Institution: Lancaster University

Unit of Assessment: B9

a. Overview

The Physics Department at Lancaster conducts research at the cutting edge of fundamental and applied physics, within numerous international and national collaborations, and has significant alignment with the RCUK Grand Challenges and Priority Areas as well as EU Horizon2020. It is composed of six groups, each of which is a cluster of excellence in the respective field: **EPP** - Experimental Particle Physics (Bertram, Borissov, Fox, Jones, Kormos, Nowak, O'Keeffe, Ratoff, 14 RAs, 18 PGs); **CAP** - Cosmology and Astroparticle Physics (Dimopoulos, McDonald, Mazumdar, 1RA, 7 PGs); **SS** - Space Science (Badman, Denton, Honary, Kosch, Wild, 6 RAs, 8 PGs); **CND** – Centre for Nanoscale Dynamics (Burovski, Cheianov, Drummond, Fal'ko, Lambert, McCann, Schomerus, Aleiner 20%, Glazman USAS 20%, 19 RAs, 25 PGs); **LTP** - Low Temperature Physics (Bradley, Fisher, Haley, Tsepelin, McClintock 20%, Pickett FRS 20%, 6 RAs, 14 PGs); **QNT** - Quantum Nanotechnology (Hayne, Kolosov, Krier, Pashkin, Ponomarenko, Prance, Young, 7 RAs, 25 PGs). We collaborate with Chemistry, Environmental Science, and Engineering, and 4 other Physics staff have been entered in the UOA15 submission; we engage with users in blue-sky and industry-led projects, and we run an active outreach programme.

b. Research Strategy

Our strategy is to foster **clusters of excellence** with critical mass of expertise and infrastructure in:

- fundamental structure of matter and the universe (CAP, EPP);
- space science and space weather (SS);
- condensed matter physics, with a focus on ultra-low temperature physics (LTP, CND, QNT);
- nanoscience, with a focus on quantum technologies and new nanomaterials (QNT, CND, LTP).

Our long-term success relies on maintaining high-quality facilities and investing in people. Strategic management is steered by the Long Term Strategy Group, chaired by the HoD. Our plans are coordinated with the SciTech Faculty, discussed at termly staff meetings and annual Away Days, and periodically reviewed by external panels (most recently, in 2012). Metrics in the Table below (publications, personal awards, outreach, use of facilities, income) demonstrate that our strategy has led to a sustained outstanding and strengthening performance. Notably, 3 of our REF outputs were cited in Scientific Backgrounds (Nobel.org) for the 2010 and 2013 Nobel Prizes in Physics.

Table	cat A FTE	RAs **	fellowships & awards	PhDs awarded	papers in ISI journals	HIJ*** papers	cites ** per REF output	meetings organised	outreach annual audience	facilities + income per FTE, £k p.a.	average facilities £M p.a.	average income, £M p.a.	Funds available in 2014 grant portfolio **
REF2014	**34.9**	**53**	**16**	**67**	**1121***	**101***	**47**	**117**	**760**	**231**	**3.52**	**4.58**	**£12.1M**
RAE2008	26.4	41	11	34	859	67	30	71	420	194	2.64	2.48	n/a
RAE2001	20.8	29	4	38	797	40	24	42	410	201	2.68	1.52	n/a

*) Papers published with Lancaster address. Total all papers authored by category A staff: 1304 (136 HIJ)

) on census date *) HIJ = Science, Nature group, Phys Rev Lett, Nano Lett, ACS Nano, JACS, Adv Mat

Below, we describe how the overall research strategy is implemented in each cluster of excellence, including **contextual results since 2008 and future plans**.

Quantum Nanotechnology **(QNT)** is the core of the **Quantum Technology Centre (QTC)**, a new initiative focused on the investigation and practical implementation of quantum phenomena in nanostructures and studies of novel materials. The QTC provides us with a platform for synergy between QNT, LTP & CND activities in Physics, Engineering and Chemistry. It combines earlier established activities in MBE growth, optical characterisation and scanning microscopy with newly acquired expertise in experimental nanoscience and low-dimensional materials. The QNT group is supported by a £4.7M University investment in a state-of-the-art nanofabrication facility with characterisation instruments (see **(d)**). QNT has attracted new talent, with 4 new academic appointments backed by: a 2012 EPSRC *Strategic Package* (Pashkin); 2012 & 2013 RS URFs (Young, Ponomarenko); 2013 Marie Curie *Reintegration Grant* (Prance).

● Our plans in superconductor-based nanostructures focus on developing coupled qubit-resonator structures for a microwave single photon source; realising a dc electric current source (with NPL and Aalto) based on single-electron pumping in SINIS transistors with an output current of (1 ± 10^{-6})nA; and we are marrying a solid state qubit with a nanomechanical resonator in a new hybrid system. These plans are built upon Pashkin's recent discovery of microwave fluorescence and electromagnetically induced transparency in an on-chip artificial atom, real-time observation of Andreev tunnelling events in normal metal – insulator – superconductor (NIS) structures, and new understanding of the sub-gap leakage and phase slips in NIS circuits.

● Our research in semiconductor quantum dot qubits develops their applications in information processing and metrology. In quantum cryptography, Young has demonstrated that classical networks can support quantum key distribution. This effort is facilitated by dedicated growth of InAsN(Sb) narrow gap dilute nitride alloys, self-assembled GaSb/GaAs quantum dots/rings and MBE growth of dilute bismides. These new materials made at Lancaster are being applied to quantum information processing, thermophotovoltaics and photo-electrolysis, and are provided to 11 academic and industry partners for the development of applications in telecom lasers, nanophotonics, solar cells, environmental protection and collision avoidance.

● Our development of combined atomic force and thermal microscopy instruments (Kolosov) led to new patented techniques for the preparation and sub-surface imaging of nanostructures and ultra-thin molecular domains. This has been used in our studies of morphology of atomically thin layers of hexagonal transition metal dichalcogenides and gallium chalcogenides, and in the first nanoscale-resolved heat transport measurements on suspended graphene structures.

● We are expanding our experimental capability into quantum transport studies in atomic 2D materials and hybrids comprising atomically-thin hexagonal transition metal dichalcogenides, hexagonal boron nitride (hBN), and graphene. This new strand, overlapping with the CND interest, is being built upon Ponomarenko's recent discovery of the interlayer electron drag in graphene-hBN multilayers, the first realisation of graphene-hBN and graphene-WS_2 vertical tunneling transistors, and his pioneering work on single-electron transport in graphene quantum dots.

Low Temperature Physics (LTP) strategy is to advance cooling technology beyond the current state-of-the-art and to perform experiments at the lowest achievable temperatures. Our 3 unique in-house built nuclear demagnetisation fridges hold several low temperature records.

● The translation of Haley's RS-URF and Tsepelin's EPSRC-AF to permanent posts and Fisher's leadership has enabled us to diversify our research portfolio. We have discovered quantum turbulence in ^{3}He, followed by the first direct measurement of turbulent energy dissipation. We have developed a real-time quasiparticle "visualisation" technique to image turbulent vortex tangles and other structures. Our unique facility for producing isotopically pure ^{4}He has been used by many groups world-wide. We have used this to study wave turbulence in superfluid ^{4}He and to image vortex tangles with He2 excimer molecules.

● Our studies of the exemplar first order phase transition between the *A* and *B* phases of superfluid ^{3}He have shown that the *AB* phase boundary can be viewed as a model m-brane, giving insight into cosmological processes in the early Universe. Ready access to extreme low temperatures resulted in the first measurements of ultra-long-lived freely-precessing NMR modes in superfluid ^{3}He-*B*, now recognised as a BEC of magnons, and the group has recently elucidated their decay mechanisms. We discovered magnetic ordering in a nanometer network of solid ^{3}He coating silica aerogel using a new demagnetisation method developed by Fisher and Bradley to cool immersed ^{3}He to record low temperatures by bypassing thermal resistance.

● Our high international reputation is recognised by the EPSRC in its recent *Portfolio and Shaping Capabilities* review, and Pickett leads the new spin-out *Lancaster Cryogenics Ltd* focused on disseminating cryogenic expertise and producing bespoke components for academia and industry. LTP is a co-founder of the FP7 European *MicroKelvin* network, and is currently commissioning an ultra-low-noise nuclear cooling machine, to study nanoscale devices and materials at record low temperatures (with QNT and network partners). Encouraged by the EC, we plan to extent the *MicroKelvin* network into Horizon 2020. In 2014-2015, we will expand our metrology base even further, with an *IsoLab* designed for high-precision ultra-low-noise measurement, co-funded by Lancaster University and the Wolfson Foundation.

Centre for Nanoscale Dynamics (CND) has a strategy to advance quantum condensed matter theory and theoretical nanoscience. The CND research portfolio includes quantum transport and quantum optics; development of new analytical methods for strongly non-equilibrium quantum systems; studies of kinetic and correlation effects in low-dimensional materials and nanostructures; advanced computational molecular electronics. CND closely collaborates with QNT, uses High End Computing facility at Lancaster, and is engaged with many UK and international partners (see **(e)**).

● In molecular electronics we model devices including the effects of gaseous, liquid or solid environments, identified new strategies for developing molecular-scale devices with giant thermopower and figures of merit, novel sensors based on single-molecule solvation-shell sensing, and proposed an original drive mechanism for carbon-nanotube-based nanomotors. These studies were performed within 3 EU networks using the *SMEAGOL* code, co-authored by Lambert, which is used by 110 groups in 29 countries for modelling nanostructures. Our theoretical predictions initiated 3 patents, two of which resulted from a BP-funded *Enhanced Oil Recovery* project.

● In strongly correlated systems, we studied the Néel transition in the 3D Hubbard model; exactly solved the dynamical properties of the 1D spin-1/2 Bose-Hubbard model near a Mott-insulator – ferromagnetic liquid transition; studied the role of magnetic impurities at the edge of a topological insulator; modelled the manifestation of Majorana fermions in hybrid superconductor structures. With Cheianov's ERC *Starting Grant* and the expertise of Burovski (in diagrammatic Quantum Monte Carlo) and Glazman, we will develop new methods to tackle non-equilibrium states in strongly correlated quantum 1D systems. In quantum optics, Schomerus (leader of a Marie-Curie EXT) developed a quantum theory of lasers with distributed gain and loss; proposed topological mechanisms for photonic wave guiding; Fal'ko studied nuclear spins in optically pumped quantum dots. We plan to study (with Sheffield) photon statistics in four-wave-mixing in non-linear microcavities and (with UCL and Leeds) atoms in an ultra-strong laser fields.

● Our research in graphene and graphene-based devices involves both the development of new theories and their test in a close collaboration with experiments at Manchester, Cambridge, UC Riverside, NHMFL-Florida, Berkeley NL. Cheianov, McCann, Schomerus & Fal'ko studied quantum transport in strained graphene and in graphene functionalised by dopants; single-electron charge pumping in graphene quantum dot circuits; optical spectroscopy, Raman scattering, and ARPES. We predicted strongly correlated low-temperature phases in bilayer graphene and electronic properties of trilayers. We produced a model for charge transfer in epitaxial graphene on SiC, explaining the observation of metrologically accurate Hall resistance quantisation in this system, thus, paving ways for the practical implementation of the universal quantum resistance standard (with NPL, Chalmers). We participated (with Manchester, GHMFL-CNRS) in a discovery of fractal spectra of electrons in graphene heterostructures with boron nitride (hBN) at high magnetic fields.

● Our future theoretical studies of 2D materials, supported by an EPSRC S&IA, CDT *Graphene-NOWNANO*, FP7/Horizon2020 *European Graphene Flagship* and ERC Synergy Grant *Hetero2D* (with Novoselov and Ferrari), will span over functionalised graphene, silicene, atomic layers of gallium chalcogenides, transition metal dichalcogenides, and their heterostructures with graphene and hBN. This effort will be enhanced by the expertise of Drummond in *ab initio* quantum Monte Carlo methods and DFT modelling and collaboration with Lancaster Chemistry.

Space Science **(SS)** group (moved into dedicated facilities in Physics in 2009) studies space plasma stretching from the surface of the Sun to the upper atmosphere of the Earth and other planets, and the related application-oriented issues of space weather.

● Honary and Kosch have developed and operate state-of-the-art instruments (e.g. Imaging Riometers and Scanning Doppler Imager) in polar regions, enabling us to study plasma interactions within the Solar system. We supplied imaging riometers to the Polar Research Institute of China and the Indian Institute of Geomagnetism. Utilising the ionosphere as a natural laboratory, Honary and Kosch have identified the mechanisms for particle acceleration and plasma instabilities by means of high power radio waves. Honary has developed a simulation code for dusty plasma dynamics, which will be used to study the near-surface dust of airless bodies, predicting their effect on robotic and human space missions.

● Using the data from NASA *Mars Global Surveyor* spacecraft, Wild has shown for the first time that flux ropes are encountered repeatedly at the southern terminator over a period spanning a Martian year, contrary to the prior assumption that these are transient phenomena.

● In the future, we plan to use the VLF wave methods (developed by Denton) that remove energetic particles from the radiation belts to develop new technology for increasing the lifespan of satellites. In the long-term, we plan to exploit the capabilities of ESA/NASA space missions (e.g.

Van Allen Probes, JUICE) to study the magnetosphere and ionosphere of other planets, enabled by the recent appointment of RAS Fellow Badman who has secured two programmes on the *Hubble Space Telescope* to study aurorae on Jupiter and Saturn; this will be further expanded by one more lectureship in space plasmas.

Cosmology and Astroparticle Physics (CAP) group studies the early Universe, the origins of the cosmic microwave background (CMB) and cosmological structure and the interplay between particle physics theory and cosmology. Our research is directly relevant to the interpretation of the latest experimental results from ESA's Planck satellite, the CERN-LHC and dark matter detection experiments. The group is a founding member of the Lancaster-Manchester-Sheffield "Consortium for Fundamental Physics", funded by a STFC Consolidated Grant.

- Dimopoulos has demonstrated the possible role of vector boson fields in generating statistical anisotropy in the curvature perturbation. Mazumdar and McDonald developed a TeV-scale framework connecting the baryon density to the density of thermal relic WIMPs and explored Higgs Inflation-type models and the unitarity problem. Mazumdar constructed a ghost-free higher derivative extension of General Relativity that can render gravity asymptotically-free in the deep ultra-violet. Our recent work was focused on the interpretation of new observations from the Planck satellite, in particular the hemispherical asymmetry and the interpretation of precise measurements of inflation observables in terms of modified inflationary vacua.
- Our future plans extend the same areas with a focus on: theoretical interpretations of the latest large angle anomaly results and precise measurements of the primordial perturbation and primordial gravity waves from Planck; exploration of the process of particle production of vector boson fields in anisotropically inflating space-times; the development of new particle theories that connect the dark matter and baryon densities at the LHC-accessible TeV-scale; and the construction of an asymptotically free quantum theory of gravity that can resolve singularities.

Experimental Particle Physics (EPP) seeks new physics, investigates transitions between quark or lepton species and their relation to CP violation and performs standard model investigations. We held important leadership positions (computing, software, algorithms & physics group convenorships, speakers board, publications committee) in *D0* at the Tevatron, in *ATLAS* at the LHC, and in *T2K* collaborations (see **(e)**).

- At *D0* Bertram, Borissov, & Ratoff contributed to many leading edge *B*-physics measurements, recognized by the 2011 IoP Prize. We probed new physics using the decay of the B_s, measuring the difference been the B_s lifetime and that of its antiparticle and constraining the associated weak CP-violating phase. We are completing our *D0* data analysis, marked by the observation of an unexplained asymmetry in the production of same-sign dimuons (3.6σ deviation from standard model). Fox contributed to *D0* Higgs searches leading to a 3σ hint at the *Tevatron*. Our experience, acquired at the *Tevatron*, is being transferred to the *LHC.*
- Following studies of the tracking and trigger performance, and a leading involvement in the software and computing systems, Borissov, Fox & Jones exploited the first years of *LHC* data, including the search for the Higgs boson and taking an important part in the discovery and investigation of the boson observed in 2012. We investigated Higgs decays to τ-leptons, crucially established the correct Higgs mass scale using the J/ψ and, now probe its properties through the decay of the top into the Higgs and subsequent decays of the Higgs. We made the most precise measurement of the Λ_b lifetime. We also investigated the strong interaction through the production of '*onia*', including the discovery of the new state the $\chi_b(3P)$, with detailed measurements of J/ψ production, and investigate top quark decays. We continue to: make CP violation measurements and lifetime difference measurements in the decay $B_s \rightarrow J/\Psi\varphi$ that challenge new physics models; to study single/double-*onium* production, *onia* in association with heavy bosons to establish the LHC potential for quartic gauge boson coupling measurements; probe the Higgs decay properties and search for other Higgs states; and look for new physics objects decaying to top quarks. Jones has led the *ATLAS UK Computing and Software* activity, since 2002, and we lead the planning for the software and computing, provide a key benchmark physics study for the tracking in the upgrade and work on the replacement tracking detector for increased luminosity in 2018-2022.
- Kormos & Ratoff took a major part in the design and construction of the electromagnetic calorimeter of the *Near Detector* in the *T2K* experiment, including building the entire downstream module in Lancaster. We worked on the calorimeter commissioning and calibration, and on the graphical event display and software systems. We contributed to finding the first evidence of a

large, non-zero mixing angle θ_{13} in the electron appearance oscillation channel and the observation of the muon disappearance oscillation channel. We will continue to exploit the *T2K* data, increasing the precision on θ_{13}, θ_{23} , Δm_{23} and related neutrino cross-section measurements, and focus on the search for first evidence of CP violation in the lepton sector. The arrival of O'Keeffe & Nowak will expand our *T2K* activities and leadership roles, including new analyses of π^0 production, elastic scattering of neutrinos off atomic electrons and a search for an anomalous neutrino magnetic moment. We are also taking our first steps into the R&D phase of next generation long baseline oscillation experiments for the 2020's within the *LBNE* and *T2HK* collaborations.

c. People, including:

I. Staffing strategy and staff development

Our staffing strategy is to provide our clusters of excellence with a critical mass of highly qualified academics and stimulate growth of internationally recognised leaders. We promote an internationally-leading research culture and stimulate an aggressive approach to impact among our academics; we exercise a selective retention policy and attract new talent via international appointments and competitive fellowships. We support our staff by professional development from the first day of their employment and excellent research infrastructure. The implementation of the principles of the *Concordat to Support the Career Development of Researchers* and their alignment with our research strategy is overseen by the Physics Committee, chaired by the HoD.

Since 2008, we have made **9 staff appointments** in our key research directions. To build up our Quantum Technology initiative, we appointed Pashkin (NEC in Tsukuba) to a Chair supported by an EPSRC *Strategic Package*, Ponomarenko (2013 RS URF, from U Manchester) to a readership and Prance (U Wisconsin) and Young (2012 RS URF) to lectureships. We used support from the EPSRC-HEFCE S&IA to expand CND by two lectureships, for Burovski (ENS Paris) and Drummond (Cavendish Lab). New EPP lecturers O'Keeffe (Oxford) and Novak (Minnesota) expand our neutrino research, and Badman (Leicester) has joined the SS group with RAS Fellowship. Our **near-term plans** include one additional SS appointment, and a further expansion of the QTC capability in metrology-class nanoscale scanning spectroscopies and in the applications-oriented research at the interface between nanomaterials, chemistry and engineering.

● The Department has hosted >50 international visitors from Europe, USA, India, and Australia. These visits were supported by the EU, EPSRC, Leverhulme Fellowships, and a Faculty-funded CND visiting programme (annual budget of £25k). Two of our long-term collaborators, Aleiner (Columbia NY) and Glazman (Yale) became part-time Research Professors at Lancaster.

Staff development. We support individuals who deliver the highest quality research to meet UK and global priorities, and we have created an environment that develops new leaders. Our vibrant research culture is supported by 'work in progress' group meetings, and by weekly seminar series in condensed matter physics, in particle physics & cosmology, and in space science. We identify and promote best practices in Away Days; we identify difficulties and the training needs of our colleagues in annual one-to-one professional development reviews, which also help them to optimise the planning of research and teaching effort. Our staff attend HR@Lancaster development courses, such as '*Being a PI', 'Project Management', 'PhD Supervision', 'Recruiting the Best'*, and undergo mandatory diversity training before participating in interviewing panels.

● Our newly appointed staff have a reduced teaching load for the first 2 years, receive Faculty and University small grants and are prioritised in the award of PhD studentships. They attend induction and early-career training courses, receive personalised advice on preparing grant applications, and all newcomers have a colleague as a mentor. All staff are required to have proposals for grants reviewed by another, experienced member of staff. Staff use sabbaticals (112 months in 2008-13 at CERN, KITP-UCSB, U Geneva, etc.) to undertake leadership roles, start new research streams and establish new collaborations. We address professional gender issues in the 'Women in Physics' group, and support flexible and part-time working regimes for those with parental duties. Our fostering of equality and diversity resulted in the *Athena SWAN Bronze* award to the University and IoP *Juno Champion Status* to Physics.

● The efficacy of our staffing strategy is evidenced by highly competitive **awards and prizes** won by our academics: 2010 & 2011 RS Wolfson Research Merit Awards (Fal'ko, Pashkin); 2013 ERC Synergy Grant (Fal'ko); 2012 ERC Advanced Grant (Fal'ko); 2012 & 2013 RS URFs (Ponomarenko, Young); 2011 ERC Starting Grant (Cheianov); 2013 RAS Fellowship (Badman);

2009 STFC Science in Society Fellowship (Wild); 2009 QinetiQ Fellowship (Lambert); 2008 IUPAP Young Scientist Prize (Tsepelin); and the 2011 IoP Nuclear & Particle Physics Division Prize (Borissov). Several Fellowships have been completed during REF period: RS URF by Haley, EPSRC AF by Tsepelin, RCUK Academic fellowships by Cheianov and Hayne, Marie Curie EXT by Schomerus. We recognize research excellence and impact acceleration activities through promotions: Senior Lectureships to Denton and Tsepelin; Readerships to Bradley, Cheianov, Dimopoulos, Haley, Hayne, Mazumdar and McCann. Borissov, Schomerus and Wild became Professors, Lambert a Research Professor, and Fal'ko a Distinguished Professor.

Research staff and RA development. Physics employs 53 RAs (versus 41 in RAE2008), supported by 14 technicians and 7 administrative staff. Our processes support the professional development of existing researchers and the induction of new ones. All RAs maintain individual career-development plans; they participate in academic staff-development programmes, including annual performance reviews. They benefit from workshops on supervising research students, writing grant applications, career planning, and on writing skills for publications and outreach. Our Emeretia Guenault (IoP Simon Prize), Lyth (2012 IoP Hoyle Medal) and Sloan (IoP Rutherford Medal) are active in mentoring RAs. The HoD holds a termly round-table *Research Staff Forum,* and RAs participate in decision making via the Physics Staff Advisory Committee.

● Our training/mentoring and help in developing individual research portfolios have **enhanced the career prospects** of our researchers. Since 2008, 31 of our RAs relocated to academia (ICL, Bristol, Sheffield, TU Budapest, CSIC in Madrid, Caltech, Stanford, British Antarctic Survey, CERN, etc) and industry (BAE Systems, NASA, DSTL, Oracle Corp, etc.), while 14 researchers have taken tenure-track posts: Abergel (Nordita), Algaragholy (Babylon U), Al-Backri (Baghdad U), Carrington (UCL), García-Álvarez (Saragoza), Clovecko (Slovak AS), Gryshin (Cornell), Gustavsson (Tromso U), Khovanov (U Warwick), Mucha-Kruszynski (U Bath), Peeters (U Sussex), Prada (U Autonoma Madrid), Toke (UTE Budapest), Seviour (Lund U).

c. II. Research students

Training and support mechanisms. Our PhD training is directed towards students becoming independent researchers and future leaders in their respective fields. We educate PhD students in the wider context of economic and societal needs by ensuring contacts with industry leaders and by involving them in the outreach to the general public.

● Training in particle physics, cosmology, space science and theoretical/experimental condensed matter physics is structured around challenging hands-on projects within the research portfolio of our clusters of excellence, and we run interdisciplinary projects in quantum technologies and nanomaterials through the QTC, Marie Curie ITNs *FUNMOLS, NanoCTM, PROPHET, MOLESCO*, and the bilateral Manchester-Lancaster CDT *NOWNANO*. Students undertake individual tasks with increasing complexity and responsibilities, often, leading a sub-project or analysis by the end of their training cycle, and they obtain international experience when visiting our partners in the EU projects and networks (see (**e)**). Students have access to Lancaster facilities (see (**d)**), the Tevatron at Fermilab, LHC at CERN and T2K facilities in Japan, the University High End Computing facility, and, in some cases, the Worldwide LHC Computing Grid.

● In QNT and CND we link the research projects to current and future industry needs. Students are engaged with our industry partners (e.g. QinetiQ, NPL, Bruker, BP, Fiat, IBM, etc) via joint projects, and they get specialist training in innovation and commercialisation of research.

● We provide discipline-specific taught courses, both internally and via 6-months *NOWNANO* taught programme (with Manchester), and using our regional collaborations in low-temperature and particle physics. We provide transferable skills training and the opportunity to gain teaching experience (taken by the majority of students). This is further enhanced through the student-run *NOWNANO* conferences, Lancaster-led *Windsor Schools in CMT and Nanoscience*, EPSRC Schools *Physics by the Lake*, early-stage researchers training within ITNs, the Cockcroft Institute education & training programme, British Universities Summer School in *Theoretical Elementary Particle Physics,* and the STFC and CERN experimental particle physics Summer Schools. We provide our PGs with travel allocations for reporting their results at conferences.

Our approach to recruitment is to attract excellent applicants, with proven knowledge of the foundations of physics. We advertise PhD opportunities widely in journals/on-line (e.g., *findaphd.com*), open days, and talks by ambassadors drawn from the student cohort. The recruitment is run using an on-line application system, followed by interviews (CND requires formal tests). CDT *NOWNANO* students are selected by the bi-institutional Management Board. Since 2008, the number of PhD applications has doubled to 150 in 2013. This enabled us to **increase both quality and size of our annual intake**, from a median of 12 in 2001-09 to 20 in 2009-13 (currently 97 PhD students registered in all years) and with a stronger overseas fraction.

Management and monitoring progress. Each student is assigned a research supervisor, deputy supervisor, and an independent advisor. This team engages the student in formulating their initial objectives and the further development of his/her project, holds termly reviews, and gives career advice. The progress of the cohort is overseen by the Departmental Postgraduate Committee which includes representatives of all research groups, and by the Faculty Postgraduate Committee. Students give feedback in reviews and course questionnaires; they have elected representatives on the Teaching Committee and Faculty PG Committee. The results are reported to RCUK via Je-S Studentship Data Portal and to EPSRC via annual CDT *NOWNANO* reviews.

The student cohort experience is enhanced by joint projects, by colocation in offices for cognate research groups, by group meetings, by seminar series in condensed matter, in particle physics & cosmology and in space science, by Departmental colloquia, by an annual Faculty Christmas Conference and by a summer PG Research Conference. Experienced PGs take part in peer training of the new intake, run bi-annual Theory Days for undergraduates, and supervise summer interns. PG volunteers participate in the preparation of Lancaster-based conferences and in outreach.

Successful outcomes of our PG training are demonstrated by the 88% PhD completion rate, with 67 PhDs awarded during the REF2014 period (versus 34 awards during the RAE2008 period); and by 92% of our PhD graduates taking jobs in academia (Imperial College, UCL, Cambridge, U Maryland, McGill-Montreal, National Tsing Hua University, EPFL-Lausanne, etc.) and industry (IBM, BAE Systems, Rolls Royce, BASF, DSTL, Oxford Instruments, EDF Energy, etc.). Our students win awards at the University, national and international level, e.g.:

- 4 Faculty of Science and Technology *Dean's Awards* for excellence in PhD studies;
- 4 EPSRC *Doctoral Training Prizes* (to Mucha-Kruczynski, Garg, Lawson, and Robson);
- 2011 IoP *Very Early Career Woman Physicist of the Year Award* to Canovan;
- 2012 and 2013 *Springer PhD Theses Awards* to Mucha-Kruczynski and Stankowski.

Our next target is to increase further the quality and volume of our PhD training, aiming at an annual intake of 30 students in 2016-2020. Some prerequisites for this expansion have recently been put in place. We have established a new PhD in Nanoscience and secured strategic partnerships in the *National Graphene Institute*, in the 75-institutions-strong EU *Graphene Flagship*, and in the new EPSRC CDT *Graphene-NOWNANO* focused on science, technology and applications of atomic 2D materials. We have set up dual degrees with An-Najah University (Palestine) and COMSATS (Pakistan), have a University-wide partnership with the Iraqi government, and we are preparing a dual PhD degree in Nanoscience with the University of Chile.

- To increase international visibility of our PhD courses and for building new partnerships, we plan to restructure, in 2014, our PhD training into two Doctoral Training Centres (DTC). One DTC will train PGs in particle physics, accelerator science (with the Cockcroft Institute and Engineering in Lancaster), cosmology and space plasmas. The other DTC *QuantumNANO* (involving Chemistry and Engineering) will train PGs broadly in experimental and theoretical nanoscience, quantum nanotechnologies, low-temperature physics, materials (beyond graphene and 2D materials) and quantum condensed matter physics. LMU in Munich, Scuola Normale Superiore in Pisa, IoP CAS in Beijing and Argonne NL have already expressed interest in a partnership with *QuantumNANO* and hosting our students for joint projects.

d. Income, infrastructure and facilities

By employing an agile approach to fund-raising, we have **expanded and diversified our research funding portfolio.** Physics income was £4.6M (in 2008/9), £4.6M (09/10), £4.3M (10/11), £4.6M (11/12), £4.8M (12/13) [versus £2.48/annum in RAE2008, Table 1], and, in 2014, funds available in active contracts will sum up to £12.1M. Our research income in-kind and the use of facilities was £17.58M. Our RCUK funding portfolio features: 4 STFC consolidated grants; an EPSRC Portfolio Partnership, Science & Innovation Award (in Graphene - jointly with Manchester); 2 Programme grants with Sheffield; a Strategic Package; and many responsive mode grants. In 2009, the SS group opened a new stream of NERC funding. We have won substantial EU funding: €0.8M in

Microkelvin network, over £2.2M in the Marie Curie Action grants: 4 ITNs, 2 fellowships, and an Excellence Team; €2.2M in 4 ICT & NMP projects and the FP7 tranche of the *Graphene Flagship*; a €0.7M ERC Starting Grant; a €1.7M ERC Advanced Grant (rolling into a €2.1M share of a Synergy Grant *Hetero2D*). We hosted three RS-URF and one RAS fellow. We received £0.75M from British Petroleum for the *Enhanced Oil Recovery* project. These grants and University funding enabled us to expand the research base and activities of our clusters of excellence. In 2014-2015, we will expand our metrology capabilities, with an *IsoLab* designed for high-precision ultra-low-noise measurement, co-funded by the University and the Wolfson Foundation. In 2014-2016, we will undertake a £9M refurbishment of the Physics Building.

● Using a £4.7M **University investment in the Quantum Technology Centre**, we have built a new clean room facility, which houses a new JEOL JBX-5500FS e-beam lithography system for nanofabrication of novel device architectures and tools for dry etching and plasma deposition. The operation of the new facility is supported by cryogenic equipment, a 12T magnet, optical and GHz measurement instrumentation, and capability for nanoscale mapping of nanomechanical and nanothermal properties of materials and devices. We operate an epitaxial growth suite with 3 VG V80 MBE reactors for nanostructured dilute nitride alloys (InAsN and InAsSbN), Sb-based quantum dots, interface misfit epitaxial layers of GaSb on GaAs, now - with Bi and carbon cells.

● Our **low temperature infrastructure** comprises three in-house built dilution refrigerators, all with base temperatures below 2.5 mK (we hold the current record of 1.75mK) and a Lancaster-style demagnetisation stage giving us access to the 100μK regime for superfluid ^{3}He. We have completed a fourth machine, dedicated to nanoscience experiments. We have also two commercial 10mK refrigerators, 1K cryostats, a He liquefier and the world's best ^{4}He purification plant.

● **SS experimental facilities** comprise: a ground-based instrument network deployed in the high-latitude auroral region, providing magnetometry (*SAMNET*), riometry (*IRIS*) and auroral imaging (*Rainbow*) capabilities; a radio frequency laboratory at Lancaster; and radars in the *EISCAT/SuperDARN* shared-resource ground facilities and on ESA/NASA Earth-orbit missions.

● In Lancaster, **EPP** uses a high-grade clean box for semiconducting tracker work, and a lower grade clean area for tasks like calorimeter assembly. We have high-quality oscilloscopes and a temperature controlled device characterisation system for QA and performance studies on new and heavily irradiated semiconductor detectors, and a programmable stage. We also have a £30k in-house PROOF farm for parallel analysis. Outside Lancaster, EPP staff make use of facilities in CERN, and in particular the *ATLAS* experiment (material costs £245M, total construction costs ~£800M) at the *LHC* (construction cost £2.8B). We use bonding and irradiation facilities at CERN, BNL and RAL for upgrade work and *J-PARC* and *Super-Kamiokande* for the *T2K* experiment. We have also used Fermilab, its local computing and the Tevatron collider and *D0* detector.

● **EPP and CND** are supported by the Lancaster *High-End Computing Facility*, with 2600 high-end core processors and over 1PB of dedicated Grid storage maintained by dedicated staff in a purpose-built area in the new ISS building; this will receive a £600k refurbishment in early 2014 and £200k/year in subsequent years. Thirty GPU-enabled nodes and 30 very high memory nodes are also available. We share the *N8 HPC*, and the *Worldwide LHC Computing Grid*, where Jones chairs the collaboration board.

e. Collaboration and contribution to the discipline or research base

Our leadership of international research collaborations and networking across the UK play an important role in setting international research strategy and in anticipating future developments.

● Examples include leadership roles in *ATLAS* (e.g. UK computing, upgrade computing & data preservation co-ordination, physics sub-group convenors), *D0* (B physics, trigger convenors) and *T2K* (*ND280* event display, offline software & π^0 group convenors). EPP staff were founder members and continue to be active participants in *GridPP* (Jones is a Project Management Board member, and he was Applications Coordinator in 2008) and in Cockcroft Institute (Ratoff is Associate Director). Jones chairs the worldwide LHC computer grid (WLCG) Collaboration Board. In addition to EPP collaborations, with >300 research groups in ~50 countries, our staff collaborate with >250 scientific groups, spread over 32 countries, evidenced by joint funding and publications.

● We led and participated in seven EU-FP7 Initial Training Networks and Projects, 2 ESF networks, EPSRC-USA Materials Network, *EuroMet* project, and EC-funded *MicroKelvin* network (12 institutions). The SS group participates in the global consortia *AARDVARK, SUPERMAG,* *EISCAT, GLORIA*. CND is a partner in two EPSRC Programme grants with Sheffield, Cambridge and Glasgow, and in two British Petroleum projects with Durham, while the CAP group is a partner in a consolidated STFC grant with Manchester and Sheffield.

● Collaborations on graphene play a special role in our Department. In addition to EC projects *ConceptGraphene* and *Granada,* EPSRC projects with Cambridge, Exeter, Tokyo, Tohoku, we are partners with Manchester in a joint EPSRC Science & Innovation Award, ERC Synergy Grant *Hetero2D*, and a new CDT *Graphene-NOWNANO*. We hosted/co-organised 5 international graphene workshops in the UK and annual international *Graphene Week* Conferences; run extended Research Programmes at KITP UCSB, KITPC in Beijing and ITN in Seattle; initiated the ESF Eurocores Programme *EuroGraphene*. As a partner in EC-funded Coordination Action, we have developed the *Graphene Science and Technology Roadmap* for the EC, and Fal'ko is on the Executive Board and a work package leader in the European *Graphene Flagship* project.

● Overall, our staff organised and co-organised **117 international/national meetings** (15 in Lancaster), attended by 20,000 participants. In particular, we led the organisation of series of *Windsor Schools in CMT and Nanoscience* and annual *Ultra Low Temperature Conferences*.

● Our staff sat on **selection/review/advisory panels** of RCUK (NERC, EPSRC, STFC); the Royal Society URF and RAS; the EC Marie Curie Actions ITN, IEF, IOF, IIF, CAR; the EC ERC; the European Science Foundation; NASA; the French ANR and AERES, German DFG Priority Programme Graphene, RPF Cyprus, Czech Science Foundation, Swiss NF, Canadian NSRS and Space Agency, RCNSE - Academy of Finland, Estonian RC, Irish IRSET, Polish NCRD, Norwegian RC, SUPA, and the UK IoP Group & main Awards Committees. Bertram served on the Particle Physics, Astronomy and Nuclear Physics Science Committee (2007-2010), and McClintock on EPSRC Physics Grand Challenges Advisory Group.

Editorial activities: McClintock is Editor in Chief of *Fluctuations and Noise Letters (FNL),* board member in *Contemporary Physics* and *Nonlinear Phenomena in Complex Systems*; Fisher is board member in *Journal on Physics and Applications* and *Journal of Low Temperature Physics (JLTP), Journal of Fluids*; Fal'ko is board member in *Solid State Communications (SSC)* and founding Editor in Chief of a new IoP journal *2D Materials*. We were Guest Editors in special issues in *Journal of Atmospheric and Solar-Terrestrial Physics* (Denton on *Solar Wind*, Kosch on *EISCAT*), *SSC* (Fal'ko on *Graphene,* in 2009 & 2011), *New Journal of Physics* IoP (Fal'ko on *Graphene Optics*), *FNL* (Haley on *Fluctuations and Coherence*), *JLTP* (Fisher on *Quantum Fluids and Solids*). Our staff referee in all major journals, including Science and Nature group journals.

Engagement with users. Staff in Physics take every opportunity to translate their research results into practical innovation, supported by a Departmental Industry Coordinator and a full time Business Development Manager. In particular, £9M of our grants and contracts won since 2008 involve collaboration with >20 private sector partners. Active research contracts with industry have generated £1.5M in research income, including a project with British Petroleum and industrial contributions to 7 CASE/ICASE studentships with QinetiQ, HMGCC, Kidde International, etc. In a new initiative, spearheaded by the QTC, we use *Technology Access Vouchers* to cover external access to our infrastructure, and our latest spin-out company *Lancaster Cryogenics* expands commercialization of our know-how in cryogenic technologies.

● We give a high priority to **public engagement and outreach** activities, facilitated by an STFC Science in Society Fellow, the Lancaster-based IoP branch, and our dedicated IoP/Ogden Trust Teacher Fellow. We run *Particle Physics Masterclass*es and developed and maintain a schools-level particle physics computer package that is recommended by the IoP to their Physics Champions schools and is part of the *CERN Particle Physics Outreach* package. We run '*Physics Enrichment Days*', laboratory visits for school pupils, the *Ogden Physics Residential course*, support sessions for school science teachers, the regional public lecture series '*Making Waves*' and give presentations in schools country-wide. We participated in the 2010 & 2013 Royal Society Summer Exhibitions, the 2012 Cheltenham Science Festival, 2012 British Science Festival, and the 2009/13 Big Bang Fairs. Lancaster staff featured in the worldwide Higgs boson discovery coverage, and our work at the *Tevatron* attracted worldwide radio, online and print media attention. Our work on quantum key distribution was highlighted in BBC News. Space weather research and Lancaster's *Aurora Watch* have attracted over 100,000 individual users, several BBC broadcasts, and they featured in the IoP film '*Physics Lives*', which won a 2013 British Film Institute Award.