BrightnESS

Building a research infrastructure and synergies for highest scientific impact on ESS

H2020-INFRADEV-1-2015-1

Grant Agreement Number: 676548

Deliverable Report: D4.4
Report on engineering design of the BRR low dimensional moderator

brightness

1 Project Deliverable Information Sheet

BrightnESS Project	Project Ref. No. 676548	
	Project Title: BrightnESS - Building a research infrastructure and synergies for highest scientific impact on ESS	
	Project Website: brightness.se	
	Deliverable No.: D4.4	
	Deliverable Type: Report	
	Dissemination Level:	Contractual Delivery Date: Month 12
	Public	Actual Delivery Date: Month 13 Revision Delivery Date: Month 27
	EC Project Officer: Mina Koleva	

2 Document Control Sheet

Document	Title: Report on engineering design of the BRR low dimensional moderator	
	Version: v1-2017.11.24	
	Available at: https://brightness.esss.se	
	Files: BrESS_D4-4_Moderator task 4-5_RevMonth27.docx BrESS_D4-4_Moderator task 4-5_RevMonth27.pdf	
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3 List of Abbreviations

BNC – Budapest Neutron Centre
BOC-EOC – Beginning of Cycle/End of Cycle
BRR – Budapest Research Reactor
CNS – Cold Neutron Source
ESPI – Energy Sensitive Pinhole Imaging
GA – Grant agreement
HEU – Highly Enriched Uranium
LDM – Low Dimension Moderator
LEU – Low Enriched Uranium
MCNP - Monte Carlo N-Particle code
LH – Liquid Hydrogen
MC – Monte Carlo
NSD – Neutron Spectroscopy Department
SANS – Small Angle Neutron Scattering
TOF - Time of Flight
VVER - Water-Water Power Reactor (type of Russian reactors)

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5 Executive Summary

The construction of the European Spallation Source is one of Europe's largest research infrastructure investments and the most important advancement in the activity of the neutron scattering community. One of the crucial components and a most innovative development in enhancing the neutron source brightness is the compact cryogenic moderator. Its principle was recently invented by the ESS target team during the design phase of ESS.

In ESS neutrons are generated by accelerating protons and directing them at a target made of tungsten, which then releases high-energy neutrons. Moderators adjacent to the tungsten target wheel slow the neutrons down to the cold and thermal energies required for experiments. Moderation inevitably leads to loss of neutron intensity, and moderator design work includes optimising geometries to minimise losses. 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.

The theoretical explanation of this unexpected behaviour is based on the large difference between the values of the scattering mean free path in para-hydrogen for thermal neutrons (in the range of 1 cm) and cold neutrons (tens of cm).

This very new idea and its technical solutions need complex simulation and experimental verification in various conditions. The Wigner Research Centre as a partner in the BrightnESS project might serve with valuable contributions to this task by the experience gained in the construction and operation of a similarly innovative cold neutron source at the Budapest Neutron Centre. BNC operates a cold neutron research facility, which includes a liquid hydrogen moderator inserted horizontally into the Be reflector around the reactor core, a supermirror neutron guide system and a suit of 8 experimental stations placed in a neutron guide hall. This Cold Neutron Source is an integral part of the 10 MW Budapest Research Reactor. The CNS was built in the end of nineties and the operation started in 2000. Its excellent neutron performance, cost efficiency and reliable operation proved it to be a very useful and valuable equipment. Nowadays the system is becoming outdated – the BrightnESS project is an excellent opportunity to start a renewal and improvement of this facility. At the same time this renewal might be coupled with the need to demonstrate and benchmark the new concept of low dimensional moderators developed for ESS. Demonstrating this novel moderator concept at BNC – at least for the reactor case - will certainly provide valuable information for the design and fabrication of the ESS moderator and significantly reduce the risk for the ESS construction project.

The current BRR cold neutron facility is one of the scarce neutron sources, where access for monitoring the CNS features is technically feasible, in this way it serves in this project as an experimental benchmark facility for testing new features of the LDM concept. The preparatory phase of the engineering design has been implemented. It has been established that the new moderator cell of the CNS for BRR has to be compact, simple and needs to be based on para-hydrogen content optimized media. As a first step an initial document has been elaborated to fix the current configuration and status of the BRR CNS facility. As a part of the LDM design various calculations and experiments with the operating current CNS have been carried out. A series of measurements with the old moderator cell has been performed. Detailed Monte Carlo simulations have been performed to optimize the neutronics performance of a new moderator chamber for the reactor case to be implemented at BRR. These MCNP calculations were compared with recent experiments performed on a BNC beamline to monitor the current CNS brilliance. The engineering design of a LDM chamber as a tube-type moderator chamber surrounded by reflecting material has been performed for optimized ortho-para hydrogen media. The Monte Carlo calculations are now being compared with those of ESS, in this way a direct feedback, based on experimentally checked results, to the ESS design and engineering solutions are expected to be provided.

6 Report on Implementation Process and Status of Deliverable

6.1 Implementing team

The team of experts for the implementation of the task has been set up. The BNC cold neutron facility is operated by the MTA EK (Centre for Energy Research) and the Wigner Research Centre for Physics, EK is responsible for the CNS operation, while Wigner takes care of the beam extraction systems (guides, neutron guide hall infrastructure) and most of the experimental stations. Thus, the implementation team has been composed of EK and Wigner staff, moreover external experts have also been invited for special tasks.

The team is as follows:

Wigner:	László Rosta – team leader
	János Füzi – Head of Dept. expert in neutron instrumentation
	Balázs Koroknai – project manager
	Márton Markó - expert in neutron optics
EK:	József Janik - CNS responsible
	Ferenc Gajdos – Head, Reactor Dept. – design engineer of the current CNS
Experts:	Gábor Patriskov – MCNP expert
	Tamás Grósz – cold moderator expert

The LDM team has regular meetings – one per month in average.

6.2 Task sharing and schedule

The LDM tasks have been carefully discussed with all participants as in 6.1 and the sharing has been defined. The task list and preliminary attribution of personnel efforts and funds has been established. The schedule has been assigned as a function of the project milestones and deliverable schedules. The reactor operation regime, fuel cycle management and regulatory/licensing conditions have been taken into account.

6.3 Definition of starting conditions and input parameters

The description of the cold neutron facility at BRR has been published in 3 subsequent papers[1]. To document the design work on the new cold moderator at BRR and in order to cope with the BrightnESS project goal these papers are used as reference. To follow recent experiments and calculations showing that the new moderator cell of CNS has to be compact, simple and needs to be based on para-hydrogen content optimized media, an initial document[2] has been elaborated to fix the current configuration and status of the BRR CNS facility. Some details of this document are presented below in this report. To support the engineering work, of course, the detailed engineering and safety documentation of BRR is used, some drawings are presented here for illustration in section 7.6.

[1] Rosta L; Cold Neutron Research Facility at the Budapest Neutron Centre, Applied Physics A 74, S52-S54 (2002); Rosta L, Cser L, Révay Zs; Gain Factors with the New Supermirror Guide System at the Budapest Neutron Centre, Applied Physics A 74, S292-S294 (2002); Rosta L, Grósz T, Hargitai T; Liquid Hydrogen Cold Neutron Source at the Budapest Research Reactor, Applied Physics A 74, S240-S242 (2002)

[2] Janik J, Rosta L, Cold neutron source replacement project at the Budapest Research Reactor, Internal Report MTA EK, Budapest June 2015 (in Hungarian).

6.4 Sequence of the engineering work

Prior to the design of a new LDM chamber various calculations and experiments with the operating current CNS has been carried out. A series of measurements with the old moderator cell has been performed. When the CNS was run with stopped reactor, the cooling down process might have modified the ortho-para rate in the moderator cell. We had to determine whether the para-hydrogen modified the neutron number in the vertical channel, and what type of system will have to be selected. These measures are also used to validate our MCNP calculation methods.

Monte Carlo simulations were performed to implement the following tasks:

6.4.1 To set up the MCNP modelling instrument for neutronics calculations with the current reactor core configuration in order to compare simulation results with experimental data obtained on BRR as well as with those of ESS.

6.4.2 To optimize the BRR moderator configuration we would like to keep the old moderator cell's volume, but modify its geometry (diameter and length);

6.4.3 Starting from an initial parameter set we will further optimize the parameters/geometry and investigate its influence on the performance, then by successive approximation the ideal state of the design features can be determined;

6.4.4 In a next step we are going to simulate certain neutronics effects of reflector materials in the new moderator cell (beryllium, graphite, lead, lead-bismuth, nano-diamond etc.);

6.4.5 The neutron reflectors' ideal combination will be determined;

6.4.6 The feasibility of manufacturing of the ideal moderator cell's shape and environment is to be studied as well;

6.4.7 Simulations/Calculation and further optimization of LDM features will have to be performed for comparison of moderator cell configurations and conditions in reactor and ESS spallation source environment.

6.5 Status of deliverable

The preparatory phase of the engineering design as given in 6.3 has been implemented and described below. Items in 6.4.1-3 – concerning the LDM design itself – have been implemented and the results are presented in the current deliverable report. Items 6.4.4-6 are in progress – this is a follow up part of the design and relates rather to the implementation of manufacturing of a new LDM. 6.4.7 is to be performed, for this purpose BNC and ESS experts have agreed on a meeting to be held in Lund in October 7, 2016.

The design has reached about 85% completeness, as regarded the preliminary engineering design work. In the process of designing i.e. performing auxiliary experiments on the current moderator and first results of Monte Carlo simulations, some new features appeared which are very important to be studied. Various factors may play in the neutron intensity gain, such as the ortho-para ratio, moderator chamber geometry, thermo-hydraulic conditions, irradiation properties from the core components, heat load distribution in a very asymmetric cell geometry etc. These parameters are being analyzed for further optimization of the LDM configuration for the BRR case.

The detailed engineering document – ready for fabrication – has to be prepared by involving external partners via subcontracting, as foreseen in the project contract (GA). For this purpose the applicable rules of public procurement procedures were carefully studied, model contract were prepared. The selection of potential partners for subcontracting is in progress for the various subtasks to be performed within the engineering activity, such as modelling of thermo-hydraulic conditions, nuclear heat load calculations and optimization for distribution in a very asymmetric cell geometry with respect to the reactor core.

7 Technical Content

7.1 Introduction

The low-dimensional moderator concept. The European Spallation Source will be the first spallation neutron facility to operate a low-dimensional moderator as part of its target systems. One of the keys to maximising neutron brightness at the European Spallation Source (ESS) is also one of the more unassuming components of the facility. As a component of the moderator-reflector system, this roughly 3 x 70 cm aluminium alloy cylinder, consisting of separate channels containing water and liquid hydrogen, plays a key role in determining the scientific impact of the world-leading research instruments designed for ESS. The moderator is the central point of neutron extraction for all beamlines at ESS. Its basic geometry, material composition and operating methods must all be optimised to maximise the number of neutrons that can be used for scientific research at ESS.

Neutron moderators for producing the slow neutrons adequate for neutron scattering research are commonly envisaged with dimensions comparable to the neutron scattering mean free path inside the moderator material (e.g. liquid H_2, D_2, H_2O etc.). This provides for good efficiency of slowing down the fast or partially slowed down neutrons arriving primarily from the reflector surrounding the moderator and achieving a reasonably homogeneous distribution of the moderated neutrons inside the moderator volume. Actually the highest equilibrium moderated neutron flux is expected to occur well inside the volume of the moderator in view of the leakage of slow neutrons at the surface. Typical examples are cold neutron sources at fission reactor facilities with usual reflector materials such as Be or heavy water and both thermal and cold moderators at spallation sources. A remarkable deviation from the envisaged homogeneity of flux distribution inside the moderator has been observed in the simulation calculations on the coupled cold moderator at the spallation neutron source facility at J-PARC. In liquid para-H_2 moderator with H_2O water pre-moderator the flux distribution leaving the moderator has shown a clear maximum near to the walls when projected back onto the moderator This observation turned out to have far-reaching relevance for the development of the ESS moderator[3] and this has also been experimentally proven[4] at J-PARC (Fig. 7.1) by measuring the brightness distribution on the surface of the operating Japanese 'volume' moderator.

[3] Low dimensional neutron moderators for enhanced source brightness. Journal of Neutron Research, Vol. 17, No. 2, 2014, p. 101-105. Ferenc Mezei, Luca Zanini, Alan Takibayev, Konstantin Batkov, Esben Bryndt Klinkby, Eric Pitcher, Troels Schönfeldt and Unperturbed moderator brightness in pulsed neutron sources, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 729, Issue null, Pages 500-505 Konstantin Batkov, Alan Takibayev, Luca Zanini, Ferenc Mezei

[4] https://europeanspallationsource.se/article/ess-2015-moderator-design-tested-j-parc

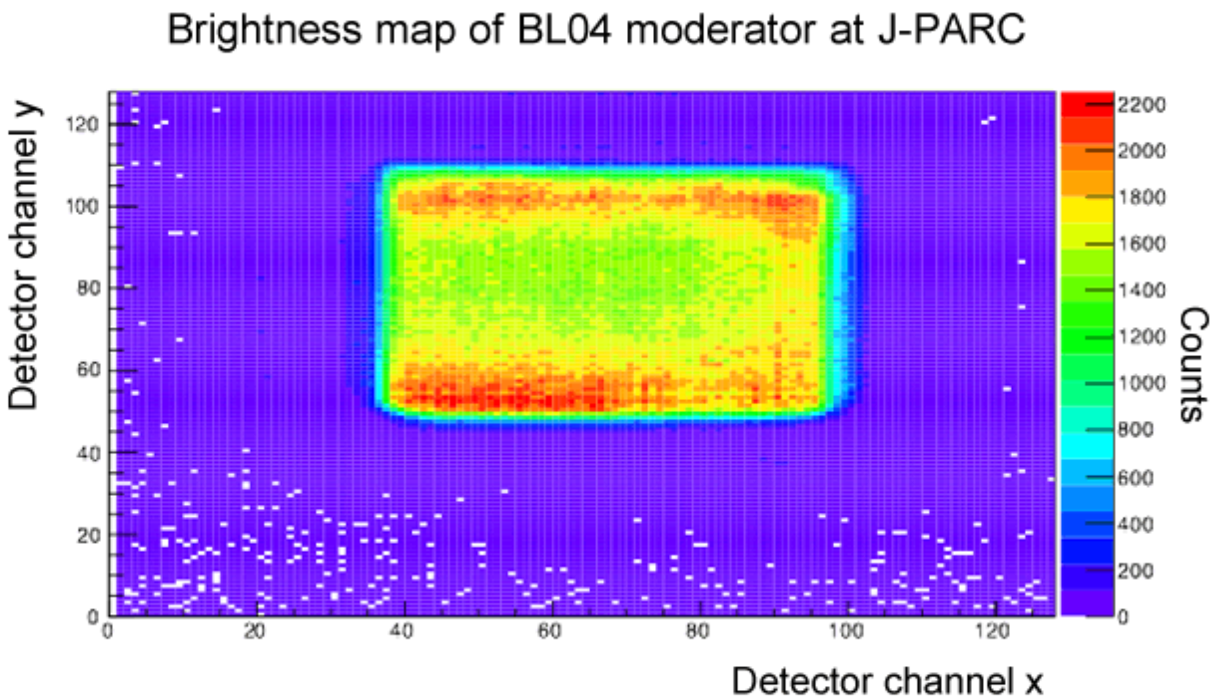

Figure 7.1: The brightness map resulting from the ESS/J-PARC experiment on beamline BL04
The map shows the neutron counts on the nGEM detector. The counts are proportional to brightness.
IMAGE: ESS/JPARC

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. The theoretical explanation of this unexpected behaviour is based on the large difference in para-hydrogen between the values of the scattering mean free path for *thermal* neutrons (in the range of 1 cm) and its much larger equivalent for *cold* neutrons.

The ESS Monte Carlo simulation data demonstrated that a lower-dimensional moderator—that is, a low-profile, flattened moderator—would produce a uniformly high-intensity distribution of neutrons across the surface of the device. While peak brightness was estimated at dimensions below 1.4 cm in height, it was decided in coordination with ESS instrument scientists that a height of 3 cm would give the highest brightness that could still be exploited by the greatest variety of instrument optics. The result was a newly engineered flat disc moderator for ESS, which became known as the "pancake" moderator, a design established in 2014. Later, the concept underwent further design optimisation by Target Division engineers and physicists, in close consultation with ESS instrument scientists, resulting in the 2015 baseline design. Due to the innovative shape of the para-hydrogen and water canisters in the interior of the flat moderator, it is now often referred to as the "butterfly" moderator.

Cold neutron source at BNC. This very new idea and its technical solutions need complex simulation and experimental verification at various conditions. The Hungarian Wigner Research Centre for Physics at the Budapest Neutron Centre (BNC-Wigner) has carried out a series of experiments to develop new moderator geometries, and to develop a conceptual design of an advanced liquid hydrogen moderator based on the ESS concept. Thus, in order to support and validate the ESS moderator design the Budapest exercise within this deliverable consists of the following 3 major tasks:

- Perform experiments on the existing cold moderator to study ortho-para features of hydrogen
- Perform MC simulations for the local reactor environment to define an optimal moderator geometry
- Create the engineering design for a LDM at BRR.

Instrumental environment at the Budapest Research Reactor. BRR operates a liquid hydrogen (LH) cold neutron source, which was realised in year 2000 as a highly cost-efficient solution for a medium flux reactor. This CNS feeds with cold neutrons a guide system and a number of instruments as shown in the figure 7.2 below (green area).

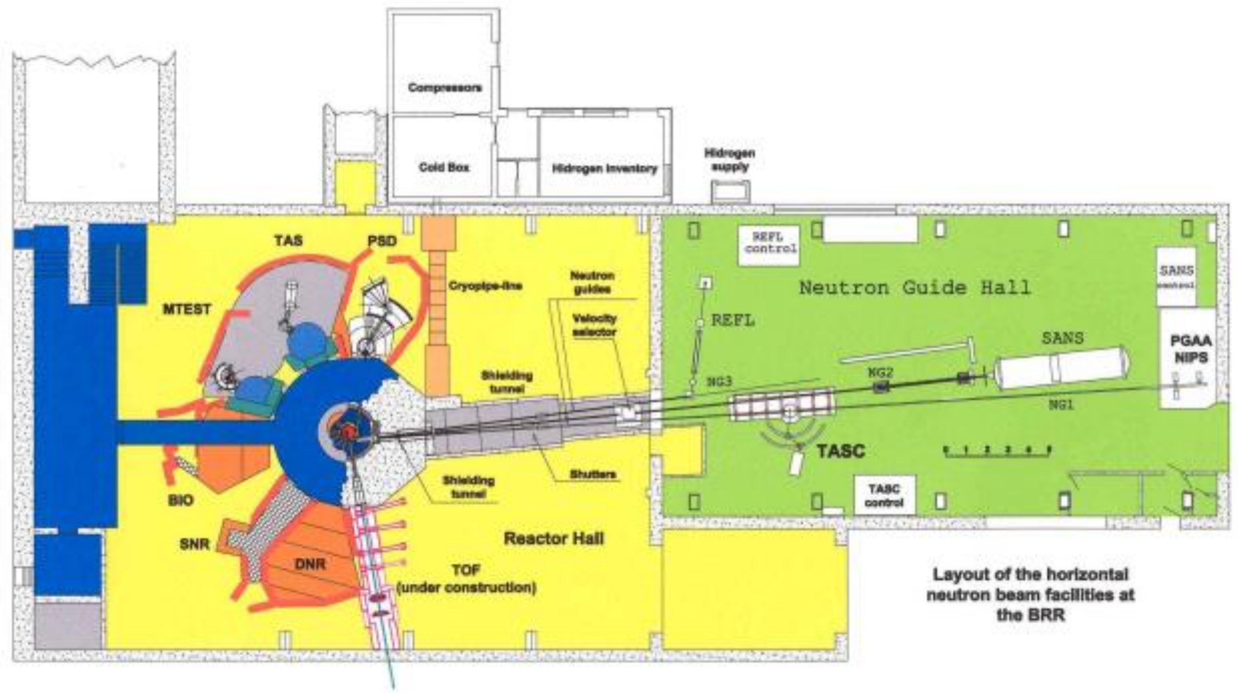

Figure 7.2: Layout of the horizontal neutron beam facilities at the BRR

It is expected to perform a modernization of the moderator and beam extraction system towards the end of this decade. The Neutron Spectroscopy Department (NSD) of the Wigner RCP, together with the Energy Research Centre (both members of the Budapest Neutron Centre – BNC consortium) in collaboration with spin-off companies have gained experience of cold moderator development and usage. The European Spallation Source ERIC has developed the novel concept of so-called low dimension moderators. Monte Carlo Simulations have shown that this concept can improve the performance of the facility (measured in moderator brightness) by a factor of three in comparison to conventional, volume moderator designs. Even though this concept promises a significant performance increase, an engineering design has to be developed and operational experience has to be gained for this new type of moderator. Thus BNC has engaged itself in the BrightnESS Project for a brighter neutron source in the cold spectral range – applied to the case of a reactor neutron source. According to the project plan new LH cell geometries are studied for optimised geometry, minimising neutron leakage in a way of maximising the unperturbed flux field and the cold neutron yield in case of reactor sources. Also a method, proposed by BNC/NSD, for moderator phase space mapping has been developed and this energy sensitive pinhole imaging (ESPI) technique is to be applied for wavelength dependent divergence mapping of the moderator and the beam path. During the current project, collaboration with the ESS project partners are being established.

7.2 Budapest Research Reactor

The Budapest Research Reactor (BRR) description is given below as a baseline to the parameter definition of the LDM design. BRR is a VVER-SM pool type reactor with 10 MW operation power. For isotope production, reactor material experiments and neutron scattering purposes vertical and horizontal channels have been set in the reactor (to understand the reactor configuration see Figure 7.3).

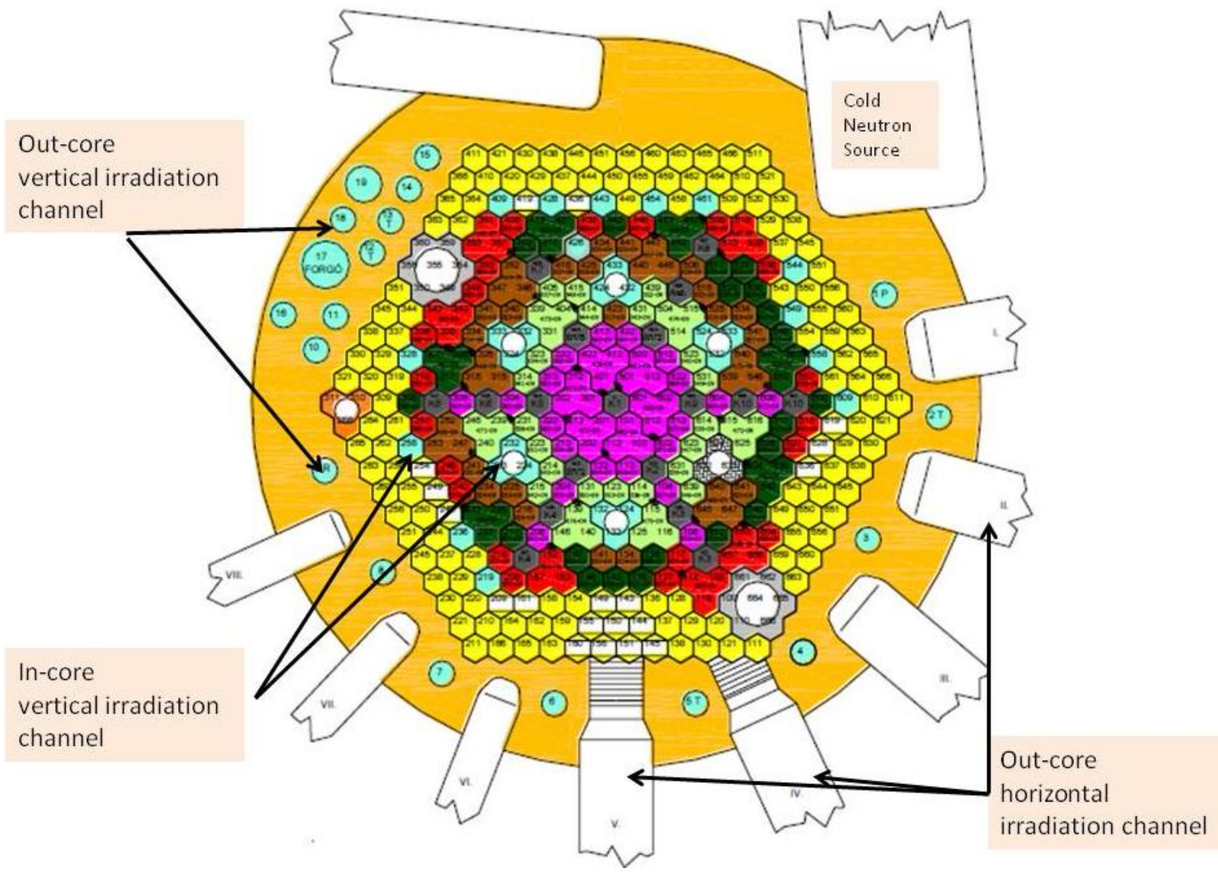

Figure 7.3: LEU Core scheme

Since 2013 – after the HEU-LEU conversion period – the BRR goes with VVER-M2 LEU nuclear fuel. The property of the low enriched Uranium fuel is presented in Table 7.1. The number of core positions filled with fuel elements is 190 for the LEU reactor core (see Figure 7.3).

	VVRER-M2 LEU
U-235 enrichment	19,7 % ± 0,3 %
fuel	UO_2+Al
average fuel mass	50,0 g ± 2,5 g
active length mm	600 mm$^{+20mm}_{-30mm}$
thickness of one part of the fuel element	2,5 mm
cladding material	reactor grade Al
cladding thickness	0,75 mm

Table 7-1: VVER-M2 LEU fuel parameters

Important to note, that the control rod withdrawal strategy strongly modifies the power. As Figure 7.4. shows, the control rod positions in the core as well as their grouping are asymmetric. First the inner control rods group, after that the second control rods group are withdrawn from the reactor in order to compensate the decreasing in-built reactivity due the depletion of the U-235. This asymmetric effect is much stronger than the power changes which could occur if only the burn-up of the fuels are changed and the rod positions are not modified. The power drop in the fuel positions surrounding the CNS is more than 10 % comparing the power distribution between the beginning and end of the cycle (see Figure 7.4.). This effect shall be taken into account in the analysis because the results of measurements performed on the beams of CNS can be influenced by schedule.

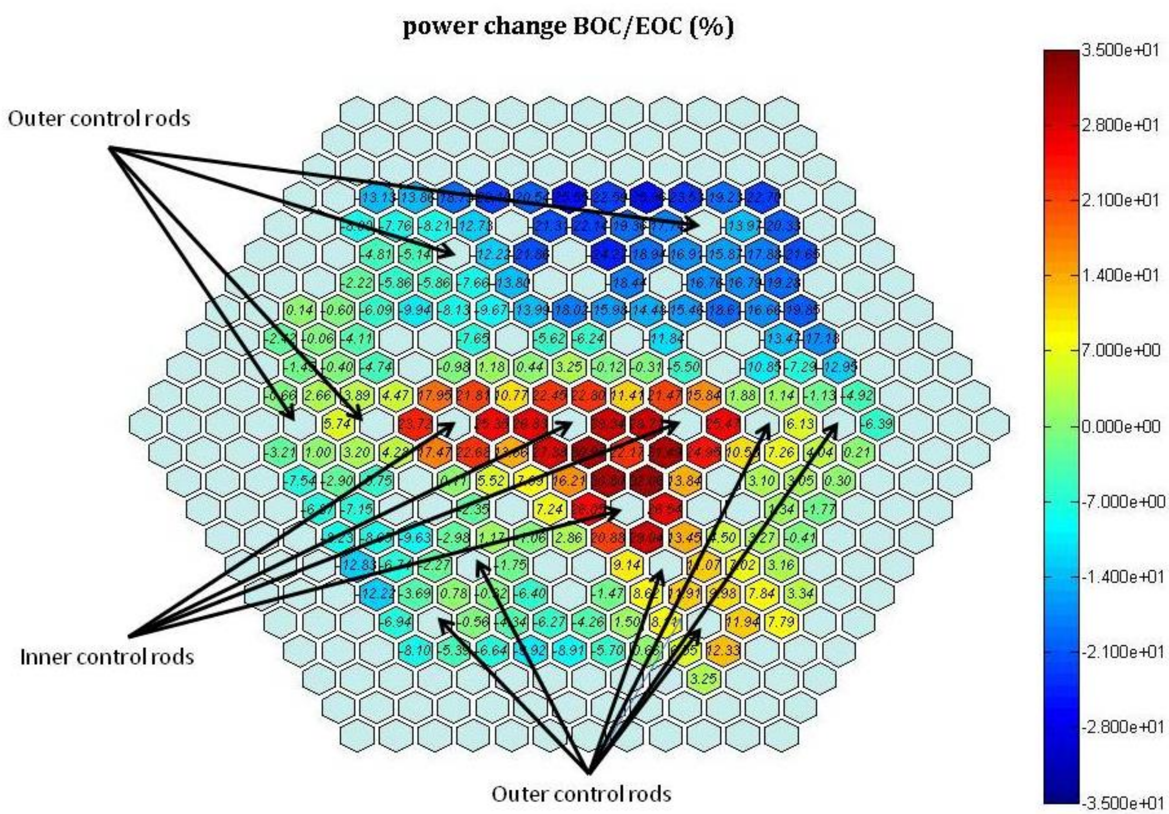

Figure 7.4: Power distribution change of the fuel elements EOC-BOC

7.3 Cold neutron source – current configuration

Followig the reconstruction of BRR – completed in 1993 – a cold neutron source (CNS) was installed in the horizontal irradiation channel N°10 in year 2000. Below, the most important parameters of the CNS – also used for neutronics calculations are presented.

The modelled part of the CNS is a high nuclear safety classified moderator cell which is a cylinder having the dimension Ø 130/47 mm. The moderator is liquid Hydrogen at 20 K cooled by Helium (18 K), the total volume of the cold moderator is 0.49 l with the dimension Ø 126/38 mm. The cell is double-walled and the used material is reactor grade Al. As it mentioned earlier in Normal-Operation (cold mode) the temperature of the liquid Hydrogen is 20 K, the density[5] is the function of the reactor power and changes in the interval 0,065-0,074 g/cm^3. For the neutronics calculation a simplified geometry is used for the existing moderator cell according to Figure 7.5.

Monte Carlo simulations and engineering advancements in moderator technology and neutron transport system have been applied for the particular case of BRR. Elaboration of engineering documents for the prototype components, such as moderator chamber, safety container, pre-moderator, cooling system, hydrogen pipe-line and buffer system, blower, catalyser for para-hydrogen, in-pile plug have been considered[6].

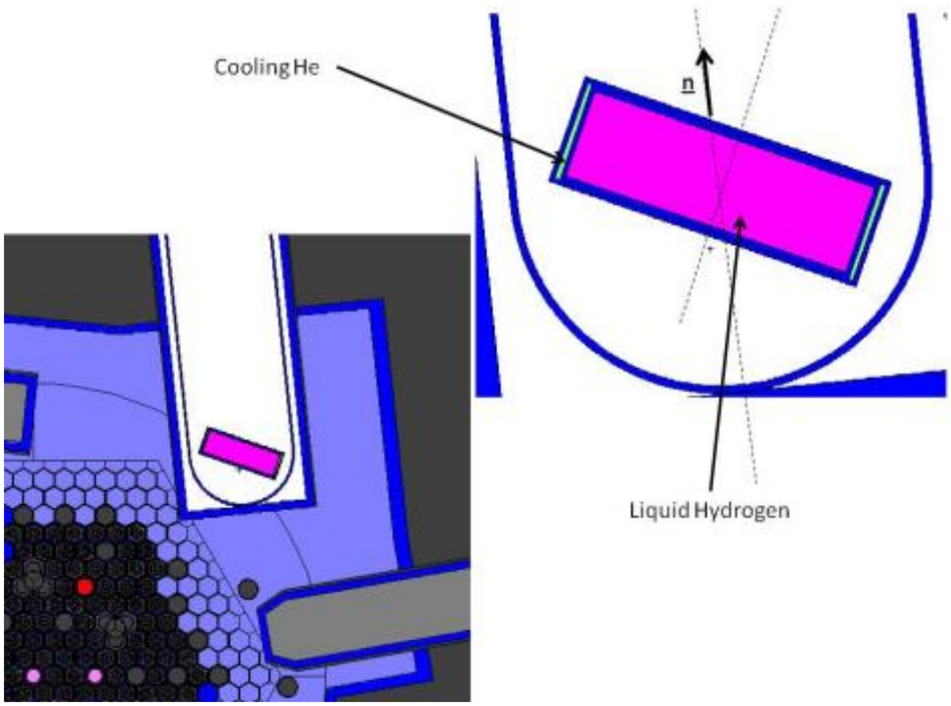

Figure 7.5: Left horizontal cross-section of the BRR at the middle axial height. Right the simplified CNS model can be seen

[5] Final Safety Assessment Report of the Budapest Research Reactor, Book 3/III Chapter 11.7.2 (Budapest, 2001)

[6] Patriskov G, Report on Monte Carlo modelling of the cold neutron source neutronics performance. Internal Report MTA EK, Budapest June 2016.

7.4 Ortho-para Hydrogen experiments

A crucial part of the LDM design is the ortho-para state consideration of the hydrogen moderator. The property of hydrogen molecule according to the singlet-triplet behavior of the spins of the nuclides (protons) is well-known. In singlet state (para-H) the scattering cross-section decreases with 2 orders of magnitude compared to the triplet state (ortho-H) which is the most important feature of the para-H that's why it is applied for moderator in a cold neutron source. The equilibrium of the ortho-para Hydrogen leads 0%-100% at 0 K and 75%-25% at room temperature. From the analysis point of view, around 20 K the ratio is 1%-99%. Some articles mention that the speed of cooling-down period and the high gamma flux can modify the equilibrium state of the ortho-para Hydrogen ratio. Therefore it is recommended to analyze the impact of the ratio changes between the two Hydrogen molecules in a wide range of condensation process parameters.

ortho-para ratio	Deviance for the reference compound (%)	highest relative error*
1%-99% (reference at 20 K)	---	**0,06**
5%-95%	43,8	0,28
10%-90%	not can be evaluated**	
75%-25% (at room temperature)	not can be evaluated**	
para	8,9	0,08
ortho	not can be evaluated**	

Table 7-2: Results of the test of the perturbation tools of MCNP5

As a part of the moderator optimisation the BRR CNS operation mode has been modified in order to allow precooling of the moderator chamber in advance to the reactor start. This required the purchase of a new control module and software of the Linde refrigerator. The new acquisition has the parameters below:

Heater R3180 control logic update
Consists of:

- Update of control logic
- Implementation of P/I controller for heater
- Setting for input output variable for heater control
- Input for OP17 HMI heater control
- Description for heater control
- Software test at Linde Kryotechnik site
- 4 hours of remote access support

This enabled us to make a series of tests with up to 14 days precooling of the moderator chamber to achieve the full conversion of H2 into the para state, the results thereof being is a prerequisite of the compact moderator design. The neutron intensity was monitored after the start of the reactor by the SANS instrument monitor, looking on the moderator through the NG2 neutron guide. The recorded intensity curves versus operation time are presented in Fig.7.6.

No precooling means that the refrigerator is started at 8 AM on the day of reactor start. Reactor starts at noon and completion of the cold regime occurs at 8 PM. Vertical scale is counts/sec on the SANS beam monitor, horizontal units are hours of reactor operation. During c3 and c4 the beam was off during the first day.

The results lead to the following observations:
- 14 days precooling (c1) yielded 10%-os intensity gain compared to the no precooling case, with slight 1% decrease during the 10 days reactor cycle;
- there was a process of helium cooling gas cleaning during c1, which lead to a 10% temporary intensity decrease, due to hydrogen boiling in the cell because of cooling power decrease. The intensity recovered within less than two hours after the cleaning process completion;
- 4 days precooling (c5) yielded a roughly 7.5% intensity gain (following an initial, more than 10% gain - this initial behaviour may also be attributed to thermal neutron flux transients related to the reactor startup);
- 1 day precooling (c6) produced a gain almost equal to that of 4 days precooling;
- without precooling the intensity slowly (3%) increases during the 10 days of reactor operation without reaching the levels obtained with precooling;
- the differences between c2, c3 and c4 show the effect of reactor fuel burnout upon the neutron beam intensity provided by the cold moderator.

Various factors may play a role in the intensity gain, in addition to the ortho-para ratio: moderator chamber geometry, thermo-hydraulic conditions and irradiation properties from the core components etc. These parameters are being analysed for further optimization of the LDM configuration for the BRR case.

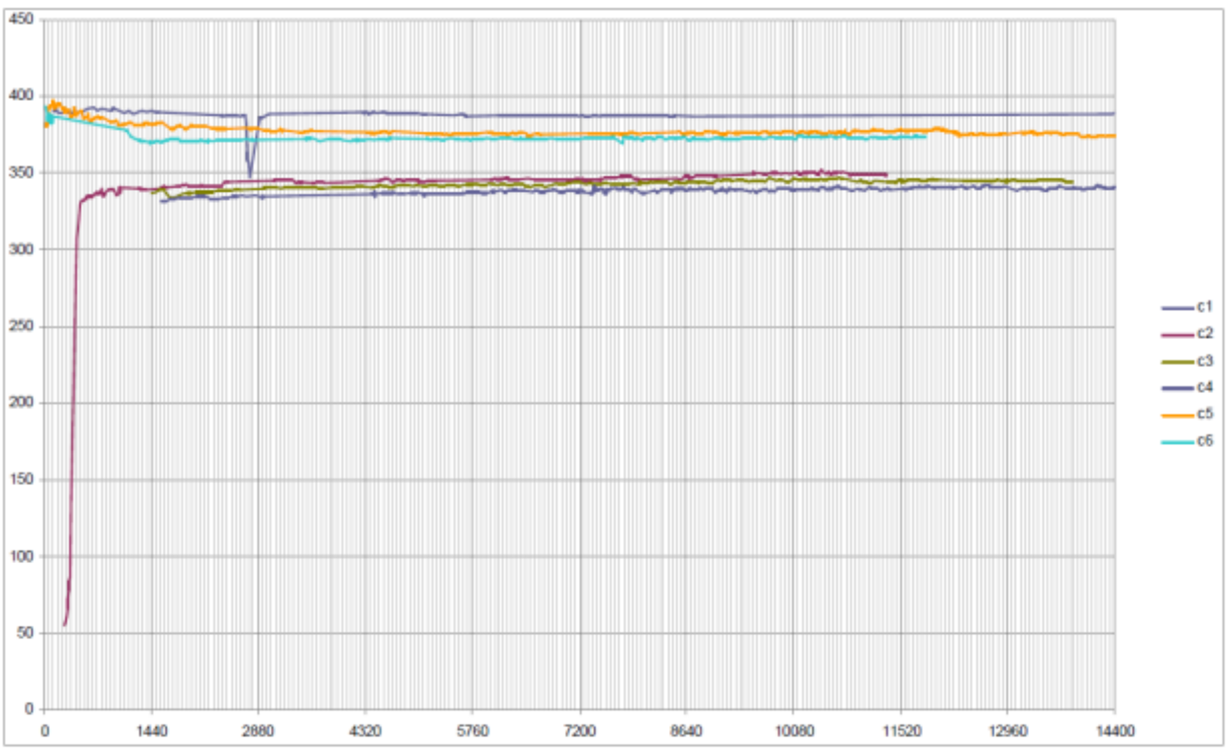

Figure 7.6: Neutron intensity variation versus reactor operation time

Curves C1-C6 show the different regimes according to the moderator cooling down in advance to the reactor start:
c1: 2015. Nov. 3-13; 14 days precooling;
c2: 2015. Nov. 17-27; no precooling;
c3: 2015. Dec. 8-18; no precooling;
c4: 2016. Jan. 19-29; no precooling;
c5: 2016. Feb. 9-19; 4 days precooling;
c6: 2016. Mar. 1-11; 1 day precooling.

From the moderator cooling down and ortho-para ratio measurements it was concluded that the neutron intensity of the current geometry CNS at BNC varies considerably according to the different regimes. Various factors may play in the intensity gain, such as the ortho-para ratio, moderator chamber geometry, thermo-hydraulic conditions, irradiation properties from the core components etc. These parameters are being analyzed for further optimization of the LDM configuration for the BRR case.

7.5 Monte Carlo simulations

The engineering design of the LDM for the BNC reactor is helped by MC simulations. According to the project Milestone MS13, MCMP calculations were performed for the case of the current configuration of the BRR LH-CNS. These simulations are being considered for comparison with the performed intensity measurements on the BRR SANS beamline.

In MCNP there is a possibility to treat the low neutron energy scattering with respect to various materials. For ortho- and para-Hydrogen there some sets of S(a,b) library[7] at 15-21 K. It shows what kind of way one can overwrite the cross-section library to use more than one cross-section in the same material for the same nuclide. In the first criticality calculation with aim of the perturbation tools of the MCNP5 an examination has been carried out how the ratio of the two types of Hydrogen modify the neutron spectrum in the wavelength range 1-28 Angstrom (the resolution of the energy bins corresponds with the 0,25 Angstrom. The results are presented in Table 7.2. In the model, the compound at 20 K was built in. The perturbation for para, ortho, at room temperature Hydrogen and for 5%-95% and 10%-90% ortho-para Hydrogen was carried on. The MCNP User's Manual recommends that the model should be recalculated if the difference between the perturbed and unperturbed tally is more than 20 %. As it can be read in Table 7.2 the perturbation for only the para Hydrogen is reliable - accept the 5%-95% ortho-para Hydrogen – in which case the maximum value of the deviance in the examined energy region was 43% to the unperturbed case with relative error more than 0,10 – for all compounds the results are questionable. In some energy bins of the neutron tally negative values are calculated which means the second order perturbation theory is not applicable for the problem, thus separate calculation should be done to examine the effect of different ration of ortho and para Hydrogen.

[7] Grammer K, MCNPX Calculation of the Ortho-Para Monitor Neutron Flux as a Function of Ortho-Para Ratio, 2012

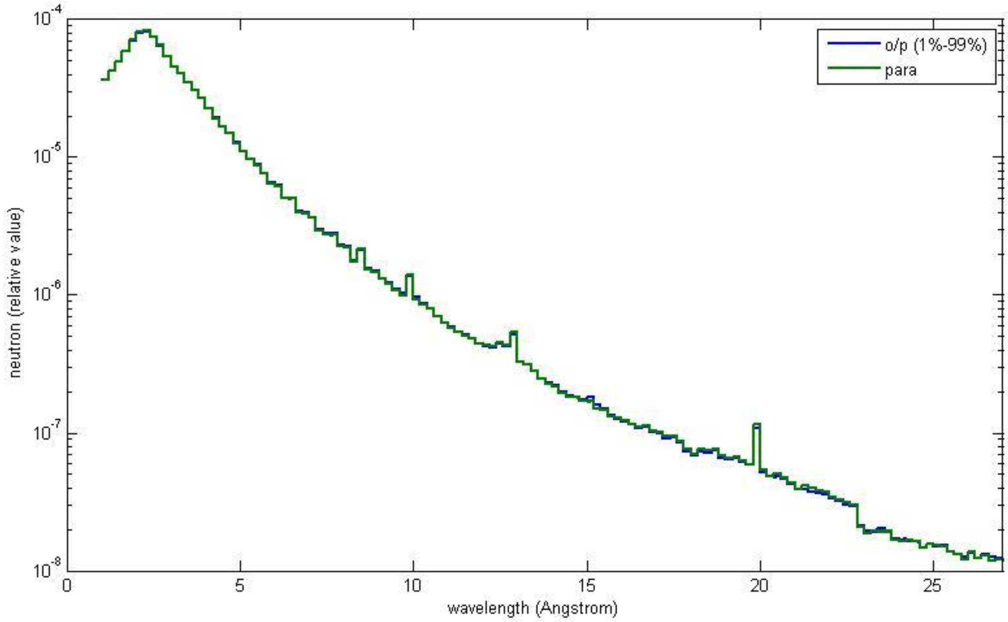

Figure 7.7: Neutron spectra in relative units for the unperturbed compounds (o/p: 1%-99%) and for para Hydrogen

The BRR CNS is set near to the reactor core, the load pattern and the other in-core properties (like Be-displacer, vertical in-core irradiation channel, and safety- and control rood) make it difficult to describe the BRR as well the CNS. Therefore common usage of different codes is recommended to determine the real fuel inventory and make a real calculation of the detailed geometry (with code MCNP5).

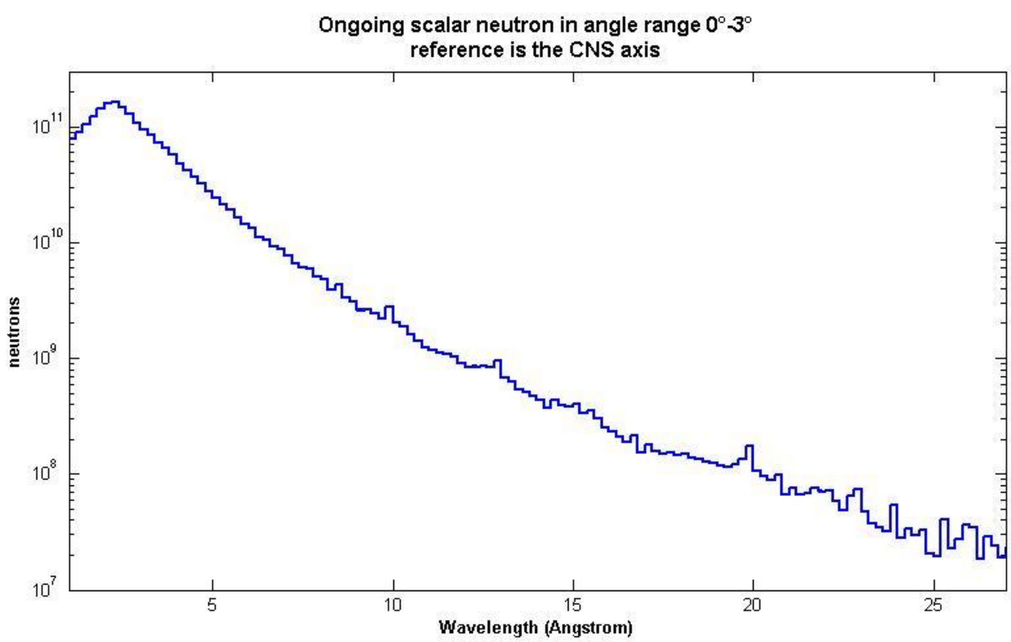

Figure 7.8: Calculated neutron distribution

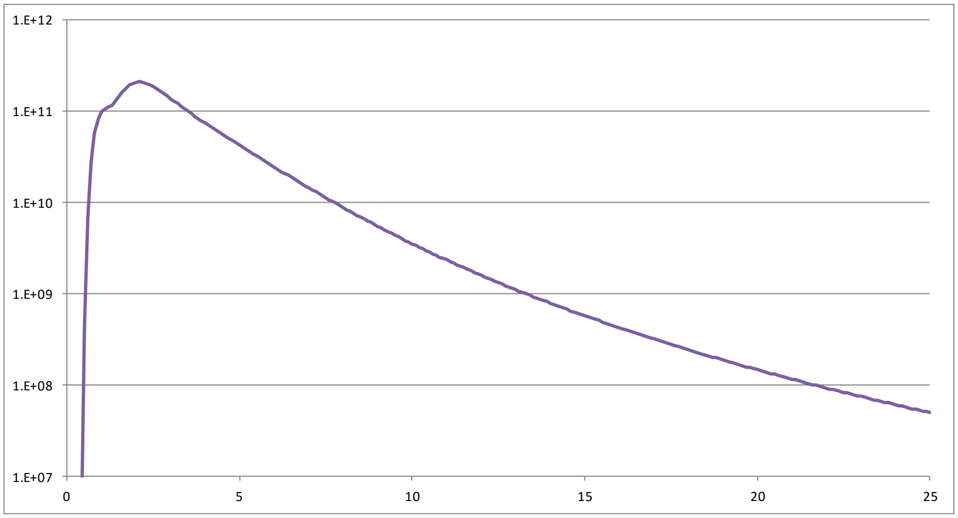

Figure 7.9: Measured cold neutron source brilliance (in neutrons/cm2/s/sr/A°) as a function of wavelength (in A°).
The result shows good agreement with the MCMP simulations
(note that on fig. 7.8 the wavelength scale starts at 1 A°).

For the BRR core a very detailed reactor model was developed for MCNP calculation in 2009-2013. All in-core properties were modelled in details in geometrical pieces and material components point of view. To handle changes in the fuel inventory – caused by the burn up and the number of the cycle – a MATLAB function family was written so that one can easily generate a new core model from an appropriate group of the reactor core output files. By variation of the MATLAB generated files the core model can be fitted to the given tasks and problems.

In order to validate the reactor model – presented in Chapter 7.2 – the experimental results measured on the SANS beam-line fed by the CNS are compared with result of the criticality calculation. The neutron spectrum in wavelength range 1-28 Angstrom is presented in Figure 7.8. Comparing the results with the measurement one can say that the maximum of the neutron yield at 2,4-2,6 Angstrom is 1,62E+11 neutrons, which is in a good agreement with the measured one as presented in Fig.7.9.

7.6 Engineering design of LDM chamber

As shown in paragraph 7.1 and in details in reference paper No.3, the 'volume' moderator at BRR should be downscaled to a quasi-one dimensional chamber of cylindrical shape. The next step – as of the current work – is to provide an engineering design, which will be the basis for further optimisation by using the above codes. Thus, the current engineering design aims to replace/modify the actual CNS configuration shown in figure 7.10. This figure here serves only for illustration to show the complexity of the engineering design items to be treated. All mechanical, electrical, cryogenic, shielding, vacuum-technique electronic control etc. components are being re-evaluated and/or newly designed and arranged to fit the new concept. Figure 7.11 below is also an illustration to shows Auto-CAD drawing of the current reactor/moderator plug design to be considered as input parameter for replacement by the new LDM cold source at BRR.

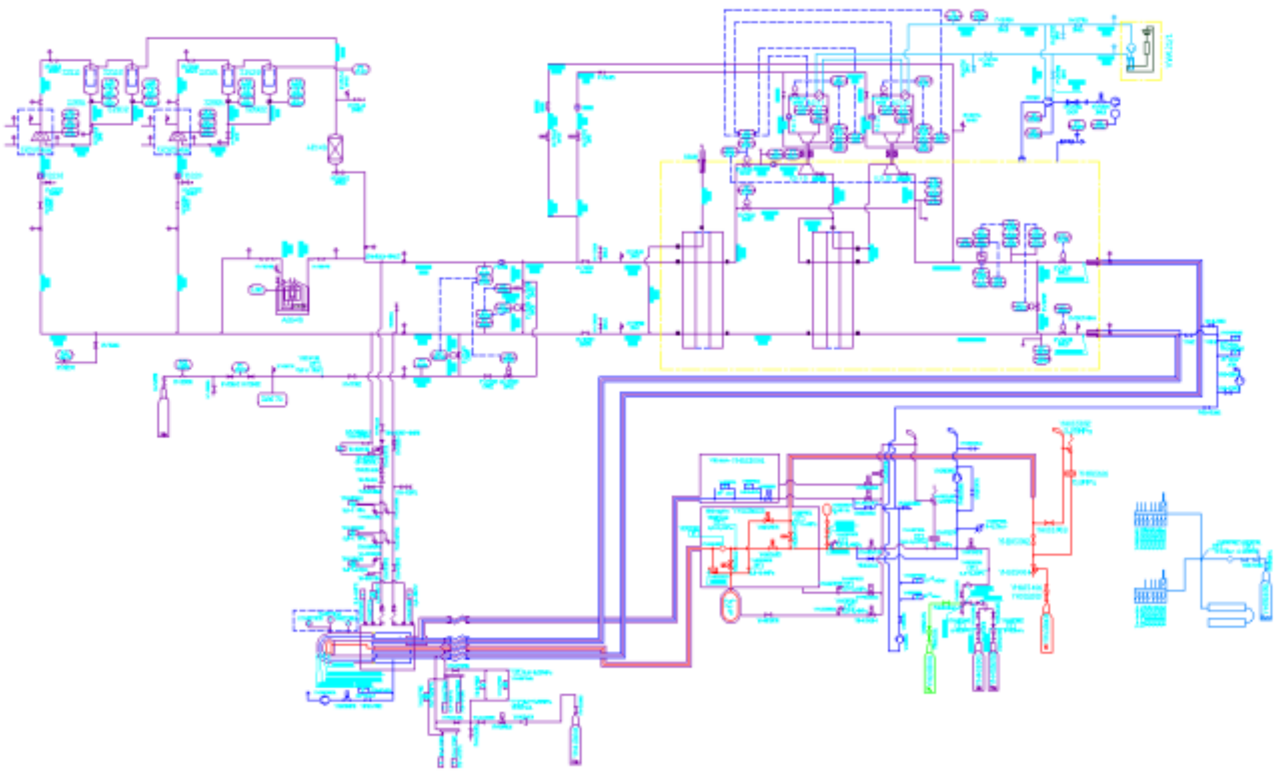

Figure 7.10: This detailed drawing illustrates the complexity of the current lay-out of the Budapest Research Reactor cold neutron source system

The engineering design of the new LDM system follows exactly the design of the current cold neutron source in terms of reactor/take-off channel geometry, cryogenic equipment, electronic control system and the safety concept. This means that the moderator insertion into the reactor is performed as a horizontally aligned in-pile plug as shown in Fig.7.11. This plug serves as the biological shielding for the beam take-off, contains the moderator chamber with its explosion proof vacuum jacket (on the right in Fig.7.12) hydrogen supply and cryogenic pipelines as well as a lead-based primary/emergency shutter at the reactor wall. The hydrogen (considering its explosive gas nature) safety is provided essentially by the He-jacket surrounding all hydrogen containing components.

The out-of-pile part of the cold source assembly will contain the same components as shown in Fig.7.10. Thus, the engineering design for the LDM relates only to minor modernisation of a few components (some electronic modules, vacuum parts), while the major components will be kept. So, the Linde cryogenerator with two He-compressors and He gas buffer tank, the hydrogen gas buffer and valve system (in a separate room) and all surrounded by He jacket, the vacuum installations as well as the control system, including gas analyser and purification units are to be used without modification.

The essential part of the engineering design for the new LDM system is the elaboration of the moderator chamber. Fort the moderator cell design various options are considered.

– Compact (in one dimension) moderator cell in a form of an elongated tube (diameter 1.5-3 cm, length 15-25 cm)
– for ortho-para conversion one has to use a circulating system for the hydrogen in the cell. It can be produced by the cell with double wall and He cooling.
– No forced circulation of hydrogen, natural convection with direct cooling on the chamber.
– Moderator chamber surrounded by beryllium or water.

The LDM cell configurations designed for BRR are shown in Fig.7.13. The cell insertion into the explosion-safe vacuum chamber is presented on Fig.7.14.

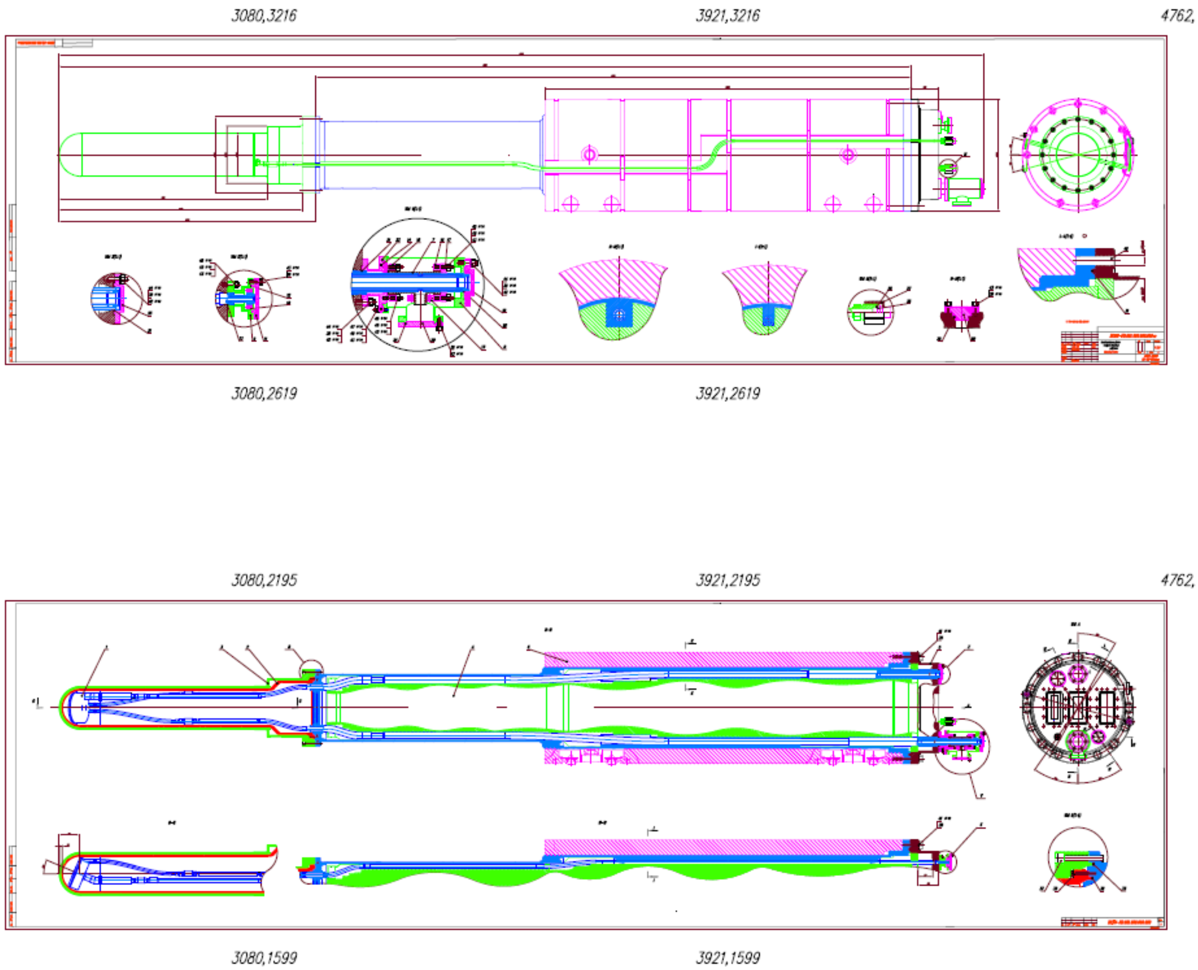

Figure 7.11: Actual reactor/moderator plug construction with the moderator chamber on the left

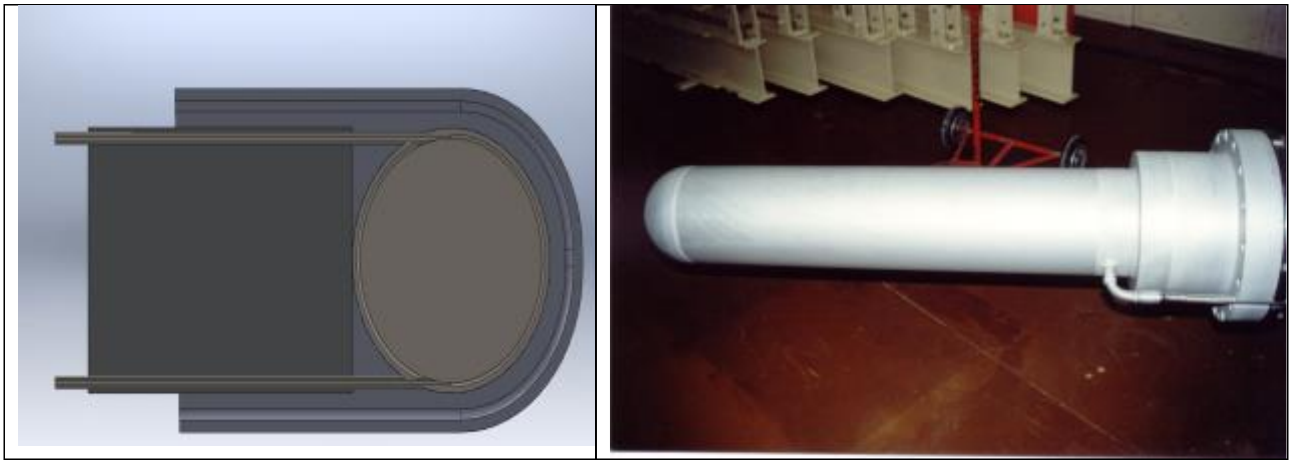

Figure 7.12: Schematic view of current moderator chamber (left) to be replaced by a LDM. This is placed into the explosion-safe vacuum chamber (right)

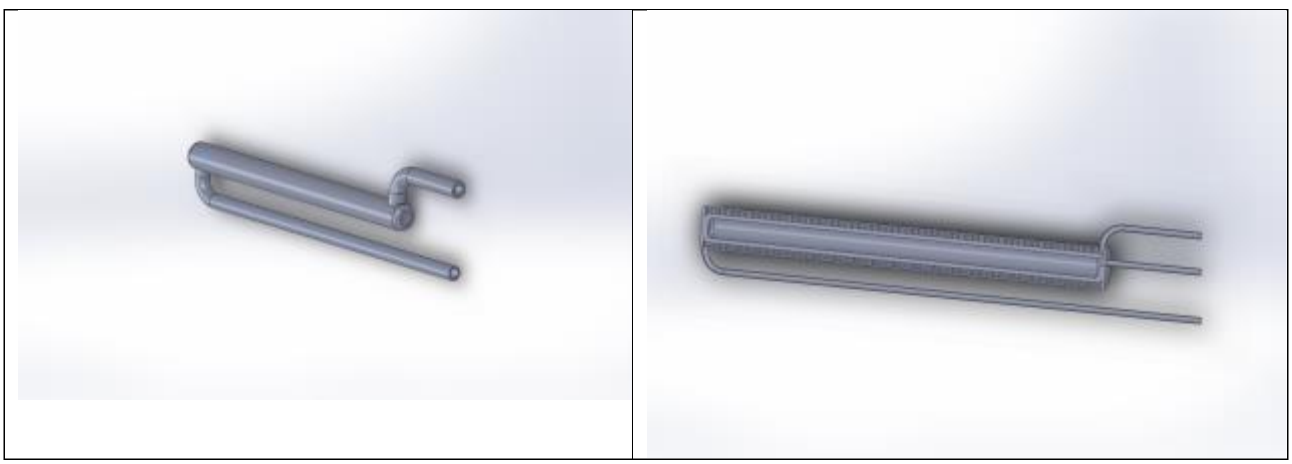

Figure 7.13: Tube type LDM configuration

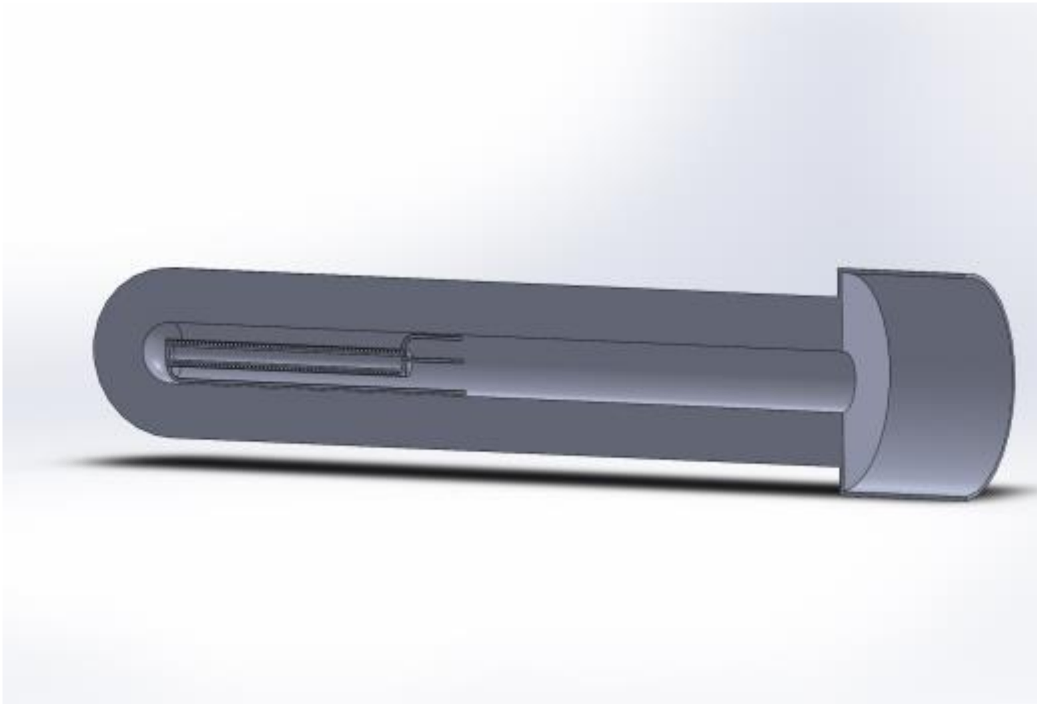

Figure 7.14: Tube type LDM in the explosion-safe vacuum chamber

8 Conclusion

The systematic approach in the experimental verification of the compact moderator concept at an existing/operating cryogenic hydrogen moderator - for the case of a rector neutron source – has shown a number of features which are to be considered as important factors influencing the design, fabrication and operation of the ESS compact moderator construction being implemented. At the cold neutron facility of the Budapest Research reactor a series of measurements has been performed to understand the ortho-para conversion features of hydrogen at nuclear heating conditions near to the reactor core. Very promising experimental results have been obtained, which will certainly greatly contribute to model the ESS moderator features as well as to elaborate a simplified scheme of a new CNS system for a reactor case. In particular, we assume, that a pre-cooling of hydrogen before the reactor power ramp-up the optimal para-hydrogen state can be preserved during the reactor operation. Thus, for a substantial modernization of the BRR cold source a compact moderator with para-hydrogen can be used without a complicated converter system. In the case of ESS, because of the very high power of the target, this option cannot be considered for a safe operation, the comparison of the two situations might, however, serve for interesting scientific-technical conclusions. Further investigation of the ortho-para conversion features is in progress. During the moderator tests at BNC it has been also understood that the monitoring of the homogeneity of the moderator as well as the beam take-off system has crucial importance. Thus, special care will be devoted to the design and construction of a test-beamline facility, which is also part of this WP. This device will be first tested at BNC, then it will be transported and installed at ESS as the first operated instrument there in order to serve with information on the source features for the construction of the ESS instruments.

Our MC simulations support the design of a LDM and for realistic fabrication-ready documents further engineering work is needed to optimize the neutron performance, calculate nuclear heat loads on the moderator chamber and thermo-hydraulic properties of the LDM cell. This work is in progress. The procedure itself performed at a real operating cold neutron facility, i.e. the modelling and parameter optimization with feedback to the engineering design and to technical solutions in fabrication is considered to be a useful contribution to the realization of the ESS moderator. In the coming period more dialog/interaction between the ESS team and the Hungarian experts is foreseen to exploit the results obtained so far and mutually advance common issues.

9 List of Publications

Rosta L. New advances in neutron techniques, Budapest Neutron Centre, CETS 2016, Neutron Training School, May 2-6, 2016

10 IPR Considerations

The novel concept of the LDM has been published by the ESS Neutronics team (Low dimensional neutron moderators for enhanced source brightness. Journal of Neutron Research, Vol. 17, No. 2, 2014, p. 101-105. Ferenc Mezei, Luca Zanini, Alan Takibayev, Konstantin Batkov, Esben Bryndt Klinkby, Eric Pitcher, Troels Schönfeldt and Unperturbed moderator brightness in pulsed neutron sources, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 729, Issue null, Pages 500-505 Konstantin Batkov, Alan Takibayev, Luca Zanini, Ferenc Mezei). The design and operation experience of the BRR cold moderator system is also of public domain. For MC calculations open codes (MCMP) have been used. The experiments performed at BRR to reveal ortho-para hydrogen features have resulted in valuable new procedures and approach for the engineering design, these are, however very specific and unique characteristics of the local BNC environment, so that no IPR relevance was considered. At the same time, innovative technological realisations in the fabrication of the prototype moderator chamber are envisaged, thus IPR protection might be envisaged in a later stage.