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Development of modulating permanent magnet sextupole lens for focusing of pulsed cold neutrons

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A R T I C L E I N F O

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A B S T R A C T

Modulating permanent magnet sextupole lens (PMSx) for focusing pulsed cold neutrons is under development. The synchronized modulation of its field gradient suppresses the chromatic aberration which arises from the Time Of Flight method. The strength of the magnetic field, the torque, and the rise of temperature during its operation are studied on a fabricated prototype. Experiments on focusing pulsed very cold neutrons (VCN) at ILL (Institute of Laue Langevin, France) were carried out and VCN with around $\lambda = 40$ Å were focused by the PMSx at a focal length of about 0.5 m. The experimental results are presented in conjunction with the principle of the neutron focusing and the modulating method of the focal strength of permanent magnet lens with the double ring structure.

1. Introduction

Neutron beams have been used as attractive probes widely in such field as material science and life science. Particularly, slow neutrons such as very cold neutrons (VCN) and ultra cold neutrons (UCN) also play important roles in nuclear physics and elementary particle physics. Many neutron optical devises [1–6] and new methods are developed in order to overcome the low intensity and increase the efficiency of the neutron beams. Among such neutron optics devices, a magnetic lens can collect the neutrons which are cut off to shape practical beams so far and focus neutrons by using the interaction between the neutron's magnetic dipole moment and the magnetic sextupole field.

There are three ways to fabricate a sextupole magnet: superconducting magnet, normal conducting magnet and permanent magnet. Because conventional normal conducting magnet uses iron poles to generate a sextupole field, the gradient is limited by the iron saturation level. Although a super-conducting magnet can exceed the normal conducting magnet in its strength, it requires cryogenic system, which is somewhat complicated and costs a lot. In superconducting magnet case, the strength is limited by the critical magnetic field. Since the multipole field increases rapidly in the radial direction ($\propto r^2$ for sextupole case), it easily reaches the critical field in coil windings, which have a finite size. The strength of permanent magnets is limited by the residual magnetic field Br, where the magnet surface can be close to an inner bore radius. Thus the permanent magnets have advantages in the strength, the cost and the easy handling. One drawback is that variability of its strength has to be added by some means.

When we apply the TOF method to pulsed neutrons for increasing the efficiency of each experiment, the observed wavelength expands in time. 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.

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A permanent magnet sextupole lens (PMSx) with capability of strength modulation can be realized with the double ring structure [10]. This lens increases the intensity of neutron beams on a target and helps to reduce an experiment time and/or to increase the spatial resolution. Thus, the neutron scattering technique is applicable to even smaller samples or spatial scan experiment becomes practical.

2. Focusing pulsed neutrons by sextupole magnet

A neutron is thrusted in a gradient magnetic field because of the interaction between the neutron's magnetic dipole moment and the external magnetic field [7–9]. Because the direction of the magnetic dipole moment is anti-parallel to the spin, neutrons of parallel-spin with the field are focused and the other is defocused in the sextupole field [7–8] described as

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

The focal length of the magnetic lens described as (2) depends on the wavelength λ (or momentum) of the neutrons and field

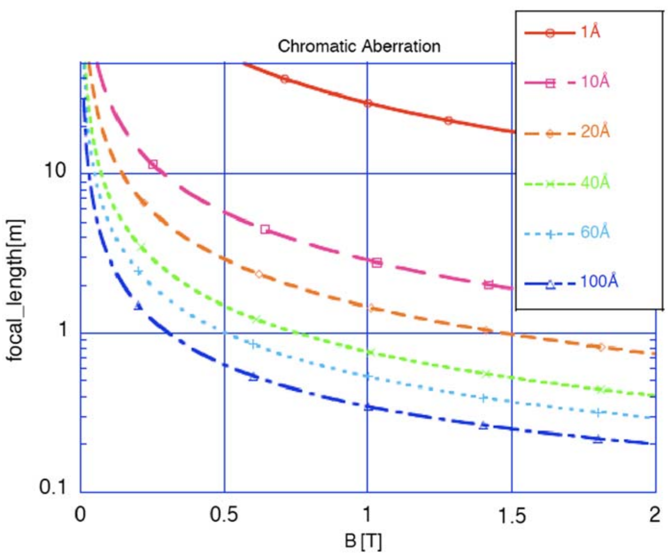

Fig. 1. The chromatic aberration.

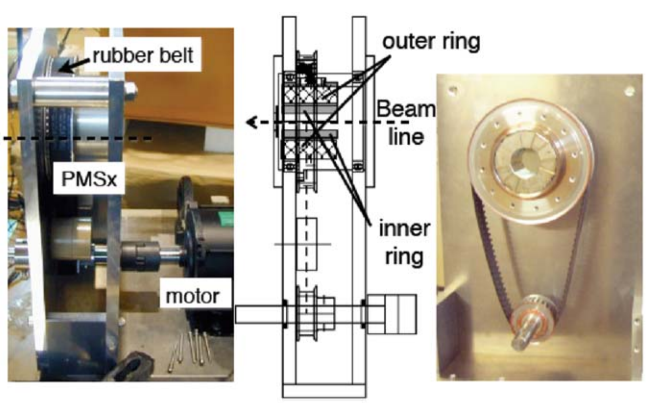

Fig. 2. (Left and centre) The overview and cross section of the prototype of PMSx. (Right) The outer ring and rubber belt.

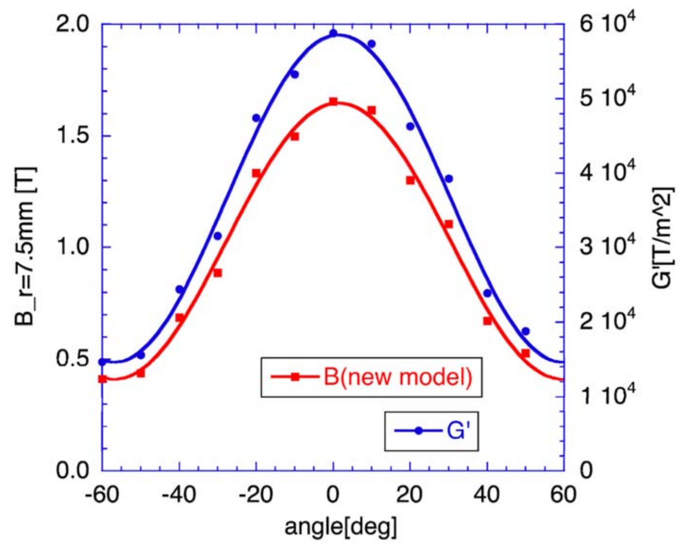

Fig. 4. The measured magnetic field modulation and derived its field gradient.

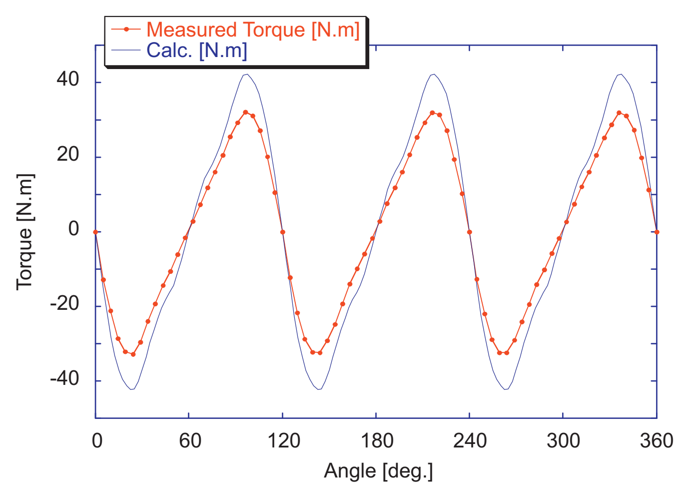

Fig. 5. The torque as a function of rotation angle.

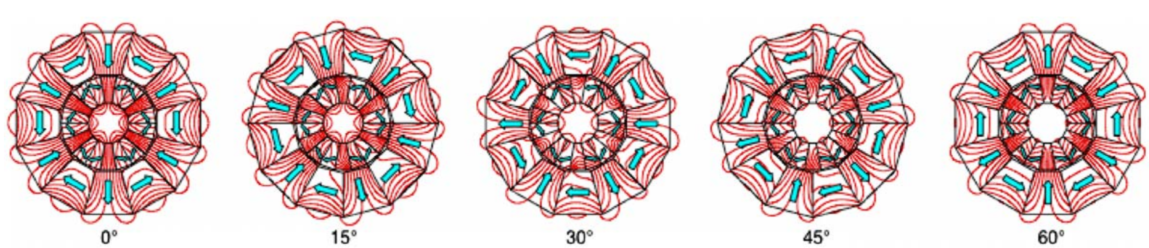

Fig. 3. The field gradient modulation of sextupole with two-nested ring structure: (a) maximum strength position (determined as 0°), (b) 30° rotated and (c) minimum strength position (60°). The arrows indicate the easy axes of the magnet pieces. The pieces without arrows are made of soft magnet material.

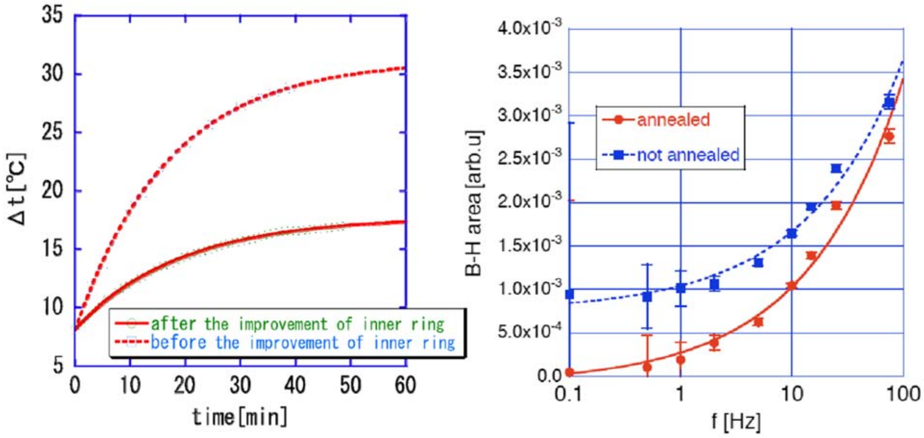

Fig. 6. (Left) The comparison of temperature rise during the continuous operation. (Right) Hysteresis loss of poles made of Permendur. It shows that annealing is effective. It also shows that the present thickness $t = 2.5\,\text{mm}$ is not thin enough.

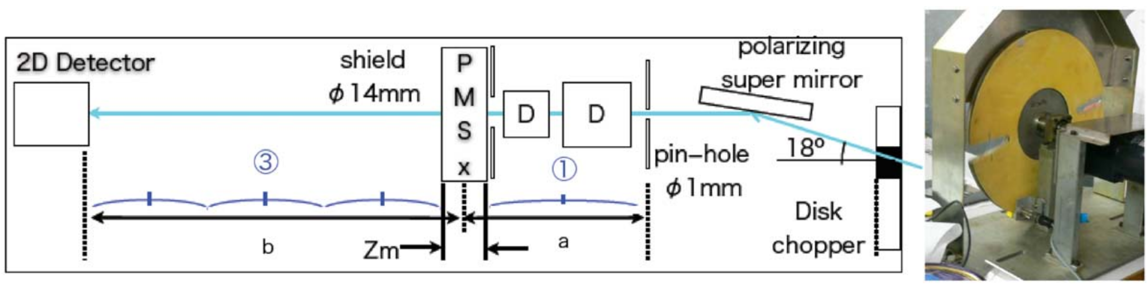

Fig. 7. (Left) The setup of experiments: $a = 720\,\text{mm}$, $b = 2140\,\text{mm}$, then $Z_f = 540\,\text{mm}$. (Right) The disk-chopper making the VCN beam pulsed.

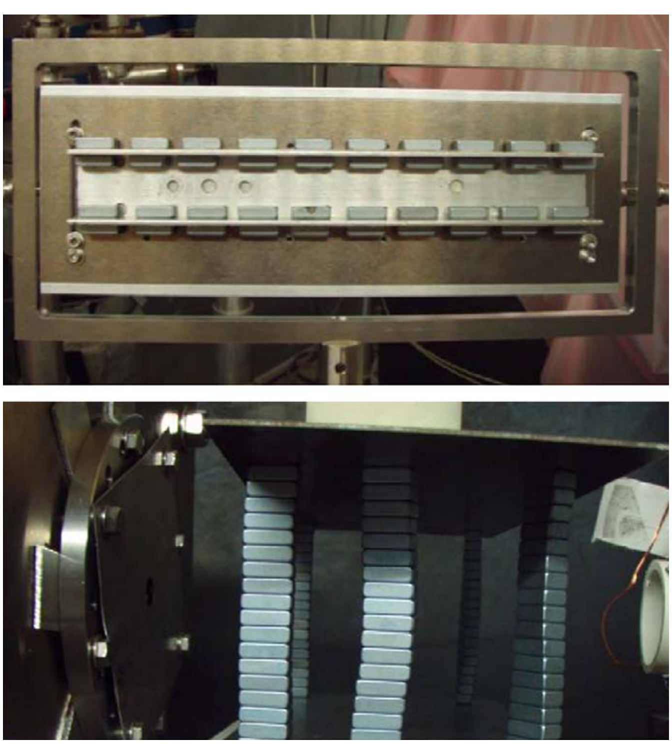

Fig. 8. The guiding field. (Top) These magnets generate the dipole field on the surface of polarising super mirror. (Bottom) Two dipoles just before the PMSx at the left are shown. Cd plate with $\varnothing$ 14 mm hole is set on PMSx.

gradient G', respectively (see Fig. 1).

$$Z_f = Z_m + \frac{h}{\omega m_n \lambda} \cot\left(\frac{\omega m_n \lambda}{h} Z_m\right), \tag{2}$$

where Z_m is the magnet length, $\omega^2 = G'\alpha$, $\alpha = |\mu_n/m_n| = 5.77\,\text{m}^2\,\text{s}^{-2}\,\text{T}^{-1}$, μ_n is magnetic dipole moment and m_n is the mass of neutron. The spin direction follows the magnetic field direction during the flight when the adiabatic condition is fulfilled or the ambient magnetic field is strong and changes slow enough. In case of applying the TOF method to pulsed neutrons, λ changes depending on the time of flight;

$$\lambda = h/m_n v \propto t, \tag{3}$$

where v is neutron's velocity. In order to keep the focal length constant independent of λ, in other words, to suppress the chromatic aberration, the field gradient has to be modulated with following relation:

$$G' \propto \lambda^{-2} \propto t^{-2}. \tag{4}$$

3. Fabrication of the prototype

3.1. Gradient modulation of permanent magnets

Fig. 2 shows a fabricated prototype of the magnetic lens using permanent magnets. 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).

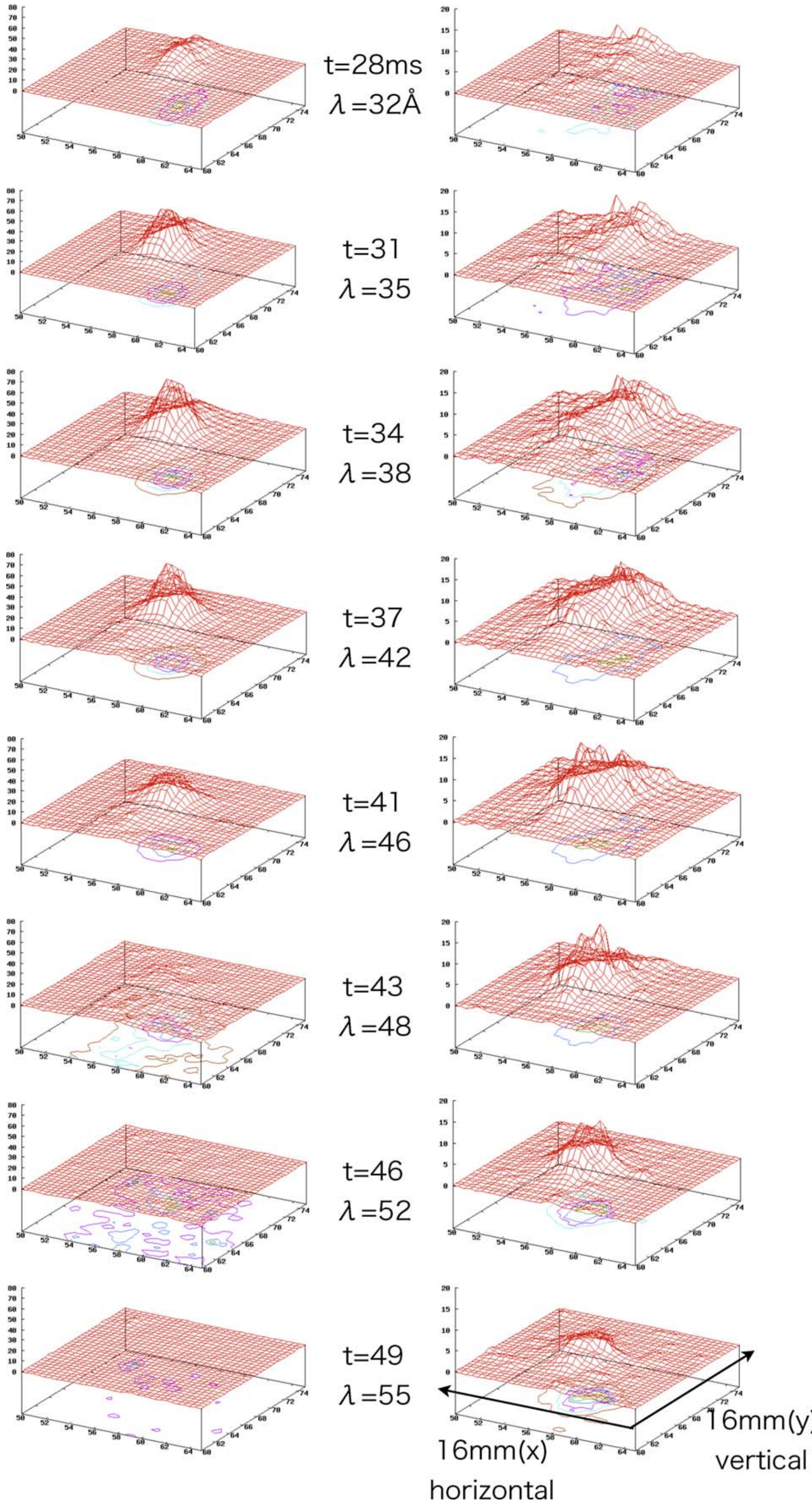

Fig. 9. Neutron intensity map on the 2D detector: the vertical axis shows counts. (Left) Fixed angle: 0° (strongest G'). (Right) Fixed angle: 31.7° (weaker G'). The neutrons with specific wavelengths are focused according to the strength of magnetic field.

Synchronizing the modulation with neutron beam pulse suppresses the chromatic aberration. Although the modulation is not proportional to t^{-2} but sinusoidal strictly speaking, we can use a part of the descending slope.

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, while the inner ring is composed of 12 magnet pieces and six Permendur ones (18 pieces total). Because it has three fold rotational symmetry, the magnetic field changes three times in one revolution of the outer ring. Thus the revolution frequency would be one third of the repetition rate of pulsed operation. The diameter of the bore is 15 mm, the repetition rate of the magnetic field modulation is 25 Hz (the same as J-PARC), and the magnet length is 66 mm.

3.2. *The measurements of the field gradient*

The magnetic field distribution inside the bore is measured. The strongest magnetic field (rotation angle is 0°) measured by single axis tesla meter (Group-3 DTM151) at the surface of poles showed 1.65 T, $G' = 5.69 \times 10^4$ ($\mathrm{T\,m^{-2}}$), and the focal length is calculated to be about 0.5 m for $\lambda = 40$ Å, which is a practical value (see Fig. 4). In SANS experiments for example, the gain factor is 20–100 with this lens instead of the second pinhole slit. The estimation is on the assumption that a neutrino beam spread uniformly just before the first slit.

3.3. *The torque to rotate outer ring*

Fig. 5 shows the torques measured at 72 angles (every 5°) rotating the outer ring. The angle dependence of the torque is not sinusoidal in contrast to that of the strength. The torque to rotate the outer ring is rather big to overcome a strong magnetic force between inner ring and outer ring. The stored energy goes back and forth through the driving axis during the operation, the energy flow through the driving axis should be reduced by converting the energy to some kinds of energy such as kinetic energy, rotation energy, and so on and storing in the system. It is planned to incorporate a torque cancel mechanism using magnetic energy storage instead of big and heavy flywheel currently being used. Another co-axial double ring placed at the outside of the PMSx will cancel the torque more compactly without much mechanical complexity and with good reliability.

3.4. *The temperature rise during operation*

When the outer ring rotates at 25/3 Hz, the temperature at the surface of the poles becomes nearly 60 °C at maximum. The main causes of this temperature rise are eddy-current in poles and hysteresis loss. Replacing the solid poles with laminated ones in order to increase the resistance against the eddy-current reduced the temperature rise to about half that of the former model (see Fig. 6 (left)).

The hysteresis loss with a raw material and annealed ones are measured and compared. The curves in Fig. 6 (right) show sum of the two losses. Because the hysteresis loss is a static effect while the eddy-current depends on the frequency, the difference at 0 Hz shows the hysteresis effect. The hysteresis loss of the annealed ones is less than the raw one. The annealing process is needed for suppressing temperature rise. Fig. 6 (right) also shows that the thickness is not thin enough for 25/3 Hz operation. These improvements will be incorporated for a next PMSx model.

4. Experiment with VCN

Experiments on focusing of pulsed VCN with TOF method in PF2 beam line were carried out at ILL. In these experiments, the outer ring rotation angle was fixed at 0°, 31.7° and 60° (see Fig. 4). The setup is shown in Fig. 7. The disk-chopper chops the continuous neutron beams to be pulsed, around 20–60 Å in their wavelengths. The detector has time resolution and 2D spatial resolution, which is composed of a scintillation screen and 2D-PMT [11]. The polarising super-mirror selects neutrons with parallel spins to the magnetic field, thus only the images of focused neutrons are detected. After the ∅1 mm slit, in order to satisfy the adiabatic condition as mentioned in Eq. (2), a dipole field needed for operation of the super-mirror (see Fig. 8, top) is continued by two dipoles to conserve the polarization (see Fig. 8, bottom). The magnetic field from the mirror to the PMSx was not less than 15 G. The wavelengths (momentum, energy) can be estimated from their time of flight when neutrons are focused by PMSx, and compared with the G'.

The results are shown in Fig. 9 and Table 1. The results are consistent with the calculation. The neutrons are focused depending on the strength of magnetic field. However, the timing offset (t_0) is not considered in this analysis. t_0 will be measured precisely soon by additional experiments. It should be mentioned that the effect of gravity might be observed from the vertical movements of the centre (see Fig. 9, right).

5. Discussions

5.1. *Further improvement*

The practical PMSx will be fabricated in this fiscal year. The lamination sheet of the pole will be thinner and annealed for less

Table 1
The results compared with calculation.

Angle (deg)	B ($r = 7.5$ mm) (T)	$G' \times 10^4$ ($\mathrm{T\,m^{-2}}$)	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

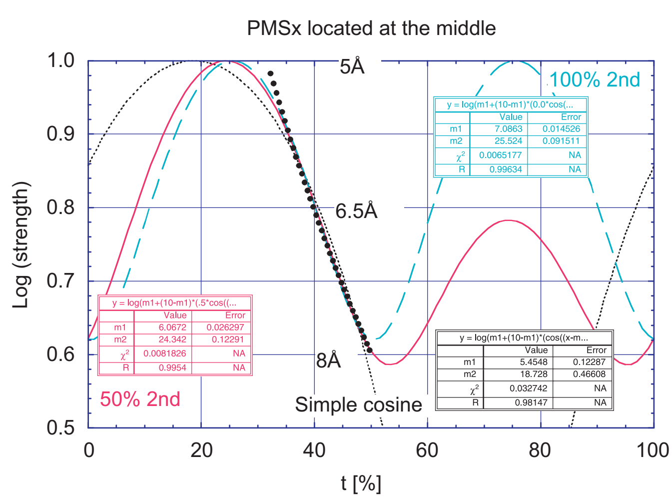

Fig. 10. Introduction of the time harmonics. Combined function represented in pink line shows wider fitting range of wavelength than simple cosine and only second time harmonics. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

eddy currents and hysteresis losses, while keeping the strength of the magnetic field as good as possible. A technique for smooth rotation of the outer ring such as a torque canceller is under investigation.

5.2. Application

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 flexibility of PMSx can be further extended when the time harmonics components are added. It will ease the adjustment of time variation of the focusing strength (see Fig. 10).

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