Neutron Science in Europe

Strengthening world-class research and innovation delivering economic and societal impact

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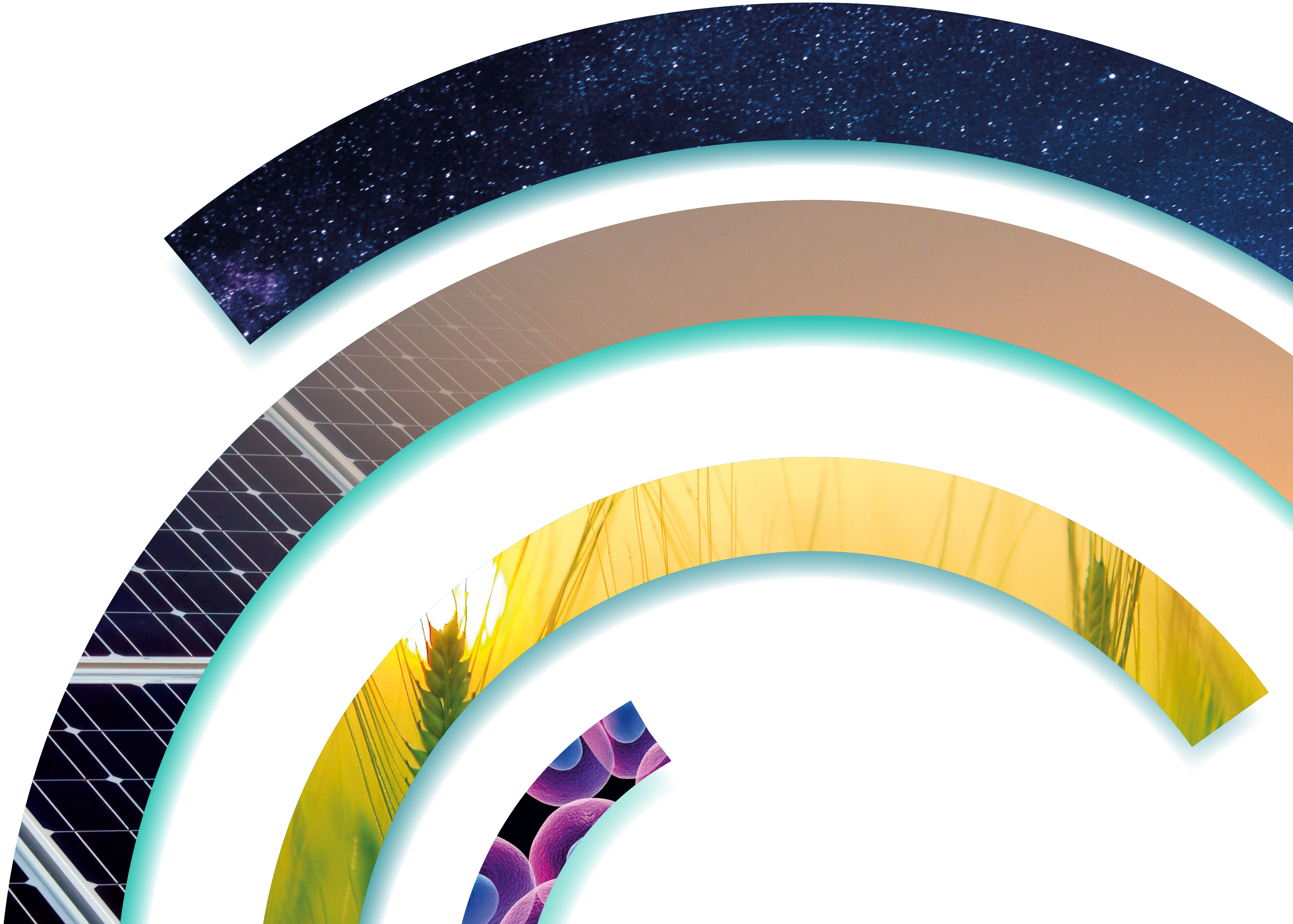
STRENGTHENING WORLD-CLASS RESEARCH AND INNOVATION
DELIVERING ECONOMIC AND SOCIETAL IMPACT

Neutron Science in Europe



The **League of advanced European Neutron Sources (LENS)** is a not-for-profit consortium working to promote cooperation between European-level neutron infrastructures that provide transnational user programs.
www.lens-initiative.org

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www.neutrons-ensa.eu

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FOREWORD

In more than four decades, first as a user and then as a manager of neutron research facilities, I have been involved in writing numerous documents and giving many presentations about their uses and benefits. I have gradually come to realise that this can be summarised in just three key points.

- The problems facing society do not go away. There was an energy crisis when I was a young researcher in the 1970's and there is an energy crisis now, although with the added complexity of climate change making it less straightforward. The development or improvement of materials and their applications is one of the key ways that we address such challenges.
- The fundamental properties of neutrons, and the reasons that we use them to investigate and characterise materials, have also not changed. However, the range of problems to which they are applied has become increasingly broad over the years.
- The impact from our work will continue to be far-reaching. As one example, rechargeable lithium-ion batteries were developed by Stanley Wittingham in the 1970's in response to the energy crisis, "but even he couldn't have anticipated the complex materials science challenges that would arise as these batteries came to power the world's portable electronics". From pacemakers to phones, from computers to cars, 40 years on he is still using neutrons to address those challenges.[1]

So, the question facing us is not 'why should we use neutrons?' but 'how do we use neutrons?'. How do we continue to build, develop and operate the necessary neutron research facilities? How do we ensure we use them in the most cost-effective and environmentally sustainable way? How do we maximise the economic and societal benefits of the research they enable?

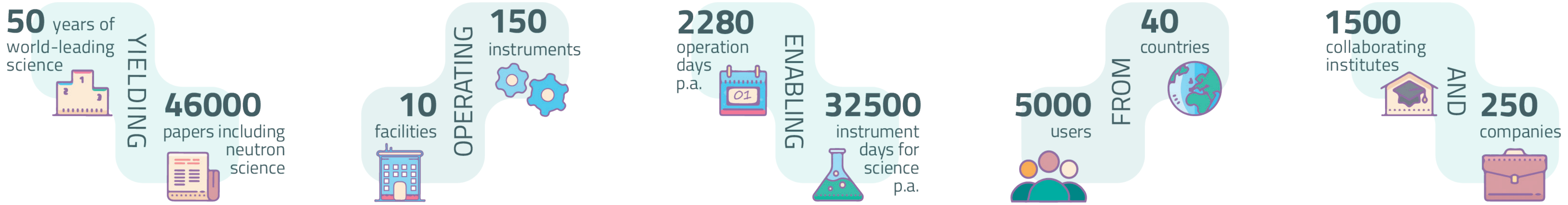
Over the last 50 years, Europe has been particularly good at exploiting neutron-based methods through an 'ecosystem' of facilities and by pioneering the 'user facility' concept, where a very large community of researchers from academia and industry benefit. But the European ecosystem is now changing and becoming less stable as a number of facilities are reaching the end of their operating life. The European neutron facilities and user communities are extremely concerned that, if no action is taken, we will lose significant scientific and economic advantage at a time when other continents are investing more.

This document is intended to form the baseline - prompting discussion and hopefully innovative ideas – as to how we create a new neutron ecosystem that will deliver the research that Europe needs for another 50 years.

Robert McGreevy
Chair, League of advanced European Neutron Sources (LENS)

KEY MESSAGES

- **For many years Europe has had a powerful ecosystem of small, medium and large neutron facilities** that was the envy of the world; supporting an expert community of 5000 researchers, and delivering science, innovation and competitive advantage through economic impact for European society.
- **Closures of a number of European facilities are reducing capacity and capability,** which is limiting scientific discoveries and innovation at the same time as there is increasing competition from North America and Asia-Oceania.
- **There are opportunities to sustain European capability** through bringing the European Spallation Source into operation, development and expansion of existing major facilities, and demonstrating the potential of High Current Accelerator-driven Neutron Sources.
- **A multi-institution 'European Laboratory for Neutron Science' could help to coordinate pan-European funding decisions,** ensure efficient delivery and maximise economic impact.
- **Neutron research in Europe will continue to deliver competitive advantage** and be a key contributor in addressing current and future societal challenges.



EXECUTIVE SUMMARY

From catalysts to cancer treatments, energy storage to quantum computing, advanced materials are key to addressing global challenges and driving sustainable economic development. Making these advances depends on a detailed understanding of material properties and the associated interactions at the atomic and molecular level, and this requires a range of sophisticated experimental techniques combined with comprehensive computing and data services. Techniques based on the use of neutrons, often referred to as neutron scattering or neutron science, are only available in centralised research infrastructures that are relatively rare.

Over the last 50 years Europe has developed the largest community in the world of approximately 5,000 expert neutron users. Their research impacts many aspects of modern life. Much of the original capacity for this research was provided by reactors built by many countries to test technologies and materials for nuclear power applications during the 1950's and 60's. Developments at reactors of this type led to the construction from the 1970's of reactors dedicated to major programmes of neutron science research, such as the Institut Laue Langevin (ILL) and the Orphée reactor in France, and the BER II reactor in Germany. These facilities were followed by the construction in the 1980-90's of equivalent accelerator-based spallation sources, the ISIS Neutron and Muon Source (ISIS) in the UK and the Swiss Spallation Neutron Source (SINQ) in Switzerland, and in the 2000's of the research reactor of the Heinz Maier-Leibnitz Zentrum (MLZ) facility in Germany.

The world-leading ecosystem of neutron facilities in Europe, supporting a world-leading community of researchers, has been created by decades of investment, but the landscape is now undergoing major changes. Many of the national reactor-based sources have closed, reducing European experimental capacity to around 80% of that available in 2019. This will decrease further in the 2030's when ILL is likely to reach the end of its operation, at which point only 60% of the former capacity will remain. Other facilities may also close on a similar timescale. At the same time, the world's most innovative countries beyond Europe are planning to bolster their capacity and capability in this sphere. Some of these losses will be mitigated by the European Spallation Source (ESS) - a new, international, accelerator-based facility under construction in Sweden - and by the further development of existing sources. However, although ESS will be the most powerful neutron source in the world once fully operational, it will initially provide less than half the current capacity of ILL.

A decline in capacity reduces the volume and quality of research programmes, resulting in fewer discoveries and socio-economic applications. Most neutron research is carried out by small groups of researchers that conduct programmes of experiments over several years, possibly using a number of neutron facilities and complemented by other analytical techniques. Capacity translates directly into the number and range of programmes that can be supported. If facility capacity decreases significantly, then the volume and quality of programmes will decrease correspondingly as researchers will be unable to access the neutrons they need, when they need them. At some point it may no longer be viable to spread the available capacity across all science areas. Having to choose between, for example, materials for energy and materials for healthcare, would inevitably reduce benefits for European society and its economy.

Critical national expertise in the development and application of neutron techniques has been maintained through 'neutron knowledge centres'. These centres – at the Jülich Centre for Neutron Science and the Helmholtz-Zentrum Hereon in Germany, the Laboratoire Leon Brillouin in France, the Institute for Energy Technology in Norway, DanScatt in Denmark and ESS-Bilbao in Spain - are mostly based around previously operational facilities. Neutron knowledge centres support their national user communities and participate in broader European collaborations by, for example, operation of instruments at other facilities and construction of instruments for ESS.

Access to a range of neutron science facilities and expertise is essential if Europe's high technology nations are to continue their future materials research programmes and secure the resulting economic and societal impact. National facilities support the majority of research and provide a platform for skills and technical development. This enables optimal use of the specialised capabilities at international facilities, which lack the capacity to do everything. The international facilities – ILL and ESS - are funded by consortia of 13-14 countries, with usage proportional to funding. The remaining major national facilities – ISIS, SINQ and MLZ – are mainly supported by national funding although they provide more than half of neutron science capacity in Europe and have up to 50% non-national usage. The ecosystem is, therefore, becoming increasingly reliant on funding from a few countries.

The key role that neutron science will play in the future research portfolios of many European countries is underlined by the significant investment being made for the construction of ESS. Small, short-term changes to funding by a single country can, however, precipitate large reductions in capacity. Furthermore, facilities require a decade or more to plan, design, construct and commission. Coordinated long-term planning and commitments for the whole ecosystem are therefore necessary in order to ensure future stability and sustainability. The possible opportunities, risks and challenges for the period up to 2040 are broadly known:

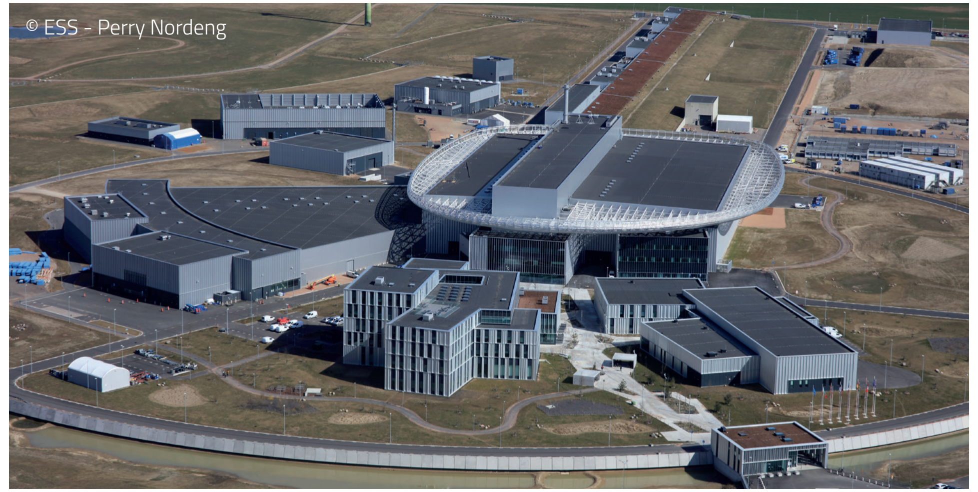
- It is unlikely that research reactor-based facilities for neutron science will be built in Europe, so new facilities will need to be accelerator-based.
- Options for the development and expansion of the existing major facilities, such as ISIS-II and a new guide hall at SINQ, are in the design phase.
- Europe's new flagship facility ESS will come into operation with significant new capability, and with the potential to further increase the source power and the number of instruments available.
- The only route for entirely new facilities with significant capacity are High Current Accelerator-driven Neutron Sources (HiCANS), which could occupy the role played by national reactor-based sources in the past. Designs need to be demonstrated in practice through the realisation of an operational facility of this type.
- Different options have their own associated risks: though expanding existing facilities is technically low-risk, the centralisation of capacity in a handful of facilities increases the vulnerability of the ecosystem to the temporary shutdown or closure of one of them.
- Expertise based around 'neutron knowledge centres' can support both national and European user communities through the operation of instruments and the development of facilities.

The effectiveness of funding decisions made by any individual country will depend on the national decisions made by other countries. Addressing the neutron capacity challenge within a constrained funding environment, where all countries have to consider and prioritise their neutron-based research in relation to other investments, will require coordination between countries whether large or small, facility owners or users. The 2016 report of the European Strategy Forum on Research Infrastructures (ESFRI) strongly recommended the formation of a pan-European group for this purpose.[2]

Collaboration within the neutron ecosystem is crucial and has always been very strong. EU funded Transnational Access programmes have helped to increase cross-facility use and build user communities in countries without national facilities, one effect of which has been to increase the number of countries funding ILL and now ESS. Technical, training and outreach collaborations are now coordinated through the League of advanced European Neutron Sources (LENS), which includes both operational facilities and neutron knowledge centres.

In order to secure a viable neutron ecosystem in Europe beyond 2030 there is now a need to take the current collaboration to the next level. The previous ecosystem cannot simply be recreated; the new ecosystem must be adapted to today's context and accommodate future requirements. Funding decisions and their operational implementations at facilities and centres need to be coordinated, leading to an optimised scientific infrastructure across Europe. LENS will establish a working group to consider the opportunities and develop the concept for a multi-institutional 'European Laboratory for Neutron Science' (ELNS), an organisation with the responsibility to ensure efficient delivery of science and innovation and maximal impact across the consortium. All options for the structure and governance of such an organisation will be considered. National funding agencies must be engaged in this discussion to facilitate timely and coordinated decisions. This approach is entirely consistent with the 2016 ESFRI report [2] and the 2020 ESFRI white paper [3] "Making Science Happen: A new ambition for Research Infrastructures in the European Research Area".

This document is intended to provide a common baseline for future discussions. It summarises the historical background, the current situation and the future opportunities, risks and challenges. The conclusions of the working group will be presented in a later report.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1. SCIENCE, INNOVATION AND SOCIETAL CHALLENGES OF THE 21ST CENTURY: THE ROLE OF NEUTRONS

NEUTRONS FOR ACADEMIA AND INDUSTRY

Neutron facilities play a key role in the European science and innovation ecosystem, making significant contributions to scientific discovery, the creation of new technology and addressing society's greatest challenges. They serve the research communities of physics, chemistry, life sciences, engineering, materials science and more with advanced experimental equipment and expertise, pushing the boundaries of methodological development in addition to the science itself. This chapter outlines the role neutron techniques play in a range of important scientific and commercial pursuits, gives specific examples and explores how neutrons will continue to provide insight and deliver innovation.

Europe thrives on its knowledge-driven economy, enjoying better health and greater wealth than ever before thanks to a rich history of scientific exploration, innovation and development. However, the industrialisation and modernisation of society over the last two centuries has also created new challenges. The overarching threat of climate change, which brings infrastructure vulnerability, health risks and food security issues in its wake, has made us reassess the consequences of our technologies. The IT revolution has reshaped our ways of communicating and working over a few short decades, and this in turn places novel requirements on societal infrastructure that also pose technical challenges. In health, globalisation has amplified the threat of pandemics, longer life expectancy has caused an increase of age-related diseases and successful treatment of infection has given rise to antimicrobial resistance.

The solution to many of these challenges can partially be found in further technological development, with a view to achieving a sustainable society with a carbon-neutral energy economy and the responsible use and reuse of raw materials. This would include better energy-storage solutions, more efficient energy-harvesting systems, lighter materials for the transport sector and greener industrial processes. The IT sector continues to develop with new technologies continuously entering the market that improve productivity, increase efficiency and reduce emissions. The health sector has a huge innovative capacity, as demonstrated by the rapid development of vaccines in response to the COVID-19 pandemic.

However, fully leveraging progress requires continued support of the knowledge-generating sector. The rich European ecosystem of universities, institutes and research infrastructures sustains a diverse and advanced science community that expands our understanding and contributes to addressing society's greatest challenges. In tandem, the industry sector hosts a multitude of advanced R&D laboratories, staffed with skilled researchers working to turn research results into novel and improved products.

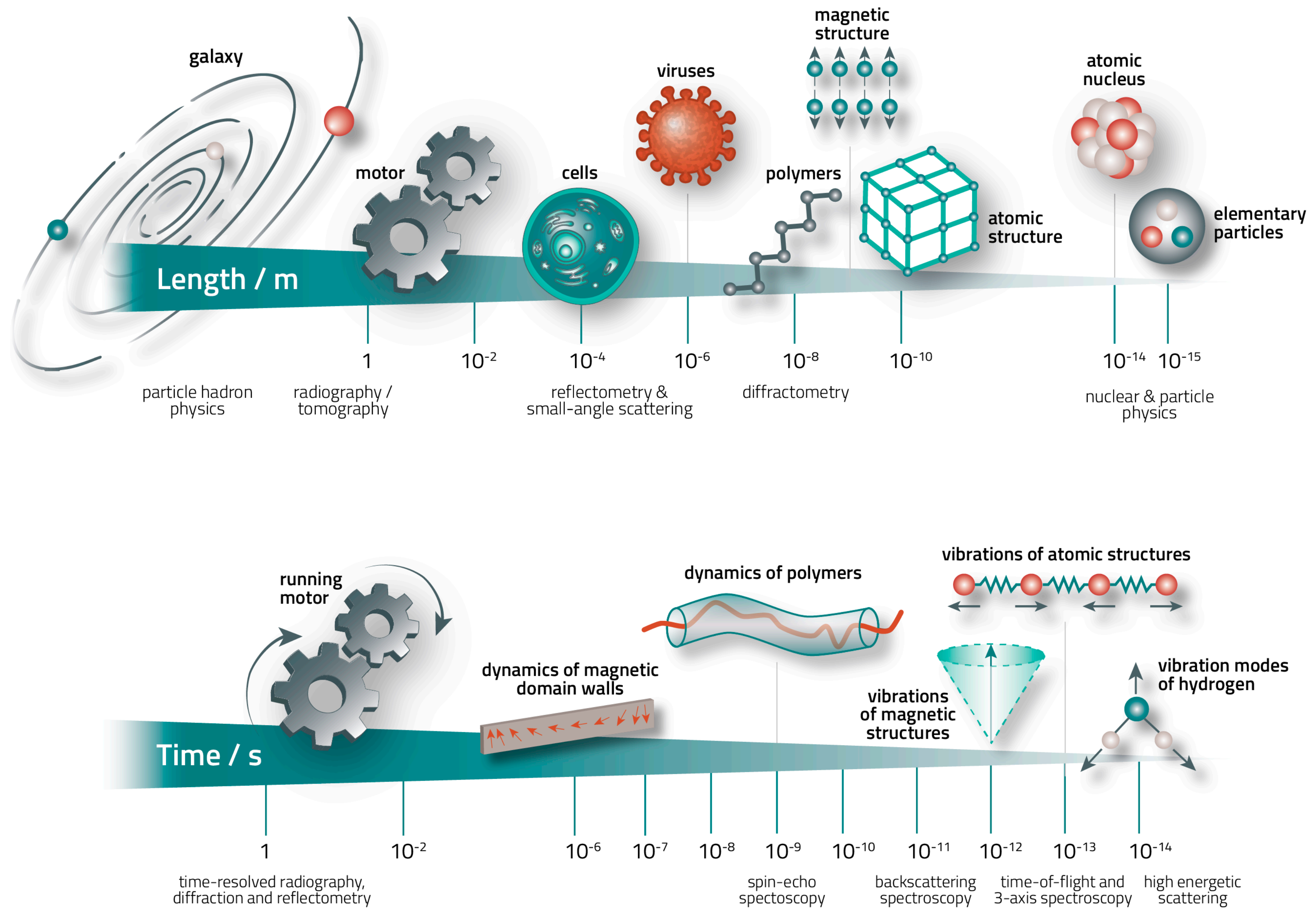
> *"Using neutron imaging, we were able to examine the... brake components with non-destructive experiments."*
>
> Mathias Kolb, Development Engineer, Audi Sport GmbH.

Neutron science plays an indispensable role in this knowledge-generating ecosystem. The advanced analytical techniques provided by neutron research infrastructures allow unique insights into matter and materials by exploiting the characteristics of the neutron. The engineering sciences benefit from the ability of neutrons to penetrate very dense, heavy objects, the life science sector utilises the heightened sensitivity of neutrons to hydrogen and water, condensed-state physics use the magnetic properties of neutrons to explore magnetic and electrical phenomena, while the non-destructive nature of neutron beams make them ideal for the study of rare cultural heritage and palaeontology specimens.

Neutron techniques make significant contributions to scientific discovery, the creation of new technology and addressing society's greatest challenges.

In addition to supporting the generation of new knowledge in academic and industrial research, neutrons are frequently employed by a range of industry sectors for quality control and the improvement of existing products and processes. The neutron facilities in Europe are used by several hundred different companies: from small and medium-sized enterprises to large global corporations across a wide range of sectors, such as the automotive, transport, pharmacological, food and consumer goods industries. The diversity of these companies demonstrates the significant contribution of neutron facilities not only to fundamental science within the academic sphere but also to innovation close to market in support of the knowledge-driven economy.

Europe is world-leading in neutron science, with a powerful ecosystem of small, medium and large, national and international facilities and the world's largest community of expert neutron users, delivering both scientific and socio-economic impact. The construction of the European Spallation Source – which will be the most powerful neutron source in the world – symbolises the intention to maintain this lead. Strengthening the neutron ecosystem in Europe will consolidate our leadership and support Europe's successful transition to a sustainable society with social, economic and environmental benefits.



Neutrons can be used in many different ways to study interactions that occur at different rates, and structures that range from life-sized to the atomic scale. © LENS – Stephanie Chapman

PROPERTIES OF NEUTRONS

STUDY DYNAMICS
Neutron energies are comparable to the time scales of molecular diffusion, vibrations and rotations.

STUDY STRUCTURE
Neutron wavelengths are comparable to the spacings of atoms and molecules.

PENETRATION POWER
Neutrons can penetrate deep into matter (including many different metals) enabling the study of large samples - even within complex sample environments.

STUDY MAGNETISM
The neutron's magnetic moment can be used to study the microscopic magnetic properties of materials.

NON-DESTRUCTIVE
Neutrons are suitable for the characterisation of delicate and precious samples.

VERSATILE SAMPLE ENVIRONMENTS
Sophisticated sample environments enable studies under operating conditions, including extreme temperatures and pressures.

SENSITIVITY TO LIGHT ELEMENTS
The neutron scattering power of nuclei varies in a quasi-random manner such that lighter atoms (e.g. H, Li) can be studied in the presence of heavier ones.

COMPLEMENTARITY
Neutron scattering is highly complementary to other techniques, such as X-ray scattering, electron microscopy, magnetic resonance and computational methods.

ISOTOPIC CONTRAST
Neutrons are sensitive to different isotopes of the same element, so isotopic substitution (e.g. H/D) can be used to highlight specific features.

CLIMATE CHANGE AND THE ENVIRONMENT

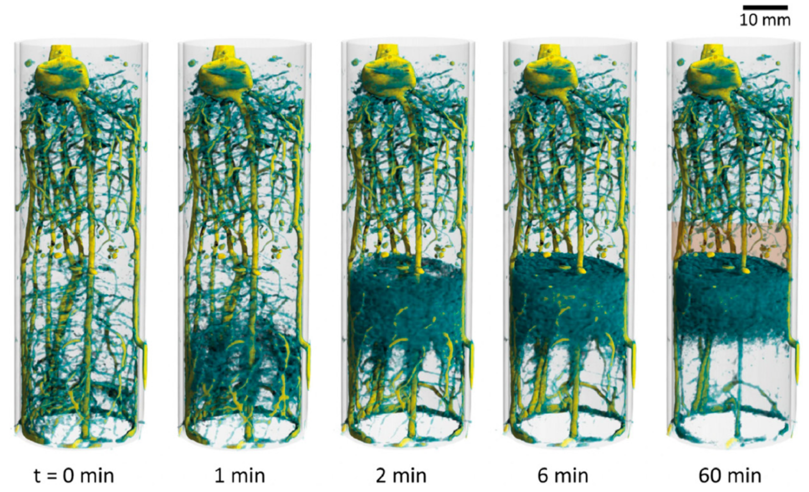
Human activity has widespread and sometimes disastrous effects on the environment, many of which are linked to climate change. The versatility of neutron techniques allows for significant progress to be made in methods for mitigating some of these effects, including emissions reduction, catalysis, clean technologies and processes as well as food security. Further related examples can be found in the Energy and Transport sections.

EMISSIONS REDUCTION
Neutron techniques have advanced understanding of the manufacture and aging of cement, a development with strong 'climate potential' as cement accounts for approximately 4% of global CO_2 emissions. Neutrons contribute to the optimisation of materials for carbon capture and storage that prevent greenhouse gases from entering the atmosphere. They have helped the development of porous materials that not only provide protection from pollutants, such as sulphur dioxide, but offer the potential to recycle this molecule industrially. When these pollutants do end up in the atmosphere, neutrons can be used to study how they affect ice crystals in clouds and advance our understanding of the role of clouds in global warming and atmospheric science in general.

CATALYSIS
Catalysts are employed extensively in industry to reduce energy use and waste production. Companies such as Evonik and Johnson Matthey use neutrons to develop better catalysis systems, ranging from industrial processes for chemical synthesis to catalytic converters in cars. Other applications include the more sustainable production of biofuels, such as recycling palm oil biomass waste for fuel production.

CLEAN TECHNOLOGIES
Neutron techniques support the development of clean technologies and processes that generate and release fewer contaminants into the environment. Neutrons are capable of revealing detailed characteristics of pollutants and how they affect the environment. There is increasing concern about nanoparticles, which are widely used by the food, cosmetics and pharmaceutical industries. Neutrons have played a key role in the development of a new technique to remove these particles from waste water, thereby preventing their transfer into the environment. Neutron science also plays an important role in the development of efficient manufacturing and recycling processes that minimise the impact on the environment of materials such as plastics.

PLANT SCIENCE
The role of plants in the global ecosystem can hardly be overestimated. In addition to photosynthetic energy conversion, plants maintain complex interactions with soil and the atmosphere that affect everything from growth zones to climate. Our understanding of the symbiotic relationships between roots, fungi and other organisms that together make up soil is very limited. Neutrons can image plant roots in soil, revealing root architecture and growth, in addition to soil hydration and structure. This work helps clarify the key factors that sustain or evolve different ecosystems, contributing to the improvement for global climate models.



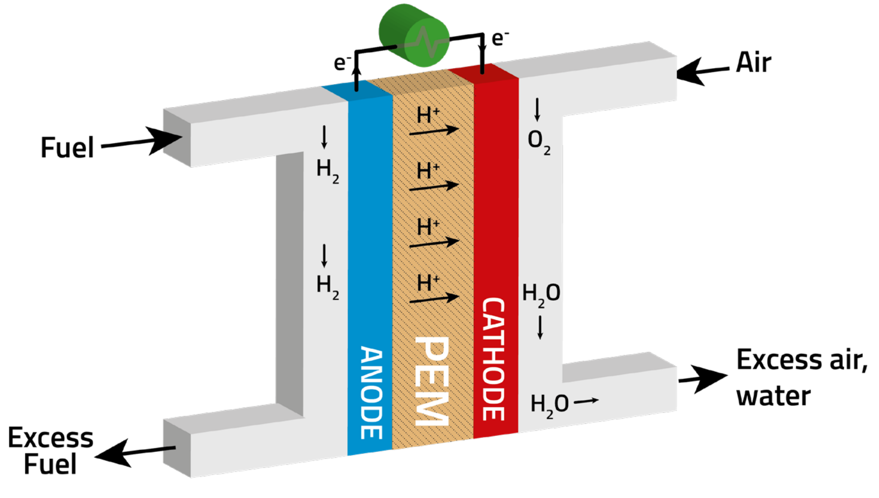
Neutrons can be used to image water absorption by plant roots to help develop more drought-resistant crops. [4]

Neutrons have made significant progress towards the development of carbon sequestration systems and the improvement of catalysts and cleaner technologies, contributing to the development of green technologies.

Neutrons are a valuable tool across the entire energy sector: from generation to storage, transport and efficient use. Applications range from batteries and fuel cells to nuclear power, wind turbines and solar cells. Many energy materials contain light elements, such as hydrogen, lithium and oxygen, that are ideal to study with neutrons. Another particular strength of neutrons is their ability to study systems *in operando*, such as fuel cells and batteries. Neutron techniques have thus enabled large automotive companies such as Toyota to improve electric vehicle technology.

BATTERIES

Advanced lithium batteries are required to provide greater power and longer run time between charges in order to accelerate the global transition towards electric vehicles. Neutrons are particularly sensitive to lithium and can monitor these ions as they move between electrode materials during the charge/discharge cycle thus guiding the improvement of battery performance and lifetime. Neutrons are also used to explore new electrode compositions and to study the numerous interfaces inside batteries.



Neutrons can be used to monitor fuel cells during charging and operation to improve design and performance. ©LENS - Stephanie Chapman

NUCLEAR POWER

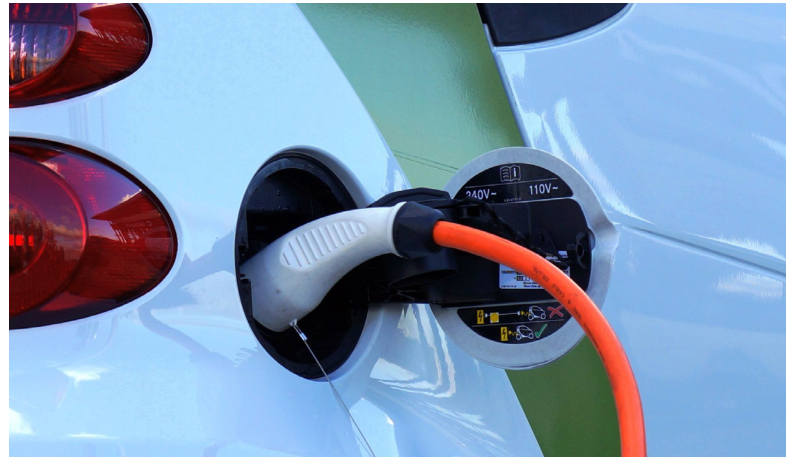
Alongside renewable energy sources, nuclear power - as one of the lowest-carbon technologies for generating electricity - will make a substantial contribution to the energy economy in the coming decades. The new generation of nuclear reactors will include improved safety features, higher efficiency and reduced waste generation. Neutrons assess the reliability and robustness of reactor components that need to operate in a high-radiation, corrosive environment under severe tensile stresses, thus informing strategies for prolonging the lifetime of these large-scale engineering components. Neutrons are also used to investigate the safe transformation and storage of nuclear waste.

> *"In order to build better batteries, a breakthrough in science and technology is needed. Only recently, technical developments at especially large-scale experimental facilities such as ISIS, have opened new possibilities for studying such material's properties."*
>
> Jun Sugiyama, Toyota Central Research & Development Laboratories, Japan and Dr. Martin Månsson, KTH Stockholm.

HYDROGEN

Hydrogen is a technically viable, clean and sustainable energy vector with the versatility to operate across the transport, heat, industry and electricity sectors. The implementation of a hydrogen economy requires the development of cost-competitive hydrogen generation, conversion and storage technologies. Hydrogen storage is also critical for hydrogen fuel cells that are emerging as a high-potential technology for an efficient, sustainable energy source in a range of industries, including automotive and aviation. Neutrons are contributing to the development of new hydrogen storage materials as well as fuel cell designs.

Neutrons contribute significantly to the development of a sustainable energy economy by exploring novel materials and technologies. Examples include safe hydrogen storage systems, next-generation batteries and improved materials for nuclear, solar and wind power.



Society is dependent on a safe and fast transport infrastructure for people and goods. The economic importance of this infrastructure was highlighted by the supply-chain disruptions caused by the COVID-19 pandemic and the long-reaching effects of a temporary blockage in the Suez Canal.

Underneath the complexities of transport logistics lie the technological and material realities of maintaining bridges, roads and railways, as well as fleets of ships, planes, trains and cars. Neutron techniques are a core component in the materials science toolbox and a number of global companies, including Rolls Royce, Audi and Airbus, in addition to their SME suppliers, use neutrons to improve their products.

Neutron techniques are particularly valuable for the study of materials placed under stress and strain, reproducing real-world conditions. Neutrons probe micro-fissures, residual stress and material weaknesses, for example in 3D-printed components, and are thus critical for the development of more resilient, high-performance materials and components with longer lifetimes and lower maintenance.

Neutrons can also be used to monitor industrial processes such as welding in real-world conditions, enabling the production process of each component to be improved. The performance of solders and alloys can be readily investigated using neutrons, in addition to whole components such as combustion engines *in operando*.

Reducing the carbon footprint of products, materials and processes constitutes an integral aspect of research and development in the transport sector. Neutrons contribute to the development of lighter materials, improved exhaust filters and greener industrial production processes.

AUTOMOTIVE AND AVIATION

Vehicle weight reduction is directly linked to improved fuel economy and lower CO_2 emissions, with significant benefits achieved by even modest reductions. Steels containing nano-sized particles of other elements have the potential to reduce weight whilst maintaining strength and the ability to manufacture complex parts. For example, vanadium is widely used in alloys to improve the performance of steel. As nanoparticles cannot be seen with an optical microscope, neutrons were used to study the formation of vanadium precipitates under different heating conditions. The results obtained provided the starting point for improved steel design and performance for automotive applications.

Modern aircraft engines use components made from high-performance alloys in order to enhance safety while reducing weight. These alloys can, however, be difficult to join together using conventional welding techniques and the application of new methods can potentially weaken the joint. Neutrons have played a critical role in evaluating the integrity of welds in aluminium alloys and in assessing their suitability for future aircraft programmes. Neutrons have also enabled the discovery of areas of potential stress and weakness in parts such as aircraft wings. The quality of engineering components can therefore be assured in parallel with the production of lighter and safer parts at a lower cost.

> *"Neutron tomography opens the door into a hidden world. It sharpens our vision so that we can continue to guarantee high quality."*
>
> Sandro Demmelbauer, Manager Quality - Life Cycle, Leister Technologies AG.

RAIL

Train wheels and railway tracks are subjected to stress and strain that inevitably lead to the formation of cracks. Neutrons can measure the distribution of residual stress at a depth of several centimetres in large and heavy components. The analysis of both new and used train wheels and railway tracks contribute to understanding how cracks begin and spread, enabling the optimisation of manufacturing and maintenance techniques, ultimately leading to an improvement in safety while reducing costs.

Neutron techniques are particularly valuable for the development of safer, lighter and more resilient high-performance materials that are needed by the transport sector. Neutrons also contribute to reducing the carbon footprint of products, materials and processes.

HEALTH

Although many diseases have been eradicated or brought under control over the past centuries, health will always be a major societal challenge. Increased life-expectancy has caused a surge in age-related conditions, chronic disease and disability, while developing countries still suffer the burden of HIV/AIDS, malaria and tuberculosis. As the COVID-19 pandemic has demonstrated, our global, mobile society makes it difficult to contain highly contagious diseases, thus we need to be ready for future health challenges while addressing those already here.

In order to confront health challenges, a thorough understanding of the complex biological processes that underlie health and disease is essential. Neutrons provide uniquely precise information on hydrogen atoms and hydrogen bonding, knowledge that is crucial for understanding the biological function of enzymes and drug efficiency, delivery and formulation. Large pharmaceutical corporations, such as AstraZeneca and Pfizer, as well as smaller life science companies use neutrons as a part of their analytical toolbox.

COVID-19

Neutrons contributed to the development of messenger RNA (mRNA) vaccines, a new type of vaccine that has emerged as one of the most effective against COVID-19. The potential applications of mRNA vaccines include Ebola, Zika, rabies and influenza, as well as cancer immunotherapy. These vaccines rely on the successful delivery of mRNA into the cell interior, which is dependent on the protection provided by nanoparticles packed around the mRNA. Neutron techniques have provided valuable information - used for the development of the BioNTech-Pfizer vaccine - on the function, biodistribution and cellular uptake of mRNA, demonstrating that more efficient vaccine delivery can be achieved by modifying the nanoparticle composition.

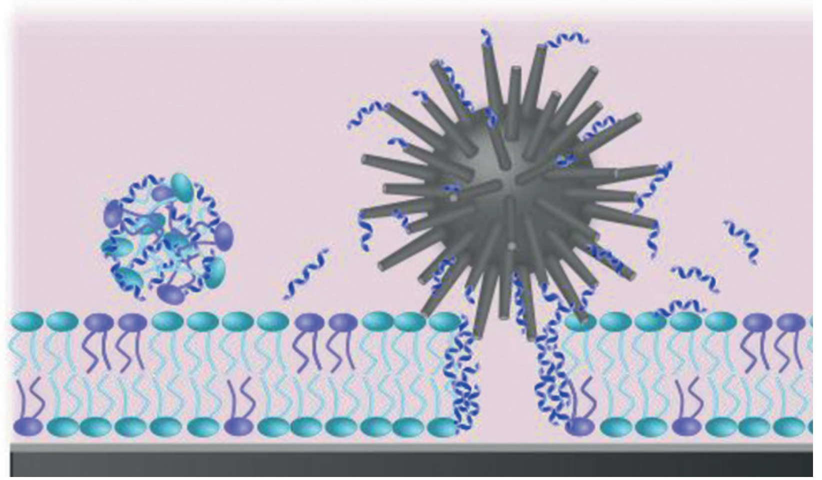
CANCER

Cancer is a large family of complex diseases with a plethora of underlying molecular mechanisms. The methods used to outsmart the disease have to be similarly diverse and flexible. Neutrons provide structural and functional characterisation, elucidating the processes that lead to carcinogenic alterations in cells that escape detection by the immune system. This information contributes to structure-based drug development against a range of cancers.

NEURODEGENERATIVE DISEASES

Neutrons provide structural information on the misfolding of the characteristic 3D shapes of protein molecules, a feature of vital relevance for a number of neurodegenerative diseases, including Alzheimer's, Parkinson's and Huntington's disease, in addition to amyotrophic lateral sclerosis.

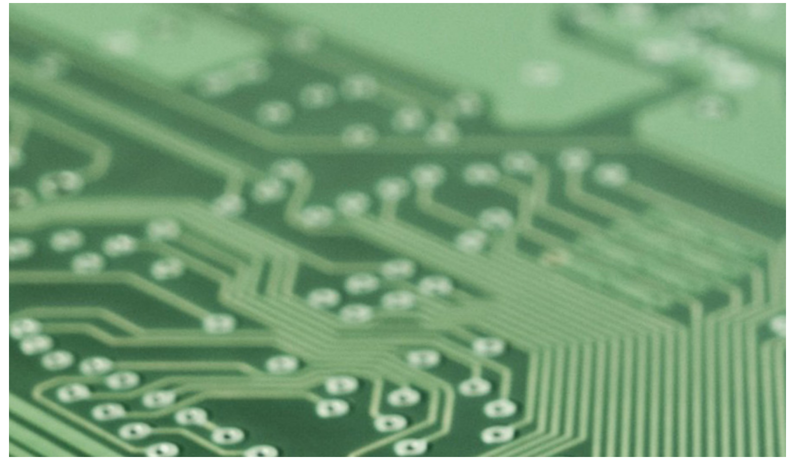
> *"Neutron scattering provides a novel approach for characterisation of the lipid nanoparticle systems used in mRNA delivery... The results are very exciting and show that this type of approach has major potential in understanding and developing mRNA therapeutics in the future."*
>
> Marianna Yanez Arteta, Associate Director, AstraZeneca Sweden.



Cell membranes are the target of 60% of pharmaceutical drugs due to their key role in disease and aging. Neutrons were used to test whether drug delivery was improved by making an antimicrobial particle resemble a virus.[5]

The sensitivity of neutrons to the biologically crucial hydrogen atoms, together with the powerful selective deuteration contrast method, enables major advancements in a wide-ranging area of health, including cancer and neurodegenerative diseases.

INFORMATION AND COMMUNICATION TECHNOLOGIES



Our knowledge-based societies are reliant on modern technologies for the storage and processing of digital information and to meet the seemingly insatiable demand for increasingly fast and small devices. There are physical bounds, however, to what can be achieved by classical computers due to the limited number of transistors that can fit on a chip and the energy required for their operation. The next technological revolution is dependent on our ability to harness the full power of quantum states in information technologies.

While most devices in current use exploit only the charge of the electron, quantum technologies also employ the intrinsic quantum states of the electron, including the coupling of spin states between neighbouring electrons. When these phenomena can be controlled on the nanoscale, more information can be encoded in the same space thus increasing information density. Energy efficiency is also improved due to the fact that spin-encoded information can be transported without heat loss, for example in spintronic devices. Major advances in processing speed are thus feasible, creating the potential for unprecedented problem-solving capabilities across a broad range of sectors including healthcare, energy, finance and security. Significant challenges remain, however, before large-scale impact is achievable.

The nuclear spin of neutrons makes them an intrinsically powerful probe of these quantum phenomena. They reveal not only the atomic-level structure of materials, but also the detailed magnetic structure and dynamics. Neutrons also penetrate the complex equipment required to carry out experiments in this domain, where novel phenomena are often discovered at very low temperatures, high magnetic fields and high pressure.

In addition to the potentially disruptive innovations that are expected from research in this area, novel quantum materials, as well as the phenomena and interactions that dictate the behaviour of these materials, have important fundamental implications and constitute an exciting frontier in condensed-state physics.

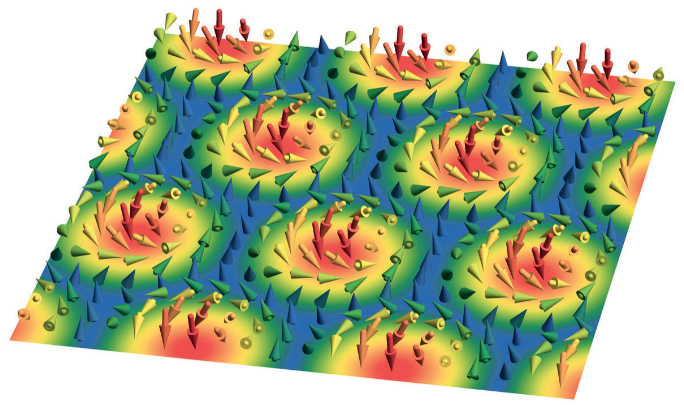
QUANTUM MATERIALS

Quantum materials exhibit unique properties such as quantum entanglement – the coupled states of a collection of quantum particles. The second quantum revolution will arrive when the control of entangled quantum systems enables quantum computing, communication and sensing.

The unique ability of neutron techniques to probe quantum entanglement was recently demonstrated in supramolecular complexes of nanomagnets, advancing these materials as promising candidates for quantum information processing. Neutrons have also been ground-breaking in the discovery of exotic phases of matter, such as spin-liquids and magnetic monopoles in solids, which could potentially lead to the development of new quantum materials.

TOPOLOGICAL MATERIALS

Neutron techniques are ideal for the study of topological materials, a class of quantum materials that holds huge potential for electronics and information technology due to their ability to support the unidirectional and virtually lossless flow of electrons. The contribution of neutrons to the discovery of topological phases – an area of great fundamental interest – was highlighted by the 2016 Nobel Prize in Physics.



Nanometre-sized swirls of spins called Skyrmions are ideal candidates for spintronics and innovative data storage applications. © M. Garst - TU Dresden

The future of information technology is quantum. Neutrons will be key to the discovery of new materials and to understanding their behaviour, further advancing the development of next-generation IT solutions.

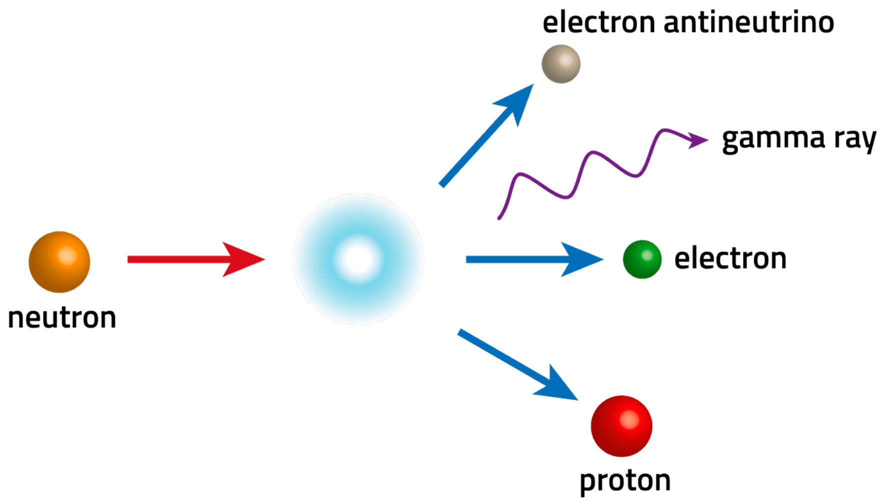
Particle physics deepens our understanding of the origin and evolution of the universe and how, at a fundamental level, matter and nature work. The current foundation of this understanding is the Standard Model which, together with theories such as general relativity, covers all known fundamental interactions and particles. However, cosmological observables now show possible deviations from the Standard Model, indicating that the Standard Model is incomplete. Very different research routes are being pursued, such as searching for new particles through high-energy collisions at CERN and exotic particles in the IceCube Neutrino Observatory in Antarctica. Neutron facilities probe the limits of particle physics by studying the properties and decay of the neutron itself.

THE WEAK INTERACTION

The weak interaction, one of the four fundamental forces of the universe, is responsible for the radioactive decay of atoms. The simplest system by which to study this decay is the free neutron; an inherently unstable particle, it decays on a timescale of 15 minutes to become a proton, an electron and an antineutrino. Neutron experiments, measuring correlations of properties of the decay particles, constitute the most stringent tests of the weak interaction within the Standard Model.

MATTER / ANTIMATTER ASYMMETRY

Assuming the same amounts of matter and antimatter were generated during the Big Bang, observations of the cosmos today indicate that it is mainly matter that has survived the evolution of the universe. The laws of physics appear to act differently for matter and antimatter, which requires violation of Charge and Parity (CP) symmetry. While this would explain the dominance of matter in our universe, it is not fully covered by the Standard Model of particle physics. Scientists are searching for experimental evidence of CP violation in the strong interaction, another of the four fundamental forces, by looking for the existence of an electric dipole moment – or an electrical charge – in the neutron. Flagship experiments use 'ultracold neutrons' that are a billion-million times lower in energy than when initially produced by fission or spallation, to provide the long observation times necessary for these extremely sensitive measurements.

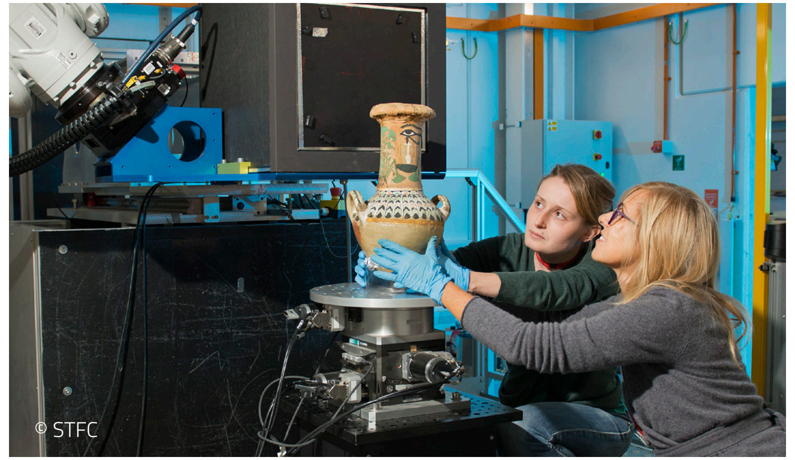


The spontaneous beta decay of the neutron holds information on the weak interaction, one of the four fundamental forces that govern the universe. © LENS – Stephanie Chapman

DARK MATTER

From observation by the Hubble Space Telescope, we know that gravity - as we understand it today - is not slowing down the expansion of the universe as previously predicted. We only appear to 'see or feel' 5% of our universe while unknown fields - dark matter and dark energy - account for the other 95%. Dark matter is obviously elusive to probe and understand but some candidate theories have been put forward: symmetron, axion and chameleon fields. These theories are being tested by exploring quantum states of neutrons, which report on gravitational interactions over short distances. New, ultra-precise experiments using neutrons are looking for deviations from the known properties of gravity, thereby testing the theoretical framework to describe dark matter so we can better understand the universe and predict how it behaves.

Neutron particle physics challenges the Standard Model of particle physics and contributes to a deeper understanding of the universe in which we live.



The same neutron techniques employed to study modern materials can be used to investigate historical artefacts and fossils. The information provided not only reveals our evolution, history and cultural development but contributes to sustainable tourism and guides restoration and preservation to ensure the secure transfer of heritage to future generations. The non-destructive and highly penetrative nature of neutrons make them valuable investigative tools for cultural heritage studies, where samples are often unique, irreplaceable and extremely fragile. The compositional and structural information provided about the sample can provide key insights into the place of origin, date of manufacture, how it was produced and what it is was made from. It has even, on occasion, shown that the object is a forgery – either ancient or modern!

WOOTZ STEEL BLADES

Wootz steel, also known as Damascus steel, is a type of high-carbon steel, produced in and around the Indian subcontinent since ancient times, that was greatly valued due to its hardness, elasticity and resilience. Attempts to recreate Wootz steel using modern technology based only on the composition of the steel failed, showing that it is both the composition and structure together that produce these superior qualities. Analysis of Wootz steel using neutron techniques has enabled the identification of a characteristic microstructure that is now used to distinguish true Wootz steel artefacts from imitations.

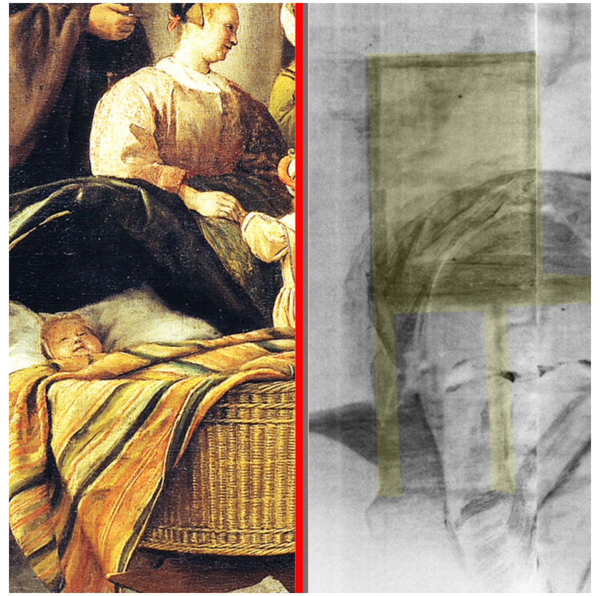
HUMANITY'S EARLIEST USE OF IRON

The famous Gerzeh iron beads, the earliest known iron artefacts, were excavated in Egypt in 1911 and dated to ca. 3000 BC. Analysis of the beads, using a range of complementary neutron techniques in combination with X-ray methods, showed that the beads contain nickel, cobalt and small but significant traces of germanium. This information confirmed the previously disputed meteoritic origin of the beads and demonstrated that humanity's earliest use of iron metal was based on meteorites, long before the invention of iron smelting. Analysis also showed that the beads were shaped by hammering, a typical metallurgical skill, and not by drilling, as was done for stone beads found in the same tomb.

Neutrons have been used to analyse iron-containing beads found in Gerzeh in Egypt, dated to 3100 – 3400 BC. [6]

PAINTINGS

Neutron techniques are valuable for the investigation of historical paintings due to their ability to non-destructively analyse sub-surface layers and distinguish between different elements thus providing insight into the creation process. For example, a considerable number of overpainted features were revealed by an investigation using neutrons of Rembrandt van Rijn's painting Susanna and the Elders from the Gemaldegalerie in Berlin.



Neutron autoradiography of the 17th century Dutch painting 'As the old ones sing, so the young ones pipe' by Jan Steen, reveals it to be an adaptation of an originally very different composition. © Helmholtz-Zentrum-Berlin.

The non-destructive nature of neutrons makes them valuable investigative tools for historical artefacts and fossils, providing insights into the place of origin and date of manufacture of a sample, in addition to how it was produced and what it is was made from.

2. THE NEUTRON SCIENCE LANDSCAPE IN EUROPE AND BEYOND

THE ECOSYSTEM IN EUROPE

Europe's world-leading position in neutron science, technology and instrumentation is founded on a unique ecosystem of small, medium and large, national and international facilities that is essential for a technique only available in centralised facilities. Together with the skills and diversity of a large expert user community, represented by the European Neutron Scattering Association (ENSA), this ecosystem has enabled neutrons to make pivotal contributions to science and innovation.

The foundations of this world-leading European ecosystem can be traced back to the development of nuclear power in the late 1940's. High intensity beams revealed the potential of neutrons as a powerful new method to study a wide range of materials and from the 1950's a number of reactors dedicated to neutron-based research were constructed. Though some of these had (and still have) significant radioisotope production, this particular application of neutron sources is beyond the scope of this document. The neutron landscape further evolved with the introduction in the 1970's of accelerator-based spallation sources, providing a complementary technique of neutron production. Generally, spallation sources are pulsed sources which means they generate bursts of neutrons at regularly spaced intervals; in contrast, most nuclear reactor sources generate a continuous stream of neutrons.

Europe's world-leading position in neutron science is founded on a unique ecosystem of facilities, combined with the skills and diversity of a large expert user community.

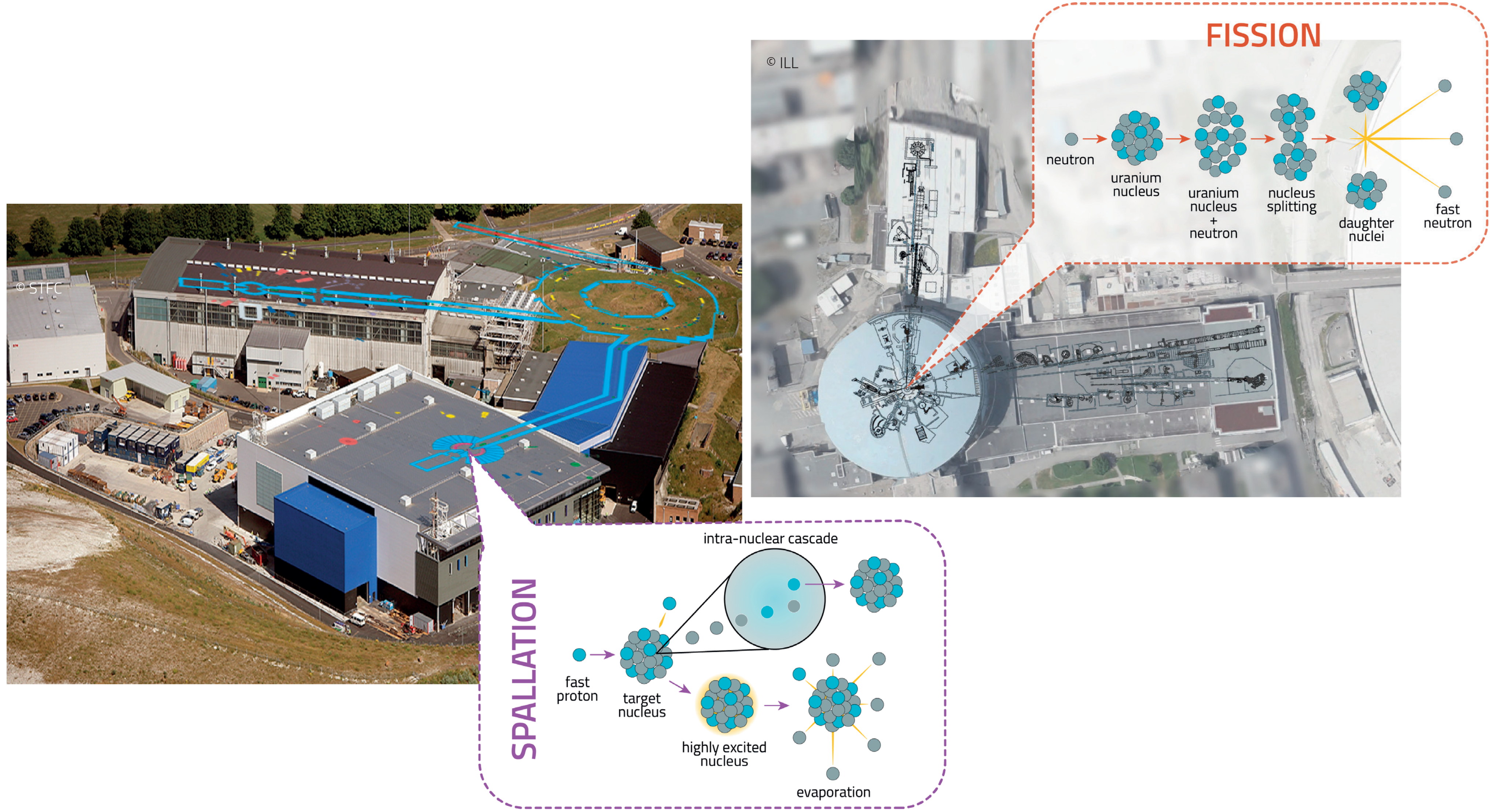
At all these facilities, whether reactor or accelerator-based, the high-energy neutrons produced are slowed to lower energies for specific applications. Continuous innovation has delivered a wide range of neutron techniques and associated instrumentation, covering time scales from femtoseconds to hours and length scales from the size of the atomic nucleus to that of aircraft components. The full exploitation of the extraordinary capability of neutrons allows these techniques to address society's greatest challenges, some of which are highlighted in the previous chapter, while key milestones in the development and application of neutron techniques are presented on the timeline overleaf.

The scale of research carried out at a major neutron facility is remarkable: 20-40 different instruments will be running simultaneously, 24 hours a day, seven days a week when a large facility is in operation. Over a year, up to 1,000 scientists make 4,000 visits to carry out experiments on topics that range from health and information technology to energy and fundamental science. Large facilities like the Institut Laue Langevin (ILL) in France or the ISIS Neutron and Muon Source (ISIS) in the UK have an asset value of over 1B€ and operating costs in the order of 100M€ per year. A new flagship facility like the European Spallation Source (ESS), currently under construction on a greenfield site in Sweden, costs approximately 3B€ to build, while the construction of smaller national facilities based around existing infrastructure might cost in the order of 100M€.

The ecosystem in Europe has been destabilised following the closure of a number of facilities causing decreased capacity and increased centralisation.

The European ecosystem is currently experiencing a period of significant change due to the closure of a number of national reactor-based sources - having arrived at the end of their operational lifetime - together with the upgrade of remaining facilities and the construction of a new flagship facility. The associated loss in capacity is destabilising the ecosystem. Though ESS will provide enhanced capabilities, these can only be fully exploited if the supporting ecosystem has sufficient strength, depth and diversity.

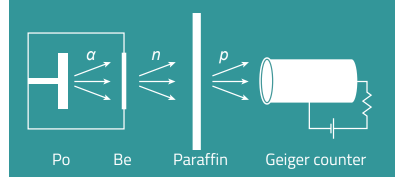
> *"Europe has dominated neutron scattering science in recent decades as measured by capabilities, capacity to support users, and scientific output. European laboratories operate two world-class facilities: the Institut Laue-Langevin (ILL) in France and the ISIS Neutron and Muon Source in the United Kingdom."*
>
> Neutrons for the Nation, American Physical Society (2018).



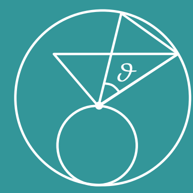
Neutrons are generated either by an accelerator-driven process called spallation (left image, ISIS) or by fission in a research reactor (right image, ILL). Both types of source serve large instrument suites. Insets © LENS – Stephanie Chapman

TIMELINE OF KEY EVENTS FOR NEUTRON SCIENCE

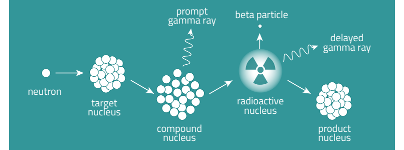
1932
James Chadwick demonstrates the existence of the neutron and is awarded the 1935 Nobel Prize in Physics for the discovery.



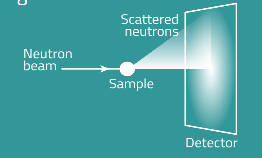
1938
Enrico Fermi is awarded the Nobel Prize in Physics for work on the atomic absorption and scattering cross-sections of slow and thermal neutrons, and for the discovery of transuranium elements.



1943
George de Hevesy, who developed a method of activation analysis based on neutron bombardment, is awarded the Nobel Prize in Chemistry for work on radiotracers.

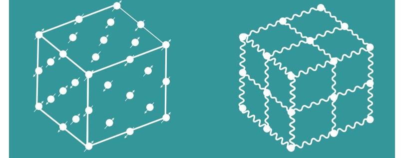


1974
Paul J Flory is awarded the Nobel Prize in Chemistry for fundamental achievements in the physical chemistry of macromolecules. His prediction that polymer chains adopt self-avoiding random walks was confirmed by small angle neutron scattering.

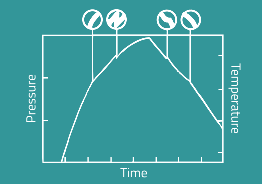


1991
Pierre-Gilles de Gennes is awarded the Nobel Prize in Physics for his work on liquid crystals and polymers. His models of polymer dynamics were validated using the neutron spin echo technique.

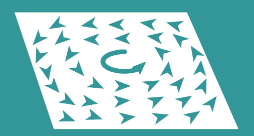
1994
Clifford Shull and Bertram Brockhouse are awarded the Nobel Prize in Physics for pioneering contributions to the development of neutron scattering techniques that show where atoms 'are' and what they 'do'.



1996
David Lee, Douglas Osheroff and Robert Richardson are awarded the Nobel Prize in Physics for discovering superfluidity in ^{3}He. Neutron scattering experiments provided important information on the different liquid and solid phases of ^{3}He and ^{4}He.



2016
David Thouless, Duncan Haldane and Michael Kosterlitz are awarded the Nobel Prize in Physics for theoretical discoveries of topological phase transitions and topological phases of matter, which were validated by neutron scattering experiments.

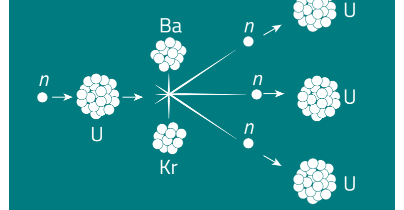


2018
The League of advanced European Neutron Sources is established.

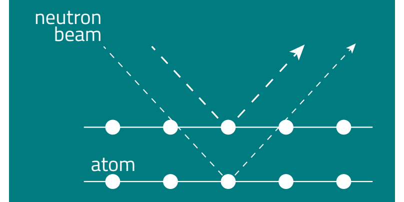
LENS

1930 1940 1950 1960 1970 1980 1990 2000 2010 2020

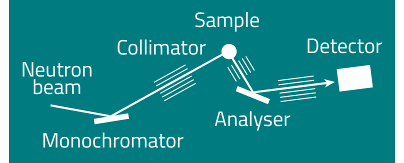
1942
Chicago Pile-1 (USA), the world's first nuclear reactor, goes critical, initiating the first controlled and self-sustaining nuclear chain reaction, providing an intense source of neutrons suitable for scientific experiments.



1946
First neutron diffraction using a reactor neutron source developed at Oak Ridge National Laboratory (USA).



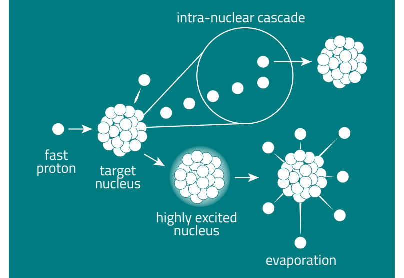
1955
The triple axis spectrometer is developed at Chalk River (Canada), enabling the study of the motions of atoms in crystals.



1967
The ILL is launched as the international flagship centre for neutron science. The first neutrons are produced in 1971.

NEUTRONS FOR SOCIETY

1972
Jack Carpenter demonstrates pulsed spallation neutron source concepts at Argonne National Laboratory (USA).



1984
ISIS Neutron and Muon Source begins operation as the first spallation neutron source in Europe.

1994
The European Neutron Scattering Association (ENSA) is formed.

1996
Inauguration of the Swiss Spallation Neutron Source (SINQ) at the Paul Scherrer Institut.

PAUL SCHERRER INSTITUT

2004
Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM II) goes into operation.

FRM II
Forschungs-Neutronenquelle
Heinz Maier-Leibnitz

2014
Construction begins on the European Spallation Source.

A number of neutron sources, including SINQ shown here, are co-located with other major research infrastructures, such as synchrotrons.

A vibrant ecosystem based on complementary facilities has enabled neutron science to thrive in Europe for more than four decades. Most neutron techniques are only available in centralised facilities; there are no small laboratory-based sources or instruments. The network in Europe currently numbers eight reactor and two accelerator-based sources, collectively equipped with approximately 150 instruments. While the facilities could be classified by size (small, medium, large) or reach (local, regional, national, international), both similarities and differences can be found between any two facilities.

The intrinsic value of a facility depends on technical characteristics that include the brightness, spectrum and availability of the neutron source as well as the quality, size and diversity of the instrument suite. Additional aspects to consider include (i) ancillary scientific support facilities, (ii) sample environments (that enable the state of the sample under investigation to be varied, for example by heating, cooling or by the application of pressure, magnetic/electric fields or mechanical processing), (iii) software to control instruments and access, visualise and analyse data, (iv) access mechanisms and (v) specialised skills of facility scientific and technical staff. Some facilities focus on specific scientific areas or technology developments, often depending on the local research environment; this is an important source of innovation and enables facilities to form an identity. Each facility therefore has unique value, with an associated purpose and role within the ecosystem.

Capacity, determined by the numbers of instruments and operational days at each facility, directly influences the quantity and range of research programmes that can be supported across Europe. The most common types of experiment use instruments that are in widespread operation across facilities, so can be performed according to availability and independently of location. Capability, the ability to carry out specific types of experiments, is however not uniformly distributed across the ecosystem. In some cases, where specialist provision is critical for specific research applications, experiments are tightly constrained by the availability of individual instruments at specific facilities. A finely-tuned combination of capacity and capability is required to broadly match supply and demand while ensuring excellence, enabling the user community to flourish and delivering successful research and innovation outcomes for society.

Each facility has unique value, with an associated purpose and role within the ecosystem.

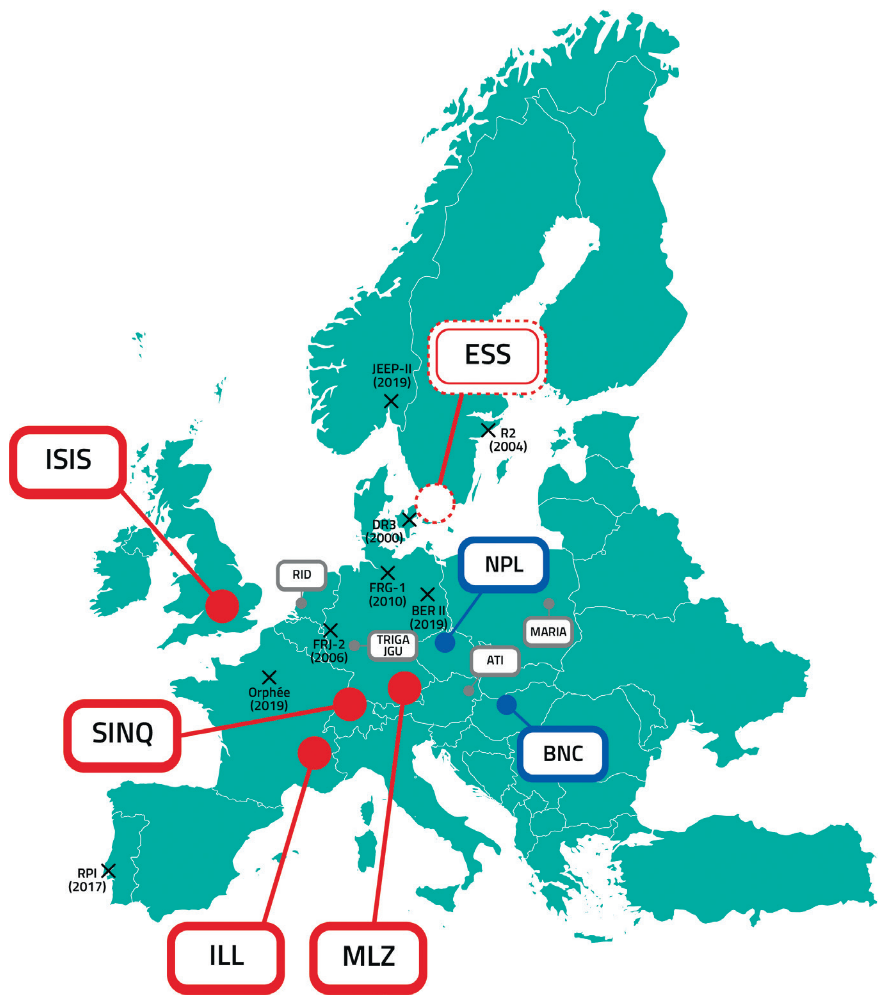
All facilities provide the capability and capacity to carry out numerous experiments that are not necessarily dependent on the brightest neutron beams. The unique capabilities of flagship facilities are mainly dedicated to carrying out research that requires the brightest beams, not accessible at any other facility, building on and advancing the science carried out elsewhere within the ecosystem. Upgrade programmes carried out at individual facilities, however, ensure pioneering developments and the continuous improvement of neutron techniques and instrumentation that can then be applied elsewhere, improving all facilities within the ecosystem. The ILL Millennium and Endurance programmes, in addition to the ISIS instrumentation programmes on both target stations, have significantly increased neutron science capability, for reactor and accelerator-based sources respectively, far beyond any development of the sources themselves.

Within this system, users access facilities according to their needs: from first contact with neutron techniques, to routine experiments and eventually higher-end experiments. The ecosystem ensures continuity of service for these users through planned (periodic maintenance and upgrades) and unplanned (equipment failure) interruptions. The ecosystem also provides the necessary training for new users, ranging from PhD students through early-career researchers to Principal Investigators, who constitute a large fraction of the users at a facility at any one time.

Collaboration on a European scale enables the creation of flagship facilities with capabilities that surpass what is achievable on a national scale. The ILL is the flagship facility in Europe and indeed has been the leading neutron facility in the world for more than four decades. Neutrons were first produced in 1971 and the facility, with almost 40 instruments in operation, is supported by 14 member countries. Offering world-leading capability, it enables ground-breaking research and has greatly contributed to Europe's leading position in neutron science. ESS is the future international flagship facility in Europe with the potential to become the leading neutron facility in the world. Scheduled to begin operation in 2026, the first instruments will provide neutron capability far beyond what currently exists, progressively opening new research opportunities across a range of scientific areas.

Though the large national facilities within Europe - ISIS in the UK, the Heinz Maier-Leibnitz Zentrum (MLZ) in Germany and the Swiss Spallation Neutron Source (SINQ) - have one owner providing the majority of the funding, each of these facilities has a significant international user base. With 20-30 instruments in operation at each facility, they are major contributors to neutron science, not just in their countries but across Europe. It is a similar situation, albeit on a smaller scale, for the other national facilities in Europe: the Budapest Neutron Centre (BNC) in Hungary and the Nuclear Physics Laboratory (NPL) in the Czech Republic operate, respectively, 12 and seven instruments that are available to neutron users in Europe. TRIGA User Facility, Johannes Gutenberg-Universität Mainz (TRIGA JGU) in Germany, the TU Wien Atominstitut (ATI) in Austria, the National Centre for Nuclear Research (MARIA) in Poland and the Reactor Institute Delft (RID) in the Netherlands complete the ecosystem and complement the instruments available to neutron users in Europe.

To preserve and continuously develop experience and expertise, a number of neutron knowledge centres have been created across Europe where sources have closed. These include the Jülich Centre for Neutron Science (JCNS, Germany – FRJ-2 reactor closed in 2006), the Laboratoire Léon Brillouin (LLB, France - Orphée reactor closed in 2019), the German Engineering Materials Science Centre (GEMS, Germany - FRG-1 reactor closed in 2010) and the Institute for Energy Technology (IFE, Norway - JEEP-II reactor closed in 2019). These centres make important contributions to the ecosystem of facilities in Europe and support both their national and the European user communities through the operation of instruments at various facilities, including ILL, MLZ and SINQ, in addition to their involvement in the construction of new instruments at ESS and the collaborative development of new neutron source technology.



Neutron facilities in Europe. Larger facilities shown in red. Dashed lines indicate a facility that is under construction. Facilities that are no longer operating are marked with an x. © LENS - Stephanie Chapman


© U.S. Department of Energy, Oak Ridge National Laboratory

The ability of neutrons to make pivotal contributions in science and innovation is recognised worldwide. It has also been widely acknowledged that, without appropriate action, the availability of neutrons will decrease. Significant new investment in other regions has caused the historical concentration of neutron science in Europe to evolve into a highly competitive, international landscape of neutron facilities. The development of facilities outside Europe contributes to the capacity and capability of neutrons available globally, but the resultant impact is generally small for the user community in Europe due to limited international access and challenging logistics.

Both flagship and large national facilities can be found in the United States. The Oak Ridge National Laboratory (ORNL) hosts two major facilities: the High Flux Isotope Reactor (HFIR), the most powerful reactor-based source of neutrons in the country, and the Spallation Neutron Source (SNS), which is currently the most intense accelerator-based source in the world. A range of world-class capabilities are additionally provided at the National Institute of Standards and Technology's (NIST) reactor-based source, the NIST Center for Neutron Research (NCNR). Significant investment for upgrades at each of these facilities is either underway (for example, a power upgrade of the accelerator and an early design for a second target station at SNS at a projected cost of well over 1B$) or planned (major upgrade of HFIR under discussion) to further develop US capability. This ongoing investment is made to address current and emergent challenges in research and maintain the strong, upward trend in neutron-based research in the US, which is clearly testing Europe's leadership. In Canada, the only major neutron source, the National Research Universal (NRU) reactor in Chalk River, reached the end of its lifetime in 2018. New investment is being made at the McMaster University reactor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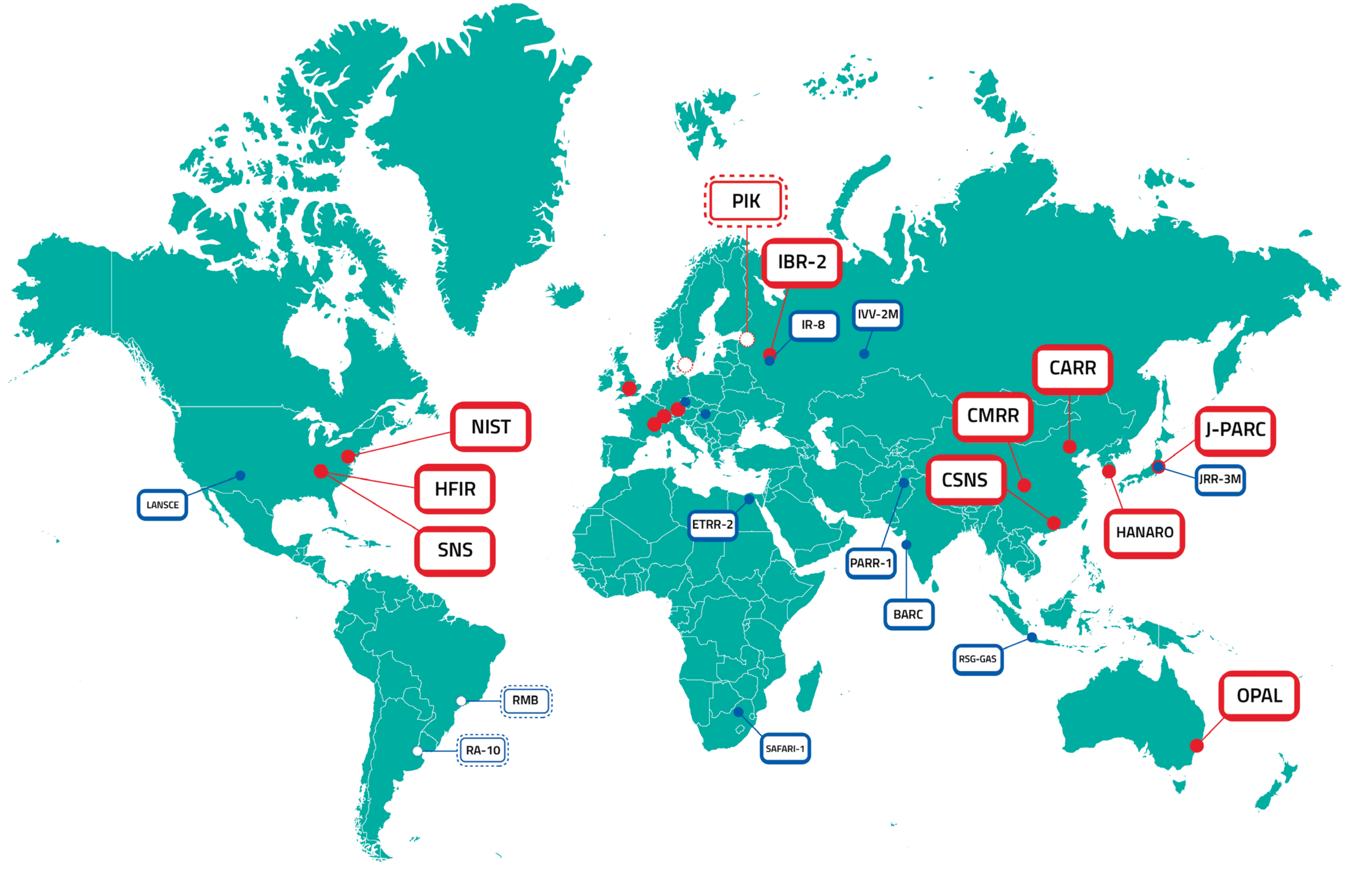

Neutron facilities worldwide. Larger facilities shown in red. Dashed lines indicate a facility that is under construction. European facilities shown previously. ©LENS - Stephanie Chapman

and new collaborations to provide access to neutron facilities in the US for Canadian neutron users have commenced. In Argentina and Brazil, the construction of reactor-based neutron sources is currently underway.

In Asia, Japan hosts two major world-class facilities: the Japan Research Reactor (JRR-3M) and the Japan Proton Accelerator Research Complex (J-PARC). Japan is one of the pioneers in accelerator-based neutron sources and J-PARC, when operating at full design power, will be the neutron source with the brightest neutron beams in the world until that title is claimed by ESS. Japan has also led the development of Compact Accelerator-driven Neutron Sources (CANS) and a network of these small university-based sources has been developed throughout the country. The strategic importance of neutrons has been established in China and neutron research, supported by significant investment, is now increasing accordingly. Capacity is provided by three main facilities: the China Advanced Research Reactor (CARR), the China Mianyang Research Reactor (CMRR), and the China Spallation Neutron Source (CSNS) which started operation in 2019 with an instrument suite that is rapidly expanding. Finally, since 1995 South Korea has operated a multi-purpose research reactor, HANARO at Daecheon, equipped with 15 instruments for neutron science.

In Russia, neutron research is supported by two national facilities: the IBR-2 pulsed reactor in operation at the Joint Institute for Nuclear Research (JINR) and the PIK reactor at the St Petersburg Nuclear Physics Institute, built in the 1970's but only now being commissioned.

Neutron research in Oceania takes place at the Open Pool Australian Lightwater (OPAL) reactor, a large national facility operational since 2007, hosted by the Australian Nuclear Science and Technology Organisation (ANSTO). OPAL is one of the few research reactors for neutron science that could significantly increase its instrumentation beyond what is currently required by the country's user community.

The world map shows a number of smaller neutron facilities, in addition to those mentioned above, which offer limited neutron capability.

Significant new investment in other regions is challenging Europe's lead in neutron science.

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Neutron researchers in Europe were among the earliest pioneers of both the 'user programme' and 'user facility' concepts, which are now integrated aspects of research infrastructures across the world. Neutron user programmes, which provide access at facilities to external researchers, have been in operation since the late 1950's. The model was extended in the 1970's with the construction of the ILL, one of the first research facilities to be purpose-built for operation as a user facility and thus dedicated to serving the research needs of a broad user community.

The landscape of neutron user facilities in Europe has enabled the development of a prolific community of users that is currently larger and more mature than in any other region of the world. This skilled and diverse community is an asset that has developed over the last 50 years and it forms, together with the ecosystem of accessible facilities, the foundation for Europe's world-leading position in neutron science, technology and instrumentation.

The European user community is a major asset developed over 50 years.

Europe's established leadership is internationally recognised, as noted by the American Physical Society's 2018 report Neutrons for the Nation: "Europe has dominated neutron scattering science in recent decades as measured by capabilities, capacity to support users, and scientific output."[7] It is also evident in the numerous notable contributions made by neutron science: 70% of neutron science papers published in high impact journals world-wide result from experiments carried out at European facilities.[2] Similarly, recent analysis carried out by ENSA of 46,000 scientific articles that employed neutron techniques, identified that the majority of neutron publications include at least one co-author in Europe.[8]

EU funding has increased the use of neutrons and extended the user community across Europe.

Access to facilities has been enhanced by schemes such as the EU funded Transnational Access programme: the first was started at the now closed DR3 reactor in Risø, Denmark in 1992, while the last - NMI3 [9] - finished in 2016. These programmes were immensely valuable for neutron science in Europe. They significantly increased the use of neutron techniques and helped extend the user community throughout Europe by including a number of countries without a national neutron facility. A quantitative measure of this effect can be found in the increased number of member countries at both ILL and ESS that finance the operation or construction of these facilities.

The strength of neutrons in addressing a wide range of scientific domains correlates with a user community that is commensurately diverse. In addition, the increasing complexity of research requires the synergistic combination of multiple complementary techniques, including neutrons. The user community thus combines increasingly multi-disciplinary scientists, researchers and engineers from a widening range of scientific fields and industrial sectors. This trend has reshaped the user community such that its 5,000 members now consist of expert users, whose research primarily uses neutrons, in addition to a growing number of periodic users, who employ neutrons

ILL-ESS user meeting of over 500 researchers in 2018. © ILL

when necessary. While periodic users ensure that the community is dynamic and diverse, they also require a significant level of expert support from facility staff: pre-experiment (education and training), in-experiment (instrument and experimental support) and post-experiment (data analysis and publication).

The current reduction in capacity limits scientific output and threatens the user community.

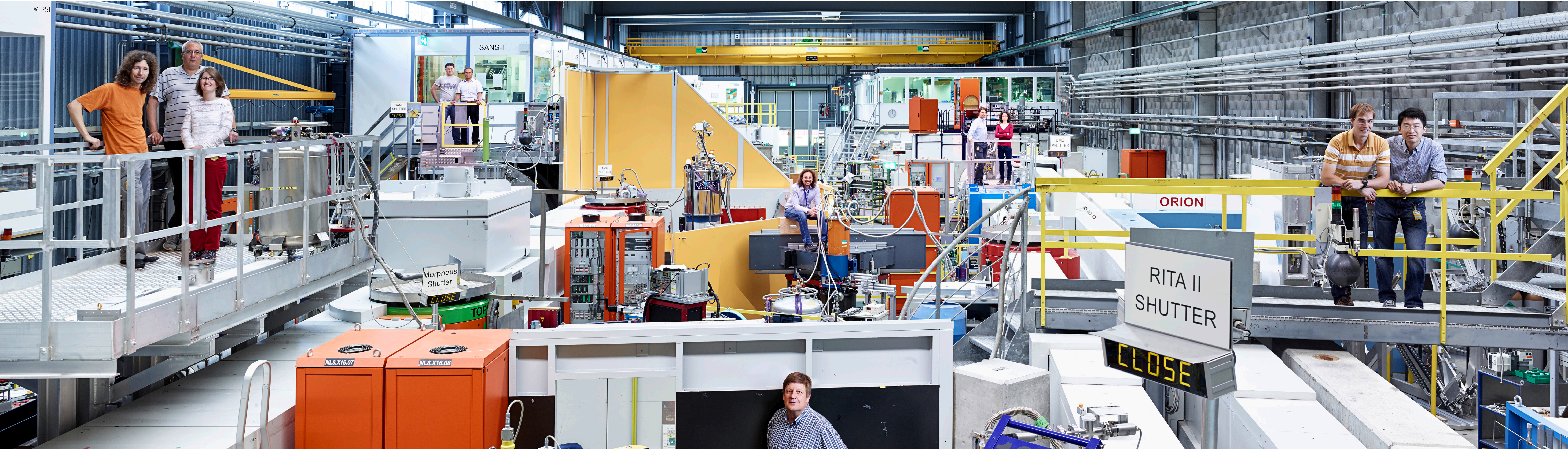
In parallel with its pioneering role in establishing user programmes, European neutron facilities have developed and refined different modes of access over several decades that are continuously adapted to reflect and respond to the changing nature of scientific research and the needs of the user community. Almost all beam time allocation involves peer review to ensure excellence, typically through a twice-yearly proposal submission process. Access modes have, however, become increasingly varied to address specific cases, such as industry, remote access, the running of multiple experiments over a period of years or rolling access. This flexibility is designed to make the best use of a finite amount of beam time and deliver the highest impact outcomes in a timely manner.

Whether expert or periodic, each user is entirely dependent on facilities for the timely provision of research capability to perform experiments within a larger research programme. Currently, the demand from users exceeds the available capacity of the ecosystem by a factor of at least two, making neutron access highly competitive. While oversubscription is often taken as a measure of quality, the balance between supply and demand is self-limiting and must be carefully managed. Any reduction in neutron capacity, as witnessed currently in Europe with the closure of several facilities, will ultimately result in a severe slowdown in scientific progress due to the limited number of research programmes and users that can be supported. The real risk, however, is that the expert neutron user community, built-up over decades, quickly declines as research programmes are adapted to the available resources in a highly competitive research environment.

Given the maturity and complexity of the neutron ecosystem in Europe, clearly coordinated, long-term, strategic planning at the European level is essential in order to avoid any significant slowdown in scientific progress due to the loss of neutron research capacity and capability. The following chapter presents the challenges and opportunities that will impact the future strategy of neutron science in Europe.

SINQ © PSI

3. THE CHALLENGES AND OPPORTUNITIES IN EUROPE



THE CHALLENGE OF COORDINATION

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As described in the previous chapters, Europe has held the world-leading position in neutron science for the four decades since the Institut Laue Langevin (ILL) was fully established as a major user facility. This success was built on a rich and complementary ecosystem of small, medium and large neutron facilities in partnership with a large and diverse community of expert neutron users working across multiple scientific domains. This powerful combination has enabled pioneering research, excellent science and the resulting socio-economic innovations.

While there is a clear scientific and industrial need for neutrons to contribute to solving societal challenges and answering fundamental scientific questions, Europe's capabilities are threatened. The closures in 2017 - 2019 of the French, German, Norwegian and Portuguese reactors - Orphée, BER II, JEEP-II and RPI - have severely impacted the ecosystem of facilities in Europe. In particular, the loss of Orphée and BER II, two high-performing facilities with unique capabilities, high scientific output and experienced staff, caused a reduction of around 20% in Europe's capacity and hence ability to carry out neutron science. This will feed through into reduced real-world outcomes. The vast majority of neutrons in Europe are now provided by only a few large facilities - ILL, the ISIS Neutron and Muon Source (ISIS), the Heinz Maier-Leibnitz Zentrum (MLZ) and the Swiss Spallation Neutron Source (SINQ) – rendering the ecosystem vulnerable to the closure or reduced operation of any one of the four.

Europe's world leadership in neutrons was hard-won over many decades, through both excellent science and policy. The task of maintaining capacity, diversity and a robust system cannot be met unilaterally by any single facility or national government; the challenge is to establish the necessary coordination between countries, facilities and neutron knowledge centres, without which neutron science in Europe cannot succeed in the future.

The challenge is to coordinate national investment and initiatives, without which neutron science in Europe cannot succeed in the future.

The closure of BER II has meant the loss of a completely unique instrument for neutron scattering in very high magnetic fields.[10]

OVERVIEW OF EXISTING NEUTRON STRATEGIES

National neutron strategies from across Europe openly acknowledge the critical role of neutrons in any advanced nation's industrial programme due to their essential contribution to advances in technology, health, engineering and energy. [11, 12]

The challenges facing neutron science have prompted the publication of a number of reports, roadmaps and strategies at the European level, all demonstrating strong consensus with the national reviews. The Organisation for Economic Co-operation and Development (OECD) identified neutrons as an economic global imperative in 1996 with a subsequent report identifying an impending and worrying "neutron gap".[13] The alarm bell was rung more emphatically by the 2016 European Strategy Forum on Research Infrastructures (ESFRI) report on European neutron science facilities.[2] This reinforced the criticality of neutrons in addressing global challenges yet noted the decline in facilities across the region. Since this report, four of the remaining European sources have closed, compensated only by the future European Spallation Source (ESS). The 2020 ESFRI white paper identified "Research Infrastructures as an essential pillar of the European Research Area, forming a healthy, sustainable and integrated Research Infrastructure ecosystem that strives for scientific excellence with impact, and provides transnational services, supporting education and skills development."; neutron facilities are a key component of this wider ecosystem.[3]

Europe's position as world-leader in neutron science has been a factor in prompting investment in new facilities and upgrades in the United States and across Asia. As the Director of the NIST Center for Neutron

"Neutrons are playing a key role in helping the UK realise an end-to-end materials R&D ecosystem: from materials discovery through materials and component scale-up to high-volume manufacturing and system and service integration."

Neutron & Muon Science and Facilities: A Strategic Review and Future Vision, Science and Technology Facilities Council (2017).

"... fulcrum of the country's future industrial strategy in sectors such as advanced materials, additive manufacturing, low carbon dioxide energy technologies, the digital economy, the pharmaceutical and biomedical industries."

A Strategic Review and Future Vision for Neutron Science in Italy, Italian Physical Society and SoNS (2019).

"Progress in each of these domains depends critically on the development of new materials and processes, and this in turn requires precise insight into their structure and dynamics at an atomic, molecular and magnetic level. One of the most incisive tools to explore these properties is the neutron and the manner in which it is scattered by such materials."

Neutron scattering facilities in Europe: Present status and future perspectives, ESFRI Physical Sciences and Engineering Strategy Working Group, Neutron Landscape Group (2016).

LENS Colloquium bringing together European scientists and policymakers, Brussels, 2020. © ESS

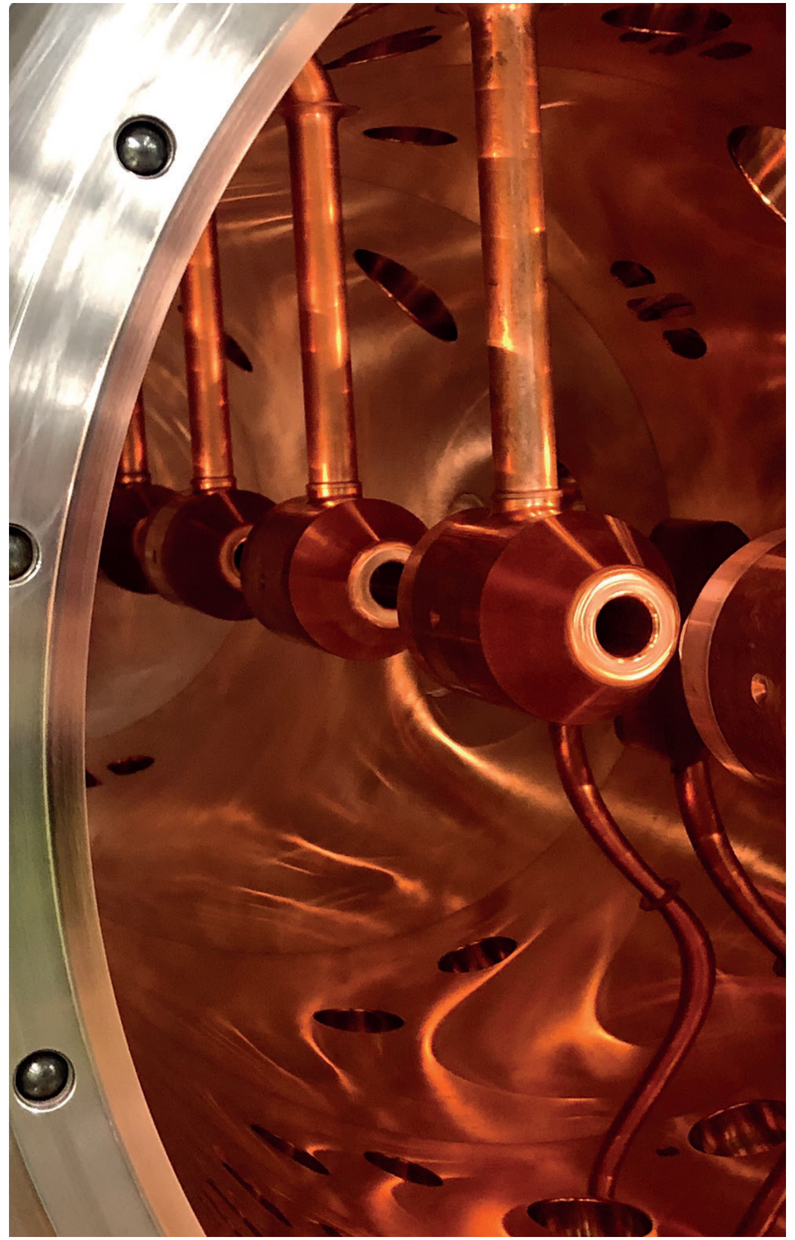
Research (USA) recently observed, "One of the areas the US has fallen behind in is neutron capacity, it's not just (about) capability … we are dwarfed by European neutron sources".[14] Fundamental then to Europe's position as world-leader is capacity, which, as the UK's 2017 strategic review noted, is critical because of "the strong correlation between neutron availability and publications" where a "… reduction in capacity… results in a major slowdown in scientific progress."[11]

The second critical component to European leadership is diversity. All strategic assessments agree that, while flagship facilities are crucial, Europe's strategic advantage is based on the range of sources and world-leading instrument capabilities. For example, the German neutron research strategy paper notes that "…focusing all efforts on ESS will hinder the functioning of the whole eco-system of neutron sources"[15], with the ESFRI report noting that it is the "network of other sources that gives structure and function to the health of neutron scattering in Europe."[2] This point is echoed in the French neutron road map that advocates for "…a source of less powerful neutrons close to the users, to provide them with the neutrons necessary for the preparation of the experiments and the expertise necessary for the analysis of their data."[16]

Finally, and particularly pertinent to Europe, it is well understood that a geographic distribution of facilities coupled with open access across borders enables the full complement of European facilities to deliver the highest economic and societal impact in the most cost-effective manner. This has been supported by EU funded Transnational Access programmes which have contributed to the development of a transnational user community whose trademark is scientific excellence. As a result of this evolution, approximately half of Europe's countries now make a direct, financial contribution to neutron infrastructure.

There is a common refrain among the national and regional strategies that the global trend toward consolidation of neutron research at only a few facilities would not be a good fit for Europe. While there is a pressing need to fill the European neutron gap, providing capacity alone is not sufficient. The resoundingly strong consensus is that for any single European neutron facility to meet its full potential, it must be embedded within a thriving ecosystem of small, medium and large, national and international facilities, that together form a 'pyramid' of capacity and capability.

ESS – THE FUTURE FLAGSHIP FACILITY IN EUROPE



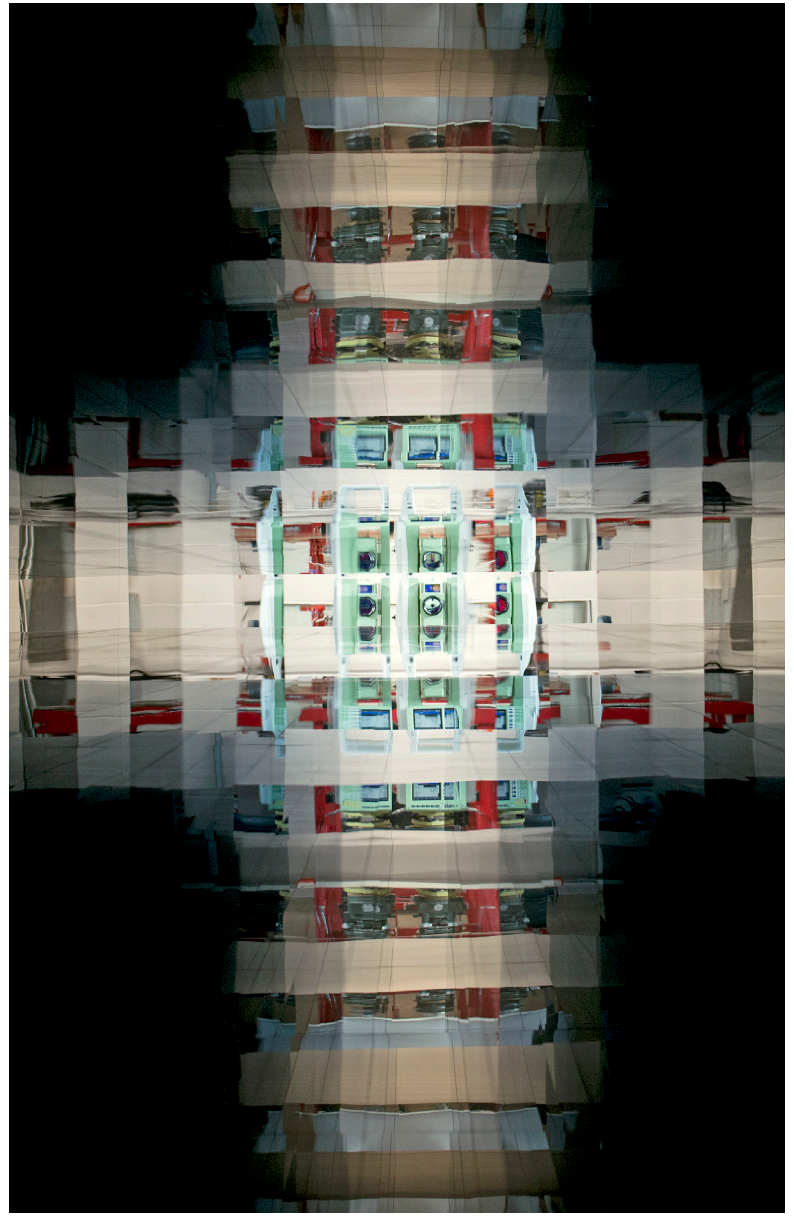
Drift tube section of the ESS linear accelerator. © ESS

ESS, the future flagship facility in Europe, represents a major opportunity for both Europe and neutron science. Scientific collaboration across Europe has enabled the unique and innovative design of the world's most powerful neutron source, equipped with cutting-edge scientific instruments.

The major challenge currently facing ESS is establishing sufficient financial support to ensure that the facility is brought to its full capability on a reasonable timescale, and then operated sustainably at this level. Though the facility can potentially accommodate 35 instruments, time will be required to achieve this full build out. Fifteen instruments are currently under construction, with the first scheduled to begin operation in 2026. Due to financial constraints, the source power is at present limited to 2 MW. Further funding is required to achieve the initial goal of the 13-member-country collaboration: 22 instruments and 5 MW source power.

The major challenge facing ESS is establishing financial support to deliver full flagship capability as quickly as possible.

One of ESS' instrument halls, showing the instrument, LoKI (a UK in-kind contribution), under construction. © ESS



Optical reflections in a neutron guide, a key component that channels neutrons efficiently from the source to the experiment. © STFC

Significant investment over many years has enabled the construction and continued development of the neutron facility ecosystem in Europe. Investment in the source and infrastructure of existing facilities maintains reliability and extends facility lifespan. New instruments are built, or new technologies are incorporated into existing instruments, in order to create additional capacity and capability. The operation of facilities at full capacity increases the availability of neutrons and ensures the highest productivity in terms of scientific output to cost ratio. Scientifically, the output of these facilities increases over time, both in terms of quality and quantity. Investment in existing facilities therefore represents a low-risk, cost-effective opportunity to increase scientific output through upgrades and optimisation.

A commonly used metric for the capacity of a facility is the number of instrument days (the product of the number of instruments and the number of operating days per year). This relates to the number of experiments that can be carried out, the size of the user community that can be supported and hence the potential scientific output and subsequent economic and societal impact. The increased performance of the source and instruments has translated into new capability, but also shorter experiments. For example, the average duration of an experiment at ILL has decreased from six to 4.5 days over the last 15 years. However, shortening of experiments cannot continue linearly due to finite measurement times, for example when measuring real processes such as battery charge/discharge, in addition to the significantly increased complexity of experiments required to address ever more challenging research questions.

ILL provides access to world-leading capacity and capability, achieved by near continuous upgrades (Millennium Programme 2001-2018, Endurance Programme 2016-2023) that have ensured improvement of both the infrastructure and suite of almost 40 instruments. The 6th Protocol for ILL has recently been signed allowing operation of the reactor until at least 2030. The main challenge now is to maximise the number of operating days and optimise scientific productivity from previous investments.

ISIS is a major contributor to neutron science in Europe. The number of instruments and range of science covered by the facility was significantly increased by the addition of a second target station, completed in 2009, while the planned Endeavour instrument upgrade programme (2023-2030) will further enhance capacity and capability. If funding for Endeavour is confirmed, the number of operating instruments will be increased from 31 to 35.

Marginal operating costs of facilities are typically only 20% of the total budget so even small budget reductions have a disproportionately high impact on output.

MLZ and SINQ are, respectively, Europe's most recent reactor and accelerator-based sources. While the upgrade currently underway at MLZ will increase the number of instruments from 27 to 33, the potential exists for a further increase to 40. SINQ, an accelerator-based spallation source providing continuous rather than pulsed neutron beams, is unique in the world. The most recent major upgrade, completed in 2020, significantly improved the performance of the majority of the 14 instruments in operation. The option to construct a second guide hall for an additional seven instruments - increasing overall capacity by 50% and adding flagship capability in key sectors such as applied materials and soft matter, for a fraction of the overall cost of SINQ - is currently being explored. A preliminary study will be completed by 2025, with construction possible towards the end of the decade.

Neutron experiments require large areas of neutron detectors, such as this 40-square-metre detector for neutron spectroscopy. © STFC

Development opportunities also exist at other facilities. The modernisation programme at the Budapest Neutron Centre (BNC) in Hungary, due to be completed in 2024, is broad-ranging and will enable the continued operation of the facility for a number of years while increasing the number of instruments from 12 to 15. Previous upgrades carried out at the Nuclear Physics Laboratory (NPL) in the Czech Republic have ensured that the facility can continue to operate until at least 2030. At the National Centre for Nuclear Research (MARIA) in Poland, refurbishments due to be completed by 2024 will make five additional instruments - transferred from the BER II reactor – available to neutron users in Europe. The OYSTER upgrade programme at the Reactor Institute Delft (RID) in the Netherlands will increase the number of instruments operated to seven with the option to add one more at a later stage.

The principal challenge for existing facilities is to ensure that the necessary resources are available year-on-year for sustainable operation and continued development. It should be noted that the fixed costs of a facility (the budget required to be fully ready to operate) are typically 80% of the operating budget while the marginal costs (the budget that scales with the volume of operation) are only 20%. A 5% reduction to the budget of any facility could therefore equate to a 25% decrease in the capacity provided by that facility.

The cost and scientific efficiency of capital investment in existing facilities is maximised by ensuring that they are fully developed and exploited for as long as possible.

Ultimately, facilities are judged on the quantity and quality of scientific output and the subsequent economic and societal impact. Two major factors that affect the conversion of experiments into output and impact are the reduced level of experience of the user community - who now typically employ a multi-technique and multi-disciplinary approach to solve ever more complex research problems – as well as the challenge of increasing data volume and complexity. Both of these factors require that facility staff numbers are increased.

Component for the first instrument at ESS. © STFC

EXISTING FACILITIES

FUTURE FACILITIES

© FRM II / TUM - Bernhard Ludewig

Continual exploration of both the technical and funding opportunities for new neutron facilities is necessary due to the significant time required for their planning, design and construction: at least a decade for even the smallest and two decades or more for larger facilities. Future facilities are likely to be based on a more diverse range of technologies, encompassing those that currently exist along with new technologies.

It seems unlikely that a new high-flux reactor of similar or higher specification to ILL will be built in Europe. New accelerator-based spallation sources can now provide similar or greater neutron science capability at an equivalent capital cost. The primary rationale for building a high-flux reactor would then be for the production of specific neutron-rich isotopes for a range of applications, including cancer therapy; neutron science would be secondary. Medium-flux reactors - similar to the Open Pool Australian Lightwater (OPAL) reactor in Australia - can be built on a commercial basis, providing capacity and capability locally on a relatively quick timescale
.

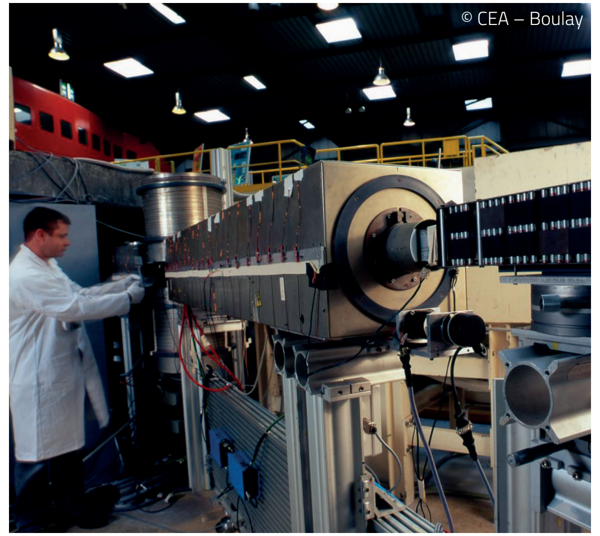
However, there is now increased interest in High Current Accelerator-driven Neutron Sources (HiCANS). These are accelerator-driven sources that produce neutrons through lower energy nuclear reactions rather than high energy spallation. Though such sources have existed for

> Future facilities are likely to be based on a more diverse range of technologies, encompassing those that currently exist along with new technologies, which will offer new opportunities and increased operational reliability.

many years, the capabilities were relatively limited until recently. Developments in accelerators, target design, moderators and neutron technologies now offer the possibility to construct and operate such facilities with significantly enhanced neutron science performance. Due to their considerable flexibility - in terms of cost, capacity and capability - HiCANS could play an important role in sustaining the European neutron science ecosystem. A recent report [17] provides more detail. The European Low Energy accelerator-based Neutron facility Association (ELENA) has been created to promote cooperation between projects in a number of countries, for example the Sonate [18] facility in France and the High Brilliance Source (HBS) [19] in Germany. A first HiCANS facility now needs to be built to demonstrate the potential of this approach.

Accelerator-based spallation sources offer a route to higher performance than HiCANS but, because of the greater accelerator energy required, have a more expensive 'entry price' in terms of construction and operating costs. The 2016 ESFRI report [2] noted that "For Europe to equate to the American and Japanese short pulse neutron sources (SNS and JPARC) by far the most cost-effective solution would be to build a MW-class short pulse facility at ISIS, reusing existing infrastructure and facilities as well as drawing upon on-site competences." Such a facility, ISIS-II, is in the early stages of conceptual design with operation potentially beginning around 2040.

Laser-based techniques for neutron generation have been demonstrated using either laser-induced fusion or 'plasma wakefield' acceleration. The latter technique will be used for high energy neutron imaging at the Extreme Photonics Application Centre currently under construction in the UK. However, the possible extension to a neutron facility with multiple instruments has not been explored.



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> The potential of High Current Accelerator-driven Neutron Sources (HiCANS) must be established by the construction and operation of a first HiCANS facility – Sonate or HBS.

EXPLOITING DATA

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One of the greatest opportunities, but also a significant challenge, is to more effectively exploit the data that is produced by current and future neutron facilities.

Although the average duration of a neutron experiment is a few days, similar to 40 years ago, the number of individual measurements and data volume for each experiment has increased by orders of magnitude. Improved software and user support are needed to analyse these large volumes, in particular for the increasing proportion of less experienced users. This has the additional advantage of diversifying the potential applications and economic and social impact of neutrons across a range of scientific and industrial fields. Artificial intelligence (AI) and machine learning techniques, paired with robotics, provide the potential to enhance the acquisition, reduction and analysis of experimental data, as well as to improve the operation and reliability of neutron facilities. Remote access, widely deployed in the context of the COVID-19 pandemic, builds on this digital transformation and will be further developed to increase efficiency. All of these aspects are ideal areas for broader cross-facility collaboration, for example under the European Open Science Cloud (EOSC).

Ultimately, it is not the number of experiments or the volume of data that is decisive, but their resultant scientific, economic and social impact. Some neutron facilities have had open access data policies for many years, but the common adoption of a European Neutron Open Access Data Policy will make the sharing of Findable, Accessible, Interoperable and Reusable (FAIR) neutron data standard practice. This will allow collection of neutron data in thematic databases, alongside data from complementary techniques, increasing effective utilisation and multiplying the societal impact of each experiment performed.

> Artificial intelligence and machine learning techniques, paired with robotics, provide the potential to enhance the acquisition, reduction and analysis of experimental data.

ENVIRONMENTAL SUSTAINABILITY

There is a significant environmental cost to building and operating large-scale research facilities such as those used for neutron science. However, the demonstrable environmental benefit of their research outcomes provides a clear rationale for continuing to do so.

It is increasingly important to understand, quantify and maximise the environmental benefit/cost ratio of neutron activities. European neutron facilities must be at the forefront of this effort and the design stage is the ideal time to secure significant energy gains. Building ESS on a greenfield site presented an ideal opportunity to integrate sustainability goals from the outset with results including sustainable materials, energy efficient design and waste heat recovery used by the district heating network.

Introducing such large-scale efficiencies at existing facilities is not realistic, so efforts focus on retrofitting existing infrastructure and upgrading equipment when it is replaced. Nevertheless, extending the working life of existing facilities and ensuring their operation at the highest capacity possible reduces the financial, energy and environmental cost per experiment.


© FRM II / TUM - Bernhard Ludewig

A viable ecosystem of neutron facilities is necessary to address current and future societal challenges. The ecosystem in Europe, however, has been destabilised following the closure of a number of facilities - with further closures expected in the future - causing decreased capacity and increased centralisation. Fortunately, ILL's three associate countries (France, Germany and the UK) have recently extended their support, sustaining continued operation of this world-renowned facility until at least 2030. This decision has helped postpone further losses in capacity, capability and scientific output until the next decade. Despite this, the overall trend is towards fewer neutron instrument days risking the decline of European research and its capacity for breakthrough discoveries and innovation.

The closure of facilities has a potentially significant impact on the European skills base. At present, the continued operation of neutron knowledge centres, in particular the Jülich Centre for Neutron Science (JCNS) and the German Engineering Materials Science Centre (GEMS) in Germany, the Laboratoire Léon Brillouin (LLB) in France and the Institute for Energy Technology (IFE) in Norway, contributes to the maintenance of national neutron expertise, supporting the current use and future development of facilities. However, to sustain such centres it is essential to attract and train new experts which becomes increasingly difficult without sufficient capacity in the ecosystem to support new projects.

The signing in 2021 of the 6th Protocol – for the operation of ILL until at least 2030 - represents a welcome 1B€ investment, but there is currently no proposal to develop a sustainable, longer-term plan for European neutron science. It is appreciated that developing a scenario for real sustainability is a complex task and crafting a plan, even though the prospective components are all well understood, will not be straightforward.

The international facilities (ILL and ESS) are owned by more than one country and funded by consortia of 13-14 countries with widely varying shares. The national facilities are owned and predominantly funded by a single country, with each deciding individually on its national needs and investment priorities. Those countries that support large national facilities (UK, Germany and Switzerland) and also contribute to ILL and ESS, are supporting a higher proportion of the total financial cost of developing and operating European facilities. Previously, a partial redistribution of this funding imbalance was achieved through EU support for transnational access, which broadened the funding base of the international facilities. Having encouraged more countries to make a financial contribution to neutron facilities, this EU funded Transnational Access mechanism has since been discontinued.

Economic return on investment is an important factor in national funding decisions. Whereas the indirect return (the benefit arising from the research and technical development) is largely independent of facility location, the direct return (the benefit arising from construction and operational funding) is predominantly to the host country.

The opportunities to ensure a viable neutron ecosystem in Europe by 2040 are already broadly known due to the significant lead time required to develop new facilities. In the 2020's, the options are to maximise the use of existing facilities such as ISIS, MLZ and SINQ, start and ramp-up user operations at ESS and deliver a first HiCANS facility. While these options are technically viable, the funding required to achieve them has not yet been attributed. For example, even the current scope for ESS - 15 instruments and 2 MW source power - is not yet fully funded.


© STFC

In the 2030's, there are additional opportunities, provided planning starts now. For example, while 3-year funding for the conceptual design and initial prototyping of ISIS-II is in place, a decade or more of work is needed for full design and prototyping. The situation is similar with HiCANS which could eventually operate up to 20 instruments each. If HiCANS facilities are to contribute to the extent and within the timescale intended – and currently only Sonate and HBS have the potential to do so - then real progress needs to start soon.

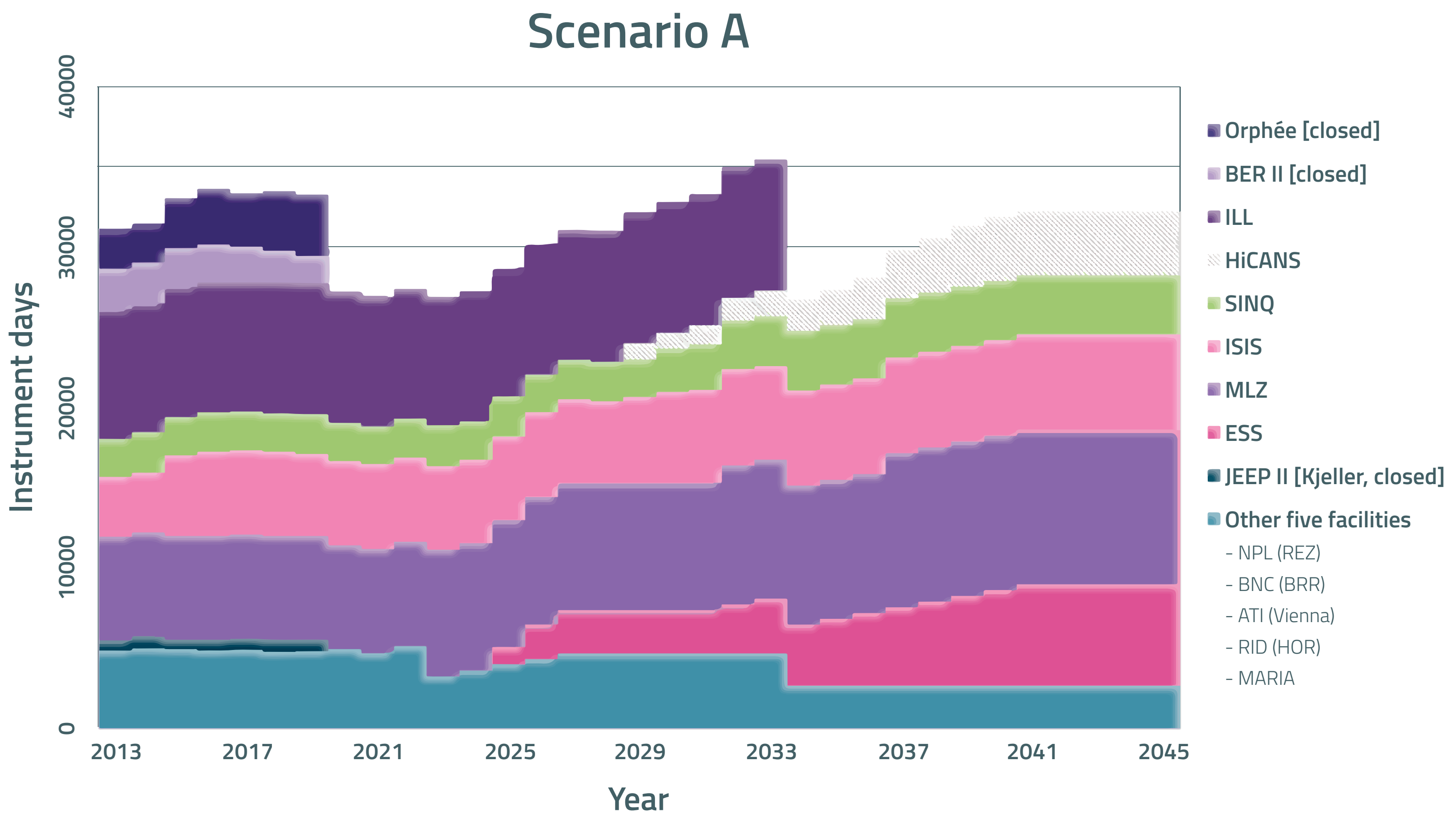
It should be noted in parallel that ILL will likely reach the end of its operation in the 2030's adding further downward pressure. The closure of ILL might only appear to represent a 25% drop in capacity in the scenario figures but, due to its disproportionately high productivity, the true impact would be a reduction in European science output of around 40%. The most cost-effective option to counter this is to build or upgrade as many world-leading instruments as possible at operational European neutron facilities, and to make real progress towards delivering full scope at ESS – 35 instruments and 5 MW accelerator power.
The funded expansion projects at national facilities will provide an addi-

tional six instruments at MLZ, five at MARIA and three at both BNC and RID. Additional options, not yet funded, would provide seven further instruments at both MLZ and SINQ and four at ISIS. These additional instruments comprise a cost-effective solution to partially compensate for already lost capacity but they will not fully bridge the decrease in capability and capacity caused by the future closure of ILL.

ESS, the future international flagship facility in Europe, is scheduled to begin operation in 2026. Though it will initially provide less than half the current capacity of ILL, there is significant scope for expansion. First, a fully funded plan must be defined in order to achieve the current scope – 15 instruments and 2 MW source power. Timely planning and investment will then establish a sustainable upgrade path for the development of a full 35-instrument suite, offsetting the impact of ILL's future closure.

To summarise the opportunities discussed, we provide two scenarios to illustrate the boundaries of what is technically possible for Europe's neutron ecosystem. The timely implementation of all identified opportunities would result in a viable European neutron ecosystem – Scenario A. This would maintain Europe's cutting-edge research by adding a significant number of new world-leading instruments to facilities over the next 20 years - key to delivering further capacity and capability in this scenario.

Scenario B only includes existing capacity and projects currently under construction, such as the project to equip ESS with 15 instruments. The total European capacity decreases drastically in this scenario on the likely closure of the highly productive ILL in the

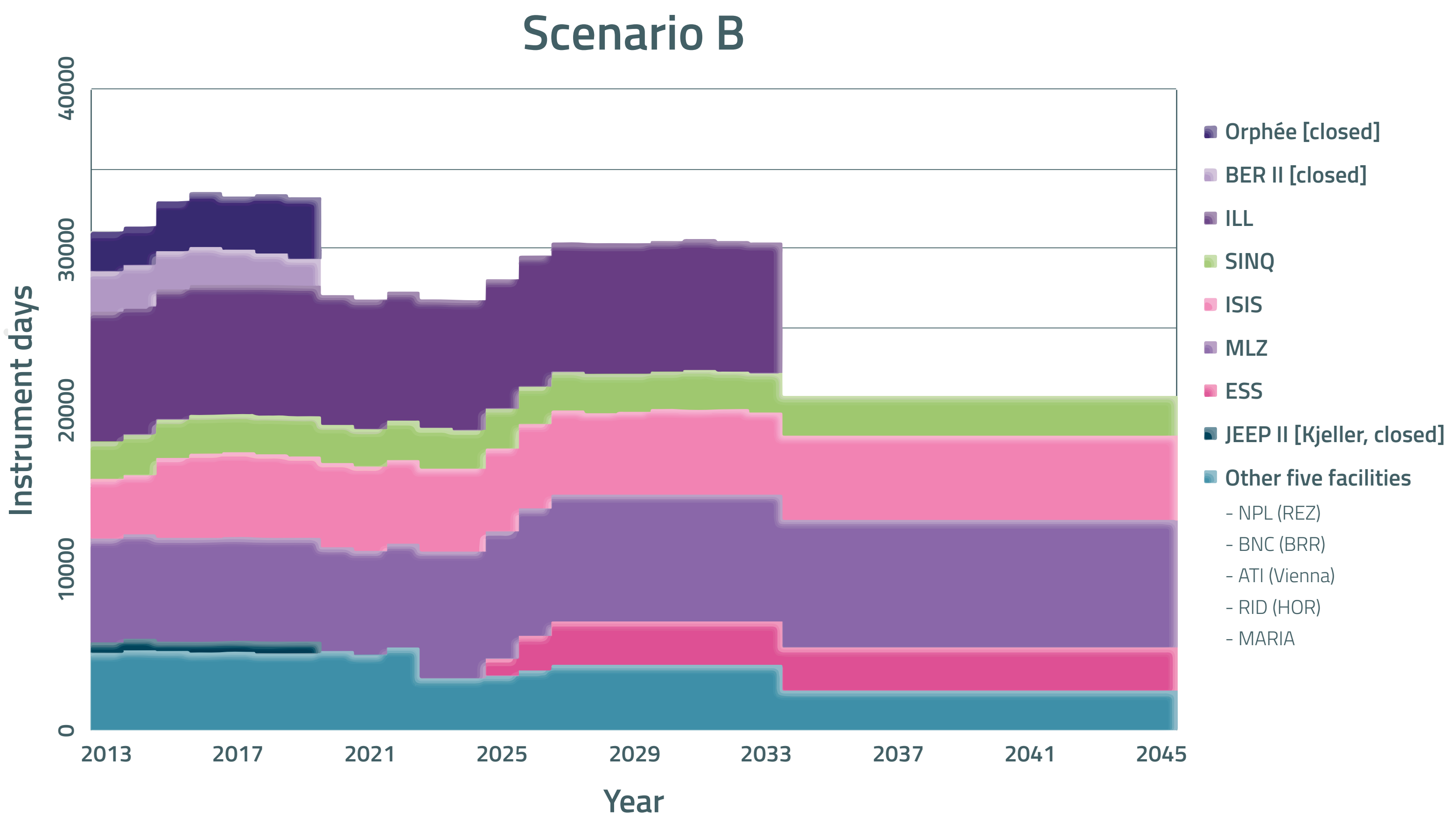


A projection of available capacity in Europe based on full implementation of all identified opportunities.
This figure updates the equivalent Figure 11 in the 2016 ESFRI report [2] and is plotted as an integral number of instrument days (number of operating days per year x number of instruments). Numbers are indicative of the relative scale of available capacity and hence the volume of research that can be supported. They do not indicate relative capabilities or resulting productivity. 'Other five facilities' includes the cumulative contribution of NPL (REZ), BNC (BRR), ATI (Vienna), RID (HOR) and MARIA to highlight the significant capacity provided by these five small facilities. The names in brackets refer to those used in the 2016 ESFRI report.

MAINTAINING A VIABLE ECOSYSTEM

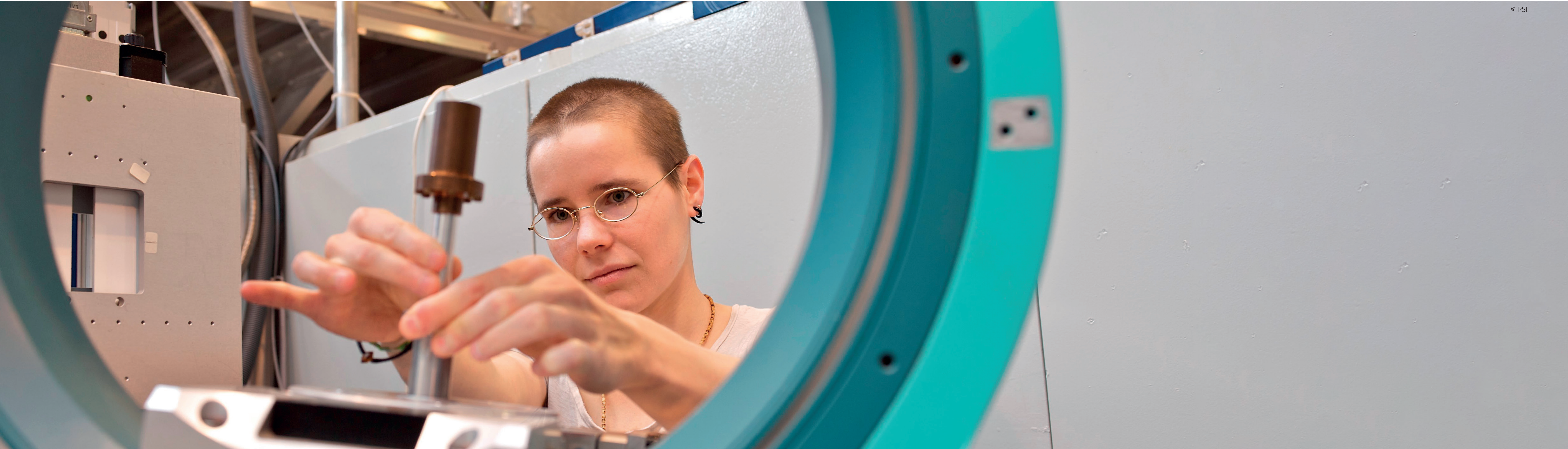
2030's. A decline on this scale would be clearly felt and severely limit the delivery of science and innovation as well as, therefore, economic and societal impact. Under this scenario other significant investors in neutron science - such as the US - may in time match, or even exceed, the much-admired European ecosystem.

It is important to recognise that the previous ecosystem cannot simply be recreated; the new ecosystem must be adapted to today's context and accommodate future requirements. The future mix of facilities – small, medium and large, national and international – will differ because the dominant source technology has shifted from reactors to accelerator-based sources. Environmental considerations will be a determining factor, with a greater use being made of automation, remote access and working, in addition to more effective use of data and machine learning. Funding decisions and their implementation at facilities and centres need to be coordinated, fostering an optimised scientific outcome across Europe. Direct and indirect returns on investment need to be equitably distributed. Strong collaboration over many years, reinforced by the establishment of the League of advanced European Neutron Sources (LENS), has motivated the development of a concept for a multi-institution 'European Laboratory for Neutron Science' (ELNS). Bringing together existing facilities, neutron knowledge centres, in addition to ESS and any other facility under construction in Europe in the future (such as HiCANS facilities), ELNS will ensure the efficient, coordinated delivery of neutron science and innovation in order to maximise impact across the ecosystem. However, the details for how ELNS would function in practice still have to be formulated and agreed.



A projection of available capacity in Europe based solely on already existing capacity and projects currently under construction.
This figure updates the equivalent Figure 7 in the 2016 ESFRI report.[2] Nomenclature the same as for Scenario A.

4. NEUTRON SCIENCE IN EUROPE – THE WAY FORWARD



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EUROPEAN LABORATORY FOR NEUTRON SCIENCE

The concept of a 'European Laboratory for Neutron Science' (ELNS) will be developed as a pan-European consortium to facilitate the sustainable development and optimal exploitation of a world-leading neutron ecosystem, with the capacity and capability to meet the research needs of a skilled and diverse community of researchers across academia and industry. The League of advanced European Neutron Sources (LENS) will evolve into ELNS, working to ensure that neutron facilities in Europe continue to deliver excellent science and innovation and therefore economic and societal impact.

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THE NEUTRON ECOSYSTEM

Operational effectiveness and efficiency, and high-quality service provision to users, are the essential foundations on which scientific excellence is built. Continuous improvement will include the development of access mechanisms responsive to the changing needs of science and industry, the particular needs of research related to global challenges, remote access and enabling technologies, and the coordination of access to multiple techniques through consortia such as ARIE (Analytical Research Infrastructures in Europe).[20] A specific focus on data, and increasing use of methodologies such as machine learning, will create new opportunities and efficiencies.

Environmental sustainability of large-scale research facilities is increasingly important. Neutron facilities have a significant environmental footprint in terms of energy use and waste material, including irradiated components, and these factors must be taken into account in the future development and usage of both new and existing facilities. The positive contribution of neutron science to enabling a climate neutral Europe will also need to be considered and quantified.

Collaborative research and development programmes will continue across facilities, collectively optimising and sharing the benefits of the available funding. This will include, for example, source and instrument technologies, sample environments, support facilities, software and training. A European Neutron Open Access Data Policy will make the sharing of Findable, Accessible, Interoperable and Reusable (FAIR) neutron data standard practice, increasing effective utilisation of this data and the corresponding economic and societal impact.

A strong and dynamic European skills base, including technical expertise in facilities and user expertise in academia and industry, has been developed over five decades of operation of neutron user facilities. This is equally as critical to effective scientific exploitation as the physical infrastructure, and represents a similar level of historic investment. A sustainable facility ecosystem will enable this skills base to thrive. The European Neutron Scattering Association (ENSA) will act as a strong representative of the user community, promoting neutron science and advocating for the needs of the community by engaging with all relevant partners.

FACILITIES AND ACCESS

International flagship facilities can only be constructed and operated through collaboration on a European scale, and can only be effectively exploited if the surrounding ecosystem of national facilities has sufficient strength and depth. The recently agreed 6th Protocol for ILL ensures operation until at least 2030. Strong political and financial support across Europe is required to complete construction of ESS and establish sustainable operation.

National facilities, in particular ISIS, MLZ and SINQ, are a cornerstone of neutron science in Europe. Their optimal exploitation, both economically and environmentally, requires operation and maintenance such that the highest number of instruments can be operated for the maximum number of days. Specialisation by individual facilities strengthens the diversity and synergy of the ecosystem, which ensures that the broadest span of scientific fields and industrial sectors are catered for in Europe.

HiCANS, High Current Accelerator-driven Neutron Sources, that use lower energy than accelerator-based spallation facilities, have the potential to be a significant part of the future ecosystem through their scalability. This could enable a larger number of countries to become facility owners or operators and provide capacity and capabilities tailored to their local or national needs. Several projects/designs are being developed but experience needs to be gained through the construction and operation of the first HiCANS facility.

Neutron knowledge centres will contribute to the continuity of expertise, and will provide additional capacity and capability to the ecosystem through their operation and construction of instruments at national and international facilities, the development of novel neutron technologies and the support of national user communities.

Cross-border open access allows users to employ the full complement of European neutron instrumentation in order to meet their research needs and attracts the best science to those facilities. Broadening the user base broadens the financial support for facility operation and development. To continue this positive evolution, maintaining significant international usage of national facilities, and its subsequent benefits, requires an equitable and sustainable funding model for neutrons in Europe.

FUNDING

New funding instruments must be explored, both European and national, aimed at for example, promoting engagement between universities and facilities or addressing challenges such as the Green Deal. However, LENS must seek to influence these instruments to ensure that facility capabilities are fully integrated in the research landscape and optimally exploited. New opportunities, such as flexibility in the use of European Structural and Investment Funds, or Widening projects, will be considered as methods for broadening the use of neutron facilities.

Coordination of national planning and funding at the European level, with organisational and funding decisions being taken within the next few years, will be critical to ensure that Europe can maintain its world-leading role in neutron science. Opportunities beyond 2030 have been presented in chapter 3. These include

- Build-up of ESS towards full capacity and specification,
- Build-up of capacity and capability in national facilities, and
- Deploying HiCANS facilities based on the delivery of a first operating facility in the 2020's.


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LIST OF ABBREVIATIONS

AI	Artificial intelligence
ANSTO	Australian Nuclear Science and Technology Organisation
ARIE	Analytical Research Infrastructures in Europe
ATI	TU Wien Atominstitut
BNC	Budapest Neutron Centre
CANS	Compact Accelerator-driven Neutron Sources
CARR	China Advanced Research Reactor
CERN	European Laboratory for Particle Physics
CMRR	China Mianyang Research Reactor
CP	Charge and Parity
CSNS	China Spallation Neutron Source
ELENA	European Low Energy accelerator-based Neutron facility Association
ELNS	European Laboratory for Neutron Science
ENSA	European Neutron Scattering Association
EOSC	European Open Science Cloud
ESFRI	European Strategy Forum on Research Infrastructures
ESS	European Spallation Source
FAIR	Findable, Accessible, Interoperable, Reusable
GEMS	German Engineering Materials Science Centre
HBS	High Brilliance Source
HFIR	High Flux Isotope Reactor
HiCANS	High Current Accelerator-driven Neutron Sources
IFE	Institute for Energy Technology
ILL	Institut Laue Langevin
ISIS	ISIS Neutron and Muon Source
IT	Information technology
J-PARC	Japan Proton Accelerator Research Complex
JCNS	Jülich Centre for Neutron Science
JINR	Joint Institute for Nuclear Research
JRR-3M	Japan Research Reactor
LENS	League of advanced European Neutron Sources
LLB	Laboratoire Léon Brillouin
MARIA	National Centre for Nuclear Research
MLZ	Heinz Maier-Leibnitz Zentrum
mRNA	Messenger ribonucleic acid
MW	Megawatt
NIST NCNR	National Institute of Standards and Technology Center for Neutron Research
NMI3	Integrated Infrastructure Initiative for Neutron Scattering and Muon Spectroscopy
NPL	Nuclear Physics Laboratory
NRU	National Research Universal
OECD	Organisation for Economic Co-operation and Development
OPAL	Open Pool Australian Lightwater
ORNL	Oak Ridge National Laboratory
RID	Reactor Institute Delft
SINQ	Swiss Spallation Neutron Source
SME	Small and medium enterprises
SNS	Spallation Neutron Source
STFC	Science and Technology Facilities Council
TRIGA JGU	TRIGA User Facility, Johannes Gutenberg-Universität Mainz

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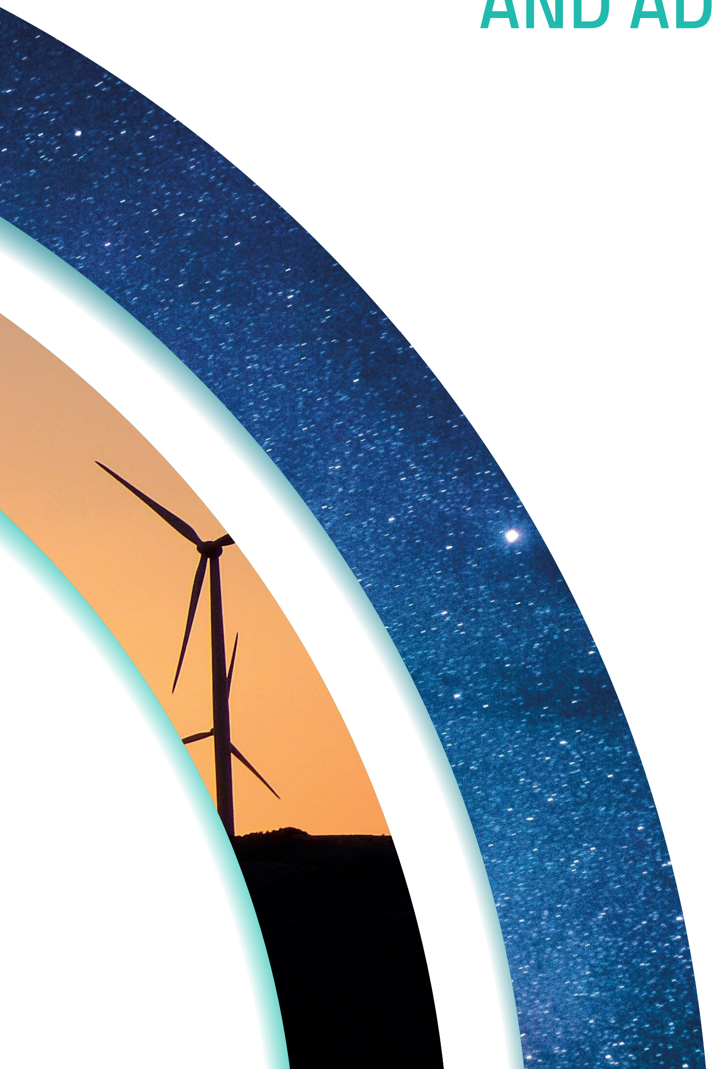
NEUTRON TECHNIQUES MAKE SIGNIFICANT CONTRIBUTIONS TO SCIENTIFIC DISCOVERY, THE CREATION OF NEW TECHNOLOGY AND ADDRESSING SOCIETY'S GREATEST CHALLENGES.



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