DEVELOPMENT OF MODULATING PERMANENT MAGNET SEXTUPOLE LENS FOR FOCUSING OF PULSED COLD NEUTRONS*

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Abstract

Cold neutron beams can be focused by a strong sextupole magnetic field. A permanent magnet sextupole lens whose focusing strength can be synchronously modulated at the rate of pulsed cold neutron beams is under development. This device should keep the focal point for pulsed neutron beams whose wavelength spreads as a function of time of flight. This kind of device improves the utilization of valuable neutrons and saves experiment time and costs. It will raise linac based small neutron sources as a good counter part to large powerful neutron facilities. Experimental results that were obtained at Institute Laue-Langevin (ILL) are also described.

INTRODUCTION

Neutron beams are well known as powerful probes for both material science and fundamental physics. The applicable research field, however, is limited by the low intensity of the neutron beams. Meanwhile, the efficiency of a neutron beam has recently been much improved by techniques such as neutron optics [1-6], time of flight (TOF) method, and so on.

Among such neutron optics devices, a magnetic lens can focus neutron beams on such targets as samples and/or detectors by using interaction between the neutron's magnetic dipole moment and the sextupole field. When we apply the TOF method to pulsed neutrons for increasing the efficiency of each experiment, the wavelength range to be covered is in the order of a few times. The time dependence of the wavelength λ is proportional to *t* (time of flight of a neutron). Then we should modulate the field gradient proportional to t^{-2} in order to keep the focal length Z_f fixed independent of λ. With these aspects, we are developing a modulating permanent magnet sextupole lens (PMSx) for focusing of pulsed neutron beams with chromatic aberration suppressed. The sextupole lens is composed of permanent magnets (NdBFe) because they can generate a strong magnetic field within limited space.

This lens increases the intensity of neutron beams on a target to reduce an experiment time with sufficient count rate and to increase the spatial resolution. Then neutron probe applications can be widely extended, for example, even the linac-based small neutron source now under development becomes practical.

FOCUSING OF PULSED NEUTRONS BY SEXTUPOLE MAGNET

The origin of the focusing force is the interaction between neutron's magnetic dipole moment and the external magnetic field [7-9]. A sextupole component of magnetic field B can be written as:

$$|B| = G'/2\left(x^2 + y^2\right) \tag{1}$$

where *G'* is a positive value indicating the strength of the gradient of magnetic field. In the sextupole field, neutrons feel the thrusting force proportional to the distance from the magnetic centre and their equation of motion is a simple harmonic oscillator described as

$$\frac{d^2x}{dt^2} = -\omega^2 x, \quad \frac{d^2y}{dt^2} = -\omega^2 y, \quad \frac{d^2z}{dt^2} = 0 \tag{2}$$

where $\omega^2 = G'\alpha$, $\alpha = |\mu_n/m_n| = 5.77$ m^2 s^{-2} T^{-1}, μ_n is magnetic dipole moment and m_n is the mass of neutron, in case the neutron spin is parallel to the local magnetic field [7-8]. When the ambient magnetic field is strong and changes slow enough (adiabatic condition), the spin direction follows the magnetic field direction. Because the magnetic dipole moment of the neutron is connected to the spin, the polarity of the force changes in accordance

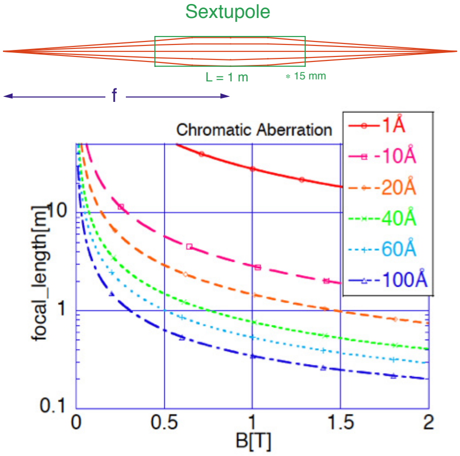

Figure 1: Focusing of neutrons by sextupole magnet and chromatic aberration.

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*Work partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (A), 18204023(2006) and 19GS0210.

with the spin polarity. The focal point is described as

$$Z_f = Z_m + \frac{h}{\omega m_n \lambda}\cot\left(\frac{\omega m_n \lambda}{h} Z_m\right). \qquad (3)$$

When λ is close to zero, Eq. 5 can be rewritten as

$$Z_f = \frac{2}{3} Z_m + \frac{1}{Z_m G \alpha}\left(\frac{h}{m_n \lambda}\right)^2, \qquad (4)$$

where h is Plank constant. The focal length of the magnetic lens depends on the wavelength (momentum) of the neutrons and field gradient (Fig. 1). For pulsed neutrons, we can apply the Time of Flight method for effective use of valuable neutrons. In that case, we need to modulate the field gradient according to the wavelength change in time. In order to keep the focal length constant independent of the λ proportional to t, in other words, to suppress the chromatic aberration, we need to follow the relation:

$$G' \propto \lambda^{-2} \propto t^{-2}. \qquad (5)$$

FABRICATION OF THE PROTOTYPE

We have fabricated a prototype of magnetic lens using permanent magnets as mentioned before (see Fig. 2). In order to adjust the strength, the magnet is divided into two nested co-axial rings, where the inner ring is fixed and the outer ring can be rotated (see Fig. 3). Synchronizing the modulation with neutron beam pulse suppresses the chromatic aberration. Strictly speaking, the modulation is not proportional to t^{-2} but sinusoidal. But we can use a part of the descending slope.

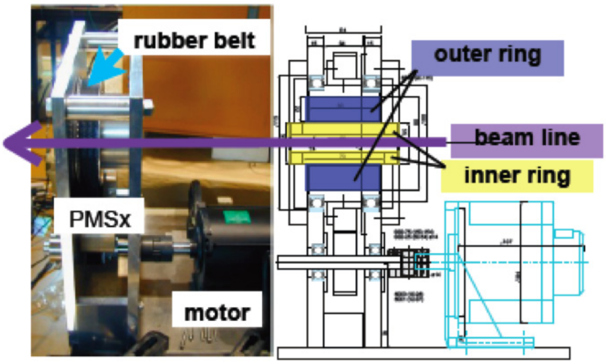

Figure 2: The overview and cross section of the prototype of PMSx

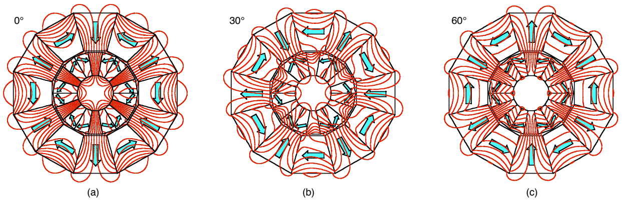

Figure 3: Sextupole with two-nested ring structure. (a) maximum strength position where the outer ring is in phase with inner ring (b) 30° rotated (c) minimum strength position where the outer ring is out of phase (60°). The arrows indicate the easy axes of the magnet pieces. The pieces without arrows are made of soft magnet material.

The magnet has Extended Halbach configuration, where one of the soft magnetic materials, Permendur, is used as pole material to generate stronger field [10]. The outer ring is composed of 12 magnet pieces and the inner ring is composed of 12 magnet pieces and 6 Permendur ones (18 pieces total). The magnetic field changes three times in one revolution of the outer ring. The diameter of the bore is 15mm, the repetition rate of the magnetic field modulation is 25Hz (the same as J-PARC), and the magnet length is 66mm. The strongest magnetic field (rotation angle is determined as 0º) measured by single axis tesla meter (Group-3 DTM151) at the surface of poles showed 1.65 T, G = 5.69x10^4 [T/m^2], and the focal length is calculated to be about 0.5m for λ=40Å, which is a practical value (see Fig. 4).

The temperature rise during the operation has been reduced [11] and is under improvement further beyond.

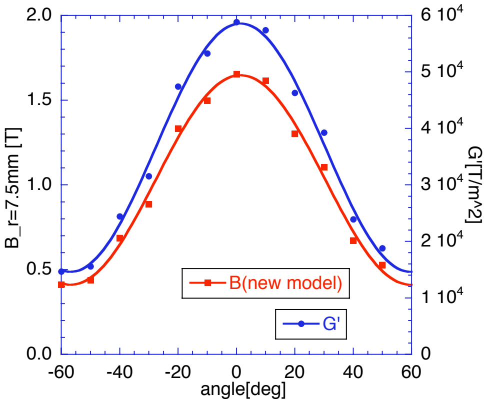

Figure 4: The measured magnetic field modulation and derived its field gradient.

EXPERIMENTS WITH VCN

We carried out experiments on focusing of pulsed VCN with TOF method in PF2 beam line at ILL. In this experiments, we fixed the outer ring rotation angle at 0º, 31.7º and 60º (see Fig. 4). The setup is shown in Fig. 5. The disc-chopper (see Fig. 5 right) chops the continuous neutron beams to be pulsed, around 20~60Å in their wavelengths. The detector has time resolution and 2D spatial resolution, which is composed of a scintillation screen and 2D-PMT. The polarising super mirror selects neutrons with parallel spins to the magnetic field, thus only the images of focused neutrons are detected. After the ø1mm slit, in order to satisfy the adiabatic condition as mentioned at Eq. (2), we placed two dipoles to keep the polarization. The magnetic field from the mirror to the PMSx was not less than 15G. We obtained the wavelengths (momentum, energy) from their time of flight when neutrons are focused by PMSx, and compared with the field gradient.

The results are shown in Fig. 6 and Table 1. The results are consistent with the calculation. We confirmed that neutrons are focused depending on the strength of magnetic field. However, the timing offset (t_0) is not considered in this analysis. We plan to determine the t_0 pre-

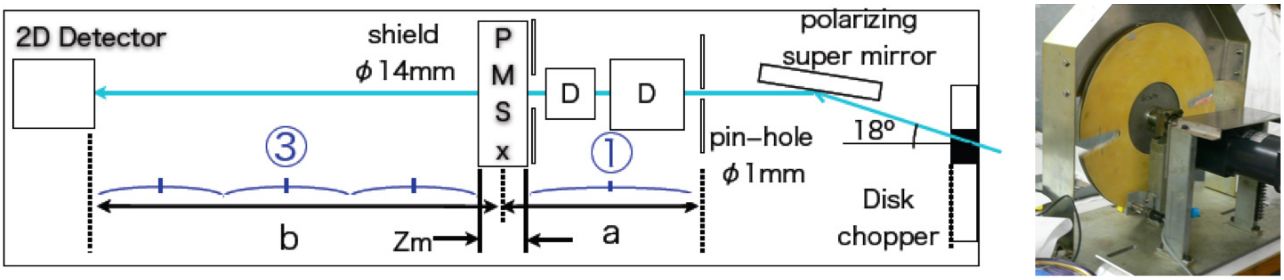

Figure 5: (left): The set up of experiments: a=720mm, b=2140mm, then Z_f=540mm. (right): The disk-chopper making the VCN beam pulsed.

Table 1: the results compared with calculation

angle [deg]	B(r=7.5mm) [T]	$G' \times 10^4$ $[T/m^2]$	λ[Å] (calc.)	λ[Å] (meas.)
0	1.65	5.88	38	39
31.7	0.89	3.15	49	50
60	0.41	1.48	75	out of focus

cisely soon. It should be mentioned that we might see the effect of gravity from the vertical movements of the centre (see Fig. 6 - right).

FUTURE PROSPECTS

We are going to develop a practical PMSx this year. Firstly, we will have the pole sliced thinner and annealed for less eddy currents and hysteresis losses, while keeping the strength of the magnetic field as good as possible. Secondly, we are going to incorporate a technique for smooth rotation of the outer ring such as a torque canceller.

The first application of this device would be Small Angle Neutron Scattering (SANS) for material science. Dr. Bleuel has carried out some focusing-SANS experiments with our PMSx after our experiments [12]. The idea of PMSx can be extended widely when we use the time harmonics. It will ease the adjustment of time variation of the focusing strength.

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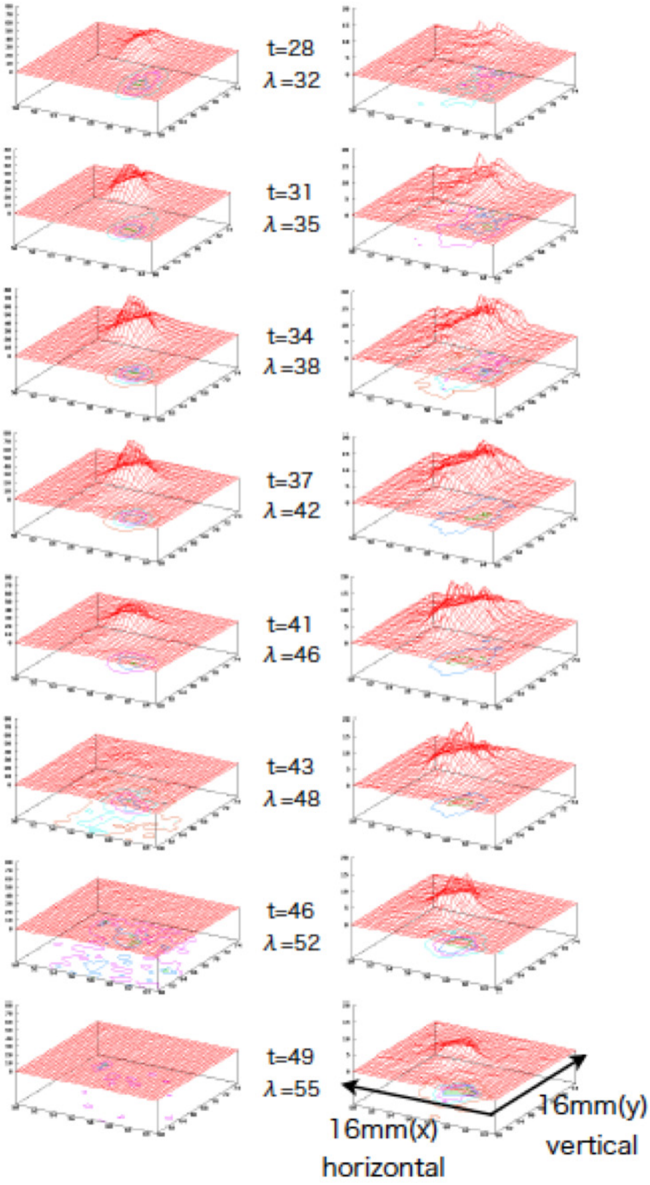

Figure 6: Neutron intensity map on the 2D detector: the vertical axis shows counts. (left) fixed angle; 0° (strongest G') (right) fixed angle; 31.7° (weaker G'). We confirmed that the neutrons with specific wavelengths are focused according to the strength of magnetic field.