Depth-graded multilayers as neutron Doppler converters at pulsed neutron source

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ABSTRACT

A moving diffractor changes the energy of elastically diffracted neutrons by the Doppler effect. Depth-graded multilayers can diffract neutrons over a large band of energy. Using a pulsed neutron source, such a depth-graded multilayer, decelerating synchronously with the incident neutron pulse, can shift the reflected neutrons into a compressed energy window. This focusing in energy is associated with a broadening of the pulse in time, but the process does not involve a significant decrease in the neutron phase-space density. The proposed method can be used to design long pulse or quasi-continuous sources of cold, very cold or ultra cold neutrons (UCN). The analysis concentrates on enhanced production of UCN at pulsed neutron sources.

Keywords: multilayers, Doppler converters, ultra cold neutrons, pulsed neutron source

1. INTRODUCTION

Shull & Gingrich[1] and Buras & Giebultowicz[2] were the first to investigate neutron Bragg diffraction from moving lattices. This phenomenon leads to many specific applications in neutron scattering instrumentation. An example is the NIST backscattering spectrometer[3], which includes two moving crystal devices: the Doppler-driven monochromator and the phase space transformation chopper. All devices using moving crystals exploit the change of neutron energy and direction due to the Doppler effect. If the crystal velocity is comparable with the neutron velocity it is possible to slow down neutrons to very cold (VCN) or ultra cold energies (UCN). The generation of UCN using moving crystals[4-7] is drastically limited by the narrow energy band-pass of the crystal, which leads to a small generation volume at pulsed neutron sources.

The concept of depth-graded multilayers was first proposed for neutron optics under the name of supermirrors[8] to enhance the angular band-pass of neutron guides, but wide energy band-pass can also be obtained by Bragg diffraction at high angles. In conjunction with the Doppler effect, the Bragg diffraction on depth-graded multilayers opens up new possibilities for generating VCN and UCN at pulsed neutron sources. Recent papers[9,10] describe rotating devices with multilayer reflecting blades (named converters or shifters) able to transform a long pulse periodical sequence of cold neutrons bursts into a quasi-continuous UCN source. Inspired by these developments the present paper will discuss the case of a depth-graded multilayer decelerating synchronously with the neutron pulse.

2. DECELERATING DOPPLER CONVERTER

We consider a depth-graded multilayer perpendicular to the main neutron beam direction determined by a straight neutron guide. The distance from a pulsed source to the multilayer at time t_0 after the neutron burst is L_0. This means the neutron velocity of neutrons reflected by the multilayer should be around $v_{n0} = L_0/t_0$. If the multilayer velocity at this moment is v_0 backward from the neutron source, then the multilayer average spacing should be $d_m = (h/m)/(v_{n0} - v_0)$ and the neutron velocity after reflection would be $v_{f0} = v_{n0} - 2v_0$. The idea of the decelerating converter is to move the multilayer along the incoming neutron path in correlation with the velocity of the neutrons arriving at a given time-of-flight, t, in order to keep constant the velocity of the reflected neutrons. The simple classical mechanics solution of this problem is:

$$\frac{v}{v_{n0}} = \frac{1+k}{2}\sqrt{\frac{t_0}{t}} - k \;\; ; \; \frac{x}{L0} = (1+k)\sqrt{\frac{t}{t_0}} - k\,\frac{t}{t_0} \qquad (1)$$

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where x is the multilayer coordinate and v is the velocity at time t after the neutron burst, and $k = v_{f0}/v_{n0}$ is the average velocity reduction factor. Curves generated from these equations are shown in Fig. 1. When $k = 1$, the average neutron energy remains unchanged. When $k = 0$, the final energy becomes 0. This is the case for UCN generation.

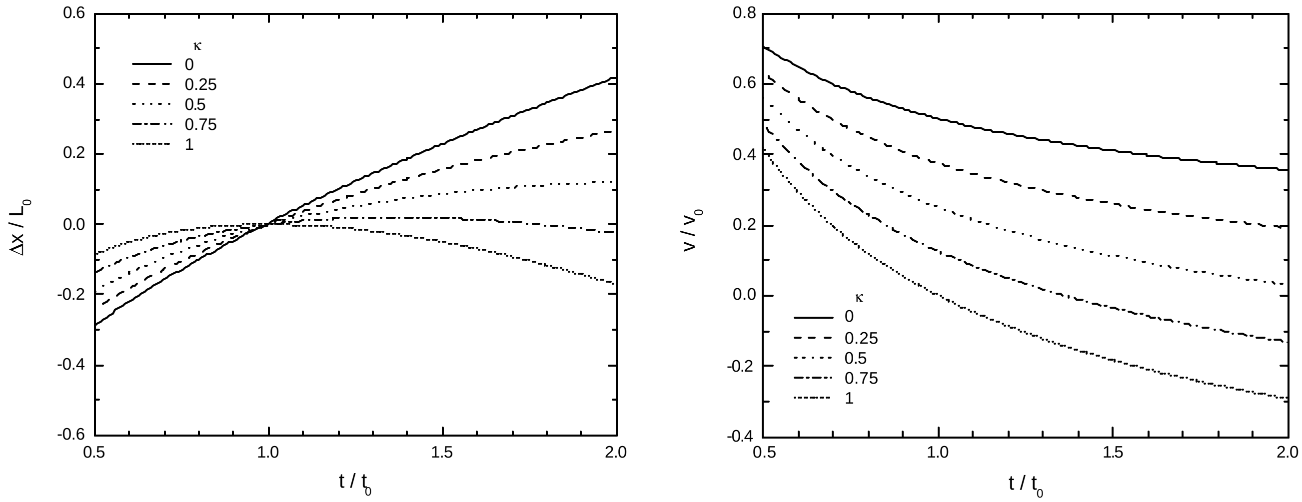

Fig. 1. Equations of motion for decelerating Doppler converter (a – distance, b – velocity)

To understand the conversion process it is necessary to use time-velocity diagrams. Let us consider a rectangular neutron pulse with, Dt_0, width, and a depth-graded multilayer with a relative spacing range $(Dd/d)_m$. Then we can calculate in the time-velocity plane the band corresponding to the incoming neutrons and the acceptance band of depth-graded multilayer. The area defined by the intersection of these two bands represents the incoming neutron time-velocity range ready to be converted by the Doppler effect. A similar picture can be constructed after reflection of neutrons from the converter. Figure 2 demonstrates the change in the time-velocity acceptance window for the case of constant average energy ($v_{n0} = v_{f0}$). For Dt_0/t_0 and $(Dd/d)_m$ the extreme values of 0.01 and 0.05 were considered in order to enhance the visual representation.

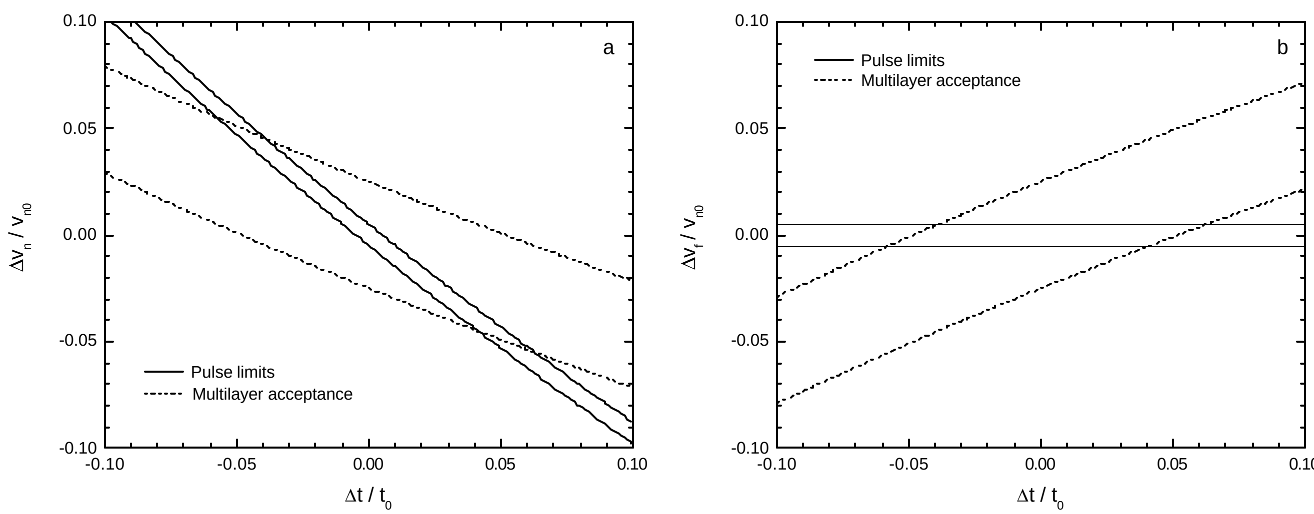

Fig. 2. Time-velocity acceptance windows for constant average energy (a – incoming beam, b – reflected beam)

The relative width of the velocity distribution after reflection, Dv_f /v_{n0}, is given by the relative time of flight spread, Dt_0/t_0, which is considerably smaller than the relative multilayer band-pass $(Dd/d)_m$. The last one determines the relative width of the pulse after reflection leading to a dramatic increase of the time width (a factor of 10 in Fig. 2). This is the cost of shrinking the velocity band by a similar factor as demanded by phase space density conservation. However it should be noted that conservation of the peak flux is close to unity if the depth-graded multilayer reflectivity is considered.

By considering an average velocity reduction factor, $k < 1$, the slope of the curves in Fig. 2a are correspondingly reduced down to the half of that for $k = 0$. If the final velocity values are divided by v_{n0} the picture from Fig. 2b stays unchanged. This means that the neutron beam velocity spread and time pulse width are roughly given by the following relations:

$$\Delta v_f^{FWHM} = v_{n0} \frac{\Delta t}{t_0}, \ \Delta t_f^{FWHM} = 2t_0 \left(\frac{\Delta d}{d} \right)_m \tag{2}$$

Thus, using a Doppler converter, we can produce long pulses of monochromatic cold neutrons, VCN and UCN at a short pulse neutron source with a high peak flux. Moreover, if the flight path is long enough and the multilayer band-pass wide enough then the pulse width becomes comparable to the primary neutron burst interval, thus obtaining a quasi-continuous monochromatic neutron source with a flux corresponding to a continuous neutron source with the same steady-state flux as the peak flux of the pulsed source.

2. GENERATION OF ULTRA COLD NEUTRONS

An UCN Doppler converter selects a phase space volume centered about an incident velocity in the cold or very cold energy range and transforms it to a velocity centered on zero. The reason for using such a device, rather than extracting the UCN directly from the moderator, is that the UCN, with velocities of less than 6 m/s, take a very long time, and also a very large number of wall collisions in a guide, before they reach an experimental staging area. Direct extraction is especially inefficient in a pulsed source, because it effectively uses the time average phase space density.

Another approach to UCN production at a pulsed neutron source is to move a down-scattering converter, consisting of a relatively thin layer of moderator material and a neutron storage container, during the pulse[11]. This method generates neutrons in the converter with considerably higher energy than the UCN limit. The converter is then stopped, and these neutrons become UCN by the Doppler effect and are trapped inside the container. Such a converter can generate UCN in a large space, but other technical limitations prohibit the use of moving converters. Even if the neutron pulse is long (~1 ms in the pulsed reactors where this method has been tried) the converter velocity must be high (~100m/s) and the length of the generated UCN cloud is only ~10 cm.

Another class of methods of obtaining UCN for experiments is the transformation of higher energy neutrons to UCN energies outside the primary source shielding. Super-cooled down-scattering sources using helium have been tested, but the results are still modest and the very low UCN generation rate prohibits the use of this kind of methods. The phase space density of neutrons initially available is much higher *during the pulse* in a pulsed source than in a continuous source of the same time-averaged flux; an effective UCN converter must take advantage of this time structure.

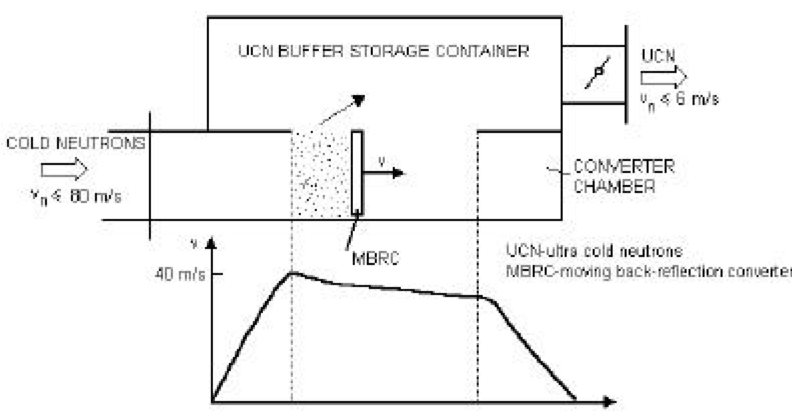

Fig. 3. The schematic of UCN converter system

A prototype Doppler converter, using a mica crystal as the reflector, was demonstrated at the ZING-P' pulsed spallation source at Argonne[7], and a similar device has recently become operational at Los Alamos[12]. The best operational UCN source, the turbine source[13] at the ILL reactor in Grenoble, France, uses multiple reflections from many curved Ni blades for the Doppler conversion. The construction of a new 1 MW spallation neutron source offers the opportunity to design an efficient UCN converter, which should significantly exceed the performance of the ILL source. In this respect the decelerating Doppler converter seems to open a new perspective.

The working principle of the UCN generator is represented in Fig. 3. After the proton pulse strikes the neutron-generating target, the back-reflection converter is accelerated inside the vacuum chamber. When the converter speed reaches the value v_0, at a distance L_0 from the neutron moderator and at time $t_0 = L_0/(2v_0)$ after the primary pulse, the Bragg back-reflected cold neutrons will have a small energy in the laboratory coordinate system. After this moment the back-reflection converter will follow a decelerating motion described in the previous chapter (*k = 0* case). If the reflector obeys this motion law, UCN will be generated while the multilayer spacing spread allows Bragg reflection. Finally, the converter is stopped with a higher deceleration and UCN are trapped in a storage container. The stored UCN can be used as a quasi-continuous source through an extraction window. The UCN are generated during a period of about 10 ms, and the UCN evacuation will last hundreds of ms to a few seconds. A filling repetition rate of about 1 Hz seems appropriate.

Decelerating the converter is essential for efficient generation of UCN. If a constant velocity Doppler converter is used, then UCN are generated only during the pulse at a fixed velocity of the incoming neutrons; the wide wavelength acceptance of the multilayer is useless. In the decelerating Doppler converter case, the reflector gradually slows down to allow the slower neutrons to “catch up” and be converted, so that UCN are generated in a large energy band-pass of incident neutrons. The peak phase space density in the primary moderator determines the maximum phase space density attainable in the converter output because Liouville’s theorem applies to the coherent process of Doppler conversion. Then the maximal attainable UCN density should be:

$$n_{UCN}^{\max} = \frac{4\pi}{3} v_{UCN}^3 \rho_N \qquad (3)$$

where ρ_N is the peak value of the neutron phase space density produced in the moderator and v_{UCN} is the upper limit (~6 m/s) of the UCN velocity. Since the velocity spread given by relation (2) along the beam is generally smaller than the UCN velocity upper limit, then the real UCN density (n_{UCN}) would correspond to:

$$n_{UCN} = \pi v_{UCN}^2 \Delta v_f^{FWHM} \rho_N \qquad (4)$$

For a cold moderator at the SNS, the maximum phase space density will approach $\rho_N \approx 10^7$ neutrons*s^3/m^6. If the converter is placed at 10 m from the moderator and the relative acceptance window is 10% then the gain factor in time is about 50 and the velocity spread is only about 0.13 m/s, more than one order of magnitude less then the transverse velocity spread delivered by the guide. The resultant UCN density for this flight path distance and a 200 μs moderator pulse is about 10^3 n/cm^3. The back-reflection converter would generate UCN along a path length of about 1 m. If a generation volume of ~10^4 cm^3 can be achieved, then the total number of UCN generated in each pulse used will be around 10^7. Note that a shorter flight path or a longer pulse increases the efficiency. Another idea is to use two decelerating Doppler converters: one to increase the pulse with and another to slow-down the neutrons. This solution will significantly increase the complexity of the UCN converter system, but an increase in the UCN density of a factor of 10 could be obtained. On the other hand the first converter will deliver a long pulse monochromatic cold neutron beam for possible use with other applications.

The buffer storage container assures the filtration of UCN and the time smoothing of UCN density fluctuations. The steady state UCN density is approximated by:

$$n_{UCN}^{\infty} = \frac{n_{UCN}}{1 + \frac{V_r}{V_g} + \frac{\Delta t}{\tau_{ev}}} \qquad (5)$$

where V_g is the volume used to generate the UCN, V_r is the volume used for accelerating and decelerating the converter without generating UCN, Δt is the cycle length and τ_{ev} is the time needed to evacuate the UCN from the active space through a window equivalent with the system exit window. The losses given by UCN expansion in the space used for converter acceleration and deceleration can be eliminated by isolating the generating space using fast UCN valves. The evacuation time τ_{ev} for an exit window cross section of 200 cm^2 lies between 1 and 10 seconds. With a cycle time of 1 second, the UCN density at the system exit can be greater than half of the local UCN density just after cold neutron conversion. This means that about half of UCN generated during a cycle will leave the system through the exit window and consequently a flux of 10^5 neutrons/cm^2 s is possible.

To reach such a high UCN density the guide divergence must match the transverse UCN velocities, and a high guide transmission is necessary. At the same time, because all of the source pulses will not be used, a special chopper must be introduced in the primary beam to stop the neutrons coming from unused pulses. These elements could decrease the phase space density and, consequently, the UCN density. The basic option for the back-reflection converter would be a material multilayer mirror based on neutron scattering amplitude contrast, but magnetic multilayer structures can also be considered. The main questions for the back-reflection converter are the reflectivity and the synchronization accuracy of its movement with the main neutron pulse.

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