First Implementation of Novel Multiplexing Techniques for Advanced Instruments at Pulsed Neutron Sources

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Abstract. Novel multiplexing techniques, such as Repetition Rate Multiplication and Wavelength Frame Multiplication imply the use of a set of monochromatic wavelengths or a set of wavelength bands coming from the same source pulse by using novel combinations of standard mechanical neutron choppers. In this case the instrumental parameters, such as wavelength resolution, wavelength band, repetition rate are not any more determined by the source parameters, but can be flexibly defined by the chopper frequencies, speeds and slits. Here we report about the first experimental implementation of Repetition Rate Multiplication (RRM) and Wavelength Frame Multiplication (WFM). For this purpose the TOF spectrometer NEAT at HZB, Berlin and TOF diffractometer at BNC, Budapest have been used in non-standard modes of operation. Our results provide full proof-of-principle of the RRM and WFM methods and clearly show the extensive capability of these methods to achieve multiply enhanced data collection rates by individually tuning for each experiment the pulse length and/or pulse repetition rate within broad limits and independently from the actual source pulse parameters.

1. Principles of the multiplexing techniques.

The major limitation of the instruments operating at the existing pulsed spallation sources is that most of the instrumental parameters such as accessible S(Q,ω) domain, resolution and repetition rate are permanently fixed by the characteristics of the source pulses. For instance, in neutron spectroscopy the source pulse length and the length of the instrument define the instrumental resolution, while the source frequency is setting the instrumental repetition rate. Low repetition frequency of the source is often the reason why most of the TOF instruments at pulsed sources suffer from modest data collection efficiency. Compared to the “ideal” pulse repetition rate usually in the 50-300Hz range data collection can be realized only in 10 – 20 % of the time due to the low source frequencies varying in the 10 – 50 Hz range. The situation is becoming more complex in the case of the future European Spallation Source. According to the current project design ESS will deliver pulses with unprecedented peak flux, but at relatively long pulses of about 2-2.8 ms pulse length and low frequency in 10-20 Hz range. Using traditional design approach one needs an instrument length of several hundred meters to
match the resolution of the instruments at ESS to those at the short pulses sources, which would increase the cost of the instruments substantially. Shortening the pulse can be achieved by introducing pulse shaping choppers; however, the low pulse repetition rate set by the source frequency would still make the use of the source peak intensity less efficient.

The main challenge in the instrument design at the future European Spallation Source is, therefore, to develop new kind of techniques to take full advantage of the high neutron peak flux and at the same time to take control over the other pulse parameters to best suit the instruments and individual experiments.

Novel multiplexing techniques, such as Wavelength Frame Multiplication [1] and Repetition Rate Multiplication [2] allow us to create instead of one long pulse a number of mini-pulses with variable frequencies and pulse lengths but with the same peak flux as the original pulse. For instance, Wavelength Frame Multiplication allows us to shape a moderator pulse to desired pulse length without the reduction of the width of the wavelength band [1]. It is realized with the help of a fast rotating chopper system that defines several wavelength bands emitted from the same source pulse. The wavelength bands arrive at the detector one after another and combined together they continuously cover the wide wavelength band sought for (Fig.1). Instead of polychromatic wavelength bands, Repetition Rate Multiplication implies using a set of several monochromatic wavelengths, which are emitted from the same source pulse. In this case the resulting instrument repetition rate increases proportionally to the number of the wavelengths used from one pulse. Furthermore, combination of several wavelength bands or monochromatic wavelengths allows us simultaneous access to larger \( S(Q,\omega) \) space domain in a single experiment. Both methods can be implemented by means of a fast rotating set of mechanical choppers. In this case the instrumental parameters, such as wavelength resolution, wavelength band, and repetition rate will not anymore be determined by the source pulse parameters, but can be flexibly defined by the chopper geometry, pulse frequency and speed.

The design of the chopper systems for realization of multiplexing methods is different from those at reactors or currently operating at short pulse sources. Similarly to the reactor based instruments the main requirement for multiplexing chopper system is to assure that a neutron detected at any given time can only come from a single pulse shaping chopper pulse. However, multiplexing entails “quantized” chopper configurations in terms of the choice of the chopper positions \( L_i \) and chopper pulse frequencies \( f_i \), respectively relative to the source and source frequency \( f \). In order to make sure that all multiplexing chopper system pulses originate at the same time at the source, i.e. at proper chopper phasing all multiplexing frames look at the source within the same time period of the same duration, the time between the pulses of multiplexing chopper \( \#i \), \( 1/f_i \) must be proportional to the distance of the chopper from the source \( L_i \). Furthermore, all frequencies \( f_i \) shall be multiples of the source frequency \( f \), which lead to two RRM relations [3]

\[
    f_i L_i = \text{const}, \quad f_i / f = \text{integer} \tag{1}
\]

It is obvious that the data collection and evaluation using multiplexing techniques is more complex. For proper data collection it is very important that multiplexing choppers create signals which are well separated in time, but allow us at the same time to continuously cover the \( S(Q,\omega) \) space. There are many issues to be addressed, most importantly how to match the information provided by different wavelengths or different wavelengths bands. We performed extended experimental studies of the multiplexing methods using reactor based instruments: the Time-of-Flight (TOF) spectrometer NEAT at Helmholtz Zentrum Berlin and the Time-of-Flight diffractometer at Budapest Neutron Scattering Center. Here we overview our published work and also present some new results regarding the implementation of Wavelength Frame Multiplication.

2. Implementation of the Wavelength Frame Multiplication.
As mentioned above, we used the TOF diffractometer at Budapest Neutron Scattering Center (BNC) for the implementation of the Wavelength Frame Multiplication (WFM). In conventional, non-
multiplexing operation the chopper system of the TOF spectrometer at BNC defines a single wavelength frame repeating itself with each pulse shaping chopper pulse [4]. In our most recent study of WFM we used the multiplexing setup illustrated in Figure 1. The first chopper was emulating the source and at 10.61 m from the “source” the second chopper was used for pulse shaping. The sample was at 13.07 m from the pulse shaping chopper, and a single detector of 12 x 30 cm² area at 169.5° scattering angle at 3.57 m from the sample. For better calibration to the incoming wavelength spectrum we placed a monitor at 13.79 m from the pulse shaping chopper.

Since the chopper control system available on the BNC TOF diffractometer was not designed for synchronizing choppers with very different rotation speeds (8 Hz and 200 Hz, respectively in this case), the data collection was realized by selecting events in the event recording [5] (list mode) data sets, when the source emulation chopper was in phase with the pulse shaping chopper within a prescribed error (10 % of the source pulse length). The choppers basically ran asynchronously, and at data evaluation events were retained only if the phases of the choppers were within desired limits from each other. Using the event recorded data (which consist of all time stamped timing signals of all choppers, in addition to the time stamped monitor and detector counting events) we were also able to verify the fully uniform distribution of the relative phases between source and pulse shaping chopper pulses.

![Figure 1](image.png)

**Figure 1** Principle of Wavelength Frame Multiplication diffractometry represented by the lay-out used for its emulation using the TOF Diffractometer at the Budapest Neutron Center. The chopper emulated long pulse source parameters are: 5.2 ms FWHM pulse length, 8 Hz repetition rate. The pulse shaping chopper parameters are: 0.139 ms FWHM pulse length, 199.97 Hz repetition rate, 10.61 m distance from source. The RRM frames (i.e. the distinct parts of the spectrum arriving at the detector in intervals separated by gaps around 20, 33 and 46 ms on the time axis) correspond to neutrons originating from subsequent pulse shaping chopper pulses.

For the present experimental emulation of pulsed source WFM diffraction we have used an Al₂O₃ ceramic sample (which was found to also contain small amounts of other phases). As mentioned above, the multiplexing chopper system must create signals which are well separated in time, but cover continuously the wavelength range. Figure 2 shows the distribution of neutron detection times measured with respect to the specific pulse shaping chopper timing signal which was synchronized to the source pulse (i.e. found simultaneous within error with the source emulating chopper timing signal
emitted at the center of its 5.2 ms long pulse). Background counts, that arrived to the detector at times when they could not originate from any of the chopper pulses, are naturally discarded in the event recording data evaluation based on the unambiguous assignment of each count to a chopper pulse. One can clearly observe the distinct multiplexed RRM frames originating from the same source pulse and subsequent pulse shaping chopper pulses, with each covering about 10 ms time frame with 2.9 ms black-out periods in-between (cf. also Figure 1). It is important to observe that the wavelength bands in subsequent multiplexing frames overlap and form a continuous broad spectrum. For example there is only a 2.9 ms black-out time gap between the wavelength frames from 7.3 ms to 17.3 ms and from 20.2 ms to 30.2 ms, respectively, while they originate from pulse shaping chopper pulses separated by 5 ms.

![Graph](image-url)

**Figure 2** Time distribution of the neutron counts at the detector in synchronous source – pulse shaping chopper operation. Due to the overlap of the wavelength bands of the in time separated RRM frames, some Bragg peaks appear two times i.e. on both sides of a black-out gap.

Thus e.g. the Bragg peak observed at 16.5 ms in one RRM frame is the same as the one at 21.5 ms in the next frame, exactly by the 5 ms pulse shaping chopper period later. The event recording data evaluation consists of determining on the basis of the time stamps of all chopper and neutron detection events the one and only one pulse shaping chopper pulse a given neutron could come from and calculate the neutron distribution as a function wavelength (i.e. the time-of-flight measured for each neutron count from the corresponding pulse shaping chopper pulse). Therefore these two peaks will combine into a single one at 11.50 ms flight time from the pulse shaping chopper, i.e. 2.733 Å in the wavelength histogram (cf. Figure 4 below).

The correction of the spectra in the area of the overlap between two neighboring wavelength bands should be handled with great care. If the choppers rotate at fixed phase difference relative to each other (synchronous operation), then the intensity at the overlap area will depend on the details of this overlap and its handling in the data evaluation. This is illustrated by our results on the first implementation of WFM described in Ref. [6], as shown in Figure 3. Here the joining together of the
subsequent RRM wavelength frames are marked by well visible dips around 0.7, 1.8 and 2.9 Å d spacings.

![Expected positions of main isolated Bragg peaks (Al₂O₃)](image)

**Figure 3.** The first neutron diffraction pattern obtained by Wavelength Frame Multiplication [6]. The dips in the background line show the regions of switching from one wavelength frame to the next. The results also illustrate the good resolution capability accessible with the pulse shaping disc choppers (25 μs FWHM).

In our more recent study we have successfully tested two methods for perfect “stitching” between the different multiplexed wavelength frames. The first approach is based on asynchronous operation of the pulse shaping chopper with respect to the source pulse frequency. In addition, we have avoided accidental synchronization by selecting 199.97 Hz for the pulse shaping chopper in order to avoid 200 Hz, a simple multiple of the 8 Hz source frequency (cf. Figure 1). In this case the RRM wavelength frames are uniformly slewed over the whole spectrum, so after a sufficient number of cycles (10⁴ source pulses or more) the transition/overlap regions between these frames (such as the dips illustrated in Figure 3) will affect every wavelength precisely the same way. The uniformity of the distribution of the chopper phases over the whole wavelength range could be easily verified in our complete event recording data set. The so observed asynchronous, phase slewing diffraction pattern observed with good statistical accuracy is shown in Figure 4.

The phase slewing mode makes multiplexing WFM exactly equivalent to any TOF diffraction method operating with a single wavelength frame, both in principle and in practicalities. The normalization to the incoming neutron spectrum remains in both cases the only calibration to perform. For this purpose it suffices to determine this spectrum under identical data collection conditions, which is in practice either achieved with the help of a calibration run (e.g. with vanadium as sample) or by the use of monitor calibrated with high precision.

The other method we have tested is based on high precision and reliable normalization to the actual combined incoming neutron wavelength spectrum over all RRM wavelength frames in synchronous, fixed phase data collection mode. This approach has the advantage that it can also be used for short scans, only consisting of a few (or even a single) source pulse. In the present work this was achieved by simultaneously using a high counting rate monitor in the incoming neutron beam. This calibration/normalization also takes care of the parameter settings used in the event recording data.
evaluation process, e.g. TOF safety margins used in assigning the correct pulse shaping chopper pulse to each retained neutron count. Our results obtained by this method are identical within statistical error to the ones shown in Figure 4 for the phase slewing data evaluation, as illustrated in Figure 5, which focuses to a wavelength domain affected by the overlap of neighbouring wavelength frames.

![Asynchron (phase slewing) diffraction pattern](image)

**Figure 4.** Diffraction pattern obtained by asynchron (phase slewing) Wavelength Frame Multiplication data collection mode. The chopper system parameters are given in the caption of Figure 1. The wavelength range shown was fully covered by 4 multiplexed RRM wavelength frames for each source pulse.

![Asynchron (phase slewing) diffraction pattern](image)

**Figure 5.** Comparison of the WFM diffraction patterns measured in the range of an overlap of neighbouring multiplexed RRM wavelength frames. The enhanced intensities in the as measured synchron (fixed phase) spectrum due to RRM wavelength frame overlap between 2.45 and 2.9 Å can be fully corrected for with the help of the variation of the corresponding monitor spectrum (blue line in the right hand side) with respect to the asynchron (slewed phase) monitor spectrum (red line).
The chopper system used for the proof of principle of WFM in [6] was actually more complex than the one shown in Figure 1. Instead of emulating the pulsed source we have used the WFM multiplexing chopper configuration best adapted for long pulse sources, due to its property of defining “virtual source pulse” periods where the neutrons are exclusively accepted from. These “virtual source pulses” can be tuned to overlap with the most intense flat top part of the real long source pulses, by which the WFM chopper system extracts its continuous neutron spectrum exclusively from the brightest intensity part of the source pulses. This means that neither the rising initial portion nor, most importantly, the extended decaying tail of the source pulse can dilute or contaminate the peak pulse intensity. Such a multiplexing chopper system consists – in addition to the pulse shaping chopper – a set of source frame overlap and RRM frame overlap choppers, as shown in [6]. (For the set-up shown in Figure 1. frame overlap was anyway negligible due to the low source repetition rate and the short source to detector distance.)

3. Repetition Rate Multiplication

The first experimental implementation of the repetition rate multiplication was realized using the reactor based TOF spectrometer NEAT in Berlin and is reported in Ref. [3] in details. In this study the pulse of the source has been emulated by the first NEAT chopper (Ch1-2), operating at low speed and delivering short (about 200 μs FWHM) “source” pulses at 40 and 23.67 Hz in two separate experimental runs. Sets of monochromatic neutron pulses have been cut out from the pulsed white beam by the last chopper (Ch6-7) at frequencies that were equal to an integer multiple of the frequency of the first chopper pulses \( \nu_{ch6-7} = m \nu_{ch1-2} \). The three choppers, placed between the first and last chopper and used for regular operation of NEAT, have been stopped in open position to enable the arrival of the full cold neutron beam spectrum to the last chopper. The integer \( m \) was chosen to allow for about 6 ms time between the different wavelength pulses selected by the last chopper. This was necessary to keep at minimum the overlap between detected inelastic spectra from adjacent pulses at the sample. The data collection has been triggered by the pulse of the first chopper, thus spectra for all monochromatic wavelengths have been recorded one after the other in one data frame.

The left side of the Figure 6 shows the signal at the monitor taken at 23.67 Hz “source” chopper pulse frequency, with the monitor placed shortly before the sample. One can see a set of 7 clear well distinguished monochromatic wavelengths emitted from the same “source” pulse. The increase of the “source” chopper frequency to 40 Hz led to observation of neutrons with longer incoming wavelengths \( \lambda_{inc} > 9.2 \text{ Å} \) emitted by the previous “source” pulse in addition to the neutrons emitted from the same “source” chopper pulse. The elimination of this frame overlap neutrons can be done by specially designed frame overlap choppers. Missing these choppers in the available instrument set-up we emulated the frame overlap correction by measuring each wavelength separately and subtracting them from the multiplexed spectra [6]. The resulting repetition rate frequency at the detector was in both cases close to 120 Hz, demonstrating very clearly that the pulse repetition rate in a multiplexing instrument is independent from the source frequency.

The right hand side in Figure 6 shows the spectra collected at the detector which was placed at 2.5 m from the sample. The shape of the polychromatic scattered spectra reproduces those taken with monochromatic wavelengths. The data demonstrate very well that there is enough time between pulses to record spectra for different wavelengths coming from one source pulse. Almost no disturbing overlap is observed between the data sets for different wavelength RRM frames even at high temperatures and wavelengths, except for very long ones, i.e. here 13.04 Å. However, the time required to record each individual scattered spectrum at different incoming wavelengths is different and need to be individually adjusted for optimal data collection efficiency. For instance in our study 6 ms was sufficient for the spectra at 3.09 Å, while 9.2 ms were required for the spectra at 11.14 Å. At a conventional instruments operating with a single wavelength the time between pulses needs to be a constant and this is commonly realized by a slowly rotating chopper letting only through every second, every third, etc…. pulse of the monochromating chopper.
However, in polychromatic mode of operation we need variable times between pulses, which can be achieved by selective pulse suppression [7]. Such suppression can be provided by the chopper shown in Figure 7. The selective suppression chopper rotates at the same frequency as the frequency of the source. The special configuration of the chopper slits allow us to transmit the first set of pulses without suppression, and then transmit only one in two, then only one in three (and so on) pulses. The application of selective pulse suppression will allow us using Repetition Rate Multiplication more efficiently for recording both thermal and cold neutrons in a single experiment.

![Selective Pulse Suppression Chopper](image)

**Figure 7.** Example of a selective pulse suppression chopper disc for Repetition Rate Multiplication combining thermal and cold neutrons. At 14 Hz rotation frequency it would select a neutron pulse sequence of 3 pulses at 3.57 ms after the previous one, followed by 2 pulses at 7.14 ms and 2 pulses at 10.71 ms.

The spectra collected in the Repetition Rate Multiplication mode can be treated exactly in the same way as spectra taken at one monochromatic wavelength only. Figure 8 shows the energy dependent spectra for 4 individual incoming wavelengths, extracted from the time-dependent polychromatic data set in the Figure 6. No artificial shifting and deformation of the line shape is observed for the vibrational peaks at the higher frequencies (5 -10 meV). Observation of the quasielastic data obviously depends on the resolution at individual wavelengths. For the analysis of the data one can advantageously combine the information provided by different wavelengths: the short wavelengths can be used for the information at higher momentum transfer, while the long wavelengths can be used for the high resolution data. In fact, in some cases using long wavelength neutrons one can relax the resolution requirements for the data at shorter wavelengths, which in turn can provide for higher intensity. In the example of Figure 8, the vibrational peaks have nearly 3 orders of magnitude higher intensity at 30 times lower quasielastic resolution at 3.09 Å incoming wavelength than at 9.13 Å.
4. Conclusions
With the help of unconventional use of existing time-of-flight instruments at continuous reactor sources we have experimentally implemented and tested for the first time various multiplexing chopper systems earlier proposed [1] as novel, high power instrumentation approaches for pulsed spallation sources. These experiments practically established the basic “quantized” design rules of multiplexing chopper systems and provide full proof of principle of these methods. Repetition Rate Multiplication (RRM) was found [3] to enhance data collection rates by up to an order of magnitude, including the quality and breadth of the information collected in a single RRM experimental run. It allows us to select the pulse repetition rate at the sample essentially independently of the frequency of a pulsed source. The Wavelength Frame Multiplication (WFM) variant of the RRM approach was found to provide unrestricted capability for flexible pulse shaping for high and variable resolution diffractometry at long pulse sources, overcoming the conventional wavelength band limitations due to the source pulse parameters. In a first experimental test [6] we were able to demonstrate in particular the important “virtual source” feature of the method for selecting the period of highest source pulse brightness for beam extraction at all wavelengths. The latest implementation of WFM on an actual long pulse source emulated by a beam chopper has provided evidence for the capability to continuously cover any desired wavelength band by a set of multiplexed wavelength frames. It has shown constant TOF resolution and unperturbed spectral distributions, fully comparable to the common single wavelength frame operation of pulsed source diffractometers, even for every single source pulse. This study also included the first successful experimental realization of phase slewing, asynchronous pulse shaping chopper operation for diffraction work on a pulsed source, which makes a long pulse source to fully behave like an ideal short pulse source with flexibly adjustable and ideally shaped sharp pulses.

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Figure 8. Energy converted spectra taken using Repetition Rate Multiplication (RRM) mode on water confined in MCM-41. It can be clearly seen; that combining the information contents from spectra at different wavelengths, all dynamical features, vibrations as well the quasielastic broadening can be defined with higher accuracy and more details.