Nuclear Instruments and Methods in Physics Research A 608 (2009) 434–439

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

New aspects for high-intensity neutron beam production

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ARTICLE INFO

Article history:
Received 15 July 2009
Accepted 21 July 2009
Available online 29 July 2009

Keywords:
Neutron physics
Ultra-cold neutrons
Neutron sources

ABSTRACT

Neutron scattering is an important tool for the investigation of static and dynamic structures of matter. As it is an intensity limited technique, many attempts have been made to increase the effective beam intensity. High neutron intensities or, more precisely, high phase space densities of neutrons can be obtained at low energies only. Such ultra-cold neutrons can be trapped inside material and magnetic bottles. When neutrons of such densities become up-scattered, highly intense, monochromatic and pulsed beams can be produced, whose intensities can overcome limitations imposed by the classical neutron source strength. We report a recent experiment that demonstrated this alternative, to our knowledge, for the first time ever. Perspectives resulting from this development of highly intense neutron beam production will be discussed. A stationary ultra-cold neutron gas produced becomes transformed into a pulsed and monochromatic cold neutron beam.

1. Introduction

Traditional neutron sources are based on research reactors where fission neutrons are slowed down in a moderator to thermal energies. Heat removal from the reactor core defines the achievable neutron flux. Advanced neutron spallation sources where the time-averaged heat production per neutron is less and where the source can be easily operated in pulsed mode have therefore been developed. Nevertheless, progress in flux increase remains moderate and therefore additional efforts are directed at improvements in the performance of neutron guides, beam optics and detectors. New developments at ISIS (GB) and SINQ (Switzerland) and new sources like SNS (US) and J-PARC (Japan), as well as the new ESS project, favour the use of the spallation method to reach peak fluxes beyond $10^{17}\,\mathrm{cm^{-2}\,s^{-1}}$. There as well, the main limitation lies in the associated heat production within the target due to the intense proton beam and spallation. The situation for recently discussed fusion-based neutron sources may have similar problems and may be speculative since inertial fusion systems are not operational yet (Fig. 1) [1]. In this paper we present a method that can complement and improve the performance of existing and upcoming dedicated neutron sources for specific applications.

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doi:10.1016/j.nima.2009.07.030

2. Basic principle

For neutron scattering experiments, the flux within a certain velocity band and angular range incident onto the sample is of relevance, i.e. the brilliance [2]. Therefore, not the integrated but the directed flux has to be increased. In this context an alternative neutron beam production method is discussed. In a first step the phase space density is increased by advanced down-scattering methods towards ultra-cold neutron energies in superfluid helium-4 [3,4] or in solid ortho-deuterium [5–8]. Ultra-cold neutrons (UCN) have kinetic energies below 0.3 μeV, velocities below 8 m/s and wavelengths of about 500 Å and can be stored in material and magnetic bottles because total reflection is guaranteed for all angles of incidence [9]. In a second step the neutrons of high phase space density are shifted to higher energies by a phase space transformer device (PST) [10] (Fig. 2). Whereas down-scattering of neutrons by fast-moving crystals [11–13] or turbine plates [14] has been reported, the up-scattering method has not been tested yet, even though only in this case a gain in phase space density can be expected. A related proposal using fast-rotating turbane plates has not been tested yet [15]. The phase space transformation without shifting the average beam energy has been successfully implemented for a back-scattering instrument at NIST [16].

The basic relations for phase space transformation can be summarized in the following way: The number of neutrons (mass m) within a phase space volume $dx\,dy\,dz\,dv_x\,dv_y\,dv_z$ behind a moderator may be approximated with a Maxwell–Boltzmann

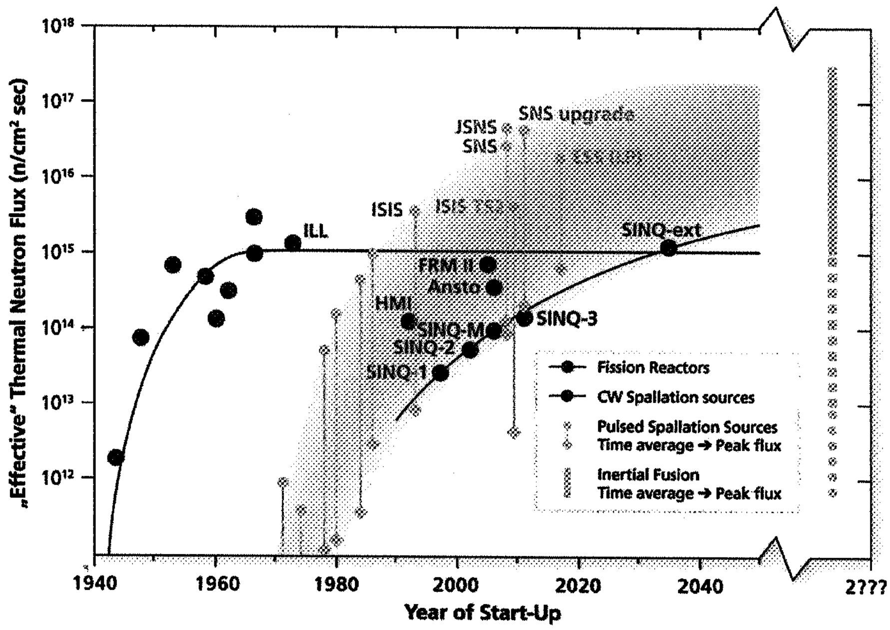

Fig. 1. Thermal neutron flux at optimal positions at research reactors and spallation sources. Courtesy of Kurt Clausen/PSI.

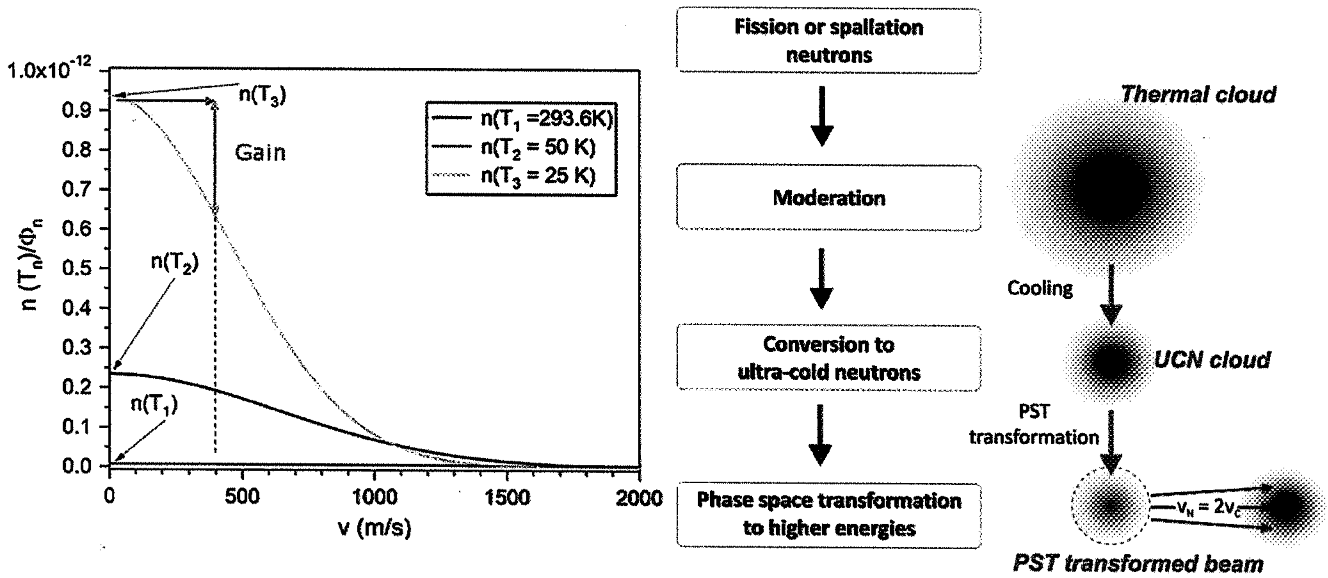

Fig. 2. Phase space density of neutrons at different temperatures (left) and principle of phase space transformation (right).

distribution as [17]

$$n(T) = \frac{\mathrm{d}^6 N(T)}{\mathrm{d}V_\mathrm{p}} = \frac{\rho(v,T)}{4\pi} = \frac{\phi_n}{2\pi v_\mathrm{T}^4}\exp\left(-\frac{v^2}{v_\mathrm{T}^2}\right).$$

The most probable velocity v_T is related to the temperature T of the neutron spectrum ($T = mv_\mathrm{T}^2/2k_\mathrm{B}$, where k_B is the Boltzmann constant), which is slightly above but similar to the temperature of the moderator and Φ_n denotes the total neutron flux. For UCN ($v \ll v_\mathrm{T}$), the related gain factor in case of cooling the moderator, which changes the neutron temperature as well ($T_2 < T_1$), can be written as $G_\mathrm{UCN} = T_1^2/T_2^2$ (Fig. 2). The phase space density, which denotes the number of neutrons within the elementary phase space volume $\Delta r \Delta k = (1/2)$,[3] has for usual neutron sources the order of 10^{-15}. Due to inelastic down-scattering processes in helium-4 or ortho-deuterium, which are essentially non-Liouvillian, intensity gain factors of 100–1000 can be anticipated. Subsequently, the phase space density of such an ultra-cold neutron gas can be shifted to higher energies by means of a suitable phase space transformer (Fig. 3). The gain factor related to the phase space transformation is $(n(v{\sim}0,T) - n(v,T))/n(v,T)$, which strongly increases when the final velocity increases (Fig. 2). An isotropic gas is accelerated into one direction with a final momentum resolution determined by the original UCN gas. Its final divergence is determined by the speed of the PST and the velocity distribution of the UCN gas. Thus the velocity (momentum) width equals the velocity (momentum) width of

Fig. 3. Experimental arrangement of the rotating phase space transformer showing the entrance tube of the UCN and the exit tube of up-scattered neutrons (left). Model of a double arm rotor (right).

the UCN gas ($\Delta v_n = \Delta v_{UCN}$) but the energy width increases as $\Delta E_n = \Delta E_{UCN}(1+2v_n/\Delta v_{UCN})$. Such up-scattering can be accomplished by inverse Bragg diffraction from a fast-moving single crystal. When back-scattering is considered, the following relation between the velocity of the reflecting crystal (v_c) and the lattice constant (d) holds:

$v_c = h/md_{h,k,l}$ i.e. $v_c\,(\mathrm{m/s}) = 1978/d_{h,k,l}\,(\text{Å})$.

The up-scattered neutron velocity becomes $v_n = 2v_c$. High linear velocities, which would be necessary for an exact fulfilment of the Bragg condition across the reflecting crystal are technically difficult to achieve. Therefore, we performed the first measurements with fast-rotating crystals, where v_c depends on the rotation frequency ν and the distance r from the rotation centre ($v = 2\pi\nu r$). In this case the above condition is only fulfilled for a small region of the crystal having distance r from the rotation centre, which corresponds to the velocity v_c. Due to the rotational motion the crystal deflects neutrons into a rather broad angular range, which is also a drawback of a rotating system in comparison with a linear moving PST.

3. Apparatus

In order to keep the mechanical stress from rotational velocities within reasonable limits, we used stage 2 intercalated graphite compounds with potassium and with a lattice constant of $d_{h,k,l} = 8.74$ Å and a mosaic spread of about 5.5° (i-HOPG) [18]. Stage 2 means the alternation of two graphite layers with one potassium layer. For the back-reflection condition this requires a crystal velocity of $v_c = 226$ m/s and produces cold neutrons with a wavelength of 8.74 Å.

We have performed experiments at the ultra-cold neutron facility PF2 at the high-flux reactor of the Institut Laue-Langevin in Grenoble [14]. A standard rotation unit from Schenck RoTec Company in Darmstadt/Germany has been adapted to up-scatter UCN when they just leave the guide tube (Fig. 3). Four i-HOPG crystals boxed into indium-sealed aluminium cassettes were mounted on the rotor with radius 32.5 cm. This gives at the optimal speed (6600 rpm, $v_c = 226$ m/s) a time sequence of pulses every 2.27 ms and a pulse width of 0.28 ms determined by the number of time the rotating crystal hits the UCN gas. The cassettes with the crystals could be tilted up to 6° out of the exact back-reflection position aiming to enhance the reflectivity and to account for the filling procedure of UCN, which comes from one side only. The horizontal angular width of the obtained cold neutron beam is dominated by the angle of revolution of the crystal while illuminated by the UCN emerging from the guide (about 14°). The vertical divergence of the beam (about 1°) is determined by the mosaic spread of the crystal and the vertical velocity component of the UCN gas.

Detailed Monte-Carlo calculations have been performed to compare the efficiencies of such a PST with rotating and linear PST systems [19]. The velocity distribution of the UCN gas behind the UCN guide tube, the reflectivity and the mosaic spread of i-HOPG crystals, crystal positions and geometrical factors were taken into account. Efficiencies of 5–7% have been calculated for the rotating system and up to 30% for the linear motion system, which could be realized using a double-arm rotor [20].

4. Results

Already first non-optimized test runs showed the appearance of Bragg peaks at the expected rotation frequency of 6600 rpm (Eq. (2)). Typical results are shown in Fig. 4 [21]. Optimal intensities appeared when the crystals were inclined by about 6° to the exact Bragg back-reflection position. In a time-resolved measurement the four peaks corresponding to the four crystals mounted at the rotation unit have been measured (Fig. 5). The rather high counting rate and the pulsed structure of the beam are visible. The slight intensity differences of the 4 peaks result from different reflectivities of the crystals. The monochromaticity of the

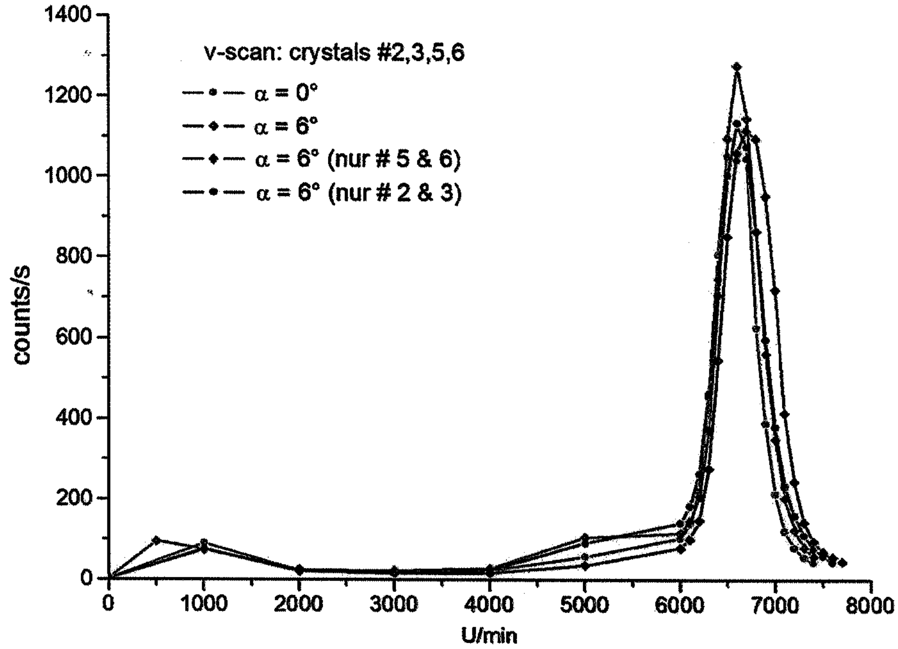

Fig. 4. Up-scattered neutron intensity as a function of the speed of the rotor (in rpm) for different combinations of crystals mounted at the rotor and for different angles relative to back-scattering.

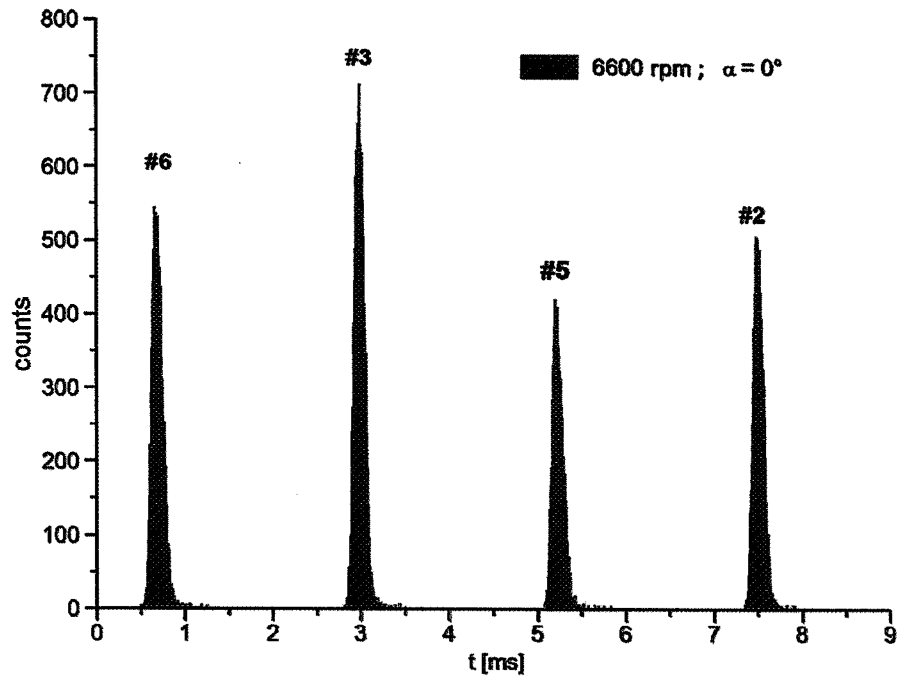

Fig. 5. Time resolved up-scattered intensities from four different crystals.

beam is determined by the velocity spread of the UCN cloud and is decoupled from the time resolution and amounts to $\Delta v/v = 0.34\%$. Small contaminations from the stage 3 ($d = 12.10$ Å) compound (up to 10%) have been observed at 5000 rpm. Measurements with only 2 crystals mounted on the rotor indicated that the "filling" time of the volume in front of the reflecting crystals is less than 2.27 ms, the time sequence of pulses when 4 crystals are used. The repetition rate can be chosen as 440 Hz when 4 crystals and 220 Hz when 2 crystals are operational. A position-sensitive detector has been used to register the spatial and angular structures of the beam (Fig. 6). The calculated time-averaged cold neutron flux in the centre of the beam is about 350 cm^{-2} s^{-1}. The UCN flux at the guide tube exit has been measured with gold foils yielding a neutron flux of about 5880 cm^{-2} s^{-1}. This results in an efficiency of the PST system of about 7% confirming the previously mentioned Monte-Carlo calculations.

5. Discussion

It can be concluded that up-scattering of ultra-cold neutrons by means of phase space transformation is an apt tool for producing highly monochromatic pulsed beams of cold neutrons with high brilliance. This method can even be extended to the

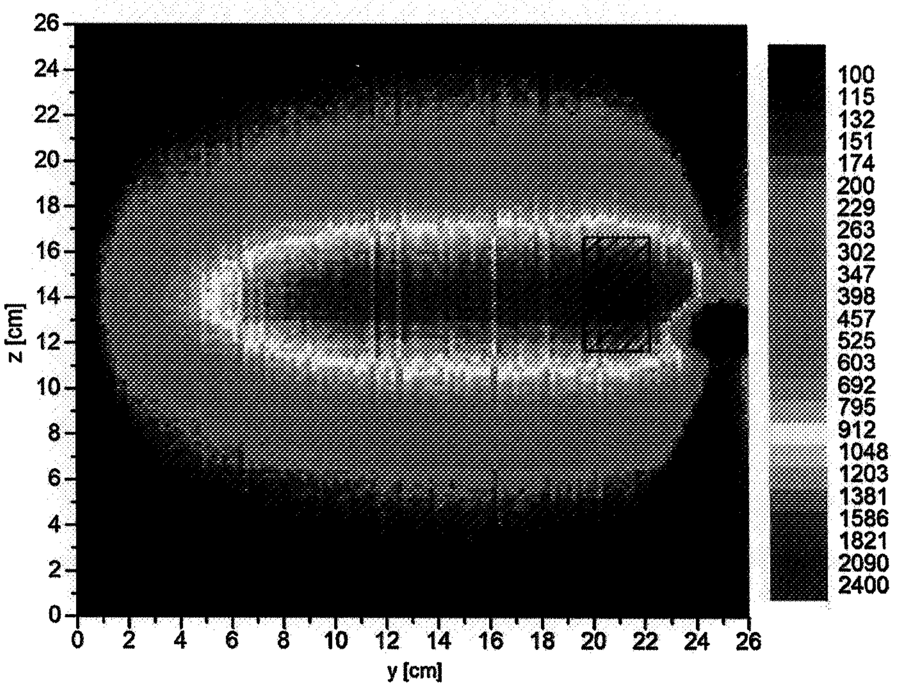

Fig. 6. Beam profile at the exit guide measured by means of a position sensitive detector.

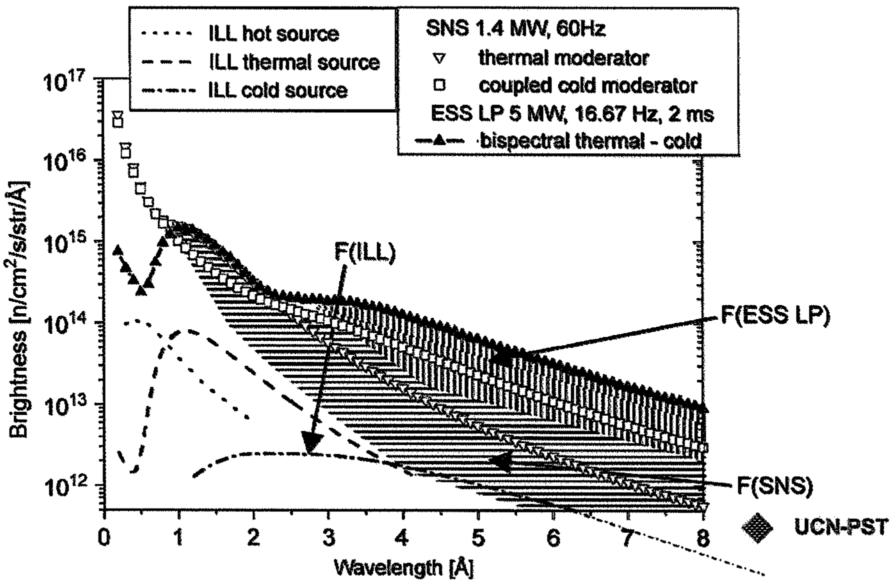

Fig. 7. Comparison of brilliances of peak fluxes at different existing and upcoming neutron sources [2].

production of thermal beams when higher velocities and linear motions of the phase space transformer crystal can be achieved. Various further improvements are feasible and must be taken into account when discussing the future of advanced neutron beam production. The following estimates are based both on analytic and Monte-Carlo calculations:

(a) A fast quasi-linear motion can be achieved by means of a double-arm rotation unit. In this case the Bragg condition will be fulfilled for the whole reflecting crystal. This will result in an intensity gain for brilliance by a factor of 4 (see Monte-Carlo calculations).
(b) A quasi-translational motion will scatter the neutrons into a smaller angular range, which results in a gain factor of at least 5 (see Fig. 6).
(c) Since only a small fraction of the UCN emerging from the UCN guide hits the crystal, the rest gets lost between the crystal paddles. By means of a back-reflecting plate below the rotor these UCN can be redirected and up-scattered by one of the next crystals. This gives a further gain factor of about 5.
(d) Next generation UCN sources are supposed to produce up to 100 times higher intensities than the existing source at ILL (see Refs. [4–8]).

These estimates show that mean intensities up to $3.5\times10^6\,\mathrm{cm^{-2}\,s^{-1}}$ in a highly monochromatic pulsed beam with a brilliance of $4.5\times10^{11}\,\mathrm{cm^{-2}\,s^{-1}\,str^{-1}\,\mathring{A}^{-1}}$ can be generated by phase space transformation of a dense UCN gas. This value is notably above intensities at well-known spectrometers as IN5 at ILL, TOFTOF at Munich or CNCS at SNS. Fig. 7 shows a comparison between existing and planned neutron high-flux facilities [2]. When the phase transformer will be used in combination with the newly developed spallation sources, even higher gain factors can be anticipated.

An optimal version of such an UCN–PST facility could be accomplished with a next generation neutron source delivering UCN into a large storage vessel ($>1\,\mathrm{m}^3$) from which the PST "shovels" UCN and accelerates them into cold neutron guides. There is also the possibility to bounce the cold neutrons back onto one of the following rotating i-HOPG crystals and reflecting them at higher diffraction order. In this case a final velocity of 4 times the rotation velocity can be achieved. However, reflection losses would reduce the gain factor by about 40%.

Consequently, up-scattering of UCN may become an attractive method to produce highly monochromatic pulsed neutron beams. Installation of such systems can upgrade existing neutron sources and their integration in new upcoming neutron facilities can open new horizons for advanced neutron research.

Acknowledgements

The support provided by the Schenck RoTec Company in Darmstadt/Germany and by the ILL staff is gratefully acknowledged. The project has been financially supported by the European Commission under the 6th FP (NMI3-NO-PST), Contract no: RII3-CT-2003-505925 and by the Austrian Science Foundation FWF (Project F1514).

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