Benefits of Research in Particle Physics

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Abstract.

Particle Physics is often refereed to as High Energy Physics (HEP) because the probing of matter on the smallest distance scales requires (due to the wave-particle duality of quantum mechanics) the use of the highest available particle collision energies. Therefore, for nearly all experimental particle physics programmes, the development of accelerator technology has proved essential. The accelerators required for particle physics are incredible engineering undertakings, requiring the largest scientific instruments ever built by mankind. The know-how acquired in meeting the challenges of the ever higher accelerator energies and particle fluxes required by particle physics has always provided the strongest stimulation to accelerator research and development, leading to many innovations of crucial importance to a wide range of scientific and industrial applications and promising many more important developments in the future. The techniques developed for the experiments that use the accelerated particles also make extreme demands in sensor and data handling technology, driving many developments finding applications in a wide range of other fields. Once the accelerator brings the beams of high energy particles to collide, the detection and measurement of the collision products requires highly sensitive detector technologies, with hundreds of millions of electronic channels, often operating and very high speed and needing to intelligently reduce the raw data rate by factors of a million in real time to produce a manageable amount of data to be stored. Even then, tens of petabytes (1 petabyte is a million gigabytes) of data will need to be stored and processed requiring a new computing paradigm, the “Grid”, which harnesses distributed computing power and disc storage around the globe to handle these colossal computing requirements. Indeed the Worldwide LHC Computing Grid (LCG) is the largest academic computing grid in existence. Finally, the skills that have to be acquired to operate successfully in this highly interdisciplinary, international and competitive environment match those required by some of the most intellectually demanding and highest value-added sectors of the economy.

One of the areas to benefit most from all the different technologies developed for particle physics has been medical physics. As examples, in this field, betatron and linear accelerators are used to administer radiation therapy in hospitals, while positron emission tomography (PET) offers a powerful diagnostic tool in conjunction with computer tomography. Synchrotron radiation was first discovered at the high-energy accelerators used for particle physics experiments. Today, it is an extremely useful tool in many areas of research, both pure and applied. Tools using synchrotron radiation are used in medical imaging, environmental science, materials science and engineering, surface chemistry, biotechnology, as well as the manufacture of advanced microchips. The scientific uses of synchrotron radiation include research into hemoglobin (the oxygen carrier in blood), and it has been important in the quest to find a cure for ALS (Lou Gehrig’s disease) and the AIDS virus.

The Nobel Prize awarded to Georges Charpak in 1992 for his outstanding work in the area of detector physics came in recognition of the immense importance of this field to particle physics and its applications in other areas, such as biomedicine. The scientific community is continually striving to find new medical applications for the technologies which emerge from particle physics. These efforts have also been picked up by other areas of research. GSI, for example, the Society for Heavy Ion Research in Darmstadt, is currently working with partners from Italy (TERA) and Austria (Med-AUSTRON) to develop the use of ion beams in the treatment of tumours.

Scintillating fibre detectors, originally developed for use in particle physics experiments, can also be used to precisely measure radiation dose distributions. This information is vital in the application of radioactivity in medical treatments, for example in the treatment of blood vessels — a process known as endovascular brachytherapy — or of eye tumours. In both cases, a tumour is directly irradiated and destroyed by a small radioactive source placed in or close to it. In order to plan and prepare for this type of radiation therapy, specialists also use special simulation programs that were first developed in particle physics for the design and optimisation of detectors. Pixel detectors were originally developed for use in the immediate vicinity of the particle collision point in the large detectors at the LHC and linear colliders. Today, they are also opening up new perspectives in biomedical imaging and protein crystallography with synchrotron radiation. In what is a direct spin-off from development work for the LHC experiments, pixel detectors can now be used in radiography applications to provide a fully digital image. This is possible because every pixel cell of the detector is able to detect and count individual X-ray quanta. There are also highly interesting applications in the field of biology. For example, using high-resolution semiconductor detectors, gas avalanche detectors or scintillation detectors together with image intensifiers, it is now possible to produce time-resolved autoradiograms of tritium used as a radioactive marker to replace the hydrogen in living cells. All these detectors were originally developed for use in particle physics experiments. Finally, microstructured large area gas detectors first developed to detect particles in experiments at HERA and at the LHC are also used in radiography for imaging purposes. These developments

have benefited enormously from the dramatic advances made possible by the use of integrated electronics, which have been available to university and laboratory researchers at a reasonable price for only about fifteen years.
For specific examples of knowledge exchange through the activities at the CERN laboratory for particle physics in Geneva see: http://technologytransfer.web.cern.ch/TechnologyTransfer/Welcome.html

"*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, comscience, cryogenics, solid state physics and applied medicine*"
Harold Varmus, Nobel Laureate in Medicine (Washington Post, 2000)

1. Brief Overview of the Scientific Goals of Particle Physics

Particle Physics represents one of the greatest endeavours of mankind. It follows the reductionist paradigm which has dominated the thinking driving the scientific revolution since the times of Galileo, Descartes and Newton. The belief that no understanding of a system is complete unless it also incorporates an understanding of its constituents is as relevant today as it was in the Seventeenth Century. High Energy Physics probes the nature of fundamental particles and of the space between them. On the tiny distance scales probed with today's facilities, quantum effects blur the distinctions between matter and forces, with virtual particles flitting in and out of existence over unimaginably time durations. At yet smaller distance scales (or equivalently higher energies) theories requiring a quantum understanding of space-time, the domain of quantum-gravity, are required. Theories attempting to link space-time, matter and all forces together result in signatures which can be searched for with the experimental facilities now nearing completion or envisaged over the next coming two decades.
Particle physics today is at a most exciting threshold. Theoretically, the masses of all the known fundamental particles are linked to one mass scale, the "electro-weak symmetry breaking energy scale" linked to the elusive and so-far undiscovered Higgs particle. Only now is a new accelerator (the LHC) coming on line that can operate with a collision energy well above (60 times) this mass scale, being able to explore for the first time the physics in this completely new regime. Many new particle states are predicted and there is even the suggestion that effects of extra dimensions may be visible at LHC energies.
Precision measurements at these energies will require a complementary facility to the LHC, the proposed International Linear Collider, which will achieve sensitivity to subtle effects such as those predicted by the most promising current models of physics at the quantum-gravity scale. Indeed, precision measurements promise glimpses of the physics well above the direct energy reach of an accelerator, but at the cost of requiring very low backgrounds and very high statistics. The first conclusive evidence of physics needing to be understood in terms of much higher energies comes from the neutrino sector where recent discoveries of neutrino masses and measurements of neutrino oscillations, along with precision studies of rare processes involving heavy quarks, are helping elucidate the puzzle of why our Universe seems to only be composed of matter with very little anti-matter left over from the Big Bang.
Fundamental particle physics explores the nature of matter and of the forces that bind matter together. This field addresses some of the oldest and deepest questions in natural philosophy. A hugely successful era of consolidating the detailed understanding of the fundamental workings of our world at energies below the electro-weak symmetry breaking scale is drawing to a close. We need to be fully equipped to face the challenges of a new era.
As far as the UK position in this highly competitive research area is concerned, one can refer to the 2005 International Perceptions of UK Research in Physics and Astronomy
(http://www.iop.org/activity/policy/Publications/file_21581.pdf).
Of UK Experimental Particle Physics it reports:

" 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."

2. Accelerator Science and Technology

CATEGORY OF ACCELERATOR	NUMBER IN USE*
High Energy (E > 1 GeV)	~ 120
Synchrotron Radiation Sources	> 100
Medical Isotope Production	~ 200
Radiotherapy Centres	> 7,500
Research Acc. (includes biomedical research)	~ 1,000
Acc. for Industrial Processing & Research	~ 1,500
Ion Implanters and Mills	> 7,000
TOTAL	> 17,500
(*) W. Maciszewski and W. Scharf, Int. J. of Radiation Oncology, 2004	

2.1. Historical Overview

The birth of particle accelerators probably dates back to Lord Rutherford's presidential address to the Royal Society Anniversary Meeting in 1927, when he publicly called for the development of multi-MeV devices for particle physics experiments. It is significant that over the subsequent five years of pioneering progress, leading up to the Nobel Prize experiments by Cockcroft and Walton on splitting the atom at the Cavendish Laboratory in Cambridge, the development team relied on very close links to Metropolitan Vickers, a leading British engineering company. The scientists specified components that forced technological advances. Physics and engineering stimulated each other from the start. Thus did the subject commence with effective academic-industrial links that have continued into the 21st century.

Meanwhile over in the USA similar high voltage accelerator tubes were already being used for x-ray diagnostics and therapy treatments. Also Ernest Lawrence had invented the Cyclotron at Berkeley and after his first small machines he determined to construct a larger one for medical applications, including radioisotope production for cancer treatment. Similar oncology developments were also initiated at the Hammersmith Hospital in London. The case for the largest cyclotron outside the USA in 1939, built by Chadwick in Liverpool University Physics Department, rested in part on a Commission led by Lord Derby reporting on its medical potential for cancer treatment and radiobiology. Particle physics had already, nearly seventy-five years ago, spawned the first of its many applications outside the subject.

After World War II a proliferation of accelerator science and technology occurred. This was still stimulated by the needs of high energy physics with developments of new device types such as linear accelerators (linacs), betatrons and synchrotrons. Synchrotron radiation, a seemingly unwanted and wasteful byproduct of electron acceleration, was discovered and has since led to enormous exploitation benefits for physics, chemistry and life sciences. High intensity proton synchrotron technology, adapted from particle physics demands, has been applied to establishing powerful spallation neutron sources for wide ranging materials science studies.

This trend continues. The ever extending extremes of particle physics needs, combined with their major associated R&D activities, lead to ongoing inventiveness together with underpinning technology developments driving industrial innovation. Some specific examples both of fundamental accelerator innovation arising from particle physics and their broader applications, including technology spin-off, are given below.

2.2. Cyclotrons

The invention of the cyclotron immediately stimulated many advances in the physics and engineering of accelerators, especially the key areas of magnet, radiofrequency (RF) and vacuum technologies. Although the dominance of the cyclotron for particle physics was short lived, being displaced by the synchrotron from the 50's onwards, it continues to have an important place in industrial and medical applications, mainly due to its high current and stable operating regimes. Radio-isotope production is a well established area that is widely exploited, one example being the commercial facilities at GE (Amersham) in the UK. The hadron therapy unit at Clatterbridge, based on a 65 MeV cyclotron, is the only such treatment centre in the UK but has had major impact in the area of eye tumours. Similar but more powerful examples can be found in Europe, USA and Japan.

2.3. Synchrotrons

The single biggest step in accelerator development was the invention of the Synchrotron, allowing compact and economical delivery of very high energy particle beams for a wide variety of applications, although initially for particle physics purposes. Such accelerators included NIMROD and NINA as major national facilities in the UK. The synchrotron evolved from the slightly earlier but much more restricted Betatron, although the latter continued to have a commercial market for relatively low energy electron uses for several decades.

Electron synchrotrons reached the regime where significant radiated energy loss challenged their efficiency, but this heralded a remarkable new application of such synchrotron radiation that has exploded in popularity in the realisation of dozens of dedicated Light Sources around the world. Initial trials in the UK on the Glasgow synchrotron and then on NINA, parasiting on particle physics provision, were so successful that the world's inaugural dedicated (thereby second generation) Light Source, the SRS at Daresbury), was operated from 1980 until the present, to be succeeded by the more advanced third generation DIAMOND from 2008 onwards. All such modern Light Sources utilise another invention from particle physics needs: the electron storage ring capable of preserving beam continuously for a full day or more, allowing efficient data collection and very stable conditions. The applications have been enormous, ranging from atomic physics through materials studies to life sciences; the latter saw the Nobel Prize for Chemistry awarded to Sir John Walker in 1990 for determination of the molecular structure of the enzyme F1 ATPase on the SRS. None of this would have occurred without the stimulation of particle physics needs predating these other applications.

In parallel another application of the high energy synchrotron also grew in the UK with the utilisation of the proton beam to create spallation neutrons from a high power target in the ISIS facility at RAL. This has allowed more than two decades of advanced materials science studies and new multi-MW sources are now under consideration. This development has benefited from ongoing accelerator spin-off that overcomes the challenge of creating and manipulation very high intensity beams, employing knowledge gained at particle physics laboratories such as CERN.

Commercial exploitation of synchrotron radiation has included access by a number of companies to the SRS beams. A more direct example of commercialisation was the design and construction of HELIOS by a collaboration of SRS designers with Oxford Instruments plc (http://www.oxford-instruments.com), resulting in sale of a compact (superconducting) light source to IBM as an x-ray lithography facility in a prototype chip manufacturing plant in the USA. In addition to the highly successful development of the machine itself (and a second one later delivered that enabled to Singapore) there was a major and extended programme of technology transfer to the company - knowledge originating in the pure research support of high energy physics at an earlier time.

Both the SRS and ISIS illustrate clearly the transferable skills that link all advanced accelerator developments. Starting with simulations employing computer codes developed at CERN and similar centres, and then utilising the commercial manufacturing base underpinned by particle physics accelerator demands, the eventual successful commissioning and operations of these modern synchrotrons owes everything to their antecedents.

2.4. Linear Accelerators

The linear accelerator (linac) is the most omniscient in its world wide impact. Once again it was initiated by particle physics needs and it continues a strong role there, either as a low energy injector or more recently re-emerging as the accelerator of choice for extremely high energy electron collisions (the ILC). Linacs are also used for hadron and ion beam applications in pure research, for example in nuclear physics. Linear accelerating structures have even been included in recirculating accelerator configurations, the latest example being the Energy Recovery Linac concept proposed for a very advanced fourth generation light source (4GLS).

The electron linac is the accelerator of choice for commercial and medical production of x-rays. It has had huge impact on health diagnostics and oncology treatment. Radiographic applications in industry include weld inspection in aircraft manufacture. Another important application is in sterilisation procedures, including food products and even clean water supplies.

Hadron linacs are less common in commercial application. However their future impact might be enormous since they have been proposed both for radioactive waste transmutation and for the sub-critical reactor known as an energy amplifier. In either case the beams will be multi-MW in power rating, well beyond current performance levels both for beam currents and target dissipation but comparable to the demands of a future Neutrino Factory that could be developed for particle physics.

2.5. The Fixed-Field Alternating-Gradient Accelerator: A Case Study

The fixed field alternating gradient (FFAG) accelerator combines the strengths of a cyclotron and a synchrotron. After early studies it was ignored for several decades but now enjoys a renaissance stimulated by its possible use at the heart of a Neutrino Factory. However its potential in other areas, most notably in medical applications, has aroused much wider interest recently. Several scaling-FFAGs have now been constructed but are quite complex. A variant is the non-scaling FFAG that offers the prospect of smaller, simpler, cheaper accelerators operating with a high frequency and a high duty cycle. The CONFORM project (http://www.conform.ac.uk/) will seek to exploit this technology, originally developed in 1956 (see D. Kerst, K. Symon, L. Laslett, L. Jones, K. Terwilliger, “Fixed field alternating gradient particle accelerators”, Proceedings of the CERN Symposium on High Energy Accelerators, Geneva, June 11–23, 1956, pp. 32–35). Its particle physics application is as a very rapid method of accelerating muons before they can decay (see Rob Edgecock and the EMMA Collaboration**,** “Introduction to the Non-scaling Electron Model FFAG EMMA”, Nuclear Physics B - Proceedings Supplements**,** Volume 155, Issue 1, May 2006, Pages 321-322) but it is also capable of supporting high beam currents and delivering variable energy output (a major medical bonus).

The CONFORM project is supported by an RCUK Basic Technology grant (£8.2M) and aims to

1. build a 20 MeV electron accelerator, EMMA to test the principle
2. design a proton accelerator for medical applications, PAMELA
3. investigate possible applications, from archaeology to zoology

Non-scaling fixed-field alternating gradient accelerators - or NS-FFAG accelerators for short - will be smaller, simpler and significantly cheaper than the synchrotrons, and more flexible than the cyclotrons, that are currently used in a variety of applications. They should have a major impact as next generation hospital-based clinical accelerators for proton and carbon ion beam treatment of cancers (http://www.basroc.org.uk/), and in diverse fields from archaeology to zoology.

No NS-FFAG accelerator has yet been constructed. CONFORM will move rapidly from the conceptual design to the construction of a model electron accelerator (EMMA - Electron Model for Many Applications) located at the Daresbury Laboratory. The experience gained in the development and operation of EMMA will inform the design and eventual construction of a prototype proton/carbon ion NS-FFAG accelerator for medical applications (PAMELA - Particle Accelerator for MEdicaL Applications).

An extensive R&D programme will evaluate the potential of NS-FFAG accelerators as proton drivers for applications in scientific and technological fields as diverse as energy and environment (eg accelerator driven sub critical reactors, waste transmutation), materials research (eg advanced neutron and muon sources for studies of the structure and dynamics of materials), and fundamental physics (eg the neutrino factory).

The NS-FFAG and similar technological developments, many of which are initially driven entirely by the requirements of particle physics, are crucial to the use of accelerators in a wide variety of applications, of which health physics and oncology provide some of the clearest examples. As in so many areas of technology, the key drivers to innovation are coming from the extreme requirements of cutting edge research and the ability of such research to bring together a critical mass of highly motivated experts.

2.6. Technologies for Accelerators

The need to control particle beams (eg bending and focusing) has generated a major magnet technology area within particle accelerator laboratories. In addition to high precision electromagnets capable of withstanding extreme environments – for example glass-epoxy insulation systems resistant to extreme radiation fields – particle physics needs have driven the rapid development of superconducting magnet technology. Rutherford Laboratory in the UK pioneered many early developments, including invention of a Nb-Ti wire used world wide for decades. Oxford Instruments plc was spun out from the Clarendon Laboratory by Sir Martin Wood, stimulated by particle physics support capabilities but then evolving into the world's leading supplier of high field MRI scanner magnets. A UK company, Tesla Engineering (http://www.tesla.co.uk/index.htm) , has an internationally leading business as a supplier of magnets for particle beam applications, including very large orders for CERN, DESY, DIAMOND etc. The company also supplies specialised components for MRI scanners which directly benefit from work for particle physics applications. More recently, the specialised demands of the light sources have led to a new generation of high precision permanent magnet systems that have required further technology transfer into industry.

In parallel with these magnet systems has been the development of modern power supplies of unprecedented accuracy at high voltage and current, together with the necessary computer interface technology. These advances have all been transferred into commercial areas.

Another major technology area that has benefited from the demands of accelerators is in radiofrequency (RF) systems. This ranges from the accelerating structures themselves, including their couplers, tuners etc, through to their power sources such as klystrons and IOTs. The klystron, so widely used in the broadcasting industry, was invented at Stanford in the USA in 1939 in connection with the particle physics programme and has revolutionised RF power transmission. The most recent RF development has been the increasing adoption of superconducting structures with all the attendant cryogenics challenges, once again involving major collaborations with industry. Successful UK companies which have benefited as commercial suppliers of power sources and associated advanced equipment include e2v (http://www.e2v.com/products/rf-and-sensors.cfm) and TMD (http://www.tmd.co.uk/products/index.asp).

Vacuum science and technology has been driven forward by the needs of advanced accelerator projects too. Storage rings demand UHV environments and this in turn requires extremely high industrial standards of production and processing quality control by industrial suppliers, only achieved after technology transfer to them. Large scale vacuum chambers are now widely available, as are the great variety of associated pumps and gauges, often themselves produced first in the accelerator laboratory.

Finally the general level of industrial engineering has risen in response to the demands in commercial contract specifications, most notably exerted by frontier particle physics needs. This extends not only to major firms delivering the largest contracts but also to SMEs and even to small local companies carrying out subcontract jobs.

Technology spin-off is not only into industry but also to other fields of science and technology. One outstanding example is in fusion sources based on tokamaks, a magnetic containment device utilising recognisable accelerator technologies such as electromagnet coils, RF probes and drivers, and vacuum chamber containment. A clear example of this is seen at JET in Culham and an even larger scale demonstration will follow on ITER at Caderache in France, now under construction. Energy research there links in closely to earlier particle accelerator developments.

2.7. The Faraday RF Partnership

In recent years it has become recognised that accelerator laboratories need to cooperate more closely with their industrial supply chains to ensure sustainability of this commercial base. This includes assistance to strategic planning by early warning of future projects, together with identification of technological challenges ahead. Faraday Partnerships were set up by the DTI to assist such interactions, including an involvement by academia to stimulate innovation, and a High Power RF Partnership was established in 2001 (http://www.scitech.ac.uk/KE/Ind/PowerFaraday.aspx). This has been a successful forum supported by industrial partners and moreover has extended from its original accelerator remit into industrial (eg concrete breaking, mineral processing) and defence. The Partnership is a model for such technology exchange and has now been adopted by the IET as a new sponsor.

2.8. Training and Development of Accelerator Science and Technology Expertise

Expertise in modern accelerator science and technology is hard won in a demanding sphere. It ranges from simulation skills thought system definition to the many component technologies. Project engineering and management skills are also necessary disciplines. This skill base resided in the universities in the early days of particle physics but over the last 30-40 years increasingly migrated into larger government (and international) laboratories. Initially the laboratories tended to construct even large scale systems themselves but this is no longer seen to be efficient so that industrial suppliers dominate procurement. This not only results in technology know-how transfer but also demands that companies match the increasing demands from the laboratories, often including extreme quality control. These companies may not initially welcome such pressure but later they find enormous advantage in the rise in their attainment standards, with subsequent commercial benefit.

Another recent trend has been the renaissance of accelerator R&D in the HEIs. In addition to the intellectual benefits for the subject this also generates a highly trained work force, including a stream of PhD students of whom a significant number are recruited into industry, either to apply these skills directly or to demonstrate in other spheres the aptitudes developed in their advanced training.

2.9. Professor Mike Poole: a Biography

Mike Poole was a graduate of Liverpool University in 1966, at a time when its Physics Department was leading the construction of the new particle physics facility NINA at Daresbury. He was encouraged to join the accelerator team under Alec Merrison and worked on a variety of topics including the extracted beam lines. In 1970 he was a member of a small team that produced a significant upgrade to NINA by addition of a pulsed quadrupole correction system. Soon afterwards he joined the design team for EPIC, a joint Daresbury-Rutherford proposal to build an electron-proton collider for particle physics. This was never funded (due to the late emergence of a German equivalent at DESY) and the British decision to join the SPS at CERN led to the closure of both NINA and NIMROD later in that decade, ending domestic particle physics accelerators. Mike by then had joined the design team for a new Light Source, the SRS, that included many members from that earlier particle physics background. He designed, built and tested the major magnet systems on the SRS and went on to head the Accelerator Physics Group at Daresbury.

New accelerator source development has occupied him for the last 20 years, including the HELIOS project that won him an SERC Inventors Award, and a leading role in the design studies for DIAMOND. He has sponsored free electron laser (FEL) development in the UK over this period, and advised on many overseas projects. In 1992 he was promoted through the Joint Research Councils Individual Merit Scheme. With the formation of the CCLRC Accelerator Science and Technology Centre (ASTeC) in 2001 he became Deputy Director and then in 2003 took over as its Director, a post he has held ever since. He holds a Visiting Professorship at Liverpool and is a Fellow of the IOP. He has a keen interest in technology transfer and industrial collaboration and was on the Steering Committee of the Faraday Partnership. His career started with his role on a particle physics accelerator but has evolved into a host of other application areas, using skills learned from those early days onwards.

3. Detector Research and Development

3.1. Historical Overview

One of the key challenges in particle physics has always been development of highly sensitive apparatus able to operate at high speed in extreme conditions, often with a significant level of built-in intelligence to handle otherwise unmanageably large data rates. Important from the start has been detector systems (sensors with their associated front-end electronics, data reduction, read-out and data acquisition systems. While sensor developments such as those that won the 1927 (Wilson), 1960 (Glaser), 1968 (Alvarez) and 1992 (Charpak) Nobel prizes have always been important, the development of associated electronics, in particular application specific integrated circuits (ASICs) and sophisticated field-programmable gat arrays (FPGAs) have been equally significant. Current detector systems tend to be very large area, using multiple technologies for different detection roles (eg highly segmented silicon planes for inner tracking, ionisation in liquid noble gases or scintillation in plastics or high density crystals for measuring energy deposition followed by wire chamber (gas) technology for high radius tracking and muon identification). Other detection systems (such as using Cherenkov light) can be employed and, in general, the requirements for reading out detection systems that yield photons has led to high sensitivity single photon sensitivity being developed using a number of different techniques.

3.2. Applications of Particle Physics Sensor Technology

Many of the developments required for particle physics have found wider application, particularly in the area of medical imaging and oncology. Nearly all the sensor technologies developed for particle physics have found roles in other fields but those based on semiconductors, scintillators and gas ionisation have been particularly important for position sensitive detector applications. Here are some specific examples of programmes taking sensor development from particle physics and applying them in other disciplines:

- Instrumentation of bio-sensors e.g. neural imaging for advances in brain science. Evaluation projects underway at RAL.
- Vision prosthesis - Developments for future eye implants for coupling cameras to the optic nerve are being developed at RAL.
- Finger print scanning – new high performance security screening systems are being developed with a US company.
- Dosimetry for radiology – we are actively pursuing new methods in 3-d tomographic imaging of dose delivery in cancer treatment.

In oncology, the current R&D frontier in cancer research and treatment is the development of online imaging for both conventional and charged particle therapy in order to track online the position of tumours in moving organs (the lungs for example). Here a list of technologies which have had specific inputs from particle physics:

- Silicon microstrip detectors. Examples of applications include dosimetry, biomedical radiography and radioscopy using silicon microstrip sensors (see for example M Caccia et al. "Imaging of β particle sources used in medical applications with position sensitive Silicon sensors", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment Volume 525, Issues 1-2, 1 June 2004, Pages 294-297 or EU Project Reference: BMH4961119)
- Hybrid pixel detectors. The initial development of hybrid pixel detector systems for particle physics was brought about to resolve ambiguities that arise when strip occupancy is very high. It also turns out that small detection elements such as these pixels have enhanced resistance to irradiation as the initial leakage current is very small. This has led to a growing number of developments that have been commercialised to some extent.
    - The Pilatus chip has been developed by a group at PSI for use in the Swiss Light Source. Following a successful chip and system development a company (Dectris) has been spun out to commercialise the system. They have been very successful in selling systems to other synchrotrons around the world – the Diamond Light Source in the UK has bought 2 of these systems. (See http://www.dectris.com/sites/dectris.html)
    - The Medipix collaboration is now on it's third generation of single photon counting pixel array readout chips implemented in a CMOS technology and hybridised (bump bonded) to a pixellated detector made from a material suitable for the envisaged application. The chip has been licensed to Panalytical plc for use in it's X-ray diffraction instruments, the technology has also been licensed to the Fraunhofer Institute for an application in Non-Destructive Testing. (See http://medipix.web.cern.ch/MEDIPIX/)
    - Pixel detectors have been supplied by Micron Semiconductors (UK) Ltd for X-ray medical imaging and the company has also secured several defence and homeland security contracts (http://www.micronsemiconductor.co.uk). The company was established in 1983 and has become a leading manufacturer of silicon detectors for the high energy physics, space, nuclear and medical research markets and now has sales offices in the US and Japan. Many of the company's products have been developed in collaboration with UK University particle physics groups.
    - One spinout from CERN, BioScan (http://www.bioscan.ch/) has developed pixel sensors for X-ray, real-time, non-destructive inspection in industrial applications: aeronautics, automotive, nuclear, electronics, space, oil and gas, including hostile environments, food, cultural and archaeological studies. Its PIXRAY system has been developed for medical diagnosis and interventional radiology which permits the acquisition of real-time images with significant dose reduction (up to 100 times compared to film) and better contrast

resolution in comparison with the standard techniques. The IRIS digital imaging system has been developed for cancer therapy to monitor the patient's position during treatment with external gamma- and X-ray beams. IRIS improves the quality of the treatment and allows more accurate visualization for localization of the treatment area during radiotherapy.

- A very recent application to emerge is "quantum dosimetry". Here the type of incident radiation can be identified by the way it deposits energy in the sensor and so by counting the numbers of each type of incident radiation a very accurate estimate of the dose may be calculated. This ability is currently being developed for the ATLAS experiment where a number of chips will be deployed to measure the radiation flux at various points inside the experiment to test predictions for the radiation environment due to the LHC. However, the technique offers much wider dosimetry possibilities for a range other applications including space, homeland security and healthcare. (http://technologytransfer.web.cern.ch/TechnologyTransfer/en/Technology/QuantumDosimetry.html)

- Charge Coupled Devices (CCDs); where the scientific demands coming from astronomy, space science and particle physics are helping to push the envelope of what is technically achievable in terms of readout speed, quantum efficiency, integrated functionality, pixel dimensions and array size. Examples of widespread use include digital cameras, including video cameras, and digital X-ray systems (see for example e2v Technologies (UK) Ltd http://e2v.com/introduction/app_dental_imaging.htm).
  Andor, Bruker, Nonius, ADSC and Marresearch are all suppliers of CCD systems to synchrotrons around the world. (See for example http://www.marresearch.com/). Recent developments for particle physics vertex detectors at the ILC, the CPCCD and ISIS concepts, have major impact for fast burst imaging of x-rays. Collaborations with Japan are forming to use these ideas to adapt designs for optical read-out to be used with X-rays, including at the ultra-high brightness TESLA X-FEL and LCLS facilities. (Since these light facilities grew out of research for the ILC, these sensors already have well matched readout design.) e2v are heavily involved in developments for the ILC which would aim to produce a 30 Gpixels array, 70 m^2 of 50 µm square pixels by ~2020 timescales.

A large range of scintillators and in particular fast scintillators. The Institute of Cancer Research have pointed out that was only the large mass scale production of fast scintillators required by HEP experiment that allowed the price of such scintillators to drop making them accessible for the medical physics community too. As an example, Hilger Crystals Ltd (http://www.hilger-crystals.co.uk) developed the CsI(Tl) crystals to be used in the electromagbetic calorimeter of the BaBar experiment at SLAC. Hilger now supply scintillation crystals on an industrial basis to manufacturers of X-ray inspection equipment used for inspecting cargo at seaports and luggage etc at airports. J. R. Telfer, their Managing Director writes: "*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*."

- Gas detectors: ionisation chambers, multi-wire proportional chambers (MWPCs) and Gas Electron Multipliers (GEMs). A former senior CERN physicist, Dr Jeavons, founded a private company Oxford Positron System Ltd, producing wire chambers and in particular High Density Avalanche Chambers (HIDAC) that were invented by him while at CERN. There is now a huge amount of activity at CERN in applying GEM detectors to the medical field and there is a rumour that CERN could try to patent the GEMs also for medical physics applications.

- Photon sensors: PMTs. Again here the latest developments are for trying to substitute them with solid state detectors (APDs and SiPM *eg* http://sales.hamamatsu.com/en/products/solid-state-division/si-photodiode-series).
- In imaging for charged particle radiotherapy, Profs Amaldi and Sauli are looking into implementing an instrumentation system (based on GEM detectors) to use the so called nuclear scattering radiography as a direct application of basic particle physics ideas and techniques.

One of the most obvious areas where particle physics technology has been seen to play a major role in medical science is Positron Emission Tomography (PET). PET offers a powerful diagnostic tool in conjunction with computer tomography. It is as vital a part for the treatment of tumours as the use of accelerators (also coming from developments for particle physics). Gas ionisation based detectors and silicon diodes are also used for QA checks to measure the dose prior to treatment in a phantom at the patient position.

In the paper D. G. Darambara "State-of-the-art radiation detectors for medical imaging: demands and trends" Nucl. Inst. and Meth. A 569 (2006) 153-158 the introduction states
"*The significant advances achieved during the last decades in material properties, detector characteristics and high-quality electronic system played an ever-expanding role in different areas of science, such as high energy, nuclear physics and astrophysics. and had a reflective impact on the development and rapid progress of radiation detector technologies used in medical imaging." and from the Conclusions 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*".
And in the text:
"*Further, the demands and requirements on detectors for high energy physics and medical physics applications are persistently driving the development of novel pixel detectors.*"

New frontiers in medical applications are:
- PET/MRI combined and high resolution PET for small animal imaging (also benefiting from detectors developed for nuclear physics), important for pharmaceutical applications. Because of the requirements of particle physics calorimeters (such as that of CMS) operating in intense magnetic fields, APDs and SiPM technologies have been developed that now allow PET to be useable in the high magnetic fields of MRI.
- Further developments of new scintillators now allow the higher granularity needed in small PET systems (see Photonics Material Ltd http://photonicmaterials.com/)
- Development of fast scintillators is opening up the possibility of using Time of Flight (well known to particle physicists) to improve PET performance for the whole body scanning.
- MRI and many other areas, also benefits from developments in superconductivity technology linked to developments for particle physics, an example being the work of Outokumpo Holton Ltd (www.outokumpu.com/holton) to develop new methods of producing high quality aluminium stabilized superconducting cables.

3.3. Large Scale Mechanical Assembly

CMS-Mechanical Design:

A Midlands manufacturing Company TM engineers gained experience and know-how on large aluminium machined parts which they did not have before. (It's a long story; theirs was the only bid we could afford). They were awarded a prize by CMS and visited CERN to collect it.

The 2006 CMS Gold award went to TK engineers mentioned for large mechanics. This year the award went to another UK company, Qudos Technology Ltd based near in Didcot for having designed, constructed and commissoined the large clean room for the Tracker Integration Facility (TIF). In the announcement on CMS it was written that Qudos exceeded the required specifications while meeting a very demanding schedule.

3.4. PETRRA: A case Study

Gas based detectors are being developed for large area cardiac imaging. RAL is now developing a PETTRA demonstrator as a prototype for a full body PET scanner with significantly increased particle efficiency. PET scanners based on scintillators and wire technologies (see http://www.petrra.com/) are being developed and used in hospitals. At the Royal Marsden, Robert Ott, Professor of Radiation Physics at the Institute of Cancer Research, has been leading these developments since 1980. Prior to this he spent 14 years in High Energy Particle Physics working at Queen Mary College in London, McGill University in Montreal, the Lawrence Berkeley Laboratory in California, the Rutherford Appleton Laboratory and CERN. Bob gained his first degree and Ph.D. in physics at the University of Southampton.
Recent clinical trials conducted at the Royal Marsden have demonstrated that the first-generation PETRRA system can produce images comparable in quality to state-of-the-art commercial PET systems. Based on these results, PETRRA is proceeding with the development of a clinical PET system.

4. Impact of Electronics and Readout Developed for Particle Physics

4.1. Microelectronics (Application Specific Integrated Circuits)

The 27km circumference Large Electron Positron accelerator at CERN served four experiments: ALEPH, DELPHI, L3 and OPAL at four collision points and operated from 1989 until 2000. In Europe it provided a major stimulation for the development of ASIC technology to allow the readout of high density detectors with of order 100,000 separate electronics channels, each needing to sense signals of pico-Coulombs, and condense the data onto < 100 actual read-out lines coming out from the centre of the experiment. Electronics developed for this have since been developed for a number of commercial imaging applications. One important area where such multi-channel readout ASICs for particle detectors have been further developed and exploited is in medical imaging. An example is the use of the Microplex ASIC (developed first for DELPHI then for OPAL) that is now used in flat panel X-ray imagers such as the ones developed by Varian and Thales
(see http://www.varian.com/xray/digital_radiography.html).
Similar designs are now used in X-ray line-scan systems that are used in the food industry to scan for foreign bodies and other contaminants. Other applications include baggage handling and fright scanning.
See http://www.senstech.co.uk/xray/xdas.html for a module with RAL ASICs in and also http://www.senstech.co.uk/xray/linx.html.
Specific further examples of collaborations with industry include:

- DpiX - Xerox spinout exploiting microplex technology for X-ray imaging;
- ETL - development of linescan systems;
- Hitachi - Low noise instrumentation for Quantum electronics used ASICs at low temperatures to form embryonic computation devices;
- Oxford Instruments – Low noise electronics.

Since the LEP programme completed data taking, the 27km tunnel has been equipped with a massive superconducting magnet system to deliver proton-proton or heavy ion collisions at rates of up to a billion interactions per second and centre of mass energies of 14 TeV. The microelectronics developed for this has had to emphasise radiation hardness to >Mrad levels, high speed (25 nano-seconds per bunch crossing), high levels of data buffering and data reduction (some sub-systems have up to 100 million channels) and robust fault-tolerant design. The UK is involved in all four of the massive experiments, ALICE, ATLAS, CMS and LHCb which are designed to access different aspects of the physics coming form collisions at this unprecedented energy.

ASIC developments with silicon vendors helped explore improving the performance of standard modern (deep sub-micron) CMOS technology for radiation hard environments. This has led to new understanding in how to use these technologies that has particularly benefited the space radiation-hardness market. It also required high densities of analogue memories that had significant yield implications. Microelectronics designers at RAL worked with the foundries and helped increase their knowledge an understanding of their own technology.

For the longer term future two projects at the energy frontier will be the Super-LHC (with ten times the interaction rate of the LHC but with much greater radiation tolerance requirements and correspondingly greater data reduction challenges) and the International Linear Collider. The development of radiation hard silicon detectors for the former has been led from the UK with a UK company (Micron Semiconductor Ltd) providing in collaboration with UK Universities, detectors proven to Grad doses. The latter programme requires very fine granularity and fast read-out detector systems and the UK has led the development of ultra fast CCD (column parallel readout) with another UK company e2v. This latter programme has also led in both the UK and internationally to the development of Monolithic Active Pixel Sensor (MAPS) technology for which a successful Basic Technology bid (MI-3) described below is exploring applications in a wide range of other scientific disciplines. Also the data driven MAPS architectures developed for Calorimetry at the International Linear Collider (Calice) are finding applications as novel bio sensors.

4.2. Complex Read-out Board Technologies

Some of the circuits needed for particle physics triggering (data filtering), data acquisition and read-out have pushed the boundaries in terms of manufacture to the advantage of companies engaged in the supply of these highly demanding and specialised products. One example being the Front End Driver (http://www.te.rl.ac.uk/esdg/cms-fed/qa_web/) board built by Exception EMS and discussed below.

Another example being the boards developed for the ATLAS experiment. In both experiments, multi-level “triggers” are used to filter the data online, but to do this, at each trigger level there needs to be buffering of data to allow time for the trigger decision. In ATLASm the readout buffers that hold the detector data while the Level-2 trigger decision is made (the so-called “ROBin” cards) are the only custom-made hardware components of the High Level Trigger system. The ROBins were developed (design, prototyping, testing) with UK expertise (at RHUL), in close collaboration with one German (Mannheim) and one Dutch (NIKHEF) group. The development process was concluded during 2005, after which the large volume production was started. A total of 350 ROBin cards (about half of the total required number for ATLAS) were produced and tested in the UK, at the industrial partner “Cemgraft Electronics Manufacturing”. The production was carried out at under the joint responsibility of RAL and RHUL and was concluded in mid 2006. The ROBin cards are now at CERN and have successfully been installed and commissioned in ATLAS.

4.3. Exception EMS Ltd: A Case Study

Following an EU wide tender the UK company Exception EMS Ltd was selected to manufacture 500 large and complex electronic boards for the readout of the world's largest silicon tracker detector for the CMS experiment at CERN. The FED board is a large 390mm by 400mm card, designed to maximise the number of channels that can be processed on each board and has a mixture of advanced optical, analogue and digital electronic components. This is the most complex readout board designed by the RAL electronics group and the largest production quantity delivered.
The FED board had a number of challenging specifications for large scale production. It is double-sided in order to accommodate the high density of components whose total number is approximately 6,000 connected by 25,000 tracks per board. A particular challenge for the company was the production assembly of a total of over 17,000 fine pitched large Ball Grid Array (BGA) devices. The reliable surface mounting of such large numbers of high value BGAs on large printed circuit boards was a new technical skill for exception and critical for the success of the project.
The company worked closely with RAL during several months of prototyping and testing in order to achieve the required quality. Test equipment for final quality control, designed by CMS UK Groups, was installed at the manufacturing plant and successfully operated by the companies own engineers.
The final production of 500 boards took place as planned over 12 months and the good board yield was in excess of 99%. The full complement of FEDs were delivered on budget and schedule to CERN in 2006. Exception EMS Ltd was rewarded with a gold award for industry presented by the CMS experiment at a ceremony at CERN in 2006.
(Contact Mr Phillip Jackson, Managing Director, Exception EMS Ltd, Calne, Wiltshire, UK.)

4.4. The MI-3 Basic Technology Programme

The development of Monolithic Active Pixel sensors was originally motivated by the needs of the vertex detector for the International Linear Collider although other particle physics programmes, RHIC Super-B have also been responsible for key developments. Applications in the UK are being looked at by the LCFI and Calice collaborations, discussed above. In 2004, the Multidimensional Integrated Intelligent Imaging Consortium (MI-3) was awarded £4.7M over 4 years by the RC-UK Basic Technology Programme.

The consortium has11 research centres: in molecular biology (LMB), radiation physics (UCL), genetics (Liverpool), cancer research (ICR), electronics and electronic engineering (Sheffield, Surrey, York), space science (STFC, Brunel) and particle physics (STFC, Glasgow, Liverpool). The project aims to develop imaging sensors based on mainstream CMOS technology and capable of expanding the traditional envelope of imaging capability with ultra-fast frame rates, flexible readout and integral intelligence. The consortium promises developments for a wide range of end-users benefitting from the technological opportunities of a sensor technology that uses standard CMOS processing and so can be embedded in a highly integrated single microchip. This promises huge advances in system integration, flexibility, compactness, speed and radiation hardness. Their work programme, has involved building important scientific and medical demonstrators, focussing on developing novel, underpinning technologies.

Their goals, stated in http://mi3.shef.ac.uk/ are:

- "*To significantly extend the effective spectral response of APSs from high-energy gammas and ionising particles to the infra-red (including the increasingly important soft x-ray/EUV regions)* *through integrating CMOS technology with novel substrates, micro-engineered electro-optical structures, etc.*

• To develop on-chip "intelligence" down to the pixel level, through adaptive signal processing/pattern recognition, to extent the limits of detectability and applicability, and mitigate the problems of data overload.

• To provide a continuing responsive export core to meet the future imaging challenge within the UK science base; to ensure through building upon existing links with industry the future availability and exploitation of APS devices and systems."

The application areas targeted by the consortium include synchrotron science, high energy physics, medicine and biology. Specific devices have been developed to demonstrate low noise operation of the sensors, a large area format has also been designed and flexible readout functionality has also been implemented on these devices. This development stems from particle physics, is in the process of being developed for other areas of science and is a candidate technology of the International Linear Collider in the future.

4.5. Training and Development of Electronics and Detector Expertise

- ASIC engineers moved to industry for low noise design, e.g. Analog Devices (Newbury)
- CASE student moved RAL/Liverpool to e2v Chelmsford
-

5. Computing, Software and Analysis Techniques

5.1. The World Wide Web and the Grid

CERN's central role in the development of the World Wide Web is well documented (see for example, "Weaving the Web", Tim Berners-Lee, ISBN 0-7528582-090-7, 1999). In it, Dr Sir Tim Berners Lee describes the developments he already found in the "*technological melting pot*" at CERN when he joined in 1980 which helped ferment the invention of the World Wide Web:

"*It had developed CERNnet, its own home-brewed network, for lack of commercial networks. It had its own e-mail systems. And it was at the forefront of gatewaying between different proprietary mail and file systems*."

Indeed, in the original proposal for the World Wide Web, (Information Management: A Proposal, Tim Berners-Lee, CERN, March 1989), Berners-Lee gives the Large Hadron Collider as a direct inspiration for the Web, starting his proposal with, "*Many of the discussions of the future at CERN and the LHC era end with the question – 'Yes, but how will we ever keep track of such a large project?'*". He goes on to describe CERN as a 'web' of thousands of creative people, with high turnover, needing a new kind of flexible, evolving way of storing and locating information.

Examining more closely the requirements set out in that original proposal, we see how many of the web's features today can be traced to CERN's needs as an organisation in 1989. Requirements described by Berners-Lee included:

"

- **Remote access across networks**. CERN is distributed, and access from remote machines is essential.

- **Heterogeneity.** Access is required to the same data from different types of system (VM/CMS, Macintosh, VAX/VMS, Unix)
- **Non-Centralisation**. Information systems start small and grow. They also start isolated and then merge. A new system must allow existing systems to be linked together without requiring any central control or coordination.

[…]

- **Live links**. The data to which a link (or a hot spot) refers may be very static, or it may be temporary. In many cases at CERN information about the state of systems is changing all the time. Hypertext allows documents to be linked into "live" data so that every time the link is followed, the information is retrieved."

Berners-Lee also specifically ruled out the need to consider security or copyright as necessary at CERN, describing them as 'non-requirements'. These are issues that web users and developers are struggling with even now.

Deciding on the term World Wide Web in May 1990 as the project was developed, the first webpage was at http://info.cern.ch/hypertext/WWW/TheProject.html. By 1991 there were web servers at particle physics laboratories across Europe and in the US at Stanford Linear Accelerator Center. Taking off at an extraordinary rate, by 1992 there were 26 web servers worldwide (http://info.cern.ch/), 500 by the end of 1993, and 10,000 by the close of 1994 (http://public.web.cern.ch/public/en/About/WebStory-en.html) – including, by then, 2,000 commercial web servers and 10 million users.

Now (see http://www.internetworldstats.com/stats.htm for example) there are (November 07) 1.24 billion users worldwide and the web is still growing fast, particularly where penetration is still low (*eg* Africa at 5% compared with Europe at 42%).

(See also http://www.internetworldstats.com/emarketing.htm and related web sites.)

The requirements of new projects at CERN have stimulated a further revolution: "Grid Computing", which uses the internet and highly sophisticated management tools ("middleware") to harness together large numbers of CPUs and data storage facilities across the globe. The Worldwide LHC Computing Grid (WLCG) is the world's largest academic Grid, developed to cope with the unprecedented (15 million Gigabytes/year) data rates that will be produced by the giant detectors at the LHC. Naturally there have been a number of spinouts, including many within the UK. These exploit the central role of UK particle physics through GridPP http://www.gridpp.ac.uk/, where the UK will contribute the equivalent of 10,000 PCs (about 10% of the total) to the WLCG. See for example:

- Imense Ltd, a small business that has developed an algorithm for searching the content of images on the web, without needing metadata created by hand. Through a small STFC technology transfer grant in collaboration with Cambridge University, Imense were able to test their software on millions of images using the GridPP infrastructure, leading directly to external funding for the company. See http://www.gridpp.ac.uk/news/-1186485671.785221.wlg
- The WISDOM project is searching for new drugs against malaria, using the Enabling Grids for E-sciencE infrastructure of which GridPP is the UK's largest part. In the latest challenge run by WISDOM, GridPP contributed more than 2 million hours of CPU time - nearly half of the total processing power used by WISDOM in their search through 140 million potential new compunds against malaria. See http://www.gridpp.ac.uk/news/-1170422779.710671.wlg
- GridPP has also contributed a hundred thousand hours of CPU time to searching for molecules that might inhibit the action of the avian flu virus. A collaboration of European and Asian researchers used the EGEE Grid to identify potential drugs against avian flu for further testing in the laboratory. See http://www.gridpp.ac.uk/news/-1146834257.668058.wlg

- Econophysica Ltd, a financial services company specialising in derivatives pricing and risk evaluation. Econophysica provide algorithmic trading services, whereby the timing and size of orders to buy and sell are generated by a quantitative model. Algorithmic trading requires substantial computing power, and Econophysica are working on a MiniPPIPS project with the HEP group at Queen Mary University of London to examine the use of Grid middleware for financial applications.
- Web security, such as the GridSiteWiki software. A wiki is a webpage that can be easily edited by a range of people, but wiki creators often have to deal with vandalism of their pages or malicious content, without ever really knowing who edited the page. Developed by a GridPP member from Manchester University, GridSiteWiki combines the function of a wiki with user authentication tools developed for Grids, allowing wikis to reliably identify their contributors. See http://www.gridpp.ac.uk/news/-1127720092.933501.wlg
- U4EA Technologies Ltd (http://www.u4eatech.com) in Bristol have benefited from network emulator technology developed for the LHC Grid employing a joint grant to themselves and CERN from the PPARC.

Internationally, CERN's openlab project (see http://proj-openlab-datagrid-public.web.cern.ch/proj-openlab-datagrid-public/) provides collaboration directly between CERN and key industrial partners such as Hewlett-Packard, Intel Corporation and Oracle as well as a training programme in these new technologies for international students.

5.2. Particle Physics Analysis Techniques

Less well known is the application by other disciplines of techniques developed in particle physics. An early example, from http://www.iop.org/EJ/article/0305-4624/17/2/301/ptv17i2p56.pdf is the use of pattern recognition developed for particle physics tracking, which has been adopted 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.

5.3. Particle Physics Generated Software

Geant4 (http://geant4.web.cern.ch/geant4/) is a software package developed for particle physics that has become widely used in other disciplines. Geant4 simulates the passage of particles through matter, and has been applied in particle physics experiments including BaBar, ATLAS and ALICE. Developed by a worldwide collaboration, it was designed for easy adaptation by a range of applications. The Geant4 Low Energy Electromagnetic Physics Working Group has extended its applications to energies low enough to be relevant to space science, astrophysics and medical physics (http://www.ge.infn.it/geant4/talks/index.html). Space and astrophysics is now a major user community for Geant4, with the need to understand in advance how spacecraft electronics and detectors will react to radiation in space. Geant4 has been used in the development of spacecraft including ESA's XMM Newton X-ray telescope and NASA's Gamma-ray Large Area Space Telescope, and the toolkit applied to applications such as optimising shielding for spacecraft from space radiation, verifying instrument and detector responses and modelling the space environment and its effects.

Medical physics is another key application area for Geant4, where the software can be used to simulate the production and transport of different types of beams in biological matter. In brachytherapy, for example, a sealed radioactive source is placed near to the area requiring treatment. Geant4 can be used in this case to both simulate the radioactive source and the dose distribution in the patient (http://wwwsis.lnf.infn.it/pub/INFN-AE-00-08.pdf). Other areas of medical physics that use Geant4 include conventional photon-beam radiotherapy, hadron therapy and boron neutron capture therapy. GATE (Geant4 Application for Tomographic Emission) provides another example, as does MCHIT (Monte Carlo for Heavy Ion Therapy). In these cases Geant4 is mainly used for dose distributions and depth-dose profiles, projectile fragmentation and production of radioisotopes in tissues, and possibly for studies of alteration to DNA and to optimise the beams and radiation sources.

Quite few groups in Enlight (http://enlight.web.cern.ch/enlight) are proposing of doing studies using Geant4 and Fluka with input into treatment planning. This includes a proposed development of a GRID framework for hadron therapy simulations and advanced treatment planning.

Geant4 is also used for optimising the geometry, quantum efficiency, response evaluation, etc. of imaging setups like PET cameras and new PET designs both for human being but also for the preclinical, e.g. small animals, PET. In particular the 2007 IEEE NSS-MIC conference had 24 talks or poster that specifically mentioned G4 and or GATE. Other areas include fluence to dose conversion for high energy neutrons linked to evaluation of doses received by civilian air crews. Another area, where G4 is used to simulate the irradiation of cellules and biological samples with light microbeams to evaluate the radiobiological effect. Linked to space there is also the Geant4-DNA project where they want to evaluate the damage to the DNA following exposure to radiation (space manned missions).
(http://geant4-tt.web.cern.ch/geant4-tt/, http://wwwsis.lnf.infn.it/pub/INFN-AE-00-08.pdf).

http://technologytransfer.web.cern.ch/TechnologyTransfer/Objects/TT/Welcome/RapportAnnuelTT.pdf

5.4. DeltaDOT: A Case Study

DeltaDOT is a spin-off company building on particle physics software developed at Imperial College London. The software was written to analyse data from particle physics experiments, but DealtDOT's founders realised that it could also have applications in analysing DNA, bacteria and viruses. Working with contacts from the biological sciences, they were able to marry the particle physics software with electrophoresis technology to produce faster, higher quality results at a fraction of the cost of conventional approaches, and used this as the foundation for their company. DeltaDOT now employs more than twenty staff, and its technology has applications in protein science, chemistry, pharmacy, plant science and forensics as well as diagnostics.
(http://www.deltadot.com/ and http://www.scitech.ac.uk/KE/Publ/CStud/csDeltaDot.aspx).

5.5. Dr Sir Tim Berners-Lee: a Biography

Tim Berners-Lee read physics at Oxford and had been working in computer consultancy in Switzerland when he heard of a contract programmer post at CERN in 1980. After work building a database, he left but remained in contact with the laboratory until applying for and winning a Fellowship, rejoining the organisation again in 1984. In 1989 he conceived the World Wide Web, with a version of the first browser working on his machine at CERN by Christmas Day 1990. Much of the familiar machinery was developed at that time but take up was initially slow at CERN and elsewhere, until his demonstration at the Hypertext 1991 conference in San Antonio provided the necessary breakthrough. International enthusiasm, particularly from the particle physics community at SLAC, helped project the WWW to global acceptance. The first World Wide Web conference would be hosted at CERN in 1992. From 1991 to 1994 use of the original WWW server (info.cern.ch) grew by a factor of ten each year as the world began to take note of this new information phenomenon.

He became a full-time staff member at MIT in 1994 starting the World Wide Web Consortium W3C. His emphasis now is very much on the "Semantic Web". From 2004 he has also taken a part-time position at Southampton University while remaining W3C Director to help further collaboration between Southampton (a leading site in Semantic Web research in the UK) and MIT.

6. Special Skills and Competencies

"*... the rise of new forms of organisation (CERN, for example) has led to a situation where scientists become craftsmen, speculators, administrators just like Giotto, Brunelleschi, Ghiberti and other Renaissance artists*."

Paul Feyerabend, Professor of Philosophy, University of California at Berkeley and Professor of Philosophy of Science, Federal Institute of Technology at Zurich (In "Farewell to Reason", p186, Verso ISBN 0-86091-184-5 1987).

6.1. Need for Investment in the Physical Sciences

In the global marketplace, it is a given that societies such as the US and the UK increasingly succeed or fail by virtue of their ability to compete in high value low volume markets where the emphasis is on new ideas and innovation. The high end sustainable jobs increasingly rely on the highest levels of training, including that provided by working in some of the most intellectually challenging research environments. Concern is mounting, that research in the physics science in particular are being under-resourced and that this will have a long-term negative impact on competitiveness.
In the USA, concern about the funding priorities can be found in the 2005 "Rising Above The Gathering Storm: Energizing and Employing America for a Brighter Economic Future" by Norman R. Augustine (Retired Chairman and CEO Lockheed Martin Corporation), Craig Barrett (Chairman of the Board Intel), Charles Holliday (Chairman of Board and CEO DuPont), Lee Raymond (Chairman of the Board Exxon Mobil) and 16 others, presented before the Committee on Energy and Natural Resources of the U.S. Senate. It particularly recommends
"*Increasing federal investment in research by 10% per year over the next seven years, with primary attention devoted to the physical sciences, engineering, mathematics, and information sciences*".
It notes in 2001, U.S. industry spent more on tort litigation and related costs than on research and development. In terms of the current wealth of the USA, they claim: "The reason for this prosperity is that we are reaping the benefits of past investments—many of them in the fields of science and technology. But the early indicators of future prosperity are generally heading in the wrong direction." As an example of this they explicitly worry that with the turn on of the LHC, "Two years from now, for the first time, the most capable high-energy particle accelerator on earth will reside outside the United States". It is absolutely clear that this panel of some of the world's leading industrialists see leading edge blue skies research in areas such as particle physics as key to ensuring the strength of America's long term economic future. Remember that their concerns are not for immediate prosperity but the fundamentals that influence where the US will be decades from now. Countries that aspire to offer their citizens a standard of living approaching that enjoyed by many in the US would be wise to take note of their concerns.

6.2. Particle Physics Training and Skills

Few would argue with the proposition that physics graduates in general are exceptionally valuable in the globalised marketplace, and this is even more clear in the case of those who have taken their interest in physics to PhD level (see for example http://student.independent.co.uk/graduate_options/article3158694.ece).
In 1995 and PPARC (now part of STFC) published "Astronomy and Particle Physics Student Career Paths", in 1999, the Institute of Physics published "Career Paths of Physics Post Doctoral Research Staff" and in 2003 PPARC published "A Fifteen Year Longitudinal Career Path Study of PPARC PhD Students". (Studies undertaken by DTZ Pieda plc Consultants.) Although the conclusions for the PPARC studies include astronomy and space science, there is no evidence that the particle physics cohort was different. What emerges is that the overwhelming reason for studying a PhD in particle physics or astronomy is the love of the subject. However, although the next most popular reason given is

to follow a career in academia, in the most recent poll, the number ending up in the private sector rose from a quarter to a half between 1999 and 2003. Of those in industry from the 2003 study, 38% found careers in IT, software or management consultancy while a further 25% became financial professionals. In the context of the latter, Christos Danias, Head of CDOs - Europe, BNP Paribas says:

"*In my experience, while science graduates are always useful in the City, physicists and most importantly particle physicists stand out I think this is because of the communication skills they have which complement the numerical skills but are sometimes in short supply when one meets PhDs in other parts of physics or science*."

Another leader in this area Mark Tagliaferri, Chairman aAIM Group Plc confirms:

"*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*."

Dr Tim Short (2000-2006 Vice-President, Asset Finance, Credit Suisse First Boston) and 1992 PhD in Experimental Particle Physics (Bristol) comments:

"Particle physics as a PhD discipline is 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, only particle physics PhDs can add some further highly desirable benefits to employers due to their having worked in large experiments:

- significant strengths in communications skills, developed in the course of frequently presenting results to demanding groups of scientific peers
- international experience gained very early in their careers, leading to flexibility, a wide network of multi-country contacts and often language skills
- an understanding of large-cost budgeting because of the major experimental and equipment costs involved
- diversity leveraging from the already high prevalence of PhDs with this background in industry and business
- proof of "team playing self-starter" capacities demonstrated by taking responsibility for production of thesis within research group environment

6.3. Dr Tim Short: a Biography

Tim Short attended a comprehensive school in Bristol, followed by a first degree in physics at Imperial College and a PhD in particle physics from Bristol University. He then continued his research interests on the same experiment in Hamburg, Germany, where he learnt to speak German fluently. After adding to his computing skills with a spell at a US computer firm, he joined the City in 1997. He worked on many large transactions and was given very substantial responsibilities early in his career. One of his first deals while at Nomura was the £3.1bn securitisation of the Ministry of Defence Married Quarters Estate, which demonstrated that UK Government assets were highly attractive to the markets when packaged correctly. This certainly vastly improved the value of other assets and also demonstrated an alternative funding route. Another transaction of public benefit to the UK was the innovative securitisation of student residences at Keele University.

This deal, led solely by Tim, produced substantial funding at low rates for the University. Other career highlights include a €525m mortgage securitisation for EBS, the Irish building society and a €750m vehicle loan transaction for Volkswagen. Having become Vice President of Fixed Income at a major US investment bank, Tim has now stepped back from a full-time role in the City, but continues to use his contacts to facilitate entry for other PhDs and is involved in continuing study at UCL.

6.4. Dr Jason McFall: a Biography

7. Summary and Conclusions

Industry has always gained significant benefits both directly and indirectly from the pursuit of particle physics (see for example D.C. Imre "Technological Spin-off from Particle Physics" (Phys Techno1 17) in 1986. The challenges are unprecedented, stimulating some of the best minds to develop new ideas and technologies (often in direct partnership with high-tech companies) which can lead to both obvious benefits through direct knowledge exchange but also more significant but less easily quantifiable improvements in innovation and competitiveness. It needs to be remembered that there are many routes or vectors for knowledge exchange, a fact sometimes neglected in the establishment of schemes to help UK industry gain maximum benefit from the undisputed excellence of UK pure science. Directly funded explicit knowledge transfer to industry (including setting up of spin-outs, Research Council schemes, industry/university initiated collaborations) is a very visible route but not necessarily the most important. Knowledge transfer via serendipity has arguably played a much bigger role, as much of the material in the preceding sections helps to illustrate. This is where industrial applications develop from ideas developed by particle physicists primarily for particle physics, with the World Wide Web providing the most famous, but by no means only, example. Another often overlooked and important path to knowledge exchange is through collaboration with industry to help industry win major orders in large international particle physics tender exercises (often multi-£M contracts or more at the leading international laboratories). Furthermore, it is often through the know-how and technical skills acquired in meeting demanding particle physics orders (possibly working with relevant scientists) that companies are able to develop both enhanced capability and prestige which directly benefit delivery in other sectors. Finally, and by n means least are the benefits of acquisition by industry of personnel trained in particle physics techniques and bringing their experience of competing in this state of the art international science arena