Institution: University of Manchester

Unit of Assessment: UoA-8

a. Overview

Chemistry at the University of Manchester (UoM) has its origins in the establishment in 1824 of the Manchester Mechanics Institute by several including John Dalton. The School of Chemistry counts 7 Nobel Prizewinners amongst its former staff and students. It is one of the largest in the UK: we are submitting 52.4 FTEs. These are augmented by 59 technical and administrative support staff, 144 postdoctoral researchers, 703 undergraduate, 41 postgraduate taught and 272 postgraduate research students.

Research in the School provides staff with access to specialised and unique interdisciplinary facilities and resources including the Photon Science Institute (PSI), Manchester Institute of Biotechnology (MIB) and Dalton Nuclear Institute (DNI). Broadly, staff work within one of five research groupings that are reflected in our REF return: **synthesis**; **materials chemistry**; **chemical biology**; **nuclear and radiochemistry**; **analytical and physical methods.** Within this framework, we can make substantial contributions towards the following societal challenges: **(a) energy and environment:** nuclear, solar and bio-energy; climate change; environmental remediation, **(b) life science and health:** drug discovery; diagnostics; food security, **(c) new technologies:** molecular machines; nanotechnology; organic printed electronics; molecular separations, **(d) sustainability:** green chemistry; efficient chemical synthesis; energy-efficient processes; biotechnology; in silico prediction.

During the REF period some key achievements include:

- first semantically encoded map of a biochemical network (Kell);
- first sequence-specific synthesis by a small-molecule machine (Leigh);
- first production of graphene by non-oxidative electrochemical methods (Dryfe);
- election of Profs David Leigh (2009) and Paul O'Brien (2013) to FRS;
- appointment of Douglas Kell as Chief Executive Officer of BBSRC in Oct 2008;
- award of the Queen's Diamond Jubilee Anniversary Prize (2012) to UoM for nuclear research in which the School plays a significant role, and the opening of its £23m Dalton Cumbrian Facility in 2013;
- establishing the Knowledge Centre for Materials Chemistry (2008) with investment of £7m;
- securing the highest value of BBSRC grants of any UK Chemistry department each year;
- key role in securing both the BP International Centre for Advanced Materials hub in Manchester in 2012 and the National Graphene Institute in 2013;
- More than 20,000 citations during the REF period, placing us 3rd amongst UK chemistry departments with >10 cites per paper, nearly doubled over the REF period.

b. Research strategy

The University's strategic plan (Manchester 2020) is based around three core goals of world-class research, outstanding learning and student experience, and social responsibility. The School's vision is to be at the forefront of the best, most innovative and significant research in Chemistry and is centred on having the highest quality people and providing them with an environment in which they can develop and flourish. Realisation would confirm us as one of the leading Schools of Chemistry, recognised both internationally and nationally for the strength and quality of our research and to reach the top three in the UK as measured across a wide range of indicators.

A number of key targets that were highlighted in our RAE2008 strategy have been achieved during the current REF period. Most notably the successful bid for the £7m establishment of the Knowledge Centre for Materials Chemistry (KCMC) that was realised in 2008. This initiative drives the interface between academia and industry in the area of materials chemistry and is a model that helps to establish direct Impact from our science. Also the £23m establishment of the Dalton Cumbria Facility (DCF) opened in 2013 to support nuclear decommissioning and associated research in the nuclear industry.

In order to attain the highest levels of research achievement, our strategy is based on three key drivers: (i) investing in and promoting world-leading research by recruiting the highest quality researchers, providing support with cutting-edge infrastructure and thereby enabling them to reach their full potential; (ii) increasing research income, across a range of sources, in particular growing

the proportion from industry (through productive interaction) and charities; (iii) providing postgraduate research and training of the highest calibre by recruiting the highest quality applicants and providing a vibrant environment in order to develop the skills base of the scientific leaders of the future. One of our progress measures for excellence is citations, exemplified by more than 20,000 during the REF period, placing us 3rd amongst UK chemistry departments with >10 cites per paper, nearly doubled since 2008. Going forward we aim by 2020 to have 28% of our papers in the top 10% most cited, equalling the top UK performance. We also seek to double our research income from its 2011 base and within that to treble the amount from business, building upon our role in the recent BP International Centre for Advanced Materials (ICAM), the largest single business award to a UK university and our successful collaboration with SMEs via our Organic Materials Innovation Centre (OMIC). To meet the university goal of providing world-leading postgraduate research, the faculty plan places an emphasis on the development of DTCs, reflected in the strong School participation in two of these during the period.

In addition, this research will be conducted in an environment of Social Responsibility, reflecting the UoM goal through exercising an awareness of global issues of sustainability, energy security and economic stability, enhancing public engagement in our science and technology, championing equality and diversity

The School's research strategy is reviewed annually in consultation with all staff and is led by the Director of Research and the Research Committee. Progress towards achieving the strategic targets and KPIs is reviewed regularly by the School Research Committee and Management Team. It also forms part of the Annual Performance Review conducted by the University's Senior Management Team with Heads of School. In addition, we benchmark our performance against other UK chemistry departments using the annual HESA data.

Our detailed strategy is rolled out via our research groupings (see below). These have recently been reorganised to build on our strengths and will provide an enabling framework over the next five years to support our strategy of world-class interdisciplinary and core research. These build on existing research areas and offer new opportunities for funding and collaboration by bringing together complementary skills. An important part of this strategy is to incorporate theoretical and computational activities within each group in order to maximise the impact of their research. As noted in Section e we also seek to work across group, School and Faculty boundaries. Strong Institute participation (30% of staff) forms a core part of this drive, particularly PSI, MIB and DNI.

Synthesis is enabling the design and realization of fantastic molecular architectures that possess unprecedented physical and biological properties. Strategic appointments, of established (Leigh and Greaney), and younger (Ingleson and Layfield) researchers, and on-going upgrades of research infrastructure for synthesis (*e.g.* a £1.4m EPSRC-funded upgrade of NMR, X-ray, and MS capability), have strengthened the group and broadened its interdisciplinary research to now be one of the strongest in the UK. This breadth is reflected in the group's current themes: supramolecular-assisted synthesis and molecular machines, synthesis of biomimetic structures, receptors and probes, the harnessing of highly reactive intermediates, integrated chemo- and bio-catalysis for sustainable synthesis, synthesis for chemical intervention in biology and medicine, and synthesis for electronics and energy. The future strategy is to grow work in catalysis and sustain our premier position in supramolecular chemistry and future appointments will reflect these priorities. Recent highlights from the group include the synthesis of an artificial ribosome, the development of sustainable metal-free technologies for cross-coupling, and the ability to communicate over 2 nm through a synthetic purinergic receptor.

Chemical Biology Staff undertake interdisciplinary research across the entire spectrum of biomolecular science encompassing nucleotide, carbohydrate and protein chemistry and this has been supported by the appointment of two younger staff members: Wong and Dixon who bring strength in biomaterials and knowledge transfer. Within the broad themes there are particular strengths in: protein/carbohydrate arrays; pathway and metabolic engineering; synthetic biology; directed evolution of enzymes; industrial biotechnology; computational methods for biomolecules; metabolomics; mimicking biological systems; riboswitches and RNA synthesis; de novo protein design and engineering; mass spectrometry; biomembranes. Strategically, industrial biotechnology and synthetic biology will play a particular role. The group derives significant benefit from its location in the MIB, which provides state-of-the-art instrumentation and laboratory space to foster

interdisciplinary research including an extensive network of collaborations with other academic and industrial groups. The Centre of Excellence for Biocatalysis, Biotransformations and Biocatalytic Manufacture (CoEBio3), a Manchester-based partnership with industry, Heriot-Watt, Strathclyde, York and the Centre for Process Innovation that provides a world-class scientific environment for the development of new biocatalyst-based processes and is a platform for future initiatives. Work in synthetic biology, glycosciences and cheminformatics (Micklefield, Flitsch, Goodacre) will be given added impetus by the return of Kell (Oct 2013). Our future strategy includes growing our income from industry through CoEBio3 as well as increasing our activities in medicinal chemistry by forming collaborations with clinicians and researchers from the faculty of Medical and Human Sciences. Recent highlights include: engineering a monoamine oxidase biocatalyst for commercial scale production of a building block for a hepatitis C drug (telaprevir); re-engineering the first orthogonal riboswitches to control gene expression in cells using synthetic molecules; development of a novel glycoarray platform for label free detection of carbohydrate-protein interactions.

Materials Chemistry Research is focussed across four major themes that include interactions with Physics, Materials and Electrical Engineering. *Graphene* is being studied by both electrochemistry and Raman spectroscopy, with a patent filed for the first non-oxidative electrochemical synthesis of graphene. There has been significant funding for energy storage in graphene (EPSRC £2.1m) and graphene-based membranes (EPSRC £2.8m) and an appointment in graphene chemistry (Casiraghi) has given critical mass. The membrane work overlaps with our work on *nanoporous materials* (Anderson, Attfield, Budd), where there have been major developments in use of polymers of intrinsic microporosity for gas storage, and use of atomic force microscopy to study early stages of crystallisation of zeolites and metal-organic frameworks. Our activity in *optical materials* includes development of new metal-organic and organic materials for non-linear optics, and synthesis and ink-jet printing of organic thin film transistors and sensors. We are world-leaders in *molecular magnetism*, with new developments including: the first organic-inorganic hybrid rotaxanes (with Leigh); energy barriers for magnetic relaxation of over 800k for lanthanide single molecule magnets and linked molecular qubits; taking the first steps towards molecular electron spin devices for quantum information processing (with Collison and McInnes, and with collaborators from France, Belgium and Italy). Future strategy revolves around major new activities including strong interactions with BP, through the ICAM (£64m centred in Manchester), with post-doctoral positions already supported with O'Brien, Quayle, Winpenny and Yeates. Budd, Casiraghi and Dryfe are strongly involved in the design of the National Graphene Institute (£61m from EPSRC and EU) opening in 2014. These will significantly strengthen our ability to become world-leading in the field of advanced materials. The future work of this group will be significantly strengthened by the recently announced CDT in Graphene.

Nuclear and Radiochemistry As the UK's leading chemical centre for radiochemistry, we are expanding our activities in nuclear and radiochemistry within the UoM DNI which incorporates the School's Centre for Radiochemistry Research (Bryan, Director) and the Dalton Cumbrian Facility (DCF) (Pimblott, Director), opened in 2013. This expansion and coordination enable us to further address the current societal and scientific challenges relating to the future of nuclear power generation, the decommissioning and clean-up of the U.K.'s nuclear legacy and nuclear safety with state-of-the-art research facilities across a broad spectrum. A combination of experiment and mathematical modelling is used to: improve the fundamental understanding of the chemistry of the fuel cycle through an extensive actinide coordination chemistry programme; study the safe disposal of radionuclides, their fate and transport in the environment and remediation techniques for contaminated land using advanced spectroscopic and computational techniques; develop predictive models of the effects of radiation on natural and anthropogenic materials using the unique facilities at DCF; improve the understanding and future design of industrial processes (e.g., recycling, effluent treatment) using our capability to handle significant quantities of the actinides and fission products. Six new appointments have been made in the nuclear group during REF (Denecke, Koehler, Law, Mills, Natrajan, Pearce). Denecke comes from Karlsruhe and brings world-leading expertise in synchrotron-based X-ray and NMR techniques for actinide speciation. The future strategy will focus on new radiation chemistry at the Cumbria facility, the application of analytical techniques for speciation studies and nuclear decommissioning and storage. Recent appointments reflect these priorities. This group will be further strengthened over the upcoming period by the recently announced extension to the Centre for Doctoral Training in Nuclear Fission.

Recent highlights from the group include: the first observation of uranyl(VI) emission quenching in polynuclear uranyl oxo-uranium assembled aggregates; the first spectroscopic and computational determination of the emission properties of uranium(IV) chlorides and U(IV) macrocyclic complexes; development of an understanding of the behaviour of plutonium in nuclear fuel storage ponds; development of a novel gamma ray imaging technique to study transport of radionuclides.

Analytical and Physical Methods Our research in Analytical and Physical Methods brings together a wide range of science sharing a core of spectroscopic, analytical and structural techniques with research focussing on novel applications and instrumental development. Strategic relationships with industrial instrument manufacturers will play an important part in the future activity of this group developing recent significant investments in positions and equipment by Waters (MS), Bruker (EPR) and Agilent (NMR). These have funded the recent appointments of Barran (Chair), and Fielding (SL). The appointment of Barran as Director of the Michael Barber Centre will ensure that Manchester remains a leading centre in mass spectrometry following Gaskell's move to QMCL. It includes globally-competitive groups in EPR (Collison, Fielding, McInnes) and NMR (Morris, Nilsson), covering the full range from the physical fundamentals of the phenomenon of magnetic resonance through methodological developments to applications in magnetochemistry (Tuna), analytical chemistry and biosciences. Raman and mass spectroscopies underpin biological applications of metabolomics and chemometrics (Goodacre), and new methodologies in mass spectrometry (Barran: ion mobility and Lockyer: surface analysis) are being explored. Optical spectroscopies are key to our programmes in plasma chemistry (Whitehead) and photon science (Jones), and X-ray diffraction (Pritchard) and computational chemistry (Hillier) are tightly integrated with other colleagues across the discipline. Our strategy will focus on: sustaining and building on the world-leading groups in NMR and EPR (in particular pulsed-EPR); analytical methods to tackle future challenges in chemical biology; establishing facilities for massive data storage and manipulation. Recent highlights from the group include: the first use of 4D-inelastic neutron scattering (INS) to measure spin dynamics in molecular magnets directly, without use of a spin Hamiltonian; the development of ultra-high resolution "pure shift" NMR methodology; design of SERS experiments with multiobjective evolutionary optimization; MS optimisation in metabolomics by using quantity control and quality assurance standards in order to correct for instrumental drift.

c. People

i. Staffing strategy and staff development

During the REF period several key appointments (17 in all including five international italicised below) have been made in line with our strategy. **Synthetic Chemistry** has been substantially enhanced by the appointment of Leigh (Chair, 2012), Greaney (Chair, 2011) and Ingleson (RS URF, 2008). **Chemical Biology** has been strengthened by two "young blood" appointments based in MIB: *Wong* (EPSRC Fellow, 2008) and Dixon (BBSRC David Phillips Fellow, 2013). **Nuclear and Radiochemistry** has been grown significantly through the appointments of *Denecke* (Chair, 2013), Natrajan (EPSRC CAF, 2009), (Law, L in analytical radiochemistry, 2011), *Koehler* (Dalton Fellow, 2009), Mills (L in inorganic chemistry, 2012) and Pearce (Dalton Fellow, 2013). In **Materials Chemistry**, the growth area of graphene chemistry, that has seen substantial recent grant income of £4.7m to the School, is supported by the appointment of *Casiraghi* (2010, L in graphene chemistry). **Analytical and Physical Methods** houses the UK EPR National Facility and this area has also been grown through appointments of Fielding (SL, 2012) and *Tuna* (RF, 2012). The School's excellence in mass spectrometry has been continued by the appointment of Barran (Chair, 2013) and the transfer of Lockyer from Chemical Engineering (2011). Jones (Photon Science Institute Fellow, 2013) is doing innovative work at the interface between photon science and biology. Of the 18 departing in the period, 5 have left to take up chairs or senior academic positions (including Gaskell to become Principal of QMU), 4 to other academic posts and 9 because of retirement or other reasons.

During the REF period, Kell became 20% upon his appointment as CEO of BBSRC in 2009 but has now returned as full-time, Nilsson moved to a 20% appointment held in conjunction with a chair at the University of Copenhagen, and Hillier changed to 20%. Seven of our staff also hold senior roles outside the School: Denecke, Co-Director of DNI; Livens, Research Director of DNI; Pimblott, Director of DCF; O'Brien, Head of School of Materials; Yeates, Faculty Associate Dean for Research; Turner N, Deputy Director of MIB; Winpenny, Director of PSI. We have also hosted more than 50 international visiting research scientists.

Staff development

All researchers and research assistants discuss and plan their careers through an annual Performance and Development Review (P&DR). Training needs may be identified that develop qualities from specific research skills to management and personal skills. The University's Staff Training and Development Unit provide suitable courses. Staff at a higher level are offered Leadership Training through a centrally run "Head Start" course, which prepares staff for senior roles in the University (e.g. Head of School and above). Four staff have attended this course in the REF period. All staff have a mentor in a programme that is supervised by the School Senior Mentor (Dryfe). The mentor meets regularly with their mentee, giving advice and guidance. It is the School's view that effective mentoring is the best way of helping staff at all stages in their career with a wide range of issues. For our developing "research leaders" who have reached a stage where they have to manage larger research groups with increased resources, we have recently established a bespoke "Emerging Researchers" course to provide extra support and training. This is delivered by experienced academics and the Staff Training and Development Unit.

For academic staff, there is an active sabbatical programme that ensures around 10% of staff are on leave at any time. Staff are encouraged to submit plans that will develop their research and its impact. Promotion pathways exist for all categories of staff, including those focussing solely on research. Clear guidance and criteria are available for all stages. The Faculty runs Promotions Master Classes to help promotion candidates to prepare their applications. During the REF period, there were 17 internal promotions wholly, or partly, on research record: 5 to professor, 8 to reader and 4 to senior lecturer (4 of the promotions were Early Career Researchers, ECRs). Unsuccessful applicants are offered face-to-face feedback from both the Head of School and Dean of Faculty.

Particular attention is given to early career researchers. The University's New Academics Programme (NAP), coordinated within the School by the Senior Mentor, ensures that the first year of a new appointment's academic life contains all the support and training needed to build a firm foundation for success in teaching, learning, research and knowledge transfer. The NAP is accredited by the Higher Education Academy (14 staff have become HEA Fellows) and is a requirement for the confirmation of probation. PDRAs and other staff can also take modules from the programme. We have an excellent track record for developing our Research Fellows. For example, Ingleson recently won an ERC award and Natrajan a Leverhulme Research Leadership Award. Our strategy of building research excellence through early career researchers by hosting holders of competitive fellowships (e.g. Royal Society, EPSRC, BBSRC, ERC) has proved very successful, with Ingleson, Natrajan and Nilsson (Readers), and Wong (Lecturer) moving to permanent contracts. To augment external fellowships, the University has created fellowships through its Research Institutes, with Jones holding a PSI Fellowship and Koehler and Pearce being Dalton Fellows. The website, "An Academic Career", was developed by the University of Manchester Careers Service and is a comprehensive guide to working in higher education. It was the winner of the THE 2011 Award for Outstanding Support for Early Career Researchers. The University also received the 2011 Scopus Fostering Young Researchers Institutional Award, given by the US-UK Fulbright Commission and Elsevier based on its number of highly-cited ECRs.

Concordat implementation

The University of Manchester's Concordat Implementation Plan ensures full support for the Concordat to Support the Career Development of Researchers; the University has received the HR Excellence in Research Award from the European Commission in recognition of this work. UoM participated in the Careers Research Online Survey 2011 to find out the views of research staff and has incorporated the results into the Concordat Implementation Plan, especially through improving research staff representation on University committees. Within the School, a Postdoc Forum was established in 2009, run by the postdocs who are also represented on the Research Committee. Working with the Faculty's Researcher Development Officer, the Forum provides a range of support initiatives, including talks from current Fellows on their experiences of the transition into an independent academic post. Faculty runs regular courses for all staff who wish to apply for senior Research Fellowships (e.g. ERC, Royal Society, RCUK etc.) and in conjunction with the Careers Service provides a range of career development training courses. An annual Research Staff Conference that provides networking opportunities. At induction, all PDRAs receive a copy of a faculty-specific Research Staff Handbook that gives important information, about

support for PDRAs to assist with their on-going personal and professional development. They are assigned a mentor who is not their line manager and have an annual P&DR to discuss progress and career aspirations.

Personal research fellowships

Nineteen staff have won fellowships during the REF period, from Research Councils, Royal Society, Leverhulme and European Commission. They include: Natrajan's EPSRC Career Acceleration Fellowship and Leverhulme Leadership Award; Greaney's EPSRC Leadership Fellowship; Popelier's EPSRC Fellowship; Ingleson's Royal Society University Research Fellowship; ERC Advanced Grant to Clayden and Starting Grant to Ingleson; BBSRC David Phillips Fellowship to Dixon.

Equality and diversity

Our efforts were formally recognised with an Athena SWAN Bronze Award in 2011 and then a Silver Award in 2013. In equality and diversity, we continue to drive policies that enhance the role of women in science and engineering, including active Equality and Diversity Training for all staff and an extensive Outreach Programme. The University is committed to providing an environment free from discrimination, bullying, harassment or victimisation, where all are treated with respect and dignity. It aims to create a culture of diversity, providing a dynamic working and learning environment, where all members are valued for their contribution and individuality. All staff must attend training on Diversity in the Workplace. The School is involved in Women in Science Engineering and Technology (WISET) and uses its outreach programme to promote the opportunities available to women in science. Our family friendly practices include sensitive structuring of work around family caring requirements. This, coupled with mentoring and P&DR, allows gender-specific issues to be raised and addressed. During the REF period, there has been a significant increase in female Postdoctoral Researchers, Early Career and Professorial staff.

ii. Research students

The School aims to recruit only the highest quality research students and provide them with a first class training in research. As the table below shows, the numbers have grown between 2008 and 2013. Funding for studentships comes from a wide range of sources including research councils, industry, UK government, international governments, EU, self-funded and university. The School uses its EPSRC DTG allocation in a strategic manner by supporting all new starters with a studentship, by supporting large grant bids and by a competition for collaborative projects that will pump-prime new research areas. The School also hosts two successful Doctoral Training Centres (DTC), which started in 2010: *NOWNano* for nanoscience and *Nuclear First* for nuclear fission. These are based in the School of Chemistry, with dedicated administrative staff, and involve several other schools in the Faculty and other universities. The School has also benefitted from the BBSRC DTP in Systems Biology and participates in the current BBSRC DTP programme. The University provides both President's and Dean's scholarships which are highly competitive enabling us to attract the very best students to Manchester. Chemistry has recruited 13 students on these awards during the REF period, and the number of home students registrations are approximately 60 p.a. during the REF period. During this period, 219 PhD students have graduated of which 70% have entered employment or further study within 6 months of graduating.

Total FTE

Year	08	09	10	11	12
TOTALS	188	181	186	193	207

PhD students numbers

International recruitment

International students made up 31% of our postgraduate student numbers during the REF period. The prime mechanism for post-graduate recruitment is through advertising on a range of websites as well as in Prospects Postgrad that includes general information about the School and programmes available. Our taught Masters Programmes are excellent vehicles to support overseas students in gaining the specific skills they need to carry out chemistry research at Manchester, making them aware of the research areas available to them and acting as a pathway to subsequent PhD study. We will continue to recruit from parts of the world where we have been very successful, *e.g.* Saudi Arabia, Libya, Iraq, China, Nigeria, South America, with an emphasis on the quality of the student intake. This involves visits to these countries as well as promoting

strategic relationships with countries such as Mexico and Brazil. We also have significant links in both Ghana and South Africa (including participation by School staff on a Royal Society sponsored M.Sc. programme with Kwame Nkrumah University of Science and Technology, Ghana. We are making positive efforts to diversify by using agencies such as the British Council to cover countries where we have recruited few students in the past.

Training and support

The overall oversight of support for postgraduate research students lies with the Director for Postgraduate Studies and the Postgraduate Committee. In addition to a supervisory team, consisting of a supervisor, co-supervisor(s) and examiner, a postgraduate student will have a mentor from the School of Chemistry, who is not part of the supervisory team, to provide general advice and guidance. Students with disabilities are offered assistance in conjunction with the University's own support unit, and the School has a named administrative contact to facilitate such referrals. Those experiencing temporary difficulties can be directed to other support services (e.g. counselling, legal advice, financial hardship support). All PGR students are required to attend a Faculty-run Graduate Development Programme including personal and professional development and skills training, to help them successfully conduct their research and maximise their future employability. Training sessions are tailored to different stages from introductory modules, academic writing, critical reading and project planning, thesis writing, viva preparation, publishing, career planning and enterprise skills. The majority of PGR students take up the opportunity to undertake laboratory teaching, after suitable training, to assist career development. A vibrant and broad-based seminar programme widens the research student experience. This comprises a balance of internationally leading researchers from the UK and worldwide, together with carefully selected rising stars and new appointees. PhD students also give research seminars in order to develop their communication skills. Over 90 international speakers have been hosted during the REF period, including 5 Nobel prize winners: Aaron Ciechanover, Jean-Marie Lehn, Kostya Novoselov, Richard Schrock and John Sulston, along with other notables such as Mark Ratner, Michael Klein and Donald Truhlar. The PSI has hosted, amongst others, Wolfgang Ketterle (Nobel Prize Winner in Physics) and Richard Zare, (Wolf Prize in Chemistry). The MIB has hosted Dame Carol Robinson DBE FRS and Peter H Seeberger, Director Max Plank Institute of Colloids and Interfaces. These are in addition to our regular hosting of RSC-sponsored events and symposia. There is an active Post-Graduate consultative committee, which ensures that our students have a forum to exchange ideas and input into policies.

Progress monitoring and student achievement

An online progression monitoring system (*eProg*) provides students with clear direction and critical milestones for their PhD, recording progress on their programme, and engagement with training and attendance. Monitoring of training and progression has led to good completion rates for research degrees, averaging 81% over 08-12. Our future aim for completion rate is in excess of 90%. Eleven students have obtained EPSRC Doctoral Prizes or PhD Plus Awards during the REF period, awarded competitively across the whole of UoM. Postgraduate students have been awarded prestigious awards during the REF period including Lilly Organic Chemistry Postgraduate Prize (2010, Collins); European Institute of Molecular Magnetism Doctoral Thesis Prize (2010, Boeer); Reaxys PhD Prize (2011, Parmar); SciFinder Future Leaders in Chemistry (2013, Fazakerley) and L'Oréal-UNESCO Regional (Sub-Saharan Africa) Fellowship for women in science (2013, Badu).

d. Income, infrastructure and facilities

Income

Over the past 5 years we have had an average annual research income of £10.3m putting us in the top 5 chemistry departments. Over the period 08/13, this income is made up of 55% from Research Councils, 21% from the European Commission, 9% from industry, 5% from health authorities and 4% from charities. New awards during 2012/3 were £25.2m, a threefold increase since 08/09 (£8.2m). At September 2013, the value of current research grants was £43m, divided across the five research groupings as follows: synthesis 22%; materials chemistry 17%; chemical biology 29%; nuclear and radiochemistry 15%; analytical and physical methods 16%. The School is consistently in the top five Chemistry departments for EPSRC funding and during the REF period we have secured 16 grants in excess of £1m. We have consistently held the highest value of BBSRC grants of any UK chemistry department throughout the REF period. There has been an

increase of 74% in EU funding since RAE2008. The strategy for the future is to increase research income per FTE by at least 10% per year by continuing to grow RCUK funding whilst significantly increasing income from other sources such as EU, charities and industry.

Half our staff are actively engaged in consultancies and professional work, ranging from the Nuclear Decommissioning Authority to Chemical Industry and Media. Staff in OMIC, such as Yeates, consult widely with the chemical using industries (e.g. Astra-Zeneca, BP, GSK, Merck, National Starch etc.) where the *Knowledge Centre in Materials Chemistry* (KCMC) acts as a conduit between our research base and industry. Our influence is international; e.g. Bryan has worked on the International Panel for the assessment of the Belgian National Nuclear Waste Repository and Morris brings NMR expertise to Swiss company Givaudan and US giant Agilent.

The School is committed to expanding its knowledge transfer activities, developing the business models established by KCMC, where there is an embedded business manager, and CoEBio3 in materials chemistry and biotechnology, respectively, using the experience gained from recent KTA funding and the appointment of researchers and business managers in this area (Holmes in KCMC, Dixon in Chemical Biology, McCairn in the School to increase IP development). We have identified areas in medicinal and biological chemistry where we will develop, and intend making KT an important income stream for the School. We are also actively supporting spin-outs, such as the new start-up company *Discovery Biocatalysis* (Turner N), with potential to yield future Impact.

Specialist infrastructure and facilities

Nuclear and Radiochemistry

The Dalton Cumbrian Facility (DCF) addresses fundamental radiation and nuclear decommissioning scientific problems associated with the nuclear industry. The facility (£23m from NWDA and UoM) opened in 2013. It is unique within the EU, housing state-of-the-art irradiation capabilities, including a 5 MV tandem accelerator and self-contained cobalt-60 gamma irradiator, dedicated analytical chemistry and environmental and material science laboratories, and a computer modelling suite. Further development of the DCF as part of the National Nuclear User Facility (£5m), funded by BIS and DECC is currently under commissioning or out for tender and will include the installation of a 2.5 MV single-ended ion accelerator, providing the ability for dual beam irradiation at energies higher than those available anywhere else in the world, and a unique shielded glove-box end-station capability for working with activated materials. Further enhancement of the capabilities of the DCF is also underway via the EPSRC funded ON-SIDE grant (£750k) which will provide RBS and *in-situ* LIBS spectrometry as well as an in-beam high-temperature autoclave. The facility will then be the highest energy dual beam capability available.

The Centre for Radiochemistry Research contains the only university labs in the UK that are capable of handling macroscopic quantities of transuranic elements and fission products (e.g. hundreds of milligrams of Np and Pu). It has a unique high active glove box, NMR, luminescence, radiometric and general chemical analysis facilities, and serves as a national focus for radiochemistry research. In recognition of its unique position, during the current REF period, the Centre received direct 'core' funding from the Nuclear Decommissioning Authority. The Centre was the only U.K. partner in the EU ACTINET-I3 integrated infrastructure initiative for actinide science.

Chemical Biology

The Manchester Institute of Biotechnology is a purpose-built research institute that brings together 60 PIs (500 researchers) from across physical, biological and medical sciences to address contemporary challenges in healthcare, energy, food security and development of novel industrial biotechnologies. MIB's interdisciplinary biotechnological and biomedical research is supported by state-of-the-art laboratories and facilities including: biomolecular NMR (800, 600 & 500 MHz); bionanotechnology and imaging (AFMs, TIRFM, FCS & FACS); protein expression and crystallography facilities. Plans are in place to host a regional GHz facility through the N8 network. Currently 12 PIs from the School are based in MIB, which provides a unique environment for research at the Chemistry-Biology interface.

The Michael Barber Centre for Mass Spectrometry is an international centre of excellence for MS, renowned for its development of mass spectrometric techniques for the analysis of biomolecules. It currently houses 6 mass spectrometers: Esquire ion trap, Ultraflex II TOF/TOF, AmaZon ETD system and Q-ToF Global, Xevo TQ, Synapt HDMS and associated ultra high pressure liquid chromatography systems for analyte separation prior to MS analysis. It interacts extensively with

members of the community at UoM, both within Chemistry and more widely with members of the Faculties of Life Sciences and Medical & Human Sciences.

The Manchester Centre for Integrative Systems Biology provides dedicated laboratory space and advanced analytical instrumentation to support multidisciplinary projects that bring together biology, 'omics-based analyses, as well as text mining and computational systems modeling. State-of-the-art equipment available includes advanced quantitative chromatography-mass spectrometry instrumentation for metabolomics and proteomics, chemostat and turbidostat cell cultivation facilities, protein purification and robotic enzyme assay equipment, as well as computational infrastructure including high-performance Condor-based computing.

Analytical and Physical Methods

The Photon Science Institute represents an investment of £20m by UoM to establish world-class facilities, only equaled in the UK by those at Rutherford Appleton Laboratories. These include CW lasers covering the range 205 to 1100 nm, line-width down to 10 kHz; Nanosecond systems based on Nd:YAG pumped dye lasers, with UV-visible output, and narrow line-width IR radiation; six ultrafast systems suitable for applications spanning THz generation to ultrafast molecular kinetics. These are being used for a range of science, including sum-frequency generation spectroscopy to study species at interfaces, including gas-solid for corrosion protection; and single-molecule spectroscopy to provide structural information on bio-molecules in solution. Since July 2011, PSI has hosted the EPSRC National Facility & Service for EPR Spectroscopy. The Facility also has an Application Scientist position funded by Bruker. It brings together five platforms for EPR spectroscopy, covering frequencies from 1 to 95 GHz, including c.w. and pulsed spectroscopies. Combining the EPR facilities with lasers is allowing new time-resolved EPR studies of photo-excited states. The laser facility is also being used to develop new approaches to EPR spectroscopy in the THz regime. PSI will also house a new £18m (HEFCE UK RPIF) Multidisciplinary Characterisation Facility for Advanced Materials which will benefit many researchers in the School. This is funded by the UK Research Partnership Investment Fund and an additional 10-year investment of > £100m from founding partners BP; Rolls-Royce; AMEC; Sellafield; NNL; FEI; Xradia; Rapiscan; AREVA; Westinghouse; EDF; and TISICS.

Materials Chemistry

Organic Materials Innovation Centre focuses on speciality organic materials and polymer industries. It is equipped with a range of bespoke equipment including: a suite for chemistry inkjet digital fabrication, further enhanced by the recently successful £1.2m EPSRC Strategic Equipment grant joint with the School of Materials and a bespoke inert atmosphere device fabrication and characterisation suite, including organic field-effect transistor and solar cell testing; vapour sensor testing facility including gas delivery and real-time monitoring of device operation; prototype surface plasmon resonance facility with in situ fluorescence detection.

The Centre for Nanoporous Materials was established in 1995 jointly with the School of Chemical Engineering and Analytical Sciences and industry to create a Centre of Excellence for nanoporous materials. It was established in conjunction with four industrial sponsors and is located in custom-built laboratories housing specialist facilities such as solid-state NMR, electron microscopy, scanning probe microscopies, X-ray diffraction, gas adsorption, synthesis autoclaves. The facility carries out contract work and collaborative ventures with industry and international academics.

Investment in infrastructure and facilities

The School of Chemistry has the full range of analytical facilities required to support internationally renowned research. The NMR service has 13 spectrometers, ranging from a 200 MHz machine dedicated to undergraduate teaching through to a recently purchased liquid helium-cooled cryoprobe, high-sensitivity 600 MHz instrument. There are also instruments dedicated to radioactive samples and to solids. The X-Ray diffraction service has 7 instruments, including current best specification SAXS/GISAXS and two single crystal diffractometers, all purchased within the last 3 years. Mass Spectrometry has a full complement of 7 machines to support all aspects of synthetic chemistry and is supported by a dedicated HPLC/GC service. There is also a full microanalysis service with recently purchased CHN, ICP, Halide analysis and TGA. The School has four AFM's now allowing dynamic scanning under liquid and also electrochemical scanning; one desktop TEM/SEM with resolution down to 2nm and a FEI SEM with resolution better than 2

nm which is equipped with lithography capability.

In order to maintain and improve these facilities funding is being sought for a further £3m within the next two years to provide cutting-edge instrumentation in the form of: high field NMR; synchrotron-matching X-Ray instrument; high-resolution mass spectrometer; sub-nanometer SEM. The Northern Universities Research Partnership (N8) has developed an on-line inventory of instrumentation and services which facilitates instrument sharing. Through industrial partnerships (Bruker, Syngenta, Waters, AstraZeneca) the School has received ca. £4.5m since 2008. Significant investment in the National EPR Facility with funding from Bruker for a Senior Lecturer and Bruker Applications Scientist (Fielding) and by Waters to fund the Directorship of the Michael Barber Centre in the MIB (Barran).

During the period 2008-2013 UoM has made substantial investment in the School. £3.5m was invested in 2012 in refurbishment to accommodate Leigh and his group. More efficient, strobic fans were installed to service 35 new fume cupboards. One floor is currently being refurbished to create ~630m^2 of synthesis and instrumentation lab space. The existing extract systems (especially fume hoods) and other mechanical and electrical services will be upgraded starting early in 2014 and expected to take up to 4 years. Over the next two years additional space suitable for work with radioactive isotopes as a core facility will be created.

Over the next six years, the University will invest ~£250m to bring all its science and engineering Schools onto a single campus providing enhanced opportunity for multidisciplinary research.

e. Collaboration or contribution to the discipline or research base

Support for research collaborations and interdisciplinary research

A key element of the School's research strategy has been to encourage staff to engage in collaborative and interdisciplinary research. Major programmes in the University Institutes MIB, PSI and DNI were described in Section b. This is facilitated by financial and recruitment processes that operate across School and Faculty boundaries facilitating interaction with other faculties such as Medical and Human Sciences, Life Sciences and Humanities. Research Support teams, centred on small groups of Schools provide pre- and post-award support for academics fostering teams of researchers drawn from several centres. Faculty Deans and School Research Directors facilitate the establishment of multidisciplinary teams to respond to particular opportunities. Internal allocations of studentships prioritise co-supervision to encourage collaboration.

School of Chemistry researchers collaborate widely with industry and academia internationally in funded research, research visits and hosting academic researchers (greater than 50 since 2008). One indicator of the extent of collaborations can be seen in the current grant portfolio where 56% of our funding involves more than one investigator and 33% results from interdisciplinary research with researchers outside of the School and the University. Another indicator comes from an analysis of our publications during the REF period where 61% of papers published involved co-authors outside of the School; 29% with international collaborators and 15% with authors from industry. Collaborations extend from one-to-one, such as Wong's collaboration with the world's most-cited chemist (Mirkin at Northwestern University) to the 60-institution, €6.2m, EU mega-project FUNMIG "Fundamental processes of radionuclide migration" involving Bryan. Joint projects exist between the School and all other schools in EPS, and with researchers in all other faculties. Significant collaborations and interdisciplinary research activities exist with other UK institutions and within Europe and beyond. For example: the £4.6m BBSRC sLoLa on enzymes for biocatalysis (Turner N) involves the Faculty of Life Sciences; the newly established £64m BP International Centre for Advanced Materials (BP-ICAM) to drive the use of materials across a variety of oil and gas industrial applications; the £1m EPSRC Core Capability bid for Chemistry Equipment involved six of the N8 northern universities. The total value of the portion of European Commission grants coming to Manchester Chemistry since Jan 2008 is over £13m.

Engagement with users of research

Staff engage widely with industry either in concerted programmes such as the KCMC and CoEBio3 or in one-to-one arrangements. As a flavour, some of the industrial collaborators include: ExxonMobil; SINTEF; Accelrys; BASF; SABIC; NDA; Areva; BP; Johnson Matthey; Astra Zeneca; GlaxoSmithKline; ACAL Energy; Astwood Projects; Avecia; Azad Pharma; Croda; EA Tech; Eni; Intertek ASG; Mölnycke; Mundipharma; Nicolaide; Philips; Pilkington; PZ Cussons; Rapra; SAFC Pharma; Syngenta; Systagenix; Ionoptika; Bruker Biospin; Waters; Syngenta.

The Manchester Chemical Biology Network (MCBN) funded by EPSRC/BBSRC/MRC led by Chemistry (Micklefield, Director) provides a unique cross disciplinary forum for uniting scientists from across chemical, biological and medical science with end users. Through network events and proof-of-concept funding, MCBN has brought together over 40 academic groups from across the university establishing new collaborative partnerships with the leading industrial groups. (e.g. AZ, Biotica, Morvus, Pfizer, GSK, Syngenta, Senexis, Link Teck, Medimmune, Evotec, Intertek]).

Our outreach and public engagement work (coordinated by Mair) reach a broad range of people from primary schoolchildren to the retired. It is based largely but not exclusively in the NW region with activities taking place within and outside the School with over 400 events during the REF period reaching over 76,000 people directly through live lectures and hands-on science events. We have participated in the Manchester Science Festival and the Jodrell Bank Summer Science Festival that alone have reached over 7,500 members of the public. Flitsch and her group exhibited at The Royal Society Summer Exhibition in 2013 reaching 10,000 visitors. Their display 'Sweet Complexity' was one of only 24 to be selected. We intend to increase the focus of our outreach activities to our own research activities in order to increase the direct impact of our research portfolio. Much of our work has also been recognized through the media. For example, the Radiochemistry Centre is frequently called upon, for example i) Radio 4 *Costing the Earth* feature on thorium reactors ii) BBC TV *Countryfile* feature on radioactive waste disposal iii) over 50 national and international media appearances (radio and TV) after the Fukushima nuclear reactor accidents March-April 2011. Simon Pimblott (DCF) has appeared on *Daybreak* (ITV, 2011), been quoted in the Sunday Telegraph (2011) and given interviews and articles for Cumbrian TV, and radio. Chemistry World podcasts have featured the work of Louise Natrajan discussing 'Tb and Yb'.

Academic leadership

Major awards and prizes

Highlights: Leigh and O'Brien, FRS; Kell, Fellow of the American Association for the Advancement of Science; Leigh, Royal Society Bakerian Prize Lecture (2012); Flitsch, Turner N, Winpenny and Clayden, Wolfson Research Merit Awards; Leigh and Winpenny, RSC Tilden Prize; Clayden and Leigh, RSC Merck Prize; Thomas, RSC Synthetic Organic Chemistry Award; Ingelson, RSC Harrison-Meldola Prize; Layfield, RSC Frankland Fellowship; Watt, RSC Josef Loschmidt Award; Micklefield, NPR Lecture Award; Greaney, SCI GSK, AZ, Syngenta and Pfizer Prize for Process Chemistry; Casiraghi, Sofja Kovalevskaja Award; Koehler, Feodor-Lynen Fellowship; Layfield, Fellowship for Experienced Researchers; Layfield and Henchman, Humboldt Fellowship; Morris, Russell Varian Prize and Wilson Baker Lecturer; Micklefield, BBSRC Public Engagement Award.

Research Council work

Nationally, Kell was appointed CEO of BBSRC in Oct 2008. Most staff have reviewed proposals and been members or chairs on the EPSRC, BBSRC or NERC Panels. Internationally, many staff have acted as reviewers for many bodies including NSF (US), DOE (USA), NSERC (Canada), ACS Petroleum Research Fund (US), EU Commission, ERC, CNRS (France), ANR (France), DFG (Germany), FWO (Belgium), FCT (Portugal), Czech Science Foundation, Skolkovo Foundation (Russia), Research Councils in Australia, Finland, Switzerland and Singapore.

Learned bodies

About 50 staff are Chartered Chemists and ~30 are Fellows of the Royal Society of Chemistry; O'Brien was Vice President of the RSC; O'Brien and Yeates were both Presidents of Materials Chemistry Division, RSC; Layfield is on Dalton Division Council and Pimblott on Faraday Council; Morris is Chair-elect, RSC NMR Group; Thomas is Chair, RSC Heterocyclic and Synthesis Group; Collison was Chair, RSC ESR group; Dryfe, Chair, RSC Electrochemistry Group. Staff are also Fellows of other learned societies; Royal Society of Edinburgh (Leigh); Institute of Physics (Muller-Dethlefs); Biological Society (Kell). Pimblott is Chair, Miller Trust for Radiation Chemistry; Anderson was secretary of the International Zeolite Association.

Editors of journals

Barran (International Journal of Mass Spectrometry); Clayden, Flitsch (Beilstein Journal of Organic Chemistry); Goodacre (Metabolomics); O'Brien (RSC SPR in Nano Science, RSC series Nano Science and Technology); Collison, Morris (Magnetic Resonance in Chemistry); Morris (Progress in Nuclear Magnetic Resonance Spectroscopy); Leigh (Chemical Science); Thomas (Tetrahedron Letters, Science of Synthesis). *Many more are on various editorial boards.*