3.4.4

Temporal Characteristics of the ESS Proton and Neutron Pulses

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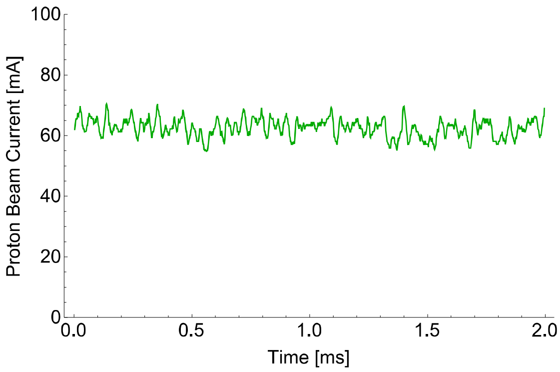
Abstract. The European Spallation Source will deliver 2.86 millisecond neutron pulses to neutron scattering instruments. The temporal character of these long neutron pulses depends on a number of factors such as the thermal neutron lifetimes in the moderator and reflector, and temporal fluctuations and trends in the proton current over the duration of the beam pulse. In addition, the proton beam delivery system produces an acceptable size on the target by transversely rastering a centimeter size beamlet during the time of each beam pulse. Since the moderator coupling depends on the proton beam position, this technique can lead to time-dependent neutron intensity. All of these factors affect the temporal structure of the neutrons delivered to the instruments in a wavelength-dependent manner. Simulation results will be presented, and the impact on instrument performance will be discussed.

1. Introduction

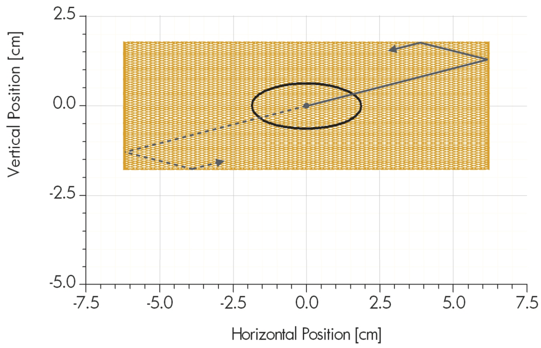
The ESS neutron instrument suite is being designed to accommodate pulses 2.86 ms long, arriving at a repetition rate of 14 Hz [1]. With this long pulse length, the temporal characteristics of the proton pulse can impact the structure of the moderated neutron pulse. Although the moderation process filters features with time constants of less than tens of μs, strong effects or those with long timescales can still impact the neutron pulse shape. Within the pulse, the two primary contributors to neutron intensity fluctuations are expected to be: 1) the fluctuating proton current on the target, and 2) the varying position of the proton beam as it is scanned across the target. Assessment of these effects may allow development of mitigation or correction techniques well in time for commencement of the ESS neutron science program.

2. Contributors to neutron intensity fluctuations

To deliver 5 MW on target, the ESS accelerator extracts pulses from a proton ion source, accelerates and transports them with low loss, finally producing 2.86 ms pulses of 2 GeV protons with a peak current of 62.5 mA. The beam delivery system then expands the millimeter-scale beam to transverse dimensions of about a centimeter, and scans it rapidly across the face of the target. Neutron intensity depends upon the proton beam current, energy, and position. The design of the accelerator allows an output energy variation of $\pm$1.5% and the time structure of this variation depends upon RF control performance that is not yet known. Therefore, only the



(a) Proton current waveform



(b) The raster pattern showing about 10 μs of the direct (solid) and inverted (dashed) scans .

Figure 1: Two primary contributors to neutron intensity fluctuations

effects of proton beam current and position have been assessed. They are expected to be the dominate contributors to variations in neutron intensity, but others will be considered as the ESS design progresses.

2.1. Proton current variation

The accelerator requirements specify an output current that remains within a ±3.5% window after averaging over any 200 μs interval. Although the low energy sections could exhibit some small variations in beam loss within the pulse, the higher energy sections must achieve a total loss far below 1%. Therefore, variations in ion source current are expected to be the dominant source of current fluctuations in the pulse that reaches the target.

Although the ESS ion source is not yet available, tests with a similar source have already been performed. In pulsed mode, test results from December of 2013 exhibit current fluctuations of about 3% RMS within the pulse. To simulate a worst case pulse waveform, a representative pulse has been scaled such that it barely meets the requirements. This results in a 62.5 mA pulse that reaches the maximum allowable current variation and contains the time structure typical of an ESS-type ion source. Figure 1a depicts 2 μs of this beam current waveform.

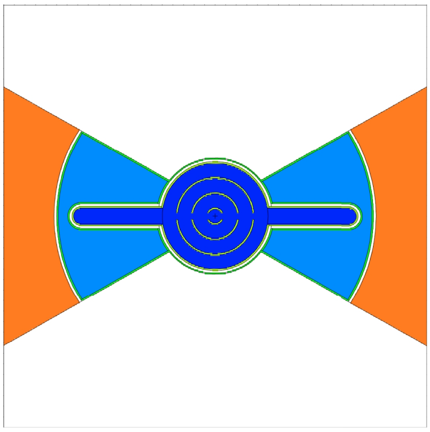
2.2. Raster scanning

Hands-on maintenance of the accelerator mandates extremely low beam loss. To achieve this, the accelerator preserves a low emittance and small transverse beam size. Because the target cannot sustain the resulting power density, a beam delivery system moderately expands the small beam from the linac to a beamlet of RMS dimensions 15.9 mm vertically and 5.3 mm horizontally as depicted by the ellipse in figure 1b. Then, during the pulse, a raster magnet system scans the expanded beam across the target with triangular waveforms of 39.55 kHz horizontally and 29.05 kHz vertically. The maximum horizontal deflection is ±63 mm and the maximum vertical deflection is ±18 mm. Figure 1b shows the resulting raster pattern. Reference [2] provides more detail about the beam delivery system while reference [3] presents the design considerations and preliminary results that stimulated the present study.

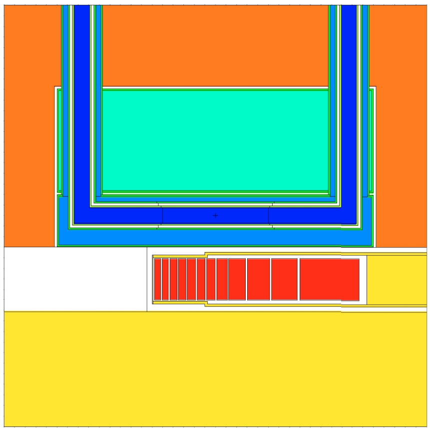
3. Neutronics simulations

3.1. Model

The moderator-reflector assembly proposed for ESS is based on the innovative concept of low-dimensional neutron moderators [4]. Figure 2 shows the geometry adopted for the present study.

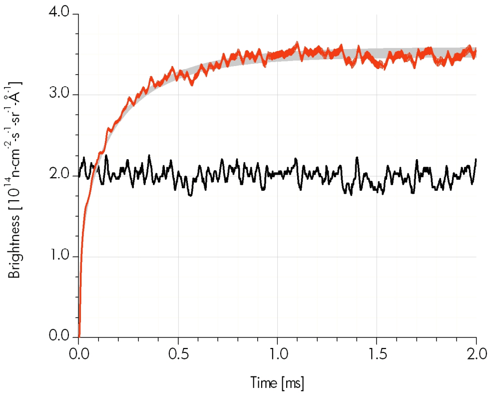


(a) Top view cross section through moderator

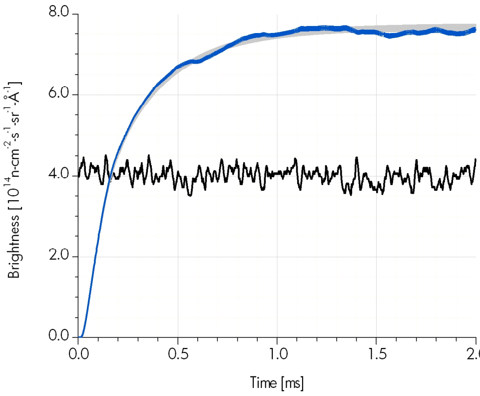


(b) Side view cross section through center of target and moderator assembly

Figure 2: Geometry of target, moderator and reflector assembly as modeled in MCNPX. Color legend: blue is liquid hydrogen, light blue is water, green is beryllium (+10% vol. water), red is Tungsten. The beam comes from the left.



(a) 0.8 Å neutron pulse produced by thermal moderator: grey line from ideal proton pulse, red line from worst case proton pulse (black line, not to scale)



(b) 2.5 Å neutron pulse produced by cold moderator: grey line from ideal proton pulse, blue line from worst case proton pulse (black line, not to scale)

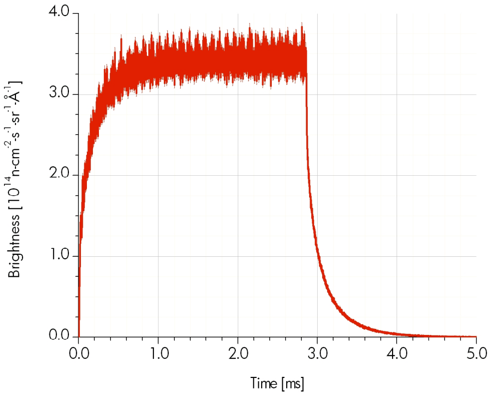
Figure 3: Neutron pulses resulting from beam on target without raster scanning

It consists of a flat, liquid para-hydrogen disk (cold moderator) within a water jacket featuring extended wings (thermal moderator). A beryllium reflector caps the moderator assembly.

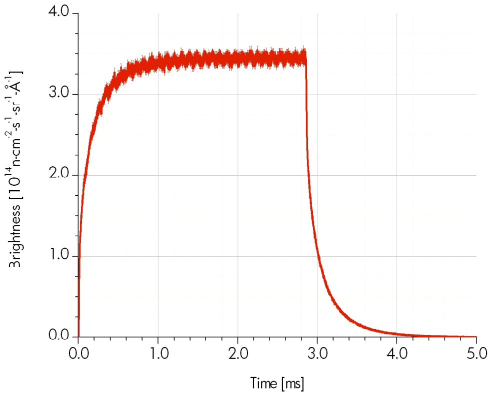
Simulations have been performed using the MCNPX Version 2.6.0 particle transport code coupled with the ENDF-B/VII.0 and JENDL-4.0 nuclear data libraries [5–7]. In all cases, a time step of 300 ns was used.

3.2. Effect of proton current variations

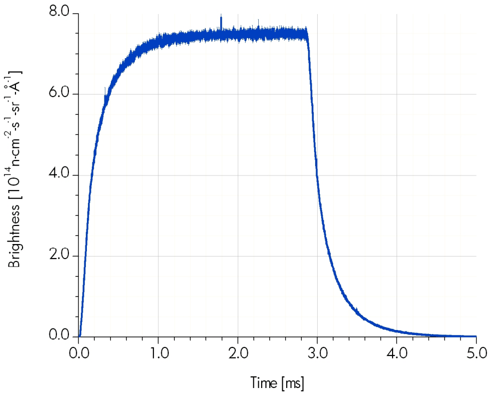
To isolate the impact of proton current fluctuations, one series of simulations used a beam with a fixed location on target and the current waveform shown in figure 1a. Figure 3 shows the resulting neutron pulse intensity versus time from both the thermal and the cold moderators. For reference, the pulse produced by a proton beam of ideal square temporal profile is also



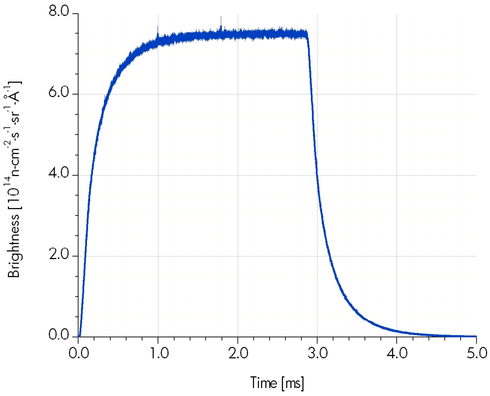
(a) 0.8 Å neutron pulse produced by thermal moderator from a single rastered pulse.



(b) 0.8 Å neutron pulse produced by thermal moderator averaged over 2 rastered pulses: direct and inverted.



(c) 2.5 Å neutron pulse produced by cold moderator from a single rastered pulse.



(d) 2.5 Å neutron pulse produced by cold moderator averaged over 2 rastered pulses: direct and inverted.

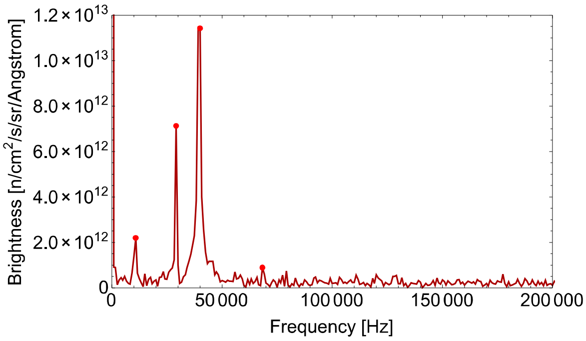
Figure 4: Neutron pulses produced by a rastered proton beam

shown. The effect of proton current fluctuations is smoothed in case of cold neutron pulse, while the thermal neutron pulse roughly follows the temporal profile of the incoming proton beam.

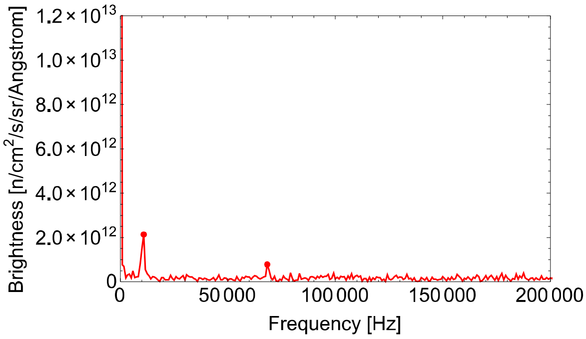
3.3. Effect of raster scanning

Earlier studies demonstrated the impact of raster scanning on neutron pulse shape [3], so a simple mitigation was developed and simulated for this study. Two pulses have been simulated based on the parameters described in section 2.2. The pulses differ only in the sign of the deflection waveforms and referred to as “direct” and “inverted” in figure 1b. The mitigation concept relies on producing a 14 Hz stream of alternating direct and inverted pulses, and then averaging over two subsequent pulses to produce a measurement nearly devoid of rastering induced fluctuations.

Figures 4 and 5 summarize the simulation results for an ideal proton pulse containing no current fluctuations. Single neutron pulses produced by this rastered proton pulse are shown in figure 4a (thermal moderator response) and figure 4c (cold moderator response). The fact that neutron pulses produced by the cold moderator do not exhibit large fluctuations can be explained by the specific properties of para-hydrogen: cold neutrons are extracted from the whole depth



(a) From single neutron pulse.



(b) From average over direct and inverted pulse.

Figure 5: Amplitude spectra of neutron intensity fluctuations induced by raster scanning the proton beam (0.8 Å neutron pulses from the thermal moderator)

of the moderating material which itself covers all positions of the proton beamlet. Meanwhile, neutron intensity fluctuations are large from the thermal moderator because thermal neutrons are extracted mostly from the water surface. Referring to the averages over two subsequent pulses as shown in figures 4b and 4d, the mitigation concept appears successful with fluctuations noticeably reduced, particularly in the case of the thermal pulse.

Although the averaging technique significantly suppresses the raster induced modulation, some residual remains above the computational noise. Given the well defined frequencies of the the horizontal and vertical raster scanning systems, spectral analysis can help to illuminate the situation. Figures 5a and 5b show the amplitude spectra of the direct and averaged thermal neutron pulses respectively. As expected, averaging over two pulses virtually suppresses the fluctuations at the rastering frequencies. Lines at the coupling frequencies (sum and difference of the rastering frequencies) are still present, but In the time domain, these result in $< 1\%$ RMS and $< 3\%$ peak-to-peak fluctuations. Table 1 summarizes the fluctuation amplitudes for the primary frequency components of the cases that were simulated.

4. Discussion

The majority of ESS neutron instruments under development use a combination of choppers and the instrument total flight path length to tailor the neutron pulse and the available wavelength band to the desired characteristics. Preferably, wavelength dependent variations in the source neutron pulse and intra-pulse fluctuations should be minimized and inter-pulse characteristics should be as reproducible as possible. The raster induced characteristics are programmable and reproducible, but a portion of the proton current variations will fluctuate from pulse to pulse. For most measurements the data normalization is performed using beam monitor information covering many neutron pulses. In the limited number of cases where single pulse measurements are required to follow kinetics, it is usual to replace the low efficiency beam monitors with high efficiency monitors and these would then allow the fluctuations to be corrected in the normalized data. Also, the beam transport though the neutron guides smooths out fluctuations of the incident neutron pulse. Most other experiments can utilize the two pulse averaging technique, and in this case, the effects of rastering are smaller that those due to the proton current variations. For experiments that allow even longer acquisition times for each measurement point, the remaining harmonics can be suppressed by modulating the raster parameters with a pseudorandom pattern. Averaging each pulse pair would suppress the fundamental lines, and averaging over more pairs would further reduce effect of rastering, pulse-to-pulse current and energy fluctuations, and other random variations of proton pulse characteristics.

Table 1: Fluctuation amplitude within neutron pulse, tabulated separately for each component

	RMS [%]	peak-to-peak [%]
Due to ion source fluctuations:		
2.5 Å	0.8	2.8
0.8 Å	1.7	8.0
Due to rastering, single pulse:		
2.5 Å, total	0.9	8.7
0.8 Å, total	4.2	20.7
0.8 Å, DC to 12 kHz	0.6	2.6
0.8 Å, 30 kHz	1.5	4.9
0.8 Å, 40 kHz	3.7	10.9
Due to rastering, 2 pulse average:		
2.5 Å, total	0.7	5.2
0.8 Å, total	1.1	6.8
0.8 Å, DC to 12 kHz	0.6	2.6
0.8 Å, 30 kHz	0.09	0.4
0.8 Å, 40 kHz	0.05	0.2

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