Institution: University of York

Unit of Assessment: 9 - Physics

1. Unit context and structure, research and impact strategy

1.1 Introduction

As a department at the forefront of pioneering research and technological development, we seek to make advances in fundamental physics that will shape the technologies of the future. Building around our major scientific themes of *Condensed Matter Physics*, *Nuclear Physics*, *Plasma Physics* and *Physics of Life*, we are increasingly interdisciplinary in our approach to research with strong links to engineering, chemistry, biology, computer science and mathematics. Whether discovering fundamental particles or designing the next generation of fusion reactors, we collaborate broadly with national and international partners whilst our diverse and robust industry connections stimulate a culture of knowledge exchange that has seen many innovative products brought to fruition. This submission includes all Category A eligible staff from the Department of Physics.

In all of the above, balancing our core research and impact strategy with a flexible and responsive outlook has allowed our group structure to evolve and flourish since REF2014. As well as launching breakout activities in *Hadron Physics*, *Quantum Communications*, and *Physics of Life*, we have targeted the establishment and expansion of key interdisciplinary research centres such as the *Centre for Energy Efficient Materials (CEEM)* and the *York-JEOL Nanocentre*. This structural network gives our researchers the means and resources to work across different groups and disciplines and has naturally led to an increase in inter-departmental collaboration with a commensurate increase in funding, high quality outputs and impact.

Specific achievements that highlight the effectiveness of our environment are as follows:

- We lead one of the four UK Quantum Technology Hubs with a total investment in excess of £50M so far and, through *Spiller,* have significantly contributed to the UK Quantum Technologies strategy and delivery.
- Our Nanoscience research has been recognised by a DBE and FRS to *Gai* (joint appointment with Chemistry) and a major upgrade to our Electron Microscopy capability led by *Lazarov*.
- In recognition of our unique position in Plasma Physics and Fusion research, we have been invited to contribute to the UK's Nuclear Fusion strategy via the UKAEA Research Programme Directorship 2017-2019 (*HR Wilson*), the Programme Directorship of the £222M STEP project (*HR Wilson*) and related contracts to *Dickinson*, *Vann* and *Dudson*.
- We lead the Physics of Life Network+ (PoLNet), now in its third phase of funding. The PoLNet steering group (chaired by *McLeish FRS*) has significantly raised the profile of the Physics of Life in the UK, has leveraged an allocation of £30M from the UKRI Strategic Priority Fund and was collectively awarded the 2020 IoP Rosalind Franklin Medal.

1.2 Achievement of REF 2014 strategic aims

In growing from 38.3 FTE in 2013 to 59.9 FTE in 2020, we have delivered on our aim of departmental expansion as a vehicle for increasing our impact on the Physics landscape. Many of the new staff were appointed through a variety of fellowships, highlighting our attractiveness to high-flyers and giving us a sustainable platform on which to further develop our plans for the future. The quality of our output has increased significantly, our second major strategic aim from REF2014, as evidenced in REF2. We have widened our interdisciplinary impact by publishing in non-Physics journals such as *British J. Cancer*, *Nature Genetics*, *Nature Methods*, *Stem Cell Reports*, *PNAS*, *JACS*, and *Nano Letters* where we had minimal representation in 2008-2013. Our research income has grown disproportionally, by as much as a factor 2, from £3.6M in 2013/14 to an average of £7.2M (3-year average between 2017/18-2019/20), **with our current EPSRC grant portfolio in the top 3 of any physics department in the UK** (see also Section 1.10). This all points to an environment in which both new and existing staff can thrive and excel.

We have sought external advice; we initiated an external advisory group consisting of senior academic, industrial and UKRI representatives in 2013 which has met annually and which was complemented by a formal external review in 2017. These external experts have critically assessed our progress throughout the REF period and have helped us to implement our strategy so successfully.

Assessing our REF2014 strategy in detail, we have exceeded our aspirations on multiple levels:

1. **Lead a university expansion in Quantum Technologies.** Our leadership of the Quantum Communications Hub attests to the outstanding success of this strategy.
2. **Enhance collaborations with national and international laboratories as well as industries.** Industrial collaboration has been particularly strong, as demonstrated by our impact case studies. We have made 7 academic appointments co-sponsored by industry and national facilities (Sections 1.3, 3.3). 15 PhD students have been directly sponsored by industry. Our strong interaction with national and international laboratories is evidenced by the total value of £35.9M in competitively awarded facility access.
3. **Expand the internationally leading cross-disciplinary YPI to develop further its world-class reputation for research and training.** The York Plasma Institute (YPI) was awarded an EPSRC CDT in Fusion Energy and a major (£4.4M) EPSRC Programme Grant, both led by *HR Wilson.*
4. **Widen collaboration with the Culham Centre for Fusion Energy.** *HR Wilson* took a secondment as UKAEA Research Programme Director 2017-19 and subsequently has led the £222M UKAEA Spherical Tokamak for Energy Production (STEP) programme.
5. **Enhance materials physics research and cross-disciplinary research.** *McKenna* formed the Centre for Energy Efficient Materials (CEEM) which has led to stronger interaction with chemists and has attracted industry partners such as Cogent Power, Cristal, Great Cell Solar and Croda. The Nanocentre has seen a major (£700k) upgrade in facilities for Nanobiology. *Leake* now leads the newly formed Physics of Life research group with significant (£470k) university infrastructure investment.
6. **Extend photonics research into more interdisciplinary areas.** *Krauss* has built strong connections to Electronic Engineering, Biology, Chemistry and Health Sciences since forming the Photonics group in 2013 and has brought significant (>£10M) funding to York by leading or contributing to EPSRC, BBSRC, MRC, HEFCE and Wellcome Trust grants.
7. **Enhance nuclear structure, astrophysics and fission research.** The nuclear structure activity has been strengthened by a number of appointments, including *Dobaczewski* (Wojciech Rubinowicz prize 2015) and *Petri* (URF 2016). Hadron Physics has been established by the appointments of *Watts* as well as Rutherford Fellows *Bashkanov* and *Zachariou*.

Examples of the exciting research enabled by this strategy are described in sections 1.5-1.9, including our major role in driving interdisciplinarity forward at University level.

1.3 Strategy relating to impact case studies

Our impact case studies showcase our strong industrial relationships (Seagate Technology, Kromek Group plc), expertise and leadership in industry-relevant software (CASTEP, VAMPIRE) and our desire for societal impact through outreach. They also reflect our strategic decision to significantly raise the profile of impact by appointing an impact champion (*L Wilson*, then *Jenkins*), an industry officer (*Lancaster*) and organising dedicated impact Away Days. These actions led to a large number of new industry connections, including EPSRC Impact Accelerator Account (IAA) awards with new industry partners. Additionally, we upgraded infrastructure relevant to our industry links, for example, the nuclear applications and magnetic characterisation laboratories. Most importantly, in line with our impact strategy, we made new appointments in every area that is now represented by an impact case study. *Ferreira* (URF),

Evans (co-sponsored by Seagate) and *Hasnip* (EPSRC Research Software Engineering Fellow) greatly enhanced our modelling expertise, while *Vallejo-Fernandez* (co-sponsored by Seagate) enhanced our magnetic characterisation capability, while *Paschalis* (co-sponsored by Kromek) was appointed to drive our nuclear applications work. Additionally, our strong foundation in outreach was significantly boosted by the appointment of *Leech* as Outreach Officer in 2013 who now runs a three-strong outreach office. The strength of our impact case studies attests to the success of this strategy.

1.4 Departmental research organisation

Our research activities are coordinated through the following four research groups:

- Condensed Matter Physics (CMP) (22 FTE) - leads one of the 4 Quantum Hubs
- Plasma Physics (16 FTE) - largest university plasma group in the UK
- Nuclear Physics (15 FTE) - largest nuclear physics group in the UK
- Physics of Life (PoL) (7 FTE) - strategic new interdisciplinary initiative

We are particularly keen to support cross-cutting activities and actively encourage our staff to be members of more than one group. This has led to emergent sub-themes such as *Biomedical Plasmas* (Plasma-PoL), *Nuclear Detectors* (Nuclear-CMP), and *Biophotonics* (CMP-PoL).

Interdisciplinary research is a particular strength at York and is supported by a significant number of University-level Centres (REF5a, 11). Physics is driving a significant number of these and has been actively involved in shaping this strategy (Section 1.9). We now describe our Research Strategy in more detail at the research group level. Where paper citation numbers are given, these refer to Web of Science figures as of 12/2020.

1.5 Condensed Matter Physics

The largest research group in the department with 22 academic staff members, 12 post-doctoral researchers, 3 experimental officers and 45 PGR students. The strategy of CMP is to create and study advanced materials and nanostructures using experimental, theoretical and computational techniques. This ambition is supported by state-of-the-art facilities, especially in the York JEOL Nanocentre, where we have established a unique leadership role in Aberration-Corrected environmental Scanning Transmission Electron Microscopy (AC-eSTEM), as pioneered by *Gai* and *Boyes*.

Experimental. Our REF 2014 strategic goal of enhancing materials physics research (Section 1.2.5) is evidenced by our leading activity in revealing material properties at the nanoscale (*Kröger* Science 2018; *Kepaptsoglu* Science 2020) and related work on the emerging class of 2D Materials. In 2D Materials, for example, we have demonstrated electrical control of water permeation through graphene oxide membranes (*Pratt* Nat Materials 2017, 208 cites, Nature 2019) and cavity-enhanced light emission from $MoTe_2$ (*Wang*). Extending our Photonics research was another strategic goal of REF 2014 (Section 1.2.6) leading to pioneering work in photonic crystals and nanostructures (*Krauss* Nat Phys 2015). Our research in magnetism and spintronics (see ICS) is another strength with highlights including the discovery of spin Hall effects in graphene (*Ferreira* Nat Comm 2014, PRL 2017), the structure and properties of magnetic tunnel junctions for memory applications (*McKenna* Nano Lett 2014) and atomistic spin model simulations of magnetic nanomaterials (see ICS). Our standing in the field of spintronics was recognised through the award of

Figure 1. A selection of journal front covers representing CMP research.

an EPSRC-JSPS Core-to-Core grant (*O'Grady*) linking York with other world-leading spintronics groups in Germany and Japan.

Theory and Modelling. Our leading work on first-principles materials modelling in areas such as magnetism, spintronics, solar energy and chemistry is highly complementary to almost all of our experimental activity above with many examples of collaborative work (*McKenna* Nat Comm 2014; *Probert* Science 2016, 519 cites). More generally, the group has a strong reputation for computational materials physics with *Probert* and *Hasnip* core developers of the density functional theory code CASTEP; CASTEP is now in use by over 1000 research groups worldwide and has been a benchmark for every UK national academic supercomputer over the last 20 years (see ICS). *Evans* is the developer of the VAMPIRE code for atomistic simulation of magnetic materials which has quickly established a 300-strong worldwide user base since it was first released in 2014 (see ICS). Continuing this exciting trend and service to the community, *Ferreira* has recently released the "KITE" code for quantum simulations of large condensed systems.

Quantum Hub. Realising our strategic ambition to establish a lead in Quantum Technology (Section 1.2.1), CMP also hosts the EPSRC Quantum Communications Hub led by *Spiller*. The Hub has so far successfully attracted Phase 1 (2014-2019, £24M), Phase 2 (2019-2024, £24M) and £4.4M of capital equipment funding. During Phase 1, the Hub has delivered major advances in quantum key distribution (QKD) technologies and is pursuing quantum communications at all scales for Phase 2. In addition, the Hub collaboration has spawned three major new (industry-led) Industrial Strategy Challenge Fund (ISCF) projects: (i) AQuaSeC, led by Toshiba to commercialise fibre-based QKD; (ii) 3QN, led by ArQit to commercialise satellite QKD receivers; (iii) Assurance for QRNGs, led by the National Physical Laboratory to provide an assurance framework for commercial quantum random number generators.

Looking to the future. We have ambitious plans to develop the York JEOL Nanocentre into a national facility based on the recent award of an EPSRC Strategic Equipment grant for a major upgrade of the AC-eSTEM (*Lazarov*, EPSRC £3M) and our membership of the EPSRC National Research Facility for Advanced Electron Microscopy (SuperSTEM); this will also be a priority area for future recruitment. Furthermore, we have identified experimental spin transport as another recruitment priority to further strengthen our connection between modelling and materials characterisation capabilities. Our Quantum Technologies research will be strengthened to expand its experimental activity (Chair appointment in 2020, Lecturer to follow in 2021) and by engaging with the York Global Initiative for Safe Autonomy (UKRPIF 2019, £10.5M).

1.6 Plasma Physics

Housed in the York Plasma Institute (YPI), which provides a unique environment for world-class plasma research, currently comprising 16 academic staff members, 2 permanent research officers, 9 postdocs and 50 PGR students. We address a portfolio of research covering the spectrum from blue skies to impact driven, across three strands: Low-Temperature Plasmas, Laser-Plasma Interactions and Magnetic Confinement Fusion. The **Low-Temperature Plasma** activity exploits non-equilibrium plasmas for next generation medical therapeutics (*O'Connell* Chemistry 2016, 123 cites) and nano-manufacturing (*Gans* PRL 2015, EPSRC £2M). **Laser-Plasma Interactions** is pushing the fundamental frontiers of laser-driven quantum electro-dynamics (QED) (*Ridgers* PRX 2018, 97 cites), laser-plasma interactions (*Murphy* PRX 2018, 98 cites) and laboratory astrophysics (*Woolsey* Nat Comm 2018, 2016).

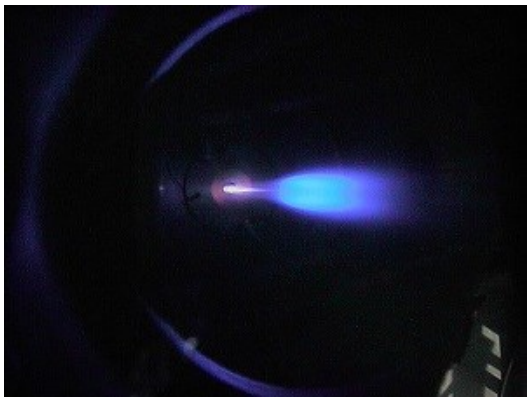

Figure 2. Magnetically confined plasma in the YPI laboratories which is crucial for developing diagnostics for the UK's MAST-U tokamak.

Our **Magnetic Confinement Fusion** activity strives to harness clean fusion energy (*Lipschultz*, *HR Wilson* Nuclear Fusion 2017, 108 cites, EPSRC Prog Grant £4.4M) with a particular emphasis on understanding instabilities and nonlinearities (*Cziegler* Nat Phys 2017).

Strategic environment. Our research is enabled through a combination of local, national and international facilities, in particular our strong connection to the UK Atomic Energy Authority (UKAEA) Culham Centre for Fusion Energy (CCFE), which was a key goal of our REF 2014 strategy (Sections 1.2.3, 1.2.4) Our activities are complemented by leading computational capabilities, including BOUT++ for magnetic confinement fusion (*Dudson*) and EPOCH (highly parallelised laser-plasma simulation code *Ridgers*, J of Comp Physics 2014, 165 cites). This unique setting also provides an excellent training environment for one of the very few global taught MSc courses in Fusion Energy and the EPSRC Centre for Doctoral Training in the Science and Technology of Fusion Energy.

Looking to the future. We will exploit upcoming opportunities. Ultra-intense lasers are pushing the frontier of matter-radiation interaction in new European facilities, such as XFEL, Germany, ELI-NP, Romania and Central Laser Facility Vulcan 2020 upgrade. The UKAEA Spherical Tokamak for Energy Production (STEP) programme (£222M) promises new opportunities in compact tokamak science and technologies, along with the £55M upgraded MAST-U tokamak. ITER is due to begin operations in the next few years, and JET is due to operate soon with real fusion fuels. The Plasma group is actively engaging with these opportunities (see also facilities Section 3.3) as well as collaborating with other disciplines, international partners and industry in order to maximise the impact of its research.

1.7 Nuclear Physics

This group is firmly positioned as one of the leading groups worldwide. Following the successful implementation of the REF2014 strategy (Section 1.2.7), the group has recently expanded to a full complement of 15 academics with broad and connected research programmes encompassing *Hadron Physics*, *Nuclear Structure*, *Nuclear Astrophysics*, *Nuclear Theory* and *applications-focussed* work. The group is supported by an experimental officer, it has 9 PDRAs and 31 PhD students. We conduct a dynamic and high-profile experimental programme at the world's leading nuclear physics facilities such as CERN, RIKEN, and Jefferson Lab, delivering high-impact nuclear science and helping to shape the science programme at future facilities such as the Facility for Rare Isotope Beams (FRIB, Michigan State) and the Facility for Antiproton and Ion Research (FAIR, Darmstadt). We pursue a vigorous research programme in theoretical nuclear structure and in nuclear astrophysics and have opened up translational opportunities with a new applications laboratory at York.

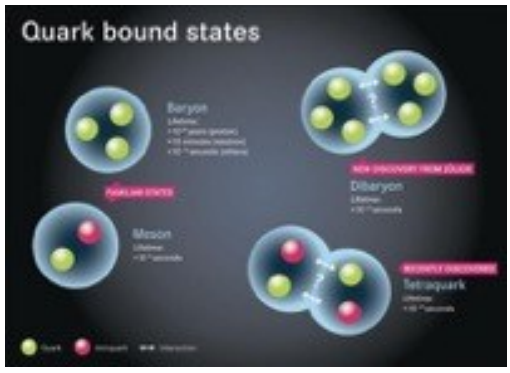

Figure 3. The hexaquark work led by York featured in the CERN Courier.

Experiment. A notable highlight of our hadron physics activity has been the first observation of the d* hexaquark, which has led to predictions of its formation in neutron stars and setting a limit on their mass (*Bashkanov* and *Pastore*) and a possible scenario for the d* being a component of dark matter (*Bashkanov* and *Watts* J Phys G 2020; 30k downloads and Altimetric > 500). Highlights of the nuclear astrophysics programme have been the measurement of the ^{23}Na(α,p)^{26}Mg reaction (*Laird, Diget*) and the study of the ^{12}C fusion reaction in massive stars (*Jenkins*, PRL 2020). Our nuclear structure research has examined the structure of neutron-rich nuclei such as ^{40}Mg (*Paschalis*, *Petri*, PRL 2020) and we have made significant contributions to understanding isospin symmetry (*Bentley*, PRL 2020). We have also clarified the shape staggering effect in light mercury nuclei (*Andreyev*, *Dobaczewski*, Nat Phys 2018), which was only possible via the very strong interaction with our theorists.

Theory. We have made an essential contribution to understanding the question of antimatter and have reported ground-breaking theoretical studies to determine the influence of asymmetric forces on the ground states of selected isotopes (*Dobaczewsk*i, PRL 2018) which are now informing experimental work at Michigan State University's SPINLAB.

Applications. Our applications work has been instrumental in the development of a wearable gamma-ray detector commercialised by Kromek plc which has led to tens of thousands of sales of the instrument worldwide (see ICS, *Jenkins*). We have also developed a new methodology for quantum-entangled positron-emission tomography (PET) (*Watts*, patented), which promises to revolutionize the sensitivity of PET imaging.

Looking to the future. We are leading two multi-institutional projects: AGATA (gamma-ray tracking array, *Bentley*) and ACPA (silicon array for ELI-NP, *Diget*) We are contributing to two large STFC co-funded projects: J-Lab2 to build on the initial UK investment in the Jefferson Laboratory upgrade, and STAR to develop a calorimeter for future radioactive beam facilities, building on our expertise in scintillator performance.

1.8 Physics of Life (PoL)

Established as a major research unit in 2018 and now comprises 7 academic staff and 24 associated research fellows, postdocs and graduate students, including several research fellowships (*Noy, McLeish, Quinn, Leake*). The formation of PoL originated from the strategic decision to establish a biophysics activity and the appointment of *Leake* and *L Wilson* in 2013 and to expand our interdisciplinary research (Section 1.2.5). *Hancock*, *Krauss, Kröger* and *Vallejo-Fernandez* span the interface with CMP, and *O'Connell* with YPI. The fact that Photonics research (*Krauss*) is now a key element of this interdisciplinary portfolio is further evidence for the success of our REF 2014 strategy (Section 1.2.6). The research in PoL is organised along three broad themes: novel tools, novel technologies, novel physics, and the activity is underpinned by diverse funding from BBSRC, MRC, EPSRC and NERC and several charitable funders, including Wellcome, Leverhulme and Alzheimer Society.

Novel tools. This theme addresses open questions in the life sciences, *e.g.* optical microscopy for single-molecule monitoring of antimicrobial resistance (*Leake,* BBSRC £1.9M) and membrane biology (*Quinn*), digital holography for rapid 3D imaging of microbial swimming (*Wilson* Nat Comm 2018, 2020, Adv Funct Mat 2018), and label-free biometrology of bone (*Kröger* Science 2018, 100 cites, Science Adv 2019) (fig.4); projects include next-generation bioimaging (*Leake* MRC £1.3M), and synthetic and systems biology (*Leake*). The group also recently won resources from the highly competitive £30M UKRI Physics of Life Strategic Priorities Fund (*Leake* £1.7M joint with John Innes Centre).

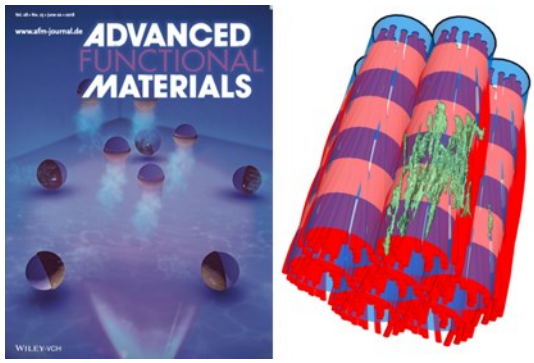

Figure 4. a) Holographic imaging of micro-swimmers, *L Wilson* and b) Micro-biometrology of bone, *Kröger*.

Novel technologies. We study techniques such as low-temperature plasmas to treat prostate cancer (*O'Connell* Brit J of Cancer 2015, 88 cites), hyperspectral resonant imaging for monitoring single-cell secretion (*Krauss* Wellcome £1M), Raman spectroscopy for monitoring pathogens and host immunity (*Hancock* Nat Genetics 2014), and tissue ablation using magnetic hyperthermia (*Vallejo-Fernandez Sci Rep* 2020). We are also developing novel handheld diagnostic technology for the detection of infection, which has already demonstrated better performance than the laboratory standard ELISA (*Krauss*, Nature LSA 2020, EPSRC £1.1M).

Novel physics inspired by biology. Here, we study the emergence of structural complexity in DNA from molecular dynamics simulations (*Noy* Nature Methods 2016, 239 cites), or flow-induced self-assembly in spider silk (*McLeish* EPSRC £1.2M). This activity uses computational and theoretical soft matter/biophysics techniques also as part of the JADE consortium in Artificial Intelligence (*Noy*).

Looking to the future. The recent (2020) University investment in a dedicated Physics of Life building will catalyse the group's ambitious goal to establish the University of York as a future national centre of excellence for Physics of Life research. The group will continue to drive interdisciplinarity at university level and has a growing international influence, which we aim to extend further, manifested through steering panel membership of several UK and EU societies and networks.

1.9 Interdisciplinary research

Interdisciplinarity is at the heart of the University's research strategy (REF5a, 4,9,11) and was an underpinning feature of the Department's REF 2014 expansion strategy (Section 1.2). The Department's leadership and commitment to interdisciplinarity is evident on multiple levels; *Krauss* was the "Technologies for the Future" University theme Champion 2015-2019, followed by *Watts* in 2020; physicists lead three of the University's interdisciplinary centres, i.e., the Biological Physical Sciences Institute (BPSI, *Leake*, 2013-19), the York JEOL Nanocentre (*Tear* 2016-, *Lazarov* 2018-) and the York Centre for Quantum Technologies (YCQT, *Spiller* 2014-). It is clear that interdisciplinarity is firmly embedded in the fabric of physics research at York.

- BPSI is a network across the Faculty of Science that organises termly symposia, seminars, funds summer studentships and facilitates research proposals to EPSRC, BBSRC, MRC, Leverhulme and the EU, totalling £1-2M per annum.
- The Nanocentre is an interdisciplinary Centre between Electronic Engineering, Physics and Chemistry which focusses on electron microscopy, also featuring multiple nanofabrication tools including electron-beam lithography, cleanroom facilities, focussed ion beam, microfluidics fabrication and a "Bioscope" atomic force microscope.
- YCQT inspires and supports the full spectrum of interdisciplinary quantum technologies research in Computer Science, Electronic Engineering, Mathematics and Physics through joint seminars, funding proposals and industry links.

1.10 Future strategic aims

Our focus will continue to be on conducting world-leading fundamental science in conjunction with applications addressing key societal challenges. The group sections above have already provided a forward look, which we summarise here:

- To grow our work in nanomaterials, building on the recent strategic equipment award of the new AC-eSTEM instrument and the establishment of the Centre for Energy Efficient Materials (CEEM).
- To expand our activities in quantum technologies to establish a world leading capability in experimental quantum communications.
- To lead activities in developing compact fusion science, such as the UK STEP programme and to exploit the opportunities arising from the development of new, high intensity, light sources.
- To grow our activity in nuclear applications, exploiting our fundamental nuclear and hadron physics research to develop technologies for applications ranging from homeland security to medical instrumentation.
- To support the growth of our research at the interface of physics and the life sciences through continued investment in the Physics of Life research group and support for the development of basic science capabilities that underpin new healthcare technologies.
- Interdisciplinarity will continue to be a main driver of our activity and we will explore mechanisms for closer engagement with other departments, both in terms of fundamental/exploratory science and translational research.

Recent research awards data indicates that we will have the means to implement this strategy. For example, our competitively won EPSRC portfolio is now amongst the top 3 in the UK; more importantly, the distribution of EPSRC PIs places us 2nd in the UK in terms of the number of independent investigators, which highlights the depth of our activity. These indicators of current and future success are evidence for the vitality and supportive nature of the environment we have created. They support our ambition to be one of the top physics departments in the UK.

1.11 Strategy for future impact

As described above, our strategy has already delivered a number of strong impact case studies and we have successfully embedded impact into the culture of the Department. We aim to increase our impact by extending the range and number of companies we engage with, building on a number of mechanisms that we have already successfully used such as KTPs (e.g. *Spiller* with ADVA; *Jenkins* with Kromek plc; *Vann* with MM Microwave; *Dedrick* with Oxford instruments), EPSRC IAAs (e.g. *Pratt* with Cogent Power; *Krauss* with Aptamer Solutions and Croda; *Thompson* with Nanoscan) and the STFC Innovation Partnership Scheme (*Paschalis*). We will co-fund further joint PhD projects with industry (see Sections 2.7 and 4.8).

We will expand our industrial network through the White Rose Industrial Physics Academy (WRIPA) established in 2014, a consortium of 5 regional universities aiming to increase the employability of undergraduates (led by *Krauss*). For example, in the 2018/19 academic year alone, we engaged with 15 companies involving 53 students through industrial final year projects, summer placements and year-in-industry placements. New contacts were made with Tracero (radiation detectors), Airbus, BT, Rolls Royce and Nestle, many of which will lead to collaborative research proposals.

Our sabbatical scheme will also help generate impact. For example, *Pratt* was able to develop his relationship with Cogent Power in the area of electrical steel characterisation in 2019 and *Krauss* will work closely with Optalysys Ltd on optical neural networks in 2021.

We are continually exploring other opportunities for generating impact. *Jenkins* and *Hancock* were supported by one-year University Enterprise Fellowships to focus on the translation of their research; *Hancock's* innovative cancer diagnostics project was co-funded by Wellcome (£70k), GrowMedTech (£60k) and direct industry funding (£37k) and started clinical trials in 2020. *Krauss* has had extensive support from the Business Development team (pump-priming, external market research) to realise his ambition of a biosensor spin-out company.

1.12 Open research environment

We ensure that our research is widely available, well-managed, and searchable by insisting that every output is deposited in the institutional repository (White Rose Research Online) wherever possible. The University (REF5a, 15-17) provides funds to ensure all journal articles are open and publicly available. We believe in fully transparent access to research data as far as reasonably possible. For example, our Nuclear Physics data is archived indefinitely at York, along with data analysis codes and provided on request to the community; PoL researchers use the GitHub databank to deposit and share all of their protein dynamics analysis software code. They use international data banks such as the Open Microscopy Environment archives for all imaging data, the BEI Resource Repository and European Nucleotide Archive for biological/genetic reagents, ExPASy and protein databases for biophysical data. Our Fusion researchers make use of the comprehensive data management and archiving systems in place at Culham and similar European facilities such as TCV; all data gathered at Culham is stored and made accessible by UKAEA. We have been particularly active in developing open source software, with CASTEP and VAMPIRE being free to academic researchers (see ICS), KITE being freely available for quantum simulations, BOUT++ for plasma simulations and EPOCH for ultra-high intensity laser-plasma interactions.

1.13 Research Integrity and Ethics

As is already evident from the above, we strongly support the principles of research integrity, such as honesty, responsibility, fairness and accountability. The "responsibility" aspect is addressed by the University's ethical framework, which is overseen by the University Ethics Committee and a number of subject-level Ethics Committees (REF5a, 14). For example, the Physical Sciences Ethics Committee considers issues such as interactions with defence-related companies and with UKAEA. For research involving human tissue (biosensor research, cancer, lymph node and bone biopsy samples) and essential animal experimentation (such as *in vivo* molecular tracking), we refer to the Biology Ethics Committee. All staff and research students must apply for ethical approval if their work falls within a sensitive area before research can proceed.

2. People

The strategic expansion of the Department was focussed around the group structure established at the end of the last REF period, including the nascent Physics of Life group. Every new appointment is carefully assessed for the new opportunities it will create and for the synergies it will promote. Following these principles, we have appointed both senior leaders, such as *McLeish FRS*, *Watts*, *Dobaczewski and Spiller,* and have attracted a significant number of independent fellows to join the department from highly ranked universities in the UK and abroad. The fellowship campaign has been particularly successful and is another testament to the success of our 2014 strategy. We also highly value the contribution from support staff. In this context, it is worth highlighting that *Helliwell*, our senior technician, received the inaugural **Institute of Physics Technician award 2019** for his dedication and contributions to practical physics training. The University of York was also one of the 36 founding signatories of the Technician Commitment (REF5a, 40) and the Department is actively involved in supporting the professional development and profile of its technical staff.

2.1 Recruitment strategy

The following new appointments were made since REF2014. Many have opened up new research areas and opportunities, for example,

- **CMP:** *Evans, Ferreira, Pratt, Spiller, Wilson-Rae, Kepaptsoglou, Wang, Hasnip.* *Spiller* leads the Quantum Hub, *Kepaptsoglu* is transformative for our Electron Microscopy research, *Ferreira* has initiated 2D Materials research at York.
- **Plasma:** *Cziegler, Dedrick, Dickinson, Higginbotham, Lancaster, Murphy.* *Dedrick* has brought plasma thrusters, *Dickinson* gyrokinetic simulations of tokamak plasmas, *Higginbotham* expertise in warm dense matter exploration using XFELs and *Murphy* in plasma-based particle acceleration.
- **Nuclear:** *Dobaczewski, Paschalis, Pastore, Petri, Watts, Zachariou, Bashkanov* *Dobaczewski* is one of the leading nuclear structure theorists in the world, *Watts, Zachariou* and *Bashkanov* have brought Hadron Physics to York.
- **Physics of Life:** *McLeish FRS, Noy, Quinn, L Wilson* *McLeish* has brought the EPSRC "Physics of Life" network to York and is driving interdisciplinarity at university level, *Noy* has opened up molecular modelling, *L Wilson* holographic imaging of bacteria and *Quinn* research into Alzheimer's disease.

New academic appointments are supported by a senior mentor from a different research unit to provide a broader view on career development. This has helped, for example, *Ferreira* to extend his original (2014-19) RS URF with an RS-EPSRC Engagement Fellowship (2015-2017), RS Research Fellows Enhancement Award (2017-2021) and an RS EPSRC Engagement Fellowship (2019-2022); *McKenna*'s original EPSRC Fellowship (2013-2018) was extended to 2018-2021 and he further enhanced it with a £800k EPSRC standard responsive mode award.

New appointees are supported by a start-up package which includes a PhD studentship and laboratory equipment/infrastructure as required. Their teaching allocation is tapered linearly from 1/3 equivalent load in year 1 to a full load in year 3.

2.2 Independent and University Fellowships

We support fellowship applications by inviting potential applicants to present their work to the department, by providing travel grants and strong mentorship, as well as organising "fellow's days" where existing fellowship holders share their experience with applicants. As a result, we have been able to support nine holders of competitive early career fellowships, i.e., *Ferreira* and *Petri* (URF), *Kepaptsoglou* (EPSRC SuperSTEM), *Wang* (RAEng), *Noy* (EPSRC Early Career), *Hasnip* (EPSRC Research Software Engineering), *Bashkanov* and *Zachariou* (Rutherford) and *Quinn* (Alzheimer Society). In addition, *Woolman* and *A Gibson* won two-year Wellcome Centre for Future Health Fellowships (co-funded with the University), which brings the total number of fellowships awarded to 11. This high number, achieved in a very competitive environment, highlights our ability to nurture talent and underlines our attractiveness to rising stars. Our commitment to their career development is reflected by the fact that all of them have achieved academic appointments (9 at York, 2 elsewhere).

At the senior level, fellowships include *McLeish* (EPSRC), *Leake* (Leverhulme and RAEng), *Vallejo-Fernandez* (Royal Society Industry), *Hancock* and *Jenkins* (University Enterprise). *Krauss*, *HR Wilson* and *Lipschultz* have been awarded Royal Society Wolfson Research Merit Awards and *D'Amico* was awarded a Royal Society Newton fellowship. In total**, 20 staff members, a third of our headcount, have won competitive personal fellowships**.

2.3 Evidence of support for Equality, Diversity, and Inclusion (EDI)

Physics at York was one of the first two departments in the UK to be awarded Project Juno Champion status in 2011, an achievement we have since built upon. The Department was led by a female Head from 2012-2017 (*Thompson*) and a female Chair of the Research Committee from 2013-2016 (*D'Amico*). We celebrate the fact that our Department is drawn from a diverse and international background where members feel welcome irrespective of gender, ethnicity, nationality, sexuality or other protected characteristics. In addition to our Project Juno Champion status (renewed in August 2018), we hold Athena Swan Silver status (renewed 2019) and are aspiring to Athena Swan Gold. We place particular emphasis on ensuring equality of opportunity for female physicists and are pleased to report that this strategy is now bearing fruit; for example, 4 out of the 7 most recent appointees are female and our f/m ratio is now 11/60 (18%). We aim to improve this ratio further over the next REF period.

The Department has a robust organisational framework to deliver equality of opportunity and reward, it has an Equality Committee (DEC) that has representation from all staff and student groups and we aim for proportionate representation on all committees. **Equality and Inclusion is a standing agenda item on all departmental meetings**. We co-developed the University's unconscious bias training, implementing this and mental health awareness training for all staff and reflect diversity in all our recruitment documentation.

Flexible working, job share and part-time working are strongly supported. Flexible retirement, unpaid leave, career breaks and term-time only working are other schemes that are well received by staff and perceived as a real benefit from our analysis of survey responses. We aim to be inclusive via our "core hours" policy with all departmental meetings taking place in the 10:00-16:00 window to support those with caring responsibilities.

We continue to expand our focus in other areas of EDI and have started to consider social categorisation (and how to avoid it), for example, by analysing recruitment data by gender and ethnicity. We have provided a stand at the annual York Pride event since 2016. Outreach is another essential part of our EDI strategy, by aiming to enthuse primary and lower secondary school girls; more recent events have seen particularly strong attendance of BAME students. We recognise that some of these interventions do not produce immediate outcomes but note that

biases established over centuries do require long-term solutions to eradicate them. We are fully committed to such a long-term view.

We are committed to EDI issues both at York and beyond. For example, *Gai* was the science representative at the OECD International Women's Day in Paris 2015 and was celebrated as a female pioneer at the House of Commons Reception for Women Firsts. *D'Amico* organised the "Gender Balance in Science" meeting of the COST Action MP1403 in Florence, Italy, in 2015. We have been instrumental in supporting the IoP Undergraduate Women in Physics conference (CUWIP) since 2015 by encouraging attendance, contributing speakers and hosting the event in York in 2020. The conference empowers delegates who identify as women and gives them the confidence to make positive decisions for a career path based on their physics knowledge and skills.

Figure 5. Delegates interacting at CUWIP 2020 in York.

As a result of our inclusive environment, our gender paygap compares favourably to the rest of the UK. The paygap was 15.5% for the UK as a whole in 2020 (ONS data), which is comparable to that of Russell group universities. At the University of York, it is 15.3% (REF5a, 21), while the paygap in Physics has reduced from 8.5% to 4.5% since 2014. Clearly, we would like to achieve parity and are working with the IoP and the University towards this goal. As an early indication, we note that for employees on research-only contracts, the paygap has now been reversed and is 6.5% in favour of female staff members. In line with the University's Code of Practice, our REF submission has been informed by an equality impact assessment which analysed our output portfolio against age, disability, ethnicity and gender.

2.4 Other support for career development

Every staff member, including post-doctoral researchers, benefits from an annual performance review (APR) with their line manager. The APR is a supportive conversation which discusses progress, identifies areas for improvement, highlights opportunities and sets objectives. Suggested interventions may involve relieving duties to focus on research output, funding (Section 3.1), or impact (Section 1.11), alternatively to consider sabbatical leave or promotion. Our sabbatical scheme affords intellectual development away from York, for example by *Probert* (TU Munich 2015, University of Lille 2016), *Jenkins* (University of Strasbourg 2014/15), *O'Connell* (Trinity College Dublin 2018), and *D'Amico* (Institute of Physics Natal, Brazil 2019). To support promotion, we have established a promotion support committee which provides independent advice from senior colleagues for the development of promotion applications. Since introducing this committee, we have seen an increase in the number of applications from female colleagues who may otherwise have been reluctant to apply, with the result that the success rate for female promotion applications is now higher than that of their male colleagues.

2.5 Support for research and impact - workload model

Our fully transparent workload model actively encourages research and impact generation. The model assumes that staff members spend 40% of their time on research, including unfunded research, because we recognise the importance of curiosity-driven research. Once a staff member attracts >15% of their salary from external sources, their teaching and academic citizenship allocation is reduced pro-rata.

2.6 Postdoctoral researchers

The University of York became signatory of the Researcher Development Concordat in 2019 (REF5a, 27) which highlights our commitment to the career development and well-being of postdoctoral and early career researchers (ECRs). They benefit from a comprehensive training package, including impact and public engagement, research integrity, open access and research data management. They have access to the university coaching scheme and its award-winning

Leadership Training (REF5a, 22). ECRs are represented on the major departmental committees to have their voice heard and to gain managerial experience. We regularly run entrepreneurial training events highlighting the benefit for both their own career development and for encouraging incorporation of impact generation into their scientific approach; this includes courses operated by the Leeds-based GrowMedTech consortium, such as “Intellectual property for medical technologies” and “Developing medical devices”. Post-doctoral researchers are encouraged to co-develop funding proposals as researcher co-investigators and they are able to apply for 3-12 months of their own salary through university internal schemes to develop their research independence.

The success of these mechanisms is apparent from the large number of successful fellowship applications, industrial and academic positions secured by our postdoctoral researchers (2.2).

2.7 Postgraduate research students

The Department operates highly effective and comprehensive postgraduate research (PGR) training. With 2.3 PGR students per FTE, we are in the top 10 of PGR student/staff ratios amongst UK physics departments. The size of this community ensures a true sense of cohort. We are also the lead institution for the EPSRC Centre for Doctoral Training (CDT) in the Science and Technology of Fusion Energy. PGR students are a key element of our research culture and fully integrated into the research activities of the department. Interdisciplinary research is supported particularly strongly, with many PhD students co-supervised by a staff member from another department.

2.7.1 PGR recruitment and training

We draw on a variety of sources to support this vibrant community. For example, in 2020, our postgraduate cohort consisted of 93 PhD and 7 MSc(R) students]. Of the MSc(R)s, 5 were self-funded and 2 were funded from external sources. Of the PhDs, 29 were directly funded by UKRI, 7 jointly between UKRI and the department, 14 by the Department or University and 7 from other external organisations such as industry (Seagate, Osram), the Royal Society and others. In addition, 15 of the PhD students were self-funded, including overseas government funding, which is particularly noteworthy and attests to the attractiveness of our postgraduate programme. The Fusion CDT supports 21 PhD students at York, many of which are funded jointly with UKAEA (10), AWE (5), ITER (1) and Eurofusion (1).

Our training and support activities are extensive and their success is evident from high on-time submission rates of PGR theses (85-90% over the REF period) and from the many prizes won by our students. Most supervisors meet their students weekly, with formally recorded meetings every 4-6 weeks. Formal meetings of the thesis advisory panel (TAP) happen twice a year, including the formal progression meeting that is not attended by the supervisor to encourage the student’s independence (REF5a, 31). Other support includes core training packages in research and transferable skills, mostly in year 1; allocation of a separate budget to encourage summer school and workshop attendance; location of students according to research topic to encourage cohort building; attendance at regular research group seminars and group meetings and award of the Stott Prize for the best PhD student. We also offer personally tailored support, including the assignment of professional mentors, for students with disabilities such as dyslexia or autism.

The success of these measures is evidenced by the many prizes won by our students, as exemplified here:

- 2019: IoP thesis prize (*Verheagh*); European Physical Society (EPS) PhD prize, Plasma Physics Division (*Tubmann*); GEC Student Award of Excellence (*Doyle*); Mazurian Lakes Conference on Physics poster prize (*Llewellyn, Lomas*).
- 2018: IoP Ion and Plasma Surface Interactions thesis award (*Shaw*); Editor-in-Chief Award of the High Power Laser Science and Engineering journal (*Bradford*); Poster prizes: Canadian Association of Physics Congress, TRIUMF Science week (*Dunling*), International Nuclear Physics Conference (*Morales*).
- 2017: Springer thesis prize (*Colas*); SPIE Photonics West poster prizes (*Pitruzzello, Colas*).

- 2016: Springer thesis prize (*Schuster*); Nature Photonics prize, Photonic and Electromagnetic Crystal Structures (*Colas*); EPS Plasma Physics Conference poster prize (*Bokshi, Willet*); awards to present at the US Biophysical Society Conference (*Miller*, *Zhou*).
- 2015: EPS Nuclear Physics in Astrophysics Conference poster prize (*Garg*)
- 2014: American Physical Society Gaseous Electronics Conference Student Award for Excellence (*A Gibson*).

A particular highlight was the participation of 2 York students at the "Falling Walls" finale in Berlin, which *Pitruzzello* attended as winner of the UK competition in 2019 after *Schuster* had done so in 2017 (REF5a, 32).

Finally, we are pleased to note that Eurofusion, in its 2016 review of fusion education programmes in all EU member states, awarded its only 10/10 grade to the Fusion CDT at York.

3. Income, infrastructure and facilities

The culture change we have achieved with respect to impact (Section 1.3) has been commensurate with a culture change in funded research. Funding opportunities, application rates and successes are discussed and celebrated at every meeting of the Departmental Research Committee. Pump-priming funding to explore new ideas, to build new collaborations and to generate pilot results is available both from the Department and the University. We use PhD stipends strategically to encourage collaborations that can open up new research opportunities. Two research facilitators in our Research Support Office aid staff members in all aspects of grant writing by highlighting suitable funding calls, encouraging submissions and helping with costings. Our internal peer-review system provides constructive criticism on all grant applications.

3.1 Research income trends

As a result of these interventions, our grant income has grown steadily over the assessment period and has doubled from £3.6M in 2013/14 to £7.2M (3-year average 2017/18 to 2019/20 to account for fluctuations due to large capital awards) significantly outperforming the increase in staff number (x1.5) and contributing to the University's increase in UKRI market share from 1.5% to 2.1% (REF5a, 38). Very importantly, we have also significantly broadened the research base; 68% of staff members are now principal investigators of externally funded grants or are lead investigators of the physics component of a grant; this wide distribution of awards is another clear indicator for the success of our diversity and inclusion strategy. As mentioned in Section 1.10, our EPSRC grant portfolio is in the top 3 of all physics departments in the UK both for its volume and for the number of principal investigators.

3.2. Infrastructure and local facilities

The Department has established a range of State-of-the-Art research facilities since 2014 and has secured the following University infrastructure investments:

- CMP Laboratories with pulsed laser deposition (PLD), X-ray photoelectron spectroscopy (XPS) and multi-chamber molecular beam epitaxy (MBE) capabilities and corresponding laboratory upgrades (£400k).
- Nuclear Applications Laboratories for the development of State-of-the-Art radiation detection systems with strong industry connections (£350k).
- A new 350 m^2 Physics of Life research building, including new biophysics and category 2 biohazard rated laboratories (£470k).
- A new 300 m^2 York Centre for Quantum Technologies, including the York-led Quantum Hub for Quantum Communications (£400k).
- Extension of the York Plasma Institute by 500 m^2, including a new post-graduate training suite and new joint laboratories with the Wolfson Atmospheric Chemistry Laboratories (£1M).

- Major upgrade of the York JEOL Nanocentre with a focus on interdisciplinary research in Nanobiology with a Category 2 Biosafety lab, a BioScope Resolve AFM and a microfluidics fabrication suite (£700k).
- Participation in the York Global Initiative for Safe Autonomy, a Research Partnership Investment Fund (RPIF £10.5M) project with a £1.2M University investment allocated to quantum physics research.

These facilities are supported by a team of expert technicians who ensure upkeep and optimal use. Each research group also has 1-2 experimental officers who support researchers and take responsibility for the infrastructure related to particular research strands. The sustainability of these facilities is ensured by the University Research Development and Capital Support funds (REF5a, 10), co-funding with UKRI (including their Strategic Equipment Fund), commercial exploitation and related income, and most significantly, through our strongly growing research income (fig. 6). We are therefore confident that we can maintain these facilities and further expand them in the future.

3.3 External facility access

Given the nature of our research, many staff members use external facilities, which in most cases involves competitive application processes; in fact, our success in this area is exemplified by the number and quality of the output resulting from facility research and the fact that **the total value of facility access secured by our staff members is comparable to the competitively won research funding.** The strength of our connections to these facilities is further highlighted by the co-funding of several staff members, in particular:

- *Cavill* lectureship funded 50% by DIAMOND Light Source 2015-18
- *Dobaczewski* "Chair in Nuclear Theory" fully funded for 3.5 years by STFC 2015-18, following an open competition to address the strategic need for nuclear theory in the UK.
- *Lipschultz* 40% funding from Culham Centre for Fusion Energy since 2014.
- *HR Wilson* Programme Director (50%) at Culham 2017-2019.
- *Kepaptsoglu* joint appointment with the EPSRC National Research Facility for Advanced Electron Microscopy (SuperSTEM, 2017-2022, 100% UKRI).

Our key facility use over the REF period is valued at £35.9M. The figures quoted below have been provided by research funders or by facility heads and their evidence is available on request.

a) UKRI Allocations (£16,401k)

Facility	User	Total (GBP)
Central Laser Facility at RAL	*Higginbotham, Lancaster, Murphy, Ridgers, Tallents, Woolsey, Pasley, Read, Antonelli*	**2,891k**
Computing: ARCHER, THOMAS	*Cziegler, Dudson, Hasnip, McKenna, Noy, Probert, Vann, HR Wilson*	**392k**
DIAMOND Light Source	*Cavill, Kröger, Thompson, Vallejo-Fernandez*	**1,516k**
SuperSTEM	*Lazarov, Kepaptsoglou, Kröger, McKenna*	**629k**
ISIS Neutron and Muon Source	*Lazarov*	**164k**
ILL	*Lazarov*	**149k**
CERN	*Andreyev, Dobaczewski, Jenkins, Pastore, Wadsworth*	**10,660k**

b) International Allocations (£19,453k)

ATLAS, Argonne Nat'l Lab (US)	*Andreyev, Petri*	**1,079k**
AUG Garching (Germany)	*Cziegler, Lipschultz*	**285k**
CSC – IT Centre for Science Ltd. (Finland).	*Dobaczewski*	**92k**
DIII-D, US DoE, San Diego, US	*HR Wilson*	**226k**
Ganil, France	*Diget, Wadsworth (Emeritus since 2018)*	**3,598k**
GSI, Darmstadt, Germany	*Paschalis*	**667k**
Jefferson Lab, US	*Bashkanov, Watts, Zachariou*	**7,935k**
NSCL, Michigan State, US	*Bentley, Petri, Wadsworth (Emeritus since 2018)*	**1,576k**
MAMI, Mainz, Germany	*Bashkanov, Watts, Zachariou*	**764k**
TCV, Switzerland	*Lipschultz*	**304k**
TRIUMF, Vancouver, Canada	*Laird*	**726k**
University of Jyvasklya, Finland	*Jenkins, Petri, Wadsworth (Emeritus since 2018)*	**1,858k**
JET Tokamak, Culham	*Gibson, Lipschultz*	**342k**

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

4.1 National and international collaborations

Collaborative research is at the heart of what we do, as already mentioned above in terms of national and international facilities, where York researchers sit on many panels. They approve and competitively win significant facility access time, such as at CERN, TRIUMF, GSI and at RIKEN for the Nuclear Physics group, UKAEA/Culham and Rutherford Appleton for Plasma Physics and at DIAMOND as well as supercomputers such as ARCHER for Condensed Matter Physics. The Quantum Hub also strongly supports collaboration between leading academic and industry groups. Interdisciplinarity is particularly driven by the Physics of Life group through joint appointments with Biology and with Archaeology. We have good links with the NHS, e.g. *Hancock* is spending her enterprise fellowship at Guy's and St Thomas' NHS Trust, London, and *Krauss* leads a Healthcare Impact partnership (EPSRC, £1.1M) with York Hospital NHS Trust. Physicists have also led the cross-faculty "Technologies for the Future" University Strategy theme since its inception in 2015.

The Nuclear physics programme is necessarily international in nature as there are no experimental facilities for this research in the UK. Accordingly, the group has strong collaborations with various experimental and theoretical groups in Europe, North America, Japan India, China and South Africa. Similarly, Plasma Physics works with Fusion reactors in Germany and the US. CMP have very strong links to Japan, e.g. via the JSPS-EPSRC core-to-core grant on spintronic devices involving York, Tohoku and Kaiserslautern in Germany. CMP now also lead the EPSRC "International Spintronics Network" with partners Leeds, Manchester and leading institutions in France, Germany and Japan.

We have partnered in a number of EU projects, most notably CMP/Magnetism (COMRAD, FEMTOTERABYTE), CMP/Photonics (ITN "PROPHET"), PoL ("SYNCROP"), Plasma ("PIONEER") and a number of Eurofusion projects.

Global Challenges. We strongly engage with the Global Challenges Research Fund (GCRF) programme and have had multiple sizeable projects funded, for example in South Africa (STFC £100k + £410k, nuclear detectors, *Jenkins*, fig.6a), in Vanuatu, South Pacific (EPSRC £1.2M,

water sensors, *Krauss* co-I, fig. 6b) or in Nepal (EPSRC £548k, water testing, *Krauss*). Being exposed to the reality of resource-poor environments and explaining technology to people from a wide range of backgrounds is an interesting exercise in customer-focussed thinking that will also benefit our impact and translation work. Related activities include a British Council grant (£150k) to *Pratt* for developing gas sensors in Vietnam, a Royal Academy of Engineering grant (£140k) to *O'Connell/Gans* for plasma medicine technologies in Thailand, a visiting scientist position for *Pasley* at TFIR, Mumbai, (STFC Newton-Bhabha grant and RS Newton, £100k-£200k ea.) as well as Newton ECRs for *D'Amico*, *Ferreira* and *Leake*.

Figure 6 a) South African researchers conducting Nuclear Physics research at York. b) *Krauss* collaborating with villagers in Vanuatu on the topic of water contamination.

4.2 Fellowships and Prizes

Dame *Prathiba Gai* (joint appointment with Chemistry, UOA8) was elevated to a Fellowship of the Royal Society in 2016, was made a Dame in the 2018 New Year's Honours list, made Honorary Fellow of the Royal Microscopical Society 2018 and won the Asian Awards 2018, all for her work on environmental electron microscopy. *Chantrell* and *O'Grady* received the 2018 Achievement Award of the IEEE Magnetics Society (first outside USA and Japan). *Dobaczewski* was awarded the Wojciech Rubinowicz prize 2015 and an honorary degree by the Claude Bernard Lyon University 2017. *O'Connell* was awarded the William Crookes Prize 2018 (EPS & IoP). *Andreyev* holds the prestigious position of Scientific Associate at CERN 2017-2018. *Cziegler* won the Simonyi Károly Memorial Prize of the Hungarian Nuclear Society 2015 and IUPAP Young Scientist Award for the Commission on Plasma Physics 2019. *Pastore* was declared an "Emerging Leader" by JPhys G as "one of the most exciting researchers of their generation". *Fulton* received the IoP Phillips Award 2016 for distinguished service to the Institute and *McLeish* the Archbishop of Canterbury's Lanfranc Award 2018. Kromek plc, translating the IP of *Jenkins*, won the IoP Business Innovation award 2016. *Leake* was elected Fellow of the Royal Society of Biology 2016. *Thompson, Wadsworth, Leake*, *HR Wilson* made Fellows of the IoP. *Leake* and *McLeish* shared the IoP Rosalind Franklin Prize as part of the "Physics of Life" team in 2020.

4.3 Shaping Policy

We have had major impact on UK Science policy, most notably in Quantum Technologies through *Spiller* and in Nuclear Fusion through *HR Wilson*. For example, *Spiller* was a main author of the influential Blackett report into Quantum Technologies, the National Security and Investment and Infrastructure Review Green Paper and he has acted as Quantum Technologies Adviser for the UK Department of International Trade. He has contributed to the UK government Science and Technology Committee 2017, Expert Roundtable on Future Technologies and Innovations, Westminster 2015, the UK-Singapore QKD Qubesat project 2018- and the UK Global Expert Mission (Quantum Technologies) to the US 2019. *HR Wilson* has shaped Fusion research by serving on the CCFE Programme Advisory Board to 2016, EURATOM Programme Advisory Committee 2014 – 2017, the Fusenet Scientific Council 2014 – 2018 and the UKAEA Executive Committee 2017-2020. He was Chair of the MAST-U Executive Board 2018-, UKAEA Research Programme Director 2017-2019, UKAEA Research Programme Director (2017-2019), UKAEA STEP Programme Director (2019 - present) and Chair of UK Tokamak Science Council

2014 – 2018. *Thompson* was IoP Vice President, Science and Innovation 2015-2019, Fulton is IoP Honorary Secretary 2017-.

4.4 Review and Advisory Panels

The depth of involvement in international facilities and our commitment to sustaining the discipline is best evidenced by the following list, which also highlights the fact that a large fraction (>50%) of staff members are involved in such strategic roles, again highlighting our inclusive environment.

Andreyev, Riken, Japan, Programme Advisory Panel (2014-), ILL, Grenoble, Programme Advisory Panel (2015-); *Bentley* STFC Nuclear Physics Programme Evaluation Panel (2018); *D'Amico* EPS Council (2017-); *Dudson*, ARCHER Plasma Physics Resource Allocation Panel (2014 – 2020); *Dobaczewski,* STFC DiRAC Oversight Committee (2017-2020), Particle Physics/Nuclear Theory sub-panel (2018-2021), Advisor to CERN-ISOLDE and Neutron Time-of-Flight Committee (2013-2016), Advisor to Belgian FNRS Commission (2010-); *Fulton*, STFC Science Board (2014, International panel member on SciDAC Review Committee, US (2017), Advisory Board for the Helmholtz Foundation Felsenkeller Underground Laboratory (2017-2020); *Gai*, RAEng Fellowship Committee 2018-2019, RS Fellowship Committee (2018-2019); *Gans*, Vice-Chair of the British Vacuum Council (2017-2020), Chair (2020-), Chair of International Union for Vacuum Science & Techniques Plasma Division (2013-2016), EPSRC instrumentation panel member (2014-2015, 2019); *Godby*, Steering Committee, European Theoretical Spectroscopy Facility (2005-); *Hasnip*, ARCHER2 Expert Benchmarking Team; *Higginbotham*, UK/US MURI project renewal panel member (2018), Chair of HiBEF Technical Advisory Committee (2014-), Member of XFEL HED Instrument Advisory Review Team (2012-2014); *Jenkins*, Consultant to BEIS on Nuclear Data (2017-2019), STFC Science Board (2019-); *Leech*, STFC Advisory panel for public engagement (2016-); *Kepaptsoglu*, SuperSTEM advisory committee member (2017-); *Krauss*, International Advisor on Helmholtz Association Funding (2017), Advisor to Methusalem large project, University of Gent 2013-; *Laird*, Program Advisory Committee, Argonne National Laboratory (2019-), STFC Cross Community Committee (2017-), STFC Education Training and Careers Committee member (2016-), Chair of Nuclear Astrophysics Working group for NuPECC Long range plan 2015; *Leake*, Secretary IoP Biological Physics Group (2019-), RS Research Grants Panel and International Exchange Panel (2018-); *Lipschultz*, DIFFER evaluation panel, NL, (2016-); *McLeish*, Royal Society Education Committee Chair (2015-2019); Royal Society Council Member (2020-), REF2021 physics panel, Chair Harvard Knox Fellowship Committee (2015-); *McKenna*, UK High-End Computing Materials Steering Committee (2018-); *Murphy*, RS Newton International Fellowship panel (2018), Plasma Wakefield Accelerator Steering Committee member (2017-); *O'Connell*, Evaluation of Portuguese Science and Technology (2019); *O'Grady*, Advisor of Institution of Engineering and Technology (IET) (2014-); *Pasley*, STFC Central Laser Facility Access Panel (2016-), STFC Computing Advisory Panel (2013-2017), EPS Beam Plasma and Inertial Fusion board (2010-2015); *Petri*, Deputy Director of the Scientific Board of R3B Collaboration (2015); *Probert*, Chair of UK Car-Parrinello Consortium, ARCHER2 Science Board member; *Spiller*, Advisory Board on the EMPIR project, NPL (2015-); *Thompson*, RS University Fellowships Panel member and Deputy Chair (2016-2021), Heads of Physics Forum Steering Committee (2014-2017); *Wadsworth*, European Neutron Detector Array (NEDA) board (2014-2020), STFC Nuclear Physics Advisory Panel (2013-2016), Legnaro National Laboratory, Italy Advisory Panel (2013-2014), ILL, Grenoble Advisory Panel (2013-2014); *HR Wilson*, KSTAR Tokamak International Programme Advisory Committee (2018-), Advisor to the Commission on Plasma Physics of the International Union of Pure and Applied Physics (2014-).

4.5 Journal editorships

Objective peer review makes an essential contribution to the health of the discipline, which we support through a number of leading roles.

Dobaczewski, Editor-in-Chief, J Phys G (2017-); *Fulton*, Board member of IoP Publishing (2018-21); *Jenkins*, Series Editor Nuclear Physics, IoP Publishing; *Krauss*, Associate Editor, Optica

(2016-2020), Deputy Editor (2020-); *Leake*, Open Science (2015-) and Scientific Reports (2015-) editorial board; *O'Connell*, Editor of IEEE Transactions on Radiation and Plasma Medical Sciences (2016-), Scientific Reports editorial board (2016-), Editor of Journal of Vacuum Science and Technology (2015-), Guest Editor Biointerfaces (2015), Plasma Medicine editorial board (2014-), Plasma Sources Science and Technology editorial board (2014-2015); *Spiller*, IET Quantum Communication editorial board (2019-); *Wagenaars*, Journal of Optical Physics (2013-2014); Wilson, Nuclear Fusion (2014-2018); *Wilson-Rae*, Journal of Optics (2015-2017).

4.6 Keynote/plenary talks

York physicists have delivered over 1000 invited talks at international workshops and conferences. Of these, >50 were keynote or plenary talks as listed below.

Andreyev, GSI, Darmstadt 2020, NN2018, Japan, "Fission at Isolde" CERN 2018; *Bashkanov*, Int. Conference on the Structure of Baryons, Florida 2016; *Chantrell*, International Symposium on Magnetism, Moscow 2017, International Conference on Hysteresis in Magnetic Materials Iasi, Romania 2015; *Diget*, Nordic Meeting on Nuclear Physics 2015; *Fulton*, 36th International School of Nuclear Physics, Erice, Sicily 2014; *Ferreira*, Brazilian Physics Society 2016, Nanoportugal, Lisbon 2018, 13th International School on Theoretical Physics, Rzeszów, Poland 2018; *Gai*, MRS Spring Meeting, 2015; *Gans*, Plathinium, Antibes, France, 2019, SAPP-EU-Japan Symposium, Slovakia 2019, International Conference on Plasma Spectroscopy, Oxford 2018; *Jenkins*, Fusion in massive stars, Turkey 2019, Int Conference on Nuclear Structure Properties, Turkey 2019; *Krauss*, Nanophotonics Berlin, 2015, Australian Inst of Physics, Perth 2018; *Leake*, Life Science Conference on Single Cells, Gothenburg 2015; *McLeish* American Chemical Society Philadelphia 2020, Science Literacy Congress, Beijing, September 2018, Flow and Assembly, Okinawa 2018 International Congress in Rheology 2016, James White Memorial Lecture, Uni of Akron, USA 2015; *O'Connell* International Conference on Chemical Kinetics, Orleans 2019, International Symposium on New Plasma and Electrical Discharge Applications, Corsica 2019, 7th International Conference on Plasma Medicine, Philadelphia 2018, 24th Europhysics Conference on the Atomic and Molecular Physics of Ionized Gases, Glasgow 2018, 5th International Workshop Plasma Science and Interfaces, Switzerland 2018, 81st IUVSTA Workshop on Response of Biological Materials to Plasma Treated Medium, Slovenia 2017; *O'Grady*, IEEE Intermag, Singapore 2018; *Pastore*, GDR-RESANT Orsay France 2018, Recent Progress in Many Body Theories 20, Toulouse 2019; *Spiller*, 2nd IEEE British and Irish Conference on Optics and Photonics London 2019, Cyber Security and Quantum Computing Symposium, Great Malvern 2018, SPIE Security and Defence Edinburgh 2016, IPAQS Symposium, Edinburgh 2016; *Wagenaars*, 15th International conference on Plasma Surface Engineering, Germany 2016; *HR Wilson*, 42nd EPS Conference on Plasma Physics, Lisbon, Portugal 2015; *Wilson* Royal Society scientific discussion meeting on Fusion power, London 2018; *Zachariou*, DSPIN Dubna, Russia 2017, European Few-Body Problems Aarhus, Denmark 2016.

4.7 Conference organisation

York researchers have made major contributions to the discipline by organising conferences in all fields of study; these are listed below. In addition, we serve on many of the leading conference committees which are too numerous to list, such as meetings of the Materials Research Society, the Optical Society, MMM-Intermag, Low-Temperature Plasmas, Gamma-Ray Spectroscopy and many others.

Conferences that we have organised or led are; *Bentley*, NUSTAR, York 2016; *Dudson*, BOUT++ workshop, York 2015-2019; *Ferreira*, First-Principles Modelling of 2D Materials, York 2018, Chair of Programme Committee for Recent Progress in Spintronics of 2D Materials, Taiwan 2016, 1-Day International Symposium on 2D Materials, York 2016; *Hasnip*, Organiser of CASTEP Developer Workshop, Oxford 2017, 2019, CASTEP Community Meeting, Oxford 2017, Workshop on "Atomic scale materials microscopy" York 2017; *Jenkins*, India-UK Seminar on Nuclear Physics with ISOLDE, Chandigarh, India (2014), Workshop on Large Arrays of Novel Scintillators, Dublin 2014; *Kepaptsoglu*, NEXT-TEM Microscopy & Microanalysis, Portland, US

2019, 7th SuperSTEM Summer School, Daresbury 2018; *Krauss*, Photonic & Electromagnetic Crystal Structures, York 2016; *Lazarov*, Microscience Microscopy Congress, Manchester 2014; *McLeish*, RS Discussion Meetings 2017 and 2020, Statistical Mechanics of Evolution 2018, Physics of Brains 2020; *McKenna*, Workshop on Charge Trapping Defects in Semiconductors and Insulators, York 2017, Psi-k workshop: Atomic scale materials microscopy, York 2017, Workshop on Interfaces in Thin-Film Photovoltaics, Durham 2020; *O'Grady*, York-Tohoku-Kaiserslautern Symposium 2019, 2017, 2015, IoP Magnetism Winter School, York 2016; *Pratt*, Emerging Trends in Magnetic Materials and Spintronics, York 2017; *Pastore*, School Director 20th STFC Summer School St. Andrews 2019; *Probert* Organiser of Theory, Modelling and Computational Methods for Semiconductors EU-TMCS-II, Cork 2016; *Probert*, New Horizons in Atomistic Modelling, York 2018; *Vallejo-Fernandez*, IoP Magnetism Winter School, York 2015, IoP Magnetism, Leeds 2015; *Wagenaars*, Workshop on the exploration of low temperature plasma physics, Netherlands 2013-2019; *Yuan*, IoP EMAG 2013-2018, MMC 2017.

4.8 Contribution to economy and society

In addition to achieving academic impact, our strategic goal of REF 2014 was to ensure industrial impact (Section 1.2.2) by closely working with a number of leading national and international industry partners; key examples are listed in the table below and in our impact case studies.

Industry partner	Sector	Collaboration	Sponsorship	PI
Seagate Northern Ireland, California, Bangkok	Magnetic disc drives	Thin film technology, advanced modelling (see ICS)	Co-funding 2 lectureships, 10 PhD studentships & lab refurb, >£1M in total; Royal Society Industry fellowship support	*O'Grady, Chantrell, Vallejo-Fernandez*
Kromek UK	Nuclear Detectors	Development of detector technologies (see ICS)	Co-funding 1 lectureship Innovate UK project (£500k)	*Jenkins, Krauss*
Intel Ireland	Computer chip manufacturing	Monitoring for plasma manufacturing	£1.5M equipment donation; £200k contract research; Support £2.5M EPSRC grant	*Gans*
Advanced Storage Tech, Northern Ireland	Information storage	Seagate, Western Digital	2 PhD students	*O'Grady*
Nedo/Toyota, Japan	Materials for novel electric motors	Advanced modelling (see ICS)	1 PhD student	*Chantrell, Evans*
Greatcell Solar, Australia	Dye and perovskite solar cells	Material design optimisation	Project partner on 2 EPSRC projects (EPSRC >£1M)	*McKenna*
Cristal Global, UK	TiO2 products for solar cells/ photocatalysis	Nanomaterial design optimisation	Project partner on EPSRC project (EPSRC>£1M)	*McKenna*
Unilever, UK	Home & personal care products	Biofilm investigation	Innovate UK project (£300k) PhD studentship	*L Wilson*
Osram, Germany	Light sources	Sensor technology development	Fully funded PhD studentship	*Krauss*
Quantum Communications Hub, UK	Quantum Technologies	ADVA, BT, ID Quantique, NPL, Toshiba	Support of >£50M EPSRC grants	*Spiller*

4.9 Public engagement with research

We have a strong ethos of engaging public audiences with research (see ICS). We reach in excess of 15,000 people annually through face-to-face interactions, with greater numbers engaged through podcasts, media appearances, and online content. Over 55% of academic staff contribute to the programme of activities. Public engagement with research is recognised at all levels: *Diget* is an STFC Leadership Fellow in Public Engagement; *Rawes* (support staff) and *Trickey* (PhD student) are members of STFC's Public Engagement Early-Career Forum. The Outreach and Public Engagement team Coordinator *Leech* is recognised nationally as a member of STFC's Advisory Panel for Public Engagement and contributing to the STFC Publication 'Pathways to Excellence in Public Engagement'. We were selected by the UK Space Agency to host one of two national Principia conferences in 2016 and the National Schools Space Conference in 2020.

We engage with **diverse communities** through our research. For example, primary school age children and their parents and carers experience hands-on exhibitions in events such as York Researchers' Night and the York Festival of Ideas (which attracts an audience of over 30,000 annually), where the Quantum Hub is also regularly represented, e.g. *Spiller* debated the Future of Cyber Security 2015 and organised the Quantum short film screening in 2019. *Spiller* was also a panellist at the "Quantum in the City" event at the Royal Institution in 2019. We run four-week Nuffield research placements and year-long programmes with regular interventions designed to encourage under-represented groups to consider Physics (including girls and widening participation students).

Our Nuclear Astrophysics research is communicated in fortnightly openings of our own observatory, the Astrocampus. Primary school children are targeted through formal education, including visits from our inflatable planetarium (the Cosmodome) and demonstration lectures (1820 attendees for 11 events in 2015/16, 3000 attendees in 29 events 2017/18), as well as through youth groups (such as Cubs and Brownies, 40 groups per year) with tailored sessions on the Astrocampus.

We run curriculum-linked Nuclear Masterclasses. Our flagship is the LEGO-based nuclear 'Binding Blocks' activity "Building the universe one nucleus at a time" which beautifully showcases our Nuclear Physics research to A-level students (see ICS, fig. 7a). The Outreach team keeps a detailed log of participation at these events; the 120-140 events it runs a year have an approximate reach of 15,000 attendees.

Figure 7. Examples of our Outreach work. a) Nuclear binding blocks; b) British astronaut Tim Peake greeting more than 400 students across 80 schools in Nov 2018; c) Astrocampus.

We communicate widely via the national media, e.g. as part of GCSE Science Live by *Lancaster*, in the company of very high-profile scientists such as Jim Al-Khalili and Maggie Aderin-Pocock, drawing audiences of thousands for each event. *Brunsden* was an astrophysics expert on Victoria Derbyshire, BBC News, BBC World News, Sky News, and BBC R5 Live. *McLeish* contributed to BBC R4 "Scientifically speaking", "The Secret History of Science and Religion" and is a regular "Thought for the Day" speaker. *Lancaster* featured in the plasma episode of "In Our Time" on BBC Radio 4 and a fusion episode of BBC CrowdScience for the BBC World Service, downloads of which are around 170k per month and rising. We offer two podcasts: Fusion-based 'A glass of seawater' (*Lancaster*) which has over 180 downloads per

month and won the Rutherford Plasma Physics Communication Prize in 2019, as well as astrophysics-based 'Syzygy' (*Brunsden*) which averages 1000-1200 downloads per month.

We work closely with the National STEM Learning Centre where we provide expertise for national teacher training courses in Nuclear, Quantum and Astrophysics; we work with local programmes that pair teacher training with school interventions to upskill teachers as well as engaging young people directly. Up to 20 schools (primary and secondary) participate in our local programme each year, often with several teachers from each school participating, and our academic staff reach around 70 - 100 teachers through national CPD courses each year.

In addition to face-to-face engagement, the Department is strongly involved in communicating research through 'Physics Review' – a quarterly magazine for A-level students that is distributed nationally and that has been edited by York researchers since its conception 30 years ago. The magazine had 3,523 subscribers in 2019-20, of which 695 were school subscriptions.