Institution: Royal Holloway, University of London (RHUL)

Unit of Assessment: 9: Physics

1. Unit context and structure, research and impact strategy

The Department of Physics are recognised research leaders in our areas of strength, **Particle Physics** and **Quantum Materials & Technologies**. Between 2013 and 2020 our work has aligned with the foremost national scientific priorities, connected strongly with the National Physical Laboratory and the Rutherford Appleton Laboratory, and grown across discipline boundaries, drawing together expertise across the School of Engineering, Physical and Mathematical Science.

Our strategic objectives over the period 2013-2020 were:

- ***to address the most fundamental open questions in Particle Physics and Quantum Materials & Technologies, in projects with the potential for breakthrough discoveries;***
- ***to develop applications of our discovery science to new devices based on quantum rules that will revolutionize information processing and sensing capabilities;***
- ***to apply these advances in quantum technologies to study fundamental physics in new ways;***
- ***to increase impact and to grow new research directions through interdisciplinary collaboration;***
- ***to create an environment that supports the development of individuals, with emphasis on promoting equality.***

1.1 Unit Structure

In 2019 the School of Engineering, Physical and Mathematical Science (EPMS) was formed from the Departments of Physics, Electronic Engineering, Computer Science, Information & Security, and Mathematics. The Physics Unit of Assessment consists of 19.1 FTE academic staff, including joint appointments and secondments. Physics academics collaborate with researchers in the EPMS, with 5 academics submitted to the Engineering UoA. Research activity in Physics is divided between the Centre for Particle Physics and the grouping of Quantum Materials & Technologies.

The Centre for Particle Physics (CPP) comprises 11 academics, 10 non-independent researchers and 31 postgraduate students. The centre hosts research sub-groups in: Accelerator Science; the ATLAS experiment at the CERN Large Hadron Collider (LHC); Dark Matter & Neutrino Physics; and Theoretical Particle Physics. This grouping maps directly onto the STFC's Frontier Physics Research Areas. The experimental programme is supported by laboratory infrastructure, advanced computing facilities, and facilities at major international laboratories (CERN, FNAL, J-PARC, KEK, LNGS, SNOLAB, SURF).

Quantum Materials & Technologies (QMT) comprises 16 academics, 12 non-independent researchers and 18 postgraduate students. It hosts four sub-groups: Condensed Matter Theory; Nanophysics & Nanotechnology; Quantum Matter; Quantum Fluids & Solids. Research is enhanced by departmental fabrication facilities and laboratories, which include the UK Centre for Superconducting and Hybrid Quantum Systems (SuperFab) and the London Low Temperature Laboratory (LLTL, a member of the European Microkelvin Platform, a European Advanced Infrastructure), as well as external facilities such as ISIS, the Diamond Light Source, ESRF, ILL and FRMII, and within the Hubbard Theory Consortium (HTC).

1.2 Research Strategy

The REF2014 research objectives were:

- to exploit the ATLAS dataset's increased reach and precision to study the Higgs boson, experimentally and theoretically;
- to search for dark matter, pushing the sensitivity frontier in experiment and theory, and to expand into neutrino physics, which shares many of the challenges of rare-event searches;
- to develop novel beam instrumentation and simulation techniques for accelerators, working towards the LHC luminosity upgrades;
- to grow into the priority area of quantum technologies, particularly in superconducting circuits, in partnership with national laboratories and industry;
- to address the new challenge of quantum behaviour in nano-devices cooled into the sub-mK regime;
- to diversify the programme of materials discovery;
- to strengthen engagement between theorists and experimentalists.

Our research spend has nearly doubled under this strategy; increasing from £13.6M in REF2014 to £22.3M during this REF period.

We have delivered our strategic aims by developing partnerships with national laboratories; resulting in joint appointments and secondments and access to world-class facilities; consolidation and growth of cross-disciplinary approaches through new structures, including the new School; and University and Research Council investment to develop world-leading infrastructure on campus.

This has resulted in major research achievements, aligned with our objectives identified in REF2014. They include:

- *Collider Physics Experiment* academics (Boisvert, Berry, Cowan, Teixeira-Dias) and Senior Research Officers (SROs) (George, Green) have major ATLAS experiment roles in: electronics and software for trigger and data acquisition; contributing computing expertise for Particle Physics by hosting a GridPP Tier2 cluster; and, in physics analyses of the Higgs boson, the top-quark, exotic processes, and statistical methods. During REF2021 Boisvert served as ATLAS Top Cross-Section Physics subgroup convener, responsible for directing the research activities of ~50 collaborators, Cowan served as ATLAS Statistical Forum convener, producing world-leading results on the mass and spin of the Higgs boson, and Teixeira-Dias was elected Deputy ATLAS-UK PI.
- *Dark Matter and Neutrino Physics* academics (Kaboth, Monroe) collaborate on dark matter searches with the LZ and Global Argon Dark Matter Collaboration experiments, and on neutrino oscillation with the T2K and DUNE experiments. Our expertise in dark matter is internationally recognized, e.g. during REF2021 serving as LZ WIMP Search working group leader (Kaboth), and Scientific Secretary in the 2019 European Strategy for Particle Physics Dark Sectors group (Monroe). The secondment of Kaboth with RAL grew our activity into Neutrino Physics, where our focus is oscillation analysis and detector R&D, producing world-leading results on CP violation in the lepton sector, serving as T2K Oscillation Analysis convener (Kaboth), and leading the CERN P-355 experiment to develop high-pressure TPC technology for the DUNE near detector (Monroe).

- *Theoretical Particle Physics* academics (Kauer, West) have made significant contributions to the understanding of the off-shell high-mass Higgs signal that facilitates the determination of the Higgs decay width and the development of novel theories of dark matter (e.g. the Freeze-in mechanism and Nuclear Dark Matter). Kauer has served continuously as convener in the international LHC Higgs Cross Section working group since 2014 and recently initiated the Off-shell Interpretations Task Force.
- *Accelerator Science* academics (Boogert, Gibson, Karataev), SROs (Bosco, Boorman, Lyapin) develop the next generation of high-energy particle accelerators, within the John Adams Institute. Karataev has led the fundamental physics development of optical transition radiation and diffractive transition radiation for non-invasive beam diagnostics.
- *Quantum Fluids & Solids* academics (Casey, Nicholls, Rojas, Saunders), SROs (Levitin, Nyeki), have world-leading expertise in ultra-low temperature physics. The group has pioneered studies of superfluid ^{3}He under nanofluidic confinement as a model system for topological superconductivity, shown atomically-layered thin films of helium on graphite substrates provide model systems for realizing 2D-quantum materials, and demonstrated a world-record low temperature for a two-dimensional electron gas. Rojas initiated superfluid optomechanics, exploiting the unique properties of superfluid ^{4}He for quantum sensing and technology applications. Impact stems from promoting access to ultra-low temperature by engineering new technologies, notably a cryogen-free nuclear demagnetisation refrigerator in partnership with Oxford Instruments and a primary thermometer for sub mK temperatures.
- *Quantum Matter* academics (Goff, Niklowitz, Voneshen), SRO (Uthayakumar) study frustrated magnetism and quantum phase transitions using neutron and synchrotron x-ray scattering, exploiting beam time at neutron and synchrotron facilities (ISIS, ILL, DLS, ESRF, FRM II). The group's pioneering work on the role of structural defects on magnetic monopole dynamics led to harnessing disorder to induce quantum spin liquid behaviour. The group has strengthened the strategic partnership with ISIS through secondment of Voneshen from ISIS to RHUL to develop the application of polarisation analysis techniques to study materials for energy applications, and collaborate on materials synthesis to grow samples for the wider neutron scattering community.
- *Nanophysics & Nanotechnology* academics (Antonov, Astafiev, Ithier, Meeson, Petrashov, Tzalenchuk), SRO (Shaikhaidarov) develop quantum device technology through the application of fundamental phenomena based on superconductivity. The group does important work in metrology: e.g., developing a charge quantum interference device; artificial atoms; a microwave absolute power meter (patented); technology of long de-coherence qubits; and studying the metrological standard of current (EU FET Open project). The joint appointment of Astafiev with NPL, and secondment of Tzalenchuk from NPL to RHUL, significantly enhanced our work on quantum technologies, together with investment in the SuperFab facility.
- *Condensed Matter Theory* academics (Coleman, Eschrig, Ho, Refson, Sordi) focus on the quantum many-body problem in condensed matter, one of the grand challenges of 21st century physics. This group runs the Hubbard Theory Consortium, which brings together experimentalists and theorists to catalyse the discovery, understanding, and design of new quantum materials. Refson was jointly appointed with ISIS to lead the theoretical modelling effort at ISIS using ab-initio simulations, in support of experiments that span condensed matter physics, materials physics and chemistry.

1.3 Approaches to enabling Impact

In REF2014, our strategic objectives were to develop impact from our research on the economy, healthcare, and society. To do this we have strengthened the impact culture and developed closer working links with users of our research. Embedding Impact across the administrative functions of the Department has been achieved by:

- *Forming an Impact team:* The Department's Director of Impact leads a team responsible for interacting with research groups to identify potential impacts of their research, share impact-promoting initiatives and best practice.
- *Embedding impact from Early Career:* The impact team works with the Research Staff Forum to identify, develop and secure seed funding from institutional resources for impact projects. This has led to non-independent researchers being directly involved with REF2021 case studies (Nevay, Lyapin, and Levitin), and submitting impact related funding applications to STFC-IPS and CLASP (Lyapin, Shields).
- *Incentivising impact*: Impact activities feature explicitly in recruitment and promotion criteria at all levels. Impact activities (consultancy, industrial meetings, outreach and knowledge transfer) are part of our quantitative workload model for staff and are incorporated in the annual Performance Development Review process.
- *Strategic investment in research with impact potential*: The impact strategy has informed appointments in the theory of Quantum Materials (Refson), in metrology (Tzalenchuk), and in nanotechnology (Astafiev). Funding is available, with support from RHUL's Research and Innovation (R&I) Department, to protect Intellectual Property and develop the frameworks needed to exploit technologies with commercial partners.

The two case studies selected for Physics emerge from these approaches to enabling impact. All members of the Physics UoA were invited to submit a short impact case at the beginning of the REF period. The impact Team supported the development of these cases and identified actions to enhance the impact during the REF2021 period. **Impact Case 1, Exploiting quantum technologies to drive a commercial functional brain imaging revolution**, received support from R&I to protect our intellectual property in the area of quantum devices and negotiated licensing agreements with a start-up York Instruments and their parent company Croton Healthcare. Appointment of Refson enabled **Impact Case 2, Driving Industrial R&D with CASTEP materials modelling software**, relating to wider economic benefits of our research in condensed matter theory, producing efficiency gains in material development for companies using the CASTEP software package, marketed through BIOVIA.

Our future strategic impact objectives are: to leverage our unique infrastructure to grow our impact; to increase our engagement with end-user beneficiaries; and to connect impact activities to our core principle of reaching gender equality. Building on our current activities, we will enable these by:

- *Leveraging our Infrastructure.* We plan to develop quantum technologies with impact on UK manufacturing industry and metrology, aligned with the national Quantum Computing agenda. We will do this via our infrastructures (LLTL and SuperFab, 3.2), which bring industrial users to campus and promote collaboration; the industry outreach programmes of the R&I Department; and, through partnership with NPL. This will be steered by an Industrial Strategy Advisory Committee.
- *Involvement with external and industry partners at all stages.* We are embedding engagement with industry into our PhD programme to develop future "people pipelines". This is promoted through Impact PhD Studentships and the South East Physics Network's (SEPNet) employer

internship programs within GRADnet. College seed-funds are available through R&I to support opportunities that maximise the impact of our research.

- *Embedding impact within our core principles.* We will expand our public engagement to promote the visibility of women in generating impact, as this is a strong attractor for recruiting diverse talent. We will grow our programme of events highlighting impact-generating research by women at all levels: to the public, e.g. in our Christmas lecture series, where in 2019 women PhD students gave talks about impact generation to a 400-strong public audience; to research councils, e.g. 2019 EPSRC Visit Day featured the CEO of Oxford Quantum Circuits, RHUL Physics alumna; and, to our students, in our Women in Physics speaker series.

1.4 Supporting Interdisciplinary research

Growth in interdisciplinary collaboration is supported by the EPMS School, and across the institution by the development of an institutional catalyst in **Advanced Quantum Science and Technologies**.

- The Engineering Research Centre was established in 2017 to coalesce engineering-focussed research across the School.
- In 2019 STFC and EPSRC launched the "Quantum Technologies for Fundamental Physics" (QTFP) call. Applications required interdisciplinary research teams from both the fundamental physics and quantum technology communities. Our strategy of collaboration across these two key areas, and our world-leading nanofabrication infrastructure enabled us to lead (1) and join (2) proposals, all of which were successful.
- The formation of the "Quantum Catalyst" in 2020 will consolidate research in Quantum Materials & Technologies across Royal Holloway.

These initiatives will open up new areas of discovery and drive challenge-led research over the next decade.

1.5 Future research strategic aims

From 2021 to 2026, our work will shape RHUL's aspirations for a future in discovery science and in supporting the second quantum revolution. The future aims, building upon the successful strategies developed during REF2021, are to:

- *Lead the catalyst for Advanced Quantum Science and Technologies*. This will accelerate the translation of physics breakthroughs in quantum materials and devices into quantum information and sensor technology. A key research direction will be to deliver our Quantum Technologies for Fundamental Physics science programme. Applying quantum measurement approaches to new particle searches spans the core capabilities of our UoA in nanotechnology, experimental and theoretical research in dark matter, and ultra-low temperature physics.
- *Expand Interdisciplinary research.* We aim to make progress on leading challenges across science, interacting across fields beyond our institution. For example, we lead a *Global Challenge Research Fund* multi-disciplinary effort to translate metrology developed for dark matter searches to detecting lead in drinking water using biosensors.
- *Create an Astronomy Group*: The top priority of the UoA strategic plan is to appoint two Astronomers. This is an area with huge discovery potential that is being transformed by advances in instrumentation, and a natural fit to our strengths in Dark Matter and Theoretical

Particle Physics. This direction strengthens our push towards gender equality as Astronomy recruits women students with higher success rates than any other sub-field in Physics.

1.6 Culture of Open and Ethical Research

Royal Holloway's Open Access Policy supports researchers to comply with the open access requirements of their funding agencies. Research outputs are input into Pure (Research Information System), and the Research Support Team arrange Open Access in line with the publisher's policy. Funds are available to pay article processing charges for open access. Examples of going beyond this standard include the European Microkelvin Platform's support of the European Open Science Cloud (EOSC).

Compliant research data management is achieved through institutional subscriptions to *Figshare* and *Dropbox*. The Research Data Management Service, *Dropbox for Business*, provides unlimited storage for research data, and enables data sharing with research students, staff and partners in other institutions. Access to raw data supports reproducibility. Servers and data storage are located in the EU and accounts are managed by Royal Holloway IT Services.

Our research is governed by the College's ethical, legal and professional frameworks and standards which act as key indicators of its statutory wellbeing and future health. The College policy that we follow is in turn based on the UK Universities Concordat to Support Research Integrity. This policy 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 the Research & Innovation Department (R&I) support researchers via an ethics review process for proposals, in order to identify potential ethical issues and report them to the College Research Ethics Committee. A Research Ethics & Integrity Manager in the R&I Department is responsible for supporting the Research Ethics Committee and an online ethics assessment system.

2. People

2.1 Staffing strategy

We promote a vibrant research culture and exercise a recruitment and retention policy to attract internationally-leading researchers to support our areas of strength, in Particle Physics and Quantum Materials & Technologies (QMT), creating a sustainable critical mass. This is achieved by appointing and promoting rising talent; and facilitating exchanges with business, industry and public or third-sector bodies through secondments. Appointments made before 2014 have been instrumental in driving our research trajectory in the REF2021 period, including Astafiev (from NEC-Japan), Coleman (Rutgers University), Eschrig (Karlsruhe University), Monroe (MIT).

The success of our staffing strategy is evidenced via the quality of the new appointments during the REF2021 period: diversifying into Neutrino Physics with Kaboth (RAL secondment); strengthening QMT Theory with Refson (joint ISIS appointment); and, expanding the scope of QMT research with Rojas (Royal Society University Research Fellow, proleptic appointment).

All submitted category A staff have a permanent appointment, this includes: 5 Lecturers, 3 Senior Lecturers, 2 Readers and 9.1 Professors. Research independence was determined following the institutional code of practice. Academics are supported in their research by 8 Senior Research Officers (in nanofabrication, low temperatures, materials discovery and particle physics). Non-

independent research staff number steadily at a ratio of ~1 per academic FTE, with a further 6 FTE research technicians in mechanical and electrical workshops.

Following our history as one of the first universities for women in the UK, equal opportunity is a core principle in Physics. Our UoA FTE now are 16% women, and our undergraduate cohort is 33% women (national figures are 12% and 24% respectively). We aim to reach gender equality in STEM. This principle is embedded across our activities, frames our staffing strategy, and informs the annual Department Strategic Plan.

Demographic changes inform succession planning, which is implemented via the input of research sub-groups into the annual Department Strategic Plan..Since 2014 there have been 6 promotions to Reader and Senior Lecturer, and 4 to Professorships; 1 retirement; and 2 departures (Eschrig to Universität Greifswald; Nikkel to Yale University).

2.2 Staff development

RHUL is committed to the career development of staff at all levels. In 2019 we received the HR Excellence in Research award, demonstrating our commitment to the principles of the UK *Concordat to Support the Career Development of Researchers*. All staff have an annual Performance Development Review (PDR), in the context of a quantitative workload model (explicitly recognising impact activities), reviewed by the HoD. Senior staff support non-independent research staff and ECRs, including mentoring of grant and Fellowship applications, and the development of impact-related research.

- *Supporting Early Career Researchers:* Newly appointed academic staff have a reduced teaching load (50-75%) during a three-year probation period. Their development is supported through mentoring by senior faculty, and the College's "Advance" training programme. This approach enabled the award of Rojas' Royal Society URF, while a PDRA at RHUL. Structures supporting this are the Department Research Staff Forum (established in 2010), which feeds into a school-wide ECR Forum, with two seats on the School Research Committee. This supports the ECR community, promoting peer-to-peer interactions, interdisciplinary research, and drives effective delivery of the *Concordat*. During REF2021, our non-independent researchers have gone on to Rutherford Fellowships (Oxford University), Fellini Fellowships (Naples University), Marie Curie Fellowships, Leverhulme Early Career Fellowships and faculty positions (Harvard University, Laurentian University), and laboratory staff scientist positions (JINR, NPL, SNOLAB, TRIUMF).
- *Promotions:* Academic staff may apply for promotion annually; criteria are evaluated in teaching, research, external engagement/impact and leadership, with recognition of impact at the same level as research activities. The Department Promotions Panel, composed of the Professoriate, reviews the CV of each staff member annually, to advise colleagues on progression towards their next promotion. This is part of our Athena Swan commitment to ensure that promotion application rates are consistent across genders. The HoD provides structured feedback to all staff annually from the Promotions Panel and the University Academic Staffing and Titles Committee.
- *Sabbaticals*: Operating the institutional sabbatical policy, this unit was granted 16 terms of sabbatical during REF2021, strategically supporting the development of new research directions (e.g. Goff's leadership of successful EPSRC proposal with Oxford and Cambridge to study Quantum Spin Liquids), delivery of large externally-funded projects (e.g. Saunders, Horizon 2020 European Microkelvin Platform), and development of new numerical tools (Kauer, Beyond the Standard Model Extension of "OpenLoops").

- *Secondments*: Research has been enhanced by an active secondment and joint appointment strategy with academia and industry (e.g. NPL, ISIS, RAL, JEOL). Approximately 25% of the academic staff are joint appointments or secondments.
- *Technical Staff:* RHUL became a signatory of the Technician Commitment in 2018, submitting an action plan to address key challenges facing technical staff. The commitment aims to raise the profile of technical staff, providing career development opportunities, recognition for their contributions to research, and promoting technical roles as an important and rewarding career path. The UoA's role is led by the Departmental Technical Operations manager, with wider coordination at the School Research Committee.

2.3 Research students

The main PhD funding sources are research grants and "matched-funding" scholarships. In addition to directly grant-funded scholarships, between 2014 and 2020, RHUL supported grant applications to Research Councils by funding accompanying PhD studentships. The "matched-funding" scholarships cement collaborations, promoting research and impact, with strategic external research partners (NPL, CERN, ISIS, Diamond, Johnson Matthey, Oxford Instruments, TRIUMF).

- *Recruiting* of PGRs is done through a yearly Physics Postgraduate Open Day, advertising on our Department web page, and via the *findAPhD* website. Bi-termly Undergraduate Women in Physics meetings promote postgraduate study as a career path to our women undergraduates and provide mentoring on applications.
- *Supervision*: Each PGR has a research supervisor, advisor and a moderator. This team conducts the Annual Review, based around a viva, student and supervisor reports, and training log. The decision to upgrade MPhil students to a PhD registration is taken after the 1st or 2nd year viva. The Department's Postgraduate Forum termly meeting, established in 2010, is run entirely by PGRs, and reports to the Department Board with a representative on School Research Committee; this facilitates communication and PGR input to decision-making. The Department runs a final year completion meeting to ensure thesis submission within 4 years.
- *Training* is tailored to the PhD project. All students access GRADnet courses, a collaborative graduate school established by SEPNet in 2015. This provides ~10 courses annually, including residential workshops, on advanced physics, and relevant professional skills training, including commercialisation of research, careers and networking events, team and leadership skills, and student-led conferences. Particle Physics PhD students take lecture programmes delivered jointly within the University of London, JAI, or the NExT Institute, and attend two-week UK-wide schools. QMT PhD students attend the ISIS Neutron Training Course, the Oxford School on Neutron Scattering, the CASTEP Workshop, the International European Cryoschool. All PGRs have the opportunity to present results at an international conference, supported by the training allocation of their scholarship. Students can develop their teaching skills by taking the RHUL Skills of Teaching to Inspire Learning programme, and are encouraged to participate in laboratory, problem class teaching and coursework marking.

2.4 Equality and Diversity

We aim to promote participation in research by demographics that represent the society we live in. A flagship commitment of the UoA is to reach gender equality. Following our early award of IOP Project Juno Champion in 2011 and Athena Swan Silver in 2012, our work on this was recognized during the REF2021 period with renewal of our Champion Award (2014, 2017) and Athena Swan Silver Award (2015, 2018). These awards certify our commitment to embed E&D

across all Departmental functions, delivering transparency of process and reporting of data to inform and underpin progress towards our goals, as well as policies for flexible/remote working, timings of seminars, training sessions and meetings, and maternity/paternity leave.

The strategy to reach equality in research requires development of the entire career pipeline. Our goals are: to reach sustained 40% female undergraduate intake over the next 5 years; to increase applications by women for research and academic positions from 20% to 30%; to increase the fraction of shortlisted women from 10% to 20%; and, to increase the fraction of women Professors from 16% to 20%. Our undergraduate (PGR) cohort is currently 25% (22%) BAME; national figures are 17% (14%). Our aspiration is to increase this in the next REF period to 35% (30%). We aim to reach these goals through:

- *Proactive Recruiting:* We actively encourage applications from under-represented parts of the community, at all levels. Examples of new initiatives in 2014-20 include: two annual residential courses with the Smallpeice Trust (for Year 10 and 12 women, 204 alumnae so far); and outreach to regional "feeder" schools, e.g. the South Bank Engineering UTC in Brixton, a STEM-focussed College with mostly BAME pupils. Our work to improve equality and diversity in staffing includes: proactively reaching out to candidates to encourage a diverse application pool; implementing guidance on writing inclusive job descriptions and person specifications; offering to pay for childcare for all interview applicants and including this information in our job advertisements; no HoD approval for all-male shortlists for academic positions; and, ensuring that all staff involved in the shortlisting process undergo Recruitment and Selection and Unconscious Bias training.
- *Enabling equal opportunities for promotion and enhancement:* All promotions and interview panels have at least one woman, we display diversity in our promotional material, and we invite gender-balanced seminar, colloquia, Women in Physics group and Employability speakers. The department routinely awards funds for PGR students to attend conferences or access training. We promote the equality agenda and share good practice both within and outside RHUL. Berry is a leader in this, serving as a member of the IOP Project Juno assessment panel (2011-17).
- *Supporting career pathways*: Most non-independent researchers join on fixed term contracts. Career progression towards fellowships and permanent positions is supported through mentoring, the Annual Performance Review process, and the *Research Staff Forum* which organizes events focussed on career progression. Research and Innovation Department offer training on fellowship application and grant writing for non-independent researchers.
- *Flexible working*: As part of our Athena Swan commitment, where possible, essential Department meetings are confined within 10:00-16:00h. During the REF period five members of staff had requests for flexible working conditions approved by the HoD to facilitate caring responsibilities, in line with the institutional policy. The policy allows for a change in working hours, the required times to work, or working from home. 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.
- *Promoting Diversity:* to raise awareness of inequality for all protected characteristics, in 2016 we evolved the Juno Committee into the "Equality and Diversity" Committee. We were one of the first eight Universities to achieve a Race Equality Charter Award, in 2015. Example activities include encouraging, and financially supporting, our BAME researchers to attend the BME Early Career conference, and our annual Physics and Diversity seminar. In 2016 we

established a departmental LGBT+ Group with termly events. Example activities include advertising staff networks (LGBT+, Cultural Diversity, Disability and the Women's network) and engaging with institutional activity to support transgender students and staff, e.g. the monthly school E&D reading group. We commit to tackling discrimination: in 2018 we created the position of Department Dignity and Harassment Officer to act as an ombudsperson to facilitate communication and reporting of issues; we mandate an "Introduction to EDI awareness" e-module in Welcome Week for students; and we embed staff completion of equality training into the annual Performance Development Review.

- *Encouraging Ambition:* We have Women in Physics (WiP) Groups for undergraduates, PGRs and all women staff, with invited speaker events twice a term; and monthly academic WiP lunch meetings with PGRs. These meetings support achieving career aspirations, through two-way mentoring, network-growth and promoting visibility of under-represented role models. We encourage, and financially support, women undergraduates to attend the annual Conference for Undergraduate Women in Physics, typically 2-5 per year. We offer formal mentoring and financially support training for women members of staff towards career progression, both academic and administrative. All women staff are eligible to participate in Springboard, which is an award-winning personal and work development programme. During REF2021, 3 members of our administrative staff were supported to undertake Springboard, and 1 member of professional staff and 1 academic were supported on the Aurora Leadership Program.
- *Equality and Diversity in the REF submission:* Research outputs were selected based on the RHUL REF2021 Code of Practice and the Equality Impact Assessment. All independent researchers nominated outputs, which were assessed by at least two UoA members, and by a reviewer from another institution, subject to approval by the College REF Steering Group. The highest rated item from each member was selected for submission. The remaining outputs were chosen by the UoA REF Lead, HoD, Director of Impact and Director of Research, selecting the highest rated outputs from all staff, discussed with and approved by each staff member. Women authored 20% of the UoA outputs, whilst making up 16% of the UoA FTE.

3. Income, infrastructure and facilities

3.1 Research Income

The total UoA research grant spend for 2014-20 was £22.3M, compared with £13.6M in the previous REF period. Funding awarded to the UoA during REF2021 totals £25.2M, from:

- *UKRI:* STFC (£9.2M), EPSRC (£9.6M), GCRF/ISCF (£0.55M), and National Laboratories (NPL, Diamond) (£0.27M);
- *Non-UKRI:* EU (£2.5M), CERN (£1.1M), other UK bodies (Royal Society, Leverhulme, industry: £1.4M);

and additional income enabling development of facilities, close collaboration with National Laboratories, and beam tests is from:

- *Institutional Investment:* in equipment and infrastructure totals £3.2M;
- *Secondments:* of staff to NPL, ISIS and RAL totals £866k*;* and*,*
- *In-Kind Income:* awarded totals £5.9M, e.g. for use of facilities at ISIS, Diamond, ILL, FRMII, and ESRF. This excludes the CERN subscription and UKRI experiment project funding on e.g. ATLAS and T2K.

Broadly, STFC, EU and CERN income have enabled significant growth into the field of Neutrino Physics, and continued success in the LHC physics programme and the high luminosity LHC accelerator upgrade. This underpins our collaboration on pioneering science results in Particle Physics in REF2021: the discovery of the Higgs boson, and the observation of non-zero CP violation in the neutrino sector.

EPSRC, EU and Institutional investment income have enabled significant growth into Nanophysics & Nanotechology, continued success of the ultra-low temperature physics programme, and major new facility development of SuperFab. QMT groups have leveraged our expertise to participate in EPSRC programme grants, including EP/K004077/1 (PI M. Pepper UCL, £6.5m), which led to our breakthrough result of cooling a two-dimensional electron gas to below 1 mK, underpinning our world-leading capability in cooling a variety of quantum materials and devices into this regime; and, EP/N017242/1 (PI J Robinson, Cambridge, £2.7m), establishing Eschrig's international leadership in the theory of superconducting spintronics.

During REF2021 a further £2.7M was awarded (from UKRI and EU funds) in collaboration with academics in the Engineering UoA, enabling the strong growth in our interdisciplinary activities. For the future, 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, £4.8M) and QsimFP quantum simulators project (PI Weinfurtner Nottingham, £4.3M).

All staff are supported equally in bidding for grants, fellowships and sabbaticals. Annual internal equipment bids are assessed openly and transparently. All facilities are open access within the College, subject only to the conditions of any grant(s) used to purchase the equipment.

3.2 Infrastructure and facilities

Our strategy has been to engage with international networks; to invest in infrastructure delivering leading capabilities for research on Quantum Materials & Technology; to maintain strong computing capability across Particle Physics; and to develop distinctive instrumentation for international Particle Physics projects. Our infrastructure and facilities provide access to national and international research communities, fostering collaboration, building new networks for ECRs, and driving diversification of research.

- **Nanofabrication:** To establish the UK as a key player in the development of a quantum computer, RHUL invested £3M in creating a new cleanroom facility **SuperFab**, hosting the *UK Centre for Superconducting and Hybrid Quantum Systems,* 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.
    - £5.8M has been awarded from EPSRC and Research England to equip SuperFab, including a world-leading electron beam lithography system and a helium ion microscope/neon focussed ion beam tool.

- The impact of research within SuperFab is accelerated through membership of an industry-led consortium, funded through a £7M Innovate UK grant (lead: Oxford Quantum Circuits).

- **London Low Temperature Laboratory (LLTL):** Research at the low temperature frontier, and into low temperature technology, underpins the second quantum revolution and is of key strategic importance to advance quantum materials and technology. Leading work on the study of helium as a quantum material, incorporating successful international partnerships, has benefitted from strong EPSRC support. The LLTL is a part of the *European Microkelvin Platform*. Two decades of investment have resulted in a distinctive platform that includes four nuclear adiabatic demagnetization cryostats, supported by a helium liquefier and closed cycle recovery system, and an innovative, cryogen-free system developed with Oxford Instruments. This platform, coupled to unique measurement capabilities, attracts external users and collaborators, further driving the enhancement of technical capabilities.
    - The EMP was awarded €9M in 2019, as a Horizon 2020 European Advanced Infrastructure.
    - Impact is ensured through innovation of new technologies, new industrial users and collaboration with National Measurement Institutes exemplified through the research supporting the new definition of the Kelvin.
- **The Materials Discovery Laboratory (MDL):** Single crystals represent perfection in the solid state and are the essential prerequisite for many experiments at central facilities. The MDL has fuelled a vibrant research programme on the study of fundamental and functional quantum materials at neutron and synchrotron facilities. The joint initiative in this area with ISIS, which co-funds a permanent SRO, extends the capabilities in materials synthesis, and provides a new source of samples for the wider neutron community. Work on battery materials and material modelling with industrial partners drives impact in this area.
- **High-throughput Computing Clusters:** All data from the ATLAS experiment flows through the TDAQ electronics co-designed by RHUL, underpinned by the CPP TDAQ laboratory. Physics analysis of ATLAS's data sets is delivered by a high-throughput computing cluster with 6000 cores and 2.4 PB of storage, located in a purpose-built data-centre. This is part of the UK GridPP project, and is integrated into the worldwide LHC Grid.
    - Supported by 3 research staff, expanded since 2013 with support from GridPP (£535k) and institutional investment (£280k); it is systematically in the top 3 UK GridPP sites for ATLAS data processing.
    - Underpins research and impact across the CPP: beyond ATLAS, it is used to simulate the LZ and DarkSide experiments; particle beam losses in the LHC; and in 2020, 10% of the available resource was donated to support research on the pandemic and COVID-19 protein folding.
- **Mechanical and Electrical Workshop:** Research across all themes is supported by skilled precision engineers and technicians in the mechanical and electrical workshops. Interactions with the workshop team promotes early career involvement in R&D. Rapid prototyping and design support is essential for the development of the research skills base. A programme of upgrades with STFC and RHUL funding has enhanced the capability with new CNC machines.

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

4.1 Supporting Collaborations

Collaborations with research networks and industry are central to our research and impact strategy. This creates a stimulating environment for PGRs and ECRs to develop their own research within the core areas and diversify into interdisciplinary research with partners attracted by our expertise. Support for these partnerships is provided through:

- *The Research & Innovation Department (R&I) Knowledge Exchange Team* support research partnerships, connect academics with industrial partners, and provide user access to the SuperFab and LLTL infrastructures. R&I provide legal services, draw up agreements with network partners, external agencies, commercialisation activities, spin-out companies, patents, licenses, consultancy and IP rights. This resulted in 167 formal legal documents in 2014-20 for the UoA, of which 48 directly involved industry, including issuing 3 licenses associated with Impact cases and 6 patent applications. Examples of user engagement include: the 2018 SuperFab open day attracting 106 visitors from 33 companies; R&I participates in the annual Quantum Showcase event; R&I supports Accelerator Science and Dark Matter & Neutrino group grants where a key deliverable is transfer of the research to non-academic beneficiaries, from the UKRI Industrial Strategy Challenge Fund and the GCRF Translation Award schemes, respectively; and R&I supported ECR Lyapin to obtain an STFC Innovation Partnership Scheme grant, in collaboration with Oxford FMB, a local SME, to develop a commercial beam device.
- *Impact PhD Studentships*: R&I provide the collaboration agreements for PGR students co-funded by RHUL and partner organisations. These studentships support delivering partnership objectives via shared student supervision and regular project meetings. Impact PhD project examples include partnerships with Oxford Instruments Nanoscience (OIN), Johnson Matthey Technology Centre, and TRIUMF Laboratory (Canada). The NPL/RHUL partnership funds Impact PhD studentships, with an average total cohort of 9 students, supporting quantum science and technology. These arrangements have helped feed a “people pipeline”: 7 former staff to Oxford Instruments Nanotechnology, 2 to NPL, and 3 to Oxford Quantum Circuits, including the CEO. In Accelerator Science, post-graduate training initiatives funded via the EU have been awarded to Karataev (as co-I) including the Diagnostics Training Network (DITANET) and Optimisation of Particle Accelerators (OPAC). These have grown collaboration with industry, most recently via an STFC Industrial Innovation Placement with UK Company Covesion, Ltd. The INSIGHTs European Training Network, led by Cowan, includes placements in industry for early-stage researchers.
- *Joint appointments/secondments* with national laboratories, comprising ~25% of the academic staff of the UoA: academics Astafiev, Kaboth, Eschrig, Refson, Sordi, Tzalenchuk, Voneshen and SROs Uthayakumar and Shaikhaidarov. Collaboration with NPL supports superconducting quantum technology including metrological applications. Collaboration with the Rutherford Appleton Laboratory enabled our expansion into Neutrino Physics and hadron accelerators. Collaboration with Diamond developed our impact in quantum materials: Eschrig provided theoretical support for the ARPES beamline at Diamond, resulting in understanding of pairing in iron-selenide superconductors. Refson was appointed to lead the theoretical modelling effort at ISIS using ab-initio simulations, in support of interdisciplinary materials science.

4.2 Research Networks & Partnerships

In Particle Physics, we collaborate on large international experiments (ATLAS, DarkSide, DEAP, DUNE, LZ and T2K) and are recognized by our peers with scientific leadership roles. In Quantum Materials and Technology, our research features collaborative grants, project partnerships on

EPSRC grants, funded sabbatical visitors, and collaboration in EPSRC Programme Grants. We have developed new pathways for contributions to the research base, connecting to commercial users and wider beneficiaries in the economy and society through networks that we lead or are founding members of:

- **European Microkelvin Platform (EMP)**, a European Advanced Infrastructure. This has driven new collaborations pushing the frontier of quantum materials and technology with: European High Field Laboratory; Max Planck Institute for Chemical Physics of Solids; Chalmers University; with approved future users from Frankfurt, Cornell and Oxford Instruments.
- **UK Centre for Superconducting and Hybrid Quantum Systems** 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, including: Oxford Quantum Circuits, SeeQC, JEOL, Chase Research Cryogenics, Kelvin Nanotechnology, Oxford Instruments Nanoscience, ColdEdge Technology, Qinetiq Ltd., and Johnson Matthey.
- **Hubbard Theory Consortium**: RHUL leads this network with UCL, Kent, Imperial, ISIS and Diamond to understand emergent phenomena in quantum materials, fostering collaboration between theorists and experimentalists. It is a member node of the Institute for Complex Adaptive Matter. HTC's annual summer programme "Condensed Matter Physics in the City" has attracted "traffic" of 177 leading international scientists, some of whom have helped capture research grants.
- **INSIGHTS**: The International Training Network of Statistics for High Energy Physics and Society is an interdisciplinary Innovative Training Network led by RHUL. Applications include the treatment of systematic uncertainties in statistical risk modelling and machine learning for financial applications, statistical methods for eruption prediction models, computer vision and pattern recognition, the prediction of extreme climate events, and profiling large databases of bank transactions to identify frauds through graph theory algorithms and Bayesian techniques. Commercial beneficiaries include CICERO (Climate Science), INGV (Volcanology), KPMG and FISCAL (Finance).
- **TRACE***:* RHUL leads this interdisciplinary network with Boulby Underground Laboratory, Autonomous University of Mexico, UNESCO Comarca Minera Geoparque, Bariloche Centro Atomico, University of Buenos Aires to develop an open-source, low-cost biosensor detector to measure lead contamination in water and food.
- **John Adams Institute for Accelerator Science, JAI:** RHUL is a founding member of the JAI together with Oxford and Imperial. Collaborating on accelerator science to simulate beam losses in accelerators has led directly to interdisciplinary impact in medical accelerator design. Commercial beneficiaries include Ion Beam Applications (IBA), FMB Oxford and iTech.
- **SEPNet:** This consortium plays an important role in the training of PG students, through GRADnet; engagement with local industry through SEPnet employability officer/team; and public engagement through SEPnet outreach officer/team. SEPnet supports our impact culture, developing connections with industry at the early career stages, via circa 20 undergraduate summer placements per-year in industry.

4.3 Academic Leadership

The contributions of staff to the research base have been recognized during REF2021 by internationally esteemed prizes; positions of scientific leadership; research network leadership; membership of strategic advisory bodies; journal editorship; authorship of invited reviews; and high-profile international conference talks.

Prizes:

- Saunders was awarded the Institute of Physics 2015 Nevill Mott Medal and Prize for ground-breaking studies at the frontiers of ultra-low temperature physics.
- Eschrig was awarded the Lars Onsager Professorship by Norwegian University of Science and Technology in 2015.
- Monroe, Kaboth and Walding were 2016 Breakthrough Prize in Fundamental Physics laureates, for the SNO and T2K experiment contributions to understanding neutrino oscillation.
- Kaboth was recognized with the 2018 Institute of Physics HEPP Group Prize, awarded to an early career researcher for outstanding contributions to particle physics research.

Scientific Leadership:

- *Higgs physics*: Cowan served as ATLAS Statistical Forum convener, which played a key role in the discovery and identification of the Higgs boson.
- *ATLAS experiment*: Teixeira-Dias was elected Deputy PI or ATLAS-UK (2019-22) and will serve as PI (2022-25), leading the 15 ATLAS-UK Institutes.
- *Neutrino physics*: Kaboth serves as T2K Oscillation analysis convener and is the DUNE DAQ Near Detector Technical Lead. Monroe led the CERN P-355 test beam experiment.
- *Dark Matter*: Monroe is PI of the DarkSide-UK STFC project (13 Institutes) and serves on the DarkSide-20k international project Executive Board. Kaboth serves/served as convener of LZ WIMP Search, LZ Calibrations, and LZ-UK Physics working groups.
- Tzalenchuk is Head of Science, Quantum Technologies at NPL.
- Coleman is co-Director of the International Institute of Complex Adaptive Matter, a global multidisciplinary organisation with 61 branches worldwide.

Journal Editorship: in addition to service on editorial boards,

- *Eur.Phys.J.C* Editor-in-Chief, Astroparticle Physics Section (Monroe)
- *American Mineralogist* (Associate Editor) (Refson)

Review Article Authorship: examples include:

- Realizing quantum materials with Helium-3, *Topological Phase Transitions and New Developments* (2019);
- Dark matter direct and directional detection, *Phys. Rept. 662, 667* (2016);
- Topological KONDO Insulators, *Annual Review of Condensed Matter* (2016);
- Spin-polarized supercurrents for spintronics, *Rep. Prog. Phys*. (2015);
- Physics Briefing Book Dark Sectors Chapter, European Strategy for Particle Physics Update 2019;
- The Statistical Data Analysis methods Section of the *Particle Data Group* review (2018) [over 7000 citations].

Conferences and International Schools:

- *High-Profile Plenary Talks and Conference Organization*: UoA staff have given invited talks at and served on International Scientific Committees for leading international conferences;
- *Examples of Named Lectures*: 2016 Lars Onsager Lecture, Norwegian University of Technology; 2015 University of Washington, Boris A. Jacobsen Memorial Lecture;
- *International Schools*: staff lecture at national and international schools; Cowan is a renowned lecturer in statistical data analysis, lecturing widely beyond RHUL. We hosted the CERN Accelerator School (2017), and the International School of Trigger and Data Acquisition (2019).

Academic Visitors and Exchanges:

- Formal academic visitors to our UoA (working on campus with us for >3 months) from Cornell University, Imperial College London (4), MIT, Northwestern University, University of California, University of Montana, and University of Houston.

- Academic Visitor appointments for UoA staff at University of Kyoto;; Norwegian University of Technology; Institut Quantique of Université de Scherbrooke; Skolkovo Institute of Science and Technology, Moscow.

4.4 Public Engagement

We have a broad programme of public engagement to promote science, supported by the SEPNet Departmental Outreach Officer. We hold circa 10 public evening lectures per year highlighting our research, attracting audiences of up to 400 each, and we engage with the wider public during the Science Open Day (6000 visitors in 2019). We were recognized with the SEPNet Group Outreach prize in 2018. The Department uses online and social media to develop research visibility, e.g. staff featured in Seeker's 2019 "How Close Are We" episode on dark matter, which has >900k views; and over 40 of our research outputs in 2014-20 have Altimetric scores placing them in the top 5% for attention, as a measure of impact outside of the traditional scientific citation indices.

4.5 Contribution to sustainability of discipline

We contribute to sustainability of the discipline through our focus on widening participation and via professional service, e.g.

- *National*: staff serve/served on the IOP Juno Assessment Committee, the STFC's Projects Peer Review Panel, Particle Physics Grants Panel for Experiment (Chair, Members) and Theory, Particle Physics Advisory Panel, Education and Training Committee, Accelerator Evaluation Panel, Large Facilities Sub-group (Chair); LHCb Oversight Committee; CMS Upgrade Oversight Committee; and Science Board.
- *International*: staff serve/served on the CERN SPS and PS Experiments Committee, the Fermilab Long Baseline Neutrino Committee, the Astroparticle Physics European Coordination (APPEC) (deputy-Chair), the International Union of Pure and Applied Physics as Chair of Commission C5 and Vice-Chair of Executive Council, the Advisory Board of the Superconducting Quantum Materials and Systems Center, led by Fermilab and funded by US DoE, the 2019 European Strategy for Particle Physics Update, the 2021 ECFA Particle Detectors Roadmap (Convener), the 2020 US DOE Basic Research Needs Study (Convener), the SNOLAB Strategic Plan Steering Group (2017-22), and the UK-ESS Project board.

Responsiveness to national and international initiatives is evidenced by: involvement in diverse international programmes in Particle Physics; success in QTFP initiatives; our role in the national Quantum Technology Programme; joint appointments with national laboratories; portfolio of collaborative grants, networks and partnerships supporting research and impact; feeding the people pipeline to industry; and investment in infrastructure aligned with the national Quantum Technology Programme and the European Quantum Flagship Programme.

4.6 Wider Contributions to Society

Beyond the impact detailed in the case studies, on exploiting quantum technologies for healthcare and supporting R&D in materials development through improving the validity of modelling software, the culture of impact has fostered collaborations with industry. Companies directly involved in commercialisation of our technologies and software include Oxford Instruments Nanoscience, a leading manufacturer of scientific cryogenic instrumentation; IBA, a leading proton therapy instrument developer; and Johnson Matthey, a global science and chemicals company, and a leader in sustainable technologies. Beyond industry, our wider contributions are in the areas of

- *Supporting Metrology*: The *International Systems of Units* is the basis of international trade and supports the global measurement quality infrastructure through national metrology institutes. Instrumentation development by the LLTL, led by Saunders, and the Nanophysics

group, led by Astafiev, were critical in the 2019 redefinition of the Kelvin and are being exploited for developing Current Standards.

- *Tackling Global Challenges*: Monroe is active in low-background radiation detector development and is applying these techniques to environmental monitoring and public health, developing a hand-held technology for distributed measurement of lead pollution. .
- *Advanced statistical methods* developed by Cowan for Particle Physics applications and machine learning approaches have been exported via the interdisciplinary training network, INSIGHTS, to impact on machine learning for healthcare and finance, and predictions of extreme climatic conditions.