Institution: Queen's University Belfast

Unit of Assessment: 9 (Physics)

a. Overview: The School of Mathematics and Physics at Queen's University Belfast (QUB) contains 7 research centres, 4 of which are presented below for consideration by the UoA9 Physics subpanel (2 of the others will be considered under UoA10 and 1 under UoA8):

- **Astrophysics Research Centre (ARC):** 10 permanent academics (Fitzsimmons, Janson, Jess, Keenan, Kotak, Mathioudakis, Millar, Sim, Smartt (Director of Research [DR]), Watson) with primary interests in supernovae, exoplanets, solar physics, solar system objects and molecular astrophysics.
- **Centre for Nanostructured Media (CNM):** 8 permanent academics (Arredondo, Bowman [DR], Dawson, Felton, Gregg, Huang, Kumar, Pollard), with interests in functional materials and devices and in understanding properties at the meso and nanoscale.
- **Centre for Plasma Physics (CPP):** 16 permanent academics (Borghesi, Currell, Dromey, Field, Geissler, Graham, Greenwood, Jung, Kar, Kourakis, Lewis, Reville, Riley, Sarri, Williams, Zepf [DR]), interested in ultra-intense, short-pulse laser interactions and applications of radiotherapy/medical-related areas.
- **Centre for Theoretical Atomic, Molecular and Optical Physics (CTAMOP):** 10 permanent academics (Brown, De Chiara, Ferraro, Gribakin, Paternostro, Ramsbottom, Scott, Shearer, van der Hart [DR] and McCann (submitted to UoA8)) who apply theoretical methods to: attosecond science and strong-field processes; atomic collisions and antimatter studies; quantum information processing and quantum mechanics.

Each centre has its own identity, strategy and infrastructural management needs and is led by its own DR. Therefore, while some elements of the research environment can be discussed in general, specific details will often be presented on a centre-by-centre basis.

b. Research strategy

b.1 ARC b.1.1 Strategy and Vision: Following RAE 2008, we targeted our 3 strongest areas (supernovae, exoplanets and solar physics) for support. With QUB backing, we aligned our future direction with the UK STFC's strategic plans. These focus on ESO and ESA, together with EU developments. Our strategy has already witnessed success.

b.1.2 Evaluation of Position: ***Supernovae:*** Smartt was awarded an ESF European Young Investigator award (2005-10), which he used to build the largest European research team in supernova studies. QUB funded membership of the Pan-STARRS1 Science Consortium (£350k) in 2008 and we now lead the Public ESO Spectroscopic Survey for Transient Objects (PESSTO). This was awarded 450 nights at the ESO (2012-17); Smartt is PI and Survey Director. Kotak was elected to the E-ELT Project Science Team in 2012 and Smartt awarded an ERC Advanced Grant (2012). To augment these world-leading observational projects, ARC deliberately targeted a theorist to broaden the portfolio, hiring Sim in 2013. ***Exoplanets:*** QUB initiated, funded and built the SuperWASP facility in La Palma, which has become the world's leading ground-based transit survey for exoplanet discovery, and led the SuperWASP team to the Royal Astronomical Society Group Achievement Award 2010. This success led to 2 strategic investments in the Next Generation Transit Survey (NGTS) facility and HARPS-North, through £650k of QUB funding. These are 2 of the highest profile next-generation ground-based searches for low-mass, rocky planets. Watson is a Co-I and Board member of the NGTS at ESO Paranal. A strategic staff appointment was made to recruit Janson to enhance this rapidly growing area. ***Solar Physics:*** Mathioudakis and Keenan designed and built ROSA (Rapid Oscillations in the Solar Atmosphere), a very high cadence imager of the solar surface. Backed by QUB funding (£200k), this has quickly achieved high scientific productivity. Its success has been underpinned by a STFC Postdoctoral Fellowship (Jess 2009-12), the William Penny Research Fellowship award to Keenan (AWE), significant STFC funding for ROSA, and a STFC ERF for Jess (2013). We are developing a similar camera for the Advanced Technology Solar Telescope (ATST), having secured £300k of University funds to lead a UK consortium with the goal of being the first light imager for this 4m-class world-leading solar telescope. Solar system research (Fitzsimmons), particularly with the Pan-STARRS1 telescope, attracted Royal Society Newton and STFC Fellowships (Lacerda, 09-10; Hsieh 07-10) and a private donation (£200k) for solar system research and public outreach.

b.2 CNM b.2.1 Strategy and Vision: CNM has progressively focused its research effort into 2 main themes: (1) nanoscale materials and (2) optical and plasmonic behaviour in increasingly complex systems. Both themes have been identified as priority areas of National (EPSRC –

Shaping Capability) and International (Horizon 2020) importance. We therefore wish to continue in these research fields, but with increased vigour driven by: (i) expertise from new staff (with experience in different materials systems, different aspects of optical physics and specific aspects of electron and scanning probe microscopy (c1.2)); (ii) new synergies among staff (e.g. in ferroic and optical characterisation); (iii) further engagement with Seagate Technology (in heat-assisted magnetic recording) and FEI Company (to develop and exploit novel microscopy techniques).

b.2.2 Evaluation of Position: CNM is in an even stronger position than in RAE2008. The scientific quality of outputs has improved such that we have generated 9 papers in Science or Nature series journals and over 40 in other high impact journals (e.g. Nano Letters, Advanced Materials, PRL and ACS Nano) during the REF period. The average impact factor of the journal outputs included in this REF submission (IF~11) has increased by a factor of 2 since the RAE2008 submission. Research in nanoscale ferroic materials has gained significant international profile (invited talks and prizes); plasmonics research is yielding high profile publications and major citation recognition. Our healthy, balanced funding portfolio (60% EPSRC / 40% others) provides a robust and sustainable base for our activity. While maintaining our commitment to fundamental science, we have significantly increased engagement with industry and have commercialised research through spin-out activities. We have secured a ~£9M investment from Seagate Technology to establish ANSIN (www.ansin.eu). Major additional infrastructure has been commissioned (see d2.2), further improving already excellent in-house facilities for nanoscale research. We aim to increasingly target the use of international facilities for specific critical experiments (e.g. electron holography).

b.3 CPP b.3.1 Strategy and Vision: CPP seeks to support and enhance its research along two principal themes: (1) ultra-intense, short-pulse laser interactions, (2) radiotherapy studies and medical plasma applications. The first theme has significant global profile already and we believe that high quality science will continue to emerge. Thus deliberate investment in new posts has been made to enhance this activity (c1.2). The second theme is strategically important, as we believe physics in medicine to be a growth area. It is connected to the high power laser research (through plasma-based accelerators) and encompasses work at Diamond Synchrotron. Collaboration with the Cancer Research Centre and Pharmacy in QUB is expected to increase.

b.3.2 Evaluation of Position: CPP has achieved substantial success in implementing its strategy. We have strengthened the laser-plasma interactions with new members of staff and are now the largest laser-plasma grouping in the UK and one of the largest in Europe. This is reflected in the publication of over 50 papers in PRL and 9 in Nature Journals during the REF period. Our high quality activity has been enabled by substantial grant success and access to excellent facilities: in-house (TARANIS laser), through RCUK (CLF lasers, primarily VULCAN and GEMINI and Diamond) and at the following international sites: France: LULI and CEA Saclay; Germany: FLASH (Hamburg), JETI (Jena), PHELIX (GSI) and LWS20 (MPI for Quantumoptics); Italy: Milano; Switzerland: SLS; outside Europe: LCLS at SLAC, the Trident laser (LANL), Titan (LLNL), JAERI (Japan). The TARANIS laser is a key component of the group strategy, as it provides CPP with instant access to the highest energy university short-pulse laser in Europe. Together with its femtosecond arm, the TARANIS laser supports both our intense laser plasma and ultrafast science. The strength of the group has resulted in significant international recognition (Zepf holds co-directorship of Helmholtz Institut Jena and Borghesi leads a group at ELI Prague) resulting in substantial synergies. The group has had major grant funding success: a programme grant for applications of laser particle accelerators to health care (£4.5M, Borghesi/Zepf) following on from the LIBRA basic technology grant (£4.7M Borghesi/Zepf) demonstrating CPP's leadership in development and applications of laser-based accelerators. The platform grant (Yotta) allows CPP to spearhead international collaboration (including MPI Heidelberg, University of Michigan and Helmholtz Institut Jena) investigating the non-linear QED frontier of intense laser interactions (£1.4M). Other major awards were for: research into Warm Dense Matter (3 grants totalling £1.6M, Riley/Lewis), producing science at the highest level at world leading facilities; radiology-related grants (Currell, £1.3M), targeting novel approaches to cancer treatment; and EPSRC Career Acceleration Fellowships (Dromey, O'Connell and Kar) rewarding emerging leaders in their field.

b.4 CTAMOP b.4.1 Strategy and Vision: CTAMOP research in theoretical atomic physics focuses on attosecond science, atomic collisions and quantum information. In attosecond science, newly available laser technology, such as free-electron lasers (FEL) and sub-femtosecond light pulses, requires development of new computational techniques to describe novel atomic dynamics. Within CTAMOP, this development comprises of time-dependent R-matrix theory (RMT) for ultra-fast

processes and 2D R-matrix propagator techniques for multi-electron emission in general atoms. We will continue in this area by combining these techniques to describe multi-electron emission in ultra-short light fields, and by transferring RMT technology from atomic to molecular codes, in collaboration with UCL and the Open University. In atomic collisions, the provision of atomic data for highly complex open-shell atoms and ions, necessitating large-scale computation, remains key. We are expanding our studies beyond systems of astrophysical interest to those of fusion science. In antimatter studies, the role of vibrational Feshbach resonances in enhanced positron annihilation will continue to be investigated, with theory to be developed for positron binding with non-polar molecules. Through 3 appointments, we have significantly expanded our efforts in Quantum Information Processing (QIP). Our work focuses on strongly correlated quantum many-body physics to investigate the relationship between thermodynamics and quantum mechanics in mesoscopic-scale systems. Using density-matrix renormalisation codes, we will study quantum correlations in open many-body systems subjected to thermodynamic processes. In collaboration with experimental groups (*e.g.* ETH Zurich, Southampton), we will also focus on non-classicality of microscopic and mesoscopic systems. We will continue to strengthen links with others, including those at free-electron laser facilities, users of atomic data in plasma physics and fusion science, and QIP groups in Barcelona, Aarhus, Rome and Vienna. Participation in European networks (e.g. Initial Training Network (ITN) CORINF, COST Actions [MP1209, CM1204]), and leadership of the STREP consortium TherMiQ (starting 2014) will support this.

b.4.2 Evaluation of Position: Within attosecond science, we have successfully developed time-dependent R-matrix codes for ultra-fast multi-electron dynamics in atoms. These codes have been applied to the dynamics generated by electron correlation, to time delays in atomic photoionization, and to harmonic generation. A 2D R-matrix propagator code has been developed for intermediate-energy electron scattering from H-like atoms and ions. Within atomic collisions and antimatter, we have undertaken the largest-scale calculations to date for electron scattering of the iron-peak elements (e.g. Ni^+, Fe^+), and linked up with astrophysical modellers investigating star formation in the early universe. An ongoing collaboration with UC San Diego has validated CTAMOP predictions on the role of vibrational Feshbach resonances in positron-molecule scattering. Within QIP, we have strengthened our links to other teams in Europe (*e.g.* Aarhus, Barcelona, Ulm). We have undertaken joint studies with experiment (*e.g.* Rome, Vienna) on quantum computation and multipartite quantum correlations. For complex many-body systems, we have developed codes for density-matrix renormalisation, and applied these to the entanglement spectrum and critical exponents in quantum spin chains. We have further developed a line of investigation in non-Markovian open quantum systems and quantum system thermodynamics.

c. People:

c.1 Staffing strategy and staff development

c.1.1 Academic Retirements and Resignations: In the REF period, 9 staff members retired and a further 5 took up positions in other UK universities (Imperial College, King's College, Warwick and York). This provided an opportunity for the School to evaluate and refocus activities, by making new appointments into the areas of research of greatest strategic importance.

c.1.2 Appointments: 17 academic appointments to the UoA were made in the REF period, with 80% from non-UK countries of origin: a welcome development in internationalisation. **ARC**: Supernovae, exoplanets and solar physics were identified as areas of current quality and great future scientific potential; 4 new lecturers were appointed as follows: *Supernovae:* **Sim** (international appointment from Australian National Univ.); *Exoplanets:* **Watson** (UK appointment from the Univ. of Sheffield) and **Janson** (international appointment from Princeton, USA); *Solar Physics:* **Jess** (from a fellowship held in QUB). **CNM**: 4 new appointments were made to augment ferroic materials and plasmonics research, while at the same time enhance microscopy expertise: **Arredondo** (transmission electron microscopy of ferroelectrics; a Mexican national, from a research fellowship in MPI Halle, Germany); **Felton** (Lorentz imaging and Magnetic Force Microscopy of nanoscale ferromagnets; a Swedish national, from a temporary lectureship at Imperial College London); **Huang** (nano-optics and plasmonics; a Chinese national with UK citizenship**,** from the University of Cambridge); **Kumar** (scanning probe microscopy of ferroelectrics; an Indian national, from ORNL, USA). **CPP**: appointments were made to further develop the world-class activity in intense laser interactions with matter: **Reville** (Oxford) extended the theoretical capabilities in the centre, while **Dromey, Kar**, **Sarri** (from EPSRC fellowships held in QUB) and **Jung** (Los Alamos National Lab., USA) enhanced the experimental activity.

CTAMOP: a concerted effort was made to invest in QIP. **De Chiara** (an international appointment from UAB-Barcelona), **Paternostro** (from an Early Career Research Fellowship held at QUB) and **Ferraro** (previously a Marie-Curie Fellow at UCL and temporary lecturer at the University of Sussex) are all active in QIP. **Brown** (from QUB PhD) enhances attosecond science research.

c.1.3 Academic Probation: New academic staff are required to serve a probationary period prior to either being confirmed in post, having an extension to probation, or having employment terminated. The Head of School (HoS) appoints a mentor who meets with the probationer once per quarter to review progress and give advice. In addition, a probation committee is formed within the School (normally consisting of the HoS, Head of Teaching, the DR for the probationer's centre and a professor from another centre). This committee meets annually to discuss reports from both the probationer and their mentor. Recommendations are communicated to the probationer and the University Central Probation Committee, who decide the course of action for employment. Clear indications of academic profiles needed are made available, and all probationers are made aware of key indicators by both their mentors and the probation committee. They are given reduced teaching and administration loads compared to established staff.

c.1.4 Academic Promotions: The School has a strong track record of successful promotions: in the REF period, 7 staff were promoted to professor and 5 to senior lecturer / reader. Success is due to strong staff performance and promotion mentoring. Those considering submission of promotion documentation (responding to the annual call) will have already discussed matters at twice yearly appraisals and will have reviewed the typical academic profile guidelines generated by QUB. In addition, they will have met with the HoS for specific advice in shaping their application. The HoS gives an annual seminar on applying for promotion, to which all eligible staff are invited.

c.1.5 Research Staff: The Concordat: Research staff are employed using the same appointment procedures as for permanent university positions. Contract researchers and independent research fellows are integrated into the workforce under the same terms and conditions as permanent staff and their progress is managed using similar formal induction, probation, project review and appraisal processes. QUB has been awarded an HR Excellence in Research Certification (Jan 2012), linked to the Concordat for the Career Development of Researchers and the QAA Code of Practice for Research Degree Programmes (that acknowledges alignment with the principles of the European Charter for Researchers and Code of Conduct for their Recruitment). QUB agreed a Concordat Implementation Plan in 2012, building on the Queen's Researcher Career Booklet (published 2010), which gave an overview of the Concordat and career development advice.

c.1.6 Research Staff: QUB Staff Development Training Unit (SDTU): QUB invests ~£150k per annum through the SDTU to provide the following support for research staff: (i) provision of a range of internal courses; (ii) access to a 'Short Courses and Conference Fund' (which funds conference, networking and dissemination activity for researchers); (iii) the 'Researcher Training and Development Fund'. This supports development ideas generated by individual research staff. In the REF period, it has been used by research fellows in the School to run microscopy-training days, paying for masterclasses with external experts. SDTU also provides support through online information and materials (http://www.qub.ac.uk/crs).

c.1.7 Research Staff: In-House Career Development: Staff who have developed their research careers, partly or entirely within the School, prior to recent appointment to permanent academic posts include: **Brown** (PhD at QUB), **Dromey, Jess, Kar, Paternostro** and **Sarri** (PhD and Research Fellowships at QUB).

c.1.8 Equality and Diversity: Equality and diversity are taken extremely seriously, as they have been major historical issues in N. Ireland. Formal diversity and equal opportunities training is compulsory. Policy details can be seen at: http://www.qub.ac.uk/directorates/HumanResources/EqualOpportunitiesUnit/EqualityandDiversityPolicy/. With support from the 'Queen's Gender Initiative', the School obtained Athena SWAN bronze (2011) and silver status (2013). Flexibility on working hours is given via part-time contracts where requested (e.g. Scott currently on 0.7 FTE).

c.1.9 Fellowships: The School recognises new significant fellowships with the award of a PhD studentship. During the REF period the following were held by academic or research staff in the UoA: **Calvert:** EPSRC Post-Doctoral Fellowship (PDF) at the Physics-Life Science interface (2010-13); **de Chiara:** Juan de la Cierva (2009-11); **Dromey:** EPSRC Career Acceleration Fellow (CAF) (2009-14); **Ferraro:** Marie Curie Fellowship (MCF) (2011-12), UAB Beca Fellowship (2010), Juan de la Cierva (2007-09); **Gribakin**: Gordon Godfrey Fellowship, University of New South Wales (2012); **Hsieh:** STFC PDF (2007-10); **Jess:** STFC PDF (2009-12), MCF (2012-13), STFC Ernest

Rutherford Fellowship (2013-); **Kar:** EPSRC CAF (2012-17); **Keenan:** William Penney Fellowship, AWE Aldermaston (2008-11); **Kjaer:** Danish Carlsberg International Fellowship (2008-11); **Lacerda:** Royal Soc. Newton Fellowship (2009-11); **Maund:** Royal Soc. URF (2011-); **Mazzola:** MCF (2012-14); **Nikolopoulos:** MCF (2007-08); **O'Connell:** MCF (2008-09) followed by EPSRC CAF (2009-11); **Paternostro:** EPSRC CAF (2008-14) and Alexander von Humboldt Fellowship (AvHF) for Experienced Researchers (2012-14); **Reville:** AvHF (2008-10); **Sarri:** Leverhulme Trust Early Career Fellow (2011-14); **Alina Schilling:** EPSRC CAF (2009-); **Joerg Schilling:** Royal Soc. URF (2005-09); **Smartt:** European Young Investigator (2005-10), ERC Advanced Grant (2012-); **Watson:** STFC PDF (2005-08); **Xuereb:** Fellowship of the Royal Commission for the Exhibition of 1851 (2011-14); **Zepf:** Wolfson Merit Award of the Royal Soc. (2005-10).

c.1.10 Visiting Scholars: Honorary research titles are awarded by the University to visiting scholars to facilitate research collaborations and to enhance academic links and research networks. Staff members apply on behalf of the proposed visiting scholar; this application is considered by the HoS and then by the Academic Affairs Department. In the REF period, 160 visiting positions were conferred on the School (60 Research Associates, 80 Fellows, 14 Senior Fellows, 6 Professors).

c.1.11 Specific Census Data Requested (as at 31st Oct 2013): FTE number of research assistants: 33.45. FTE number of technicians, scientific officers and experimental officers: 12 (8 technicians, 1 facilities manager (electron microscopy) and 3 computer support officers).

c.2 Research students

The School Post-Graduate Research (PGR) Coordinator (Mathioudakis) oversees the logistics associated with managing the research student body. He acts as a key point of contact and monitors PGR progress, as well as the overall PGR environment by formal report and feedback from staff-student consultative meetings and student forums (facilitated by an academic acting as a PGR Careers Officer). Research centres also appoint a member of staff charged with PGR management and development within each centre.

c.2.1 Sources of Funding and PGR Numbers: The UoA typically receives funds from the Department for Employment and Learning (DEL) in N. Ireland for ~10 PhD studentships per annum (pa). Prior to changes in policy, additional positions were obtained through RCUK 'project studentships' (~5 pa); these have now been replaced by an EPSRC University DTA allocation. Direct industrial funding, knowledge exchange partnerships and EU grants also support PhDs. Until the 2013 EPSRC competition, QUB was ineligible to apply for DTC/CDT funds. Nevertheless, we secured partnership in a CDT (light) on "Applications of Next Generation Accelerators" (8 studentships in 3 years). During the REF period, almost 100 PhD students qualified from the UoA.

c.2.2 Appointment and Training (General): PhD positions are advertised internationally. All applications satisfying basic eligibility criteria are then considered. Usually, there is a minimum entry requirement of a 2:1 Honours degree. Preference is given to those with MSci (over BSc) and to those with 1st class Honours. For international students, the University Admissions Office establishes equivalency of qualifications. Appointments are made following interview and uptake of references. Once appointed, our PhD students undertake a training programme to develop a range of professional skills, help ensure success in their research and enhance their employability. This programme includes: training on generic skills co-ordinated by the Postgraduate Office (see c.2.3 PRDP); subject-specific training delivered by the School; training offered by RCUK and Professional Bodies; skills development through presenting their research work at internal meetings and external conferences, generating publications and teaching or demonstrating. Examples of subject-specific training developed by the School are: the international workshop on methods for computational atomic physics (held 4 times over the REF period in collaboration with Lund and Rennes) and a training course on "How to apply for fellowships".

c.2.3 Postgraduate Researcher Development Programme (PRDP): The PRDP links directly with the national Researcher Development Framework (http://www.vitae.ac.uk). Its aim is to support PG research students to develop their research and transferrable skills, as well as enhance their career development and employability. The programme is designed and delivered in line with the National Researcher Development statement and framework. Details of the PRDP can be found at http://www.qub.ac.uk/prdp. There is a dedicated PG training team as well as state-of-the-art facilities within the International and PG Student Centre. As an illustration of scale, 4000 attendees undertook 275 training workshops during the 2011-12 period. QUB also organises a peer-mentoring programme that enables 2nd and 3rd year PG research students to support 1st year

peers. An online 'Personal Development Planner' tool has been developed to assist students (and supervisors) to carry out a training and development needs analysis and shape future training and development activity. Online materials have been created for students to use, including academic writing guides and webinars; online videos are available which support students in managing their research degree programmes. A Researcher Plus award is available to PG research students, which provides accreditation for the development of a range of skills, transferrable beyond the research degree. This is an initiative that has been welcomed by employers. The Postgraduate Research Experience Survey highlights activities undertaken in supporting PG research students.

c.2.4 Progress Monitoring: At the start of the research project, the principal supervisor helps the student draw up a research plan with targets, against which progress can be monitored. This plan is designed to aid in the timely submission of the thesis. Student progress is regularly monitored through meetings with supervisor(s) or submission of written work. A formal 'Initial Review' takes place within 3 months after first registration and assesses whether or not the research plan is still feasible. All postgraduates are initially registered as undifferentiated. The differentiation process determines whether a student will proceed towards PhD or MPhil; it is conducted, within 12 months of registration, by a panel comprising of at least 3 academic staff, with supervisors in a minority. A formal monitoring exercise is carried out annually. If there are issues for concern, the student is required to undergo more frequent reviews.

c.2.5 Noteable PGR Awards: Jess received the RAS Keith Runcorn Thesis Prize (2008); **Dromey, Waskoenig** and **Nedawoska** were awarded Thesis Prizes from the European Physical Society (2008, 2012, 2013); **McQuaid** was awarded the Undergraduate Awards Ireland Gold Medal for his MSci thesis (2009) and the IoP Franks Prize for his PhD (2013); **McClure** and **Green** were awarded the Rosse Medal of the IoP (2008, 2011).

c.2.6 Prof. Caldwell Travel Scholarship: Through private donation, the Prof. Caldwell Travel Scholarship has been established for PhD students to perform research overseas. Students have undertaken research at Auburn University, the University of Kentucky, ICFO (Barcelona) and Tokyo using this fund.

d. Income, infrastructure and facilities

d.1 Income and Facility Time

d.1.1 External Income: Direct Spend (1 August 2008 - 31 July 2013): The total spend funded from external sources across the UoA was almost £29M, the majority of which was administered through RCUK; ~£2.7M was from industry and ~£2.1M from the EU. The large proportion of RCUK spend reflects the quality of our research and the robustness of our science against peer review. However, we recognize that the economic climate means that over-reliance on RCUK funding may be a risk. We are therefore encouraging staff to diversify funding sources. The spend profile attributable to specific research centres was as follows: **ARC:** Total: ~£6.5M, with ~£4.6M (71%) administered by RCUK, ~£0.5M from UK charities and the remainder from a mixture of the EU, US Air Force, space agencies, industry and regional development agencies (RDAs). **CNM:** Total: £5.8M, with ~£3.4M (59%) from RCUK, ~£0.5M from European grant funding and ~£1.5M (26%) from industry (the remaining spend coming from UK charities, the Technology Strategy Board and RDAs). **CPP:** Total: £8.3M, with ~£7.1M (86%) from RCUK, ~£0.6M from European sources and ~£0.6M from UK charities, industry and RDAs. **CTAMOP:** Total: ~£2.7M, ~£2.4M (89%) of which was from RCUK, and over £0.3M from EU sources.

d.1.2 Facility Awards (RCUK-funded): Primary users of RCUK-funded facilities, such as telescopes, high-power lasers and computers are in ARC, CPP and CTAMOP. The total facility cost awarded was ~£24M (**ARC** £10.5M; **CPP** £9.5M; **CTAMOP** £4M). We see an increasing need for central facility time in the future. The most heavily used facilities were: **ARC:** ESO (£3.7M), Gemini (£1.1M), ING (£0.3M); **CPP:** RAL (£7.6M), Diamond (£0.6M); **CTAMOP:** HECToR (£3.9M).

d.1.3 Facility Time Awarded (non-RCUK-funded): ARC: Dunn Solar Telescope (65 days); Michelson Doppler Imager (9 days); Spitzer Space Telescope (4.1 hrs); Swedish Solar Telescope (35 days); Hubble Space Telescope (12 orbits); Australian National High Performance Computing Facility (0.71M CPU hrs). **CNM:** ESTEEM2 European Network for Electron Microscopy – CEMES-CNRS, Toulouse, France (8 weeks), LMA-INA, Zaragoza, Spain (4 days); CNMS, Oak Ridge National Lab, USA (4 months), APS, Argonne National Lab, USA (14 days). **CPP:** LULI – Ecole Polytechnique TW Laser Facility (17 weeks); LNS Catania (219 hrs); CUSBO Attosecond Laser (Milan) (3 weeks); Los Alamos Trident (50 weeks); Titan Laser (3 weeks); Osaka ILE (3 weeks); LCLS (60 hrs); UHI-100 CEA Saclay (4 weeks); JETI (8 weeks); Phelix GSI Germany (3 weeks).

d.1.4 Financial Support from QUB: In addition to external grants, centres are supported through internal university funds. Each year, the university typically allocates ~£300-350k to the School for general consumables and travel and ~£200-300k for minor equipment. Funds are distributed to the centres predominantly on the basis of the amount of overheads and fEC earned in the previous year. Support is thus given to the centres that display the greatest levels of vitality and ongoing need for resource. DRs submit annual plans as to how this funding will be used. In addition, the university periodically seeks bids for larger infrastructural investment (using the Central Research Infrastructure Fund (CRIF)). The School has a strong track record in such bids, honed by internal prioritization procedures: in the period, CNM were awarded ~£200k for a Scanning Near-Field Optical Microscope (SNOM) and ARC ~£1M for Pan-STARRS, HARPS-N, NGTS and ROSA.

d.1.5 Consultancies and Professional Services: Nag Ltd. commissioned 56 months of software development time in CTAMOP, from 2009 to 2012. The electron microscopy facilities, within CNM, generated £35k of consultancy with clients ranging from public bodies (*e.g.* Garda Siochana, Ulster Museum) to local and transnational companies (*e.g.* Montupet, Schrader Electronics Ltd., ALMAC, ICEMOS Technology, Denman Intl. Ltd.).

d.2 Infrastructure

d.2.1 Building Infrastructure: Our buildings play a major role in facilitating our research: ARC, CNM and CPP are housed in the IRCEP building (a 4500m^2 build opened in 2005), with 4 floors of state-of-the-art laboratory space and a top-floor (mainly glass-walled) interaction area with a terrace overlooking the Botanic Gardens. This space is used by the entire School for hosting formal receptions. It also acts as an informal interaction area for journal clubs, discussions and cross-centre student interaction events. CTAMOP is housed in the nearby David Bates building (completed in 2007), which contains bright modern offices, meeting and lecture rooms. It is part of the £50M+ McClay Library development (completed in 2009). Our buildings are located within the university 'main site', which acts as a focal point for student activity and university cultural events.

d.2.2 Infrastructure within Research Centres: ARC: ARC utilises a range of computational systems. Aside from desktop computing, there is a Linux cluster composed of 376 Xeon cores and 250TB of hard disk RAID space, as well as Xeon Phi and nVidia Kepler co-processors. These are housed in the main university data centre (in the McClay Library). We also have access to the 900-core central university Linux cluster, and a local 60-core Mac OS X cluster. Central facilities play a major role in our observational programmes (d1.2, d1.3), but ARC also has a diverse portfolio of private infrastructure projects. Over £1.5M has been invested to build ROSA and NGTS and to join the Pan-STARRS and HARPS-N projects. Our excellent computational resources support these data driven projects; e.g. we run the Pan-STARRS "Transient Science Server" which tracks all supernova and transients found in the 1TB daily data stream and we house the ROSA data reduction and storage centre. **CNM:** For a university-based laboratory activity, CNM has outstanding equipment infrastructure. Before 2010, our facilities included materials synthesis, physical vapour and electrochemical thin film deposition, cleanroom micro-fabrication capability, high-end field-emission electron microscopy (SEM and TEM) and ion beam processing (broad-beam and focused ion beam [FIB]) with chemical and crystallographic (X-ray) characterisation, plus a functional property metrology lab and a suite of scanning probe microscopes (AFM, STM and PFM). In 2010, Seagate Technology donated 20 large equipment items, worth £8M, including: UHV and cluster tool sputter systems, wafer processing apparatus, SQUID and VSM magnetometers, optical and functional metrology and a dual-beam FIB; a SNOM was added in 2011 (d.1.4). To manage the equipment, we have a dedicated Facilities Manager (Mr S McFarland). For our suite of microscopes, maintenance contracts are essential. Hence, all users pay access rates, to cover running costs and a fraction of the maintenance contracts. CNM members build both microscopy and salary costs into research grants, which generate £130k pa, covering the Manager's salary as well as maintenance contracts. The ANSIN environment showcases university-industry collaboration and has become a routine stop-off point for VIP tours (hosted by the vice-chancellor) and outreach activities. **CPP:** CPP operates the £2M Taranis laser facility funded by QUB and EPSRC. This is the highest energy, short pulse laser in a UK university and boasts an 80TW, 0.5ps laser and lasers with fs pulse duration. Taranis is located in dedicated space in the IRCEP building; it has 3 distinct target areas and was recently upgraded with a large experimental chamber. The laser-plasma infrastructure is competitive on an international scale. CPP also has a jointly funded computational cluster (operated by MPQ Garching) and dedicated access to the QUB cluster (through CPP-funded nodes), used for running massively parallel

computation codes in support of theory activities. Low temperature plasma research has a wide range of plasma devices (GEC cells and atmospheric plasma devices), pulsed tuneable lasers and gated detectors. **CTAMOP:** Within the group, 188 cores are available for computation and the 900-core QUB facility is available. Via CCP2 /CCPQ, CTAMOP can access dedicated staff support (currently 0.75 FTE) at Daresbury Laboratory for code development.

e. Collaboration or contribution to the discipline or research base

e.1 Collaborations: The UoA had many external collaborations in the REF period (200 leading directly to funding/publications); the most significant are discussed below: **ARC:** We have an institutional partnership with Harvard, strongly supported by the QUB International Ambassador together with £700k. This funded our Pan-STARRS project and HARPS-N membership and has resulted in strong ties with the Centre for Astrophysics in supernovae, solar system and exoplanet physics (Stubbs, Berger, Holman, Charbonneau, Latham). The solar physics team works closely with the theory group at University of Sheffield (Erdelyi) to enhance the observational work led by QUB. We have a strategic partnership with the US National Solar Observatory for development and deployment of our instruments (ROSA in particular). In supernovae, we lead the European ESO PESSTO Survey with key partnerships with Schmidt (Nobel Laureate, FRS, SkyMAPPER project leader) and Baltay (Yale). Main collaborators in Europe are Universities of Padova, Stockholm, Southampton, MPI for Astrophysics (Munich) and Wiezmann Institute of Science. Within the Pan-STARRS project we work closely with Johns Hopkins University and Riess (Nobel Laureate) in particular. **CNM:** In the nanoscale ferroelectrics activity, we primarily collaborate with Scott (FRS, Cambridge); through this a large international collaboration has evolved which now includes: Alexe (MPI Halle/Warwick), Gruverman (UNL), Catalan (Barcelona), Noheda (Groningen), Paruch and Triscone (Geneva). In applied physics, our relationship with Seagate is globally unique. Through ANSIN we have become their largest university research partner for medium to long-term activity in materials and photonics for data storage developments. This engagement ensures that our research in materials and plasmonics is informed by user need and has resulted in cohorts of graduate students being recruited (8 in 2011, 4 in 2013 and a further 9 planned in 2014-16). CNM is also involved in a host of international collaborative schemes such as a Leverhulme Trust International Network, Materials World Network (NSF-EPSRC), British Council 'Alliance' grants and EU COST programmes. We are also engaged in the EPSRC UK Active Plasmonics Programme and 5 EC 'Framework 7' STREP projects. **CPP:** CPP is internationally extremely well connected with many active collaborations in Europe and beyond. We have a strategic link with Helmholtz Institut Jena (where Zepf is a director) as well as: MPIs in Munich and Heidelberg, DESY in Hamburg, GSI Darmstadt, University of Düsseldorf, CEA Saclay, LULI, University of Michigan, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Vanderbilt University and Ohio State University (USA) where QUB is a partner in a recent $1.6M grant, University of Milano, University of Pisa, INFN Frascati, INFN Catania, JAERI, Tokyo Institute of Technology. CPP is also part of the wider Laserlab Europe Framework and participates in the LASSIE FP7 ITN network. **CTAMOP:** CTAMOP is a key partner in collaborative computational project CCP2/CCPQ, supported by EPSRC. De Chiara has a strong collaboration with Sanpera and Lewenstein (UA/ICFO Barcelona). Van der Hart participated in EU COST programs CM0702 (2008-12) and CM1204 (2013-17), and in the EU ITN CORINF (2011-15). Paternostro participates in COST program MP1209, and collaborates with Zeilinger (Vienna), Vedral (Oxford, Singapore), Mataloni (Rome), and Palma (Palermo). Ramsbottom and Scott participate in ADAS-EU for atomic data of use to plasma diagnostics and modelling (2010-13). The QIP group is a partner of Univ. Federal do ABC (UFABC) under a Science without Borders grant (2012-15). Collaboration with UC Cork was supported through a SFI North-South grant (2009-11) and we were a partner in the Nordic Network in fundamental atomic processes (2008-11).

e.2 Conferences Hosted: The quality of our built environment and overall location make the School and its environs an attractive venue for conferences. During the REF period, 11 conferences or formal workshops have been hosted (along with associated satellite meetings) attended by a total of ~2400 delegates. Highlights were: **2008:** RAS National Astronomy Meeting (650 attendees); **2011:** XXVII International Conference on Photonic, Electronic and Atomic Collisions (600); **2011:** 30th International Conference on Phenomena in Ionized Gases (400).

e.3 Invited Lecture Series: *Larmor lectures*, named in honour of Sir J Larmor, have been running annually in the School since 1969. All staff and students are invited and the lectures are open to the public. In the REF period, speakers were: Dunne (Rutherford Appleton Laboratory, 2008);

Priest FRS (St Andrews, 2009); Coey FRS (Trinity College Dublin, 2010); Series (Warwick, 2011); Spaldin (ETH Zurich, 2013). *Tyndall lectures* are pitched at a level that should be appreciated by secondary school students. They are usually demonstration-based and highly entertaining. *Institute of Physics (IoP) Lectures* are given by scholars, invited by the IoP, to present research-level talks throughout Ireland. Recent lecturers include Bouchaud (Ecole Polytechnique, 2008), Adams (Durham, 2009), Esslinger (ETH Zurich, 2009) and Ekert (Singapore and Oxford 2011).

e.4 Academic Leadership: e.4.1 ARC: STFC Panels/Funding Committees: ***Fitzsimmons*** (Aurora Science Panel 2013, vice-chair); ***Mathioudakis*** (Review Panel 2008-11); ***Millar*** (PPAN Science Committee, 2009-); ***Smartt*** (Fellowship Panel, 2010). Telescope Time Allocation Committees (TACs): ***Kotak****:* GEMINI TAC (2010-12, chair in 2011), HERSCHEL Space Observatory TAC (2011), ESO TAC (2009-10); ***Fitzsimmons****:* ESO Observing Program Panel (2010-11, 2013 (vice-chair)), Hubble Space Telescope (HST) TAC (2010); ***Maund****:* HST TAC (2013); ***Millar****:* ALMA Proposal Review Panels 3C, 4A (chair, 2011-12); ***Watson***: STFC TAC for Isaac Newton Group (2011-13). Other Advisory Boards/Funding Panels: ***Fitzsimmons****:* Liverpool Telescope Users Group (2013-14, chair), Isaac Newton Group Management Board (2008-10); ***Kotak****:* European-ELT Project Science Team (2012-), NASA Astrophysics Data Analysis Program Grant Panel (2009, 10, 12), US NSF Panel (2013), Science Board ESO Large Public Spectroscopic Survey programme (2012-); ***Keenan****:* Georgian NSF Grants Review Panel (2008-); ***Mathioudakis****:* European Solar Telescope, Science Working Group (2008-), Preliminary/Critical Design Review Panels for the US Advanced Technology Solar Telescope Visual Broad Band Imager (2010-11, chair); ***Maund****:* Swedish National Space Board Panel (2012); ***Millar****:* Board: James Clerk Maxwell Telescope (chair, 2005-08), IAU Division VI `Interstellar Matter' (president, 2006-09), International Advisory Board: International Conference on Atomic and Molecular Data and Their Applications (2005-08), Astrophysical Chemistry Group of the RSC and RAS (chair, 2010-), International Board of the Dutch Astrochemistry Network (2010-14), IAU Commission on Astrochemistry (president, 2012-15); ***Sim****:* US NSF Panel (2008); ***Smartt****:* Pan-STARRS Science Council (chair, 2007–), Liverpool Telescope Users Group (2013-), Royal Society URF Panel (2011-13); ***Watson****:* Astronomical Science Group Ireland (chair, 2013-), Royal Irish Academy (RIA) Astronomy and Space Science Committee (2008-), UK Optical and Near-Infrared Telescope Users Group (UKON). International Plenary (P)/Invited (I) Conference Presentations: ***Fitzsimmons*** 4(I); ***Jess*** 1(I); ***Kotak*** 9(I); ***Maund*** 3(I); ***Millar*** 1(P), 13(I); ***Sim*** 7(I); ***Smartt*** 16(I). Conference Committees/Session Organisation/Chair: ***Fitzsimmons*** 6; ***Keenan*** 1; ***Kotak*** 5; ***Mathioudakis*** 6; ***Millar*** 5; ***Sim*** 1; ***Smartt*** 11, ***Watson*** 2. Prizes/Awards/Honours: ***Fitzsimmons*** *and* ***Keenan****:* RAS Group Achievement Award (2010) for SuperWASP Consortium; ***Jess***: Member of UK Solar Physics Council (2012-), R. H. Goddard Exceptional Award for Science (2008), NASA Group Achievement Award (2009), RAS Keith Runcorn Prize (2008), Andor Insight Award (2010) (with ***Mathioudakis***); ***Millar***: Elected Member of the RIA (2011); ***Smartt***: Elected Member of the RIA (2012), National Central Univ. Taiwan – Delta Electronics Lectureship Award (2012). Invited Reviews/Editorials: ***Smartt****: Ann. Rev. Astron. Ap.* **47** 63 (2009), News and Views *Nature* **491**, 205 (2012).

e.4.2 CNM: EPSRC College Members: ***Bowman, Gregg****.* EPSRC Funding Panels: ***Bowman****:* April 2009; ***Dawson****:* Oct 2008; ***Gregg****:* May 2008, Oct 2009 (chair), Feb 2011 (chair), Sept 2012 (chair). Other Funding Panels: ***Bowman***: Flemish Funding Agency (IWT) SIM (€94M Strategic Initiative in Materials) (2009) and follow-up €21.5M (2011); ***Gregg***: US NSF Panel (March 2011). Other Advisory Boards: ***Bowman***: Oversight board for INSPIREnano (€32M Integrated Nanoscience platform for Ireland); ***Gregg****:* Functional Materials Industrial Advisory Board to the NPL, Proposal Review Committee for the Center for Nanophase Materials Sciences (ORNL) (2012-), Facility research review for Romanian Ministry for Education (2012). Roles in Learned Societies: ***Bowman***: IoP: Council Member and Trustee (2009-13), Chair, Nations and Branches (2011-13), Science Board (2010-11), Fellowship Review Panel (2008-13), Audit and Risk Committee (2012-). International Plenary (P)/Invited (I) Conference Presentations: ***Arredondo*** 1(I); ***Bowman*** 5(I); ***Gregg*** 3(P), 25(I); ***Huang*** 3(I). Conference Committees/Session Organisation/Chair: ***Arredondo*** 1; ***Bowman*** 2; ***Dawson*** 1; ***Gregg*** 10; ***Huang*** 1; ***Kumar*** 1. Journal Editorships: ***Gregg***: Editorial Advisory Boards for Journal of Physics: Condensed Matter (2007-) and Physica Status Solidi (2011-). Prizes/Awards/Honours: ***Gregg***: 'International Award of Ferroelectrics and their Applications' (formerly the 'Ikeda Prize') from Ferroelectrics Community of Japan (April 2012); ***Kumar****:* 2012 Division Director Award for Professional Excellence (CNMS, ORNL), 2011 Microscopy Today Innovation Award. Invited Reviews/Editorials: ***Gregg****:* News and Views *Nature*

Nano., **3**, 380 (2008), Perspectives *Science*, **336**, 41 (2012).

e.4.3 CPP: EPSRC College Members: ***Borghesi***, ***Dromey***, ***Field***, ***Graham***, ***Kar***, ***Lewis***, ***Williams***, ***Zepf***. EPSRC Funding Panels: ***Borghesi***: Feb 2009, July 2010; ***Graham***: Jan 2008, Dec 2008, Feb 2012, Dec 2012; ***Lewis***: July 2009, March 2012; ***Williams***: June 2008 (chair), Dec 2009 (chair), June 2011; ***Zepf***: Nov 2010, April 2012. Other Funding Panels: ***Borghesi***: US DoE Review Panel (March 2012); ***Lewis***: Facility Access Panel of STFC Central Laser Facility (chair, 2008-); ***Williams***: ESF Grant Awarding Panels (UK rep) for European funding of Cold Quantum Matter Research (2007-12). Other Advisory Boards: ***Borghesi***: User Representative Committee and Access Board of LASERLAB Europe (2012-); ***Currell***: Highly Charged Ion Conference International Advisory Board, Atomic Processes in Plasma (APiP) Executive Committee, Belfast Cancer Research-UK Centre Development Committee; ***Graham***: Governing Board of CRANN Trinity College Dublin (2006-09), ITS LEIF: EU Integrated Infrastructure Initiative Board (2006-10), Physical Sciences Review Panel, Univ. College Cork (2009), External Advisory Board of the DoE Plasma Science Center for Control of Plasma Kinetics, Univ. of Michigan (2010-), Physics Panel for the Romanian RAE (2011), review panel for National Centre for Plasma Science and Technology, Ireland (chair, 2013); ***Lewis***: Deutche Forschungsgemeinschaft (DFG) Review Panel for Transregio 18 (2008 and for funding extension 2012), Leibniz Association Review Panel for funding of Max Born Institute, Berlin (2012), EPSRC Grand Challenges Advisory Group (2010-11), STFC Photon Advisory Panel (chair, 2009-11), STFC Photon Science (Central Laser Facility) Advisory Board (2009-), STFC ad hoc Expert Peer Review Panel for HiPER (2013); ***Reville***: External Reviewer for Greek Programme ARISTEIA (2011-12); ***Zepf***: International Advisory Committee for EU Facility 'Extreme Light Infrastructure (ELI)' in Prague/Czech Republic (chair), STFC Physics and Lifesciences Committee and Photon Advisory Panel, STFC 10PW Project Panel. Roles in Learned Societies: ***Currell***: Irish Radiation Research Society Committee; ***Greenwood***: Treasurer of Atomic and Molecular Interactions Group (AMIG), IoP (2007-10); ***Williams***: IoP Ireland Committee (2009-12). International Plenary (P)/Invited (I) Conference Presentations: ***Borghesi*** 2(P), 20(I), ***Currell*** 1(P), 4(I), ***Calvert*** 3(I), ***Dromey*** 13(I), ***Field*** 1(P), 10(I), ***Graham*** 7(I), ***Greenwood*** 4(I), ***Jung*** 1(P), 1(I), ***Kar*** 7(I), ***Kourakis*** 1(P), 15(I), ***Lewis*** 1(I), ***Reville*** 9(I), ***Riley*** 8(I), ***Sarri*** 3(I), ***Williams*** 1(I), ***Zepf*** 19(I). Conference Committees/Session Organisation/Chair: ***Borghesi*** 6; ***Currell*** 2, ***Dromey*** 1, ***Field*** 2, ***Graham*** 7, ***Kourakis*** 3, ***Lewis*** 5, ***Sarri*** 1, ***Williams*** 4, ***Zepf*** 3. Journal Editorships: ***Borghesi*** Associate Editor of 'Medical Physics' (2010); ***Graham*** Associate Editor of 'Plasma Sources Science and Technology', will become Editor in Chief in 2013; ***Kourakis*** Editorial Board Member of 'Open Plasma Physics Journal'. Prizes/Awards/Honours: ***Borghesi***: Fellow of the IoP (2011), ***Dromey***: EPS Plasma Physics Division PhD Award (2008); ***Graham***: ICPIG Conference Von Engle and Franklin Prize (July 2013); ***Jung***: Los Alamos LAAP Award (2012); ***Kourakis***: Visiting Scholar, Univ. of Sidney (2009); ***Riley***: Fellow of the IoP (2010); ***Zepf***: Joint Director of Helmholtz Institut Jena. Invited Reviews/Editorials: ***Williams***: *Physics Reports* **491**, 1 (2010).

e.4.4 CTAMOP: EPSRC College Members: ***Paternostro***. Other Advisory Boards: ***Gribakin***: European Group on Atomic Systems Board; ***Paternostro***: Advisory Board "Anne McLaren Fellowship Scheme", Univ. of Nottingham (2011), doctorate programme at Univ. di Camerino (2012), postdoctoral programme at the Univ. of Milan and the Superior Council of the National Fund for Scientific and Technological Development in Chile (2012); ***Scott***: steering panel of CCPQ collaborative computational project; ***Shearer***: RIA Committee for Mathematical Science (2005-09); ***van der Hart***: ICPEAC General Committee (2011-15), Management Committee for COST Action CM0702 (2008-12), steering panel of CCPQ collaborative computational project; International Plenary (P)/Invited (I) Conference Presentations: ***De Chiara*** 3(I), ***Ferraro*** 5(I), ***Gribakin*** 1(P), 4(I), ***Mazzola*** 1(I), ***Paternostro*** 9(I), ***Shearer*** 1(I), ***van der Hart*** 3(I). Conference Committees/Session Organisation/Chair: ***De Chiara*** 2; ***Gribakin*** 1; ***Paternostro*** 2; ***Ramsbottom*** 2; ***Scott*** 2, ***Shearer*** 2, ***van der Hart*** 1. Journal Editorships: ***Paternostro***: Editorial board Phys. Rev. A (2012-15), QMTR (2012-), Scientific World Journal (2012-), guest editor New J. Phys. (2011). Prizes/Awards /Honours: ***Burke*** *(Emeritus)*: Will Allis Prize of the APS (2012). Invited Reviews/Editorials: ***Gribakin***: *Rev. Mod. Phys.* **82**, 2557 (2010); ***Paternostro***: Viewpoint APS *Physics* **5**, 113 (2012); ***van der Hart***: Perspectives *Science* **328**, 1645 (2010); ***Walters*** *(Emeritus)*: Perspectives *Science* **330**, 762 (2010).