1959
60
2019

BUDAPEST RESEARCH REACTOR

60 YEARS

OF RESEARCH & INNOVATION

1959
BUDAPEST
RESEARCH
REACTOR
2019

BUDAPEST RESEARCH REACTOR

60 YEARS
OF RESEARCH & INNOVATION

1959
- First criticality
- Education & training
- Nuclear "culture"

1960
- Nuclear fission research
- Neutron capture research

1963
- Isotope production

1965
- Neutron diffraction

1966
- Correlation n-spectroscopy
- Condensed matter research

1967
- First reconstruction

1968
- Neutron activation analysis

1969
- Neutron Spin Echo principle

1970
- Time-Of-Flight neutron spectroscopy

1973
- Triple axis spectrometry

1974
- Supermirror principle

1978
- (n,n'γ) spectrometer

1983
- Neutron and X-ray imaging

1984
- Small angle neutron scattering
- Gas turbine lifetime extension

1986
- Second reconstruction

1990
- Cold neutron guide hall - building

1992
- Biological irradiation rig
- BNC consortium

1994
- Industrial technology transfer

1995
- Prompt-gamma activation analysis
- Neutron induced γ-spectrometry PGAA

1996
- γ-spectroscopic data base
- Supermirror design and production

1999
- Direct condensation cold moderator

2000
- Cold neutron source in operation
- Cultural heritage research
- European TransNational Access

2002
- Neutron holography
- TOF frame multiplication principle
- Position sensitive ^{3}He detectors
- Radiography of helicopter blades

2004
- TOF guide hall - building
- Spent fuel repartiation 1
- NMI3 (TNA in all topics)

2005
- NAP VENEUS 05 (R&D)
- SANS of Formula 1 Ferrari engines
- European Spallation Source involvement

2006
- ANCIENT CHARM (Archeometry)

2007
- EFNUDAT (nuclear data)
- Combined element analysis & imaging

2008
- Spent fuel repartiation 2
- NAP VENEUS 08 (R&D)
- In-beam chemical catalysis

2009
- CHARISMA (Archeometry)
- Reflectometry & polarized neutrons

2010
- Polarizing supermirror optics

2011
- Core conversion to low enrichment

2012
- NMI3-II (TNA in all topics)
- ERINDA (nuclear data)
- CERIC-ERIC (materials & multi-analytics)
- Archeometry - Egyptian iron beads

2015
- ESS in-kind contribution
- IPERION CH (Archeometry)
- CHANDA (nuclear data)
- BrightnESS (infrastructure development)
- SINE2020 (implementation & sevice)

2017
- Archeometry - Budapest Horse & Rider

Reactor facility · *Scientific excellence* · *International cooperation* · *Research infrastructure* · *Innovation* · *Social impact*

Budapest Research Reactor -
60 Years of Research & Innovation

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Introduction

The Budapest Research Reactor (BRR) turned 60 – it went critical for the first time on March 25, 1959, a golden milestone in the development of science and technology in Hungary. Since then BRR has remained the largest operating Research Infrastructure in the Central-European region. 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) science, health physics as well as in nuclear chemistry, radiation protection. It has even enabled Hungary to start the design and production new nuclear equipment and to venture into isotope production. Besides basic research, innovation and technology transfer as well as commercial applications have been in the focus of BRR activities.

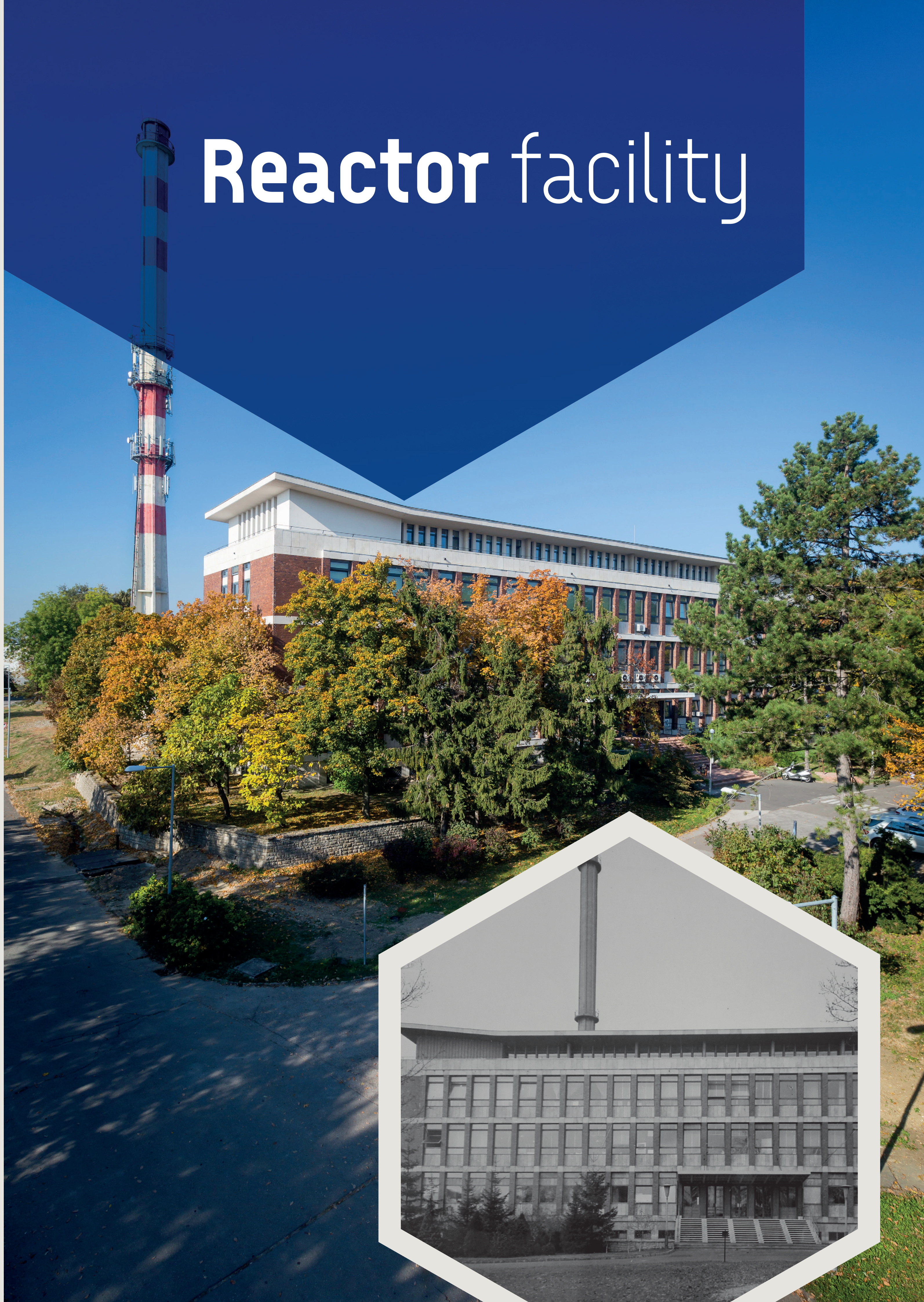
In 1993, following the general reconstruction (1986-92), the reactor started operation with a 30 years' licence in its present form - 10 MW power, cold source and guide system and 16 experimental stations. At the same time a consortium, named the Budapest Neutron Centre (BNC), was founded by four academic institutes to coordinate the reactor utilization to ensure scientific excellence and management of the utilization strategy, providing access to the international neutron-user community through a peer-reviewed proposal system as advised by an international Scientific Council. In this way neutron research has become the major scope of the reactor utilization. BNC is a member of the European network of neutron centres, and a partner in EU Framework Programme projects. It is strongly committed to train future scientific professionals. In cooperation with Hungarian universities, it accommodates students for laboratory practice in studying techniques related to nuclear science and technology. To train the young scientists and attract new users, BNC regularly organizes the Central European Training School on Neutron Techniques.

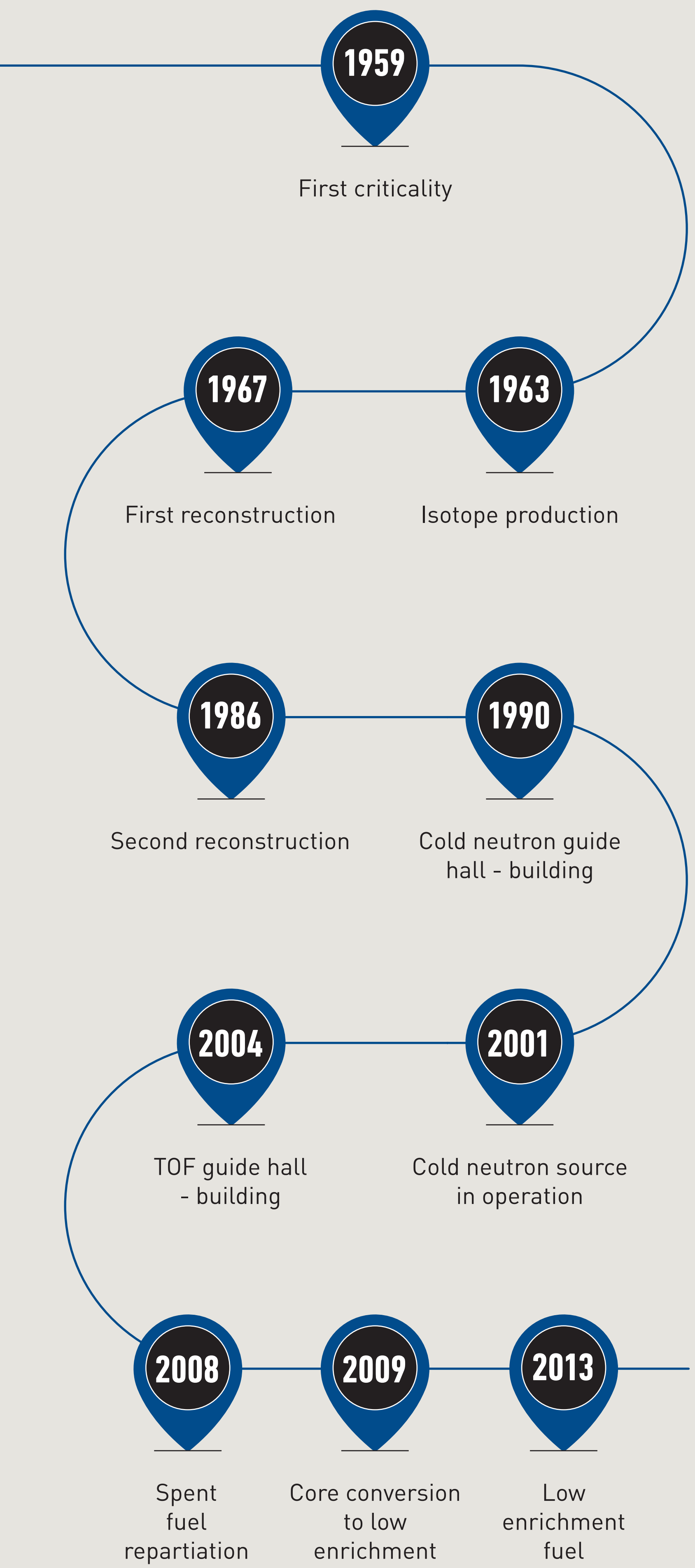
BRR, with its facilities and the perspective to be operational in the next decade, has become an important component of the European network of neutron source facilities. This is underlined by the fact that there is a decision shut down several research reactors in Europe. Thanks to this home based facility, the Hungarian neutron/reactor user community of nearly 200 researchers (some 50 "professionals" and 150 "users") is the second largest in Europe per capita (after the Swiss community). The nuclear research infrastructure and especially the neutron landscape in Europe is about to drastically change in the decade to come. New and powerful large scale facilities are intended to fulfil the needs for neutron research of the entire continent (namely the European Spallation Source), studying properties of irradiated materials (Jules Horovitz Reactor, Cadarache, France) and producing radioisotopes (High Flux Reactor, Petten, the Netherlands). The BRR is one of the few medium size facilities likely to remain operational for a decade or so – a 10 year's prolongation of the license is being prepared. The activity of BRR is crucially important in the transition period, thus the BNC is ready to offer improved services to the international user community to prepare themselves for the future use of leading edge European facilities as well as to establish the indispensable experimental base of a next generation of domestic neutron research facility.

Dr. Ákos Horváth
director general

BUDAPEST RESEARCH REACTOR

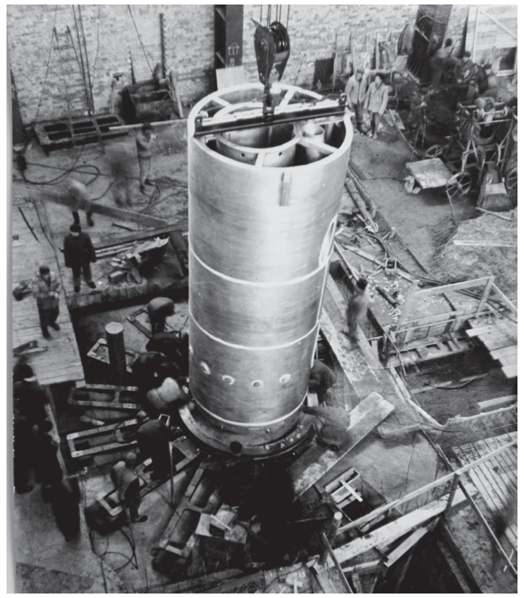
Reactor facility

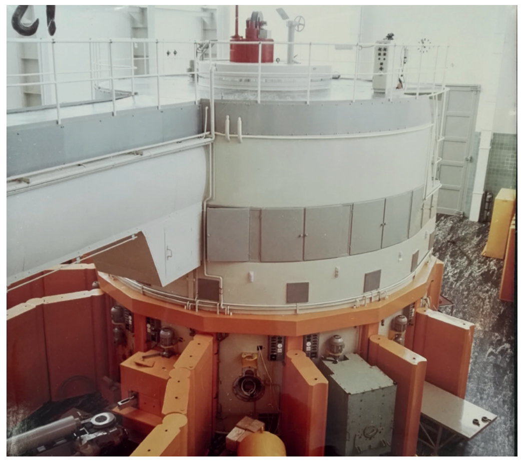




The Budapest Research Reactor was the first nuclear facility in Hungary. The construction of the reactor started in summer 1957 and was completed in 1959. The reactor is a standard VVR-S tank type reactor, with light water moderation and cooling designed and constructed by Soviet companies. The reactor went critical for the first time on 25 March, 1959. Using EK-10 (10% enriched ^{235}U) fuel the reactor power was originally 2 MW. The reactor is placed in a cylindrical reactor tank, made of a special aluminium alloy. The tank's diameter and height are 2300 and 5685 mm, respectively. The heavy concrete reactor block is situated in a rectangular semi-hermetically sealed reactor hall.

The BRR, since its initial criticality, has been utilized as a neutron source for research and industrial applications in nuclear and material science as well as for education and training in nuclear technology.





In 1967, after 8 years of operation the reactor power was increased from 2 MW to 5 MW with a change of fuel type from EK-10 to VVR-SM. The core was also modified by the installation of a solid beryllium reflector surrounding the core. After this first upgrade the reactor remained in operation until 1986 when it was a shut down for a second upgrade.

Such research reactors can produce radioactive isotopes in a traditional way for industrial use and for medical applications (cancer diagnosis and therapy). The isotopes are produced by irradiation of the most suitable target materials, using the (n,γ) and (n,p) nuclear reactions. The BRR has 40 vertical channels, which are potentially usable for isotope production. Isotope production in the BRR started in the 1960s, producing ^{32}P, ^{35}S, ^{90}Y, ^{99}Mo, ^{125}I, ^{131}I, ^{153}Sm, ^{166}Ho and ^{188}W isotopes. Among those the ^{99}Mo is of highest importance, because 80% of the routine diagnostic examinations are performed using ^{99m}Tc, a daughter of the ^{99}Mo parent nucleus. ^{126}I, ^{131}I and ^{166}Ho are also commonly used in nuclear medication.

The first studies demanding a reactor upgrade are dated as early as 1974. These studies enumerated the demands from the points of view of fundamental and applied research, education and training, as well as of industrial applications. The reactor reconstruction plan took into account the new trends in nuclear research, the modern reactor safety requirements (according to the IAEA's recommendations), and the available options concerning fuel issues, core configuration, operation and maintenance. The reconstruction started in May 1986 and all parts of the reactor were replaced except the civil engineering construction. Although technically the upgrade was completed by the end of 1990, due to the political changes in the country and other non-technical conditions, the upgraded 10 MW reactor received the license for operation only in November, 1993. The main parameters of the renewed reactor are: neutron flux: 2.5x10^{14} n/cm^{2}s (thermal in the flux trap), 1x10^{14} n/cm^{2}s (approx. max. fast flux in the fast channel), core: 227 fuel assemblies (36% ^{235}U), Be-reflector (~20 cm); operation: 3500 hours per year, typically fifteen 10 days reactor cycles.

While waiting for the reactor's operation license three research institutes of the Hungarian Academy of Sciences founded a consortium, the Budapest Neutron Centre (BNC) to coordinate utilization of BRR. BNC started to build and operate neutron instruments around the reactor and manage user operation. It became obvious that the BNC could effectively represent the user interests, while the reactor management needed to focus on the safe reactor operation. Thus, a decision was made to separate the reactor operation from reactor utilization.

For neutron beam measurements, different types of horizontal channels are available: six radial thermal, two fast neutron channels and two tangential beam tubes. To substantially enhance the research capacity of the reactor, development and installation of a cold neutron source (CNS) was decided. Although the CNS installation was an important part of the upgrade program in 1986-92, it could not have been implemented due to drastic changes in the safety regulations. Instead, the reactor core, tank and the proper horizontal beam tube (channel No. 10, one of the tangential tubes) were prepared to later accommodate the CNS. A 15x27 m^2 guide hall extending from the reactor hall, housing three neutron guides was also constructed. In the period 1993-2000, as a temporary solution, the guide system and 5 instruments in the guide hall were operated with thermal neutrons. The installation of the cold neutron source and the pile-out-test were performed during 1998-2000. Following the CNS installation the old neutron guides were replaced by a new supermirror guide systems. Since then the cold neutron source has been routinely operated.

In 2002, a project, named the Russian Research Reactor Fuel Return Programme (RRRFRP) was launched and coordinated by the US Department of Energy. In the framework of this programme the spent nuclear fuel (SNF) containing highly enriched uranium (HEU) was to repatriate to the Russian Federation from various research reactors in Eastern Europe and Asia. BRR joined this program in 2005. One part of the project was the site preparation for the transfer of HEU spent fuel, the other part was to prepare for core conversion. For choosing the new type of low enrichment (<20% ^{235}U) enrichment fuel, the criteria were that the geometric and thermo-hydraulic parameters of the new fuel should be identical and its nuclear features should be similar to the previously used fuel. The Russian type VVR-M2 type fuel satisfied these demands.

Core conversion took place in 2009-2012 with a mixture of HEU and LEU fuels, by gradually decreasing the number of HEU fuel assemblies. Since 2013, the reactor has been fully fuelled with low enrichment (under 20%) fuel assemblies.

The IAEA was one of the parties participating in the arrangements for the HEU fuel removal from Hungary, and provided advice on safety and security for the shipment. In addition, the casks (VPVR/M) used for storage and shipping the spent fuel assemblies were procured by the IAEA in 2006, with financial support from the U.S. Department of Energy.

The first shipment - of all fuel assemblies irradiated before 2005 - was successfully carried out in September 2008.154.5 kg of HEU SNF was loaded in 16 VPVR/M Skoda casks and transferred to Russia via road, rail and sea. This was the biggest SNF transfer in the frame of the RRRFRP programme.

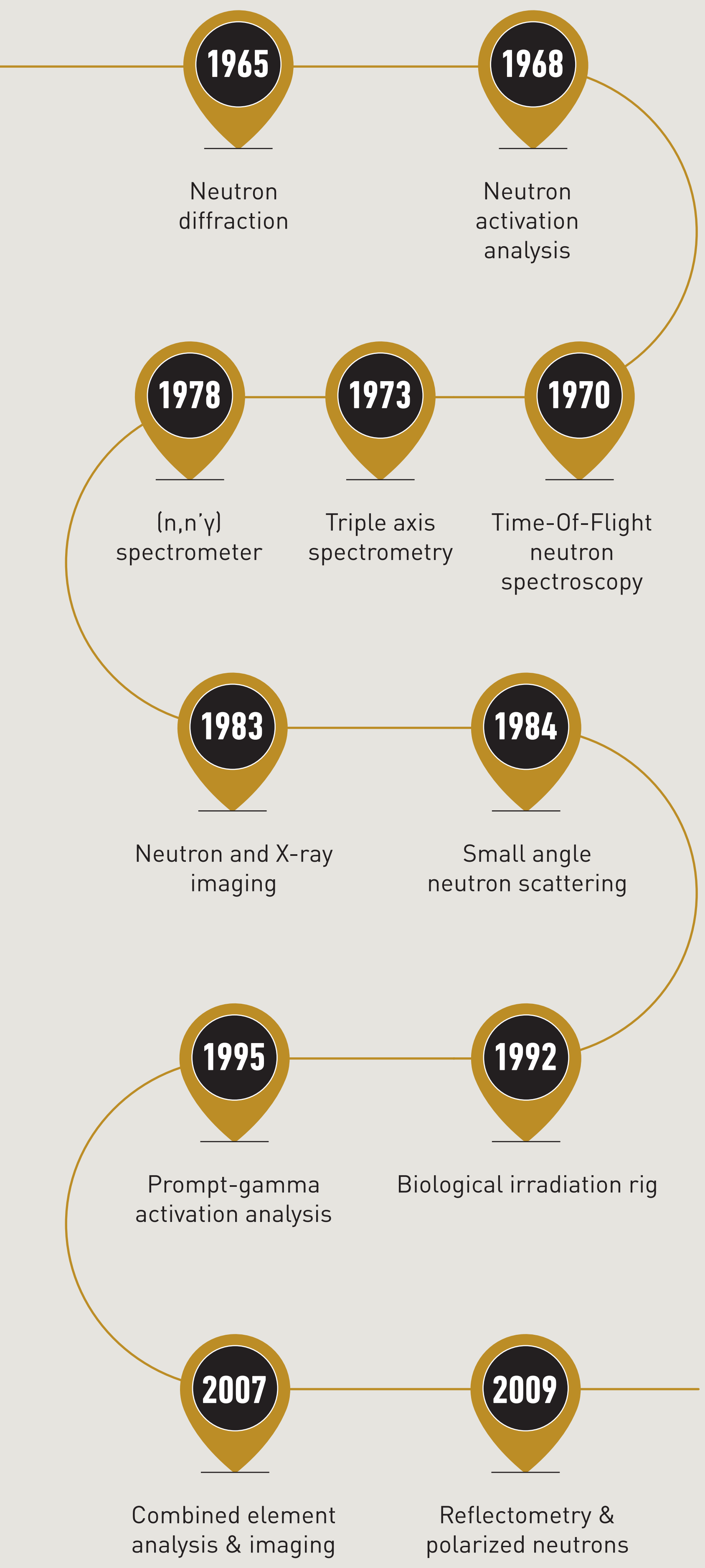
The second transportation in 2013 contained the HEU fuel assemblies used during the core conversion. The spent fuel assemblies were placed into six Skoda VPVR/M casks and each Skoda cask was put in a TUK-145/C titanium transport package at the BRR site. They were then transported via public road to the Budapest International Airport where they were loaded in an Antonov-124 cargo plane to be transported to Russia. The 49.2 kilograms of HEU spent fuel was transported by three air-shipment operations.

Loading the casks with spent fuel

The first transportation by road, railway and sea

Air-shipment

Research infrastructure



From the time of its construction in the 1950s, the Budapest Research Reactor has been an important melting pot of basic and applied research. On the one hand, the reactor operation and the quest to understand details of the nuclear chain reaction addressed crucial theoretical problems, like neutron fluctuations and random processes in general, which initiated the search for theoretical and technical solutions. Theory and practice developed hand in hand. Examples range from e.g how the Pál-Bell equation established the practice of the safe start-up of the reactor, or how, over the decades, the discovery of the neutron supermirror principle was introduced in the design of almost every neutron laboratory in the world. The numerical and computational procedures necessary to describe random neutron dynamics proliferated in various, even distant fields of natural sciences. The need for massive computations in science made the research campus of the Budapest Research Reactor the first production site of programmable nuclear analyzers and soon after, of digital computers in Hungary.

On the other hand, early applications of the neutron beams for irradiation, structural investigations, analysis and imaging triggered important practical developments, which, by now, have developed into the Budapest Neutron Centre, a large-scale research facility of neutron instruments and service laboratories. It is the leading research infrastructure in Hungary and one of the largest in Central-Europe. BNC now operates 16 instruments, which have already utilized neutron beams in studies of crystals, amorphous materials, nano- and mesoscopic structures and their irregularities, defects, segregations, internal strain, radiation damage, magnetics, soft matter structures, such as gels, foams, surfactants, colloids and emulsions, multilayers and other heterostructures, layering and transparency of biological and bio-inspired membranes, nuclear structure, elementary excitations, phonons and magnons, atomic diffusion on different time scales, adsorption, structural and temporal correlations, elemental analysis with negligible matrix effects, occasionally combined with imaging of complicated and precious objects to apply the results in material science, functional and energy materials' research, in cases under *in-situ* or *in-operando* conditions.

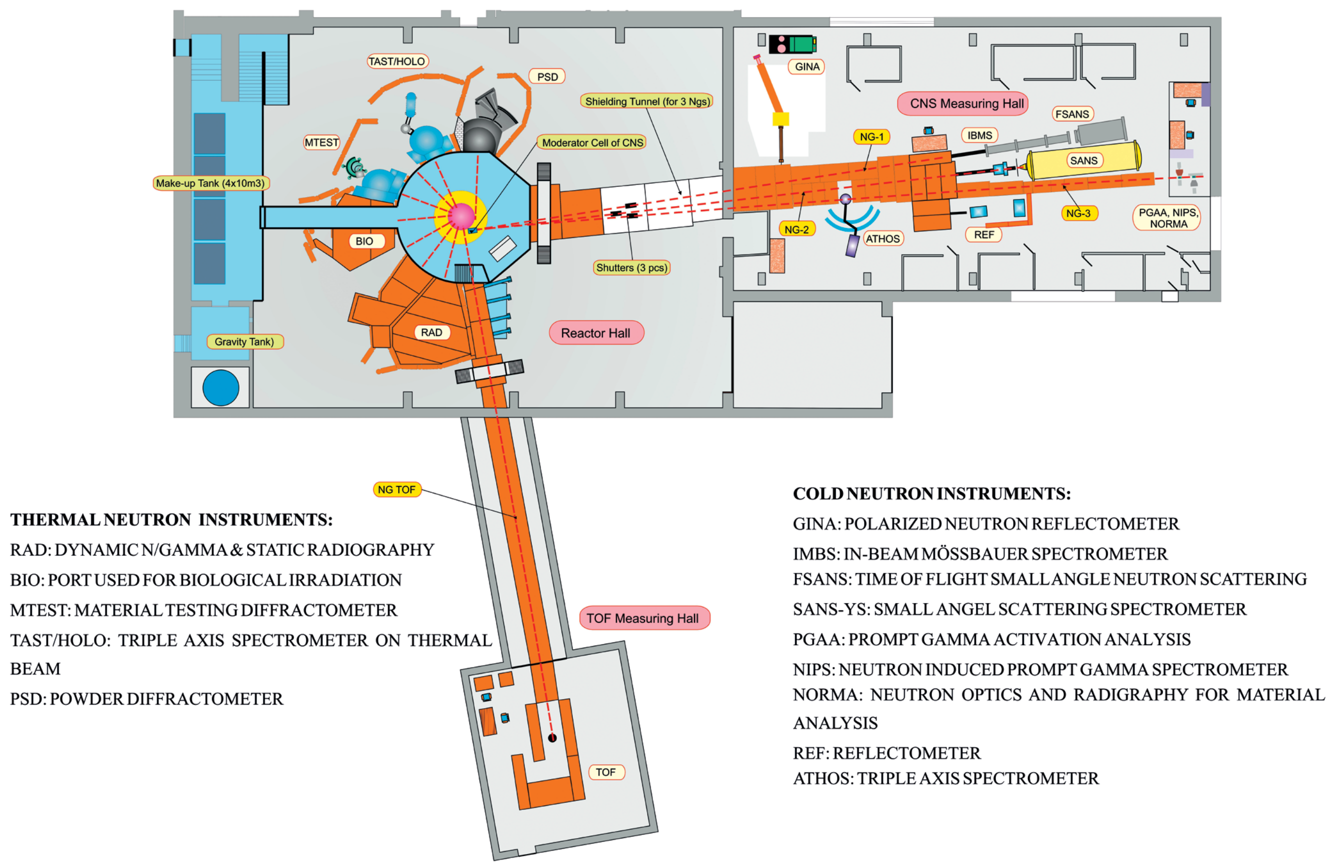


Figure 1: the layout of the Budapest Neutron Centre

Presently fourteen beam instruments and two reactor tank irradiation sites are operational at the Budapest Neutron Centre to explore the unique wave and particle, scattering and absorption, as well as nuclear and magnetic characteristics of neutron beams in tracing the structure and composition of materials on a very wide range of length scales and their process dynamics on a similarly wide range of time scales. Details about the instruments can be found on the BNC web pages at www.bnc.hu. Their locations in the BNC experimental halls are illustrated in Figure 1.

The relevant length and time scales of various neutron techniques and instruments are illustrated in Figure 2 (Picture by: Karin Griewatsch, Kiel University, KFN).

Most instruments at BNC have been built by local scientists and engineers. As compared to research centers of large countries, the handicap of insufficient financial support for instrument construction often led to considerably longer construction times, but – admittedly, in several cases – also resulted in discoveries of novel and, in some cases, even patented solutions by the local scientists and engineers.

For instance, the SANS-YS instrument utilizes a novel multidisc velocity selector design and multi-beam focusing, both solutions being unique in the world at the time of construction.

The otherwise regular, medium-resolution thermal beam triple-axis spectrometer, TAST, gained special importance when tweaked to accommodate the proof-of-principle experiment of neutron holography, discovered and applied for the first time by BNC scientists.

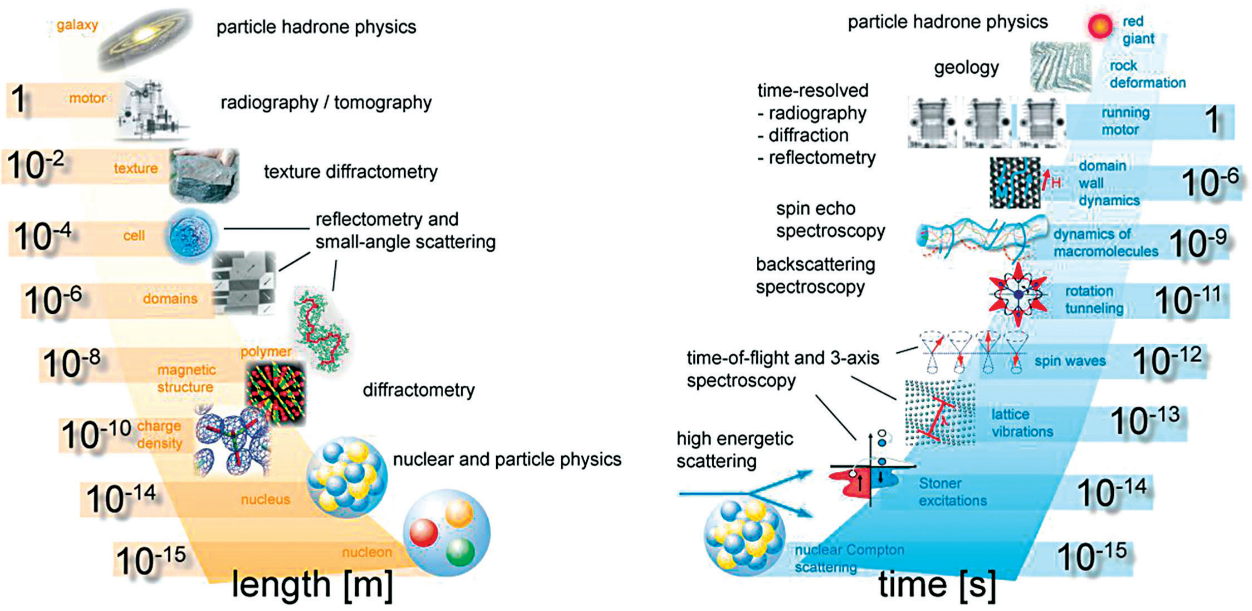
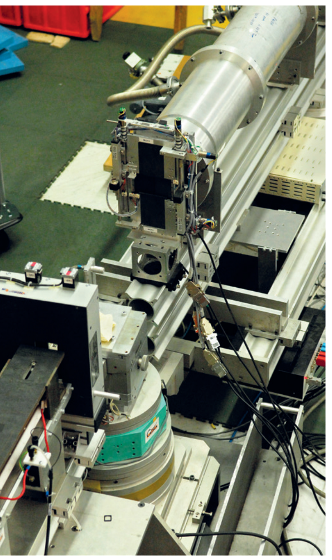


Figure 2: the relevant dimensions and time scale of neutron techniques

At construction time TOF-ND was the first and the only high-resolution (back-scattering) neutron diffractometer in the world making use of the frame multiplication principle and the list mode data acquisition approach, the latter having made use of the synergy with particle physicists and engineers on the KFKI science campus.

TOF-ND

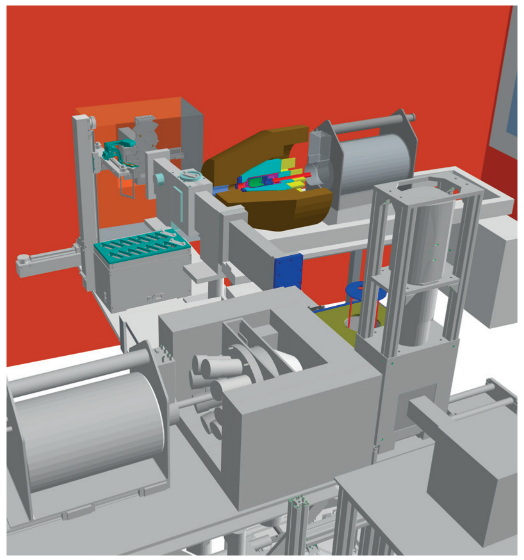


GINA

GINA, the polarized cold beam neutron reflectometer at BNC, which uses some major components of a previous instrument – generously given over to BNC by collaborators at MPI for Metals Research, Stuttgart – was installed with novel adiabatic spin flippers and a unique four-bounce neutron polarizer of exceptional efficiency and transmission.

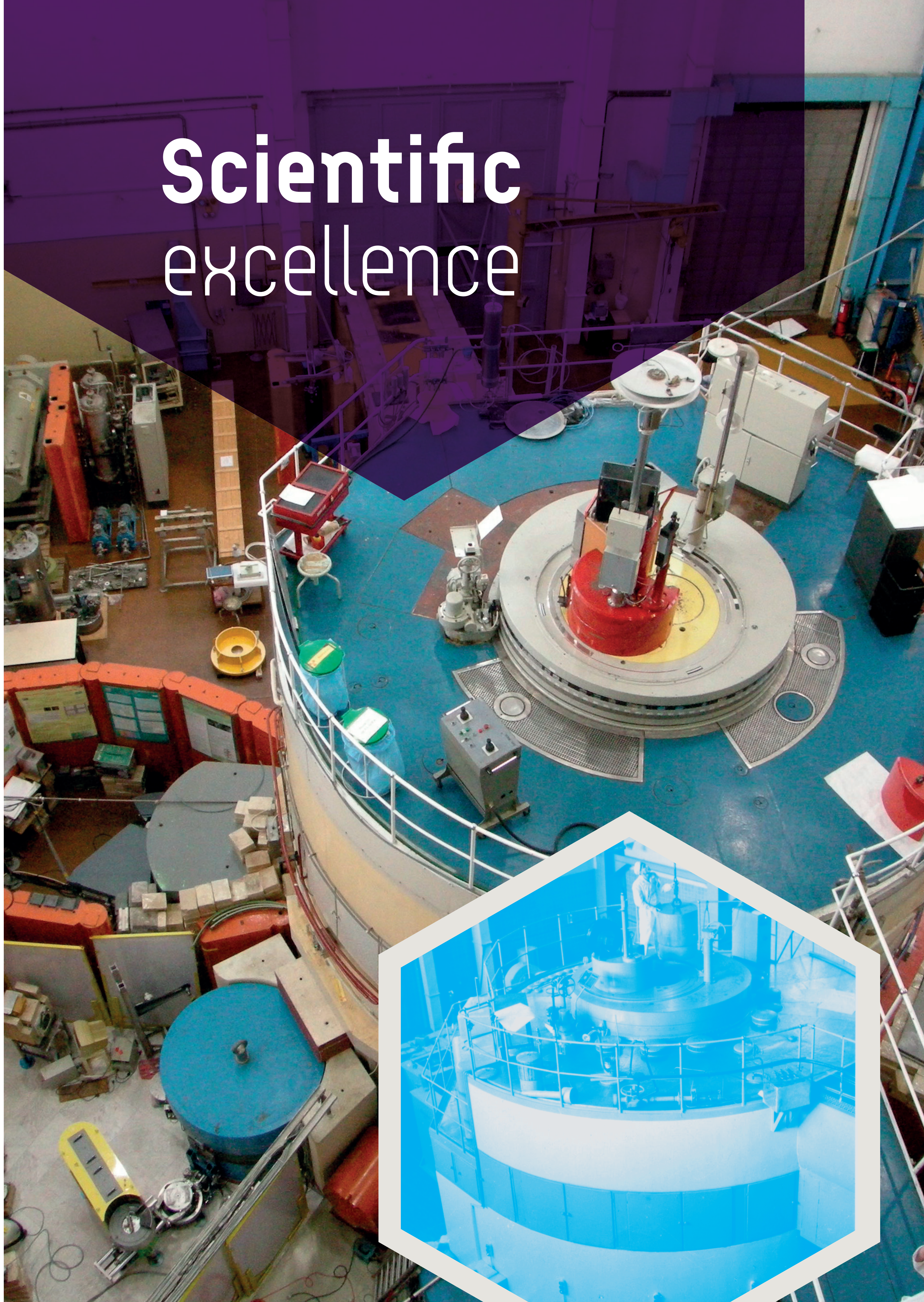
The PGAA system was the best in the world in its class for two decades in terms of background conditions and spectrum quality.

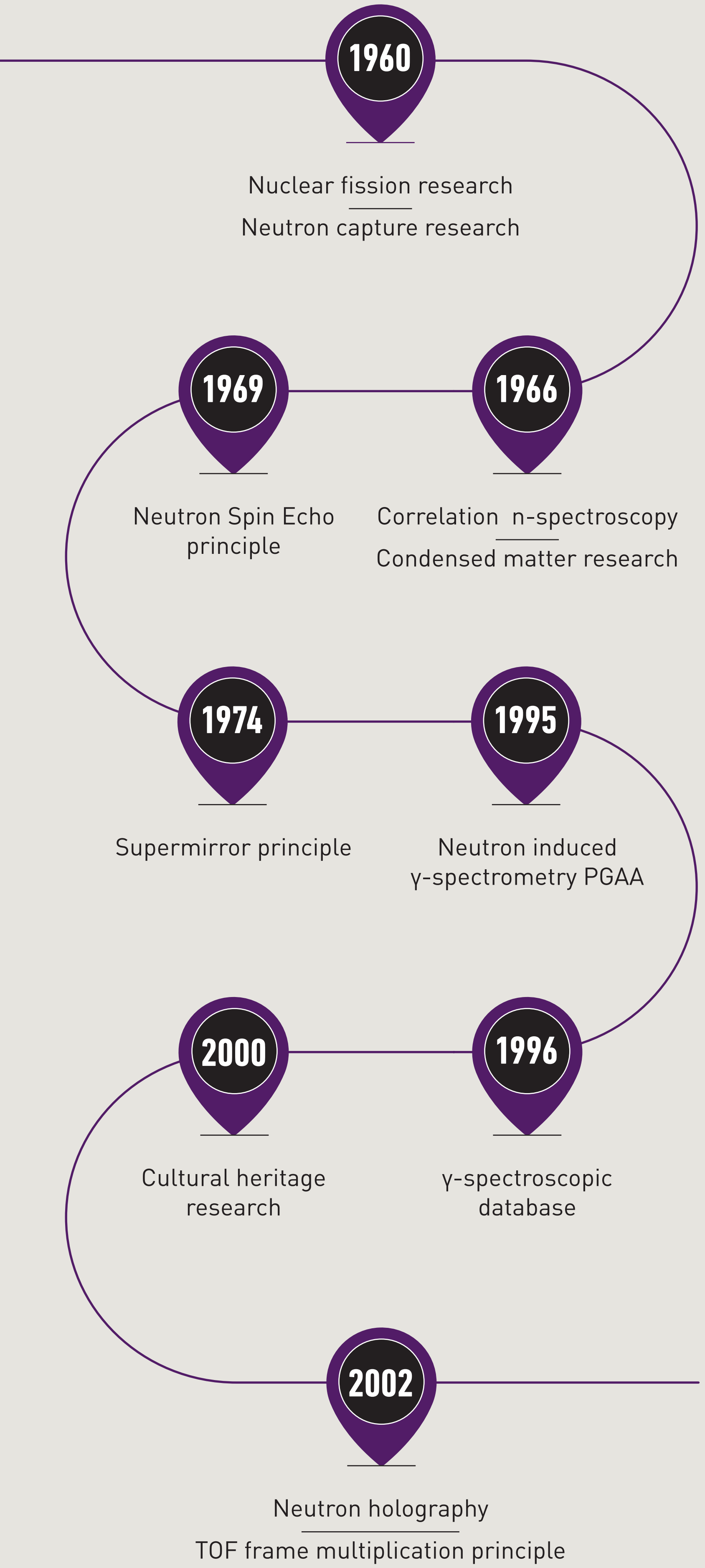
NIPS-NORMA was the first ever permanent facility to combine position-sensitive element analysis and imaging into a single instrument, in order to expand the scope of prompt-gamma activation analysis applied to non-homogeneous samples. This idea found a multitude of successful applications in material science and cultural heritage research.



PGAA-NIPS

Scientific excellence





Solid state Physics

Neutrons are particularly suited for condensed matter research at the atomic level, revealing where the atoms are and how the atoms move in a structure. Neutron scattering experiments used for the investigation of static or dynamic structure of materials suffers from the problem of low beam intensity, resulting in long measurement times. Thus, the selection of the proper resolution versus intensity is a crucial issue both in designing an instrument and planning a measurement.

Less than a decade from first criticality of the Budapest Research Reactor, groundbreaking results (published in 1966) emerged from neutron diffractometry of magnetic structures, revealing the antiferromagnetic-antiferromagnetic phase transition in Mn-Pt alloys.

BRR researchers also played an important role in the development of so-called quasi-statistical or correlation spectroscopy. The technique relies on the modulation of the neutron beam with a quasi-statistical chopper sequence. Neutrons moving with the same speed hold the time structure, while neutrons with different speeds arrive at different times to the detector. The original (or the scattered) spectrum - intensity *vs* speed - can be reconstructed by evaluating the correlation between the measured time-dependent intensity and the original quasi-statistical sequence. L. Pál et. al. used magnetic modulation of the neutron beam for the pioneering demonstration measurements in the 1960's. Later, both the description and the technique of the correlation spectroscopy were improved at BRR by László Cser and others. Presently the CORELLI spectrometer at SNS in Oak Ridge, USA uses the correlation method to distinguish between the signals coming from the static and from the dynamic structure.

An important milestone in quasielastic neutron spectroscopy was the 1972 invention of the neutron spin echo spectroscopy by Ferenc Mezei, the first awardee of the Walter Haelg Prize (1999). This technique allows direct measurement of the density-density correlation with respect to momentum transfer and time, providing an immense improvement of the achievable energy resolution. The technique is especially suited for studies of slow relaxation processes, typical for the dynamics of macromolecules.

The atomic resolution neutron holography has been proposed by László Cser based on the idea that stability of the sample-detector position within inter-atomic distance range can be achieved by using atoms of the sample in the role of either source (incoherent scattering by e.g. hydrogen) or detector (high neutron adsorption cross section) atoms. L. Cser's team conducted the first successful experiment proving the feasibility of the internal detector concept. Further results of the team showed that atomic resolution neutron holography is a suitable and unique method to directly measure the local lattice distortions with sub-picometer accuracy. At present, a dedicated neutron holographic instrument operates at the BNC (below).

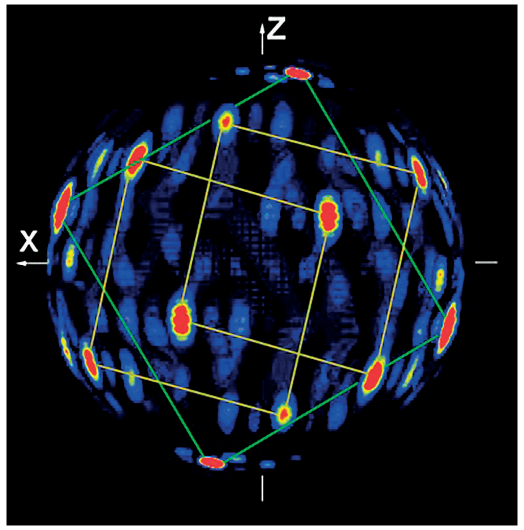


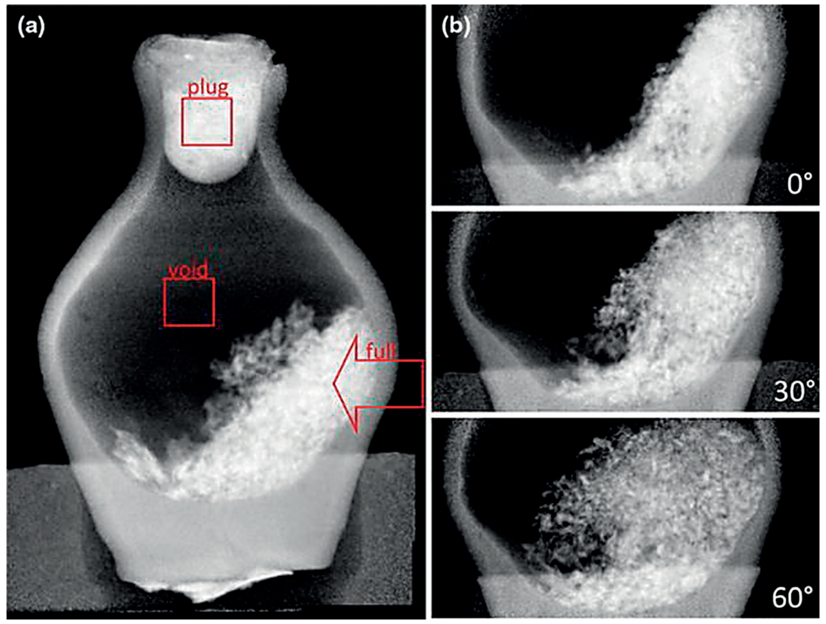
Figure 1.
Neutron holographic picture (selected as Cover page of Physical Review Letters, PRL) of a Pb(Cd) crystal. The spots represent the positions of the twelve nearest neighbor Pb atoms of the internal detector Cd nucleus, displayed on the surface of a sphere of 3.5 Å radius.

Nuclear physics

Nuclear reactions initiated by thermal neutrons was the research field of the team led by Prof. D. Kiss who studied radiative neutron capture reactions as early as in the 1960s, by observing the gamma-ray angular distributions and prompt neutron energy spectra emitted in neutron-induced fission of ^{235}U and ^{239}Pu.

Inelastic neutron-scattering-induced gamma-ray spectroscopy was invented and experimentally established by G.L. Molnár and coworkers using a fast neutron channel of the BRR in 1978. The group has discovered the shape coexistence caused by intruder states in Mo isotopes.

With the advent of the cold neutron source installed during the refurbishment of BRR, a new topic, the Prompt Gamma Activation Analysis (PGAA) emerged in 1995, by G.L. Molnár and coworkers set down the basics of an analytical method based on the radiative neutron capture reaction. Measurements on stoichiometric chemical compounds of all elements were carried out to build a complete spectroscopic data library for elemental/isotope analysis of materials. The results were



Dried herbs inside an Egyptian sealed pottery. Red symbols show the positions where element analysis was performed.

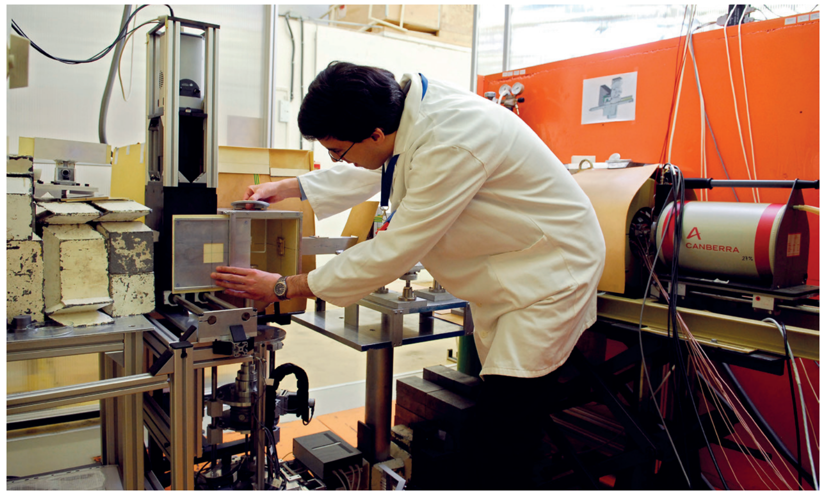
published in the Handbook of PGAA in 2004 and the Database for Prompt Gamma-ray Neutron Activation Analysis was made available on the web site of the IAEA's Nuclear Data Section.

In 2004, two-step cascade experiments were carried out on an iron sample which revealed low energy enhancement of the gamma-strength function. The results were published in Physics Review Letters, which initiated dozens of experiments positively proving the foreseen low-energy enhancement.

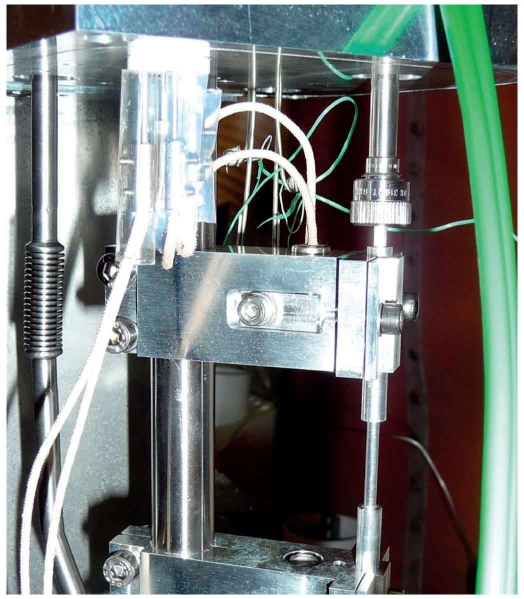
The nondestructive nature of the PGAA method suits very well to Cultural Heritage (CH) research. The method was first applied by Zs. Kasztovszky (BNC) in 2000 and later it was complemented by the n-TOF and neutron radiography/ neutron tomography (NR/NT) techniques to reveal undecomplex structure of CH objects.

An Eighteenth Dynasty Egyptian sealed pottery, stored at the Museum of Aquitaine (Bordeaux, France), has been investigated using neutron-, terahertz- (THz) and X-ray imaging. Neutron tomography affirmed the method used to seal the jar, as well as determined the finer structure of the inner content without opening it. Position-sensitive prompt gamma activation analysis was finally applied to measure the elemental composition of the content, which is supposed to consist of dried germinated seeds.

A series of in-beam PGAA measurements were performed on a Pd catalyst in a carefully designed chemical reactor to measure the hydrogen content of the catalyst - *in operando*. This experiment revealed the role of hydrogen species in palladium-catalyzed alkyne hydrogenation. The results were published in Science, the flagship journal of natural sciences. The continuation of these in-beam experiments led to the development of cheap and effective catalyst materials to replace the expensive Pd. Later, the studied catalytic Deacon reaction was considered as an environmental friendly and energy-efficient alternative to NaCl electrolysis. The results of the studies were published in Nature Chemistry, Nature Materials and other prestigious journals.

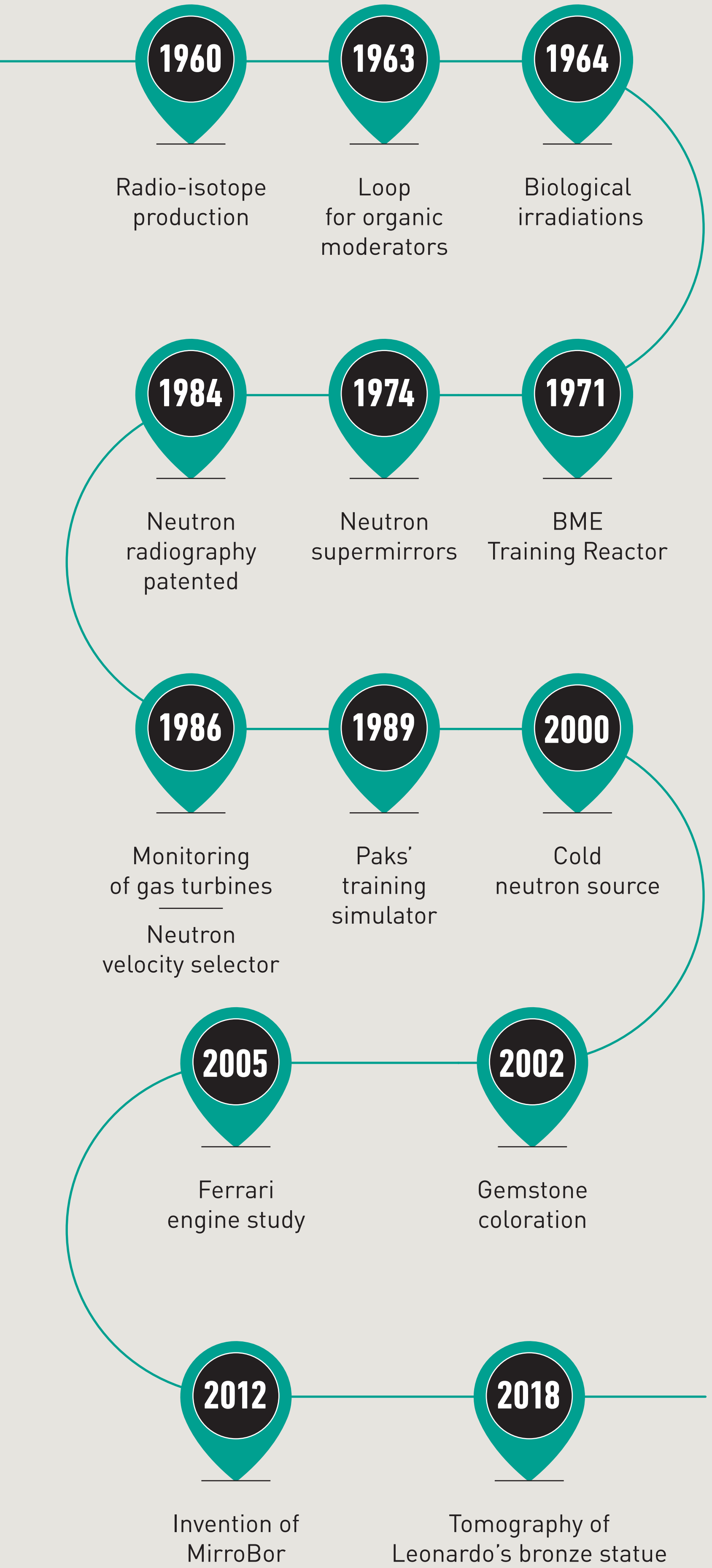


The NIPS-NORMA facility



Chemical flow reactor tube placed in the neutron beam of the PGAA station

Innovation



By vitue of the physical nature of the neutrons, neutron science is interdisciplinary. As a consequence, the Budapest Research Reactor has always been a welcoming environment for applications, innovation and technology transfer. As will be shown below, the reactor utilization has been profitable. On the one hand, application of the reactor itself – irradiation facilities and neutron beam techniques – supplying products and services to various sectors of the society, industry, healthcare, commerce, and education made a significant direct economic impact. On the other hand, development of scientific methods and tools for the nuclear/neutron research sector have produced an indirect economic impact. Milestones of applications are enumerated below in a chronological order. Isotope production as well as technical support for the nuclear energy sector have made significant contributions to the multi-billion HUF economy. The commercial value of the BRR neutron equipment suite can also be estimated: The 16 instruments + cold source were installed at a cost of 20 M€ (including all labour and equipment) while their commercial value is about 42 M€. Technology transfer and production of neutron instrumentation by the spin-off SMEs resulted in an export commercial income of about 45 M€ during the past 20 years (for comparison, the current yearly operation cost of the reactor is 2.4 M€, including the fuel-cycle).

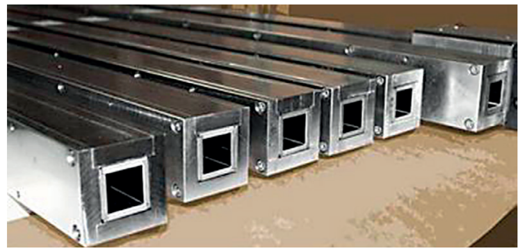
Innovation

Materials exposed to neutron irradiation may convert into other elements or radioactive isotopes. Some of these radioactive products are used for diagnostics and therapy. The radio-isotope production at the BRR started as early as 1960. Thanks to the advanced technologies introduced, the quality of the products from BRR surpassed that of the products imported from the Soviet Union or UK at that time. By the nineties the isotope supply by BRR for healthcare reached about half a million patients, 5% of the Hungarian population.

The Training Reactor of the Budapest University of Technology (the basic facility for education in domestic nuclear engineering) was commissioned in 1971 with major design and development contributions from the teams at BRR and KFKI.

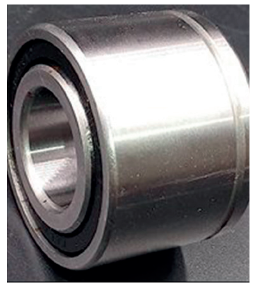
The neutron supermirror (SM) principle was invented by Ferenc Mezei in 1974. The high tech thin-film technology enabling large scale production of SMs has become available in 1995. Since that time SMs used as neutron guides and polarising optical components have become integral parts of neutron research facilities worldwide. MIRROTRON Ltd, a spin-off company was essentially founded for SM production by physicists and engineers around BRR. Mirrotron's share today of this multi-million-euro world market is about 25%. Thanks to the SM story Ferenc Mezei and MIRROTRON Ltd. received the "Innovation-Award" – the highest prestige award of its kind in Hungary – on 28 March 2019.

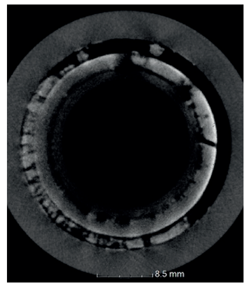
The first applications of neutrons for radiography dates back to 1983. Non-destructive testing of bulky objects by neutron transmission has now become a widely used industrial method for technology development and quality assurance. BRR scientists have played a pioneering role in advancing this neutron beam technique. The principle and instrumentation of the so-called "Dynamic neutron radiography" was patented in 1984 (Pt.190322, Balaskó M, Sváb E, Cser L). Thanks to the continued development, the BRR imaging facilities – neutron and X-ray radiography/tomography, sometimes combined with elemental analysis by prompt-gamma activation analysis and supported

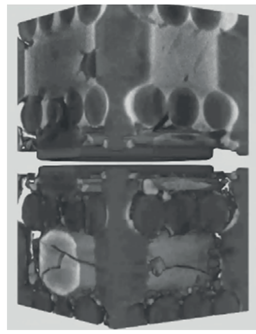


"Metal-glass sandwich" type neutron guides (patented) – highly demanded at spallation neutron sources in Japan, UK and USA and the ESS.

by advanced visualisation techniques – are considered amongst the best in the world. In a recent experiment (2018) of failure analysis – the cracking features of the internal part of bearings (used in a top-class vehicle) was visualized.

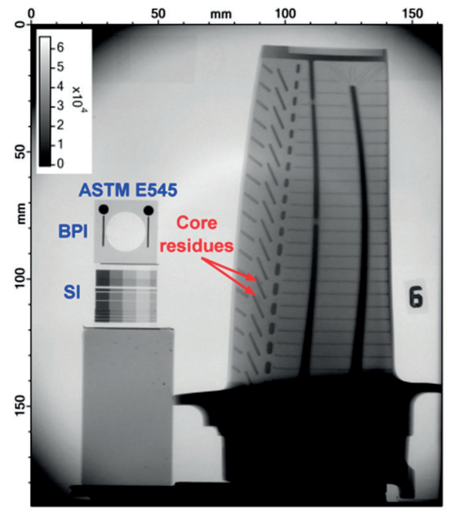




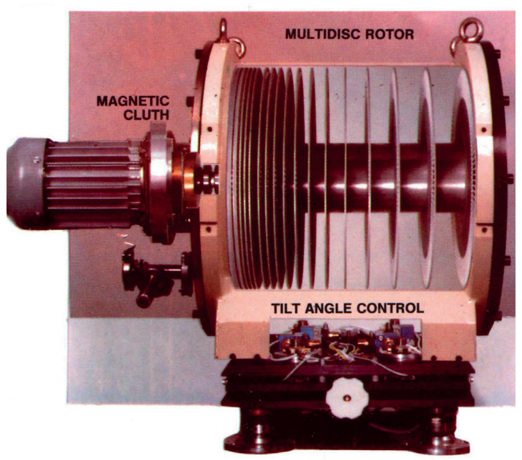


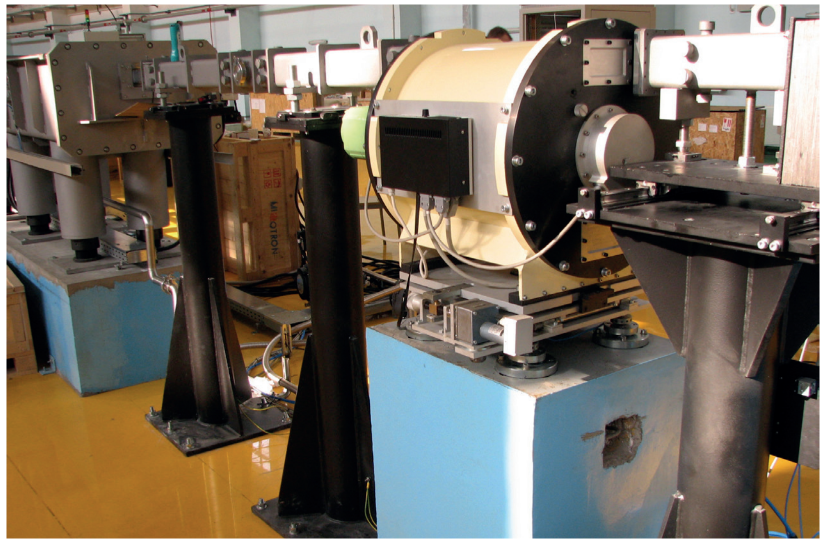
Photos and neutron tomograms of unused and failed bearings

In 1986 the non-destructive inspection of expensive super-alloy blades of heavy-duty gas-turbines in an emergency power plant was required for their life-time extension. As an innovative approach, a combination of neutron radiography and small-angle scattering measurements revealed the precipitate formation, which is a fatigue mechanism of the blades. Later a similar SANS experiments were performed on a General Electric produced gas-turbine wheel to compare the results with strain simulations.



Neutron radiography reveals the core residues in the cooling channels of a gas-turbine blade.





The actual commercial value of a selector is about 200 k€.

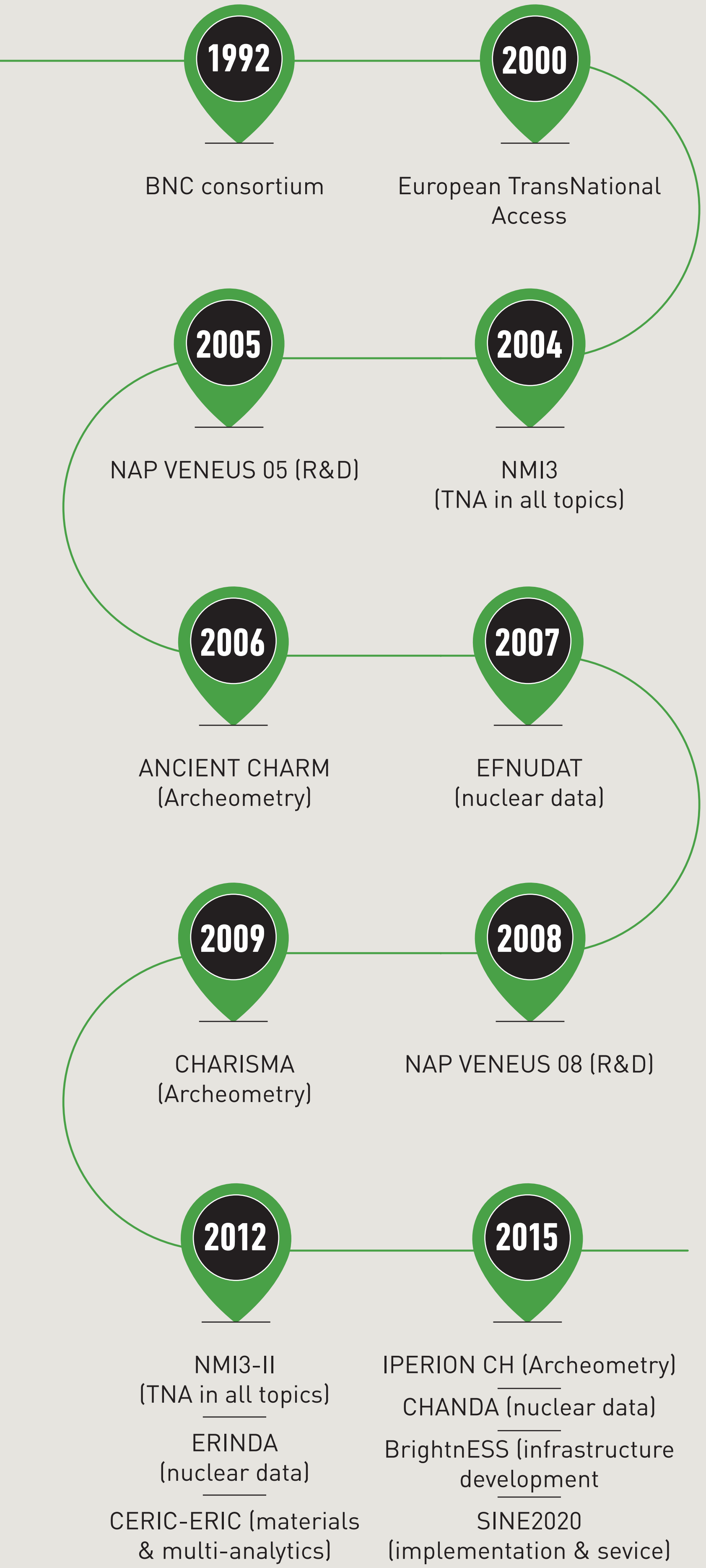
In 1986 a mechanical velocity selector was engineered on the basis of the so-called multi-blade principle. Such a selector is in use e.g. at the BRR Yellow Submarine small angle scattering (SANS) machine, since 1993. The selector was patented, and the team received a Jánossy-Award in 1987. The selector, its high-tech mechanical rotor, as well as its control electronics, has been developed into a commercial product. Many of such devices have been produced and installed in neutron laboratories all over the world. For example, 3 selectors were purchased by National Institute of Standards and Technology (Washington, USA) for the SANS machines financed by the Exxon oil company, to perform a series of secret SANS tests to explore the shale oil resources in the USA and develop the extraction technologies. It is a typical success story of technology transfer. Now such selectors are produced by MIRROTRON Ltd., while BRR is also a beneficiary of each sale.

A special application of fast neutron irradiation in the reactor is the production of jewellery-quality gemstones – an activity far from being of high relevance in science, but it is one of the most profitable commercial activities of the BRR. This activity is continuous since 2002. 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 one houndred. The colouring technology has been developed at BRR and many tens of tons of topaz crystals were irradiated in the past 15 years, providing a significant income for the Reactor.

A new material for neutron radiation protection was invented in 2012. A highly-efficient, boron-containing flexible plastic neutron shielding material has been developed, which turned out to be far better than any competing material on the market. Thanks to the technology transfer, MIRROTRON Ltd. has developed this material into a commercial product (protected under the brandname MirroBor), which, by now, has become the best seller of the world market in its category.

MirroBor is used as a reference neutron shielding material in several leading nuclear centres.

International cooperation



The international collaborations have always been the pledge of success of the activities around the research reactor.

In the early times, during construction and start up, help and guidance from colleagues at the Kurchatov Institute, Moscow was crucial. The key scientific and technical personnel received training at the most recognized nuclear knowledge centres of that time, the Lomonosow University and the International Joint Institute for Nuclear Research, Dubna. During the reactor reconstruction in 1967, the knowledge transfer from the Kurchatov Institute was again substantial, making it possible that the 1986-1992 reconstruction could have already been managed solely by Hungarian companies.

The political changes around 1989 then opened up the chances for BRR to expand the collaborations westward and allowed the BNC to position itself as a prominent centre of the European neutron research landscape.

The International Atomic Energy Authority (IAEA) catalysed these efforts by technical cooperation and scientific exchange visits, and, over the years, BNC became a center of IAEA practical trainings in neutron beam experiments and research reactor technology.

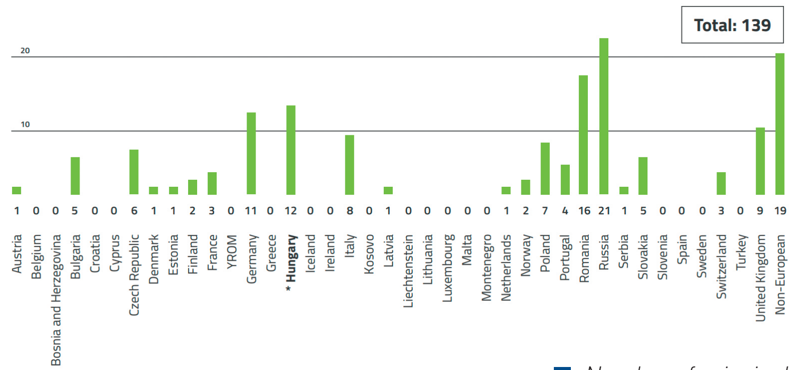
In 1992, the BNC came to be a pioneer in the country by winning one of the first three EC grants awarded to Hungary. The VENNET project was a consortial grant with French and Austrian partners. The second EC–funded project contributed to the establishment of the cold neutron source infrastructure. It counts an even more significant milestone when BNC declared to be an open user facility and started its transnational access (TNA) program.

Soon after, BNC became a partner in the NMI3 (Neutron Muon Integrated Infrastructure Initiative) collaboration, and received funding from the EU FP5 (2004-2008), FP6 (2009-2013) and FP7 (2012-2016) European framework programs. This was not only significant to sustain the user operation, but proved to be extremely important in terms of science management, since the established User Selection Panel and International Scientific Advisory Committee could include well-known experts of neutron science, and the User office was organized. Further, within the joint research activities with European centers, best practices could be shared and long-term technical and scientific collaborations were initiated. Several of these were converted to bilateral agreements to promote the cooperation at the research-group level. Within the TNA activity, BNC provided 1110 days of beam time in total to 205 users during this 12-year period, which resulted in over 110 scientific publications. Around 2005, in addition to the general-purpose NMI3, BNC was successful in entering application-oriented collaborations with several key communities via thematic excellence programs.

Hands-on training of CETS students

The nuclear data measurements in the cold neutron beams research program mentored by the IAEA Nuclear Data Section – dating back to the late nineties as a bilateral collaboration with Lawrence Berkeley National Laboratory (LBNL) – gradually gained attention and BNC became one of the 10 partners to participate in the FP6 EFNUDAT (European Facilities for Nuclear Data project, 2006-2010). This was followed by three similar initiatives, the FP6 ERINDA (European Research Infrastructure for Nuclear Data, 2011-2013), the FP7 CHANDA (solving CHAllenges in Nuclear DAta for the Safety of European Nuclear Facilities, 2013-2018) and the ARIEL (Availability and use of nuclear data research infrastructures for Education and learning, 2019-). BNC established long-term collaborations with both CERN and EU JRC IRMM (Institute of Reference Materials and Measurements) in this context and gained access to unique (isotope-enriched) target materials.

Other fields where the neutron methods became very successful are related to the cultural heritage research. The CHARISMA project (Cultural Heritage Advanced Research Infrastructures: Synergy for a Multidisciplinary Approach to Conservation/ Restoration, 2009-2014) set up a new user-oriented common platform of large-scale facilities (including synchrotron and ion-beam techniques, FIXLAB) and mobile instrumentation (MOLAB) to bridge the gap analytical and the cultural heritage user communities. The successor project, IPERION CH (2015-2019) comprises already 24 partners from 13 countries, and it



Number of principal investigators per country

Meeting of the International Scientific Advisory Committee (ISAC)

is expected to further expand into the E-RIHS ERIC (European Research Infrastructure for Heritage Science) framework from 2021, in which BNC is a committed partner. In terms of methodological development, EU FP6 NEST ANCIENT CHARM (Analysis by Neutron resonant Capture Imaging and other Emerging Neutron Techniques: new Cultural Heritage and Archaeological Research Methods, 2006-2009) was indeed a success in adopting the base element analysis, imaging and scattering techniques to the requirements of characterizing complex art objects. Cooperation with research groups at STFC ISIS, UK are still ongoing.

In the field of material and bioscience, BNC is the single Hungarian Partner Facility of the CERIC-ERIC (Central European Research Infrastructure Consortium), a regional, excellence-based distributed infrastructure.

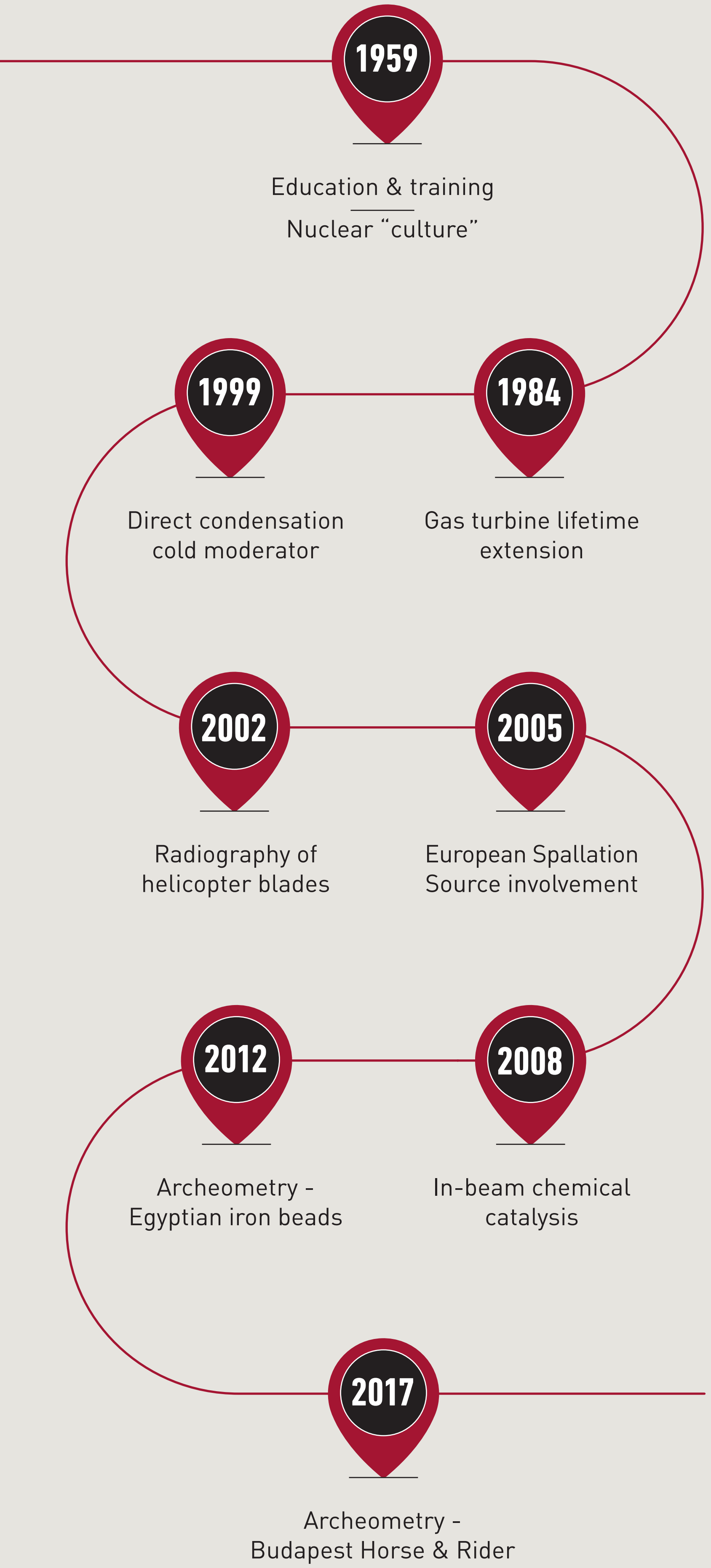
Thanks to the NAP VENEUS 05 and 08 grants, substantial improvement of the neutron beam infrastructure was achieved. The GINA station was built in collaboration with Max-Planck-Institut für Metallforschung Stuttgart. The funding made it possible to advance Hungary's activities related to the ILL, as part of the Visegrád-Four (V4) countries.

BNC has been involved in activities related to construction of The European Spallation Source (ESS, Lund, Sweden), a multi-disciplinary research facility based on the world's most powerful neutron source, from the very beginning of the project. As a benefit of the BrightnESS project (Building a Research Infrastructure and Synergies for Highest Scientific Impact on ESS, 2015-2018) and Hungary's in-kind contribution, BNC contributed to the technical design of the NMX instrument, to various detector systems, and biological shielding, as well as to the assessment of the long-term environmental impacts. The SINE 2020 (Science and Innovation with Neutrons in Europe in 2020, 2015-2019) programme, which aims at preparing Europe for the unique opportunities of the ESS and to develop the innovation potential of the neutron Large Scale Facilities, gave a boost to Industry Consultancy and Training activities, while several successful R&D projects with our specialized instrumentation could be completed. BNC is presently the coordinator for Introductory Neutron Schools which organizes training for early-carrier scientists not only within our Central European Training School of Neutron Techniques (CETS), but also at many other knowledge hubs in Europe.

We participate in networking activities of regional and European neutron sources, being founding members of the Eastern European Research Reactor Initiative (EERRI), and more recently of the League of advanced European Neutron Sources (LENS).

Project meeting of the NMI3 collaboration

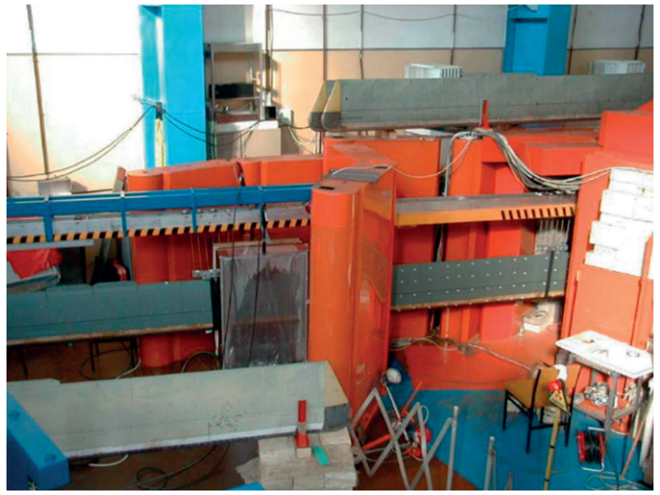
Social impact

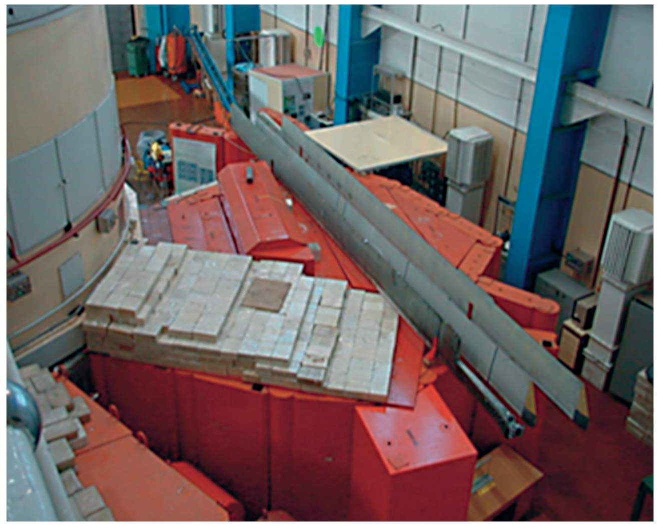


Non-destructive structural integrity analysis of helicopter rotor blades

For the prolongation of the service lifetime of military helicopter rotor blades, the inspections of a structural failure performed at the Budapest Research Reactor were crucial. Neutron Radiography, X-ray Radiography and Vibration Diagnostics with Statistical Energy Analysis were used to study the composite structure of the rotor blades.

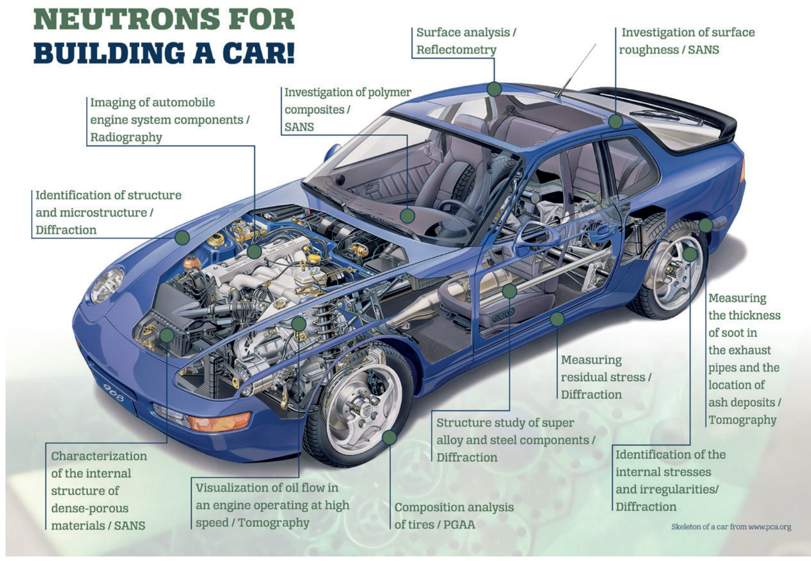
The most important points of the study were the visualization of the possible imperfections in the honeycomb structure, like inhomogeneities of the resin materials on the core honeycomb surfaces; defects at the adhesive filling; water percolation at the sealing interfaces of the honeycomb sections; quality control of resin-rich mended areas; verification of the position of metal parts; corrosion effects.





Pioneering technology serving the automotive industry

The Hungarian automotive industry has arrived at the point, where technological innovations should be built into the production chain. Through the neutron beam-line analytical applications, new possibilities are opening up to look into the deepest layers of a physical object's structure, where rather detailed information can be achieved or unknown features may be discovered. Experiments at the BNC can give answers to several questions of the automotive industry's stake-holders. These include, but are not limited to: visualization of mass flow, abrasion, aging- and sedimentation, the structure of alloys, residual stress analysis by means of neutron diffraction, and determination of the composition and optimization of composite materials.



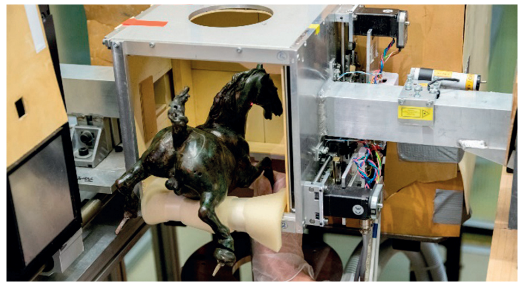
Relevance to national heritage: A neutron study of Leonardo's bronze statue

As opposed to many short-lived attributions of sculptural works to Leonardo da Vinci, the authorship of the Budapest Horse and Rider [a magnificent small bronze from the Collection of Sculpture before 1800 of the Museum of Fine Arts, Budapest] has aroused a lively discussion of art historians for a century. In order to resolve if the small bronze was only inspired by Leonardo's ideas or could it be by the master's own hand, comprehensive neutron-based investigations were carried out at the Budapest Neutron Centre in 2017-18.

The 3-dimensional (3D) neutron tomography was able to provide high-quality images of the inside of the statue with a resolution of one tenth of a millimeter.

The neutron transmission experiments visualized traces of the core material, which remained inside the objects after the lost wax casting process. The elemental composition of these remnants was also determined by prompt-gamma spectroscopy while neutron diffraction proved that the horse and the rider were cast from the same bronze material, but the casting process was different.

In October 2018 the Museum of Fine Arts was reopened after a 3 years thorough reconstruction and the main attraction was a temporary exhibition of this small bronze statuette and a collection of Leonardo's statue-study drawings from the British Royal Collection of Windsor. A movie illustrating the neutron technical investigations was an integral part of this exhibition, which received visitors as many as 65 000 people from Hungary and abroad.



"Beads from Heaven" – Neutron Techniques Reveal Five-Thousand-Year-Old Iron Smithing Skills

The nature and origin of humankind's earliest iron artefacts, the 5000-year-old Egyptian iron beads have been a matter of debate for over a century. In 2013 a study published in the Journal of Archaeological Science revealed that the iron beads had been hammered from pieces of meteorites.

The experimental work was performed at the BNC. Using neutron techniques the nature of a material even after complete corrosion of the iron metal could be determined. Prompt-gamma activation analysis, neutron diffraction and neutron radiography revealed the elemental composition, the crystalline/amorphous structure and the topology of the beads.

Charged-particle-induced X-ray emission also contributed to the full understanding of the compositional data and affirmed that the beads were made from meteoritic iron.

This discovery proves that already in the fourth millennium BC metal workers had mastered smithing of meteoritic iron, (an iron-nickel alloy) which is much harder and brittler than copper the commonly worked metal in those times.

Education & training

In order to promote the activity of the national and Central-European regional user community (of about 500 professionals and to contribute to instrument development, as well as to facilitate the access of new users to the neutron facilities international meetings have been regularly organized at BNC from as early as 1992. BNC is presently the coordinator for Introductory Neutron Schools to organize training for early-stage scientists, not only in the framework of the Central European Training Schools of Neutron Techniques (CETS) but also at many other knowledge hubs in Europe.

Disseminating Nuclear "culture"

The BRR and BNC are strongly committed to train the future generation of professionals. In cooperation with Hungarian universities (Budapest University of Technology and Economics, Roland Eötvös University of Sciences, Budapest, the University of Pannonia, Veszprém), BNC accommodates students for laboratory practices in studies of nuclear science and technology. In collaboration with IAEA, BNC organizes nuclear science and technology oriented training courses for international students on a regular basis. The Budapest Research Reactor is open to tours by the general public. Thematic presentation are given by BNC experts throughout the country around 3 November, every year as part of the Hungarian Science Day – organized by the Hungarian Academy of Sciences.

BRR Reactor Department Heads:

1956-1962	-	Győző Verle
1962-1977	-	Lajos Várkonyi
1977-1990	-	Géza Vizdos
1990-1991	-	Lajos Gácsi
1991-2002	-	Tibor Hargitai
2002-2010	-	Ferenc Tőzsér
2010-2018	-	Ferenc Gajdos
2018-	-	Péter Juhász

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