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2016 J. Phys.: Conf. Ser. 746 012036

(http://iopscience.iop.org/1742-6596/746/1/012036)

Journal of Physics: Conference Series **746** (2016) 012036 doi:10.1088/1742-6596/746/1/012036

High brilliant thermal and cold moderator for the HBS neutron source project Jülich

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Abstract. The proposed High Brilliance Neutron Source (HBS), recognized within the Helmholtz Association of German Research Centres, will optimize the entire chain from particle source through particle accelerator, target, moderator, reflector, shielding, beam extraction, beam transport all the way to the detector, utilizing the nuclear Be(p,n) or Be(d,n) reaction in the lower MeV energy range. A D_2O moderating reflector prototype (MRP) and a cold source were constructed and build according to MCNP parameter studies. The MRP was tested in a feasibility study at the TREFF instrument at MLZ (Garching). Cold beam extraction from the flux maximum within the moderator based on liquid para H_2 and other cold moderators will be tested by energy spectroscopy via TOF-method. Different ratios of liquid ortho/para H_2 will be fed to the cold moderator. The ratio will be controlled by feeding from reservoires of natural liquid H_2 and a storage loop with an ortho/para converter and determined via online heat capacity measurement.

1. Introduction

The continuing shutdown of research reactors in Europe and the simultaneous rise of the European Spallation Source (ESS) will increase the demand for medium flux neutron sources for simple capacity, medium flux experiments, education and instrument development. This demand for a wide fundament of sources in the neutron community can be met by compact accelerator driven neutron sources (CANS) as a network of multiple, local, medium flux sources, taking advantage of the recent developments in accelerator and neutron optics design to produce a brilliance to rival those of current medium flux reactors at a price tag affordable for a national project. The Jülich Centre for Neutron Science (JCNS) has proposed to build the High Brilliance Neutron Source (HBS) on the basis of a CANS design as a project recognized within the Helmholtz Association of German Research Centres as part of the German neutron strategy.

2. HBS - High Brilliance Neutron Source

The High Brilliance Neutron Source (HBS) plans to utilize the nuclear Be(p,n) or Be(d,n) reaction in the lower MeV energy range. Since much lower energies are used, compared to GeV spallation, much more sophisticated methods of neutron extraction can be employed, so that the brilliance at the sample should be able to reach levels comparable to those of medium flux research reactors. While in common neutron sources the neutron density maximum within the thermal moderator is highly delocalized (in the case of research reactors) or not accessible (spallation sources), in CANS one can place the neutron extraction mechanism, that is used to feed a neutron guide, right in the center of the neutron density maximum. In the case of the HBS this will be achieved by an extraction mechanism called (thermal and cold) Finger Moderator taking the principle of low dimensional moderator[6], to be applied at the ESS[3], to the maximum approaching a one dimensional "finger" shape.

2.1. Thermal moderating reflector

In the HBS concept there is no strict difference between a classical thermal moderator and reflector, since the materials in the simulation found to be most efficient (graphite, D_2O and beryllium) have high scattering and low absorption cross sections in the reference energy range, thus fulfilling both tasks at the same time. Classical hydrogen rich thermal moderators like light water or polyethylene were found to be contra productive due to their high absorption cross section, compared to the previously mentioned moderating reflector materials. In current spallation sources, light water premoderators of a few centimeters are used to moderate the incident fast neutrons within a small distance. These premoderators play a role in the upcoming ESS moderator too, where their heat removal capabilities are also very convenient from an engineering point of view. In the HBS, however, the lower neutron energies decrease the necessity of hydrogen based thermal moderators and make it possible to omit them completely, saving absorbing material in the center of neutron density.

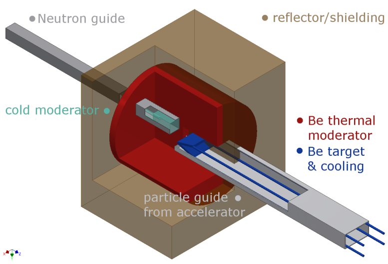

Figure 1. Sketch of target/moderator combination. 125l Be volume, water cooled multipurpose target from LNL[7] and graphite reflector/shielding.

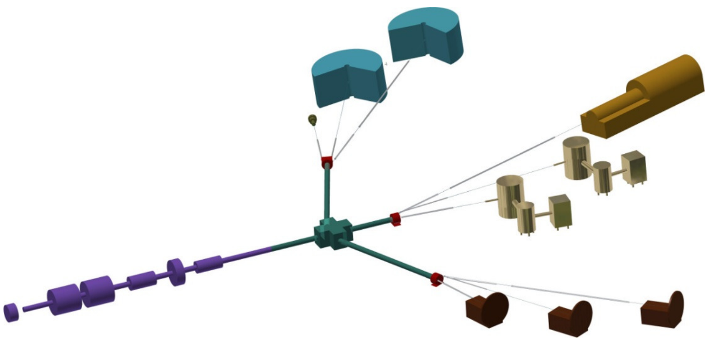

Figure 2. Sketch of a possible HBS facility. One accelerator feeds different target/moderator stations, emitting different puls lengths and neutron energy spectra.

2.2. Cold Finger Moderator

A cold neutron source (Cold Finger Moderator) was designed according to parameter studies of NET and constructed by ZEA 1 - Jülich to be inserted into the Thermal Finger of the moderating reflector. The dimensions are optimized according to the principle of low dimensional moderators proposed for the ESS[3] to be used with liquid para H_2, whose mean free path for energies above 15meV is of the order of 1cm and below 15meV of 10cm[2].

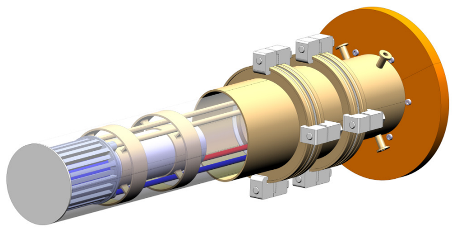

Figure 3. Cold Finger Moderator to be inserted in the moderating reflector prototype.

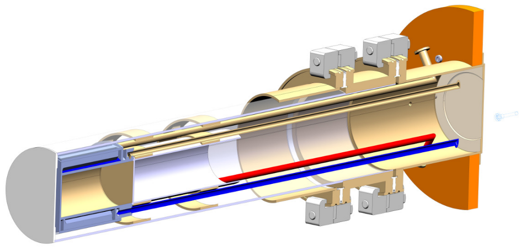

Figure 4. Vertical cut through the Cold Finger. Helium intake (blue) and outtake (red) are located at the bottom.

Fed from all sides with thermal neutrons, a preferred direction for cold neutrons to exit the finger along its alignment axis will be established. Each Cold Finger Moderator fulfills the role of a cold neutron source serving only one beamline and its instruments. Therefore the cold source can be specifically tailored to the needs of a certain instrument and provide neutrons with the needed phase space and energy distribution (e.g. flat vertical liquid H_2 vessel with small divergence in horizontal direction for reflectometry). In addition, neutron lenses can be used directly at the source to decrease divergence and/or enhance the flux.

2.3. Ortho/para configurations

The peak in energy distribution of neutrons emitted from a pure liquid para H_2 moderator is 5meV higher than those of a solid methane moderator, making solid methane more suitable for a majority of scattering applications if only moderating properties are taken into account. By increasing the amount of ortho H_2 in the moderator volume the energy peak can be shifted to lower temperatures at the cost of total flux. In addition, any moderating volume of H_2 will undergo conversion from ortho to para and para to ortho by induced heat from the scattered neutrons and natural conversion at low temperatures, so that in all practical cases one will rarely have a pure, homogeneous para state. However, mixtures of ortho/para H_2 are difficult to simulate using MCNP, so that we will aim to measure these properties experimentally. In addition to feeding the Cold Finger Moderator with pure para and natural H_2, we will also install a storage loop with a catalyst producing pure para H_2 to be mixed with natural H_2 gas, which will be condensed in the cold moderator vessel. The ortho/para ratio of the inserted gas will be controlled by heat capacity measurement of gas samples drawn during the measurements in realtime.

2.4. Time structure

Due to the rather large volume of the moderating reflector the time the neutron cloud stays within the moderator would seem rather large at first sight. However, since the Finger Moderator is extracting neutrons from within the moderator rather than from its surface, neutrons do not spend many collision processes in thermal equilibrium, but are extracted shortly before or after they reach energies equivalent to room temperature, thus shortening the overall pulse. First simulations show that 90% of the emitted thermal and cold neutrons leave the moderator after 0.02-1ms. Further simulations on that matter will be made, when we will be able to verify them at a suitable pulsed neutron source.

3. HBS Moderator test at the AKR-2

The MCNP calculations of NET of RWTH Aachen and MLZ will be validated at the AKR-2 reactor at TU Dresden which provides a source strength of 10^8 n/s with the fission spectrum delivered to our prototype moderator surface. The AKR-2 was chosen due to its extremely well characterized neutron spectrum calculated with MCNP by TU-Dresden (last update 2015) and verified experimentally in the epithermal and fast energy regime by measurements with scintillation technique (800keV - 12MeV), recoil proton proportional counters (20keV - 5MeV) and Bonner spheres (<20keV)[1]. The nominal thermal power of 2W and the relatively low flux guarantee that thermal energy transfer to the cold moderator, activation of the components used, radiation damage and tritium production in the D_2O are negligible.

3.1. Cold source

The Cold Finger Moderator prototype consists of a reservoir of 120ml (r=2.5cm, h=6cm) and a He heat exchanger inside an Al vacuum tube of 3.5cm outer radius. If the radius would have been optimized on brilliance alone, the radius should have been reduced even further at the cost of integral flux. But to create a flux suitable enough for the experimental validation (order of 10^3 cold neutrons per second at the detector position) at the AKR-2 and for manufacturing purposes the radius of 2.5cm was chosen. The final design is suitable not only for liquid H_2 but also for solid methane, mesithylene and comparable candidates for cold moderators. Those cold moderators would be ideal with other geometries (lower height of the cylinder), according to the simulations, but due to comparability of different moderator types by a given geometry and practical purposes this fixed final geometry was chosen and produced. The design profits from the conditions at the AKR-2, where the thermal energy intake by the neutrons scattered in the liquid H_2 is negligible and the whole setup is operated at 1.5bar H_2 and 1bar He pressure, so that the wall thickness can be considerably reduced compared to the supercritical ESS setup. However, the Cold Finger Moderator was tested up to 5bar and tests from the cold source of the Budapest Research Reactor[5], which is similar in size, show, that cooling in the region of 300W cooling power is feasible. Therefore, no engineering changes in the design would have to be done for the current prototype to be used in a medium flux source. The Cold Finger Moderator can be changed within 30min and the condensation time can be significantly reduced if needed.

Figure 5. Cold moderator vessel, leakage test during welding 10^{-9}mbar/s at 3bar He pressure and 500-77K temperature.

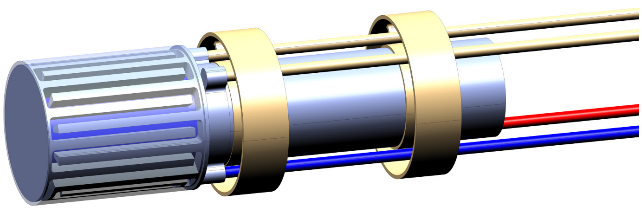

Figure 6. Cold Moderator Vessel with insulating spacer. Helium intake (blue) and outtake (red) at the bottom.

3.2. Experimental validation

A feasibility study was conducted at the TREFF instrument at MLZ (Garching). The cylindrical D_2O moderating reflector prototype (MRP) ($r = 31cm, h = 35cm, V = 100l$), designed for the test at AKR-2, was fed with cold neutrons ($\lambda = 4.75\mathring{A}, \lambda/2 = 2.38\mathring{A}$ and $\lambda/3 = 1.58$ at a ratio of approx 22 : 6 : 5) which were moderated to thermal equilibrium at $E = 26meV \hat{=} 1.8\mathring{A}$. The Thermal Finger is inclined at 15° with respect to the cylinder axis. The detector was rotated around the intersection of MRP axis and Thermal Finger axis. Results in (Fig. 7) are fitted with a gaussian distribution with a FWHM of 5° and 7° centered close to the exiting angle. It is noted, that the surface of the moderator itself is not emitting any significant amount of neutrons and that all flux is solely generated by the Thermal Finger.

The energy spectra were recorded by TOF method using a three-window-chopper at the Thermal Finger's beam window with 6667rpm providing 3ms pulses at the detector recorded in 100 timechannels. The inset in Fig. 7 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 $\lambda = 4.75\mathring{A}$ beam.

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 indicator for the working of the Finger Moderator principle until more sophisticated experiments have been made.

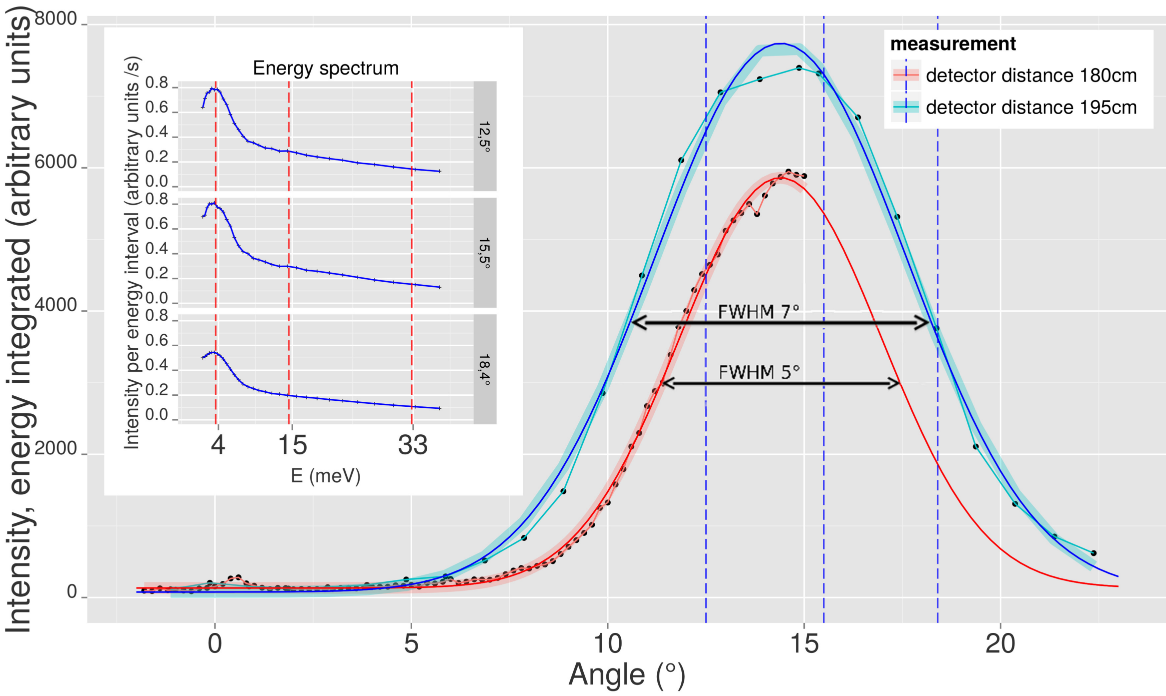

Figure 7. Angle dependent emission of Thermal Finger. The dashed blue lines indicate the position of the energy spectra (inset). The dashed red lines in the inset indicate the energy of incoming neutrons.

4. Conclusion

Making a CANS compatible in brilliance to a medium flux reactor or spallation source is all about gain factors, which are allowed in CANS and forbidden in others sources due to high energies and radiation damage. MCNP simulations have shown[4], that with the Thermal and Cold Finger extraction mechanism in a Be thermal moderator we can already gain orders of magnitude in bridging the gap between spallation and nuclear Be(d,n) reactions without taking the advantages of beam transport into account. The experiments at AKR-2, which will start in October 2015, will not only validate the simulations, but also enable cold moderator tests, which can not easily be simulated and provide a first version of an advanced moderator prototype.

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