Possible future upgrades of the direct-geometry chopper spectrometer 4SEASONS

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Abstract. 4SEASONS is a direct geometry time-of-flight spectrometer installed in the Materials and Life Science Experimental Facility, the Japan Proton Accelerator Research Complex. It is used to study atomic and spin dynamics in the energy range of 100 meV to 102 meV. Since more than a decade has crossed after the first inelastic scattering experiment, it is essential to consider upgrading the instrument to improve its flexibility and performance. In this paper, we discuss the possible medium-term upgrades of key components of the instrument like the chopper system, which are achievable with the current technology and at reasonable cost. Herein, we demonstrated that 4SEASONS can improve the energy resolution by a factor of two, remove frame overlap of adjacent incident energies, significantly improve the asymmetry in the pulse shape, and increase the flux by a factor of ~1.5, without major technical difficulties.

1 Introduction

4SEASONS, also known as SIKI, is one of the inelastic neutron scattering instruments in the Materials and Life Science Experimental Facility (MLF) in the Japan Proton Accelerator Research Complex (J-PARC). It is a direct geometry time-of-flight spectrometer that utilizes a Fermi chopper as a monochromator to study atomic and spin dynamics in the energy range of 100–102 meV. This instrument was originally constructed for examining high-critical-temperature superconductors and was associated with high intensity and high efficiency [1]. Thus, the instrument is now considered as a middle-resolution and high-intensity spectrometer that covers the middle momentum-energy region in the inelastic/quasielastic neutron spectrometers in MLF [2–4].

The first inelastic scattering experiment using 4SEASONS was conducted in 2009 [5], and since then, its research target has been expanded to include quantum magnets, frustrated magnets, itinerant magnets, multiferroic materials, thermoelectric materials, glasses, and catalysis. Hence, this calls for serious consideration of upgrading the instrument to improve its flexibility and performance. We have made several upgrades to the instrument, such as minimizing background scattering, introducing new sample environments, filling the detector vacancy, replacing malfunctioning or aged equipment, etc. [6–11]. These short-term upgrades were undertaken as per the requirement to ensure the instrument provides its designed performance. In the present study, we discuss the possibilities of medium-term upgrades of key components of the instrument such as the chopper system. Here, we discuss the upgrades achievable using the current technology and within reasonable cost. We also focus on the effectiveness and feasibility of these upgrades in improving the performance and flexibility of the instrument. We set aside long-term upgrades requiring the redesign of the instrument from scratch or new technology currently unavailable, which will be considered in the future accompanying an upgrade of the whole MLF or construction of the second target station.

2 Instrument layout

Figure 1 shows the schematic top and side views of 4SEASONS [1]. 4SEASONS is located at the beamline 1 (BL01) viewing the coupled moderator [12]. The sample is located at L1 = 18 m from the moderator. The supermirror-coated guide is placed between the 2.3 m and 15.8 m positions to minimize the loss of neutrons during the beam transport. It has an elliptically converging shape with one of the focal points being located at the sample. The incident neutron beam transported by the neutron guide is monochromatized by the Fermi chopper. It is located at L3 = 1.7 m upstream of the sample and rotates at 600 Hz at maximum. The scattered neutrons are detected at 3/4-in-diameter and 2.5-m-long position-sensitive detectors (PSDs) surrounding the sample cylindrically at a distance of L2 = 2.5 m from –35° to +130° with respect to the incident beam. The PSDs are 3He tubes with a 3He partial pressure of 16 atm. In addition to the Fermi chopper, 4SEASONS has a T0 chopper and two disk choppers. The T0 chopper rotates at 100 Hz at maximum and is placed

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at 8.45 m from the moderator. It is used to suppress the prompt pulse. On the other hand, the two disk choppers are installed at 9 m and 12 m and rotate at 12.5 Hz or 25 Hz. These two choppers are used to define the usable incident energy band and to eliminate the frame overlaps of very low energy neutrons.

3 Candidates of upgrade items

3.1 Fermi chopper and optimum resolution

The Fermi chopper of 4SEASONS utilizes straight-slit package. This package is advantageous in multi-\( E_i \) measurements using the repetition rate multiplication (RRM) [5, 13–15] because of the equal transmissions at the \( 2\pi \) and \( (2n + 1)\pi \) rotations (\( n \) is integer). The ratio of the width \( (w) \) to the length \( (D) \) of each slit is 0.02 [16]. The parameters of the slit package were designed to produce approximately 5% energy resolution at elastic scattering under the “optimum” condition in which the chopper opening time \( \Delta t_{ch} \) is equal to the moderator pulse width \( \Delta t_m \), i.e., \( \Delta t_{ch} = \Delta t_m \) [1, 17, 18] [Fig. 2(a)]. The above condition can be fulfilled at \( E_i \) below 500 meV by considering that the minimum of \( \Delta t_{ch} \) is 5.3 \( \mu s \) in full width at half maximum (FWHM) at 600 Hz rotation [Fig. 2(b)]. This \( E_i \) is sufficient to cover the target dynamic range of the instrument.

However, the energy resolution at low energy transfers may be insufficient with the above condition. This is because the contribution of the Fermi chopper to energy resolution increases substantially at low energy transfers [19, 20]. This further limits the usability of the instrument, even though the low energy transfer region can be covered by lower \( E_i \)s available via the RRM. It is likely that the above condition was too naïve for 4SEASONS, and we should reconsider the optimum condition for low energy transfers based on the idea that the Fermi chopper contributes to the energy resolution similarly to others [21].

The resolution of the energy transfer relative to \( E_i \) is given by [22]:

\[
\frac{\Delta E}{E_i} = \left( \frac{2}{\tau_{ch}} \right)^{1/2} \left[ \frac{L_1}{L_2} \left( \frac{E_i}{E_f} \right) \right]^{1/2} + \frac{2}{\tau_{ch}} \left[ \frac{L_1}{L_2} \left( \frac{E_i}{E_f} \right) \right]^{1/2} + \frac{2}{\tau_{ch}} \left[ \frac{L_1}{L_2} \left( \frac{E_i}{E_f} \right) \right]^{1/2},
\]

where \( \Delta L_2 \) is the uncertainty of \( L_2 \) because of the sample and the detector sizes. Let us neglect the contribution from \( \Delta L_2 \) for simplicity because it is independent of \( \Delta t_{ch} \) and \( \Delta t_m \). Equating the \( \Delta t_{ch} \) and \( \Delta t_m \) terms in Eq. (1) leads to the following optimum condition as shown in literature [21, 23],

\[
\frac{\Delta t_{ch}}{\Delta t_m} = 1 - \frac{L_{ch}}{L_1 + L_2 (E/E_f)^{3/2}},
\]

where \( L_{ch} \) is the distance between the moderator and the Fermi chopper (\( L_{ch} = L_1 - L_2 \)). The condition \( \Delta t_{ch} = \Delta t_m \) corresponds to the extreme case when \( E \) is its maximum, \( E_f \). However, for general cases, Eq. (2) is less than unity, and it becomes

\[
\Delta t_{ch} = \frac{L_2 + L_3}{L_1 + L_2} \Delta t_m,
\]

when \( E = 0 \). Eq. (3) becomes 0.20\( \Delta t_m \) with \( L_1 = 18 \) m, \( L_2 = 2.5 \) m, and \( L_3 = 1.7 \) m.

Figure 2(a) shows energy resolutions as a function of \( E_i \) calculated using the moderator pulse width of BL01 [24] and Eq. (1) by varying \( \Delta t_{ch} \) from \( \Delta t_m \) to 0.1\( \Delta t_m \). The increase below \( E_i \sim 50 \) meV is due to the broadening of the pulse width of the coupled moderator, while \( \Delta E/E_i \) is almost constant above this energy because \( \Delta t_m \) is proportional to \( E_i^{-1/2} \) [25]. The energy resolution for \( \Delta t_{ch} = \Delta t_m \) becomes 5%–6% above \( \sim 50 \) meV as designed. By decreasing \( \Delta t_{ch} \), the energy resolution smoothly decreases. With \( \Delta t_{ch} = 0.2 \Delta t_m \), we can obtain less than 3% resolution above 20 meV, and 4% resolution even at 10 meV. Such values of resolutions are comparable with those of
existing chopper spectrometers and are good enough for a middle-resolution and high-intensity spectrometer like 4SEASONS. It should be noted that the improvement in the resolution slows down with decreasing $\Delta t_{ch}$ and becomes almost saturated at $\Delta t_{ch} < 0.2\Delta t_{m}$. This is because the resolution is dominated by contributions other than the Fermi chopper at such a small $\Delta t_{ch}$.

Figure 2(b) shows the moderator pulse width in FWHM and the one multiplied by 0.2 together with the chopper pulse widths obtained from the present Fermi chopper for several rotation speeds. The condition of $\Delta t_{ch} = 0.2\Delta t_{m}$ can be achieved only below $E_i \approx 30$ meV using the present Fermi chopper whose maximum rotation speed is 600 Hz. Since it may be technically difficult to increase the maximum rotation speed, we should introduce a new Fermi chopper with a finer slit package to overcome the limitation of $\Delta t_{ch}$. For example, if we employ the slit package whose $w/D$ is half of the present value, i.e., $w/D = 0.01$, the condition of $\Delta t_{ch} = 0.2\Delta t_{m}$ is available up to about 100 meV. This value of $w/D$ is feasible because Fermi choppers with a similar value [26] or even a finer value of $w/D$ [27] are actually used. Figure 3 shows how the fine slit package improves the energy resolution. The energy-transfer spectra are compared with $w/D = 0.02$ and 0.01 when the Fermi chopper is rotated at its maximum speed of 600 Hz. The data were obtained by Monte Carlo simulation using the ray-trace simulation package McStas [28–32]. $\Delta E/E_i$ estimated by the FWHMs are 3.1%, 3.6%, and 4.4% for $E_i = 50, 100$, and 200 meV, respectively, when $w/D = 0.02$. When $w/D = 0.01$, the estimated $\Delta E/E_i$ reduce to 2.1%, 2.5%, and 2.9%, respectively. These results are consistent with the analytical estimation in Fig. 2. About 70% reduction of the resolution is significant, but the use of fine slits and high rotation speed of the Fermi chopper reduce the neutron transmission. This loss in neutron flux can be compensated by adopting curved slits. The curved slits will be less efficient in multi-$E_i$ measurements because of low transmissions at the $(2n+1)\pi$ positions. Thus, the combination of the present sloppy straight-slit Fermi chopper and a new fine curved-slit Fermi chopper should be considered to be used in 4SEASONS to improve its flexibility.

### 3.2 Suppression of frame overlaps of incident pulses

One of the most important features of 4SEASONS is the simultaneous utilization of multiple $E_i$’s via RRM by

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**Figure 2.** (a) Calculated energy resolutions as a function of $E_i$ when $\Delta t_{ch}$ varies from $\Delta t_m$ to $0.1\Delta t_m$. The cases of $\Delta t_{ch} = \Delta t_m$ and $0.2\Delta t_m$, are indicated by thick lines. The sample size is 20 mm in diameter. (b) The moderator pulse width of BL01 $\Delta t_{m}$ and $0.2\Delta t_{m}$ as a function of $E_i$. Broken lines indicate the chopper pulse width for the 4SEASONS Fermi chopper rotated at 100–600 Hz.

**Figure 3.** Energy-transfer spectra for $w/D = 0.02$ (broken lines) and 0.01 (solid lines) obtained by Monte Carlo simulations for (a) $E_i = 50$ meV, (b) 100 meV, and (c) 200 meV. The Fermi chopper with $D = 20$ mm is rotated at 600 Hz. The sample is a 1-mm thick hollow cylindrical vanadium that is 20 mm in diameter and 20 mm in height. The peak intensities are normalized to units.
the Fermi chopper. In recent years, this feature has become the standard for direct-geometry chopper spectrometers [23, 33–40]. However, the overlap of scattering from the adjacent $E_i$ may limit the usable energy-transfer range, particularly at low $E_i$s. Suppose we choose $E_i = 200$ meV and subsidiary $E_i$s as typical experimental condition at 4SEASONS while rotating the Fermi chopper at 300 Hz. Then, this results in a series of $E_i$ = 200, 75.1, 39.0, 23.9, and 16.1 meV. If we calculate the maximum energy transfer $E_{\text{clean}}$ below which scattering from the next lower $E_i$ never overlaps [5], $E_{\text{clean}}/E_i$ becomes 95%, 87%, 75%, 59%, and 40%, respectively. It is known that the intensity of up-scattering from the next lower $E_i$ drastically decreases as its energy transfer decreases toward $-\infty$ following the Bose population factor $n(E, T) = [\exp(E/k_BT) - 1]^{-1}$, where $k_B$ and $T$ are the Boltzmann constant and temperature, respectively. Thus, the usable energy transfer range can be enlarged, particularly at low temperatures. However, the above example has clearly shown that the overlaps of incident pulses becomes a serious problem for $E_i \sim$ 10 meV or lower. To mitigate this problem, the new direct-geometry chopper spectrometers are equipped with pulse-removal choppers to control spacings between incident pulses. These pulse-removal choppers are usually disk choppers that are placed either adjacent to [23, 35–37] or away from the monochromatizing choppers [38–40]. However, 4SEASONS, which is one of the first chopper spectrometers to implement the RRM capability [5], does not have choppers dedicated for such a purpose, though it can select a single $E_i$ by combining the opening times of the two band choppers.

In this study, we briefly discuss the feasibility of adding a pulse-removal chopper to 4SEASONS. Since the pulse-removal chopper thins out the incident pulses defined by the monochromatizing chopper, it has more advantages when placed closer to the Fermi chopper. However, the spatial constraint and the possibility of using the chopper as a pulse-shaping chopper, which will be discussed in the next subsection, need to be taken into consideration. Thus, we suggest the chopper to be placed at half of the distance between the moderator and the Fermi chopper. Figure 4 shows the cutaway view of a part of 4SEASONS near the $T_0$ chopper and the first disk chopper. The position at $L_{\text{ch}}/2 = 8.15 \text{ m}$ is marked by a down arrow. A chopper can be installed at this position without disturbing the existing choppers if the short section of the neutron guide is removed or replaced. In our case, the pulse-removal chopper can remove each second pulse if its opening period $\tau$ is the same as that of the Fermi chopper. For the straight-slit Fermi chopper rotating at 600 Hz, the required minimum opening period is 1/1200 $s$. The maximum rotating speed of a typical disk chopper is about 300 Hz. So, $\tau = 1/1200 \text{ s}$ can be achieved if we use a disk with four equally spaced apertures. On the other hand, a disk chopper with unequally spaced apertures [36, 40] or that with two disks rotating at different speeds [35] provides uneven elimination of $E_i$s. The latter type of disk chopper also needs to be considered in the case of selectively removing low $E_i$s with more serious frame overlap.

### 3.3 Pulse shaping

We have confirmed the feasibility of adding a chopper at the $L_{\text{ch}}/2$ position. Next, we discuss whether this chopper can also be used for pulse shaping. The pulse-shaping chopper is mainly used for two purposes. One purpose is to obtain a finer energy resolution by sharpening the neutron pulse width prior to the monochromatization with the Fermi chopper. The other purpose is to cut the pulse tail to improve the symmetry in the pulse shape. In order to obtain a finer energy resolution, the opening time of the pulse-shaping chopper $\Delta_{\text{ps}}$ must be in the same order as the moderator pulse width. In quantitative terms, the time width at the moderator defined by the pulse-shaping chopper and the monochromatizing chopper is

$$\Delta_{\text{m}}^{\text{ch+ps}} = \frac{L_{\text{ch}}}{L_{\text{ch}} - L_{\text{ps}}} \Delta_{\text{ps}} + \frac{L_{\text{ps}}}{L_{\text{ch}} - L_{\text{ps}}} \Delta_{\text{ch}},$$

where $L_{\text{ps}}$ is the distance of the pulse-shaping chopper from the moderator [33]. The $\Delta_{\text{m}}^{\text{ch+ps}}$ should be similar to or less than $\Delta_{\text{m}}$ to effectively control the energy resolution by the pulse-shaping chopper. If $L_{\text{ps}} = L_{\text{ch}}/2$, $\Delta_{\text{m}}^{\text{ch+ps}}$ must be less than $\Delta_{\text{m}}/2$ even for the limiting case of $\Delta_{\text{ch}} = 0$. The beam width at the candidate position of the pulse-shaping chopper ($L_{\text{ps}} = 8.15 \text{ m}$) is $\sim 80 \text{ mm}$. In the case of a typical fast-rotating disk chopper having 300 mm radius at the beam center, 80 mm slit width, and 300 Hz rotation speed, $\Delta_{\text{ps}}$ of this chopper becomes 141 $\mu\text{s}$. If we use a disk chopper with two counter-rotating disks, $\Delta_{\text{ps}}$ becomes 70 $\mu\text{s}$ at most. In any case, $\Delta_{\text{ps}}$ is larger than $\Delta_{\text{m}}$ in most of the energy range of 4SEASONS [see Fig. 2(b)]. Therefore, this type of the pulse-shaping chopper cannot be used to obtain finer energy resolution. A narrow-slit disk chopper or a Fermi chopper can achieve sharper $\Delta_{\text{ps}}$. However, such choppers are associated with significant loss in neutron flux. 4SEASONS can potentially achieve 2.5%–3% resolution, as discussed in §3.1, without the pulse-shaping chopper. Higher resolution should be left to other high-resolution spectrometers in MLF, such as HRC and AMATERAS.
Conversely, the required conditions for \( \Delta \mu \) should be mitigated for the tail cutter. The pulse tail is particularly prominent at \( E_i \leq 50 \text{ meV} \) where the pulse width of the coupled moderator is enhanced. The tail hampers the quantitative analysis of the observed spectra irrespective of nominal energy resolutions in, for example, quantitative estimation of line width or observation of spin gap. Therefore, suppressing the pulse tail by the pulse-shaping chopper will be useful even if the nominal energy resolution is not improved.

We plot a time-wavelength acceptance diagram in Fig. 5, following Refs. [23, 41], to examine whether the pulse-shaping chopper can cut the pulse tail effectively. Red and white lines indicate the time-wavelength regions of neutrons at the moderator that pass through the pulse-shaping chopper and the Fermi chopper, respectively. We plot the cases for 10 meV (2.9 Å) and 50 meV (1.3 Å) neutrons. The pulse-shaping chopper has a 300-mm radius and an 80-mm-wide slit as discussed above, and its rotation speed is 300 Hz. The color map in Fig. 5 shows the pulse structure of the moderator at BL01. Here, \( \Delta \mu \) is 90 \( \mu \text{s} \) and 18 \( \mu \text{s} \) at \( E_i = 10 \text{ meV} \) and 50 meV, respectively. Figure 5 indicates that the pulse-shaping chopper can substantially cut the pulse tail for 10 meV neutrons, though the pulse-shaping chopper is less effective for 50 meV or higher-energy neutrons due to the sharp moderator pulse width. We, thus, conducted a Monte Carlo simulation study using McStas. Figure 6 shows simulated energy-transfer spectra for \( E_i = 10 \text{ meV} \) and 50 meV at the detector. The rotation speeds of the Fermi chopper \( f \) were chosen to be 200 Hz and 300 Hz for \( E_i = 10 \text{ meV} \) and 50 meV, respectively, so that the energy resolutions \( \Delta E / E_i \) became about 5%. The short guide section at \( \sim 8 \text{ m} \) was removed to place the pulse-shaping chopper (see Fig. 4). Without the pulse-shaping chopper, the spectra show significant tails in the energy gain (\( E < 0 \)) sides. The rotation of the pulse-shaping chopper at 300 Hz results in a finite decrease in the tails. In particular, the impact of the pulse-shaping chopper is evident at \( E_i = 10 \text{ meV} \) [Fig. 6(a)]. The peak intensity slightly decreases by pulse-shaping, but it is acceptable. If we can rotate the pulse-shaping chopper at 600 Hz, the tail is significantly suppressed even at \( E_i = 50 \text{ meV} \) [Fig. 6(b)]. Such a high rotation speed is not feasible with the currently available disk chopper, but a counter-rotating double-disk chopper can effectively achieve this speed. The tail cut by the pulse-shaping chopper becomes more effective at lower \( E_i \)s where the moderator pulse width becomes broader, while it is less effective at \( E_i \)s higher than 50 meV. However, the pulse tail becomes less prominent at high energies because of the decrease in the moderator pulse width (Fig. 3). Therefore, we conclude that the pulse-shaping chopper in 4SEASONS is effective.

3.4 Beam transport

The upgrades discussed above focused mainly on improving the resolution or pulse shape. However, these upgrades
Generally decrease the neutron flux on the sample in compensation for the better pulse shape. Here, we discuss a possible upgrade of the beam transport to increase the neutron flux.

The current neutron guide is designed to transport high neutron flux at the sample [42]. It has an elliptically converging shape and uses high-critical-angle supermirrors whose $m$ values are 3.2–4 ($m$ is the critical angle relative to that of the nickel mirror). Given the relatively short flight path to the sample, modifying the design of the existing guide will not be effective in increasing the neutron flux.

On the other hand, 4SEASONS still has a room for extending the neutron guide. Figure 7 shows a cutaway view of 4SEASONS at the end of the neutron guide and the sample position. The neutron guide ended 0.5 m before the Fermi chopper, resulting in a substantially large space between the Fermi chopper and the sample. This space is left for future upgrade, and beam collimators made of $\text{B}_4\text{C}$ are currently installed. Thus, the neutron guide can be extended by about 1 m. Currently, the total length of the neutron guide, excluding the length of gaps for the choppers, is about 12.7 m. The total flight path between the moderator and the sample without the neutron guide is 18 m$–$12.7 m = 5.3 m. If the flight path with the neutron guide is extended by 1 m, the flight path without the neutron guide becomes 4.3 m. Suppose the neutron guide transports neutrons by 100% for simplicity, then we need to consider only the flight path without the neutron guide. Thus, a rough estimate of the flux gain becomes $(5.3 \text{ m}/4.3 \text{ m})^2 = 1.5$. The 50% increase in flux is significant and should be examined in detail.

Figure 8 shows a more practical study of the gain by extending the neutron guide. We assumed that the $50 \text{ mm} \times 50 \text{ mm} \times 580 \text{ mm}$ beam collimator placed after the Fermi chopper (indicated by a red dotted circle in Fig. 7) was replaced with a supermirror-coated neutron guide having the same dimension. Thus, the gain in intensity at a $20 \text{ mm} \times 20 \text{ mm}$ sample was calculated by Monte Carlo simulation using McStas. By adding only this short neutron guide, we obtained a positive result. If we use the $m = 4$ supermirror, which is the same as that used in the downstream part of the present neutron guide, we can obtain a finite gain at a wavelength longer than 2 Å (~20 meV), and the gain reaches about two at 4 Å (~5 meV). Recently an $m$ value higher than 5 is commercially available; this will be beneficial for shorter wavelengths. If the sample size is larger, then the gain at short wavelengths will be larger, while the gain at long wavelengths will be enhanced by utilizing a focusing shape. Thus, there is a need for a more detailed analytical and numerical study to optimize the specifications of the extended guide.

3.5 Flight paths

In the previous sections, we have discussed practical upgrades without changing the key flight paths of $L_1$, $L_2$, and $L_3$. This is because the modification of these flight paths requires complete redesigning of the instrument, which is out of the scope of the present paper. Nevertheless, understanding how changes in flight paths affect the performance of the instrument will help in preparing for future major upgrades or development of a new spectrometer. To finish this paper, we briefly discuss this issue in terms of the energy resolution.

The energy resolution of the direct-geometry chopper spectrometer improves with the increase in $L_1$ and $L_2$ and the decrease in $L_3$. However, the contribution of $L_1$ saturates as $L_1$ increases [see Eq. (1)], and $L_1$ longer than ~15 m is not advantageous to the energy resolution at short-pulse facilities, including J-PARC [17, 43]. Figure 9(a) shows calculated energy resolutions as a function of the energy transfer for $L_1 = 18$ m, 20 m, and 30 m when $E_i = 50$ meV and $f = 300$ Hz. Even if $L_1$ is extended by 12 m, the energy resolution will improve by only 0.5% at elastic scattering. Similarly, shortening $L_3$ shows little improvement in energy resolution, as shown in Fig. 9(c). If $L_3$ is reduced to 1 m, which is the practical minimum value...
considering the required space for sample environment devices, the energy resolution will improve by only 0.2% at elastic scattering. Conversely, lengthening $L_2$ is the most effective way to improve energy resolution. As shown in Fig. 9(b), increasing $L_2$ by only 0.5 m improves the energy resolution by 0.8% at elastic scattering. In reality, the flight paths are limited by spatial constraints as long as 4SEASONS continues to reside at BL01. However, $L_2$ can be extended by ~0.5 m and should be considered when reconstructing the vacuum scattering chamber in the future.

4 Conclusion

In this paper, we discuss the possible upgrades of the key components of 4SEASONS to examine their feasibility in improving the performance and flexibility of the instrument. We demonstrated that 4SEASONS can improve the energy resolution by a factor of two, remove frame overlap of adjacent incident energies, significantly improve asymmetry in the pulse shape, and increase the flux by a factor of ~1.5, without major technical difficulties. The findings of this study will contribute to the development of future upgrades for the 4SEASONS spectrometer. More detailed quantitative studies, including numerical simulations and prioritization based on scientific needs, budget, and human resources, are required to further elucidate the proposed upgrades.

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