Institution: The University of Nottingham

Unit of assessment: 9

a. Context

Research within the School is organised into six research groups

- Astronomy (*Astro*)
- Cold Atoms and Quantum Optics (*ColdAtoms*)
- Condensed Matter Theory (*CMTh*)
- Experimental Condensed Matter and Nanoscience (*ECMN*)
- Magnetic Resonance Imaging (*MRI*)
- Particle Theory (*PTh*)

Since 2008 we have successfully derived impact from our research in the areas of the economy, health, public policy, environment and society. This has been achieved using mechanisms that are tailored to the specific sub-disciplines represented within the School.

The *ECMN*, *CMTh* and *ColdAtoms* groups generate economic impact through the development of new materials, devices and technologies. The relevant user-groups for our semiconductor research include major electronics companies such as Hitachi, Sharp and e2v. In addition, interdisciplinary projects, particularly in biophysics and nanoscience, are linked closely with industrial and clinical user-groups in healthcare, energy and scientific instruments. Research within the School has also been successfully translated across discipline boundaries; for example algorithms developed in the *Astro* group have been applied to problems in fluid flow that are relevant to aeronautical engineering and flood management.

The user-groups for *MRI* research are hospital-based clinicians, food and drug companies, governmental organisations with regulatory responsibility for health, and manufacturers of medical imaging equipment. The ultimate beneficiaries are patient groups and the general public.

Impact in the area of society, culture and creativity is realised through the translation of the research of all groups into outreach activities and the promotion of the public understanding of science, in particular through innovative use of social media. Here the relevant user-groups are teachers, the media and the general public.

b. Approach to impact

b1 Interactions with non-academic users, beneficiaries and audiences

Since 2008 the School has developed, and maintained, links with user-groups which range in scale from strategic partnerships agreed at senior company and University level, to more focused project-specific interactions at the level of research groups or individual academics.

At the strategic level we highlight the alliance with e2v Technologies, a company with over 1500 employees and a turnover, in 2013, of £200M. In 2011, e2v established a centre, embedded within the School, to manufacture high-frequency microwave and THz devices, and to develop new device concepts by drawing on semiconductor research in the *ECMN* and *CMTh* groups. This new venture resulted from discussions with e2v which were initially focused on research collaborations, but subsequently expanded in scope to encompass re-location of the company's microwave semiconductor facility from a site in Lincoln. The infrastructure and expertise which the School has built up over the last 25 years provided strong motivation for e2v to re-locate to Nottingham, and this move also met a strategic objective of the company for expansion of links with university researchers. A dedicated cleanroom area (90 m^2) has been converted through a joint investment by the University (£150k) and e2v (£350k). This space is leased to e2v (contract value £650k), who also have access to our technical expertise and infrastructure. Devices fabricated within the School since 2011 have generated over £7M of sales for e2v (see related Case Study for further details of the outcomes and background). The company are currently exploring options to extend their lease beyond the initial five-year period.

The partnership with e2v provides a direct route for the exploitation of our semiconductor research and has already resulted in a joint Knowledge Transfer Secondment (KTS) which, in turn, led to a three-year Knowledge Transfer Partnership (KTP; £190k; 50% funded by e2v). The KTP is led by *Fromhold*, and was awarded by the Technology Strategy Board (TSB) to develop a simulation tool for novel p-i-n diodes used in radar. In addition, a £35k Hermes Fellowship (a University-administered scheme to facilitate knowledge transfer using funds from the Higher Education

Innovation Fund (HEIF)) was awarded to *Patanè* (*ECMN*) to work with e2v on THz technology. The School has also appointed an Experimental Officer to support knowledge transfer in this area.

Much of our research is highly interdisciplinary and knowledge transfer is facilitated through a network of collaborations with industry, medical practitioners, governmental organisations and academics in other disciplines. An exemplar is our *MRI* group, who have a longstanding track record of translating physics-led innovations into advances in MRI scanner performance, clinical practice, nutrition, and drug delivery. Since 2008, the group has collaborated with NHS-based clinicians in Nottingham, Derby, Cambridge, London, Manchester and Oxford. In addition, the *MRI* group were partners in the establishment of two National Institute for Health Research (NIHR) Biomedical Research Units in, respectively, Hearing, and Digestive Diseases. These units were formed in 2008 and focus on translational research. Both units were funded for a further 5-year period in 2012.

Since 2008, our work on the MRI of the placenta has informed clinical practice and governmental guidelines and, in collaboration with clinicians, we have also established new methodologies to investigate liver disease, multiple sclerosis, and lung conditions. Industry-sponsored MRI projects include those with: VSM Medtech (£0.18M) on the integration of magnetoencephalography (MEG) with functional MRI (fMRI); SABMiller (CASE award) on flavour perception; Brain Products (£15k) on simultaneous acquisition of electroencephalography (EEG) and MRI data. A DTI award with Pulseteq Ltd and three other Universities (£0.16M to Nottingham) on the use of high-temperature superconductors for radio-frequency coils, successfully concluded in December 2009.

Three of the four MRI-related Case Studies involve further links with industry. These Case Studies describe: biophysical models of the human digestive system including contract work and collaborations with Unilever, Proctor & Gamble, Reckitt Benckiser, GSK and others; innovative approaches to the design of gradient and shim coils that have been exploited by Agilent and Paramed Medical Systems; the development of high-field scanners (3T and 7T) which has involved links with Oxford Instruments and Philips Healthcare. A further MRI-related Case Study, relevant to public policy, describes research on the physiological effects of (electro)magnetic fields which has been used in setting international exposure guidelines.

Several new projects started by the *ECMN* group since 2008 are already yielding impact. Raman imaging of skin has been applied to screening for cancerous tissues, and detection of exposure to chemical weapons. These projects have led to, respectively, a new collaboration with Nottingham City Hospital, and a consultancy for *Notingher* with the Defence Science and Technology Laboratory, and are supported by NIHR (£0.7M) with additional University support for three PhD studentships, £0.3M CIF funds for new equipment, and the costs of filing two patents. Electrospray deposition has been developed by *O'Shea*, and the equipment constructed for this application has been commercialised by Molecularspray Ltd (sales to date £200k) with whom we now have a CASE student. The development of new methods for producing hyperpolarised materials to enhance contrast in MRI was funded through: a £150k award from Bruker UK, with whom we have filed a joint patent; University support for two PhD studentships and a year-long sabbatical to *Owers-Bradley*. A TSB-funded joint project with Sharp Laboratories of Europe (£0.6M) resulted in the filing of a patent for the growth of cubic wide band-gap nitride semiconductors. In addition we have continued our long-standing partnership with Hitachi focused on spintronic materials.

The new *ColdAtoms* group (established in 2007) has rapidly established a network of links with industrial and governmental organisations focused on the development of atom chips for portable gravity sensors. End-users include TOPTICA Photonics, NKT Photonics and IBM, who are all partners in the recently-awarded EU Initial Training Network (ITN), QTea, led by Nottingham. Links with Nottingham medics are also being developed through a University/EPSRC Bridging the Gaps award to pump-prime collaborative work on the development of cold-atom biosensors.

b2 Partnerships with other disciplines and their user-groups

Much of the impact derived from our research arises from the enabling role of physics in other disciplines, and, in some cases, end-users engage with our academic partners in other Faculties. To promote such links, the School supports one-day themed workshops, held twice a year, to bring together physicists and Nottingham academics in the Faculties of Science, Medicine and Engineering. Several new projects have emerged from these meetings, such as the application of Smooth Particle Hydrodynamics (SPH), developed by our *Astro* group within the Virgo consortium, to the analysis of complex fluid flow. This has led to a collaboration on engine lubrication with Rolls

Royce through their University Technology Centre (with Nottingham's Faculty of Engineering), with additional University support for two PhD studentships. The application of SPH also underpins work with Ambiental, a company specialising in computer modelling of flood management.

b3 External funding and support for collaborative projects with non-academic users

Since 2008, researchers within the School have competed successfully for £0.4M of University-administered HEIF and/or EPSRC funds that support knowledge exchange and transfer. These include KTS awards (2 awards; total £68k), the EPSRC Research Development Fund (12 awards; total £185k), EPSRC Impact Acceleration Account (IAA: 1 award; £15k), EPSRC PhD Plus scheme (2 awards; £86k) and Hermes fellowships (2 awards; total £45k).

We have successfully targeted EU ITNs as a mechanism for developing industrial links, for example with IBM and Omicron in atomic force microscopy (see also ITN on cold-atom sensors discussed in b1). In addition, we lead the HiMR ITN on high-field MRI which has five industrial partners including GE Healthcare and Siemens. Together with sponsored studentships, these funds have supported proof-of-concept studies, technology demonstrators and secondments with many of the companies identified above.

b4 Stimulating public interest and engagement in science

In addition to standard public engagement activities such as lectures in schools and colleges, community open days, popular science articles, 6th form conferences, A-level Masterclasses and Sutton Trust residential courses, we have initiated several major outreach projects. In the *Sixty Symbols* series of YouTube videos, a range of topics, including original research, are presented by our staff (see associated Case Study). The channel now (July 31st 2013) has 212 uploaded videos, over 266,000 subscribers and over 21.2M video views. This success has led to funding from Google for several new channels (for example *Numberphile* and *Deep Sky Videos*), and an invitation for *Merrifield* (*Astro*) to speak at the BrainSTEM 'unconference' on YouTube science held at the Perimeter Institute in 2012. The *Citizen Science Alliance*, an international collaboration with partners including Oxford and John Hopkins Universities, and in which Bamford (*Astro*) is the Science Director, goes beyond conventional outreach by engaging the public in the scientific process itself. We also commissioned (August 2011) the *Inflativerse*, an inflatable planetarium, which we have exhibited at schools and community events across the East Midlands.

Our activity on MRI of the liver was presented at "The Scarred Liver" exhibit at the 2013 Royal Society Summer Exhibition, and *Moriarty* (*ECMN*) was one of six scientists who, with artists, created the "Giants of the Infinitesimal" exhibition. This included several images acquired by the *ECMN* group and opened at the Museum of Science and Industry in Manchester in October 2010, before moving to Magna Science Adventure Centre, South Yorkshire, in May 2012.

b5 Institutional support for pump-priming and translation of research

Resources to support impact-related activity include: sabbatical leave for staff; PhD studentships; funding for equipment, consumables and travel to support collaborative activities with end-users; costs for the protection of intellectual property rights (IPR). The University Business Engagement and Innovation Service (BEIS) plays a key role in advising on, and negotiating over, IPR, consultancy and licensing agreements, as well as the filing and protection of patents. In 2009, the School appointed a Business Development Executive, Dr Peter Milligan, to identify, and realise, opportunities for the commercialisation of our research, and to liaise with BEIS.

c. Strategy and plans

c1 Strategy and management of knowledge transfer

Our overall aim is to maximise the benefit to society of our research activities. School policies have been shaped by the extensive experience of commercialisation, IPR management and technology transfer which was gained in the 1980s and 1990s following the invention of MRI in Nottingham. Members of the *MRI* group have since taken on senior management roles (notably *Bowtell* who chaired the Research Committee (RC) from 2003-2008 and has been Head of School (HoS) since 2008), facilitating the transfer of their experience into other research areas in the School. This has led to the development of policies and culture within the School that encourage effective linkage of fundamental physics to potential applications.

Our strategy is aimed at identifying new opportunities that arise from our research and ensuring that all stages of the pathway to realising impact are supported appropriately within the School. We have introduced several managerial changes to help realise these aims. A Strategic Advisory

Board (SAB) was established in 2011 with an external membership drawn from industry (e2v, Experian, Hitachi, Huawei, Pfizer and Rolls Royce) and government agencies (British Geological Survey, the Diamond Light Source and STFC). The SAB provides: external evaluation of our policies; advice on new opportunities arising from our research; access to commercial approaches for evaluating and monitoring technological exploitation.

Within the School, *Patanè* (a member of the RC) was appointed to a new role as Impact Champion in 2013 (funded by the EPSRC IAA) with responsibility for co-ordinating impact-related activities. *Patanè* is supported by *Milligan*, and *Woolley*, previously a HEIF-funded Innovation Fellow and spin-out director. This group monitors our interactions with user-groups, identifies new opportunities for the exploitation of our research, and promotes impact-related funding schemes.

We have also begun to draw on the technical and business expertise of the SAB, for example Dr. Paul Russell, Director of Analytics, Experian UK, on the use of business information databases such as Mint, and to evaluate the Technology Readiness Level (TRL) of specific projects. This information is used to identify potential industrial partners who are now being approached with structured proposals for collaborative projects and possible funding streams for technology transfer. We also plan to use a series of seminars by visiting industrialists, recently introduced by *Patanè*, to develop links with targeted companies.

As discussed in Section b5, the School provides a range of support for impact-related activities. Progress linked to these resources is evaluated critically by the SAB and we make adjustments to our policies in order to maximise the impact of our research on the relevant beneficiaries.

c2 Current scientific and technological priorities

We will extend our investigations of disease states, neuroscience and physiology using MRI, and also aim to extend the translation of research into biomedical applications beyond the *MRI* group, with Raman microscopy and biosensors based on cold-atom chips providing exciting prospects. The collaboration with e2v provides a natural route for knowledge transfer for our semiconductor physicists, with particular opportunities in modelling, nitride semiconductors and high-frequency electronics. There are also excellent prospects for the growth of the links, described above, with Bruker, Rolls Royce and Molecularspray. In addition, we anticipate impact-related opportunities arising from our new activity on the growth of graphene by molecular beam epitaxy, funded (£1.3M) by EPSRC in 2013. We will also continue to develop the *Sixty Symbols* project, broadening the coverage of our research with support from HEIF (£30k/annum from 2012-2015).

c3 Supporting staff in knowledge-transfer activities

The annual Personal Development and Performance Review (PDPR) provides a focus for staff to develop plans for knowledge transfer through discussion with a senior academic, and to evaluate plans from the previous annual cycle. All staff are expected to include specific impact-related goals in PDPR. These may include impact-related grant applications, translational research, commercialisation, consultancy, interdisciplinary activities and/or outreach. Exceptional performance is rewarded through salary increments and knowledge exchange is considered in the University's promotion procedure. In addition, all academic staff are contractually entitled to perform 50 days per year of consultancy with external organisations.

d. Relationship to case studies

We attach the following Case Studies:

- **A New Manufacturing, Research and Development Centre for e2v**
- **Testing Functional Foods and Pharmaceutical Formulations using Dynamic Imaging of the Gastrointestinal Tract**
- **Optimising Gradient and Shim Coils for Next-Generation MRI Systems**
- **Catalysing the Clinical Application of High-Field MRI**
- **Regulatory Framework for Electromagnetic Field Exposure Limits for MRI**
- **Communicating Research to the Public through YouTube**

The success of the *MRI* group in technology transfer is reflected in our selection of four Case Studies related to this area. The underpinning research related to these Case Studies pre-dates, at least in part, the introduction of formal mechanisms within the School for the support of impact-related research. Nevertheless, the *MRI* group were supported over a sustained period by the School through prioritisation of infrastructure awards, the appointment of new staff, and the allocation of PhD studentships to foster interdisciplinary links.