Institution: University of Manchester

Unit of Assessment: UoA 9 PHYSICS

a. OVERVIEW: All UoA-9 staff (64.9 FTE) are members of the School of Physics and Astronomy at the University of Manchester (UoM), one of the largest UK departments, with research covering most major areas in the discipline. These include fundamental curiosity-driven programmes, interdisciplinary projects reaching beyond the traditional subject, and research applied to problems beyond academic spheres. Since the Research Assessment Exercise in 2008 (RAE08), the School has restructured into Research Divisions, each encompassing cognate areas: the Particle, Nuclear and Accelerator Physics Division, the Cosmology and Astrophysics Division and the Condensed Matter Division. A cross cutting Theoretical Physics Division enables experimental and theoretical physicists to work together. The UoA runs Jodrell Bank Observatory (JBO), which hosts the Square Kilometre Array (SKA) Organisation HQ. Staff also play key roles in the Photon Science Institute (PSI), National Graphene Institute (NGI), and Cockcroft Institute of Accelerator Science, which provide institutional foci for interdisciplinary research. Recent highlights include:

- Transformational research in 3D heterostructures, cosmology and Higgs physics.
- Award of Nobel Prize 2010 for Physics to Geim and Novoselov.
- Award of one of 12 Regius Professorships by the Queen, the only one in physics.
- Election of two staff members [Novoselov and Wyatt] as Fellows of the Royal Society.
- Rise in Academic Ranking of World Universities in physics 09-13, 37^{th} to 13^{th}.

b. RESEARCH STRATEGY

School Research Strategy: The over-arching aim for the UoA is to maintain and grow research quality and international reputation across *all* activities. We perform world-leading research in major fundamental areas, and employ physics expertise to solve important multidisciplinary challenges. We aim to optimise knowledge transfer to non-academic areas, to continue to perform significant public-engagement activities and to harness high-quality research to produce an excellent environment for student training. This vision is closely aligned with research elements of the UoM 2020 strategic plan, progress against which is assessed annually by review. It is epitomised by our aim to produce the highest quality research and to achieve impact that generates social, economic and cultural benefits, by taking advantage of areas of critical mass and of interdisciplinary capabilities. The overall UoA strategy is summarised first, followed by approaches in different physics areas.

After meeting the challenges of merging two departments in 2004, we saw an advantage to bringing together common interests and cultures, complementary ideas and expertise. This helps to foster cooperation across traditional research substructures and to address important research questions that are increasingly at interfaces. So in 2010, the UoA adopted a structure with 3 divisions to group together cognate activity. A strategy was also adopted to harness benefits where theoretical work can be closely allied to experiment, so each division encompasses both activities. In order to facilitate collaboration on wider theoretical matters, appropriate staff are also members of a crosscutting Theoretical Physics Division. Each division is chaired by a respected researcher who acts as a champion, helps to develop research strategies, fosters links between different activities including theory and experiment, and identifies new opportunities. Divisions provide a useful tool for targeting initiatives. Each division has an annual meeting with the Executive to reflect on performance and identify new opportunities. The divisions are evolving to suit differing needs across the UoA and maximising their potential is part of our on-going strategy. They have already clarified strategic thinking, fostered collaborations beyond traditional research groupings, and provided support for staff development. Specific examples of outcomes are indicated below.

Our vision can be achieved only with strategic thinking at all levels, which is supported in several ways. The Director of Research has overall responsibility for research matters and chairs a Research and Enterprise Committee composed of Division Chairs, Director of Enterprise, and senior administrators. This reports to the Head of School and Executive and to the Engineering and Physical Sciences (EPS) Faculty Research Committee. Scientific strategies are developed within specific research areas and reviewed in annual Divisional meetings to focus effort on high impact projects. Since RAE08, we have held a series of Away-Day meetings of all academic staff to discuss strategy. A combination of these discussions, and clarity arising from the divisional reorganisation, has led to plans for growth areas and for staffing (see Section C) attracting broad consensus support, giving ownership by the whole School.

Our successful approach to foster interdisciplinary activities has continued during the period, with a focus on developing partnerships to contribute to global/national grand challenges. 30% of staff are members of University Research Institutes, which, since merger, have successfully embedded an interdisciplinary culture into the University. We have consolidated and increased participation in the Photon Science Institute, resulting in growth of research in energy. This will be enhanced with future plans to increase collaboration within the Dalton Nuclear Institute. New accelerator physics staff have strengthened participation in the Cockcroft Institute. We have a parallel strategy to initiate, develop and support partnerships with industry and business (REF3a), in which the National Graphene Institute will play a particularly important role (details below).

We see the development and support of excellent researchers as key to enhancing research quality, with policies, activities and plans to attract, develop and nurture staff at all career stages (Section C). Initiatives have been put in place to enhance internal review of applications, optimise the academic impact of research outputs, and manage individual performance.

PARTICLE, NUCLEAR AND ACCELERATOR PHYSICS DIVISION: focuses on the nature of the matter making up the fabric of the Universe, fundamental constituents and their interactions, alongside the development of the necessary experimental tools for these endeavours. Strategic thinking is based around high-impact scientific projects, matching divisional interests and technical capabilities, allowing strong international contributions.

Research in ***particle physics*** has focused on understanding the interactions of fundamental particles and the origin of matter-antimatter asymmetry. At RAE08, activity was centred on hadron colliders, with exploitation of the D0 experiment at Fermilab and the BaBar experiment at SLAC, in parallel with construction and development of ATLAS at CERN (particularly the silicon tracker and high-level triggers). During the period, physics interests at D0 transferred to ATLAS as LHC operations began, allowing seamless and synergistic physics output. One important example was the study of spin correlations in top quark pair events at D0, prefacing their first observation at ATLAS. Indeed, D0 results observing the first evidence for decays of Higgs to *bb* complement the dramatic LHC Higgs discovery. ATLAS physics will remain a priority for at least the next decade, with strong leadership in top and electroweak research projects. Participation in BaBar created the opportunity to grow involvement in the LHCb experiment, with leadership facilitated by staff recruitment (Section C). With this strategy, exciting LHCb results (e.g. first tests of CP symmetry in the charm quark sector at a precision better than 10^{-3}) and leadership in LHCb upgrade projects have been achieved, in collaboration with Divisional accelerator-physics expertise. Successful alignment of experimental and theoretical activity continues to combine the strengths of experimental and theoretical activity, ensuring maximal exploitation of data to constrain theories. Joint experiment/theory PhD projects develop crosscutting ways of thinking. This approach has led to advances such as the development of a novel approach to study the kinematics of Z bosons and will be a continuing feature of collider-physics research.

Major parts of the SuperNEMO $0\nu\beta\beta$ demonstrator have been designed and built locally, as planned at RAE08, developing leadership opportunities for future full-scale construction. Commitment to neutrino physics has been grown to balance activity in collider-based work, allowing involvement in long-baseline neutrino projects, currently MINOS+. Achievement of critical mass in this area facilitates plans for future leadership in LBNE experiments. The Theoretical Physics Division has facilitated a nascent collaboration at the interface of particle theory and cosmology. Driven by data from Planck and strengthening cross-divisional links, we will invest in this area to develop understanding of dark matter and energy.

The ***nuclear physics*** programme is driven by the long-term aim to understand nuclei with significant neutron/proton excess. The strategy has been to exploit previous capital and intellectual investments in laser studies of ground-state properties, transfer-reaction measurements, and γ-ray spectroscopy of exotic nuclei. These have led to new results including those arising from exploitation of the cooler buncher at CERN, lifetime studies in proton unbound nuclei and experimental insights into $0\nu\beta\beta$ matrix elements. Our strategy for the next period is to provide focus by aligning activities around new facilities, best matched to interests, initially HIE-ISOLDE at CERN (as a step towards EURISOL) and use of FAIR, once operational. Divisional interests in

0νββ that arose independently as nuclear and particle initiatives will be combined around SuperNEMO. A programme of applied nuclear physics research, supported by EPSRC, NWDA and NDA, began during the period, as planned at RAE08, to address the nuclear data needs of industry. Membership of the neutron time-of-flight (nTOF) collaboration at CERN represents the first UK involvement with this international effort. Fission-fragment work has been re-focussed to provide required mass- and energy-distribution data at the ILL reactor, complemented in the future by a fast-neutron facility such as nTOF. Projects transferring expertise in γ-ray spectroscopy to medical single-γ CT have also been initiated. Planned growth in applied areas will benefit from added value arising from enhanced participation in the Dalton Nuclear Institute and by acting as a focus for energy, security and health activities within the Division.

The ***accelerator physics*** programme develops novel accelerators to address both the fundamental nature of matter and as solutions for practical problems. Specialist competencies at RAE08 have been expanded to include novel acceleration methods, medical applications, non-neutral plasmas and the use of lasers. Accelerator activity is part of the wider Cockcroft Institute, which includes Liverpool and Lancaster Universities and Daresbury Laboratory (DL). Collaboration within the Cockcroft is key to strategy, providing critical mass for large projects by drawing on skills/expertise not available to a single university. Fruits of this approach are typified by work on beam dynamics, lattice design and commissioning of the 1st European energy-recovery linac, and design and construction of the world's 1st non-scaling electron FFAG accelerator, both sited at DL. Divisional policy of strong international engagement has led to a focus at CERN, where added value arises from strong UoM presence in several projects. During 08-13 these included: understanding machine influences on LHC experiments; leading role in the ALPHA anti-hydrogen experiment; contributions to rf design and beam dynamics of the HIE-ISOLDE accelerator. Involvement of nuclear and particle physicists in the Division has been important in these achievements. CERN continues to play an important role in future plans, such as the LHC luminosity upgrade. Links to other Divisions will be exploited, e.g. with photon physics by developing low-emittance sources with laser photocathodes and diagnostics, and laser spectroscopy for ALPHA. We will develop a significant activity in the medical area, in partnership with the Christie Hospital where a new proton therapy facility will be sited.

COSMOLOGY AND ASTROPHYSICS DIVISION: includes the Jodrell Bank Centre for Astrophysics, Jodrell Bank Observatory (JBO), e-MERLIN/VLBI National Facility and the UK ALMA Regional Centre. The Project Development Office of the Square Kilometre Array (SKA) (08-12) was a component before transferring to the SKA Organisation, an external body with headquarters on the JBO site. Expertise extends across the electromagnetic spectrum, with long-standing specialisation in the radio/sub-mm domain. Building on this, the overall strategy is to grow activity which positions the UoA as the key partner in SKA and next generation Cosmic Microwave Background (CMB) mission (COrE). This is being achieved by strong roles in pathfinder telescopes and precursor science projects. In the latter, underpinning theoretical modelling in cosmology, galaxy formation, astrochemistry and plasmas enhances observational research. A strategy of high-quality technological developments, supporting and enabling science, has been pursued, key to new achievements including the e-MERLIN Facility and results from the Planck mission.

Research in ***cosmology and extragalactic astronomy*** aims to understand the birth and evolution of the Universe and formation of structure within it, with recent emphasis on exploitation of observations from the Planck CMB satellite. Technological leadership in the construction of low-noise amplifiers for the Low-Frequency Instrument, and in the optical design of the High-Frequency Instrument, has facilitated key Planck results constraining the parameters of the standard cosmological model, Interfacing with galactic astronomy, important advances have been development of an understanding of galactic foregrounds for Planck and undertaking the CBASS galactic polarisation survey. Plans are in place to exploit CMB data from the Large Scale Polarization Explorer (LSPE) and QU&I Joint Tenerife Experiment. Expertise in gravitational lensing will be used to provide powerful cosmological diagnostics, in addition to cosmic shear measurements using e-MERLIN and the Dark Energy Survey. Further anticipating SKA cosmology, a new low-cost telescope design is underway employing neutral-hydrogen mapping to study baryonic acoustic oscillations. In the longer term, cosmology effort will transfer to SKA and future CMB missions to make all-sky polarization measurements.

Continuing leadership in the area of ***radio pulsars*** develops the physics of extreme environments via searches for new objects and high-precision timing measurements, where the Lovell Telescope (LT) is essential. Continuing strategy is to collaborate with other observers, particularly γ-ray satellite missions, e.g. FERMI-LAT, and gravitational-wave observatories, e.g. LIGO. Combining their initial observations with our LT timing measurements characterises newly discovered pulsars, fully realising scientific opportunities provided by the surveys. The LT is also used as a key element of the European Pulsar Timing Array to produce high precision data. These initiatives have developed understanding of the radio emission and physics of pulsars. Pulsar-timing data were used to make searches in independent observations for associated direct gravitational-wave emission. Part of our on-going strategy is leadership in pulsar programmes for SKA precursors (LOFAR & MeerKAT) and in defining scientific and technical requirements for SKA pulsar research, spearheading implementation for “non-imaging” data processing.

Galactic astronomy incorporates studies of molecular clouds, astrochemistry, and stellar formation and evolution, making important contributions to understanding life cycles of baryonic matter in a galaxy. Research combines observational results with a range of modelling techniques, the former obtained from a wide range of telescopes from radio (e.g. e-MERLIN and JVLT) through sub-mm (e.g. JCMT and ALMA) to optical/IR observations (e.g. VISTA and Spitzer). In particular, a continuing strategy exploiting the UK ALMA Regional Centre enables productive use of this new facility as it comes into full operation. Solar plasma expertise, used to understand coronal heating and magnetic reconnection, will be transferred to star-formation processes and late stages of stellar evolution. Time-domain optical/IR studies of variable stars, facilitated by a leading role in the VVV Survey, were used for studies of both galactic structure and to constrain the population of extra-solar planets, the ultimate products of circumstellar disks arising from star formation. A strong track record in micro-lensing planet searches will be further developed within the EUCLID mission.

Targeted ***astronomy technology*** has been the foundation to many achievements, typified by Planck and e-MERLIN described above. Our expertise in cryogenics, low-noise amplifiers (LNAs), novel waveguide devices, optical design and quasi-optical components using planar lithographic technology has resulted in key contributions to several construction projects. More fundamental technological research is also undertaken, allowing step changes in performance vital to next-generation projects. Projects benefit from long-standing collaboration with the School of Electrical Engineering. Future science directions will be enabled by several on-going/planned projects, including: waveguide designs for the first-light 19-beam receiver for the giant Chinese 500-m Aperture Spherical Telescope; large diameter mesh filters and half-wave plates (HWP) for LSPE; waveguide components for a large "radio camera" for the Sardinia Radio Telescope. Step-change performance development includes: ultra-large HWPs in preparation for a future ESA CMB spacecraft; developing ultra-broad band LNAs for ALMA, allowing Bands 2 & 3 to be combined; and exploring LNA performance at lower temperatures than standard. Based firmly on the success of e-MERLIN, the Division is leading consortia developing both the “signal and data transport” and “synchronisation and timing” work packages for SKA.

CONDENSED MATTER DIVISION: brings together activity in graphene, quantum fluids, atomic and photon physics, liquid crystals, biological materials and complexity, forming a continuous spectrum from hard to soft condensed matter physics. Considerable interaction between staff in these fields is brought to bear on problems requiring multiple approaches. Aims range from understanding quantum phenomena in materials, through to concepts of self-assembly and statistical physics, which are also applied to understand complex physical and non-physical systems. The Division fosters synergistic approaches internally and more widely. Collaboration is common with other UoM schools [Chemistry, Computer Science, Mathematics, Materials, Chemical/Electrical Engineering], faculties [Life Sciences; Medical & Human Sciences; Humanities] and centres/institutes [Centre for Mesoscience & Nanotechnology (CMN), the Photon Science Institute (PSI), National Graphene Institute (NGI)]. Networks have evolved over the period to form capabilities that address societal grand challenges, particularly in health and energy. The Division has brought physics understanding to practical device applications, including during the period, graphene electronics, biosensors, photocells, contact lenses, and white LEDs.

The theme of research in ***quantum fluids*** is the study of liquid and solid phases of ^{3}He and ^{4}He as “ideal” systems in condensed-matter physics, with emphasis on hydrodynamics and topological defects. Strategy has been to concentrate on three science areas, enabled by a newly-constructed rotating cryostat: quantum turbulence in superfluid ^{4}He in the zero-temperature limit; interplay of flow, quantized vortices and domain walls in superfluid ^{3}He-A; and dynamics of dislocations in solid ^{4}He. Achievements include high-resolution torsional-oscillator studies that show formation of coherent quantum states of different chirality in the ^{3}He-A phase. Plans focus on vortex structures in superfluid ^{3}He as examples of topological states in condensed matter.

A flagship activity is ***graphene-related research***. The new class of freestanding 2D crystalline materials, including graphene, hexagonal boron nitride (hBN), MoS_2 and others, have been pursued. A distinctive element of on-going strategy is to harness the range of Divisional expertise (photonics, plasmonics, magnetism, liquid crystals, mesoscopic transport, superconductivity, nanotechnology/fabrication) in a complementary fashion to address optical, electronic and mechanical material properties. During the early REF period, this resulted in key breakthroughs in 2D-crystal science: a graphene-based liquid-crystal device; graphene derivatives (graphane and fluorographene); finding that optical transparency in graphene depends only on the fine structure constant; and super-permeability of water through He-tight graphene-oxide laminates. More recently, a new kind of 3D material was demonstrated, assembled layer by layer from individual atomic planes in a precisely chosen sequence. The strategy has been to refine technologies and expertise in the complex processes of constructing composite layers and making electrical contacts, to produce different and more complex heterostructures. In parallel, the most promising candidates for detailed study in terms of new physics and applications are identified. The area is growing rapidly; key initial achievements demonstrated many-body effects in heterostructures, such as Coulomb drag between graphene layers isolated by an hBN insulator and tunnelling effects between layers. The first vertical graphene-based transistor has been demonstrated with external gate controlling tunnelling through hBN or MoS_2 layers. Future refinement of devices will target improvements in performance, such as ultra-high frequency operation, investigation of other types of electronic devices, and exploitation of novel many-body effects. Development of the applications of 2D crystals and 3D heterostructures has been supported by collaboration with other UoM schools, facilitated by CMN; and will be enhanced as NGI comes into full operation (see later sections).

In the area of plasmonics, nano-optics and metamaterials, the first 3D plasmonic tweezers, ultra-narrow plasmonic resonances and cascaded enhancement of electromagnetic fields have been demonstrated. A strategy has been to link strongly with graphene work, leading to the recent production of the first hybrid graphene-plasmonic photocells and studies of interactions between plasmonic structures and graphene. Future work includes active plasmonics based on graphene gating and supersensitive plasmonic sensors based on phase detection.

Strategy for ***liquid crystal*** research in the period was based around understanding of self-assembly and has embraced new systems, discovering novel electro-optic and photonic phenomena. Work has been undertaken on spontaneous chirality and biaxiality in nematic systems, blue phases, polymer-stabilised materials, functional particle/nanotube dispersion and graphene (see above). Liquid-crystal solutions in applied problems are part of on-going strategy; work on sensors for perishable goods industries and developments in tuneable contact lenses led to separate 3 patents. Future plans include understanding self-assembly and self-organisation in novel photonic materials, liquid-crystalline graphene and biological systems.

Research in ***photon physics*** aims at developing an understanding of fundamental photon-matter interactions that can also be applied to solve problem-driven themes. For example, atomic-physics expertise in electron-impact ionisation and cold-atom trapping has recently initiated development of low-emittance ion sources in collaboration with accelerator physics. Capabilities developed during RAE08 have since been focussed onto energy-related issues, with 2 major themes in photovoltaics and LEDs. Studies of nanoclusters were initiated during RAE08, but a wider range of expertise has since been assembled: in the electronic structure of interfaces, in ultrafast dynamics, and in quantum-dot manufacture from UoM Chemistry and industry (Nanoco). This strategy has elucidated technological issues in solar cells, particularly with observations of efficient carrier multiplication and fast surface trapping of photo-generated charge in several quantum-dot systems. In a parallel initiative, semiconductor expertise is being used in a systematic study of nitride LED efficiencies to overcome poor efficiency at high currents in lighting applications. Future plans will continue development of photonic materials for energy and other applications. Facilities and expertise within PSI are essential, enhanced by a newly funded infrastructure (see Section D).

Biological physics research follows physical approaches to the molecular/cell level, applying physics tools to biological systems, particularly interactions at interfaces, molecular self-assembly and mechanical bioprocesses. Following RAE08 plans, focus has been on bio-interfaces and theoretical modelling of physiological systems, using computational tools from descriptions of non-linear/complex systems. For example, “whole-system” models were developed to understand sites critical for ventricular fibrillation, a major cause for sudden death, which enable clinically useful inferences. The on-going strategy combines fundamental work with its translation to practical problems. Applied projects on techniques for investigating wet and bio-surfaces, biomimetic interfaces, micro/nano rheology and thermo-responsive films for cell growth and harvesting, led to filing 2 patents and an industrial licence agreement. Future plans focus on developing functional biointerfaces and biomaterials, and biomedical applications of graphene.

Application of statistical-physics methods to non-physical ***complex systems*** has continued in the period. Potential projects are identified by dialogue with other disciplines, including physical, life and social sciences, economics, business studies and linguistics. Models developed with physical methods are built to help solve problems in a variety of complex systems in an explicitly interdisciplinary approach. This has been a successful in generating results relevant to a range of subjects, including evolution, epidemiology, finance and linguistics. New findings offer insight into learning algorithms that generate inherently unpredictable behaviour. Recent work indicates that the concept of biological species might not be applicable to smaller organisms. Future developments will encompass effects induced by intrinsic noise generated by the discrete constituents of the model, which are frequently missed in conventional analyses.

c. PEOPLE, including: (i) STAFFING STRATEGY AND STAFF DEVELOPMENT

Our ***staffing strategy*** has 3 related features: (i) expansion of existing strengths in areas with clearly identified opportunities; (ii) establishment of new areas with significant scientific promise; and (iii) nurturing staff at all levels. Since RAE08, 7 lecturers, 1 reader and 3 professors were appointed via international searches. We mentor *all* early-career researchers, but for prestigious fellowships, high-achieving fellows aligned with our research strategy are carefully considered for academic appointment. In the period, 4 terminating fellowships transferred to new academic positions and 4 more were given proleptic positions. In total 13 staff retired or left, balanced by a total of 15 new and 4 proleptic appointments, of which, 9 came from positions overseas. The relationship to research strategy is outlined below.

Over the period, departures created the opportunity for a strategic professorial hire in line with our aim to secure leadership in LHCb. To build on significant success in the past from close collaboration between particle theory and experiment, a fellow converted to a lectureship in 09. The appointment of a lecturer consolidated SuperNEMO work, giving critical mass to realise future leadership opportunities in neutrino physics. RAE08 plans to grow accelerator physics continued with 4 appointments, bringing expertise in medical applications, novel acceleration methods, non-neutral plasmas, and lasers, enabling scientific strategies in Section B. In astronomy, retirements of 3 senior academics and loss of a younger staff member to a position overseas created the opportunity to strengthen areas of future priority. Appointments were made of 2 professors, a reader and 2 lecturers, with 4 fellowship conversions, significantly strengthening our capability to achieve strategic aims associated with SKA and COrE. In other areas, following RAE08 plans, complex systems research was consolidated with the appointment of an RCUK Fellow; arrangements have also been made for a fellowship conversion in pure/applied nuclear physics.

Our successes have created opportunities for further significant investment. Initially this involves at least 7 new appointments in the near future, across growth areas identified to meet the strategic scientific aims in Section B:

- Condensed matter physics: to seize opportunities associated with graphene research and associated industry/business via the National Graphene Institute.
- Photon science: to expand “energy grand challenge” activities.
- Applied nuclear physics: to expand nascent initiatives to form a significant new activity.
- Accelerators: to realise opportunities in medical areas, in partnership with Christie Hospital.

- Dark energy/matter: to grow activity at the interface of particle theory and cosmology into a significant new research area.
- Soft-matter physics: to address scientific opportunities in the "self-assembly grand challenge" area and new photonic materials with industrial relevance.

Some appointees will have significant experience with industry and business as part of a strategy to facilitate non-academic impact of research (REF 3a). Increasing overall staff numbers will ensure on-going sustainability of high-quality research output in the future.

The UoA received a large number of international visitors over the period, with more than 40 visiting for at least 5 days from over 22 different countries, with numerous shorter visits.

Personal Research Fellowships: All research areas have seen an increase in numbers of ad-hominen fellowships, from 7 at RAE08 submission to 14 currently in post. Contributing to this is support whereby senior academics mentor and review every application, and provide mock interviews. Overall during the period, staff held 22 *early-career* fellowships: 11 STFC Rutherford/Advanced, 5 RS-URF, 2 Leverhulme, 1 1851 Exhibition, 1 RCUK and 2 EPSRC Career Advancement Fellowships. Additionally 12 other Marie-Curie, EPSRC/STFC post-doctoral and RS Newton fellowships were held in the UoA. 10 early-career fellows have been successful in obtaining academic positions here and elsewhere, e.g. an EPSRC Life Science Interface Fellow took up a readership at Bristol. Staff also held 5 European Research Council Starter grants during the period. At a *senior* level, staff held 1 RS-Anniversary and 1 RS-Industry fellowships and 2 senior academics have RS Wolfson Merit Awards.

Staff Development: We aim to create an environment where all staff (from ECRs to established academics, including technicians/support staff) can reach their full potential, harmonising individual career development with the long-term interests of the UoA. Initiatives are run in concert with those provided by Engineering and Physical Sciences Faculty (EPS) and UoM, creating a range of professional and career-development opportunities. Specifically, the UoM Concordat Implementation Plan, which received the HR Excellence in Research Award from the EC, ensures full support for the Concordat for the Career Development of Researchers. UoM participated in the Careers Research Online Survey 2011 to seek views of research staff, incorporating results into the plan, particularly improving researcher representation on committees.

Induction processes for staff (including PDRAs) at School and Faculty level provide information needed to settle quickly into new roles, with staff handbooks covering key contacts, policies, information and advice on support & training. Mentors are allocated to staff at all levels taking up new positions.

The EPS Researcher Development Programme is a suite of training initiatives that promote researcher independence and personal/career development, helping all staff excel in a global environment that calls for expertise in collaboration, communication, public engagement and KT. A wide-ranging programme with 38 different workshops/courses is arranged around 5 key themes: Career Management, Communication, Leadership & Management, Research & Enterprise, and Teaching & Learning. These courses complement wider training from UoM Staff Training & Development Unit. As a probation requirement, all new academics must successfully complete a New Academic Course, including teaching, personal skills, research project management and grantsmanship. Opportunities are available to prepare for academia by undertaking teaching, after relevant training. The EPS Programme also provides support to managers or mentors.

Within the UoA, a Researcher Development Forum, chaired by a young academic acting as an ECR Champion, offers an independent discussion forum representing PDRA and research staff. The Champion is a member of the Research Committee, allowing a route for all researchers' input to be communicated to management. The Forum works on a range of projects that have recently included improvement of induction information, fellowship preparation and career-planning workshops. Representatives provide PDRA and support staff input to other committees.

Annual Performance and Development Reviews with senior managers are provided for all, including PDRAs and support staff, to discuss research performance. These set objectives to guide and monitor progress, and identify development needs and resources required.

Sabbatical leave and secondment are important in developing senior staff. On average 6 sabbaticals per year were approved during 08-13, approaching our target of 10% of staff. Leave is granted on the basis of an application with plans and deliverables; there is no specific entitlement after a period of service. Leave policy is family-friendly and can be taken locally. We take a flexible approach to secondment requests; 4 were approved in 08-13. For example, secondment of Diamond to Director of Australian Astronomy and Space Science was important to his subsequent appointment as SKA Director General. Support is provided for senior staff making the transition to academic leadership by the UoM Head Start Leadership Development Programme.

Promotion pathways exist for all types of staff contract, including those focussed on research, for which clear guidance and criteria are available. EPS run Promotions Master Classes to help improve promotion cases. During the period, 38 promotions were wholly or partly based on research. Academic promotions included: 15 to professor, 8 to reader, and 9 to senior lecturer. Early-career fellowship holders were also promoted: 2 to professorial research fellow, 1 to reader, and 3 to senior research fellow. The Head of School and the Dean of Faculty offer unsuccessful applicants personal feedback. Recruitment and promotion reviewers are obliged to undertake relevant training in equality, diversity and good practice in these activities.

Equality and Diversity (E&D): Our strong commitment to an environment with equal opportunities where everyone is treated with respect and dignity, is embedded through structures and policies. E&D is a standing item for School Executive and Board. An E&D Committee has overall responsibility, and oversees implementation of cognate UoM policies (career breaks; flexible & part-time working; maternity, paternity, adoption leave). It is chaired by a senior professor, populated in a gender-balanced way with academics, PDRAs, PG and UG students, and support staff, and is supported by an Academic Services Officer, who is also a member of the IoP Diversity & Inclusion Committee. Annual reports are made on diversity in research (e.g. appointments, promotions, leavers, seminar speakers, awards & applications) and on equality issues (e.g. adaptations for disability and caring/parental responsibilities). A biennial E&D staff survey monitors the progress of initiatives. Training in E&D is mandatory for appointment/promotion panels. We have held IoP Juno Practitioner Status since 2010 and will apply for Champion Status in 2014. UoM holds an Athena SWAN Charter bronze award; we are applying for an individual award in late 2013. In the UoA, a Women Researchers' Network, led by a senior female professor, offers support and career advice, and works closely with the EPS Women in Science, Engineering and Technology network for female staff and students. Two senior academics influence national agendas by membership of the IoP JUNO Review Committee and the Athena Swan Awards Assessment Panel; both are members of the IoP Women in Physics Committee. While gender balance in physics remains a serious issue, the number of female professors in the UoA has doubled from 2 to 4 since 2008.

ii RESEARCH STUDENTS: 175.5 PhDs graduated 08-13. The majority (69%) of the 183 PhDs started since 08 were funded by RCUK stipends, 11% had external support from industry (including CASE) or other organisations and 15% received internal support. The overseas (non-EU) component is 13%. Each year School scholarships are used to support EU (4×£7.5k) and overseas (3×£14.2k) students. UoM competitive President's Doctoral Awards for outstanding students have supported 10 PhDs in the UoA since inception in 12/13. EPS provides similar awards, 5 in physics since 11/12. The UoA directs the Now-Nano DTC and has PhDs from the Nuclear-First and Metallics DTCs. DTCs foster interdisciplinary relationships, which we aim to enhance with a recently awarded nanotech CDT. External bodies supported 30 students during 08-13 including Unilever, NDA, Syngenta, E2V, QinetiQ, Merck, Christie Hospital, British Heart Foundation and the Farfield Group. 8 students have obtained EPSRC Doctoral Prizes or PhD+ Awards during the period, selected competitively across the whole of UoM. PG students won more than 20 external prize awards, including 4 Springer Thesis Awards, recognising outstanding PhD research, Liquid Crystal Society Young Scientist Prize and Institute of Physics Early-Career Award.

PG Recruitment: Administrative support (1.5-FTE) is provided for this activity, assisted by staff in the Divisions. Annual PG Open Days are held giving advice on PG matters and showcase specific opportunities in the UoA. Internal events are run for local undergraduates. Both include presentations by past students and visits to research areas. A number of UG final-year courses focus on research topics, assisting internal recruitment. International recruitment is facilitated by our collaborative research contacts, but we benefit from targeted UoM initiatives to enhance recruitment from leading overseas universities in, for example, Brazil and Mexico. All suitable applicants are invited to visit, with interview to ensure excellence. Diversity is monitored: the proportion of female students (08-13) was 22%, slightly better than our UG cohort; success rates

(08-11) are the same for female and male applicants, the former being more likely to accept offers.

PG Training and Support Mechanisms: PG training is overseen by a senior academic (PG Director) and PG Committee, including student members. Administrative support (1 FTE) is provided. Each student has a supervisor directing PhD research, a specialist co-supervisor and an advisor providing pastoral support and oversight. Two academic mentors monitor overall PG welfare and provide additional individual advice when needed. Students are integral members of their research area and division, providing considerable informal support and advice.

Given the individual nature of research, a flexible approach is taken with specific plans agreed between a student, their supervisors and PG Director. Requirements are set for progression; for example, in first year, a satisfactory assessment of a report is required with a deadline in the 8th month allowing problems to be addressed before year-end. This ensures that in unresolved cases there is time to graduate with other qualifications (e.g. MPhil) rather than just dropping out. Taught courses are taken according to need from a portfolio of specialised courses at PG level (11) and at UG Level-4 (33), extended with additional PG assignments. These are available without assessment for those interested in broadening their knowledge. Students are required to attend EPS introductory sessions and to maintain personal development plans.

EPS has a Graduate Development Programme, with personal and professional development and skills training, to assist PhD completion and to maximise employability. In 12/13, 98 EPS training sessions were available: from introductory modules, academic writing, critical reading and project planning; through to thesis writing, viva preparation, publishing, career planning and enterprise skills. Advice and support is also provided for supervisors, advisors and mentors. Typically more than 66% of students undertake tutorials and laboratory teaching in the School after suitable training, which assists career development. Wider ranging training in higher-education teaching is available from EPS. Avenues for expressing PG views on matters including support and training are provided via PG representatives on School and Faculty Committees.

PG Progress Monitoring: An online progression monitoring system (*eProg*) provides students with clear direction, critical milestones and a structured framework for progress on their programme. It provides access to, and records engagement in, training opportunities and allows monthly-attendance monitoring for all students. *eProg* monitoring supports excellent PhD completion rates, averaging 86% over 08-11.

d. INCOME, INFRASTRUCTURE AND FACILITIES

Research Funding Portfolio: Our direct research funding (08-13) totals £71.1m, with an additional £52.6m and ~£63m income in-kind from the use of RCUK and non-RCUK facilities. Direct income increased by 15% to 11/12, with last year tempered by the transfer of the SKA Project Office support to SKA-HQ, an external organisation. The majority of income (~80%) is from RCUK, with a 2:1 split between STFC and EPSRC, significant funding from the Royal Society and notable grants from other councils. We plan to grow and diversify RCUK income, encouraging applications to a wider range of councils, where possible. Income from EU government bodies is more than three times higher than the RAE period; we plan to maintain this growth, partly via opportunities within the Graphene Flagship. Direct industrial income (£906k) is x3.5 that in the RAE08 period; but it is still a relatively small proportion of revenue with opportunity for significant growth. Increased interaction with potential external partners, following strategies for impact (REF3a), is a priority; a recently announced £5M partnership with Bluestone Global Tech is a first step towards this goal. Positive influences on research also arise from industrial support of PhDs, totaling >£0.5M 08-13 (including CASE) with significant in-kind contributions. Consultancy is encouraged in order to form new relationships, but is kept at a low level by a policy to convert activity into collaboration at the earliest opportunity.

Infrastructure and Facilities: The School is housed in neighbouring Schuster and Turing Buildings. The latter is a £59m new-build in 2007. Renewal projects in 08-13, totalling over £9m for windows, foyer/theatres and workshop, complete a £30m refurbishment of Schuster started in 05. These estate developments have resulted in a single site with generous modern state-of-the-art laboratories in all areas. We host several local facilities including: the UK ALMA Regional Centre, the GRID Tier II centre for particle physics, clean rooms and detector labs for nuclear/particle physics, rotating cryostats with He liquefier/recycling plant.

Technical services underpin research labs and facilities, as well as supporting research offsite via production/testing of equipment, computing support etc. A large mechanical workshop is equipped with CNC machines and 10 technicians, including 2 new apprentices; a new £0.7M initiative will improve and expand capabilities. An electronics/computing workshop has 4 staff with facilities for design and manufacture. A design office has state-of-the-art CAD and 3D-printing systems with 2 design engineers. Each research area has dedicated technical support.

The School operates *Jodrell Bank Observatory* (JBO), the largest UoM facility. With 33 operations staff, it includes the Lovell Telescope, the World's 3rd largest fully steerable radio telescope, and several smaller devices. JBO operates the e-MERLIN/VLBI National Facility, co-funded by STFC (£2.5m/yr) and UoM (£0.5m/yr). It provides UK contributions to the European VLBI Network, linking telescopes across Europe, Asia and Africa. Over 350 astronomers at 92 institutions in 25 countries use e-MERLIN, with 90% outside UoM and 70% non-UK. The SKA Organisation HQ is sited at JBO; UoM funded the £3.3m building. The newly refurbished Discovery Centre attracted >100,000 visitors in 2012 alone, enhancing our public engagement activities. State-of-the art laboratories are available for LNA construction and testing. In total, UoM has invested £20M in JBO over the past 8 years and plans to invest a further £15M in the next five.

Significant facilities are available at our research centres and institutes. *Manchester Centre for Mesoscience and Nanotechnology* has infrastructure for fabrication, visualisation and characterisation of devices from µm to a few 10 nm, including optical and electron-beam lithography, scanning electron microscopy and material fabrication/processing. The *Photon Science Institute* provides state-of-the-art tunable light sources across a comprehensive range of wavelengths, laser fluences, powers and temporal characteristics with an extensive set of detector, sensor, calibration and diagnostic resources. A recently funded £100m Multidisciplinary Characterisation Facility will enhance this provision. Large-scale investment (£61m) is underway to build the *National Graphene Institute* with state-of-the-art laboratories for collaborations between UoM, other UK-HEIs and industry, acting as a commericalisation hub. At Daresbury, accelerator test facilities and associated infrastructure are available via participation in the *Cockcroft Institute*.

Use of Non-RCUK Supported Facilities: Staff access many non-RCUK facilities via international peer review, particularly in particle/nuclear physics, photon science and astronomy. The total value is estimated at £5.5m as PI and £57.5m as Co-I. These comprise of: nuclear-physics facilities [3,000 / 3,592 hours, costing £2.07m / £6.17m], light sources [4,368 / 336 hours, costing £1.274m / £98k] and astronomy facilities [16,311 / 299,467 hours, costing £2.17m / 6.12m] where numbers are quoted PI / Co-I and costs based on a UK nuclear-physics community survey and notional costs of: light source £7k per day, radio or 2-m telescope £5k per day, 4-m telescope £15k per day, and space mission £5k per hour. As Co-I, we used SLAC and Tevatron amounting to 32,133 hours, estimated at £45m, and the Modane Underground Laboratory, estimated at £174k.

e. COLLABORATION OR CONTRIBUTION TO THE DISCIPLINE OR RESEARCH BASE

Academic Collaboration: Staff provide leadership in many large national and international projects from ultimate spokesperson through the UK-PI role to leaders of work groups, often after election from the relevant community. Collaborative webs operate in all areas to bring expertise together behind projects; national/international partnership is the normal mode of operation. Staff are supported in collaborative roles by a flexible approach to the allocation of teaching and administrative duties, which is facilitated by the large size of the School. Sabbatical leave also is used strategically to support such activity (details in Section C & examples below).

Examples of leadership of large international projects: ~7 staff over 08-13 including: D0 spokesperson FNAL (USA) [Soldner-Rembold 09-11]; Chair of European SKADS Programme [Wilkinson 08-10, sabbatical 08/09]; EU Graphene Flagship Project [Geim and Novoselov].

Examples of UK leadership in large projects: >9 staff, including: UK-LHCb PI [Parkes]; FAST-UK PI [Maffei, sabbatical 13/14]; FP7-MetaChem UK-PI [Grigorenko, sabbatical 09/10]; leadership roles in significant collaborative EPSRC grants, e.g. Graphene Science and Innovation Award [Geim], Biaxial Nematic Liquid Crystals [Gleeson, sabbatical 10/11].

Examples of work group leader within large projects: >20 staff, including: Chair of Radiometer WG for Planck Low Frequency Instrument [Davies]; Planck WG7 leader [Dickinson]; ALPHA Technical/Experiment Coordinator [Bersche]; 3D-ATLAS R&D Project Leader [Da Via, sabbatical 12/13]; Lead Scientist of ALMA Regional Centre [Fuller].

Collaboration Outside Academia & Influence of Research Users: Collaboration exists with a range of external bodies including hospitals, agencies, institutes and industry. Our expertise is brought to play on shared projects with commercial and societal importance, particularly energy, healthcare and security. Collaborations in the period have included work with Unilever, Astra Zeneca, Samsung, Thales Underwater Systems, AWE, NanoCo, Baxter Healthcare Corp, Galileo Avionics SpA, Thales Optronics, and Farfield Group, in addition to PhD support noted in Section C.

Collaboration with non-academic bodies is also supported by sabbaticals and flexible work allocation (see above) but is underpinned in several other ways. UoM Contracts Team provides professional services in checking and negotiation of research contracts and disclosure agreements. UMI^3, UoM agent for intellectual property (IP) commercialisation, manages UoM-created IP; identifies, protects and evaluates the commercial potential; and commercialises IP via an appropriate route (sale, licence or spin-out). UMI^3 holds UoM patent budgets, manages Proof of Principle (PoP) award scheme and provides access to spinout investment funds. UMI^3 has access to extensive networks of industry experts, consultants, advisers and investors. UMI^3 received 78 IP disclosures from the UoA leading to 10 distinct patent families and 1 license agreement in 08-13.

Business Engagement Support provides external partners with services covering research, KT, consultancy and commercialisation. KT resources managed by them (KTA, KTP, IAA) have supported 5 projects in 08-13 with partners including Fairfield Group Ltd and Thales Underwater Systems. Support is also provided by umbrella agreements between UoM, EPS and third parties.

UoM and the UoA plan to build on the world-leading position in graphene research by supporting application development and business opportunities through partnership with firms and commercialisation of intellectual property, and by providing highly trained people with scientific and entrepreneurial skills. The National Graphene Institute will be operated to bring academia and commercial organisations together into specialist laboratories and clean rooms for collaborative research and to establish high-tech accommodation in close proximity for expansion of commercialisation. Core partnerships with major companies are being established to cover key sectors, e.g. Bluestone Global Tech a major graphene manufacturer, with wider opportunities developed to address interactions across the range of business activity including SMEs.

Staff have many long-standing collaborations with research users and have developed research agendas formed by mutual interest. During the period, several new interactions have altered research strategy in different ways. Nascent research collaborations are often secured via placement of UG students working on the initial steps as final-year project. Critical mass provided by UoM research institutes, in particular, acts as magnet enhancing this effect.

Examples of non-academic collaboration: (see also Section B) (i) Expertise in wet interfacial measurements using neutron scattering, cell structure and surface biocompatibility led to a successful collaboration with Unilever R&D Port Sunlight Labs to develop personal-care products making skin/hair improvements at the molecular level whilst reducing reliance on petroleum-derived materials. The partnership has been successful in securing support for 3 separate KT projects. (ii) Inventions based on locking-in temperature-dependent polarisation of ferroelectric liquid crystals by polymerization were used in a cross-faculty project (physics, chemistry and engineering) supported by TSB, with industrial collaborators and funding (Syngenta, Kingston Chemicals and Xennia). This produced a time/temperature sensor system for the perishable goods industry using printable plastic electronics, readable with RFID tags. This project was initiated via a Syngenta-University partnership; rights to 2 patents from the UoA were assigned to Syngenta under this agreement. (iii) A co-supervised MPhys project hosted by the Christie Hospital aimed at improving the resolution of single-γ emission CT using techniques drawn from nuclear physics has cemented a collaboration that has gone on to be successful in the STFC Innovation Partnership Scheme with both mini and full awards. (iv) Collaboration with Nanoco Technologies, a manufacturer of quantum dots (QDs), led to joint EPSRC funding and development of a solar cell based on light-harvesting QDs. Use of both PSI and Nanoco facilities were essential. Nanoco's need to diagnose ultrafast photophysics of QDs has led to initiation of a high-power THz spectrometer project (with STFC ASTeC) funded by the STFC Global Challenge Scheme.

Interdisciplinary Collaboration: Interdisciplinary research in the UoA is supported by the University and Faculty, which provide strategic investment and policies, fostering connections within the rich diversity of expertise in such a large HEI and minimising barriers to cross-disciplinary work in structures and processes. Approximately 30% of staff are members of research centres and institutes that provide environments cutting across traditional boundaries, with several examples in Section B. These include: Centre for Mesoscience & Nanotechnology, Photon Science Institute (PSI), Dalton Nuclear Institute, Cockcroft Institute and National Graphene Institute.

Examples of interdisciplinary collaboration (see also Section B): (i) Complexity research involves strong interdisciplinary collaborations, where statistical physics methods are applied to solve problems in disparate areas. As an example, collaboration with UoM Institute for Social Change, Sociology Department, and Centre for Policy Modelling at Manchester Metropolitan University uses complex chains of agent-based models to understand social/political phenomena such as voter turnout, employment and migration. The sheer range of expertise across UoM supports collaboration with colleagues in life sciences, mathematics, computer science, linguistics, economics and business studies. These are often initiated in workshops funded by EPS Strategic Funds. (ii) Research into liquid crystals for contact lenses with switchable focal lengths suitable for presbyopia involves collaboration between physics and optometry, and industry (Ultra Vision CLPL). Starting from an MRC-funded CASE, UMI[3] PoP funding was awarded for two PDRAs and business development to take designs to clinical trial stage. Work is on going, but a patent has been filed. (iii) Collaboration between photon physics and material science & metallurgy at Cambridge has assembled expertise in construction and characterisation of nitride-based white-light LEDs that benefits from expertise and facilities available in PSI and was successful in obtaining an EPSRC Platform grant to investigate developments in low-energy lighting.

Exemplars of Leadership in the Academic Community: Staff served on *advisory boards*, including: at CERN (LHC-Experiments & Scientific-Policy Committees, BIS Committees on CERN [Wyatt], INTC & nTOF Board [Billowes], CLIC-CDR Review Board [Soldner-Rembold]); in ESA (Chair of EUCLID Assessment & Astronomy Working Group [Leahy]); in ESO (Observing Programme Panel [Zijlstra (chair)]; Users Committee [Fuller]) & other *international programme advisory committees* including ATLAS Argonne USA, JYFL Accelerator Lab (chair) [Freeman], Effelsberg Telescope [Stappers]; Soleil, Swiss Light Source, MAXlab [Flavell]; ESRF [Waigh].

Staff participated in *RCUK advisory positions* including: RCUK Advisory Group on Capital Investment [Lafferty]; EPSRC Strategic Advisory Team [Gleeson, Flavell]; EPSRC Physics Grand Challenges Panel [Browning], STFC Science Board [Lafferty, Freeman]; STFC PPAN Committee [Lafferty]; UKSA Science Policy Advisory Committee [Leahy]; STFC New Light Source Coordinator & Photon Science Institute Board [Flavell]; ISIS Access Panel [Lu]. Staff chaired *RCUK Peer-Review Panels* in all major STFC areas [Seymour, Freeman, Zijlstra] and 10 were members. 7 staff sat on STFC advisory panels & ETC Committee. Many participate in EPSRC's peer-review college.

Staff provided *leadership roles in professional bodies*, including IoP Science Board [Gleeson], RAS Council [Davies], IEEE [Da Via], International & British Liquid Crystal Societies [Gleeson(vice-chair) and Dierking(chair) respectively], with much input to IoP Subject Groups.

Staff chaired (or have been 1 of 2 co-chairs) of 11 large *international conferences* including: UK-Germany Astronomy Meeting NAM2012 [Zjilstra/Browning] (935 delegates); Tevatron Impact 2012 [Soldner-Rembold] (461); Rutherford Centennial Conference 2011 [Freeman] (230). Staff contributed to many other conferences with >350 invitations to give keynote/plenary presentations.

Staff sat on *editorial boards* of 15 journals, including Phys. Rev. X & J.Phys. G [Billowes]; European Physical Journal [Birse, Wyatt]; Euro Physics Letters [McKane]; PLOS-One [Waigh].

The most prestigious of the *prizes and awards* was the Nobel Prize for Physics 2010; Geim and Novoselov were each recipients of a further 14 and 9 national & international honours, recently Royal Society Copley & Leverhulme Medals. Novoselov and Wyatt were elected to FRS, joining 6 others in current & emeritus staff. The School was awarded 1 of 12 Regius Professorships by The Queen, the only one in physics. There were 5 awards of UK Honours for services to science: Kt [Geim, Novoselov], OBE [Cox, Gleeson, Davies]. Staff were awarded 21 other prizes, including IoP/SPF Holweck Medal & British Liquid Crystal Society Gray Medal [Gleeson]; IoP Chadwick Medal [Wyatt], APS-Dawson Award for Plasma Physics [Bersche]; Hilsum Medal [Dierking]; STFC Halliday Fellowship [Brown]; Honorary Doctorate Copernicus University [Wilkinson].