Institution: UNIVERSITY OF BIRMINGHAM

Unit of Assessment: UoA 9 - Physics

a. Overview

The School of Physics and Astronomy – the largest of the nine Schools in the College of Engineering and Physical Sciences – has established international leadership in a broad spectrum of high impact research. This has built on areas of historical strength, whilst opening up new opportunities, driving the subject both on a national and international level, achieved through a process of selective investment both in people and infrastructure, facilitated through significant internal University strategic investment. Research is organised thematically (with sub-topics):

Astronomy:
Gravity and gravitational waves, helio- and astero-seismology, and extragalatic astrophysics.

Particle and Nuclear Physics:
Higgs boson and physics beyond the Standard Model (the energy frontier), proton structure and heavy quark flavour physics, quark-gluon-plasma, exotic nuclei and applied nuclear science.

Quantum Matter and Nanoscale Science:
Ultracold atoms, condensed matter, metamaterials, nanoscale physics and theoretical physics.

b. Research strategy

The School's overall research strategy has the following key elements:

- Appoint the most able people the School can attract.
- Gather established posts to focus on new areas of research.
- Encourage senior staff and enable younger staff to enter leadership positions in their sub-disciplines.
- Construct routes to develop impact via applied science and engineering.
- Ensure the School's visibility in the discipline by international collaboration.
- Renew and develop our physical infrastructure.
- Provide the best possible research environment for staff, postdocs and research students.
- Have a significant role in Public Engagement

Examples of the applications of these principles are:

- The appointment of Prof Zhang, who invented the best optical frequency metamaterial structures, amongst the 11 new appointments during the REF period;
- The growth of the Cold Atoms Group since RAE2008 and establishment of the Metamaterials Research Centre, with around £4M start-up between them.
- Prof Charlton becoming Spokesperson for the ATLAS experiment at CERN.
- The applied nuclear programme attracting £2M University interdisciplinary investment.
- The 21 EU and joint NSF-EPSRC grants which we led or participated in during the REF period
- Rebuilding 600m^2 of laboratories (Cold Atoms, Metamaterials and the Positron Emission Centre and 200m^2 dual-use advanced undergraduate/research laboratories) and renovation of 480m^2 of office space (same groups and Nuclear Physics) over the REF period.
- Leading a second HEFCE SDF/STFC grant for £3.3M to develop the STFC side of the Midlands Physics Alliance Graduate School.
- Participation in Royal Society Summer Exhibitions (2010-13), appearance on "In Our Time".

Our research income has grown under this strategy, per FTE staff per annum, by 46% over the REF period. The number of individuals with over 100 citations for their 4 REF publications increased by 60%. The School has produced over 25 publications in *Science* and *Nature* family, produced more than 50 *Physical Review Letters* in the EPSRC area and given in excess of 300 invited talks at international conferences. Individuals were awarded EPSRC Leadership Fellowships (*Bongs*, *Palmer*), held or were awarded Royal Society URFs (*Smith*, *Lazzeroni*, *Goudzovski* and *Béri*), ERC grants (*Lazzeroni* and *Goudzovski*) and major prizes including the IoP Rutherford (*Freer*) and Payne-Gaposchkin (*Elsworth*) Medals, the John Yarwood Memorial Medal and Senior Prize of the British Vacuum Council (*Palmer*) and the IUPAP award in Optics (*Zhang*).

The strategic growth of each of the three research themes over the REF period, the major achievements arising from the strategy and the future plans are described below (numbers reflect total permanent academic staff complement):

Astronomy: *Academic Staff (12)*
Our strategy here has been driven by two factors. Firstly the explosive development of asteroseismology (and Birmingham's leadership roles within it – aided by judicious sabbaticals), due to the Kepler data, linked with growth of Birmingham exoplanet work. Secondly the imminent observation of gravitational waves and the following transition to astronomical observations using gravitational waves. The three new appointments (*Mandel*, *Miglio* and *Farr*) over the period reflected these strategic priorities. The potential of both of these areas was identified in RAE2008, and this has now borne fruit in terms significant contributions to the field, reflected by many publications in Nature and Science.
Gravity and Gravitational waves (GW): As the dawn of GW astronomy approaches, the School has strengthened its capabilities in the astrophysical application of GW data, with two new staff: *Mandel* joined from MIT in 2012, and *Farr* (from Northwestern in 2013) has taken up a Birmingham Fellowship and proleptic lectureship. This greatly enhances our expertise in the statistical and dynamical study of merging compact objects, which will provide strong tests of General Relativity and is designed to enhance Birmingham's leadership both nationally and internationally.
The experimental side of the group has two strands: innovating optical technology for gravitational waves – in the near (Advanced LIGO, Lisa Pathfinder) and longer term (Einstein Telescope)- and laboratory measurements on fundamental aspects of gravity. The breakthrough to GW detection is expected to be achieved by the Advanced LIGO detector, for which our group *(Freise)* designed and built the sensors for the mirror suspension systems. We are developing key technologies for future GW instrumentation, such as quantum limited interferometry, with leading roles in the design of the Virgo and GEO 600 detectors, and plans for a future "Einstein Telescope". *Speake's* fundamental work has two aspects. His work in the best precision measurement of G to date has culminated in a publication reflecting a decade of work. He is developing a precision setup for determination of gravity at micron scales to probe the possibility of "large" extra dimensions.
Helio and Astero-seismology: The group have seized upon the scientific opportunity to transfer their expertise from helioseismology to the study of a wider range of stars through involvement in the Kepler and CoRoT missions. The asterosesimic constraints provide better characterisation of the stellar parameters across the Hertzsprung-Russell diagram. Particular successes have been in the first survey of main sequence stars using the combination of classical and seismic data and also a method to provide concrete observations on the internal structure of evolved, red giant stars. This work has also allowed the search for extra-solar planets to be combined with the characterisation of the host star in the bid to provide detailed constraints on Earth-Sun like systems. The discovery potential here is significant and the School has appointed *Miglio* to build and sustain the future of this research activity. He brings particular expertise in stellar modelling and in population studies that are important in a wide astrophysical context. The appointment of *Farr* creates a new dimension in terms of exoplanet modelling and also building connectivity to the GW research. Reflecting the well-established Birmingham leadership in helioseismology techniques and unparalleled data portfolio, the current solar focus is on the previous deep solar minimum and the evolution of the current, rather weak, cycle.
Extragalactic Astrophysics: The Birmingham extragalactic group is prominent in the study of groups and clusters of galaxies. Constraining cosmological parameters by cluster observations depends critically on our ability to estimate cluster masses. A major effort led by Birmingham (*G. Smith*) is determining the accuracy of such mass estimates by combining gravitational lensing, X-ray measurements and optical/infrared observations of cluster galaxies. This work underpins one of the Birmingham leading roles within the large XXL X-ray survey of clusters, and lays the foundations for major future surveys such as that which will be conducted by ESA's Euclid mission. We are also recognised as leading players in the study of hot gas within groups, and its use as a probe of cosmic feedback. Recent successes include the award over 500 hours of time on the GMRT radio-telescope for these studies. The future will see this extended to higher redshift using data from the XXL (X-ray) and GAMA (optical) surveys.

Quantum Matter and Nanoscale Science: *Academic Staff: Nanoscale Physics (3), Metamaterials (2), Ultracold Atoms (3), Condensed Matter (2), Theoretical Physics (4)***.** The REF period has seen the development of our strategy articulated in RAE2008 to build up experimental work in ultracold atomic gases. We have also instigated metamaterials research (supported by £2M of strategic investment from the University) while maintaining a small, high-quality group in condensed matter, which is developing in collaboration with the newly reformed magnetism group in the School of Metallurgy and Materials (*Laver*).

Ultracold Atoms: Using £2M from the EPSRC/HEFCE Science and Innovation Award, Science City and University funds, this new group under *Bongs* has built 280m^2 experimental labs from scratch and obtained Bose-Einstein condensation as an initial building block of their research programme into high precision quantum metrology. In parallel *Boyer* has developed quantum optics to create entangled images from 4-wave mixing. One focus area is applied quantum technology, where they are coordinating 2 and play a leading role in another 3 European Networks on atom interferometry and optical clocks. Newly formed collaborations with industry, European national metrology institutions (NPL, PTB, SYRTE, INRIM), engineering and archaeology schools within the University as well as an interdisciplinary EPSRC project, open up opportunities related to oil and mineral exploration, defence, urban and historical infrastructure and space research.

Condensed Matter Physics: With EPSRC funding (£1.3m), *Blackburn* and *Forgan* have developed a portable cryomagnet that provides the world's highest continuous magnetic field for use in neutron scattering experiments. This magnet can be used for all types of scattering experiment, and has been used at multiple large-scale (neutron and x-ray) facilities around Europe. This new capability has placed the group at the forefront of new developments in high-temperature superconductivity, where their discovery of charge density wave ordering has resolved the long-standing mystery of the origin of the Fermi surface reconstruction seen in these materials. This magnet's experimental capabilities are being expanded into the mK region, bringing the powerful tools of scattering to bear on new regions of parameter space.

Metamaterials: In 2010 the School identified metamaterials and transformational optics (and acoustics) as an area of growth to build a group with strength in both theory and experiment. £2M strategic investment funding from the University has provided substantial equipment start-up and the refurbishment of 200m^2 of laboratories (£500k). The appointment of leaders in the field, *Zhang* (experiment) and *J.Li* (theory), created a group with immediate successes such as the first optical invisibility cloak which shrouds a macroscopic object for one single polarization of light (selected "top 10 breakthroughs for 2010" by Physics World) and a meta-lens capable of convex and concave behaviour in a single lens. Within the College a new appointment in Electrical Engineering developing microwave metamaterials work is enhancing the environment of the group. Future directions are: unconventional Spin Hall effect of light, photonic topological insulators, supersymmetric and PT symmetric metamaterials, high efficiency metasurfaces for information storage and 3D display.

Nanoscale Physics: The Birmingham Science City project Advanced Materials, flagged in RAE2008, brought in £3.5M for new equipment. This 10-year project, which started in 2008, provides £3M of funding for eight new instruments to the Nanoscale Physics group and £0.5M for Ultracold Atoms equipment. This has given the group new capabilities for atomic-scale imaging of nanostructures, e.g. 3D imaging and dynamics of single dopant or adsorbed atoms (one atom limit) in clusters/nanowires via aberration-corrected STEM and the resolution of the true atomic structure of self-assembled monolayers via low temperature STM. Newly established collaborations with Environmental Health Sciences, Chemistry and Cancer Studies are bringing atomic-scale imaging to bear on problems in nanotoxicology, advanced materials synthesis and novel cancer treatments.

Theoretical Physics: The group works on coherence in many body systems and small structures, applied to cold atoms and condensed matter. One-dimensional interacting systems (both in cold gases and condensed matter) have provided the most surprising and significant results over the REF period. *Gangardt* has shown that the algebraic positional order in 1d cold gases is sufficiently “periodic” to support Bloch oscillations of an impurity particle. *Lerner* has shown the weak-strong duality of impurity scattering in the Luttinger model is extended to coupling to phonons with the scaling to one of an ideal metal or insulator preserved. *Schofield*’s collaboration has witnessed the first experimental signatures of spin-charge separation beyond the (highly idealised) linearized regime. We have recently appointed *Béri* (as a Birmingham Fellow, and Royal Society URF). He straddles the areas the group covers: he works on correlated topological phases (e.g., fractional

topological insulators) and novel, correlated mesoscopic devices based on Majorana fermions. His research interests fit excellently with the Ultracold Atoms and the Metamaterials Research Centres.

Pure and applied science are both reflected in the broader future strategy for the Quantum Matter and Nanoscale Science area. The physics of light, atoms and matter, and their mutual control, will present many challenges over the next decade, and the coherent growth of capability across this area positions the School well: there are already collaborations between Metamaterials and Cold Atoms and both of those groups and Astrophysics. To build impact the groups will increase exploitation of the College structure in cross-disciplinary research and KT. The Theory Group is involved in collaboration with both Cold Atoms and Condensed Matter. The Nanoscale Physics group has begun a major new project (EPSRC Fellowship plus four further grants) to scale-up size-selected cluster production by 5+ orders of magnitude, with potential applications in e.g. catalysis, biosensing, coatings and photonics.

Particle and Nuclear Physics: *Academic Staff: Particle (11), Nuclear (6)*
Particle physics: The group is a long-standing centre of excellence in detector and trigger construction and data analysis at world-leading facilities. Its current activity is focussed on CERN, where it has as diverse a portfolio as any UK group, with involvement in 4 experiments. Major roles have been in the discovery of the Higgs boson and in probing rare processes with high sensitivity to phenomena beyond the current Standard Model of Particle Physics.
Since the start of the REF period, in addition to ATLAS and ALICE, the group has established itself in two world-leading flavour physics experiments, probing the decays of beauty (LHCb) and strange (NA62) quarks (replacing the legacy activities at DESY (H1), SLAC (BaBar) and CERN (NA48 and NA57)). The School has strategically supported this diversification through the academic appointment of *Lazzeroni* (NA62 and LHCb) and the proleptic appointment of *Goudzovski* (NA62). It has also strengthened its involvement in the top-priority Higgs programme at ATLAS through the proleptic appointment of *Nikolopoulos*. Both *Goudzovski* and *Nikolopoulos* hold Birmingham Fellowships, the former also holding a RS URF. The resulting three main themes are: **Energy Frontier Physics** (searching for new physics such as the Higgs boson at the ATLAS experiment); **CP Violation** (investigating asymmetries between matter and antimatter at the LHCb experiment); **Flavour Physics** (probing ultra-rare decays of particles containing strange quarks at the NA62 experiment).
Birmingham has well-established leadership in the ATLAS experiment at the LHC (*Charlton*, now spokesperson), having delivered the crucial first level calorimeter trigger and components and assembly of the semiconductor tracker. Birmingham is currently working on upgrades of these. Aside from the central contributions to the Higgs discovery, key analyses include the first observation of a new particle at the LHC ($\chi_b(3P)$), the first observation of correlations between the spins of top and anti-top quarks produced in the same event and the first detailed measurements at LHC energies of diffractive scattering. Birmingham also provides and manages a significant site on the 'Grid' distributed computing network. With an eye to the future, Birmingham has developed UK and international leadership in plans for an electron-proton and electron-ion collider based on the LHC (LHeC, *Newman*) and in a Higgs factory based on a linear electron-positron collider (N *Watson*). A further key component of our strategy has been the establishment of an internationally leading public understanding of science outreach programme.
Nuclear physics: Research is divided into 3 strands; quark-gluon plasma (QGP), nuclear structure and moments, and applied nuclear studies. The strategic development of the research has resulted in a strong focus on areas in which it has clear national and international leadership investing in exotic nuclei/nuclear structure and ALICE.
Since RAE2008, the QGP activities have been consolidated in ALICE at CERN, fusing the efforts from STAR at BNL and the existing ALICE work. The ALICE trigger, designed and constructed by Birmingham, has ensured the group plays a leading role in the analysis of the *First Physics* to emerge. The Birmingham group is developing a prominent role in the analysis phase, particularly strangeness. The focus for the future is leading the upgrade of the central tracker.
The exotic nuclei research has been supported through the appointment of *Wheldon* (following his Advanced Fellowship). Major advances include the work on the Hoyle state in carbon-12 – a state responsible for the formation of carbon in stars and organic life. We are also involved in the UK flagship NuSTAR project at FAIR through the construction of the R^3B tracking detector. The

School's MC40 cyclotron supports the internationally leading positron emission particle-tracking, PEPT, programme (Parker, submitted to Chemical Engineering UoA) with significant industrial collaboration from chemical engineering to mining and minerals extraction. PEPT was recognised as a strength in RAE2008, benefiting from >£500K refurbishment in the REF period.

Overall Future Vision: Beyond the evolution of the key research areas outlined above, the further crucial strategy is to build impact and interdisciplinary research over the next REF period is using a "***knowledge escalator***". This knowledge escalator conveys our work via the engineering Schools in the College to end-users in industry. *Parker*'s work above was the prototype for this activity. A recent example is the £2.5M EPSRC-funded collaboration between *Bongs* and Civil and Electrical Engineering on gravimetry. This principle is seen in 3 large projects for the next REF cycle:

- The metamaterials research centre: This will expand with 2 additional physics posts (a theorist and an experimentalist) and collaborate widely with the synergistic appointments and facilities in the Schools of Electrical (RF/microwave strengths) and Mechanical Engineering (nanofabrication facilities).
- Developing a new, cross-cutting, optics theme: New appointments will target the already fruitful interface between STFC and EPSRC – territory bridged by optical metrology techniques. Joint research has already attracted funding from EPSRC (*Bongs*, *Freise*, *Vecchio*) and Leverhulme (*Speake*, *Zhang*). This strategy will provide further funding resilience and new opportunities including the development of ESA funded, space-based, projects in partnership with 2 new space-research appointments in the School of Electrical Engineering.
- The Centre for Nuclear Education and Research: the University has already committed £2M to fund facility upgrades and 5 posts (2 in physics) to establish this new Centre. Our 2 nationally unique facilities will be expanded. The MC-40 cyclotron will develop a materials irradiation programme in partnership with the nuclear industry and School of Materials and Metallurgy. The Dynamitron, (3MV, accelerator) will be upgraded for the development of a binary boron neutron capture (cancer) therapy (BNCT) and a neutron materials irradiation facility.

In all areas we will grow leadership in fundamental science. Examples of next-generation STFC where leadership roles are developing include: the LHeC *(Newman)* or the linear electron-positron collider *(N.Watson)* in particle physics; the Einstein telescope for gravitational waves *(Freise)*; TESS and PLATO for asteroseismology *(Chaplin)*; and to exploit LHeC for the QGP area and possibly the electron-ion collider proposal at BNL (*Evans, Jones*).

c. People, including:

i. Staffing strategy and staff development

Staffing is the single most important element in the vibrancy and sustainability of research in the School and our strategy is to nurture and grow academic excellence at all career stages.

Recruiting academic staff: The 11 new members of academic staff appointed during the REF period illustrate the principles of our recruitment strategy. Some were recruited via the University's Birmingham Fellowship scheme, while others were through a specific job opening in the School. In all cases though, excellence is the preeminent criterion for appointment and this supersedes perceived need. It is a Darwinian approach - for the best candidates are naturally attracted to the leading research groups. All appointments begin with an international search for talent, an open advert followed by a rigorous selection processes. By successfully identifying rising stars early in their career the School has been able to make appointments ahead of their becoming highly visible. The new staff have come from the USA [*Zhang* (Berkeley), *Mandel* (M.I.T), *Nikopolous* (Brookhaven), *Farr* (Northwestern), and *Boyer* (NIST)] from UK Institutions [*Béri* (Cambridge), *Goldwin* (Imperial), *Wheldon* (Birmingham)], from Europe [*Miglio* (Liege) and *Goudzovski* (CERN)] and from China [*J.Li* (Hong Kong)]. New staff are guided and financially supported through the visa application process and given a relocation package as well as start-up funds.

Establishing new staff: all new appointments (not just Birmingham Fellows) are excused from all teaching and administrative duties for at least the first year of appointment – and longer for those establishing an experimental lab. In subsequent years, as new staff move gradually towards a balanced contribution to research and teaching, their teaching is initially weighted towards specialist courses (masters level or postgraduate level) and research project work. New staff are assigned a mentor who is a professor in a different research group. They meet regularly with the mentor and with the Head of School as part of a probationary process which emphasizes

probationers rapidly reaching their full potential. New staff are prioritized for PhD student allocation.

Supporting the academy: The intellectual vibrancy of the School is fuelled by interaction. All research groups have a weekly seminar programme and most also have student-led journal clubs. The fortnightly colloquium is attended by the whole School and begins with tea for all and concludes with dinner, paid for by the School, for five postdocs and academic staff to meet with the speaker. Monday morning coffee provides a regular meeting point for academic staff in the School and there is a weekly newsletter. The termly formal School meeting has a focus spot on a topical research paper published.

Staff Development: All staff have an annual performance and development review (PDR) with a senior professor or Head of School. The review shaping objectives for the coming year and identifies training and support needs. Training is provided for reviewers and also the University's staff development section organizes training events and courses (with physics staff typically accounting for 30 days/year of activity). A key aspect of the reviews is mapping out the path to promotion. Every candidate for promotion is assigned a mentor through the process and the School promotions panel hones each case before it leaves the School. Mock interviews are arranged for promotions to titles. The School has an unparalleled record in promotions over the REF period with 8 staff promoted to Professor during this time. The School offers sabbaticals to staff and encourages these to be used to establish new research directions: examples since 2008 include *Chaplin* (developing asteroseismology), *Raychaudhuri* (establishing new astrophysics links with India), *Palmer* (preparing a successful Established Career EPSRC Fellowship bid). The School has also developed a strategy for retirement planning through the annual reviews which can shape duties and objectives accordingly. There are several retired members of staff who capture external funds and remain research active (e.g. *Cruise*, *Forgan*, *Vinen*), and retired staff are encouraged to participate in School life such as the colloquia.

Postdoctoral research associates (PDRAs) and research fellows: The School values the critical contribution made by PDRAs to research in the School, and hence is committed to the key principles of the "Concordat to Support the Career Development of Researchers". As members of staff, all PDRAs are encouraged to take part in all the activities of the School. During the REF period the School has instituted a "researchers network" which is run by PDRAs and allows researchers from disparate research groups to meet and also to shape School policy. Researchers have annual objectives decided by PDRs with the PI or Head of Group. A mentoring process has been established to provide additional career advice independent of the PI funding their position. Personal fellowships are encouraged and candidates are actively supported through the application process with advice on application forms and research proposals as well as running mock interviews. The School's success rate remains high with the School holding 3 Royal Society URFs, 2 Dorothy Hodgkin, 2 Daphne Jackson and 2 Ernest Rutherford fellowships in the REF period (with more appointed for 2014). Ensuring fellowship holders and PDRAs progress in their careers is paramount and the REF period has seen 17 of our PDRAs and fellows securing permanent academic appointments

Supporting **equality and diversity** is a high priority within the School and, together with health and safety, are the two standing items on the School management committee. In securing the IoP Juno Practitioner status the School is working through an action plan designed to become a Juno Champion. All staff are required to take diversity training. The School Equality and Diversity Committee (chaired by *Bongs*) has representation from all quarters within the School and can directly make policy decisions. A particular priority within the School is to ensure carers and staff returning from career breaks are supported in their research activities and promotion and the School has been an advocate with research councils and the University to seek additional funding and concessions where needed. The School success is reflected in external recognition for returners (*M.Watson* featuring in Physics World and Research Fortnight, and T. Wheldon used by the Daphne Jackson trust as a case study).

ii. Research Students

The Midlands Physics Alliance Graduate School lies at the heart of the School's strategy for its research students. This provides a US-style graduate level training equipping students with a breadth of physics beyond the more focused training Centre for Doctoral training might give. Established in 2007 to cover physics in EPSRC's remit, it was expanded in 2010 with a further

£3.3M to encompass that of STFC. More than 60 modules are available via access grid lecture theatres (two in each department) with our major partners in Nottingham and Warwick. Following its success, access to the courses has now been extended to 4 other Midlands universities. Birmingham students are required to take at least two modules per term for the first 4 terms as well as attending workshops and joint conferences. University and College scholarships augment by about 50% the number of RCUK studentships and studentships funded by EU/Leverhulme grants. These are awarded competitively to enable the School to recruit world-class researchers including those beyond the confines of the EU. The best students can win prestigious Postgraduate Training Assistantships which, in return for undertaking some paid teaching, pay an additional stipend and yield a 4 year funded PhD. PGTAs receive comprehensive training within the School.

Research students are assigned a primary and a secondary supervisor. In addition to the day-to-day supervision, monthly meetings are documented and a six monthly progress review meeting is reported on. This review includes discussions around a student's wider development needs with recommendations to attend courses (e.g. on CVs and Viva preparation) at the University Graduate School. Students are required to pass a mid-term exam after 12 months that consists of a report and viva. Students are encouraged and funded (via an endowment) to attend conferences and present their work. A student's first experience of interdisciplinary presentation is often at the College annual research conference where a competition rewards the best student work. Research groups have social spaces for students and staff, encouraging a lively debate around seminars and journal clubs. Finally, all students are offered industry placements fully funded through the Midlands Physics Alliance. These can occur at any stage during the PhD under a University arrangement that 'stops the clock' on their PhD. For some these placements have provided a route to employment on graduating.

d. Income, infrastructure and facilities

Specialist facilities within the School include:

MC40 Cyclotron and Positron Emission Particle Tracking PEPT facility: (internal investment of >£500k on refurbishment of laboratories and facilities)

The Cyclotron produces medical isotopes (Krypton generators) commercially. The operating profits (£250K per annum) are reinvested in developing our research facilities. The MC40 operates partly as a user facility for projects including: the development of detectors for the ATLAS upgrade, detectors for medical imaging, proton therapy characterisation, studying of biological and cellular systems under irradiation, mechanical studies (e.g. tribology). Sustainability is ensured by the acquisition of parts of the MC40 Hammersmith Hospital cyclotron for spares.

Nanoscale Science Facility has been boosted by eight new instruments with value £3M funded by Advantage West Midlands and the ERDF under the Birmingham Science City Project. They include a low temperature scanning tunnelling microscope size-selected cluster beam source and deep plasma etching system. The flagship is a 200 keV spherical-aberration corrected scanning transmission electron microscope (JEOL), equipped with high-angle annular dark-field imaging, electron energy-loss spectroscopy and high-energy X-ray dispersive detectors, which provides imaging and analysis to sub-atomic resolution in the fields of advanced materials, nanotechnology and molecular, including biomedical, sciences.

Clean room and fabrication facilities: We have 200m^2 of clean room space supporting Astrophysics, Condensed Matter, Nanoscale Physics and Particle Physics. This includes a grade 100000 room for the ATLAS and ALICE experiments and upgrades, with the Astrophysics facilities ESA-approved for Flight PCB assembly with certified staff. Within the REF period we renovated the supporting 230m^2 suite of additional centralised electronic laboratories and test facilities. For space work we have a 70m^2 environmental testing unit.

Mechanical Workshop: The School has a 270m^2 Mechanical Workshop with 6 technical staff and a suite of tools, including 5 CNC machines, driven by cutting edge CAD/CAM workstations.

M5 equipment/facilities sharing: M5 is a group of research-intensive universities formed from Birmingham, Leicester, Loughborough, Nottingham and Warwick (recently Aston), enhancing research collaboration via improved sharing of equipment. Physics offers, and gains access to, a range of research facilities.

Large Scale Computing: The School benefits from access to BlueBEAR: the Birmingham Environment for Academic Research - a cluster which consists of 848 core processors capable of a peak performance of 15 TFlops; used by Particle Physics and Nanoscale Science groups.

Investment in infrastructure:

Cold Atoms Laboratories: Over the REF period investment has been made (using the resources acquired from EPSRC, HEFCE Science City and the University) of £1M in equipment and £1M in laboratory refurbishment (280m^2, in addition to the refurbishment of 200m^2 of offices for staff, postdocs and research students for both Cold Atoms and Condensed Matter groups. **Metamaterials Research Laboratories** (internal investment £500k, refurbishing 200m^2 laboratory space and state-of-the-art equipment £1.4M). Metamaterials has been recognised as a Grow theme by the EPSRC. This research area is seen as a high priority for growth; the School will actively seek to further develop these facilities in collaboration with Engineering Schools and UK industry.
Applied Nuclear Research Laboratories and Nuclear Physics Offices: £500K refurbishment of 200m^2 of laboratories, including hot facilities for the Positron Emission Centre This re-sites previously scattered activity together on one floor of the Medical Physics building. Reconfiguration also provides space for growing collaboration with the School of Metallurgy and Materials. We have refurbished 200m^2 of office accommodation for the Nuclear Physics group.

Future infrastructure investment:
Dynamitron, 3MV, accelerator (Future up-grade programme) The Dynamitron is a 3MV electrostatic accelerator capable of delivering high currents (mA) of protons. Physics are collaborating with the University Hospital Birmingham to develop the BNCT programme – BNCT is a unique potential therapy for the treatment of high grade gliomas which accounts for around 1% of cancer diagnoses, so 2000-2500 per year in the UK. This is part funded from STFC because of the interest to UK accelerator science. Over the next REF cycle the facility will be upgraded to deliver beams of up to 30 mA of protons and deuterons to i) take BNCT through clinical trials ii) explore the development of a neutron materials irradiation facility – it would have **the highest neutron flux available in the UK**, iii) contribute to the development of high power targets in the UK.

Funding Portfolio and Future Plans:
The funding portfolio over the REF period is given below:

Theme	Research Income (k£)	In-kind Research Income	
		RCUK (k£)	Non-RCUK (k£)
Astronomy	11,456	5,659	6,400
Particle and Nuclear	12,177	21,739	1,100
Quantum Matter and Nanoscale	13,644	2,216	4,610
Total	37,277	29,614	12,110

The overall result is a ~**46% increase per FTE staff member per annum** of grant award over the REF period. There has been strong growth in Quantum Matter and Nanoscale Science since RAE2008, in part reflecting new research areas, and sustained income in the STFC disciplines. There are **two main planks for the future research and funding strategy**: **First** and foremost it is to ensure the pure physics component of the programme remains of the highest quality and maintains its vitality; through periodic review of current research directions and horizon scanning. This is to ensure the highest quality science and to optimise funding from traditional research council sources (EPSRC, STFC) and opportunities in Horizon2020, building on an already strong EU portfolio. **Second** to take advantage of Birmingham's College structure to grow applied interdisciplinary research. Current examples are: Nanoscale Science collaborations with Chemistry and Chemical Engineering on new resists for photolithography and biological imaging; and in Cold Atoms where high precision quantum gravimeters are being developed for Civil Engineering applications. Future plans: metamaterials - bringing together metamaterials research in optical systems (Physics) and microwave materials (Electrical Engineering); and magnetic materials - design and development of new magnetic materials (Mechanical and Materials Eng.) and state-of-the-art characterisation and fundamental understanding (Physics). This combination of research strength across the campus provides a *knowledge escalator* will enhance the impact of research and open up collaborative research and funding opportunities with industry.
In Kind Funding From Use of Non RCUK and RCUK International Facilities
Particle and Nuclear Physics (£22.8M):
RCUK In-kind (£21.7M): CERN £20.48M, PPRAL £1.26M
non-RCUK (£1.1M): ANU £63k (18 days), GANIL France £166k (10 days), ORNL USA £75k (5 days), Munich Germany £179k (35 days), iThemba SA £469k (30 days), Orsay France £49k (5

days) Notre Dame £51k (10 days). Costs based on beam time used and operating costs provided by facilities total beam-time 113 days.

Astronomy (£12.1M):

RCUK (£5.7M): Including ESA, ESO, Newton/Integral, Herschel, Gemini usage.

Non-RCUK (£7.8M): Use of large ground based optical telescopes (Subaru) £0.5M (11 nights) radio-telescopes (GMRT) £1.3M (37.1 days) and space observatories (Chandra) £4.0M (200 hours), GALEX £1.4M (70 hrs), Kepler £600k (fraction of continuous data). Estimates for the value per night of large telescope time (£35k/night) and (£20k/hour) for space-based observatories.

Quantum Physics and Nanoscale Science (£6.8M):

RCUK facilities (£1.41M)

Non-RCUK (£4.61M): SINQ Switzerland £2.25M (225 days), NIST USA £430k (43 days), SuS Switzerland £220k (22 days), SNS USA £260k (26 days), Sping8 Japan £60k (6 days), ALS USA £240k (24 days), APS USA £160k (16 days), FRM-II Germany £180k (18 days), HFIR £130k (13 days), DESY Germany £450k (45 days), HZB Germany £230k (23 days). Based on allocated time at light and neutron sources and £10k/day operating costs. Total of 461 days.

e. Collaboration or contribution to the discipline or research base

Research Collaborations and Leadership (examples only):

All of these examples are major international research endeavours in which Birmingham is playing a role in shaping the scientific programme and objectives. Charlton was ATLAS Physics Coordinator (to 2009), Deputy Spokesperson (2009-13) and now Spokesperson; Nikolopoulos is principal author on all papers for Higgs decays to Z-bosons; Evans is the UK spokesperson for ALICE; Goudzovski is NA62 Physics Coordinator; Lazzeroni is UK Spokesperson of NA62; A Watson is Project leader of ATLAS `L1Calo' (first level calorimeter trigger) project; Newman is on the Steering Committee of the LHeC project and the Executive Committee of the H1 Collaboration; N Watson is joint analysis coordinator of the CALICE collaboration (calorimeter development for ILC); Villalobos Baillie is one of only 6 on the *Physics Team* for the ALICE collaboration, in a collaboration of over 1000 scientists; Freise has key roles in the Advanced Virgo and is in the governing council of the Einstein telescope gravitational wave projects; Raychaudhury has chaired the Chandra time allocation panel; Mandel has a leading role in parameter estimation for the LIGO (gravitational wave) Scientific Collaboration; G. Smith heads the LoCuSS project and has been invited to lead a working group in XXL; Vecchio is a member of the GEO (gravitational wave detector) Executive Committee; Chaplin leads the programme of the NASA Kepler Mission devoted to the asteroseismic investigation of solar-type stars, managing and coordinating the work of 170 international scientists; Lerner was director/co-director of 5 international conferences, including biannual conference series “Fundamentals of Electronic Nanosystems” and “New phases in Anderson Localization”. Elsworth is on the management group for the Kepler red giant asterosiesmology. These leadership positions ensure that Birmingham has the opportunity to steer the future directions of these, typically, large scale scientific programmes.

The Midlands Physics Alliance has established a coordinated research grouping and a joint Graduate School with the critical mass to compete with the top US and EU Universities. The Graduate School has been developed via two tranches of funding from HEFCE (£4m in 2007-12 and £3.3M involving STFC as well in 2010-15). The coordination of research is exemplified in the Midlands Ultracold Atom Research Centre (£9m funding from EPSRC, HEFCE and the Universities of Birmingham and Nottingham) which targets cutting-edge interdisciplinary research at the rapidly evolving interface between cold atom, condensed matter, and optical physics. As part of the cold atoms research we are partners of EU STREPs SOC-II and Matterwave, EU ITN QTEA, ESA STE-QUEST mission consortium. The Alliance coordinated Warwick’s entry into the ATLAS experiment.

Exemplars of Interdisciplinary Research and Research with Industry:

The Birmingham Science City (BSC) project “Creating and Characterising Next Generation Advanced Materials,” is a 10-year Birmingham-Warwick collaborative project led by Birmingham *(Palmer),* and supports advanced research across the disciplines. Five years in, it is the most successful of the six BSC projects in achieving its targets. For example, >300 publications and presentations have arisen, 37 jobs have been created, 64 business assists and collaborations delivered, 217 people trained, more than £15M additional funding levered and four companies established in, or attracted to, the region (all led by Nanoscale Physics; involving 6 Schools at two Universities).

As well as the societal benefit of the production of medical isotopes, the MC40 cyclotron produces positron tracers for the PEPT facility. Manufacturing processes have been studied by this technique (Birmingham Chemical Engineering, Astra Zeneca, Merck, Procter & Gamble and Johnson Matthey Catalysts), and the School of Metallurgy and Materials science use PEPT for understanding casting. Many external users have used the MC40 for diverse purposes, from radiotherapy to equipment for the ATLAS upgrade at CERN. Currently the facilities are being upgraded for studying irradiation of materials for the nuclear sector (with Birmingham Metallurgy).

The cold atoms sensors work is regarded by the University as an exemplar of connecting fundamental research to engineering – currently atomic interferometers are being developed to provide precision measurements of gravity gradients, with the current activity by *Bongs* being: PI on *GG-TOP* research collaboration on applications of cold atom gravity gradient sensors with Civil and Electrical Engineers and Archaeologists (EPSRC, £2.5M); Coordinator of EU STREP *iSense* on cold atom quantum devices, e.g. a backpack sized gravity sensor (8 partners, €2.5M); Coordinator of EU ITN *FACT* on *Future Atomic Clock Technologies* (14 partners, €3.9M).

Exemplars of Research leadership:

International Conference Invitations and Advisory Boards:

Members of the School have given over 300 talks at international conferences within the REF period, with major contributions from *Chaplin* (20), *Freer* (26) and *Palmer* (40). The School has a strong commitment to citizenship for the health and vitality of the discipline. Many of these contributions are via invitation, again in recognition of Birmingham's scientific leadership and standing. The following a series of examples illustrating these contributions:

Bongs: Editor of the "Annual Review of Cold Atoms and Molecules" by World Scientific, Main Scientific Organiser for Atomic Sensors and Clocks Session in COSPAR 2012 & 2014, UK representative on the ESA STE-QUEST Study Science Team, Member of the UKSA Space Environments Working Group; Blackburn: ESS Science Advisory Panel, Oak Ridge National Lab neutron beam-time allocation panel; Chaplin: Max Planck Society's Scientific Council; Elsworth: Oversight Committee for the US Solar Observatories (run up to the major new observing facility of ATST), Oversight Committee for Kiepenheuer-Institut für Sonnenphysik in Freiburg, SEPNet Advisory Panel; Freer: Chair of STFC Nuclear Physics Advisory Panel, IoP Science Committee, Chair of GANIL Programme Advisory Panel, France, EU-EURONs Advisory Board; Forgan: Chair of Large Scale Structures Committee, ILL, Hawkes: CERN LHC Committee; Gunn: Chair of Standing Conference of Physics Professors, International Advisory Board, SUPA, Kuwait Foundation Physics Prize Committee, Physical and Life Sciences Panel, STFC, Photon Science Facility Board, STFC, IoP Awards Committee; Jones: Chair of STFC Projects Peer Review Panel; non-core member STFC Science Board; Lazzeroni: IPPP Durham Steering Committee, STFC Projects Peer Review Panel; Li: Council member of Hong Kong Institute of Science; Mayhew: Chair, IoP Molecular Physics Group; Newman: CERN SPS and PS Committee, STFC Particle Physics Advisory Panel (now Chair); Ponman: RS Newton Fellowships Panel and STFC Astronomy Grants Panel; Schofield: International Adviser for 3 SCES Conferences; 7 EPSRC panels (2 as Chair); Vecchio: non-core member STFC Science Board; N Watson: STFC Particle Physics Grants Panel, MICE oversight committee; Wheldon: Hon Sec. Nuclear Physics Group; Wilkin: IoP Council and Finance Board, Hon. Sec IoP Quantum Optics, Quantum Information and Quantum Control Group.

Learned Societies, Prizes and Awards:

The School has been successful in having the success of its research recognised through awards and prizes. These include: IOP HEPP Group Prize 2008 (Newman), IoP Rutherford Medal 2010 (Freer), the IUPAP award in Optics 2010 (Zhang), Payne-Gaposchkin Medal 2011 (Elsworth), British Vacuum Council John Yarwood Memorial Medal and Senior Prize 2013 (Palmer), MBE for contribution to Physics 2013 (Gunn), Joint Institute for Nuclear Research annual prize 2011 (Goudvoski), 2012 Royal Astronomical Society's Harold Jeffery's Lectureship prize (Chaplin), NESTA Crucible Fellow 2008 (Blackburn); Elected Fellows of Institute of Physics: Bongs, Charlton, Freer, Jones; Fellow of the Royal Society of Chemistry (Palmer). The Richardson Medal 2013, awarded for outstanding service contributions to the International Glaciological Society and to glaciology (Glen).