Physics: investing in our future

Powering the new industrial era

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Contents

Executive summary

The UK needs a clear, comprehensive and long-term vision for R&D, which instils confidence among researchers and innovators, and unleashes ingenuity wherever it is found.

Changes are needed so that each of the core pillars of the physics R&D system – discovery, business innovation, people and infrastructure – is providing the support needed to drive a step change in the performance of the UK's R&D system.

This report is the first of the IOP's programme of work aiming to unlock the full potential of physics R&D for society and the economy. It identifies the key challenges and opportunities in the physics R&D ecosystem, and sets out some of the changes needed to enable more, and more impactful, physics R&D to take place in the coming years.

"Increasing R&D investment to 2.4% of GDP by 2027 would generate an additional 80,000 jobs and £30.5bn in GDP[1]."

Our aim is to present a blueprint for the future so that the UK meets and then exceeds target levels of public and private R&D investment and we transform the physics R&D landscape. In doing so, the IOP has identified the following principles that will guide our future work and the development of a thriving physics R&D system in the UK:

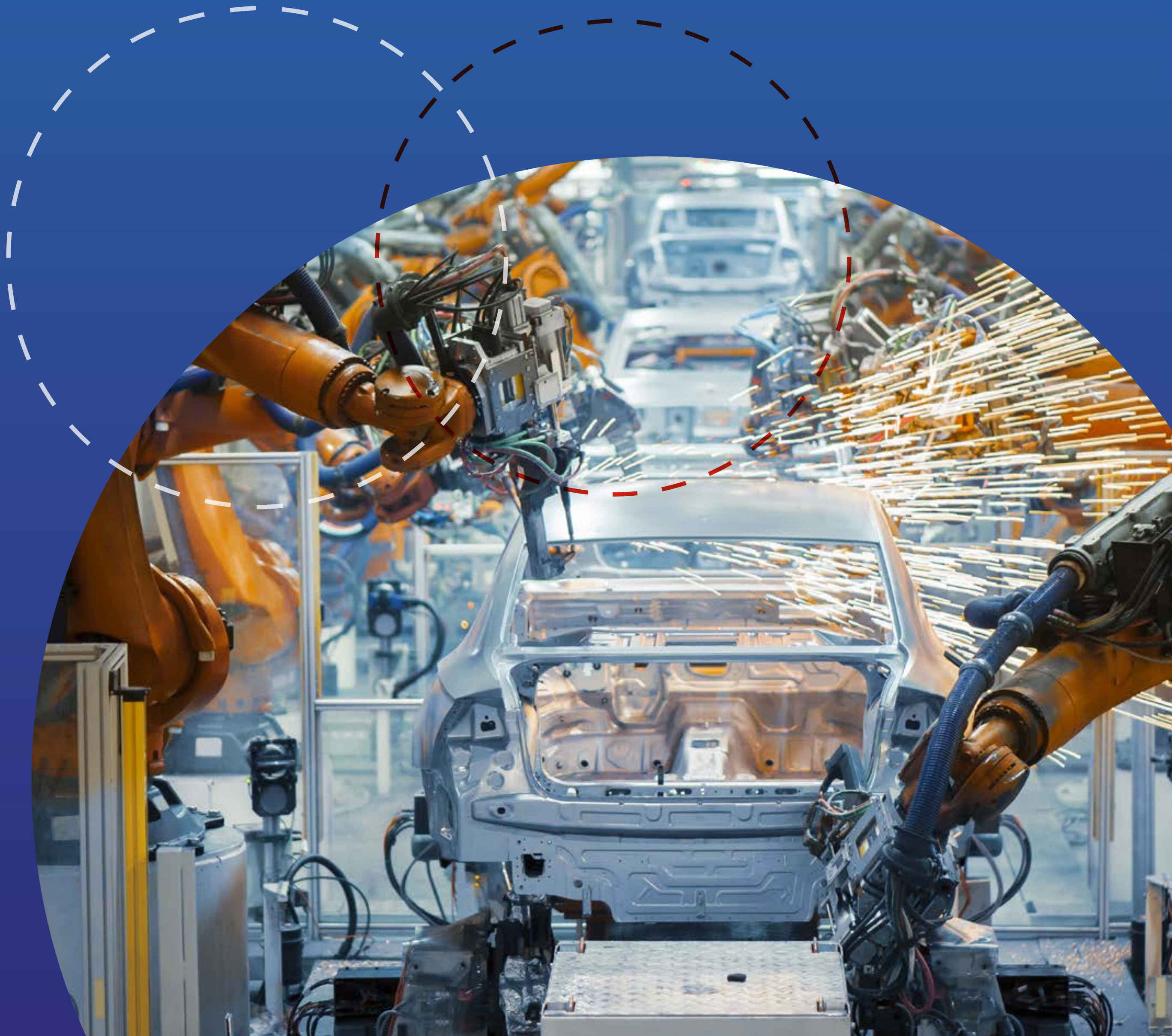
- The UK needs a **clear, comprehensive vision for R&D and a stable policy environment**, to build confidence among the research community and potential investors
- **R&D funding must be long-term and sustainable**, to enable people and disruptive ideas to flourish and drive tomorrow's breakthroughs
- **Funding and governance processes must recognise and nurture a broader range of excellence** across all types of institution and all stages of research
- Approaches to **career progression and skills development must be versatile enough to prepare people to succeed in a variety of R&D careers**, to foster innovation across the whole economy
- **Learning and working cultures must be welcoming and inclusive to people from all backgrounds**, to build a thriving, diverse physics R&D workforce.

Throughout history, physics has transformed our world. From fibre optic communications to magnetic resonance imaging, UK physics has been indispensable to many of the world's most impactful and successful innovations. Physics will continue to transform our world in the coming years. A new wave of innovation enabled by physics is set to break, promising zero-carbon energy generation, radically accelerated drug discovery, self-repairing infrastructure, and myriad other benefits we cannot yet predict.[2]

By making the changes needed to build a thriving physics R&D system, we can deliver transformative benefits in every part of the UK. We can attain global leadership in science and innovation, and the substantial economic rewards such leadership offers. We can create a more productive, more equitable and greener economy. And we can all lead more prosperous, healthy and sustainable lives.

Our international competitors are significantly scaling up their R&D efforts to seize the opportunities on offer. The pace of competition is such that, even if the UK succeeds in realising the highly ambitious increase in R&D activity the UK Government chose to target only five years ago, we will still fall short of the OECD average. The UK is at a critical juncture: we can take action, and invest in physics to secure a place at the forefront of the new industrial era; or we can maintain the current course and be left behind.

"Reaching and maintaining the 2.4% target requires £17bn more private sector R&D investment in 2027 than in 2017[3] and an additional 150,000 people in the R&D workforce by 2030[4]."



The potential of physics

Throughout history, physics has driven economic and social progress. The impact of fundamental physics discoveries upon the world can often take time to realise in full, but their transformational nature is indisputable.

A century passed between Michael Faraday's demonstration of the world's first electric motor in 1821 and their widespread use in industry and domestic life; today, some 800 million are sold annually across the world and electric motors play a vital role in cutting emissions across transportation, construction and heating.[5]

Physics will continue to transform our world in the coming years. A new wave of technological innovation is about to break. Emerging technologies, enabled by UK physicists' breakthroughs in fields such as materials science and quantum physics, promise to radically transform the way we live and work, and create new business opportunities and open up new markets.

But the UK's ability to harness the benefits of this new industrial era, and respond effectively to the challenges facing society, depends on an effective physics R&D system. The UK's R&D system already produces world-class physics research and innovation, but we have yet to truly unlock the full potential of physics R&D – through fostering new discoveries, catalysing private sector innovation, unleashing people's ingenuity and developing world-class infrastructure.

Changes are needed so that each of the core pillars of the physics R&D system – discovery, business innovation, people and infrastructure – is providing the support needed to drive a step change in the performance of the UK's R&D system. In some areas, relatively minor adjustments can make a significant difference; in other areas, more radical reform is needed to build a thriving physics R&D system. For example, above inflation increases in the Research Councils' core budgets would go a long way to providing a stable environment in which discovery science can flourish, while models of funding progression through research training and careers require a more fundamental re-examination.

"The UK's ability to harness the benefits of the new industrial era depends on an effective physics R&D system."

INNOVATION IN ACTION

Data storage technology boosts research and development in Northern Ireland[8]

Physics research at the Centre for Nanostructured Media (CNM) at Queen's University Belfast (QUB) has resulted in advancements in data storage technology, such as improvements to hard disk drives. The research, which began in 2004, encouraged a collaboration between QUB and data storage company Seagate, a partnership with wide-ranging impacts in Northern Ireland.

In 2010, Seagate established an advanced materials hub, ANSIN, at QUB to facilitate low technology readiness level (TRL) research, encourage collaboration with third parties, and to train doctoral students. This facility, as well as further developments from QUB and Seagate, has led to £81 million of foreign direct investment being channelled into Northern Ireland, generating 60 R&D jobs, industrial collaboration that supports two QUB Centres for Doctoral Training, and industry-funded PhDs.

By making these changes, we can unlock the full potential of physics R&D and deliver transformative benefits to our society, namely:

1. **Global leadership in science and innovation**

UK physics research is world-class and has been indispensable to many of the world's most impactful and successful innovations, from fibre optic communications to magnetic resonance imaging. Creating an environment in which world-class physics discoveries proliferate can offer the UK:

- recognition as a location of choice for international collaboration and investment
- greater international influence, through scientific and technological leadership
- the capability and agility to respond to emerging opportunities and first-mover advantage in the development and commercialisation of new technologies.

2. **Increased economic growth**

Physics fuels private sector innovation. Physics-based businesses across the UK are increasing investment in R&D and generating significant returns to the economy, equivalent to 11% of GDP.[6] Given the right conditions, physics-based businesses can deliver a step change in R&D activity and generate:

- increased business growth, competitiveness and productivity in every region and nation
- increased inward investment.

3. **Improved wellbeing and living standards**

Physics knowledge and skills provide access to rewarding careers and above-average salaries,[7] and drive technological innovation, in organisations in every nation and region of the UK. Enabling physics to play an even greater role in our economy can enhance our everyday lives and increase prosperity through:

- creation of productive, well-paid jobs in all parts of the UK
- advances in healthcare, transport and consumer technologies.

4. **Accelerated transition to a green economy**

Physics' creative approach to solving complex problems is valued by employers as they look to decarbonise their businesses and has led to technological breakthroughs such as nuclear fusion power and lithium-ion batteries that will be essential to reducing emissions. A thriving physics R&D system can accelerate the UK's progress towards net zero through:

- advances in green technologies, including clean energy generation, storage and distribution, climate modelling and monitoring, and carbon capture, utilization and storage (CCUS)
- physics-trained workers driving development and implementation of more sustainable practices across the economy.

INNOVATION IN ACTION

Nanoparticle-based inks lead to lucrative applications in defence and sustainability[9]

Since 2016, the Materials Physics Group at the University of Sussex has been developing highly conductive nanoparticle-based inks, using graphene and other 2D materials. The viscosity of these inks can be customised, enabling a range of practical applications.

In 2017, Advanced Material Development (AMD) was formed to commercially exploit the work of the Group while funding further research. Direct funding from AMD has allowed the Materials Physics Group to demonstrate potential scalability of the inks, as well as develop innovative radio-frequency identification (RFID) tags that are recyclable and environmentally friendly compared to their single-use predecessors. Further work includes the development of an advanced eye protection system with the US Government, protecting personnel such as police officers and pilots from direct laser radiation exposure. This work allows AMD to be a part of the rapidly-growing directed energy weapons protection market, which is expected to be valued at $75 billion by 2028.

AMD, as a result of this valuable physics-based research, has generated a significant patent portfolio, while attracting seven figure funding programs and partnerships with industry leaders and international organisations. The company directly employs 9 people, and funds 7 post-docs and 3 PhDs at the University of Sussex.

An R&D blueprint for physics

The IOP is embarking on a multi-year project to drive changes to the R&D system that will enable the UK and Ireland to realise the full societal and economic benefits of the new industrial era.

This report marks the conclusion of the first phase of the project, which focused on extensive consultation with actors across the research and innovation landscape, including those in academia, industry, government and the wider public sector, to identify the barriers faced and opportunities ahead.

The subsequent sections of this report explore each of the core pillars of the R&D system in turn, highlighting the most pressing barriers, recommending changes that can be made in the short-term, and signposting future work the IOP will undertake to identify more radical reforms required to unlock the full potential of physics.

The IOP

The R&D blueprint draws on the IOP's 100+ years of expertise as the UK and Ireland's learned society and professional body for physics, and the unique role our 22,000 members play today in linking physics research, innovation and education. The R&D blueprint also features insights from IOP Publishing, a wholly owned subsidiary of the IOP and one of the world's leading publishers in physics and related disciplines.

Discovery

Almost every modern-day technology has its origins in fundamental physics discoveries. From building particle detectors and satellite platforms to better understand our planet and universe, to using advanced materials to build lighter, stronger, more efficient structures, or developing new cancer diagnostics and treatments to improve patient outcomes, physics has driven many of the world's most impactful and successful innovations.

The UK has been a major beneficiary of these and many other breakthrough discoveries because of its world-class physics research base. 95% of physics outputs assessed in the 2021 Research Excellence Framework were rated as 'internationally excellent' or 'world leading', compared to 83% of outputs across all disciplines.[10] And world-class physics research takes place, and drives excellent impact, in every nation and region of the UK.[11]

Breakthroughs in physics have established the UK as a global leader in the development of transformative technologies such as photonics and compound semiconductors, which now underpin multi-billion pound industries[12] and thriving economic clusters in Glasgow and Cardiff. Breakthroughs in physics are unleashing a new wave of innovation in areas such as advanced materials and quantum technologies, which promise radical improvements in capability across all major sectors of the economy.

While we cannot predict the breakthrough discoveries of the future, we can create an environment in which they will flourish. The ideas, researchers and institutions that will fuel tomorrow's breakthroughs need nurturing today.

INNOVATION IN ACTION

UK photonics industry (all figures from 2020):

£14.5bn
UK photonics industry output

£85,000
GVA per employee

£6.5bn
Gross Value Added (GVA)

76,700
People employed by in UK photonics

The UK photonics industry employed twice the number of people employed in UK pharmaceutical production

The photonics industry is larger than the fintech or space industries in the UK

Source: https://csconnected.com/media/ryunhxaa/csconnected-annual-report-cardiff-university-business-school.pdf

The historic leadership that the UK has been able to demonstrate will only be sustained if investment in physics R&D is at levels that match, or exceed, our international competitors, and the physics landscape is transformed to further innovation, discovery, research, growth and debate. More effective, long-term support which enables researchers to pursue excellent, creative research ideas can ensure the UK is well-placed to seize emerging opportunities and accelerate future breakthroughs.

Barriers to unlocking potential

In consultation with the physics community, the IOP has identified the following, most significant barriers which are preventing the UK from creating a thriving physics R&D system in which discoveries can flourish.

1. Lack of stable funding and strategy

Disruptive research requires long-term stability to flourish. Short-term funding and shifting priorities prevent researchers from pursuing the sorts of bold and creative ideas that have historically led to transformative breakthroughs over time,[13] and hinder an efficient and productive R&D system.

The UK's approach to R&D funding has undergone a number of significant changes in recent years, with current and future sources of funding affected by the supersession of the UK Government's Industrial Strategy by the Plan for Growth, cuts to Official Development Assistance (ODA) funding, the ongoing uncertainty around the UK's participation in Horizon Europe and the slowly emerging clarity regarding the role of the Advanced Research and Invention Agency (ARIA), and repeated short-term spending reviews.

As noted by the independent review of UKRI, since its inception, UKRI has engaged with at least seven different government strategies with a focus on research and innovation and, until late 2021, only had one-year funding settlements.[14] Many of those consulted for this work highlighted the disruptive impact on their research of the continuous cycle of applying for funding, driven by a preponderance of relatively short-term grants and low success rates, as well as the complexity of funding opportunities on offer as a result of changing priorities. In England, Northern Ireland and Wales, the relative reduction in quality-related (QR) research funding, which enables universities to pursue novel, long-term research avenues, is likely to exacerbate this instability.

A changing funding landscape

While overall levels of R&D investment in the UK lag significantly behind the OECD average (at 1.7% of GDP vs 2.7%), funding for physics research from UKRI has increased substantially over the past decade, partly through establishment of the Industrial Strategy Challenge Fund and increases in funding for applied science. Support for mission and challenge-led innovation is increasingly important to UK physics, bringing together cross-disciplinary researchers and innovators to help solve some of our biggest challenges, such as achieving net zero.

As a result, the apparent balance of funding for discovery, applied and experimental development research has shifted – between 2009 and 2019, the proportion of total R&D funding from civil government departments, the Research Councils and Innovate UK allocated to discovery research decreased from 42% to 31%.[22] By international standards, the UK invests relatively little in discovery research, at 0.31% of GDP in 2019 compared to 0.44% across all OECD nations for which data is available.[23]

UK universities' physics departments have played an indispensable role in much of the ground-breaking physics research that has set the direction and pace of social and economic progress, and their outputs – fundamental knowledge, novel insights and highly skilled, adaptable people – will also be needed for the future technological advances that will drive the UK's economic engine and shape the society we live in. But research in the UK's universities is currently funded at levels below its full economic cost, with the total deficit for research activity in universities in England and Northern Ireland at nearly £4 billion in 2020/21.[24]

Advances in discovery physics have paved the way for the seven technology families identified in the UK Government's Innovation Strategy. To ensure the UK is able to continue driving transformative developments in the future, we must continue to invest in the pipeline of ideas provided by our discovery physics research base.

The UK needs a coherent, long-term (i.e. over at least the next decade) R&D strategy, with multi-year funding commitments that allow for predictable and stable support and build confidence in the private sector. The latter is particularly important given the substantial, but often overlooked, role of the private sector in driving discovery research. While discovery research only accounts for 10% of total private sector R&D activity, as businesses are by far the biggest investors in R&D in the UK, this represents more than a third of total discovery research expenditure in the UK.[15]

2. Lack of investigator-led support

Many of those consulted observed a relative lack of flexible funding to support investigator-led research. Investigator-led grants and fellowships give researchers greater freedom to explore novel and creative ideas, and provide an essential complement to project-based funding, which tends to favour lower-risk and more incremental research.[16] These types of funding also provide much needed support to those in the earlier stages of their careers; this will be explored further in the People section of this report.

Across UKRI's scientific research councils, success rates for fellowship applications are around half that of standard research and innovation grants. Only 8% of fellowship applications to STFC received an award in 2020/21.[17] This suggests that, across UKRI's Councils, excellent, bold ideas are going unfunded. In the event that the UK does not associate to Horizon Europe, the loss of access to European Research Council grants – recognised for their focus on high-risk, investigator-led research – will place further strain on domestic schemes unless a direct replacement is implemented.

3. Concentration of funding among institutions

Levels of R&D funding continue to vary significantly across the UK, with London, the South East and East of England accounting for 54% of total R&D expenditure in 2019[18] and the Research Councils spending over four times more per researcher in the South East than in Northern Ireland in 2020/21.[19] While 'internationally excellent' physics research takes place and creates impact in institutions in every part of the UK, just seven universities received more than half the total amount of publicly funded physics research grants awarded to UK universities in 2019/20.[20]

Funding must be available to foster research and innovation strengths across a wider range of institutions, to ensure the benefits of increased public investment – including spillover benefits to local businesses – are felt in all parts of the UK. The UK Government has recognised the importance of science and technology to regional economic growth in its Levelling Up white paper; however, the stated aim to increase R&D funding outside the greater South East by a third by 2024/25 does not exceed the proportional increase that would be expected as part of the previously announced UK-wide £20bn budget, and will simply maintain the current geographical distribution of funding.

INNOVATION IN ACTION

Advanced medical imaging and improved patient outcomes from astronomical data techniques[25]

Identifying and analysing changes between different medical scans is a critical, and sometimes challenging, part of many medical diagnoses. Research carried out in the School of Physics and Astronomy at the University of Edinburgh has allowed this process to be carried out with much greater speed and confidence than existing methods, improving diagnoses and thus health outcomes.

The research, which was originally intended for use in astronomy to analyse galaxy surveys, involved the invention of a data compression algorithm, MOPED, which allows for rapid and accurate analysis of images. The spinout Blackford Analysis Ltd was established based on the research, creating the Blackford Platform of medical image analysis tools, with which over 2 million medical scans per year are now analysed.

The Blackford Platform can speed up the analysis of radiology images by 10-50%, comparable to treating an extra 200,000 patients per year, and is in use at over 750 sites around the world. As well as meaning patients receive faster and better-informed treatments, the success and growth of Blackford Analysis Ltd has benefitted the Edinburgh economy, with 42 jobs gained by 2019.

Actions needed

As initial steps towards addressing the challenges above, and unlocking the full potential of physics R&D, we recommend the UK Government takes immediate action to:

- Commit to providing above inflation increases in the Research Councils' core budgets to 2027, to provide a stable environment in which discovery science can flourish
- Dedicate a proportion of cross-UKRI funding to pilot and evaluate more experimental approaches to funding novel, high-risk research, while rationalising core funding streams
- Implement a target to increase discovery research spend in line with the OECD average, as part of the 2.4% investment target.

We also call on the UK and devolved Governments to:

- Invest in a world-leading and sustainable university research base by increasing the proportion of full economic costs recovered on all publicly-funded research grants, as well as increasing QR funding to reverse the declines seen in England, Northern Ireland and Wales over the past decade[21] and ensure real terms, above inflation increases in each of the nations.

As part of the next phase of the R&D blueprint, the IOP will carry out more detailed work to explore:

- Innovative models of funding for discovery research
- Measures to strengthen the financial sustainability of physics in higher education.

INNOVATION IN ACTION

Wales compound semiconductor cluster:

£194m
GVA (direct) as of Q4 2021

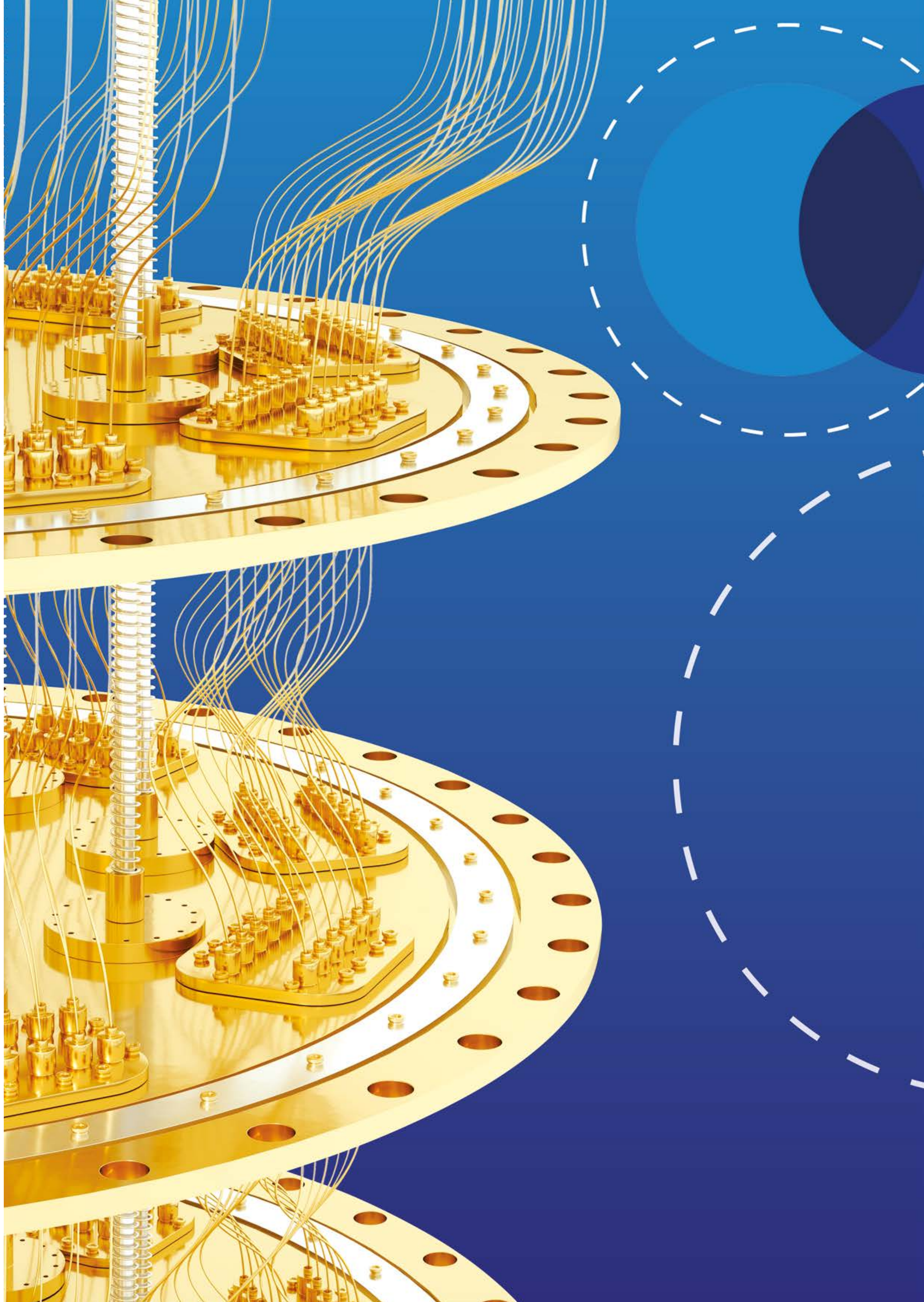
Around
£121,000
GVA per employee in 2021

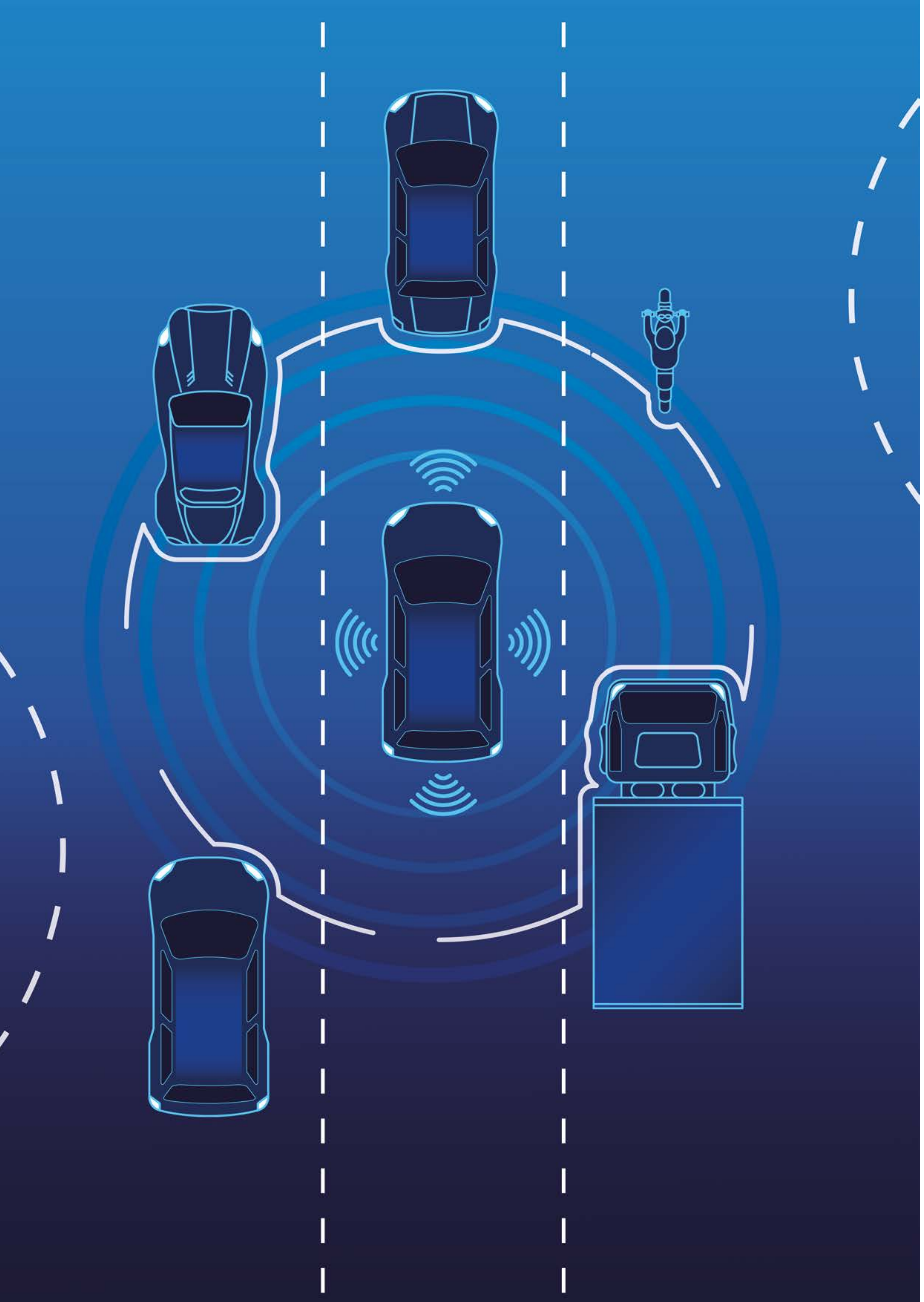
2,390
Direct + indirect cluster employment as of Q4 2021

96%
of the value of industry sales are exports, with the vast majority destined for markets outside of the EU

60%
Salaries in the cluster are 60% above the average in Wales

Source: https://photonicsuk.org/revolutionising-our-world/uk-photonics-output





Business innovation

Physics fuels private sector innovation. Across every part of the UK, physics-based businesses are actively investing in R&D, driven by the desire to develop new products and services, grow their company, and meet evolving customer needs.

Their innovative nature makes physics-based businesses a significant and highly productive contributor to the UK economy, generating £230bn in gross value added – equivalent to 11% of UK GDP – in 2019.[26]

Amid a rapidly changing technology landscape, a step change in private sector innovation is needed to boost growth, productivity and competitiveness and secure the UK's future prosperity. Businesses' ability to harness physics can be a catalyst that drives this transformation.

Physics-based businesses are already major contributors to private sector R&D, with those businesses that rely most strongly on physics research responsible for a third (or £8.9bn) of total private R&D expenditure in the UK.[27] And despite the disruption caused by the Covid-19 pandemic, physics-based businesses are renewing efforts to boost growth through innovation, with two thirds of physics innovators expecting to increase their R&D spending over the next five years[28] and recruitment at record levels.[29]

Physics-based businesses can therefore propel progress towards the 2.4% R&D investment target and the transition to a more innovative economy. But they face challenges. Difficulties accessing finance, facilities and skills, and cultural barriers which prevent ideas progressing from lab to late-stage development, are just some of the challenges that put planned increases in R&D investment at risk.

Given the right conditions and support to overcome these challenges, physics-based businesses can deliver a step change in R&D activity, and boost growth, employment and competitiveness across the UK.

Barriers to unlocking potential

In consultation with the physics community, the IOP has identified the following, most significant barriers which are preventing the UK from significantly scaling up innovation in the private sector.

1. Limited incentives for translational research

The UK has a world-class discovery research base. Capitalising on this strength, and taking bold ideas from initial concept through prototyping and demonstration to commercial manufacture and launch, requires a healthy translational research base and a well-integrated R&D landscape.

There are examples of fruitful engagement between academics and industry on translational research and business-led initiatives such as EPSRC's Prosperity Partnerships which aim to align early-stage research with industry need to accelerate impact. The UK National Quantum Technologies Programme was cited by many of those consulted as an exemplar of how to foster technological innovation and effective collaboration between academia and industry, with its success attributed to the significant up-front investment made by the UK Government, integrated support from UKRI's councils (and other government departments and public agencies) and focus on end-user needs. The quantum technology hubs and their active industrial advisory boards have been particularly effective at enabling UK-based companies to play a greater role in directing and shaping the direction of university research.

But these examples are by no means the norm and translational research is not yet celebrated as an integral part of the UK's R&D system. The current R&D system creates few incentives for early-stage researchers to engage with late-stage developers.

Many of those consulted for this work noted how the current mechanisms designed to recognise and reward excellence within academia, such as the Research Excellence Framework, are heavily weighted towards publication records, despite the benefits industrial engagement can bring to early-stage research. (The particular challenges created by the current narrow view of research careers in the UK will be explored in the People section of this report.)

A wider cultural shift is needed within academia to encourage greater focus on translating excellent ideas into real-world impact, given the potentially transformative role HEIs could play as convenors of translational research collaborations within their local economies. Technology transfer (and wider knowledge exchange) functions within higher education institutions (HEIs) already play an important role in leveraging commercial impact from academic research. However, during consultation for this work, concerns were expressed about the lack of consistency in approaches to technology transfer, including the relatively large equity stakes sought by some HEIs compared to their international counterparts and undue focus on IP licensing rather than co-investment. While recognising that a variety of models may be appropriate given the diversity of needs, greater adoption of best practices across the sector could be beneficial, building on existing initiatives such as the Lambert toolkit[30] and TenU collaboration of leading technology transfer offices.[31]

This cultural shift must be accompanied by funding. Public funding is essential at the earliest stages of research, where risks are high, but has an equally important role in driving later stage innovation in conjunction with private investment. During consultation for this work, a frequently reported gap in public support is that spanning the mid TRLs, bringing together early-stage researchers with late-stage developers.

The UK's public sector research establishments (PSREs) also play a critical role in bridging the gap between academia and industry to deliver impact, given their mission-driven nature, but require stable, long-term funding and strategy. This will be discussed further in the Infrastructure section of this report.

"Amid a rapidly changing technology landscape, a step change in private sector innovation is needed to boost growth, productivity and competitiveness and secure the UK's future prosperity."

2. Difficulty accessing finance

According to research commissioned by the IOP and conducted by CBI Economics, the direct costs of innovation are the most significant barrier to private sector physics R&D in the UK. Cost pressures are most acute in the later stages of the innovation process, as businesses move on to large-scale prototyping and production. The latter is also the phase in which it is most difficult to secure funding, presenting a risk that physics innovators look to move outside the UK to scale-up their businesses.

Public funding for private sector R&D provides essential support to physics innovation, enabling the development of products and services that would not otherwise be viable and leveraging private investment. Seventy percent of physics innovators that had received public R&D funding within the last 5 years said that it fills a financing gap without which the activity would not take place, and separate evidence suggests that every £1 of public R&D investment stimulates between £1.96 and £2.34 of private R&D investment in the long run, with the majority of private investment crowded in five years after the public investment.[32] When asked which policy enhancements would enable them to undertake more R&D activity in the next five years, the highest proportion of physics innovators selected greater access to direct funding for early-stage R&D (67%), with strong support also expressed for long-term funding schemes (61%) and greater access to direct funding for late-stage development (42%). Many of those consulted for this work pointed to the complexity of the public funding landscape as a barrier to accessing available support. This is a particular challenge for small and new businesses, many of which seek assistance from external advisory firms, and may in part explain why large businesses are more likely to be recipients of public funding than smaller businesses (two thirds of large physics innovators have received government funding compared to half of small innovators).

Physics innovation is economically beneficial, but can be expensive, and the development of physics-related ideas and technologies into commercially viable products and services typically involves a higher level of risk and longer timescales to generate a return on investment than in other technology areas. As a consequence, physics innovators can find it challenging to build trust among private investors, and secure finance such as venture and patient capital, as they seek to grow their businesses. However, high-growth companies in physics intensive sectors appear to be highly successful at attracting equity and overseas investment, securing 19% of equity deals and 16% of foreign direct investment between 2012 and 2021 while only representing 10% of all high-growth companies.[33] This suggests there may be room to promote best practice among physics-related businesses in preparing successful cases for investment and among investors to encourage their familiarity with the investment potential of physics-related and other deep technology fields.

3. Poorly targeted tax incentives

According to the CBI Economics research, a more attractive tax rate (including an expanded tax credits scheme) for R&D activity would enable the majority of physics innovators to undertake more R&D activity in the next five years. Many of those consulted for this work expressed support for widening the scope of qualifying expenditure to include, for example, capital expenditure (such as equipment and patenting), as well as staff training and development costs.

In addition, many smaller businesses – which account for 99% of all physics-based businesses – find the tax environment complex to navigate, leading them to appoint specialist agencies to complete claims on their behalf. This still requires businesses' time, while also effectively reducing the proportion of relief that can be reinvested in R&D. Greater clarity regarding which types of expenditure are eligible for tax relief would be particularly welcome.

R&D tax credits in the UK

By international standards, the UK is unusual in the level of indirect support provided for business R&D activity. Tax incentives accounted for 80% of total government support for business R&D in the UK in 2019 and equated to 0.33% of GDP. This is the highest level of support among OECD nations [34], yet business investment in R&D in the UK remains well below average.

Evaluations suggest that for each £1 of tax relief claimed, the R&D expenditure credit (RDEC) scheme for large businesses generates £2.40-£2.70 of additional R&D expenditure, while the SME scheme generates £0.60-£1.28[35]. However, a recent analysis estimates that, as a percentage of GDP, self-funded business R&D expenditure is between 10 and 15% lower than before R&D tax credits were introduced.[36]

Given the scale of public investment, and physics-based businesses' desire for more direct support for R&D, it is essential that the UK's R&D tax incentives are effectively targeted to deliver the greatest impact.

4. Difficulty accessing knowledge, skills and facilities

Physics innovation is often highly specialised and technology intensive, requiring a skilled in-house workforce and access to facilities and expertise from external organisations. But two thirds of physics innovators report having suspended R&D activity in the past five years due to skills shortages, and a lack of suitable equipment and facilities are a barrier to a significant minority. Skills and facilities will be explored in further detail in subsequent sections of this report.

While the majority of physics innovators reported having positive engagement with universities, there is scope to increase collaboration further, with PSREs and the Catapults, which can help support late-stage development activities such as testing and demonstration, as well as with other businesses within their supply chains. The complex landscape of research and innovation organisations in the UK was highlighted as a challenge, but new models of collaboration may be needed to foster innovation across supply chains and to deepen business–university links.

Actions needed

As initial steps towards addressing the challenges above, and unlocking the full potential of physics R&D, we recommend the UK Government takes immediate action to:

- Deliver planned uplifts in public R&D funding required to meet the 2.4% target at the earliest opportunity, to build business confidence and maximise the amount of private investment leveraged by 2027 and beyond
- Provide additional long-term funding for business innovation which spans the breadth of technology readiness levels, from early-stage R&D to development-stage activities
- Provide funding to create (and maintain) networks that enable knowledge exchange and facilitate collaboration between industry and academia in emerging technology areas.

Action is also needed from actors across the wider R&D landscape to:

- Support businesses to navigate the complex innovation landscape, in particular financing routes, intellectual property protection, and access to external expertise and facilities, building on existing support provided by Innovate UK EDGE and the IOP's Business Innovation and Growth group
- Upskill small and/or new businesses in developing successful business cases when seeking private investment, as well as fostering greater confidence among private investors in physics-based and other highly innovative businesses by showcasing successes and demonstrating the typical timescales to generate return on investment
- Promote best practice across technology transfer offices to boost skills at a broader range of HEIs.

As part of the next phase of the R&D blueprint, the IOP will carry out more detailed work to explore:

- Policy levers to enable radical increases in private sector R&D expenditure, in consultation with the current biggest investors in physics R&D.

"Actions to address the challenges faced by physics-based businesses can propel progress towards the 2.4% R&D investment target and the transition to a more innovative economy."

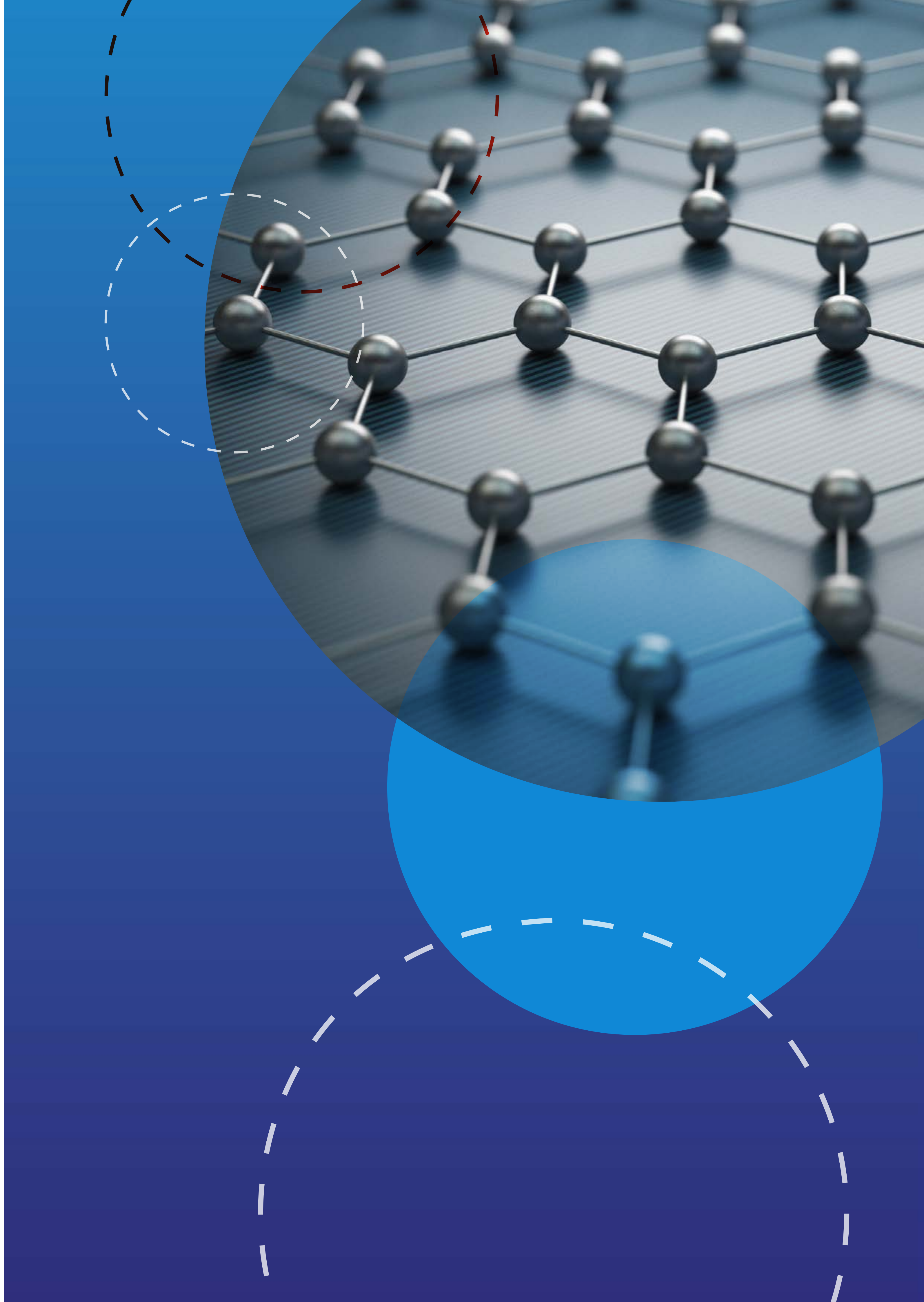
INNOVATION IN ACTION

Successful commercialisation of quantum cryptography for secure communications[37]

Awarded a Business Innovation Award by the IOP in 2021, Toshiba Europe has successfully commercialised quantum cryptography, leveraging decades of pioneering research in quantum information to develop new technologies and products, already being deployed around the world.

By harnessing the unique behaviour of quantum light, Toshiba has demonstrated long-distance, high-quality communications where security is guaranteed by the laws of nature. This approach is a paradigm shift from current communication security, which relies on assumptions about the limited computational resources of an attacker.

Toshiba's technology, known as quantum key distribution, integrates years of R&D into a compact product which can be seamlessly integrated into existing communication infrastructures to provide quantum-secured communication. This has already been deployed in networks around the world, protecting medical data moving between hospitals, sensitive IP between manufacturing sites, and even to secure government communications. Toshiba's innovations also benefit UK plc as the devices are manufactured wholly within its Cambridge facility, stimulating high-value job creation and the growth of a UK quantum ecosystem.



People

Innovation is powered by people, by their knowledge, skills and experiences. For the UK to become a more innovative economy – and realise the full benefits in terms of improved growth, prosperity and living standards – it requires a strong, diverse and adaptable workforce.

However, major challenges are preventing the UK from developing the workforce needed for physics R&D to thrive. Employers are struggling to find people with the requisite skills among the current workforce, forcing them to scale back planned R&D. Too few young people are choosing physics-related education and training beyond the age of 16, to fuel future innovation. And both of these problems are compounded by a lack of diversity among those studying and working with physics, which limits opportunity and innovation outcomes.

The impact of these problems is not confined to the scientific sector. Physics knowledge and skills are powerful drivers of productivity and innovation and open doors to a range of rewarding careers across the entire economy. Owing to their diverse application, physics knowledge and skills already support one in 20 jobs and underpin critical industries in every part of the UK. But significant unmet demand exists for people with physics skills at all levels[38] and is negatively impacting UK employers' ability to grow and innovate. Two thirds of physics innovators report having suspended or delayed R&D activity in the past five years due to skills shortages, jeopardizing ambitions to increase private sector innovation.

"Physics knowledge and skills are powerful drivers of productivity and innovation and open doors to a range of rewarding careers across the entire economy."

INNOVATION IN ACTION

Rapid thermal imaging techniques fight global biodiversity loss[56]

To help tackle the crucial problem of rapid biodiversity loss, researchers at Liverpool John Moores University have developed an innovative method of monitoring animal populations with drones to efficiently inform conservation strategies. The technology, which can make animal surveys up to 100 times faster, uses detection systems originally used in astrophysics to interpret thermal-infrared astronomy data.

The research successfully demonstrated that astrophysics techniques can be adapted for conservation biology, allowing for the high-precision interpretation of thermal camera data from drones. Combined with machine learning techniques, the technology can monitor endangered species, such as orangutans in Malaysia, and has caused conservation agencies across the globe, including WWF, to review their animal monitoring strategies.

The speed and efficiency at which surveys can be conducted, especially when compared to previous labour-intensive methods, saves significant money and time, directly contributing to slowing down biodiversity loss. The project has significant public reach, and is expected to have long-term and significant impacts, for example via the implementation of a national framework and regulations for drone operations in Madagascar.

Demand for people with physics skills is growing. As the UK Government seeks to increase R&D activity, and as employers respond to technological challenges such as decarbonization and digitalisation, the need to build a vibrant physics R&D workforce grows more pressing. Without urgent action to equip more people with physics skills and to make better use of existing talent, universities, businesses and R&D organisations across the country will not be able to capitalise on the next wave of innovation and the UK risks being left behind.

The UK Government's R&D People and Culture Strategy rightly recognises that people are at the heart of R&D and the need to unleash a new wave of talent.[39] More effective development and deployment of physics skills at all levels could significantly increase the capability and diversity of the R&D workforce, enabling more people to access productive, well-paid jobs and powering the UK's transition to a greener, more innovative economy.

Barriers to unlocking potential

In consultation with the physics community, the IOP has identified the following, most significant barriers which are preventing the UK from developing the workforce needed for physics R&D to thrive.

1. Teaching workforce challenges

Building the workforce of the future begins at school. For students to have the best experience of physics, to leave school with well-developed physics knowledge and skills and to aspire to further work or study related to physics, they need excellent physics teachers.

However, there are serious shortages of teachers with a physics background in secondary and further education. Every year, too few physics teachers start in the profession and too many leave it. Enrolments in initial teacher education courses in physics fell significantly below the respective targets in England (22% in 2021/22[40]), Scotland (50% in 2021/22[41]) and Wales (60% in 2020/21[42]). When coupled with the relatively high numbers leaving the profession, this persistent under-recruitment increases the reliance on non-specialist teachers to teach physics – only 42% of those teaching secondary-level physics in Wales in 2021 were trained in the subject, a proportion that has continued to fall in recent years.[43] In response, the Department for Education, for example, is attempting to address poor recruitment and retention in England with measures such as increased teacher pay, with particular uplifts to starting salaries and early career pay. However, even with these measures in place recent modelling by the National Foundation for Educational Research suggests that only 23% of the targeted enrollments in physics in England will be met in 2025/26.[44]

Teacher shortages and consequent regional and socio-economic disparities in the quality of physics teaching must be addressed, to increase the supply of students leaving school with well-developed physics knowledge and skills, and pursuing further work and study in a variety of fields and disciplines (including those that may not obviously appear to be physics-related).

2. Lack of diversity and inclusive culture

Physics thrives on creativity and the diversity of thought that comes from diversity of background. However, across education, training and work, the physics community is not as diverse as it could and should be. Women, people from disadvantaged backgrounds, disabled people, those who identify as LGBT+, and minority ethnic groups are all underrepresented. The causes of this underrepresentation are clear. Too many young people from these groups do not pursue physics as they are told it is not for them, they feel they don't fit in, or they don't see it leading to a viable career (with a particular lack of guidance available on physics-related technical routes post-16,[45] despite growing employer demand for the skills that higher technical education provides[46]). Too many of those in the workforce face poor workplace cultures and discrimination.

The resulting lack of diversity in physics has both social and economic consequences. People from underrepresented groups are denied access to the rewarding careers that physics opens doors to, and organisations across the UK are missing out on valuable talent and skills.[47] As an example of the scale of the current problem, only 10% of STEM apprenticeships were started by women in England in 2018/19, despite the potentially substantial wage returns they can offer[48], particularly for those from disadvantaged backgrounds.[49] Such underrepresentation contributes to an engineering workforce (which evidence shows relies heavily on physics skills and knowledge) in which only 14% of workers are female, 1.7% are Black, African, Caribbean or Black British (compared with 3.5% of workers in non-engineering occupations), and 11% have a disability (compared with 15%).

3. Inflexible research careers

Innovation flourishes in environments that facilitate the open exchange of ideas and know-how across businesses, universities and other R&D organisations. People are the ideal conduit, and dynamic and diverse research career paths can aid the flow of knowledge and skills so that all parts of the economy benefit from investment in research training.

But the current view of research careers in the UK is narrow, with career structures, development support and progression criteria creating few incentives for industrial engagement, preventing people from moving easily between academia and industry (back and forth), and between academic and technical roles, and failing to adequately prepare them for such flexible careers. Many of those consulted for this work stressed how improving current approaches to career development and progression, through changes to funding and research culture, would enable more people to realise their full potential in productive careers across the whole economy and ensure the benefits of R&D investment are felt beyond academia.

In particular, the vast majority of PhD graduates go on to work outside of higher education,[50] yet training programmes – and consequently students' expectations – are in many instances geared towards academic careers. Providing more realistic careers advice, as well as more workplace-oriented skills development,[51] would ensure that these highly skilled workers are able to apply their talents, and meet the needs of employers, in all sectors of our economy.

Those graduates who do go on to work in academia face tough competition for roles. Instabilities in higher education funding, coupled with the mismatch in demand versus supply for postdoctoral positions, have created a dependence on short-term, temporary contracts. The negative impact of poor working conditions for early career researchers on their ability to explore their ideas, and build the networks that will see these ideas come to fruition, was highlighted frequently during consultation for this work. Initiatives such as the Researcher Development Concordat are positive steps towards healthier and more supportive working environments, but planned uplifts in R&D investment provide an opportunity to address the financial instabilities in higher education which give rise to this precarious stage in research careers. Stable core funding which allows universities to commit to their researchers and offer more secure, open-ended contracts, rather than depend on contracts tied to short-term project grants, would enable the UK to more effectively capitalise on ingenuity and nurture the next generation of research leaders.

4. Difficulties attracting overseas workers

The UK's scientific strength is, in part, a result of its ability to attract talent from across the globe.[52] The uplift in R&D activity required to meet the 2.4% investment target by 2027 will be impossible to deliver without skilled workers from overseas. Many businesses, in particular, look to recruit workers from overseas to fill skills gaps in the short term.

However, this has become more difficult in recent years, first as a consequence of the UK's departure from the EU and then due to the challenges posed by the Covid-19 pandemic, with a quarter of physics innovators citing Brexit as a contributing factor to their recruitment difficulties.[53] High visa costs for workers and their families pose a particular concern, with upfront costs up to six times higher than the average of leading science nations.[54]

INNOVATION IN ACTION

The world's first desktop-sized super resolution microscope[57]

Awarded a Business Start-up Award from the Institute of Physics in 2018, Oxford Nanoimaging (ONI) has commercialised the Nanoimager, the world's first desktop-sized super resolution microscope. The research behind the Nanoimager began in a University of Oxford physics lab in 2005, with the aim of creating an alternative to existing microscopes that were unstable, inconvenient and extremely large, limiting their applications and accessibility.

The first successful Nanoimager prototype was created in 2013, leading to the formation of the spinout ONI in 2016. ONI grew quickly, and now has over 100 employees and a base in the USA, with over £5 million worth of microscopes sold worldwide. The Nanoimager is much smaller, cheaper and easy to operate than previous microscopes of the same type, and has now attracted over £22 million of investment.

As well as being built from many UK parts and stimulating the local economy, the Nanoimager is furthering UK science with its wide ranging applications, including drug discovery and development at AstraZeneca, and the building of 3D images of breast tumours at Cancer Research UK's IMAXT Laboratory to improve breast cancer diagnosis and treatment.

Actions needed

As initial steps towards addressing the challenges above, and unlocking the full potential of physics R&D, we recommend the UK Government takes immediate action to:

- Provide additional funding to support more long-term research fellowships (domestic and international), such as UKRI's Future Leaders Fellowships, as well as programmes which enable researchers to focus on career development activities outside of their core research, such as EPSRC's Open Plus fellowships
- Expand the use of industrial placements across UKRI-funded PhD training programmes, beyond BBSRC, to better prepare graduates for opportunities outside of academia
- Implement changes to tax reliefs which incentivise employers to invest in employees' upskilling and reskilling.

Action is also needed from actors across the wider R&D landscape to:

- Ensure progression and promotion frameworks employ a holistic approach to recognising skills, building on the Royal Society's Resume for Researchers and UKRI's Resume for Research and Innovation.

As part of the next phase of the R&D blueprint, the IOP will carry out more detailed work to explore:

- Future technology-driven skills needs
- Improving representation, diversity, equity and inclusion among those undertaking publicly funded R&D
- The role of PhD training and models of funding progression through research careers.

Beyond the R&D blueprint, the IOP is undertaking complementary work to:

- Increase the number of people engaged in physics-based apprenticeships and technical roles, including through ensuring availability of a variety of physics-related education and training pathways, and addressing issues which prevent employers from investing in employees' upskilling and reskilling
- Dismantle stereotypes that influence young people's choices and deter them from pursuing physics post-16, as a critical component of the Limit Less campaign and Planet Possibility careers consortium funded by the IOP
- Address challenges in teacher recruitment, retention and development, so that everyone has access to high-quality physics teaching
- Review the impact of government funding strategies on the career prospects of early career researchers and identify support mechanisms needed
- Create a new inclusion model that will supersede the current Juno[55] and will incorporate all forms of diversity and inclusion to transform physics departments, schools of physics, laboratories and facilities for future generations.

INNOVATION IN ACTION

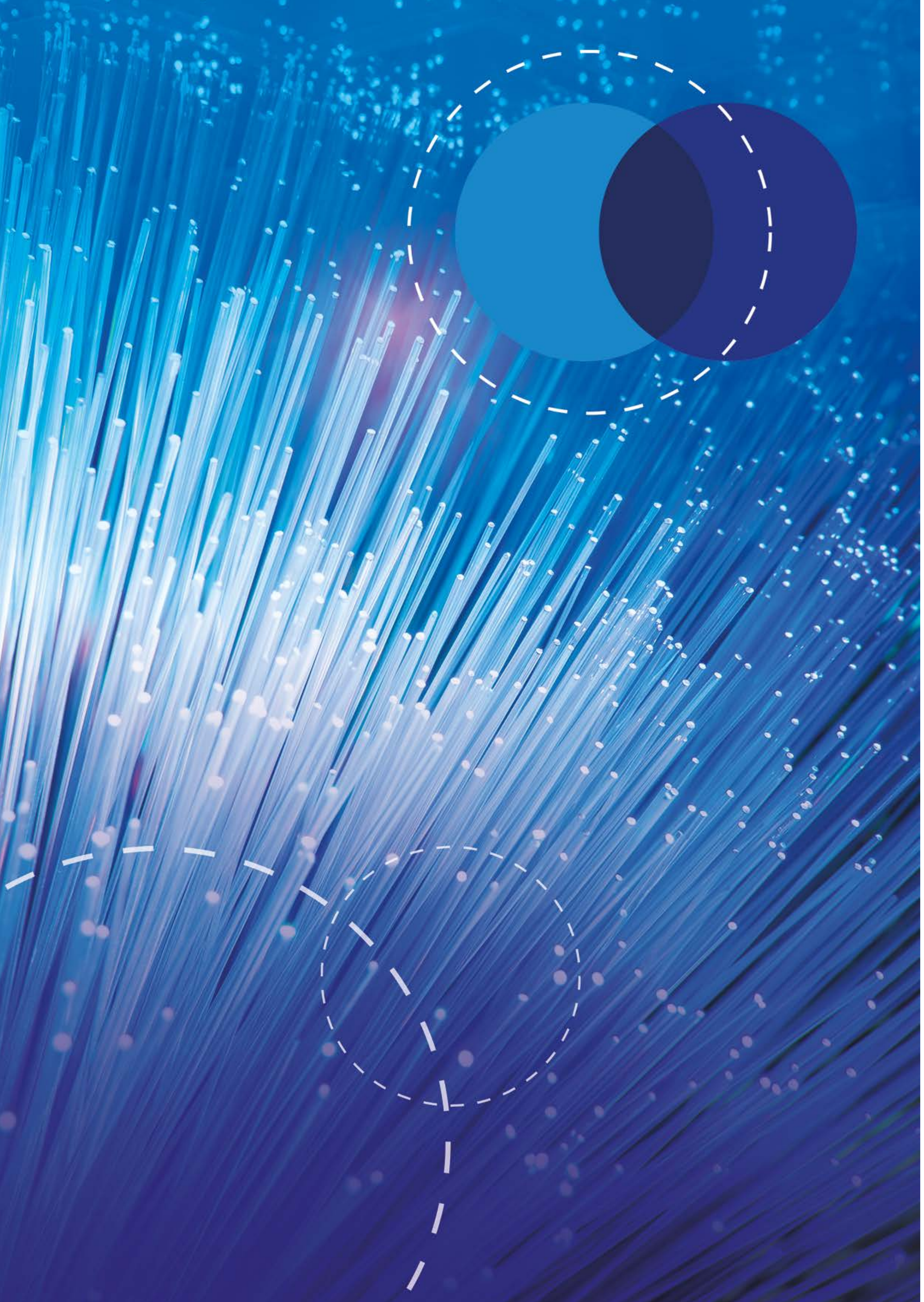
Delivering affordable clean energy to power the journey to net zero

Rolls-Royce SMR is using established nuclear technology and knowhow to develop a factory built power plant that generates low-cost, low-carbon electricity using a small modular reactor (SMR).[58] By 2050, the UK SMR programme is forecast to create 40,000 jobs, generate a £250 billion export market and return £52bn to the UK economy.

A single SMR will occupy around one tenth the size of a conventional nuclear power plant, while producing enough energy to power a million homes.[59] The SMR's innovative design means that 90% of its manufacture and assembly can take place in factory conditions, reducing on-site disruption and supporting international roll out, and around 80% could be delivered by a UK supply chain, creating significant export opportunities for UK businesses.

With the next phase of development backed by £210 million in government funding and matched by more than £250 million of private sector funding,[60] Rolls-Royce's SMR programme exemplifies the role public R&D investment can play in leveraging significant private investment to accelerate innovation and deliver societal and economic impact.

"Without urgent action to equip more people with physics skills and to make better use of existing talent, universities, businesses and R&D organisations across the country will not be able to capitalise on the next wave of innovation and the UK risks being left behind."



Infrastructure

R&D infrastructure underpins an innovation economy. Researchers and innovators require ready access to a range of equipment, facilities and networks to develop new ideas, technologies, products and services.

Cutting-edge domestic infrastructure, as well as access to major international facilities and collaborations, are essential to positioning the UK as an R&D leader and location or partner of choice for overseas researchers, innovators and businesses.

Infrastructure primarily used in the physical sciences and engineering accounts for just over a quarter of the UK's research and innovation infrastructure, and provides critical cross-disciplinary support across the wider research landscape and in particular to the biological sciences, health and food, environmental sciences and energy sectors[61]. The benefits of R&D infrastructure are also felt beyond the research sector and across the wider economy – according to UKRI's infrastructure landscape analysis, around a third of physical sciences and engineering infrastructures stated that all or most of their work was directly with UK businesses[62].

However, physical sciences infrastructure is typically expensive to establish and run, requiring significant overheads, maintenance and staffing costs, and decades of planning and investment. Given the large scale and cutting-edge nature of physical sciences infrastructures, many can only be realised through international collaborative efforts. In addition, continued development and review is required to ensure the capacity and capabilities of the UK's R&D infrastructure meet the needs of all users. A significant minority (17%) of physics innovators, for example, report a lack of access to suitable equipment and facilities as a major barrier to their ability to undertake R&D; in some areas, such as Yorkshire & Humberside and the North East, the proportion rises to around 30% of innovators, suggesting regional inequities in access to facilities.[63]

Investment in new R&D infrastructure, as well as in upgrading, maintaining and widening access to existing domestic and overseas infrastructure, will strengthen the UK's capability to undertake world-leading science and innovation, and attract international talent, collaborators and investment.

Barriers to unlocking potential

In consultation with the physics community, the IOP has identified the following, most significant barriers which are preventing the UK from developing the world-class infrastructure required to underpin an innovation economy.

1. Lack of long-term funding and strategy

Given the expense and lifespan of R&D infrastructure, it is essential that it is used effectively and strategically, with an appropriate balance between investment in new capabilities and continued operation and further development of existing facilities.

Funding was the most frequently mentioned barrier to the effective operation of research and innovation infrastructure in UKRI's infrastructure review, with respondents highlighting the short-term nature of funding, as well as lack of support for ongoing operation and maintenance[64]. While 60% of infrastructure had an expected operational lifetime over 25 years, only 41% felt able to plan more than three years ahead. National facilities need predictable and ongoing investment to support excellent science. This is particularly important in light of recent increases in the cost of energy, which can significantly impact the budgets of large-scale facilities.

Additional investment in new, world-leading physics infrastructure would attract international collaborators and investors to the UK and offer spill-over benefits to the local economy such as job creation. This investment must form part of a clear, long-term strategy for the UK's R&D infrastructure though and should be undertaken following a review of future opportunities for UK physics facilities.

2. Threats to international collaboration

International collaboration, and the frameworks which support it, are critical to the success of science and innovation. As well as access to world-leading knowledge and expertise, international collaboration provides valuable access to the types of large-scale research infrastructure that are typically beyond the means of any single nation. This dependence on international collaboration is particularly important to the physical sciences and engineering, which has the largest proportion of infrastructures located outside the UK of all of UKRI's scientific sectors[65].

The UK has a long history of productive participation in major European physics collaborations, such as the European Organisation for Nuclear Research (CERN), the Joint European Torus (JET) and the European Synchrotron Radiation Facility (ESRF). However, unless association with the Horizon Europe, Copernicus and Euratom programmes is secured, UK scientists and innovators are set to lose access to critical international R&D collaborations and infrastructure. Researchers consulted in this work have already highlighted instances of the UK having to relinquish its leadership role in European Commission funded projects.

3. Ineffective use of the innovation landscape

The UK is home to a diverse range of public and non-profit research organisations, including PSREs, research and technology organisations (RTOs) and innovation centres. These organisations have a variety of different missions, but a commonly cited benefit is the crucial role many play in providing academics and industrialists alike with access to equipment, facilities and expertise to progress technologies through the middle stages of development.

A relative lack of nationwide planning or strategic coordination, however, has led to a fragmented organisational landscape, which potential users find complex to navigate and access the most appropriate support from.[66] Perhaps as a result, many of those consulted for this work remarked that the UK's national laboratories are under-resourced and under-utilised compared to those of competitor nations.

INNOVATION IN ACTION

Development of the world's first compound semiconductor cluster[67]

The Condensed Matter and Photonics Group (CMP) at Cardiff University have carried out innovative research into compound semiconductors, highly conductive materials that underpin many modern industrial and consumer technologies. The CMP research allowed for improvements to the design, manufacture and applications of compound semiconductors. This resulted in a strategic partnership with the international compound semiconductor company IQE, based in South Wales, leading to the development of the world's first compound semiconductor cluster.

The strategic partnership encouraged IQE to further develop their presence in South Wales, and in 2015, IQE and Cardiff University created a joint venture company, the Compound Semiconductor Centre (CSC). IQE invested £12 million into CSC to commercialise Cardiff research, creating over 70 jobs across South Wales. Further developments that the region has attracted include the UK's Compound Semiconductor Applications Catapult, and IQE's Newport Mega Foundry, now a leading global semiconductor facility.

Overall, the South Wales Compound Semiconductor Cluster has led to more than £167 million in investments, and has supported over 1,600 manufacturing jobs in the area.

In particular, the necessarily diverse range of business models used across the landscape demands greater flexibility in public funding programmes, to ensure (where appropriate) they are accessible to all types of R&D organisation. For example, many UKRI grants are awarded on the basis of the higher education sector's dual support system, in which the full economic costs of research are met through a combination of Research Council funding and block grants; such research grants can pose a financial challenge to R&D organisations which lack an equivalent secondary income stream.

"Investment in new R&D infrastructure, as well as in upgrading, maintaining and widening access to existing infrastructure, will strengthen the UK's capability to undertake world-leading science and innovation."

Actions needed

As initial steps towards addressing the challenges above, and unlocking the full potential of physics R&D, we recommend the UK Government takes immediate action to:

- Develop a long-term strategy for R&D infrastructure investment
- Ensure a clear role for PSREs is embedded within strategic plans relating to research and innovation, to encourage greater use and support long-term planning
- Continue to ringfence the funding set out in the Autumn 2021 Budget for association to Horizon Europe or for alternative programmes if necessary, and publish the immediate arrangements and funding profile for the period either until association to Horizon Europe is agreed or until long-term UK alternatives are operational.

As part of the next phase of the R&D blueprint, the IOP will carry out more detailed work to explore:

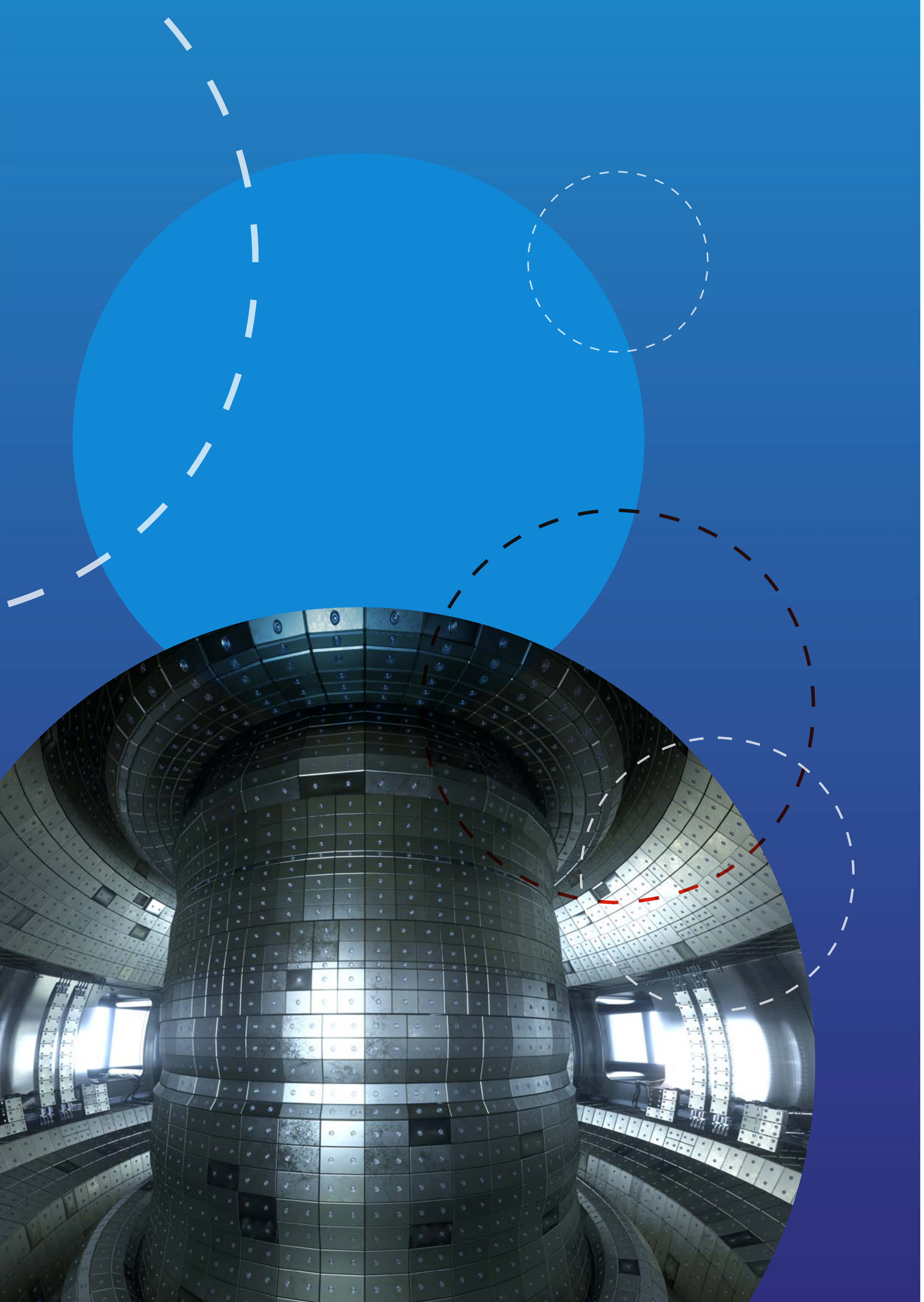
- Future opportunities for physics facilities, drawing on insights from UKRI's infrastructure review and an IOP-commissioned review of major physics-related facilities (subject to consultation with stakeholders).

INNOVATION IN ACTION

Optics expertise leads to innovative low-cost air pollution sensors with global applications[68]

Work into the characterisation of atmospheric aerosols, based on expertise in optical and laser light-scattering techniques, led by the University of Hertfordshire has resulted in significant commercial returns, and improvements to public health protection from poor quality air. In the UK alone, it is estimated that long-term exposure to man-made air pollution has an annual effect equivalent to 28,000 to 36,000 deaths. Over a decade of research into improving optical particle counters (OPCs), instruments that measure airborne particulates, resulted in high quality and low-cost sensors that were lighter than high-end alternatives, requiring less power and less maintenance.

The low-cost OPCs, commercialised by UK SME Alphasense Ltd, have had major impacts across the world, such as being part of a UN Environment Assembly low-cost air quality monitoring device to map emission hotspots in developing countries, helping to prevent deaths as a result of air pollution. The technology is also being used by World Athletics at 1,000 outdoor athletics tracks, meaning the relationship between air quality and athletic performance can be investigated, allowing the best times for athletics events to take place to be determined based on air quality. As of the end of 2020, nearly 20,000 Alphasense OPCs have been purchased for air quality monitoring in 70 countries, generating £5.2 million in revenue and directly creating new jobs.



Transforming the R&D system

Physics has the potential to transform our economy and society in the coming years. But for it to do so, the UK needs a thriving physics R&D system.

An R&D system in which discoveries proliferate, businesses take full advantage of the new industrial era, people can grow and make best use of their talents, and world-class infrastructure attracts researchers and innovators from across the globe.

This report marks the end of the initial consultation phase of the IOP's R&D blueprint. The subsequent phases of this multi-year project will see the IOP explore the priority areas for action in further detail and work with the community to develop proposals for the radical reforms needed to build a truly thriving physics R&D system.

Monitoring progress

Alongside this work, the IOP will develop a set of indicators to monitor progress towards a thriving physics R&D system in the UK. These will include but not be limited to:

- Total and business expenditure on R&D, and expenditure on discovery R&D, as a proportion of GDP (1.7%, 0.92% and 0.31% in 2019 vs 2.5%, 1.6% and 0.44%[69] across all OECD nations)
- Percentage of firms in high-physics-intensity industries that are innovation active (53% during 2016-2018 vs 38% of all firms)
- Employment and output per worker in physics-based industries (2.7 million FTE and £84,300 per worker in 2019)
- Number of people enrolled in physics-related education and training (broken down by type of qualification) beyond age 16.

INNOVATION IN ACTION

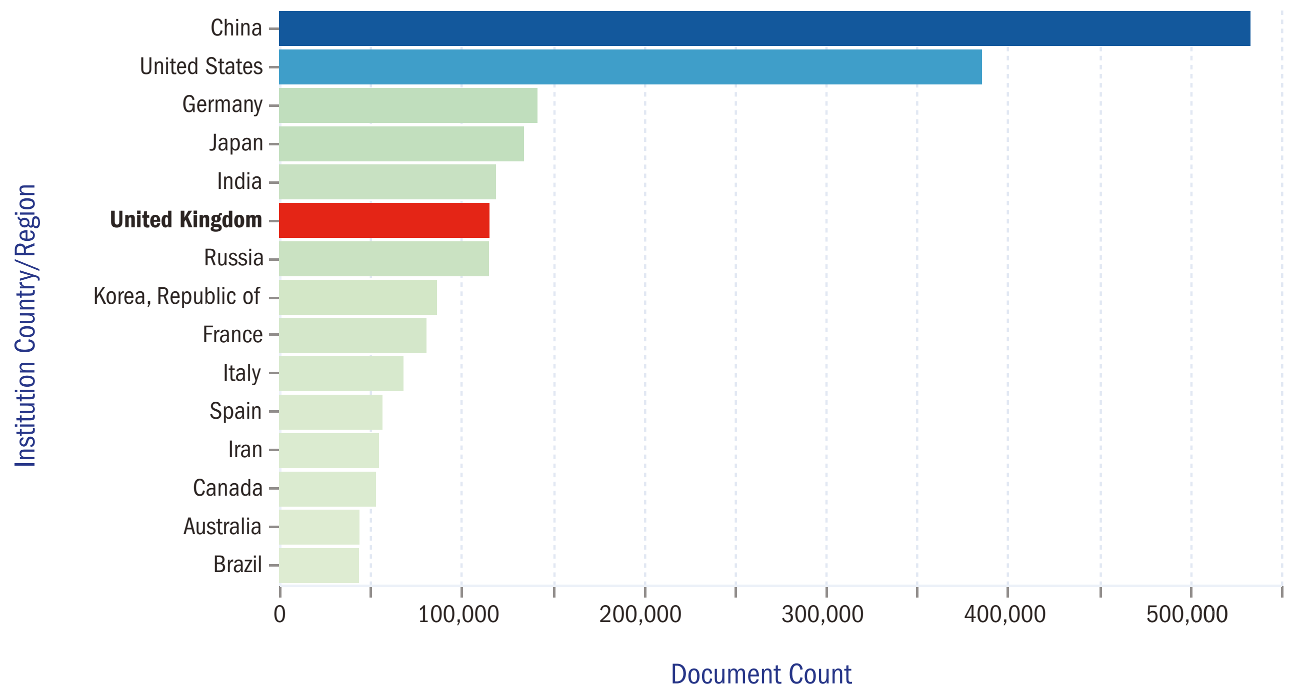
Innovative fusion energy technologies for future clean energy generation[70]

Fusion energy has great potential to deliver safe, sustainable, low carbon energy for generations to come. It is based on the same processes that power the sun and stars and has the potential to transform our energy usage across the world, helping nations reach net zero in decades to come. UK physics research is a crucial component in achieving fusion energy. Landmark results announced earlier this year by scientists at UK Atomic Energy Authority (UKAEA) and EUROfusion, set a new world-record of sustained fusion energy with JET (Joint European Torus), currently the largest operating tokamak in the world. In addition, UKAEA's MAST-U research programme has developed a world-first 'Super-X divertor' - an exhaust system designed to reduce heat and power loads from particles leaving the plasma, a key issue to be resolved to make fusion energy commercially viable.

With £500 million of funding committed to fusion facilities, infrastructure and R&D, the UK fusion programme is ambitious, aiming to establish a world-leading fusion industry and to develop a prototype fusion power plant known as STEP (Spherical Tokamak for Energy Production) which is targeting operations by 2040. The UK is at the forefront of fusion energy technologies, and this is recognised globally, with General Fusion, a Canadian Energy company, planning to build its first fusion demonstration plant in the UK.

Graphic detail: The UK's scientific output

The UK punches above its weight in terms of scientific output relative to its size. UK physics is no exception to this, with 115,306 journal articles published between 2012 and 2021, the 6th largest output worldwide, and outperforming many major global economies.



44,122 Australia	43,712 Brazil	53,023 Canada	533,022 China	80,946 France
141,737 Germany	119,062 India	54,773 Iran	68,118 Italy	134,354 Japan
86,612 Korea, Republic of	115,129 Russia	56,780 Spain	115,306 United Kingdom	385,784 United States

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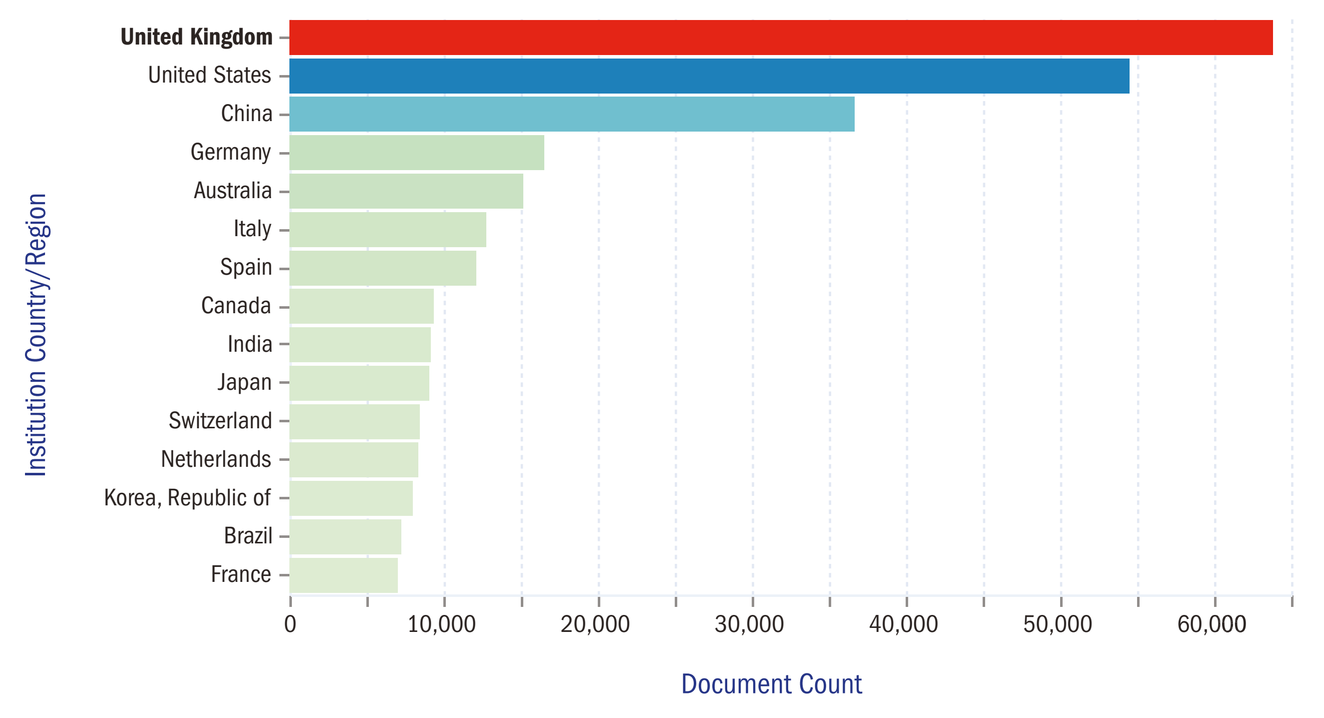
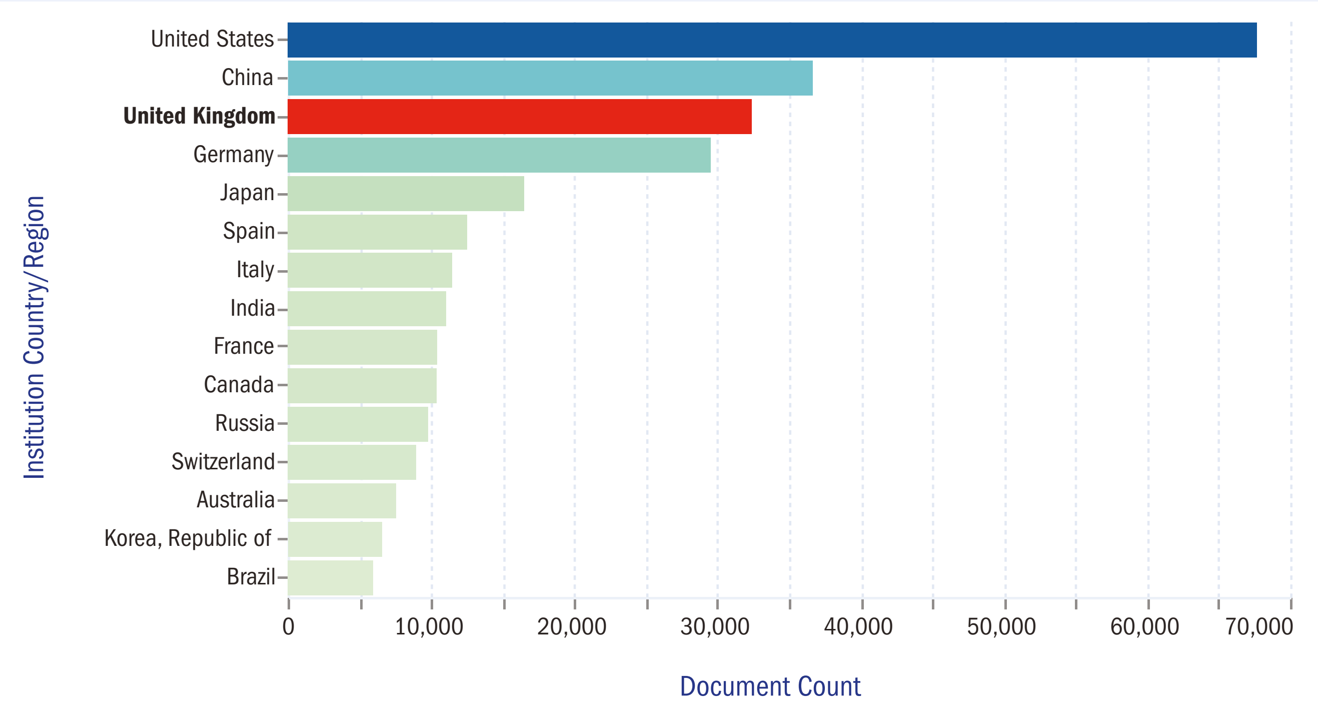
When considering publications in key physics-enabled technologies, the UK performs even better and is:

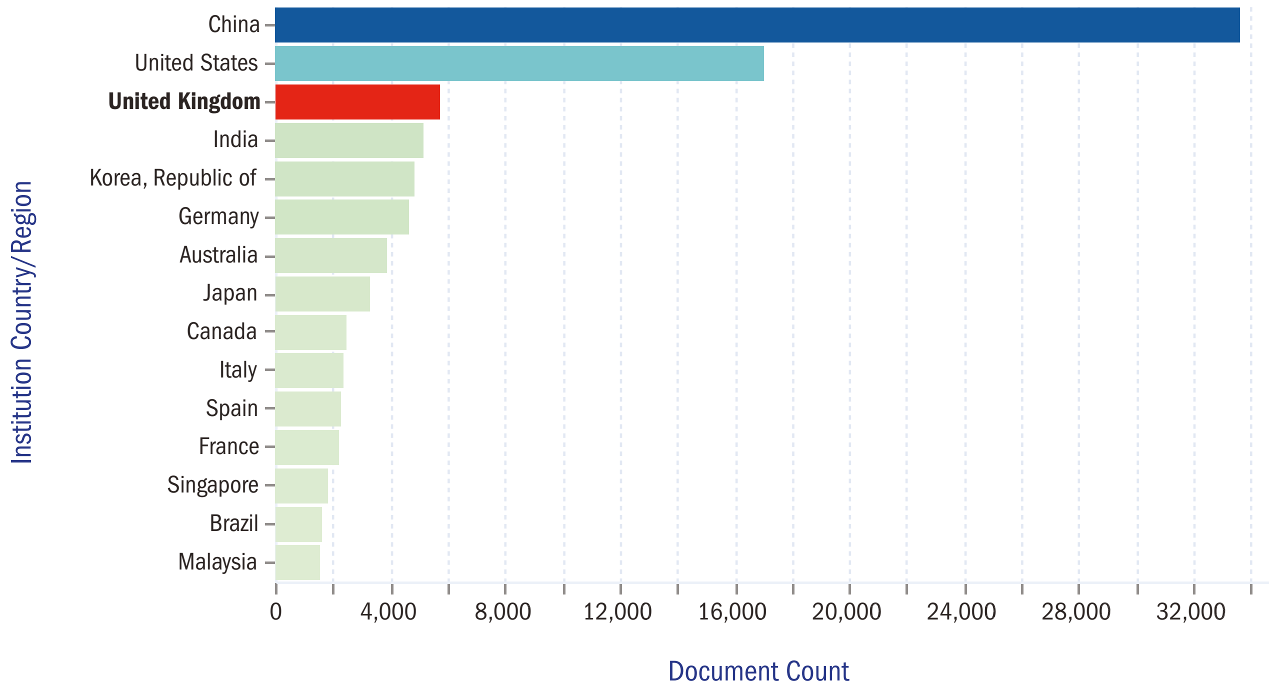
- The world leader in sustainable materials (63,805 articles)



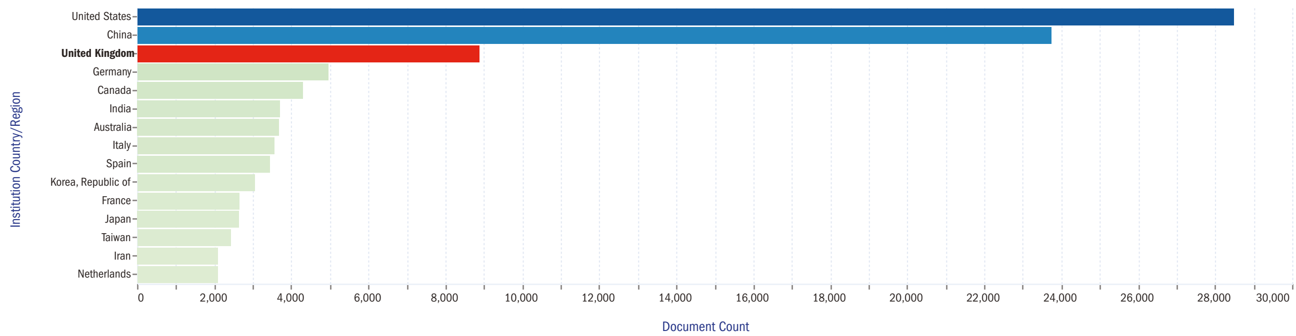
- 3rd worldwide in quantum technology (32,394)



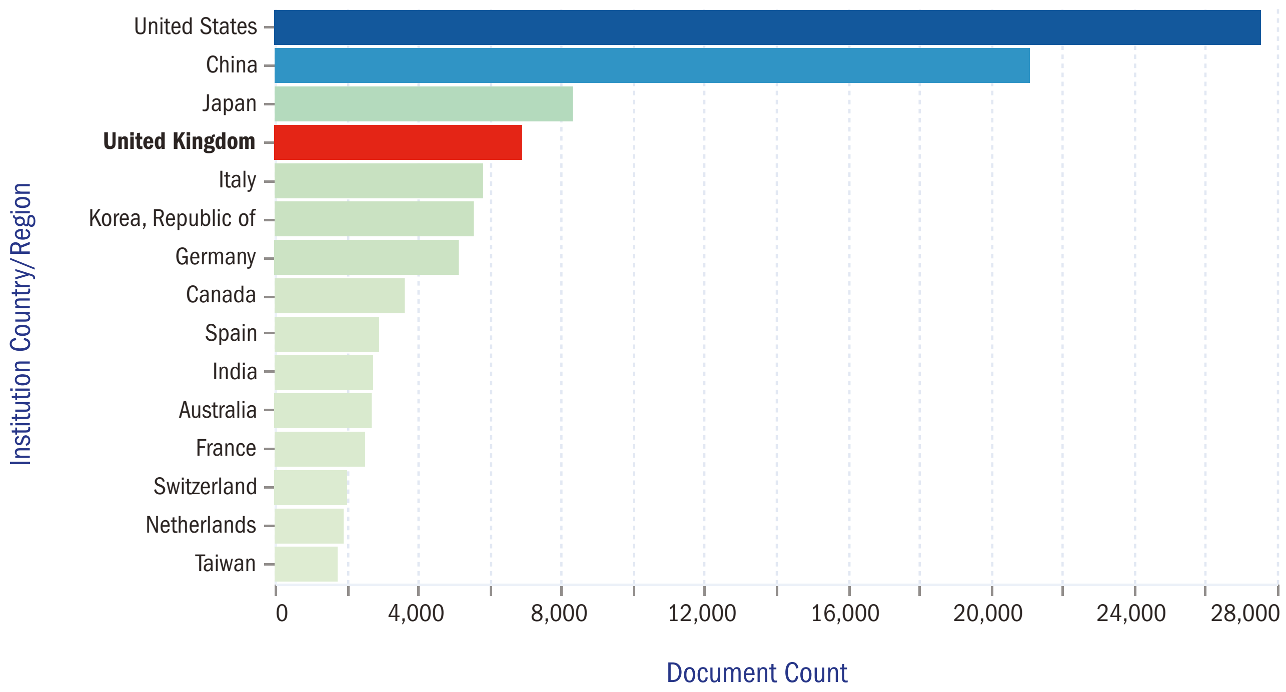
- 3rd worldwide in materials for energy (5,731)



- 3rd worldwide in big data/data science (8,879)



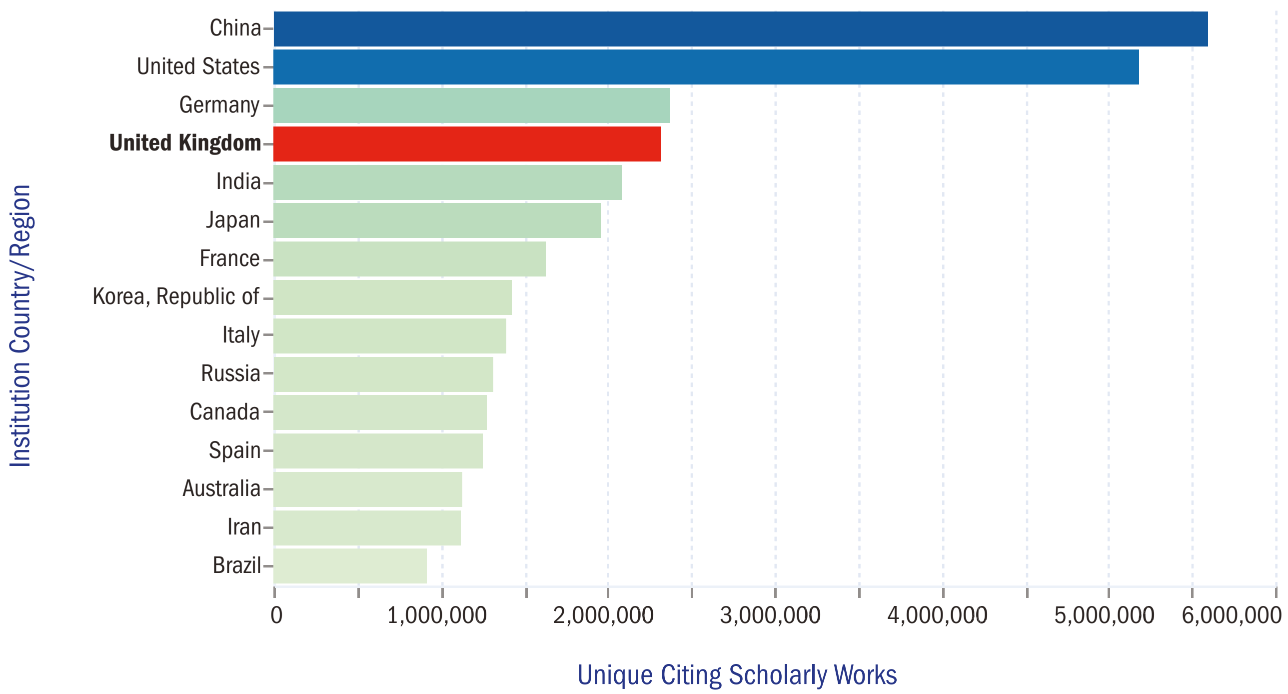
- 4th worldwide in robotics (6,917)



This illustrates that, while the UK is a major global player in physics overall, it has particular scientific strength in technologies that will be critical to harnessing the benefits of the fourth industrial revolution.

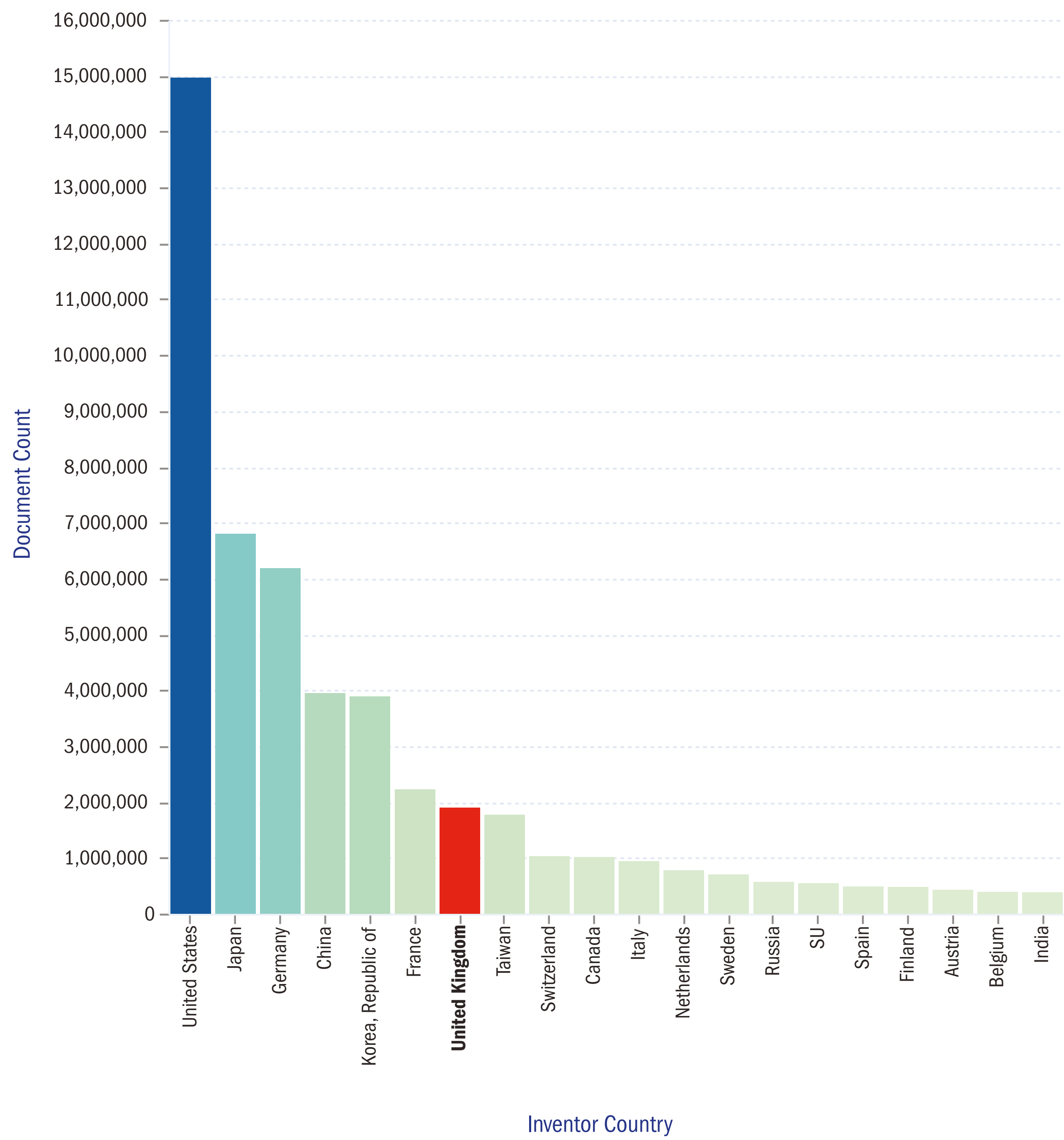
Citations

UK physics also performs strongly in terms of citations of scholarly works, placing 4th worldwide in unique citations (2.3 million).



Patents

Although the UK is a leading country in generating general physics patent applications, placing 7th worldwide, it is outperformed by economies such as the US, Japan, Germany and China. For example, at the time of writing, there have been 1.9 million patent applications generated in general physics by UK inventors.



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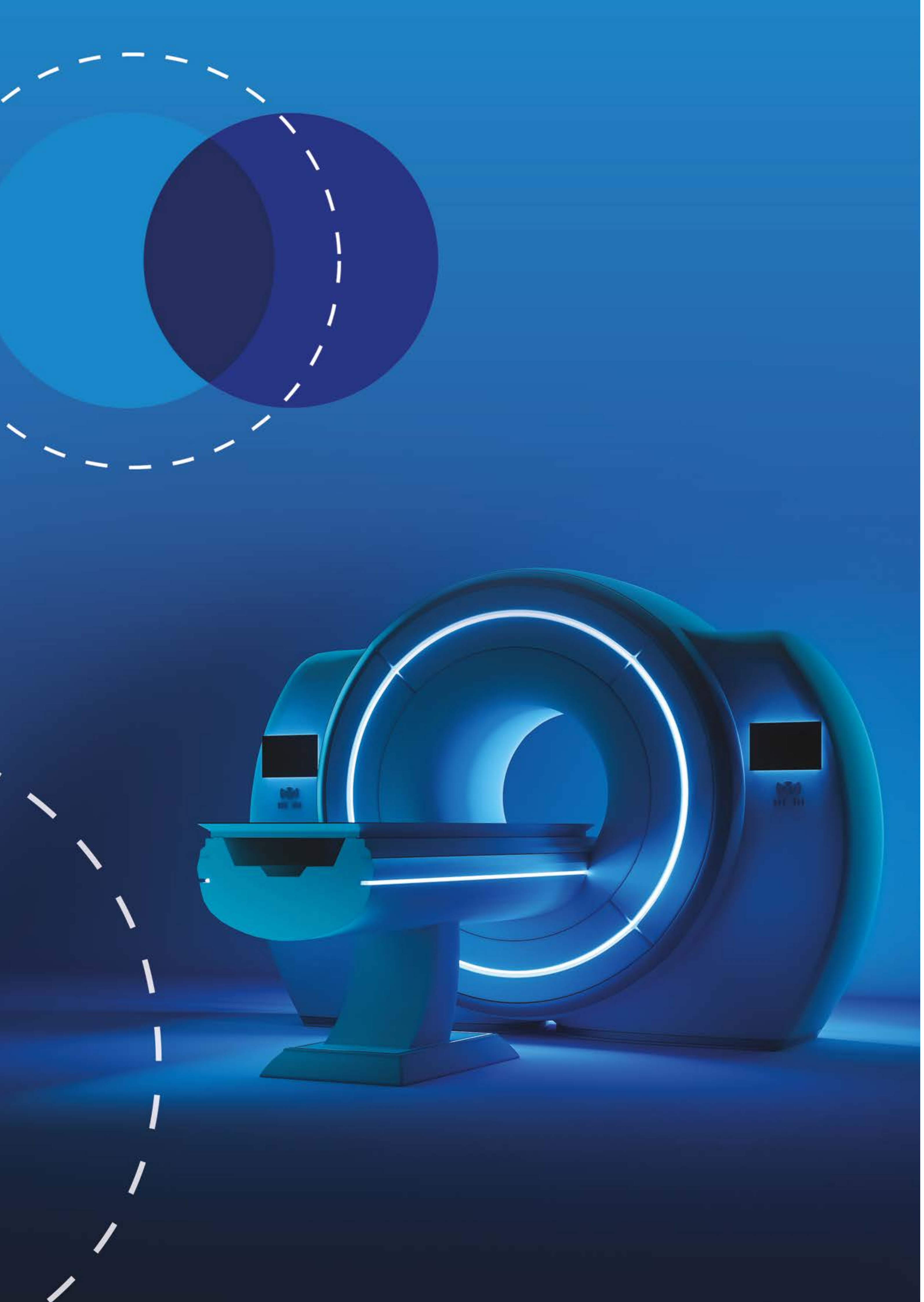

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