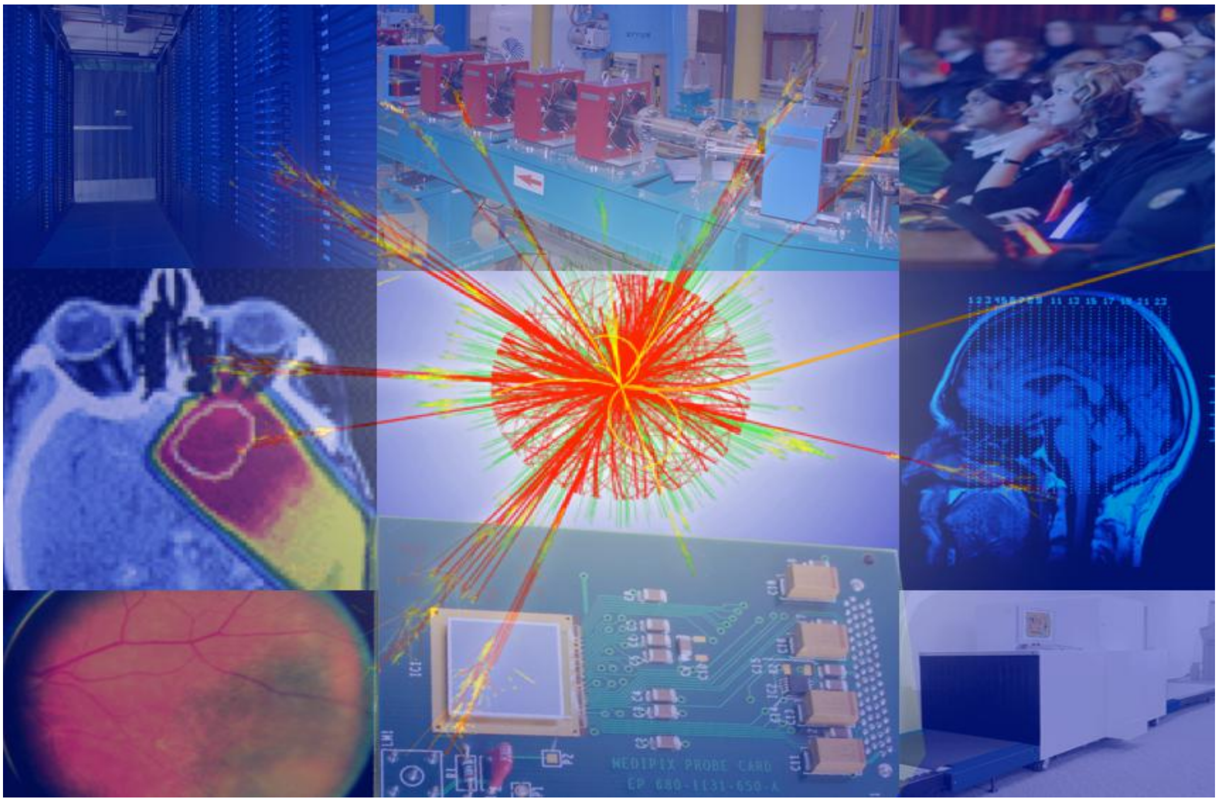
# FUNDAMENTAL IMPACTS

**A Study of the Cross-Discipline and Societal Benefits of UK Research in Particle Physics**

Institute of Physics

High Energy Particle Physics Group




**Executive Summary**

The fundamental questions that Particle Physics research is addressing inspire students to study physics at university. The nature of the research continues to require paradigm shifts in accelerator, sensor, microelectronics, data acquisition, computing and analysis techniques and technologies. These technologies, developed through industrial and international collaboration, now underpin a wide variety of other disciplines, particularly those in the medical and life sciences. Despite prodigious advances in our knowledge of fundamental physics, there remain many unanswered questions that will require significant technological innovation to address. This innovation will enable advances to be made in other disciplines and the technologies developed will be particularly relevant to medical treatments, sustainable energy and security.

In this document, we summarise the science questions that Particle Physics research is seeking to address in the next 20 years and what advances in technology are being pursued and the cross-disciplinary and economic benefits these advances will bring. It is the fundamental science that attracts students to study physics and drives the technological innovation; neither can proceed in isolation.

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May 2008

# 1. Introduction

Particle Physics seeks to understand the evolution of the Universe in the first fraction of a second after the Big Bang in terms of a small number of fundamental particles and forces. It is this fundamental physics that ultimately resulted in the atoms for human life. Despite prodigious advances in our knowledge, there remain many unanswered questions e.g. what is mass and why is there a preponderance of matter over anti-matter. Such questions fascinate students of all ages and are a key driver in attracting students to study physics in UK universities (see section 6.2). The diverse technological, computational and analysis training that Particle Physics research students obtain in an international setting is much sought-after by employers, particularly in the high value-added areas of industrial research, finance and computing.

Particle Physics research is conducted at 21 universities and 4 national centres in the UK and is recognised as internationally leading [1]. The challenging nature of the research necessitates paradigm shifts in accelerator, sensor, microelectronics, data acquisition and computing technologies and development of novel analysis techniques in the context of large-scale international collaborative research. The technologies developed through industrial and international collaboration are vital to other disciplines, particularly in the medical and life sciences. Further innovation via Particle Physics research will enable advances to be made in other disciplines, particularly medical treatments, sustainable energy and security.

In this document, we summarise the science questions confronting Particle Physics research in the next 20 years, what advances in technology are being pursued and the cross-disciplinary benefits likely to accrue. The fundamental science attracts students to study physics and drives the technological innovation; neither can proceed in isolation. There can be no knowledge transfer without knowledge.

# 2. Scientific Questions Addressed by Particle Physics

In the next decade Particle Physics seeks answers to fundamental questions:

- what is the origin of mass ?
- why is there a preponderance of matter over anti-matter ?
- what is Dark Matter and the origin of the highest-energy particles in the Universe ?
- can a unified theory incorporating gravity at the quantum scale be realised, and are there extra spatial dimensions ?

While Particle Physics research over the past 70 years has been remarkably successful with the award of over 30 Nobel Prizes, it is arguably about to enter its most productive era. The above questions cannot be answered with a single accelerator: multiple facilities each demanding unique technological innovation are required. Furthermore, a complete understanding of the evolution of the Universe from its earliest stages requires links with and technological innovation from other disciplines, e.g. cosmology, chemistry, material science, engineering etc.

## 2.1. The Origin of Mass

Fundamental particles at the Big Bang are believed to be massless; their mass was "generated" shortly after. However, the mechanism of this generation is unknown. One of the most elegant theories is due to a UK physicist Peter Higgs, who has proposed that particles acquire mass through interactions with a new particle named the Higgs boson. This particle has yet to be experimentally observed. If the particle exists, it will be copiously produced by the *LHC* at *CERN,* due to begin taking data this year. Should the Higgs boson not be responsible for mass, it is known that any mechanism responsible for generating mass must produce new physics in the energy region probed by the *LHC*. Measurements at the *LHC* in the next decade will therefore tell us how mass is introduced into the Universe.

## 2.2. The Preponderance of Matter over Anti-Matter: the Elusive Neutrino.

At the Big Bang, matter and anti-matter were produced in equal amounts, but a few minutes later the majority of the anti-matter disappeared; matter predominated in a ratio of approximately $10^{10}$ to 1. The mechanism responsible for matter's preponderance is not yet known but one of the most compelling explanations requires the existence of very massive unstable neutrinos at the start of the Universe, as implied by the recent observation of neutrino oscillations. This implies that the neutrino has a tiny but non-zero mass, overturning a belief held for 70 years that it was massless. Measurements of the properties of the three neutrino species are required to determine whether the neutrino is the source of the preponderance of matter. This requires two distinct types of experiment – *neutrino factory* and *neutrino-less double-beta decay experiment,* both of which are extremely challenging. Since neutrinos can only be measured through their very low probability of interaction with a medium, it is essential to produce an enormous flux of high-energy neutrinos if they are to be studied in detail. Since neutrinos are produced from the decays of unstable particles produced when a proton interacts with matter, a *neutrino factory* requires a very high-powered proton beam and the ability to accelerate these particles rapidly before they decay. The technological advances required to produce multi-MW proton beams are also being pursued to produce the next generation of high-power neutron sources used for material science and structural biology. *Neutrino-less double-beta decay* experiments require very sensitive, high-resolution scintillator detectors. There are applications of this type of detector in the context of nuclear proliferation. Neutrinos emitted from fissile material will escape any shielding and can be detected, pinpointing and identifying the fissile material.

## 2.3. What is the nature of Dark Matter and the Origin of the Highest Energy Particles in the Universe?

The observed rotation speed of galaxies implies that the majority of the matter in the Universe is of an unknown type that does not emit or reflect radiation. Without this so-called Dark Matter it would not have been possible to form galaxies. The earth is moving through this Dark Matter; underground detectors are looking for the interaction of these particles, which may be explained by the theory of supersymmetry, which predicts new families of fundamental particles interacting weakly with ordinary matter. The lightest supersymmetric particle could form the Dark Matter; it could be produced directly by collisions at *CERN's LHC*.

The *LHC* will provide the highest energies yet achieved in a terrestrial accelerator; however the most energetic particles that we observe are actually produced from the interactions of cosmic-rays in the upper atmosphere. The origin of these cosmic-rays, whose energies can be more than a million times that of the protons in the *LHC,* is unknown. It requires several $km^2$ of the earth's surface to be instrumented to see the particles produced from the interactions of these energetic cosmic-rays.

## 2.4. Can a Unified Theory Incorporating All the Forces Including Gravity be Realised at the Quantum Scale and Are There Extra Spatial Dimensions ?

At the energies currently probed by Particle Physics experiments, the effect of the gravitational force is tiny in comparison to the other two forces (electroweak, strong). The apparent weakness of gravity on the quantum scale is a mystery. One explanation why gravity is so weak in our 4-dimensional space-time world is that our Universe exists as part of a higher-dimensional structure.

There are additional spatial dimensions in which only gravity acts wherein the gravitational flux is dissipated. It may be possible to infer the presence of macroscopic extra dimensions from cosmological observations, or from precision measurements of gravity. If the extra dimensions are microscopic, high-energy particle accelerators and cosmic-ray experiments are the only ways to detect them e.g. via the production of rapidly evaporating microscopic black holes. The *LHC* will be sensitive to such microscopic extra dimensions.

The unification of forces requires the identification of new symmetries that will explain the pattern of fundamental particles. Such symmetries can be crudely probed by the *LHC* experiments but more precise experiments e.g. a high-energy $e^+e^-$ collider, such as the proposed *International Linear Collider (ILC)* and experiments searching for rare decays, will be necessary to understand any new physics discovered at the *LHC*.

## 3. Technological Innovations Driven & Required By Particle Physics Research

Particle Physics began in earnest in 1927 when Rutherford, addressing the Royal Society, called for the development of techniques of multi-MeV acceleration. Subsequent developments, leading up to the Nobel Prize-winning experiments by Cockcroft and Walton, relied on very close links to a leading British engineering company. This pattern of synergy between Particle Physics and engineering has continued for 80 years [2].

Technological innovation in Particle Physics continues to be in four main areas:

- accelerators
- precise and sensitive radiation detectors
- microelectronics and high-speed data acquisition
- computing and modelling.

The success of any new Particle Physics experiment relies on innovation in all these areas. Typically new experiments introduce requirements at least an order of magnitude beyond current capacity e.g. in data throughput, radiation tolerance, spatial resolution, with each requiring paradigm shifts in technology and significant advances in industrial capability.

At least ten types of accelerator originated from Particle Physics. These have resulted in over 20,000 accelerators world-wide with applications as diverse as: medical treatment and imaging, environmental science, material science, engineering, surface chemistry, biotechnology, as well as the manufacture of advanced microchips. There have also been concurrent advances in RF, magnet and vacuum systems. Amongst the most recent developments being pursued for Particle Physics are non-scaling Fixed Field Alternating Gradient (NS-FFAG) accelerators. These have the potential to provide hadron and ion cancer therapy with smaller, simpler, and cheaper accelerators that could then be based at hospitals. Such developments for a *neutrino factory*, including multi-MW proton beams, can also be utilised to transmute nuclear waste and drive novel sub-critical nuclear reactors.

Applications using accelerators, e.g. the precise treatment of tumours, can only be achieved with sensitive detectors of radiation and charged particles; examples include scintillating fibre, single photon pixel, gas avalanche, multi-wire proportional, silicon microstrip, monolithic active pixel, CCDs, avalanche photo-diode, etc. These are used in applications as diverse as: PET scanners, radiation dosimetry (with medical and security applications), X-ray diffraction, large area cardiac imaging, cargo and luggage scanners, food scanners and fissile nuclear material detection. All these detectors had their origins in Particle Physics; four Nobel prizes have been awarded for detector innovation in Particle Physics. Detector innovation continues for the *Super-LHC* and *ILC*. These next-generation Particle Physics detectors are being developed with very fine granularity and ultra-fast readout capable of operating in MGy radiation environments. Such detectors are also required at next generation light-sources and pulsed neutron sources and have wide applicability outside Particle Physics. For example "quantum dosimeters" can be developed from the silicon pixel detectors under design for the *Super-LHC* that will vastly improve the accuracy of radiation dose estimates in cancer therapy.

The high intensity and energy of new accelerators requires a commensurate increase in data rates, processing and selection. This is achieved through high-speed microelectronics attached directly to the detectors and further electronics connected via optical links. Multi-channel readout ASICs developed for Particle Physics experiments at CERN in the late 1980s are now routinely used in flat-panel X-ray imagers with applications in homeland security, non-destructive testing and medical imaging. More recently, CMOS readout chips capable of single-photon counting developed from *LHC* electronics are widely used in X-ray diffraction and non-destructive testing. Microelectronics with excellent time resolution designed for the *LHC* are now used in chemistry in time-of-flight spectroscopy to analyse peptides and other large biological molecules.

The large amount and complexity of data from Particle Physics experiments requires significant advances in computing and modelling. The most obvious and ubiquitous example is the World Wide Web developed at CERN in the early 1990s. Recently, distributed computing *grids* making thousands of CPUs seamlessly available to users and capable of analysing the copious LHC data have been developed. Recently the UK Particle Physics Computing Grid provided two million hours of CPU time to test millions of prototype malaria drugs and a hundred thousands hours to search for molecules that might inhibit the avian flu virus. A sophisticated programme developed for Particle Physics (GEANT4) simulating the passage of charged particles and radiation through matter is now routinely used in medical physics, e.g. in optimising the design of the next generation of PET scanners.

In the following sections we amplify how Particle Physics is impacting the recently defined [3] RCUK strategic areas: lifelong health and wellbeing, energy, environmental change, global security, nano-science applications and the digital economy. A summary is given in Table 1. Particle Physics is playing a vital role in addressing two key recommendations of the Sainsbury Report [4], namely increasing international collaboration and increasing the supply of university STEM students (and teachers). These technological advances are achieved through close interaction between Particle Physicists and industry. A list of UK companies with whom collaborations have been established is given in Appendix 2 and cross-referenced with [cx]. There has also been considerable knowledge exchange through the UK's participation in CERN. This is documented extensively [5]. A list of large grants (£50k+) made to consortia utilising Particle Physics technologies in other applications is listed in Appendix 3 and cross-referenced with [ax].

| | Health | Energy / Environment / Security |
|---|---|---|
| ***Accelerators*** Linacs, betratrons, hadron beams, ion beams, multi-MW proton beams, RF/klystron systems, synchrotrons, cyclotrons, electron storage, superconducting magnets, vacuum & cryogenic systems. | Radiation cancer therapy, pharmaceutical, viral and protein imaging using synchrotrons, food and water sterilisation. | Nuclear waste transmutation, accelerator driven sub-critical nuclear reactors, conversion of waste hydrocarbons to natural gas, RF earth monitoring, radar, ion implantation in semiconductors, non-destructive testing/imaging. |
| ***Detectors*** Silicon microstrips, scintillation crystals/fibres, pixel detectors, gas avalanche, multi-wire proportional, CCDs, photo-multipliers, avalanche photo-diodes. | Radiation dose measurements, medical imaging, food scanning, light-source detectors, PET scanners, combined PET/MRI scanners, small animal imaging (drug tests), | Detection of fissile material & non-metallic landmines, cargo scanners, whole body scanners. |
| ***Microelectronics*** Deep sub-micron CMOS technology. | Eye implants, readout for optical tweezer experiments, medical imaging e.g. digital autoradiography, peptide analysis. | Radiation tolerant PCBs for earth monitoring, security. |
| ***Computing*** World Wide Web, Grid computing, GEANT4. | Design of new PET scanners, new drug simulations, separation of bio-molecules. | Digital reconstruction using grid of marine biological communities (global warming), radiation tolerant design for space technology, identifying new oil reserves. |

Table 1: Examples of Particle Physics technologies and their applications.

# 4. Applications of Particle Physics Technologies to Medical and Life Sciences

"*Medical advances may seem like wizardry. But pull back the curtain, and sitting at the lever is a high-energy physicist, a combinational chemist or an engineer. Magnetic resonance imaging is an excellent example. Perhaps the last century's greatest advance in diagnosis, MRI is the product of atomic, nuclear and high-energy physics, quantum chemistry, computer science, cryogenics, solid state physics and applied medicine*"
Harold Varmus, Nobel Laureate in Medicine (Washington Post, 2000)

## 4.1. Overview

The accelerators, detectors and microelectronics developed in Particle Physics underpin much of medical physics. The accelerator's role in medical treatment goes back to Chadwick and Lawrence in the 1930s. The first linac used in a medical context was in Hammersmith hospital in 1953 [6]. Betatrons and linacs are used to administer radiation therapy in hospitals and cyclotrons produce radio-isotopes; PET offers a powerful diagnostic tool particularly in conjunction with computer tomography. The world's first X-ray light source, the SRS at Daresbury, originated from a Particle Physics accelerator. Ten thousand accelerators world-wide are being used in a medical capacity [7]. Today, synchrotron radiation is a vital tool in many areas of research, from medical imaging, environmental science, material science and engineering, surface chemistry, biotechnology to the manufacture of advanced microchips.

The need to bend and focus particle beams generated magnet innovation. Precision magnets and associated technology e.g. glass-epoxy insulation systems were developed to withstand extreme radiation environments. The push to higher energies in Particle Physics rapidly developed superconducting magnet technology. The UK's Rutherford Laboratory invented a Nb-Ti superconducting wire used world-wide for decades and without which MRI and similar techniques would not have been possible. Oxford Instruments plc [c1], spun out from Oxford University by Sir Martin Wood with aid from Particle Physics infrastructure, evolved into the world's leading supplier of high-field MRI magnets. Power supplies of unprecedented accuracy at high voltage and current have been developed, together with the necessary computer interfaces. These advances have all been transferred into commercial areas.

## 4.2. Present Accelerator Applications

The accelerator remains central to cancer treatment in the UK. The December 2007 NHS cancer reform strategy [8] identified a need to increase radiotherapy provision by funding the construction of 167 new linacs. The hadron therapy unit at Clatterbridge [9] has treated over 1600 eye tumours since 1989. GE Healthcare in Amersham [10] has an annual turnover in excess of £1B, producing radio-isotopes for PET imaging and radiotherapy. Eight thousand accelerators are used in radiotherapy centres, with others used for medical radio-isotope production, to irradiate cells, monitor the onset of diseases and for accelerator mass spectrometry.

The non-scaling fixed-field alternating-gradient accelerator (NS-FFAG), a development for a *neutrino factory* that combines the strengths of a cyclotron and a synchrotron, can be used to provide a small, high-duty-cycle accelerator to produce beams of variable energy to treat cancer. Protons and heavy ions offer the best treatment of tumours near sensitive structures or organs since energy deposition is more localised than in a conventional radiation treatment. Development of a significant hadron therapy capability in the UK is cited in [8] particularly for treating cancers in children. The CONFORM [11] and BASROC [12, a14] consortia, led by Particle Physicists, are pursuing the development of a NS-FFAG accelerator supported by a £8.2M RCUK basic technology grant [a14]. A 20 MeV electron accelerator, EMMA [13], will be built at Daresbury Laboratory to test the NS-FFAG principle, leading to the construction of a prototype proton/carbon ion NS-FFAG accelerator for medical applications. A UK company, Tesla Engineering [c2], has provided the magnets for EMMA and for other international accelerators at CERN, DESY and the DIAMOND synchrotron. The company also supplies specialised components for MRI scanners that have evolved from Particle Physics. The specialised demands of light sources have led to a new generation of high-precision permanent-magnet systems with further technology transfer into industry. These developments from Particle Physics highlight that the key drivers to innovation come from the requirements of cutting-edge research.

## 4.3. Present Detector Applications

Particle Physics detectors have traditionally been the detectors of choice in medicine and the life sciences. Those based on semiconductors, scintillators and gas ionisation which offer precise position information have found applications in medicine for diagnostic imaging, dosimetry and in oncology for beam diagnostics and target imaging, as well as at X-ray light and neutron spallation sources.

### *4.3.1. Applications of Particle Physics Semiconductor Detector Technology*

> "*The requirements imposed by basic research in particle physics are pushing the limits of detector performance in many regards, the new challenging concepts born out in detector physics are outstanding and the technological advances driven by microelectronics and Moore's law promise an even more complex and sophisticated future*".
>
> "*The demands and requirements on detectors for high energy physics and medical physics applications are persistently driving the development of novel pixel detectors.*"
> D. G. Darambara [14].

In oncology, the current R&D frontier is the development of fast, online imaging of the position of tumours in moving organs e.g. the lungs. This requires high-speed, high-resolution detectors such as the semiconductor detectors used in Particle Physics. Such **Silicon microstrip detectors** [15] have applications in dosimetry and biomedical radiography and radioscopy. A more recent development is in **silicon pixel detectors,** originally designed for fixed-target Particle Physics experiments and now used extensively at the *CERN LHC*. Their small detection elements make them ideal in high-radiation environments such as light sources. Each pixel cell is able to detect and count individual X-ray quanta, providing a fully digital biomedical image. At least five developments of pixel detectors have medical or life-science applications: Dectris [c3] has developed the Pilatus chip, which is in use at DIAMOND; the Medipix collaboration [16] including Glasgow University has developed pixel-array readout chips counting singe photons which has been licensed to Panalytical plc [c4] for use in its X-ray diffraction instruments and to the Fraunhofer Institute; Philips healthcare with CERN are to extend the Medipix [a10] to 2D and 3D X-ray imaging; a UK company, Micron Semiconductors [c5], has developed pixel detectors in collaboration with UK Particle Physics groups for X-ray medical imaging; Bioscan [c6], a CERN spinout company, has developed two medical imaging systems.

The Bioscan PIXRAY system acquires real-time images with significant dose reduction (up to 100 times compared to film) and better contrast. Its IRIS digital imaging system has been developed to improve the quality of cancer treatment by monitoring the patient's position during exposure. The company has also developed pixel sensors for use in real-time, non-destructive inspection using X-rays that have found use in many industries. A recent application to emerge from *LHC* is a quantum dosimeter [17] that can determine the type, quantity and position of the incident radiation, allowing very accurate dose estimates. The technique offers much wider dosimetry possibilities for applications including space, homeland security and healthcare.

**Charge Coupled Devices (CCDs)** have widespread use in digital cameras and video cameras but also in digital X-ray systems. e2v [c7] Technologies (UK) Ltd has developed X-ray dental image sensors [18] offering high-performance imaging with lower radiation dose than film. Experimenters preparing for the *ILC* are collaborating with the Japanese on CCD R&D to produce a detector for the high burst rate and intensity of the TESLA X-FEL [a18] and LCLS light sources. The e2v company through their collaboration on *ILC* detectors expects to increase the resolution of large-scale CCD arrays in the next ten years by a factor of 30.

**Silicon photon detectors** are being developed in Particle Physics [19], using solid-state technology to replace PMTs e.g. avalanche photo-diodes, (APDs) and Silicon photomultipliers (SiPMs) [20] with Hamamatsu [c8]. These have applications in combined PET/MRI scanners where the high magnetic field requirements of MRI preclude the use of conventional photon detectors.

**Active Pixel Sensors** (APSs) were originally developed for the *ILC.* In 2004, the Multidimensional Integrated Intelligent Imaging Consortium (MI-3) [21,a6], containing particle physicists from STFC, Liverpool and Glasgow, was awarded £4.7M over 4 years by the RC-UK Basic Technology Programme [a2]. The project also contains molecular biologists, radiation physicists, geneticists, cancer researchers, engineers and space scientists. It aims to develop CMOS imaging sensors with improved imaging capability, high-rate capture, flexible readout and integral intelligence in a single microchip. The sensors will extend the effective spectral response of present active-pixel sensors into the infra-red and soft X-ray regions with applicability to space science, medicine and biology, e.g. real-time *in-viv*o brain imaging to study brain function and fully digital 3D mammography. Prototype CMOS active-pixel sensors have been developed as retina implants to act as stimulators and partially restore sight to the blind [22,a9]. Electrode array technology is being developed for the study of cortical slices [23] in a collaboration sponsored by EPSRC between Particle Physicists and neurobiologists based at the Salk Institute in San Diego [a3].

### *4.3.2. Applications of Particle Physics Scintillator Technology*

A large range of scintillators, in particular fast-response scintillators, has been developed for Particle Physics. They are now widely used in X-ray mammography, radiation-dose distribution measurements and PET scanners. Scintillator crystals e.g. Bismuth Germanate, have excellent energy resolution and detect the 511 keV gamma rays from PET with high efficiency. The Institute of Cancer Research has stated that only the mass production of fast scintillators for Particle Physics experiments produced a price drop to a level appropriate for medical physics applications. For example, Hilger Crystals Ltd [c9] produced 10,000 thalium-doped CsI crystals for the BaBar experiment at SLAC, producing the capacity to fulfil larger orders for other applications. The Crystal Clear Collaboration [24] at CERN is a multi-disciplinary partnership between Particle Physics, medicine and industry to develop improved energy and time resolution in such crystals. The 3D-RID [25, a1] collaboration led by the University of Glasgow is developing structured scintillator films for a variety of commercial applications using semiconductor micro-machining technology from Surface Technology Systems [c10] and scintillators from Applied Scintillation Technologies [c11].

### *4.3.3. Applications using Gas-Based Position Sensitive Detectors*

Three examples are **multi-wire proportional chambers (MWPCs), gas electron multipliers (GEMs)** and **high-density avalanche chambers (HIDACs)**. They produce large signals through avalanche multiplication in high electric fields, making them highly sensitive and able to work without low-noise electronics. The HIDAC was invented at CERN and has resulted in a spin-out company, Oxford Positron System Ltd [c12] that is now providing biomedical scanners [26] that can image both temporally and spatially with high precision and low noise. GEMs offer high potential for medical physics, particularly in nuclear scattering radiography. They can be combined with CsI photocathodes to achieve a single-photon threshold, thereby enhancing capability to distinguish between malignant and benign tissues in early stage tumours.

#### *4.3.4. Particle Physics Technologies used in Positron Emission Tomography*

Positron Emission Tomography (PET) offers a powerful diagnostic tool particularly in conjunction with computer tomography. The technology is still being improved via innovations in Particle Physics to provide better resolution for whole-body scanning, for small-animal imaging (drug-testing studies) and to provide dual MRI/PET scanners.

A Particle Physics spin-out, PETRRA [c13] is developing cheaper, more convenient and performant whole-body scanners using fast $BaF_2$ scintillating crystals and a MWPC that is much simpler than conventional whole-body PET cameras. The system will combine excellent energy, time and spatial resolution over a large area. Recent clinical trials have demonstrated that the first-generation PETRRA system can produce images comparable to state-of-the-art commercial PET systems.

Traditional PET scanners using PMTs cannot easily be combined with MRI scanners since PMTs cannot operate in the high magnetic fields required by MRI scanners. This can be overcome by using semi-conductor photon counters (APDs, SiPMs) [a17] that have been developed to work in the high magnetic fields encountered at the *LHC*. The MRI/PET technique coupled with the development of new scintillators will considerably improve the imaging resolution for whole-body scanning and the imaging resolution on small animals used in drug trials.

### 4.4. Particle Physics Computing Applications in Medicine

The World Wide Web has revolutionised the lives of all in the developed world. A new development from Particle Physics, the computing grid, promises further developments for example in medicine. The UK Particle Physics Grid (GRIDPP) [53] is one of the largest components of the worldwide *LHC* Computing Grid (LCG) and the multidisciplinary EU Grid (EGEE) that comprises 55,000 CPUs. The WISDOM [27] project used more than 2 million hours of GRIDPP CPU time to search through 140 million potential new drugs against malaria. Drugs to combat the recent avian-flu outbreak were also investigated by European and Asian researchers using 100,000 hours of GRIDPP CPU time [27]. This follows the use of Grid technology to establish a cutting-edge communication network, called the Access Grid, among quarantined hospitals across Taiwan, in response to the SARS outbreak in 2003 [29].

GEANT4 [30] is a software package developed for Particle Physics that simulates the interactions of charged particles and radiation with matter. It has become widely used in other disciplines and is the most-cited Nuclear Science and Technology publication with over 132,000 citations. Developers [31] have extended its applications to energies low enough to be of use to medical physics where it is widely used to simulate the response of biological matter to radiation. In brachytherapy, for example, GEANT4 can be used to simulate the sealed radioactive source and the dose distribution in the patient. Photon-beam radiotherapy, hadron therapy and boron neutron-capture therapy also utilise GEANT4. GATE [32] (GEANT4 Application for Tomographic Emission) provides another example, as does MCHIT [33] (Monte Carlo for Heavy-Ion Therapy). GEANT4-DNA [34] simulates the impact of radiation on biological systems at the cellular and DNA level. This has particular application in assessing the cancer risk in manned space flights and civil aviation. GEANT4 is being used by the European Network for Light Ion Therapy (ENLIGHT) [35] to optimise the design of potential heavy-ion cancer treatments and also for the next generation of high resolution, full-body PET scanners.

GEANT4 provides open-source software without charge to other disciplines, but there are other examples of Particle Physics software techniques being used in the commercial biomedical sector. For example DeltaDOT's [36, c14] application of Particle Physics software techniques has speeded up the non-destructive analysis of biomolecules by at least a factor of five. DeltaDOT now employs more than twenty staff, and its technology has applications in protein science, chemistry, pharmacy, plant science and forensics.

# 5. Uses of Particle Physics in Electronics, Energy, Environment and Security

> "*The know how and technical expertise acquired meeting the demanding particle physics orders led to an enhanced capability for delivering in other sectors such as X-ray imaging and homeland security applications*."
> J. R. Telfer; Managing Director, Hilger Crystals Ltd.

## 5.1. Accelerator Research and Development

Eight thousand accelerators are used in the semi-conductor industry, producing beams of ions for implantation in semiconductors; they are essential for the construction of all modern integrated circuits. Indeed the first X-ray lithography system, HELIOS, was bought by IBM from Oxford Instruments, who developed the compact, superconducting light source in collaboration with SRS designers at Daresbury. Oxford Instruments has acknowledged that this would not have been possible without fundamental research in areas such as Particle Physics [37]. A further 2,000 accelerators utilise electrons and X-rays for non-destructive testing/imaging e.g. for weld inspection in aircraft manufacture, for the irradiation of food and to provide clean water.

Developments in NS-FFAG magnets offer significant potential in three key areas: nuclear waste transmutation, sustainable energy and neutron spallation sources. A high-powered proton beam incident on a lead target will produce copious amounts of neutrons [38] of the correct energy to transmute long-lived radioactive waste into isotopes of a much shorter half-life that present a much-reduced environmental threat, while a thorium target can produce the neutrons necessary to sustain a sub-critical nuclear reactor [a16]. This produces fissile $^{233}U$ without producing significant plutonium, thereby reducing nuclear proliferation. Such a reactor can be prevented from going critical simply by turning off the proton accelerator and the accelerator itself can be powered using the electricity generated from the fissile $^{233}U$. The provision of multi-MW proton beams can produce the intense source of spallation neutrons needed for materials science studies. The present generation of neutron spallation sources e.g. ISIS at RAL, has benefited from the transfer of expertise from R&D in Particle Physics in creating, manipulating and sustaining high-intensity beams.

Three major technology areas that have benefited from the demands of accelerators are RF systems, ultra-high-vacuum technology and high voltage and power management. The klystron was invented at Stanford in the USA in 1939 and contributed to early developments in radar. It has revolutionised RF power transmission. The technology now finds many applications in radar and broadcasting and most recently has been deployed to convert waste hydrocarbons to oil and natural gas [39]. The most recent RF development has been the increasing adoption of superconducting structures with all the attendant cryogenic challenges, once again involving major collaborations with industry. Successful UK companies which have benefitted as commercial suppliers in these advanced equipment areas include e2v [c7], TMD [c15] and Outokumpo Holton [c16]. Vacuum science and technology has also been driven by the needs of advanced accelerator projects. Storage rings demand ultra-high vacuum (UHV) and this in turn requires extremely high industrial standards of production and quality control, aided by technology transfer from Particle Physics. One direct beneficiary of advances in Particle Physics accelerator technology is the nuclear fusion industry. Tokamaks utilise accelerator technologies such as electromagnet coils, RF probes and drivers, and large vacuum systems.

Government, recognising that accelerator laboratories and HEIs need to cooperate more closely with their industrial suppliers to ensure sustainability of the commercial base, established industrial Faraday partnerships [40] to stimulate innovation in UK industry and to give companies the competitive edge by improving product quality and reducing costs. Accelerator/Particle Physicists developing high-power RF supplies were amongst the first to participate in these partnerships. This partnership is viewed as an exemplar for future initiatives. The subsequent rise in companies' attainment standards after exposure to the demands of Particle Physics often brings significant commercial benefits, particularly in the security or energy sectors.

The recent renaissance of accelerator R&D in universities has in addition to the intellectual benefits for the subject also generated a highly trained work force, including a stream of PhD students, a significant number of whom will be recruited into industry, either to apply these skills directly or to demonstrate in other spheres the aptitudes developed through their advanced training.

## 5.2. Particle Physics Detector Developments Relevant to Electronics, Energy, Environment and Security

### *5.2.1. Overview of Silicon Technology Developments for Particle Physics*

Experiments at CERN in the '80s and '90s stimulated the development of Application Specific Integrated Circuit (ASIC) "microchip" technology. Electronics developed for these experiments have since found commercial imaging applications, e.g. the Microplex ASIC [41] is now used in flat-panel X-ray imagers such as the ones developed by Varian [c17]. Similar designs are now used in X-ray line-scan systems used in the food industry to scan for foreign bodies and other contaminants and in baggage handling and freight scanning. Low-noise ASICs developed at RAL initially are in use in a variety of non-medical products commercialised by Senstech [c18], Dpix [c19] and Oxford instruments [c1].

The *LHC* detectors require even more sophisticated ASICS. The microelectronics developed for the *LHC* can withstand 10-100 kGy radiation levels, accumulate and buffer data at 40 MHz and undertake real-time data reduction with unprecedented reliability in systems containing up to 100 million channels. Microelectronics designers and physicists at RAL and CERN have worked with the major foundries (such as IBM), helping increase their understanding of their own technology. UK Particle Physicists, working with smaller companies such as e2v [c7], Hamamatsu [c8] and Micron [c5], have helped to improve the performance of silicon sensors for radiation-hard environments, with direct relevance to Earth monitoring missions. Collaboration between Micron and Liverpool University for the *Super-LHC* has already provided detectors capable of withstanding MGy doses. The technologies developed have now been taken up by other suppliers, in particular Hamamatsu Photonics (HPK) in Japan [c8] and e2v [c7] in the UK. The fast electronics and rapid data capture techniques developed for the *LHC* have been transferred to chemistry to allow time-of-flight mass spectrometry. This has become the principal method of analysis for peptides and other very large molecules of biological interest. This technique has now been coupled with imaging using low-noise Particle Physics detectors to produce an analytical method that is capable of providing a visual image of the chemical contents of both animal and vegetable tissue.

The training provided in detector and microelectronics development for Particle Physics at the Universities and STFC Laboratories has provided expert personnel who have moved into the electronics industry.

### *5.2.2. Scintillator Technologies Relevant to Homeland Security*

Large scintillator-crystal orders for experiments at CERN and SLAC has led to Hilger Crystals Ltd winning contracts to supply scintillation crystals on an industrial basis to manufacturers of X-ray equipment for inspecting cargo and luggage at seaports and airports. A partnership between Corus [c20,a19] and Sheffield University is developing large-area laminar scintillation detectors to detect neutrons indicating the presence of fissile nuclear material. These neutron detectors are also likely to find applications in moisture gauges and the detection of non-metallic landmines. The same partnership in conjunction with Particle Physicists at Glasgow University is sponsored by EPSRC and the Home Office [a4] to develop scintillator detectors to be used with sealed-tube neutron generators (STNG) to identify explosives and drugs in air cargo. The presence of fissile material can also be determined through the detection of high-energy neutrinos that cannot be shielded. Large scintillating-liquid detectors being developed for *neutrino-less double-beta decay* experiments could potentially be placed on ships to detect fissile material over long distances.

## 5.3. Extending engineering capabilities through Particle Physics Detectors and Electronics

The unprecedented requirements of the LHC experiments have led to interactions between universities and industry that have led to new industrial capabilities. There are several examples in the area of complex readout boards, including Stevenage Circuits [c21], Cemgraft Electronics [c22] and Exception EMS [c23], who worked with RAL and Imperial College (IC) to provide 500 front-end-driver (FED) [42] boards of unparalleled complexity for the CMS experiment. Seventeen thousand high-value Ball Grid Array (BGA) devices had to be surface mounted onto the PCBs, developing new technical skills for the company, which worked closely with RAL/IC during several months of prototyping and testing in order to achieve the required standard. Test equipment designed by Particle Physicists for final quality control was installed at the factory and operated by the company’s engineers. The order was delivered on time with only a 1% failure rate.

The construction of Particle Physics detectors involves not only major firms delivering the largest contracts but also SMEs. Examples of work involving small UK companies include TM Plastics [c24], who provided the anti-static transport boxes for forward silicon tracker modules for the *LHC* ATLAS experiment and CAE Engineering (Wirral) [c25] who carried out similar work for LHCb. Denholm, Rees and O'Donnell [c26] fabricated the suspension frame for transport of the $10m^2$ ATLAS silicon EndCap-C array by road from Liverpool University to CERN. A larger-scale company, TM Engineers [c27], provided two endplates to support 22,000 kg of scintillator crystals and PMTs of the CMS endcap calorimeter. These endplates had to be machined under constant temperature to tolerances of a few microns over an area of $50\ m^2$. Qudos Technology Ltd [c28] designed, constructed and commissioned the large clean room where the silicon detectors for the *LHC* CMS detector were assembled.

## 5.4. Particle Physics Computing Applications Contributing to Energy, Environment and Security

Computing Grids are being used in a collaboration of BAE Systems [c29] with Hewlett-Packard, Cardiff and Swansea Universities for advanced simulation and visualization [43]. Nuclear fusion researchers from Spain have been using the grid to simulate divertors, which act as exhausts, removing the waste products from fusion burning plasmas. The JET laboratory in Culham, Oxfordshire has contributed a substantial site to the *LHC* Grid, supporting not only fusion research but also the *LHC* and biomedical simulations. GEANT4 is now being routinely used by the space industry to determine how electronics in space will be affected by radiation and to design radiation shields for spacecraft. The grid has also been used to study the population evolution of marine biological communities and to determine their impact on global warming [44].

# 6. Underpinning the Knowledge-Based Economy

It is widely recognised [4,45,46,47,48,49] that future economic competitiveness requires sustained investment in the physical sciences. Particle Physics has a vital role to play in two further recommendations of the Sainsbury Report:

1. Increasing international collaborations to help attract researchers from abroad and link British researchers with the best and brightest researchers globally.
2. Increasing the supply of students (and teachers) studying science, technology, engineering and mathematics (STEM) subjects at university.

Transferrable skills particularly in the areas of large-scale data analysis, and mathematical modelling accumulated during a Particle Physics PhD are in particular demand in the computing and financial sectors. As has already been discussed, the technological skills in instrumentation and microelectronics are in demand in other research disciplines and industry.

## 6.1. Increasing International Collaboration

Particle Physics continues to thrive from international collaboration. For example, the ATLAS experiment at CERN has scientists from 37 countries spanning 167 institutes, including 300 scientists from the UK. More than one third of all Particle Physics academics in the UK are from overseas, as are more than 50% of post-doctoral researchers. Particle Physics thus fosters international collaboration with world-leading researchers. PhD students and post-doctoral researchers from the UK often spend considerable periods receiving training overseas, giving them experience much sought after by employers.

"*We have employed a number of PhDs in particle physics at aAIM and we have found them to be highly flexible and numerate, with an analytic mindset and the type of international experience which enables them to make a significant contribution very quickly. We would definitely like to see more people with this background becoming available for employment in the City*."

Mark Tagliaferri, Chairman aAIM Group Plc.

## 6.2. Increasing the supply of Physics Graduates and Post-Graduates

A survey (see Appendix 1) of 829 undergraduate students conducted in November 2007 at 8 UK universities confirmed that a significant interest in Particle Physics (and nuclear and astrophysics) is responsible for attracting students to study physics at university and that this interest is retained through to post-graduate level. In more detail, the conclusions of the survey are:

- the three most popular subject areas that 1st year undergraduate students cited as being of "significant interest" in terms of attracting them to study physics are: Fundamental Particles & Quantum Phenomena (72%), Nuclear Physics (61%) and Astrophysics (53%); 90% of students expressed a significant interest in at least one of these three areas.

- only 37% of 1st year undergraduate students expressed a significant interest in applied physics or medical physics. It is fundamental physics that attracts students to study physics at university; these students will then ultimately transfer their skills from a physics degree to more applied disciplines.

- 89% of 4th year students expressed some or significant interest in Particle Physics with similarly high percentages in Astrophysics/Cosmology (73%) and Nuclear Physics (82%).

- Only 11% of students expressed no interest in Particle Physics, the lowest “no-interest” fraction of all subject areas.

## 6.3. Transfer Of Particle Physics Training and Skills : Computing / Finance

Over 50% of Particle Physics post-graduates end up in the private sector within three years of completing a PhD [50]. Skills in large-scale data analysis and mathematical modelling accumulated in an international and collaborative environment are in particular demand in the computing/IT, management consultancy and financial sectors. Indeed these sectors have consistently expressed a wish [51] for more Particle Physics graduates.

*“Particle physics PhDs are at the very greatest level of demand, especially in the highest value added sections of the market such as the City. It is well-known that there are many lucrative "quant" roles available to such specialists, but also they can fill a wider role in more client-facing positions. Some sought-after qualities, such as high levels of computing skills, analytical mindset and wide adaptability within a methodical approach are hallmarks of all PhD physicists. However, particle physics PhDs can add some further highly desirable benefits to employers due to their having worked in large international experiments.”*

Dr Tim Short: Vice-President, Asset Finance, Credit Suisse First Boston.

Training to a high level in computing is provided not only within the framework of the Particle Physics environment but also in a private sector context through the CERN OpenLab initiative [52] where students receive training from Intel, HP and ORACLE.

The expertise that led to the invention of the World Wide Web at CERN has recently been applied to the problems associated with analysing millions of Gb of *LHC* data via computing grids. The challenging technological demands of access to *LHC* data for thousands of scientists are driving Grid Computing innovations. The Worldwide *LHC* Computing Grid (WLCG) is the world’s largest academic Grid, developed to cope with the unprecedented (15 million gigabytes/year) *LHC* data rates. The access requirements for *LHC* data have led to a suite of sophisticated management tools (middleware) being developed for the WLCG that are now being widely exploited outside Particle Physics. The UK through GridPP [53] is playing a leading role in these developments and is providing around 10% (10,000 CPUs) to the WLCG. Three examples of companies benefiting from the UK Particle Physics Grid Computing innovations are:

- Imense Ltd [54,a11,c30], in collaboration with Cambridge University and with seedcorn funding from STFC has now secured external funding tenfold that of the original investment. Imense used the UK Particle Physics Grid to prototype its product and utilised the expertise within GridPP for handling millions of distributed files. It plans to use the open source Grid technologies from the Particle Physics domain in its commercial product to identify web images lacking associated metadata.

  *“Our work with the Grid has let us demonstrate that our software can handle millions of images, at a time when we were a small company and couldn't supply the computing power needed ourselves. This in turn impressed the investors we spoke to, and led to funding for our company.” : David Sinclair, Imense Ltd.*

- Econophysica Ltd [a21,c31], in collaboration with Queen Mary University of London is using Particle Physics Grid middleware to model the optimum timing and size of purchasing derivative options.

- U4EA Technologies Ltd [a5,c32], in collaboration with CERN have developed an emulator to determine the conditions under which other critical distributed computing networks may fail e.g. those providing emergency services and internet telephony.

While the analysis techniques of Particle Physics are most often applied in the financial context, there have been other notable examples. For example pattern-recognition algorithms used to measure the trajectory of charged particles have been adapted for applications as diverse as measurement of meteorological records at Oxford, scanning for malignant cells in cervical smears at Nijmegen and cartography and computer-controlled drafting at Cambridge. Axomic [55, c33] based on software developed at CERN have commercialised a digital asset management product for architects, civil engineers and construction companies that enables them to store and search for images.

## 7. Conclusion

Industry has always gained significant benefits both directly and indirectly from Particle Physics. Industry benefits from the enhanced capabilities and the new skills developed in fulfilling challenging orders and from the influx of Particle Physics trained personnel. Particle Physics drives innovation in the areas of accelerator, detector, microelectronics and computing technologies. These innovations continue to enable advancement in many areas, particularly medicine and the life and material sciences. Some of this innovation is serendipitous but no less valuable for that; the World Wide Web provides the best example. The challenging science questions of the next decade will demand future paradigm shifts in technology; Particle Physics can provide some of these and will continue to drive innovation and attract students to study physics to an advanced level.

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"UK research in the field of particle physics is of a high quality and internationally very visible. UK particle physics has, for many years, made effective use of frontline accelerators worldwide. Researchers from around 25 universities are performing a broad experimental programme and are involved in most major experiments around the world. Research is focused on the central questions of the field, both through involvement in current experiments and through a strong engagement in the high-potential experiments of the coming years and decades. UK physicists carry the responsibility for key detector components and often hold leadership positions."

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"It's scientists and engineers, working together, who make these advances, and these collaborations are becoming ever closer. The advantages of meshing the design and function of these large scientific experiments are becoming apparent, and every time we on talk to the people involved with them, they tell us that closer collaboration will lead to further advances and quicker exploitation of possible commercial spin-offs..

…you can't underestimate the power of these experiments to get people interested in science and technology. Universities always complain how hard it is to persuade students onto these 'difficult' courses. Think how much harder it will be to grab them without the prospect of access to these spectacular devices."

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## Appendix 1: Results of undergraduate survey

In November 2007, a survey of 829 undergraduate students was conducted. One question was asked of 1st year undergraduates and two of final year (4th year) undergraduates. The questionnaires were completed at the end of undergraduate lectures. The surveys were conducted at 8 universities. The sampling of 673 1st year students represents approximately 20% of the 1st year physics and astronomy undergraduate students in the UK. The breakdown by institute is given below.

| Institute | # Year 1 Surveyed | # Year 4 Surveyed |
|---|---|---|
| Durham | 111 | |
| Glasgow | 107 | 17 |
| Imperial | 190 | 22 |
| Liverpool | 48 | 29 |
| Manchester | | 41 |
| Oxford | 93 | |
| UCL | 91 | 32 |
| Warwick | 33 | 15 |
| | | |
| Total | 673 | 156 |

The question: ***Which aspects of physics attracted you to the subject ?***

was presented to 673 first year undergraduates and divided into subjects according to the major themes in the A-level syllabus. A summary of the results is given in the table below:

| Subject Area / % interest | No Interest | Some Interest | Significant Interest |
|---|---|---|---|
| Mathematical aspects | 11 | 44 | 45 |
| Fundamental Particles, Quantum Phenomena | 5 | 22 | 73 |
| Mechanics & Kinetic Theory | 6 | 55 | 39 |
| Electricity & Magnetism | 14 | 63 | 23 |
| Properties of Solids | 37 | 52 | 11 |
| Waves and Optics | 21 | 60 | 19 |
| Nuclear Physics | 4 | 35 | 61 |
| Astrophysics | 12 | 34 | 54 |
| Medical Physics | 55 | 34 | 11 |
| Electronics | 36 | 49 | 15 |
| Applied Physics | 11 | 57 | 32 |

The question:
**Do you intend to continue physics research after your degree either at the post-graduate level or in industry ?**

was presented to 156 final year (4th year undergraduates) and the results are summarised below.

| | |
|---|---|
| Yes at postgraduate Level (PhD, MSc) | 55% |
| Yes in Industry | 11% |
| No | 34% |

A second question:
**If you intend to continue physics research, which areas of current physics research are of interest?**

was also presented to the final year undergraduates. The results are below:

| Subject Area/ % interest | No Interest | Some Interest | Significant Interest |
|---|---|---|---|
| Atomic & Molecular Physics | 19 | 68 | 13 |
| Lasers, optics & photon Physics | 34 | 51 | 15 |
| Particle Physics | 11 | 43 | 46 |
| AstroPhysics/Cosmology | 27 | 33 | 40 |
| Superconductors/fluids | 47 | 45 | 8 |
| Nuclear Physics | 18 | 48 | 34 |
| Materials, nanotechnology, condensed matter Physics | 43 | 37 | 20 |
| Quantum computing/communication | 35 | 45 | 20 |
| Medical/Biological Physics | 54 | 33 | 13 |
| Environmental Physics / Renewable energy | 35 | 44 | 21 |
| Geo-Physics | 66 | 26 | 8 |

10% of students cited an interest in non-listed subject areas which could broadly be assigned to: particle physics (4%), computing (2%), cosmology (2%), materials/nanotechnology (2%).

## Appendix 2: List of UK Companies Engaged With Particle Physics Research

The technological advances made by Particle Physics are only possible through the close interaction between physicists and engineers at universities and national centres with industry. Listed below are the UK companies or companies that have a UK base that have or are engaged in active collaboration with Particle Physics researchers. Companies directly spun-out of Particle Physics Research are marked with "s". Companies utilising technology pioneered in Particle Physics are marked with "p".

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Superconducting Magnets.

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Magnets for MRI and accelerators.

[c3]s Dectris (Villigen, Switzerland)
http://www.dectris.com
Hybrid Pixel X-ray detectors.

[c4] Panalytical (Almelo, Netherlands but also Cambridge, UK)
http://www.panalytical.com
Medipix chip for X-ray detectors.

[c5] Micron Semiconductor (Lancing, UK)
http://www.micronsemiconductor.co.uk
Silicon detectors.

[c6]s BioScan (Geneva, Switzerland)
http://www.bioscan.ch
Digital imaging systems for health, aeronautical, automotive, nuclear, electronics, space, oil, gas and food industries.

[c7] e2v (Chelmsford, Lincoln, High Wycombe, UK and France, Switzerland, Taiwan, USA)
http://www.e2v.com
CCDs.

[c8] Hamamatsu (Welwyn Garden City but Japanese)
http://www.hamamatsu.com
PMTs.

[c9] Hilger Crystals (Margate, UK)
http://www.hilger-crystals.co.uk
Scintillator crystals.

[c10] Surface Technology Systems (Newport, UK)
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Semiconductor processing equipment

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Specialist scintillator production

[c12]s Oxford Positron Systems Ltd (Weston-on-the-Green, UK)
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High Density Avalanche Chambers (HIDAC).

[c13]s PETRRA Ltd (Didcot, UK)
http://www.petrra.com
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[c14]s DeltaDot (Imperial College, UK)
http://www.deltadot.com
Instrumentation and automation for separation and analysis of bio-molecules.

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Microwave tubes, high voltage power supplies, radar transmitters, RF testing.

[c16] Outokumpo Holton Ltd (Bournemouth, UK)
http://www.holton-conform.com
Aluminium stabilized superconducting cables.

[c17]p Varian (US but with UK base in Crawley)
http://www.varian.com
Oncology Systems including linear accelerators, X-ray imaging.

[c18]p Senstech (Aberdeen, UK)
http://www.senstech.co.uk
Sensor technology for condition monitoring.

[c19]p dPix (Palo Alto, USA)
http://www.dpix.com
High-resolution amorphous silicon (a-Si) sensor arrays.

[c20] Corus (various UK locations)
http://www.corusservices.com
Neutron detectors/Radiation Portal Monitors (RPMs).

[c21] Stevenage Circuits (Stevenage, UK)
http://www.stevenagecircuits.co.uk
PCBs.

[c22] Cemgraft Electronic Manufacturing (Newbury, UK)
http://www.cemgraft.co.uk
PCBs.

[c23] Exception EMS Ltd (Calne, UK)
http://www.exceptionems.com
PCBs.

[c24] TM Plastics (Runcorn, UK)
http://www.tmplastics.co.uk
Plastic Engineering.

[c25] CAE Engineering (Wirral ,UK)

[c26] Denholm, Rees & O'Donnell (Liverpool, UK)
Mechanical Engineering.

[c27] TM Engineers (Kingswinford, UK)
http://www.tmengineers.co.uk
Mechanical Engineering.

[c28] Qudos Technology (Didcot, UK)
http://www.qudostechnology.co.uk
Cleanrooms.

[c29] BAE Systems

http://www.baesystems.com

[c30]p Imense Ltd (Cambridge, UK)
http://www.imense.com
Content-based image retrieval.

[c31] Econophysica (London, UK)
http://www.econophysica.com
Grid computing

[c32] U4EA Technologies
http://www.u4eatech.com
Internet Communications

[c33]p Axomic PLC (London, UK)
http://www.axomic.com/

[c34] ET Enterprises Limited (Ruislip, UK)
http://www.electrontubes.com
PMTs.

[c35] ACCEL Instruments GmbH (Bergisch Gladbach, Germany)
http://www.accel.de
Superconducting RF cavities.

[c36] Icemos Technology (Belfast, UK)
http://www.icemostech.com/ice
Silicon wafers.

[c37] Dynex semiconductors (Lincoln, UK)
http://www.dynexsemi.com
Power supplies.

[c38] Western Park Hospital (Sheffield, UK)
http://www.sth.nhs.uk/westonpark

[c39] Photek (St Leonards on Sea, UK)
http://www.photek.com
Image intensifiers - specialized cameras

[c40] Exception PCB (Tewkesbury, UK)
http://www.exceptionpcb.com
PCBs

[c41] ClusterVision (Gloucester, UK)
http://www.clustervision.com
PC clusters

[c42] Viglen (St. Albans, UK)
http://www.viglen.co.uk
PC clusters

## Appendix 3: Cross-Discipline / Technology Transfer Grants

The financial value from knowledge exchange with industry is in many cases difficult to quantify and commercial confidentiality often prevents information being provided in a public document. Many Particle Physics projects have led to improvements in production facilities that subsequently benefit the future output of a company. In recent years, government policy and research council funding has actively encouraged knowledge exchange with the award of grants. This can be quantified. The table below lists the grants (£50k+) to consortia including Particle Physicists to develop applications from Particle Physics technology in the last 5 years. There has been a marked increase in the variety and number of projects engaging Particle Physicists in the last 2 years. This list does not include the project R&D grants awarded by STFC which in many cases are conducted in parallel with the explicit technology transfer grants and many of which involve significant industrial contracts.

| | | | |
|---|---|---|---|
| [a1] | £2.3M<br>U. Glasgow | 01/10/01-30/09/04<br>EU | Micromachining techniques to development of novel radiation detection structures |
| [a2] | £0.07M<br>H. Kraus | 01/07/02-30/06/04<br>PPARC | Low temperature scintillators for the health sector. |
| [a3] | £0.25M<br>K. Smith | 01/12/02-30/11/05<br>EPSRC | *In-vivo* measurement of retinal response. |
| [a4] | £0.12M<br>C. Buttar | 01/10/03-30/09/05<br>PPARC | Microstrip dosimeter for characterisation of medical radiotherapy and radiosurgery systems |
| [a5] | £0.1M<br>B. Martin | 01/10/03-30/09/05<br>PPARC | Testing and validation for predictable networking using a high performance network emulator |
| [a6] | £4.7M<br>N. Allinson | 01/06/04-31/03/08<br>RCUK | Active pixel sensors for use across the UK science base. |
| [a7] | £0.15M<br>H. Gamble | 01/06/05-31/05/07<br>PPARC | Monolithic active pixel detectors using bonded wafer substrates. |
| [a8] | £0.14M<br>E. Daw | 01/08/05-31/07/08<br>STFC | Glass-Free UV Photomultiplier Arrays for Large Cryogenic Liquid Scintillation Detectors |
| [a9] | £0.12M<br>K. Mathieson | 2005<br>RSE | Retinal prosthesis using active pixels. |
| [a10] | £0.13M<br>C. Parkes | 01/05/06-30/04/09<br>EPSRC | 3D detectors for synchrotron applications. |
| [a11] | £0.15M<br>A. Parker | 01/11/06-14/04/09<br>STFC | Grid technology for commercial scale content image retrieval. |
| [a12] | £0.07M<br>S. Manolopoulos | 01/02/07-31/1/08<br>CLIK | A Novel Dosimeter for Small Field Dosimetry |
| [a13] | £0.16M<br>V. O'Shea | 01/03/07-31/08/08<br>BBSRC | Ultra-fast single photon camera for spatial imaging of fast cellular events. |
| [a14] | £8.5M<br>R. Barlow | 01/04/07-30/09/10<br>RCUK | Compact high energy particle accelerators (NS-FFAGs) for use in science, technology, medicine. |
| [a15] | £0.22M | 01/08/07-31/07/10 | Electrode array technology for neuro- |

| | | | |
|---|---|---|---|
| | D. Gunning | EPSRC | physiological studies of cortical slices |
| [a16] | £0.14M<br>R. Barlow | 01/10/07-31/03/09<br>EPSRC | Innovative Accelerator Technology for Accelerator Driven Subcritical Reactors |
| [a17] | £0.08M<br>B. Camanzi | 2007<br>CLIK | Fast time-of-flight PET with solid-state PM read-out. |
| [a18] | £0.38M<br>V. O'Shea | 2008<br>STFC | Flat panel imaging technology for XFEL. |
| [a19] | £0.75M<br>J. McMillan | 01/05/08-30/04/11<br>EPSRC | Neutron scanning techniques for airborne cargo. |
| [a20] | £0.20M<br>N. Geddes | 01/06/08 - 31/05/10<br>STFC | Integration of gLite (Grid software) for the commercial trading of computer resources |
| [a21] | £0.1M<br>S. Lloyd | 01/07/08-30/06/08<br>STFC | Feasibility of the Grid Based Algorithmic Trading Platform |