Institution: The University of Liverpool

Unit of Assessment: 9 Physics

a. Overview

The University of Liverpool's Physics Department is part of the Faculty of Science and Engineering's School of Physical Sciences. Our four main research groups are: Accelerator Science (AS); Condensed Matter Physics (CM); Nuclear Physics (NP); and Particle Physics (PP). Research in AS is carried out in the framework of the Cockcroft Institute (CI) at the Daresbury Innovation Campus. The CI was formed in collaboration with Lancaster and Manchester Universities and the STFC's Daresbury Laboratory (DL) in 2006. Much of our CM group research is relevant to energy provision and we expanded work in this area by establishing the Stephenson Institute for Renewable Energy (SIRE) on the Liverpool campus in 2010.

The NP group studies exotic nuclei, nuclei at the extreme of high angular momentum and the properties of nuclear matter. The group is a world leader in Ge sensor technology.

The PP group's primary interests are in experiments at the Large Hadron Collider (LHC) and in the study of neutrinos. The PP group is internationally recognised in the field of radiation hard Si detectors.

b. Research strategy

Our vision for the Department is to lead and contribute to research on questions recognised to be of national and international significance in AS, CM, NP, and PP. To achieve this, our strategy is built around creating excellent teams of researchers focused on a number of both long-standing and emerging research areas. We ensure that these teams achieve "critical mass" by facilitating collaboration between our staff and through new strategic appointments. In addition, we constantly develop and maintain the technical expertise and the equipment and instrumentation base necessary for our programme. This combination of research expertise and instrumentation capability allows us to contribute to international progress in our research fields through the proposal, design, construction, commissioning and operation of experiments, and through the analysis and publication of the data they produce. The success of our approach is illustrated by the leadership roles held by Liverpool physicists in many of the experiments in which we are involved during the REF period (examples in section **e**).

To ensure the vibrancy of the Department's research over the longer term, opportunities for expanding the programme in line with our interests and both national priorities (e.g. the Research Councils' "road maps") and international priorities (e.g. the European Strategy Forum on Research and Innovation and other international road maps) are continually assessed and acted upon.

Examples of new initiatives in the REF period that expand upon our capabilities are the establishment of the SIRE; significantly enlarging our CM team and research portfolio in the nationally prioritised area of Energy; the development of a NP programme (Chartier) at ALICE-CERN (A Large Ion Collider Experiment on the LHC); and the initiation within the PP group of research with the Cherenkov Telescope Array (CTA) consortium – a leading project on European and American astrophysics road maps (Greenshaw and new appointees Daniel and Rose).

Future research directions are developed by the AS, CM, NP and PP groups and steered by the Department's Research Committee. All research staff contribute to the direction of their group's programme and help to shape the Department's research portfolio at annual strategic planning sessions. For example, the Department's proposal to expand its CM programme and create the SIRE was discussed at an Away Day in 2009, before the establishment of the Institute.

Alongside our regular meetings, there are many informal opportunities within the Department that

promote collaboration and the exchange of ideas between research groups. As an example, the work of Weightman (CM group) on ALICE-DL (Accelerators and Lasers in Combined Experiments at DL), one of the major AS activities in the REF period, arose through informal networking before being developed more formally within the Department. A Faculty reorganisation in 2009 that combined Physics, Mathematics and Chemistry in the School of Physical Sciences has aided interdisciplinary research. Regular meetings of Physics research group leaders with their counterparts in Maths and Chemistry are held to discuss School research strategy. These meetings facilitated the formation of the SIRE and are now the forum through which new interdisciplinary research programmes are discussed.

Key activities in each of the Department's research areas are described below, along with developments in relation to RAE2008 plans and objectives:

Accelerator Science

The AS group has been significantly strengthened since the RAE. New research directions include: developing novel acceleration techniques using lasers, plasmas and meta-materials (Chattopadhyay, Hock, Welsch); new computational methods (Hock); beam dynamics (Newton, Wolski); beam monitoring (Welsch); optimising operational and designing new accelerators (Chattopadhyay, Newton, Welsch, Wolski).

A recent highlight was the commissioning of ALICE-DL. Tomographic analysis of the beams of this accelerator was carried out by Liverpool physicists (Hock, Holder, Wolski) and its electron beam was used to generate the most intense broadband terahertz radiation source in Europe for a beamline developed by Liverpool (Weightman), achieving a goal mentioned in the RAE. A further new accelerator, EMMA (Electron Machine with Many Applications), was commissioned at DL (Hock, Holder, Wolski). This is the world's first non-scaling Fixed-Field Alternating Gradient (FFAG) electron accelerator.

Liverpool's studies of new accelerator facilities for PP have included the Damping Rings (Wolski) and polarised positron sources for the International Linear Collider (ILC). Future effort in this area is dependent on international support for the ILC. Our Liverpool team also led studies for the current LHC through the design of the Longitudinal Density Monitor that is used to measure the profile of the LHC beams (Welsch), and of upgrades to the LHC (Newton, Wolski). These latter studies include the high luminosity and high energy LHC upgrades to the proton-proton accelerator, and a CERN/ECFA/NuPECC sponsored study of the LHeC (led by Klein, PP).

In the field of NP, Liverpool AS designed the ultra-low energy anti-proton storage ring for FLAIR, part of the international Facility for Anti-proton and Ion Research (FAIR) in Darmstadt (Newton, Welsch), and worked on the anti-proton trapping system for ALPHA at CERN (Chattopadhyay).

Condensed Matter Physics

A strategic decision was taken to significantly strengthen the CM group and to expand into studies of photovoltaic materials and fuel cells. Discussions with Chemistry – where related research is carried out – led to the establishment of the SIRE, an interdisciplinary institute based in Physics and Chemistry with strong connections to Engineering and Earth and Ocean Sciences. £6 million has been invested in this Institute and its laboratory space. Aided by the synergies between the work of existing and new CM staff, this has resulted in EPSRC-funded programmes on solar energy and photovoltaic materials, EU funded research on nanotechnology for solar cells (Sobona, Nanoembrace) and the recent announcement of a Centre for Doctoral Training (CDT) in New and Sustainable Photovoltaics, led by Liverpool.

Fuel cell research is continuing with a focus on experimental and theoretical studies of bimetallic materials to identify catalysts that are more effective and cheaper than pure platinum (Lucas). This research forms part of an international programme on Material Design from Fundamental Principles, involving collaborators in the EU, Switzerland and the USA. Research on the structure, properties and applications of complex intermetallics remains a focus of the group (McGrath,

Sharma), with elements of this work strengthening the portfolio of the SIRE, e.g. the studies of catalytic steam reforming of methanol. New directions in this research, again relevant to Energy, include studies of clathrates and thermoelectric energy generation.

This major expansion of CM and energy research has addressed to a degree the Department's reliance on STFC funding; the main sources of support for our CM research are EPSRC and EU grants.

Nuclear Physics

The NP group investigates nuclear structure and nuclear matter, addressing questions on the properties of exotic and superheavy nuclei, nuclei at high spin and the nature of hadronic matter. The investigations are currently carried out using stable particle beams at Jyväskylä, Argonne and GSI, "slow" radioactive beams at ISOLDE (CERN) and TRIUMF and "fast" radioactive beams at GSI and RIKEN. As was described for the RAE, one element of the group's strategy is to make major contributions to the future European facilities HIE-ISOLDE and the Facility for Anti-proton and Ion Research (FAIR). We have been successful in this: Butler has led HIE-ISOLDE instrumentation studies and Chartier is leading construction of silicon (Si) tracking detectors for the R3B instrument, part of the NuSTAR experiment at FAIR which will provide a basis for some of our future NP programme. Further, the NP group is developing a programme at ALICE-CERN, ensuring the future of their nuclear matter research, and will maintain a strong presence at Jyväskylä, GSI and within the AGATA collaboration.

The Department has world-leading expertise in and facilities for the study of Ge detectors in the Liverpool Germanium Characterization Laboratory (LGCL). We also have superb facilities in the Liverpool Semiconductor Detector Centre (LSDC) for the development of Si detectors. The investment in these facilities has led to new research opportunities, for example through invitations to join experiments such as the CERN anti-hydrogen experiment ALPHA, for which we constructed the Si detector crucial to measurements of the collaboration's first successful trapping of anti-hydrogen (Nolan). This, and the leadership roles at HIE-ISOLDE and R3B and other experiments, illustrate again the success of our strategy of developing and maintaining instrumentation capabilities.
The NP group is also working on detectors for use in fields such as medicine, security and nuclear decommissioning, e.g. the ProSPECTus Compton Camera-based system for Single Photon Emission Computed Tomography (SPECT) is being taken to pre-clinical trials (Boston) and a portable gamma-ray imaging system using cadmium (zinc) telluride (CZT) sensors was developed for monitoring radioactive materials at sea and air ports that will both locate and identify any radioactive isotopes (PorGamRays – Nolan). This instrumentation and application programme is supported by the STFC and EPSRC with additional funding coming from the AWE and BAE.

Particle Physics

The REF period has seen the start-up of the LHC, leading to the discovery of a Higgs boson and searches for new physics at unprecedented energies. As reported for the RAE, for more than a decade, the PP group has invested a large proportion of its instrumentation effort in the design, construction and commissioning of major elements of two LHC detectors: the Semiconductor Tracker Endcap C for the ATLAS experiment and the Vertex Locator (VELO) of LHCb. Both of these are now operating successfully, meeting two major goals of the PP group.

A further aim of the group was to establish leading roles in the analysis of ATLAS and LHCb data. During the REF period, ATLAS and LHCb work became the highest priority of researchers who had previously been working at Fermilab, DESY and at SLAC and new appointments were made in this area. The resulting strong team's contribution to LHC data analysis has been recognised by the ATLAS and LHCb collaborations, e.g. through the appointment of D'Onofrio as leader of ATLAS Supersymmetry studies, of Uta Klein as chair of the ATLAS Standard Model working group and Parton Distribution Function (PDF) fit forum, and of Shears as leader of the LHCb QCD, Electroweak and Exotica working group.

Another major element of the PP programme is the study of neutrinos. The main thrust of the group's neutrino work is in the Tokai to Kamiokande (T2K) experiment at JPARC in Japan, to

which Liverpool's hardware contribution was the ND280 electromagnetic calorimeter (Touramanis, Coleman). Again, this has been successfully commissioned and T2K has been taking data during the REF period. Measurements of neutrino mixing parameters have been made (McCauley). McCauley's expertise led to an invitation for Liverpool participation in the SNO+ experiment, currently searching for neutrinoless double beta decay at the Sudbury Neutrino Observatory in Canada.

Liverpool is working with the NA62 Collaboration at CERN which is currently constructing and commissioning the apparatus needed to investigate extremely rare K decays. The Department's contribution to this experiment includes elements of the Cherenkov detectors NA62 will use for particle identification (Dainton, Fry). The PP group have recently received STFC funding to work on the g – 2 experiment at Fermilab (King, Maxfield).

The Liverpool PP group also contributes to future experiments. Discussions on the development and production in Liverpool of an upgraded VELO, using pixel rather than strip sensors, are ongoing (Bowcock). Studies of the upgrade of the ATLAS semiconductor detector are also underway (Allport, Casse). Liverpool expertise in radiation hard Si sensors and the strength of the Liverpool mechanical and electronic design team has led to the appointment of Allport to the leadership of the ATLAS Upgrade. These developments will ensure that we are well placed to contribute to the ATLAS and LHCb programmes throughout the anticipated several decade lifetime of the LHC.

The same strategy has led to the initiation of research on novel neutrino detection techniques using two-phase liquid argon systems (Touramanis). The Liverpool group has constructed and is successfully operating a two-phase LAr detector. We are thus well placed to contribute to the next generation of neutrino experiments (e.g. LAGUNA at CERN, LBNE at Fermilab).

Knowledge transfer has also formed part of the PP group's strategy. The group worked with Micron Semiconductor and Hamamatsu, ensuring these companies' ability to produce the radiation hard sensors needed for ATLAS and LHCb, but also allowing them to expand their product lines. "Real world" applications of the PP group's sensors are also being sought, e.g. the use of radiation hard Si detectors at the Clatterbridge Cancer Centre (CCC) mentioned below.

In line with the Department's overall strategy, effort is being invested in developing instrumentation for new projects. One of these is the study of Dark Energy through atom interferometry (Coleman and visiting Prof and Nobel Prize winner, Marti Perl). As mentioned above, Liverpool has joined CTA, expanding our portfolio into astrophysics research. Liverpool (Greenshaw) now leads the development of the Small Size Telescope (SST) section of CTA during its EU funded Preparatory Phase. Prototyping of a camera for the SST is being carried out in the UK (Daniel, Rose, Greenshaw).

c. People, including:

i. Staffing strategy and staff development

There are two elements to our staffing strategy: the first concerns the attraction and recruitment of outstanding academics; the second addresses how we ensure staff are able to develop their careers and experience a supportive and creative environment.

Recruitment: We aim to attract the best possible staff to our existing and developing research portfolio in line with our strategy of ensuring all groups have critical mass. As Physics is an international activity, many of our staff come from universities and research organisations outside the UK.

At the time of the RAE, the AS group consisted of CI Director Chattopadhyay and Wolski. Since then, lecturers Hock and Newton have been appointed, as has reader Welsch (Heidelberg). Wolski and Welsch now have professorships. These appointments have allowed us to pursue a programme designed to place Liverpool at the forefront of accelerator developments for NP, PP

and CM, but also to open up opportunities for exploitation of accelerators in medical and other fields.

The CM group, through the formation of the SIRE, has been strengthened by the appointment of a professor (Durose), a reader (Veal) and three lecturers (Alaria, Jäckel – LMU Munich, Proskuryakov). Sharma was appointed to a lectureship upon completion of his EPSRC Advanced Fellowship. A Royal Society University Research Fellow (Gründer) has recently joined the CM group and the SIRE, increasing their complement from 7 at the last RAE to 13.

Since the RAE, Helen Boston has been appointed as a lecturer in the NP group, which has also been joined by the STFC Advanced Fellow, Cheal. An EPSRC Advanced Fellow, Joss, has been appointed to a lectureship. We are now advertising a new position in NP to strengthen the experimental programme and a further appointment in the area of applied research is planned for 2014.

Kretzschmar (Hamburg) has been appointed to a lectureship in the PP group, which has also been joined by STFC Advanced Fellow D'Onofrio (Barcelona), significantly enhancing the ATLAS research programme. Neutrino studies were strengthened through the arrival of the Royal Society University Fellow Coleman, and Rose, who is also involved in the CTA programme. A further neutrino physicist (Andreopoulos) has been appointed to a joint position with the Rutherford Laboratory.

Physics seeks to attract fellows supported by the Research Councils and the Royal Society. In the REF period, fellows include: Coleman, Gründer and Shears (Royal Society University Research Fellows); Cheal and D'Onofrio (STFC Advanced Fellows); Joss and Sharma (EPSRC Advanced Fellows). All those colleagues who have joined us with a fellowship have become permanent members of staff.

Support and Development: The research groups help Early Career Researchers (ECRs) to establish their programmes at Liverpool. Teaching loads in the first year of appointment are half the standard allocation. New appointees are also mentored by experienced staff and, where appropriate, supported through the University's ECR Programme, which offers personal and professional development opportunities including: core research skills; personal and professional skills; teaching courses and other career support. The success of our ECRs is testament to their ability but also to the quality of the support they have received (e.g. D'Onofrio, leads SUSY research at ATLAS). The University has recently introduced an Outstanding ECR Award, which was won by Coleman in 2012.

All staff are eligible for one semester of research leave after five semesters, an offer that has been taken up by Shears, Mehta and others during the REF period and has, for example, enabled Shears to take on the leadership of the LHCb QCD, Electroweak and Exotica working group. Our annual Personal Development Review (PDR) process provides an opportunity to review research and teaching roles; discuss progress against objectives; and discuss and agree future plans, promotion opportunities, development and support needs. Our staff have access to exceptional family-friendly working practices, options which have been taken up by Chartier and Helen Boston who have been supported via flexible working arrangements to allow then to maintain/return to successful research careers following maternity leave.

The University has Athena SWAN bronze status, and the Department is an Institute of Physics Juno Supporter, with an application for Bronze status in preparation, attesting to our commitment to Equality and Diversity. Shears has recently been appointed as the first female professor in the Department's history. Uta Klein, D'Onofrio and Chartier have recently been promoted to readerships. 15% of our staff are female. The School's Equality and Diversity Committee, of which Chartier and Greenshaw are members, is preparing a School-level application for Athena SWAN bronze status and is working to continually improve the environment for all in the School, but in particular for women and minority groups. The Department (Greenshaw) also supports the Liverpool Women in Science and Engineering (LivWISE) group, which organises events

celebrating the achievements of female scientists and engineers and provides mentoring for female members of staff. The University of Liverpool is a signatory to the Concordat to Support the Career Development of Researchers. Our commitment to the Concordat has been recognised by the award of the European Commission's "HR excellence in research" badge.

i. Research students

Recruitment: In accordance with our strategy of ensuring a critical mass of researchers in each of our groups, we typically recruit 1 to 2 Research Council supported PGR students to the AS group, 2 in CM, 3 to 4 in NP and 3 to 4 in PP per year. We also seek additional support for further PhD students and have been successful in winning funding through EU grants such as the DITANET, LA^3-NET, oPAC (the largest Marie Curie network ever funded) and INFIERI Initial Training Networks (ITNs) and the Laguna/Modes ERC grant. We have also attracted industrial CASE studentships (e.g. with Micron Semiconductor Ltd). Since 2012, the School has funded 3 PhD positions per year in Physics. These are typically used to leverage additional support, e.g. we have 2 PhD positions (AS and NP) in collaboration with the RIKEN Laboratory in Japan. During the REF period, we have typically enrolled 20 PhD students per year and currently have 90 PhD students. The Department is now leading the EPSRC CDT in New and Sustainable Photovoltaics, which is a national consortium of 6 institutions and will result in a further 2 to 3 PhD studentships per year in Liverpool from 2014.

Training and Progression: The Director of Graduate Studies and the Department's Post Graduate Research Committee oversee our graduate training programme. This consists of lectures and skills sessions (physics, instrumentation, computing, statistics) provided by the Department's research groups, e.g. the Cockcroft Postgraduate Lecture Series in Accelerator Physics, run jointly with Manchester and Lancaster. Research students also attend national and international summer schools, e.g. PP students attend the national Rutherford PP Summer School at the end of their first year and the CERN Summer School at the end of their second. These are supplemented by research skills and careers information provided by the School in a week-long course during the first year. The latter was originally devised for young researchers on the DITANET ITN coordinated by Physics (Welsch). This course was selected as "best practice" by the Higher Education Academy and the European Commission. Regular meetings of the research groups allow research students to describe their work and obtain feedback. PhD students typically spend about a year abroad, either in one visit (PP) or in several shorter visits (AS and NP and to some extent CM).

The annual assessment of progress of PhD students is based on a rigorous procedure incorporating a seminar presentation, submission of a detailed report and interviews conducted by an assessment panel. Student progress is documented via an online University system which records formal training and interactions with supervisors and facilitates reflection on their achievements and targets. The University requires all research students (normally in their second year) to present a poster on their work at a University-wide session attended by external visitors. Students from the Department have won prizes (e.g. Gaffney, IoP Nuclear Physics Early Career Award, now at the University of Leuven; Harkness, IoP Very Early Career Woman Physicist award, 2012), fellowships (e.g. Chavez, CERN Fellowship, 2012; Putignano, RSE/STFC Enterprise Fellowship, 2012); and gone on to academic positions in the UK (e.g. Smerdon, lecturer at UCLAN) and overseas (e.g. Ledieu, Charge de Recherche, CNRS Nancy).

d. Income, infrastructure and facilities

Income: The research spend of the Department since 2008 has been £33.5M, 90% of which results from Research Council and Royal Society grants. The annual spend has remained constant at circa £7M despite flat cash funding to RCUK from BIS. This is partly due to an increase in EU research income, e.g. EU spend in 2008 was £187k and in 2013 was £1030k. (Our success in attracting EU grants means that we now have a 5 person strong EU projects team in the Department.) The number of grants valued at more than £1M held by Department staff in the REF period was 22. Among the most significant grants are:

- Particle Physics Consolidated Grant (STFC, renewed in 2012) £9M.
- Cockcroft Institute for Accelerator Research (STFC, renewed 2009) £16M.
- XMaS beamline at ESRF (EPSRC mid-range facility, renewed in 2012) £3.25M.
- Nuclear Physics Rolling Grant (STFC, renewed in 2008) £2.4M.
- Grants associated with the ALPHA Project at CERN (EPSRC) total £3M.
- DITANET, oPAC and LA^3-NET Initial Training Networks (EU FP7), total £6.8M.
- NA62 at CERN (ERC, 2011) £1.2M.

We have also won support for our extensive instrumentation programme, for example:

- Grants to develop the AGATA NP spectrometer totalling £2.15M (Nolan, STFC).
- Funding for the SAGE NP spectrometer (Herzberg, STFC) £1M.
- Grant for disease diagnosis using spectro-chemical imaging £2.15M (Weightman, EPSRC).

Funding has also been obtained for developing applications of our research, for example:

- Applications of Ge Compton Cameras in SPECT and Positron Emission Tomography (Nolan and Boston, STFC) total £1.4M.
- Heavy tamponades in vitreo-retinal surgery (Garvey, Wellcome) £340k.
- Use of radiation hard sensors in proton radiotherapy, PRaVDA (Allport, Wellcome) £473k.

The funding we have obtained has allowed us both to recruit and retain the staff we need to support our research programme and to maintain and enhance our facilities.

Infrastructure and Facilities:

The Department has developed internationally competitive facilities to support its research. The LSDC consists of 450 m^2 of clean rooms containing an extensive suite of wire bonding, wafer probing and metrology equipment that allows us to characterise Si and other detectors both electrically and mechanically. This has been crucial to the major contributions that have and are being made to the ATLAS, LHCb, T2K and NA62 experiments in PP, and to AGATA, GREAT, SAGE, LISA, ALPHA and NuSTAR in NP.

The Physics Workshop, one of the best-equipped in UK physics departments, contains 3- and 5-axis milling machines, wire erosion equipment and lathes, allowing the construction of the support structures for the detector systems of all the experiments on which we work in NP and PP and the provision of vacuum components for the AS and CM groups.

The LGCL is one of only three laboratories worldwide that can characterise position sensitive Ge sensors, work which has been extended to CZT detectors. The LGCL has allowed development of Ge detectors for use in spectrometers such as EXOGAM at GANIL, AGATA (currently at GSI) and, together with position sensitive Si detectors, for AIDA at FAIR and GREAT, SAGE and LISA at Jyväskylä.

Designing and constructing lightweight carbon fibre support structures has become an increasingly important element of our activities and has led to the recent establishment of the Liverpool Composite Materials Laboratory with pattern cutting equipment and an autoclave.

The suite of techniques available to the CM group includes ultra-high vacuum and electrochemical deposition, scanning tunnelling microscopy, low energy electron diffraction, x-ray photoelectron spectroscopy and ultraviolet photoelectron spectroscopy.

The Department maintains and improves all its facilities with University support (e.g. the recent purchase of the 5-axis milling machine for the Workshop and a portable laser tracker for the LSDC, which allow us to build more complex mechanical structures and survey them at the locations in which they are used). We also obtain support from the research councils for our equipment (e.g. through the NP and PP Consolidated Grants) and make specific infrastructure bids (e.g. for bump bonding apparatus for the LSDC, which would allow the construction of more compact detector systems). We are exploring equipment sharing initiatives with members of the N8 group of Northern Universities to give us access to a broader range of apparatus.

We have developed a team of expert technical staff who work in our world-class facilities and

provide training to enhance their abilities, e.g. in the use of the recently purchased 5-axis milling machine.

We have excellent staff retention rates with many having been with us throughout their careers (e.g. Evans, McCormick and Wormald).

Currently, research activities are supported by 7 staff in the mechanical workshop, 4 mechanical design draughtsmen, 4 electronics engineers and 5 software engineers. New appointments include an experienced electronics engineer in 2013 and 2 apprentices in the Workshop. In addition, there are typically 15 research council funded expert staff who are dedicated to the detector development and instrument support programme.

The research work of the Department is supported by a number of research council funded post-doctoral staff, typically 35 at any one time. These research associates give vital support to the programmes at Liverpool and at international laboratories, where some spend extended periods.

The Department makes use of a wide range of international facilities where beam time is awarded through peer review. We have been successful during the REF period in obtaining time at ILL, ESRF (40 days), BESSY, SSRL, DIAMOND and the APS for CM physics, Jyväskylä (over 190 days), GANIL, GSI (5 months), CERN-ISOLDE (44 days), CERN-AD, ATLAS-ANL, HRIBF-ORNL, TRIUMF (over 12 days) and RIKEN for NP, as well as ALICE-DL, EMMA, Frascati, Fermilab, SLAC, DESY, and J-PARC for AS (and in the ALICE-DL case CM).

The Department has excellent computing facilities. For example the PP group runs an STFC-funded Tier-2 Grid cluster with over 568 cores and 1.5 TB of RAM as well as a Tier 3 cluster with 9 dedicated 64-bit 8-core nodes and 60 shared Linux PCs for interactive analysis and batch processing.

The University library provides the vast majority of journals required for Physics research in electronic format. Licenses for a wide range of software having general office functionality as well as more specialised applications (e.g. MATLAB and ProEngineer) are also centrally provided.

e. Collaboration and contribution to the discipline or research base

Collaborations: Most of the work of the NP and PP groups is performed in international collaborations. Liverpool staff have held, or are holding, positions of responsibility within many of these, e.g. Project Leader for the VELO LHCb (Bowcock); Upgrade Coordinator for the ATLAS experiment (Allport); leader of the SST project and member of the Project Committee in CTA (Greenshaw); leader of the R3B (FAIR-NuSTAR) Si Tracker project (Chartier); leader of the upgrade of AGATA (Nolan) and instrumentation for a storage ring at HIE-ISOLDE (Butler); Chair of the ATLAS Publications Committee (Max Klein); leadership of the LHCb QCD, Electroweak and Exotica working group and of the LHC Electroweak Working Group that spans all LHC experimental and theoretical physicists (Shears) and of the ATLAS Standard Model working group and PDF fit forum (Uta Klein). Liverpool staff also lead collaborative networks on AS (DITANET, oPAC and LA^3-NET, Welsch) and are responsible for managing facilities (XMaS beamline at ESRF, Lucas).

Leadership in the academic community: Liverpool staff have also played many roles in national and international committees and in advising overseas laboratories. Examples include: Butler chaired the programme advisory committee of HRIBF-ORNL and the INTC programme advisory committee at CERN and co-chaired the Comparative Review of Nuclear Structure and Nuclear Astrophysics for the US DOE; Wolski is Chair of the Board of the EPS Accelerator Group, of the Technical Board of the KEK Accelerator Test Facility (Japan), and of the STFC's Front End Test Stand oversight committee; Dainton chairs the STFC's CMS oversight committee, chaired CERN's SPS and PS committee, was a member of the Scientific Policy Committee at CERN and chaired the review of the INFN Super Flavour Factory (Italy); Touramanis chairs the LHC Resources Scrutiny Group, is a member of the Conseil Scientifique of the Groupement Research Neutrino

(France) and of the Governing Board of the University of the Aegean; Herzberg is currently a member of STFC's Projects Peer-Review Panel, Affolder of their Particle Physics Grants Panel, while Shears chairs their Education Training and Careers Committee; McGrath chaired the EPSRC Physics Programme Prioritisation Panel; Nolan chaired the AGATA steering committee and Boston is now a member of the AGATA Management Board; Weightman was chair of the CM Physics division of the IoP. These roles allow Liverpool physicists to contribute to national and international discussions on future research directions and provide us with intelligence which informs our strategic thinking.

Physics staff have been awarded prizes by the learned institutions, for example: Butler (IoP Rutherford Medal and Prize, 2012), Max Klein (Max Born prize of the IoP and DPG, 2012) and Weightman (British Vacuum Council Senior Prize and John Yarwood Medal, 2011). Dainton is a Fellow of the Royal Society.

Liverpool staff have given many summary talks at international conferences, e.g. at Position Sensitive Detectors 2008 (Allport); at the Workshop on New Opportunities in the Physics Landscape at CERN 2009 (Butler); the plenary talk at INPC2013, Florence (Boston); a summary talk at the International Symposium on Nuclear Physics, Mumbai, 2009 (Herzberg); a summary talk at Rencontres de Moriond on Electroweak Interactions and Unified Theories, La Thuile, 2012 (Kretzschmar); a keynote lecture at the XXII Congress and General Assembly of the International Union of Crystallography, Madrid 2011 (McGrath); plenary talks at the 14th International Conference on Solid Films and Surfaces, Dublin, 2008 and at the International Symposium: Terahertz Radiation, Generation and Application, Novosibirsk, 2010 (Weightman).

They also contribute to the organisation of international conferences in Liverpool (e.g. Aperiodic 2009, McGrath; The Violent Universe, 2013, Greenshaw) and elsewhere (e.g. Violations of Discrete Symmetries in Atoms and Nuclei, Trento, 2010, Butler; International Particle Accelerator Conference, New Orleans, 2012, Wolski).

Interdisciplinary research and interaction with research users: The Department is working in many interdisciplinary areas and with many research users. Examples include:

i) Medical science and healthcare: The surface interactions of biological molecules and cells are being studied by Weightman and Martin in collaboration with Liverpool medical departments. Barrett's Scanning Tunnelling Microscopy image analysis routines are being used in many areas including Medical Physics and are being taken forward to clinical trials. First studies using the infrared free electron laser and Scanning Near-field Optical Microscope (SNOM) on ALICE-DL (Weightman) have shown their potential for early diagnosis of oesophageal, cervical and prostate cancer. EPSRC funding has been obtained to continue and expand this activity in collaboration with other UK universities and hospitals. Casse and Patel have worked with medical physicists at the Clatterbridge Cancer Centre (CCC) on studies of their proton therapy beam, using sensors developed in Liverpool for the LHCb VELO. Work is ongoing to convert this one-off measurement into a beam monitor for the CCC (Welsch).

ii) Security: Coleman's Dark Energy detection system can be used as an extremely precise gravitometer. AWE have provided funding to explore the application of this system for the detection of high density materials such as uranium. Boston has received funding from BAE Marine to develop a portable gamma ray detector suitable for submarine deployment.

In all of these projects, interactions with and feedback from research users are critical in refining the goals of the research.