Institution: Royal Holloway University of London

Unit of Assessment: 12 Engineering

Section 1. Unit context and structure, research and impact strategy

In 2016 Royal Holloway made the strategic decision to strengthen Engineering in the College by establishing Electronic Engineering as a new department. New appointments in Electronic Engineering and sustained growth in engineering research within the Department of Physics and the Information Security Group (ISG) led to the creation of the **Engineering Research Centre** (ERC) in 2018. The Engineering Research Centre represents Royal Holloway's first submission to panel 12.

The Engineering Research Centre acts as the focal point to develop our engineering community, unconstrained by departmental boundaries. Together with new appointments in Electronic Engineering since 2016, the Centre incorporates flourishing activities such as the Smart Card and Internet of Things Centre, Quantum Materials and Technology and Accelerator Engineering. Engineering research has been strengthened by the formation of the School of *Engineering, Physical and Mathematical Sciences* (EPMS), part of the College-wide six-School structure created in 2019. EPMS comprises Electronic Engineering, Physics, Information Security, Computer Science and Mathematics. The foundation of Electronic Engineering was supported by £23m investment in the new state-of-the-art Beatrice Shilling building, opened in March 2019.

Engineering is playing a key role in all four of the new College Research Catalysts, as part of the Royal Holloway Strategy 2020-2024 (Ref5a). The catalysts will capitalise on key strengths and expertise to address contemporary challenges and provide a structure for the increasingly interdisciplinary nature of future research. Engineering is taking a leading role in two of the Catalyst subject areas, namely "Advanced Quantum Science and Technology" and "Transformative Digital Technologies, Security and Society", and will also actively participate in the other two: "Digital Futures in the Creative and Cultural industries" and "Living Sustainably".

1.1 Unit structure

The Engineering Research Centre comprises nine staff from Electronic Engineering, five from Physics and four from Information Security. Our strategy has been to organise around four central research themes, to which staff activity contributes:

Nanomaterials and devices: Five academics contribute to this theme. Electronic Engineering researchers (Liu, Bryan) join engineering-focussed staff based in the Department of Physics (Meeson, Casey, Nicholls) to study a broad range of quantum materials and devices.

Digital and security engineering: Digital and Security Engineering is the largest area of activity in engineering at Royal Holloway. It connects our expertise in Cyber-Physical Security and the Internet of Things (Markantonakis, Mayes, Wolthusen, Hurley-Smith) with signal processing, electronic hardware and devices (Howard, Cheong, Tisan).

Microwave, photonic and accelerator engineering: The engineering team in Accelerator Physics (Boogert, Gibson, Lyapin (Senior Research Officer) and Microwave Photonics and Sensors (Haxha) joined to form the Microwave, Photonic and Accelerator Engineering Theme. This consolidates our flagship strengths in advanced electromagnetic engineering.

Energy: The energy theme draws together staff with interests in energy generation and distribution with wind and solar (Kuenzel, Nduka, Haxha and Hogg), conservation and efficiency via lightweight structures (Hogg, Haxha), and cyber security linked to critical national infrastructure and energy grids (Haxha, Wolthusen, Mayes).

1.2 Research strategy 2014-2020

Key research objectives in Engineering during the period 2014-2020, identified by each research theme, with achievements are as follows:

Nanomaterials and devices *research on* superconducting quantum devices for quantum information operating at low temperatures; development and study of novel materials and structures for room-temperature spintronic data processing; emergent phenomena in a range of topological quantum materials with potential device applications. Key technological capability was established in the fabrication of superconducting quantum devices (of central importance in the strategy of the National Centre for Quantum Computing).

During 2014-2020, the staff in this research theme have won (as PI/CI) £13.3m in grants, published 81 peer reviewed publications and two monographs.

Digital and Security Engineering provides wide-ranging expert capability, supporting industry and the digital economy, including the application of industry 4.0 principles with secure communications, supporting clean growth, boosting the expansion of the creative industries, all within robust frameworks of security privacy and trust. A major component of the theme is the Smart Card and Internet of Things Research Centre (SCC) which has undertaken significant collaboration with the University of Southampton and the 5G centre at the University of Surrey. The world-class research base at the College in Cyber Security, AI and Machine Learning located in Computer Science, Information Security and Physics has recently been augmented by creative digital experts on VR/AR in Media Arts, working in collaboration with Electronic Engineering within the AHRC £11m Story Futures Initiative (Howard is a CI). A further example of interdisciplinary reach is the EXFILES project (Markantonakis), funded by Horizon 2020 from July 2020, which is a multidisciplinary collaboration to extract forensic information from encrypted smartphones for law enforcement agencies.

During 2014-2020, the staff in this research theme have won (as PI/CI) £8.8m in grants from industry, published 77 journal articles, four books, 21 book chapters and over 60 conference publications in the cyber security field.

Microwave, photonic and accelerator engineering develops step changes in speed, miniaturisation and reliability in device applications, in the fields of charged particle accelerators and high-speed communications. This theme supports substantial overlaps in both underpinning methods and applied instrumentation between the fields of charged particle accelerators and high-speed communications. Research and applications in this theme has motivated a shift to higher frequencies (THz and optical) and new challenges.

Current research programmes include non-invasive laser and high bandwidth electro-optical sensors for particle beam instrumentation, which share the technology base with single-mode telecommunication devices in novel architectures. The more traditional part of the spectrum is represented by electromagnetic devices for particle beam diagnostics in accelerators and complementary research into analogue radio over fibre, with novel frequency up-/down-conversion and nonlinear waveguide devices.

During 2014-2020, the staff in this research theme have won (as PI /CI) £6.8m in competitive research grants, published a total of 89 peer reviewed publications and two patents applications.

Energy research supports the generation of renewable energy and energy efficiency, by contributing to the development of enhanced wind turbines and solar cells, improving the distribution, storage and security of energy supply via the modelling of power grids. Kuenzel and Nduka (both ECR's) work with Wolthusen, on modelling energy grids with integrated low-carbon technologies, including photovoltaics, energy storage and electric vehicles. This establishes links with the Digital and Security Theme. Wolthusen is contributing his expertise on the analysis of real time cyber-physical systems to the security of power grids. Kuenzel is working on optimising power systems for renewables and energy storage, and as part of an interdisciplinary project on the impact of the large-scale roll-out of smart meters on freedom of choice and privacy.

Research on solar cells is undertaken by Haxha, who has been focusing on improvements in the efficiency of silicon-based thin-film solar cells exploiting 3D layer structures and incorporating graphene and Au/Ag nanoparticles.

Research on the structure of wind turbine blades is undertaken by Hogg in collaboration with the University of Manchester. The focus is on lightweight, damage tolerant, and fatigue resistant composite structures. This includes work on fundamental damage processes and toughening mechanisms in fibre composites, with an emphasis on the use of textile formats such as 3D woven fabrics, interlayers and the use of hybrid comingled fibre tows.

During 2014-2020, the staff in this research theme have won (as PI /CI) £1.05m in competitive research grants and published a total of 50 peer reviewed publications.

1.3 Strategic aims 2021-2026

The Engineering Research Centre aims to support the delivery of innovation from discovery science across the EPMS School and Royal Holloway as a whole.

- **Exploit the interdisciplinary structures of College Catalysts to maximise the potential of our themes.** The *Nanomaterials and devices* theme will play a central role in the College Catalyst on Advanced Quantum Science and Technology. The *Digital and Security Engineering* theme is central to the Transformational Digital Technologies, Security and Society catalyst and will contribute to Digital Futures in the Creative and Cultural Industries catalyst. The *Microwave, photonic and accelerator engineering* theme will play a central role in the Advanced Quantum Science and Technology Catalyst, through established expertise and industrial links in quantum communication, to the interface with superconducting quantum technology, where the marriage of quantum-aware RF engineering to superconducting microwave resonators and quantum devices is critical. The *Energy* theme will contribute to the Living Sustainably Catalyst that incorporates research on fossil fuels and geothermal energy, new battery science and biodigesters.

- **Further develop shared underpinning infrastructure**. Invest in RF engineering for quantum technologies and wireless communications, building on expertise and capabilities within microwave, photonic and accelerator science theme. For example: a high frequency radiofrequency (RF) test and measurement suite (already under development) and enhanced facilities for SCC and automation/autonomy and robotics (planned).

- **Promote and grow internal and external research partnerships and strategic collaborations.** As the ERC and Catalysts evolve and strengthen, expand collaborative research with regional HEIs, laboratories (e.g. National Physical Laboratory), National Centre for Quantum Computing, companies (e.g. Leonardo) and organisations (QCHQ, NCSS). Underpinned by internal investment in staff through joint appointments, PhD studentships and support for research grant applications.

1.4 Further support of Interdisciplinary Research

Our interdisciplinary research, embedded in the College research strategy, aims to encourage collaboration to solve pressing real-world problems. This strategy has resulted in the development of the interdisciplinary research Catalysts, which will strengthen our links with industry and government. In other initiatives, interdisciplinary collaborations are supported by PhD studentships (Section 2.2). The collaboration between supervisors underpins applications for interdisciplinary grant funding. Collaboration with Psychology on sonic guidance for the blind using light detection and ranging (LIDAR) is an example.

1.5 Strategy for enabling Impact

The impact strategy of the ERC is to work on a mixture of pure and applied research, in collaboration with industry, government and standardisation bodies, at regional, national and international level. Our objective continues to be to support the national and regional industrial strategies, through our chosen themes. The Royal Holloway Research and Innovation office actively seeks opportunities to work with industry, interacting with the Local Growth Hubs, LEPS, and Chambers of Commerce. Hogg, when Vice Principal for Enterprise, was the HE representative on the local LEP (Enterprise M3) from 2017-20 and played a significant role in shaping the Local Industrial Strategy and Regional Economic Plan. He was a major contributor to the Science Innovation Audit for the South of England (Innovation South) published in 2018, which identified the major engineering strengths of the region. This informed Royal Holloway on the importance of digital enabling technologies and identified how Royal Holloway could act as an Anchor Institution for the regional economy in the areas of cyber security, AI and quantum technologies. The Local Energy Strategy (2020), developed by three LEPs (Coast to Capital, EM3 and Southeast LEP) as South2East, has also outlined where Royal Holloway can support regional energy projects in areas such as microgrids, solar, wind and domestic energy efficiency.

Each theme in this Unit has its distinctive approach to enabling impact:

Digital and Security Engineering: Cyber security is a key driver for regional business both in terms of protecting existing businesses and creating new cyber security start-ups. We will continue to be fully engaged with government via GCHQ/NCSC strategy, expanding academic activity in cyber security alongside investment in the Smart Card and IoT centre (SCC) to provide a practical vehicle for a range of applied research and developing impact with industry.

These long and trusted relationships with industry and government are underpinned by a commitment to ethical security research and responsible disclosure; and this has led to important contributions to international security standards. Mayes' work on evaluating the TUAK algorithm for telecommunications standards (**Impact case study 1**) was in support of the European Telecommunications Standards Institute, the GSM Association, and the Third Generation Partnership Project (3GPP).

The current focus of the SCC is on hardware and cyber-physical security systems applied to business sectors including telecommunications, fintech, land transport, aerospace and other

critical infrastructures. Delivering impact will rely on the long-standing and established structures for industrial engagement within the ISG.

Microwave, Photonics and Accelerator Engineering: We continue to work closely with industry, both within established partnerships and exciting new ones, directly adapting our expertise to address their needs. This relies on a combination of industry and UKRI funding. Two examples illustrate this approach:

In communications technology, our research has been supported by direct industry funding (Leonardo-Electronics, Defence & Security Systems). This has allowed us to successfully develop and patent technologies that will be exploited by sponsors. For example, microwave frequency mixing technologies in an analog photonics link have been developed, delivering improvements in performance factors that allow higher data transmission rates for 5G/6G Networks. A novel approach to photonic microwave filtering, using non-linear optical waveguides, allows practical optical links with an unprecedentedly broadband dynamic range, free from spurious signals.

In accelerator science, our strategy was supported by STFC through the John Adams Institute and STFC-IPS grants. Royal Holloway developed a device that controlled electron beam alignment, a key component for commercial Free Electron Lasers (FEL). This work was driven by demand for smaller-scale FEL facilities for industry, but business models tend to be hampered by the lack of commercially availability of essential components required to build them. Licensing our technology to an internationally-leading synchrotron component company in 2019, resulted in the world's first commercially-available device of its type. This approach is captured in **Impact Case Study 2**.

Our future strategy builds on this approach, pursuing diverse opportunities for exploiting our expertise. New and emerging areas encompass advanced particle acceleration techniques using solid-state materials and plasma; applications of novel acceleration and beam transport techniques; simulation tools in radiobiology, medical imaging and cancer treatment.

Nanomaterials and Devices:
Our aim has been to contribute to the second quantum revolution by establishing key capabilities. The strategic approach was to create a new nanofabrication facility, with UKRI and College support: the *UK Centre for Superconducting and Hybrid Quantum Systems.* Prior to this the development of quantum technologies was hampered by a lack of scalable capacity in superconducting hardware that could deliver transformative products for sensing, security and information processing at commercial scale. The development of foundry and measurement services that will underpin major commercial developments across the economy places Royal Holloway at the heart of the UK's ambition to lead the international race in commercialising quantum technologies. This key role in the national supply chain to industrialise the design, manufacture and test of superconducting quantum devices, has significant Innovate UK support (consortium led by Oxford Quantum Circuits).

A related strand of activity is the long-standing relationship with Oxford Instruments based on research that exploits the specialised facilities of the London Low Temperature Laboratory (LLTL) and nurtured by seven former research staff and students moving to the company from Royal Holloway, with knowledge exchange codified by memoranda of understanding. This has shaped research conducted under the framework of the European Microkelvin Platform towards novel cryogenic platforms.

Energy:
This featured a strategic interdisciplinary response to the government's Advanced Manufacturing Supply Chain Initiative in the area of lightweight composites, benefitting from the direct industrial experience of Hogg in this sector. We examined the ability of the UK supply chain to adopt and benefit from new technology applications, considering factors such as skills, labour availability, finance and upstream and downstream supply.

Selection of impact cases for REF submission
The two selected case studies emerged from our relationships with industry, government and standardisation bodies, representing our approach to enabling impact. Academics submitted proposals; these proposals were supported (and acknowledged in workload models) and reviewed. After due consideration, two were selected for submission by the Engineering REF team. **Impact Case 1:** Standardisation of the TUAK Algorithm for eSIMs: Transforming Security for Internet of Things and Consumer Devices Worldwide, resulted from an invitation to support international standards based on recognition of Royal Holloway security expertise. **Impact Case 2:** Transforming the manufacture and global market in enabling technologies for Free Electron Lasers, relied on forming industrial partnerships (FMB-Oxford and Instrumentation Technologies (iTech, Slovenia)), to exploit Royal Holloway designs for Cavity Beam Position Monitors, in the supply chain for international Free Electron Laser facilities.

1.6 Open Research, Ethics and Reproducibility
Royal Holloway's Open Access Policy requires researchers to submit copies of their research publications to Royal Holloway's research information systems (Pure) within three months of the date of acceptance. Outputs are checked by the Research Support Team, who arrange Open Access in line with publishers' policies. Funds are available either from research grants or centrally to pay article processing charges that make papers freely available.

A new Research Data Management Service was introduced at Royal Holloway after REF 2014; Dropbox for Business provides secure unlimited storage for research data. The servers and data storage are in the EU and the accounts are managed by Royal Holloway IT Services. We can share data from our Dropbox accounts with Royal Holloway research students and with research partners in other institutions, ensuring data reuse and reproducibility. Long term storage of data is provided using figshare.

Our research is governed by the ethical, legal and professional frameworks and standards of Royal Holloway. This policy is in turn based on the UK Universities Concordat to Support Research Integrity. It applies to both unfunded and funded research and to all employed staff, students or other individuals acting on behalf of the College. Heads of Department and Research Directors are responsible for providing ethical reviewers and supporting researchers via peer review process to address potential ethical issues and report them to the Royal Holloway Research Ethics Committee. A Research Ethics & Integrity Manager in the Research and Innovation office is responsible for supporting the Research Ethics Committee and an online ethics system.

Section 2. People

2.1 Staffing Strategy and Staff Development

The Engineering Research Centre (ERC) draws together engineering focussed staff with teaching and research contracts across three Departments in the School of Engineering, Physical and Mathematical Sciences (ten category A staff from Electronic Engineering, five from Physics and three from Information Security). All Departments share College staffing policies and support structures, with implementation and strategy are coordinated through the School. Electronic Engineering is based in an attractive new building, purpose-built to be open, safe and welcoming for diverse groups of academics, staff and students.

Staffing and Recruitment

Recruitment has centred around establishing the Department of Electronic Engineering, which now hosts 12 academic staff members, of which 50% are from under-represented groups (based on gender and ethnicity). The ERC is supported by 10 technical staff and eight PDRAs. The recruitment strategy ensures that all new research and teaching staff are of the highest quality; to achieve a mix of theoretically-based and practical applied research, while supporting the succession and expansion plans of the core research themes. Recruitment is based on merit, and attempts are made to ensure that shortlists contain a good mix of candidates with a range of gender and other protected characteristics. Interview panels are always of mixed gender, and panellists receive interview and unconscious bias training, which led to diversity in our engineering staff.

Staff Development Strategy

The home departments for engineering (EE, Physics and ISG) make use of Royal Holloway resources for staff development, including the “Advance” programme for in-service training. In 2019 Royal Holloway received the HR Excellence in Research award, demonstrating our commitment to the principles of the *UK Concordat to Support the Career Development of Researchers*. The College Research Expectations document gives guidance to staff, at all career stages. All staff have an annual Performance Development Review (PDR), reviewed by their line manager. Annual workload allocation to staff is the responsibility of each Head of Department, using a quantitative workload model. This balances teaching and administrative duties and explicitly recognises impact activities and research grant submissions. An Individual Research Plan is an integral part of the annual Personal Development Review. The Research & Innovation Department supports grant applications by holding clinics where examples of both successful and unsuccessful applications are examined. All colleagues are supported by internal reviews of research grant applications before submission. The Engineering Research Centre provides an additional layer of mentoring and advice with senior staff from different departments encouraged to assist junior colleagues in reaching their goals, particularly with cross-discipline opportunities, and to nominate high-performing staff for the annual reward scheme.

Recognition and Reward

All staff are invited to apply for promotion annually. All promotions are considered anonymously and assessed against a criteria matrix under four headings: Research, Teaching, External Engagement, and Leadership and Enhancement. Royal Holloway also has an annual reward scheme to recognise exceptional staff contribution. Excellence within the ERC has been recognised and rewarded by four promotions to Reader and Senior Lecturer level and three Professorships (Boogert, Markantonakis, Meeson); and externally, through the award of a Royal Academy of Engineering personal fellowship (Liu).

Supporting Early Career Researchers

An EPMS school-wide ECR Forum, with two seats on the EPMS Research Committee, supports the ECR community, promoting peer-to-peer interactions, interdisciplinary research, and contributing to effective delivery of the Concordat. There is a small grant scheme that has been developed to allow ECRs to bid for up to £5K to support a research application, facilitate early-stage experiments, encourage innovation, or undertake research visits. Newly appointed academic staff, usually ECRs, have a probation period of three years with a lighter teaching load. Early career staff are mentored by senior colleagues, including help with writing research applications and advice on impact-related research and research funding. At its launch, the immediate priority in Electronic Engineering was undergraduate education delivery and a number of early career staff were recruited on teaching-focused contracts. Two were converted to teaching and research contracts, in recognition of their research potential, leading subsequently to promotion to Senior Lecturer (Kuenzel) and Reader (Liu). As a further example Bryan was promoted from a post-doctoral researcher to a permanent academic post in 2019.

Policies for Research, Impact Leave/Sabbatical Leave

All staff become eligible for a sabbatical of one teaching term for every five terms actively engaged in teaching. Staff may accumulate the qualifying teaching terms and take extended sabbaticals with the approval of the Head of School. To be granted this leave, a research plan must be submitted. For example, the sabbatical of Mayes (started 2018), was to explore research on the boundary of engineering and cyber security. This was supported with equipment from the MULTOS industry consortium and resulted in seven collaborative publications, including one on smart grid security, and work to underpin and quantify **Impact Case 1**. The sabbatical of Markantonakis (2017), expanded our research portfolio on memory protection and device forensics, and enable related grant applications.

Exchanges and Secondments

Staff are encouraged to apply for secondments and exchange programmes, to benefit their career development or support a specific research goal. So far take-up is limited, although staff taking visiting roles have been funded by research grants e.g. Cheong with the university of Jaen in Spain and Markantonakis with the Université de Bordeaux. Recent secondments (Mayes) were prevented by the pandemic.

2.2 Research Students

Recruiting Doctoral Students

PGR studentships are advertised across departmental web pages and on external web sites. The allocation of PGR students to supervisors is undertaken via direct discussion between potential supervisors and students. Application details are circulated to all staff in the students' area of interest. Where student/supervisor teams are competing for limited studentships, in the CDT for cyber security or the Leverhulme Doctoral School, an independent panel is constituted that assesses the merits of each research proposal. The College hosts a Leverhulme Doctoral Centre that focuses on individual freedoms in the digital age. Ten studentships/year were funded for three years with the college providing 50% of the funds. It was mandatory that each studentship had a co-supervisory team drawn from at least two departments, with both Electronic Engineering and ISG participating in the programmes, linking technical research with consideration of ethics, legal and societal concerns. Since 2013 the ISG has run EPSRC doctoral training centres focussed on cyber security, where it is common for students to have two supervisors, from different disciplines and departments.

Support and Monitoring

A Code of Practice governs PhD supervision. All students are interviewed and allocated a

supervisory team with at least two staff members (typically a supervisor and advisor). The frequency of meetings is monitored, and training needs are identified at annual review. These reviews are attended by a third and independent person, and upgrades from MPhil to PhD are considered within 20 months of full-time study or part-time equivalent. A Doctoral School, led by the Deputy Principal (Academic), was created in 2019 to further bind our community of PhD students together and provide training, administrative support and social activity. The School of EPMS Director of Post Graduate Research Education liaises with the Doctoral School, reports to School Research committee and serves on the Research Degree Programme Committee. These are also attended by student representatives. Induction events, social gatherings and an annual research symposium are regular features of the research community.

Skills Development and Careers

Each of the departments contributing to Engineering (Physics, EE and ISG) has bespoke training programmes to support and assist students to acquire practical skills with relevant equipment and analytical techniques. For example, the sequence of CDTs focussed on cyber security have supported training for their EPSRC funded students. The Physics department is a member of the SEPnet consortium of South East university Physics departments and this collaboration runs a PhD training programme linking students from all participating universities. All PhD students can present results at an International Conference, funded by the training allocation of their scholarship or the research grants of their group. Those students without an explicit allocation are supported by their host Departments.

The CDT uses external experts to discuss intellectual property and start-ups arising from students' work. The SCC (Markantonakis), engages students in practical development work which has led to funding (Set-squared/Innovate UK) of two start-up opportunities (PrineSec and Seclea) within the past two years.

2.3. Equality and Diversity

Supporting career pathways and equal opportunities

Royal Holloway has had a strong ethos of encouraging diversity in its staff and students since the founding of the original constituent colleges (Bedford College and Royal Holloway) which were both women-only colleges at their inception. The College carries out a comprehensive annual equality and diversity data monitoring and review exercise. For the Engineering Research Centre, the implementation of policy is reinforced by exchange of best practices across the EPMS School, supported by its Equality and Diversity lead, reporting to School Executive.

We illustrate this environment as follows. Physics is a long-term Institute of Physics Juno Champion and Athena Swan Silver Award recipient, with a consistently above average recruitment of women at all levels. Within the engineering group, ISG (with the Department of Mathematics) recognised the importance of encouraging and funding the creation of WISDOM (Women In the Security Domain and/or Mathematics). The WISDOM group is an Equality and Diversity (E&D) success story, and was founded in May 2016 by two women, both PhD students, who wanted to raise the profile of women, working and studying in the field and encourage more women into these academic disciplines. The scope of WISDOM has since expanded, stretching across the EPMS School and addressing equality and diversity in its broadest sense. WISDOM greatly enriches the environment of the School and its achievements were recognised in 2017 with the Principal's award for enhancing fairness. Electronic Engineering has a founding objective to overcome the national *gender imbalance* by attracting more women to the subject, and has

recruited over 30% female students with an overall academic staff complement that includes 33% women. The category A staff promoted in the assessment period were both women.

Flexible working. All members of staff with at least 26 weeks service, are eligible for flexible working according to Royal Holloway policy. They may request changes in their working hours, including changing from full-time to part-time. Adjustments are agreed through discussions with the line manager and HR. One member of academic staff (from EE) has taken 12 months maternity leave in two 6 month blocks. Teaching and essential meetings are confined within 10:00-16:00h under institutional policy. During COVID-19, following a shift to working from home for many staff and PGR students, equipment (laptops, graphics tablets, webcams, and mobile phones) and Internet access were made available to enable productive remote research.

Support for conference attendance for those with caring duties follows College policy, as does support for those with protected characteristics. Office facilities, such as standing desks, have been provided where the need is identified.

Encouraging ambition and supporting wellbeing

Career pathways for part-time and fixed term staff are strongly supported by the Advance training programme and peer-to-peer groups such as the School ECR forum (reporting to School committees) and WISDOM and. WISDOM offers a strong support network of students and staff, who are interested in exploring ways that more women and minorities can enter and prosper within academia. Activities include monthly lunch meetings, workshops, discussion groups, outreach activities and social events.

Equality and Diversity in the REF submission

Based on the Royal Holloway Code of Practice for REF2021, all unit staff members assessed as independent researchers, were asked to nominate up to five preferred research outputs on Pure, the research information system used by Royal Holloway. The unit REF Lead and the heads of the three Departments have ensured a rigorous assessment of the quality of the outputs of each submitter. Assessment involved a critical engagement with the work by academic colleagues from our research themes and assessed internally by two reviewers. Where no suitably qualified academic staff was available to undertake this, or there was an indecision around borderline outputs, we engaged an external reviewer with the approval of the Chair of the College REF Steering Group. The REF Lead selected the highest rated item for each independent researcher for submission. The remaining items for selection to make up the required number was chosen by selecting the highest rated outputs from current and previously employed staff, taking Equality Impact Assessment into account. No gender or minority bias was detected in the selection of outputs.

Section 3. Income, infrastructure and facilities

3.1 Research Income

The Engineering Research Centre plays a pivotal role in delivering innovation from discovery science. A key achievement has been to win a string of equipment grants to develop a unique portfolio of capabilities for manufacturing superconducting quantum devices, thereby supporting our strategy for growth. Successful bids were led by Meeson to EPSRC Strategic Equipment (2018) and EPSRC Capital Core equipment (2019), building on prior awards. This established the **SuperFab** nanofabrication facility, hosting the *UK Centre for Superconducting and Hybrid Quantum Systems.* Key to this success was a strong collaborative team involving National Physical Laboratory (NPL) and Oxford Instruments. This facility and expertise led to a major Innovate UK grant of £7m led by Oxford Quantum Circuits with the objective to industrialise the design, manufacture and test of superconducting quantum devices. This was part of the largest ever government grant (£7M in total) aimed at the commercialisation of superconducting quantum technologies, and positions the UK as a global leader in the field. This activity is a main thrust of Royal Holloway's Advanced Quantum Science and Technology Catalyst.

We have leveraged our expertise to participate in several large EPSRC programme grants. Nicholls (co-I): EP/K004077/1 (PI M Pepper UCL, £6.5m) explored technology and applications of nanoelectronic based quantum physics; EP/R029075/1 (PI M Pepper UCL, £7m) will experimentally realise a system with many body localisation for applications in quantum information and topological quantum protection. In related research Wenqing Liu's work on topological spintronics has been enabled by an EPSRC New Investigator Award (EP/S010246/1) and a Royal Academy of Engineering/Leverhulme Trust Senior Fellowship. The London Low Temperature Laboratory is part of the European Microkelvin Platform (EMP), funded as a European Advanced Infrastructure from 2019. Casey's participation in EMP has helped drive innovation in cryogenic technology with Oxford Instruments (an industrial partner in EMP), where the focus is on cryogenic platforms and thermometry, essential to future superconducting quantum technology.

The Nanomaterials and Devices theme (Liu, Bryan) has secured access to the Diamond Light Source, with over £2m in beam time awarded over the REF period. This has been essential in pioneering studies of surface magnetism in topological insulators and to complement electrical transport studies. Liu also secured research time on specialised fabrication facilities in the USA and China.

Significant and sustained STFC funding for the John Adams Institute has enabled the accelerator science group to both support next generation particle accelerators and exploit expertise to develop new technologies for industry and interdisciplinary applications.

3.2 Infrastructure and Facilities

Our strategy has been to engage with national and international priorities and organisational structures; including investment in infrastructure delivering leading capabilities for research on Quantum Science and Technology. Across the Engineering Research Centre our facilities provide access to national and international research communities and industry, fostering collaboration, building new networks for ECRs, and driving diversification of research.

The Electronic Engineering department has developed its in-house research facilities from scratch, largely around the new purpose-built Beatrice Shilling Building. This building

represents a £18m investment from the Royal Holloway together with £5m from HEFCE to support the Royal Holloway objective of developing a diverse and inclusive department with the building designed to feel safe and welcoming (e.g., for students working late at night) and to foster creativity and inclusivity. It features collaboration spaces for group working and networking of staff and students.

Research laboratories in the new Shilling Building include a dedicated laboratory to facilitate industrial collaboration with defence electronics company Leonardo. This laboratory is focusing on quantum communications using photonics, and the laboratory has been equipped by substantial donations from Leonardo. These capabilities will be boosted further, by the new EPSRC capital equipment and UKRI World Class Laboratory funded EPMS radio-frequency laboratory, with a 70 GHz Vector Network Analyser, spectrum analyser and other equipment.

To establish the UK as a key player in the development of a quantum computer, Royal Holloway invested £3M in creating a new cleanroom facility **SuperFab**, hosting the *UK Centre for Superconducting and Hybrid Quantum Systems* (Director Meeson), in association with NPL and JEOL. Opened in 2018, it is a user facility serving academia and industry; supporting fundamental research into superconducting quantum devices and technology. UKRI investment has established SuperFab as a key part of the supply chain in the global race for a quantum computer based on superconducting qubits, recognised by the *National Quantum Computing Centre* as a leading technology and investment priority. The nanofabrication facilities also support the wider nanomaterials and devices theme.

Activities at Royal Holloway in Digital and Security Engineering have a track record of working closely with industry and government. The ISG was established in 1990 to serve the needs of industry and government, recognised with a Queen's Award for Industry in 1998. In 2002 the Smart Card Centre was created with backing from the telecommunications industry (Vodafone and Giesecke & Devrient) and emphasis on SIM cards, which later evolved through card payment systems (UK Cards Association, VISA) into transport (Transport for London, ITSO) and into an IoT and embedded systems security centre (the Smart Card and IoT Centre, SCC). Industry supporters (Barnes, Comprion, Gemalto, Infineon and Mastercard) donated equipment for test and development of cryptographic algorithms, protocols and system implementations.

Since 2019, the SCC has been hosted in a modern dedicated laboratory and development suite within the refurbished Bedford building. This facility allows building and testing of physical systems that can be evaluated for IoT applications, autonomous vehicles and in the near future broadcasting equipment. The SCC regularly invites companies to explore the security of their products within the centre.

Advanced audio research work is supported within the Story Futures Academy by a 24.1 ambisonic studio with control room and voice recording space.

Mechanical and Electrical Workshop**:** Research across all themes is supported by skilled precision engineers and technicians in the mechanical workshop (located in the Department of Physics) and electrical workshop (located in the Departments of Physics and Electronic Engineering). Interactions with the workshop team promotes early career involvement in R&D. Rapid prototyping and design support are essential for the development of the applied research skills base. A programme of upgrades with STFC and Royal Holloway funding has enhanced the capability of the mechanical workshop with new CNC machines. An RF Test and Measurement laboratory is

will to house high end equipment, including that recently funded an EPSRC Core equipment grant, and UKRI World Class laboratory support.

3.3 Addressing equality and diversity

All facilities are open access within Royal Holloway. Annual internal equipment bids are assessed openly and transparently. All staff are supported equally in bidding for grants, fellowships, sabbaticals, with input invited from WISDOM, the relevant Athena Swan Champion, Heads of Department and the Head of School.

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

4.1 Supporting Collaborations

Members of the Engineering Research Centre have established a number of high-profile collaborations both before and during this REF period.

The **John Adams Institute for Accelerator Science** (JAI, Deputy Director Gibson) was established in 2004 by Royal Holloway and the University of Oxford, with Imperial College joining in 2011. It receives regular block funding (e.g. £1.5 million in 2017) from STFC. The JAI has made major contributions to the design and development of UK x-ray and neutron facilities and international particle physics accelerators. It has been instrumental in training a new generation of accelerator engineers. It supports the application of accelerator technology to areas such as cancer therapy, where we have recently collaborated through simulating proton beam facilities with the Université Libre de Bruxelles and Ion Beam Applications.

Royal Holloway is strongly engaging with the UKRI Quantum Technology Programme through the **UK Centre for Superconducting and Hybrid Quantum Systems** (SuperFab, Director Meeson) and the wide spectrum of collaborations it supports. SuperFab involves collaboration with NPL, JEOL and Lancaster. Access to this facility is free to UK academic users, driving collaboration on quantum technologies across academia and industrial engagement, with Innovate UK support. Partners include: Oxford Quantum Circuits, SeeQC, JEOL, Chase Research Cryogenics, Kelvin Nanotechnology, Oxford Instruments Nanoscience, ColdEdge Technology, Qinetiq Ltd., and Johnson Matthey. Quantum Technologies for Fundamental Physics awards, announced after REF2021, will enable our interdisciplinary work on applying quantum sensing to fundamental particle physics. We lead the £3.4M QUEST-DMC consortium (PI Casey, RHUL), and collaborate on the QSHS axion search development (PI Daw Sheffield, co-I Meeson, £4.8M).

The €10M EU Horizon 2020 **European Microkelvin Platform, a European Advanced Infrastructure**, links all major ultra-low temperature laboratories across the EU with several industrial partners including Oxford instruments. A further exemplar of international collaboration at the highest level is the **International Cyber Security Center of Excellence (INCS-CoE)** formed in 2019; with Mayes a Director and current Vice-Chairman. INCS-CoE was created to support international cyber security research, education and collaboration between academia, industry and government. There are six Founder institutions: Royal Holloway and Imperial College (UK), Northeastern University and the University of Maryland Baltimore County (USA) and Keio and Kyushu (Japan) The Centre is expanding, with the addition of the University of Cambridge (UK), Technion and Ben Gurion Universities (Israel).

4.2 Contributions to the Economy and Society

Royal Holloway is within the region of the Enterprise M3 Local Enterprise Partnership (LEP) and Hogg was an elected board member and chaired its Higher Education Working Group (2017-2020). He also served on the steering group of the “Innovation South” Science Innovation Audit (2018) that identified the strengths of the South of England in engineering. and stimulated new collaborations between its key universities and industry. Examples include: Story Futures; Collaboration in Quantum Technologies; Cyber security/AI links between University of Surrey, Royal Holloway and Brunel. We are active in influencing government policy on cybersecurity matters; Mayes was instrumental in the creation of the Cyber Security All Party Parliamentary Group, and now provides the secretariat, as well as being a guest expert in the security strategy workshops of the Royal United Services Institute (RUSI).

Consultancy projects have often been linked to key national priority areas, such as energy, security and communications, as well as related international standardisation. Key organisations including, the National Grid, STATNETT (Norway), WSP, Pyterra, Leonardo, BSI, HP, GCHQ, ETSI, GSMA, have engaged Kuenzel, Cheong, Hogg, Shyqyri, Mayes and others. Haxha, served as CEO for the major Kosovo state telecoms business before moving to the UK, has now developed eight patents, mainly linked to the telecommunications and is working closely with Leonardo.

Working with Composites UK, we created the first functional database for the industry. The database, maintained by Composites UK, has become a vital tool for businesses in the UK who are looking to source partners, products, technology and skills in this sector. This initiative was supported by an industrial consortium led by Solvay and Bentley and the UK Trade Association, Composites UK.

Through the Story Futures Academy, Howard has advised creative industries on practical 3-D sound rendering and is developing technology to guide the blind through environments based on Light Detection and Ranging (LIDAR). In January 2020, Howard's work on synthesising the voice of the Mummy Nesyamun by CT scanning to produce a vocal tract output sound captured world-wide public imagination and was widely published in the international press with the original article being downloaded more than 360k times.

Casey and co-workers contributed to a consortium of National Measurement Institutes to redefine the temperature unit (kelvin) adopted by the body responsible for the *International Systems of Units* (SI). Our focus was on the temperature range of critical importance for the cryogenic industry and or commercial superconducting quantum computing technologies. Thermometry developed by Royal Holloway, operating over a wide temperature range from 4K to sub-mK temperatures, were used to support and disseminate the scale.

4.3 Contributions to the Sustainability of the Discipline

The Information Security Group (ISG) was one of the first to be recognised by GCHQ and the National Cyber Security Centre (NCSC) as an Academic Centre of Excellence in Cyber Security Research. As a leading centre for cyber security, Royal Holloway seeks to help develop the next generation of practitioners. At Infosec 2017 (the largest security exhibition/trade-show in Europe) the ISG won the award for best cyber security education programme. In 2018, a group of our female students won the award for best cyber security students. Boogert has organised the annual CERN Accelerator School.

Cheong has a visiting research post at the university of Jaen in Spain, while Markantonakis is a visiting researcher at the Université de Bordeaux, the Université de Limoges and the Foundation of Research (FORTH), Heraklion, Greece. Hogg is a guest Professor at Beihang University, Beijing, Harbin Institute of Technology and Zhejiang University of Science and Technology, and has recently been appointed as Chair of the British Composites Society, a division of the Institute of Minerals, Materials and Mining. Mayes is an Adjunct Professor at the University of Maryland Baltimore County (USA).

Multidisciplinary collaboration is very evident in the AHRC funded Story Futures project in which Royal Holloway collaborates with the University of the Arts, Brunel University and a consortium of industrial partners. Electronic Engineering (Howard) works with media arts, psychology and computer sciences at Royal Holloway in combining creative concepts and ideas with engineering hardware and software, to develop new technology platforms. This is in line with the national

priority to support the creative industries. The related Story Futures Academy, established in 2019, is a joint activity between Royal Holloway and the National Film and Television Institute. It is funded by the "Listening Across the Disciplines" AHRC industrial strategy challenge fund. It trains industry in these new technologies (400 professionals so far). It has leveraged £3.3 million, created 229 jobs and supported 18 productions (annual report 2020). Howard is also an Invited Member of the Steering Group, for a separate "Listening Across the Disciplines" Project run by the University of the Arts, London and the University of Southampton.

4.4 Contributions to the Research base

Editorships

Staff are active as Editors for journals such as: "IEEE Transactions on Sustainable Energy"; "IEEE Power Engineering Letters" (Kuenzel); "IEEE Transactions on Neural Network; Learning Systems" (Cheong); Materials Science in the Sage Journal Composites and Advanced Materials (Hogg) and guest and associate editors for MDPI Sensor Journal Special Issue: Optical and Photonic Sensors, Associate Editor of IEEE Sensors Journal (Haxha), Guest Editor on special issue on Deep Representation and Transfer Learning for Smart and Connected Health at IEEE Transactions on Neural Networks and Learning Systems, 2021, Guest Editor on special issue on Deep Neural Network Representation and Generative Adversarial Learning at Elsevier Neural Networks, July 2020 (Cheong) and Associate Editor for "Journal of Modern Power Systems and Clean Energy" (Kuenzel). Others, Mayes, Howard and Markantonakis serve on editorial boards. Mayes and Markantonakis have also edited: "Smart Cards, Tokens, Security and Applications" Springer (updated 2017), and "Secure Smart Embedded Devices, Platforms and Applications" (2014).

Grant committees

Staff regularly review proposals for EPSRC, STFC. Mayes reviewed for the Christian Doppler Forschungsgesellschaft, Austria and the Agence Nationale de Recherche, France. He is an invited mentor to the London Office for Rapid Cybersecurity Advancement and an invited advisor to Bwtech, the cyber security incubator of University of Maryland Baltimore County. Hogg has reviewed major proposals for the Research Council of Norway, chaired EPSRC equipment panels and regularly reviews industrial proposals for Innovate UK. Markantonakis is an expert reviewer for Horizon 2020, the Israeli Ministry of Science and the Netherlands Organisation for Scientific Research. Boogert is an STFC Reviewer for Ernest Rutherford Fellowships and Innovation Partnership Schemes and a UK representative on the European Committee for Future Accelerators. He participated in STFC's 2018 Accelerator Review, is a STFC Strategy Board member, and recently stood down as a core member of the STFC Science Board. Hogg and Howard, both members of the 2014 REF sub- board UoA11 Electrical Engineering and Materials.

Fellowships, prizes, recognition

Staff are active via professional institutions such as the IET, IOP and the IoM3 with Hogg, Mayes, Howard, Haxha being Fellows. Howard was made a Fellow of the Royal Academy of Engineering in 2016. Haxha is President of Kosovan British Academic Academy (KBAA). ECRs Kuenzel and Nduka both received the President's award for an outstanding research team for their work at Imperial College prior to 2016.

Keynotes and presentations

Highlights from major international technical conferences include: Keynote presentations from Mayes, "Post Quantum Crypto Algorithms and MULTOS" at the MULTOS Annual meeting 2019; Markantonakis at SECITC 2015, "Secure and Trusted Application Execution on Embedded Devices" and SECITC 2017 "Ambient Sensing Based Relay Attack Detection in Smartphone

Contactless Transactions". Five Keynotes from Howard "Acoustics of performance spaces and how to work best with them" at Ars Choralis 2017 Valetta, Malta; "In tune with pitch" at PEVOC-13 in Copenhagen; "Voice pitch and choral singing" at "Spheres of Singing 2020" in Glasgow; "The influence of timbre and other matters on unaccompanied choral singing" at TIMBRE-20 (on-line); "Restoring the voice of the 3000-year-old Egyptian High Priest, Nesyamun" to Foniatrian Luentokoulutusohjelma Syksyllä 2020. A Keynote from Casey "Extending cryogen-free experimental platforms into the microkelvin regime" was presented at the APS March Meeting, Texas, 2015.

A number of significant presentations influencing strategy and policy include: Mayes to the All Party Parliamentary Group on cyber security: "Modern Challenges in Information/Cyber Security" July 2016: "Stand and deliver! Ransomware: how it works and how to combat it" and December 2017: "Soft Cyber-Power- how our cyber security can be influenced through academia and the supply chain" June 2020. Casey presented "Implementing the new kelvin" at Quantum Fluids and Solids, QFS2019, Edmonton, Canada. Hogg presented papers on the future directions of the advanced composites industry, "The Role Of Textiles In The Next Wave Of Revolutions In The Fibre-Composite Industry (2016)" and "Evolution and Revolution: Parallels Between the Development of the Carbon Fibre Composite Industry in The Aerospace and Automotive Sector (2018)" at the Sino-British forum for Collaborative Partnership and Advanced Materials in Chengdu.