Institution: University of Liverpool

Unit of Assessment: UoA 9 Physics

1. Unit context and structure, research and impact strategy

Our vision is to be at the forefront of major breakthroughs in physics over the coming decades. Through a programme of physics exploration and discovery, we are addressing the most fundamental questions in physics. We ensure that the detector, accelerator and other technologies that we develop have wide-ranging applications for societal benefit, and we share our enthusiasm for physics with broad and diverse audiences.

1.1 Unit Structure

The Department of Physics is part of the School of Physical Sciences, within the Faculty of Science and Engineering. Our research is structured across four clusters: Accelerator Science, Condensed Matter, Nuclear Physics and Particle Physics. We also play a key role in a number of interdisciplinary institutes and initiatives (Fig. 1).

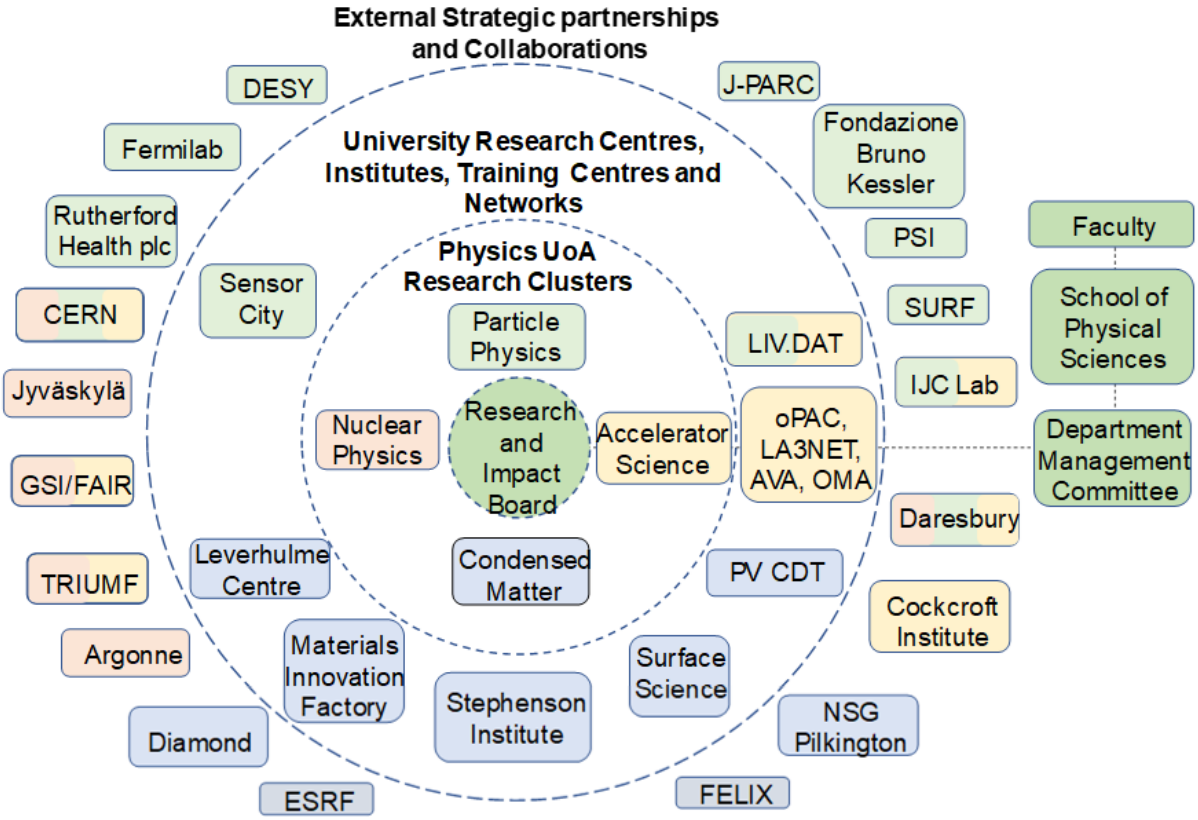

Figure 1: Research and impact structure. Connections to clusters are colour-coded.

1.2 Research and impact strategy

Progress since REF2014 includes several new appointments (§2.1), substantial increases in PhD numbers (§2.3) and total research income (§3.1), new investment in infrastructure (§3.2, §3.3), and a broadening of impact generation activities (§4). Acronyms refer to projects familiar to the physics community; names of staff contributing to REF appear in bold.

1.2.1 Achievement of REF2014 research and impact strategies

Our REF2014 research strategy articulated three principal aims:

(i) To lead and contribute to research on questions of national and international significance;
(ii) To create excellent teams of researchers focused on both long-standing and emerging research areas;
(iii) To develop and maintain the technical expertise and instrumentation base necessary for our programme.

This strategy has delivered many important outcomes: in this REF period 2,024 papers have been published attracting 58,593 citations (Scopus) with 90% involving international collaborators. Prestigious awards include the Breakthrough Prize in Physics, the Rutherford Medal, the Rosalind Franklin Medal of the Institute of Physics and the Altarelli Prize. We are ranked among the top 25 institutions globally who collaborate with CERN. During this REF period we have employed 56 academic staff including 2 Fellows of the Royal Society, and 136 doctoral degrees have been awarded. In 2020 we had 85 PDRAs, 128 research students and 20 technical support staff. Research income over the REF period increased by 81% from £33M in REF2014 to £60.4M for REF2021. Research income-in-kind was £84.5M.

Our REF2014 impact strategy concentrated on energy, health, security, and society. Overseen by our Research and Impact Board,

- Energy impact includes: development of novel transparent conducting oxide coatings in collaboration with Nippon Sheet Glass/Pilkington and collaborations with Mirion in nuclear energy and CapeSym in nuclear waste.
- Healthcare impact includes: dose verification in radionuclide therapy; treatment of retinal detachment; sensors for proton therapy; infrared imaging for early detection of cancer and low-cost ventilators for OECD countries in response to COVID-19.
- Security impact includes: imaging sensors for explosive devices and drug screening.
- Societal impact includes: outreach activities for non-traditional audiences and engaging visually impaired adults and children.

Impact is further discussed in section §4.2. Cluster research achievements include:

Accelerator Science

- As a key member of the High Luminosity Large Hadron Collider (HL-LHC) UK collaboration, jointly funded by STFC and CERN, we have pioneered a novel gas jet-based beam profile monitor, which will be used for characterisation of the HL-LHC beam and the Hollow Electron Lens. We also had a central role in measurements at CERN's Super Proton Synchrotron, where crabbing of a high-energy proton beam was demonstrated for the first time.
- We initiated and led four pan-European research and Marie Skłodowska-Curie Innovative Training Networks (ITNs) on Accelerator Optimisation (oPAC), Laser Applications at Accelerators (LA3NET), Optimisation of Medical Accelerators (OMA) and Accelerators Validating Antimatter physics (AVA), (details in §3.1) and trained more than 70 Fellows.
- We are a key partner in the AWAKE collaboration, which has successfully demonstrated electron beam acceleration in a proton-driven plasma.

Condensed Matter Physics

- We have focused on advanced low-cost materials and device concepts for the next generation of photovoltaic products, by identifying opportunities for increasing efficiency and improving fabrication and characterisation of advanced solar cells. This work has been supported by significant EPSRC funding (£2.91M), the EPSRC CDT in New and Sustainable Photovoltaics (£5.26M) and two EU Marie Skłodowska-Curie ITNs, "NanoEmbrace" and "INDEED".
- We have developed specialist capabilities in single crystal bulk growth and thin film growth, particularly of transparent conducting oxides and ferroelectric materials. As part of the Leverhulme Centre for Functional Materials Design we have developed new capabilities in materials synthesis and characterisation methods. In partnership with Warwick University we

lead the EPSRC National Research Facility, XMaS, based at the ESRF in Grenoble (total funding of £7.2M during REF2021).

- We are developing new tools for cancer diagnostics and image analysis for medical and biological applications. We were a founder member of the UKRI Physics of Life Network and the Rosetrees Physics of Medicine Network. Aspects of this work have been patented (European Patent: PCT/GB2019/050998).

Nuclear Physics

- We have focused on the structure of exotic nuclear systems and the properties of QCD matter at high temperatures. Highlights include investigating octupole deformation and collectivity of radium and radon isotopes to guide future studies of CP violation; elucidating the origins of shape coexistence in mercury isotopes; and using charge radius measurements to probe the nuclear shape change at doubly magic ^{132}Sn. We have established that flerovium is a volatile metal, performed the first optical spectroscopy of nobelium and independently confirmed the discovery of element 117 (tennessine). We have observed enhanced production of charmed baryons in proton-proton, proton-Pb and Pb-Pb collisions and of multi-strange hadrons in proton–proton collisions, as well as an enhanced J/φ elliptic flow in Pb-Pb collisions, shedding light on complex hadronization mechanisms and the properties of the quark-gluon plasma (£6.5M of STFC funding during this REF period).
- We have continued to lead the development of new instrumentation through STFC-funded projects. In this REF period we led the design and construction of the ISOLDE Solenoidal Spectrometer (£1.2M); upgraded the ALICE Inner Tracking System (£1.2M); developed the Segmented Inverted Coaxial Germanium Detector (SIGMA) for gamma-ray spectroscopy and imaging (£0.6M); and embarked on the next phase of the Advanced Gamma Tracking Array (AGATA) project (£0.8M).
- We have used our expertise in silicon detector systems to construct and operate the vertex detector for the ALPHA antihydrogen experiment at CERN, which led to the first characterisation of the 1S-2S transition in antihydrogen and reduced the upper limit on the charge of antihydrogen by a factor of 20 (EPSRC funding totalling £1.4M).
- We have worked with external partners to apply our gamma-ray detection and imaging techniques for impact (described in §4).

Particle Physics

- Within the ATLAS experiment on the LHC at CERN, we have made seminal measurements of the Higgs boson properties and other Standard Model parameters. We have led searches for new physics including new heavy particles and dark matter candidates. We are a key institution in the design, prototyping and building of the upgraded detector trackers of both the ATLAS (£3.1M) and LHCb (£0.3M) experiments for the High-Luminosity phase of the LHC.
- Through LHCb at CERN we have contributed to precision quark flavour physics as well as searching for new physics through violation of lepton universality. We have delivered milestone results such as the first observation of dimuon *B*-decays. We extended our STFC-funded flavour programme in this REF period to include the precision muon experiments, g-2 (£0.6M), Mu2e (£0.3M) at Fermilab and Mu3e (£0.2M) at PSI.
- Our neutrino physics programme has set the first limits on the CP violating parameter δ in the neutral lepton sector with the T2K experiment in Japan, and we are leading activities towards next-generation experiments, DUNE (USA) (£1.7M), SBND (USA) and Hyper-K (Japan) (£0.4M). The SNO+ experiment (Canada) has commenced data taking.
- We search for evidence of dark matter interactions in the Lux-Zeplin (LZ) experiment (SURF, South Dakota) and are developing new technologies to search for axion dark matter at lower masses (MAGIS100, AION).
- Our silicon detector R&D, performed jointly with Fondazione Bruno Kessler (FBK) (§4.1), focusses on the development of low mass detectors, compatible with operation in high rate and high radiation environments. We also conduct R&D on the readout of future underground neutrino and dark matter experiments. We are part of the WATCHMAN consortium and we pioneered a novel optical readout technology through the ERC-funded ARIADNE project

(£1.7M). We also developed an optical calibration system for future use in Hyper-K and already deployed in Super-K and Lux-Zeplin.

1.2.2 Evolution of research and impact strategies during the REF period

Research and impact strategies have been refined through external review and internal consultation.

International expert advisory panel established in 2015
To assess our strategy, an international external review panel (Äystö, Friend, Knight, Rowan, Stewart Smith and Wark) was convened in October 2015. The panel endorsed our aim of achieving leadership in physics questions of international importance, and recommended some key supporting strategies, including strengthening partnerships and looking at interdisciplinary opportunities.

Departmental consultations
Inclusive research and impact away-days were held in June 2015 (to review outcomes of REF2014) and July 2019 (to plan strategy for REF2021 and beyond). Strategic discussions are held at monthly Research and Impact Board and cluster-level meetings. Evolving strategies are presented at monthly staff meetings.

1.2.3 Future plans for research and impact

Following the processes described above, we have refined our **strategic priorities as follows**:

SP1 *further develop and **lead research** on physics questions of international significance;*
SP2 *grow cross-cluster **collaboration** and promote **interdisciplinary research** initiatives.*
SP3 *build and enhance a research environment which develops our **people** and embodies **Equality, Diversity and Inclusion**, including Juno and Athena SWAN principles;*
SP4 *develop **impact** as an integral outcome of our research activities in our focus areas of Energy, Health, Security, and Society;*

Plans for achieving **SP3** and **SP4** are principally described in §2 and §4, respectively. These are also underpinned by supporting strategies for academic recruitment and funding described in §2.3 and §3.1. **SP1** and **SP2** priorities are addressed via the following departmental and cluster-level actions:

Achieving SP1 - research leadership

International community consensus prioritises the scientific questions that are being addressed in major international facilities. We proactively engage with national and international community consultations that define these priorities including UK prioritisation exercises, the European Strategy for Particle Physics, the European Long-Range Plan in Nuclear Physics and the US Snowmass process. We align our research programmes based on these outcomes.

Cluster plans

Accelerator Science
In the next decade we will focus on the LHC at CERN, where we lead work on the development of gas jet monitors for the high luminosity upgrade; on R&D into the exploitation of the CLARA facility on Daresbury campus to explore next-generation FEL technologies; and on optimization of low energy beam transport and efficient injection into traps at the Antiproton Decelerator.

As part of the AWAKE project, we will continue our efforts on novel (high gradient) acceleration techniques. Following the successful demonstration of proton-driven wakefield acceleration in 2018, we are leading the development of novel diagnostics that will give more detailed insight into

the physics of the acceleration process. We will expand simulation and experimental studies into micro-accelerators using carbon nanotubes and dielectric structures.

For impact, we will carry out R&D into least invasive beam and dose monitors, to help reduce exposure times hence improve patient treatments. We will continue to develop digital radiography systems with Adaptix Ltd. and study different operational scenarios that help optimize image quality. We will grow our spinout company D-Beam, targeting a product portfolio that benefits accelerator facilities around the world.

Condensed Matter Physics
Our activities align with the EPSRC research themes of Energy, Physical Sciences and Research Infrastructure and with the University research themes of Advanced Materials, Climate Futures and Personalised Health.

In energy, our aim is to develop means for supplying sustainable energy whilst reducing CO_2 emissions. This includes solar fuels, solar photovoltaic materials and devices including novel earth-abundant solar cell materials, transparent conducting oxides, materials for thermoelectrics, and materials for energy conversion and storage.

In nanoscience and materials**,** we will investigate the physics of matter and processes on the nanometre scale. This includes surface physics, spintronics, electrochemical interfaces, hybrid nanomaterials and functional materials. Operando studies using well-characterised thin films incorporating novel artificial materials will further our understanding of structure-stability-reactivity relationships across multiple length-scales.

Our activities will make extensive use of the growing shared equipment base at Liverpool (the Stephenson Institute for Renewable Energy (SIRE) and the Materials Innovation Factory (MIF), Chemistry, Engineering, Microscopy, see also §3.6) and synchrotron radiation sources such as Diamond Light Source, the ESRF and other facilities worldwide.

Nuclear Physics
Using AGATA we will study neutron-rich nuclei in the vicinity of the highly-deformed double mid-shell nuclide ^{170}Dy that are predicted to have a frozen internal structure persisting up to high spin, search for ultra-high spin bands in Lu nuclei, and investigate the predicted band termination in the super-deformed bands.

At CERN we will exploit detector systems including the ISOLDE Solenoidal Spectrometer to investigate how nuclear pear shapes evolve as a function of the number of neutrons and protons, and we will measure the properties of odd-A Ra isotopes relevant to atomic EDM studies. We will continue collaborating with three atomic physics groups (Michigan/TRIUMF; Argonne/FRIB; and MIT/ISOLDE) involved with searches in these Rn and Ra systems.

We will pursue studies of exotic nuclei, investigating new proton emitters to understand how decay properties and level energies are influenced by deformation and the evolving occupancies of valence orbitals; characterising chemical, atomic and nuclear properties of super-heavy elements; and charting the evolution of ground-state shapes and single-particle states towards self-conjugate nuclei below ^{100}Sn where anomalous isomer shifts have been observed. These endeavours will exploit instrumentation we have developed at the international laboratories Jyväskylä and GSI/FAIR.

Using the upgraded ALICE experiment in LHC Run 3 we will study the quark-gluon plasma by means of inclusive and, for the first time, exclusive heavy quark flavour production and decay.

We will deliver impact through our leadership of the STFC Cancer Diagnosis Network+, and work with partners such as the Clatterbridge Cancer Centre to develop novel medical imaging technologies for cancer diagnosis and therapy. We will continue to work with key stakeholders in

the nuclear energy sector (Mirion, Sellafield) to deliver solutions for characterisation of nuclear waste.

We will continue collaborating with the Condensed Matter and Particle Physics clusters in the development and deployment of radiation detectors and digital signal processing techniques. We will contribute to high-profile particle physics experiments in the USA by characterising and integrating High-Purity Germanium detectors for the LEGEND and Mu2e experiments.

Particle Physics
The physics programme at the LHC will remain a key focus. We continue to analyse LHC data, developing new searches and analyses, setting stringent limits on BSM models and making precise SM measurements. We are building major components for the LHCb and ATLAS detectors to ensure our programmes continue to be competitive. We have joined the FASER experiment at CERN, which will look for new physics in hidden sectors.

In the neutrino sector we will exploit T2K/Super-K and have a major involvement in the future long-baseline neutrino programme in Japan (Hyper-K) and the US (DUNE). We will deliver results on sterile neutrinos and neutrino interactions through the Fermilab short-baseline programme and we will also continue to search for neutrino-less double beta decays (SNO+, LEGEND).

We will search for dark matter in direct search experiments (LZ, Darkside), with the Cerenkov Telescope Array and, in an entirely new way, with the MAGIS100 large atom interferometer experiment, which we co-initiated. Magis-100 is also sensitive to gravitational waves in the cross-over region between LIGO and e-LISA.

In our precision muon programme key results on the muon magnetic moment and electric dipole moment will be delivered through the g-2 experiment. In parallel we are currently building two experiments searching for charged lepton flavour violation in muon decays (Mu2e, Mu3e).

Finally, we collaborate on the development of future experiments and facilities, including proton and muon-EDM experiments, LHeC, and the Future Circular Collider. Our physics goals will be underpinned by our detector development programme, focussed on silicon sensors and liquid argon detectors (see §3.6).

1.3 Achieving SP2: collaboration and interdisciplinarity

In line with our strategic priority **SP2** (*collaboration and interdisciplinarity*), and following advice from our 2015 external review panel (see §1.2.2), we have engaged strongly with a number of University and multi-institutional interdisciplinary initiatives. We are members of SIRE and MIF, both described in §3.6. The Cockcroft Institute, also described in §3.6, is a multi-institutional interdisciplinary institute for accelerator science, with Liverpool input from Physics, Engineering and EEE. Our STFC-funded Centre for Doctoral Training LIV.DAT is a cross-cluster initiative which also involves computer science and Liverpool John Moores University. Several of our activities are conducted in collaboration with University cancer research groups and the University theme of Personalised Health. These are described in §4.1. These initiatives have established critical mass and expertise to address key questions in our research and impact portfolio.

1.4 Open research environment

Research data
Research code and data that we produce are deposited in open access repositories. Much of our research involves usage of international facilities which have their own data curation facilities. For locally generated data, the University provides *DataCat*, which allows researchers to create records of information about their research data, and to save those data in a secure on-line environment. We also use the *DataCite* service to assign digital object identifiers to these datasets.

Outputs
We ensure all outputs of our research are at minimum green open access level by depositing them in our institutional repository upon acceptance for publication via *Liverpool Elements*. This online tool helps manage information about all research and impact activities. It collects a range of data from multiple sources (including existing internal systems and web resources such as Scopus) and offers a single web-based interface. All of the work published in particle physics collaborations is open access via the SCOAP^3 consortium.

1.5 Research integrity

The University's Research Ethics Policy mandates that all research is conducted in accordance with ethical principles. **D'Onofrio** is a member of the University Responsible Metrics Advisory Group and **Martin** is a member of the Faculty Ethics Committee and acts as liaison from this group to the Department, to ensure compliance with Ethics policy. Our academic staff and researchers complete on-line modules 'Research Integrity' and 'Research Ethics Training' covering Research with Human Participants, Ethics and Regulation, Informed consent, Confidentiality, Liability and inducement. Researchers also take mandatory training courses on GDPR and information security essentials, the Bribery Act 2010 and Managing Safety.

Our postgraduate researchers receive ethics training through the Liverpool Doctoral College. This covers ethical approval for healthcare technology projects, and safeguarding in delivery of public engagement activities.

2. People

2.1 Staffing strategy and staff development

Recruitment
We appoint staff whose research focus aligns with one or more of our clusters and who provide complementary expertise. ED&I considerations are embedded into all aspects of the recruitment processes; advertisements include ED&I statements, panels for short-listing and interviews are gender diverse and members have received unconscious-bias training; candidate visits are arranged with balanced gender representation, and start-up discussions are aimed at parity of support.

Table 1: Academic staff during the REF period:

Accelerator Physics				
Chattopadhyay[P,D]	Hock[D]	Newton[D]	Welsch[P]	Wolski[P]
Condensed Matter Physics				
Alaria	Clark[A,D,E]	Dhanak[P]	Durose[P]	Grunder[F]
Jaeckel	Lucas[P]	Major[F]	Martin	McGrath[P]
O'Brien[E]	Sharma	Veal[P]	Weightman[P]	
Nuclear Physics				
A. Boston[P]	H Boston	Butler[P,D]	Chartier[P]	Cheal[P]
Gaffney[A,E,F]	Harkness-Brennan	Herzberg[P]	Joss[P]	Nolan[P,D]
Page[P]	Paul	Pusa		
Particle Physics				
Allport[P,D]	Andreopoulos[P]	Bowcock[P]	Burdin	Casse[P]
Coleman[F]	Dainton[P,D]	D'Onofrio[P]	Gao[A,D,E]	Greenshaw[P]
Hutchcroft	M. Klein[P]	U. Klein[P]	Kretzschmar	Mavrokoridis
McCauley[P]	Mehta[P]	Shears[P]	Touramanis[P]	Rose
Rompotis[A,E]	Vilella Figueras[A,E,F]	Vossebeld[P]		

Key: Orange: female, A: Appointed during REF period, E: Early Career Researcher, F: Fellowship holder, P: Professor, D: Retired/departed during REF period.

New appointments
Mavrokoridis (Lecturer/ERC Grantee) and **Andreopoulos** (0.5 FTE, Reader, now Prof.) were appointed to strengthen the neutrino research group in the particle physics cluster. Other recruits in particle physics were **Gao** to work on ATLAS and **Rompotis** to contribute to both ATLAS and Mu3e. Involvement in the Materials Innovation Factory was strengthened by the appointments of **O'Brien** and **Clark** (joint Chemistry/Physics).

Staffing profile
We are returning 47 staff (44.35 FTE). There has been a positive change in gender balance in the Department for REF-eligible staff over the course of the REF period from 6 to 8 female staff (13% to 17%). 40% of our submitted staff are non-UK. 5 independent researchers have been included (11%) of which 2 are female.

Supporting researchers to win Fellowships
These include **Major** (EPSRC), **Mavrokoridis** (ERC), Alexandrova**,** Murdoch and Schnellbach (Royal Society of Edinburgh/STFC Enterprise Fellowship), **Gaffney** and Ruggiero (STFC Ernest Rutherford Fellowships), Farry (Royal Commission of 1851 Fellowship). Others with Fellowships within this REF period were **Cheal** and **D'Onofrio**, (STFC Advanced), **Veal** (EPSRC Career Acceleration). **Gründer** and **Coleman** have held Royal Society URFs and were supported in achieving fellowship extensions in this REF period. **Vilella-Figueras** won a prestigious UKRI Future Leaders Fellowship (2019).

Support for new academic staff
New staff have a phased-in teaching load during their three-year confirmation in appointment period. They are assigned a PhD studentship and offered a comprehensive **induction** programme, including discussions of their role, responsibilities and aspirations with the Head of Department and their cluster leader. A departmental **mentor** is assigned; new staff can also access the University's Mentoring Network and are supported to complete the Postgraduate

Certificate in Academic Practice or a higher qualification. Welcome events hosted by the School of Physical Sciences promote networking with other new staff.

Support for academic staff at other career stages

An annual Professional Development Review (PDR) discussion is held between every staff member and the Head of Department. This covers achievements, training and facility requirements, future plans, and career aspirations. Promotion opportunities and training needs identified in this process are actioned by the HoD. Many CPD opportunities are available via the University's training Academy, such as Head of Department programmes (**Veal, Welsch**), and the Heilbron leadership programme (**Harkness-Brennan**).

Figure 2: Ken Durose (right) with colleagues at IIT Delhi.

Research and impact leave particularly supports mid-career staff and gives individuals time to reformulate their research and impact goals and activities. **D'Onofrio** had two years leave in conjunction with her STFC Advanced Fellowship to convene the ATLAS Supersymmetry group (~350 members) and then the Physics Modelling group (~150 members) and was promoted to chair in 2017. **Kretzschmar** had a two-year leave to convene the ATLAS Standard Model group (~400 members) and was promoted to senior lecturer in 2019. **Mehta** had a year period of research leave at CERN, he was promoted to chair in 2018. **Touramanis** was at CERN (2016-18) taking international leadership of the technology evaluation programme for future long baseline neutrino detectors. **McGrath** was on research leave in 2018-19 developing a collaboration with engineering on quasiperiodic metamaterials. **Bowcock** had research leave at CERN(2019-20) to oversee the installation and commissioning of the LHCb upgrade detector. **Durose** had leave in 2018-19 in India, the US and Australia to develop collaborations on photovoltaic materials and devices and wrote a successful EPSRC grant application during this time. **McCauley** was a visiting professor at the University of Tokyo in 2018, helping to develop the Hyper-K project, and was promoted to chair in 2018.

Supporting our research staff

Currently the department hosts 85 research staff. We implement the principles in the *Concordat to Support the Career Development of Researchers* in supervision of these staff. They have annual PDR meetings with their supervisors, and have access to the same parental leave and flexible working arrangements as academic staff. We engage in the School's Researcher Forum, which facilitates consultation and information exchange with the University. The Forum chair sits on the School's leadership team and the role rotates among Departments; Samantha Colosimo (Physics) was Chair from 2016-2018. University-level support for post-doctoral researchers is described in §3.3.2 of the Institutional environment statement, including the Research England-funded "Prosper" project, which provides researchers with the broader attributes needed to thrive in diverse careers.

Researcher Development awards and events

The Researcher Forum has helped create the School of Physical Sciences Postdoctoral Development Awards, introduced in 2016 to provide funding of up to £2,500 to support development opportunities. Four of the awards have been held by early stage researchers in the Physics Department (two male/two female). For example, Alexandrova spent 5 weeks at Adaptix Ltd, a sensor and imaging company.

Half-day researcher development events are co-organised in the School on a two-year rolling basis. These include: “Applying for Fellowships”, “Taking Part in a Grant Panel”, “Transitioning from Academia to Industry”, “Research Grant Writing” and “Career Coaching”.

Figure 3: Alexandra Alexandrova was seconded to Adaptix in 2018.

Facilitating academia-external engagement

A keystone of our industry engagement has been the recruitment of STFC Innovation Partnership Fellows (Palumbo 2012-2016; Astreos 2018-). The Fellow sits on the Department Research and Impact Board and develops and maintains industry partnerships. A number of academic and research staff members have been recruited from industry: **Harkness-Brennan** from leading detector company Kromek; this link resulted in an STFC IPS project (2019) to develop an optimised system for low dose molecular breast imaging; Cheetham from NSG-Pilkington who are now project partner on grants, contribute to PV CDT training and fund PhD students. Mumtaz (co-founder of Enecsys, a solar PV micro-invertor company) works to commercialize PV research in SIRE.

Recognition

The achievements of staff and PhD students are highlighted in a fortnightly e-mail bulletin to all staff and students, in monthly staff meetings and via the department website and social media.

Promotion

Cluster leaders offer advice on application materials, and the Head of Department gives pre-interview briefings on promotion cases. Since 2014 there have been 28 promotions:12 to Chair (25% ,17% ethnic minority); 5 to Reader (60% female); 11 to Senior Lecturer (27% female, 9% ethnic minority). We have 4 female chairs compared to only 1 in REF2014 (increase to 15% from 6%).

2.2 Achieving SP3 - Equality, Diversity and Inclusion

We seek to address gender and other protected characteristic imbalances at all career levels. We are partners in the School Equality, Diversity and Inclusion group, which is chaired by **McGrath**. In this REF period this group has promoted joint events with the staff BAME, LGBT and Disability networks. As part of the School of Physical Sciences we have held Athena SWAN Bronze (April 2013) and Athena SWAN Silver (November 2016) awards. We have considerably improved our gender and ethnic balance at senior levels since REF2014 (see §2.1 ‘Promotions’, above).

Other initiatives include annual visits (2015-2020) to the XMaS beamline at the ESRF for sixteen year 12 schoolgirls (“XMaS Scientist Experience”); the “Liverpool Women in Physics” network established in 2019; and a “Girls and Women in Science” day social media campaign that reached more than 100,000 people. With LMU (Munich) and CERN, we co-organised Marie Skłodowska-Curie Day in 2017; the European Commission’s Director General, Martine Reicherts, contributed a message and the event reached more than 500,000 people. Our HoD **Welsch** is one of 5 invited UK representatives to the International Conference for Women in Physics in 2021.

Figure 4: Participants on the 2017 XMaS Grenoble trip.

Arrangements for supporting flexible working
Staff may declare when they are unavailable for teaching duties for caring reasons.

Career pathways for part-time and fixed-term staff
The University has a redeployment scheme, which includes research staff; for example Birkett moved to a PDRA position in MIF following a three-year position in SIRE (2019). Career progression and development are a particular focus in PDR discussions with fixed-term staff.

Support for staff and research students returning from periods of leave
The school has a "flexible working" adviser to help staff prepare for maternity and paternity leave. Two staff members (one male, one female) have recently used the shared parental leave scheme (**Harkness-Brennan**, **Jaeckel**). Staff and PhD students can also take advantage of a Parents' Network. Ten "keep-in-touch days" are provided for staff on maternity leave. Those returning from extended leave are offered phased-in teaching, PhD studentships, and mentoring. PhD student leave for maternity, paternity, illness or other extenuating circumstances is arranged through the suspension and extension provisions within the University's PGR Code of Practice. The School provides additional funds for PhD students whose contracts do not include maternity pay.

Wellbeing
We offer advice and support to new staff on practical issues such as housing and schools prior to their arrival. Social events for staff and students include a monthly coffee morning, a summer barbeque, graduation party, special events for major staff anniversaries and awards, and an end of year celebration. Our School Wellbeing group organises workshops and activities.

Equality and diversity in preparation of the REF submission
The departmental REF panel had oversight of all of all REF selection activities and ensured compliance with the University REF Code of Practice. Everyone involved in formal preparation undertook Advance HE half-day training on equality, diversity, inclusion, and unconscious bias. Particular attention was paid to ethnic and gender diversity in our selection panels.

2.3 Research students

There has been a significant increase in the number of PhD students since REF2014 with a view to supporting our strategic goals. We have recruited an average of 30 students per year with 136 PhD students graduating in this REF period.

Funding and partnerships
The Department receives Doctoral Training Programme funding from STFC and EPSRC, a total of approximately 8 studentships per year. The School of Physical Sciences has funded an additional 5 PhD studentships per year in Physics since 2012. We have utilised these studentships to attract matched funding from strategic research partners, including universities, research centres, and industry. The Department has also coordinated and participated in several Marie Skłodowska-Curie ITNs (**Welsch, Durose**). Eleven Fellows funded through these ITNs also registered as PhD students in Liverpool (see §3.1). A number of CASE studentships have been established with industry, for example with the Defence Academy of the United Kingdom for submarine reactor monitoring with anti-neutrinos, and with NSG-Pilkington as part of the EPSRC National Productivity Investment Fund scheme.

The Department leads the Big Data Science STFC Centre for Doctoral Training (CDT) LIV.DAT (**Welsch**), which currently has 36 students, and the EPSRC CDT in New and Sustainable Photovoltaics (2014-2020) (**Durose**), with 62 students nationwide. Many LIV.DAT students have supervisors in other Departments including Computer Science and EEE, the National Nuclear

Laboratory, and other partner organisations. They undertake a 6 months placement in industry. A LIV.DAT Fellow, Kukstas, specialising in Data Intensive Science and Machine Learning/AI, supports LIV.DAT research and training activities and industry partnerships, including IBM Research, ATOS, NVIDIA, Ultra Electronics and Amey Ltd. Involvement in other CDTs includes the EPSRC Risk and Uncertainty (two students) and Next Generation Nuclear (six students) CDTs, as well as the STFC CDT ASHE (one student).

Strategic collaboration agreements on joint PhD projects with partners such as CERN (2019), GSI/FAIR and TRIUMF (2020) have defined a programme where students spend their first and final year in Liverpool and middle two years at the partner organisation. Students may benefit from short visits and long-term attachments: 4-18 months at international facilities or up to 2 years in co-funding overseas partner institutes including CERN, FBK (Italy), DESY (Hamburg), JPARC and RIKEN (Japan), FNAL (Illinois), LIP (Coimbra), Soleil and LAL (France), and Jyväskalä (Finland). Students co-funded with the University of Jyvaskyla enrol in a dual doctorate scheme.

Recruitment
Projects are advertised via the University's central PhD project website and external sites, such as findaphd.com and international facility newsletters. We also nurture a pipeline of PhD students from our undergraduates; final year students conduct a project in one of the research clusters. We organise bi-weekly *Principal Investigators show their amazing activities* (PIZZA) Nights, where academics present their research and highlight PhD opportunities.

Personal and business skills development
Each student initially undertakes a Development Needs Analysis, which leads to a bespoke "Training and Assessment Plan". We offer training opportunities in physics, instrumentation, computing, statistics and research integrity, provided by the research clusters, ITNs, CDTs and in the case of Accelerator Science, the Cockcroft Institute. First year students have a week-long skills training programme focussing on project management, presentation skills, commercialisation, entrepreneurship and industry-academia collaboration. The Higher Education Academy (HEA) considered this as outstanding and sponsored a workshop to disseminate the scheme to other HEIs in June 2014. In their final year, students attend a two-day workshop on 'Advanced Researcher Skills', which focuses on CV writing, interview skills, international networking, grant writing and international career avenues, a two-day workshop on 'Technology Transfer' which looks at the market potential of specific project outcomes, and a one-day 'Researcher Careers' workshop.

Research students also attend national and international summer schools. Particle Physics students attend the Rutherford Summer School in their first year and the CERN Summer School in their second or third years. The Photovoltaics CDT training programme has showcase and summer school events. As part of the ITNs oPAC, LA3NET, OMA and AVA we have organized dozens of international workshops, schools and conferences.

Support, monitoring and completions
At least two supervisors are assigned to every PhD student. Early career academics are paired with experienced academics. Progress of PhD students is assessed annually. Support mechanisms for PhDs include drop-in sessions to signpost support services such as counselling and the mental health advisory service, described in §4.5 of the Institutional Environment Statement.

Awards
Outstanding PhD students are nominated for awards. Examples include Whittles, Springer thesis prize, 2018 and IOP Thin Films and Surfaces Woodruff prize; Norman, ALICE thesis award, 2018, **Gaffney**, the EPS NP Division Dissertation Award 2015. A prize is presented after each graduation ceremony to the best PhD graduate following nominations by supervisors.

3. Income, infrastructure and facilities

3.1 Funding

Liverpool's Physics Department is consistently in the top three UK departments in terms of STFC awards. In this REF period, we doubled our EU research income to around £2M per annum.

Funding strategy
We aim for a portfolio of longer-term consolidated grants supplemented by individual project awards. This is achieved by:

- Applying for STFC consolidated grants to support core research programmes in Particle Physics, Nuclear Physics and Accelerator Science;
- Exploiting our expertise and infrastructure in applications for STFC project grants to develop and participate in the most exciting experimental programmes;
- Engaging with EPSRC strategic initiatives to supplement the Condensed Matter cluster responsive mode and framework programme funding, such as the Photovoltaics Network+;
- Engaging with collaborative interdisciplinary initiatives, such as the Leverhulme Centre for Functional Materials;
- Support of ECRs in Fellowship applications and external Fellowship applicants;
- Seeking further funding opportunities beyond UKRI as appropriate such as EU programmes, Leverhulme Trust, and the Royal Society.

Support mechanisms
With the University Research Support Office comprehensive support is offered for research funding applications, with particular emphasis on support for ECRs and Fellowship applications. This includes peer review of draft grant applications and mock interview panels. Discussion of grant writing plans forms part of the PDRs of all academic staff. Specific calls from UKRI and other funders are highlighted at staff meetings and the internal biweekly Physics Bulletin newsletter. Horizon-scanning of new areas is facilitated through feedback from colleagues engaged with the research councils (see §4.4) and from the University's Research Policy unit.

Funding Profile
The total value of grants awarded in the REF period was £52.5M (distinct from research income of £60.4M). Figure 5 shows the breakdown of total awards by all funders (left), and (right) by the individual funding councils.

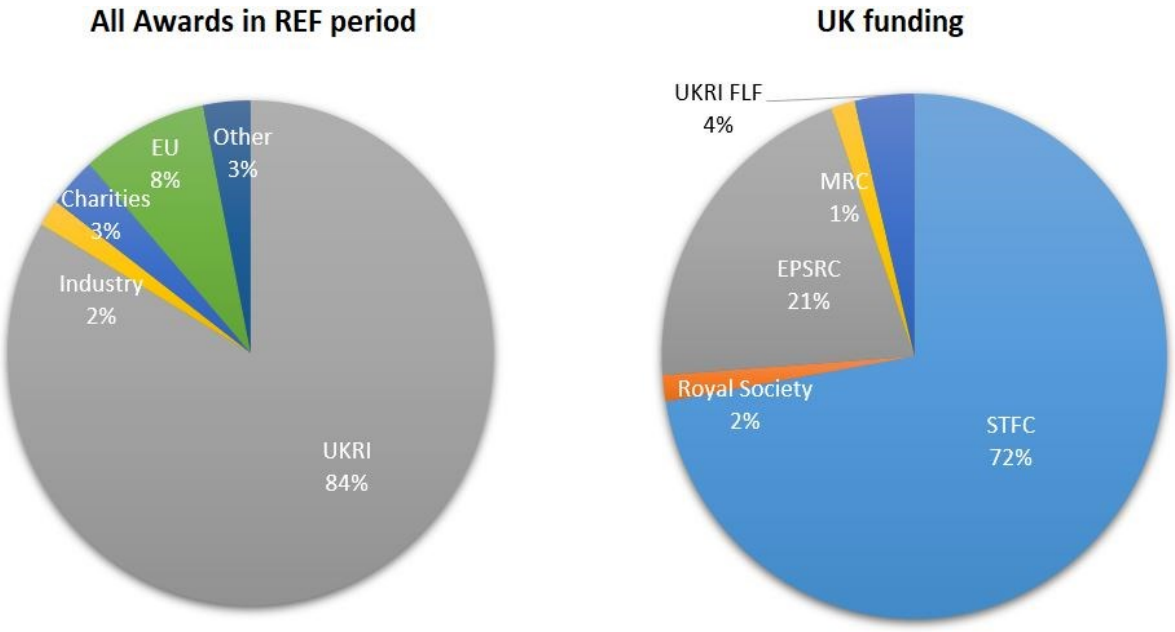

Figure 5: (left) Breakdown by funding source for awards to UoA staff; (right) Breakdown of UKRI awards to UoA staff by research council and other UK funding bodies. For collaborative awards, only the % owned by UoA staff is included.

Large awards include:

STFC:
- Particle Physics Consolidated Grant (2015) £8.6M and (2019) £9.2M.
- Nuclear Physics Consolidated Grant (2017) £3.1M.
- ATLAS Upgrade Production (2018) £2.2M.
- LIV.DAT CDT (2017) £2M
- Cockcroft Institute (2017), £1.9M
- DUNE Development and Production Grants (2017) £1.7M
- ATLAS Upgrade Development (2014) £1.4M total.
- ALICE (2015) £1.2M
- ISOL-SRS (2015) £1.1M
- AGATA (2020) £0.9M

EPSRC:
- CDT in New and Sustainable PV (2014) £5.3M.
- XMaS beamline at ESRF (2018) £3.8M.

Other:
- ARIADNE Starter Fellowship (ERC, 2016) £1.5M.
- Accelerators Validating Antimatter physics (EU, 2017), £1.4M
- HV-CMOS UKRI-Future Leaders Fellowship (2019) £1.2M

European Training Networks in Accelerator Physics
In this REF period we have coordinated four pan-European Marie-ITNs (oPACLA^{3}NET, AVA and OMA). In total, more than €18M (€6M directly to Liverpool) of EU-funding has allowed coordination of the training of more than 70 highly skilled early stage researchers. 11 of the funded Fellows registered as PhD students in Liverpool in this REF period, either with staff in the Department or based at collaborating institutions. By organizing a large number of international workshops, schools and conferences, we have had significant impact on the global accelerator science community.

Funding for impact and industry engagement

To support impact, we have used STFC Impact Acceleration Awards (£455k), EPSRC Impact Acceleration Awards (£53k), Knowledge Exchange and Impact Vouchers (£29k) and Higher Education Structure Funds (£17k). This funding has supported projects with industry partners including the development of a strategic relationship with Adaptix on 3D X-ray imaging, Bioclough Consultants, Canberra, Ecodynamics, Mirion Technologies, Micron Semiconductor, D-Beam, IKONICS, Proxivision, NSG-Pilkington, Sensor City, and Rutherford Health Partners (thin solid state dosimeter charge integrators for proton beam therapy). Alexandrova was awarded a Royal Society of Edinburgh/STFC Enterprise Fellowship (2015) to commercialise beam diagnostics prototypes through establishing the spin-off company D-Beam Ltd with **Welsch.** STFC selected the D-Beam spinout project on "Next generation Particle Accelerator diagnostics" as an STFC IAA success story 2020. The company was invited to the STFC-CERN Business Incubation Centre and subsequently attracted funding from Horizon 2020 and STFC. We received Proof of Concept funding from the EU ARIES scheme (**Welsch**, £50k), and have had an MRC Proximity to Discovery award and an InnovateUK/Cancer Research UK "Innovation to Commercialisation of University Research" (ICURe) award.

We have hosted a number of industrial engagement events. *Physics Innovate* (June 2016) was part of the International Festival for Business. *EuPRAXIA Symposium and industry exhibition* (July 2018) saw over 20 companies discussing opportunities for joint R&D in the area of novel accelerators. *Particle Colliders: Accelerating Innovation* (March 2019) included keynote talks; an industry exhibition; careers fair; an industry-academia co-innovation workshop (100 participants). More than 900 participants joined the event.

Funding for outreach

We employ an Outreach officer who provides coordination and support of outreach activities undertaken by our staff and students. The position is funded jointly by the University and the Ogden Trust (Sapple, 2012-2016, Annand since 2016).

3.2 Organisational infrastructure supporting research and impact

Our Research and Impact Board oversees strategy and recommends resource allocation (e.g. PhD studentships) to the Management Committee and HoD. The Chair sits on the Department's Management Committee. We have a unique research support environment with five project-funded administration staff, including several experienced project managers, and a communications expert. We also benefit from University and School professional services research support teams, who offer peer reviewed demand management for selected calls (such as Fellowships), training courses on accessing funding, research professional membership, and circulation of relevant calls (see Institutional statement §5.1).

Support to achieve research funding

As outlined in §2, we offer support for all staff, and particularly new staff unfamiliar with the UK funding landscape.

3.3 Operational and scholarly infrastructure supporting research and impact

Strategic priorities are underpinned by our technical expertise and equipment and instrumentation base. These facilities are also a key pillar of the national infrastructure in detector development.

Technical staff

Research activities are supported by 7 technical staff in our mechanical workshop, 4 mechanical design draughtspersons, 4 electronics engineers and 5 software engineers. In addition, we have typically 15 UKRI-funded staff dedicated to the detector development programme. Many of these staff have been with us throughout their careers. The workshop also offers apprenticeships in collaboration with local training agencies. We supported our workshop apprentice, Liam Boynton, to win University "Apprentice of the Year" awards in 2016; we have also supported two technical research staff onto PhD programmes.

Computing facilities
The Particle Physics cluster runs a STFC-funded Tier-2 Grid cluster with over 568 cores and 1.5 TB of RAM as well as a Tier 3 cluster with 9 dedicated 64-bit 8-core nodes and 60 shared Linux PCs for interactive analysis and batch processing.

Oliver Lodge Laboratory
The Oliver Lodge Laboratory is our main location on campus, and has undergone a major refurbishment (£7M) between 2016-2020 that significantly improved the general working environment, office accommodation, learning and teaching spaces, accessibility and inclusivity of the building, including gender-neutral toilet facilities.

Research and development facilities
We host R&D facilities which are of national and international importance, underpinning large-scale projects in particle and nuclear physics.

- **The Liverpool Semiconductor Detector Centre** comprises over 100 m^2 at ISO Class 5, and roughly 300 m^2 at ISO Class 7. Major projects have included the construction of straw trackers for g-2 and pixel modules for the ALICE ITS upgrade, the design and build of the inner Si detector for the ALPHA anti-hydrogen experiment, the ongoing construction of the LHCb VeLo upgrade and preparations for the construction of the Mu3e pixel tracker and the ATLAS ITk upgrades; the protoDUNE DAQ design, optical calibration systems for Hyper-K and LZ and a novel optical readout for Liquid Argon detectors and the design and construction of the ISOLDE Solenoidal Spectrometer at CERN.
- **The Physics Workshop** manufactures precision components and support structures for the detector systems for local and external experiments.
- **The Advanced Materials Laboratory** manufactures carbon fibre reinforced composite components for experiments including the ATLAS tracker upgrades, R^3B and the Cerenkov Telescope Array.
- **The Liverpool Germanium Characterisation Laboratory** is one of only three laboratories worldwide that can characterise position sensitive Ge sensors for use in spectrometers such as EXOGAM at GANIL, AGATA (currently at GSI), together with position sensitive Si detectors, for AIDA at FAIR and GREAT, SAGE and LISA at Jyväskylä.

3.4 Equality and diversity aspects of funding and infrastructure

Accessing specialist infrastructure
Access to departmental facilities is offered to all members of the department through regular open calls by facility leads. As part of their induction process, new staff are briefed on the facilities and how to access them. Access is granted on a case-by-case basis with particular emphasis on supporting impact activities, ECRs and PhD students.

3.5 Utilising infrastructure, facilities and expertise for impact

Our approach to all aspects of impact including the use of technical assets is described in §4.2.

3.6 Specialist research infrastructure and facilities

There are several specialist facilities that we lead or are partners in**:**

Stephenson Institute for Renewable Energy
SIRE opened in 2013 as a Physics-Chemistry centre (£13M University investment) and consists of five purpose-built laboratories equipped to support the broad spectrum of research into energy materials, including photovoltaics (**Durose, Major**), energy materials (**Alaria, Jaeckel** and **Veal**), battery research in collaboration with the Faraday Institution (**Dhanak** and **Veal**), fundamental electrochemistry (**Lucas** and **Gründer**) and Nanomaterials Characterisation (**Dhanak**) which underpins activity with Electrical Engineering funded through the ESPRC, GCRF and UKIERI-III. In 2016, **Alaria** won a £0.5M EPSRC grant for a Rigaku multipurpose X-ray Diffraction System as

a Faculty-wide facility. **Durose** was SIRE Director from 2015-2018; the current director is Hardwick (Chemistry).

Materials Innovation Factory (MIF)
Founded on strategic partnerships between the University, Unilever and UKRI, the £81M MIF is dedicated to accelerating and transforming academic and industrial R&D for computer aided materials science and opened in 2018. MIF houses a large range of shared equipment and facilities for synthesis and characterisation (£20M), and is available to academics in the Faculty though a ticketing scheme. **Alaria** and **O'Brien** are members. This facility also incorporates the Leverhulme Centre for Functional Materials Design, (£10M, 2017-2027) where **Alaria** and **Veal** are co-Is.

Cockcroft Institute for Accelerator Science and Technology
We are partners in the Cockcroft Institute alongside Manchester, Lancaster, Strathclyde and STFC's Accelerator Science and Technology Centre (ASTeC). The focus of Cockcroft is on combined physics/engineering solutions to accelerator challenges. The Liverpool accelerator science cluster is led by physicists, but has also recruited academic staff in Engineering (Corner, Dearden) and Electrical Engineering and Electronics (Bradley) to take a holistic approach to accelerator science, as endorsed by the 2015 external advisory panel (see §1.2.2). Shared laser facilities were established (£0.5M) providing a basis for the Dielectric and THz Acceleration (DATA) programme which enables R&D between the Cockcroft stakeholder universities and ASTeC. We run several optics and beam diagnostics labs on Daresbury campus.

Spintronics
A new laboratory (£0.3M) was established by **O'Brien** to study the applications and development of magnetic nanostructures, thin film magnetic materials, and spintronic devices. Specialist equipment includes a dual-purpose MOKE magnetometer that performs both spatially resolved surface magnetometry and wide-field-of-view MOKE microscopy; and a SQUID magnetometer.

Faculty shared research facilities
Departmental researchers have access to a range of Faculty supported facilities for specialist measurements. These include the Albert Crewe microscopy centre at Liverpool (~£10M asset base), which houses Transmission and Scanning Electron Microscopy instruments, and focussed ion beam. **McGrath** is the academic lead of the steering group. **Alaria** is the academic lead for the x-ray diffraction facility and **O'Brien** is the lead for the recently-funded nanolithography facility.

3.7 Shared/collaborative use of research infrastructure including major facilities

Most of our scientific activity requires the use of specialist accelerator facilities. UKRI research income-in-kind for use of facilities was £84.5M, the majority being for access to CERN. This income is supplemented by peer-reviewed access to other non-UKRI-funded facilities. Such facilities do not normally quote a cost for access, so in Table 2 we list the approximate number of days awarded. Not included in this table are LHC test beams; beam-line access at FNAL, DESY and PSI; JPARC beam for T2K/SK and Fermilab beams for g-2 and the long and short baseline neutrino programme.

Free Electron Laser Facility (FELIX)
Weightman is the UK lead on the FLUENCE project (£0.5M) to facilitate access by UK scientists to the FELIX suite of accelerator-driven light sources in the Netherlands.

Table 2: Usage of non-UKRI facilities

	Time awarded
Accelerators	
GSI	131 days
JYFL	296 days
ANL	66 days
ISOLDE	47 days
TandemAto	7 days
iThemba	12 days
Light Sources	
ESRF	30 days
Swiss light source	20 days
SOLEIL	5 days
LLB	6 days
FELIX	5 days
APS	12 days
Neutron and muon sources	
ILL	3 days

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

4.1 Research collaborations, networks and partnerships

Support mechanisms for developing collaborations include:

- **Resource:** The Research and Impact Board allocates PhD studentships (5 per annum) strategically to develop and support collaborations (priority is given in allocation to projects with matched funding from external sources). A base of facilities which can be used free of cost to individual investigators to develop new collaborations is available (Workshop, electronics support, X-ray diffraction). Our IT infrastructure includes a virtual reality suite in the MIF and physical space for hosting networks, workshops and conferences.
- **Training and Advice:** Skills training workshops are offered by the University central training team (the Academy) and by the School of Physical Sciences to ECR and PDRA staff (teamwork, project management, scientific writing, collaboration, grant writing, and peer review). We have a dedicated team of 5 professional services staff in our department to manage and promote network activities funded through EU and UK training programmes. The role of the STFC Innovation Partnerships Fellow (§2.1), is to grow our industry and impact activities.
- **Time:** As discussed in §2, research and impact leave is available to develop new collaborations.
- **Legal:** Support from the Research, Partnerships and Innovation and Legal departments is available to establish formal links where appropriate: Memoranda of Understanding (MoU) are established which facilitate joint research activities and collaborative exchange of researchers. These are in place with TRIUMF, GSI/FAIR, CERN and others.

We have entered into the following **strategic collaborations**:

CERN
Liverpool physics is listed by Nature in the top 25 of institutions globally who collaborate with CERN (Nature 575 (2019) S29). We top the list of UK institutions for STFC CERN-related funding (STFC/Technopolis report 2020). UKRI income-in-kind for access to CERN totals £81.3M. We are exploiting the potential of the LHC through ATLAS, ALICE and LHCb and developing new technologies for its upgrade. We are also working on the antiproton decelerator, protoDUNE with **Touramanis** as spokesperson, and have joined the FASER project. **M. Klein** was ATLAS collaboration board chair and is spokesperson for the LHeC and newly formed PERLE Collaboration to build a new generation 10 MW power ERL facility. **Welsch** is the scientific project manager of AWAKE-UK. We led the development of the ISOLDE Solenoidal Spectrometer and lead exploitation of Miniball and the ISOLDE Decay Station. A strategic MoU forms the basis for collaborative R&D and both staff and student exchanges.

STFC Daresbury Laboratory
The Nuclear Physics cluster has a joint STFC consolidated grant with Daresbury; together we host almost all of the STFC support “cross community staff”. Recent jointly awarded project grants include AGATA, NUSTAR, ALICE (CERN) inner tracker upgrade, ISOL-SRS-project for ISOLDE CERN, joint work on the DUNE APA frames. Applied R&D joint projects include ProSPECTus (medical imaging spectrometer), PGRIS (security imaging) and SIGMA (specialist detector for future research). The Accelerator Science cluster is primarily based at the Cockcroft.

Fermilab
Particle physics collaborations centred at Fermilab include DUNE, SBND, g-2, and mu2e. We constructed key components and lead the physics preparations for the SBND experiment, and are a leading member of the DUNE Far Detector collaboration. Through a MoU, we are now also targeting shared PhDs that are jointly funded. These US-based collaborations are facilitated by membership of the Universities Research Association (URA); Liverpool is one of very few non-US members.

University of Jyväskyla, Finland
In this long-standing partnership we have developed instruments for nuclear spectroscopy such as the JUROGAM gamma-ray spectrometer, the GREAT spectrometer and the SAGE gamma-conversion electron spectrometer, which are permanently deployed at the University of Jyvaskyla Accelerator Laboratory. We have a joint doctoral programme, with the first PhD student having graduated in 2020.

ESRF
We lead the UK Materials Science CRG synchrotron beamline, XMaS, at the European Synchrotron Radiation Source (ESRF) in Grenoble, France. This is an EPSRC National Research Facility in operation since 1997 and is funded (£7.2M 2018-2023) primarily to support the UK Materials Science community. It is run by four on-site staff and is directed by **Lucas**. The beamline comprises a unique combination of instrumentation for x-ray diffraction, scattering and spectroscopic techniques. XMaS has leveraged additional funding with participation in two European metrology research programmes (*Nanostrain* 2013-2016, *ADVENT* 2017-2020). A collaboration between XMaS and Huber Diffraktionstechnik GmbH has resulted in joint commercialisation activities under eight separate licence agreements (REF2014 Impact case) with additional projects in monochromator design under development.

Fondazione Bruno Kessler
We have a strategic partnership with the FBK Centre for Materials and Microsystems (Milan). The Director (**Casse**) holds a 0.2 FTE appointment in the Department. The technical and applied physics expertise at FBK in the area of industrial R&D complements our own expertise in detector systems.

4.2 Impact: relationships with key research users and beneficiaries

Our impact strategy **SP4** as outlined in §1 is to concentrate on Energy, Health, Security and Society. We have significant activity in each of these areas:

Energy
- **Photovoltaics**: we are collaborating with NSG-Pilkington in the development of novel transparent conducting oxide coatings and in photovoltaic devices. Paul Warren of the NSG-Pilkington European Technical Centre is a visiting Professor.
- **Training**: we are collaborating with Mirion in developing software and hardware to train employees from the nuclear energy industry with skills for digital measurements and have undertaken collaborative research projects with Mirion funded by the STFC IPS scheme.
- **Nuclear Sector Training**: we are collaborating with Mirion in developing software and hardware to train nuclear energy sector employees with skills for digital measurements and have undertaken collaborative research projects with Mirion funded by the STFC IPS scheme. James Cocks, Division President at Mirion, is a visiting Professor.

Health
- **Novel tamponade agents:** we have developed novel tamponade agents to prevent fluid flow through retinal breaks as a treatment for retinal detachment in partnership with Clinical Engineering at Liverpool and with Fluoron GmbH; this forms a **REF2021 case study**.
- **Grid computing for healthcare services:** AIMES Grid Services was founded on the basis of our particle physics research and the IP we generated in the development of the MAP2 computer for CERN. Since 2014, AIMES has generated economic impact as well as improvements to health service design and commissioning, and improvements for NHS practice and operations; this is a **REF2021 case study**.
- **Optimization of Medical Accelerators (OMA):** We coordinated this £3.5M research network developing novel accelerating techniques, sensors for beam and patient imaging, as well as underpinning beam physics and dose delivery simulations to improve proton and ion beam therapy.
- **Ventilators for OECD DAC patient care:** We are leading the software development to control and operate new low-cost ventilators as part of a UKRI GCRF/Newton Fund Agile Response

award. The team are working with clinicians in Brazil and regulators in the UK. **Bowcock** is part of the CERN against COVID task force and a member of the World Health Organisation (WHO) expert respiratory panel.

- **Advances in cancer detection and therapy:** Funding from the STFC IPS scheme is being used to develop algorithms to improve breast cancer detection for patients with dense breast tissue, in collaboration with Kromek. We obtained funding in the 2014/2015 STFC CLASP competition for two projects: Quantitative SPECT for Dosimetry in Molecular Radiotherapy, and Imaging on Gamma Emissions during Proton Cancer Therapy. Both are in collaboration with medical institutions and OEM manufacturers (Royal Marsden NHS Trust, Clatterbridge Cancer Centre, and Kromek). We are leading a multi-institute, multidisciplinary STFC Cancer Diagnosis Global Challenges Research Network and are members of The North West Cancer Research Centre and the EPSRC-funded Centre for Mathematical Sciences in Healthcare.
- **New sensors for proton therapy:** we have contributed to sensor systems for proton computed tomography (PCT), based on those developed for LHCb, and carried out research with FBK on deep learning to improve pattern recognition for PCT.
- **Commercialising detectors:** A project on **sensors for proton therapy** developed in our radiation detection laboratory has received support from the Wellcome Trust. We have delivered prototype detectors based on ATLAS sensors, to estimate energy deposition in the human body, and signed a contract with Rutherford Health Plc in 2017 to build a commercial version, and an optical beam loss monitor for machine protection and optimization supported by STFC IPS in 2020.

Security

- **Compton gamma ray imaging systems**: we are accelerating the development of a hand-held prototype system for security applications in collaboration with the Metropolitan Police, Kromek, STFC and Canberra.
- **The development of an antineutrino detector:** We are collaborating with the National Nuclear Laboratory (NNL) on the design and in-situ testing of novel measurement devices to support the UK nuclear industry. This project has secured funding from Innovate UK (£0.4M) in collaboration with JCS Ltd and support from NNL.

Society

- **Exhibitions at museums and festivals**: We showcased our particle physics research and its history in the University's Victoria Gallery; developed a Royal Society Summer Exhibit on antimatter (**Shears**) that has toured science and education fairs; donated LHCb detectors, built at Liverpool, to the London Science Museum's collection, seen by 5 million people around the world as part of a travelling exhibit (COLLIDER) and donated detectors to the updated CERN Microcosm exhibit. At local level we have exhibited at festivals such as the Big Bang North West and Liverpool's Africa Oyé.
- **Inspiring school pupils and engaging teachers**: the annual Physics of Star Wars event offers hands-on themed activities to explain accelerator physics in an accessible way to pupils and has generated media interest around the world (**REF2021 case study**). Hundreds of pupils attend the annual Liverpool Physics Olympics events, nuclear physics and particle physics masterclasses. In 2020, we developed teaching material for remote learning during the COVID-19 national lockdown that was used by over 800 school pupils nationally. We have built partnerships with local teachers over many years by hosting the Physics Teachers Conference and visiting schools. Overall, we have reached >20,000 school-children during the REF period.
- **Communicating our research**: we have given over 100 talks and interviews locally, nationally and internationally to explain our research through major print, radio and broadcast media including BBC Radio 4, The Guardian, Financial Times, New Scientist, BBC Breakfast, and ITV News (**REF2021 case study**).
- **Collaboration with the arts**: we have explored concepts with musicians, philosophers, novelists, and artists: for example, a collaboration of CERN, FACT, and the University of Liverpool won Collide International awards from Arts at CERN for three years, culminating in an exhibition at FACT which is now touring internationally and has been visited by over

200,000 people (**REF2021 case study**). In 2017, we co-hosted a public poetry event by physicist/poet Prof. Iggy McGovern on the life of William Rowan Hamilton.

- **Short science films:** Working with the Royal Institution (October 2013 - 2020), **Shears** co-created and presented six short videos about major LHCb research developments including antimatter, the Standard Model, and pentaquarks, which have been viewed online 877,275 times during the REF period. We created films about our research with Peter Higgs and Rolf Heuer, former CERN DG, which were shown at public events in Amsterdam, Brussels and Vienna. They received extensive media coverage including BBC, NBC, Nature, Frankfurter Rundschau, Die Welt and others, as well as social media promotion by CERN, STFC, the Ogden Trust, and the European Commission. We collaborated with CERN on a film "Busy bees and mighty magnets" which presents an unexpected example of knowledge transfer: how accelerator technology is helping to verify the authenticity of honey. The European Commission identified our public engagement activities as best practice.
- **Regional engagement**: **McGrath** was the University academic lead for the development of the Liverpool City Region Science and Innovation Audit published in 2017 and has acted as University representative at the Local Enterprise Partnership Innovation Board.

4.3 Engagement with diverse communities

Tactile Collider: this multi-sensory experience aims to communicate accelerator science to visually impaired audiences and was developed at the Cockcroft Institute in 2017. In July 2019 this project won the European Physical Society High Energy and Particle Physics prize for outreach and a "See Differently" award from the RNIB in November 2019 (**REF2021 case study**).

Figure 6: Chris Edmonds (left) demonstrating the tactile collider

Science Jamboree: aimed at young people (Beavers, Cubs and Brownies) the event enables young visitors to earn science badges through science activities developed by staff/student teams. 1,500 young people have participated since 2016. We received a Community Partner Award from Merseyside Scouts and were invited to join a national collaboration investigating mentoring between UGs and local GCSE pupils (£0.5M, the Education Endowment Foundation).

4.4 Contributions to the discipline, national and international leadership and service

International leadership roles

For ATLAS, **M. Klein** was chair of the Collaboration Board. **Kretzschmar** has been Standard Model working group convenor; **D'Onofrio** has been SUSY working group and Physics modelling convener. **U. Klein** was a Member of the Speakers Committee and then of its Advisory Board. For ALICE, **Chartier** is deputy chair of the Collaboration Board, and member of the Operations Board. **Shears** was the LHC Electroweak working group convenor. **Casse** is co-spokesperson of the RD50 project. In T2K and Hyper-K, **McCauley** convened the ND280 calibration group. **Vossebeld** is UK PI and Pixel Tracker Project lead for Mu3e. **Burdin** is responsible for LZ outer detector calibration system delivery. **Touramanis** was spokesperson for ProtoDUNE and co-lead in DUNE, and Chair of the CERN LHC Resource Scrutiny Group. **Mavrokoridis** is TPC manager, and **Andreopoulos** physics coordinator, in SBND. **Andreopoulos** is also co-spokesperson of the Genie collaboration. **Page** is the spokesperson of the ISS Collaboration and member of the ISOLDE Decay Station steering committee. Roles in AGATA include PSA team-leader (**Harkness-Brennan**), member of the management board (**A. Boston**), member of the collaboration council (**H. Boston**). **Herzberg** is spokesperson of the SHE@NuSTAR collaboration. **Gaffney** is a member of the ISOL-SRS Management Committee. **Greenshaw** is UK PI for the Cerenkov Telescope array and the Small Sized Telescopes project lead. **McGrath** is secretary-general of the 25-member European Network on Complex Metallic Alloys. **Lucas** leads the UK-CRG beamline XMaS at the ESRF.

National Advisory Roles
We have had national leadership roles include STFC Science Board Chair (**Shears**), and STFC Accelerator Science Board chair (**Wolski**). We have also contributed to national committees in STFC: PS&EAP (**Gründer**), Fellowships (**D'Onofrio, Harkness-Brennan, Joss, Page, Shears**), PPRP (**D'Onofrio, Harkness-Brennan**), PPGP (**Vossebeld**), PPAP (**Burdin**), UKCC (**Shears**), CERN UK Fellowships, ETCC (**Shears**), PPE programme (**D'Onofrio),** NPGP (**Joss**), NPAP chair (**Boston**, then **Page**), NuPECC (**Nolan**, then **Herzberg**), Small Awards Panel (**Greenshaw**), Newton Malaysia and GCRF (**Harkness-Brennan**). We have six Members of the EPSRC College and have participated in EPSRC panels, including Chair roles (**Lucas, Veal, Weightman**, **Major**). We have been members and chairs of facility review panels (Diamond, ISIS) (**Clark, Gründer, Lucas, Veal**), **Shears** is a member of the UKRI Future Leaders Fellowship panel and also a member of the IOP nominations committee.

International advisory roles
Internationally we are represented on review activities in: ECFA (**M Klein**), CERN LHC Resource Scrutiny Group (**Touramanis**), US-CMS oversight (**D'Onofrio**), ESRF and Swiss Light Source beamline and proposal review panels (**Lucas**); Greece (Demokritos, and University of the Aegean - **Touramanis**), Spain (CSIC Particle Physics Panel - **Casse**); Academy of Finland (**Shears**), FCT Portugal (**Shears, Butler**), Foundation for Polish Science (**McGrath, Dhanak**), France (GDR Neutrino Scientific Council, **Touramanis**) , Australian Renewable Energy Agency (**Durose**), Qatar National Research Fund (**Durose**), and the Germany (GSI FAIR programme, **Touramanis**). **Wolski** sits on the DESY advisory board. **Welsch** coordinated 4 Marie Skłodowska-Curie ITNs during this REF period.

Conference and other contributions
Our researchers have given > 300 invited talks at national and international conferences, of which > 50 were plenary or keynote talks, and >200 invited colloquia at UK and non-UK universities and research institutes. Our staff have chaired >40 conferences during the REF period, served on >10 editorial boards for academic journals and on IOP Group committees and supported the Merseyside branch of the IOP.

Awards and Prizes
Nolan was awarded the Rutherford Medal of the Institute of Physics in 2014. In 2016 members of the neutrino group shared the Breakthrough Prize for T2K. **Kretzschmar** was awarded the Altarelli Prize in 2016. **Durose** and **Major** were awarded the Institution of Chemical Engineers Global Award for Energy 2015. **Weightman** was a co-recipient of the IOP 2020 Rosalind Franklin Medal and Prize as a member of the Physics of Life steering group. **Dainton** is a Fellow of the Royal Society. **Butler** was awarded an honorary doctorate by the University of Jyväskylä (2019) and became a Fellow of the Royal Society in 2019.