Institution: Queen's University Belfast

Unit of Assessment: 9

1. Unit context and structure, research and impact strategy

1.1 Structural Overview and Mapping of Research Interests

Queen's University Belfast (QUB) has continued to be an excellent environment for high-quality physics research throughout the REF2021 period, evidenced by:

- Publication of ~1,500 peer-reviewed physics articles in internationally recognised journals (garnering ~30,000 citations, with a collective h-index of ~70);
- Almost £50M spend from competitively-awarded external grants;
- 16 new academic appointments, augmenting strategically important research themes;
- Extensive collaborative networks (illustrated in outputs and research contracts);
- Almost £10M spend (by QUB) on building refurbishment;
- Prestigious fellowship funding;
- A multi-institutional Centre for Doctoral Training (and its renewal to 2028);
- Graduation of 167 PhDs, and the appointment of 110 new post-doctoral researchers;
- Honours and awards, notably Stephen Smartt's election to the Fellowship of The Royal Society;
- Significant recognition in the Stanford University Bibliometrics top 100,000 scientists (16% of our staff members are included in this list);
- Renewal of our Athena SWAN Silver Award.

At census there were 51 independent researchers (49.7 full-time equivalent, FTE), distributed across 5 research centres:

- ***Astrophysics Research Centre (ARC)*:** research in supernovae, exoplanets, solar physics, solar system objects and molecular astrophysics. 11 independent researchers [10.5 FTE]: *de Mooij*, *Fitzsimmons*, *Jess*, *Keenan*, *Mathioudakis*, *Millar (0.5)*, *Milligan*, *Schwamb*, *Sim*, *Smartt*, *Watson*;
- ***Atomistic Simulations Research Centre (ASC)*:** develops theoretical and computational tools to model matter at the nanoscale (Density Functional Theory, Time-Dependent Density Functional Theory, classical molecular dynamics, Monte Carlo and machine learning) and applies them to: optical properties, magnetism, 2-D materials, plasmonics, laser/ion-matter interactions, radiation damage in biology and nuclear materials, conduction in nanowires, nucleation and crystallisation. 8 independent researchers [7.2 FTE]: *Dundas*, *Gruening*, *Kohanoff*, *Suraud (0.2)*, *Stella*, *Todorov*, *Tribello*, *Wilkins*;
- ***Centre for Nanostructured Media (CNM)*:** research on functional materials (primarily ferroelectrics and 2D systems), but also activity in plasmonics. 8 independent researchers [8 FTE]: *Arredondo*, *Bowman*, *Felton*, *Gregg*, *Huang*, *Kumar*, *McQuaid*, *Pollard*;
- ***Centre for Plasma Physics (CPP):*** research in intense laser-matter interactions, the laser-driven generation of secondary radiation sources and their applications (including biomedical). 13 independent researchers [13 FTE]: *Borghesi, Dromey, Field, Greenwood, Kar, Margarone, Palmer, Riley, Sarri, Williams, White, Wu, Yeung*;
- ***Centre for Theoretical Atomic, Molecular and Optical Physics (CTAMOP):*** develops and applies theoretical methods to: attosecond science and strong-field processes; atomic collisions and antimatter studies; quantum information processing and quantum mechanics. 11 independent researchers [11 FTE]: *Abah*, *Ballance*, *Belenchia*, *Brown*, *De Chiara*, *Ferraro*, *Green*, *Gribakin*, *Paternostro*, *Ramsbottom*, *van der Hart*.

1.2 Strategic Aims in Research

1.2.1 Astrophysics Research Centre (ARC):

Throughout the REF2021 period, *ARC* advanced its international leadership in the areas of supernovae and explosive transients, exoplanets and stellar disks, solar system and solar physics. Across supernovae, explosive transients and solar system physics we have a common requirement for digital, time domain, wide-field sky surveys. We led the data processing for two major wide-field surveys (Pan-STARRS and ATLAS), resulting in discoveries of the first interstellar asteroid and a number of significant high energy explosions (requiring new physical insights), as well as several new comets. We also led the Public European Southern Observatory (ESO) Spectroscopic Survey for Transient Objects (PESSTO) programme, which culminated in the ground-breaking discovery of the electromagnetic source of gravitational waves (in 2017). Our expertise has placed us at the helm of large-scale projects that will shape the next decade, including: the Rubin Observatory (the most ambitious survey telescope ever built); ENGRAVE (the leading programme for the follow-up on gravitational waves in the optical and near infrared at ESO - we chair the Governing Council) and a new spectrometer for ESO, which will lead to a dedicated 5-year programme for transients and solar system science.

In collaboration with atomic data specialists (section 1.2.5), we have a theory strand which produces model spectra for supernovae, transients and kilonovae, underpinned by large awards on DiRAC and other high-performance computing facilities. This combination of observational programme leadership, theory and application to the new field of multi-messenger astronomy (combining photons with gravitational waves and neutrinos) is core to our strategic direction.

In solar-system physics, our activity led to involvement in the European Space Agency's Comet Interceptor mission and leadership of the Rubin Laboratory's Solar System Science Collaboration. In solar physics, our flagship project is building a first light instrument for the world's largest solar telescope: the 4-metre DKIST, under construction in Hawaii. In exoplanets and protoplanetary disks, our investment in the Next Generation Transit Survey (NGTS) facility and HARPS-North has facilitated discoveries of lower mass, rocky planets and allowed leadership of programmes on ESO's Very Large Telescope to probe exoplanet atmospheres. We lead detector development with an industrial partnership (Oxford Instruments), enabled by our long-standing expertise in very high cadence imaging.

Our diverse science has a common theme of rapid processing of high throughput data-intensive instruments, in combination with the application of novel algorithms and machine learning techniques. We have strategically developed these programmes, making us a renowned centre for data processing, rapid analysis and scientific discovery.

1.2.2 Atomistic Simulation Centre (ASC):

ASC focuses on modelling and simulation of matter at the atomic scale. In recent years, our expertise has expanded into new directions (rare events in molecular dynamics, supervised machine learning and functional properties of low dimensional materials). However, we have also maintained existing world-leading activities in electron transport in nanostructures, irradiation of materials and biological matter and laser-matter interactions. We have advanced modelling techniques and theoretical approaches, such as: machine learning algorithms to analyse high-dimensional data from molecular dynamic simulations; real-time many-body approaches for nonlinear optics in crystals; and time-dependent density-functional approaches for extreme nonlinear optics in molecules. Such advances are provided to the research community through free-access open-source software, such as Plumed (for molecular dynamics), Yambo, Questaal and EDAMAME (for theoretical spectroscopy).

We collaborate with experimental groups in the British Isles (*e.g.* Cambridge, Tyndall, TCD, TUD) and worldwide (*e.g.* Stanford, Purdue, Virginia Tech), by applying modelling to key challenges in areas such as Green Chemistry, Healthcare and Energy (*e.g.* thermoelectrics, low-energy consumption devices).

Activities are supported by a robust grant portfolio and strong research outputs have resulted (>100 publications, ~40 of which are in journals with impact factor [IF] > 7), mostly in condensed matter physics, materials science and chemistry, with contributions to chemical engineering, pharmacy, biochemistry and environmental science.

For the future, the aim is to lead areas of electron transport in nanostructures, irradiation of materials and biological matter and laser-matter interactions, by developing theoretical and

computational tools that describe and predict how energy is deposited and then transferred among electronic and vibronic degrees of freedom and the environment. Such developments will rely on our expertise (approaches to non-adiabatic dynamics and nonequilibrium molecular dynamics of open systems) and our collaborations, enhanced by participation in the COST action on modelling intense electronic excitation and in the EU-RISE programme on light-matter interaction.

1.2.3 Centre for Nanostructured Media (CNM):

CNM has enhanced its leadership in fundamental aspects of ferroelectrics and nanoplasmonics, while simultaneously delivering impact: strengthening our engagement with industry and pushing our spin-out company (Causeway Sensors Ltd.) forward.

In ferroelectrics, we have focused on domain walls (moveable 2D sheets with functional properties distinct from the bulk). We have developed a world-leading position in characterising their electrical transport and created novel proof-of-principle devices (such as domain wall memristors). We have led the UK effort on this theme (co-ordinating a multi-million-pound EPSRC critical-mass grant involving Cambridge, Warwick and St Andrews). In addition, we have pioneered a renaissance in understanding how domain walls might allow active control of thermal transport at the nanoscale (acknowledged by the award of a UKRI Fellowship). Our nanoplasmonics research has blossomed, particularly in plasmonic interactions with 2D materials, and we have started a novel research strand in molecular magnetism. Pursuits in magnetic thin film heterostructures and nanowire arrays have shifted towards end-user impact. Seagate (the data storage multinational) has continued to invest (£1.4M of direct funding in the REF period to *CNM*) and has acted as the anchor industrial partner in a Centre for Doctoral Training (CDT), involving 2 awards: 1 from 2014 to 2022 and its renewal from 2019 to 2028. Our spin-out company (Causeway Sensors Ltd.) builds directly on our nanoscale patterning and plasmonic research, commercialising biosensor technology for pharmaceutical drug development. Increasing venture capital was awarded, in four tranches (~£100k (2013-15); ~£0.5M (2016-18); ~£1.2M (2018-20) and ~£5M (2020-22)).

Our drive to remain at the forefront of experimental materials physics requires us to keep in-house facilities at the cutting edge: new microscopy infrastructure was commissioned and installed, funded through a multimillion EPSRC and QUB investment (housed in the “Ewald Microscopy Facility”). We integrated in-house capability with national and international central facilities (*e.g.* SuperSTEM, Diamond, ORNL, the Berkeley Lab, SOLEIL and the Ernst Ruska Centre) and this has helped ensure inventive and novel research (we published over 20 original papers in high-impact journals [IF>13] and had over £10M of UKRI-funded programmes active during the REF period).

In the future, we will continue to push our fundamental research, pursuing globally disruptive targets, such as the demonstration of ephemeral domain-wall electronics and nano-circuitry, wall-based nanoscale thermal switches and 2D-materials-enabled plasmonics. Our interaction with industrial partners will continue to be a priority.

1.2.4 Centre for Plasma Physics (CPP):

CPP has enhanced its principal research theme of ultra-intense, short-pulse laser interactions. The TARANIS laser facility has been a springboard for experimental projects. Its operation and upgrade are part of our long-term vision. The size of the group allows us to have important activities in other areas too, such as warm dense matter, low temperature plasmas of industrial/medical interest and laboratory astrophysics. These have attracted UKRI funding and ensured breadth in our research portfolio. We place emphasis on high-quality academic output, as evidenced by the publication of 15 papers in Nature/Science series journals and 18 papers in Physical Review Letters during the REF period.

The REF2014 future plans were along 2 principal themes: (1) Ultra-intense short-pulse laser interactions and (2) radiotherapy studies and medical plasma applications. The first theme continues and is enhanced with the arrival of *Palmer* and *Margarone*, who bring considerable independent track records. The second theme has changed, with personnel changes (*Currell* went to the University of Manchester), and hence the radiotherapy aspects of our research have contracted. Nevertheless, work on high-dose-rate-effects, using laser-accelerated protons, is continuing. Work on medical-related plasmas also continues, with research in plasma jets.

Our approach to impact has been to combine our fundamental research with work aimed towards advancing applications. This often involves groups beyond physics, usually those related to medical science and technology:

- We collaborate with QUB Pharmacy to evaluate the physical parameters of plasma jets that they use (in our labs) to expose bacteriological samples;
- In the wake of COVID-19, work has begun to look into decontaminating PPE using plasma discharges;
- We have worked with international co-authors on using lasers to develop nanostructure scaffolds, for enhanced drug delivery as well as surfaces for enhanced wear performance in orthopaedic alloys.

1.2.5 Centre for Theoretical Atomic, Molecular and Optical Physics (CTAMOP):

CTAMOP has consolidated areas of historical strength (*e.g.* attosecond science, atomic collisions, the interaction of positrons with atoms and molecules) while developing leading roles in emerging areas of quantum information processing.

In attosecond science, new laser technology (free-electron lasers and sub-femtosecond light pulses) requires computational techniques to describe atomic dynamics: time-dependent R-matrix theory (RMT) for ultra-fast processes and 2D R-matrix propagator techniques for multi-electron emission in general atoms. These techniques have been developed for the assessment of attosecond transient absorption spectroscopy, strong-field re-scattering and XUV-initiated high harmonic generation. We intend to combine these techniques to tackle multi-electron emission in ultra-short light fields, and uplift RMT codes from atomic to molecular systems.

In atomic collisions, the provision of atomic data for heavy, complex, open-shell atomic systems has been key. We have expanded our studies from astrophysics to fusion science, with calculations underpinning the understanding of impurity influx of plasma-facing materials into tokamaks. With local (*ARC* and Armagh planetarium) and international (Observatoire de Paris, the Harvard Center for Astrophysics, Auburn University, General Atomics) collaborations, these endeavours have been sustained by UKRI support [~£1M]. Large-scale computation has used significant time on ARCHER and ARCHER 2 high-performance computing facilities, the US Summit supercomputer (16 million CPU hrs) and the German Hawk HLRS facility (20 million CPU hrs). We published >20 research papers in top-tier journals within the fields of high-performance computing, fusion, astrophysics and atomic and molecular physics and optics.

In antimatter studies, emphasis has been on the investigation of positron bound states and their annihilation in polyatomic molecules. We have worked on new approaches to positron-molecule interactions by constructing positron-molecule correlation potentials, calibrated by experiment. Through a new appointment (*Green*), we are internationally centre-stage in many-body theory of positron interactions with atoms and molecules, evidenced by the award of an ERC Starting Grant [~€1.3M] and funding from EPSRC [~£0.6M].

In quantum information, we focused on the investigation of the roles of emerging quantum features when considering non-equilibrium (thermo-)dynamics. We studied protocols for the synthesis of non-classical states of atomic, mechanical and photonics systems and addressed the foundations of quantum theory, from an information theoretical perspective. In collaboration with experimentalists (ETH Zurich, Aarhus, Copenhagen, Rio de Janeiro, Rome, Vienna), we focused on understanding entropy-production processes in quantum evolution and investigated the efficiency of microscopic quantum engines, supported by significant funding from the EU [coordinating the first FET Collaborative Grant on thermodynamics of quantum systems, TherMiQ, €2.1M], the EPSRC [~£0.9M], and the Templeton Foundation. Our leadership in quantum information is evidenced by 15 papers in high-impact journals (IF > 7) on the topic, during the REF period. Significant success has been achieved in the foundations of quantum theory, where we have established new methodologies for the investigation of collapse models in mesoscopic quantum systems and the study of the potential quantum nature of gravity, supported by EU funding [TEQ consortium, ~€4.3M]. We will continue developing research in the thermodynamics of quantum systems, expanding towards assessments of thermodynamically consistent open quantum systems and the theory of mesoscopic quantum systems (from optomechanics to cold atoms); concurrently, we will explore the application of machine learning to quantum physics.

1.3 Directors of Research

During the REF period, each research centre had its own Director of Research (DR), acting as a key management contact point, representing staff views and interests to senior managers. DRs were extremely important in our research structure and culture: they were responsible for the research agenda and future planning within their area; they set the tone, in terms of standards of research integrity, informed by university-level policy documents (https://www.qub.ac.uk/Research/Governance-ethics-and-integrity/Policies-procedures-and-guidelines/), as well as the national-level Concordat to Support Research Integrity (including its 2019 update); they acted as key mentors for all research staff in their centres (performing "Appraisals" and "Personal Development Reviews") and were particularly important for guiding Early Career Researchers (ECRs): in most cases, playing an active role in helping ECRs to formulate cases for support and key outputs; they decided on how university resources (allocated annually) were spent, to further the research agenda. The Head and Deputy Head of School oversaw DR performance and a common research culture across the School was maintained through discussions at senior management boards (*e.g.* School Research Committee, Faculty Research Strategy Group).

1.4 The Impact Champion and the Impact Pipeline

1.4.1 Impact Champion: The School appoints an Impact Champion whose remit is to promote, support and encourage end-user engagement. They sit on key strategy groups and committees, liaise with DRs and the university "Research and Enterprise" unit (which offers funding, support and advice for impact-related activity) and chair the Employers' Advisory Board (EAB). The EAB brings together major physics and mathematics graduate employers in N. Ireland (from technology, software and finance backgrounds) to guide the manner in which we engage our research teams for short-term consultancy, as well as longer-term joint projects. They also advise on education provision. Currently, membership includes: Seagate, First Derivatives, Intel, Oxford Instruments, Camlin, General Electric, Citi Group and Deloitte.

1.4.2 The Impact Pipeline: The Impact Champion fosters end-user-related research. This helps develop the mature impact case studies, considered in REF (interactions with *Andor / Oxford Instruments*, *Seagate Technology* and *Causeway Sensors Ltd.*, as well as our *Public Outreach* programme). In addition, it creates an "impact pipeline": a collection of activities which may grow and constitute significant impact in the future, if the research input eventually has sufficient commercial value and if the companies involved (and their markets) evolve favourably. Some examples in the "impact pipeline" are:

- *Improving Signal-to-Noise Light Detection for RANDOX Laboratories:* Randox makes sensor chips for detecting a variety of constituents in biological samples. Positive molecular detection is indicated by chemi-fluorescence, which can give a binary diagnostic (either the target molecule concentration is above or below a threshold). Sophisticated light detection can be used to indicate molecular concentration and this is highly desirable. However, absolute emission intensities are low. Moreover, the Randox CCD cameras, used as standard, have sensitivity levels that make fine resolution of molecular levels challenging. Rather than replace their cameras, Randox commissioned our researchers to use their expertise to increase the signal-to-noise from the output of the CCD camera chips, through modelling and background subtraction. ~£2.5M (£500k specifically to QUB) was provided through our regional economic development agency. Lab-space, optical benches and dark-rooms, as well as workshop help, were internally arranged. This allowed full experimental characterisation of the CCDs. Statistical techniques were then employed to dramatically increase signal-to-noise.
- *Optimising Performance of Dielectrics for Syfer / Knowles:* In a research programme funded by the Technology Strategy Board we worked with Syfer / Knowles (among others) to create a new lead-free high-performance dielectric for integration into high-temperature multilayer capacitors. Syfer / Knowles used this as a starting point for full product development, which has recently been "soft"-launched and is awaiting full launch given positive market feedback. The School provided ready access to the extensive facilities available in our laboratories to support this work. The Impact Champion has maintained ongoing dialogue; hopes are that significant product sales worldwide might be evidenced within the next REF-cycle.

- *Plasma-Processing Diagnostics for Intel, Camlin and Seagate:* some of our research has been on high-sensitivity negative ion mass spectrometers. We canvased commercial interest in using such spectrometers for in-situ monitoring of industrial plasma-etching. To develop resulting interactions with Intel and Camlin, a staff impact sabbatical was granted. Intel and Camlin both invested funds (~£300k) to part-support PhD students and a PDRA through the Knowledge Transfer Partnership (KTP) scheme. With help from the Impact Champion, an Impact Acceleration Award was also obtained. Results are promising and Seagate is now keen to support future research.
- *Nanobiotix:* Other researchers have been applying their expertise, in the physics of radiation-nanoparticle interactions, to help the biotechnology company Nanobiotix, who are using nanoparticles such as hafnia to concentrate energy transfer from radiotherapy into tumour cells. Products with which we have been involved are currently in clinical trials and may result in both commercial impact and improved healthcare outcomes for patients.

1.5 Open Research Environment

We have a strong culture of open access publishing: many make use of community repositories (such as *arXiv*). In addition, we post our outputs onto the QUB repository system "PURE". The QUB library ensures that the appropriate versions of outputs (preprint, post-print etc) are saved and that embargoes and copyright conditions are not violated. Our funding portfolio also allows us to use UKRI open access publication funds for "gold access". A support team monitors adherence to open access regulations and we consistently show high rates of compliance (92.4% across the REF period). Data Management Plans address all data (including associated metadata) needed to validate the results presented in scientific publications and other curated or raw data (including metadata) generated by research done within the UoA. Data generated or collected include published results of experimental measurements and numerical simulations. These data are collected and catalogued, using a data-set reference and name, description, standards and metadata. Wherever possible (and unless specific requirements prevent it) data are deposited in repositories such as Zenodo or Github, or in central facility archives when appropriate, as well as in the university's PURE system.

2. People

2.1 Staffing Strategy and Development

2.1.1 Academic Staff Flux:

We see a modest turnover in academic staff (~4% each year). We view this positively: new appointments bring fresh ideas and interactions while those moving on increase our reputation and influence both nationally and globally. Of those that had been in post for the REF2014 exercise, 7 retired during the REF2021 period (*Dawson*, *Geissler*, *Graham*, *Lewis*, *McCann*, *Scott, Shearer*); a further 6 resigned (*Currell*, *Jung*, *Kotak*, *Kourakis*, *Reville*, *Zepf*), mostly as a result of "head-hunting" to new academic positions in the UK (Manchester University), Europe (MPI Heidelberg, Helmholtz Institute Jena, University of Turku) and Middle East (Khalifa University of Science and Technology). One of our Royal Society University Research Fellows (*Maund*), present in REF2014, relocated to the University of Sheffield.

16 new appointments were made, augmenting excellence in strategically important themes. While 4 moved on within the period (to institutions such as the Universities of Edinburgh, Stockholm and Potsdam), 12 were still in employment at 31/07/2020: theorists and observational physicists were embedded in teams with similar interests and with access to appropriate computational facilities (*Ballance* 2015, *Green* 2015, *Milligan* 2019, *Schwamb* 2019, *de Mooij* 2019, *Wilkins* 2020). Experimentalists were appointed into areas offering cognate support, as well as established laboratories, such as the TARANIS Laser Lab (*Yeung* 2015, *Margarone* 2019, *White* 2019, *Palmer* 2020) or the ANSIN laboratory and Ewald Microscopy Facility (*McQuaid* 2017). *Suraud* was appointed on a 4-year 0.2 FTE contract, to support interdisciplinary research, as part of a university "World-Leading Researcher" scheme.

Vacant posts are not refilled automatically. Strategic need, staff-student ratios and budgeting constraints or opportunities all play a role in making decisions on new posts.

As a matter of policy, holders of specific fellowships are offered a permanent academic position at the end of their fellowship. This career safety-net has ensured a vibrant community of fellows (see sections 2.1.5 and 4.2.5).

2.1.2 Career Development Support:

- *Probation:* New academic staff are required to serve a probationary period prior to either being confirmed in post, extending probation, or having employment terminated. Probationers are given reduced teaching and administration. The Head of School (HoS) appoints a mentor who meets with the probationer regularly to review progress and give advice. In addition, a gender-balanced probation committee is formed (the HoS, Director of Education, DR and a professor from another centre). This committee meets annually to consider reports from the probationer and their mentor and to discuss progress. At the end of probation, candidates' cases for "confirmation in post" are considered. All probationers are made aware of expectations and key indicators. Decisions concerning "confirmation in post" are made at the School level.
- *Promotions:* Physics has a strong track record in promotions. There was a total of 19 in the REF2021 period: 9 to Senior Lecturer, 8 to Reader and 2 to Professor. In working towards promotion, members of staff are given input from annual appraisals (in the past) or (more recently) "Personal Development Reviews" (PDRs). PDRs adopt a developmental approach in the discussion of staff performance, consistent with the university *People First* promise to 'create opportunities' to build the capability of our staff. PDR provides a two-way conversation between staff and line manager, to discuss future plans and career aspirations, as well as priorities and development goals. Typical academic profile guidelines, associated with each grade, have been generated by the university and are useful in honing promotion applications. Staff are encouraged to meet with the HoS for promotions advice. Indeed, the HoS chairs an annual meeting on applying for promotion. Members of staff who receive offers of employment elsewhere may approach the HoS, to see whether a counter-offer might be made for retention purposes. The process for consideration of counter-offers necessarily operates outside the normal promotion timetable. A similar process can be used if a member of staff achieves something genuinely exceptional for their grade, where immediate promotion is overwhelmingly appropriate. In the period (2018), such a promotion was given to *Green* on the basis of exceptional success and validation through external competitive review.

2.1.3 Staff Age Demographic: The age profile of staff, as at the REF census date, is represented in figure 2.1. In the 30-60 range it is reasonably flat. We think this is healthy, as differences in perspective, that might be age-group related, are well-represented. The homogeneous profile helps in succession planning, since there are no "pulses" in particular age-groups that might lead to either a sudden crisis in future hiring, or stagnation in making new appointments.

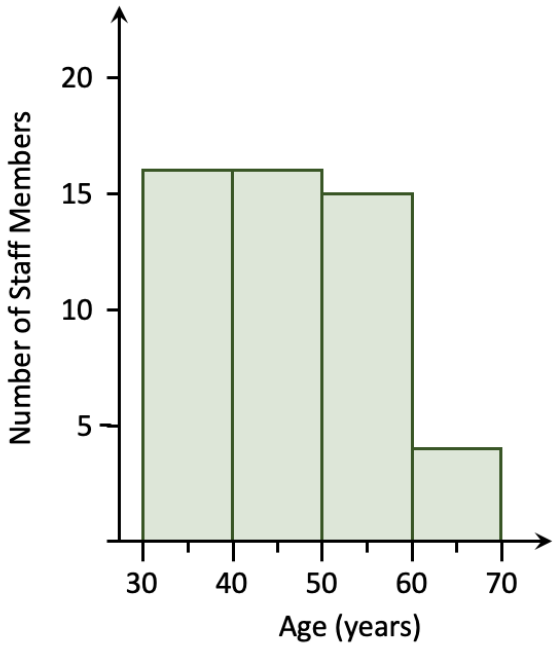

Figure 2.1: Age profile of staff members as at the REF census date (31/07/2020) binned into decades. In general, the distribution of staff ages between 30 and 60 is relatively homogeneous. The dip above 60 is largely due to retirements.

2.1.4 Integration of Fellows and Post-Doctoral Research Assistants (PDRAs): During the REF period, 110 fixed-term contract researchers were appointed to the UoA, employed using the same appointment procedures as for permanent university positions. They were integrated into the workforce under the same terms and conditions and their progress was managed using similar induction, probation, project review and PDR processes. We have informal interdisciplinary group-mentoring schemes, where established academics meet with up to six PDRAs on a regular basis. QUB adheres to the Concordat for the Career Development of Researchers and is committed to reacting positively to the results and recommendations arising from the 2018-19 Concordat review.
Within the UoA, we support the community through a postdoctoral forum and by funding coffee mornings (usually every fortnight) to allow contract staff to mix and informally discuss issues with their peers. We fund an annual careers day, or overnight retreat (if desired), with invited speakers and careers sessions, giving key information and allowing experiences and aspirations to be shared.

2.1.5 Fellowship Academy: This is a forum to support people who have evidenced themselves to be future research leaders, either because of their success in obtaining a QUB Vice-Chancellor's Fellowship (through the "Illuminate" scheme, for example: https://www.qub.ac.uk/directorates/HumanResources/fellowships-at-queens/illuminate-vice-chancellors-fellowship-scheme/), or because of a prestigious external award (such as The Royal Society University Research, UKRI Future Leaders and EPSRC Early Career Fellowships). The Faculty and UoA are proactive in developing potential applicants for fellowship applications, offering support in building proposals and giving mock interviews.

2.1.6 Central QUB Support for Researchers: The Research and Enterprise Directorate supports researchers in a number of ways, providing guidance on ethics and governance, project funding, working with partners, and commercial developments. For building grant applications, they advise on suitable funding bodies, how proposals might be constructed and how costings should be done. They also look after contracts when awards have been made.

2.1.7 QUB People First – Learning and Development: The university supports individuals who wish to engage in Continuing Professional Development through the provision of formal courses, secondments, coaching and mentoring schemes (https://www.qub.ac.uk/directorates/HumanResources/learning-and-development/).

2.1.8 Examples of In-House Career Development: Staff members who have developed their research careers partly or entirely within the School, prior to their appointment to academic posts (within the REF period) include: *Green* (appointed from fellowship initially to a lectureship and then reader position), *Santos* (appointed from fellowship to lectureship prior to his move to the University of Edinburgh), *Yeung, McQuaid* and *White* (all appointed from PhD and QUB post-doctoral positions to lectureships). *Maguire, Gibson and Milligan* obtained PhDs from QUB and, after building experience elsewhere, were awarded fellowships allowing them to return. *Maguire and Gibson* subsequently moved to assistant professorships in Trinity College Dublin, while *Milligan* is still a research fellow in QUB (see table in section 4.2.5).

2.1.9 Sabbatical Leave: There is an annual internal application process for sabbaticals. In general, they are given for applications in which new collaborations, or a new avenue in research are intended. Those seeking time away from teaching and administration, without a focused plan, are generally unsuccessful. Sabbatical leave generating non-academic impact is particularly encouraged: *Pollard* used an impact sabbatical to accelerate growth of the spin-out company Causeway Sensors Ltd.; *Field* used his impact sabbatical to enhance industrial collaborations, resulting in the graduation of a fully-funded PhD student with Intel (in 2016), a part-funded PhD student with Camlin (in 2019) and signing a non-disclosure agreement with an oil industry service provider (2019).

2.1.10 Staff Forum: In 2016, a staff survey revealed the need for more opportunities for employees to voice issues openly at university level. In response, the “Staff Forum” was established (June 2018), chaired by the Vice-Chancellor, with representatives from each School, Directorate and Global Research Institute (major theme-based interdisciplinary research centre). The Forum provides an opportunity for staff to share views and input into university strategies and policies that influence the working experience. It also allows senior university management to engage with key representatives, gather feedback and listen to suggestions for positive change. Since its inception, it has reshaped the appraisal process, launching the new *Personal Development Review* (PDR). Forum members worked to support the 2019 staff survey and gathered the feedback required to help create the recent “Survey Institutional Action Plan”. It is a useful vehicle for engagement and we have a physics representative in place.

2.2 Postgraduate Training and Supervision

2.2.1 Overview: The School has a postgraduate research (PGR) student population of 190 (174 in physics), the largest in the Faculty. The physics PGR student population has grown steadily from 141 (2014-15) to 174 (2019-20). Across the REF period, 94% of students completed their degrees within 5 years. Students are funded through a variety of sources including internal university funds, the Northern Ireland Department for the Economy (DfE), UKRI and industry; alternatively, they may be self-funded or hold independently obtained scholarships. We commit to supplying each student with a new laptop and a budget for travel and conference attendance, when this is not automatically part of their studentship.

2.2.2 Post-Graduate Researcher Appointment and Supervision: PGR projects are externally advertised and potential candidates are invited to interview. Each PGR student is assigned to a research centre and is supervised by a team of two subject-expert academics. A third supervisor is appointed, if the research is interdisciplinary, or if some of it is performed away from the university. Academic staff members, new to supervision, must attend centrally-provided supervisor training courses. Individuals are not normally appointed as primary supervisors for more than 6 full-time students concurrently. PGR students enjoy a close relationship with their supervisor with regular meetings: University Regulations state that students must have at least 10 formal (documented) meetings each year; at least half of these must be attended by the second supervisor. A record, including a report and action plan, is lodged online as part of the “QUB Student Lifecycle”.

2.2.3 The QUB Graduate School: provides a hub that connects students across all disciplines to one another, to mentors, leaders and employers within the university and beyond. Training requirements are tailored to suit the individual student and project. The associated Postgraduate

Development Programme supports PGR students in the development of research and transferable skills, to enhance their employability. It is based on the requirements of the Researcher Development Statement and Researcher Development Framework. The Graduate School also offers the use of a dedicated building of inspirational architectural beauty for PGR students to use for study, meetings or seminars (https://www.qub.ac.uk/graduate-school/information/facilities/).

2.2.4 Additional Training Opportunities: Students have the opportunity to assist in undergraduate teaching and many find this valuable. In addition, we run summer schools on specific topics (such as the use of "Cloudy") which they can attend. Students may also benefit from courses on entrepreneurship, that are offered as part of the Innovation Academy (run by QUB, Trinity College Dublin and University College Dublin), which aims to transform some of the brightest doctoral scholars into resourceful entrepreneurial achievers.

2.2.5 Centres for Doctoral Training: The School currently leads an EPSRC Centre for Doctoral Training (CDT). Within this CDT, high levels of industrial engagement and sponsorship have helped to create a diverse and vibrant research community, where research projects align closely with industry road maps. Extensive networks lead to plentiful opportunities for placements, nationally and internationally, with students having spent time with partners in Europe and as far afield as Japan. The CDT delivers a cohort-based student experience, where students themselves drive the training agenda, organising annual events, such as a summer "Conclave" (with industry keynote speakers and panels) and a winter school (which draws on the skills and expertise of academics across partner institutions).
Crucially, the CDT fosters peer-to-peer learning and supports networks across the student body (invaluable during the COVID19 pandemic).
50 UK-registered candidates are enrolled on the CDT's unique, jointly awarded PhD and EngD programmes, with a further 7 (rising to 25) with our Science Foundation Ireland partner (the Irish Photonic Integration Centre). 9 doctoral researchers have completed the programme to date; all have gained employment – 4 within the technology sector (Seagate, the National Physical Laboratory and Huawei); 5 in post-doctoral positions (QUB, Imperial College London and Trinity College Dublin).

2.2.6 Science Technology and Facilities Council (STFC) Accreditation: Our Physics Research Degree Programme was accredited by the Science Technology and Facilities Council (STFC) in the REF period and received its first quota awards in 2019. These annually allocated STFC awards enhance our PGR portfolio, provide the students with access to STFC funding for training and include an enhanced training grant. The School continues to secure UKRI training courses on supercomputing.

2.2.7 PGR Board Input and Monitoring: The School works with potential employers through the Employers' Advisory Board (EAB). Student satisfaction and the effectiveness of PGR training is monitored through:
(i) The School Postgraduate Research Board (both student and staff representation);
(ii) The Postgraduate Research Experience Survey and
(iii) The Athena SWAN Committee (2.3.1).
PGR students have reported high degrees of satisfaction, above the QUB and Russell Group averages, in the areas of resources provided, quality of supervision and research culture.

2.3 Equality and Diversity (E&D):
We are committed to the promotion of equality of opportunity and to creating and sustaining an environment that values and celebrates diversity, evidenced by a SWAN Silver Award in 2016 and renewal in 2020.

2.3.1 Athena SWAN Committee and JUNO:
The Athena SWAN Committee has a broad remit. Below are a number of areas where we promote E&D:

- All recruitment adverts include a statement of the School's commitment to E&D and recruitment panels must have female representation;
- An annual career day is organised for research students, fellows and PDRAs;
- Depending on circumstances, the teaching and administration load is reduced for staff returning from maternity/paternity or health-related leaves of absence;
- An internal travel fund is available to all staff;
- We encourage fellowship applications (*e.g.* the Dorothy Hodgkin Fellowship; see section 4.2.5) that enable a flexible working pattern;
- Wellbeing and mental health issues are addressed through regular training activities and the annual Mental Health Awareness Week;
- A healthy work-life balance is supported by scheduling meetings between 10am and 4pm;
- Flexible work, various career leaves and part-time contracts are available and advertised to all staff;
- For career development such as: promotion, leadership positions, prizes, access to internal funds and submission of funding applications, all members of staff are encouraged to apply or are nominated by their line managers, DRs and the HoS.
- Training on unconscious bias is compulsory for all staff involved in recruitment.

We are active in the JUNO project (the Institute of Physics diversity initiative). The JUNO team is embedded within the Athena SWAN Committee, but focuses primarily on the challenges involved in physics (as opposed to mathematics). We have had continuous JUNO Champion status since 2014.

2.3.2 Involvement in EPSRC-Funded Inclusion Matters Initiative:
The School Athena SWAN and JUNO teams have co-investigator representation on a Faculty-wide £500k grant, funded by the EPSRC Inclusion Matters Panel (EP/S011919/1). The programme focuses on developing a variety of resources to engage engineering and physical sciences staff with gender and equality issues, in a positive and effective way, and to see how lessons learned might be shared across QUB and other institutions.

2.3.3 Invited Lectures: We value external speakers. Seminars are organised by research centres, with open attendance. We also run prestigious named lectures, such as The Larmor and John Bell Day lectures. We monitor speaker invitations and deliberately seek to promote balanced representation. Recently, the invited female speaker fraction increased to a third, well above our female academic staff fraction, and this has been correlated with an increase in female PGRs.

2.3.4 E&D and REF2021 Preparations: The selection of outputs for REF was made according to the anticipated quality grading, judged by both internal (panel balanced by gender and career stage) and external peer review. Where the judged quality of outputs could not be differentiated with confidence, selections were made to reflect the full gamut of our research portfolio. Any possible tendencies to unconscious bias were monitored annually by the university (after output selections had been proposed), set against 11 different diversity characteristics (such as ethnicity, religion, disability, gender etc). No signs of bias were evident at any stage.

3. Income, infrastructure and facilities

3.1 Infrastructure and Facilities:
3.1.1 Buildings Housing our Research: We have a genuinely inspirational built environment for research (and teaching). We are located within the original red-brick campus of the university. Our staff offices and research teams are distributed across two buildings, separated by a pedestrian walkway leading from the campus entrance to the university library. One building is a wing of the main university courtyard. It was built in 1911 and adjoins the historic Lanyon Building. It overlooks the formal gardens, in which graduation ceremonies are held. The other building overlooks the city's Botanic Gardens and the Ulster Museum, with south-facing out-door social space on the top floor. This building has two sections: one erected in the 1950's and used

for staff and research student offices; the other is a 4,700m^2 purpose-built laboratory space, constructed in 2005 (costing £9.4M). During the REF period, the university invested significant resource to refurbish our office areas. This was part of a larger project, in which all teaching spaces (save for the Larmor, Bell and Emeleus lecture theatres) were converted to become research-only. At the same time, teaching facilities for the entire School were relocated to (and centralised into) a third building, also on the pedestrian walkway to the library. The result is a geographically tight cluster of three refurbished buildings, only metres away from the main library, in which all teaching and research in Mathematics and Physics is housed. The cost of the entire project was ~£9.5M. It was initiated in 2014, finished in 2018 and involved several phases of staff relocation, but only temporary disruption to research. In 2018, in response to an EPSRC equipment grant for new microscopes, further specific laboratory refurbishments were undertaken, at a cost of ~£100k to QUB.

3.1.2 In-House Equipment and Facilities:

- *ARC:* Data processing is a vital part of our astrophysics research. We maintain a large local cluster that processes all of the datasets generated by the ATLAS, PAN-STARRS and PESSTO projects. It is maintained and supported by two senior software developers, who had been employed under external grants, but have recently been made permanent university employees.
- *ASC:* Besides accessing national high-performance computing facilities and the investments needed to upkeep and upgrade our local cluster, we participated in a consortium to create a national Tier 2 Hub for materials and molecular modelling. Hardware was funded by EPSRC (~£4M), while the consortium paid for maintenance and IT support (QUB contributed £300k to this project). A similar grant, for funding an upgrade of this Tier 2 high performance computing facility, has recently been submitted.
- *CNM:* We need access to extremely well-found in-house laboratory equipment, which exists in two main spaces – one associated with the ANSIN materials research hub, which is a large space containing thin film growth and materials-properties characterisation tools (initiated by a ~£9M donation from Seagate in 2009); the other is associated with the Ewald Microscopy Facility (EMF) which contains a suite of microscopy tools and an x-ray diffractometer. The range of experimental facilities available, as a result, is enviable: in growth, we have a number of sputtering tools, a large-wafer pulsed-laser deposition system and several evaporators; for patterning, we have a photolithography suite, 2 focused ion beam microscopes and atomic force microscopy machining; for characterisation, we have electron microscopes, optical and plasmonic measurement systems, suites of scanning probe microscopes, magnetic and magneto-optic measurement systems, electrical characterisation suites, the x-ray diffraction system and a dedicated thermal transport laboratory.
  During the REF period we spent ~£3.5M (~£2.5M from the EPSRC) to: replace our X-ray Diffractometer (in 2015); enhance our optical and plasmonic characterisation (in 2017); replace our transmission electron microscope (TEM) (in 2018); replace our focused ion beam microscopes (in 2018); add to our scanning probe microscopy suite (in 2018); upgrade our cryostats and SQUID systems (2019); create a cryogenic thermal diffusion measurement facility (2019) and introduce new TEM in-situ gas environment specimen holders (2019).
- *CPP*: The TARANIS laser is an important and significant investment. In the REF period, ~£1M EPSRC funding has gone into developing additional capabilities (ultrashort pulses). In the near-medium term, a facility upgrade will be needed to ensure that TARANIS remains a competitive mid-range facility for our future research needs. The recent, QUB-funded, development of a biological laboratory in the proximity of TARANIS is an important step towards more extensive interdisciplinary usage.
- *CTAMOP:* maintains a local computer cluster, but our research teams are also heavy users of national and international computational facilities (such as ARCHER-2, the US Summit supercomputer and the German Hawk HLRS facility).

3.1.3 Kelvin and Kelvin-2 Hubs: QUB (in conjunction with Ulster University) maintains and runs a high-performance computing hub which is used by almost all the research centres within the

UoA. In its initial incarnation, this hub was called "Kelvin". Recently, with significant EPSRC support (£2.1M awarded in 2019) and with considerable university backing, Kelvin has been significantly upgraded ("Kelvin-2") and its importance has been officially recognised in becoming a National Tier 2 facility. It is a useful intermediary between our in-house clusters and Tier 1 National facilities.

3.1.4 Professional Support Staff: We have our own well-equipped mechanical workshop, with 3 highly-skilled engineers. The close, friendly interaction between workshop and academic teams has been invaluable for finding rapid and pragmatic solutions to laboratory-related problems. A separate microscopy management team helps the Ewald Microscopy Facility Director (an academic) to manage and maintain the suite of high-end equipment and coordinate the annual maintenance contracts needed. We have 2 in-house laser engineers who help to manage the TARANIS facility, as well as deal with more general chemical processing logistics and safety. In terms of administrative research support, we have 4 people involved: 2 to help run the CDT and 2 for more general activities. On top of this, we have 4 computer support officers, who oversee the installation, maintenance and upgrades of our in-house research machine clusters, as well as the provision of laptops for PhD students and staff.

3.2 Research Funding:

3.2.1 Direct Research-Related Spend from External Awards: The spend profile from external research grants is presented in figure 3.1. The total spend was over £49M (in REF2014 it was < £30M), with the majority (>£29M) coming from the UK Research Councils (dominantly EPSRC and STFC). The total from UK central government and local authority funding was over £10M, with ~£5M from EU grants. Direct funding from industry was significant (>£3M over the REF period).

We believe this illustrates an emphasis on awards from sources with rigorous peer-review (UKRI and EU research funding), balanced by a reasonable breadth in portfolio and a noteworthy element of industrial support. EU funding represented ~10% of our portfolio. We will be keen to engage in new frameworks which allow our pan-European research engagement to continue at a healthy level.

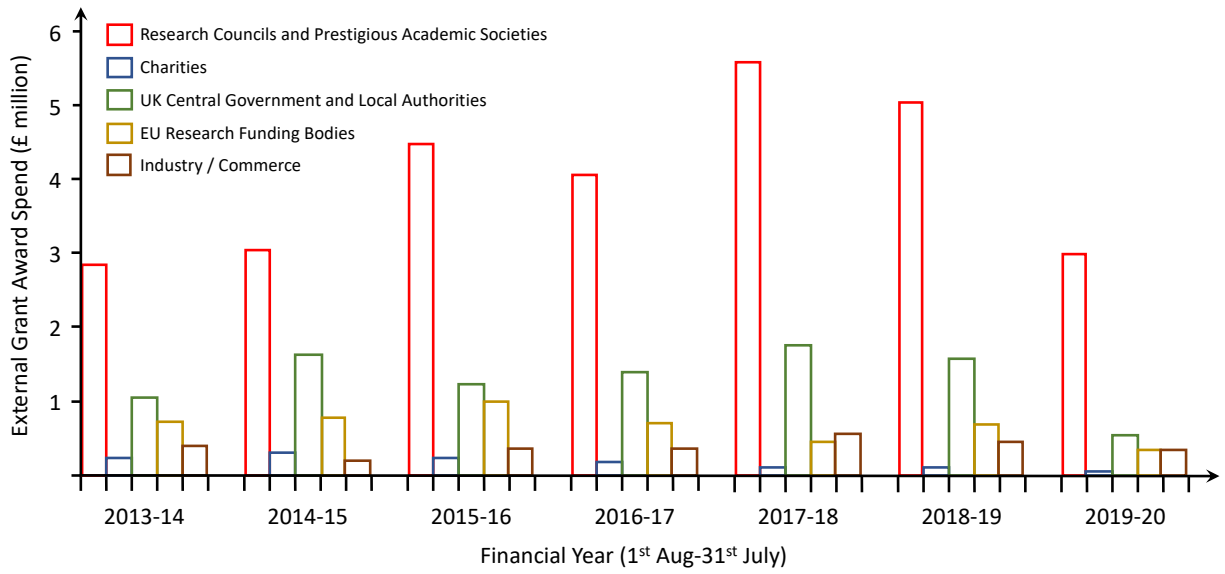

Figure 3.1: Spend on external grant awards from different sources during the period 1st Aug 2013 to 31st July 2020.

3.2.2 Externally Awarded Grants Active in each Research Centre:

Astrophysics Research Centre (ARC): Most Principal Investigator (PI) research funding has been from the STFC (~£9.5M across 9 grants), with almost £5.5M associated with Consolidated Grants. This has been augmented by some EU funding (£0.3M) and direct industrial support (£0.5M from Randox).

Atomistic Simulations Centre (ASC): PIs on 13 grants (totalling ~£3.4M) awarded during the period:

- 4 from the EPSRC (total ~£880K);
- 5 from the N. Ireland Department for the Economy (~£1.6M, ~£1M of which came from the US-Ireland Research and Development Programme);
- 1 from The Royal Society (~£100K);
- 3 from EC-H2020 (~£795K).

Co-investigators (CIs) on 3 further EPSRC grants (~£2.5M), where PIs were either in *CPP* (~£2M) or in Chemistry and Chemical Engineering (~£0.5M).

Centre for Nanostructured Media (CNM): PIs on ~40 externally awarded grants active during the REF period (totalling ~£16M):

- 12 from the EPSRC, including a "Critical Mass Grant" on ferroic domain walls (PI for the £2.2M UK consortium);
- A significant infrastructure grant (£1.8M from EPSRC for "The Queen's University Imaging and Patterning Centre");
- Centre for Doctoral Training awards (£7.2M investment for PhD training in Photonic Integration and Advanced Data Storage);
- 6 from the N. Ireland Department for the Economy (total ~£1.8M, ~£1.4M of which came from the US-Ireland Research and Development Programme);
- 2 venture capital awards (total ~£1.7M for the spin-out company Causeway Sensors); note that the 3rd award at the ~£5M level has been agreed in principle, but formally begins outside of this REF period;
- A grant from Seagate (~£1.4M of direct funding);
- 11 from Invest Northern Ireland (totalling ~£0.3M to support Causeway Sensors)
- 8 others (totalling ~£1.2M) from The Royal Society, The Royal Academy of Engineering, EC H2020 and Innovate UK.

Centre for Plasma Physics (CPP): 14 EPSRC grants active during the period, with a total value exceeding £12M, and including a number of major funding initiatives:

- The "A-SAIL" ESPRC Programme Grant (£4.5.M) supported research in laser-ion accelerators towards healthcare applications;
- The NanoRad Platform grant (~£1.4M) boosted research in fundamental radiation-matter interactions, and was followed up by a large EPSRC grant to specifically investigate ultrafast ion interactions with matter (£870k);
- Significant grant funding has also supported warm dense matter / lab-astrophysics studies (4 grants for a total of ~£1.5M);
- The development of high harmonic sources (£800k in 2 grants) and laser-driven neutron beams (£800k).

Centre for Theoretical Atomic, Molecular and Optical Physics (CTAMOP): PIs on 5 EPSRC grants awarded during the period (totalling ~£1.8M). In addition, significant funding has been obtained from:

- EC H2020, FP7-ICT and COST programmes;
- The Leverhulme Trust;
- N. Ireland Department for the Economy (through the Science Foundation Ireland-DfE scheme).

CIs in STFC Astronomy Observation and Theory Consolidated Grant (£2.4M – PI from *ARC*).

3.2.3 RCUK-Funded "In-Kind" Support Associated with Central Facility Access: Access to national and international central facilities is at the core of a significant proportion of our research activity. In terms of RCUK-funded time, we have used the Central Laser Facility at the Rutherford Appleton Laboratory heavily (the equivalent of ~£10M in facility time was used in the REF period) for access to GEMINI and VULCAN, as well as a variety of telescopes (European

Southern Observatory [~£5.2M], William Herschel Telescope [~£670k], Liverpool Telescope [~£480k], Isaac Newton Telescope [~£170k], Hubble [~£13k]). Our STFC supercomputing access (DiRAC) has been valued at ~£160k, but we have also used ARCHER and ARCHER-2 regularly.

3.2.4 Non-RCUK Funded "In-Kind" Support for Central Facility Access:

- *Lasers and accelerators:* Orion high-powered laser facility (2 weeks with notional value ~£510k); systems in France (LULI, CELIA, GANIL), Czech Republic (PALS), Germany (Helmholtz Jena), Italy (CUSBO, LNS) and the USA (Facet II and LCLS at SLAC, TITAN laser at LLNL).
- *Telescopes:* the Subaru Telescope (Japan).
- *Microscopes:* Ernst-Ruska Centre for Microscopy (14 days), Berkeley Laboratory Molecular Foundry (almost unlimited time over a 3-year period which is still ongoing).
- *Synchrotron:* European Synchrotron Radiation Facility (ESRF) (8 days).
- *High-Power Computing:* The Swedish Machine (Beskow) through the "Distributed European Computing Initiative" (6.4M core hours); 30-40 CPU hours per annum on the Hazel Hen Cray XC40 in Germany; up to 3 million CPU hours (Director's Discretion time) on the Cray at the Oak Ridge National Laboratory.

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

4.1 Collaborations:

4.1.1 Interdisciplinary Collaborations within QUB: In 2015-16, the university invested significant resource to create a number of interdisciplinary research programmes (Pioneering Research Programmes (PRPs)). Their mission was to bring together QUB academics, from different backgrounds, to focus on global challenges that cut across traditional disciplines. Physicists engaged in two of these PRPs: one on "Sustainable Energy" – a £5.2M investment involving biologists, chemists, mechanical engineers and physicists; it focused on energy conversion and storage, transportation and sustainable chemical manufacturing. The other was the "Centre for Applied and Interdisciplinary Radiation Research" (CAIRR) – a £1.4M investment bringing together teams from physics, pharmacy, biology and medicine to push forward an understanding of the interactions between radiation and biological matter.
Our input is evidenced through the emergence of noteworthy interdisciplinary publications. For example:

Sustainable Energy: papers on ionic liquids for green processing (*e.g.* Boyd *et al.* Green Chemistry **21** 2583 (2019), Grossi *et al.* J. Phys. Chem. B **121** 6436 (2017)), cement encapsulation of nuclear waste (*e.g.* Dezerald *et al.* Environmental Science and Technology **49** 13676 (2015)) and photocatalytic reactors (Boyle *et al.* Ind. & Eng. Chem. Res **58** 2727 (2019)).

CAIRR: papers on radiation-nanoparticle interactions for cancer treatment (*e.g.* McQuaid *et al.* Sci. Rep **6** 19442 (2016)), laser-induced proton beam tumour therapy (*e.g.* Hantonl *et al.* Sci. Rep. **9** 4471 (2019); Manti *et al.* J. Inst. **12** C03084 (2017)), novel laser-plasma X-ray sources for high resolution tomography (*e.g.* Cole *et al.* PNAS **115** 6335 (2018)) and novel materials for direct phototherapy (Guo *et al.* ACS Applied Materials & Interfaces **11** 27269 (2019)).

The PRPs also resulted in impact developments, such as the relationship with *Nanobiotix* described in 1.4.2.

4.1.2 Collaborations Beyond QUB:
Research Contracts and Outputs: Our research grant portfolio illustrates our enthusiasm for collaboration and the globally-connected nature of our activities:

- *Research Council Grants:* ~£50M-worth of directly funded UKRI research grants (STFC and EPSRC) were active in the UoA at some point during the REF period. Over 70% (by value) were co-funded with investigators from other institutions. Most involved other UK universities (Glasgow, Strathclyde, Cambridge, Oxford, Imperial College London, University College London, Warwick, Bristol and the Open University featured strongly).

Many, however, involved international teams, as researchers from the rest of the world were named as "*coinvestigators*" in >10% and "*project partners*" in ~30% (by value), most notably involving institutions in the USA, China, Germany, Holland, Italy, Sweden, Switzerland and Australia.

- *US-Ireland R&D Partnership Grants:* 3 teams (1 each from the USA, Ireland and N. Ireland) are involved in each collaborative contract. Proposals are assessed by the National Science Foundation (NSF) and must be above the funding quality threshold for awarding US-domestic NSF grants. The scheme is restricted to particular themes, one of which is nanoscale science and engineering. Over the REF period, we held 8 contracts, each worth around £1M, about a third of which supports activity within QUB. US partners were: Georgia Tech., UCLA Berkeley, Virginia Tech., Purdue, Washington University, University of Nebraska-Lincoln, University of Notre Dame and the Illinois Institute of Technology, while Irish partners were: Trinity College Dublin, University College Dublin, University of Limerick, Dublin Institute for Technology and the Tyndall National Institute.
- *EU H2020 Grants:* We have led, or acted as key partners in, a number of European Commission Framework (FP7), H2020 and Marie Sklodowska-Curie Action (MSCA) Programmes. These are strongly collaborative, involving a great many institutions and companies. Specific examples include: "Testing the Large-Scale Limit of Quantum Mechanics" (€4.3M), "Thermodynamics of Mesoscopic Quantum Systems" (€2.8M), "Advanced Radiotherapy, Generated by Exploiting Nanoprocesses and Technologies" (€3.7M), "High-Intensity Coherent Nonlinear Optics" (€2.3M), "Materials for Neuromorphic Circuits" (€4.1M), "Enhancing Sustainable Chemical Technologies through the Synergy of Computer Simulation and Experiment" (€670k), "Enabling Smart Computations to study space Radiation Effects" (€1.3M), the "Advanced Theoretical Network for Modeling Light-Matter Interaction (ATLANTIC)" consortium and COST Action programmes: "Quantum Technologies in Space" (involving 15 EU countries and over 200 scientists) and "TUMIEE" (involving 32 EU countries and over 252 researchers).

An analysis of outputs listed on Web of Science (published between 2014 and 2020 and authored or co-authored by staff members in place at the census date) reveals: the vast majority (~90%) of publications include co-authors from institutions external to QUB. Inter-institutional collaboration is hence at the heart of our scientific output. Some (~5% that rely on large national or international facilities) involve "Group Authorship", in which long lists of names are given in alphabetical order. These, by definition, report results and insights from strongly internationally collaborative ventures. Of the others, around 20% of the co-author institutions are from the UK, ~10% from Germany, ~10% from Italy and ~20% from the USA. Our remaining co-author institutions span the globe (~60 different countries).

4.1.3 Industrial and End-User Interaction: We refer the reader to section 1.4.2. As described therein, we have significant collaborations with multinational industry, most notably Seagate and Oxford Instruments (Andor), as evidenced in our impact case studies. Impact pipeline projects have also been developing well with Randox, Syfer/Knowles, Intel, Camlin and Nanobiotix. In addition, the ongoing Centre for Doctoral Training has interaction with industrial partners at its heart (see https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/S023321/1 for example). Our outreach programmes, as described in our "outreach" impact case study, are vibrant and seen as a priority in the UoA, not only for dissemination, but also for inspiring children and thereby securing the future health of the discipline. We re-emphasise the importance of our impact management structure (section 1.4).

4.2 Contributions to Research Base:

4.2.1 Editorial positions

- *Members of Editorial / Editorial Advisory Boards:* 10 academics acted on editorial boards or editorial advisory boards for 18 different journals during the REF assessment period: *Borghesi* (Phys. Rev X [2014]); *Bowman* (J Phys Materials [2018-]); *De Chiara* (Quantum Measurement and Quantum Metrology); *Ferraro* (Quantum Measurement and Quantum Metrology); *Gregg* (Journal of Physics: Condensed Matter [until Dec 2016], Physica Status Solidi); *Kar* (Applied Sciences [MDPI, from 2017], Sci [MDPI, from 2018);

Millar (ACS Earth & Space Chemistry); *Palmer* (High Power Science and Engineering [from 2019]); *Paternostro* (Physical Review Research, Scientific Reports, New Journal of Physics, European Physics Journal Quantum Technologies, Entropy); *Santos* (Graphene, Crystals).

- *Guest Editors:* 4 academics acted as guest editors for 5 special issues of different journals: *Borghesi:* Applied Sciences (MDPI); *Jess:* Special Issue of the Philosophical Transactions of the Royal Society A; *Sarri:* special issues on Applied Sciences (MDPI) and Journal of Plasma Physics (2016-17); *De Chiara:* Special Issue in Entropy (MDPI).
- *Associated Editor Positions: Stephen Smartt:* Royal Society Open Science Journal (from 2019); *De Chiara:* Physical Review A.
- *Editors: De Chiara:* Founding Editor of Quantum; *Paternostro:* Chief Editor of De Gruyter Quantum Measurement and Quantum Metrology.

4.2.2 Invited Editorials and Reviews: We have been invited to write a number of editorial pieces for Nature (*Gregg and Kumar* 2014, *Smartt* 2015 and *Ferraro* 2019), Nature Materials (*Gregg* 2019 and 2020), Nature Photonics (*Dromey* 2016) and Nature Reviews Physics (*Brown* 2020). In addition, we have written prestigious reviews for Nature Reviews Physics (*Gregg* 2020), Reports on Progress in Physics (*De Chiara* 2018) and a scientific "road map" piece for J Phys B (*Gribakin* 2019).

4.2.3 Stanford's Bibliometrics Rankings: We have significant presence in Stanford University's most recent ranking of the top 100,000 scientists throughout the world (on the basis of bibliometric analyses https://data.mendeley.com/datasets/btchxktzyw/2): 16% of our current staff are included for career achievement (*Borghesi, Gregg, Gribakin, Keenan, Paternostro, Smartt, Todorov* and *van der Hart*) and 10% for the 2019 one-year snapshot (*Borghesi, Gregg, Huang, Paternostro* and *Smartt*).

4.2.4 Grant Committees: Academics in the UoA are regularly involved in committee service for UKRI panels (representation on ~20 EPSRC panels and on STFC AGP and PPRP panels in the REF period), The Royal Society Fellowship panels (*Paternostro, Smartt*), EU panels and on allocation panels for central facility time in the UK and abroad (particularly telescope time).

4.2.5 Fellowships: A range of funded fellowships were awarded, or were in the process of being awarded (McQuaid 2020 was not formally announced until Oct 2020), during the period:

Year	Name	Position	Coming from:	Gone to:
2020	Ray McQuaid	UKRI Future Leaders Fellowship	Internal	-
2020	David Wilkins	QUB Illuminate Fellow	EPFL, Switzerland	-
2018	Mauro Paternostro	Royal Society Wolfson Research Fellowship	Internal	-
2018	Penny Wu	STFC Daphne Jackson Trust Fellowship	Bartol Research Institute	-
2018	Alessio Belenchia	Marie Slodowska-Curie Fellowship	Institute for Quantum Optics and Quantum Information, Vienna, Austria	-
2017	Robert Bowman	Royal Academy of Engineering Research Chair	Internal	-

2017	Ryan Milligan	STFC Ernest Rutherford Fellowship	University of Glasgow	-
2017	Peter Keys	Leverhulme Trust Early Career Fellow	University of Sheffield	-
2016	Obinna Abah	Royal Commission for the Exhibition of 1851 Fellowship	Friedrich-Alexander-University of Erlangen-Nürnberg	-
2015-2020	Elton Santos	QUB Vice-Chancellor's Research Fellow	Stanford University	University of Edinburgh
2015-2019	Neale Gibson	Royal Society University Research Fellowship (URF)	European Southern Observatory	Trinity College Dublin
2015-2019	Kate Maguire	STFC Ernest Rutherford Fellowship	European Southern Observatory	Trinity College Dublin
2015-2018	Wes Fraser	QUB Vice-Chancellor's Research Fellow	Herzberg Institute of Astrophysics, Victoria	Herzberg Institute of Astrophysics, Victoria
2015-2018	Dermot Green	EPSRC Postdoctoral Fellowship	Durham University Joint Quantum Centre	-
2015-2017	Bernhard Mueller	QUB Vice-Chancellor's Research Fellow	Monash University	Monash University
2014-2016	Alessio Morelli	Marie Slodowska-Curie Fellowship	Czech Academy of Sciences	Ulster University
2014-2015	Gary Ferland	Leverhulme Trust Visiting Professor	University of Kentucky	University of Kentucky

Note: *Green* was awarded a Leverhulme Trust Early Career Fellowship, but declined it to accept his EPSRC Postdoctoral Fellowship (listed above). In 2019, he was also awarded an EPSRC Early-Career Fellowship, but declined it to be able to accept his ERC Starting Grant.

4.2.6 Prizes: The following external prizes and prize lectures were conferred:

- *Smartt:* Royal Irish Academy (RIA) Gold medal in the Physical and Mathematical Sciences (awarded once every 4 years) 2018, Royal Astronomical Society (RAS) George Darwin Lecture 2018 and the Kavli Lecture at the University of Cambridge 2020;
- *Jess:* RAS Fowler Award (G) 2018 and VC Early Career Researcher Prize;
- *Schwamb:* AURA Science Award 2019 and Carl Sagan Medal for Excellence in Public Communication in Planetary Science 2017;
- *Fitzsimmons:* Sir Arthur Clarke Award 2019;
- *Borghesi:* John Dawson Excellence in Plasma Physics Award, American Physical Society, 2017;
- *Green:* ICPEAC Sheldon Datz Prize 2017 (International), the QUB Vice-Chancellor's Research Prize (Postdoctoral Category) 2018 and the Institute of Physics David Bates Prize 2019
- *Margarone:* Knight of the Order of the Star of Italy 2020
- *McQuaid:* Japan Trust International Research Cooperation Award 2018
- *Belenchia:* First place in the Gravity Research Foundation essay competition 2019.

4.2.7 Admission to Prestigious Academic Societies: Fellow of The Royal Society in 2020 (*Smartt*), Fellow of the American Physical Society (in September 2013 - *van der* Hart), Member of the Royal Irish Academy 2015 (*Zepf*), 2018 (*Gregg*), Fellow of the Institute of Physics 2018 (*Arredondo*).

4.2.8 Invited Talks: We gave ~400 plenary / invited talks and seminars in the period. The spread of geographical locations in which different numbers of talks were delivered can be seen from figure 4.1. There is wide coverage, with an obvious concentration around Europe and the USA. During the COVID lockdown some talks were postponed or cancelled, but several were successfully given online before 31/07/2020.

4.2.9 Conference Chairs: We have acted as chairs, technical programme chairs or session chairs in around 70 conferences or workshops in 21 different countries across the globe.

4.2.10 Refereeing: All research-active members of staff are involved in refereeing for both international journals and for grant awarding bodies. We typically referee for the journals in which we publish (including journals from the Nature Publishing Group, AAAS, Physical Review, ACS, Wiley and Elsevier) and estimate our contributions at several thousand peer review reports over the REF period.

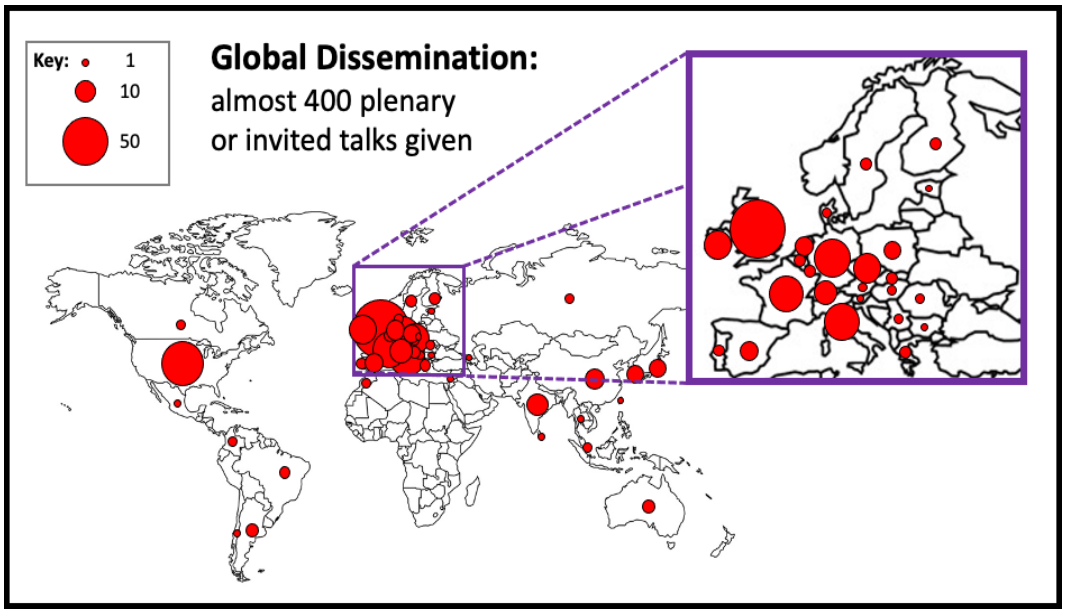

Figure 4.1: Geographical spread of invited talks given during the REF2021 assessment period.

4.2.11 Collaborative Post-Graduate Research Training: We have been training-partners in 2 Centres for Doctoral Training (CDTs), with a third continuation award:

- CDT "Lite" (EP/J500094/1 - £1.9M) "Application of Next Generation Accelerators" (2011-2018): this PhD training programme brought QUB together with the universities of Strathclyde, Manchester and Huddersfield to create a cohort of trained "embedded" experts in the application of accelerator beams, to become proficient in accelerator science and technology;
- CDT (EP/L015323/1 - £3M) "EPSRC Centre for Doctoral Training in Photonic Integration and Advanced Data Storage" (2014-2022): this programme is run by QUB and the University of Glasgow and is focused on pushing forward research and post-graduate training in the areas of advanced materials, plasmonic systems and laser devices relevant to Heat-Assisted Magnetic Recording technology. A number of industrial partners are involved, most notably Seagate, who have been able to provide excellent context from the perspective of state-of-the-art device requirements;
- CDT (EP/S023321/1 - £4.2M) "EPSRC and SFI Centre for Doctoral Training in Photonic Integration and Advanced Data Storage" (2019-2028): this programme brings together

academic excellence and expertise from across QUB, the University of Glasgow and the Irish Photonic Integration Centre in Cork and Dublin. It is a continuation of the CDT described above, but with a focus on photonic and plasmonic integration.

In addition, we have been training-partners in several EU Innovative Training Networks (ITNs):

- CORINF (2011-2015), https://cordis.europa.eu/project/id/264951, aimed to model multielectron dynamics in polyatomic molecules and clusters in intense light fields and to test these models against experiment. The consortium brought QUB physicists together with those at the University of Strathclyde, University College London, the Max Born Institute in Berlin, CNRS, University of Trieste and LMU Munich;
- ARGENT (2014-18), https://cordis.europa.eu/project/id/608163, was a network on Advanced Radiotherapy, focused on the use of nanoparticles to enhance radiation therapy efficacy. It was led by the CNRS, with QUB, GSI Darmstadt (D), Open University (UK) and CSIC (Spain), plus a number of companies: CHEMATECH, NANOH SAS (France) and QUANTUMWISE (Denmark);
- MANIC (2019-2023), https://cordis.europa.eu/project/id/861153, is a consortium of chemists, materials scientists, physicists and circuit designers training 15 PhD researchers in aspects of research relevant to neuromorphic technology. QUB physicists are collaborating with universities in Groningen (coordinating institution), London, Cambridge, Amiens, Julich, Twente and Lausanne with industrial input from IBM Zurich.