Institution: Heriot-Watt University

Unit of Assessment: 9 Physics

a. Overview

Physics at Heriot-Watt University (HWU) has always produced outstanding pure and applied research in photonics and light-matter interactions in the areas of quantum information, quantum physics, condensed matter physics, optical physics, advanced imaging, and ultrafast photonics, with substantial links into engineering, chemistry and life sciences. Collectively, notable success has been achieved since RAE2008 with publications in Science/Nature-Stable/Physical Review Letters up 62% and annual grant income/FTE up by 61%. Major new grants include two European Research Council Starting Grants, the renewal of a successful EPSRC Platform Grant, an EPSRC Challenging Engineering Award, and a new EPSRC Interdisciplinary Research Centre for in-vivo imaging technologies. Research and innovation spanning applied product development in, for example, fibre optic sensing and laser materials processing sit alongside research at the frontiers of quantum information and device physics.

A new interdisciplinary approach to research across HWU provides an effective structure for addressing research challenges across traditional discipline boundaries. This has seen the evolution of the former Department of Physics, (as a widely acknowledged early pioneer in lasers and photonics in the UK since the 1970's), into research-focused institutes within the School of Engineering and Physical Sciences. In 2012, photonics researchers created a single research institute - the Institute for Photonics and Quantum Sciences (IPaQS) while at the same time, a major strategic investment in both staff and infrastructure focussed at the Physical Science/Life Science interface coalesced into another new research institute, the Institute of Biological Chemistry, Biophysics and Bio-engineering (IB3). With 32 academic staff members, IPaQS has sufficient critical mass to deliver sustained academic and societal impact in photonics and quantum sciences. 19 IPaQS staff are submitted here to UoA9 Physics while the research of 12 of the most applied IPaQS staff have been submitted to UoA15 General Engineering and 1 to UoA8 Chemistry. IB3 comprises 15 established researchers with 3 whose physics research is key to novel bio-imaging activities and who are included in UoA9. Physics plays a key role in providing the unique breadth of IPaQS and IB3 research and contributes to a stimulating environment supportive of energetic researchers and graduate students.

b. Research strategy

Heriot-Watt University's collective vision is to be world-leading within all its specialist areas of science, technology, engineering and business while remaining true to its heritage of creating and exchanging knowledge for the benefit of society (as detailed in the REF3 documents). Our record shows that our research and teaching are always relevant to societal needs and we produce graduate researchers who have a distinctive and strong professional orientation. To deliver on this shared Institutional ambition, physics research has:

- Invested in and supported the most promising early-career physics researchers (e.g. £800k spent upgrading laboratory space for new appointments made in period);
- Supported our existing and emerging research leaders in developing and maintaining research excellence (e.g. the Heriot-Watt Crucible staff development programme);
- Increased the number and quality of research students commensurate with an expanded research landscape (e.g. through the James Watt PhD scholarships ~6 per annum);
- Promoted interdisciplinary fields of research, emphasizing economic and societal benefit in order to generate high-impact outputs and attract significant research funding thereby maintaining critical mass and coverage (e.g. through the establishment of IB3 and resulting collaborations);
- Fostered new strategic collaborations through national and international academic and industrial research alliances (e.g. the Scottish Universities Physics Alliance (SUPA) and with the Atomic Weapons Establishment (AWE), Renishaw and Selex ES);

- Supported entrepreneurship and innovation in the creation and exploitation of new enterprises (e.g. through the Converge Challenge competition).

Strategic developments anticipated in our RAE2008 submission have been delivered. Specifically:

- *"Make staff and equipment investment in the area of nanofabrication"*: Investments totalling over £2M in nanofabrication facilities have been made (see section d below) Two new Lectureship appointments, Ferrera (integrated photonics and plasmonics) & Chen (nano-optics and metamaterials) as well as a chair appointment for Pollnau further expanded the nanophysics activity.

- *"Development of a broad programme in bio-physics research"*: This ambition has been realised far beyond what was envisioned with the inception of a complete new research Institute, the Institute of Biological Chemistry, Biophysics and Bioengineering (IB3) with six new appointments. Three physics staff (Greenaway, Lu, Dalgarno), are now primarily active in bio-imaging and have obtained major funding awards in support of their research (details below).

- *"Foster greater linkage of our theoretical strength with experiments in atomic, molecular and condensed matter physics"**:*** New theory/experiment collaborations have been nurtured leading to high profile papers in Nature, Science and PRL – Galbraith (Nature Comms. with Surrey), Andersson & Buller (Nature Physics & Nature Comms. with Glasgow & Strathclyde), Andersson (PRL with Max Planck, Erlangen), Öhberg with Gerardot (Nature), Biancalana (Science paper with Max Planck, Erlangen). New appointee, Hartmann, (supported by the Emmy Noether programme) whose activities include quantum dynamics of mechanical systems, also supports this strategic objective.

- "*Appoint key new staff in laser-based physics & 'solid-state routes to single photons"*: Strategic Alliance partners Selex-ES have supported the creation of a chair in laser application now filled by Esser, and we have also appointed Metzger to a lectureship. Due to the applied nature of their research they have been returned to the General Engineering UoA 15. Gerardot, a Royal Society URF was appointed as a lecturer in 2009 and promoted to professor in 2013. Leach returned from Prof Boyd's group in Ottawa to a lecturer appointment.

Further excellent appointments are detailed in section **c** below.

Implementation of the research strategy above enabled us to generate research activities at a sustainable scale. Since RAE2008, publications in Science/Nature-Stable/PRL, which make up 51% of selected outputs, are up 75% from 7.4 to 12 pa and annual research grant income/FTE is up 61%. Our major research activities are outlined below highlighting a few of the most significant achievements and how these relate to our strategy.

***Ultrafast photonics**:* Faccio reported (PRL 2010) the first ever evidence of Hawking-like emission from an artificial event horizon created using intense laser pulses. This attracted considerable attention with articles in The Economist, New Scientist, Scientific American, Wired and other mass-media journals and newspapers. Follow-up research has led to the discovery of a novel role played by negative frequencies in nonlinear optics (PRL 2012) which in turn has opened up a new research area in ultrafast photonics and formed the basis of a successful ERC Starting Grant award. Kar is pioneering laser-based waveguide technologies for the creation of novel devices such as the photonic lantern (that allows the multiplexing of signals for astrophotonics applications) and new time-of-flight, fibre-based spectrometers that are being applied, to give just one example, to novel bio-sensors for water contamination control. Using solid immersion lensing Reid has achieved a 30-fold resolution increase in laser scanning microscopy (Nature Photonics 2008).

***Quantum sciences**:* IPaQS has established the critical mass and excellence to achieve a significant international profile in single photon science and technologies, and is well positioned to effect the transition of single photon technologies from the research lab into the real world. This well-funded activity is underpinned by the recently renewed EPSRC Platform Grant (~£1M, Buller, Gerardot, Leach). Research highlights on sources include Gerardot's demonstration of coherent population trapping within a single quantum dot (Science, 2009) and the use of a dark exciton in a single quantum dot as a long-lived quantum bit (Nature Physics, 2010). Ferrera contributed significantly to the field of on-chip quantum and nonlinear optics with the demonstration of parametric oscillation and nonlinear optical effects on a waveguide chip (Nature Photonics, 2008

and 2010) leading also to hybrid components, e.g. an all-optical integrator (Nature Comms., 2010). These advances fit well with Gerardot's current research in waveguide QED and scalable quantum networks. Other highlights include the strong experimental and theory collaboration of Buller and Andersson resulting in the first demonstration of quantum digital signatures (Nature Comms., 2012) and the observation of higher dimensional entanglement (Nature Physics, 2010).

Maniscalco recently uncovered a new quantum phenomenon, the sudden transition from classical to quantum decoherence, providing the first evidence of a quantum system in which quantum correlations are completely unaffected by environmental noise (PRL, 2010 - top 10 by citations out of 3350 PRLs published in 2010). Biancalana pioneered a series of novel applications of photonic crystal fibres ranging from hollow-core fibre-based plasma physics (PRL 2011 & 2012) to twisted photonic crystal fibres that support orbital angular momentum modes (Science 2012, PRL 2013).

***Imaging and Biophotonics**:* Imaging at Heriot-Watt covers a wide breadth of applications: from astrophysics to bio-medical to quantum imaging. Buller and Leach have investigated quantum imaging and high-dimensional entanglement with Padgett (Glasgow) and Boyd (Ottawa) and have published a number of significant papers in Nature family journals. At the time of RAE2008 one strand of the institutional strategy was to forge a new research strength at the interface between Life Sciences and Physical Sciences. A natural evolution then lead to the formation in 2012 of the Institute of Biological Chemistry, Biophysics and Bioengineering (IB3) where three 'physics' staff relevant to this submission are engaged in the areas of advanced bio-imaging (Greenaway, Dalgarno, Lu). Greenaway's group forms a key part of the £9.5M EPSRC Interdisciplinary Research centre "Multiplexed 'Touch and Tell' Optical Molecular Sensing and Imaging". The centre brings together physicists, chemists, engineers and clinicians to design, make and test a cutting-edge bedside technology platform to aid intensive care unit doctors in rapid and accurate diagnosis, ensuring patients get the right treatment, promptly.

***Condensed matter**:* Gerardot characterised and tuned the hyperfine interaction between a single spin and ensemble of nuclear spins (Nature 2008, PRL 2008, 2011), demonstrated that tunnel interactions between a confined spin and Fermi sea leads to Kondo-like signatures (PRL 2008) and the non-linear Fano effect (Nature 2008). Current research goals of his ERC Starting grant are to engineer or manipulate spin coherence by controlling either the mesoscopic environment or the single particle wavefunction (Nano Letters 2012). Theoretical condensed matter research includes the investigation of ultracold gases for quantum simulations where Öhberg has demonstrated the possibility of simulating an interacting gauge theory with ultracold Bose gases (PRL, 2013). Pigeon, with co-workers at Surrey, demonstrated the coherent optical control of Rydberg states in silicon (Nature, 2010). Linking condensed matter and astrophysics, Galbraith, with the same team, showed that phosphorous donors in silicon provided an accurate laboratory analogue for hydrogen in white dwarf stars and validated the theoretical approaches at extreme (10^5 T) magnetic fields (Nature Comms., 2013).

c. People:

i - Staffing strategy and staff development

Recruitment strategy remains true to the legacy of focussed excellence and is centred on hiring rising star researchers in photonics and cognate areas, while providing a supportive environment in which they develop their careers. Working alongside our critical mass of photonics-based researchers (both physicists and engineers) adds significant richness to their research horizons. Almost all submitted staff started at HW as early career researchers and developed strongly – recent examples being the promotion to Chair of Gerardot and Faccio, and to Reader of Öhberg and Andersson.

Looking to the future the 2013-2018 University strategy commits to a net expansion comprising ten new academic staff returned in the Physics UoA. This is in addition to continuing the expansion of staff in the IB3 areas of bio-medical imaging and in photonics-based manufacturing. Such appointments spanning the gamut of photonics will maintain the existing critical mass of excellence necessary to compete at the highest level.

In the current period we have already strengthened the physics activity with the recruitment of eleven new staff clustered around the areas of Ultrafast photonics and Quantum Sciences:

Biancalana (from Max Planck Institute, Erlangen, Germany), Dalgarno (from U. of St Andrews), Faccio (from Università dell'Insubria, Como, Italy), Gerardot (from HW, previously UCSB, USA), Hartmann (from TU-Munich, Germany), Leach (from U. of Ottawa, Canada), Maniscalco (from U. of Turku, Finland), Ferrera (from Purdue, USA), Bennett (from DCU, Ireland) , Pollnau (from U of Twente, Netherlands) and Chen (from U. of Birmingham). In this period, five staff departed for promoted posts (Ebbecke, Fisher, Hadfield, Titov, and Warburton).

In the area of Quantum Sciences we have consciously built up a world-class activity related to our other strength in photonics. New theory appointments (Maniscalco, Hartmann) and experimental appointments (Leach, Faccio, Gerardot) consolidate a critical mass of excellent research. Appointments in the area of nano-fabrication and nano-optics (Ferrera, Chen and Biancalana) capitalise on our new e-beam writing facilities (see below) for their research in integrated and nonlinear photonic structures. Prof. Markus Pollnau, a 2013 winner of an ERC Advanced Grant (€2.5M), was also recruited, supporting a strong interdisciplinary activity focused on advanced optical sensing.

Our young staff and new appointments are our future leaders (14 of the 23 staff submitted are under 45) and we vigorously support them in their early years though a dedicated mentor system (mentors are senior, research active academics but not direct collaborators). Teaching and administration loads are built up gradually over the first three years to enable the establishment of an independent research presence. Priority allocation of a PhD studentship is given to new staff, as is the refurbishment of suitable lab space.

Research career development at all levels (academic staff, Research Associates and PGR students) in the University is coordinated by the 'Research Futures' section within our award-winning "Centre for Academic Leadership and Development" (Times Higher Education awards for 'Outstanding Support for Early Career Researchers', 2010 and 'Leadership & Management' 2013). Research Futures offers a full programme of staff and PGR student training courses and opportunities. HWU was amongst the first in the UK to receive the "HR Excellence in Research" recognition from the European Commission in 2010 (and renewed, 2012), This award recognizes the positive actions that the University has taken to support the career development of researchers and the actions in place to implement the principles of the "*Concordat to Support the Development of Researchers*". PGCap (Postgraduate certificate in academic practice) is offered to all incoming early career staff as part of a three year probationary period, and the university operates an annual Performance and Development Review (PDR) for all staff.

Heriot-Watt created and runs the Scottish Crucible as a pan-Scotland professional and personal leadership programme (developed initially by NESTA for the UK) funded by SFC and the Scottish Government (www.hw.ac.uk/scottishcrucible). The scheme enables talented early career researchers developing independent research from any discipline to explore innovation, policy, and interdisciplinary collaboration, and expand their creative capacity and problem-solving potential in new directions. Heriot-Watt was the first HEI to develop an institutional version, Heriot-Watt Crucible, and launched the first European Crucible. Eight physics academics and RAs have benefited from these activities since 2010 leading to several new interdisciplinary collaborations e.g. "quantum gaming" where computer games are developed which overlay a complex quantum problem. Players unknowingly find optimized solutions to the problem by playing the game.

IPaQS have been successful in attracting excellent young staff holding Royal Society, Royal Society of Edinburgh, EPSRC, STFC personal fellowships (six in period Gerardot, Hadfield, Lovett, Thomson, Bookey, Leburn) and these staff are integrated into the academic cohort exactly as new lecturers are. This extends to all training, mentoring and other activities. Hadfield, and Lovett subsequently left for promoted posts elsewhere. We strongly support such Fellowship applications from researchers demonstrating the highest potential and internally give strong guidance e.g. holding mock interviews with ex-selection panel members and external members. The same applies to prestigious EU schemes such as the ERC starter grants, where our approach bore fruit with the award of two ERC Fellowships (Gerardot, Faccio) totalling ~ £2.5M.

For all staff (not just academics) annual professional development reviews are carried out with line managers: the completion of the past years' plan is assessed, forward job plans for the coming year are agreed and any training needs identified. Staff returning from maternity leave have a

reduced teaching load to help them re-establish research momentum and senior staff who have shouldered a heavy administrative burden for a number of years benefit from lighter teaching duties for the same reason.

Commitment to gender equality is demonstrated by our IOP Juno and Athena Swan Bronze awards at Heriot-Watt. SUPA policy is for all partner Universities to achieve at least Athena Silver status. Locally the Head of EPS, under which Physics falls, has taken the lead in driving this issue within the University and the action plan from the latest Athena award is being implemented. Specifically we are seeking to increase the number of female academics in STEM subjects to mirror at least the proportion we see in undergraduate cohorts. With only 10% representation in the current submission finding the right appointees is a high priority. Local actions such as the provision of on-campus child care and ensuring the visibility of good role-models (e.g. colloquia speakers) is important to our postgraduate and research associate staff. Sabrina Maniscalco is an excellent such role model both locally and internationally; e.g. in 2013 she addressed the L'Oréal-UNESCO For Women in Science Soapbox as one of a dozen of the UK's top female academics. Externally produced online equality and diversity training has been followed by all physics staff as part of the Athena process.

The stimulus of high profile research visitors is key to research vitality and we provide this in a number of ways (i) Carnegie grant of £40k for visitors in the broad area of quantum coherence, ~22 visits (typically 10 days). (ii) We funded a series of public lectures (in our £4.5M new and dedicated Postgraduate Centre building) by major international physicists, including seven Nobel Prize winners and their peers (in 2010–M. Berry, R. Friend, K. von Klitzing, G. t'Hooft, A. Fert, 2011–R. Penrose, C. Cohen-Tannoudji, S. Haroche, A. Zeilinger, 2012–T. Steitz, D. Shechtman, R. Heuer). These were video-conferenced to all SUPA sites and much appreciated by students, (iii) a Carnegie Professorship visit from Prof David Miller from Stanford – an outcome of the EPSRC-funded Science Bridges programme, SU2P, in which our photonics researchers teamed with researchers from Stanford and Caltech on joint development projects and exchanges and (iv) visits are afforded by the SUPA Distinguished Visitor programme and we have hosted several such visits e.g. Prof Ewan Wright, U. Arizona (2008 & 2013), Prof Brian Wilson (U. Toronto, 2011), Prof. Matteo Paris, (U. Milan, 2013).

ii- Research students

We are fully committed to two EPSRC-funded Centres for Doctoral Training. Firstly, together with Edinburgh and St. Andrews we run the Scottish Doctoral Training centre in Condensed Matter Physics (cm-dtc.supa.ac.uk) which funds 10-15 PhD places per annum across the Centre. These are recruited centrally and students can select from ~13 supervisors at Heriot-Watt. Secondly, the Industrial Doctorate Centre in Optics and Photonics Technologies (www.idcphotonics.hw.ac.uk) is centred at Heriot-Watt with partners in Glasgow, St Andrews and Strathclyde and directed by Prof Derryck Reid. Launched in 2001 and recently renewed until 2018, the Centre currently supports around 50 active Research Engineers distributed across the UK within around 35 different companies. Our EngD programme was heralded as a model of Photonics advanced training in Laser Focus World ("How to begin a career in photonics," Laser Focus World 48,(4) (2012)). Activities carried out by the Research Engineers make a positive difference to the capabilities and competitive position of our industrial partners, e.g.,

"The Research Engineer's work is of direct commercial benefit to the company. We will commercialise by building and selling machines to implement the processes developed. We can see a significant market opportunity arising from this." (M-Solv)

Both Centres have International Advisory Boards who benchmark the student assessments and training against the highest international standards: best practice then filters through to all PhD students and courses. The University has shown its unwavering commitment to both areas by investing around £1M in each centre in the form of 20 tied scholarships and infrastructure support over the 5 years of the awards.

For almost a decade the Scottish Universities Physics Alliance (SUPA), of which Heriot-Watt is a founding member, has successfully stimulated pan-Scotland collaborations between Physics Departments. The SUPA graduate school is one plank of our excellent postgraduate training. A

minimum of 40 hours of graduate level lectures are required to be taken by all our PhD students as well as around 80 hours of transferable skills training ranging from presentation and writing skills, entrepreneurial training, outreach and proposal writing activities. Extensive video-sharing of graduate level lectures (> 600 hours) spanning all sub-fields has transformed the education of all SUPA PhD students. Now expanded in scope to incorporate strategic themes in 'Energy' and 'Physics and Life Sciences, further deepening and widening interactions, SUPA remains a mainstay of our collective strategy in the coming five years.

Research students are each assigned two research supervisors, one of whom may be at another SUPA institution or, where relevant, in a company. A University Code of Practice guides all aspect of the graduate student experience and makes clear what is expected of the student and what the student can expect from the supervisor. All PGR students are subject to an annual monitoring to assess suitability to continue and an informed decision is made on progression based on reports, vivas and assessments tailored for the year of study.

Students participate in the HW Postgraduate Research Conference, organised annually by PGR students themselves, who select an overarching theme and secure eminent external speakers. Annually we hold a School-wide Research Poster competition with prizes for the best students in each cohort which propagates our overarching cross-disciplinary strategy.

Recruitment of the best PhD students is highly competitive and the University has invested heavily in this area during the period, supporting over 20 PhD studentships from University funds. Such scholarships allow us to recruit the best students from all over the globe. The high visibility SUPA Prize studentship, with over 250 applicants remains a strong attractor and recruiting tool for high quality overseas students.

d. Income, infrastructure and facilities

Income: Compared to RAE2008 our per-FTE annual research income has increased by 60% with aslightly larger staff complement. All established members of staff submitted held substantive (>£300k) research grants in the REF period. Major new physics grants in period include:

- *Creating, detecting and exploiting quantum states of light*,
  Buller, EPSRC Platform grant, award and renewal, £1.9M total.
- *Extreme light-matter interaction in the solid-state for quantum technologies*, Gerardot,
  EPSRC Challenging Engineering award, £1M.
- *MOLIGHT: Light in a Moving Media, Faccio*, ERC Starting grant, £1.2M.
- *SEQUOIA: A Scaleable Quantum Architecture*, Gerardot, ERC Starting grant, £1.2M.
- *Next generation in optical imaging*,
  Greenaway, Lu, Dalgarno with IB3 partners MRC/BBSRC/EPSRC/STFC/EU, ~£2M.

We support the participation of researchers in major joint activities, both within the UK and beyond. Major (£1M+) collaborative funding involving multiple institutions awarded in period includes:

- *Hawking Radiation in Dielectric Horizon Analogues* (£1.1M EPSRC),
  Faccio (HW) & DiFalco (St. Andrews)
- *Advanced waveguide laser source development using ultrafast laser inscription*,
  (£1M EPSRC), Kar/Reid (HW) & Ferrari (Cambridge)
- *Near infrared single photon detection using Ge-on-Si heterostructures* (£1.2M EPSRC),
  Buller (HW), Reed (Surrey), Leadley (Warwick) & Kelsall (Leeds)
- *Physics of organic semiconductor devices* (£1.4M EPSRC),
  Galbraith (HW) & Samuel (St. Andrews)
- *Full-field Coherent Quantum Imaging*, (£1.2M EPSRC)
  Buller (HW), Padgett & Barnett (Glasgow)
- *Network of excellence for micro-optics*, (€6.4M- EU)
  Taghizadeh (HW) & ~30 EU partners.

- *METROCOMB* (€1.5M – EU)
  Reid (HW) with Neuchatel, M-Squared Ltd, Fraunhofer CAP + several SMEs
- EPSRC-Industry Centre for *Innovative Manufacturing in Laser-based Production Processes* (£5.6M EPRSC, £4.5M industrial support), IPaQS-led linking the Ultrafast Laser activity led by Reid with Industrial Laser and Manufacturing Process activities within the General Engineering portfolio, cements our excellent record of applying photonics to industry.
- *Multiplexed 'Touch and Tell' Optical Molecular Sensing and Imaging* (£9.3M)
  EPSRC IRC Greenaway (HW), with IB3, Bath and Edinburgh Universities and Edinburgh Royal Infirmary.

The last in each list above exemplify how a strategic move into new areas can open up funding opportunities beyond the usual physics first call on EPSRC.

Infrastructure and Facilities: Reflecting our heritage in photonics research we have a base of over twenty excellent, well equipped optics labs which benefit from a rolling programme of refurbishment as new staff arrive and new activities begin. At the School level we have planned a coherent strategy of capital investment to support our recruitment and our existing research strengths. This has delivered significant investment in new and upgraded photonics laboratories, nanofabrication facilities, laser facilities and a general purpose clean room. Approximately £4M of investment in infrastructure projects has been made in the last five years to meet the requirements of ten new members of this UoA and the expanding needs of our existing research leaders.

University-supported SUPA2 funding brought a new nanofabrication facility with a state of the art electron beam writer, focused ion beam system and reactive ion etching (£350k Scottish Funding Council and £900k University). This new facility underpins research in nano/quantum photonics as well as solar cell research returned in the General Engineering activity. The School has invested a further £900k in consolidating the existing clean room equipment in a bespoke laboratory which will provide a sustainable processing, fabrication & characterization facility. The School also invested around £1M in upgrading eight physics laboratories to high standards for incoming and existing research active staff (including Faccio, Gerardot, Leach, Buller, Reid). One of these new areas is the EPSRC-funded "Horizons laser facility" (£210k, Faccio/Miller) comprising a range of the state-of-the-art femtosecond laser systems and detectors that are accessible to external (academic and industrial) users. The first external users (Harrison, Chemistry Dept., Aberdeen) have already benefitted from this new facility. A further investment in a picosecond laser machining system (£250k) was also made.

HWU has invested heavily in Life Sciences Interface infrastructure for IB3 (Greenaway, Lu and Dalgarno from this submission), establishing the 'Life Science Interface Laboratory' which contains £3M of high-end microscopes and associated equipment funded with £1.1M of HWU funds, £100k of Robertson Trust donation and £200k funds from MRC and the Wellcome Trust. This activity was recognised in December 2012 with the award of ~£2M from the MRC/BBSRC/EPSRC/STFC 'Next generation in optical imaging' initiative, further bolstered with £110K from the BBSRC and £175K from EU FP7 (all commenced in 2013), all in the area of nano-scale live cell imaging. These awards include £550k of additional imaging equipment adding to the already excellent local infrastructure helping to establish the only advanced imaging facility of its kind in the UK, with much of the equipment unique in Europe.

To help design and fabricate state of the art experiments we benefit from an excellent dedicated 'instrumentation' workshop with staff having decades of experience in opto-mechanical and vacuum system design. This specialist facility is in addition to general machine shop and new (£150k) student training workshop facilities which are available within the School.

e. Collaboration or contribution to the discipline or research base

Collaboration: A pillar of our strategy for industrial collaboration is fostering strategic alliances with key partners. This currently involves long-running relationships with Renishaw, Selex ES and the Atomic Weapons Establishment. Such alliances are valuable in sustaining a long-term relationship where the fit is real leading to a lasting, mutually beneficial, relationship. One concrete example of

this is the Renishaw Advanced Metrology Centre (for which Renishaw have provided equipment to the value of £500k) that facilitates both teaching and research in modern metrology and materials analysis using highly accurate co-ordinate measuring machines, laser calibration equipment, and a sophisticated Raman spectroscopy system. These alliances have supported our research with an additional £500k of funding in the REF period.

The EPSRC-funded Sciences Bridges programme SU2P established a strong collaboration between Heriot-Watt Physics and Stanford University, along with our partners in St Andrews, Strathclyde and Glasgow. SU2P funded two 1-year Entrepreneurship Fellows, who travelled from HWU to apply their research expertise in synergistic projects at Stanford University – specifically, Dr Lamour (ultrafast optical parametric oscillators, from Reid's research) and Dr Natarajan (superconducting nanowire single-photon detectors, from Hadfield's group – now Glasgow). SU2P's staff exchange programme supported Kar's visit to apply his research in ultrafast laser inscription to Stanford's project on optical multiplexing. The benefits of SU2P have been felt by both Stanford, in terms of the research enabled by high-quality Fellows from HWU, and by the wider community of academic and industrial stakeholders in the consortium, who have committed to self-fund SU2P after EPSRC funding has ended.

Heriot-Watt are also a partner in the International Max Planck Partnership entitled "Measurement and observation at the quantum limit" between key Scottish Physics departments and five Max Planck Institutes in Germany. This collaboration, formally launched in 2013 and supported by significant funding (£750k) from EPSRC and the Scottish Funding Council, aims to further strengthen links between physicists at Scottish Universities (HWU, St Andrews, Strathclyde, Glasgow and Edinburgh) and the Max Planck Society. The consortium will fund visits and collaborative research workshops in emerging areas in this field.

Heriot-Watt Physics have also set up a formal collaboration with MIT's Media Lab, led by Prof Ramesh Raskar. This collaboration, which was started by a joint workshop in 2013, will fund exchange visits by PhD students and supervisors and is mainly concentrating on our strengths in imaging and ultrafast lasers (Leach, Buller, Faccio).

Locally we collaborate very closely with other disciplines within the School, in particular with Engineering (Hand, MacPherson, Maier, Thomson, Moore, Wang, Esser, Baker, Hall, Shephard), Life Sciences (Duncan, Rickman) and Chemistry (Paterson, Townsend) where there are numerous jointly funded research programmes and publications. We also collaborate on 'quantum gaming' with computer scientists of the School of Mathematics and Computer Sciences (Louchart, Robertson). This exemplifies the University strategy of fostering interdisciplinary research across Heriot-Watt University.

***Contributions to the Discipline**:* Staff have collectively delivered over 110 invited/plenary talks at international conferences, including for example, Faccio, (CLEO US 2013, Photonics West, USA 2013), Buller (CLEO Pacific Rim, Shanghai 2009, Photonics West 2011), Taghizadeh (OSA Ann. Mtg, Baltimore 2010), Gerardot, (MSS 2009, Photonics West 2011). We have chaired or co-chaired 7 major international conferences (e.g. Pollnau, CLEO-USA 2008, CLEO-Europe 2011). The Ultrafast Photonics Summer School was organised and hosted at HWU (Director - Reid) in 2011, while Galbraith and Öhberg were involved in two summer schools associated with the Condensed Matter Doctoral Training Centre (Condensed Matter 2010, Condensed Matter and Energy 2011).

As a University we actively support disciplines through the Learned Society activities. Buller sits on the Institute of Physics Science Board, the Royal Society International Exchanges Scheme Panel, the Steering Committee for the EPSRC National Centre for III-V Technologies, and Science minister David Willetts' EPSRC/BIS Quantum Technology Roundtable. Prof A Miller is Royal Society of Edinburgh Fellowships chair and on the Royal Society's URF selection Panel, Prof J.D.C. Jones sits on IOP council and the UK Photonics Leadership Group, and Reid organised the IOP-Edinburgh lectures at Royal Society of Edinburgh. Buller was elected FRSE in 2009 while Faccio was elected to the Royal Society of Edinburgh, Young Academy in 2011. Jonson sits on the Nobel Prize for Physics Selection Committee for 2013 and is a Member of the Advisory Board of NTT Basic Research Laboratories, Japan.