Design of a $\mu$SR spectrometer with ultrahigh arrays at China Spallation Neutron Source

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ABSTRACT: A new muon source has been proposed to conduct muon spin rotation/relaxation/resonance ($\mu$SR) measurements at China Spallation Neutron Source (CSNS). Only 1 Hz of the CSNS proton beams (25 Hz in total) will be allocated for muon production. To make better use of muons in every pulse, an ultrahigh-array $\mu$SR spectrometer (UHAM) with thousands of detector channels is under design. Due to such a high granularity of detectors, multiple counting events generated from particle scattering or spiral motions of positrons in a strong longitudinal field should be carefully considered in the design. Six different structures were modeled and simulated based on two types of angular orientations (parallel arrangement and pointing arrangement) and three kinds of spectrometer geometries (cylinder, cone and sphere). A quality factor, $Q$, was proposed to evaluate the performance of these structures by integrating their impacts on the overall asymmetry, the counting rate and the percentage of multiple counts. According to the simulation, the conical structure with detectors pointing to the sample has the highest $Q$ in both zero field and longitudinal field. The results also show that all kinds of structures cannot be operated under strong longitudinal fields with a strength over 2 T. The full simulation of a $\mu$SR spectrometer can provide good guidance for the construction of the UHAM in the upcoming upgrade of CSNS.

KEYWORDS: Muon spectrometers; Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); Simulation methods and programs

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1 Introduction

Muon is one type of lepton, possessing a spin of 1/2 and a unit electric charge. Muons can be produced in pion decays that are generated from the bombardment of high energetic particles on a production target. In addition, pions decay into muon neutrinos. In the reference frame of a pion, its daughter muon and neutrino are emitted in opposite directions. The spin of a positive muon is antiparallel to its momentum (parallel in the case of negative muons) due to the weak nature of the decay. Muons are also unstable and decay into positrons, muon neutrinos and electron neutrinos with a lifetime of $\sim 2.2 \mu s$. According to the parity violation in weak interactions, positrons are emitted asymmetrically in space and preferentially along the direction of their parental muon spin. The precession of muon spin in magnetic fields makes muons sensitive to the local magnetic property of materials. Therefore, the magnetic properties of materials can be characterized by muon spin rotation/relaxation/resonance ($\mu$SR) techniques.

For general $\mu$SR experiments, a muon beam, a spectrometer and a sample environment are all required in muon facilities [1–5]. For different experimental purposes, the $\mu$SR spectrometer can work in zero or nonzero magnetic fields. The precision of $\mu$SR data directly depends on the counting rate and the asymmetry of the spectrometer. The counting rate depends on the beam intensity, the solid angle occupied by the detector system, and the pile-up rejection capability of a single detector. The placement of the detector system also determines the asymmetry of the spectrometer. The quantitative treatment of the muon decay is based on the weak interaction and the positron emission probability per unit of time as a function of the solid angle and the emission energy, which can be expressed as [6]:

$$
\frac{d\Gamma}{d\Omega} = \frac{1}{4\pi \tau_{\mu}} 2\varepsilon^2 (3 - 2\varepsilon) \left[ 1 + \frac{2\varepsilon - 1}{3 - 2\varepsilon} \cos \theta \right] d\varepsilon d\Omega \tag{1.1}
$$

where $\Gamma$ is the positron emission probability, $\tau_{\mu}$ is the lifetime of muons, $d\Omega = \sin \theta d\theta d\phi$ is the solid angle, $\varepsilon$ is the ratio of positron emission energy to the maximum positron emission energy (52.8 MeV), and $a(\varepsilon) = \frac{2\varepsilon - 1}{3 - 2\varepsilon}$ is the asymmetry term. The asymmetry of a $\mu$SR spectrometer is the
asymmetry term $a(\epsilon)$ integrated by all positrons recorded by detectors. Therefore, decay positrons are emitted asymmetrically around their parental muon spins.

In a pulsed muon beamline [3–5], a detector records all events once their amplitudes are higher than the threshold. It is possible that the multiple counts are generated from one positron in a muon decay event when the deposition energy of positrons in multiple detectors are higher than the threshold. There are mainly three types of multiple counting events: 1) positrons penetrate multiple adjacent detectors by scattering or spiral motions in a strong magnetic field, 2) secondary particles such as electrons or gamma rays are generated by positrons or muons, and 3) positrons are generated outside the sample. For the first two cases, both positrons and their induced secondaries carry the same asymmetry information. This leads to errors in the counts of each detector, which affects the asymmetry of different detector rings. Consequently, the statistical errors of the data will increase [7]. For the last case, the real information of the local field of materials will be mixed with those from outside the sample [8]. For all cases, multiple counts will increase the counting rate. As a result, the asymmetry will deviate from its true value, which will distort the $\mu$SR spectra. To reduce the multiple counts in every positron event, it is required that only one detector has the positron deposition energy higher than the threshold. Therefore, a high threshold can effectively reduce the multiple counts. Besides, thick metallic absorbers placed between detectors can also reduce the multiple counts. However, thick absorbers will take up a large fraction of the solid angle covered by the spectrometer, leading to the reduction of detection efficiency. Therefore, such a solution is not considered in this work.

A muon source was proposed in Phase II of China Spallation Neutron Source (CSNS) [9–13]. Approximately 4% of the proton beam power (500 kW, 1.6 GeV, 25 Hz) will be assigned to the muon source. Only 1 Hz of the proton repetition rate will be used to make muons. Due to the limit of the repetition rate, an ultrahigh-array $\mu$SR spectrometer (UHAM) dedicated for this muon source should have several thousand detector units to make use of each muon as much as possible. The detector material is made of plastic scintillators with a model type of EJ200 [14]. Thus, the total counting rate of the spectrometer is comparable with those in ISIS [3] and J-PARC [4]. However, the percentage of multiple counts will increase due to the high granularity. Hence, the percentage of multiple counts was used as an important parameter to evaluate the performance of a spectrometer in addition to the counting rate and asymmetry. Accordingly, a quality factor, $Q$, was proposed to comprehensively evaluate these parameters.

In the design of the UHAM, there are two options for the arrangement of detectors. Detectors can be placed parallelly along the beam direction or pointing to the sample, which are called the parallel arrangement or pointing arrangement, respectively. In addition, detectors can be placed in various geometries including cylinders, cones and spheres. Considering the two scenarios above, six different detector structures have been modeled. In this work, the quality factors of these structures have been simulated and optimized using musrSim [15] compiled on the Geant4 toolkit [16–18].

2 Spectrometer structure

Figure 1 presents the root mean square (RMS) envelops of the muon beam with a spot size of $20 \times 20$ mm$^2$ in the sample position. Main parameters of the muon beam are listed in table 1.
Figure 1. RMS envelopes of the muon beam along the beam direction. The beam spot size in the sample position is $20 \times 20 \text{mm}^2$.

Table 1. Basic parameters of the muon beam in simulations.

| Parameter                                | Value        |
|------------------------------------------|--------------|
| Beam spot (full width at half maximum)   | $20 \times 20 \text{mm}^2$ |
| Mean value of momentum                   | 28 MeV/c     |
| Standard deviation of momentum           | 1.83 MeV/c   |
| Total number                             | $10^7$       |

Figure 2. Schematic illustration of (a) parallel and (b) pointing arrangement of detectors in a $\mu$SR spectrometer. Circles in both panels are envelopes of detectors on their inner surfaces.

As illustrated in figure 2, detectors can be placed either parallelly along the beam direction [19–21] or pointing to the sample position [22, 23]. In the parallel arrangement shown in figure 2(a), detector arrays are placed step by step like stairs. Therefore, every positron decaying from the sample can only penetrate one scintillator along its trajectory. To place several thousand
scintillators in a compact geometry, the length (along the beam direction) of each scintillator should be relatively short. In this work, the dimensions of detectors with a parallel arrangement are uniformly set to $10 \times 10 \times 10 \text{mm}^3$. In the pointing arrangement shown in figure 2(b), the cuboid shape was selected for every single detector instead of the frustum shape to enhance the angle discrimination ability [24, 25]. As the positron incident angle increases, the average pathlength of positrons penetrating the detector decreases, resulting in a decrease of the average deposition energy. The upper and lower sides of a frustum detector have different lengths. Due to the difference of detector geometries, the influence of the positron incident angle on the positron average pathlength in a frustum detector is smaller than that in the cuboid detector. As a result, the distribution of the average energy deposition as a function of the incident angle is steeper for the cuboid detector. Thus, the cuboid detector has a better angle discrimination capability than that of the frustum detector when setting the same energy threshold. Different from the parallel arrangement, the length of detectors with a pointing arrangement is not limited, as any positron decaying from the sample only penetrates one scintillator. According to a previous study [24], scintillators with a length of 50 mm are longer enough to achieve the optimal angular discrimination ability. Therefore, the dimension of scintillators with the pointing arrangement is set to $10 \times 10 \times 50 \text{mm}^3$. Additionally, scintillators with dimensions of $10 \times 10 \times 10 \text{mm}^3$ are also placed with the pointing arrangement for the comparison of the parallel arrangement with the same detector sizes. The pathlength of positrons penetrating the detector is longer in the 50-mm detector, so the deposition energy is higher. Thus, a higher energy threshold can be set when the detector length is 50 mm. Secondary particles or positrons decaying from muons outside the sample can also deposit energy in the detectors. However, their deposition energy is relatively lower compared with the positrons emitted from the sample, because their average pathlength is much smaller. Setting a higher energy threshold can significantly reduce these impacts. In this work, the threshold for 10-mm and 50-mm detector are set to 0.8 MeV and 4 MeV, respectively.

For the geometry of the whole spectrometer, detectors can be placed like cylinders, cones or spheres. Accordingly, six types of UHAMs are simulated in this work, as shown in figure 3. The detector length of structures “2”, “4”, and “6” can be either 10 or 50 mm. Each structure is tagged as “A-B” in which ‘A’ denotes the structure number (1–6 shown in figure 3), and “B” denotes the detector length (10 or 50 mm). For every structure as exemplified in figure 4 and figure 5, the components modeled in the simulation include a beam pipe, a cruciform-like sample chamber, plastic scintillators, a sample and related accessories: sample stick, sample holder and sample rod. The material of the sample is silver.

As shown in figure 2, the envelopes of the detectors resemble their spectrometer geometries (cylinder/cone/sphere). For UHAMs with the same envelopes, structures can be approximately set with the same envelope. Therefore, each structure covers the same solid angle with either a parallel arrangement or a pointing arrangement. If so, cylindrical geometry with a pointing arrangement can only place a small number of detectors with large separations between detector rings to avoid geometric overlaps. In contrast, cylindrical geometry with a parallel arrangement can place a large number of detectors as detector separations are not needed. Therefore, the envelope of cylindrical geometries with a parallel arrangement and a pointing arrangement are not the same to compromise the number of detectors and the covered solid angle.
Figure 3. Schematic diagram of the six UHAMs. Detectors in upper panels are placed parallelly, while those in the bottom are placed pointing to the sample. The spectrometer geometries are (1, 2) cylinder, (3, 4) cone, and (5, 6) sphere.

Figure 4. Schematic diagram of spherical geometry with a pointing arrangement.
Below are the descriptions of the envelopes for the six spectrometer structures. Table 2 lists the number of detector rings, the total number of detectors and the percentage of covered solid angle of the six different UHAMs.

1) Structure “1”: for a cylindrical geometry with a parallel arrangement, its envelope is approximately expressed as:

\[ x^2 + y^2 = 86^2 \quad (85 \text{ mm} \leq |z| \leq 335 \text{ mm}) \]  

(2.1)

where x, y and z are the position of a scintillator on the envelope in mm. Equation (2.1) describes a standard cylindrical surface. This structure has 50 detector rings and 2650 detectors.

2) Structure “2”: for a cylindrical geometry with a pointing arrangement, its envelope is approximately expressed as:

\[ x^2 + y^2 = 96^2 \quad (80 \text{ mm} \leq |z| \leq 321 \text{ mm}) \]  

(2.2)

This structure has 26 detector rings and 1586 detectors.

3) Structures “3” and “4”: for a conical geometry with a parallel arrangement or a pointing arrangement, its envelope is approximately expressed as:

\[ x^2 + y^2 = (z - 283)^2 \quad (83 \text{ mm} \leq |z| \leq 200 \text{ mm}) \]  

(2.3)

Equation (2.3) describes a standard conical surface. The conical geometry with a parallel arrangement has 26 detector rings and 2468 detectors, while the geometry with a pointing arrangement has 34 detector rings and 2932 detectors.

4) Structure “5” and “6”: for a spherical geometry with a parallel arrangement or a pointing arrangement, its envelope is approximately expressed as:

\[ x^2 + y^2 + z^2 = 229^2 \quad (65 \text{ mm} \leq |z| \leq 213 \text{ mm}) \]  

(2.4)

Equation (2.4) describes a standard spherical surface. The spherical geometry with a parallel arrangement has 32 detector rings and 3408 detectors, while the geometry with a pointing arrangement has 44 detector rings and 4290 detectors.
Table 2. Basic parameters of different UHAMS.

| Structure ID | Arrangement | Geometry | Detector Ring | Detector | Solid Angle (%) |
|--------------|-------------|----------|---------------|----------|-----------------|
| 1            | parallel    | cylinder | 50            | 2650     | 30.6            |
| 2            | pointing    | cylinder | 26            | 1586     | 36.5            |
| 3            | parallel    | cone     | 26            | 2468     | 60.0            |
| 4            | pointing    | cone     | 34            | 2932     | 60.4            |
| 5            | parallel    | sphere   | 32            | 3408     | 63.2            |
| 6            | pointing    | sphere   | 44            | 4290     | 64.9            |

3 Results and discussion

3.1 Simulations in the zero field

In experiments, the number of positrons detected by a positron detector is in variation with time, which can be expressed as [26, 27]

\[ N(t) = \frac{N_{\mu,0}\Delta\Omega}{4\pi\tau_{\mu}} e^{-\frac{t}{\tau_{\mu}}} [1 + A \cos \theta(t)] \]

\[ = N_0 e^{-\frac{t}{\tau_{\mu}}} [1 + A \cos \theta(t)] \]  \hspace{1cm} (3.1)

where \( N_0 \) is the initial number of positrons detected, \( \Delta\Omega \) is the covered solid angle of the positron detector relative to the sample position, \( A = \int_{\varepsilon_1}^{\varepsilon_2} a(\varepsilon) \cdot 2\varepsilon^2(3 - 2\varepsilon)d\varepsilon \) is the asymmetry term calculated by integrating over the positron energy from \( \varepsilon_1 \) to \( \varepsilon_2 \) detected by detectors. The number of positrons detected as a function of time by forward and backward detector is expressed as

\[ N_B(t) = N_0 e^{-\frac{t}{\tau_{\mu}}} [1 + A \mathbf{P}(t) \cdot \hat{n}_B] \]

\[ N_F(t) = N_0 e^{-\frac{t}{\tau_{\mu}}} [1 + A \mathbf{P}(t) \cdot \hat{n}_F] \]  \hspace{1cm} (3.2)

where \( N \) denotes the total positron counts in detectors, the footnote F (or B) denotes detectors placed in the forward (or backward) direction of the muon polarization.

From the equation (3.2) describing the raw counts in detectors, the asymmetry spectrum can be directly extracted by

\[ A(t) = \mathbf{P}(t) = \frac{N_B(t) - N_F(t)}{N_B(t) + N_F(t)} \]  \hspace{1cm} (3.3)

In simulations, the asymmetry of a \( \mu \text{SR} \) spectrometer is determined by:

\[ A = \frac{N_B^+ - \alpha N_F^+}{N_B^+ + \alpha N_F^+} \]  \hspace{1cm} (3.4)

\[ \alpha = \frac{N_B^- + N_F^-}{N_F^+ + N_F^-} \]  \hspace{1cm} (3.5)
where the plus (or minus) sign of $N$ denotes the positive (or negative) polarization set in musr-Sim [15], and $\alpha$ is the correction factor. In experiments, the absorption of positrons in a sample, a sample chamber and beampipes can affect the real asymmetry. Routinely, these influences are calibrated by the correction factor, $\alpha$, which is measured by a weak transverse field experiment [19, 27]. In simulations, $\alpha$ can be determined by setting the muon polarization in the positive or negative direction in two separate runs.

The counting rate is normally expressed as the number of positrons recorded per unit time. In this work, $R$ is defined as:

$$R = \frac{N}{N_0}$$

(3.6)

where $N$ is the number of positrons counted by detectors, and $N_0$ is the total number of muons. In this work, each simulation generates a number of $10^7$ muons to suppress statistical errors.

To comprehensively analyze the influence of spectrometer structures on the asymmetry and the counting rate, a figure of merit (FoM) [19] is defined as:

$$\text{FoM} = A^2 R$$

(3.7)

Positrons with higher kinetic energy carry higher asymmetries. Placing degraders before detectors to shield low energy positrons is an effective way to enhance the asymmetry of the whole $\mu$SR spectrometer. The degrader is placed between the detectors and the cruciform-like sample chamber. Only positrons with higher energy can pass through the degrader and then reach the scintillation detectors. Thus, the asymmetry can be enhanced by using the degrader. In this work, brass is used as the degrader material. It can be replaced by other types of materials that have similar shielding effects but with different thicknesses.

The length of detectors for all spectrometer structures is set to 10 mm in the beginning to take a quick look at the impacts of degraders on the counting rate and the asymmetry. It should be noted that the degrader thickness of structure “1-10” can only reach 10 mm, otherwise geometric overlap will occur. As shown in figure 6(a), the asymmetry of all structures gradually increases to the maximum and then decreases as a function of the degrader thickness. Structures with cylindrical geometries reach the maximum asymmetry more quickly followed by spherical and conical geometries. For structures with the same geometry, detectors placed parallel to the beam direction achieve higher asymmetries. In contrast, the counting rate of all structures decreases as a function of the degrader thickness as shown in figure 6(b). When the degrader thickness is zero, the differences in the counting rates of the three spectrometer geometries are consistent with the differences in their covered solid angles as listed in table 2 except structure “1-10”. The counting rate of the spherical geometry is higher than that of the conical geometry, and both of them are higher than that of the cylindrical geometry. The abnormal counting rate of structure “1-10” is due to the fact that most of the counts are multiple counts. For spherical and cylindrical geometries, detectors with a parallel arrangement have a higher counting rate than those with a pointing arrangement. Such an effect (a lower covered solid angle leads to a higher counting rate) is related to the multiple counting which will be discussed later. The rank of the counting rate changes when increasing the degrader thickness particularly with sizes over $\sim 5$ mm.

Figure 7 presents the FoMs of six UHAMs based on equation (3.7). The variation trend of FoM behaves similarly to that of the asymmetry (see figure 6(a)) as a function of the degrader thickness.
Figure 6. (a) Asymmetry and (b) counting rate of six UHAMs as a function of the degrader thickness. Curves are visual guides.

The cylindrical geometry rapidly peaks at a degrader thickness of ~1 mm, while the spherical and conical geometries gradually reach their maximum asymmetries at ~6 mm and ~10 mm, respectively. For cylindrical and spherical geometries, detectors with a parallel arrangement have higher asymmetries than those with a pointing arrangement. This difference is inverse for the conical geometry.

Figure 7. FoM of different UHAMs as a function of the degrader thickness. Curves are visual guides.

The comparison of UHAMs with different detector lengths is presented in figure 8 for the pointing arrangement. The variation trends of the asymmetry or the counting rate of spectrometers with different detector lengths are almost the same for any given geometry. However, detectors with a length of 50 mm have higher asymmetries but lower counting rates than those with a length of 10 mm for the same geometry. This is due to the energy threshold setup. The mean energy deposition of positrons in 50-mm detectors is nearly 4 times higher than that in 10-mm ones. A much higher threshold is set for the longer detectors. As a result, the 50-mm detectors lose some percentage of positrons. Positrons with higher energy carry higher asymmetries. A higher threshold
for longer detectors leads to higher asymmetries for the whole spectrometer. Figure 9 gives the FoMs of these spectrometer structures, which present similar increasing-decreasing trends. The maximum FoMs for 50-mm detectors are slightly higher than those for 10-mm detectors for any given spectrometer geometry. Among them, the conical geometry with a 50-mm detector achieves the highest FoM.

![Figure 8](image1.png)

**Figure 8.** (a) Asymmetry and (b) counting rate of UHAMs with pointing arrangements and different detector lengths. Curves are visual guides.

![Figure 9](image2.png)

**Figure 9.** FoMs of different UHAMs with pointing arrangements and different detector lengths. Curves are visual guides.

As mentioned in section 1, the performance of a μSR spectrometer can be affected by the multiple counting effects with high granularity. The percentage of multiple counts, $M$, can be determined by:

$$M = \frac{N_{\text{mul}}}{N} \times 100\%$$

where $N_{\text{mul}}$ is the total number of multiple counts. According to the running experience of HiFi at ISIS Muon Facility, the $M$ is tolerable below 30% [7, 19, 21]. In continuous muon beam, the
beam intensity is lower than that of a pulsed beam at least by an order of magnitude. Muons enter the sample one by one, so the energy deposition in different detectors at the same time all come from the same positron. A centroid algorithm might be used in continuous muon beam to identify the muon-positron pair event by event. But in pulsed muon beam with a pulse width in a magnitude of 100 ns, the beam intensity is very high. Positrons generated in each pulse are almost detected by the spectrometer. It is impossible to relate each positron to its parental muon. Thus, the multiple counts cannot be reduced by applying a centroid algorithm in pulsed muon facilities, such as CSNS. Figure 10 presents the percentage of multiple counts of all 9 spectrometer structures simulated above. It is obvious that structure “1-10” has the highest $M$. Due to the placement of scintillators in detector rings with a fixed radius along the beam direction, positrons can easily pass through multiple adjacent detectors along their trajectories at the same time. In addition, the variation trend of structure “1-10” is different from all other structures as a function of the degrader thickness. The $M$ for other structures increases to the maximum and then has a decreasing trend. Comparing detectors with the same length (“1-10” with “2-10”, “3-10” with “4-10’ and “5-10” with “6-10”) and the same geometry, structures with a pointing arrangement obtain lower $M$. This is due to the relatively better angular discrimination ability with pointing arrangements [24]. According to our previous study [24], the angular discrimination ability reaches the maximum when the detector length is over ~ 50 mm. Therefore, multiple counts are significantly suppressed in pointing arrangements with a detector length of 50 mm.

![Figure 10](image.png)

**Figure 10.** Percentage of multiple counts of different UHAMs as a function of the degrader thickness. Curves are visual guides.

Although the FoM is widely used to evaluate the performance of a $\mu$SR spectrometer, the impact of multiple counts is ignored in this parameter. In $\mu$SR experiments, a higher $M$ will lead to worse performance of a $\mu$SR spectrometer. To comprehensively consider the influences of spectrometer structures on $A$, $R$ and $M$, a quality factor, $Q$, can be used as:

$$Q = A^2 R (1 - M)^2$$

As the $M$ can affect both the counting rate and the asymmetry of a spectrometer, its exponent is set to 2 in the equation. Accordingly, the $Q$ values for all mentioned structures are presented in
figure 11. All data show an increasing-decreasing trend as a function of the degrader thickness. It is obvious that the structure “4-50” achieves the optimal $Q$ when the degrader thickness is ~ 4 mm. Table 3 lists the degrader thickness, $M$, $A$, and $R$ for all structures at their maximum $Q$ values.

Table 3. Maximum $Q$ and related parameters of different UHAMS in the zero field.

| Structure ID | Maximum $Q$($\times 10^{-3}$) | Degrader Thickness (mm) | $M$ (%) | $A$ | $R$ |
|--------------|-------------------------------|-------------------------|---------|-----|-----|
| 1-10         | 3.38                          | 3.5                     | 53.8    | 0.316 | 0.158 |
| 2-10         | 10.7                          | 1.0                     | 10.6    | 0.261 | 0.197 |
| 3-10         | 10.4                          | 5.0                     | 14.5    | 0.225 | 0.281 |
| 4-10         | 12.8                          | 5.0                     | 13.0    | 0.244 | 0.282 |
| 5-10         | 12.1                          | 3.5                     | 15.4    | 0.231 | 0.315 |
| 6-10         | 9.33                          | 3.0                     | 13.8    | 0.206 | 0.297 |
| 2-50         | 12.2                          | 1.0                     | 10.7    | 0.292 | 0.179 |
| 4-50         | 15.2                          | 4.0                     | 12.4    | 0.282 | 0.248 |
| 6-50         | 10.1                          | 3.0                     | 12.6    | 0.243 | 0.224 |

3.2 Simulations in longitudinal fields

Apart from the zero field, magnets that can generate a tunable longitudinal field are also essentially required in $\mu$SR spectroscopy. To measure the full muonium repolarization curve in a longitudinal field, the field strength should have the power to be scanned from 0 to up to 5000 G [28]. In addition, a $\mu$SR spectrometer that operates with high magnetic fields in the few Tesla range enables the investigation of a wider range of dynamics, access to different regions in the phase diagram, spectroscopy and molecular dynamics of various new systems and the ability to perform a combination of RF-$\mu$SR and NMR experiments [21, 29]. Therefore, two longitudinal field ranges (0–5000 G, and 0–several Tesla) are normally deployed in international muon facilities [30–32].
Phase II of CSNS, the construction of the first $\mu$SR spectrometer will start with a longitudinal field lower than 5000 G. In this work, a longitudinal field range of (0, 10 T) is scanned in simulations to study the feasible field range of the current spectrometer design. The direction of the magnetic field is (0, 0, -1).

![Graphs](image)

**Figure 12.** (a) The asymmetry, (b) counting rate, (c) FoM and (d) percentage of multiple counts as a function of the field strength. Curves are visual guides.

As the $M$ of structure “1-10” is quite high in the zero field, it is not considered in the longitudinal field simulations. Figure 12 presents the $A$, $R$, FoM and $M$ of different UHAMs scanning the longitudinal field from 0 to 10 T with a step length of 0.5 T. The asymmetry in figure 12(a) peaks at $\sim$ 1 T and then decreases with some fluctuations. The variation trend of the counting rate in figure 12(b) is different between the cylindrical geometry and the other two geometries. The counting rate of the cylindrical geometry peaks at a field strength of $\sim$ 1.5 T, while the other geometries continuously reduce to 0. As positrons do spiral motions in a strong longitudinal field, the radius of spiral motions is inversely proportional to the field strength. Positrons cannot hit detectors with the radius of detector rings larger than the radius of spiral motions. Hence, the counting loss of detectors tends to be more obvious with conical and spherical geometries in strong fields. According to the variation trends of the asymmetry and the counting rate, the FoM in figure 12(c) peaks at a field strength followed by rapid reduction. The percentage of multiple counts in figure 12(d) confirms that the spiral motions of positrons lead to an increase in multiple counting probability. For any given spectrometer geometry, detector placed pointing to the sample with a length of 50 mm can more easily suppress multiple counting mainly due to the spiral motions of positrons. Figure 13 presents the overall influences integrating all parameters of figure 12. In the range of (0, 2 T),
the structure “4-50” has the optimal $Q$ over the other ones. For the field strength over 2 T, the $Q$ of all structures reduces to very low values compared with their initial values in the zero field. Therefore, the design of UHAMs in this work can be well performed in the required longitudinal field ($< 5000$ G). The design accepts the upgrade of the longitudinal field up to 2 T in the future. If a field over 2 T is needed, the arrangement of the UHAM should be updated to fit the strong field.

![Figure 13](image.png)

**Figure 13.** Quality factor of different UHAMs in variation with magnetic field. Curves are visual guides.

According to the simulation in the zero field and a tunable longitudinal field, the conical geometry with a pointing arrangement and a detector length of 50 mm has the optimal quality factors. This can be a reasonable reference for the construction of the first $\mu$SR spectrometer at CSNS.

### 4 Conclusions

In this work, six different structures of UHAMs have been modeled and simulated for the construction of a muon source for CSNS. According to the requirement of a magnetic field in real $\mu$SR experiments, the simulation is performed in both the zero field and a tunable longitudinal field. The performance of these structures are compared by their overall asymmetries, counting rate and percentage of multiple counts. A quality factor is proposed to comprehensively compare these parameters. The simulation confirms that detectors pointing to the sample have the advantage of multiple counting suppression. Detectors with a large aspect ratio can enhance this capability. Simulations in both the zero field and longitudinal field support that the spectrometer structure has optimal performance with a conical geometry, a pointing arrangement and a detector length of 50 mm. For longitudinal field experiments, the spectrometer design can work well in the required field range ($< 5000$ G). It has the potential to be operated up to 2 T if the magnets are required to be updated to extend the research field of $\mu$SR techniques at CSNS.

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