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Full Length Article

‘Newton’ fast shutter system for neutron scattering instruments at the ESS and ISIS neutron sources

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ABSTRACT

Interfacial processes are involved in many areas of chemistry, physics and biochemistry, but following the structural changes of surfaces and thin films at relevant timescales remains challenging. Time-of flight neutron reflectometry can determine changes in surface composition and film thickness, but the speed of these measurements is typically limited by the neutron flux over the range of wavelengths available at existing instrumentation. This necessarily means that, even using the time-of-flight method, measurements over several angles of incidence are required to cover the full Q-range important for structural determination. The very high intensity of the ESS pulsed source makes such configuration changes very inefficient, as the measurements can potentially be recorded in seconds or even milliseconds. Here, we present a conceptual design and some preliminary results from a new type of fast beam shutter system that will allow efficient measurement of broad angular ranges at sub-second timescales. The shutter system is conceptually also potentially useful for a fast aperture application on the ZOOM instrument at the ISIS Target station 2. By using two perpendicular shutters with slits cut into them, it is possible to create a square aperture within the beam as the neutron pulse passes. We believe that the flexibility demonstrated will mean that this system has the potential to be generally useful in many neutron instrumentation applications.

1. Introduction

FREIA is a reflectometer currently under construction at the European Spallation Source (ESS) in Sweden [1]. The novel design uses an elliptical guide to deliver a wide divergence beam onto a fixed sample position. It has a horizontal sample surface which enables access to free-liquid surfaces for research studies in soft condensed matter and life sciences, where both the structure and kinetics are of interest during the formation of thin films or in their response to environmental changes (see [2] for example). Other than the absolute flux provided by the ESS source, there are two key design features of FREIA that make the instrument particularly well suited to time-resolved measurements. Firstly, due to the broad range of incident angles (>3.5°) delivered by its elliptical guide, it is possible to selectively collimate the beam to three different angles without moving the sample. This saves a significant amount of time, particularly for free liquid surfaces and kinetics experiments, where the full reflectivity curve requires all three angles covering a scattering vector, Q_Z-range up to 0.39 Å. Most existing reflectometers [3,4] require the insertion of a supermirror to deflect the beam in order to change the incident angle, with a corresponding physical movement of the sample position. This typically results in a time latency of a few minutes, which is generally a small proportion of the overall measurement time for the full Q_Z-range. Measurements that require faster time resolution are thus limited to a smaller proportion of this Q_Z-range achievable with one fixed incident angle. The high flux expected from ESS means that the measurement times expected on FREIA will be significantly faster, meaning that latency from sample movement would be a significant fraction of the measurement time. Instead, the three incident angles for FREIA are each defined by a pair of adjustable 3-aperture slits, which remain in fixed positions throughout the measurement and can be independently opened and closed as required.

The second feature that is part of the conceptual design of FREIA is the ability to rapidly change incident angles using a set of fast shutters, see Fig. 1. This concept would allow the possibility of switching between incident beam angles on a pulse-by-pulse basis and avoids

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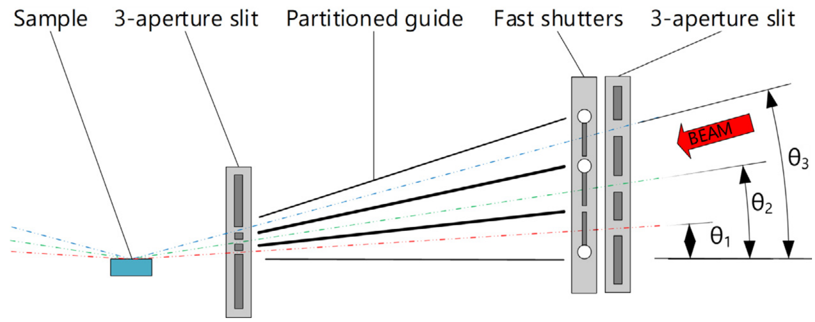


Fig. 1. FREIA instrument collimation concept based on series of adjustable apertures are partnered with individual fast shutters.

potential background issues related to the simultaneous measurement of all angles. In order to function according to this concept, three individual fast shutters need to be synchronized with the ESS pulse (14 Hz) and open or close in under 15 ms. The particular advantage of this approach, over something that would resemble a traditional chopper, is that the timing and sequence can be arbitrarily adjusted to suit the necessary time resolution and counting statistics.

The ZOOM small-angle scattering instrument at ISIS Target Station 2 (TS2) was intended to measure scattering from very large-scale structures — such as viruses, lipid nanoparticles, vesicles and geological samples. In its current state, it is very similar to the existing SANS2d beamline on the neighbouring port [5]. This will only be possible by using focusing optics: a system of compound refractive lenses (CRLs) coupled with a fast aperture. This aperture has strikingly similar requirements to the FREIA shutters, since it will need to be able to close to create a small aperture as the neutron pulse reaches the focal wavelength of the lenses. These two projects therefore initiated a collaboration to develop a shutter/aperture system that can be implemented in both cases. This paper presents the testing of a prototype of such system.

2. Fast shutter system for FREIA

For a typical time-of-flight reflectivity measurement, the full Q_Z-range is covered by a combination of the incident angle and the wavelength bandwidth of the neutrons. For FREIA the bandwidth is approx. 8 Å, which means that to cover the desired Q_Z-range, measurements at three different angles are necessary. One could partially overcome this limited Q_Z-range by operating the instrument in a pulse-skipping mode, which extends the bandwidth to 2-18 Å [1]. This would marginally extend the Q_Z-range for a given angle: For example, for a minimum $Q_Z \simeq 0.01$ Å^{-1} the single pulse mode has a maximum $Q_Z \simeq 0.055$ Å^{-1} ($\theta = 0.5°$), while the pulse-skipping mode has a maximum $Q_Z \simeq 0.09$ Å^{-1} ($\theta = 0.85°$). This is not enough to cover the full Q_Z-range required for a typical full structural measurement (circa 0.01–0.2 Å), so a pulse-skipping mode would also require at least two angles for an equivalent Q_Z-range. Pulse-skipping also results in a lower overall neutron flux, a reduction in the integrated flux (by a factor of two) from skipping every other pulse combined with the inherent lower flux of the longer wavelengths from the source spectrum. An additional complication is that the wavelength-frame-multiplication chopper system on FREIA is not functional in pulse-skipping mode, which means that such measurements would not be possible with high resolution. Thus, while there is no doubt that the pulse-skipping mode of FREIA will have some useful applications, the fast shutter system described here offers significant advantages for flexible fast measurements over a wide Q_Z-range.

Since the reflectivity falls away with, Q_Z^{-4}, the intensity of the specularly reflected beam for each of these three angles is significantly different. As a result, it is necessary to count for longer at higher angles to achieve equivalent counting statistics. Counting times for each angle are dependent upon the sample, and so the ability to tune the counting time for each angle is a real advantage since it allows time-resolved measurements to be optimized on a case-by-case basis. The concept of fast actuating shutters, that open and close in any arbitrary order during the time-gaps between source pulses (14 Hz) allows this flexibility to balance time resolution versus the counting statistics required for each angle. While there are potentially many ways that this could be achieved, for example using a rotating chopper-like disk, space constraints are a severe limitation to such a solution. Instead, we are developing a reliable and cost-effective solution based on a set of three fast servo-motors equipped with blocking paddles, each enabling or disabling one of the three angular ranges, allowing for on/off operation. With this design, the positioning accuracy of the shutters is less relevant because the collimation is independent of the shutters. Similarly, the timing accuracy requirement is significantly reduced and easier to implement, compared to a chopper-like system.

Fig. 2 presents the envisaged design. Three independent servo motors[1] are equipped with blocking paddles. The radial dimension of each paddle is sized to the angular range that is required for each angle: 53 mm, 33.5 mm and 12 mm for the top, middle and bottom shutter respectively. The motors positions are planned such that 90° movement is enough to block the neutrons in the given range and will not overlap with the other ranges.

This design allows for very high acceleration of the paddles, as the accuracy for the resting position is relaxed because the neutron beam path is already precisely defined by the 3-aperture slits. Furthermore, the beam will be fully blocked as soon as the paddle clears at most 85° travel (depending on the exact position of the collimated beam with respect to the paddle) and is maintained for the next 10° of the movement. One other constraint on the system is that it will be placed within the FREIA collimation vacuum vessel. It therefore needs to operate in medium vacuum (circa 10^{-3} mbar), which imposes requirements for heat dissipation to ensure that long term performance of the motors can be maintained.

3. Fast aperture system for ZOOM

The ZOOM instrument was specified to deliver a focused neutron beam in order to access larger length scales (VSANS). It is envisaged that this system will take the form of a compound refractive lens (CRL) system, similar to those successfully deployed on reactor based instruments for many years. As the CRL system is a chromatic component, the design calls for a flexible aperture which can rapidly create a 1-5 mm source in order to focus an appropriate wavelength (i.e. the correct part of the ISIS TS2 pulse) onto the detector surface. The choice of wavelength to be focused will depend on the number of lenslets in use, sample type and environment. It is envisaged that long wavelengths >1 nm would be most commonly utilized. The device needs to switch

[1] Beckhoff AM8122-1F00 motor with resolver controlled individually by EL7211 servomotor terminal.

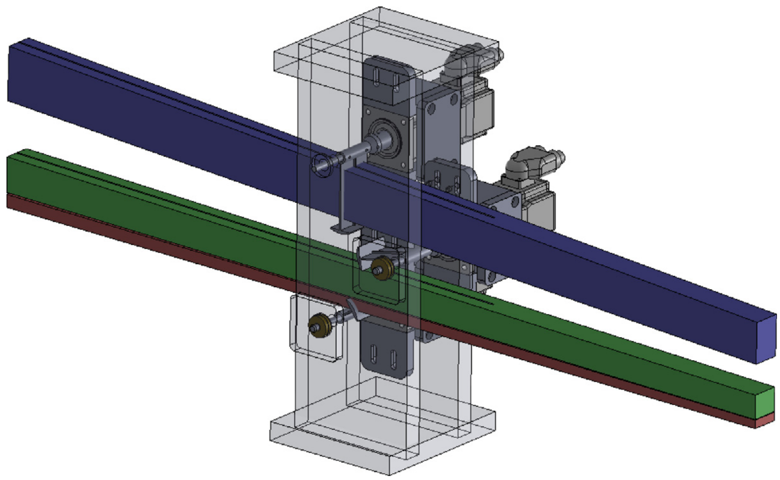


Fig. 2. Schematic arrangement of the fast shatter paddles in the neutron beam. Three independent stepper motors are equipped with blocking paddles. Coloured parallelepipeds represent the possible range of angular of the collimated neutron beams in the three angular regions.

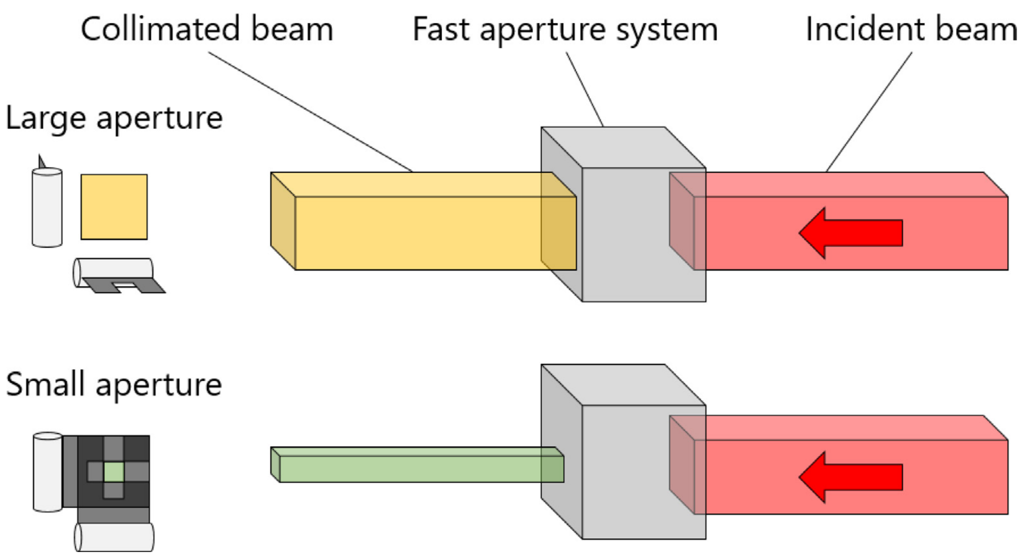


Fig. 3. ZOOM instrument concept. Left: two slotted paddles forming an aperture. Right: the 2 aperture modes and collimated beams foreseen for ZOOM instrument.

between 2 collimating aperture sizes (as shown in Fig. 3, right) and be synchronized with the ISIS TS2 beam pulse (10 Hz). Each aperture must remain in a static open position for a fixed period of the beam pulse as the instrument collects scattering data, and then manoeuvre to the next aperture for the remainder of the pulse. The start of the open time can be controlled to select different neutron wavelengths. The apertures should operate in "rough" vacuum environment (1×10^{-2} mbar). Due to large similarity with the FREIA instrument shutters development, a fast aperture system based on similar solution was proposed for ZOOM.

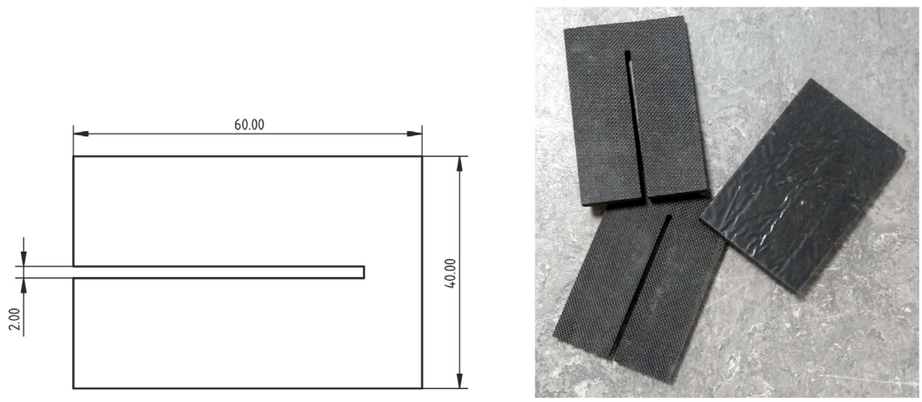
The concept is built around two orthogonal axes of motion control, each with a slotted paddle, where the width of the slit in each paddle defines the reduced aperture size in that dimension. Thus, a static large aperture that is created by the beamline collimation system can be quickly reduced to a small aperture formed by rotation of the two paddles, see Fig. 3. The small aperture is actually formed already halfway (45 degrees) through the movement of the paddles and does not change even with large variation of the final rotational position of the paddles, thus fulfilling the operational requirement on position accuracy and repeatability. This leads to a fast change between the apertures, minimizing the transition time when the aperture is not strictly defined (manoeuvre period) and maximizing the available time for data collection.

4. Shutter prototype

In order to test these two design concepts, we have built a simple prototype that can be tested both with and without beam. The prototype consists of a vacuum-mounted single motor equipped with a paddle. The paddle was built of aluminium frame with neutron absorbing boron carbide/epoxy composite-cladding glued on top. For offline testing this paddle can be tested without the cladding, but for the tests with beam, two versions of the neutron absorber were prepared, one that would uniformly attenuate the beam and one with a 2 mm slit (see Fig. 4). The performance of each version was measured and compared during the tests with different movement scenarios. A vacuum chamber with the motor mounted inside was equipped with sapphire windows to allow transmission of the neutron beam. Vacuum level during the test was kept at pressure of $<10^{-4}$ mbar.

5. Control system

The control system of the prototype was based on the Beckhoff Programmable Logic Controller (PLC), the same system that will be used at both ESS and ISIS beamlines. The PLC can be controlled independently or, for the tests with beam, was integrated with the ISIS Data Acquisition Electronics (DAE) system. In the latter case, the PLC



(a) (b)

Fig. 4. The dimensions of the paddle (left) and the boron carbide/epoxy composite used as the cladding for the shutter (right).

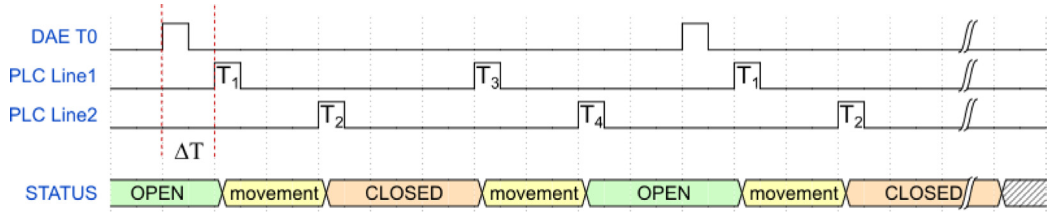


Fig. 5. Timing diagram of the control system.

was triggered from the DAE informing of the incoming beam, initiating the movement (DAE T0 signal, see timing diagram in Fig. 5). During the manoeuvre logical signals notifying when each portion of the movement has started/finished were sent back to the DAE (PLC line 1 and 2, with signals T1, T3 and T2, T4 respectively. The ISIS DAE system, upon receiving the signals, recorded the time and combined it with the detector data to subsequently save a complete data file including both instrument configuration and shutter timing. Different shutters and different movement scenarios were tested during the experiment.

6. Experimental methods

6.1. Offline experiments

The first tests carried out were offline to check the performance, investigate the effects of heating of the system in vacuum and to quantify the long term stability of the transition time of the shutter. To this end, the prototype was equipped with the largest foreseen paddle, and tested in the vacuum environment of 10^{-2} mbar pressure. The timing of the movement was recorded using feedback from the motor's encoder (via the PLC) and verified using an optical laser system with a photodiode power sensor. The laser was positioned such that the light could pass freely through the chamber when the shutter was at the start (0°) and end position (90°), but was immediately interrupted during the movement between the two states. The interruption was detected with the power sensor and read out by an oscilloscope, where the width at 50% level of the transition time was measured and defined as the flat-top time, thus giving an independent estimate of the manoeuvring time. The prototype was continuously operated over several hours in on/off mode (90° rotations) at 14 Hz, while the temperature of the motor and the transition time were monitored and recorded.

6.2. Online experiments

The online testing was performed using the ZOOM instrument at ISIS. The shutter prototype was installed in its vacuum chamber (10^{-5} mbar pressure) at the sample position in the arrangement shown in Fig. 6. The instrument beam collimation was set to give a beam of 12 mm × 12 mm at the sample position, with source to sample and sample to detector distance of 4 m to maximize flux. Since, without a sample, the majority of this beam would hit the beam stop, a 2 mm path length quartz cuvette of H_2O was positioned after the shutter in order to produce a flat scattering background onto the detector. The incident and transmitted beam monitors, part of the standard SANS setup for the ZOOM instrument, were used to measure transmission through the device. The PLC was integrated with the instrument DAE system, as described above, and received a pulse signal of 10 Hz (the ISIS TS2 source frequency). Measurements were made under several configurations, including with a slotted or solid paddle, with and without a water-scatterer and under different motion patterns.

The PLC was programmed to open and closed the shutter at a specified time delay after the T0 signal was received (ΔT in the timing diagram). For the purposes of the tests, the time delay was chosen so that the shutter movement occurred during the neutron pulse so that the change in transmission could be measured. It is worth noting that this is not the intended mode of operation for FREIA, as the shutter movement would be completed in-between neutron pulses.

7. Experimental results

For the offline test the shutter was run predominantly at the highest foreseeable frequency, i.e. 14 Hz, for up to 8 h per day, over a period of two weeks. During operation, the motor temperature gradually increased towards a plateau that was dependent upon the frequency, peaking at 70 °C for 14 Hz operation after 4 h. A direct correlation was observed between the temperature and speed of the shutter. Fig. 7 shows the changes in the transition time versus the temperature of the motor, comparing the results from the encoder data (orange crosses) and the laser system (blue line). We found a very good agreement between the laser system and the encoder results, with a transition time below 13.4 ms during the whole test. The transition time increased during the operation at the rate of approximately 15 μs/°C, starting

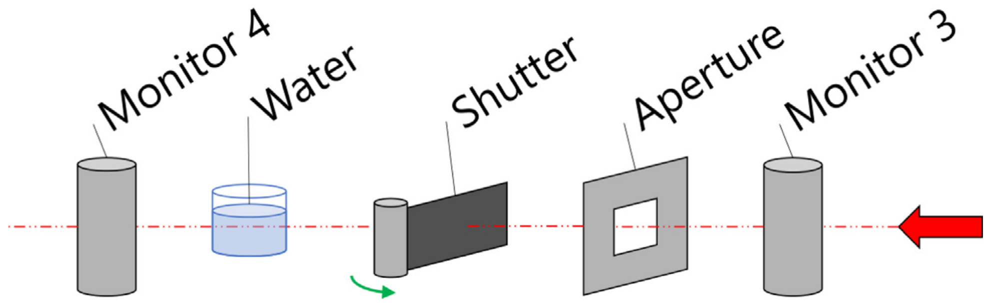


Fig. 6. Experimental setup.

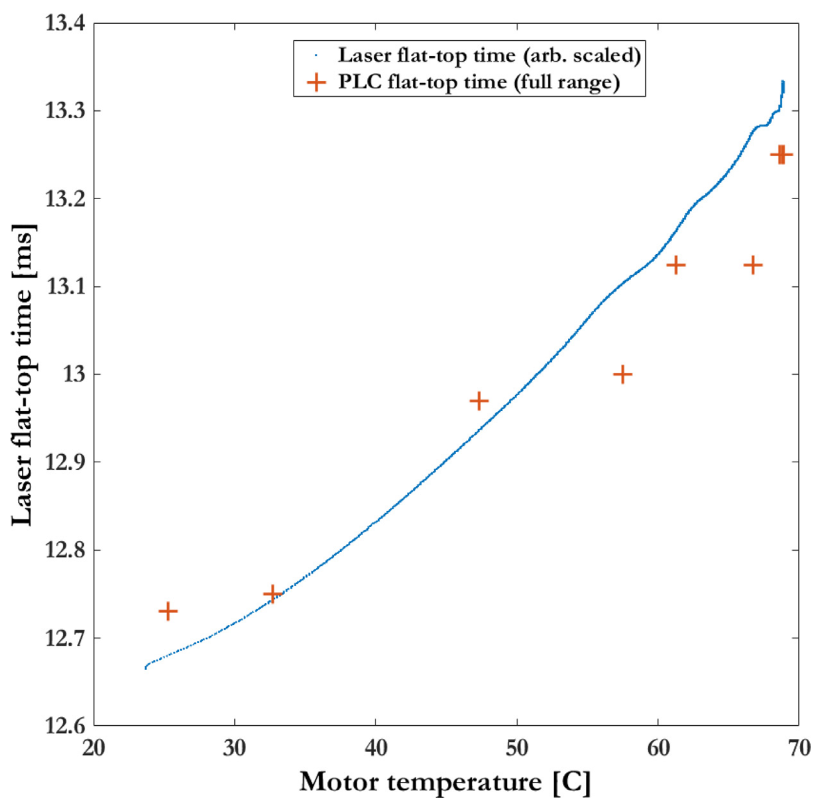


Fig. 7. Independent measurement of the temperature effect on the shutter opening time. Laser data in blue, PLC registered transition times in orange.

at 12.65 ms at 22 °C and increasing to 13.35 ms at 70 °C, which was the final stable temperature of the motor at the end of the continuous operation test. The performance of the prototype did not change during the two-week test period.

The result confirms that the motor can be actuated and move at the required speed for the intended applications on FREIA and ZOOM beamlines. We were therefore able to move to testing with beam to ensure that the control system can be adequately synchronized with the facility timing signals.

In the first test on ZOOM, the PLC was programmed to open and close the shutter on alternating T0 pulses, and the neutron flux measured as a time average. Fig. 8 shows the count rate on the two monitors as a function of time-of-flight (and wavelength) and compares it to the shutter paddle rotation angle on the same timescale. Initially, the shutter was open (shutter position 0°). After a specified delay (ΔT = 2 ms in this case) from the PLC detecting the T0 signal, the shutter transitioned to closed (shutter position 90°) for the remainder of the pulse. At the specified delay time after the subsequent T0 pulse, the shutter transitioned back to the open position. The time averaged counts thus includes data from periods when the shutter is both open and when it is closed. However, since the start time of the shutter transitions relative to T0 are identical for opening and closing, there is a period of overlap where the neutron beam is blocked in both the opening and closing transitions. This leads to a clear drop in flux between the monitors at the time corresponding to the paddle movements (note that the differing absolute magnitudes of the spectra is not significant, as these are raw spectra from monitors that use substantially different technologies).

To demonstrate that the beam was indeed blocked during the intended periods of each pulse, Fig. 9 shows a sequence of detector images for two sequential single pulses as a function of time-of-flight (correlated to the time-integrated spectra in Fig. 8.

The first two images (Fig. 9a and b) show the beam detection as the initial neutrons from the first pulse arrive at the detector.

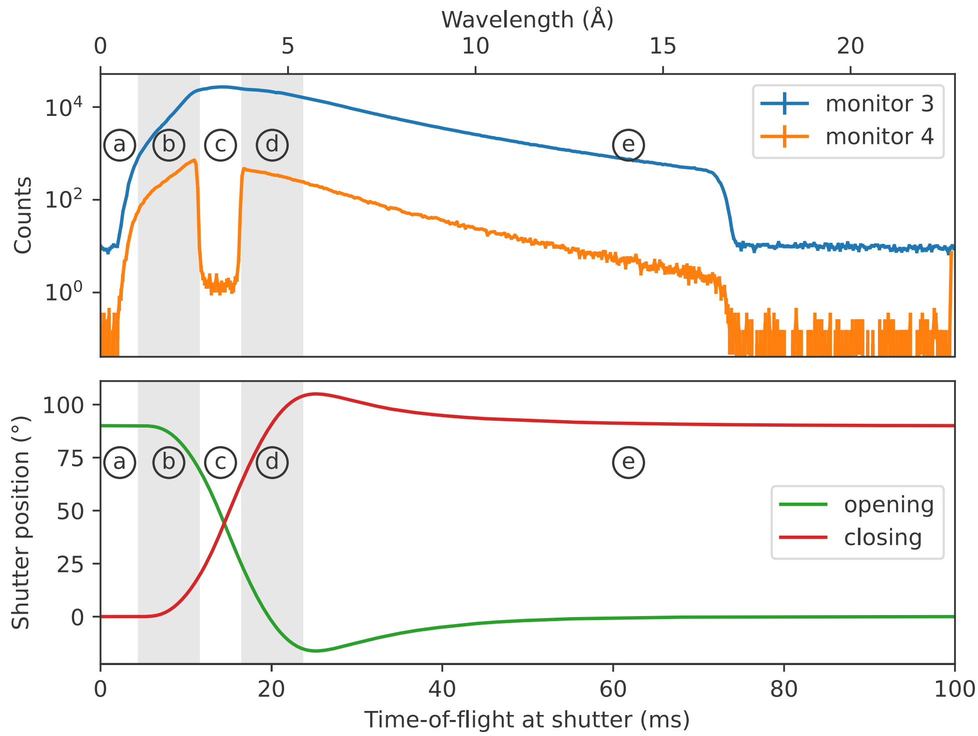


Fig. 8. Time-integrated spectra from the two monitors with shutter position over time. Period a: the shutter is stationary. Neutrons are able to pass the closing shutter, as it is still in the open position. Period b: the shutter begins to move. In the opening transition, the shutter is still blocking the beam. In the closing transition, the shutter remains open. Period c: the shutter is moving, and is fully blocking the beam in both opening and closing transitions. Period d: the shutter continues to move until it reaches the set-point. In the opening transition, the shutter is no longer blocking the beam. In the closing transition, the shutter is now closed. Period e: overshoot is corrected, and the shutter settles to the set-point.

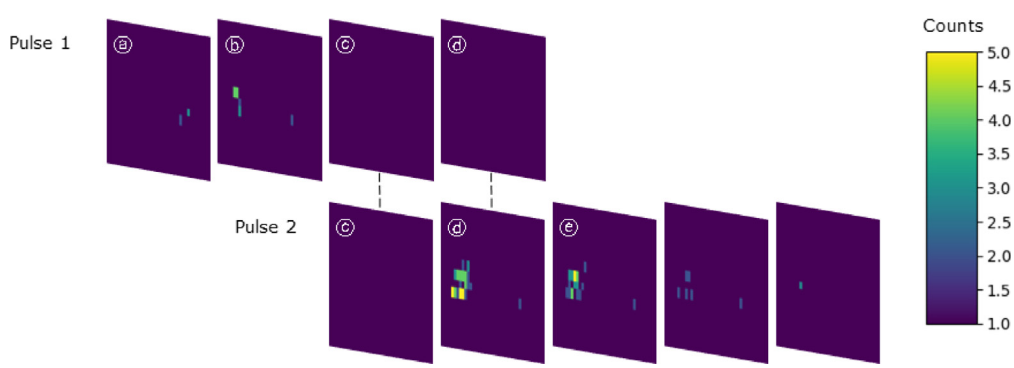


Fig. 9. A series of detector images for two sequential pulses at times that approximately correspond to the labels in Fig. 8.

These images were collected with a cadmium beam stop in place to protect the detector from exposure to the unscattered direct beam. This reflects the normal mode of operation during SANS and transmission measurements. Therefore, what we see on the detector is a combination of the 'penumbra' around the beam-stop (which is the pinhole image of the source aperture and parasitic scattering from slits/windows) and the incoherent background scattering from the hydrogen content in the water filled cuvette. As the shutter moves into place, it blocks the beam for the remainder of the pulse, meaning no further neutrons are detected (Fig. 9c and d). For the second pulse, the shutter is still in place until the time corresponding to Fig. 9c. It then opens for the rest of the pulse, allowing the detector to image the last neutrons from that pulse (see Fig. 9c, d, e and beyond)

In the second test, we were able to demonstrate that the timing of the shutter movement can be selected arbitrarily. The ΔT delay between the T0 signal and the shutter motion was varied (between 5, 10 and 30 μs), resulting in the blocking of different sections of the wavelength band, as shown in Fig. 10.

In a third test, we replaced the shutter paddle with a slotted paddle similar to the type intended for use in the ZOOM design concept. The data from this test is presented in Fig. 11 and shows that when closed, a significant proportion of the beam is still transmitted. Furthermore,

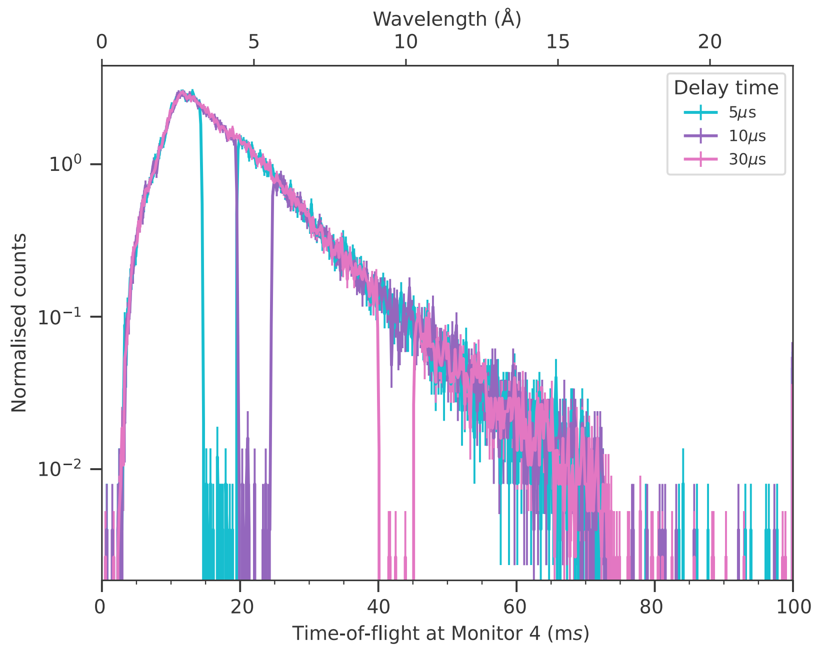


Fig. 10. Spectra with varying delay times.

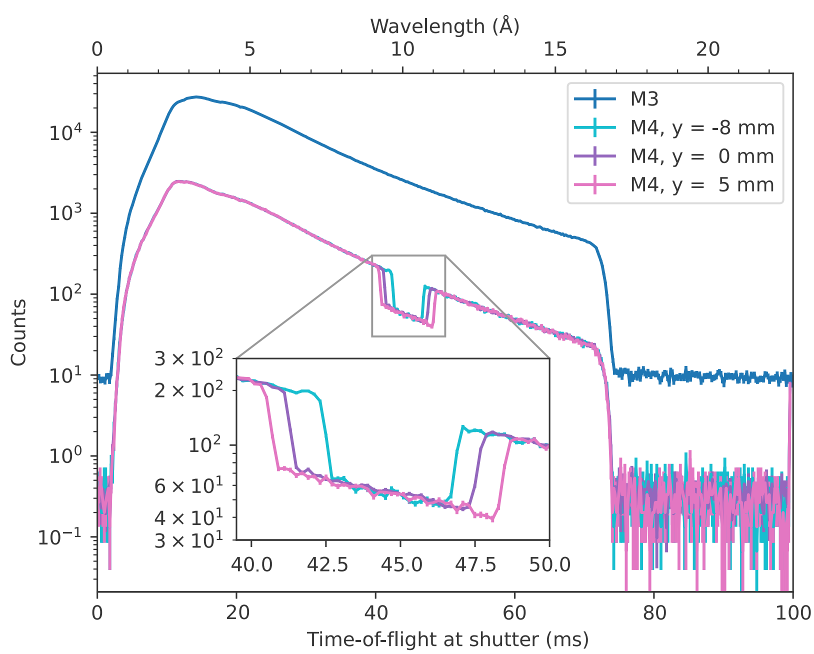


Fig. 11. Spectra with varying position of the shutter perpendicular to the beam (y). Negative *y* corresponds to a movement of the shutter further into the beam. In this case, the shutter was slotted, meaning that some beam is still transmitted when the shutter is closed.

we were also able to demonstrate that the time taken for the shutter to block or unblock the beam was directly related to its position relative to the beam. Since the time taken for the shutter paddle to sweep across the beam is related to the distance of the beam to the paddle pivot point, we are able to vary the bandwidth of the wavelength band cutout by varying the horizontal position of the shutter within the beam. This is also shown in Fig. 11 where the width of the cutout correlates directly with the position of the shutter perpendicular to the beam (y). Here a negative *y* position corresponds to moving the shutter closer to the beam and thus the shutter interrupts the beam earlier during the movement.

The final test was to ensure that the performance of the shutter is sustainable for the timescales one might expect during a real experiment. Long run measurements were taken over 6.5 h, with the start and stop time of each motion recorded by the DAE system. The timing signals each arrived within a range of 600 μs (i.e. 3 bins of 200 μs width)

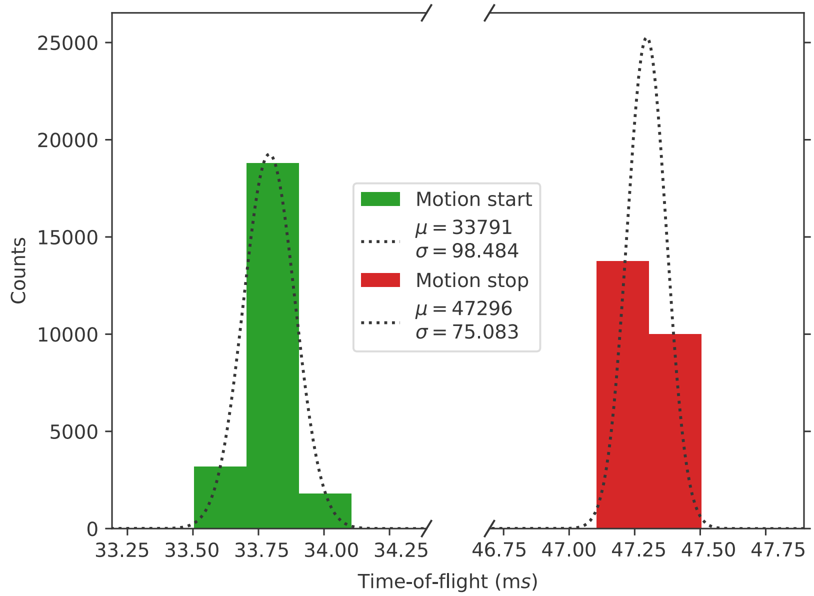


Fig. 12. Timing signals recorded by the DAE system over 6.5 h (1 movement per second ≈ 23400 movements), with Gaussian fits. The average movement time was 13505 μs.

as shown in Fig. 12. The mean movement time was 13,505 μs, with a standard deviation of 123.8 μs. This is in keeping with the PLC sample time of 100 μs. This clearly demonstrates that the timing of shutter movement is consistent and does not systematically degrade over the measurement period, even over 6.5 h. The online tests of the prototype at ISIS neutron beam line lasted for 48 h and no deterioration of the performance was observed during this period.

8. Discussions

It is clear that the design of shutters based on these motors is likely to achieve the performance required for both FREIA and ZOOM applications. The test measurements were successful in demonstrating the application with a shutter transition time ≤13.5 ms (results confirmed by independent measurement), well within the requirements of the FREIA and ZOOM instruments. A thermal dependence of the transition time was observed, although this drift was well within the acceptable limits. Given that the temperature of the motor in vacuum is related to the efficiency of heat dissipation, the implementation of this concept into the real instruments will need to ensure sufficient cooling capacity to maintain a stable temperature during operation.

Another observation that is yet to be fully quantified was that of vibration. There was also some oscillation of the shutter paddle around the open and closed positions in the dwell time, and this could be physically felt as a small vibration of the prototype on touching the vacuum vessel. The final design concept will place these shutters into proximity of sensitive high-precision neutron optics, and so the transmission of vibrations will need to be minimized in final design. Despite these important but relatively minor complications, it is clear that this concept presents a cost-effective technical solution both in terms of reliability and price.

The action of this shutter is somewhat reminiscent of a cat-flap and one can easily imagine the action of the shutter opening and closing to admit individual neutrons. Since it is an urban myth that Sir Isaac Newton invented the cat-flap [6] we suggest the name of "Newton Shutter" for this concept.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request

Acknowledgments

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