Design of a three-detector system on LUOSHU: a small-angle neutron scattering instrument at China Mianyang Research Reactor

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The LUOSHU small-angle neutron scattering instrument is one of the neutron scattering instruments under construction at the China Mianyang Research Reactor. Research interests in the fields of materials science, physics, chemistry and biology require that LUOSHU provide a wide range of measured scattering vector magnitudes (Q), a large dynamic Q range and high resolution. A movable and combined three-detector system that consists of a high-resolution position-sensitive 3He multi-tube rear detector and two L-shaped front detectors is designed in order to expand the Q range and dynamic Q. Analytical calculations validate that, with the three-detector system, LUOSHU can cover a Q range of four orders of magnitude. Also, the three-detector system will extend the dynamic Q range and provide simultaneous Qmax/Qmin higher than 800 in operation, satisfying the requirements of in situ experiments.

1. Introduction

As an advanced technique widely used in biology, chemistry, materials science, physics and other fields, small-angle neutron scattering (SANS) can be used to study metal alloys, magnetic materials (Sokolov et al., 2019), colloids (Stradner et al., 2004), polymers (Chen et al., 2003; Kimata et al., 2007; Siewert et al., 2020), biomolecules (Lapinaite et al., 2013; Siewert et al., 2020) and other materials containing nanostructures. Statistical information including size, morphology, composition and volume fraction in the agglomeration or evolution of structures of nanometre to sub-micrometre size can be detected and collected under different applied conditions or sample environments by means of SANS. Most worldwide neutron research institutions are equipped with one or several SANS instruments, for example, SANS 1 (Kohlbrecher & Wagner, 2000) at the Paul Scherrer Institute; YuMO (Kuklin et al., 2021) at the Joint Institute for Nuclear Research in Russia; NGB and NG7 at the National Institute of Standards and Technology (NIST) (Glinka et al., 1998); Quokka (Wood et al., 2018) and Bilby (Sokolova et al., 2019) at the Australian Nuclear Science and Technology Organisation (ANSTO); and D11 (Ibel, 1976), D22 (Courtois et al., 2006) and D33 (Dewhurst, 2008) at Institut Laue–Langevin (ILL). Currently, there are three stable operating SANS instruments in China, the 30 m SANS instrument at the China Advanced Research Reactor (Zhang et al., 2014), BL01 at the China Spallation Neutron Source in Dongguan (Ke et al., 2018) and the Suanni SANS instrument at the China Mianyang Research Reactor (Peng et al., 2016).
Along with the development of cross-scale science and technology, the most important in situ studies of reactions and dynamics via structural changes can be performed within a wide scattering vector magnitude ($Q$) range via SANS. As one of the most powerful and requested neutron-scattering techniques, SANS can capture statistical information on material structure that would be hard to obtain by means of electron microscopy, optical microscopy, atomic force microscopy etc. Hence LUOSHU is designed to cover a broader range for time-resolved measurements, two or more independent measurements are usually needed at different instrument configurations (collimation and detector positions). It would be highly desirable to eliminate this limitation with a suitable detection system including the position-sensitive $^3$He multi-tube detector with a pixel size of 5 mm.

In this work, the design and analytical calculations of a moveable three-detector system on the LUOSHU small-angle scattering instrument are applied and simulated. The overall design of the LUOSHU small-angle scattering instrument is described, and the general analytical calculations of the detection system including the $Q$ range, the dynamic $Q$ range and the $Q$ resolution are determined. The innovative detection system on LUOSHU is expected to extend the $Q$ range and dynamic $Q$ range.

2. General layout for the detection system in LUOSHU

LUOSHU mainly consists of a bender part, velocity selector, collimator system, sample platform and detection system, as depicted in Fig. 1. Different collimation distances and detection distances can be achieved by switching the guides in the collimator system and the distance between the detector and the sample platform.

The bender part in LUOSHU is necessary to reduce the interference of thermal neutrons on the detection signal and hence improve the signal-to-noise ratio, as well as to deflect the neutron beam to realize the operation of the neighbouring Suanni SANS instrument at the same time. The general parameters of the bender part can be determined under the existing conditions: the total length of the bender part is limited within 8.5 m and the deflection angle is 4°. According to calculations and simulation, the parameters needed to achieve the best neutron intensity are determined, including the number of channels, which is four, while the length of the bender is 7 m and the length of the guide G2 is 1.5 m.

LUOSHU will offer flexibility in the choice of $\Delta\lambda/\lambda \simeq 5$–20% when performing well defined size distribution measurements. Two velocity selectors, each usable within the wavelength range 3.5–17 Å with nominal bandwidths of 12% (5–13% under rotation) and 20% (10–20% under rotation), can be chosen accordingly.

![Diagram of LUOSHU](image-url)
The collimator system consists of an 18 m-long series of super-mirror neutron guides \((m = 3)\), which consist of six 2.5 m-long and one 3 m-long neutron guides near the velocity selector side, and a 1.5 m-long retractable vacuum tube, which can be manually changed from 0.5 to 1.5 m. The four-knife slits are used to reduce the experimental background with adjustable size. Also, the four-knife slits can be switched with the multi-pinhole slits to obtain an acceptable neutron intensity for different experimental scenarios including the grazing incidence module (Wang et al., 2018). Therefore, different collimation modes are available through the selection of different slits and apertures. The last section of the neutron guide can be replaced by the focus mirror to expand the minimum \(Q\). Different collimation lengths (source-to-sample distance, defined as the distance from the exit of the closest guide to the sample) including \(L_{SS} = 19.5, 14.5, 9.5, 4.5\) and 1.5 m can be realized by selectively moving the four neutron guides into or out of the beam. The source and sample apertures can be changed. The beam size can be adjusted by changing the sample aperture, the diameter of which is 4–16 mm.

A large detector ensures large solid-angle coverage and therefore a large dynamic \(Q\) range, accessible in one single instrument configuration. LUOSHU will use three position-sensitive \(^3\)He multi-tube detectors in total, two front L-shaped detectors of \(~0.2 \times 1\) m in area and one rear detector of \(~1 \times 1\) m, as shown in Fig. 2. Each L-shaped detector consists of two sets of \(^3\)He tubes placed perpendicular to each other. The position resolution along the tube of the detectors is determined by the intrinsic resolution of the \(^3\)He tubes and is estimated to be 5 mm. The axial resolution is decided by the spacing and the diameter of the tubes; in the case where the tubes are closely arranged in a single plane (‘planar arrangement’), the radial resolution is the 5 mm tube diameter, which will be the narrowest option that is commercially available. The spatial resolution can be further enhanced if the tubes are placed in a ‘zigzag arrangement’ (Noda et al., 2016; He et al., 2015). So the horizontal and vertical spatial resolution of the three detectors is initially determined to be 5 \times 5 mm. The two front detectors count neutrons scattered to wider angles while the rear detector counts scattered neutrons at smaller angles. \(L_{SPS}\), the distance between the sample platform and the rear detector, is set according to \(L_{SS}\) for the best resolution (see Section 3.3). Two detection modes are available with the two L-shaped detectors, including L-shaped mode and frame-shaped mode. The two front detectors can be separated to expand the effective detection area for isotropic particles. Otherwise, they can be combined to form a frame-shaped detector for anisotropic materials. The L-shaped detectors are centred on the rear detector and can be translated outward within 0.1 m along the lateral direction to expand the accessible \(Q\) range. They can also be moved inward within 0.3 m to avoid blocking the rear detector. Further configurational details are described in Section 3.2.

3. Analytical calculations of the three-detector system in LUOSHU

Analytical calculations, including the \(Q\) range, dynamic \(Q\) range \((Q_{\text{max}}/Q_{\text{min}})\) and corresponding \(Q\) resolution, which are closely related to the various parameters of the instrument,
are applied to obtain the optimized design of the detection system in LUOSHU.

3.1. The $Q$ range

The range of scattering vector magnitudes of a small-angle scattering instrument determines the scale range of the object that can be measured. According to the basic formula, $Q = \frac{2\pi}{\lambda}\sin \theta$ where $\lambda$ is the wavelength of neutrons and $\theta$ is the scattering angle. To detect particles in a larger size range, neutrons of longer wavelengths are needed. As illustrated in Fig. 3, the minimum detection angle $\theta_{\text{min}}$ is determined by the source aperture radius $R_1$, sample aperture radius $R_2$, detection distance $L_{SD}$ and pixel size of the detector $\Delta D$ as (Han et al., 2007)

$$ R_{\text{min}} = \left( \frac{L_{SD}}{L_{SS}} R_1 + \frac{L_{SS} + L_{SD}}{L_{SS}} R_2 + \frac{\Delta D}{2} \right), $$

$$ \theta_{\text{min}} = \tan^{-1} \left( \frac{R_{\text{min}}}{L_{SD}} \right). $$

Therefore, the minimum $Q$ can be calculated by $Q_{\text{min}} = \frac{(2\pi/\lambda)\sin \theta_{\text{min}}}{L_{SD}}$ at the longest collimation when all guides in the collimator section are moved out, for which $R_1 = 8$ mm, $R_2 = 4$ mm, $L_{SS} = 19.5$ m and $\Delta D = 5$ mm. When the detection distance $L_{SD}$ reaches the maximum length of 23 m, the minimum $Q = 0.00031$ Å$^{-1}$ can be achieved.

The maximum detection angle $\theta_{\text{max}}$ is determined by the size of the short edge of the front detectors $L_{\text{front}} = 0.2$ m, the size of the rear detector $L_{\text{rear}} = 1$ m and the detection distance $L_{SD}$ as

$$ R_{\text{max}} = L_{\text{front}} + \frac{L_{\text{rear}}}{2}, $$

$$ \theta_{\text{max}} = \tan^{-1} \left( \frac{R_{\text{max}}}{L_{SD}} \right). $$

Therefore, the maximum $Q$ can be calculated as $Q_{\text{max}} = \frac{(2\pi/\lambda)\sin \theta_{\text{max}}}{L_{SD}}$ at the shortest collimation distance when all guides in the collimator section are moved in, for which $R_1 = 8$ mm, $R_2 = 4$ mm, $L_{SS} = 0.7$ m and $\Delta D = 5$ mm. When the detection distance $L_{SD}$ reaches its minimum of 0.7 m, the maximum $Q$ of 1.27 Å$^{-1}$ can be achieved.

According to the available neutron wavelength range and the required $Q$ range, a three-detector system is adopted, as described above. Thus, the $Q$ range is $0.00031$–$1.27$ Å$^{-1}$ according to the above parameters, and the detection distance $L_{SD}$ is optionally $0.7, 1.5, 3, 4.5, 7, 9.5, 12, 14.5, 17, 19.5$ or $23$ m to exhibit specific variation of $Q$ with different detection distances at several typical wavelengths (3.5, 5.3 and 17 Å). In addition, to achieve a smaller scattering vector magnitude, the minimum scattering vector value can be improved by one order of magnitude while the neutron beam intensity can be increased by adding a focusing lens group (Choi et al., 2000). For comparison with similar SANS instruments, the 30 m NGB at NIST can cover the $Q$ range $0.001$–$0.85$ Å$^{-1}$ (Glinka et al., 1998), the 40 m Quokka at ANSTO can cover the $Q$ range $0.0006$–$0.7$ Å$^{-1}$ (Wood et al., 2018) and the 40 m D33 at ILL can cover the $Q$ range $0.001$–$0.7$ Å$^{-1}$ (Dewhurst, 2008). So LUOSHU could provide a comparable $Q$ range when in operation.

The calculated $Q$ ranges of the 46 m LUOSHU instrument with different configurations are given in Fig. 4. The accessible $Q$ ranges are $0.0015$–$1.27$ Å$^{-1}$ for 3.5 Å, $0.001$–$0.838$ Å$^{-1}$ for 5.3 Å and $0.00031$–$0.26$ Å$^{-1}$ for 17 Å. At the ‘extreme’ detector configuration, the front detectors can be positioned at 0.7 m from the sample, and the rear detector can be positioned at 23 m from the sample. Note that the $Q$ range quoted above for a given neutron wavelength can be only accessed by the extreme configurations ($L_{SS} = L_{SD} = 0.7$ m and $L_{SS} = 19.5$ m, $L_{SD} = 23$ m). Meanwhile, the entire $Q$ range can only be obtained by adjusting different neutron wavelengths.

3.2. The dynamic $Q$ range ($Q_{\text{max}}/Q_{\text{min}}$)

A large dynamic $Q$ range (i.e. $Q_{\text{max}}/Q_{\text{min}}$) is important to maximize the detector coverage in single-shot experiments. LUOSHU would use three detectors, in the same line and
within the same detector tank to increase the dynamic $Q$ range for one instrument configuration.

To guarantee that the three-detector system is capable of acquiring continuous images, a certain detection distance is required between the twin L-shaped detectors and the main detector to avoid overshadowing. In addition, due to the motion track and other devices in the detection chamber, the closest detection distance should be 0.5 m. Furthermore, the closest distance between the front detector and the sample position is 0.7 m, and the farthest detection distance of the rear detector is up to 23 m.

For isotropic particles, the L-shaped configuration of the detection system can be adjusted to extend the $Q$ range at one single measurement, as shown in Fig. 5(a). The two front detectors arranged in this way are geometrically equivalent to one large detector at the rear position but require a smaller detector tank; in addition, this allows more flexibility in configuration. The $Q$ range of three common combinations of detection distances are calculated. Each of the three detectors is positioned approximately half the distance from the subsequent detector to ensure continuous $Q$-range coverage. At the high-$Q$ setting from 0.0049 to 0.57 Å$^{-1}$, short detection distances of 0.7, 1.5 and 4.5 m are used, and a dynamic $Q$ range of 116 can be achieved; by offsetting the front detector 0.1 m perpendicular to the beam, the maximum $Q$ can be extended to 0.89 Å$^{-1}$. At the low-$Q$ setting from 0.001 to 0.10 Å$^{-1}$ with detection distances of 4.5, 10.5 and 23 m, a $Q_{\text{max}}/Q_{\text{min}}$ of 210 can be attained, and the $Q$ range can be extended up to 0.21 Å$^{-1}$ when the front detector is outwardly shifted by 0.1 m in this setting. In the case of another commonly used configuration of detection distances of 2.5, 4.5 and 10.5 m, the $Q$ range 0.0021–0.20 Å$^{-1}$ and a dynamic $Q$ range of 100 can be realized, and $Q_{\text{max}}$ can be further extended to 0.36 Å$^{-1}$ with 0.1 m outward shift of the front detector.

(a) **L-shaped configuration**

(b) **Frame-shaped configuration**

Figure 5

(a) L-shaped and (b) frame-shaped configurations of detection and corresponding $Q$ ranges of different configurations at a wavelength of 5.3 Å.
For example, the evolution of nanoscale spherical precipitates in metals can be measured in the L-shaped mode. The use of one-step or two-step heat treatment enables the manipulation of precipitate size distributions in metal systems. After a low-to-high heat treatment, coarse second phases are dissolved, while plenty of fine phases and some core–shell composite particles are precipitated. In an Al–Li system, the small precipitates are usually around several nanometres while the larger precipitates can reach hundreds of nanometres (Shi et al., 2020; Krug et al., 2011; Radmilovic et al., 2011a,b). In these cases, the evaluation of all the precipitates in various size and volume fractions can be achieved with SANS via LUOSHU, which can eliminate the need to make several measurements of the same sample at different instrument configurations. With the three detectors in different positions, information on precipitates of sub-nanometre to sub-micrometre size can be collected synchronously. In the L-shaped configuration, the three detectors can be separately set at 0.7, 1.5 and 4.5 m from the sample at a detection distance of 23 m, and the combined frame-shaped configuration as displayed in Fig. 5(b), the dynamic $Q$ range at different wavelengths (3.5, 5.3, 17 Å) is given in Table 1. The dynamic $Q$ range of over 300. Therefore, fewer adjustments in detection distance of LUOSHU will be needed to cover the whole size range of objects in a single experiment.

<table>
<thead>
<tr>
<th>$\lambda$ (Å)</th>
<th>$Q_{\text{min}} = 9.2$ m ($\AA^{-1}$)</th>
<th>$Q_{\text{max}} = 23$ m ($\AA^{-1}$)</th>
<th>$Q_{\text{max}}/Q_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>0.49</td>
<td>0.0014</td>
<td>350</td>
</tr>
<tr>
<td>5.3</td>
<td>0.33</td>
<td>0.001</td>
<td>330</td>
</tr>
<tr>
<td>17</td>
<td>0.10</td>
<td>0.00031</td>
<td>323</td>
</tr>
</tbody>
</table>

For a small-angle scattering instrument with a slit-mode collimation structure, the variance $(\delta q)^2$ is the sum of the variances of geometry and wavelength (Peng et al., 2016; Pedersen et al., 1990), which can be calculated as follows:

$$ (\delta q)^2 = \frac{4\pi^2}{\lambda^2} (\delta \theta)^2 + q^2 \left( \frac{\delta \lambda}{\lambda} \right)^2. $$

The first term in the equation corresponds to the geometric contribution to the resolution of the instrument in a specific setup and the second term is a $Q$-dependent component. $(\delta \theta)^2$ and $(\delta \lambda)^2$ are the variances in $\theta$ and $\lambda$, respectively.

3.3. The $Q$ resolution

The $Q$ resolution $\delta q/q$ is one of the main uncertainties of a small-angle scattering instrument, determining its ability to distinguish particles with different sizes. The $Q$ resolution is composed of geometric resolution and wavelength resolution. For a small-angle scattering instrument with a slit-mode collimation structure, the variance $(\delta q)^2$ is the sum of the variances of geometry and wavelength (Peng et al., 2016; Pedersen et al., 1990), which can be calculated as follows:

$$ (\delta q)^2 = \frac{4\pi^2}{\lambda^2} (\delta \theta)^2 + q^2 \left( \frac{\delta \lambda}{\lambda} \right)^2. $$

The first term in the equation corresponds to the geometric contribution to the resolution of the instrument in a specific setup and the second term is a $Q$-dependent component. $(\delta \theta)^2$ and $(\delta \lambda)^2$ are the variances in $\theta$ and $\lambda$, respectively.

3.3.1. Wavelength contribution. A reactor-based SANS instrument typically uses a wavelength band of $\Delta \lambda / \lambda \approx 10\%$ full width at half-maximum, selected using a neutron velocity
selector. When faced with well defined size distributions measurements, a much tighter wavelength resolution is required. LUOSHU will offer flexibility in the choice of $\Delta \lambda / \lambda \simeq 5\text{--}20\%$ in these situations. Two velocity selectors which can be used within the wavelength range 3.5--17 Å, with nominal bandwidths of 12% (5--13% under rotation) and 20% (10--20% under rotation), can be chosen accordingly. The design of the switchable velocity selector system is similar to the design of two interchangeable velocity selectors in the Quokka SANS instrument at ANSTO (high-flux mode with the resolution 7--18% and high-resolution mode with the resolution 4--14%) (Wood et al., 2018).

The wavelength resolution $\Delta \lambda / \lambda$ of a velocity selector is determined by $\Delta \lambda / \lambda = \beta \alpha$, where $\alpha$ is the screw angle of the blades and $\beta$ is the angle between the blades (Wagner et al., 1992).

In order to improve the wavelength resolution without changing the structure of the velocity selector, the angle $\nu$ between the rotor axis of the velocity selector and the neutron beam can be changed to adjust the effective screw angle $\alpha_{\text{eff}}$, $\alpha_{\text{eff}} = \alpha + \nu L_{\text{NVS}} / R_{\text{NVS}}$, where $L_{\text{NVS}}$ is the length of the rotor and $R_{\text{NVS}}$ is the window radius (Glinka et al., 1998).

The effective screw angle $\alpha_{\text{eff}}$ of the velocity selector can be changed by inclining the rotor angle of the velocity selector within a certain range, thus improving or reducing the wavelength resolution. So, Monte Carlo simulation was carried out for the velocity selector at different effective screw angles via McStas (Willendrup & Leifmann, 2020). The parameters of the Airbus neutron velocity selector (NVS071, Airbus DS GmbH, Germany) are used for simulation, with nominal bandwidth $\Delta \lambda / \lambda$ of 12%. The wavelength resolution improves as the inclination angle increases to $5^\circ$ ($\alpha_{\text{eff}} = 2.9^\circ$), the resolution is 12.5%. And at the extreme inclination angle, $10^\circ$ ($\alpha_{\text{eff}} = 5.8^\circ$), the resolution is 11.3%. However, when the inclination angle decreases to $-5^\circ$ ($\alpha_{\text{eff}} = -2.9^\circ$), the resolution is 16.2%. And at the extreme inclination angle ($\alpha_{\text{eff}} = 5.8^\circ$), the resolution is 19.3%. To sum up, the rotor inclination angle of $\pm 10^\circ$ (2.9) can change the resolution by about 8%. Thus, we can adjust the wavelength resolution of the selector by adjusting its inclination angle to provide a neutron beam that meets the requirements of the particular experiment.

3.3.2. Geometric contribution. The geometric contribution to the resolution is determined by the incident and scattered neutron beam divergences and the detector position resolution.

The contribution in the horizontal direction is expressed as

$$
(\delta \theta)_h^2 = \frac{1}{4} \left( \frac{R_1}{L_{SS}} \right)^2 + \frac{R_2^2}{4} \left( \frac{1}{L_{SS}} + \frac{1}{L_{SD}} \right)^2 + \frac{1}{12} \left( \frac{\Delta D}{L_{SD}} \right)^2,
$$

(6)

where $L_{SS}$ is the collimation distance, $L_{SD}$ is the detection distance, $R_1$ is the radius of the source aperture, $R_2$ is the radius of the sample aperture, and $\Delta D$ is the pixel size in both the horizontal and vertical directions. Considering the gravity effect on the neutron trajectories, the geometric resolution in the vertical direction can be given by

$$
(\delta \theta)_v^2 = \frac{1}{2} \left( \frac{R_1}{L_{SS}} \right)^2 + \frac{R_2^2}{2} \left( \frac{1}{L_{SS}} + \frac{1}{L_{SD}} \right)^2 + \frac{1}{6} \left( \frac{\Delta D}{L_{SD}} \right)^2 + A^2 \left( \lambda^2 - \lambda_{\text{geo}}^2 \right)^2,
$$

(7)

where $A = L_{SD}(L_{SS} + L_{SD})gm^2/(2h^2)$, $g$ is the acceleration due to gravity, $m$ is the neutron mass, $h$ is Planck’s constant, $\lambda^2 = \lambda^2 / \left(1 + 1/6(\Delta \lambda / \lambda)^2\right)$ and $\lambda_{\text{geo}}^2 = \lambda^2 / \left(1 + (\Delta \lambda / \lambda)^2 + 1/15(\Delta \lambda / \lambda)^4\right)$ (Hammouda & Mildner, 2007). Although the effect of gravity is stronger for longer wavelengths, the contribution of gravitational effects to the geometric resolution in the vertical direction is less than 1% at the longest collimation of 19.5 m and $L_{SD}$ of 23 m with $\lambda < 17$ Å for LUOSHU (0.853% for 5.3 Å, 0.975% for 8.5 Å and 0.998% for 17 Å). Therefore, the geometric resolution at any azimuthal angle can be approximated as

$$
(\delta \theta)^2 = \frac{1}{2} \left( \frac{R_1}{L_{SS}} \right)^2 + \frac{R_2^2}{2} \left( \frac{1}{L_{SS}} + \frac{1}{L_{SD}} \right)^2 + \frac{1}{6} \left( \frac{\Delta D}{L_{SD}} \right)^2.
$$

(8)

The frequently chosen configuration setups on LUOSHU are $L_{SD} = 1.5, 4.5, 9.5, 14.5, 19.5$ and 23 m; $L_{SS} = 9.5, 14.5$ and 19.5 m; $R_1 = 8$ mm; $R_2 = 4$ mm; $\Delta D = 5$ mm; $\lambda = 5.3$ Å; $\Delta \lambda / \lambda = 0.1$. The geometric resolution improves with increasing detection distance and collimation distance, as displayed in Table 2.

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Table 2. Geometric resolution parameters for the normal setups of LUOSHU.

<table>
<thead>
<tr>
<th>$L_{SD}$ (m)</th>
<th>$L_{SS}$ (m)</th>
<th>$R_1$ (mm)</th>
<th>$R_2$ (mm)</th>
<th>$\Delta D$ (mm)</th>
<th>$\lambda$ (Å)</th>
<th>$(\delta \theta)_v^2$ (nm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>9.5</td>
<td>8</td>
<td>4</td>
<td>5</td>
<td>5.3</td>
<td>$6.97 \times 10^{-6}$</td>
</tr>
<tr>
<td>4.5</td>
<td>9.5</td>
<td>8</td>
<td>4</td>
<td>5</td>
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<td>$6.97 \times 10^{-6}$</td>
</tr>
<tr>
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<tr>
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<td>4</td>
<td>5</td>
<td>5.3</td>
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</tr>
<tr>
<td>19.5</td>
<td>23</td>
<td>8</td>
<td>4</td>
<td>5</td>
<td>5.3</td>
<td>2.64 \times 10^{-7}</td>
</tr>
</tbody>
</table>

**Figure 6**

Neutron intensity and resolution at the sample stage under different effective screw angles of the velocity selector ($\Delta \lambda / \lambda = 12\%$).
The wavelength distribution transmitted by the velocity selector is assumed to follow a Gaussian function and can be expressed as

\[
\left( \frac{\delta \lambda}{\lambda} \right)^2 = \frac{1}{8 \ln 2} \left( \Delta \lambda \right)^2.
\]

(9)

The values of \(\delta q/q\) at low, medium and high \(Q\) are shown in Fig. 7, divided by the different \(L_{SS}\) accordingly. The variance of the low \(Q\) resolution can be deduced to be \((\delta q)^2 = 2.52 \times 10^{-7} + 0.0018 q^2 (\text{Å}^{-1})^2\) under the setup of \(L_{SD} = 19.5\) m. The variance of the medium \(Q\) resolution can be deduced to be \((\delta q)^2 = 1.06 \times 10^{-6} + 0.0018 q^2 (\text{Å}^{-1})^2\) under the setup of \(L_{SD} = 9.5\) m. The variance of the high \(Q\) resolution can be deduced to be \((\delta q)^2 = 9.80 \times 10^{-6} + 0.0018 q^2 (\text{Å}^{-1})^2\) under the setup of \(L_{SD} = 1.5\) m. In theory, the uncertainty at low \(Q (<0.004 \text{ Å}^{-1})\) is higher than 10%, which is dominated by the geometric resolution. In contrast, wavelength resolution plays a dominant role in the high-\(Q\) region (>0.03 Å\(^{-1}\)).

The detection system of LUOSHU is designed in such a way that it provides different configurations for various experimental scenarios. Both high-resolution and high-flux modes can be chosen to suit the characteristics of the investigated system.

4. Conclusions

The three-detector system in the LUOSHU instrument has the following aims: (1) A wide \(Q\) range from 0.00031 to 1.27 Å\(^{-1}\) is covered, with up to 23 m detection distance at wavelength ranges from 3.5 to 17 Å, which can be adapted to the specific requirements of individual experiments using a variable neutron flight path. (2) A high dynamic \(Q\) span \((Q_{\text{max}}/Q_{\text{min}})\) of up to over 300 is realized, which can accommodate most types of \textit{in situ} experiments. The system can be operated in L-shaped or frame-shaped configuration accordingly. (3) High \(Q\) resolution of the instrument is supported by the \(^3\)He position-sensitive detectors with a pixel size of 5 mm, and a switchable velocity selector system with high-flux and high-resolution modes.

According to the analysis and simulations, the detection system is expected to provide a well adapted platform for \textit{in situ} measurements in various research fields with high efficiency and resolution.

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