DEVELOPMENT OF PERMANENT MANGNET SEXTUPOLE LENS FOR FOCUSING OF COLD NEUTRONS

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Abstract

A modulating permanent magnet sextupole lens that can focus pulsed cold neutrons is under development. The magnet is based on the extended Halbach configuration to generate stronger magnetic field. In order to adjust the strength, the magnet is divided into two co-axial nested rings, where the inner ring is fixed and the outer ring can be rotated. Synchronizing the period of the modulation with that of pulsed neutron beam suppress the chromatic aberration.

We have fabricated a half scale model as a prototype and studied the strength, the temperature rise caused by eddy current. We have reduced the temperature rise about half of the former model by making the poles laminated structure. We are considering further improvement of the temperature rise and the system of rotating the outer ring with energy loss minimum. We are also measuring the very-cold neutrons focused by the half scale model.

INTRODUCTION

Low velocity neutron beams are well known as very effective probes for condensed-matter physics, biological physics, fundamental physics, and so on. But the applicable research field is limited by the low intensity of the neutron beam. Neutron focusing lenses, one kind of the neutron optical devices, solve the problem; they can increase the intensity of the neutron beam on the target effectively. Especially the refractive optical devices increase the intensity with the divergence of the neutron beam suppressed [1-6]. Then the neutron scattering technique is applicable to even smaller samples or spatial scanning becomes practical. Even small linac-based neutron sources raise their head and neutrons become handy probes.

The origin of focusing power is the interaction between neutron's magnetic dipole moment and the external magnetic field: they are thrusted in a gradient field [7-8]. The thrusting force is proportional to the gradient. Because the thrusting kick force has to be proportional to the distance from the beam axis for focusing purposes, the magnetic field distribution should be a quadratic function. Because the magnetic dipole of the neutron is connected to the spin, the polarity of the force changes according to the spin polarity.

The focal length of the magnetic lens depends on the wavelength (momentum) of the neutrons. When the neutrons can originally be pulsed, we can apply the Time of Flight method for effective use of valuable neutrons. In that case, we need to modulate the strength according to the wavelength change in time. Synchronizing the modulation with neutron beam pulse suppresses the chromatic aberration. 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.1).

We have fabricated the half-scale model as a prototype and studied its strength, torque and temperature rise during the operation. We have also modified the inner ring to suppress the temperature rise, which was successfully achieved.

FOCUSING OF PULSED NEUTRONS BY SEXTUPOLE MAGNET WITHOUT CHROMATIC ABERRATION

A sextupole component of magnetic field B can be written as:

$$|B| = \frac{G}{2}(x^2 + y^2), \qquad (2)$$

where G is a positive value indicating the strength of the gradient of magnetic field. The equation of motion of neutrons in the magnetic field is described as

$$\frac{d^2x}{dt^2} = -\omega^2 x, \frac{d^2y}{dt^2} = -\omega^2 y, \frac{d^2z}{dt^2} = 0, \qquad (3)$$

where $\omega^2 = G\alpha$ with $\alpha = |\mu_n/m_n| = 5.77$ m^2 s^{-2} T^{-1}, μ_n is magnetic dipole moment and m_n is the mass of neutron, in case the local magnetic field is strong enough to satisfy the adiabatic spin transport condition and the neutron spin is parallel to the local magnetic field [7-8]. When the neutrons are injected in parallel to the axis of the sextupole, they will be focused to the focal point described as

$$Z_f = Z_m + \frac{h}{\omega m_n \lambda}\cot\left(\frac{\omega m_n \lambda}{h} Z_m\right). \qquad (5)$$

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

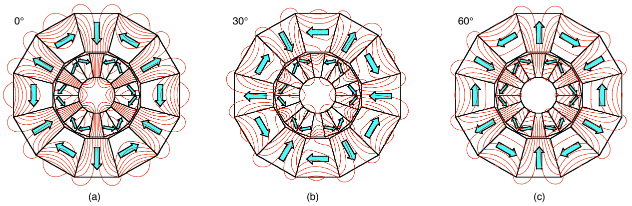

Figure 1: Sextupole with two-nested ring structure. (a) maximum strength position where the outer ring is in phase with inner ring (b) 30° rotated (c) minimum strength position where the outer ring is out of phase (60°). The easy axes of the magnet pieces are indicated by the arrows. The pieces without arrows are made of soft magnet material.

$$Z_f = Z_m + \frac{1}{Z_m G\alpha}\left(\frac{h}{m_n \lambda}\right)^2 . \qquad (6)$$

In order to keep the focal length constant, we need following relation:

$$Z_f = const \Rightarrow G \propto \lambda^{-2} \propto t^{-2}, \qquad (7)$$

where t is the time of flight.

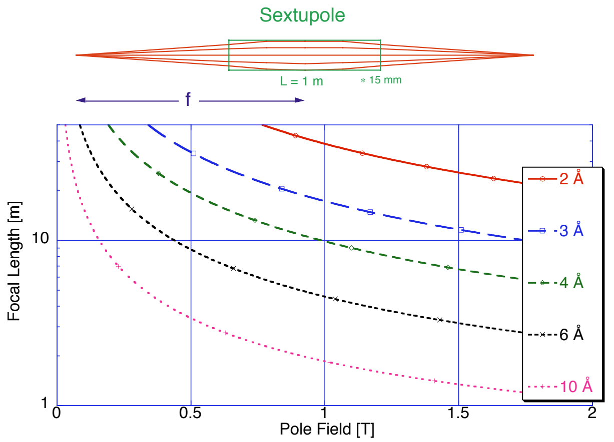

Figure 2: Focusing neutrons by sextupole magnet and chromatic aberration.

FABLICATION OF THE 1/2MODEL OF PMSX

We have fabricated a half-scale model of Permanent Magnet Sextupole (PMSx) as a prototype (see Photo 1). The magnet is divided into two nested co-axial rings, where the inner ring is fixed and the outer ring can be rotated continuously. The strength change of PMSx is sinusoidal and the strength slope down to the bottom can be applied to the t^{-2} function as discussed above (see Fig. 2). Synchronizing the modulation with neutron beam pulse suppresses the chromatic aberration.

The magnet has Extended Halbach configuration, where one of the soft magnetic materials, Permendur, is used as pole material to generate stronger filed [9-12].

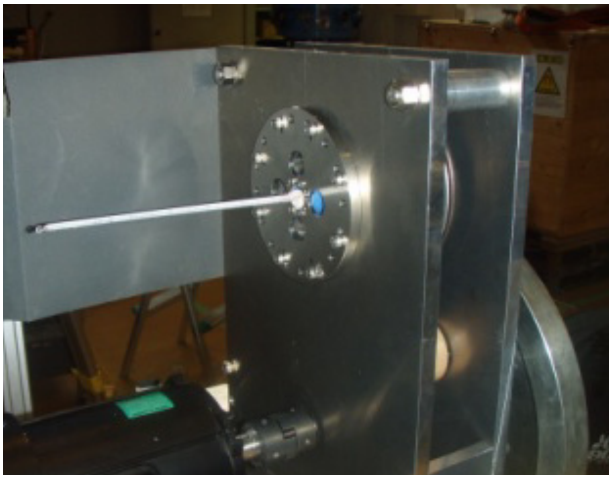

Photo 1: The half scale model.

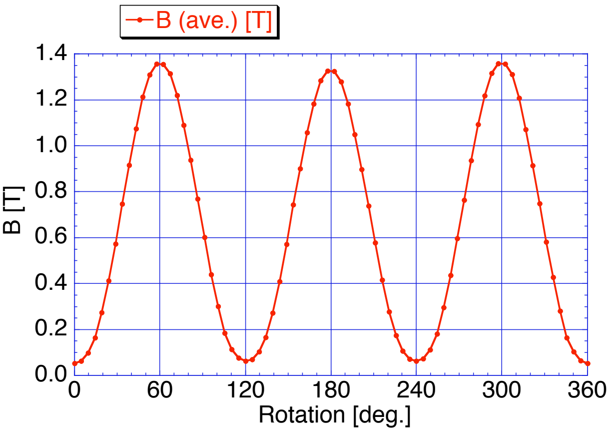

Figure 3: Sextupole strength as a function of rotation angle.

The outer ring is composed of 12 magnet pieces and the inner ring is composed of 12 magnet pieces and 6 Permendur ones. The change of the magnetic field repeats three times in one revolution of the outer ring. The radius of the bore is 15mm, the repetition rate of the magnetic field change is 25Hz, and the magnet length is 66mm. The magnetic field measured by single axis tesla meter (Group-3 DTM151) at the surface of poles showed 1.6 T, G = 5.7x10^4 [T/m^2] and the focal length is calculated to be about 0.5m, which is a practical value.

MEASUREMENTS AND IMPROVEMENT

The temperature rise during the operation

When we operate it, the temperature inside the bore becomes nearly 60ºC at the maximum. The main causes of this temperature rise are eddy-current in poles and hysteresis loss. We modified the solid pole with laminated one in order to increase the resistance against the eddy-current. The temperature rise was reduced about half of former model (see Fig. 4). We measured the

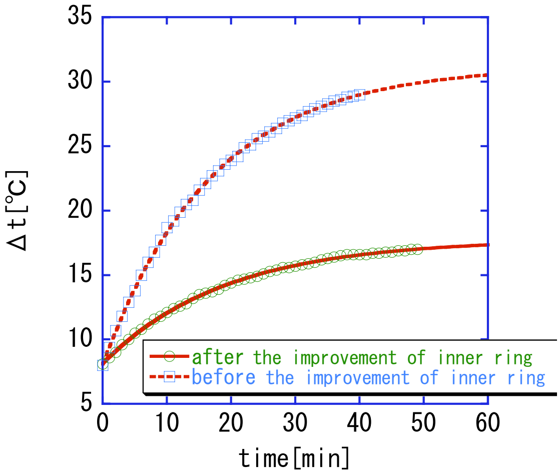

Figure 4: The comparison of temperature rise during the continuous operation. After the modification, it became the half of former model.

hysteresis loss with a raw material and an annealed one (see Fig. 5). The hysteresis loss of the annealed one is less than the raw one. The annealing should have better effect for suppressing temperature rise.

Fig. 5 also shows that the thickness is not thin enough for 25Hz operation. We are going to incorporate these improvements when we fabricate the full-scale model this year.

The torque for rotating the outer ring

We measured the torque at seventy-two points (every five degrees) rotating the outer ring (Fig. 5). The angle dependence of the torque is not sinusoidal in contrast to that of the strength. The torque for rotation of the ring is so big even at the half-scale model because there is strong magnetic force between inner ring and outer ring. While the stored energy goes back and forth through a drive axis during the rotation, we need to smooth it out by converting the energy to some kinds of energy such as kinetic energy, rotation energy or so on. With such energy storage, we can reduce the torque required for the driving motor. In the half-scale model, we use flywheel of which diameter is 400mm because of its simplicity. Because the flywheel is not practical for the full-scale model of PMSx, we have to apply new scheme of storing and smoothing the energy exchange.

DISCUSSIONS

We are going to develop a full-scale model this year. Firstly, we will have the pole sliced thinner and annealed for less eddy current and hysteresis loss, while keeping the strength of the magnetic field as good as possible. Secondly, we have to apply new system to rotate the outer ring with minimum energy loss instead of the big heavy flywheel currently used.

The first application of this device would be Small Angle Neutron Scattering (SANS) for material science. In order to suppress the divergence of the beam, conventional SANS uses two collimators between a neutron source and a sample. On the other hand, when we can use a neutron lens such as PMSx instead of the second collimator, we make use of much more neutrons to increase the intensity on the sample. We have carried out an experiment of the focusing for very-cold neutrons (VCN) this June at ILL, France, and confirmed that the PMSx can focus the VCN. Further analysis is needed to confirm the possibility of this device and to feed back to the development of the full-scale model.

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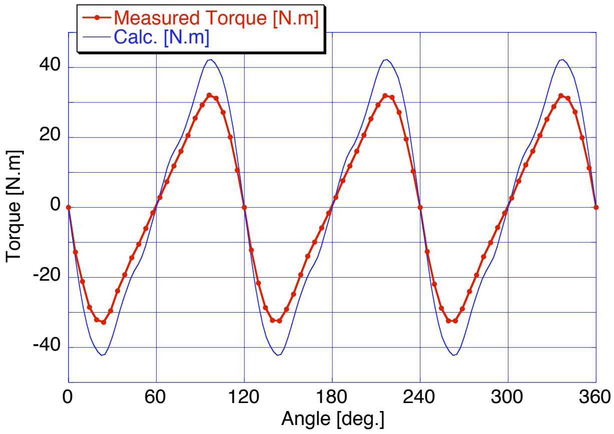

Figure 5: The torque as a function of rotation angle.

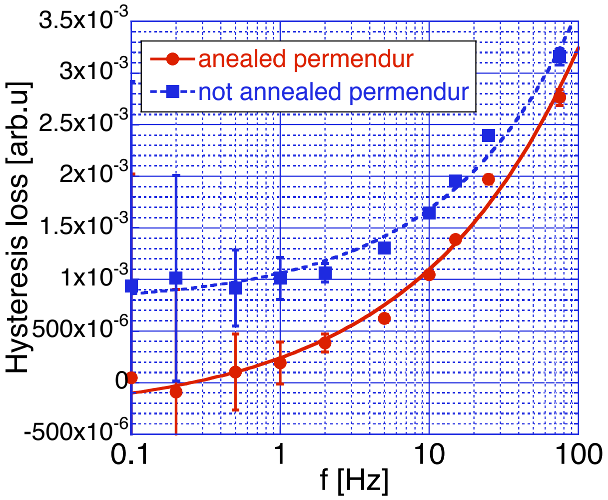

Figure 6: Hysteresis loss of poles, which is made of Permendur. It shows that annealing is effective. It also shows that the present thickness t=2.5mm is not thin enough.

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