Diamond Light Source Ltd

2021/22

> ***"The past years have not been easy, and I wanted on behalf of the entire Diamond Board to thank everyone involved in delivering extremely valuable science as part of the response to the pandemic in challenging circumstances."***

Foreword

2022 celebrates a double anniversary for Diamond - 20 years since the company was set-up to design, build and operate the UK's national synchrotron and 15 years of delivering science and innovation to the science community. Diamond has made some considerable growth and leaps in this timeframe that have made a major contribution to science in general and the UK's global leadership in this field. Indeed, the socio-economic study published in the past year highlighted a cumulative monetised impact of at least £1.8 billion from the impressive contribution of Diamond to UK Science and the economy through our many strands of output including research, patents, software and applications, training, and our extensive programme of external engagement.

The next exciting chapter for Diamond rests with the large upgrade Diamond-II programme. Budget pressures are felt everywhere but I believe that this investment in science is essential for the UK to move forward and cement its leadership position on the global stage. The Board is committed to making the case to the Government on this basis and to fight for appropriate funding that secures our bright future for the next 20 years.

Finally, the past years have not been easy, and I wanted on behalf of the entire Diamond Board to thank everyone involved in delivering extremely valuable science as part of the response to the pandemic in challenging circumstances. Diamond has kept its doors open to researchers exploring a wide range of scientific endeavours. Diamond's ongoing success is down to the outstanding people in all areas of the organisation.

Professor Sir Adrian Smith
Chairman of the Board of Directors

CEO Welcome

As the financial year is ending, the pandemic has become an endemic disease that we are all trying to manage as best as possible whilst returning to our day-to-day activity of running the facility. A sense of caution matched with a desire for normality is hard to balance but at Diamond we have done our best to keep going, managing risks as we could under the new circumstances. Added to this challenge, the war in Ukraine has unsettled many staff and members of our user community. As always, we have been resourceful in the face of such challenges and deployed a range of measures supporting staff and users in relocating their affected families to safety. In 2022 we do however have much to celebrate with a special double anniversary for Diamond, marking 20 years since the company was first created through the Joint Venture Agreement between the UK Government through the Central Council of the Laboratory of the Research Councils and the Wellcome Trust at the time, as well as 15 years since we first opened our doors to our research community. We will be marking this important milestone with multiple activities across the year including a large-scale photographic exhibition.

Our first socioeconomic impact report carried out together with Technopolis, along with support from our funding agencies, was launched in May last year. The report received over 2,000 views and some 1,500 downloads and has become an influential piece of work within the research infrastructure community with many learning from its methodology and approach. With 14,000 researchers interested in using our instruments, our position remains very strong given that Diamond has for the period 2007-2020 achieved a cumulative monetised impact of at least £1.8 billion whilst costing each UK taxpayer only £2.45 per year for this amazing impact. These tremendous benefits are a credit to our dedicated staff, contractors and agency workers who enable innovation, push the boundaries of what can be measured and offer excellent support and service to the science delivered internally as well as externally.

Our peer review publications have reached 11,500 as we close the year. We are heartened that 50% of the catalogue is now published straight away with open access and the quality remains very strong with over 42% in journals with impact factors of five and above. COVID-19 made it impossible to allow users back on site for experiments for much of the past two years, so it was difficult to continue to support more specialised experiments despite the heroic work of many at Diamond to compensate for the loss of hands-on user engagement. We anticipate therefore a temporary drop in the annual number of publications, noting that it takes two to three years from measurement to publication.

Ensuring our science is widely disseminated has always been a priority and one of the highlights of the past year was welcoming Sir David Attenborough to the facility where he hosted a major BBC documentary on the last days of the Dinosaurs. Other successful campaigns included the COVID Moonshot, which is driving five drug compounds into the first stages of clinical trials required. We have also seen an amazing cataloguing of high-resolution images of beetles for the Natural History Museum, enabled by the transfer of robotics technology for sample changing from MX beamlines to the imaging beamline 13.

For the period 2021-2022, we received 1,116 proposals for experiments on our instruments via peer reviewed access routes, requesting a total of 12,635 shifts. After peer review, 719 proposals were awarded beamtime. This resulted in 6,983 experimental shifts being awarded across 33 beamlines and eight electron microscopes. We welcomed 2,460 on-site user visits from academia across all instruments, with an additional 4,253 remote user visits. The machine continues to perform to a high standard with 97.4 % uptime and 110 hours mean time between failures (MTBF). Diamond also provides services critical to industry in the UK, with over 200 companies making use of the facility since operations began, normally paying £3 million per annum for proprietary access.

The Diamond-II upgrade programme, an integrated upgrade of the synchrotron, beamlines and computational facilities, critical to maintaining our world-leading status, further progressed with preliminary funding allocated by Science and Technology Facilities Council (STFC) and Wellcome in early summer 2021. A major milestone in securing full funding from the UK Government was achieved with approval of the Outline Business Case (OBC) by the Department for Business, Energy and Industrial Strategy (BEIS) and Her Majesty's Treasury (HMT). This approval also builds on an early commitment of support from Wellcome for their funding share. Together with the Technical Design Report (TDR) for the machine completed and approved by the Diamond Machine Advisory Committee, alongside Conceptual Design Reports (CDRs) for three flagship beamlines, Diamond is in a very strong position to complete the Full Business Case later in 2022, which is the last stage of approval required for release of full funding for the Programme.

Success to date in planning and securing funding for Diamond-II owes a tremendous amount to Dr Laurent Chapon, who took a lead in developing the science case, introduced the idea of increasing the energy of the storage ring to optimise performance of beamlines for the key needs of our research community, and was the first Diamond-II Programme Director. Laurent has now taken up the position of Associate Laboratory Director for Photon Sciences and Director of the Advanced Photon Source at Argonne National Laboratory, USA – chapeau !

This year it has been very pleasing to witness the rise of the DIAD beamline. This is the first in the world able to switch between imaging and diffraction in a matter of seconds and its presence is already drawing an international community positioning Diamond as world-leading once again. Scientific success abounds elsewhere in Diamond too, illustrated throughout this Review. For example, this year on I04, an international team investigated the potential of new molecules with antibiotic properties, examining how these interact at a molecular level, with the aim to develop a new family of antibiotics. Our integrated facilities also achieved great science with a collaborative team from University of Queensland, University of Leeds, University of Cambridge and University of Paris-Saclay who studied next-generation composite glass at the electron Physical Sciences Imaging Centre (ePSIC) that can be used for smartphones or solar panels by determining the structure of this new material.

Throughout 2021, Diamond undertook an assessment process run by the National Co-ordinating Centre for Public Engagement (NCCPE), and in October we were delighted to be presented with the Bronze Engage Watermark award. This recognises the commitment of Diamond to Public Engagement with over 80,000 visitors reached so far through a programme of engagement at the heart of the facility supporting the UK Skills' agenda in science, technology, engineering and mathematics (STEM). Our work with undergraduates and postgraduates is also strengthening with a total cohort this year reaching 136 in total - PhDs (109), Year in Industry (12) and Summer Placements (15). Using the methodologies developed to integrate virtual activities into visitor numbers, Diamond has had over 7,300 significant interactions with 'virtual' visitors. These include 2,949 for scientific and technical events, 267 undergraduate and postgraduate interactions, 3,828 school students and members of the public, and 279 VIPs and Stakeholders. Over 95% of all these were virtual while we continued to adjust to the second year of the pandemic. Amongst the few in person interactions, we worked hard to maintain within ongoing restrictions at the time, was the Diamond Academy – a work experience programme for secondary students organised by our Public Engagement team. We were delighted to welcome 36 students to work alongside Diamond volunteer supervisors on 18 different projects across the organisation.

"Diamond has for the period 2007-2020 achieved a cumulative monetised impact of at least £1.8 billion whilst costing each UK taxpayer only £2.45 per year for this amazing impact."

Diamond is a flagship investment for the UK with returns far beyond the science delivered and I remain very optimistic that our future Diamond-II upgrade will enable us to remain world-leaders in the field. However, the greatest asset Diamond has in delivering transformative science and innovation is the staff in every single part of the organisation, all of whom play an essential role in our success. Every staff member deserves a special thank you!

Added to this, I have been greatly impressed over the past year with the work of the employee led inclusion groups, for example the proactive changes brought around disability awareness through the universal accessibility group, which resulted in improved processes, website, education for managers and staff as well as enhanced support for those affected. Widening participation is another important issue, and we hope that many interested in applying to Diamond, would experience a welcoming and nurturing environment. Probably the biggest challenge we face as an organisation is continuing to recruit and retain excellent people at a time when public sector pay was frozen (this is now lifted) so a priority for the future for Diamond must be to persuade policy makers that major investment in capital must be matched by appropriate investment in people.

Professor Andrew Harrison OBE
CEO Diamond Light Source

Governance and Management

Diamond Light Source Ltd was established in 2002 as a joint venture limited company funded by the UK Government via the Science and Technology Facilities Council (STFC), now under UK Research & Innovation (UKRI), and by Wellcome, owning 86% and 14% of the shares respectively. Diamond now employs 786 scientists, engineers, technicians and support staff from 44 countries worldwide. The Chief Executive and Directors are advised by committees representing key stakeholder groups, including the Science Advisory Committee (SAC), Diamond Industrial Science Committee (DISCo) and Diamond User Committee (DUC).

Diamond is free at the point of access for researchers accessing Diamond via peer review, and provided the results are published in the public domain for everyone's benefit. Allocation of beamtime is via a peer review process to select proposals on the basis of scientific merit and technical feasibility. Twelve peer review panels meet twice a year to assess the proposals submitted for each six-month allocation period. Diamond also welcomes industrial researchers through a range of access modes including proprietary research.

SAC: Advises Diamond Management on scientific and technical issues, including facilities and operation.

DUC: Represents the views of users to Diamond Management on matters relating to the operation and strategy of the facility.

DISCo: Advises Diamond Management on all matters relating to industry and industrial users of the facility, including opportunities to engage industry, best practice for industrial engagement and industrial research priorities.

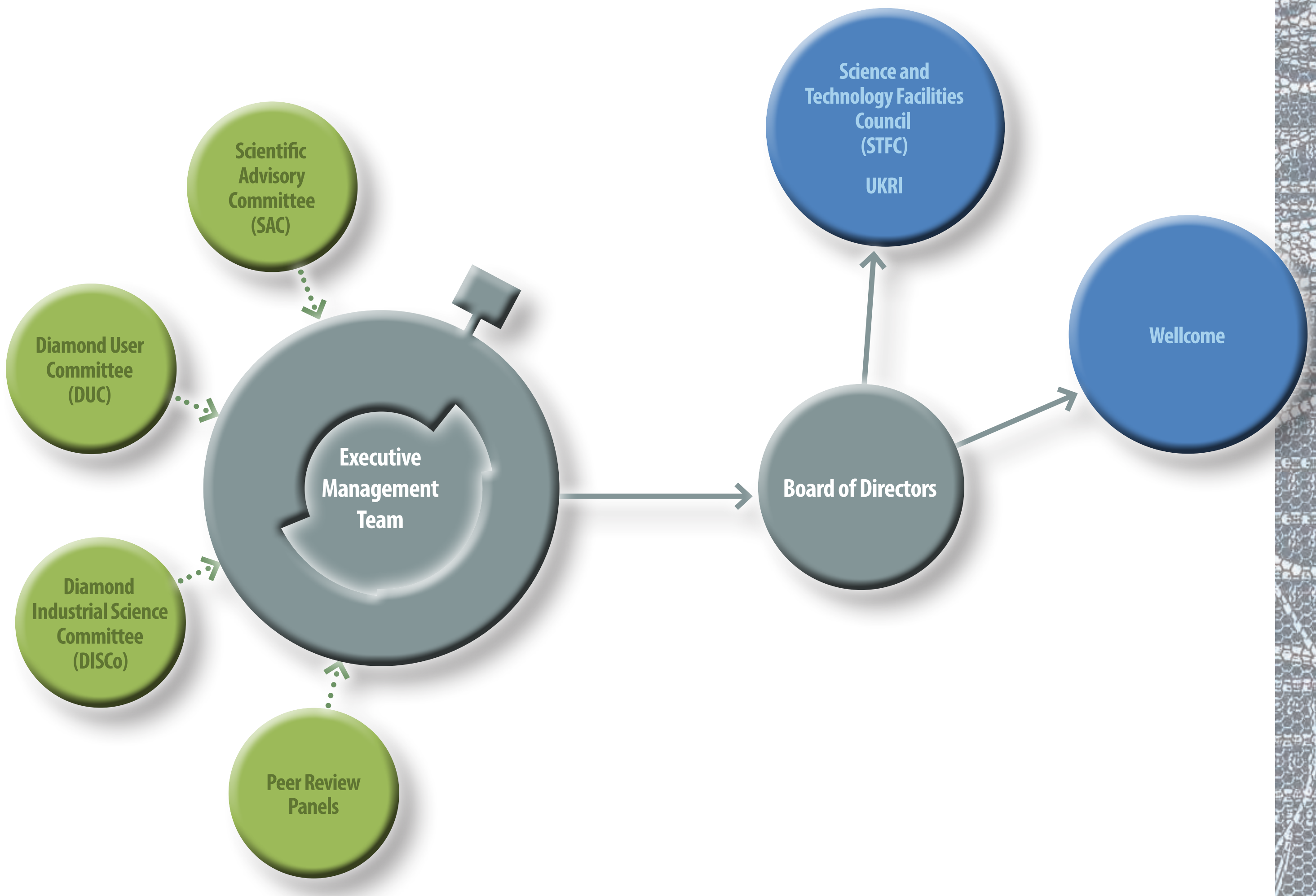
Peer Review Panels: Assess scientific merit of proposals to use the synchrotron and provide recommendations to Diamond Management on the allocation of beamtime to each project.

Executive Management Team: Hears from representatives from around Diamond and provides recommendations on strategy and operation to the Board of Directors.

Board of Directors: Decides on matters relating to Diamond's strategy and operation, and reports to Shareholders.

STFC: Holds 86% of shares as a joint venture partner. Hears from the Board and makes wider strategic decisions.

Wellcome: Holds 14% of shares as a joint venture partner. Hears from the Board and makes wider strategic decisions.



Staffing and Financial Information

Outline Organisational Chart

Chief Executive's Office

Communications, Engagement & Impact
Industrial Liaison
Safety, Health & Environment

Science Division

Science Groups:
Biological Cryo-Imaging
Crystallography
Imaging and Microscopy
Macromolecular Crystallography
Magnetic Materials
Soft Condensed Matter
Spectroscopy
Structures and Surfaces

Scientific Software, Controls & Computation Groups:
Accelerator Control Systems
Beamline Control Systems
Data Acquisition
Scientific Computing
Scientific Software

Detector Group
Experimental Hall Labs Services
Optics & Metrology
Planning & Projects Office
User Office

Technical Division

Accelerator Physics
Diagnostics
Engineering
Insertion Devices
Installation & Facility Management
Operations
Power Supplies
Radiofrequency Systems
Vacuum

Finance and Corporate Services

Corporate IT
Commercial Management, Governance & Legal
Finance
Human Resources
Procurement & Goods Handling
Soft Facilities

Summary of Financial Data

	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22
Operating Costs £m	33.5	36.5	39.9	42.5	44.5	54.6	56.9	62.8	64.5	65.7	69.2	68.7
Total Staff (Year End)	419	438	481	507	534	582	609	639	680	742	775	786
Capital Expenditure – Operations £m	8.6	5.1	8.0	7.5	6.2	8.0	10.5	12.8	17.4	17.8	24.1	21.2
Phase II £m	16.2	9.9	2.8	0.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phase III £m	3.0	10.3	14.2	17.2	23.7	20.6	11.5	3.7	1.0	0.0	0.0	0.0
Other capital projects £m					4.8	5.6	7.3	4.3	5.3	1	2.1	2

Figures up to and including 2014/15 exclude VAT, thereafter figures include VAT.

Diamond-II Update

Diamond Light Source has established itself as a world-class synchrotron facility enabling research by leading academic and industrial groups in physical and life sciences. Diamond has pioneered a model of highly efficient and uncompromised infrastructure offered as a user-focussed service driven by technical and engineering innovation. To continue delivering the world-changing science that Diamond leads and enables, Diamond-II is a co-ordinated programme of development that combines a new machine and new beamlines with a comprehensive series of upgrades to optics, detectors, sample environments, sample delivery capabilities and computing. The user experience will be further enhanced through access to integrated and correlative methods as well as broad application of automation in both instrumentation and analysis.

There are several steps to take toward achieving the Diamond-II vision of expanding the UK's research capabilities. In the first year of preliminary funding, a significant project milestone was passed in November 2021 in securing the Outline Business Case (OBC). Since then, Diamond's dedicated project teams of engineering and research professionals have shifted the focus to the Technical Design Report (TDR), due for completion later this year. Additionally, the priority flagship beamlines have engaged with their respective user communities and issued Conceptual Design Reports (CDRs) that outline their advanced research capabilities.

This comprehensive programme of scientific and technical updates will push the boundaries of UK research into new territories. The associated phases of the project fall under four distinct work packages:

Machine – to cover every stage of machine upgrade from design, procurement and testing through to removal of old components and assembling and installation of new components.

Beamlines – to include modification of existing beamlines to accommodate the new beam source and building of new flagship beamlines.

Data and Computation – to manage a new IT infrastructure, including software developments to manage instrumentation, control, acquisition & detector readouts and data analysis for high rate applications.

Infrastructure – to oversee requirements for the additional ~10,000 m^2 of assembly/storage space required for the upgrade (on and off site), upgrade infrastructure systems for the new machine and provide necessary general manpower effort across technical groups.

A new generation of lightsources

We are entering a new era of opportunity with the advent of fourth generation synchrotrons, the so-called Diffraction Limited Storage Rings (DLSRs). The progress in accelerator technology and the decrease of the electron horizontal emittance between one and two orders of magnitude offers the scientific community the opportunity to exploit much brighter photon beams and an increased coherence over a large energy range.

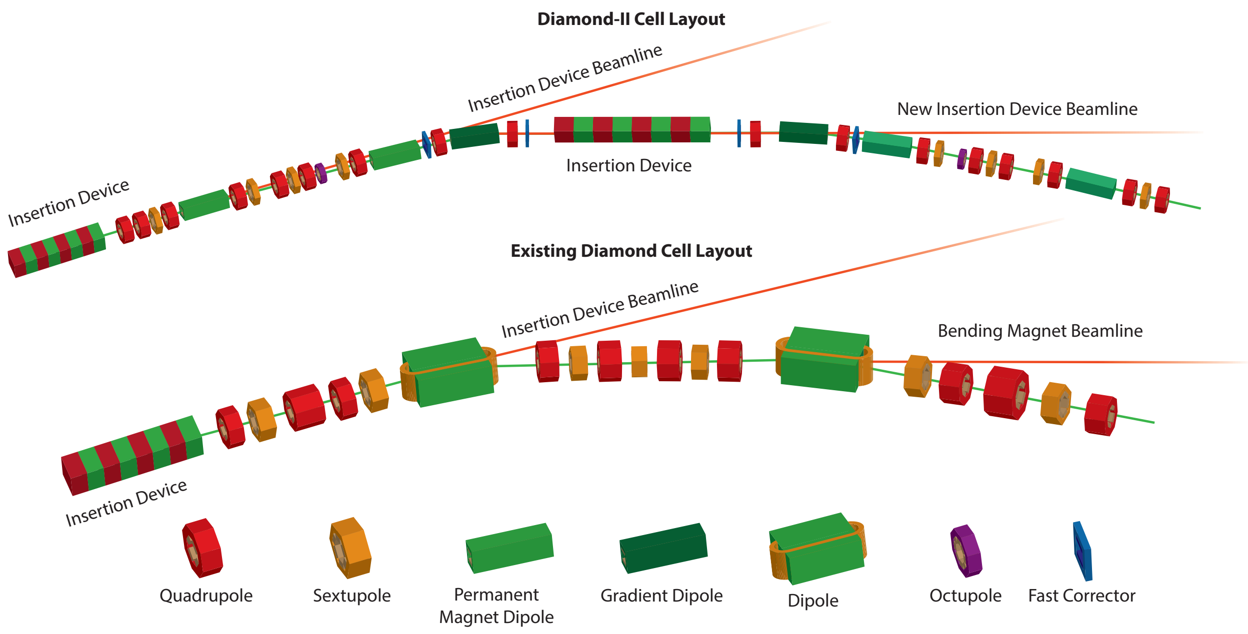
The proposed Diamond-II new machine lattice will be based on Double Triple Bend Achromats (DTBAs). This means an increased brightness and coherence of a factor of up to 70 and provides mid-section straights to retain and enhance all beamlines on bending magnets while offering additional sources for five new beamlines.

This design increases the electron beam energy from 3.0 to 3.5 GeV providing greatly increased photon flux at higher energies.

To match the extraordinary gains offered by the Diamond-II machine there will be a major renewal and upgrade of existing beamline technologies to meet the new scientific demands. Diamond-II will see enhancements in beam quality and beam stability through new X-ray optics and instrumentation, state-of-the-art sample delivery, and manipulation through the development of optimised sample environments and scientific software solutions that meet the beamline demands for the acquisition, visualisation and analysis of data.

This transformational upgrade will take several years of planning, a dark period of 18 months during which there will no light for the user community, followed by a period to launch the five flagship beamlines and a comprehensive series of other upgrades, which will bring a total of 38 instruments around the synchrotron ring.

Architect's impression of the Diamond Extension Building (DEB), bottom right, to be constructed as part of the Diamond-II project, and link bridge to the synchrotron.



Schematic of the current Diamond DBA (Double Bend Achromat, bottom) and the proposed design for a DTBA (Double Triple Bend Achromat) for Diamond-II (top).

Delivery of flagship beamlines for Diamond-II

Three new beamlines will be available for day one operations six months after the dark period following extensive commissioning with the new machine. K04, an ultra-high throughput beamline for MX and XChem; SWIFT, the beamline for fast operando spectroscopy; and CSXID, beamline for Coherent Soft X-ray Imaging and Diffraction. Two other flagship beamlines, BERRIES, beamline for X-ray Raman Scattering and pink-beam X-ray Emission Spectroscopy (XES), and the beamline for nano-Angle-Resolved Photoemission Spectroscopy (ARPES) will be available at a later stage in the Diamond-II programme.

K04 beamline

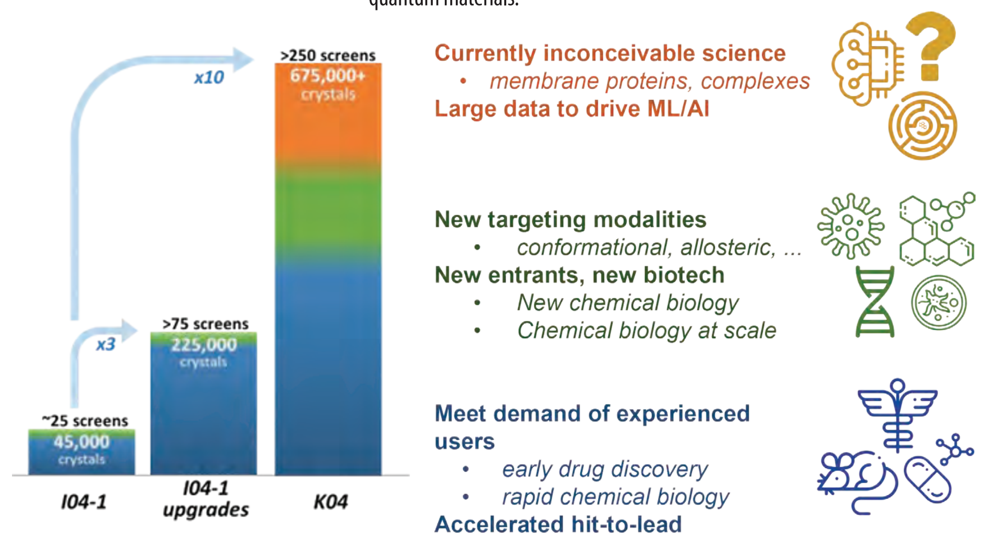
The K04 XChem flagship builds on the success and oversubscription of the XChem fragment screening facility, developed in tandem with the evolution of beamline I04-1. The Diamond-II machine configuration necessitates removing beamline I04-1, providing the opportunity to rebuild it on the new K04 straight, delivering a beamline of vastly increased flux and brilliance, along with extreme automation. The resulting order-of-magnitude increase in throughput will fundamentally shift the scientific scope of crystallographic fragment screening.

SWIFT beamline

This new beamline, called SWIFT (Spectroscopy WithIn Fast Timescales), will be a high flux beamline optimised for the study of samples under operando conditions, and with the added potential to investigate sample heterogeneities at the 20 µm scale. The beamline will exceed the capabilities of the other X-ray Absorption Spectroscopy (XAS) beamlines at Diamond for experiments that require an element of time resolution in dilute samples, and will bridge the existing spatial resolution gap between beamlines I18 and B18. It is expected that SWIFT will serve a very broad scientific community and that it will also significantly enhance Diamond's capabilities for industrially relevant X-ray spectroscopy.

CSXID beamline

Today, there is global effort to further understand and control the emergent properties of quantum materials, with the promise of next-generation low-cost, energy-efficient devices. The Coherent Soft X-ray Imaging and Dynamics (CSXID) beamline will be for high-resolution, element selective 3D imaging and dynamic studies of new and novel materials. With an array of leading-edge sample environments and detectors coupled to a high-intensity polarised soft X-ray beamline specifically designed to take full advantage of the large increase in coherent flux from the Diamond-II upgrade, CSXID will revolutionise our ability to explore the static and dynamic 3D nanotexture of quantum materials.



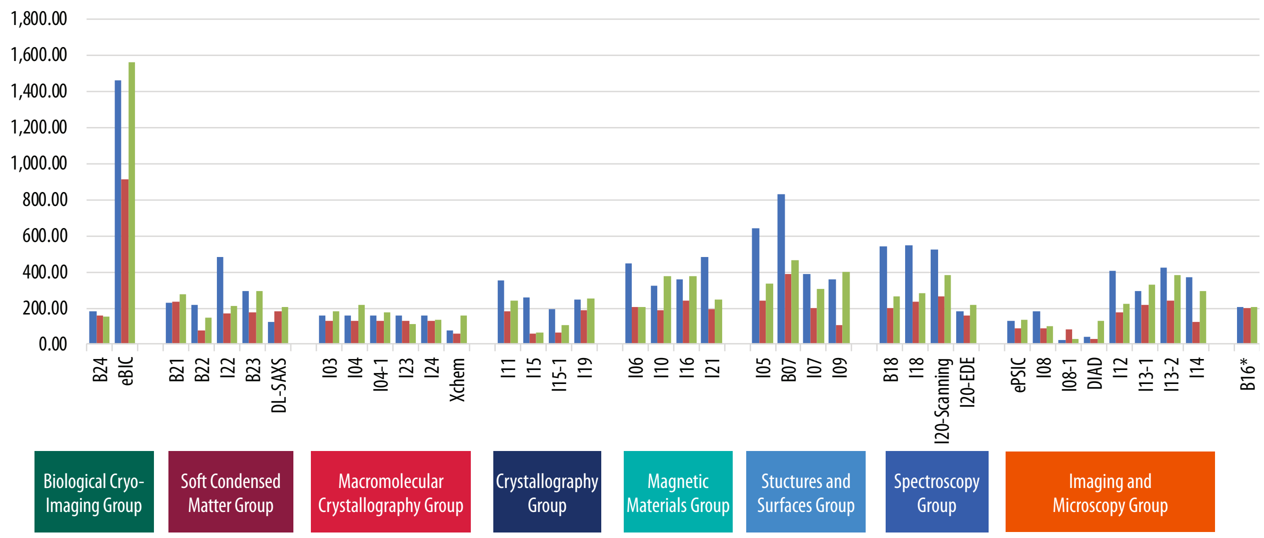
The capacities offered by the new K04 beamline.

Key Facts and Figures

Facility usage

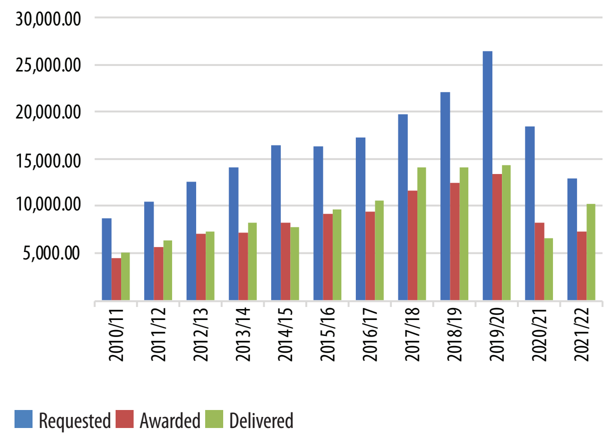
In our fifteenth year of operations (1st April 2021 to 31st March 2022), we received 1,116 proposals for experiments on our instruments via peer reviewed access routes, requesting a total of 12,635 shifts. After peer review, 719 proposals were awarded beamtime. This resulted in 6,983 experimental shifts being awarded across 33 beamlines and the six electron microscopes delivering time to academic users. Throughout April and May 2021, the weekly operating hours continued to be limited to four days due to the pandemic; there was less experimental time available and the user programme was adjusted as a result. We also experienced a reduction in the number of proposal submissions due to the pandemic. However, from June 2021 we reverted back to our usual six day operation and across the full year we welcomed 2,460 onsite user visits from academia across all instruments, with an additional 4,253 remote user visits. The machine continues to perform to the highest standard with 97.4% uptime and 107.9 hours mean time between failures (MTBF).

User shifts requested, awarded and delivered by group, beamline and electron microscope 2021/22

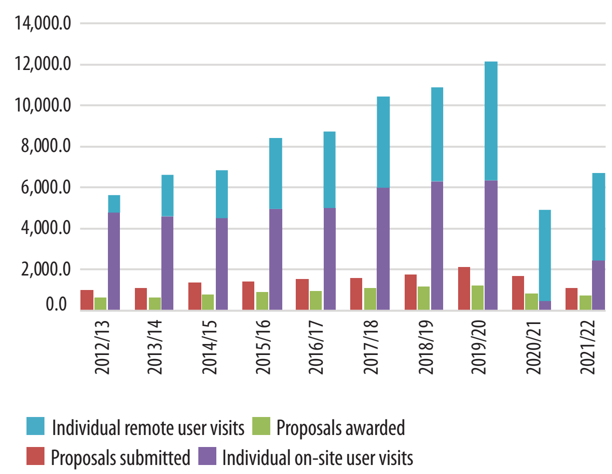


* B16 is the Test beamline, with 50% of beamtime for users. The rest is used for in-house developments for all beamlines.

Total user shifts requested, awarded and delivered



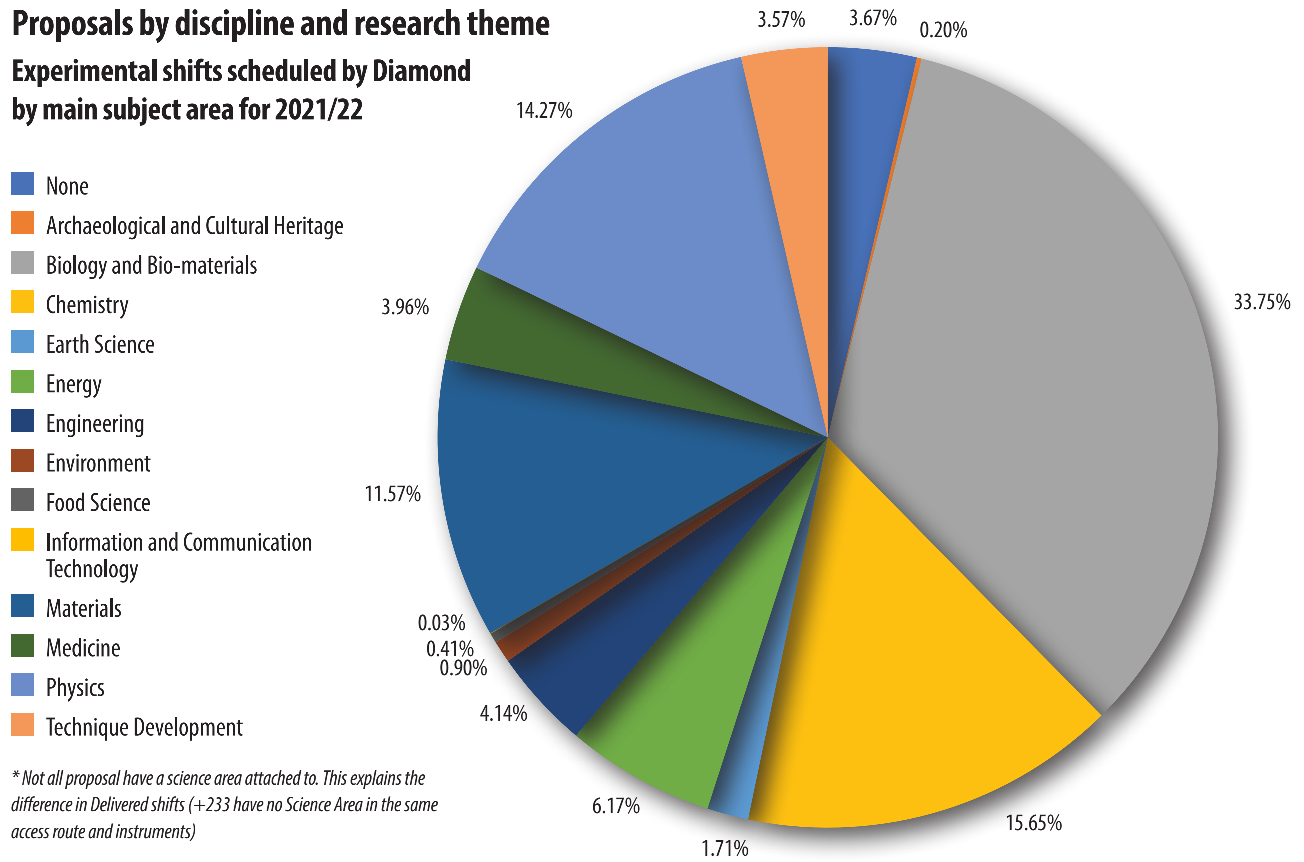
Total numbers of proposals and users per year



Staff visits are now included for academic access routes, in house research is still excluded

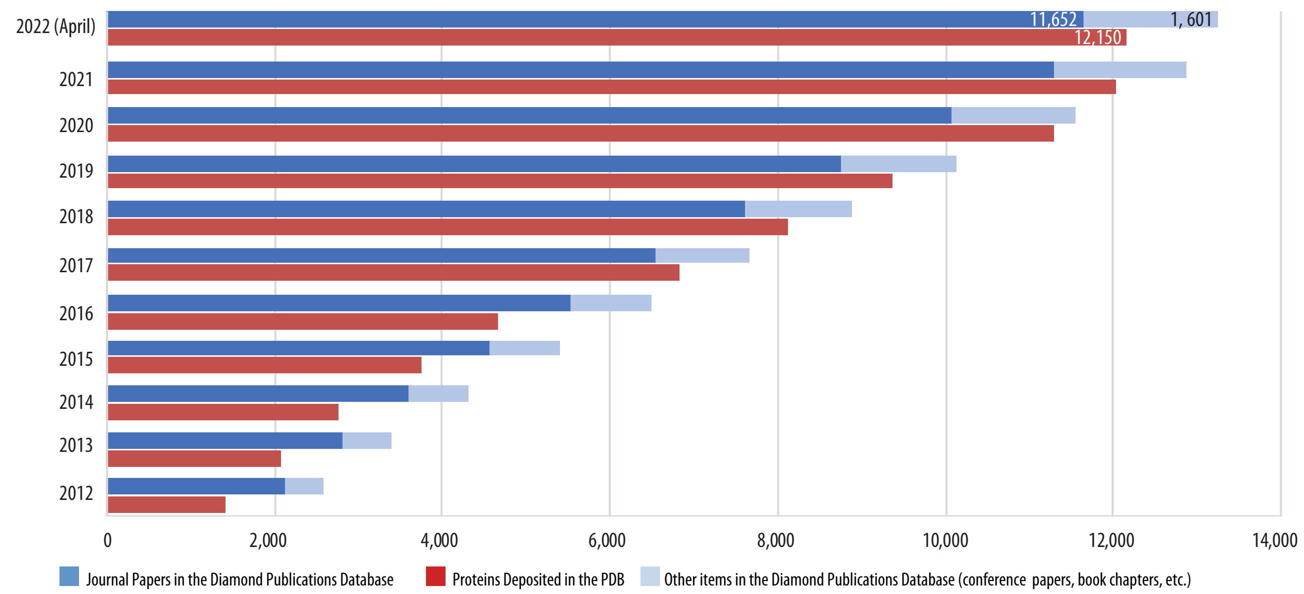
Proposals by discipline and research theme

Experimental shifts scheduled by Diamond by main subject area for 2021/22



** Not all proposal have a science area attached to. This explains the difference in Delivered shifts (+233 have no Science Area in the same access route and instruments)*

Cumulative number of items in Diamond Publications Database by our scientists and users and cumulative number of protein structures solved



Machine performance

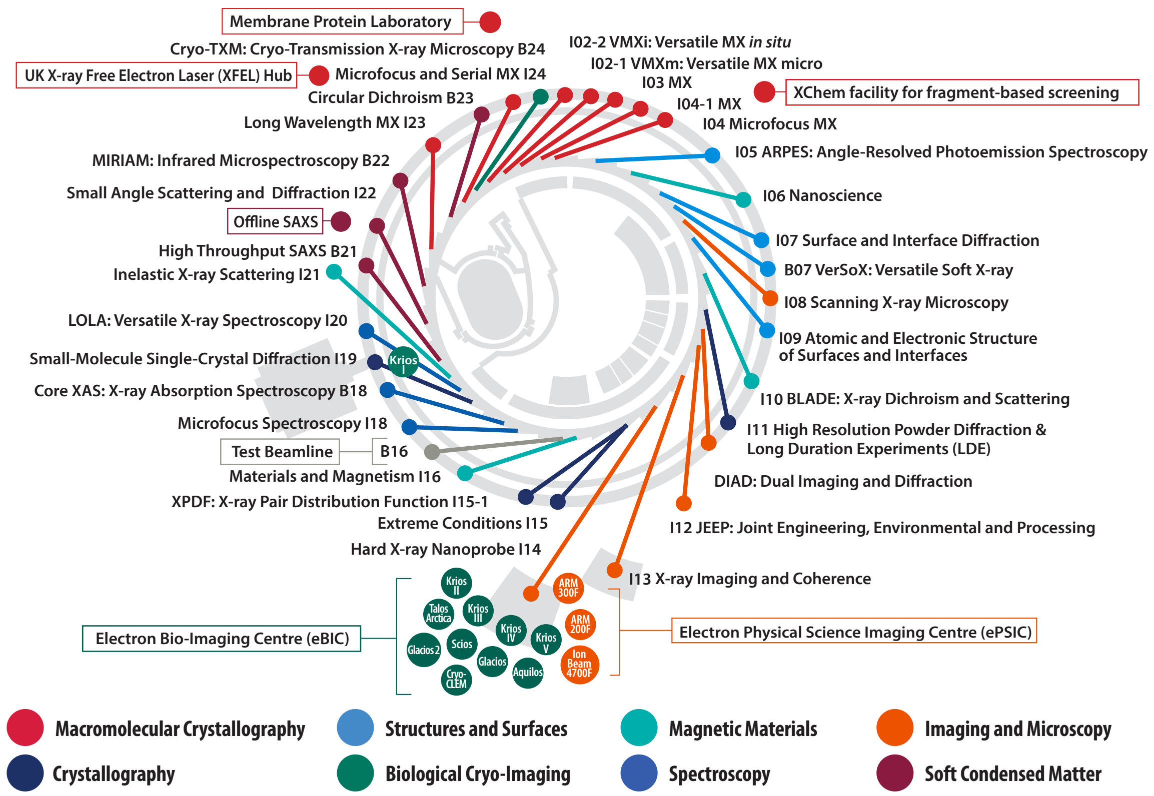
	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22
Total no. operational beamlines by end FY	19	20	22	24	25	26	28	31	32	32	33	33
Scheduled hours of machine operation	5808	6000	5832	5976	5808	5928	5688	6072	5904	5913	4345*	5396*
Scheduled hours of user operation	4728	5064	4872	5088	4944	5040	4584	5160	4992	4992	3445*	4532*
Machine uptime %	97.5	97.7	98.3	98.2	97.6	97.6	98.7	98.2	98.4	98.1	96.2	97.4
Mean time between failures (hours)	28.5	55.4	52.4	60.3	38.6	119.4	103.1	79.9	90.3	104.7	132	107.9

** hours reduced due to COVID*

Beamline Development and Technical Summary

In its fifteenth year of experiments, Diamond is now operating with 33 beamlines and eight electron microscopes dedicated for experiments. A further five instruments are available for experiment support and sample preparation. Ten of the instruments specialise in life sciences and make up eBIC (electron Bio-Imaging Centre), with two provided for industry use in partnership with Thermo Fisher Scientific. Two of the electron microscopes are dedicated to advanced materials research and are supplied by Johnson Matthey and the University of Oxford. These, along with a further instrument for sample preparation, form ePSIC (electron Physical Science Imaging Centre) and are operated under strategic collaboration agreements to provide for substantial dedicated peer reviewed user access. Both eBIC and ePSIC are next to the Hard X-ray Nanoprobe beamline (I14). Along with eBIC and ePSIC, the UK X-ray Free Electron Laser (XFEL) Hub, the Membrane Protein Laboratory (MPL), the XChem fragment screening facility and the Offline SAXS facility make up the complementary integrated facilities available at Diamond. For academic research, Diamond instruments (beamlines and microscopes) are free at the point of access through peer review. For proprietary research, access can be secured through Diamond's industry team.

The instruments and beamlines are organised into eight science groups as described below.



Electron Microscopes

Microscope	Main Capabilities	Accelerating Voltages	Operational Status
Titan Krios I	Cryo-EM, Cryo-ET	80, 120, 200, 300 kV	Operational
Titan Krios II	Cryo-EM, Cryo-ET	80, 120, 200, 300 kV	Operational
Titan Krios III	Cryo-EM, Cryo-ET	80, 120, 200, 300 kV	Operational
Titan Krios IV	Cryo-EM, Cryo-ET	80, 120, 200, 300 kV	Operational
Titan Krios V	Cryo-EM, Cryo-ET	80, 120, 200, 300 kV	Operational
Talos Arctica	Cryo-EM, Cryo-ET, MicroED	200 kV	Operational
Glacios	Cryo-EM, Cryo-ET	200 kV	Operational
Glacios 2	Cryo-EM, Cryo-ET, MicroED	200 kV	Operational
Scios	Cryo-SEM, Cryo-FIB	3 to 30 kV	Operational
Aquilos 2	Cryo-SEM, Cryo-FIB	3 to 30 kV	Operational
JEOL ARM200F	Atomic scale STEM imaging, EELS, EDX, electron diffraction	80, 200 kV	Operational
JEOL ARM300F	Atomic scale TEM and STEM imaging, electron diffraction, 4D-STEM, EDX	30, 60, 80, 160, 200, 300 kV	Operational
JEOL Ion Beam 4700F	SEM, FIB	1 to 30 kV	Operational

Diamond's beamlines: current operational status April 2022

Beamline Name and Number	Main Techniques	Energy / Wavelength Range	Status
I02-1 - Versatile MX micro (VMXm)	Micro- and nano-focus in vacuum cryo-macromolecular crystallography (VMXm)	7 - 28 keV	Optimisation
I02-2 - Versatile MX *in situ* (VMXi)	*In situ* microfocus macromolecular crystallography, Serial Synchrotron Crystallography	10 - 25 keV	Optimisation
I03 - MX	Macromolecular crystallography (MX), Multiwavelength Anomalous Diffraction (MAD)	5 - 25 keV	Operational
I04 - Microfocus MX	MX, MAD, variable and microfocus MX	6 - 18 keV	Operational
I04-1 - Monochromatic MX	MX, XChem fragment screening	13.53 keV (fixed wavelength)	Operational
I05 - ARPES	Angle-Resolved PhotoEmission Spectroscopy (ARPES) and nano-ARPES	18 - 240 eV; 500 eV	Operational
I06 - Nanoscience	X-ray Absorption Spectroscopy (XAS), X-ray photoemission microscopy and X-ray magnetic circular and linear dichroism	80eV - 2200eV	Operational
I07 - Surface and Interface Diffraction	Surface X-ray diffraction, Grazing Incidence X-ray Diffraction (GIXD), Grazing Incidence Small Angle X-ray Scattering (GISAXS), X-ray Reflectivity (XRR)	6 - 30 keV	Operational
B07 - VerSoX: Versatile Soft X-ray	Branch C: Ambient Pressure XPS and NEXAFS	110 - 2800 eV	Operational
	Branch B: NEXAFS and High-Throughput XPS	45 - 2200 eV	Optimisation
I08 - Scanning X-ray Microscopy	Scanning X-ray microscopy, NEXAFS/ XANES, X-ray fluorescence	I08 branch: 250 eV - 4.4 keV	Operational
		I08-1 - Soft and Tender X-ray Ptychography branch: 250 - 2000 eV	Optimisation
I09 - Atomic and Electronic Structure of Surfaces and Interfaces	XPS (including HAXPES), X-ray Standing Waves (XSW), Near Edge X-ray Absorption Fine Structure (NEXAFS), energy-scanned photoelectron diffraction	Hard X-rays: 2.1 - 18+ keV Soft X-rays: 0.1 - 2.1 keV (currently 0.1 - 1.9 keV)	Operational
I10 - BLADE: Beamline for Advanced Dichroism Experiments	Soft X-ray resonant scattering, XAS and X-ray magnetic circular and linear dichroism	Circular: 400-1600eV; Linear Horizontal: 250-1600eV; Linear Vertical: 480-1600eV	Operational
I11 - High Resolution Powder Diffraction	X-ray powder diffraction	7 - 25keV (1.7 - 0.5 - 2.1 Å)	Operational
DIAD: Dual Imaging and Diffraction	Simultaneous time-resolved X-ray imaging and X-ray powder diffraction	8 - 38 keV	Optimisation
I12 - JEEP: Joint Engineering, Environmental and Processing	Time-resolved imaging and tomography; 2D detector for time-resolved powder diffraction, single crystal diffraction and diffuse scattering; energy dispersive X-ray diffraction (EDXD); high-energy small angle X-ray scattering (limited capability)	53 keV - 150 keV monochromatic or continuous white beam	Operational
I13 - X-ray Imaging and Coherence	Phase contrast imaging, tomography, full-field microscopy (under commissioning), coherent diffraction and imaging (CXRD,CDI), ptychography and photocorrelation spectroscopy (XPCS) (under commissioning), innovative microscopy and imaging	Imaging branch: 8 - 30keV Coherence branch: 7 - 20keV	Operational
I14 - Hard X-ray Nanoprobe	Nanofocus X-ray fluorescence (XRF), X-ray absorption spectroscopy (XAS), and transmission diffraction (XRD) mapping., differential phase contrast (DPC) imaging,), ptychography and tomography	5 - 23 keV	Operational
I15 - Extreme Conditions	Powder diffraction, single crystal diffraction	Monochromatic and focused 20 - 80 keV White beam	Operational
I15-1 - XPDF	X-ray Pair Distribution Function (XPDF)	40, 65, and 76 keV	Operational
I16 - Materials and Magnetism	Resonant and magnetic single crystal diffraction, fundamental X-ray physics	2.5 - 15 keV	Operational
B16 - Test beamline	Diffraction, imaging and tomography, topography, reflectometry	4 - 20 keV monochromatic focused 4 - 45 keV monochromatic unfocused White beam	Operational
I18 - Microfocus Spectroscopy	Microfocus X-ray Absorption Spectroscopy (XAS), X-ray fluorescence (XRF) and X-ray diffraction (XRD) mapping and tomography	2.05 - 20.5 keV	Operational
B18 - Core XAS	X-ray Absorption Spectroscopy (XAS)	2.05 - 35 keV	Operational
I19 - Small-Molecule Single-Crystal Diffraction	Small-molecule single-crystal diffraction	5 to 25 keV / 0.5 to 2.5 Å	Operational
I20 - LOLA: Versatile X-ray Spectroscopy	X-ray Absorption Spectroscopy (XAS), X-ray Emission Spectroscopy (XES) and Energy Dispersive EXAFS (EDE)	Dispersive branch: 6 - 26 keV	Operational
		Scanning branch: 4.5 - 20 keV	Operational
I21 - Inelastic X-ray Scattering	Resonant Inelastic X-ray Scattering (RIXS), X-ray Absorption Spectroscopy (XAS)	Currently 250 - 1500 eV (to be upgraded to 250 - 3000 eV)	Operational
B21 - High Throughput SAXS	BioSAXS, solution state small angle X-ray scattering	8 - 15 keV (set to 13.1 keV by default)	Operational
I22 - Small Angle Scattering and Diffraction	Small angle X-ray scattering and diffraction: SAXS, WAXS, USAXS, GISAXS. Micro-focus.	7 - 20 keV	Operational
B22 - MIRIAM: Multimode InfraRed Imaging And Mircrospectroscopy	FTIR microscopy & FPA imaging FTIR and THz spectroscopy NEW FTIR nanospectroscopy s-SNOM and AFM IR	microFTIR: 5,000-500cm^{1}(2-20μm) FTIR/THz:10,000-10cm^{1}(1-1000μm) nanoFTIR: 14000-800cm^{1}(2.5-12.5μm)	Operational (AFM IR commissioning)
I23 - Long Wavelength MX	Long wavelength macromolecular crystallography	2.1 - 11 keV (1.1 - 5.9 Å)	Operational
B23 - Circular Dichroism	Circular Dichroism (CD)	Module A: 125-500nm for CD Imaging at 50 μm spatial resolution, and 96-cell HTCD. Module B: 180-650nm for MMP Imaging at 50 μm spatial resolution.	Operational
I24 - Microfocus and Serial MX	MX, MAD, Serial Crystallography, high energy MX	7 - 30.0 keV	Operational
B24 - Cryo Transmission X-ray Microscopy (TXM)	Full field X-ray imaging	200eV - 2600eV	Operational

Macromolecular Crystallography Group

Macromolecular crystallography (MX) exploits the hard energy, high flux X-rays created at Diamond Light Source to enable our user community to investigate the structure and function of biological macromolecules at atomistic resolution and up to millisecond timescales. This provides deep insight into the details of biological activity key to our understanding of the processes of life.

Diamond provides access to a suite of seven MX beamlines (I03, I04, I04-1, I23, I24, VMXi and VMXm) to a large international academic and industrial user community. The beamlines cover a very broad range of capabilities from high throughput, micro- and nano-focus beams, extremely long wavelengths, room temperature *in situ* collection from crystallisation plates, (time resolved) serial synchrotron crystallography (SSX), a fragment-based screening platform (XChem) and the Membrane Protein Laboratory.

Important research studies conducted this year included new insights into the activity of the anticancer protein tubulin, the development of new antibiotics and determining the structure of a valuable protein used in neuroscience studies.

Understanding the vital anticancer protein tubulin

Tubulin plays an essential role in cell functions including cell division. Tubulin molecules form tube-like structures, called microtubule filaments, that give cells their shape and help transport proteins and other cellular components. Tubulin can bind to many proteins and small molecules, but the total number of binding sites was previously unknown. Swiss and Italian researchers investigated that question by using a unique combination of computer simulations and crystallographic fragment screening performed at the XChem facility and beamline I04-1.

For the fragment screening, the team exposed hundreds of tubulin crystals to solutions containing fragments of molecules. Then, they used beamline I04-1 to create X-ray diffraction patterns for each soaked crystal, showing which molecule fragments bound to the tubulin and where their binding took place. Their results uncovered 11 previously unknown binding sites on the protein and identified 56 fragments that bind to tubulin and could be used in future drug development. The team's approach can also be used to investigate other proteins and could help to discover new binding sites in other pharmaceutically important molecules.

Mühlethaler T *et al.* DOI: 10.1002/anie.202100273

Designing effective new antibiotics

Relatively few antibiotics were introduced over recent decades, and overuse has led to the development of significant bacterial resistance. With some bacterial infections becoming untreatable, new antibiotic discovery is now a priority. An international team of researchers in the UK and Slovenia designed a series of new molecules with antibiotic potential. These new antibiotics, called Novel Bacterial Topoisomerase Inhibitors (NBTI's) kill bacteria and act against a well-validated target, DNA gyrase. By forming a complex with the enzyme and DNA, they stabilise single-strand DNA cleavage breaks, preventing the enzyme from functioning, which leads to cell death. To enable the design of further molecules, the team needed to know the molecular structure of the new molecules bound to gyrase.

They used beamline I04 to evaluate the relevant potency of several NBTIs against gyrase. In addition, they solved the crystal structure of gyrase bound to one of the new inhibitors, revealing the existence of bifurcated halogen bonds between the enzyme and the inhibitor molecule - an unprecedented observation in a biological system. This new biochemical and structural information informs the intelligent design of new molecules for use in clinical medicine.

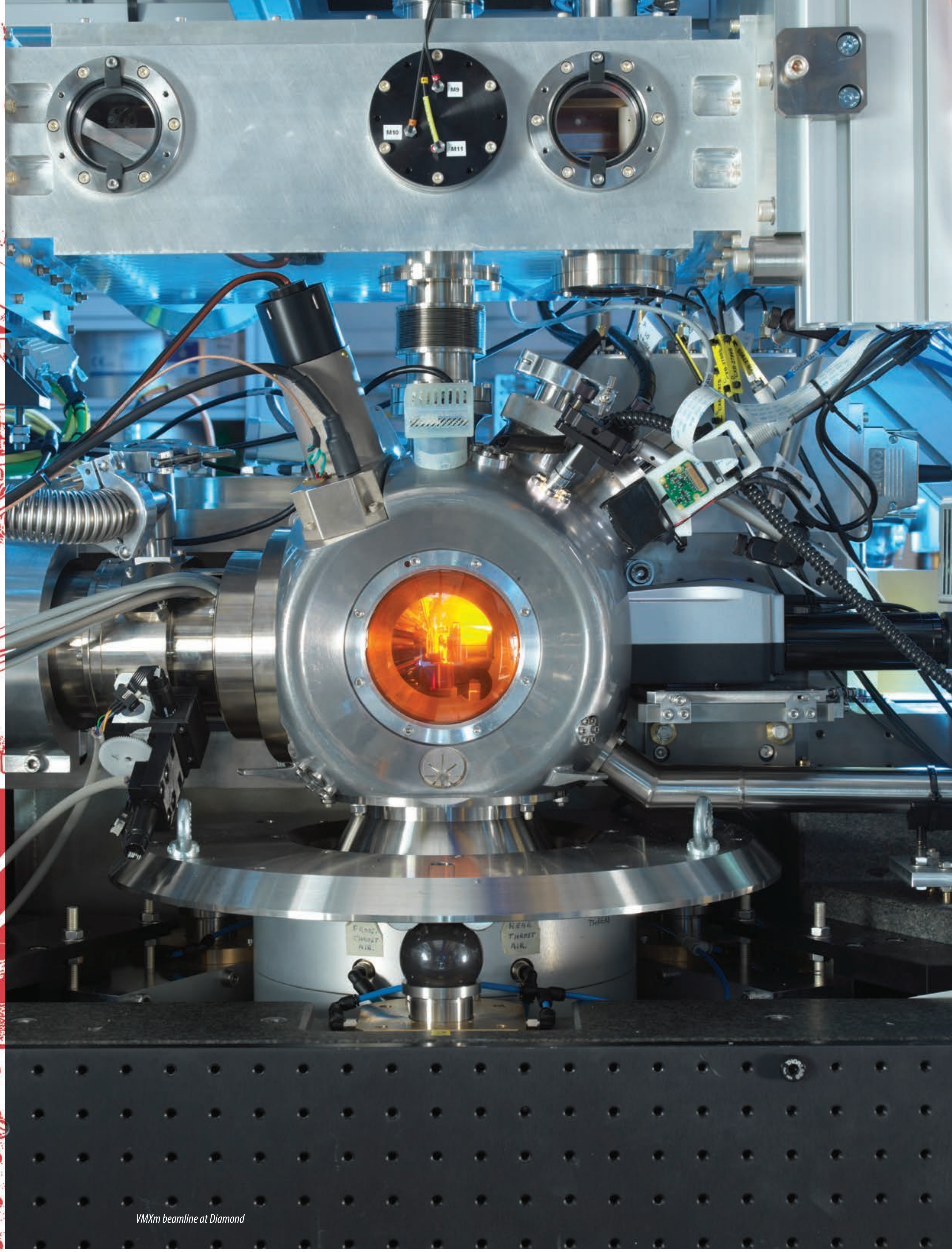
Kolarič A *et al.* DOI: 10.1038/s41467-020-20405-8

Developing new tools for neuroscience

Archaerhodopsin-3 (AR3) is a light-sensitive protein expressed by the bacterium *Halorubrum sodomense* that is found in the Dead Sea bordering Israel and Jordan. Mutants of the protein are routinely used in neuroscience experiments to selectively silence individual nerve cells and detect changes in transmembrane voltage. However, these mutants are designed without knowledge of the protein's structure. An international team of researchers were able to visualise the photoreceptor at unprecedented resolution using the I24 and B23 beamlines and reported the first ever structure of the ground state of AR3.

The team was also able to crystallise the photoreceptor in a second conformation, a desensitised state that AR3 adopts in the prolonged absence of light. The superb resolution achieved for these AR3 structures is among the highest for a wild-type membrane protein deposited in the Protein Data Bank. The high-resolution crystal structures were essential for understanding the workings of the protein. These data provide structural biologists and protein engineers with the 'blueprints' to AR3, opening the way for the development of new tools and methodologies in the fields of neuroscience, cell biology and beyond.

Bada Juarez JF *et al*. DOI: 10.1038/s41467-020-20596-0



VMXm beamline at Diamond

Biological Cryo-Imaging Group

The Biological Cryo-Imaging Group brings together dedicated facilities for X-ray, light, and electron microscopy at Diamond Light Source. The electron Bio-Imaging Centre (eBIC) is the national centre for Cryo-Electron Microscopy (cryo-EM) in the UK and provides a range of capabilities and supporting facilities for cryo-EM and Correlative Light and Electron Microscopy (CLEM). Beamline B24 hosts a full field cryo-transmission X-ray microscope dedicated to biological X-ray imaging and has also established a cryo super resolution fluorescence microscopy facility, which is a joint venture between Diamond and the University of Oxford. It provides a unique platform for correlative light and X-ray microscopy, and cryo-EM. A recent external beamline review rated the B24 facility as excellent and world leading. In particular, the panel commended the beamline team on establishing an internationally unique correlative platform combining two high-end 3D cryo-microscopy techniques (Cryo Soft X-ray Tomography (Cryo-SXT) and Cryo Structured Illumination Microscopy (Cryo-SIM) with user friendly protocols.

Recent studies on B24 and eBIC this year include those to understand the detailed 3D structure of human cells, insights into cell division to tackle cancer cells and determining the structure of key proteins involved in the degeneration of nerve fibres.

Understanding 3D cell structure

It has previously been challenging for researchers to produce 3D, nanometer resolution images of filamentous actin, which is the finest and most dynamic component of the cytoskeleton in cells. Previous imaging of one set of cellular features using one microscope has invariably missed relevant features that can only be captured by different microscopy methods and correlation of imaging data across methods has proved difficult.

New techniques have been developed at Diamond to allow researchers to have a greater understanding of the role of actin filaments in many cellular functions such as intracellular transport, membrane remodelling and cell motility. The research team used beamline B24 ensuring the capture of the native ultrastructure in human fibroblasts without the need for chemical or mechanical modification. They then combined two new and powerful imaging techniques (Cryo-SXT and Cryo-SIM) to capture the 3D ultrastructure of the cell and the chemical localisation of filamentous actin, and to correlate these data in 3D. Their findings confirm the applicability of high-resolution cutting-edge 3D cryo-microscopy methods at beamline B24 in the study of biological processes.

Koronfel M *et al.* DOI: 10.1107/S2059798321010329

Determining the structure of cell division mediators

Inadequate cell division during mitosis can transform normal growing cells into cancer cells. The protein separase is an important mediator of this complex cell division process and is responsible for the faithful and timely cleavage of the cohesin ring which effectively glues together the sister chromatids inside the cell before mitosis takes place.

An international team of researchers using Cryo-EM at eBIC were able to determine the structure of human separase and its two inhibitory binding partners (securin or the CDK1-cyclin B1-CKS1 (CCC) complex). The structure of separase bound to securin confirmed previous studies but the structure of the separase-CCC complex revealed novel and fascinating aspects of separase regulation which mediate binding to specific separase sites. This work highlights the many important roles of separase in cell cycle progression and illustrates the power of Cryo-EM to visualise disordered regions that provide crucial insights into the function of enzyme regulation.

This pioneering work may allow new drugs to be sourced to block these sites to prevent the premature chromosome separation which is often observed in cancer cells.

Yu J *et al.* DOI: 10.1038/s41586-021-03764-0

Tackling nerve fibre degeneration

SARM1 (sterile alpha and TIR motif 1) is a key player in nerve fibre (axon) degeneration and a promising new therapeutic target for neurological diseases, including peripheral neuropathies and traumatic brain injury. In healthy nerve cells, SARM1 is present but inactive. Disease and injury activate SARM1, which results in rapid breakdown of the 'helper molecule' nicotinamide adenine dinucleotide (NAD^+) and ultimately destruction of the axon. Defining the molecular mechanisms upstream and downstream of SARM1 enzyme activity could yield potential drug targets against neurodegenerative diseases.

Using data collected at eBIC and other facilities the researchers were able to determine the structure of SARM1 in its inactive state. They then used X-ray crystallography, to determine a structure of the regulatory domain of *Drosophila* SARM1 in complex with an allosteric activator. Together these structures explain how the protein maintains an inhibited (off) state and the critical steps required for its activation. These results allowed them to propose a molecular mechanism for SARM1 activation. They also provide a molecular framework for the design of novel drugs targeting a wide range of neurodegenerative diseases.

Figley MD *et al.* DOI: 10.1016/j.neuron.2021.02.009

Structures and Surfaces Group

The Structures and Surfaces Group includes four beamlines, each consisting of multiple end-stations that are optimised for a specific type of experiment: I05 (Angle Resolved Photoelectron Spectroscopy – ARPES), I07 (Surface and Interface X-ray Diffraction), B07 (Versatile Soft X-ray Scattering – VERSOX), and I09 (Atomic and Electronic Structure of Surfaces and Interfaces). They offer a variety of techniques to examine the atomic scale structure, chemical nature and electronic state at buried interfaces or the surfaces of materials. The group continue to benefit from many key developments during remote working restrictions, such as enhanced automation, but recognise that many of the more complex studies rely on the expertise of the user groups, especially for sample preparation and experiment planning. It has also been a busy year for beamline upgrades and a strategic focus on outlining the facilities to be offered as part of the Diamond-II programme. The important role that surfaces and interfaces play in broader research areas such as battery technology, photovoltaic structures, and catalytic/electrochemical systems under *operando* conditions are key drivers for these developments.

This year's studies include improving the design and performance of industrial catalysts, developing energy efficient information technologies, and designing next generation electronic devices using 2D polymers.

Improving catalyst design and performance

Hydrogen spillover is an important phenomenon during catalysis which facilitates the improvement of hydrogen storage properties of porous nanomaterials and affects the reaction performance of multiphase catalytic reactions. It typically takes place over a metal on the support structure where a dihydrogen molecule undergoes dissociative chemisorption to form hydrogen atoms on the metal active centre, followed by the migration of atomic hydrogen from the metal surface to the catalytic support. To date, there has been no direct visualisation of this process at an atomic level, and the interchangeable pathway between the various hydrogen species on the metal/support is still unknown.

A team of researchers from the Wolfson Catalysis Centre at the University of Oxford investigated the process using the Versatile Soft X-ray (VerSoX) beamline B07, which can probe the oxidation state change of the catalyst in real-time and monitored the change in concentration of the surface hydrogenic species on the support structure under reaction conditions. This is critical to determining the electronic structure and the surface composition of the catalyst. The results provide important guidance for the future improvement of hydrogenation catalysts.

Wu S *et al.* DOI: 10.1021/jacs.1c02859

Developing energy efficient information technologies

Mobile devices waste much energy in the form of heat. Our ever-growing need to access, process and store information makes it increasingly important that we develop new, more energy-efficient technologies. These are currently based on electron charge, but one avenue for future development is to use the electron spin - an intrinsic magnetic property of electrons - to achieve more energy-efficient information processing. Theoretical predictions suggest that certain magnetic materials exhibit spin polarised electrons at their surface with unusual 'topological' properties. In the future, such topological surface electrons might enable information processing without heat loss in electronic devices.

An international team of researchers used Angle-Resolved Photoelectron Spectroscopy (ARPES) measurements on beamline I05 to verify these predictions. This allowed ARPES measurements with high energy resolution and a small beam spot. The experiments confirmed that the compounds $MnBi_4Te_7$ and $MnBi_6Te_{10}$ display spin-polarised, topological surface electrons. In the future, although significant challenges lie ahead, further optimisation of such materials could provide applications in electronic high-precision metrology (the scientific study of measurement) without the need for external magnetic fields.

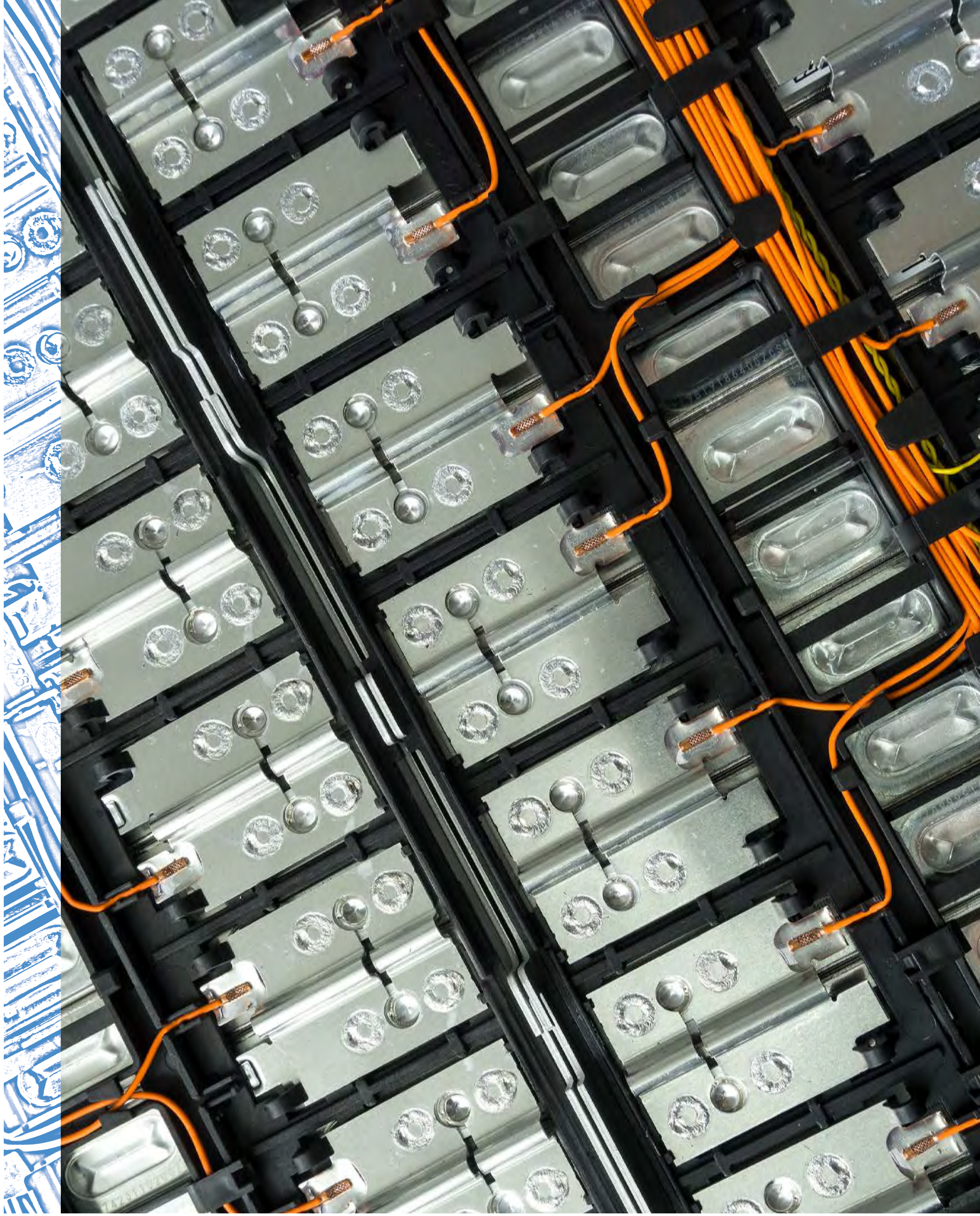
Vidal RC *et al*. DOI: 10.1103/PhysRevLett.126.176403

Designing new generation electronic devices

Researchers continue to investigate new materials for potential applications in phototransistors, photodiodes, and memory devices. 2D polymers (2DPs) are a new generation of atomically/molecularly thin organic 2D materials, with repeated units linked via covalent bonds with long-range order in two distinct directions, that have recently emerged as interesting candidates in this area. Synthetic van der Waals heterostructures (vdWHs) are made by stacking different 2D crystals and offer great potential due to their tuneable physicochemical properties and designable functions.

However, it has been challenging to synthesise structurally defined 2DPs and assemble them precisely with other 2D materials in a defined vdWH sequence. German researchers have now demonstrated a general but reliable on-water synthesis and assembly strategy for preparing large-area 2D polyimide-graphene vdWH. The team used Grazing Incidence Wide-Angle X-ray Scattering (GIWAXS) on the Surface and Interface Diffraction beamline I07 to demonstrate the successful formation of vdWHs. The on-water surface synthesis approach holds promise as a general method for preparing organic-inorganic vdWHs.

Liu K *et al.* DOI: 10.1002/anie.202102984



DIAMOND LIGHT SOURCE ANNUAL REVIEW 2021/22

Magnetic Materials Group

The Magnetic Materials Group develops and uses a range of polarised X-ray probes, including Resonant Inelastic X-ray Scattering (RIXS), Resonant Elastic X-ray scattering (REXS), X-ray Absorption Spectroscopy (XAS) and PhotoEmission Electron Microscopy (PEEM) on beamlines I06, I10, I16, and I21 to tackle a variety of challenges and opportunities in exploiting the changes in magnetic properties of materials. Areas covered include topological states of matter, superconductivity, spintronics (the study of electron spinning and associated magnetism in solid state devices), two-dimensional systems, skyrmions (particles that may provide new forms of data storage) and multiferroics. Over the last year, our research community has used these probes to gain fundamental insights into new materials and how to tune materials to discover exotic new properties.

Research from this group this year has included developing new methods of fast and energy efficient computing storage and discovering new superconductors that operate at closer to room temperature.

Developing a new approach to computing memory

So-called 'racetrack non-volatile memory', developed by IBM, is one of the most innovative information technology concepts to emerge in the past two decades. It works by creating tiny 'disturbances' in an otherwise uniform magnetic medium, which are stored and retrieved by moving them along a track when needed. The difficulty of stabilising the disturbances and propelling them at high speed has prevented this concept from reaching the market.

Previous work at Diamond showed that the antiferromagnetic material α-Fe_2O_3 supports a family of disturbances (known as textures) that are potentially very stable. The team, from institutions in Singapore, the UK and USA, is now investigating how to gain full control over the formation of these textures. Antiferromagnetic textures are difficult to visualise, and the team used the powerful imaging techniques on beamline I06 to map the antiferromagnetic textures in exquisite detail. Using X-ray Photo-Emission Electron Microscopy (X-PEEM), they acquired images of these textures over a field of view of a few microns.

This is potentially a ground-breaking application for fast and energy-efficient computing. Understanding the formation and control of such textures and their application in energy efficient computing represents a significant milestone in the field of information and communication technology.

Jani H *et al.* DOI: 10.1038/s41586-021-03219-6

Sourcing the next generation of information storage

A South Korean research group is also using Diamond facilities to look for the next generation of information carriers. Ideal candidates need to be stable against external disturbances such as temperature or field fluctuations, allow for low-power manipulation and easy readout, and have a small footprint that allows for high packing densities. Magnetic skyrmions are stable whirling topological configurations in magnetic materials that make them promising candidates for the next generation of computer storage devices. Crystalline magnetic skyrmions are among the most promising replacements for conventional ferromagnetic computer memory.

The researchers looked for direct evidence of the existence of magnetic skyrmions in ultra-thin $SrRuO_3$ films by using temperature-dependent Resonant Elastic X-ray Scattering (REXS) on beamline I16. The team observed exciting Hall effect data which is the fingerprint of magnetic skyrmions. Their results showed a new magnetic order with the same temperature dependence topological Hall effects, which they believe corresponds to skyrmion lattice structure. This new quasi quantum particle could soon be used for magnetic racetrack memory.

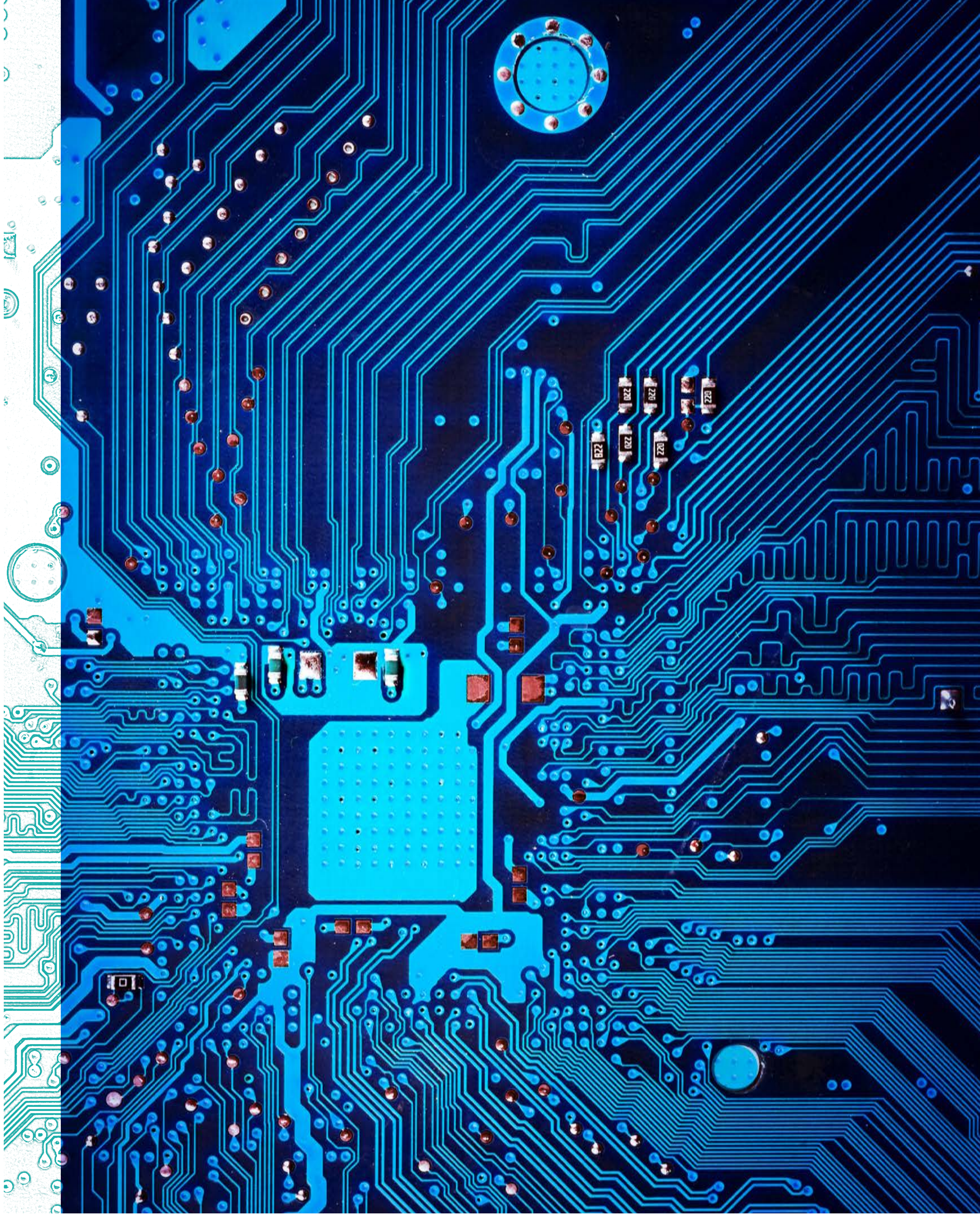
Sohn B *et al.* DOI: 10.1103/PhysRevResearch.3.023232

Discovering new superconductors

Scientists have been searching for materials that are superconducting at closer to room temperature since the 1986 discovery of cuprates (copper oxide materials that superconduct at high temperatures). The discovery of infinite-layer nickelate (nickel oxide) superconductors has drawn a lot of attention. An important research focus has been whether nickelate superconductors are strongly correlated electronic systems like cuprates.

A team of researchers from the SLAC National Accelerator Laboratory, Stanford University and Diamond investigated the structure of magnetic excitations in the nickelate. They recently made the first measurements of magnetic excitations that spread through the new material. They collected data on beamline I21 using the Resonant Inelastic X-ray Scattering (RIXS) instrument. RIXS is presently the only instrument that can extract magnetic excitations in the momentum space from thin film samples. The high energy resolution and high photon flux available at I21 also played a vital role in the success of this experiment. Early results provide direct experimental evidence that support the possible exhibition of strong correlations in infinite-layer nickelates. This work reveals the microscopic electronic structures of the nickelate and will inform the future design and synthesis of new unconventional superconductors.

Lu H *et al.* DOI: 10.1126/science.abd7726



Imaging and Microscopy Group

The Imaging and Microscopy Group brings together eight experimental facilities (I08, I08-1, DIAD, I12, I13-1, I13-2, I14 and the electron Physical Science Imagine Centre [ePSIC]), which use electrons and X-rays to image samples under different experimental conditions across a diverse range of length scales and time scales. The soft X-ray ptychography branchline I08-1 and DIAD the dual imaging and diffraction beamline entered their first year of operations. Together, these beamlines bring new world-leading tools to the imaging community, and we are entering an exciting phase of designing and performing new experiments with the user community which exploit these new capabilities. The ability to extract image sample properties in minute detail lends itself to a wide range of scientific areas, from chemistry and catalysis to environmental science, materials science, biology, medicine, and cultural heritage.

Studies from the group this year include those to improve the design and efficiency of semiconductors and optoelectronics used in many devices, and solid-state batteries for electric vehicles.

Improving semiconductor efficiency

Lead halide perovskites are a family of synthetic semiconductor materials used for solar panels, LEDs, displays, sensors, and many other applications. However, these materials have limited stability over time and can leach toxic chemicals into the environment. For example, $CsPbI_3$ is sensitive to temperature, air, light, and water, limiting its practical applications. An international team of researchers addressed this challenge by encapsulating the material in a matrix made of a new type of glass derived from metal-organic frameworks, using a technique called liquid phase sintering. The composite showed orders of magnitude higher efficiency for light emission and significantly enhanced stability, providing high-quality light for more than a year.

The research team used advanced tools to understand the new material's performance. They used the E02 microscope at ePSIC to see individual nanometre scale crystals and determine the type of crystal within the glass. They also used Scanning Transmission Electron Microscopy (STEM) to examine the material and document how the glass preserves and locks in the correct, light-emitting perovskite crystals. These results explain how to make long-lasting light-emitting glass composites, while preventing toxic lead leaching and improving the mechanical properties of the material to prevent breakage.

Hou J *et al.* DOI: 10.1126/science.abf4460 DOI: 10.1126/science.abf4460

Refining solid-state battery design

High energy density solid-state batteries, with ceramic solid electrolytes and lithium metal anodes, promise to address the range anxiety and safety issues associated with current electric vehicles. However, practical application of solid-state batteries is limited by electrolyte cracking and short circuits at high charging rates due to the propagation of lithium filaments called dendrites through the ceramic electrolyte.

An international team led by the University of Oxford conducted a study aimed at improving the design of ceramic electrolytes to provide fast-charging solid-state batteries. They used beamline I12 to image dendrite-induced cracks using high spatial resolution X-ray Computed Tomography (XCT) and located lithium dendrites by spatially mapped X-ray diffraction.

This combination of techniques provided reliable evidence of the correlation between cracks and dendrite growth into the cracks and showed the exact cause of the short circuits seen in these batteries at high charging rates. This work suggests that an effective way to prevent dendrite growth in solid-state batteries is to inhibit the development of dry cracks in the ceramic electrolyte. Therefore, strategies that toughen the ceramic electrolyte, such as fibre reinforcement and transformation toughening, may help to enable fast-charging, safe and highly energy-dense solid-state batteries.

Ning Z *et al.* DOI: 10.1038/s41563-021-00967-8

Improving anticancer drugs

Transition metal catalysts have potential as therapeutic agents to treat cancer and other diseases. However, there is a need to improve the design of these catalysts to make them more efficient, so they can be used in lower doses, and hasten progress towards clinical use. Researchers from the University of Warwick have designed a series of advanced organo-osmium catalysts that can transform an essential ketone in cell metabolism inside cancer cells. This can cause selective destruction of cancer cells, but not healthy cells. Using synchrotron X-ray Fluorescence, researchers can track the catalysts in cancer cells and observe how long they remain intact and active.

The Hard X-Ray Nanoprobe beamline (I14) allowed the team to study biological samples with a range of X-ray imaging and spectroscopic techniques using a nano-focused photon beam. This provided valuable insight into the distribution and chemical properties of the metal complexes inside cells. The results obtained suggest a strategy for improving the design of catalytic organo-osmium anticancer drugs. This work also demonstrated the wider potential of experimental approaches using X-ray based techniques for the fields of chemical biology and medicinal chemistry. This approach can contribute to the design and development of new classes of transition metal complexes as therapeutic and biotechnological tools.

Bolitho EM *et al.* DOI: 10.1002/anie.202016456

Crystallography Group

The Crystallography Group comprises the High-Resolution Powder Diffraction beamline (I11), the Extreme Conditions beamline (I15), the X-ray Pair Distribution Function (XPDF) beamline (I15-1), and the Small-Molecule Single-Crystal Diffraction beamline (I19). Having these beamlines together in one science group allows us to fully exploit the technical and scientific expertise within its teams to provide the basis for future development and pioneering experiments. The Group's beamlines use various techniques to study structural properties of crystalline, amorphous, and liquid materials in different conditions. These powerful facilities are used in a wide range of science disciplines, including Condensed Matter Physics, Chemistry, Engineering, Earth and Materials, and Life Sciences. Studies in the past year have included improving effectiveness of photocatalysts, developing new battery materials and molecular knotting technologies.

Improving the efficiency of photocatalysts in water splitting

Materials containing titanium dioxide (TiO_2) powder have been widely studied as efficient photocatalysts for splitting water into its constituent parts and are used in many technological applications such as fuel cells, solar energy production, and catalysis. Their benefits include low cost, photo-responsivity, earthly abundance, and chemical/thermal stability. The recent breakthrough of nitrogen-doped TiO_2 shows an impressive visible-light absorption for photocatalytic activity. Although their electronic and optical properties have been extensively studied, the structure-activity relationship and photocatalytic mechanism remain ambiguous.

Researchers from the University of Oxford performed structural characterisation of nitrogen-doped TiO_2 using X-ray powder diffraction with data collected at beamline I11. They identified a new cubic titanium oxynitride phase for highly-doped anatase TiO_2, which provides important information on the fundamental shift in absorption wavelength, leading to excellent photocatalysis using visible light.

These results show that visible light can drive efficient photocatalytic water-splitting over nitrogen-doped TiO_2, yielding plentiful hydrogen gas at elevated temperatures. Crucially, the absorption profile is shifted to longer wavelengths relative to undoped TiO_2, which absorbs primarily in the ultraviolet region. Strong absorption of visible light enables more complete and effective use of the solar spectrum.

Foo C *et al.* DOI: 10.1038/s41467-021-20977-z

Developing new materials for electric car batteries

The demand for lithium-ion batteries in the automotive industry is increasing rapidly and new generation batteries using affordable materials are urgently needed. A class of transition metal oxides are cost-effective candidates for electrodes but there has been limited understanding of how these materials change during battery cycling.

Researchers from the University of Oxford used beamline I15-1 to characterise the nanoscopic phases present in the battery materials. The beamline's high flux and high energy X-rays, together with its optimised *in operando* electrochemistry setup, allowed the researchers to collect high-quality pair distribution function data. This was crucial for investigating any nanostructured components and their phase behaviours in real time.

Results of the study provided new mechanistic understanding of how these materials react and showed the origin of their slow electrochemical performance, providing new insights into effective strategies for further development. In addition, the study reported the experimental observation of the non-equilibrium metal monoxide polymorphs for the first time. This opens exciting new avenues for electrochemically-assisted synthesis to explore non-native metal oxides with new functionalities.

Hua X *et al.* DOI: 10.1038/s41467-020- 20736-6

Designing new materials with molecular knots

Knots have been used for thousands of years to create tools and materials. They also play an important role at the nanoscale and are found in DNA and proteins, where they profoundly impact their stability and biological activity. Synthetic polymer chains also spontaneously tie into knots with the resulting effect determining macroscopic material properties such as stiffness and viscosity.

The ability to knot molecular-sized threads, approximately 100,000 times thinner than a human hair, could make incredibly strong novel materials. These knots have unique molecular structures that have already been shown to catalyse chemical reactions, act as sequestering agents and kill cancer cells. However, methods of knotting such small threads are lacking, so researchers from the University of Manchester have developed a new technique for weaving at the molecular scale.

They identified a suitable template that could control the weaving process by guiding the strands into a grid structure and used single crystal X-ray diffraction on beamline I19 to probe the relative positions of molecular strands. This research provides new understanding of the value of molecular knotting and new strategies to develop molecular knotted materials.

Leigh DA *et al.* DOI: 10.1038/s41557-020-00594-x

Spectroscopy Group

The Diamond Spectroscopy Group consists of four beamlines: the Microfocus Spectroscopy beamline (I18), the Core EXAFS beamline (B18), and the two independently operating branches of the Versatile X-ray Absorption Spectroscopy beamline, I20-Scanning and I20-EDE. These spectrometers are highly complementary, most notably in the energy ranges they cover, the size of their focussed beam spots, and the time resolutions they can reach. This complementarity means that they can support research across many different scientific disciplines, from chemistry and catalysis through materials science, condensed matter physics, environmental and life science, and cultural heritage. Two new flagship beamlines will be added to the Group as part of the Diamond-II programme: SWIFT (Spectroscopy WithIn Fast Timescales) is a high flux beamline optimised for the study of samples under operando conditions, and BERRIES (Bright Environment for x-ray Raman, Resonance Inelastic and Emission Spectroscopies), that will offer two new techniques to the Diamond user community: pink-beam X-ray Emission Spectroscopy (pink-XES) and X-ray Raman Scattering (XRS).

This year's studies included improving essential trace element yield in crops, optimising propene production from methanol, and designing new catalysts with metal-organic frameworks.

Optimising selenium supplementation in crop plants

Selenium is an essential trace element for human health and is taken in through eating appropriate foods such as wheat. Regions with low soil selenium levels provide inadequate dietary intake, and this affects up to 14% of the world's population who remain at risk of developing chronic degenerative diseases. Soil fertilisation (biofortification) with selenium is practiced in different parts of the world but high levels can hamper the normal development of plants.

A plant biostimulant can significantly reduce the stress experienced by wheat during selenium-biofortification processes. However, little was known about the effect of the biostimulant in the selenium metabolisation pathways. A Spanish research team investigated selenium present in wheat grains using beamline I18 to gather data on the distribution of the elements and the chemical species present. The study showed that the biostimulant has a key role in enhancing both the number of grains produced per spike and their dry biomass without hindering the selenium enrichment process. Based on the successful results on wheat plants, similar enrichment studies are planned on other plants such as alfalfa. This information will be useful to minimise both plant toxicity and economic cost and move towards more effective and plant-healthy selenium supplementation.

Xiao T *et al.* DOI: 10.1016/j.plaphy.2021.01.025

Improving propene production

Propene is a key compound used in the production of a wide range of chemicals. With rapidly growing demand, the world faces a shortage of this crucial ingredient unless more efficient production methods can be developed. Commercial methanol-to-propene (MTP) plants use zeolite catalysts (ZSM-5 and SAPO-34) to produce propene from methanol. However, this process is poorly understood and produces a range of by-products, such as coke which results in low propene selectivity and rapid catalyst deactivation. Investigations of the process and development of more selective and stable catalysts are important goals for ongoing MTP research.

A team from the University of Manchester synthesised a new zeolite and used beamline I20-EDE to study the MTP reaction. They also used complementary measurements on beamline I11 to examine the configurations of adsorbed methanol molecules in zeolite pores. The results show that the new zeolite offers remarkable propene selectivity (51%), and catalytic stability (>50 hours) at full methanol conversion. Combining *in situ* synchrotron X-ray powder diffraction and X-ray absorption spectroscopy at Diamond with inelastic neutron scattering, the team was able to uncover key details of the process to add to fundamental understanding. This work will help develop sustainable manufacturing techniques using renewable resources such as biomass and CO_2.

Lin F *et al.* DOI: 10.1038/s41467-021-21062-1

Assessing metal organic frameworks as catalysts

The presence of metal species that can easily exchange their oxidation states is of paramount importance in the field of catalysis and photocatalysis, among others. Metal-organic frameworks (MOFs) are ideal candidates for these processes, and their synthesis is crucial if they are going to progress from laboratory curiosity to real applications.

Researchers are developing synthetic routes to prepare bimetallic MOFs with redox properties. However, the preparation and characterisation of these mixed-metal MOFs are challenging. To understand the success of the synthesis and the MOFs' properties, the local structure of the metal must be fully understood. A Spanish group used X-ray Absorption Spectroscopy on beamline I20 to define the local structure of the metal *in operando*. Using their results, the team has found a synthetic route to prepare true-mixed metal MOFs to modulate the crystal morphology and the electronic nature of the metal cations. Their results give us a new way to prepare bimetallic redox MOFs, which have the potential to be applied as catalysts in many different reactions, including selective hydrogenation, oxidation or Meerwein-Ponndorf-Verley reactions.

Ronda-Lloret M *et al.* DOI: 10.1002/adfm.202102582

Soft Condensed Matter Group

The Soft Condensed Matter (SCM) Group is comprised of four beamlines at Diamond: High Throughput Small Angle X-ray Scattering (SAXS) (B21), Multimode Infrared Imaging and Microspectroscopy (MIRIAM) (B22), SAXS and Diffraction (I22) and Circular Dichroism Microspectroscopy (B23). This unique portfolio of instruments enables studies of non-crystalline materials at nano- to meso-scale resolutions that include two-dimensional thin-films (photovoltaics, OLEDs), living mammalian cells, three-dimensional matrices (metal-organic frameworks, gels, and waxes) and nanoparticles in non-crystalline states. SCM science is "the science that underpins continued improvements to quality of life" and was critical to the rapid development of the COVID vaccines from Pfizer-BioNTech and Moderna. These vaccines are lipid nanoparticles encapsulating a modified messenger RNA stabilised in a non-crystalline environment. The SCM user community is international, with nearly 70% of our peer reviewed allocated beamtime to UK users with the remaining time shared between other international users.

Studies this year have included those developing new drugs that could treat cancer and muscle weakness and designing new materials to limit environmental pollution.

Improving the design of new anticancer drugs

Numerous pharmaceutical compounds have been developed over the years to tackle a variety of cancers. These drugs, including platinum- and palladium-based agents have aimed to improve antineoplastic activity and decrease drug resistance and deleterious side effects. However, the low bioavailability and toxicity of these so-called metallodrugs, and the development of resistance to them, remain severe limitations in cancer treatment.

To overcome these drawbacks, a research team from Portugal aimed to understand the mechanisms underlying drug transport and resistance which control the agent's biodistribution and availability at its pharmacological target. They used beamline B22 to monitor biomolecular binding and conformational rearrangements, and a combination of coherent synchrotron-radiation TeraHertz spectroscopy and inelastic neutron scattering to investigate two platinum- and palladium-polyamine agents that have yielded promising results toward some types of human cancers. Their results revealed an impact of the agents on protein structure, conformational behaviour, and overall flexibility, similar to former observations on the effect of this type of metallodrugs on DNA. These findings are expected to contribute to a better understanding of the drug's mode of action and will assist in the design of improved anticancer agents with higher bioavailability at the target, lower acquired resistance and decreased adverse side effects.

Batista de Carvalho L *et al.* DOI: 10.1016/j.bpj.2021.06.012

Developing materials to break down pollution

Some pollutants such as the organophosphates used in pesticides persist in the environment. Designing self-decontaminating materials with enzymes to break down long-lasting pollutants could alleviate environmental pollution or even form smart personal protective equipment.

Researchers have developed a method to incorporate enzymes into materials such as plastics or polymers by modifying the surface of an enzyme with a mixture of anionic and cationic polymer surfactants. To investigate their compatibility with manufacturing fabrication techniques, an international research team studied the protein structure to ensure the enzyme remained folded and active under the conditions required for material fabrication. The unique B23 beamline facilities offered the power and reliability to assess the protein secondary structure of the solvent-free enzymes. The beamline also allowed accurate characterisation of the thermal dependent unfolding transition of the melts above 100 °C up to 250 °C, unattainable with bench-top CD instruments. Temperature-dependent Wide-Angle X-ray (WAXS) studies were conducted on beamline I22 to investigate the transition of the conjugates from lyophilised powders to annealed melts. This research showed that these fabrication methods allowed organophosphate-degrading enzymes to retain their active structure and were reproducible, leading the way for potential commercial application.

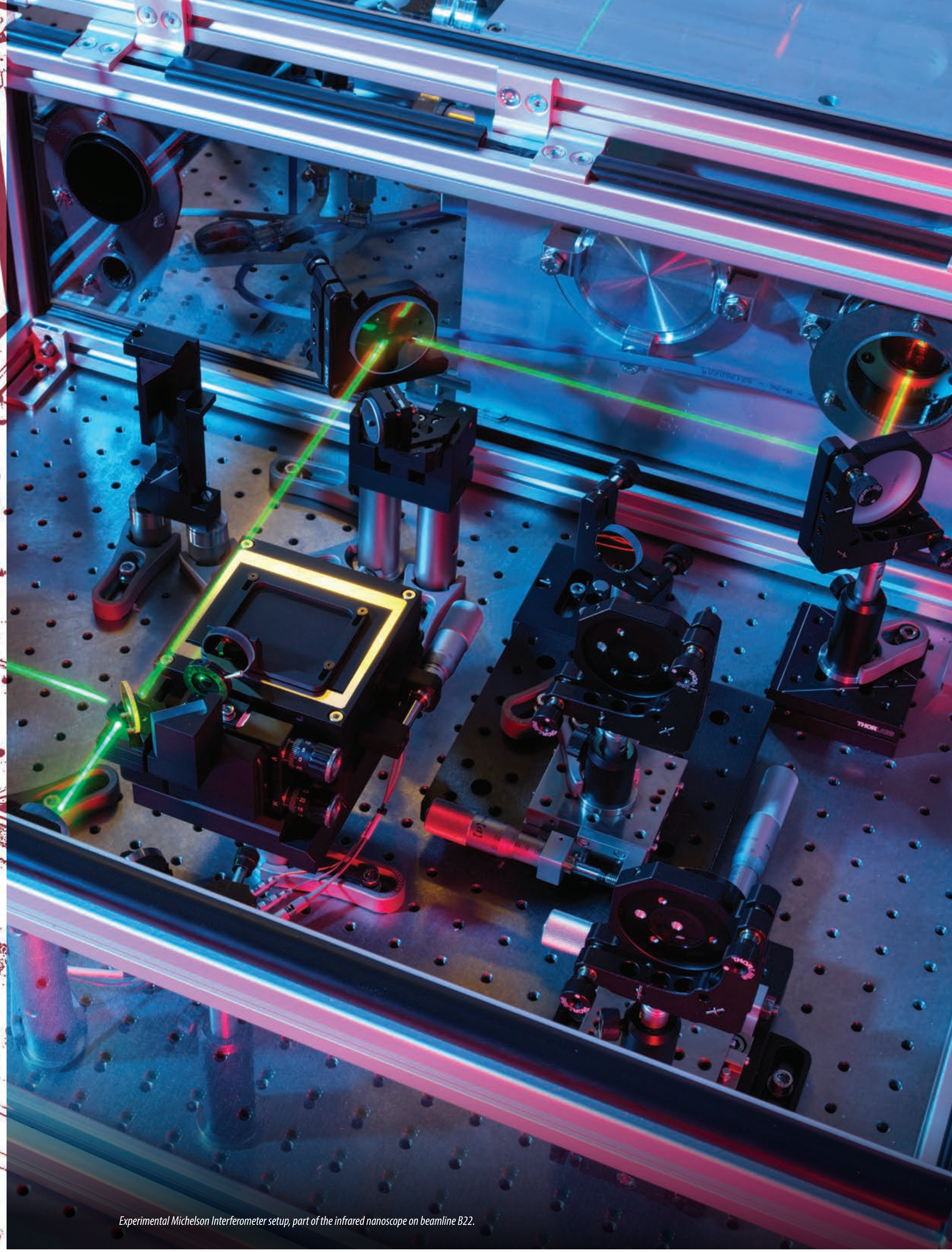
Zhang WH *et al.* DOI: 10.1021/ acsapm.1c00845

Developing drugs to improve muscle strength

Muscle weakness caused by disease and ageing significantly impacts quality of life. Although these changes are generally associated with loss of muscle mass, the intrinsic strength of a given mass of muscle is also reduced. The basic mechanical response of a skeletal muscle cell to the electrical stimulus it receives from the central nervous system is called a twitch. The structural changes that control muscle activation can be followed by measuring the diffraction of X-rays by the motor arrays, but muscles diffract X-rays very weakly, and these experiments require an extremely bright X-ray source combined with a sensitive X-ray video camera that can record 200 diffraction patterns every second. Beamline I22 is one of few facilities worldwide that meet these demanding requirements.

A team from King's College, London was able to uncover the molecular structural factors that limit the strength of skeletal muscle in its normal twitch response. This pioneering work allows those structures to be used to design and test potential drugs that could increase muscle strength. Almost identical mechanisms operate to limit the strength of the heartbeat and could also be targeted to treat heart failure.

Hill C *et al.* DOI: 10.7554/eLife.68211



Experimental Michelson Interferometer setup, part of the infrared nanoscope on beamline B22.

Supporting International COVID-19 Research

Diamond has continued to give international COVID-19 researchers high priority access to beamtime throughout the year, despite lockdown restrictions. Over the past year, 530 shifts were delivered across all instruments for COVID-19 research. The work taking place at Diamond is grouped into projects developing understanding of the virus structure and function, new vaccine design and efficiency, new therapy and drug development.

Understanding how the virus operates

Several studies continued to develop detailed understanding of the SARS-CoV-2 viral mechanisms and structure. These fundamental research efforts have already resulted in the licensing of several vaccines which have been rolled out to millions around the world in rapid vaccination programmes. In addition, neutralising monoclonal antibodies (mAbs) have been developed.

A research group led by Professor Peijun Zhang maintained their work on unlocking the structure of the SARS-CoV-2 virus[1]. The team used the cryo-EM facilities at eBIC to investigate viral replication. Their approach gave a holistic view of SARS-CoV-2 infection from the whole cell to individual molecules. The study confirms the value of cryo-EM and soft X-ray tomography as techniques to investigate whole cell morphology. Professor Jonathan Grimes (Diamond Fellow) worked in collaboration with several Oxford University colleagues on two projects studying coronavirus mechanisms. The first aimed to improve understanding of the mechanism of coronavirus RNA capping which is poorly understood[2]. In the second study a group performed further characterisation of the virus using biochemical techniques[3]. This work highlighted domains that could be possible targets for antiviral drugs and identified several drugs and molecules that could be developed or re-purposed.

Efficacy of the vaccine

The rapid development of vaccines and mAbs against COVID-19 through intensive international collaboration has been one of the positive highlights of the pandemic. Although current vaccines elicit neutralising antibody responses to the virus spike derived from early isolates, new strains have emerged with multiple mutations. Many studies are assessing the impact of these therapies against the new variants of the virus and the ability of these different variants to evade antibody responses. Recent studies include data collected automatically at Diamond on macromolecular crystallography beamline I03.

A large international group studied the ability of mAbs and convalescent and vaccine sera to neutralise two Delta variant viruses that spread globally[4]. The group used beamline I03 at Diamond to determine the crystal structures of the variants. Although neutralisation of both viruses was reduced compared with earlier strains there was no evidence of widespread antibody escape.

The Titan Krios is a state-of-the-art fully automated electron microscope designed for rapid, stable, high-resolution data collection on frozen-hydrated samples.

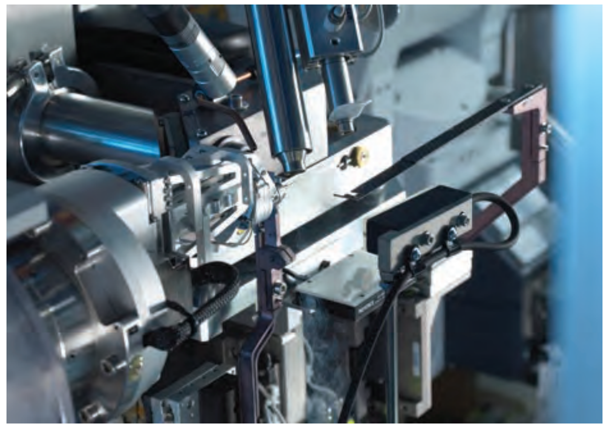


Image of beamline I03.

The Beta variant has been particularly difficult to neutralise using serum induced by the early pandemic. To understand this, an international collaboration performed a study to understand its antigenic landscape[5]. The study included an in-depth structure-function analysis of potent mAbs from volunteers infected with the Beta variant. Structural analyses took place using data gathered on beamline I03 to assist the development of future vaccination strategies. This group also performed analysis on different variants[6]. Structural analysis at Diamond showed that mAbs neutralise all three variants.

In another recent paper in *Cell* an international research group studied the neutralisation of Omicron by a large panel of sera collected from early infected individuals and those vaccinated with three doses of the Oxford/Astra Zeneca or Pfizer vaccines[7].

The study revealed Omicron to be structurally similar but the most antigenically distant variant and that the variant escaped neutralisation by most mAbs. However, the researchers showed that protection from severe infection will be maintained and that a third vaccine dose is effective in boosting neutralisation titres against Omicron.

Drug development (repurposing and new drugs)

To defeat the current pandemic and manage the impact of SARS-CoV-2 in the future, a combination of new drugs, repurposed drugs and other therapies will be required. Diamond is playing a key role supporting research groups around the world to develop effective therapies. Major screening studies are taking place to identify new drug candidates, repurposed antivirals are being investigated and there is ongoing development of vaccines to tackle new variants.

A research collaboration between Diamond, Exscientia (Oxford), Scripps Research Institute in California and Leuven University aimed to accelerate the path to clinical trials for potential antiviral treatments. The group conducted extensive experimental screens of the drug repurposing ReFRAME library[8] which identified two potential drug candidates, the caspase-1 inhibitor SDZ 224015 and tarloxotinib, a clinical stage epidermal growth factor receptor inhibitor. Diffraction data were collected from crystals cryo-cooled at Diamond with X-ray diffraction data collected at beamlines I04-1 and I24.

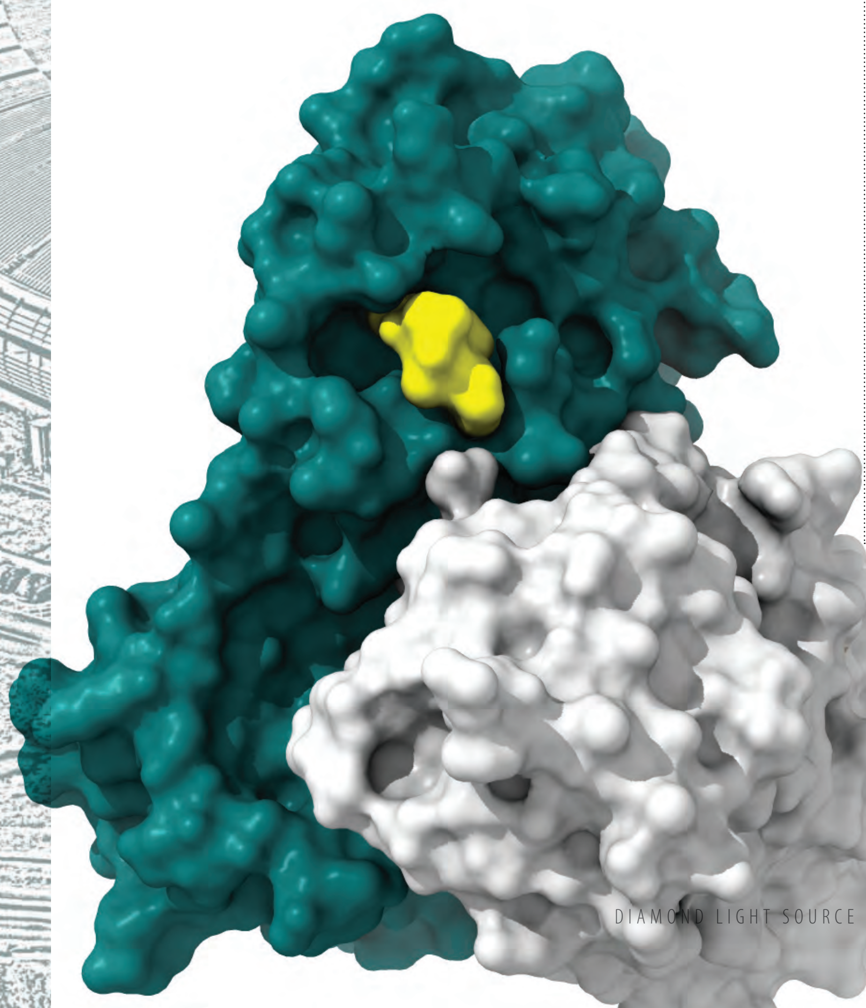
A collaboration between Diamond and Israeli research groups designed a computational pipeline to help identify irreversible inhibitors based on structures of targets with non-covalent binders[9]. The so-called *covalentiser* was developed to identify covalent analogues of non-covalent binders. The group used a pre-compiled database of *covalentiser* results to discover several covalent kinase inhibitors and a potent covalent COVID-19 protease inhibitor. Co-crystal structural data were collected on beamline I04-1 to confirm the computational model.

Other therapies

An international team continued their work on neutralising single domain antibodies (nanobodies) which have significant potential as an effective treatment against COVID-19[10]. Their small size and stability mean they can be formulated for respiratory administration with improved bioavailability, easier administration, and improved therapeutic compliance. Four nanobodies were found that neutralised the virus *in vitro* with picomolar potency. X-ray crystallography diffraction data were collected and processed at beamlines I03, I04 and I24 at Diamond. Cryo-EM results were obtained at eBIC. Treatment with a single dose of the most potent nanobody prevented disease progression in a hamster model. It was suggested that combinations of nanobodies targeting different epitopes may improve resilience in combating new variants of the virus.

References

1. Mendonça L. *et al*. DOI: 10.1038/s41467-021-24887-y
2. Walker A. *et al*. DOI: 10.1093/nar/gkab1160
3. Baddock H. *et al*. DOI: 10.1093/nar/gkab1303
4. Liu C. *et al*. DOI: 10.1016/j.cell.2021.06.02
5. Liu C. *et al*. DOI: 10.1016/j.chom.2021.11.013
6. Dejnirattisai W. *et al*. DOI: 10.1016/j.cell.2021.03.055
7. Dejnirattisai W. *et al.* DOI: 10.1016/j.cell.2021.12.046
8. Redhead M. *et al*. DOI: 10.1038/s41598-021-92416-4
9. Zaidman D. *et al*. DOI: 10.1016/j.chembiol.2021.05.018
10. Huo J. *et al*. DOI: 10.1038/s41467-021-25480-z



Crystal structure of SARS-CoV-2 M^{pro} with a pre-clinical candidate from the COVID Moonshot bound (shown in yellow). The COVID Moonshot, of which Diamond is a founding member, has received funding of £8 million from Wellcome, on behalf of the COVID-19 Therapeutics Accelerator to develop a globally accessible antiviral.

Integrated Facilities and Collaborations

As a world-leading centre for synchrotron science and a cornerstone of a world-class site for scientific discovery and innovation at Harwell, Diamond Light Source has powerful synergies with its neighbouring research institutes and beyond the campus, through collaborations and shared visions. The integrated facilities at Diamond present academic and industrial users with a one-stop-shop for research opportunities, enabling them to combine cutting-edge techniques and capabilities to advance their studies. Several partnerships are highlighted in this section.

Integrated Facilities

The Membrane Protein Laboratory

The Membrane Protein Laboratory (MPL) is a state-of-the-art facility for membrane protein research and is open to user applications from anywhere in the world. Scientists visiting the MPL are supported by state-of -the art equipment and our experienced scientists. Membrane proteins are important targets for biomedicine with over half of all medicines altering membrane protein function. Understanding the structure and function of these proteins in isolation will help us to develop new therapeutics to tackle disease.

The MPL has been awarded £1.5m of Wellcome funding to support its research for a further five years. The new funding will enable wider sample support for Diamond beamlines and microscopes and form a foundation for integrative membrane protein structural biology. Two recently published works detail the molecular basis of regulation of bacterial capsule assembly by Wzc[1] and a systematic study of small-scale transient expression of eukaryotic membrane proteins in Expi293F cells[2].

1. Yang Y. *et al.* DOI: 10.1038/s41467-021-24652-1
2. Krasnoselska GO *et al*. DOI: 10.1007/978-1-0716-1406-8_5.

Fragment screening (XChem)

Alongside the full return of the XChem user programme the XChem team has continued to support the COVID Moonshot, a global open science, structure enabled drug discovery campaign targeting the SARS-CoV2 main protease. Researchers were able to discover a novel chemical scaffold and developed it into orally bioavailable inhibitors with clinical potential within two years. These inhibitors are currently being evaluated in pre-clinical studies funded by an £8 million award from Wellcome on behalf of the COVID-19 Therapeutics Accelerator[1].

It has been proposed as part of the Diamond-II project to build a new beamline capable of underpinning the next revolution in rational drug discovery over the coming decade. This will allow increased throughput of XChem to both meet user demand for ultra-high-throughput fragment screening and to exploit new experimental modalities. This new beamline K04 will be a flagship project of Diamond-II with building taking place in the run up to the Diamond dark period, minimising the downtime of a key UK infrastructure.

Reference

1. https://www.diamond.ac.uk/Home/News/LatestNews/2021/27-09-21.html

Highlighted publications:

- The COVID Moonshot Consortium. DOI: 10.1101/2020.10.29.339317
- Singh AK *et al.* DOI: 10.1038/s41467-021-27409-y
- Piticchio SG *et al*. DOI: 10.1021/acs.jmedchem.1c01108
- Bajusz D *et al.* DOI: 10.1038/s41467-021-23443-y
- Mahy W *et al.* DOI: 10.1021/acs.jmedchem.0c01391

XFEL (X-ray Free-Electron Laser) Hub

The XFEL Hub at Diamond continues to provide support to the UK community engaged in serial crystallography and XFEL-related life science research. The Hub also organises the Block Allocation Group 'Dynamic Structural Biology at Diamond and XFELs' for serial crystallography and time-resolved studies.

During the year, members of the Hub participated in 13 XFEL experiments at the LCLS in the USA, PAL-XFEL in Korea, or the European XFEL in Germany, mostly by remote access. In March 2022, several members of the XFEL Hub travelled to the LCLS to participate on-site in experiments.

MPL Laboratory in RCaH.

The XFEL Hub continued two major projects at Diamond that will establish methods for time-resolved serial crystallography studies using on-demand sample delivery and reaction initiation strategies that can be correlated with tr-XES. The plans also include a deeper collaboration with one or more XFEL facilities which may also host the sample delivery capabilities developed at Diamond. The Hub has also been testing prototypes for sample delivery and XES data collection at Diamond beamline VMXi.

Highlighted publications:

- Rabe P *et al*. DOI: 10.1126/sciadv.abh0250
- Butryn A *et al.* DOI: 10.1038/s41467-021-24757-7

Collaborations

The Rosalind Franklin Institute

The Diamond-Franklin collaboration in electron imaging and diffraction methods is moving from strength to strength. This past year has seen the delivery of the Franklin's first Titan Krios microscope, Dorothy, and the second-generation plasma focused ion beam (pFIB), called Franklin to enable large volume cellular tomography using novel sample geometries as part of a close collaboration with Thermo Fisher Scientific. The developments are funded by Wellcome through the Electrifying Life Science grant that also funds the development of the HeXI dedicated electron diffraction beamline. The Dorothy microscope was delivered in July 2021, commissioned by Diamond and Franklin staff throughout the summer and is now fully operational in the Rosalind Franklin Institute Hub building offering state of the art capability to Franklin and Diamond scientists.

Research Complex at Harwell (RCaH)

The Research Complex at Harwell (RCaH) is a joint venture between Diamond and the UK research councils, now UKRI, and provides a research hub for the physical and life sciences. Research facilities or consortia based at RCaH include the Membrane Protein laboratory, the Central Laser Facility (CLF), CCP4 and CCP-EM. This welcomes around 500 scientific visitors and users yearly.

RCaH provides most of the wet laboratory space for Diamond, hosts the MPL, the UK XFEL Hub, XChem and the Harwell crystallisation facility. The latter is run as a partnership between Diamond, RCaH and the Rosalind Franklin Institute and provides state-of-the-art facilities which have recently undergone a major upgrade.

A new ThermoFisher scientific Glacios™ 200 kV cryo-transmission electron microscope equipped with a falcon IV detector installed at eBIC provides Harwell groups with a state-of-the-art cryo-TEM. This is complemented by dedicated facilities for cryoEM sample preparation.

The massive push to SARS-CoV-2 research has led to further work on the SARS-CoV-2 proteases and the use of nanobodies directed against the SARS-CoV-2 spike protein.

Catalysis Hub

Since 2013 the UK Catalysis Hub has had a Block Allocation Group (BAG) for X-ray Absorption Spectroscopy (XAS) at beamline B18. The BAG is open to every academic working in catalysis in the UK and is designed to support new users to develop proposals and to train them in data analysis. XAS has become one of the most important analytical tools available at Diamond for catalysis research.

Over 80 publications have directly resulted from the B18 BAG with recent highlights including the study of aqueous phase reforming (APR) of glycerol which is an important reaction utilising renewable feedstocks such as biomass for the renewable production of hydrogen.

The Hub has recently been awarded a further BAG for X-ray Pair Distribution function analysis (XPDF) at beamline I15-1. The new XPDF BAG will introduce new users to XPDF and to develop a broad user base from within the UK catalysis community.

Active Materials Laboratory

The new Active Materials Laboratory (AML) provides space for radioactive materials research, enabling experiments that were previously impossible in the UK. This is part of phase 2 of the Government's National Nuclear User Facility (NNUF) project to provide state-of-the-art experimental facilities for research and development in nuclear science and technology.

The AML has a wet and dry lab for experimental use. Portable beamline equipment can be brought into the AML if required. There is also a characterisation room with a gamma spectrometer and a liquid scintillation counter and a storage room, with safes, fridges, and a freezer for samples to be stored when not in use in the labs or beamline. Access is designed principally for those with beamtime at Diamond but can also be obtained without beamtime through the offline facilities scheme. Access is free for non-proprietary research via either route, and currently extra support funding is available through the NNUF II scheme.

The University of Manchester at Harwell

The University of Manchester at Harwell (UoMaH) is hosted by Diamond. This provides the interface with the Harwell national facilities, enabling UoM researchers to access world-class research at Diamond and all the Science and Technology Facilities Council facilities at Harwell.

UoMaH has a growing contingent of Research Fellows based at Harwell: two working on resilience and catalysis are sponsored by Diamond, one working on fusion is sponsored by ISIS, one working on Data science is sponsored by STFC/SCD and one 'extreme science' Fellow is currently being recruited. These strengthen the University's link with Harwell by bringing their research, networks and new users from industry and Faculty academics to Diamond.

In May 2021, UoMaH partnered with Diamond, CLF, UCL, the Health and Safety Executive (HSE) and the UK Health Security Agency (UKHSA) to support the National Core COVID-19 PROTECT Transmission and Environment Study. UoMaH is being funded to manage the study during its final year.

InFUSE Prosperity Partnership

Technological mobilisation is now required on an unprecedented scale to meet the ambitious national targets for net-zero CO_2 in line with the Paris Climate Agreement. A paradigm shift in the UK's research and development capabilities is needed to reduce time to market for novel and sustainable solutions. This will require close partnership between academia and industry.

One of the key strategies for CO_2 reduction is optimising solid-fluid interfaces. Improving understanding of interfaces will allow researchers to design new materials, devices, and optimised processes that have reduced energy demand or longer life times.

InFUSE is a five-year EPSRC (Engineering and Physical Sciences Research Council) funded Prosperity Partnership between Imperial College London, Diamond, and Shell, that will examine how technologies like batteries, lubricants, chemical production, and carbon capture and storage can be improved by understanding interfaces in these systems. The partnership will fund more than 20 new PhD studentships to increase our fundamental understanding of interface behaviours by studying morphology, structure, and chemistry from the atomic to the macroscale, and their dynamic evolution under a range of extreme operational parameters.

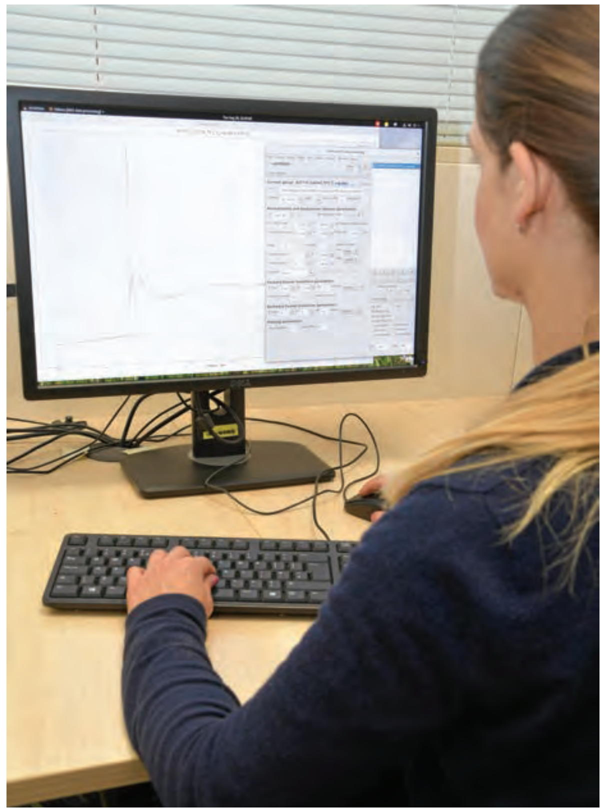
Industrial Liaison

It has been a pleasure to see clients returning to the site although there have been fewer in- person meetings and events this year. Despite the challenges of the pandemic the industrial programme at Diamond is thriving and we have had our busiest year to date. Many years of work to establish efficient and reliable workflows for remote and mail-in experiments have shown their worth, enabling the team to respond quickly and provide seamless support for our clients. Our data collection services continue to be extremely popular and have gained widespread adoption with our clients who value the flexible approach and trust us to collect precious data with professionalism and care.

The physical science industrial programme is once again fully operational, and we continue to build our programme for diffraction, spectroscopy, scattering and imaging experiments. The life sciences industrial programme was paused very briefly in early 2020 and since then has continued to grow at great pace. Demand remains high for our macromolecular crystallography, cryo-Electron Microscopy, fragment screening and small angle scattering services and a new crystallisation service has been launched to help support clients at the early stages of drug discovery and give access to Diamond's facilities and expertise.

Although our primary focus remains our client projects, the ILO team continues with our own research and were the first users of the Versatile Soft X-ray (VerSoX) Beamline (B07-B) to measure the C, N and O K-edge spectra of a range of solid, organic crystal systems using Near Edge X-Ray Absorption Fine Structure (NEXAFS).

Examples of our collaborative work include a study of the hydration behaviour of fluconazole, an antifungal drug, with scientists from Pfizer and the University of Manchester[1]. The team used high resolution powder diffraction studies on the High Resolution Powder Diffraction Beamline (I11) to show that both age and polymorphic form impact the drug's kinetic stability to hydration. An initially undetectable monohydrate form of the drug was shown to have a seeding effect which impacted the hydration kinetics.



Anna Kroner conducting X-ray spectroscopy experiments.

Jitka Waterman loading pucks for MX experiments.

The B24 beamline team worked with Activirosomes Ltd on a large project to characterise a novel vaccine platform using a 3D correlative microscopy approach. Active virosomes (AVs) are novel vaccine formulations that provoke an 'anti-viral' immune response. The target virus antigens selected for this work were Chikungunya and Zika viruses that have no drug treatment or vaccine currently available. Combining cryo-Structured Illumination Microscopy (cryo-SIM) and cryo-soft X-ray tomography allowed visualisation of the 3D structure and antigen loading of AV populations and assessment of morphological variations across batches[2]. Preliminary results showed the effectiveness and robustness of the technique for characterising novel vaccine formulations such as AVs.

Diamond continues to support industrial clients across a wide range of techniques and facilities with experiments ranging from routine analysis to complex bespoke solutions. Please do not hesitate to contact us on industry@diamond.ac.uk to discuss your analytical needs, we would be happy to help.

References

1. Basford PA *et al*. DOI: 10.1021/acs.cgd.1c00100
2. Okolo, C. A. *et al*. DOI: 10.1111/ jmi.13054

Alex Dias and Ailsa Powell preparing pucks for XChem experiments.

Education, Training and Engagement

Over the past year the COVID pandemic meant we needed to focus on developing and delivering remote engagement activities. We have had nearly 7,000 significant interactions with 'virtual' visitors, which included those for scientific and technical events, undergraduate and postgraduate interactions, school students and members of the public, and VIPs and stakeholders. We have also been able to start welcoming some visitors back on-site and engage at offsite events.

> *"The Diamond Tour is always the highlight of the week when we have residential training."*
>
> *A coordinator from a PhD student visit*

Public and schools

We adapted to the changing needs of audiences during the pandemic and are developing new videos, workshops and 'zines' to engage with school students. We also had limited on-site activities including work experience and group visits as the year progressed. In October we were presented with a Bronze Engage Watermark award from the National Co-ordinating Centre for Public Engagement (NCCPE) which recognises the commitment of Diamond to Public Engagement.

> *"There is an exemplary public engagement team, who had really led effective engagement."*
>
> **Feedback from the NCCPE on the award of a Bronze Watermark Award**

Diamond has continued its commitment to widening participation and delivering outreach activities in areas of lower science engagement including distributing our Board Game to hundreds of schools to inspire and inform about careers in science research.

Higher Education

Our undergraduate and postgraduate programmes play a vital role in Diamond's wider mission to be a world-leading centre for synchrotron science and to keep the UK at the forefront of scientific research. The programmes provide exciting opportunities to nurture a career in STEM and contribute to the wider skills agenda in the UK. Our 2020 Year in Industry cohort was successfully completed, and we welcomed 12 new students in 2021. The 15 Summer Placement students worked in a hybrid fashion on-site and from home, covering life and physical sciences, engineering, and software computing.

> *"My experience at Diamond has trained me professionally and personally, training which I don't think I would have received elsewhere.*
> *I'll fondly remember the experience for many years to come."*
>
> *Harry Rostron, 2021 Summer Placement Student*

The 2021 PhD Cohort co-funded by Diamond and 15 universities and world leading facilities brings the total number of active Diamond PhD Studentships to 109 and we will be welcoming 21 new students in October 2022. Despite the challenges of the pandemic, we were also able to host several visits from undergraduate and postgraduate groups.

Scientific workshops and conferences

It has been a busy year of online workshops and webinars with several new events introduced to the virtual events calendar such as the B24 Correlative Cryo-Imaging workshop and the DIAD User workshop. The Early Career Scientist Symposium worked particularly well online seeing a record number of over 270 delegates. Several User Working Group meetings engaged our user community in preparation for the new beamlines for Diamond-II. August 2022 will see Diamond hosting IXS2022, our first international conference since the pandemic and we are excited to welcome the Inelastic X-ray Scattering community to Oxford to share new scientific discoveries and the latest developments.

Our 2021 Year in Industry students (right to left: Parnavi, Ishika, Zaeem and Alex) in discussion during our Peer Review Training session.

Amy Griffin presenting a thermal camera to children at the IF Oxford Science festival.

Africa-UK Collaboration Tackles Energy and Health Needs

In June 2021, we celebrated the achievements of the Synchrotron Techniques for African Research and Technology (START) programme[1]. Funded by a £3.7M Global Challenges Research Fund (GCRF) grant from the UK's Science and Technology Facilities Council (STFC), the GCRF START programme equipped labs, supported research posts, and trained early-career scientists from 2018 to its close in 2021[2]. Diamond played a pivotal role providing access to synchrotron techniques, beamtime, training and mentoring.

Research focused on structural biology and energy materials to address key United Nations' Sustainable Development Goals. Scientists explored solar cells, batteries, and fuel cells, as well as catalysts. The work also included studies for drug targets and vaccines, and 'green' biotechnology.

Structural biology highlights

The structural biology landscape in South Africa was transformed by increased understanding of potential treatments for many diseases including SARS-CoV-2, HIV, tuberculosis, malaria, and many others. New infrastructure was built at seven institutions, which included six protein crystallography laboratories that can access synchrotrons worldwide. A total of four labs now own X-ray diffractometers and, uniquely in Africa, the University of Cape Town's Aaron Klug Centre for Imaging and Analysis now houses a cryo-electron microscope equipped with a direct electron detector. Groups at eight institutions regularly collected X-ray diffraction data at Diamond and cryo-EM data at eBIC.

Access to beamline I04-1 at Diamond enhanced research prospects for early career scientists like Dr Blake Balcomb and Dr Anton Hamann (University of Stellenbosch) in their work to design medicines for tuberculosis, malaria, and *S. aureus* infections. Likewise, Dr Carmien Tolmie's studies on enzymes to develop drug targets for fungal infectious diseases are benefitting from access to X-ray crystallographic fragment screening.

After using beamlines I04, I04-1 and I03 at Diamond, Professors Lynn Morris and Penny Moore and Dr Thandeka Gwete-Moyo from South Africa's National Institute of Communicable Diseases (NICD) were able to determine a broadly neutralising HIV antibody structure. Thandeka said, "START has given me opportunities I could have never imagined".

Some key outcomes from START

- More than 66 papers published, and dozens of protein structures deposited in the global Protein Data Bank.
- Over 264 Diamond synchrotron shifts carried out through more than 61 beamtime sessions.
- Over 40 post-doctoral research associates (PDRA) and technicians funded for 3 years (31 African; 10 UK).
- 25 leading Principal Investigators and Co-Investigators (7 from the UK and 18 from Africa) trained and mentored more than 92 postgraduates.
- Over 50% of 23 structural biology positions funded by GCRF START held by female scientists.
- Workshops and conferences hosted hundreds of international participants.
- START's Sci-ART project collaborated with the Keiskamma Trust, a South African community-led NGO[1].

Energy materials highlights

Affordable, clean, and sustainable energy solutions are urgently required. Scientists from Zimbabwe, South Africa, UK, and Egypt partnered with START to start to tackle these issues.

Groups from the Universities of Witwatersrand (Wits) and Oxford used cutting-edge techniques to develop photoactive layers for solar cell prototypes. START also provided valuable X-ray Absorption Spectroscopy (XAS) data analysis skills for Wits PhD students who are studying potential cathode materials for lithium-ion batteries and renewable energy storage systems. Exposure to new skills led to new opportunities, including the award of British Council Newton Travel Grant to Kenyan researcher Dr Francis Otieno for research visits to Diamond and Oxford University.

Dr Mohamed Fadlalla from Cape Town and MSc student Chris Mullins identified parameters of iron-based bimetallic catalysts which led to enhanced CO_2 hydrogenation performance. The work involved new collaborations with several UK centres. Subsequently, Dr Fadlalla was promoted to Research Officer and awarded prestigious university and national grants for his research going forward.

Building on START's legacy

Reflecting on the success of the programme, Professor Chris Nicklin, Diamond Science Group Leader said, "START has been an exciting journey, which has reaped fantastic results in a remarkably short space of time". He added that African researchers are keen to apply synchrotron techniques to their research problems and find African and joint solutions to global challenges. There is now a huge appetite for a 'START 2,' especially if the ambition of an African Light Source is to be realised.

References

1. https://start-project.org/
2. Nicklin C *et al*. DOI: 10.1080/08940886.2022.2043684
3. https://start-project.org/keiskamma-sciart-collaboration/

Dr Carmien Tolmie using an X-Ray diffractometer at the University of the Free State, South Africa. Photo Credit: R. Machado. ©Diamond Light Source.

diamond

Diamond Light Source Ltd
Harwell Science & Innovation Campus
Didcot, Oxfordshire OX11 0DE
Tel: +44 (0)1235 778 639
Fax: +44 (0)1235 778 499
www.diamond.ac.uk

Acknowledgement:
We would like to thank the authors and all colleagues who contributed to this publication.

MIX
Paper from responsible sources
FSC® C007881
FSC www.fsc.org

Printed on Forest Stewardship Council (FSC) accredited paper stock.

Published June 2022

2022

Celebrating Diamond's 20th anniversary and 15 years of research and innovation