thereby ensuring greater resilience and helping secure high value photonics manufacturing within the UK."* [A]

4.2 Laser applications and safety

The UK Roadmap for Laser-based Manufacturing, published by the EPSRC CIM-LbPP and the Association of Industrial Laser Users, calls for an increase in the use of lasers to enable the UK to compete internationally. The Hull Laser Group underpins this roadmap through our interactions with our industrial partners and, in this way, the importance of our work continues to develop.

Dr Snelling was invited by The Welding Institute (TWI) to lead the laser interaction work for the H2020 Indium Free Novel Technology (Infinity) programme. This project required heat treatment of thin film compounds already formulated by TWI, whilst not compromising the integrity of a polymer substrate suitable for flexible electronics. The HLG has a wide range of laser sources that cover wavelengths from the vacuum ultraviolet to the far infrared, and pulse durations from milliseconds to femtoseconds. This facility, unavailable elsewhere in the UK, allowed the HLG to study the physics of the laser interaction, and to define appropriate laser characteristics (rather than reformulating the chemistry to match a preselected laser source). The success of the Infinity programme in developing such a tailored laser process has reduced the need for indium in display and photovoltaic devices. Studying the physics of the interaction of light with matter (rather than preselecting a laser for the process) is a defining feature of how the Hull Laser Group works. This was recognised by the TWI Manager – New Business Streams, who wrote:

> *"Engagement between this group and TWI has demonstrably enabled industrial challenges to be successfully addressed in a far more rapid and satisfactory manner than would otherwise have been achieved."* [C]

The HLG has paid sustained attention to the fume hazard associated with laser processing of materials. This research interest dates back to the first EU programme on laser safety in the 1990s. More recently, a 2009 Knowledge Transfer Partnership on the filtration of laser-generated gases and particulates was undertaken with Purex International Ltd. This successful project, together with outputs from the H2020 Infinity work package on fume, brought our research to the attention of BOFA International Ltd (fume and dust extraction leaders) and generated our current research collaboration with them on fume capture devices. We have used the fume collection techniques and analysis protocols that we have developed to jointly produce an in-factory, laser-produced fume sampling system. The research and development manager at BOFA says:

> *"It affords us the unique position of being able to offer testing of laser installations, and from it ensure the correct specification of extractor is used in order to ensure compliance with ever tightening emission regulations."* [D]

The international scale of BOFA's business and the global reach of their products ensures that our research impact will improve the safety of many other industries such as canning, packaging, soldering, and clothing. BOFA consider that working with Hull has:

> *"…embedded knowledge of the sampling and testing process into the* company and opened new areas of investigation. *We learned about analytical techniques and processes that were previously not part of our toolkit. In this way, the collaboration transformed the way that our company considers laser-generated fume.*" [D]

4.3 Talent pipeline

As identified by the UK national strategy for laser-based manufacturing, the UK lags other manufacturing nations in the wider industrial uptake of laser technologies. This deficiency cannot be addressed without an appropriately trained and skilled workforce. The wider range of laser systems researched at Hull (compared to the more limited range used at some institutions), together with our decades of collaboration with laser-based industries, puts HLG in a unique position to equip students with the skills and experiences that are tailored to the needs of industrial employers. This capacity was formalised in the EPSRC-funded Laser Applications in Micro-machining and Processing (LAMP) MSc that ran from 2001 to 2007 and was then incorporated into MPhys final year modules. The technology and innovation director of Luxinar Ltd says of his team trained at Hull, that:

> *"The skills and knowledge they have learned from Hull's laser research have greatly contributed to our product and process development."* [A]

North-Eastern England is a region with proportionately few high-tech laser manufacturers and a relatively weak socio-economic profile. In this context, our undergraduates and research students underpin recruitment to local high-technology companies and reinforce the region's development. Quoting Luxinar again:

> *"Attracting high quality graduates and postgraduates with the necessary skills and knowledge into the Humber region has been extremely challenging for a number of years. Therefore, having a local educational establishment of the quality of the University of Hull has been pivotal to our success."* [A]

Equally, alumni of the HLG are currently deploying their laser-related expertise at companies and institutions around the UK and abroad [E]. In summary, our talent pipeline in laser technologies has underpinned industries regionally and nationally. The sustainable relationships we have built over the past decades make us confident that the impact described here will grow further and contribute additionally to the UK's laser expertise.

5. Sources to corroborate the impact

[A] Testimonial letter, Technology and Innovation Director, Luxinar Ltd, 13/1/21

[B] LXR 100 – 100W femtosecond laser source, Luxinar Ltd. https://archive.vn/yXITp

[C] Testimonial letter, Manager - New Business Streams, The Welding Institute, 15/2/21

[D] Testimonial letter, Research and Development Manager, Bofa International Ltd, 18/1/21

[E] Examples of companies where alumni have current laser-related jobs: AWE, FORTH Institute (Greece), GFH GmbH (Germany), HELL Gravure Systems (Germany), Luxinar, Manchester University, OpTek Systems, Oxford Lasers, Powerlase Ltd & TWI, PragmatiC, Schott Minifab (Australia), Winbro Advanced Machining.