Compact Sextupole Permanent-Magnet Lens: A Practical Approach to Focus Pulsed Neutrons

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Abstract

The focusing of pulsed neutrons can increase neutron flux, reduce sample volume, and enable access to smaller scattering angles. Consequently, it represents a critical challenge for next-generation spallation neutron sources. The primary difficulty stems from the inherent chromatic aberration of white neutrons. Here, a new compact Nested Rotating Sextupole Permanent Magnet (Nest-Rotating-SPM) lens, with a total length of 200 mm, was developed and tested at the Very Small Angle Neutron Scattering (VSANS) instrument at the China Spallation Neutron Source (CSNS). Through synchronization of the outer sextupole lens rotation with the neutron pulse from the source, we achieved aberration-free focusing of neutrons with wavelengths between 11.0 Å and 15.5 Å for the first time. The implementation of water cooling and carbon fiber winding ensures both magnetic field stability and mechanical robustness of the inner sextupole. The compact design incorporating bridge sextupoles enables Lego-like assembly of multiple lens units for focusing pulsed neutrons with wavelengths shorter than 10.0 Å, making it practically useful in a pulsed neutron instrument to enhance neutron flux or access lower scattering vectors. Additional research is required to mitigate background noise.

Full Text

Preamble

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Abstract

Focusing pulsed neutrons can increase neutron flux, reduce sample volume, and enable access to smaller scattering angles, representing a critical challenge for next-generation spallation neutron sources. The primary difficulty stems from the inherent chromatic aberration of white neutrons. Here, we developed and tested a new compact Nested Rotating Sextupole Permanent Magnet (Nest-Rotating-SPM) lens with a total length of 200 mm at the Very Small Angle Neutron Scattering (VSANS) instrument at the China Spallation Neutron Source (CSNS). By synchronizing the rotation of the outer sextupole lens with the neutron pulse from the source, we achieved aberration-free focusing of neutrons with wavelengths between 11.0 Å and 15.5 Å for the first time. Water cooling and carbon fiber winding ensure both magnetic field stability and mechanical robustness of the inner sextupole. The compact design incorporating bridge sextupoles enables Lego-like assembly of multiple lens units for focusing pulsed neutrons with wavelengths shorter than 10.0 Å, making it practically useful in pulsed neutron instruments to enhance neutron flux or access lower scattering vectors. Additional research is required to mitigate background noise.

Keywords: Magnetic neutron focusing; Sextupole permanent magnet lens; Nested Rotating Sextupole Permanent Magnet (Nest-Rotating-SPM) Lens; Spallation neutron source; Very small angle neutron scattering (VSANS)

Introduction

Focusing has long been a critical consideration in neutron instrument design due to the persistent limitation of neutron flux at neutron sources [**?**, **?**]. By converging divergent neutrons onto the sample [**?**], the neutron flux can be increased by orders of magnitude, or by directing neutrons onto the detector surface, smaller scattering vectors can be accessed [**?**], extending the application of small angle neutron scattering (SANS) instruments [**?**]. Neutrons cannot be focused through electric fields like electrons due to their charge neutrality. Fortunately, the trajectory of a neutron can be bent by strong magnetic field gradients [**?**, **?**], taking advantage of the neutron's intrinsic magnetic moment. The magnetic field of a sextupole permanent magnet (SPM) exhibits a gradient proportional to the square of the sextupole radius [?], enabling the SPM to function as a lens that focuses spin-up neutrons while defocusing spin-down neutrons [?].

For pulse sources, magnetic focusing offers overwhelming advantages over material lenses. Material lenses provide an alternative focusing method for neutron beams [?, ?], bending neutron trajectories at material interfaces through refractive effects similar to optical lenses, and they are maintenance-free [?, ?]. Consequently, MgF_2 refractive lenses have been widely used in SANS instruments at reactor sources, such as NG7 and NGB [?] at the NIST Center for Neutron Research (NCNR), SANS-J-II [?] at the Japan Atomic Energy Agency (JAEA), 30 m SANS [?] at the China Advanced Research Reactor (CARR), Suanni [?] and Luoshu [?] at the Mianyang Research Reactor (MYRR). The primary limitation of material lenses is their ability to focus only monochromatic neutrons, rendering them unsuitable for spallation neutron sources that utilize pulsed white neutrons. This limitation arises from chromatic aberration, analogous to that in optical systems, which cannot be effectively mitigated through compound lens configurations as is possible in optical microscopy. With multi-slit focusing geometry, multiple beams can be converged to the detector surface to access lower scattering vectors [?, ?], but the problem of slit smearing of the data remains to be solved [?, ?]. Elliptical or Wolter mirror techniques can also be used to focus chromatic neutrons, with groups from the United States [?], Japan [?], as well as Tsinghua and Tongji universities in China [?, ?] having explored this approach. However, practical application requires advanced techniques for polishing the mirror surface to atomic-level precision together with alignment accuracy at the micrometer level.

Notably, the magnetic field gradient of sextupole lenses can be readily adjusted, thereby modifying the lens's focal point. The magnetic gradient can be altered by changing the electrical current in electromagnetic sextupole lenses [?], and that of permanent sextupole lenses can be modulated by rotating an outer sextupole lens over the inner sextupole lens [?]. Conventional electromagnetic sextupole lenses [?] often lack sufficient field strength for typical neutron wavelengths, whereas superconducting systems [?] present prohibitive energy and performance demands on power supplies and superconducting materials when applying large alternating currents. The Nested Rotating Sextupole Permanent Magnet (Nest-Rotating-SPM) lens offers a highly economical and practical approach to focusing pulsed neutrons in spallation neutron sources [?, ?]. Colleagues from Kyoto University et al. have produced a Nest-Rotating-SPM and tested the device with ultra-cold neutrons with wavelengths from 27 to 55 Å [?, ?] and with standard samples [?]. To put the device into practical use, shorter wavelength neutrons must be focused. Neutrons emitted from the cold source or moderator follow the Boltzmann distribution [?], meaning the neutron flux exhibits exponential decay over wavelength. In addition to losing more than half of the neutrons filtered by the polarizing supermirror, only when neutrons with wavelengths shorter than 10 Å are focused might SANS experiments become practical. Zuo et al. identified three key challenges in putting the Nest-Rotating-SPM into practical use [?].

First, the strong alternating torque may destroy the permanent magnets of the inner sextupole, necessitating the use of strong fibers such as carbon fiber or Kevlar to strengthen the inner sextupole [?]. Second, heat from eddy currents and hysteresis loss in the inner circle may raise the temperature and disable the permanent magnets. Third, the motors must be synchronized with the repetition rate of the neutron source. Our research team has performed comprehensive theoretical modeling and finite element simulations to analyze these problems. In this study, building on prior research, we constructed and tested a prototype of the Nest-Rotating-SPM at the VSANS instrument [?, ?] at CSNS [?, ?]. The results show that with a 200 mm length Nest-Rotating-SPM, neutrons with wavelengths from 11.0 Å to 15.5 Å can be focused without chromatic aberration. This work steadily paves the way for the practical use of the Nest-Rotating-SPM in a spallation neutron source for neutron focusing and imaging [?, ?].

Design of the Sextupole Lens and the Focusing Experiment

The principle and calculation of the focal point of the sextupole lens have been discussed in previous references. It functions similarly to an optical convex lens. When the source aperture is positioned at twice the focal length of the lens and the detector is also placed at twice the focal length, the image of the source aperture will be observed on the detector surface. If the source aperture is set between one and two times the focal length, an enlarged image of the source aperture will appear on the detector. The geometry of the VSANS instrument has been configured with the source aperture (a four-blade slit) placed 9.92 m from the lens center and the lens center to detector distance of 12.82 m, as shown in Figure 1

(a). To achieve optimal focusing, the focal length of the lens should be 5.59 m, as calculated with formula (1). If the focal length is between 5.59 m and 9.92 m, the image of the source aperture may not be visible on the detector; instead, a focused beam spot with diameter larger than that of the source aperture will be observed.

$$\frac{9.92\,\mathrm{m} \times 12.82\,\mathrm{m}}{9.92\,\mathrm{m} + 12.82\,\mathrm{m}} = 5.59\,\mathrm{m}$$

As shown in Figure 1(a), pulsed neutrons from the moderator are collimated by a small source aperture, then the spin-up neutrons are reflected by a polarizing mirror and absorbed by the boron carbide wall. The transmitted spin-down neutrons are then flipped to spin-up neutrons and focused by the sextupole lens onto the detector surface. In a neutron pulse, neutrons with different wavelengths reach the lens sequentially, and the changing field in the sextupole lens

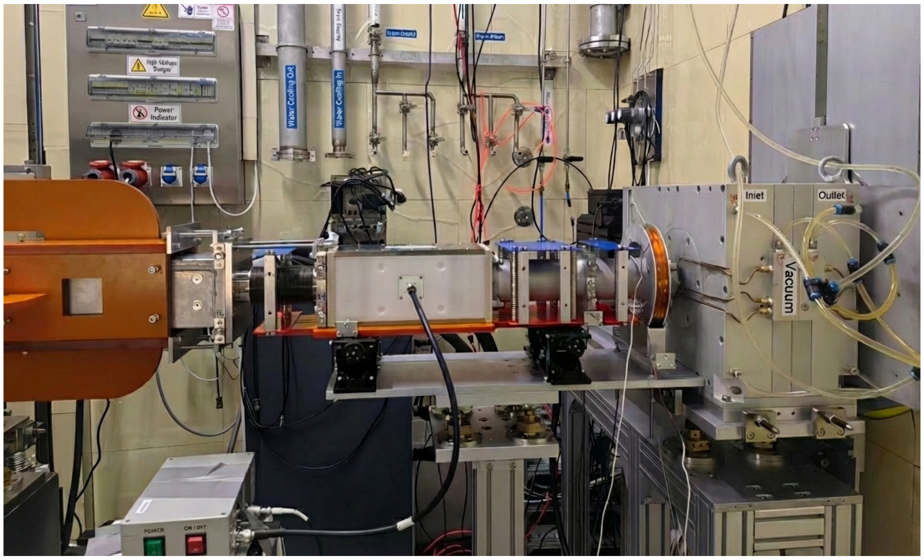

Figure 1: Figure 1

synchronizes with the pulsed neutrons to maintain a constant focal length for all neutron wavelengths. Images of the polarizer, flipper, and sextupole lens are presented in Figure 1(b). A double-V cavity polarizer with an m-value of 5 is located at the front end, approximately 9.85 m from the sample position, but it can only polarize 2.0-11.0 Å neutrons which cannot be focused by the sextupole prototype in this work. Therefore, a single plate Fe/Si polarizing supermirror purchased from SwissNeutronics with m-value equal to 3 [**?**] is used (Figure 1). A permanent magnet guide field and a coil guide field direct polarized neutrons between components adiabatically. Since spin-up neutrons will be focused while spin-down neutrons will be defocused, the beam spot at the GEM detector can be controlled by switching the RF-flipper. The RF-flipper was also purchased from SwissNeutronics with flipping ratio higher than 98% in the working wavelength range. A 22-kW motor drives the outer sextupole to rotate with a frequency of 8.333 Hz, which is 1/3 of the repetition rate of the proton pulse at CSNS. The synchronization and phase of the rotation relative to the proton pulse are achieved with a circular grating scale installed at the axis of the gear (Figure 2 FIGURE:2(b)). To protect the lenses, cooling water is divided by three beryllium copper channels and flows through the center of the Fe49Co49V2 sheet of the inner sextupole to remove heat caused by eddy currents.

Mechanical design and photographs of the Nest-Rotating-SPM are shown in Figure 2(a)(b). The motor drives a fan gear, which in turn drives two large gears fixed to the two outer sextupole lenses with a reduction ratio of 3. The grating scale is fixed at the axis of the fan gear to monitor the speed and phase of the motor. The compact design of the Nest-Rotating-SPM ensures that identical units can be easily connected to form a larger lens with shorter focal length. The core components of this Nest-Rotating-SPM are two sections of nested NdFeB permanent sextupole lenses, each 100 mm long, with magnetization directions shown in Figure 2(c). The six parts of the inner sextupole with a circular hole at each center are stacks of 0.35 mm Fe49Co49V2 plates. The Fe49Co49V2 plates and permanent magnets are mechanically interlocked and glued together with special heat-conductive glue. Three copper pipes and three copper wires go through the six holes to strengthen the structure, with cooling water running through the three pipes to remove heat. To further strengthen the inner sextupole, carbon fibers are wound onto the surface as shown in Figure 2(d). The bore diameter of the inner sextupole lens is 20 mm and there is a 35 mm gap between the two sextupole lenses. Neutrons may depolarize when passing through this gap, which will be discussed in the next section.

To ensure that polarized neutrons do not depolarize while passing through the 35 mm gap, the length of the inner sextupole lens is extended from 100 mm to 106 mm, while the length of the outer sextupole lens remains at 100 mm. A small sextupole, with a length of 29 mm, a bore diameter of 20 mm, and a thickness of 2 mm, is then inserted into the gap. A Finite Element Analysis (FEA) model of the two sections of the Nest-Rotating-SPM, with and without the small sextupole, is constructed to simulate the magnetic field through the bore (Figure 3 FIGURE:3 and (c)). Due to system symmetry, only one section of the Nest-Rotating-SPM and the small sextupole are simulated (see the inset of Figure 3(c)). The worst-case scenario, with a 60-degree phase difference between the inner and outer sextupole lenses, is also simulated. The minimum magnetic field at the center of the gap increases from approximately 12 Gauss to around 50 Gauss by adding the small sextupole lens, and the dramatic drop in the field at the edge of the sextupole is also mitigated. However, a field strength of 50 Gauss alone is insufficient to ensure neutron polarization. The adiabaticity parameter, which is the ratio of the Larmor frequency to the geometric rotational frequency experienced by neutrons passing through the gap, must also be considered.

Larmor precession occurs when a magnetic field is applied non-parallel to the magnetic moment of a neutron. In this case, individual neutron spins precess around the magnetic field vector, and the polarization is the time-averaged projection of the spin vectors along the magnetic field vector. The time-dependent change in the polarization vector can be described by the Larmor equation [**?**]:

$$\frac{d\mathbf{P}(t)}{dt} = \gamma(\mathbf{P}(t) \times \mathbf{B})$$

The polarization vector of the neutrons revolves around the magnetic field vector with Larmor frequency defined as:

$$\omega_L = \gamma B$$

When the orientation of the quantization axis (magnetic field vector) is changed, the polarization vector is not always able to follow. We now consider the quantization axis stationary in magnitude but changing its orientation along the neutron flight path. For this, a geometric rotation angle α_g and frequency ω_g can be defined. The neutron velocity v determines how quickly the change is experienced by the neutron when traveling along the z-axis:

$$\omega_g = \frac{v}{R}$$

The ratio between these two frequencies is often called the adiabaticity parameter:

$$k = \frac{\omega_L}{\omega_g}$$

A rule of thumb [**?**] is that if $k \geq 10$, the transition is adiabatic and the polarization degree is conserved. If $k \leq 0.1$, the transition is rapid, resulting in a well-defined reorientation of the polarization vector relative to the magnetic field. If $0.1 \leq k \leq 10$, the transition leads to more complex reorientation of the polarization vector; in practice, this scenario is typically avoided. It is well known that neutron velocity is inversely proportional to its wavelength, meaning neutrons with longer wavelengths will have smaller ω_g values according to equation (4). We selected 10 Å neutrons to calculate the adiabaticity parameter, or k-factor, based on formulas (3) and (5), as well as the simulated magnetic field along the bore. The results show that with the bridge sextupole, the k-factor remains higher than 10 throughout the gap. In contrast, without the bridge sextupole, the k-factor drops below 0.1 for some trajectories at the edges of the two sextupole lenses.

The key feature of the Nest-Rotating-SPM is that the magnetic field at the inner surface of the inner sextupole lens varies sinusoidally. If this oscillation is synchronized with the repetition rate of the pulsed neutron source, a wide wavelength band can be focused with nearly the same focal length. We measured the maximum magnetic field of the two inner sextupole lenses while rotating the outer sextupole lens (Figure 4 FIGURE:4). The maximum field is approximately 1.680 T, and the minimum field is about 0.286 T. This implies that the G-factor can vary from 33,600 T/m^2 to 5,720 T/m^2 over time, as described by formula (6), assuming a radius of 10 mm.

The inner sextupole is heated by eddy currents despite the use of 0.35 mm Fe49Co49V2 plate stacks. Therefore, three circular cooling water channels are designed to remove heat and keep the temperature of the inner sextupole below the working temperature (100 °C) of the NdFeB magnet. Experimental results indicate that with an ambient temperature of 23 °C and a 15 °C cooling water supply, the temperature of the inner sextupole lens's inner surface gradually rises from 23 °C to 35 °C over 45 minutes.

Experimental Results and Discussion

The neutron focusing experiment was conducted at the VSANS instrument at CSNS (Figure 1(b)) with a wavelength range from 11.0 to 15.5 Å (Figure 6 FIGURE:6(b)) because the polarizer can only polarize neutrons with wavelengths longer than 11.0 Å. To avoid neutron reflection on the inner surface of the lens, two apertures with a diameter of 18.0 mm are placed at the front and end of the lens. The focused and defocused beam spots, as well as their horizontal and vertical distributions, are shown in Figure 5 [FIGURE:5]. The focused and defocused beam spots take a hexagonal shape, reflecting the geometry of the sextupole lens. The Full Width at Half Maximum (FWHM) of the focused and defocused beams is 5.3 mm and approximately 52.0 mm horizontally and vertically (with gravity fall correction in the vertical direction). This indicates that the sextupole works properly in both directions. The horizontal and vertical distributions of the focused beam do not resemble a Gaussian profile. Background noise may arise from scattering by the multilayer polarizing supermirror and from unpolarized neutrons.

To ensure that all neutrons are focused with the same focal length, the wavelength range from 11.0 Å to 15.5 Å is divided into six lambda bins. The horizontal distributions of the focused and defocused beams across these wavelength sections are shown in Figures 6(c) and 6(d). Both figures demonstrate that the distributions across all wavelength sections are nearly coincident. The FWHM is 5.3 mm for the focused beam and 52.3 mm for the defocused beam. This study marks the first instance of focusing pulsed neutrons with such short wavelengths without chromatic aberration. The previous record involved focusing neutrons with wavelengths of 27 Å to 55 Å using three sections of 66 mm nested rotating sextupole permanent magnet sections by Yamada et al. Their lens has a maximum G-factor of 5.51 T/m^2, which may be able to focus neutrons with wavelengths shorter than 10 Å under the geometry of the VSANS instrument. However, their bore diameter is about 15 mm and the length is difficult to extend because of the complex three-motor design.

This study aims to determine the focal length of the lens and the critical length of the nested rotating permanent sextupole magnet (PSM) for focusing neutrons with wavelengths shorter than 10 Å in future experiments. The focal length of the lens is given by Equation (7) [**?**]. Using equation (7), with a focal length of 5.6 m and a G-factor of 33,600 T/m^2, neutrons with a wavelength of 8.5 Å can be properly focused. As neutrons with wavelengths ranging from 11.0 Å to 15.5 Å are used, they may be over-focused.

$$z_m = \frac{2\lambda}{GC}\alpha \cot\left(\frac{\lambda G\alpha}{2}\right)$$

Where z_m is the length of the lens (m), C is a constant (quotient of Planck's constant and neutron mass, 3965.2 Å · m/s), λ is neutron wavelength, G is the magnetic gradient factor (T/m^2), and α is the ratio of neutron spin magnetic moment to neutron mass (-5.7687 J/T · kg or $m^2/T \cdot s^2$).

A simulation offers an intuitive understanding of the neutron focusing configurations. A Python script was developed to simulate neutron trajectories under the influence of the lens. For simplicity, the simulation is conducted in a two-dimensional plane. Incident neutrons (blue lines in Figure 7 FIGURE:7) are emitted from a 3 mm wide source at 9920 mm and strike a 100 mm diameter lens at 0 m. Focused neutrons (red lines in Figure 7(a)) are directed onto a detector located 11.82 m from the lens. The distributions of the virtual neutrons at the detector are plotted in Figure 7(b) and compared with experimental data. The focal length of the lens in the simulation was adjusted to ensure that the FWHM of the simulated and experimental results align. Two focal lengths, 5.0 m and 6.5 m, satisfy the conditions for over-focused and under-focused scenarios. Given that the lens can focus 8.5 Å neutrons at a 5.6 m focal length, it is inferred that neutrons in the 11.0 Å to 15.5 Å range are over-focused. The experimental peak shows greater broadening below the FWHM compared to simulated predictions. This broadening may arise from small-angle neutron scattering (SANS) signals from the m=3 polarizing supermirror and spin-down neutrons incompletely filtered by the polarizing supermirror. Typically, the polarizing supermirror is positioned before the source aperture, but this was not feasible in the test experiment. However, this configuration is feasible in future experiments, as a double-V polarizing cavity is available at the front end of the VSANS instrument at CSNS.

Using Equation (7), the relationship between neutron wavelength and the G-factor is derived, as presented in Figure 7(c). It shows that with a G-factor ranging from 11,000 T/m^2 to 24,000 T/m^2, a 0.2 m lens can focus neutrons in the 11.0 Å to 15.5 Å range at a focal length of 5.0 m. The maximum G-factor of the lens is 33,600 T/m^2. Using the maximum G-factor, the possible wavelength range was calculated in Figure 7(d). It shows that with just two 0.2 m lenses, neutrons from 6.1 to 11.9 Å can be focused with a focal length of 5.6 m, which coincides with the usual wavelength range of the VSANS instrument (6-10.5 Å). Longer sextupole lenses exhibit diminishing marginal returns in performance. With a 0.6 m lens, the shortest wavelength is 5.1 Å, and with a 0.8 m lens, the shortest wavelength is 4.4 Å. Extended lens configurations yield diminishing returns in performance improvement.

Conclusion

A compact nested rotating sextupole permanent magnet (Nest-Rotating-SPM) lens was constructed and tested at the VSANS instrument at CSNS. Using carbon fiber reinforcement, water cooling, and a bridging sextupole lens, two 100 mm nested lens sections were connected and synchronously rotated to focus neutrons in the 11.0 Å to 15.5 Å range. This is the first time that pulsed neutrons with such short wavelengths have been focused without chromatic aberration. Further analysis indicates that a 400 mm lens or two 200 mm lens sections can focus neutrons in the 6.1 Å to 11.9 Å range using the existing VSANS instrument geometry. A longer lens can focus neutrons with shorter wavelengths, but diminishing returns occur, with a 1000 mm lens capable of focusing neutrons down to 4 Å.

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