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2016-4-19

IL NUOVO CIMENTO **38 C** (2015) 192

Development of a moderator system for the High Brilliance Neutron Source project

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received 22 February 2016

Summary. — The project for an accelerator based high brilliance neutron source HBS driven by Forschungszentrum Jülich forsees the use of the nuclear Be(p,n) or Be(d,n) reaction with accelerated particles in the lower MeV energy range. The lower neutron production compared to spallation has to be compensated by improving the neutron extraction process and optimizing the brilliance. Design and optimiziation of the moderator system are conducted with MCNP and will be validated with measurements at the AKR-2 training reactor by means of a prototype assembly where, *e.g.*, the effect of different liquid H_2 ortho/para ratios will be investigated and controlled in realtime via online heat capacity measurements.

PACS 24 – Nuclear reactions.
PACS 29.25.Dx – Neutron sources.
PACS 28.20.Gd – neutron moderation.

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1. – HBS - High Brilliance Neutron Source

Research with neutrons, with its many diverse applications, requires a hierarchy of neutron sources from smaller and medium flux sources for education, user recruitment, method development, specialized applications and mere capacity to high flux sources such as the future European Spallation Source ESS for entirely new types of experiments which cannot be done elsewhere. In view of the ongoing decommissioning of medium flux research reactors, there is a need to develop new compact accelerator driven neutron sources (CANS) to complement ESS. These sources use nuclear reactions with primary particles in the lower MeV range. While these neutron production processes are less efficient than spallation, this disadvantage can partly be compensated by the fact that significantly less higher energy particles are produced, reducing the requirements for shielding and allowing to employ more efficient moderators and beam extraction systems.

In the HBS facility thermal and cold neutrons are extracted directly from the neutron density maximum within the thermal moderator by means of the innovative Finger Moderator. The geometric and moderating properties of the Finger Moderator are optimized towards brilliance according to the principle of low-dimensional moderators proposed for the construction of the ESS Butterfly Moderator [1].

Experiments to verify the MCNP model calculations will be conducted at the AKR-2 reactor at TU Dresden which is operated at a nominal power of 2 W providing 10^9 n/s with a full fission spectrum at the experimental channel. The prototype consists of a D_2O volume equally acting as thermal moderator and reflector (moderating reflector prototype, MRP) and is equipped with an optimized cold moderator. Thermal and cold beam extraction from the flux maximum within the MRP will be tested by energy spectroscopy via the TOF method. The AKR-2 was chosen due to its extremely well characterized neutron spectrum at different measurement positions [2].

2. – Thermal Finger Moderator

2·1. *MCNP calculations*. – In extensive parameter studies the optimal configuration is found to be a cylindrical Be moderator with $r = 31$ cm and $h = 41.4$ cm ($V = 125$ l). The Be target is located on the moderator front surface and both, target and moderator, are surrounded by a graphite reflector, see fig. 1 (left). In this configuration the maximum thermal flux is obtained on the symmetry axis of the cylinder at a depth of 9 cm.

To maximize the brilliance neutrons are extracted from the thermal flux density maximum inside the moderator rather than from its surface. Analogous to the streaming effect known from reactor physics, vacuum channels are implemented into the MRP originating from the point of maximum thermal flux. Such a configuration is referred to as a Finger Moderator. The impact of the vacuum channels are investigated in comparative simulations which utilize a simulation model described hereafter. Vacuum channels with 2 cm aperture are implemented at different positions, see fig. 1 (left). The angular distribution of thermal neutrons leaving the beryllium at the Finger opening is recorded and set in ratio to the angular distribution for the case of a filled Finger. Results are shown in fig. 1 (right) for the first 10°. The amount of thermal neutrons leaving the Finger in a cone with 1° aperture angle can be increased by up a factor of 6, depending on its position. This can be understood by considering the decrease of the thermal flux density

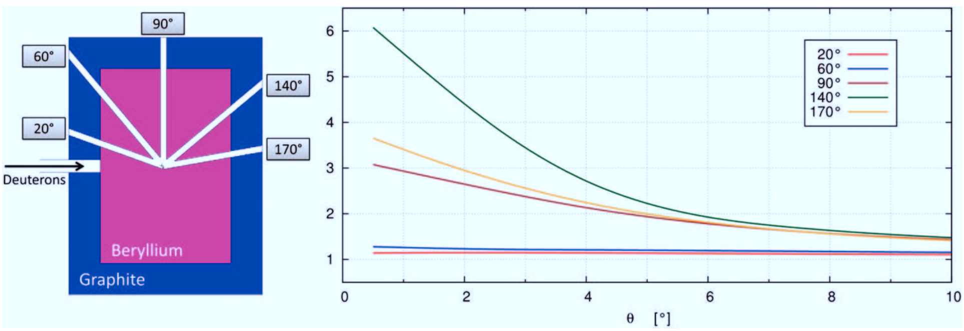

Fig. 1. – Left: 2D-cut of the moderator system MCNP model with different positions of the Thermal Finger. Right: gain of thermal flux (angle dependent with respect to Finger axis) compared to solid MRP surface.

towards the surface. Accordingly, the fraction of neutrons with radial direction decreases towards the surface as well. The objective of the Thermal Finger is therefore to extract neutrons with radial direction from the thermal flux maximum inside the moderator preventing these neutrons from further collisions and hence diverging.

2·2. *Experimental validation.* – A feasibility study was conducted at the TREFF instrument at MLZ (Garching). A cylindrical D_2O MRP ($r = 31\,\text{cm}, h = 35\,\text{cm}, V = 100\,\text{l}$) was fed with cold neutrons ($\lambda = 4.75\,\text{Å}, \lambda/2 = 2.38\,\text{Å}$ and $\lambda/3 = 1.58\,\text{Å}$ at a ratio of approx $22 : 6 : 5$) which were moderated to thermal equilibrium at room temperature. The Thermal Finger is inclined at 15° with respect to the cylinder axis. The detector was rotated around the intersection of the MRP axis and the Thermal Finger axis. Results in fig. 2 are fitted with a Gaussian distribution with a FWHM of 5° and 7° centered close to the exiting angle. The surface of the moderator itself is not emitting any significant amount of neutrons and the total flux is solely generated by the Thermal Finger.

The energy spectra were recorded by a Time-Of-Flight measurement using a three-window-chopper at the Thermal Finger beam window with 6667 rpm providing 3 ms pulses at the detector recorded in 100 time channels. The inset in fig. 2 shows energy spectra at the three different angles indicated by dotted blue lines. It can be seen that the main range is well spread over the thermal region in addition to a peak disrupting the regular distribution close to the energy of the incoming, undermoderated $\lambda = 4.75\,\text{Å}$ neutrons.

The feasibility study confirms the mechanism of the extraction process from the flux maximum of neutrons in the MRP and can be seen as a first indication for the working of the Finger Moderator principle until more sophisticated experiments have been made.

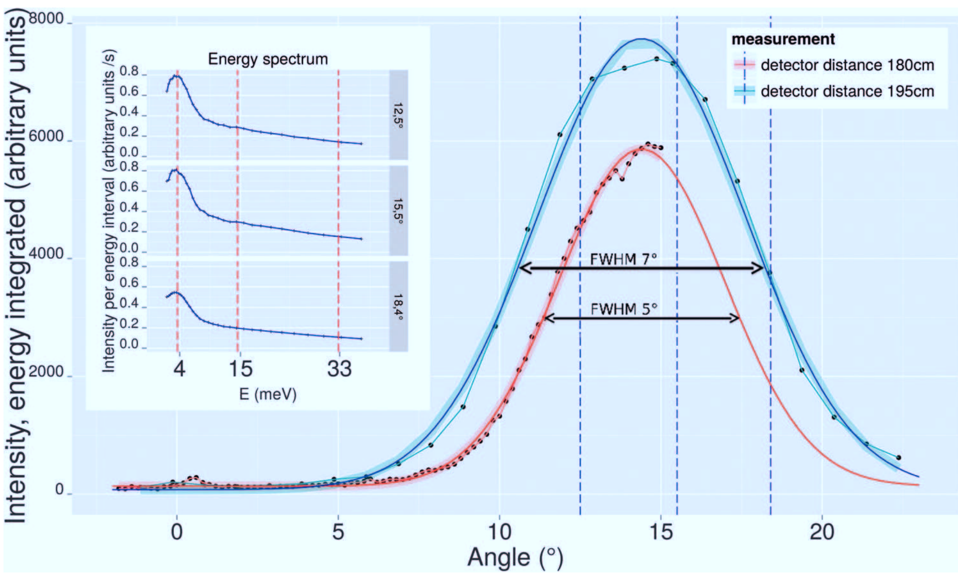

Fig. 2. – Angle-dependent neutron emission of the Thermal Finger. The dashed blue lines indicate the position of the energy spectra (inset). The dashed red lines in the inset indicate the energy of incoming neutrons.

3. – Cold Finger Moderator

Typical materials for cold moderators are liquid hydrogen and solid methane. The former exist in two different spin states (ortho and para). The scattering cross section of para-hydrogen exhibits a steep increase at 20 meV which implies that the mean free path for cold neutrons $L_\mathrm{c} \approx 10\,\mathrm{cm}$ is much larger than for thermal neutrons $L_\mathrm{t} \approx 1\,\mathrm{cm}$ [3]. This property can be exploited in terms of low-dimensional cold moderators as proposed for the ESS [1].

3˙1. *MCNP calculation.* – In our simulations a cylindrical cold moderator has been placed at the bottom of a Thermal Finger. The optimal values for length and radius of the cold moderator at 20 K are determined in terms of the highest cold neutron yield in forward direction on the outwardly directed surface of the cold moderator. Because of $L_\mathrm{c} \gg L_\mathrm{t}$, optimal moderator shapes of para-hydrogen tend to be rod-shaped with $l = 5\,\mathrm{cm}$ and $r = 1.5\,\mathrm{cm}$ while the best configuration for solid methane is more compact with $l = 2.5\,\mathrm{cm}$ and $r = 1.5\,\mathrm{cm}$. Simulations have shown that solid methane delivers a slightly higher cold neutron yield with a smooth maximum at 3 meV while the flux maximum in para-hydrogen is achieved at 8 meV due to the low scattering propability for neutrons below 10 meV, cf. [3].

3˙2. *Experiments planned.* – Verification of the MCNP calculations for the cold moderator are planned for the end of 2015 at the training reactor AKR-2 of the TU Dresden. The neutron extraction and measurement will be conducted similar to the feasibility study at MLZ but with a longer TOF flight path of up to 4 m. Measurements with solid methane, mesithylene, and liquid ortho/para H_2 are currently being planned. The ortho/para ratio will be controlled online via heat capacity measurement.

4. – Conclusion

MCNP calculations provide necessary parameters for the development of new compact accelerator driven neutron sources and all experimental data so far confirm their realiability up to the point of prototype construction. The lower energies proposed for the HBS neutron source enables simulations to exert its full potential for parameter studies in regions which are unfeasible in high-energy sources due to heat and radiation constraints. Geometric and pulse properties of moderating reflector and phase space of the neutron density can thus be shaped for specific purposes and instruments, with a brilliance to rival those of much bigger sources.

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