Strategy Paper
on

Neutron Research in Germany: 2015–2045

Sebastian Schmidt*)
Forschungszentrum Jülich (FZJ)

Andreas Schreyer
Helmholtz-Zentrum Geesthacht (HZG)

and

Helmut Dosch
Deutsches Elektronen-Synchrotron (DESY)

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*) in cooperation with T. Brückel and D. Richter (FZJ)

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1. Summary

- From the outstanding scientific advances achieved with neutron research during the pioneering years to solutions to the grand scientific and technological challenges of the future: neutrons are probes that are and will remain irreplaceable and are becoming more and more important in an ever increasing number of disciplines.

- Making available high-performance neutron sources with an optimized range of instruments is an important research policy task for Germany and Europe.

- A hierarchical system of neutron sources with a European top-class source that builds on a network of national neutron sources is a necessary scenario to achieve this goal.

- The status quo in Germany is based on a concentration of efforts for FRM II and the source at HZB, which specializes in complex sample environments. ILL in Grenoble takes on the role of the European top-class source.

- The future of neutron research will be dominated by spallation sources. It is therefore necessary to replace ILL with the European Spallation Source ESS in the medium term.

- In terms of the construction and, in particular, the instrumentation of ESS, Germany should build and operate about six instruments as a contribution in kind, in accordance with the size of its user community.

- In analogy to JCNS's involvement in SNS, a Helmholtz branch lab should be established at ESS to operate the instruments that will be provided by Germany as a contribution in kind and make them available to European users for their research.

- It will take a decade from the first neutron at the target until all instruments at ESS are fully functional. It is therefore essential for the European neutron community that ILL operation overlaps with the initial years of ESS operation.

- The high-flux reactor currently under construction in Gatchina (Russia) could complement research opportunities at ESS in the medium to long term. German involvement in the construction of instruments and components, their scientific use, and the establishment of an international user centre is therefore desirable.

- In the longer term, the current network of medium-flux reactors in Europe will have to be replaced with national spallation sources. A high-brilliance spallation source in Germany should be initiated after 2030.

2. Introduction

The development of new high-performance materials and more efficient active pharmaceutical agents is among the grand challenges facing our society. Tailor-made materials are required for all key technologies, from renewable energy concepts to more environmentally friendly transport systems and biocompatible medical applications. Many of these future materials and active pharmaceutical agents will be synthesized on the molecular level. This requires state-of-the-art, high-resolution (in situ) analytical methods to control the processes in a reliable manner.

Neutron probes are one of the pillars of the analytical techniques applied to solve these grand challenges. Advanced neutron sources are large-scale instruments used in numerous disciplines across the entire range of science and technology development. The European GENNESYS Study (2009) summarized the future demand for analytical techniques involving X-rays and neutrons for all areas of research and technology development up to and including industrial applications /1/.

Germany is considered to be one of the pioneering countries in the development of modern neutron research. Its reputation is based on the design of powerful neutron sources and novel instruments as well as their scientific use.

Making available state-of-the-art high-performance neutron sources with an optimized range of instruments is an important research policy task for Germany and Europe.

3. Future scientific applications of neutron research

Future flagship areas of research with neutrons can be found in the appendix. Additional information on future areas of application for neutrons in research and technology development are outlined in the Committee for Research with Neutrons (KFN)'s 2013 framework paper on neutron research for the scientific challenges of the future ("Neutronenforschung für die wissenschaftlichen Herausforderungen der Zukunft") /3/. These areas of application include fundamental studies on the structure and dynamics of matter as well as energy research, materials research, and research on active pharmaceutical agents.

4. Note on the range of applications of neutrons in research as compared to other analytical methods

Neutrons are just one of many types of probes that have proven to be essential for understanding the structure, dynamics, and function of materials. Other important probes used for state-of-the-art materials analysis include X-rays, electrons, methods such as NMR, as well as different types of optical microscopes and scanning probes (STM, AFM, etc.).

In modern solid-state and materials research, these methods are often used to complement each other in gaining as complete a picture as possible of complex materials and processes by combining different types of information.

The specific properties of neutrons provide information that cannot be obtained with other methods. These characteristics include:

- the nature of the interaction of neutrons with matter, which facilitates the observation of particularly light elements (e.g. hydrogen) and usually provides high contrast even between neighbouring elements in the periodic table,

- the energy of the neutrons used for scattering experiments, which is within the range of typical excitation levels for lattice vibrations, magnetic excitations, as well as diffusion and tunnelling processes, makes neutrons a particularly suitable probe for studying the dynamics of materials,

- the high penetration depth for studying large objects or in complex sample environments,

- the magnetic dipole moment, which enables a simple analysis of magnetic structures,

- the very low radiation damage in comparison to X-rays and electrons (which is particularly important for biomaterials), and

- the sensitivity for different isotopes of an element.

It is often a combination of several of these properties that is crucial for analysing a material.

An example from applications-oriented research for future energy systems: using neutrons to study the processes that occur in a hydrogen tank during the filling process provides a wealth of information, because neutrons combine a high penetration depth (through the tank) with a high sensitivity for hydrogen. Such information is of great significance for the development of modern hydrogen storage technologies.

In Germany there are research groups, namely in solid-state and materials research, that use the entire analytical portfolio of synchrotron radiation, neutron methods, and electron methods (microscopy, spectroscopy) on a regular basis. Whether neutrons or other methods are more suitable always depends on the individual case, for example:

- While neutrons are typically used as a probe for magnetic structures, the development of resonant magnetic X-ray scattering has enabled important new methods of analysis due to its element selectivity and capability of differentiating between the spin angular momentum and the orbital angular moment. However, due to the usually low X-ray excitation energies, the penetration depth of X-rays is often lower than that of neutrons. In addition, the absolute determination of the total magnetic moment is often only possible with neutrons due to the much less complex magnetic interaction.

- State-of-the-art electron microscopy methods provide structural information with the highest resolution. However, this information is only available for thin samples prepared in a complex process and for surfaces, and the statistical information provided is limited due to the small volume of the samples that can be studied using this method. X-ray or neutron scattering considerably increases the information depth because samples with a larger volume can be studied; neutrons are the method of choice when their specific properties listed above are required (e.g. prevention of radiation damage and contrast variation by substituting isotopes, etc.).

5. Status of neutron sources worldwide

The leading position of research with neutrons in Europe is based on national sources, which cater for the large number of users who perform experiments that do not necessarily require the highest neutron fluxes, and also on transregional top-class facilities for the cutting edge of neutron research.

The most important national sources are LLB (France), SINQ at PSI (Switzerland), and ISIS (UK), as well as BER II and FRM II in Germany. The transregional top-class facility in Europe is currently Institut Laue-Langevin (ILL) in Grenoble (France), which has the highest-flux reactor (HFR) and the most advanced instruments (approx. 40 instruments). ILL also takes a leading position in an international comparison.
There are few large centres worldwide that combine a high neutron flux with a broad range of instruments (see Tab. 2 and Fig. 1).
At all of these centres, beam time is allocated by independent experts. The overbooking factor is typically 2 to 3.

Source **German contribution**	Start of operation	Thermal power [MW]	Nominal integral flux [cm^{-2} s^{-1}]	Nominal peak flux [cm^{-2} s^{-1}]	Nominal op. time [days/a]	User instruments	Potential no. of instruments	User stays/ a	Ann. op. budget
FRM II (special role of universities) **national**	2005	20	$8 * 10^{14}$		240	23 operational 7 under construction	35	1000	€ 55 m
BER II **national**	1991	10	$1.2 * 10^{14}$		220	11 operational 3 restricted	20	400	€ 22 m
ILL **25 %**	1971 (1995)	58	$1.3 * 10^{15}$		200	27 + 10 CRG	> 40	1400	€ 80 m + 5 CRG
ESS **10–15 % under negotiation**	**under construction (planned for 2019)**	**5 MW LP**		**$4 * 10^{16}$**	**200**	**20 from 2025**	**> 20**		**€ 140 m**
PIK	under construction (planned for approx. 2020)	100 MW	$1.2 * 10^{15}$			approx. 25	up to 40		---
LLB **----**	1985	14	$3 * 10^{14}$		200	22 external use 3 internal use	25	600	€ 25 m
SINQ **----**	1996	1 MW cont.	$1.5 * 10^{14}$		200	15	20	800	€ 30 m
ISIS/ISIS-II **----**	1985/ 2009	200 µA SP		$4.5 \cdot 10^{15}$	180	27	35	1500	€ 55 m
IBR-2 BMBF Dubna contract	1984/ 2010	2 MW	10^{13}	10^{16}	108	16			

Table 2: Relevant neutron sources in Europe (sources highlighted in colour play an important role in the national roadmap)

Outside Europe, apart from the new MW spallation sources SNS at ORNL in Oak Ridge, USA, and JPARC in Tokai, Japan, above all NIST in Gaithersberg near Washington D.C., USA (2 * 10^{14} n/cm^2 s), the HIFR reactor at ORNL (10 * 10^{14} n/cm^2 s) and the JRR-3M reactor in Tokai (2 * 10^{14} n/cm^2 s) are of particular importance. In the Asia-Pacific region, the OPAL research reactor was put into operation in 2007 at ANSTO in Sydney, Australia, (2 * 10^{14} n/cm^2 s), and South Korea operates the Hanaro reactor, which has a comparable flux.

China, with its expanding economy, performs its research with neutrons for the development of innovative materials at the CARR reactor near Beijing (8 * 10^{14} N/cm^2 s) and is working on a project for a spallation source in Dongguan (CSNS, comparable to ISIS).

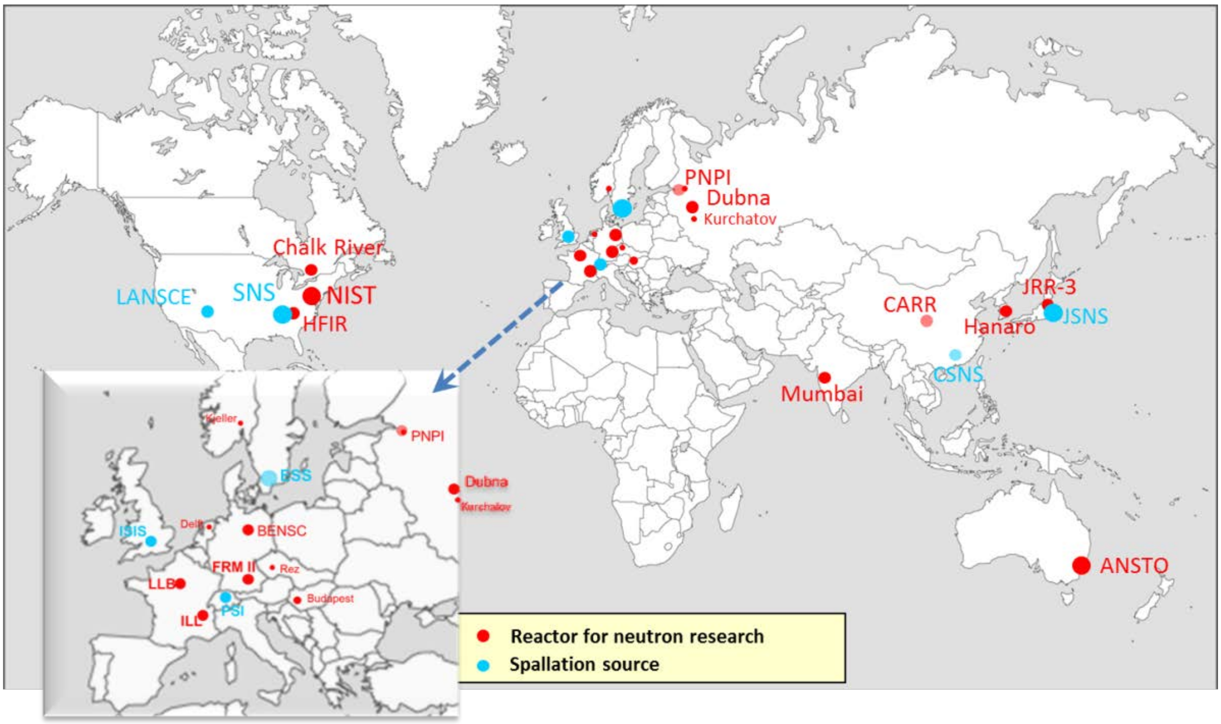


Fig. 1 Worldwide neutron sources for beam-tube experiments (BENSC designates the BER II reactor in Berlin)

6. German user community

Germany has a long tradition of science-driven methods development and instrument construction in neutron research and there is no doubt that it is one of the leading countries in this field worldwide. Germany has the expertise for building high-intensity neutron sources, as exemplified by the compact core design at FRM II and the development of spallation neutron sources.

A recent survey by KFN recorded **1199 registered neutron users** in Germany. They come from all sectors of the German science system (universities, Max Planck Society, Helmholtz Association, and the Leibniz Association). This analysis /4/ is in good agreement with a more recent analysis of the utilization of the high-flux reactor by the ILL Associates, which shows that the HFR was used by **1300 users with a large number of publications from Germany** between 2000 and 2009 (France: 1700 [location of ILL], UK: 1100). In terms of the number of publications, Germany has the most productive neutron user community in Europe /2/.

One of the strengths of the German neutron user community is the strong networking between the operators of the neutron sources, the user facilities, and the universities. This network is supported by collaborative research, which enables groups from universities to set up instruments at neutron sources. This kind of support widens the range of opportunities developed for using the sources and for training excellent young researchers.

The scientific focus of the neutron users has changed substantially. Today, it is characterized by a multitude of scientific disciplines that are increasingly governed by current social and scientific challenges instead of the conventional categories of science (see Fig. 2).

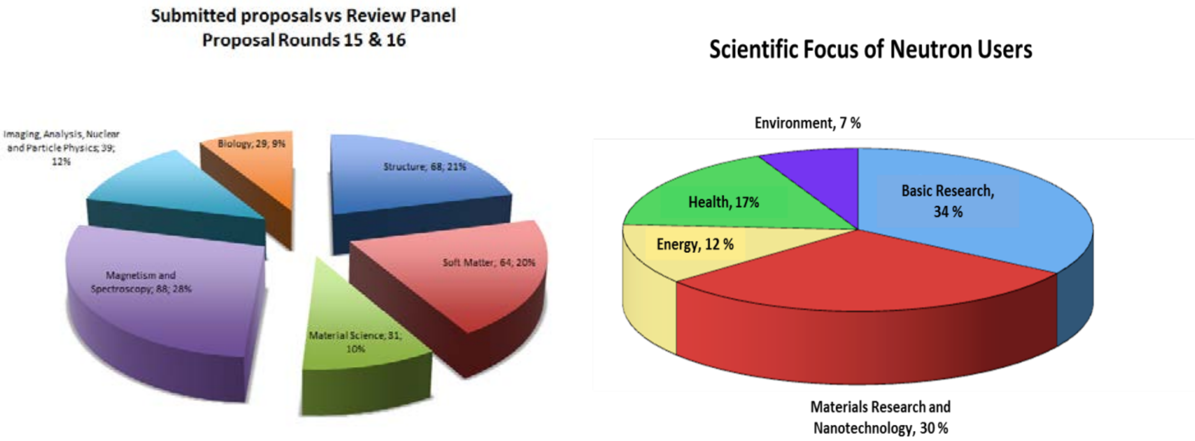


Fig. 2: Left: Distribution of demand for beam time at MLZ (FRM II) across different scientific disciplines (review during second half of 2012 and first half of 2013). Right: Submitted proposals averaged over applications to ILL, ISIS, and LLB according to topics of relevance for society (Report from the ILL Associates Working Group on Neutrons in Europe for 2025)

7. National roadmap for neutron research 2015–2045

The long lead times for the realization of new neutron sources require long-term planning to ensure that science and industry can continue to work with powerful neutron sources in the future without any prolonged interruptions.
It is to be assumed that Forschungszentrum Jülich and, to a lesser extent, HZG will remain the most important research institutions in the Helmholtz Association for research with neutrons providing user support in the foreseeable future.

The experiments by German neutron users currently focus on the following sources:

- FRM II with MLZ in Munich,
- HFR (ILL) in Grenoble, and
- BER II at HZB in Berlin.

German scientists also perform a considerable number of experiments at ISIS, SINQ, and the American spallation source SNS.

The neutron landscape in Germany and Europe is set to change significantly during the next few decades:

- BER II in Berlin is likely to have stopped operation in 2020.
- The European Spallation Source (ESS) is scheduled to be put into operation in the years following 2019.
- The high-flux reactor HFR (ILL) in Grenoble is expected to reach the end of its lifetime in around 2030.
- The Russian high-flux reactor PIK in Gatchina will start operation in around 2020.

Based on this scenario of developments in the European neutron infrastructure, this paper proposes a national roadmap for neutron research for 2015–2045 that

- **takes into account the long-term strategic development of the portfolio of neutron sources to cover the demand of science and industry in Germany,**
- **taps the special potential of neutrons for research and innovation further,**
- **exploits future possibilities for German users from science and industry in an optimal manner,**
- **builds on the successful synergy between European top-class sources and a network of medium-flux sources,**
- **guarantees the operation of at least one national neutron source for research and training,**

and, at the same time, ensures that

- **the financial margins for research with neutrons funded by Germany do not exceed the current order of magnitude,**

and that

- **known international framework conditions/obligations are taken into account.**

The following considerations are based on the assumption that neutron sources typically have an operating life of 40 to 50 years.

The national roadmap 2015–2045 consists of the following elements:

7.1 FRM II, Heinz-Maier-Leibnitz-Zentrum (MLZ)

Scientific user operation at FRM II is divided equally between TU Munich (TUM) and the Helmholtz Association (FZJ and HZG) and coordinated by the Jülich Centre for Neutron Science (JCNS). MLZ is the result of implementing BMBF's strategic goal of optimizing the possible uses of the most powerful German neutron source as part of a cooperation agreement between TUM and the Helmholtz Centres. The integration of universities in the construction and operation of instruments is a particularly important element in this process. At FRM II, 23 neutron instruments are currently being operated (FZJ 11, HZG 2). Seven additional instruments are in the construction or planning phase.

In future, the Helmholtz Association will play a key role in the operation and further development of the research instruments through its relevant competence centres, JCNS at FZJ and GEMS at HZG.

Future role and further plans:
- FRM II will be the only national source in the medium term, i.e. when BER II is taken out of operation, and therefore plays a key role for German users.
- The reactor should therefore be developed further with the same level of funding as is currently the case.

7.2 BER II, HZB, Berlin

BER II is operated by HZB in Berlin. By focusing on complex sample environments in connection with state-of-the-art instruments, the source has become a top-class facility for international neutron research despite its relatively low flux. For example, the combination of very strong magnetic fields and very low temperatures enables unique experiments with neutrons. BER II is available not only to German users, but also to a wide range of scientists from abroad.

Future role and further plans:
- BER II is scheduled to be taken out of operation in 2020.
- A number of options exist for the use of its state-of-the-art instruments after permanent shutdown.

7.3 HFR, ILL, Grenoble

ILL is currently the best neutron source in the world by far, both in terms of the quality of its neutron beams and the instruments available, and provides German researchers with unique research opportunities. Germany bears about 25 % of the costs of the high-flux reactor at ILL in Grenoble. FZJ as the German partner is directly involved in the operation of three instruments in cooperation with other partners.

Future role and further plans:
- Until the ESS is fully functional, operation and use of the HFR is of vital importance for the German research groups. The overlap between ILL and ESS operation should therefore be as large as possible. It is currently estimated that HFR operation will end in around 2030.
- The funds that will then become available could be invested in the long-term development of the source portfolio, e.g. for a future national spallation source, or to expand the German contribution to ESS.

7.4. Contribution to the American spallation source SNS, Oak Ridge

SNS at Oak Ridge National Laboratory is currently the most powerful neutron source. JCNS at FZJ's contribution to SNS is laid down in a cooperation agreement, and JCNS provides German users with access to the neutron spin echo spectrometer and two other instruments (beam time allocation through MLZ).

Future role and further plans:
- The use of instruments at SNS by German users is also of significance for preparing the German user community for ESS operation.
- The term of the current agreement between FZJ and SNS is ten years.

7.5 Contribution to the European Spallation Source ESS, Lund

The European Spallation Source ESS will be a pulsed source in the MW range. Since it will be of similar importance as ILL in Grenoble in the long term, the ESS is of great strategic significance. According to the current status of planning, it will be the most powerful spallation neutron source in the world. It is envisaged that the European Spallation Source

ESS, a collaborative project of 17 European countries, will be put into operation in 2019. The objective is to reach full-scale ESS performance by 2025.

In the medium and long term, ESS in Sweden will become the most important neutron source for German users. A visible contribution of Germany to ESS guaranteeing access to this new source is therefore indispensable.

Future role and further plans:

- It is planned to construct about six German instruments at ESS and to operate them as part of national and international cooperations when the ESS is put into operation. The Helmholtz Centres involved are FZJ and, to a lesser extent, HZG.

- The possible (in-kind) contribution of FZJ and HZG to ESS operation could be the funding and operation of the Helmholtz instruments at ESS (staff for operation and user support, running expenses). This will also guarantee optimal support for German users. For this purpose, we propose to establish a Helmholtz outstation at ESS, operated by the Helmholtz Centre FZJ in cooperation with HZG.

- The Helmholtz Association, at its Assembly of Members on 11 September 2013, decided that it will not make a contribution to the construction and operation of the ESS. This does not affect the involvement of individual centres.

7.6 German contribution to the Russian high-flux reactor PIK, Gatchina

The new high-flux reactor PIK (neutron flux for beam-tube experiments comparable to ILL) in Gatchina near Saint Petersburg, Russia, will presumably be put into operation at the end of this decade. PIK can play a significant role in the European neutron landscape in the long term. An appropriate German participation in PIK should be discussed as soon as possible, in particular considering the significant Russian involvement in XFEL and FAIR. Russia has a long tradition of neutron research, and a German contribution to the construction and operation of instruments would open up new opportunities for important cooperations between German and Russian scientists.

Future role and further plans:

- HZG transferred eight instruments from the FRG-1 research reactor, which was taken out of operation in 2010, to the PIK reactor to Gatchina. The relevant contract stipulates that, in return, HZG is allocated 15 % of the beam time on these instruments for an unlimited period of time. Whether this beam time can also be made available to other German users is a matter of negotiation. In October 2013, FZJ and the Kurchatov Institute organized a PIK workshop in Gatchina in close coordination with BMBF and with the participation of TUM, HZG, KFN, and ILL. German involvement in the construction of instruments and components, scientific use, and the establishment of an international user centre provides extensive scientific opportunities. HZG and FZJ are involved in developing a concept for the range of instruments in intensive consultation with Gatchina.

- Funding for the instrumentation has been earmarked by the Russian side.

- In order to enable research operation and access to measuring time in accordance with international standards, an International Scientific Advisory Board (PIK-ISAB) should be established in good time.

- German–Russian project funding (possibly managed by IRI) for neutron research at PIK and at MLZ is desirable to support German–Russian cooperations.

7.7 Cooperation with China

Powerful modernized instruments were sold to the new CARR research reactor in China when the DIDO research reactor in Jülich was decommissioned. Jülich researchers provided support for installing and commissioning the instruments before handing over operation to the scientists at CARR. Apart from affording the right to a German share in beam time, this cooperation serves as a focal point for future German-Chinese cooperation in neutron research and beyond.

Future role and further plans:
- German–Chinese cooperation in research with neutrons should be explored further.
- There will be no financial obligations.

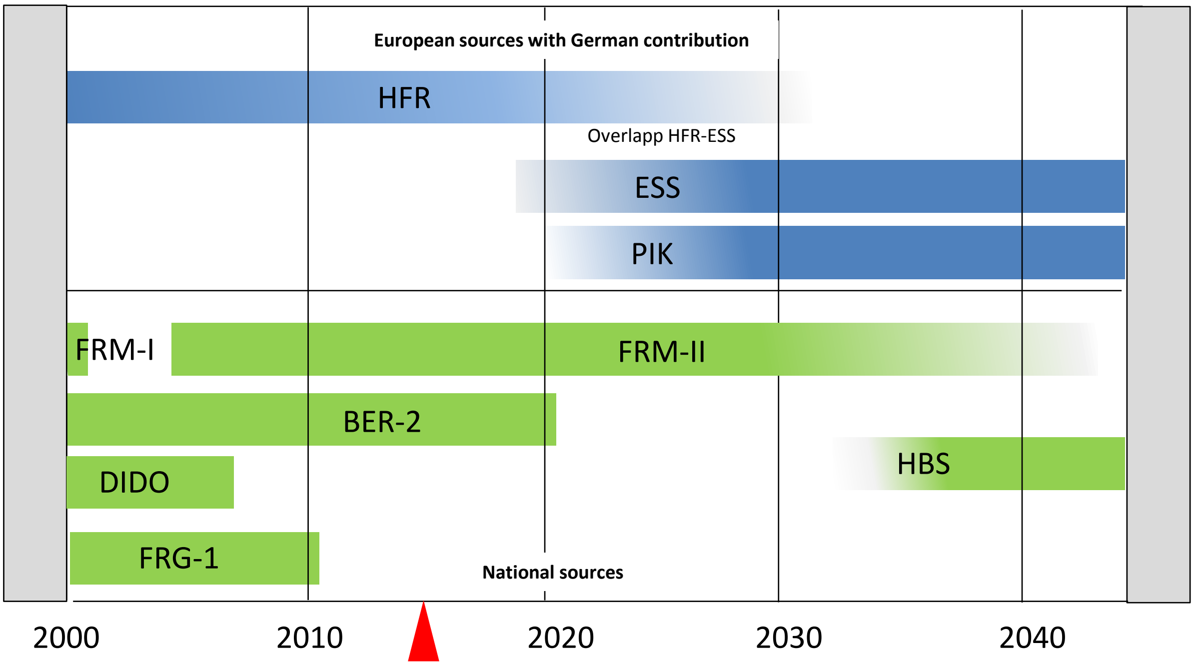
7.8 Plans for a national high-brilliance neutron source

Against the background of limited operating lives, whether a national pulsed spallation neutron source (high-brilliance source, **HBS**) will be built in the long term (2030–2040) should be considered in good time. From the present perspective, Germany will need a fully functional national neutron source, even in the long term. The aim is to design novel concepts for the moderator, reflector, and beam transport that enable the targeted emission of the moderated neutrons in the direction of the instruments.

Future role and further plans:
- Planning for a future national neutron source should begin in good time.
- This future source could be a high-brilliance spallation source.
- The relevant German institutes and research centres should perform design studies for this purpose.

7.9 Proposed neutron scenario

A rough timetable based on 6.1–6.9 is shown in the figure below.



6. References

/1/ GENNESYS White Paper, H. Dosch, M. van de Voorde, Max Planck Institute for Metals Research, ISBN 978-3-00-027338-4 (2009)

/2/ KFN paper "Perspektiven der Neutronenforschung in Deutschland im Licht der kommenden neuen Europäischen Spallationsquelle" (2011)

/3/ KFN paper "Neutronenforschung für die wissenschaftlichen Herausforderungen der Zukunft" (2013)

/4/ Report by the ILL Associates Working Group "Neutrons in Europe for 2025"

Appendix 1: "Flagship Areas" of Research with Neutrons

The multidisciplinarity of current neutron sources, as well as the future ESS, has an effect on the entire range of science and technology development. It is therefore impossible to predict whether individual future flagship experiments will be successful. However, we can project with considerable certainty those areas of science and technology where research with neutrons, particularly at the ESS, will have a major impact. The following is a brief outline of these "flagship areas":

A1.1 Energy

The continuous availability and affordability of energy is one of the foundations of our industrial civilization. A sustainable energy economy is therefore one of the key challenges facing society in the 21st century. Neutrons provide ideal access to the structure, kinetics, and dynamics of numerous materials and processes that are of great importance for energy generation, conversion, and storage. For example, neutrons can be used to optimize the structural materials that play a key role in mobility concepts and energy generation, from steam turbines and rotor blades for wind turbines to materials for fusion reactors. Hydrogen is an ideal fuel for mobility solutions. The technological challenge consists in developing hydrogen storage systems that combine low costs and weight with a high capacity. Neutrons with their high sensitivity for hydrogen atoms are an ideal probe for this purpose. Self-assembly is an important principle in the development of solar cells from organic polymers. The contrast variation made possible by neutrons will play a decisive role in unveiling the prerequisites for this process. This is also true for the elucidation of the processes involved in the production of biofuels and for research into novel materials for electrolytes, which are one of the key components of batteries and fuel cells.

A1.2 Medicine and health

Neutron research will have an impact on three areas in this field: (i) It will help to optimize materials in biomedicine, e.g. for implants. (ii) It will play an important role in studying the molecular causes of diseases. (iii) It will play a part in elucidating underlying biomolecular processes. Examples for (i) include the optimization of biocompatible surface layers for artificial hip joints and the use of hydrogels to improve surgical procedures. The molecular causes of diseases (ii) include topics such as amyloid aggregation, in particular in the early stages of Alzheimer's disease, and the interaction of drugs with the target molecules, specifically taking into account the dynamics. Special examples are cholesterol transport and its effects on neurodegenerative diseases and heart disease, and the distribution and dynamics of neurotransmitters in polymeric eye implants. (iii) For the elucidation of underlying processes, a combination of neutrons and X-rays is of great significance. While X-ray radiation provides information on the molecular structure, neutrons can be used, for example, to clarify the detailed protonation states in close proximity to the catalyst atoms in enzymes. In particular, neutrons also lend themselves to understanding the role of the dynamics in biophysical processes, e.g. allostery and functional dynamics in enzymes, and in the movement and function of proteins in dense environments such as cells. The functionality and dynamics of membrane proteins in their environment can become another new field of research. The ESS will make a huge difference to answering most of these questions. Many of the current neutron sources are unsuitable for research into these topics due to their limited intensity.

A1.3 Electronics and information technology

The discovery of the giant magnetoresistance effect (GMR), i.e. magnetic fields that influence the electric resistance, was honoured with a Nobel Prize in 2007 and became the starting point for a field of research referred to as "spintronics", an information technology that is based on the electron's spin. This has numerous advantages, for example, ohmic heat loss can be avoided, which enables further miniaturization. Today, the GMR effect is the basis for the read heads in magnetic storage media. Deciphering the underlying magnetic structures was made possible by the use of neutrons and their high sensitivity for magnetic properties. For the future development of this technology, the use of neutron beams to optimize spin structures and kinetics will be of the essence. In future spintronics, novel materials and thin-film material systems will be used, many of them based on complex transition metal oxides. At their interfaces, these materials display unexpected emergent properties that lead to new functionalities. Neutrons enable a depth-resolved determination of the order of the degrees of freedom of spin, orbit, and charge, which is the most important prerequisite for understanding the interface phenomena and therefore for developing novel components. Examples include multiferroic materials that combine magnetic, electrical and mechanical properties. They could become the foundation for non-volatile, fast data storage systems with an ultrasmall switching power suitable for a multitude of sensors. Neutrons play an essential role in deciphering their structural and magnetic properties. Further miniaturization will lead to the development of molecular magnets, which are already being discussed as possible qubits for quantum information processing. Neutron radiation is important for investigating their structural and dynamic properties. Another field of research is the coupling of electronic circuits with biomolecules and cells. The circuit surface is of decisive importance for their function. Neutron reflection experiments will provide important insights.

A1.4 Industrial applications and engineering

Materials science and engineering are the key to new technologies, growing prosperity, and sustainable growth. Numerous diagnostic tools are used to optimize materials, processes, and components. Neutrons provide insights into the structures as well as the kinetics and dynamics. In construction materials, for example in aircraft engineering, controlling internal stresses is of the greatest significance. Airbus, for example, is currently in the process of replacing rivets with weld seams in aircraft. Since internal stresses add up to outer loads, controlling them is extremely important for the safety of an aircraft. Neutrons are used to validate the welding processes. In vehicle construction, increasingly lighter components prevent unnecessary fuel consumption. One example is the optimization of multiphase materials made up of aluminium and silicon. Their strength depends on the exact control of the casting processes as well as the solidification process. In situ neutron experiments with the high-intensity neutron beams at the ESS will extend the knowledge base considerably. The same is true for the in situ characterization of welding processes, which requires fast measuring techniques with a high intensity. Neutrons penetrate deep into materials and, at the same time, they are particularly sensitive for light atoms. In this way, the behaviour of lubricants in engines during operation can be observed and optimized. In batteries or fuel cells, it is possible to investigate the lithium distribution and the evolution of water in the catalytic conversion during operation. The exchange between light and heavy hydrogen also makes it possible to study the kinetics of exchange processes.

A1.5 Materials in the chemical industry

Materials in the chemical industry often consist of numerous components that assemble themselves on the scale of nanometres and micrometres, thus determining the behaviour of the entire system. Examples include functional materials that react to external stimuli, such as stress, temperature, and electrical fields, in a very controlled manner, and soft matter, which displays both solid-like as well as liquid-like behaviour. Soft matter comprises colloids, e.g. varnish, paint, or microemulsions of detergents, pharmaceutical products with active pharmaceutical agents, solvents for tertiary oil recovery, or gels in the form of ointments, creams, and other personal hygiene products, and many more materials. The contrast variation offered by neutrons is an indispensable tool for deciphering the structures of individual components and their movements. This applies to the molecular causes of rheological behaviour, a key factor in polymer processing, as well as the stability of foodstuffs, which are usually a highly complex combination of a wide variety of substances. An example from industry is the use of CO_2-based solvents for the extraction of oil from reservoirs, which boosts oil output by up to 30 %. Neutron experiments can provide information on the underlying formulations. The same applies to replacing organic solvents with ionic liquids in the pharmaceutical industry. Here, structure investigations with neutrons are of great significance. Another field is the optimization of catalysts, such as the Lindlar catalyst from Evonik and catalysts for PVC synthesis from Ineos Chlorvinyls. Since the materials under consideration are complex and the processes must be studied with a high temporal resolution, the intensity of the neutron radiation is a decisive element. The ESS will make it possible to considerably broaden the currently small range of applications in industry.

A1.6. Quantum technologies

Even today, technologies based on findings from quantum physics contribute more than a quarter of the gross national product in modern industrialized societies. Examples of quantum technologies include magnetic resonance imaging and X-ray imaging in medicine, photovoltaic cells in energy technology, and semiconductor components in information and communications technology. Macroscopic quantum phenomena in solids, such as magnetism and superconductivity, are particularly fascinating, because they reflect quantum mechanics in properties that can be observed on a macroscopic level. Ever since the discovery of superconductivity in compounds of copper and oxygen and the finding that the high transition temperatures can be attributed to electronic correlations, it is generally assumed that, in principle, room-temperature superconductivity can be realized. This would be a spectacular breakthrough for energy technology, because superconducting power cables would be associated with much lower losses during energy transmission and storage. Although the principle behind high-temperature superconductivity is still not fully understood, neutrons have already made a significant contribution to a better understanding of the fundamental principles, because they are able to throw light on the interaction between superconductivity and magnetism as well as superconductivity and lattice vibrations. In particular, magnetic fluctuations were found in the superconducting state that some theories consider to be decisive for the high transition temperatures. In the past few years, iron-based high-temperature superconductors were also discovered in which neutron scattering unveiled a similar phenomenon: another milestone on the road to a targeted search for room-temperature superconductors. This year, scientists were able to demonstrate by means of neutron scattering that a collective ground state exists in magnetism that is produced by the Higgs mechanism in analogy to superconductivity. This collective state of magnetic monopoles will allow innovative approaches to be developed for a new kind of spintronics, if this state can be achieved at higher temperature and if monopole fluxes can be controlled appropriately. This requires a better understanding of the magnetic spectrum – and this is where neutron scattering comes into play once again!