Institution:
Heriot-Watt University

Unit of Assessment:
Sub-panel 9: Physics

1. Unit context and structure, research and impact strategy

Introduction

Physics at Heriot-Watt has continued to build on its strong heritage in photonics and condensed matter research by evolving into a number of related areas, in particular quantum science and technology, ultrafast photonics, and the interface with chemistry, manufacturing and life sciences. There has been a significant increase in high profile journal publications being selected as UoA outputs in REF2021, namely a **49% increase** in the proportion of Nature titles/Science/Physical Review Letters/Optica publications compared with REF2014. **Our annual grant income per FTE has increased by 84%**, and the **number of graduated PhD students per annum has increased by 85%**, in keeping with our REF2014 strategy. Major new initiatives shaping our research environment include our substantial engagement with the National Quantum Technology Programme, and securing an EPSRC Programme Grant in Quantum Technology. Of the four national EPSRC Quantum Technology Hubs which have recently been renewed (> £20M awarded to each Hub which typically contains 8-10 Universities), Heriot-Watt Physics is the second largest partner in both the Quantum-Enhanced Imaging Hub and the Quantum Communications Hub, leading much of the research in single-photon lidar, quantum communication components and quantum entanglement networks. We also play a significant role in the EU Quantum Flagship programme. We have gained significant success in personal Fellowship funding in period, having been granted 9 substantive new Fellowships worth £8.7M from the EPSRC, RAEng, and the Royal Society of Edinburgh, in addition to three ERC Starting Grants and two ERC Consolidator Grants totalling €10.3M. The majority of the Fellowship awards have been awarded to early stage academics, demonstrating the success of our strategy to recruit and develop new academic talent. In this UoA'S REF2021 return, **43% of those submitted have been recruited since REF2014 and are in their first independent academic post**. Taken together, this substantial funding and influx of new talent underscore the existence of an excellent environment for world-class research at Heriot-Watt Physics.

Heriot-Watt Physics has adhered to its REF2014 strategy: investing in new academic talent and new facilities; targeting research growth in impactful areas of quantum technology and ultrafast optics; improving gender diversity of staff; developing new research funding streams; and expanding our PhD cohorts:

- As we committed in our REF2014 strategy, we recruited and nurtured 10 academic starts since REF2014, 9 of whom are in their first substantive academic post. Our overall cohort has slightly increased from 20.8 in REF2014 to 21 for this submission.
- Increased our **female representation in Physics UoA staff to 19% from 9.7%** in 2014, and improved gender balance at all levels in the UoA, as detailed in our REF2014 strategy.
- Increased the number of PhD students, partly through the University-funded James Watt Scholarship scheme. Our **PhD graduations have increased from the REF2014 figure of 7.2 per annum to 13.3 per annum** for REF2021.
- Invested in laboratory space for new academics at a cost of £2,265,000 and modernised clean-rooms at a cost of £1,037,000.

- Fostered new strategic collaborations through national and international academic and industrial research alliances (e.g. the National Quantum Technologies Programme, the EU Quantum Flagship, the Scottish Universities Physics Alliance (SUPA) and Strategic Alliances with the Atomic Weapons Establishment (AWE), Renishaw and Leonardo.
- Supported the training and networking of new academic staff via the Heriot-Watt and Scottish Crucible programmes and our Heriot-Watt Research Futures Academy.
- Supported entrepreneurship and innovation via our Research Engagement and Enterprise Directorates and, facilitating the creation and exploitation of new enterprises, as evidenced by our long track record in successful spin-out activities.

Research Highlights

The sustainable critical mass of research in photonics and quantum sciences, resulting from our REF2014 strategy, has enabled HWU physicists to make ground-breaking contributions as evidenced by the following research highlights:

1. **Fedrizzi** used a six-qubit photonic quantum computer to implement an extended version of the Wigner's friend paradox, showing that quantum mechanical observers may experience alternative facts. This is a major milestone in quantum foundations research, forcing an update to virtually all interpretations of quantum mechanics and rendering some more likely than others. Research in quantum foundations capture the public imagination - more than 700,000 have read the accompanying outreach article in The Conversation.
2. **Gerardot's** discovery of strain-induced quantum emitters in atomically thin semiconductors led to the deterministic positioning of high-purity single photon emitters that can be coupled to a tunable Fermi sea in a two-dimensional platform. **Gerardot** pursued highly tunable moiré superlattice potentials to create arrays of quantum dots with highly unique spin and polarization properties. Beyond the single-particle picture, strong carrier correlations arise due to the flat bands and narrow bandwidths in moiré superlattices. This opens new avenues to create, probe, and engineer emergent or topological quantum phases such as quantum spin liquids.
3. **Andersson** and **Ohberg** worked with **Thomson** (of UoA 12) using photonic lattices to realise dispersionless light propagation in waveguide arrays fabricated using ultrafast laser inscription. In such a situation light behaves as if it has an infinite effective mass. Such light can provide a route towards correlated states with photons when nonlinearities are present. This result opened up the path towards topological photonics where it was shown how light can emulate topological quantum matter in close analogy with electrons in strong magnetic fields.
4. **Buller** and **Leach** extended their ground-breaking work on novel aspects of quantum-enhanced optical imaging: e.g. single-photon light-in-flight imaging, imaging around corners , imaging through camouflage and complex scenes , through obscurants and high-speed imaging in three dimensions . Other work included the first implementation of ghost imaging across a quantum network, illustrating the pathways necessary for quantum teleportation of spatial states of light in the form of images, and following their work on entanglement swapping of spatial states of light. This work points towards a quantum network for high-dimensional entangled states and provides a test bed for fundamental quantum science.
5. **Reid's** demonstration of femtosecond optical parametric oscillation (OPO) in the semiconductor orientation-patterned GaP proved that mature λ~1μm laser sources could

be converted directly into widely tunable 5–13μm radiation, achieving tuning ranges and output powers surpassing all other femtosecond OPOs and DFG sources in this spectral region. This OPO opened the route to standoff spectroscopy and dual-comb spectroscopy in this critical molecular fingerprint region by providing a benchtop source with spectral and spatial brightness exceeding all other high-repetition-rate sources, including synchrotron radiation.

6. **Travers'** discovery of soliton dynamics in gas-filled hollow capillary fibres was published in a landmark paper in Nature Photonics, demonstrating world-record peak-power (43GW) optical attosecond pulses. Subsequently, **Travers** demonstrated 2fs pulses with 27GW peak power at λ=1800nm, providing a key driving mechanism for soft-X-ray high harmonics. Furthermore, tuneable few-femtosecond pulses across the vacuum ultra-violet (UV) and deep UV were generated. These soliton-driven light sources form the foundation of a new generation of pump-probe spectroscopy experiments, for example in molecular spectroscopy and as a pump source for X-ray imaging experiments.
7. **Malik** demonstrated transport of high-dimensional entanglement through a scrambling complex medium for the first time. The complex medium consisted of a commercial multi-mode fibre supporting hundreds of spatial modes. In a quantum twist, the medium was characterised using the entangled state itself, the entanglement being unscrambled without manipulating the medium or the incident photon. This was a major breakthrough for quantum communication and imaging methods through optical fibre. This result was the cover highlight of Nature Physics in November 2020 and received coverage by the BBC, Physics World, and Physics Today.

Unit Structure and Strategy

The current state of the art and the present funding climate demand researchers collaborate on larger projects which address grander challenges. Physics at Heriot-Watt is embedded in a structure designed to support this, without the obstacles of traditional discipline boundaries. Since 2012 Physics has sat within the Institute of Photonics and Quantum Sciences (IPaQS), one of five strategic research institutes within the School of Engineering and Physical Sciences. Research in IPaQs extends from applied topics such as industrial laser processing, to fundamental concepts in condensed matter physics and quantum optics. IPaQS brings together 33 physicists and mechanical and electronic engineers to work in one of the UK's largest concentrations of quantum and photonics researchers (see table below summarising the interdisciplinarity nature of IPaQS').

IPaQs Groups	Staff Submitted to REF2021
Quantum Photonics and Quantum Information (Quantum)	14 Staff, all included in this submission: Andersson, Bonato, Buller, Donaldson, Fedrizzi, Ferrera, Galbraith, Gauger, Gerardot, Leach, Maccarone, Malik, Mazzera and Ohberg
Ultrafast Photonics Group	11 Staff, 7 included in this submission: Biancalana, Cataluna, Chen, Kar, Reid, Saleh and Travers. 1 submitted to UoA Chemistry (quantum control of fundamental molecular processes), 3 submitted to UoA Engineering
Applied Photonics	8 staff, all submitted to UoA Engineering

There is significant interaction and collaboration between these two submitted Groups, as evidenced by joint high-profile publication outputs and collaborative projects described below. Annual strategy sessions are held in each Group to identify research and funding opportunities and to leverage University investments in research infrastructure. These have led to several successful collaborative funding bids (e.g. EPSRC Strategic Equipment Grant for Two-dimensional Photonics Fabrication Facility (£582k); DSTL Advanced Vision (£400k)). There are numerous examples of research between Groups and different UoAs. For example, quantum theorists (**Ohberg** and **Andersson**) worked with photonics specialists on ultrafast inscription (in B12), to create dispersionless light.

Physics at Heriot-Watt continues to benefit from its active involvement in the Scottish Universities Physics Alliance (SUPA), which is an alliance of 8 Physics Departments in Scotland, representing a significant critical mass of physicists. SUPA provides added value to Heriot-Watt Physics in a number of areas, particularly the Graduate School but also with staffing strategy, knowledge exchange and industry engagement. SUPA is theme-led, with Heriot-Watt Physics being particularly active in the Photonics and Condensed Matter Themes. Physics at Heriot-Watt is represented on the SUPA Management Committee by the IPaQS Head **Ohberg**.

Strategic Aims

Through our annual School Strategic Plan which feeds into the University's Strategy 2025 initiative, our strategic aims for the coming period are:

1. Enhance our leading position in Photonics and Quantum Sciences through research excellence.
2. Widen our range of non-EPSRC funding sources to grow our base of researchers in a sustainable way.
3. Grow our interdisciplinary collaborations and use our expertise to address challenges in fields such as astronomy, robotics, healthcare and life sciences.
4. Sustain our impact on commercial and scientific partners through maintaining and widening our Strategic Alliances and jointly funded research activities, and by pursuing patent, licensing and spin-out company opportunities.
5. Improve the gender balance of academic staff to >40% female representation.
6. Continue to grow academic staff through recruitment of Early Career Researchers.
7. Continue growth in PGR numbers.

Impact strategy

We strongly encourage our staff to engage in commercial impact of their research in a variety of ways, for example by instilling key attributes of collaboration, interdisciplinarity, innovation and leadership through our Research Futures programme and Enterprise Boot Camp at Heriot-Watt. For new academic this is a critical part of the induction process, along with our Crucible programme. Additionally, Heriot-Watt offers entrepreneurial expertise via Heriot-Watt's recently formed Enterprise Team. The accelerating involvement of industry in the quantum technology field will lead to significant commercialisation opportunities. Our Enterprise Team - housed in our new £30M GRID facility - has targeted Quantum Technology as one of the University's two prime focus areas (along with Robotics) and is forming a commercialisation plan in conjunction with our Quantum Group. This five-year plan, to be launched in Q1 2021, will include provision and budget for patenting, licensing, and spin-out company development in the quantum technology space.

A key feature of Heriot-Watt Physics since the 1970s has been engagement with industry, encouraging commercial exploitation of our research in a variety of ways, including through

collaborative projects and establishment of spin-out companies. These thriving companies include Edinburgh Instruments; Helia Photonics; PowerPhotonic; OptoScribe; Chromacity. We continue to maintain links with these companies in a range of ways, for example as Company Directors or advisors, or through student placement. This close engagement has helped in company recruitment and partnership in numerous UKRI research projects.

This UoA has been active in patent protection, having filed a total of 5 patents from 5 different members of the UoA. During this REF period, there were 3 patents published that were filed during the previous REF period.

UoA Future Strategic Development

We will continue to develop our active participation in the EU Quantum Flagship and the UK National Quantum Technology Programme, as the subject makes its transition from a purely academic endeavour to the embryonic UK Quantum Technology industry, outlined in the 2020 BEIS UK R&D Roadmap as a "transformational new technology". Heriot-Watt Physics will continue to recruit in fundamental aspects of quantum sciences to develop this work to higher technology readiness levels. The materials aspects of quantum sciences will be supported by our continuing investment in cryogenic optics labs and bespoke clean room facilities. We will capitalise on our strengths on spin-based quantum sensing and quantum 2D materials to create a world-class quantum magnetometry facility to investigate many-body physics and magnetic ordering in 2D heterostructures.

In ultrafast optics, in collaboration with optical instrumentation groups in UoA12, we will recruit staff in astro-photonics and continue to expand our work supported by non-EPSRC sources, such as STFC. The skills of our current cohort of QT and ultrafast academic staff, complemented with appropriate new academic recruitment, will move into developing areas of biomimetics, bioinformatics and optogenetics. This will require new academic strengths, for example in mid-infrared fibres and THz technology, and will be done in close collaboration with Heriot-Watt Physics's existing biophotonic teams within the School, where we continue to have critical mass of scientists submitted under other UoAs.

Another exciting interface area where we have a unique blend of skills is the application of quantum-inspired active imaging in autonomous vehicles, particularly for use in challenging environments, such as turbid media, or in the presence of atmospheric obscurants. Where ultrafast video rates are necessary this presents a significant technological challenge. This work will take advantage of Heriot-Watt's world-class activities in robotics, coalescing around the Heriot-Watt-based National Robotarium - a £33M investment through the Edinburgh Region City deal, comprising robotics, manufacturing, undersea, and computer vision talents.

Approach to Research Culture and Governance

Our research meets the highest standards of research integrity and conforms to the Heriot-Watt Research Ethics Policy (updated March 2020) which defines the lines of ethical responsibility in research projects. Ahead of each research proposal submission, all ethical approval must be sought and a bespoke data management plan must be written in advance which defines consent, storage, and anonymity. The UoA adheres to the University's Open Access policy for published research. As an example, 100% of this UoA's published work submitted in REF2 meet the REF2021 open access requirements. Our academics are encouraged to work beyond the REF2021 open access guidelines, in terms of access to software and data to encourage a transparent and open research culture. The UoA is committed to responsible innovation, and many

UoA members have participated in the Responsible Research and Innovation events organised via the EPSRC Quantum Technology Hubs, for example. This included active participation in the EPSRC Quantum Technologies Public Dialogue which organised several workshops to gather public opinion on the implications of quantum technology research.

2. People

Staffing Strategy

In this REF period we achieved our REF2014 objective to **increase our female representation in the Physics UoA staff to 19% from 9.7%**. We have slightly increased the total number of staff to 21 FTE from 20.8, however a significant number of physicists are included in other UoAs, particularly B12 where 11 other IPaQS academics are returned. Our recruitment strategy has been to target early stage researchers in quantum and ultrafast photonics, offering them a welcoming research environment that will help their careers flourish. We have recruited 10 new staff who are returned in this UoA, including many from the major international laboratories in our research fields: **Fedrizzi** (from Queensland); **Malik** (Vienna); **Travers** (Max Planck Erlangen); **Gauger** (Oxford); **Bonato** (Delft); **Mazzera** (ICFO, Barcelona); **Saleh** (Max Planck Erlangen); **Cataluna** (Dundee); **Donaldson** (Heriot-Watt, RAEng Fellowship); **Maccarone** (Heriot-Watt, RAEng Fellowship). With the exception of **Cataluna**, 9 of these 10 new academics are in their first substantive academic post. Since the last submission, the following staff have left through planned retirement: Pidgeon, Taghizadeh, Greenaway and Jonson. Staff leaving the UoA were Leburn (to Heriot-Watt spin-out company Chromacity, returned as an Impact Case Study); Bennett (University of Technology, Sydney); Maniscalco (Chair in Turku); Hartmann (Chair at Erlangen); Faccio (Chair at Glasgow).

Our strategy of hiring talented up-and-coming researchers as academic staff uses two main hiring mechanisms. The first funds a vacancy via a University recruitment vehicle, the Bicentennial Research Leader Scheme (**Mazzera**, **Bonato**, **Cataluna**, and **Travers**). The second offers open-ended contracts to early stage researchers who obtain prestigious externally-funded Fellowships, such as EPSRC, Royal Academy of Engineering, and Royal Society of Edinburgh schemes (**Donaldson**, **Fedrizzi**, **Gauger**, **Maccarone**, **Malik**, and **Saleh**).

Each new-start academic receives a start-up package of dedicated modern laboratory space, PhD studentship provision (£75k each), and resources for consumables and travel - typically overall value is £250k. In this REF period, the experimentally-oriented **new-start academics have collectively benefitted from institutional investment of £2,265,000** in laboratory refurbishments provided to their specification. Each is supported in their transition to an academic position by an experienced mentor. All new academics are provided a detailed induction programme via Heriot-Watt's Research Futures Academy, which assists early career researchers to develop their professional capabilities. They are encouraged to participate in the Scottish Crucible, a scheme for Scottish Universities to invigorate our early stage academics with skills in networking, creative thinking and societal responsibilities.

Over this REF period, personal and professional development activities and resources have been made available to all staff through the Research Futures Academy. All staff have attended the mandatory training courses including research ethics, PhD/PDRA supervision, information governance, and health and safety. These courses reflect the importance the University places on ethics and diversity as well as PGR supervision. Staff regularly also attend more diverse courses,

such as: staff mentoring; knowledge exchange; time management; public engagement impact; and mental health awareness training for managers.

Postgraduate Research (PGR) Students

The Heriot-Watt Physics PGR community has grown considerably, with **85% more doctorate graduations per annum** than REF2014. Substantial internal investment by the University (19 James Watt Scholarships in period) and our strong track record of success in competitively awarded studentships and training grants have enabled us to recruit the best students in the UK and internationally. Highlights include IPaQS's three EPSRC CDTs in Applied Photonics and Industry-Inspired Photonic Imaging, Sensing and Analysis and Condensed Matter Physics.

Heriot-Watt Physics provides a positive research culture for postgraduate researchers, underpinned by a supportive supervisory environment, high-quality training and a robust University Code of Practice which guides all aspects of the graduate student experience and makes clear the expectations of both students and supervisors. With Physics sitting within the larger EPS School, PhD students are encouraged to perform interdisciplinary research, often with supervisors from two different subject areas. Each student is assigned two supervisors, one of which may be from industry or another SUPA institution, plus a further HWU mentor from outside their field who can offer confidential professional and pastoral advice. In addition to a formal annual progression process, monthly online reporting allows areas of concern to be raised and resolved promptly. PhD students maintain a Professional Development Plan throughout their studies, to record and reflect on their capabilities, and find connections to relevant training opportunities. Completion of the PhD remains a priority throughout the duration of the PhD, and throughout this REF period we have reduced the average time to formal degree approval to 4.2 years, slightly more than our aspiration of 4.0 years. (However, note that many of our cohort have 4 years studentship funding).

Through our active participation in the SUPA Graduate School (established 2006), all students receive a highly developed and closely integrated programme of graduate education in Physics. This offers over 60 advanced technical courses (over 800 lecture hours) for physics PhD students across Scotland, as well as professional development training tailored to physicists. Courses, accessing the knowledge and skills of world leading researchers drawn from across the eight partner universities are mostly delivered by live video links using SUPA's e-learning portal with dedicated state-of-the-art video classrooms. There are also tutorials, lab classes, workshops and international summer schools (SUSSP). These courses are aligned to pan-SUPA research themes (Astronomy and Space Science, Condensed Matter and Material Science, Nuclear and Plasma Physics, Particle Physics, Photonics) and two impact themes (Energy and Physics & Life Sciences) that cover all areas of physics and astronomy research. Each PhD student must take at least 40 contact hours of Advanced Physics courses and 20 hours of Professional Development courses in their first two years.

As the largest Physics graduate school in the UK, the SUPA Graduate School continues to have a major impact on Physics research and graduate education. Indeed, the SUPA Graduate School has grown substantially since the last REF: over the REF2021 assessment period a total of ~1050 postgraduate students have commenced study within SUPA, and an average of ~110 PhDs have been awarded per year (as compared with an average of ~58 per year during RAE2008 and 78 during REF2014). Over the same 2014-20 period the SUPA Graduate School has delivered ~100,000 hours of training, comprising ~80,000 hours of Advanced Physics technical training and ~20,000 hours of Professional Development training. In addition to the PhD students, ~500

Masters-level students have enrolled on SUPA courses, as well as PhD students from adjoining disciplines benefitting from the large range of graduate-level training on offer. As further evidence of the sustained strength and impact of SUPA in recent years, total research awards have exceeded £550 million over the REF2021 assessment period.

Several initiatives provide students with valuable experience of research dissemination, to prepare PhD students for their future presentations at international conferences. Our annual Heriot-Watt Postgraduate Research Conference is convened by PGR students themselves, who select an overarching theme and invite eminent external speakers. An annual School-wide Research Poster competition propagates our cross-disciplinary strategy. Part of our Physics PGR activities include a weekly seminar series which comprises high-profile speakers in the field from other institutions, interspersed with occasional talks by our PGR students and recent PGR graduates. In addition, PGR students in the quantum field organise the "QTech" seminar series, where each week a PGR student will discuss their work in a less formal environment.

Centres for Doctoral Training (CDT)

In addition to the training programme received by all students, enhanced doctoral training in condensed matter physics and photonics is delivered through three EPSRC Centres for Doctoral Training, recognising HWU's excellence in these areas and ensuring the continued health of these disciplines:

1. EPSRC Centre for Doctoral Training in **Condensed Matter Physics**, 2009-23 (renewed 2014), with Edinburgh and St Andrews (lead). HWU Director – **Galbraith**. 24 industry partners. Total value £2.23M. 19 PhDs graduated at Heriot-Watt Physics in this REF period.
2. Centre for Doctoral Training in **Applied Photonics**, 2014-23 (continuous EPSRC funding at HWU since 2001). HWU-led (**Reid**), with St Andrews, Glasgow, Strathclyde and Dundee. 29 different industry partners. £7.2M total. 29 graduated at Heriot-Watt Physics in this REF period. Mainly EngD provision.
3. Centre for Doctoral Training in **Industry-Inspired Photonic Imaging, Sensing and Analysis**, 2019-28. HWU-led (**Reid**), with Edinburgh, Dundee, Glasgow, Strathclyde, St Andrews. 20 different industry partners currently. £8.1M total, 24 students enrolled (2 cohorts) and 55 to be trained by REF2028. Mainly EngD but some PhD projects.

These CDTs offer students:

- Doctoral-level technical training over 48 months across multiple academic partners.
- Skills training in IP, entrepreneurship, including MBA-accredited modules for photonics EngD students.
- Outreach opportunities through links with partners such as Glasgow Science Centre.
- Links to industry, including large enterprises and SMEs, offering future collaboration or employment opportunities. EngD industry partners contribute £50,000 per project, and include Renishaw, Taylor-Hobson, BAE Systems, MBDA, BT, Leonardo, Canon, ST Microelectronics.
- Our EPSRC CDTs have International Advisory Boards who benchmark the student assessments and training against the highest international standards: best practice filters through to all PhD students and courses.

The CDTs provide sustainability of condensed matter physics and photonics:

- Improvements in gender representation in Applied Photonics (45% female in the two most recent cohorts)
- 4 EngD graduates have founded companies, two have won Royal Commission for the Exhibition of 1851 Industrial Research Fellowships. 137 papers and 14 patent applications have arisen from EngD CDT projects.
- International impact through all three CDTs' regular summer schools which attract early career researchers from 10 countries, and via our international advisory boards.

Heriot-Watt Physics is a member of the International Graduate School for Quantum Technologies (IGSQT), along with Glasgow and co-ordinators Strathclyde (from 2019-). IGSQT offers tailored taught courses and a specific PhD training programme covering the advancement and application of Quantum Technologies from fundamental physics to practical technologies. IGSQT also offers PhD positions embedded in industry.

Our CDT involvement helped secure a critical mass of PhD and EngD students in key areas of photonics, condensed matter and quantum technology, whilst ensuring the highest international standards. Commercial relevance and collaboration are instilled in the doctoral students by the strong contribution of industrial sponsorship.

Equality and Diversity

Physics at Heriot-Watt continues to be an outward-looking diverse community, with the 21 returned staff originating from 10 different countries, with those staff of non-UK origin representing **71%** of the total. Physics at Heriot-Watt continues to ensure that we engage with University strategy in going beyond our legal requirements and Athena Swan commitments, as detailed in the University's Equality and Diversity Policy, overseen by the University's Equality and Diversity Group. All academic staff, researchers and PhD students must complete the basic ethics and diversity awareness and training, and have the option to extend the training with other workshops that include diversity in the workplace, diversity in learning and teaching and equality analysis, equality essentials, equality impact assessment and cultural awareness training, offered through the University's Research Futures Academy.

Whilst there has been a significant improvement in gender balance in this UoA, we have a firm commitment to deal with the challenge of further improvement throughout the next REF period. In 2020, Heriot-Watt made a successful submission to renew our Athena Swan Bronze Charter Award; this has been conferred until 2026 reinforcing our ambition to put EDI at the heart of our future strategy. In addition, this UoA is part of the School's Athena Swan Bronze Award, which was renewed in 2020, with a 2023 target for a Silver application. From 2020, **Ohberg** is Chair of the School Athena Swan team, with support from **Mazzera**, **Malik** and a Physics PhD student representative. As part of our action plan the following been implemented:

- Academic Returners Scheme to support staff and their groups during career breaks, offering funding for a postdoc to support supervision and managing research activities, and funding for PhD students to undertake placements during absences.
- Phased returns from career breaks, including no requirement to develop teaching materials in their first semester back.
- All school meetings held within core hours of 10am-4pm to ensure staff with caring commitments can participate.
- Annual networking event for women in STEM and to celebrate Athena Swan achievements.

We have worked to address the gender balance in the Physics UoA, by implementing best practice in gender neutral advertising, unconscious bias training for all staff, and insist on gender balanced interview panels. We are conscious of our gender balance which is at 19% female representation for academic staff which, although improved from REF 2014 (9.7%), remains similar to the national Physics average. In terms of PDRA's we have 18% female representation, whilst at PhD level it is 24% for PhD graduates in period, both indicating an improving trend compared to REF2014. Notably, two recent winners of the MacFarlane Prize, the annual award for the most outstanding PhD work in Heriot-Watt University, are female physics graduates: Dr Megan Agnew (2018) for her work on quantum networks; and Dr Rachael Tobin (2019) for her work on quantum-enhanced imaging.

3. Income, infrastructure and facilities

Income

Since REF2014, our per-FTE **annual research income has increased from £142,242 to £262,333 per FTE per annum**. All returned members of staff held substantial (>£300k) research grants in the REF period. Compared to the previous REF, we have more firmly established non-EPSRC funding streams including DSTL, Innovate UK, ERC, STFC and direct industry funding.

The UoA is supported by Heriot-Watt Research Engagement Directorate (RED), which provides specialist support with research funding, including the application process, and all legal aspects of collaboration agreements and intellectual property. RED has assisted with our diversification of funding sources, in particular with our successful Innovate UK collaborations, and our engagement with DSTL research funding, both described in Section 4.

A high-profile example of our proactive approach to research funding has been Heriot-Watt Physics's involvement in the UK National Quantum Technology Programme. **Buller** sat on the seven-member EPSRC Quantum Technology Advisory Panel (2013-14) which was central to setting the foundations for this programme. Heriot-Watt Physics has been a founding member and major partner in two (of four) Quantum Technology Hubs, the Quantum Communications (QuComms) Hub and Quantum-Enhanced Imaging Hub (QuantIC), each funded with more than £20M for the first phase commencing December 2014. **Andersson** was a named contributor to the 2017 Blackett review, *The Quantum Age: Technological Opportunities*, which heralded much of the future direction of the National Quantum Technology Programme. The programme has a strong industrial-focussed element to enhance and encourage commercialisation of QT, administered by Innovate UK. This UoA is a major partner in six large collaborative, industry-focussed projects totalling £1.54M to Heriot-Watt Physics (see Section 4).

- EPSRC Platform Grant *Creating, detecting and exploiting quantum states of light* (**Buller**, **Gerardot**) 2013-17 - £1.01M
- *EPSRC Quantum Technology Hub in Quantum Communications* (**Buller**, **Anderson**, **Gerardot**) 2014-19 - £2.2M
- *EPSRC Quantum Technology Hub in Quantum-Enhanced Imaging* (**Buller**, **Leach**) 2014-19 - £2.8M
- ERC Consolidator 2DQP: *Two-dimensional quantum photonics* (**Gerardot**) 2018-22 - €2.0M
- ERC Starting Grant *UPTIME* (**Cataluna**) 2015-22 - €2.0M
- ERC Starting Grant *HISOL* 2016-21 (**Travers**) - €1.87M

- *EPSRC Quantum Technology Hub in Quantum Communications – Phase Two* (**Buller**, **Andersson**, **Fedrizzi**, **Donaldson**) 2019-24 - £2.15M
- *EPSRC Quantum Technology Hub in Quantum-Enhanced Imaging* (**Buller**, **Leach**) 2019-24 - £2.6M
- Industry funding (ASML) *Universal light sources* (**Travers**) 2019-24 - £1.54M
- EPSRC Programme Grant *Single Photons - Expanding the Spectrum* (**Buller**, **Leach**) 2020-25 - £2.0M (leading a collaborative £5.2M grant)
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- ERC Starting *PIQUaNT: Photonics for High-Dimensional Quantum Networking* (**Malik**), 2021-26 - €2.05
- ERC Consolidator Grant *XSOL: Extreme Soliton Driven Light Sources* (**Travers**) 2021-26 - €2.4M

The Platform Grant and Challenging Engineering projects provide the funding of staff that paved the way for the hiring of **Bonato** and **Mazzera** with complementary investment in clean room facilities, described below.

A feature of this REF period has been Heriot-Watt Physics's strong performance in Fellowship awards, particularly for academics at early career stages. In 2014 Heriot-Watt formed a Fellowship College to improve applicants' opportunities in gaining prestigious Fellowships. The Fellowship College acts to disseminate best practice across the University, provide expert feedback at multiple stages of the application (from initial concept to interview preparation), and an active mentoring scheme to take the applicant through initial application and into the Fellowship period. The Fellowship College has led to significant success for Physics during this REF period by helping obtain 9 major Fellowships in period, 7 of these awards being made to academics who joined since 2014.

Fellowship awards active during this REF period are shown below. The significant time available to these Fellows to dedicate to research has enabled a step-change in research output quality of the UoA, contributing to at least 20% of our REF2021 Outputs.

These include:

- RSE Fellowship (**Saleh**), *Novel Nonlinear Phenomena in Microstructured Wave*guides, 2014-19 - £333k
- RSE Fellowship (**Gauger**), *Biomimetic energy harvesting with quantum nanostruct*ures, 2014-19 - £357k
- EPSRC Established Career Quantum Technology Fellowship (**Buller**), *Next Generation Imaging using Sparse Single-Photon Data*, 2015-20 - £1.4M
- EPSRC Early Career Fellowship in Quantum Technology (**Fedrizzi**), *QuigaByte-Gigahertz-clocked telecom cluster states for next generation quantum photonics*, 2015-20 - £1.2M
- EPSRC Early Career Fellowship (**Malik**), *Putting Chaos to Work: Multi-Photon Entanglement in Complex Scattering Media*, 2018-23 - £1.2M
- EPSRC Early Career Fellowship (**Bonato**), *MOSQUITO: MObile Spin-based QUantum Information sTOrage*, 2019-24 - £1.2M
- *RAEng Chair in Emerging Technologies* (**Gerardot**) 2019-28 - £2.0M
- RAEng Fellowship (**Donaldson**), *A mobile optical ground station receiver for satellite-based quantum communication*, 2018-23 - £487k
- RAEng Fellowship (**Maccarone**), *Underwater three-dimensional optical imaging based on quantum detection*, 2020-25 - £500k

- Royal Society URF (**Gerardot**), *Quantum optics of tunable zero-dimensional solid-state emitters*, 2009-17 - £0.84M

Laboratory facilities

The University has made considerable investments in laboratory facilities during this REF period, which have underpinned many of the major grant successes. These investments total £2,265,000 supporting the research of most of the academics in this UoA through photonics laboratory refurbishments. In addition, we have invested in modernising our fabrication clean-room costing £1,037,000, predominantly used by this UoA. These University investments align with our major grant funding in quantum technology – e.g. EPSRC Hubs and Fellowships and the SPEXS Programme Grant – and in ultrafast photonics, e.g. ERC funding of UPTIME and HiSol.

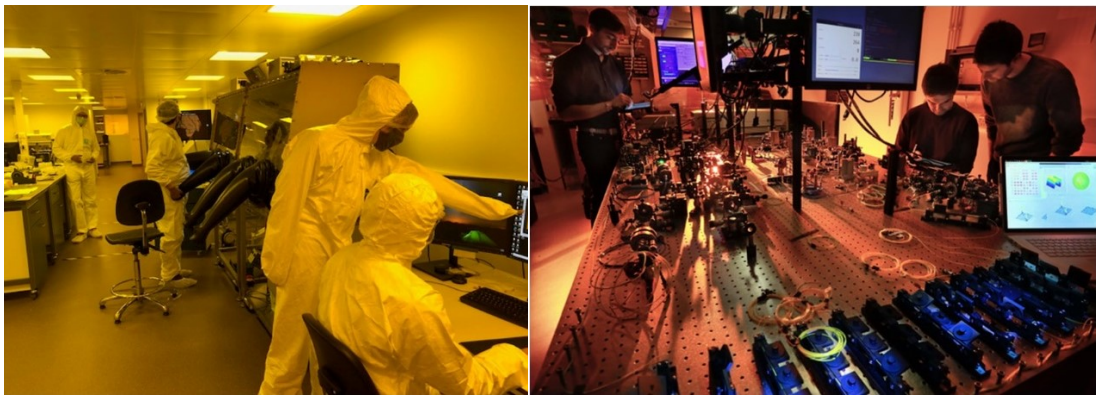

Figure 1: Images of new clean-room facility (left); and part of new inter-connected Quantum Technology Hubs laboratory suite (right).

Our clean-room facilities benefitted from a **£581,515 EPSRC Strategic Equipment** grant "*Two-dimensional Photonics Fabrication Facility*" (**Gerardot**, **Chen**, **Ferrera**, **Buller**) for investment in a new facility, including laser writing and broadband ellipsometry for analysis of two-dimensional films. This grant benefitted from an additional 30% University contribution. This was in addition to the original 2015 **University investment of £1,037,000** to expand and modernise the existing clean-room facilities. This clean-room is specifically designed to address our activities in fabrication of layered semiconductors, preparation and packaging of semiconductor-based single-photon detectors and novel metasurface designs, and integration of quantum photonic components via flip-chip bonding. We have thereby created a unique clean-room capability that addresses our requirements for research in quantum technology and ultrafast photonics.

In 2016, as part of our University commitment to the EPSRC Quantum Technology Hubs, we delivered a further interconnected 119m² suite of laboratories, custom designed for the requirements of quantum photonics. The laboratory suite has been equipped to the highest modern standards for Investigators active in the QuantIC and QuComms Hubs at a cost of **£823,000**. The laboratories are fully interconnected to facilitate collaboration, as evidenced by the on-going enhanced joint research between **Gerardot**, **Fedrizzi**, **Buller**, **Donaldson**, **Leach** and **Malik** and proved instrumental in the award of **Donaldson's** and **Maccarone's** RAEng Fellowships.

Major investment in laboratories has been made for **Travers**' ultrafast photonics research. State-of-the-art clean ultrafast laser facilities have been constructed at a value of **£940,000 with £696,000 from University investment**. These facilities meet the exacting demands of ultra-intense laser experiments. This includes the 2016 investment of **£267,000** for a laboratory within

which the world's brightest and shortest vacuum ultraviolet pulse source has been constructed under the ERC "HiSOL" project. More recently **£429,000 has been invested in an industrial ultrafast light source laboratory**, currently under construction, which is being built to complement **£1,540,000 industry investment**, through which fundamental laser science in hollow-core photonic crystal fibres (PCF) will be applied to the semiconductor sector.

A **University investment of £621,000** was made to support **Cataluna's** ERC "UPTIME" project (2017). The 65m² laboratory supports the development of new methods that will enable the simultaneous high-speed visualization of ultrafast phenomena and the capture of in-depth spectroscopic information in both temporal and spectral domains – all of these at unprecedented speeds, several orders of magnitude faster than the current state of the art. It is anticipated that the access to such timescales, currently not accessible, will generate unique insights into fast transformations such as chemical reactions, phase transitions, laser ablation and other irreversible phenomena in physics, biology and engineering.

4. Collaboration and contribution to the research base, economy and society

Support for Effective Research Collaborations

Physics at Heriot-Watt continues to collaborate widely in the UK and internationally, through its networks involving academia, industry and national laboratories. By focussing on its key strengths in quantum technology and ultrafast photonics, the Unit has forged vital collaborations in this REF period, an essential component in these research areas. The management of Heriot-Watt Physics has encouraged collaboration, setting aside funds for pump-priming activities, and allowing flexibility in the teaching timetable to allow academics to travel to key meetings. Academics are strongly encouraged to share information on new funding and collaborative initiatives, for example, from EPSRC, DSTL, EU, ERC, Innovate UK.

Academic Collaborations

All areas of Physics at Heriot-Watt are involved in academic collaboration at national and international levels. For example, 72% of our submitted outputs in REF contain an author with an overseas affiliation (SciVal), Heriot-Watt Physics has played key roles in collaborations:

- Instigated a number of key collaborations through participating in almost all aspects of the UK National Quantum Technology Programme, including QT Hubs, QT EPSRC Research Fellowship Programme, and industry-led Innovate UK collaborations.
- Developed new major industry and academic collaborations in ultrafast processes in hollow-core photonic crystal fibres, partnering with e.g. Max Planck Institute and Stanford.
- Developed our defence-funded themes in quantum-enhanced imaging and ultrafast lasers.

Quantum

As described in Section 3, Heriot-Watt Physics has been a leading partner in the National Quantum Technology Network from its inception, playing major roles in the QuantIC and QuComms Hubs, the QT Fellowship Programme and the industrial aspects of the Network.

The QuantIC Hub is a collaboration involving academic partners Glasgow, Strathclyde, Oxford Warwick, Bristol, and Edinburgh and has 20 industrial partners including Leonardo, Thales, Teledyne e2V, Jaguar Land Rover, BP, AstraZeneca, Renishaw, BAE Systems, Toshiba, Optos. Heriot-Watt Physics was a key partner in the £23.1M First Phase (2014-2019) engaging in collaborative research directly with Glasgow, Edinburgh, Bristol and Strathclyde. In the £21.6M

Second Phase of QuantIC (2019-24), there are a total of 8 academic partners, with new additions Imperial College London, Exeter and Southampton. Heriot-Watt Physics increased its role in the Second Phase to become the largest academic partner after leaders Glasgow. In both phases, Heriot-Watt Physics has examined the use of quantum detection in next generation imaging including light-in-flight imaging, non-line-of-sight imaging, imaging through obscurants and turbid media.

The QuComms Hub's £25.1M First Phase involved academic partners Heriot-Watt Physics, York, Royal Holloway, Bristol, Cambridge, Sheffield, Strathclyde and Leeds with partners BT, Toshiba, Adva, Airbus, Oclaro, National Physical Laboratory, amongst others. Heriot-Watt Physics has played a leading role in this Hub, leading research in quantum digital signatures and other new quantum communication protocols, on-demand single-photon sources, probabilistic quantum amplifiers, and quantum random number generators. In the £24M Second Phase of the QuComms Hub, the Hub has expanded to 11 academic partners by adding Queens Belfast, Kent and Oxford, Heriot-Watt Physics's work on satellite quantum communications and entanglement networks will take a more prominent role. Heriot-Watt Physics will take an enhanced leadership role becoming the largest partner after leaders York, with **Buller** becoming overall Hub Principal Investigator for 2021-24.

Heriot-Watt Physics has developed strong relationships with the European quantum community. **Gerardot** contributes to the S2QUIP EU Quantum Flagship project, realising on-chip multiplexed entangled quantum light sources as a building block for quantum communication, photonic quantum simulations, and sensing. Heriot-Watt Physics will integrate 2D material photon sources on scalable silicon-based photonic integrated circuits, to reach photon generation rates of 5 GHz. For S2QUIP, Heriot-Watt Physics has partnered with 7 institutes in 5 countries and industrial partners Laser Quantum (UK) and VLC Photonics (Spain). We participate in two large EU FET projects (QuanTELCO and QUROPE) aimed at realising practical quantum repeaters to extend the range of secure quantum communication. QuanTELCO is developing a quantum repeater operating in the telecom O-band based on silicon carbide, a semiconductor that uniquely enables integration of spintronic, electronic, and photonic functionalities. In QuanTELCO, **Bonato** is leading the work-package on high-fidelity control of single spins for the repeater's quantum memory. The project involves 9 EU partners, including the QTLabs Gmbh (Austria). QUROPE is developing a hybrid quantum repeater architecture based on dissimilar quantum systems, where **Mazzera** will build a telecom-wavelength broadband quantum memory, based on rare-earth doped crystals. The consortium includes six academic groups and industrial partners Atrineo AG and Single Quantum. **Malik** leads a European QuantERA consortium (QuompleX) to harness complex scattering media as a new dynamic platform for the manipulation and transport of photonic qudits, high-dimensional analogues of quantum bits. Together, these projects have raised **£1,007,000 in collaborative European grants to Heriot-Watt Physics**.

Ultrafast Photonics

The Ultrafast Photonics Groups continues Heriot-Watt's reputation for collaborative research in nonlinear optics, doing so through four interconnected themes of theory, materials, fibre nonlinear optics and ultrafast sources.

Biancalana and **Saleh** collaborated closely with Max Planck Institute (MPI) Erlangen (Philip Russell), developing simulations describing the extreme conditions governing the propagation of pulses in photonic crystal fibres and underpinning experimental research by **Travers** in fibre nonlinear optics. Research in soliton propagation in nonlinear waveguide arrays was conducted with the external MPI group at Le Quy Don University (Vietnam) from 2013 until 2019.

Biancalana (with **Buller**) helped create the International Max Planck Partnership (IMPP) between selected Scottish Universities (HWU, Glasgow, St. Andrews, Strathclyde and Edinburgh) and Max Planck Institutes in Germany (Hannover, Erlangen, Garching, Dresden and Stuttgart). The IMPP (2014-19) generated £5M funding shared amongst the Scottish partners. Heriot-Watt Physics used this funding for studentship and consumables support for projects with Erlangen, and to support exchange visits to Russell's group in Erlangen, leading to 15 high-profile publications. With IMPP funding, **Biancalana** organised 'The Nonlinear Meeting' in Edinburgh in 2014, which gathered 50 top international scientists from Nonlinear Optics and is still regarded as one of the field's highest profile workshops. In 2015, Faccio (with St Andrews' di Falco and Erlangen's Aiello) used IMPP funding to organize a meeting on 'Optical Analogues for Fundamental Quantum Field Theories', which helped Heriot-Watt Physics develop connections with top North American researchers. The IMPP specifically supported research around the theme of 'Measurement and Observation at the Quantum Limit'. which has relevance for hi-tech industry sectors including metrology, cyber-security and quantum information processing.

Kar's experimental collaboration on 2D materials with the National University of Singapore and the Chinese Academy of Sciences studied the highly controversial optical nonlinearity of graphene, describing the sign of the third-order nonlinearity which was previously misunderstood. More recently, with materials such as transition metal dichalcogenides (TMD), **Gerardot**, **Biancalana** and **Galbraith** have laid a theoretical framework for light matter interactions in TMD, with **Biancalana** having established links with Ornigotti at Tampere University, Finland, funded by the Finnish Academy of Science.

Theoretical insights developed by **Biancalana** and **Saleh** enabled ground-breaking experiments by **Travers**, that provided vacuum- and deep-UV generation at unprecedented efficiencies by exploiting photoionization within hollow-core PCF containing noble gases. The practicality of these new UV sources allowed **Travers** to establish a strategic partnership with ASML, a leading semiconductor lithography company, leading to its £1.54M direct investment. **Travers** developed further international collaborations, including with the Linac Coherent Light Source (LCLS), the free-electron laser at the SLAC National Accelerator facility (Stanford University) and the European X-Ray Free-Electron Laser Facility, Hamburg. These collaborations strive to install a new platform tool for atomic and molecular optics and x-ray imaging experiments at these facilities, offering the shortest optical pulses across the vacuum and deep ultraviolet spectral region yet produced. The same underlying optical technology is also the basis of research collaborations with the Max Born Institute, Berlin, the attoscience group at CNR-IFN, Milan, and Imperial College. In each case, the technology developed by Heriot-Watt Physics enables fundamentally new science. The advanced sources of deep-UV light developed at Heriot-Watt are also the basis of U-Care, £6.3M Healthcare Technology Programme Grant, led by Thomson (UoA 12) with Co-I **Travers**, in collaboration with clinicians (UoA 1) at Edinburgh and physicists at Bath.

The Materials theme concentrates on 2D meta-materials. **Chen's** current research in flat optics is focussed on transformative integrated optical devices to extend current imaging, display and measurement capabilities, performing tasks impossible using classical methods. This interdisciplinary area led to collaborations with Birmingham, St. Andrews, Edinburgh, Glasgow Universities and institutions in Germany, China, Singapore and Korea. **Ferrera**, in collaboration with Purdue University (Shalaev and Boltasseva) and Morandotti at INRS-EMT, Canada, uncovered the interaction between pulses and epsilon-near-zero (ENZ) thin films based on transition metal oxides. In particular, **Ferrera's** PhD students have visited Purdue University (Boltasseva) funded by US Air Force Office of Scientific Research (AFOSR).

Since 2013, continuous STFC funding held by **Reid** has provided a basis for the strategic development of laser frequency combs (LFCs) for astronomy ("astrocombs"), with a notable collaboration being the first on-sky demonstration (2016) of an LFC on the Southern African Large Telescope, which immediately improved the telescope's spectrograph calibration precision by 2× and corrected an error in the measured resolution of the instrument. This led to the incorporation of **Reid's** group into the international Extremely Large Telescope Programme.

Industrial collaboration

The National Quantum Technology Network has fostered significant industrial interaction as it seeks to stimulate the growing UK Quantum Technology industry. This interaction takes place at the Hub level and via several Innovate UK funding vehicles. An important aspect of the Hubs is developing commercial research, and the Hubs employ industrial engagement staff to facilitate collaboration. 20% of Hub resource devoted to Partnership projects which can be used to encourage industrial collaboration, and industrially-relevant PhD studentships. Heriot-Watt Physics led several QuantIC Partnership Resource projects and studentship projects with partners Leonardo, DSTL, Jaguar Land Rover, Lockheed Martin and Sonardyne. Heriot-Watt Physics also took part in the Networked Quantum Information Technologies Hub (NQIT) Hub through a Partnership Resource projects, with a collaboration with Clas-SiC Ltd, a silicon carbide wafer foundry to use quantum sensing techniques to monitor device electric fields, and RouteMonkey (now part of TrakM8 Ltd), a fleet routing specialist interested in using quantum algorithms to optimise services.

Heriot-Watt Physics plays a prominent role in the Innovate UK strand of the National QT Programme, and is now the 4th highest funded University. Heriot-Watt Physics is a key partner in 6 major industrially focussed projects: AQuaSec (total value £8.8M); 3QN (£4.3M); Next-Generation Satellite QKD (£6.7M); SPIDAR (£5.7M); QUeOD (£3.38M); Airguide (£7.7M). There are 23 unique industrial partners in these six projects, and prominent industrial partners include: BT; BP; Toshiba; Leonardo, Thales, Teledyne e2V; Network Rail; IQE. SMEs are also involved in the six projects, and these include: CST; PhotonForce; Arqit; QLM; Wideblue; Aeqiq; Nu Quantum; Bay Photonics; ORCA Computing. In these projects, Heriot-Watt Physics's contribution is in single-photon detector research, satellite-to ground quantum key distribution and single-photon LIDAR. The overall **contribution to Heriot-Watt Physics for these 6 projects was £1,540,000**.

Heriot-Watt Physics has developed its relationship with DSTL in this REF period, particularly in quantum-enhanced imaging and ultrafast lasers. Grants awarded include **nine DSTL/CDE/DASA research awards totalling £1,420,000**, and 4 fully-funded PhD studentships (£550k) and 1 EngD student (£74k). In March 2016, **Buller's** team represented the UK at the NATO SET 205 field trials in Virginia, USA for long-distance imaging in competition with teams from USA, Canada, France, Germany and Sweden. Heriot-Watt Physics's contribution proved highly successful and later appeared on the cover of the US-based Optical Engineering journal in March 2018. **Leach's** team participated in the 2017 NATO white-out field trials in Alpnach, Switzerland. Heriot-Watt Physics has since engaged in three more DSTL field trials. DSTL has also supported **Reid's** laser frequency comb research (also funded by NPL and Renishaw) and resulted in the development of ultrafast optical parametric oscillators with unsurpassed tunability (4.5 – 13.5μm) and power (100mW at 10μm wavelength). These sources were commercialised collaboratively in 2016 with Heriot-Watt spin-out Chromacity Ltd. and have since been sold to end-users in USAF, Sandia National Labs, and DSTL where the technology is accelerating the development of a sovereign capability in remote chemical warfare agent detection.

PGR Collaboration

We continue to collaborate with academic and industrial partners to deliver high-quality postgraduate research education. These formal arrangements have allowed efficient exchange of good practice between institutions. For the duration of the REF period, we have been an integral part of the SUPA Graduate School involving seven other Scottish Physics Departments, as described in Section 2. The CDT Industry-Inspired Photonic Imaging, Sensing and Analysis is led by Heriot-Watt and is a collaboration with 5 other Universities focussing mainly on EngD degrees with industrial partners. The EPSRC CDT in Condensed Matter is also a close collaboration with St Andrews and Edinburgh Universities.

Public Engagement

Heriot-Watt Physics has led several major activities in public outreach for a range of local and national events. Heriot-Watt Physics designed the "*MacroPhoton*" demonstration on quantum cryptography which has been exhibited to a wide variety of age groups at numerous events at the Cheltenham Science Festival (2018), New Scientist Live (London, 2018), Glasgow Science Festival (2018), and the Association for Science Education (Birmingham), and the Quantum City at the Royal Institution event (2019), as well as a host of schools' events. In 2014 we led the '*Creative Cameras*' exhibition (with support from University of Glasgow) which was selected for the Royal Society Summer Exhibition, attended by over 10,000 members of the public. Creative Cameras was subsequently exhibited at the Edinburgh Science Festival and the Edinburgh Festival Fringe. We followed this with our '*Atomic Architects*' team led by **Gerardot** and containing **Galbraith**, **Bonato**, **Biancalana** and their groups. *Atomic Architects* was selected for the 2018 Royal Society Summer Exhibition where our research into two dimensional layered materials was showcased and, again, was visited by over 10,000 members of the public. Atomic Architects has since exhibited at many public-facing events, including the Scottish Science Advisory Council Report Launch (2019) and the Quantum City event at the Royal Institution (2019).

Conference Activities

Physics UoA staff have given 151 invited presentations at major international conferences in photonics, materials science, and quantum science and technology. Examples include CLEO, Photonics West, ECOC, Frontiers in Optics, APS March Meeting, MRS Fall Meeting, IEEE Photonics, OSA Frontiers in Optics, SPIE Optics and Photonics, SPIE Security and Defence, SPIE Defense and Commercial Sensing, QCrypt and numerous other events. These conferences are typically organised by leading learned societies, e.g. IEEE, Optical Society of America (OSA), SPIE, APS. These 151 international conference invitations were at conferences located in North America (34%), Europe (28%), Asia (20%). These **conference invitations were extended to 17 different members of this UoA, comprising 81% of the total number of FTE** – remarkable given the experience range of UoA staff. In terms of conference organisation, this UoA has continued to be active as Subject Chairs and Programme Committee members in a number of major conferences in the field, including CLEO, CLEO-Europe, Euro-Photon, SPIE Security and Defence, SPIE Defense and Commercial Sensing, QCrypt.

Wider Community Contributions, Awards and Recognition

The UoA plays an active role in contributing to the wider physics community. During this REF period, this includes EPSRC Peer Review Panels (**Galbraith**, **Buller**, **Ferrera**, **Gerardot**); Royal

Society Evaluation and peer review panels (**Gerardot**); Royal Academy of Engineering Panels (**Gerardot**); STFC Review Panels (**Reid**); Science Foundation Ireland (**Reid**); Max Planck Evaluation (**Biancalana**). In journal editorial roles: **Andersson** - Associate Editor of Physical Review A; **Bonato**, **Ferrera** and **Cataluna** - Associate Editors, Scientific Reports; **Ohberg** – Editorial Board, Physica Scripta. Guest Editorships have been held by **Buller** (Optical Engineering), **Chen** (J. Phys D); **Cataluna** (IEEE J. Selected Topics Quantum Electronics); **Travers** (IEEE J. Selected Topics Quantum Electronics and Journal of OSA). **Reid** was elected Fellow of the Royal Society of Edinburgh, and **Cataluna** and **Gauger** were elected to the Royal Society Young Academy of Scotland. **Reid** was elected a Fellow of the Institute of Engineering and Technology. **Gerardot** won a Royal Society Wolfson Merit Award. **Buller**, **Kar**, **Reid** become Fellows of the OSA and **Malik** a Senior Member. In 2017, Faccio won the RSE Senior Public Engagement Award. In 2020, **Malik** won a Hind Rattan Award, one of the highest Indian diasporic awards.

The UOA has contributed to Advisory Boards for a number of initiatives some described previously, others include: Fraunhofer-CAP; Photonics 21; OPTIMA CDT; Future Compound Semiconductor Manufacturing Hub (Cardiff); IoP Science and Innovation Committee; EPSRC III-V Semiconductor Facility Steering Group; Wallenberg Centre for Quantum Technology, Chalmers University, Gothenburg.

The UoA hosts regular weekly seminars form visiting scholars and visitors have had extended stays, funded by sources, e.g. SUPA. For example, visits by Heriot-Watt alumnus David Miller, Stanford, and Norbert Lutkenhaus, University of Waterloo.

UoA staff have been active in the media promotion of their work, including numerous BBC appearances and articles in the New Scientist, Times, Daily Mail, New York Times, Independent, and numerous other international outlets.