Roadmap for neutron research in Hungary

Forward look to 2033 and beyond

Synopsis

The purchase of fuel for the Budapest Research Reactor (BRR) for operation until 2027 has been finalized in 2019 by the Hungarian government with a vendor in Russia. This makes the Budapest Neutron Center (BNC) the fifth strongest neutron source facility available for the European neutron scattering community for the next seven years to come, following past and imminent further shutdown of major research reactors in France and Germany.

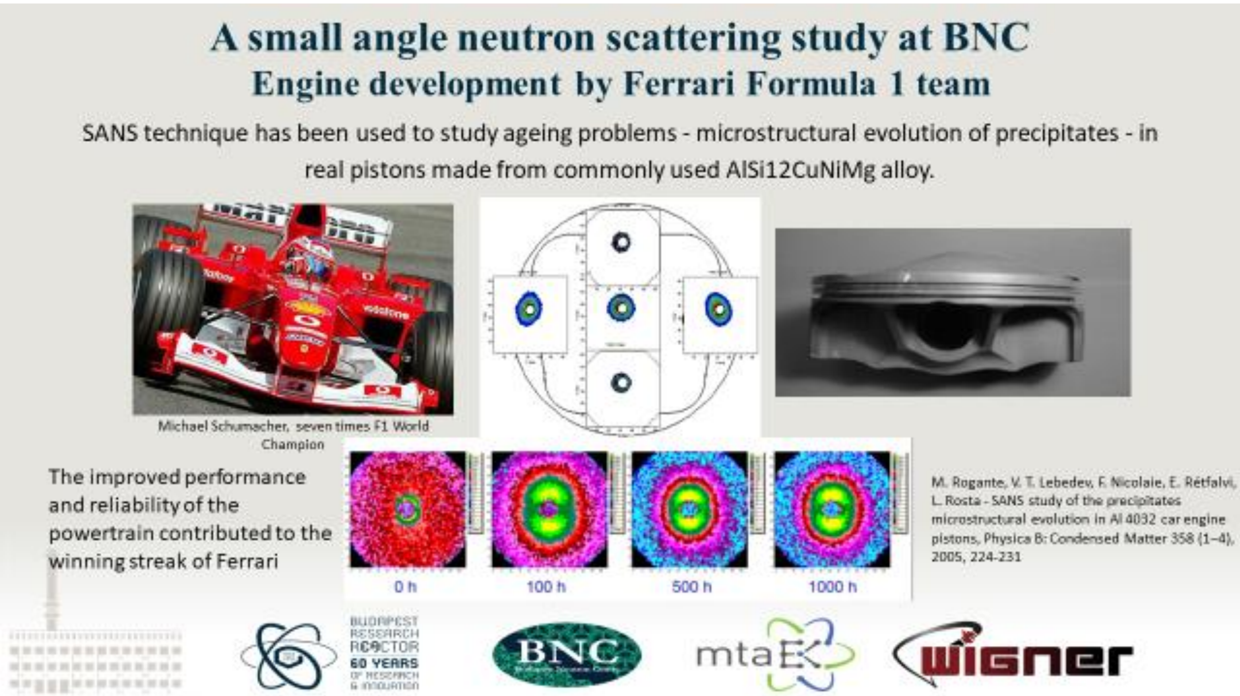
a) In order to live up to this role, a world-class inelastic scattering spectrometer needs to be timely added to the BNC suite of instruments. For this purpose, the broad band TOF spectrometer VOR – destined to ESS – has to be built up and commissioned for users at BRR, well before it becomes possible to actually transfer and put it into operation at ESS. The potential and awaited availability of the current best state-of-the-art TOF spectrometer NEAT from HZB Berlin for use at another European neutron source facility offers a particularly fast and very cost effective path to achieve this goal, years before ESS becomes accomplished to host VOR at its site.

b) After having spent the fuel stock (2027), the Budapest Research Reactor should be converted into a proton accelerator driven compact neutron source. Using latest moderator technology and with enough power, this facility should continue to provide comparable or superior performance for neutron beam research for a few decades – with much reduced operational costs at its 60 years old historic site.

c) Beyond operating BNC as one of the important neutron user facilities in Europe and for the broader European community, Hungary should remain engaged in the most powerful European international neutron centers, ESS, ILL and the emerging PIK, on the basis of balanced and mutually advantageous cooperation amongst European research infra-structures.

December 2019

Content



A success story from the 25-year records of the Budapest Neutron Centre

Executive summary

Neutron science and technology has great traditions in Hungary. The most important experimental suit for this field of research has been the *Budapest Research Reactor,* commissioned 60 years ago. Thanks to the continued development of this large-scale facility, BRR has become and remained the largest open-access research infrastructure in the country serving also a sizable international user community. In order to coordinate multidisciplinary research and liaison with industry, the reactor-based laboratories on the KFKI campus were organised to form the Budapest Neutron Centre consortium in 1992. Over 3500 experiments were performed on BNC's experimental stations; resulting in 2500 publications and 75 PhD theses, almost 500 proprietary research or grant related reports – to mention significant achievements of BNC in the past 25 years. During this period the number of domestic users has grown from 50 to 200. BNC has developed extensive international cooperation both at bi- and multilateral levels. Thanks to the EU research infrastructure (RI) programmes BNC has been particularly successful in European projects, e.g. to be among the first in Hungary to win a Framework Programme grant in 1993. Then, engagement in 20 further EU projects resulted in substantial amount of grants. Outstanding achievements of Hungarian scientist and BNC teams are well recognised at international level.

According to recent analysis of research trends by EU panels and national institutions, neutron research – as an experimental technique for various disciplines in science and technology, including health, industry, energy and food – will remain to play an important role in the innovation ecosystem for many decades to come. At the same time the landscape of neutron facilities in Europe is in a period of drastic transformation. Several research reactors are to be shut down or facing operation difficulties. The experimental opportunities are becoming increasingly concentrated at top-class mega-facilities. Thanks to new technological advancements compact accelerator-based neutron sources (CANS) might replace medium class reactors or spread at a smaller laboratory scale. Hungary has taken the lead to realise the first small scale facility of this type – as private enterprise, but involving academia. Upon these changing circumstances the decision in Hungary of how to maintain nuclear culture and neutron research for over a decade and beyond, requires a well-established and detailed outline of the extension programme.

BRR will be supplied with fresh fuel, with that it will remain operational until 2027. In parallel the operating license will be extended by 2033. After having spent the fuel stock, the reactor – using the latest moderator technology and advancements in instrumentation – shall be converted into a proton-accelerator-driven neutron source and maintain to provide sufficient power for neutron scattering research at considerably reduced operational costs and a comparable or superior performance – at its over 60 years old historic site. BRR today as a reactor and neutron source as well as its community requires enhanced support to maintain this momentum and capitalize on the unique opportunities. The following major tasks are considered. 1) Improving operation conditions and more efficient use of BRR facilities by performing an immediate refurbishment of the reactor infrastructure and modernization of the major part of the neutron beam equipment. This should include the realization of a few world class instruments such as a new low dimensional cold moderator, an out-of-pile moderator test beamline and installation of a broadband time-of flight (TOF) spectrometer. This upgrade activity has been formulated as a 4-year project, and a proper grant application has been submitted to the Government. 2) The project of transforming the reactor into a compact accelerator-based neutron source shall be prepared. 3) Hungary shall remain engaged with the most powerful European international neutron centers, ESS (the world most powerful neutron facility being built), ILL (today's world leading neutron research center) and PIK (top-class reactor in St. Petersburg close to commissioning). The national scientific/industrial community utilizing and related to these neutron source facilities should take part and benefit, in particular, from the development and construction of ESS and PIK, underway. 4) BNC and the neutron community need to seek improved effectiveness and higher visibility by enhancing education and training, active industrial and public outreach as well as a reinforced cross-fertilization between various scientific disciplines and techniques.

Preamble

Changing circumstances. Imminent rapid changes and new advancements on the neutron landscape in Europe, makes it inevitable to scrutinise neutron research activities in Hungary and establish a proper national Roadmap. 2019 is a crucially important year at an international and a domestic level alike. On the one hand, three research reactors – major components of the European network of neutron sources – are closed this year at IFE (Norway), HZB (Germany) and LLB (France). Some other reactors are facing problems on fuel supply (e.g. HEU challenge). On the other hand, a healthy growth and vital activity of the neutron community, approaching the start-up of ESS and a new wave of creating compact accelerator-based neutron sources (at small to larger scale), together with preparation for the next framework programme, Horizon Europe and progress foreseen on the ESFRI Roadmap, require a new vision on the European neutron landscape. In March 2019, the League of Advanced European Neutron Sources, LENS was officially founded to coordinate the European efforts, to analyse the neutron source situation, the scientific and societal needs and position the European neutron research within the global scene. All these call for an elaboration of a new strategy for the next decade. This year's landmark on a national level is the government's decision to finance continued operation of BRR by procurement of a new fuel stock for the next seven years. The current licence of the reactor is valid until 2023; the preparation of a life-time and licence prolongation to 2033 has been started.

Research Infrastructures. The update of the national RI Roadmap is underway. Establishing the Hungarian RI Roadmap dates back to 2008. A 'Register' of single-site, distributed and virtual infrastructures grouped RIs according to the ESFRI categories by disciplines. 106 units have been classified as 'Strategic Research Infrastructures'. Four of them are, however, single-sited real large scale facilities. The Budapest Research Reactor and the Debrecen Atomki Accelerator complex are only those ones, which are currently in operation and open for domestic and foreign users, based on excellence. The ELI-ALPS (Szeged) laser facility is in the commissioning phase and the automotive test track facility (Zalaegerszeg) is under construction. Thus, BRR deserves special attention since it is the largest operating RI in the country (and in the Central-European region) and it is amongst the top-five facilities of this type in Europe.

The operation and utilization of BRR aim for:

1. Research and development for the energy sector: scientific and safety support for the Paks nuclear power plant (NPP), research in energy-saving and alternative energy production;
2. Provision of a complex source of irradiations for materials testing and modification, diagnostics in nanotechnologies, engineering, healthcare, radiation damage, etc.;
3. Operation of neutron beam facilities on the horizontal channels of the reactor, serving for an experimental basis for exploring materials features in a wide range of disciplines;
4. Graduate and professional training.

Besides basic research – innovation and technology transfer as well as commercial applications have been and will remain in the field of vision of BRR activities. The 100 kW training reactor at the Budapest University of Technology and Economics (BME) makes also part of the national nuclear research and education domain, with an operating licence valid until 2027. Its function and planning for future prospects is to be inserted into the current Roadmap.

Below a short description follows on, BRR's operation and utilisation in general. Focus will be placed, however, on *neutron research*, which is the most extended activity at BRR. Neutron research in Hungary outside the BRR framework will also be mentioned. The Budapest Neutron Centre is described as an equipment suite and an organisation for the utilisation of the reactor. The national user community is introduced and the most important connections to international neutron centres and research organisations are listed. A short term programme of utilisation and upgrade of BRR will be outlined followed by a longer-term vision (2033 and beyond) on neutron research in Hungary considering the BRR infrastructure and accelerator-based compact sources.

The Budapest Research Reactor – a source of neutrons

This year BRR turned 60 – it went critical for the first time on the 25th March, 1959. This was a major milestone in the development of science and technology in Hungary. Since then BRR has remained the largest operating Research Infrastructure in Hungary. This new facility triggered a large number of activities in the research on various physical phenomena, especially in neutron and reactor physics, solid-state (condensed matter) physics, health physics as well as in nuclear chemistry, radiation protection, and it has even enabled Hungary to start to design and produce new nuclear equipment and also to venture into isotope production.

The Budapest Research Reactor has been utilized as a neutron source for basic and applied research or direct applications in various fields of industry, healthcare as well as in exploration and conservation for objects of cultural heritage. In 1992 a consortium, named the *Budapest Neutron Centre*, was founded to group the reactor-related laboratories and coordinate the reactor utilization. BNC provides access to the international neutron user community through a peer-review system, it has been a partner in various EU Framework Programme projects.

Since 1992 the domestic neutron community has grown from a few tens to 200 researchers (regular users) today. In this period over 3500 experiments were performed, many hundreds of users served – mostly from the Central European region. 2500 scientific papers and nearly 500 technical reports were produced. Hungarian researchers have made significant contribution to this field of science and technology: invention of the neutron spin-echo, neutron holography; combination of imaging with elemental analysis, outstanding studies of archaeological objects – just to mention a few highlights.

BRR history, traditions, reactor utilisation and the user community aspects are outlined in more details in Annex I.

The changing neutron landscape

Position in Hungary. BNC has become an important member of the European network of neutron facilities, thus BNC management and the Hungarian neutron user community is engaged in the continued operation of the reactor for the ~7 years to come (using the current stock and recently procured fresh fuel) and seeking for solutions to extend high-quality neutron beam availability in the country even afterwards (the application for licence prolongation to 2033 has been started). With that BNC is committed in fostering the collaboration of the European neutron centres at long-term. In the changing world, where neutron research is going to be concentrated at very high power/capacity centres, BNC is a scarce medium-size facility likely to remain operational for a decade and beyond, in order to satisfy the needs – basically – of the regional neutron user community. A recent advancement in this field is to be considered that Hungary has also engaged itself in the development of compact accelerator-based neutron sources to be built and operate at affordable costs. A first European prototype of this latter class of facilities is under construction in Martonvásár (near Budapest) as a joint venture of the academic and private sector.

Planning future neutron activities. In medium term, to about 2027, BRR operation will be continued according to the current regime (10 MW power, ~120 days/year, a suit of 14-16 instruments). It is vital, however, that BNC offers improved services to its users, thus an urgent refurbishment of the reactor and a modernisation of the instrument park is needed. This is to be performed without longer shut-down, this upgrade project is described later and its details are given in Annex III. In this transition period, also, BNC staff and other players of the domestic neutron research scene (users, involved academic institutions, companies, agencies) should engage themselves for partnership and utilisation of the major European leading-edge facilities (ESS, ILL, PIK) as well as to maintain the high-level activity of the local communities for preparing and establishing the indispensable national experimental basis of a next-generation neutron facility in the country.

In 2016 the Hungarian Government initiated the assessment of a for the 100kW Training Reactor of the Budapest University of Technology and Economics (BME) and the 10 MW Budapest Research Reactor. A comprehensive document [1] has been elaborated by the BRR and BME teams. The major aspects of the life-time prolongation considerations are briefly outlined in Annex II.

Short and long term scenarios at BNC. Following the exercise in 2017-18 of considering the fuel supply, the Government decided to allocate 3.6 billion HUF (~11 M€) for fuel procurement in December 2018 (MK 1748/2018). In July 2019, followed by a public procurement procedure, the contract with the Russian TVEL Company was signed, thus the continuous operation of BRR for the next 5-6 years is assured. Parallel to the fuel supply procedure, BNC teams have started to work out a comprehensive research and equipment-modernization proposal [3] for the period of 2020-25. The update of this proposal should be made along the lines considering the following scenarios for the BRR operation:

i) Short term programme by running the reactor according to the current operating regime consuming the actual and newly supplied fuel by 2027.

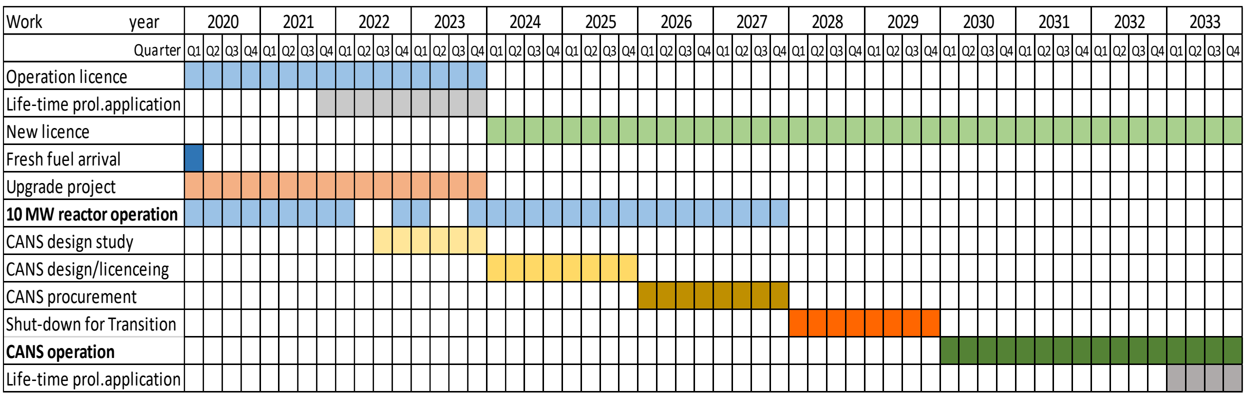
ii) The BRR operating licence is valid until 2023. Considering the technical status of the reactor and other life-time limiting conditions (e.g. the core-vessel degradation), there are no technical obstacles to apply for a next 10-years prolongation (until 2033) of the operation licence.

iii) Having consumed the reactor fuel stock in 2027 a "brown-field" decommissioning of BRR is envisaged:

- The reactor is shut-down and the spent fuel is removed – the nuclear label of the site is terminated;
- Transforming the reactor and its infrastructure into a compact accelerator-based neutron source (CANS) according to the patent of Mezei-Zanini [4] – establishing another 3-4 decades of operation of a modern medium flux neutron facility in Budapest.

A decision on item iii) must be made no later than 2024. Both in terms of national Research, Development & Innovation strategies and international neutron landscape contexts the long term operation of BNC/BRR is desirable. It has been shown previously [5], that long term operation of the reactor has a clear positive fiscal impact at macroeconomic level while the decommissioning has a negative fiscal impact, meaning that the reactor shut-down/decommissioning should be postponed until any technical, political or economic circumstances would require otherwise.

The BNC short and long term operation scenarios are also shown on the chart below.



Consequently, the items i)-ii) – as short/medium term, as well as the item iii) as long-term solution should be considered in details. The essential refurbishment of the reactor infrastructure, reinforcement of safety-sensitive components and upgrade of instrumentation are required. Investments will be made for the refurbishment of the reactor building. The cold moderator components, upgrade of the neutron guide system and efforts of improving instruments are envisaged. Five groups of activities are considered: 1. The reactor itself and the surrounding infrastructure; 2. Neutron beam forming system; 3. Neutron beam instruments; 4. Transition to accelerator-based neutron source; 5. Basic and applied research at BNC (scientific case, user system). This modernisation project is outlined in details in Annex III. An application to fund this project has been submitted to the National Research, Development and Innovation Office.

New equipment at BNC. To highlight the modernisation plan, the central part of the 4-year programme is presented below. The realisation of world-class (or unique in the world) equipment consists of 3 major components:

High brilliance low dimensional cold neutron source. One of the crucial components and a most innovative development in enhancing the neutron source brightness is the compact cryogenic moderator. Its principle was invented by the ESS target team during the design phase of ESS. The most efficient cold neutron moderator materials for neutron scattering purposes are hydrogen-containing substances, in particular, liquid ortho/para H_2 at cryogenic temperatures. Cylindrical or spherical 'volume' moderators are in use since decades, but a detailed numerical optimization study during ESS design lead to the invention that a liquid para-hydrogen cold neutron moderator delivers much higher cold neutron brightness if it takes the form of a quasi 1 or 2-dimensional tube/disc, in contrast to the conventional more voluminous shapes used by now. BNC operates a cold neutron research facility, which includes a liquid hydrogen moderator inserted horizontally into the Beryllium reflector around the reactor core. This Cold Neutron Source renewal will be coupled with the realisation of a novel moderator concept at BNC for the first time for a research reactor case.

Construction/installation of the VOR/NEAT instrument. VOR (Versatile, Optimal Resolution Chopper Spectrometer) has been one of the 16 approved instruments to build at ESS. The timeline of its construction agreed well with the availability of the Hungarian in-kind funding, about 7.2 million Euro in the period 2020-25. With the delays of the ESS start of operation and instrument delivery, VOR cannot be accomplished at ESS within the 2020-25 timeframe. On the other hand, it can be accomplished at the Budapest Research Reactor, whose full power (10 MW) operation period is now extended to 2025 or beyond. In this process an additional chopper close to the reactor would turn the continuous reactor source to emulate the long pulse mode of ESS, and VOR could be installed fully commissioned and tested in operation within the period of the availability of the Hungarian in-kind funding for ESS. It could also provide beam time for ESS needs, both for neutron scattering work and effectively replacing the ESS test beamline at HZB, which will cease its operation by the end of 2019. The best state-of-the-art TOF spectrometer NEAT at HZB is expected to become available for use within Europe outside Germany after the shutdown of the Berlin reactor. Hungary already signalled to HZB that it is interested in operating NEAT, which can be refurbished at moderate costs to realize VOR. Along the line with the upgrade programme at BRR the neutron guide hall will be extended to accommodate NEAT/VOR.

Cold moderator test-beamline. A new in-beam moderator testing station is currently being designed at the Budapest Research Reactor (BRR), to be deployed on a beam port with direct view of the reactor core. Transmission and reflection/scattering properties of the investigated moderator material will be measured by means of dedicated energy sensitive pinhole imaging equipment. The effects of moderator material, physical conditions, moderator cell and environment geometry (reflecting bodies and beam extraction voids) will be explored. The moderator cell is placed in a cryostat specially designed to allow placement of various size and shape containers in the vicinity of the beryllium reflectors. The cryostat with the investigated moderator is placed at the beam port, outside the reactor shielding wall, and two imaging lines are installed, one in transmission (horizontal, radial) and another in scattering configuration, including full sets of mask, chopper, beam tubes, 2D detector, shielding and beam dump.

Start-up of a compact neutron source facility

The use of neutron beams has already played an important role in practical applications in industry or heritage science studies since decades. However, due to the costs and limited accessibility of neutron sources, these applications only became routine practice where their use was considered unavoidable. By the development of neutron instrumental methods, the available neutrons can now be put to use with an efficiency some 1000-10000 times superior to that commonly achieved just 20 years ago. Compact accelerator-based neutrons sources (CANS) have the potential to replace medium power nuclear reactors for a broad range of activities such as fundamental research in solid-state physics and nuclear physics, material science research, neutron radiography activities, radio-isotope production or boron neutron capture therapy. A category of smaller size compact neutron sources with low costs, intensity and footprint now make neutron beam studies much more accessible in industrial and university environment. A first European prototype of such a compact source is being built in ***Martonvásár*** (Hungary) as a European structural fund supported project by a consortium led by Mirrotron. Neutron beam production is expected in 2021. BNC and the Martonvásár CANS facility will complement each other. While BNC is intended/continues to serve a wide range of user application both in science and applied research fields, the CANS machine is foreseen on one hand, as a prototype of such kind of equipment to be developed for various purposes to be utilised eventually at university, industry, healthcare environment, on the other hand to serve as neutron testing device for Mirrotron own supermirror production as well as to build a neutron irradiation facility for biological applications.

BNC and international relations

It is vital for BNC and the Hungarian neutron community to properly position itself in the European (and global) research environment. In its Statutes in 1992 BNC was declared an open-access facility for the domestic and international scientific community, i.e. to welcome experiments to be performed free of charge, provided the results obtained become publicly available in national or international publications. Proprietary research for industrial applications were also declared also possible upon payments for the beam-time utilisation according to the terms of individual contracts.

BNC was among the first in Hungary to win a project within the EU Framework Programmes (WENNET, 1993) Then it has been a partner in many EU FP neutron-related projects with the aim of developing European collaboration via networking partnerships, and also for providing access to BNC facilities for the European user community (either for general purpose activities – NMI3 projects, or for the Cultural Heritage community – CHARISMA, IPERION, or for nuclear data - EFNUDAT, ERINDA, CHANDA and ARIAL) as well as to participate in a wide range of methodological development programmes (detectors, neutron optics, moderators etc.). BNC has been partner in various projects and training activities initiated by IAEA, too.

The most significant partnerships in international organisations or bilateral collaborations are outlined in the Annex IV.

Seeking improved effectiveness and higher visibility

Education and training is an important mission of the Budapest Neutron Centre. Lectures and hands-on-training for university courses as well as summer courses are provided for students and new-comers to the field. The annually organized Central European Training School on Neutron Techniques - CETS - is a 5 days international event for recruiting new users.

For improving *communication*, the BNC strategy should aim for extending internal and external communication, enhancing the information and school/training programmes, involving the 'associated partners' platforms (LENS, ENSA etc.), being present in the social networks (FB, Twitter).

Profiting from the *multidisciplinary nature of neutron research*, cross-fertilisation between scientific disciplines and complementary use of various scientific tools might enable the growth of the neutron user community and more efficient use of the facilities to produce excellent science or pragmatic applications. Multidisciplinary teams have been shown to be an effective way to facilitate collaboration between professionals and hence improve scientific merit. It is essential to integrate the different methods to understand the physical/chemical properties of the different kind of materials, important for various applications. Examples are outlined in ANNEX V.

Improving *liaison with industry* is a top-priority at BNC. Creating a formal ILO position at BNC level might be envisaged. So far, also considerable effort has been devoted to bring together our research staff with engineers, industrial experts, new-comers, students who have already used, or are potentially interested in utilizing large research infrastructures, in particular neutron techniques available at the Budapest Neutron Centre. This is in line with the policy of the European Union and the Hungarian Government that paid special attention to promote innovation and the efficient transfer of scientific results into industrial sectors, so improving their prompt economic impact.

Conclusions

The national Neutron Roadmap has aimed to give an analysis of the rapidly changing situation at a European and domestic level, as well as to describe the opportunities and possibilities to maintain/develop nuclear culture and neutron research in Hungary within the context of the European trends. While the six decades of operation of the Budapest Research Reactor gives a solid tradition, the strong commitment of the country for long term production and utilization of nuclear energy, requires high quality scientific and technological background by further operation and extended utilization of the BRR. Also, there is no doubt that neutron research – as an experimental technique for various disciplines in science and technology, including health, industry, energy and food – will remain a pivotal component of the innovation ecosystem for many decades to come. The landscape of neutron facilities in Europe is in transition. Three major trends are clearly seen: a) several research reactors are shutting-down or facing operation difficulties; b) the experimental possibilities are being concentrated at top-class mega-facilities (typically meaning higher costs and more complicated access); c) accelerator-based compact sources might become available and replace medium class reactor facilities or may even be available at university or industrial laboratory scale, providing a wide training and experimental ground at national/regional level.

The Budapest Research Reactor – to be supplied with fresh fuel and with the prolongation of the operating license – is likely to remain operational until 2025-26, then its suggested transformation into a powerful proton accelerator driven compact neutron source with further decades of operation will maintain BNC’s position as an important component of the European landscape. BRR today as a reactor and neutron source as well as its community requires enhanced support to maintain this momentum and capitalize on the unique opportunities. The training reactor at BME should be considered also as an important part of the domestic neutron/nuclear Roadmap, regarding its complementary skills with respect to the long term vision on accelerator-based facilities, while the nuclear energy sector might require at least one research/training reactor facility to remain in the country.

Thus, a focus of this national Neutron Roadmap should be made according to the following major tasks: a) Improving operation conditions and more efficient use of BRR facilities by performing an immediate refurbishment of the reactor infrastructure and modernization of the major part of the neutron beam equipment, and at the same time increasing the number of staff not only at the scientific instruments but the reactor operation and maintenance as well. This should include the realization of a few world class instruments such as a new low dimensional cold moderator, an out-of-pile moderator test beamline and installation of a NEAT/VOR type spectrometer. b) The project plan of the reactor transformation into a compact accelerator-based neutron source should be prepared. c) Hungary should remain engaged in the most powerful European international neutron centers, ESS (to become the world most powerful neutron facility), ILL (today's world leading center) and PIK (top-class reactor in St. Petersburg close to commissioning). The national scientific/industrial community utilizing/related to these neutron source facilities should take part and benefit, in particular, from the development and construction of ESS and PIK underway.

Documentation

[1] Belgya Tamás, Gadó János, Gajdos Ferenc, Szentmiklósi László, Vidovszky István (MTA EK) Rosta László (MTA Wigner), Czifrus Szabolcs, Fehér Sándor, Szalóki Imre, Szieberth Máté, Zsolnay Éva (BME NTI): *A Budapesti Kutatóreaktor és a BME Oktatóreaktor jövőjére vonatkozó elképzelések* (Perspectives of the BME and BRR reactors, in Hungarian), MTA, pp 1-57, Budapest, April 16 (2016).

[2] Gadó J, Rosta L: *A Budapesti Kutatóreaktor perspektívái a következő másfél évtizedre* (BRR perspectives for the next 15 years, in Hungarian), Ministry of Foreign Offers, May (2016)

[3] Rosta L, Gillemot F, Hózer Z, Horváth Á: *Javaslat Paks2-vel kapcsolatos kutatásra. MTA EK és Wigner FK javaslata* (Joint proposal of Wigner & EK for nuclear research for the Paks NPP, in Hungarian), September (2017 – in Hungarian)

[4] Mezei F, Zanini L, *A method for providing a neutron source,* Patent pending WO 2017/198303 A1 (2017)

[5] Rosta L, *Kiegészítés a (Annex to) „Budapesti Kutatóreaktor és a BME Oktatóreaktor jövőjére vonatkozó elképzelések" c. dokumentumhoz* (2017– in Hungarian).

Abbreviations

BME – Budapest University of Technology and Economics
BNC – Budapest Neutron Centre
BRR – Budapest Research Reactor
CH – Cultural heritage
ESFRI – European Strategy Forum for Research Infrastructures
ESS – European Spallation Source (Lund, Sweden)
HEU – Highly enriched uranium
HS – Heritage science
HZB – Helmholz-Zentrum-Berlin
IAEA – International Atomic Energy Agency
IFE – Institute for Energy Technology (Kjeller, Norway)
ILL – Institut-Laue-Langevin (Grenoble, France)
LENS – League of advanced European Neutron Sources
LLB – Laboratoire Léon Brillouin (Saclay)
MTA – Hungarian Academy of Sciences
PIK – High-flux reactor at the "Kurcsatov Institute" (Gatchina, Russia)
RI – Research Infrastructure
TOF – time-of-flight
VOR – Versatile, Optimal Resolution Chopper Spectrometer

Budapest, 10th December, 2019.

This version of the Roadmap was elaborated by the members of the BNC Executive Board: Rózsa Baranyai, Tamás Belgya, László Bottyán, Margit Fábián, János Füzi, László Rosta and László Szentmiklósi. Recommendations by the BNC International Scientific Advisory Council have been considered (Budapest meeting, 18th October 2019).

Compiled by László Rosta (rosta@bnc.hu)

The Budapest Research Reactor – history, utilisation, user community

BRR has been always the home basis of neutron research and it has been a welcoming environment for applications, innovation and technology transfer. Originally, the reactor was started with a power of 2 MW in 1959, but it was upgraded to 5 MW in 1967. A full-scale reactor refurbishment was started in 1986, fully designed and performed by Hungarian companies. The reactor reconstruction was partly supported by the IAEA, while the project of the new instrumentation received domestic, IAEA and EU funds. The reconstruction was completed and the license for the reactor start-up was issued in 1992, the reactor reached its 10 MW nominal power in May 1993. Thanks to a continuous development the number of experimental stations has grown to 15 and the research staff has grown by now to nearly 60 scientists. In 2010 the reactor core was converted from high enriched uranium to low (20 %) enriched uranium. All spent fuel elements have been transported back to Russia.

The major fields of the reactor utilization are:

1) BRR is a research and development basis for the energy sector. 40% of electricity in Hungary is produced by the Paks NPP (4 blocks of 550 MW electric power). The expertise and knowledge accumulated at BRR during the past decades provides a solid basis for scientific and safety support of the Paks NPP as well as for the national nuclear regulatory body. BBR also serves as a scientific and development tool in other fields of energy research, both in energy saving and production (e.g. development of new materials for energy production and storage, research of materials and structural components for fusion energy or new generation reactors, development of new energy-saving technologies such as superconductors or catalysts). Beside the materials research, nuclear physics and nuclear data measurements for reactor and nuclear astrophysics have always been an important scientific field. These experiments frequently have been performed in collaboration with the International Atomic Energy Agency (IAEA) ever since the start of the reactor. These activities support nuclear databases, essential tools of reactor design, radio-pharmaceutical production and understanding the elemental synthesis in the universe.

2) This reactor is also a complex source of irradiations for materials testing and modification, diagnostics in nanotechnologies, engineering, healthcare radiation damage etc. The radioisotope production – using vertical irradiation channels of the core – is essential for the society. For example, 60 hospitals in Hungary have been supplied by isotopes produced at BRR and nearly 5% of the population has been involved in the usage of isotopes for diagnostics and therapy. A fast rabbit system at BRR serves as a pneumatic irradiation facility, situated in the reactor core; it provides convenient production of short-lived isotopes as well as neutron activation analysis for environmental chemistry, geochemistry, biological and medical research. BAGIRA, the gas-cooled irradiation rig is positioned in a dry channel inside the reactor core. It serves for irradiation-induced ageing studies of materials of nuclear reactor vessels and fusion equipment. The irradiation facility is complemented by a laboratory equipped for hot sample handling. A special application of fast neutron irradiation in the reactor is the production of jewellery-quality gemstones. Neutron irradiation creates defects in the crystal structure of topaz, which appear as colour centres. Thus the colourless polished stones turn blue, increasing the jewellery value by a factor of 100. This ***colouring technology*** has been developed at BRR and many tens of tons of topaz crystals were irradiated in the past 15 years. This activity is far from being of high relevance in science, but it has been one of the most profitable commercial activities of reactor usage.

3) The most extended utilization of BRR is neutron-beam research. This activity is described in more details later in this document. Some typical numbers representing the significant results and utilisation of BRR/BNC in the last 25 years (1993-2018):

Number experiments: 3500
Number of publications: 2500
Project/Contract reports: 1000
Number of PhD works: 75
User experiments: 40%

Collaborative research: 30%
In-house research: 30%
Foreign users from the CE region: 60%
New users/year: 15%
Female users: 25%.

4) University education, postgraduate as well as professional training in the nuclear field, have always been important tasks at BNC. The first international neutron scattering school was organised in 1999 together with the 2nd European Conference on Neutron Scattering in Budapest (this was an exceptional occasion for several hundreds of neutron scientists to visit BRR). This first training school has developed into a series of regional events over the years. For example, the 13th Central European Training School (CETS) was held at BNC in May 2019. These schools provide an introduction to neutron scattering with special emphasis to hands-on-training at the BNC facilities. Regular courses of 4-6 weeks length are organised for training of scientists coming from developing countries with special emphases on topical/instrumental purposes e.g. in neutron reflectometry, internal strain scanning, PGAA, reactor operation, radiation safety, etc., the latter being usually arranged in collaboration with Hungarian Atomic Energy Authority (HAEA) and/or the IAEA.

The major fields of reactor utilization with direct economic/societal impact are:
a) Application of irradiation facilities and neutron beam techniques for supplying products to various sectors of the society, such as industry, healthcare, commerce, education…

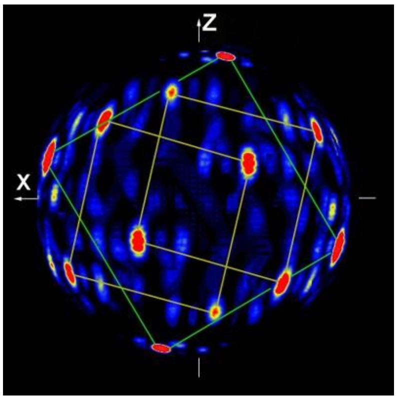
b) Developments of scientific methods and tools; for example, isotope production, technical support for the nuclear energy sector. These activities have made multi-billion HUF contributions to the Hungarian economy.

c) Technology transfer and production of neutron instrumentation by spin-off SMEs resulted in an export commercial income of about 45 M€ during the past 20 years (for comparison, the current annual operating cost of the reactor is 2.4 M€, including the fuel-cycle, i.e. a value comparable to the commercial income).

Neutron research and the user community. Thanks to BRR as domestic facility, the Hungarian neutron/reactor user community of about 200 researchers (some 60 "professionals" and 140 "users") is the second-largest (after the Swiss) in Europe per capita. Besides the researchers of the BNC laboratories the domestic users are coming from about 20 other establishments (university laboratories, research institutes, museums, industry), the most relevant partners are as follows: the BME, ELTE, ME, DE, Atomki, TTK, SZBK). Over 85% of the national community are users at BNC, and about 15% uses only other European facilities (ILL, ISIS, FRM-II, PSI etc.) In the period of 2005-13 Hungary was a partner in the CENI consortium – in this framework about 60 scientists from 18 institutions were users at ILL. The number of executed 'Hungarian' experimental days had always exceeded the paid quota. Hungary was a formal member of JINR-Dubna until 2011 – also with regular utilisation of the IBR-2 pulsed reactor.

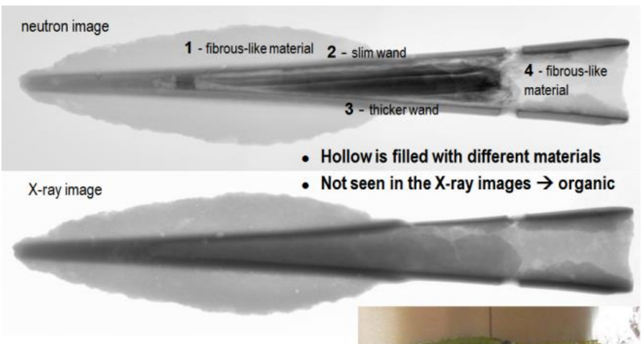
The Hungarian neutron community has made a significant contribution to neutron research for many decades. Some outstanding achievements are related to inventions of our leading scientists like Ferenc Mezei, who invented neutron spin-echo spectroscopy (1972), neutron supermirrors (1976) and the long pulse spallation source concept (1995). The installation of a highly cost-efficient hydrogen cold moderator (2000), the invention and realisation of the pin-hole camera technique for spatial and spectral characterisation of moderator and optical components (2002), the first experimental realisation of the TOF frame multiplication technique (2004) are to be mentioned. László Cser was the first to propose and realize neutron methods for atomic-scale

holography (*The image below is a neutron hologram showing the twelve lead atoms occupying the first neighbourhood of the Cd atom in the PbCd alloy; Cover picture of Phys.Rev.Letters 2002).* BNC teams have played a pioneering role in development of combined dynamic neutron-gamma radiography that has found a widespread application in various industrial fields. In the middle of nineties researchers of BNC-IKI installed a Prompt Gamma Activation Analysis (PGAA) instrument on a cold guide position, later on, with a second instrument – a combined PGAA-Radiography setup – this prompt-gamma assembly became a world-leading facility that time. The largest impact works from this team are the foundation of a coherent PGAA library and the use of in-beam neutrons to *in-situ* observe adsorption and absorption in heterogeneous catalytic processes. This activity was extended to use for the first time neutron tomography and elemental analysis simultaneously in a single experiment. At the PGAA facilities a worldwide acknowledged nuclear data program has been running as well since the introduction of the cold source. In the past decade BNC – with its unique portfolio of neutron and complementary techniques – has become a major European hub for non-invasive neutron beam investigations of objects for heritage science. (The page-bottom picture shows a neutron/X-ray radiography image.)



The Budapest Neutron Centre - facilities, user operation. For neutron beam measurements different types of horizontal channels are available at BRR: six thermal and two fast neutron radial channels and two tangential beam tubes. A 15x27 m^2 guide hall extending from the reactor hall, housing 4 neutron guides, was constructed in 1990. The construction of a liquid hydrogen cold neutron source (CNS) was followed by the installation of a new supermirror guide system both for the in-pile and out-off pile part. A second guide hall was constructed to house a thermal beam time-of-flight instrument (high-resolution diffractometer). The reactor is operated in 5-10 days cycles (ca. 120 days/year). The reactor and the instrument suite are serving for in-house activity (40%) and external users (60%). Diffraction, small-angle scattering, reflectometry, inelastic scattering, radiography/tomography, in-beam gamma capture and in-pile irradiation facilities are available. Basic research, as well as innovation in industrial and medical applications, are addressing issues of chemistry, physics, engineering & technology, life-science, material science and also cultural heritage. BNC is strongly committed to the training of future scientific professionals. In cooperation with universities BNC accommodates students in studying nuclear-based techniques.

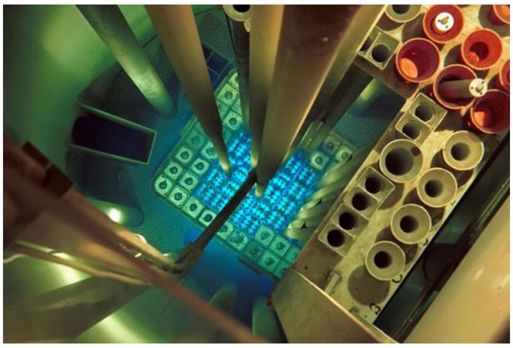
There is also a new situation at organisation level starting from January 2020. It has been decided that – as part of the overall restructuring of the research network of MTA institutes – neutron related activities/infrastructures (BNC laboratories including the reactor itself) are going to be assembled under the umbrella of Centre for Energy Research (EK), a single legal entity.



A bronze spearhead from the Hungarian National Museum

Life-time extension programme for training and research reactors

The assessment for the operation prolongation of the 100kW Training Reactor (picture below) of the Budapest University of Technology and Economics (http://www.reak.bme.hu/en/) and the 10 MW Budapest Research Reactor (www.bnc.hu) has considered the following aspects:



- The Hungarian Government has signed a contract with ROSATOM company for building two 1200 MW electric power nuclear reactor blocks by 2025-26 for the replacement of the current reactor blocks and extension of electric supply in Hungary at the current 40% level and beyond. This NPP investment is underway. Thus, training, technical and research support for the power plant programme as well as for regulatory authorities from the side of BME and BRR is indispensable. In this respect the EU COUNCIL DIRECTIVE (2014/87/EURATOM of 8 July 2014) that establishes a Community framework for the nuclear safety of nuclear installations obliges the government of member states that any regulatory decision-making process should take into account competences and expertise, which may be provided by technical support organisations. This expertise should be based on state-of-the-art scientific and technical knowledge, including from operational experience and safety-related research, knowledge management, and adequate technical resources.
- Considering the neutron landscape in Europe with a tendency of decreasing access capacity to neutron facilities, the operation of BRR and BNC facilities is crucially important to maintain and satisfy the needs of the Hungarian and regional scientific communities.
- A cost-benefit analysis [5] for various scenarios of closing down or further operation of the reactor has shown a clearly positive outcome for the continued operation in terms of macroeconomic balance, employment, decommissioning issues, impact on education, healthcare and industry (including production and export of research equipment).
- Planned compact accelerator-driven neutron sources of national/regional scale to be constructed by the middle of 20s will provide new opportunities for research, training, and commercial purposes. The construction of such a prototype facility has started in Hungary by a grant support of the government. Smaller scale, purpose-built such neutron sources can be commercially applied in various sectors of the society. In the longer-term, the upscaling of such an accelerator-driven facility can eventually replace BRR. In the meantime, BNC facilities should serve as research and training ground for a decade or so, until compact sources become available and go to routine operation.

Example of a compact accelerator-based neutron source in Japan.

Annex III.

Refurbishment and equipment modernisation programme at BRR (2020-2023)

In 2017 the Minister responsible for the Paks2 NNP programme and the Academy (HAS) initiated a project under working name Simonyi-plan to extend the programme “Perspectives of the BME and BRR reactors” submitted to the Government. This short term proposal had foreseen the substantial refurbishment of the reactor infrastructure, reinforcement of safety-critical components and upgrade of instrumentation. This modernisation programme can be implemented in collaboration with the BME reactor facility to aim for basic and applied research, training in nuclear sciences and technologies as well as for recruiting young researchers to ensure a sustainable growth of this field. Investments will be made also for the refurbishment of the reactor building infrastructure (seismic analysis, façade repairs, esthetical paints are inevitable). The cold moderator components, upgrade of the neutron guide system and efforts of improving instruments are envisaged. Five groups of activities are considered.

1. The reactor itself and the surrounding infrastructure
    - 1.1. Reactor and its safety components
    - 1.2. The ensemble of the reactor building
    - 1.3. In-pile irradiation equipment (isotope production, topaz irradiation, BAGIRA etc.)
2. Neutron beam forming system
    - 2.1. Neutron beam take-off systems
    - 2.2. Biological shielding
    - 2.3. Cold neutron source
    - 2.4. Neutron guide system
3. Neutron beam instruments
    - 3.1. Thermal beam instruments
    - 3.2. Cold neutron instruments
    - 3.3. New beamlines and instruments
4. Transition to accelerator-based neutron source
5. Basic and applied research at BNC
    - 5.1. The scientific case
    - 5.2. BNC structure
    - 5.3. User system
    - 5.4. BNC/BRR in the KFKI environment

1. The reactor itself and the surrounding infrastructure

1.1 The Reactor and its safety components. The Budapest Research Reactor was the first nuclear facility in Hungary. The reactor is a standard VVR-S tank-type reactor, with light water moderation and cooling designed and constructed by Soviet companies. The reactor went critical for the first time on 25 March, 1959. After the first upgrade in 1967 the reactor remained in operation until 1986 when the second upgrade started. The reconstruction plan took into account the new trends in nuclear research, the modern reactor safety requirements (according to the IAEA’s recommendations), and the fuel issues, core configuration, operation and maintenance. During the reconstruction all parts of the reactor were replaced except the civil engineering construction. The upgraded 10 MW reactor received the license for operation in 1993. BRR joined the Russian Research Reactor Fuel Return (RRRFR) programme, and part of this project the spent and fresh high enriched uranium (HEU) nuclear fuel stored at the BRR site were repatriated to Russia and the BRR core was converted from HEU to low enrichment uranium (LEU 20%) fuel.

In Hungary, the safety requirements of nuclear facilities are regulated by two main pieces of law: The Act CXVI of 1996 on Atomic Energy (Atomic Law) and Govt. Decree 118/2011 (VII. 11.). The decree shall apply to nuclear facilities to be constructed as well as to those already operating within the territory of Hungary. The adaptation of the decree is controlled by the Hungarian Atomic Energy Authority (HAEA), which supervises the following activities: commissioning, operation, modifications, decommissioning and termination.

After 26 year operation, BRR is still in a good technical condition, therefore it gives us the possibility to plan the further operation beyond 2023. BRR was originally planned to operate 144000 hours during 30 years on 20 MW thermal power. The performed operation was 80000 hours during almost 30 years on 10 MW thermal power. This fact also provides opportunity for further operation for the next 10 years. The lifetime extension requires, however, several technical modernization or partial refurbishment. The lifetime extension needs to be formally approved by HAEA, thus we need to develop and implement an Operation Time Extension (OTE) programme. The main elements of the OTE are:

- Submission of the actual Periodical Safety Review (PSR 2014-23),
- The results of the PSR define the life expectancy of the systems and subsystems,
- Identification of the systems which requires modification for OTE,
- Prepare the OTE program, which contains the tasks, the deadlines, the responsible persons,
- Submission of the OTE programme to HAEA,
- Implementation of the approved programme,

The estimated main technical tasks:

- Replacing the primary loop pumps (obsolete system without spare part supply),
- Renewal of the monitoring/display system in the control room,
- Partial renewal of the radiation measuring system,
- Partial replacement of the secondary pipelines,
- Replacing the emitted air filters.

1.2 Ensemble of the reactor building. The reactor building was constructed 65 years ago, thus a thorough revision and maintenance is required both in terms of structural components and functions as well as aesthetic aspects. Both neutron guide halls require a refreshing paint and maintenance of the infrastructural components. The construction of a new guide hall is required to host the NEAT/VOR instrument.

1.3 In-pile irradiation equipment (isotope production, topaz irradiation, BAGIRA etc.) The ensemble of the vertical irradiation system does not require substantial renewal, although isotope production needs might yield in the extension of some components.

2. Neutron beam-forming system

2.1 Neutron beam take-off systems. The high-level operation of the suite of the neutron beam instruments require even more sophisticated beam-forming system. The current configuration of the reactor horizontal channel arrangement provides one tangential and 6 radial thermal as well as 2 epithermal neutron beam take-offs. A special beam-port serves for the cold neutron source plug insert and neutron guide system take-off. No major modification of this system is required except the replacement of the cold neutron source plug (see 2.3) and the rearrangement of the out-of-pile part of the current biological irradiation facility (channel No.5), where the new moderator testing device is planned to be installed.

2.2 Biological shielding. In order to improve the experimental background conditions and dosimetry/safety circumstances, the obsolete boric-acid tank shielding components will be replaced by special concrete blocks to protect the local environment of each channel/spectrometer. In this way a partial refurbishment of the biological shielding system will be implemented.

2.3 Cold neutron source. A liquid hydrogen cryogenic moderator is in operation since 2000. It provides cold neutron beams via a 3(4) branch guide system for 8 spectrometers. The replacement of this moderator is required for technical reasons because of service-life expiration of some components as well as to benefit higher performance thanks to the new concept of low dimensional moderators developed at ESS and BNC. The cold source modernisation concerns the following items:

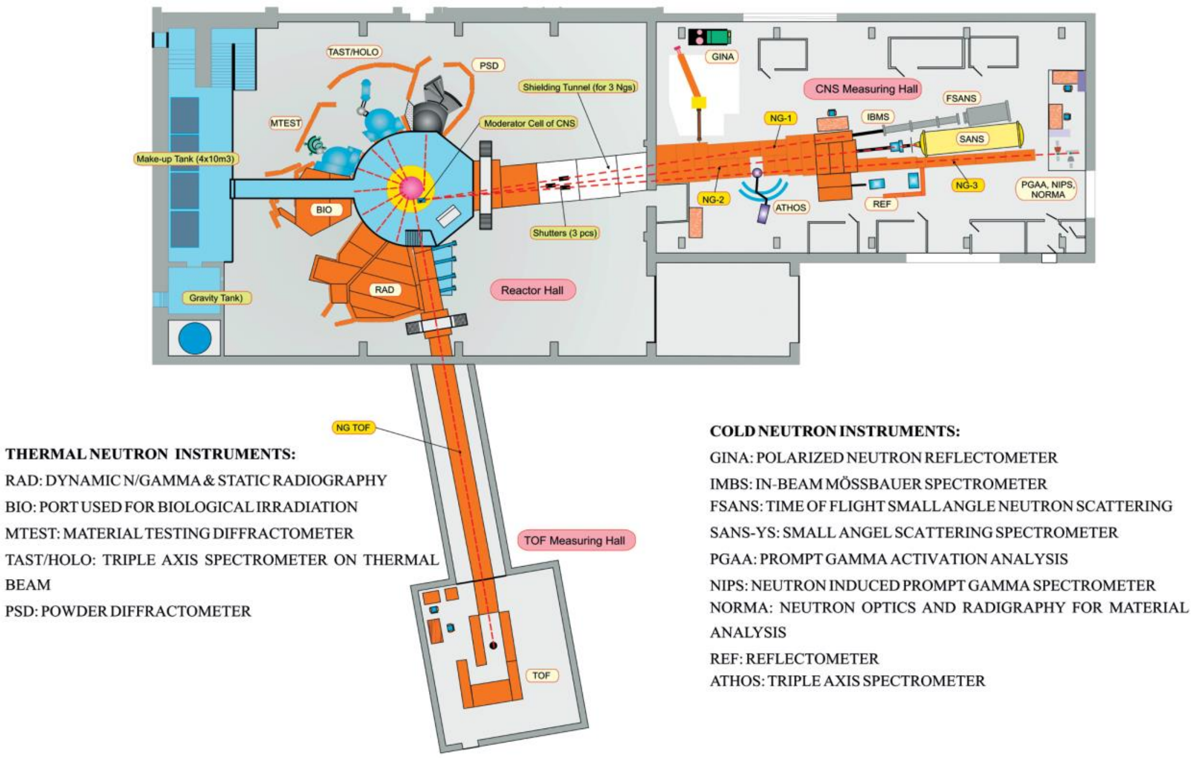
- replacement of the moderator vessel by a low-dimensional hydrogen chamber,
- replacement of the compressors,
- upgrade of the cold box,
- replacement of the cold pug.

2.4 Neutron guide system. The new cold moderator geometry requires optimised neutron optical components and considering that in the past 20 years neutron optics has progressed tremendously, the guide system is to be redesigned. The envisaged new equipment (NEAT/VOR) should also be inserted into the guide configuration. Advanced MC simulation techniques, mastered at a high level by BNC staff scientist and the high-tech background for manufacturing guide components by domestic companies, will allow to design and install a world-class neutron guide system to serve an ensemble of instruments with several factor of improved signal/background parameters.

3. Neutron beam instruments

Research priorities set for the Simonyi-project cover the initial period of the upgrade programme such as materials science for the energy sector, especially for nuclear energy, functional materials, structural biology and support for the transport industry as well as heritage science. According to current trends, it seems to be important to reinforce BNC capabilities in neutron beam techniques for imaging, strain analysis, powder diffraction, structural biology equipment (reflectometry, SANS). Methodical developments are also in the focus of short term activities – mostly driven by ESS instrumentation projects as well as the new equipment to be designed for CANS laboratories.

The suite of BNC experimental stations is shown in Figure 1. and listed in Table 1. below.



The reactor has 10 horizontal beam tubes, one of the tangential beam tubes is equipped by a liquid hydrogen cold neutron moderator. Three supermirror guides transport neutrons to the measurement sites in the guide hall. A thermal guide serves for a high-resolution time-of-flight diffractometer. 3 experimental stations are using reactor core irradiation, while 14 beam-line instruments are grouped into 3 categories according to their type of functioning: scattering (diffraction, small-angle scattering, inelastic scattering), irradiation/in-beam gamma capture and imaging.

The following instruments are considered for substantial upgrade:

3.1 Thermal beam instruments

Full-scale upgrade of the PSD instrument. This neutron diffractometer offers atomic structure investigations of amorphous materials, liquids and crystalline materials. The mission for PSD neutron diffractometer is to provide scientists with a good parameters diffractometer at the reactor which can be used to carry out high-impact science. The neutron diffractometer has been installed at the No. 9 tangential, thermal channel of the Budapest Research Reactor. The monochromised and collimated neutron beam is scattered on the investigated specimen, and the scattered diffractogram is detected by a linear position-sensitive detector system. In 2002 we upgraded the detector system, but over the last fifteen years the basic layout has not changed. In the near future a substantial upgrade is needed. With the planned reconstruction and development would be able to study a broad range of materials with highest resolution. Here we suppose cost-efficient plan to upgrade our diffractometer to be more competitive. We plan to build-in two new monochromator crystals (installation of 1. oriented mosaic Ge crystal, 2. oriented mosaic Cu crystal, 3. goniometer for monochromator positioning); to be able to measure with different wavelength, allowing measuring special materials. A new detector system, a banana-shaped high resolution detector (20X60 cm^2 2D position-sensitive detector based on high-pressure 3He gas) is the major upgrade item. A new, compact and dedicated electronic control system for movements, detection and data acquisition purposes is envisaged. The new electronic equipment will use the EPICS software. The new integrated system includes all steps of the control system, data collection and processing and design of several types of measurements with the new possibilities connected to the upgraded instrument and also for the in-situ sample environment equipment.

Improvement of the MTEST (materials testing) neutron diffractometer covering the applicability the range to medium-resolution powder, liquid and amorphous total diffraction measurements in accordance with the need of the current user community (mainly from the Central European region, 20-30 user days/year) allowing accelerated data collection. The diffractometer is equipped with a working furnace to perform studies up to 600 °C and for a short time up to 1000 °C. Developing the instrument might focus on three areas: reliability, ancillary equipment and development of the instrument components. Taking into account reliability, the weakest points of the instrument are the motors, encoders and the motor control electronics, which was produced at least 40 years ago. The ancillary equipment is important as they extends the applicability of an (or a group of) instrument(s) in a very cost-effective way by increasing the research outcome. For this purpose, furnaces for high-temperature studies, cryomagnet/closed-cycle refrigerators are proposed. 8 new ^{3}He position-sensitive detectors are needed to achieve an internationally competitive setup. Background suppression should also be improved (extended shielding, vacuum tube in the monochromatic beam). The monochromator changer should be equipped with a sagittal focusing option. This allows smaller amount of samples like for levitation (container-less) melting.

RAD facility upgrade. The present configuration of RAD uses a radial neutron beam with a wide energy range, from meV to MeV. The neutrons with different energies are suited to solve different problems, analyze different object sizes. To achieve the best scientific quality and versatility, optimal beam conditions shall be achieved, e.g. either thermal or fast neutrons shall interact with the sample. With appropriate exchangeable beam filters (e.g. sapphire, B, Pb, …) one or the other component of the neutron beam can be suppressed or enhanced, so that the beam's energy distribution could be tailored to the specific imaging application, in a single facility. On the other hand, the X-ray imaging is an excellent complement to neutrons in terms of contrast, so either a cross-beam X-ray configuration with a flat panel array detector or a standalone micro/nano X-ray imaging station would greatly enhance the BNC capabilities for both scientific and industrial imaging applications.

Table 1. ***Experimental stations at the Budapest Neutron Centre***

	Acronym	Instrument	Planned modification
1	TOF-ND	Time-of-flight diffractometer, Thermal beam No.1	Minor upgrade
2	MTEST	Materials test diffractometer, Thermal beam No.6	Substantial upgrade
3	PSD	Powder diffractometer, Thermal beam No.9	Substantial upgrade
4	YS-SANS	Small angle scattering spectrometer (Yellow Submarine), Cold guide No.2	Minor upgrade
5	F-SANS	Focusing small angle scattering spectrometer, Cold guide No.3/2	Minor upgrade
6	GINA	Polarised neutron reflectometer, Cold guide No.3/1	Minor upgrade
7	REF	Neutron reflectometer, Cold guide No.1/2	Reconstruction by adopting the Berlin reflectometer
8	ATHOS	Three-axis spectrometer, Cold guide No.1/1	Substantial upgrade
9	TAST	Three-axis spectrometer on a thermal beam, Thermal beam No.8	No modification
10	NIPS	Neutron Induced Prompt-Gamma Spectroscopy, Cold guide No.1/4	Minor upgrade
11	PGAA	Prompt gamma activation analysis, Cold guide No.1/3	Minor upgrade
12	BIO	Biological irradiations, Thermal beam No.5	Replacing by the moderator testing equipment
13	RAD	Dynamic/static radiography, Thermal beam No.2/3	Substantial upgrade
14	NORMA	Neutron Tomography, Cold guide No.1/4	Minor upgrade
15	DÖME	The Low-Level gamma-spectroscopy facility DÖME	No modification
16	RNAA	Fast-rabbit system and activation analysis, Reactor tank	Minor upgrade
17	BAGIRA	Controlled temperature irradiation rig, Reactor tank	Minor upgrade

A high-energy/high-resolution X-ray generator and its accessories, in combination with the computer-exchangeable neutron beam filters and an evacuated flight tube would open the way to implement the routine multi-modality imaging and characterize the sample by multiple means of radiations at once. This reconstruction implies a larger facility footprint, so the bunker of the RAD facility shall be enlarged. The safety features and the shielding shall be completely redesigned to fully comply with the present regulations.

3.2 Cold neutron instruments

ATHOS control system upgrade. The ATHOS cold triple-axis spectrometer can be used for inelastic scattering experiments to study condensed matter dynamic properties at atomic level. This instrument, however, with its highly flexible functioning features has been used for a large variety of application of industrial relevance as well as for methodical developments. Thus, this multipurpose device was selected as representative test equipment for the EPICS integration programme of the BNC instrument park. The complex, 14 axes motion system of the instrument and adjacent detector test rig is being completely refurbished and endowed with a PLC-based control system. The maintenance of the mechanical hardware system is also performed.

YS SANS and FSANS modernization. The most stringent improvement required on the YS SANS instrument is a new detector, data acquisition system and a refurbished motion system within the flight tank for the detector and the beam stop. A small size, high count rate detector will be placed on the beam-stop in order to save the transmission measurement time. A vertical beam stop position adjustment system is envisaged in addition to the existing horizontal one. A new automated diaphragm and collimator changer is also expected to save valuable measurement time. The integrated motion control and sample environment parameter control system meets the requirements of the EPICS surveillance system. The FSANS instrument requires an improved chopper control system providing real time phase accuracy information, sample positioning equipment and focusing neutron optics.

Sample environment equipment. A suite of generic sample equipment items – cryostats, furnaces, stress-strain rigs, pressure cells, electromagnets, flow cells – will be developed to serve several instruments. The design is based on the sample environment space constraints and parameter requirements of the various instruments. The control of these devices is envisaged to be integrated into the EPICS instrument surveillance system.

PGAA and NIPS facilities. BNC has two stations for non-destructive element analysis via radiative capture: PGAA and NIPS. Also to allow improved nuclear physics and data measurements at the PGAA station important upgrade is needed to improve the PGAA system with higher count rate handling and digital Compton suppression option. At the moment the performance bottleneck is the throughput of the ageing NIM-based electronics. The data are taken at a low count rate (< 2000 cps), while the most recent digital gamma spectrometers already provide 64k bin size, digital Compton-suppression and most importantly, about one order of magnitude increased event rate, resulting in enhanced productivity and better utilization of the beam time. The NIPS facility is unique worldwide in obtaining spatially-resolved elemental concentrations via 3D scanning. This isovolume-based measurement requires strong collimation of both the impinging neutron beam and the gamma detection. Recently, a pixelated semiconductor detector became available that can make use of the Compton-camera concept, and thereby bypass the need of any collimation. This detection technology can, therefore, bring a factor of 10-100 speed improvement in elemental mapping applications. This would significantly improve the productivity. At the same time the flexibility of the setup shall be improved by using exchangeable target chamber to decrease the detector-sample distance or enabling user-supplied and equipment.

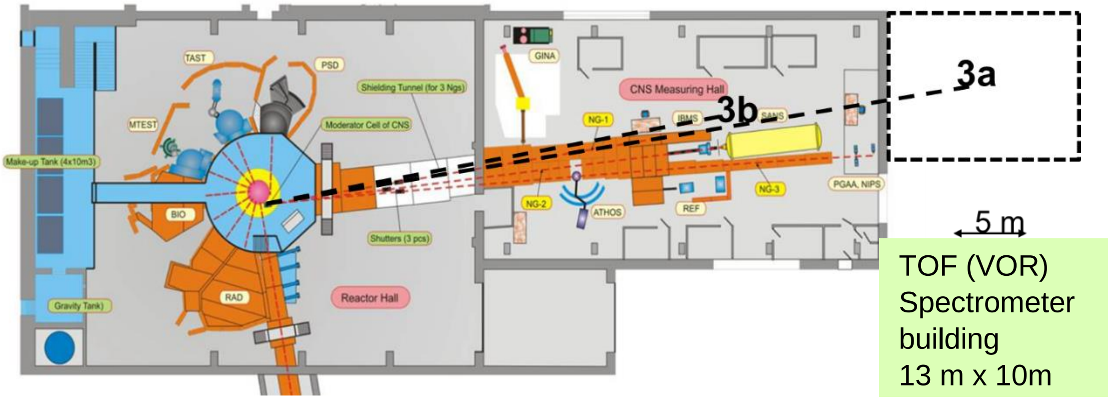
NORMA cold neutron imaging station. The NORMA can work as a standalone imaging station with cold neutrons, or as an integral part of the NIPS station to integrate the imaging and element analysis functionalities. In this context this is the only permanently operating facility worldwide.

In order to enhance the present 200 µm spatial resolution down to 30-40 µm, a 5-6 MPx sCMOS camera, motorized light-tight box, and appropriate optics are required. A WIDEPIX camera in combination with a beam copper would allow for energy-selective imaging, offering more contrast than the present white-beam.

3.3 New beamlines and instruments

Reflectometer transfer from Berlin. The polarized cold neutron reflectometer V14 will also be transferred from HZB to BNC. A double monochromator system that changes the incident phase space from the existing vertical to a horizontal geometry required by the instrument will be designed and deployed on one of the neutron guides in the BNC cold neutron guide hall. This would also change the instrument position from roughly orthogonal to parallel to the neutron beam, where more space is available. In parallel, dismantling at HZB, transport and installation at BNC of the existing V14 components will be performed.

NEAT transfer from Berlin. The NEAT direct chopper spectrometer is envisaged to be transferred from HZB to BNC. A major upgrade of the neutron delivery guide system and amenities (including a new building for the sample environment and detector) are required to efficiently accommodate the instrument on the BRR site. This is foreseen to be accomplished in the time frame of the BRR cold neutron moderator and guide system replacement. The NEAT transfer is considered to be combined with the VOR instrument construction as described in 'New Instruments' chapter.



Cold moderator test beamline at BRR Channel 5. An out-of-pile cold neutron moderator test equipment is envisaged on the thermal Channel #5 of the Budapest Research Reactor. The aim of this new instrument is to allow systematic investigation of moderator geometry, reflector layout and neutron slowing material efficiency. Experimental verification of numerical simulation kernels for various materials in a wide range of physical parameters will also be possible. The beam has direct view towards the reactor fuel zone. Neutron transmission and scattering will be measured simultaneously by two neutron beam spectrum analyzers and energy-sensitive imaging systems. This requires a special cryostat providing beam transmission in one inlet and two outward directions. The cooling system allows in situ H_2 liquefaction.

4. Transition to accelerator-based neutron source

A feasibility study (including licencing issues) and conceptual design for transforming the reactor and its infrastructure into a compact accelerator-based neutron source (CANS) is to be envisaged according to the patent of Mezei-Zanini[1] – establishing another 3-4 decades of operation of a modern medium flux neutron facility in Budapest.

[1] Mezei F, Zanini L, *A method for providing a neutron source,* Patent pending WO 2017/198303 A1 (2017)

5. Basic and applied research at BNC

5.1. The scientific case. The Hungarian neutron community has made a significant contribution to neutron research for many decades. The BNC modernisation will significantly contribute to the continuation of valuable scientific research and innovation both in the context of international trends as well as national R&D priorities. Neutrons have special and some unique properties, thus they must be made increasingly available to science and industry. The neutron is a unique probe with characteristics that cannot be supplanted by other methods. Neutrons allow scientists to understand the world at the atomic and molecular level in a non-destructive manner. Neutron imaging techniques can reveal macroscopic topologies, inhomogeneities or hidden objects inside even larger objects. This makes neutron science one of the most useful analytical techniques deployed across numerous science and technology disciplines. Due to the characteristics of neutrons – well suited to investigate magnetic properties, light elements, thin films or large samples – they are an essential tool used in support of the science addressing society's Grand Challenges and have a legacy of significant socio-economic impact. Hungary has a strong position in neutron science, it has been achieved and is sustained thanks to the six decades operation of BRR, its rich and storied legacy in the development of neutron research techniques, along with the related expertise of facility staff and supplier companies. The use of neutrons by industry, which currently accounts for 15-20 % of BNC beam time, serves to strengthen the knowledge transfer from basic science to applied research, and accelerates the development of novel products and services.

In particular, the domestic neutron research programme shall be focused on areas like nuclear industry, energy production and saving by research of alternative energy resources and new materials technologies, biology related topics related to biotechnology, food security, healthcare and pharmaceutical industry. Materials science problems of transport industry, including the supply chain for the automotive sector, aviation and space technologies as well as research for heritage science are high on the agenda. The BNC staff is strongly committed to work in the above fields as well as serve to and collaborate with domestic and international research groups to advance science and technology by means of the BNC research infrastructure.

5.2. Organisational matters. Neutron related activities/infrastructures at BNC (including the reactor itself) are going to be grouped under the umbrella of a single legal institution, the Centre for Energy Research (EK). The ILO, project management, communication (home page), training activities are to be set in a BNC Terms of References (ToR).

BNC structure. A new organisation chart is considered. The role of BNC administrative function is to be redefined at various levels. The management responsibility lies on the director-general of EK. He is helped by a BNC Executive Board, which consists of a few number of leading scientists of EK/BNC. The International Scientific Advisory Council (ISAC), an assembly of distinguished scientists from Europe, is advising the management in strategic matters. Expert units in the organisation fulfil functions of different tasks run by BNC. Open access and user service remains the most significant mission of BNC, thus running a User Office to assist the implementation of user experiments as well as the User Selection Panel to insure scientific excellence in the experimental programme should remain in the BNC structure. To comply with the intention to enhance innovation-related activities the setup of a sort of an Industrial Liaison Office is required.

5.3. User system. The Budapest Neutron Centre runs an open-access national and international user programme including 14-17 neutron instruments and some service laboratories. Calls for proposals are announced on the BNC website and via mailing lists. To apply for beam-time on an instrument requires to submit a research proposal electronically to the BNC User Office. The beam time provided by BNC is free of charge for public domain research, however experimental reports are required within three months succeeding any experiment at BNC. The user support system is to be redefined. The utilisation of instruments is to be monitored by a proper software programme, which is to be channelled to the requirement of open data and open science system. It means that the acquired data must be stored in a common format described in the PaNOSC project, in which CERIC is involved. The system should comply with the CERIC[2] data policy.

5.4. BNC/BRR in the KFKI environment. As part of the overall restructuring of the network of institutions of HAS, the home of BRR, i.e. the KFKI campus might change its character. The Ministry of Innovation (or its newly established institution, the Roland Eötvös Research Network) might decide to turn the campus into a 'Science & Technology Park' based on the existing large scale facilities (BRR, CERN Data-Centre and distributed infrastructures as network of electron-microscopes, X-ray and optical spectroscopy devices etc.), largest physics library in the country and technology-oriented firms already on site; as well as extending it by stimulating R&D related companies to be installed here. A conference centre with guest house facilities might be also envisaged.

The transition of BRR into an accelerator-based neutron source would mean a "brown-field" decommissioning. The major part of the buildings and reactor equipment could be saved and transferred for the new equipment, while the site will become free of fission materials and nuclear waste, thus its 'nuclear-facility' label and treatment could be released. At the same time BNC and the campus will remain a major hub and infrastructure for R&D in the country.

[2] https://www.ceric-eric.eu/users/open-access/

International relations

The Budapest Neutron Centre and the Hungarian neutron community has been always open to international co-operations. In 1992 at its foundation BNC was declared to be an open-access facility for the domestic and international scientific community. Numerous formal collaboration agreements have been established both at multi- or bilateral level. The most significant partnerships in international organisations or bilateral collaborations are outlined below:

- Dubna. Hungary was a founding member of JINR Dubna from 1956. The IBR-2 reactor facilities are regularly used by Hungarian scientists. Thus, the re-establishing the JINR membership is to be kept on the agenda, even though that the commercial instrument deliveries by Hungarian SMEs to Dubna laboratories substantially exceed the membership fee to be agreed, which means that in-kind type contribution could be easily envisaged. (The neutron activity makes about 30% of the Dubna relations).
- ILL-Grenoble. The ILL membership was also mentioned above. ILL will remain the most productive neutron source in the world, at least by 2030. Advanced negotiations have prepared the eventual return of Hungary to ILL as a scientific partner.
- CERIC. One of the first European research infrastructure consortia, that was created is CERIC, which is a network/distributed infrastructure of a set of important Central-European analytical facilities, led by the Elettra synchrotron in Trieste. BNC is the neutron provider in this RI by offering access to a given number of spectrometers at BRR. The operation of instruments and providing user access services is a sort of an in-kind contribution to CERIC. It is an emerging task to raise international (e.g. H2020 or Horizon Europe) funds for the coming years to operate CERIC after its successful start-up, and also desirable to create a proper budget at the national level for the in-kind contribution – inserted in the Roadmap.
- The cooperation with the "Kurcsatov Institute" has also long traditions both with the Moscow reactor as well as the Gatchina Institute near St. Petersburg. Scientific and methodical exchange projects were performed with most of the European neutron centres, especially with LLB, HZB, PSI and MLZ. After the sudden closure of the IFE reactor (Norway), BNC might offer to host state-of-the-art instruments or components.

Current and future activities are planned to focus on the following projects:

- European Spallation Source. Hungary has been a founding member of the ESS ERIC. 17.6 M€ (2013 value) is going to be spent as a 1% contribution to the ESS construction in the period of 2015-25. 70% is delivered as in-kind. HAS institutes, Atomki, EK, and Wigner have been the initial partners to provide in-kind contributions. While the in-kind part of the first years until now was devoted to several activities, the idea from the beginning was to devote the in-kind part for the years of 2020 – 2025 for the construction as lead country of an instrument at ESS, and the choice of VOR for this instrument was already agreed upon when VOR was one of the 16 approved instruments to build. The timeline of its construction agreed well with the availability of the Hungarian in-kind funding, about 7.2 (2020 indexed value) million Euro in the period 2020-25. For the scientific interest of the Hungarian neutron community and research effort in connection with ESS is crucial that this share of the in-kind effort is devoted to a Hungarian lead instrument project. The planning was made to help to fit the original ESS timeline, with the other participating countries having their in-kind effort timed earlier. With the delays of the ESS start of operation and instrument delivery, VOR cannot be accomplished at ESS within the 2020-25 timeframe. On the other hand, it can be accomplished at the Budapest Research Reactor, whose full power (10 MW) operation period is now extended to at least 2025. In this process an additional chopper close to the reactor would turn the continuous reactor source to emulate the long pulse ESS, and VOR could be installed fully commissioned and tested in operation within the period of the availability of the Hungarian in-kind funding for ESS. It could also provide beam time for ESS needs, both for neutron scattering work and effectively replacing the ESS test beamline at HZB, that will cease operation at the end of 2019.

Ákos Horvát (DG EK), Péter Lévai (DG Wigner RCP), László Rosta (STC delegate) at the Foundation Stone Ceremony on October 9, 2015.

- Collaboration with Germany. The best state-of-the-art TOF spectrometer NEAT at HZB is expected to become available for use within Europe outside Germany after the shutdown of the Berlin reactor, since MLZ in Munich found no room at MLZ for its accommodation at the reactor there. Hungary already signalled several months ago to HZB that it is interested in operating NEAT, which can be refurbished at moderate costs to realize VOR. Along the line with the upgrade programme at BRR the neutron guide hall will be extended to house NEAT/VOR. This task is financed from the ESS in-kind budget.
- Contribution to PIK reactor. The commissioning of the 100 MW PIK reactor at St. Petersburg – the world's most powerful research reactor with the highest neutron flux is expected in 2021-22. The PIK owner 'Kurchatov Institute' is prepared to organise an International Centre of Neutron Research with Germany as primary partner contributing to PIK instrumentation up to a level of 30 M€. Hungary has been also invited and the Government is ready to finance – at given conditions – an in-kind contribution by the turn-key supply of a state-of-the-art new neutron spectrometer to PIK. This can serve the needs of the Hungarian scientific community as well as give right to access to the full suite of instrumentation at PIK.

European organisations play important role in representing the neutron community at various levels of national or international administrations (EU, ministries, agencies…) as well as in the coordination of scientific, networking, fund-raising etc. activities. With its nearly 6000 to 8000 users (depending on the statistical approach) the neutron community is most probably the best organised coherent scientific community in Europe (although significantly smaller than the 35 000 member synchrotron community). Hungary was a founding member of ENSA established in 1994. ENSA has made a significant contribution to the high level organisation of the community by creating the series of ECNS (large conference every 4 years, e.g. in Budapest in 1999), awarding prestigious prizes (e.g. Walter Halg-prize, F. Mezei as first winner in 1999) and also in coordinating proposals for EU framework project, where the support for the neutron activities was significant. In March 2019 LENS was created with BNC as a founding member. While ENSA remains the representative of the users (association of national user organisation), LENS has the mission to coordinate strategy-forming as well as actions in fundraising on the side of neutron facilities. The Hungarian participation/representation in ENSA and LENS is to be formulated as a part of the National Roadmap.

Key activity domains for higher impact

Education and training. An important mission of the Budapest Neutron Centre is to provide training and education for both instrumentation designers and users. Hands-on-training for university courses as well as summer practice for students are held at the instruments and expert supervision is provided for BSc and MSc theses. In collaboration with university doctoral schools PhD works are performed in the field of nuclear techniques as well as in various scientific areas where neutron instruments are applied as tools of research. Further efforts are needed to enhance collaboration with universities by inserting neutron methods into the graduate training programme at BSc and MSc level. Especially physics, chemistry, materials science and also various engineering courses are to be targeted.

The annually organized Central European Training School on Neutron Techniques - CETS - is a 5 days event providing insight into neutron scattering, activation analysis and imaging as well as applications for studies on structure and dynamics of condensed matter. Besides theoretical lectures given by lecturers from the main European Neutron Centres, the participants can train their experimental skills and become familiar with the interpretation of the experimental data. The school also offers a forum for presentation and discussion of actual research works of the attending young scientists. The experiments demonstrate to the students the art of utilization of instruments at a large-scale facility. They get acquainted with sample preparation, experiment planning and running as well as data processing and interpretation of results. The participants are divided into groups of maximum 5 students in order to facilitate individual involvement in the performance of the experiment. Each group performs one or two neutron experiments per day and each group works at 5 different instruments. In 2018 a comprehensive handbook on the experimental training was edited and made available for the trainees. The 13th event of the series took place in May 2019. In the above pictures participants of CETS 2015 and CETS 2018 are featured.

Communication strategy. „To be successful, you have to provide visibility into what is being done day-to-day as well as how this fits into the big picture."[3] In the case of BNC we need to apply this

---

[3] https://www.workfront.com/blog/project-visibility-35-tips-to-see-more-of-whats-happening-in-your-work-and-work-better

- for internal and external communication
- enhancing the information and school/training programme
- by making involved the associated partners' platforms (LENS, ENSA etc.)
- being present in the social network (FB, Twitter)

The following objectives have been identified:

- to create an innovative and attractive image associated with the promotion of BNC in the EU
- to facilitate the BNC user programme
- to disseminate and increase the awareness of BNC related users on current improvements
- to reach sustainable high-quality professional schools/trainings
- to improve the competitiveness of innovative solutions
- to involve relevant partners.

Identifying the audience is crucial to choose the most effective ways of communication. The target groups are the following: professionals (scientists, students and engineers), companies, public entities (authorities, policy makers). Different tools and materials can be used that shall carry the message to the audience (e.g. the CETS Handbook, "Neutron techniques for non-destructive materials testing" – review article in Hungarian). The event used to be held such as user meetings, conferences, thematic scientific group workshops, forums, schools (e-learning), science day etc. For example, more than 60 scientists took part at the users' workshop organised by the ILL in November 2018, or 100 participants were gathered from industry and universities to attend the BNC conference entitled 'Science, innovation, competitiveness' on 3 May 2019 at BME. Materials (newsletters, press appearance, brochures, progress reports), as well as corporate image building should help to improve the visibility and identification of the BNC (images with logo, colours, properly designed presentation & templates etc.).

Greater collaboration between scientific disciplines. Profiting from the multidisciplinary nature of neutron research, cross-fertilisation between scientific disciplines and complementary use of various scientific tools might enable the growth of the neutron user community and more efficient use of the facilities to produce excellent science or pragmatic applications. Multidisciplinary teams have been shown to be an effective way to facilitate collaboration between professionals and hence improve scientific merit. It is essential to integrate the different methods to understand the physical/chemical properties of the different kind of materials, important for various applications. Examples are outlined in ANNEX 3.

Improving liaison with industry is a top-priority activity at BNC. Research performed with neutrons, application of BNC facilities for problems in industry, healthcare and heritage science has got special attention in the past few years, in particular, thanks to the EU sponsored SINE2020 project. An 'industrial liaison office' (ILO) was formed by grouping this type of activity of a few BNC staff members helped by external experts. Creating a formal ILO unit at BNC level might be envisaged. Considerable effort has been devoted to bring together our research staff with engineers, industrial experts, new-comers, students who have already used, or are potentially interested in utilizing large research infrastructures, in particular neutron techniques available at the Budapest Neutron Centre. This is in line with the policy of the European Union and the Hungarian Government that paid special attention to promote innovation and the efficient transfer of scientific results into industrial sectors, so improving their prompt economic impact. Regarding domestic features of industrial liaisons the following activities are to be promoted:

- Enhancing awareness of neutron/nuclear techniques especially in the SME sector by calls for applications within the „triangle type" of „Research Infrastructure – University – Industrial Company" – in this way to increase the scientific and research potentials in the industrial supplier chain and so the enhancement of SMEs' competitiveness for the large producers (e.g. multinational companies) in the country.

- Dissemination on neutron research capabilities with special attention on the priority sectors like automotive industry, healthcare (pharmaceutical industry), food security, energy production and saving (nuclear sector) etc. Roadshows, thematic conferences, direct marketing at targeted companies, demonstration of specific neutron experimental case studies are those tools, that have already been practiced.

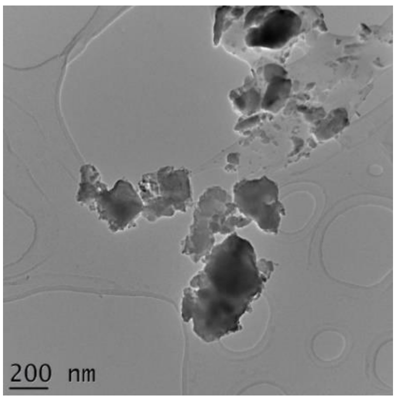
Collaboration between scientific disciplines and complementarity of various scientific tools

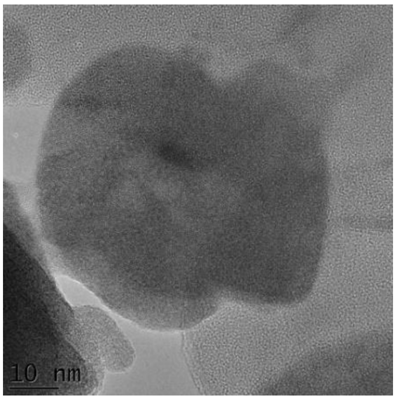
In many cases, structural characterization of materials has been limited so far, because of the large complexity of components of the studied samples. Due to the high number of contributing elements it is difficult to derive adequate structural data from a single experiment. The situation can be improved by combining different methods, e.g. the information of X-ray and neutron diffraction experiments provide complementary information, since the different ways in which X-rays and neutrons interact with atoms, they have different sensitivities for different types of atoms. Or, Nuclear Magnetic Resonance (NMR) spectroscopy - dedicated and very effective method to see the surroundings of special atoms - also might play an important role in the characterization of materials; High-Resolution Transmission Electron Microscopy (HRTEM) analysis can deliver information on the composition and homogeneity of the materials. All of these can be accessed in the CERIC-ERIC and many possibilities exist at the EK in electron microscopy, especially the new aberration corrected TEM which can also provide atomic resolution.

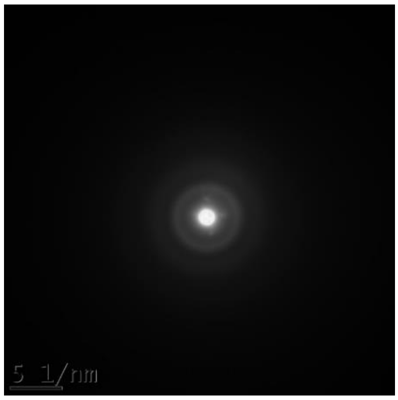
Although diffraction experiments provide the most suitable tool to get information on the atomic configuration, - like first neighbor distances, coordination numbers, etc. -, for Rare Earth-glasses this is a rather difficult task because of the several different atomic pairs and their overlapping distances. A glassy system with k different types of atoms, can be described by $k(k+1)/2$ partial distribution functions. For a five-component glass, this is 15, which would need 15 independent experiments to understand the basic network structure of our samples, which is impossible. In order to (try to) overcome this problem, besides neutron diffraction measurements we performed X-ray diffraction measurements and additional NMR and HRTEM investigations. For diffraction data treatment we use Reverse Monte Carlo (RMC) simulation program, which is widely used to model the structure of disordered (non-crystalline) materials.

Case study: structure study of the Mo-Nd-B-O system

Rare-earth molybdate phases exhibit a great variety of important physical properties including high ion- and electron conductivity of fast oxide ion conductors, non-linear optical response and luminescent properties. In contrast to crystalline molybdates, the preparation and structural information on amorphous molybdate systems are far not well known. Here we present a multidisciplinary study on Mo-Nd-B-oxide system. In order to get structural information, both the traditional Fourier transformation technique and the reverse Monte Carlo (RMC) simulation of the neutron and X-ray experimental data have been applied. In the below pictures HRTEM shows







that $50MoO_3$-$25Nd_2O_3$-$25B_2O_3$ sample is fully amorphous.

Neutron and X-ray diffraction experimental data were simulated by reverse Monte Carlo modeling. The first- and second neighbor correlation functions, atomic distances and coordination numbers have been revealed. From the analyses of the obtained structural parameters we have concluded that the glassy network is formed by trigonal BO_3 and tetrahedral BO_4, MoO_4 groups, with significant medium-range order. Concentration dependence was found for the BO_4/BO_3 fraction, it increases with increasing B_2O_3 content. The experimental ^{11}B NMR spectra show two characteristic distributions related to $^{[4]}B(BO_4)$ and $^{[3]}B(BO_3)$ structural units. According to the HRTEM observations, no crystallization or phase separation was detected for the studied samples.

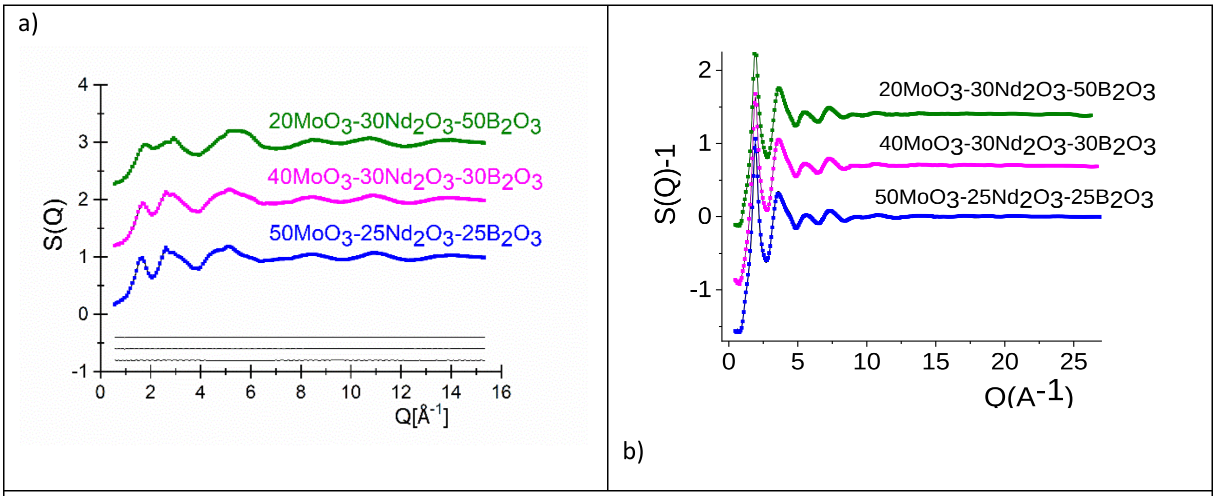


Figure 1. Neutron diffraction (a) and X-ray diffraction (b) structure factor, $S(Q)$ of the boromolybdate samples, experimental data (marks) and RMC simulation solid line (The curves are shifted vertically for clarity).

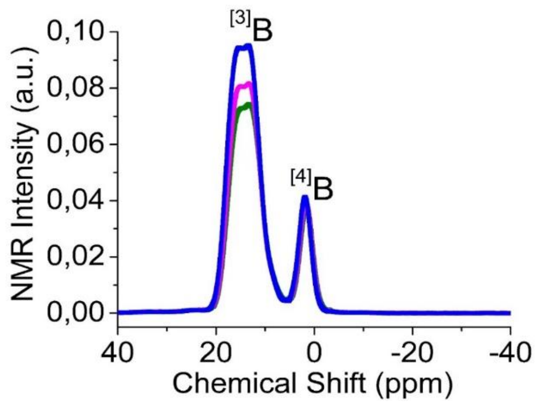
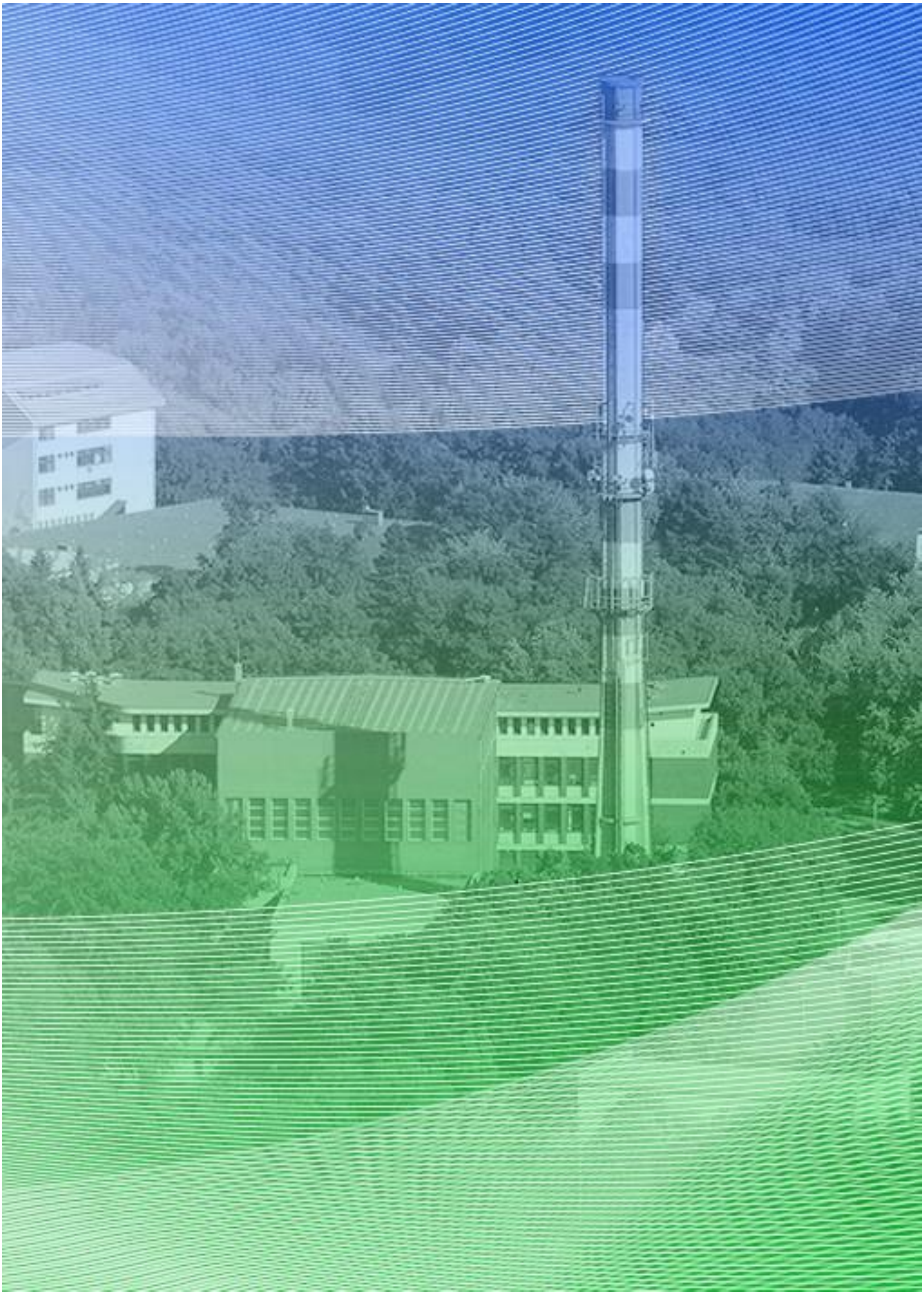


Figure 2. ^{11}B NMR spectra of boromolybdate glasses: $20MoO_3$-$30Nd_2O_3$-$50B_2O_3$ (green), $40MoO_3$-$30Nd_2O_3$-$30B_2O_3$ (magenta) and $50MoO_3$-$25Nd_2O_3$-$25B_2O_3$ (blue).



Front page images *(from the top):* 1. Bird's eye view of the Budapest Research Reactor complex. 2-3. The small bronze statue of Leonardo da Vinci from the Museum of Fine Arts, investigated by neutron spectroscopy. 4. The experimental hall of BRR. 5. BNC staff at the BRR control room.