Multiplexing neutron chopper systems and pulsed neutron source design

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Abstract

The time-of-flight technique for delivering neutrons with well defined velocities to the sample opened up the way to make neutron sources vastly more efficient in neutron scattering experiments by making them pulsed. A key challenge in the design of pulsed sources is to provide at the same time short enough pulses to meet high neutron velocity resolution requirements in some experiments, while striving for highest beam intensity by trying to avoid making this resolution better than really needed in each expeiment. Multiplexing chopper systems – developed in the past 15 years since the introduction of the concept of Repetition Rate Multiplication in 1994 – offer a uniquely flexible and efficient tool to accomplish this task for a broad range of neutron pulse lengths from a few μs to ms. In doing this, they allow us to achieve 2 – 10 times higher beam intensities under very advantageous conditions of flexible, case by case optimization of pulse lengths and shape and enhanced reliability of operation, in comparison to the traditional short pulse approach consisting of one-sidedly making for the whole facility the proton beam pulses short enough to match the highest thinkable neutron velocity resolution.

1. Introduction

Pulsed spallation sources grant us the best opportunities to provide highest data collection rates and sensitivity in neutron scattering investigation of matter. The highest flux reactors built by now have been operational for several decades (HIFR at Oak Ridge and ILL at Grenoble) and they also turned out to represent the reasonably cost effective technological limits of continuous sources for neutron scattering research.

The pulsed reactor source concept, developed and realized in Dubna from the 1960's, opened up an important way to enhance the efficiency of neutron sources: by utilizing a higher fraction of the neutrons produced to start with. Spallation, an alternative technology primarily pioneered at Argonne National Laboratory in the 1970's to extract free neutrons from nuclei for beam research purposes, enhanced the source efficiency in another fundamental way: by involving less energy per neutron produced.

The key design challenge for a pulsed source is to make short enough neutron pulses available to provide for reasonable wavelength resolution by using the time-of-flight (TOF) method, which is the basis of the enhanced efficiency of pulsed sources. In the first generation of pulsed spallation sources (IPNS, ISIS, Lujan Center, KENS) this has been achieved by firing sub μs length proton pulses to the spallation target with the help of ring accelerators or accumulator rings, while the actual duration of the generated neutron pulses ranges between some 3 and 300 μs. These sources of modest accelerator beam power (much less than 1 % of the thermal power of the high flux reactors) have most successfully achieved neutron beam performances comparable to those of the top reactor sources. The enhanced power versions of these vanguards, SNS and J-PARC most recently attained a new level of neutron beam intensities for scattering experiments which very substantially surpasses the best that could be achieved by continuous sources.

In practice, however, this apparently comfortable “one for all” approach of delivering short proton pulses on the spallation target turns out to be expensive, technologically unnecessarily complex and challenging, and ultimately wasteful for neutron production and delivery. The present paper is devoted to a fundamentally different approach: the use of multiplexing mechanical neutron beam chopper systems. By reviewing the developments of such systems in the past 15 years we find that they offer a much more efficient method than ring accelerators for delivering the short neutron pulses needed in a variety of neutron scattering experiments. By this they open up the way to another order of magnitude gain in beam intensity for neutron scattering research and meet the next challenge for neutron source design, the exploration of the full potentials of the giant leap that pulsed spallation technology can bring to neutron source performance.

2. Producing short neutrons pulses: the alternatives

Linear accelerators offer the most efficient method for delivering high power pulsed proton beams. In pulses of a few hundred μs length (typically 500 μs) they can deliver 20 – 100 kj proton beam energy. These long pulses are then traditionally compressed in accumulator rings to about 1 μs and directed to the spallation target. The pulse length of the so produced neutron pulses is, however, much longer than the μs length of the proton pulses, due to the response time of the moderator-reflector assembly, which varies with neutron wavelength and type of moderator. For example, for cold neutrons the most intense coupled moderators emit pulses with about 250 μs FWHM duration (the RMS pulse lengths is more than 500 μs), while the poisoned moderators produce some 50 μs pulses with about 8 times fewer neutrons per pulse than the coupled ones. This actually means that the compression of the proton pulse is in actual fact little productive for cold neutrons.

Indeed, in order to prepare the linac beam for the injection in the accumulator ring we accept a beam intensity loss of nearly a factor of two, in addition to some 150 M€ extra investment in the accumulator ring, in special injection related beam transfer (achromat), in more sophisticated ion source (H^- instead of protons), in higher accelerator vacuum, in additional beam dumps, etc.

Furthermore, all this added complexity practically doubles the operational costs and stochastically reduces the operational reliability of the accelerator system. Thus if we just suppress the ring – together with the injection specific requirements (intermittent proton beam with about 2/3 duty cycle, strict removal of beam fringes), the linac operating under the same conditions can deliver a continuous beam during the pulse duration with about 80 – 90 % more protons on the target. If in addition we invest a major fraction of the money saved by eliminating the accumulator ring into enhancing the power of the linear accelerator, we end with a capability of delivering in a 100 μs pulse the same energy, as the linac we could envisage together with the accumulator ring would do in some 500 μs. In view of the intrinsic about 250 μs response time of the coupled moderator system for cold neutrons, this means that we obtain without the accumulator ring exactly the same pulse length and neutron intensity for the intense cold neutron pulses than with the ring, cf. Figure 1. We will refer to such a pair of accelerators (i.e. linac + accumulator ring and linac alone for same costs) as equivalent. For an example note that the planned linac power of ESS will correspond to about 15 kj proton beam energy in 100 μs, close to the 16.6 kj/pulse of SNS at the by now achieved 1 MW power level of operation. Conservatively, we assume in this paper that the coupled moderators at long pulse sources have the same neutron yield than what has been already achieved by coupled moderators on short pulse target stations, which contain substantial neutron absorbing structures. This certainly underestimates the long pulse source performance, but it is not reliably known yet by how much.

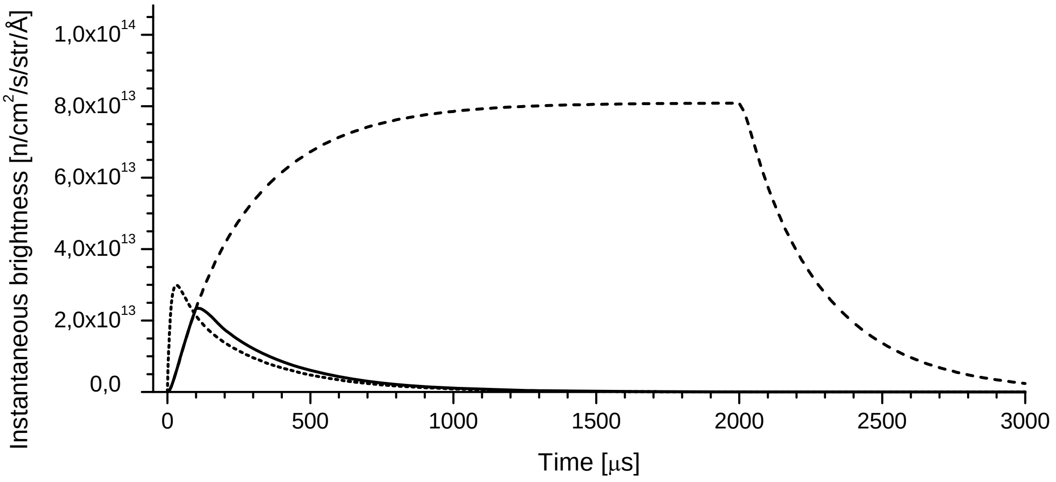

Figure 1. Coupled cold moderator response at λ = 4 Å to different proton beam pulses: short ring accelerator pulse, 15 kj/pulse (dotted line), 100 μs long equivalent linac pulse, 15 kj/pulse (continuous line) and 2 ms long linac pulse, 300 kj/pulse (dashed line)

It is even more significant, that eliminating the accumulator ring opens up far reaching new opportunities which actually vastly enhance the source performance. If instead of limiting the equivalent linac pulse length to 100 μs, sufficient to emulate coupled cold moderator short pulses, we leave the linac "on" for 1 – 2 ms, we obtain compared to using the equivalent short pulse accelerator:

a) 10 – 20 times more neutrons per pulse for the most intense moderators (both for thermal and cold neutrons)
b) Enhanced peak intensity in the pulse, which will amount to 25 – 50 % more for thermal neutrons and a factor of about 3 for cold neutrons.

c) Flexible delivery of short neutron pulses of higher intensity and improved line shape for the instruments according to the individual experimental needs.

Point b) and c) is the crux of the matter. For some experiments, such as small angle scattering (SANS) and neutron spin echo (NSE) the 1 – 2 ms long source pulses deliver sufficient TOF wavelength resolution, thus the intensity gain per pulse under point a) is fully effective.

For higher resolution work, multiplexing mechanical neutron chopper systems offer us the capability to cut out short pulses with a sharp, tail free shape from the approximately flat top region of the long pulses, with intensities per pulse 2 – 5 times superior to those one would have obtained with the accumulator ring. Indeed, beyond the gain in peak flux under point b), the sharper pulse shape produced by choppers makes the same resolution correspond to larger FWHM pulse width, typically by about a factor of 1.5 [1].

Another significant advantage of the mechanical neutron chopper systems is that the pulse length can be varied at each instrument by choosing another chopper slit width or another speed. For example we can have some 10 μs pulse length at all neutron wavelengths, if needed for highest resolution, or up to 200 times higher beam intensity in longer pulses, if lesser resolution is sufficient and intensity is the priority. This potential to trade resolution for order of magnitude higher intensity on the same beam line could, arguably, be characterized by another factor of 2 effective gain of instrumental flux available for the science program, as an average over high resolution and vastly higher intensity experiments for which lesser resolution is acceptable (such e.g. as some 1 % in diffraction).

To illustrate the mechanism of the comparison: a high resolution poisoned thermal moderator with the accumulator ring will provide about 15 μ FWHM pulses at 1 Å neutron wavelength. Eliminating the accumulator ring in favor of making the linac more powerful in the proportion discussed above will lead e.g. in 1.25 ms linac pulses to 100 times more neutrons per pulse (of which a factor of 8 corresponds to the difference in neutron yield between the poisoned and coupled moderators). In view of the exponentially decaying long tail of the short pulse source neutron signal even for poisoned moderators, the same resolution will be achieved by cutting out a triangular pulse of about 25 μs FWHM from the long pulse, which will carry 1/50 of the total intensity of the 1.25 ms long pulse. This shows that even in the worst case of short thermal wavelengths and high resolution, the linac + multiplexing chopper systems combination offers a factor of 2 intensity gain compared to the equivalent linac + accumulator ring combination. Note that highest resolution at short pulse sources is commonly achieved in the thermal wavelength range by using cold poisoned moderators, which deliver here about 30 times less neutrons per pulse than the coupled thermal moderator. For this more relevant case the advantage of the linac + choppers combination doubles. Thus the total gain over various resolution requirements, as discussed above, amounts to a factor of 4 – 8 at the short thermal wavelengths and increases to a factor of 10 – 12 for cold neutrons.

It is to be stressed for completeness, that the pulse repetition rate becomes in a wide range a neutral parameter for the long pulse source performance at high and medium resolutions. Indeed, assume that in the above example of an equivalent long pulse source (12.5 times more proton per 1.25 ms long pulse) operates at 1/3 of the frequency of the short pulse source, i.e. its total power is only about 4 times superior. Thus a diffractometer at the long pulse source will have to have 3 times longer sample to detector distance in order to cover exactly the same wavelength band. (Supermirror based neutron guides grant for essentially loss free beam delivery over such extended distances for thermal and cold neutrons.) This means, that for the same resolution the pulse length can be 3 times longer, which – with an even sharper, trapezoidal shape – will more than compensate for the smaller number of pulses per second. Thus the intensity gain scales with the peak flux in the long pulse and not with the time average power!

Finally, the equivalent short and long pulse sources considered here are defined by about the same costs of construction and operation (although for the linac only facility the operational costs could be lower due to much less complexity and similar power consumption: only a minor part of the electricity consumption is related to actual proton acceleration, rather than operating all kinds of equipments, such as pumps, magnets, liquefiers,…). So there is no reason to limit the linac power by the equivalence to a short pulse facility. Actually both state-of-the-art linac technology and target design allow for long pulse spallation source powers in excess of 10 MW, which provides for over an order of magnitude gain in neutron flux across the board in all thermal and could neutron applications, with respect to the top facilities of today, SNS and J-PARC. Most significantly, this another order of magnitude gain after that what has been achieved in about the past half century, is ready to be realized within a decade of construction time by ESS.

3. Multiplexing chopper systems: TOF spectroscopy

The previous considerations show the overwhelming superiority of the unrestricted use of standard mechanical neutron beam choppers – assumed to be feasible – compared to the expensive and demanding alternative of accumulator rings. It remains to review the proposed multiplexing chopper systems, actually based on components well established in current practice of time-of-flight (TOF) instrument design, both at CW and pulsed sources.

Repetition Rate Multiplication (RRM) is the starting point of these systems [2]. It can be used at any pulsed source to enhance performance in TOF spectroscopy by making the pulse repetition rate at the sample essentially independent of the repetition rate of the source and eliminating the dead time in data collection between distant source pulses. This is of particular significance even for cold neutrons at pulsed neutron sources of lower repetition rates (10 – 25 Hz), where there is sufficient time between source pulses for accommodating a large number of pulses on the sample at the typical instantaneous rates of 50 – 1000 Hz, commonly used at CV source TOF spectrometers.

The principle of RRM is illustrated in Figure 2 by the layout of the first chopper system of this type developed at Los Alamos some 10 years ago [3, 4]. The multiplexing feature of extracting from each source pulse several pulses of neutrons with different flight times (i.e. wavelengths) on the sample is accomplished by chopper #6, which delivers up to 240 Hz RRM pulse rate to the sample at a 20 Hz source. Choppers # 1 and #2 define the range of possible incoming neutron wavelengths. Chopper # 3 determines the pulse length of the multiple pulses from each source pulse and chopper #4 is the specific RRM frame overlap chopper making sure, that neutrons at the sample at any time come from the same pulse of chopper #3. Thus choppers #3, #4 and #6 are those directly involved in one form or another in the multiplexing function. Chopper #5 (not shown) is used to optionally only let through every second, third, … RRM pulse from the basic 240 Hz rate, if the long neutron wavelengths used require more time for propagation between sample and detector. Recent experimental realizations of the method have shown that each of these RRM pulses of different incoming neutron energy can deliver useful, often complementary information, enhancing the data collection rate accordingly [4,5]. The RRM multiplexing approach thus offers crucial new flexibility concerning the repetition rate of the source. Most significantly, it makes TOF spectroscopy benefit from higher data collection rates by concentrating the source power into a lower number of more intense pulses, while the total number of pulses on the sample remains independent of the source repetition rate.

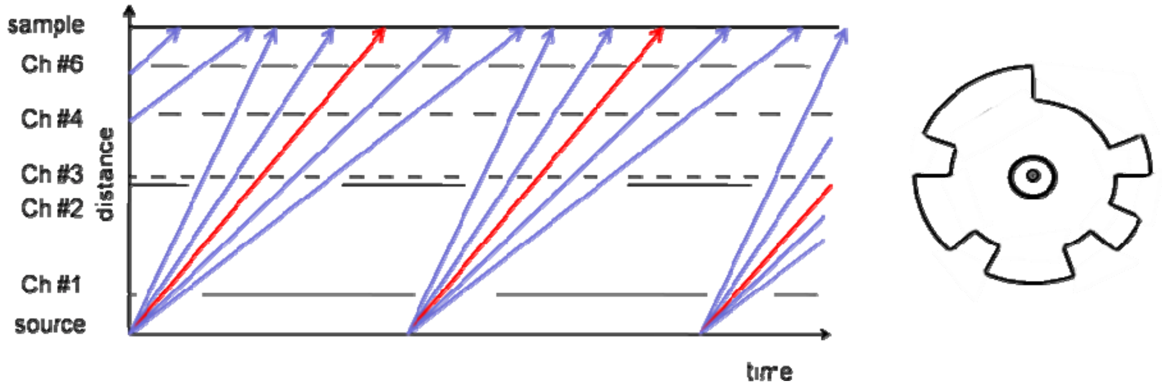

Figure 2. Left: The principle of multiplexing chopper system for TOF spectroscopy with Repetition Rate Multiplication (RRM). Right: example of advanced selective pulse suppression chopper (chopper #5, not shown in the figure on the left, placed close to chopper #6) [6].

RRM works with best efficiency on long instruments collecting data in the second or higher source frame, which makes the differences in the incoming neutron wavelengths smaller between RRM pulses on the sample (e.g. about 0.28 Å steps between subsequent pulses at 60 m distance and 240 Hz RRM pulse frequency, within a 3 Å wide incoming wavelength band at a 20 Hz source, that could be situated for instance between 3 and 6 Å, [4]). In order to avoid overlap of the inelastic spectra embodied by the neutron time-of-flights in the detector chamber, the minimum required time between pulses on the sample varies proportionally to the incoming neutron wavelength; it is 1 – 2 ms per Å for typical sample to detector distances. A reasonable compromise can be found for a not too broad wavelength band for all wavelengths. The energy resolution is another parameter which rapidly changes with the incoming neutron wavelength.

Recent developments allow us to refine RRM chopper systems to deliver pulse parameters matched to the variation of the incoming neutron wavelength between RRM pulses. The so called “magic” Fermi chopper under development at J-PARC [6] will deliver pulse lengths proportional to the neutron wavelength. Similar behavior can be achieved by a parallel rotating pair of disc choppers at a few cm distance from each other [2].

The most recently proposed selective pulse suppression method makes possible to individually adjust the instantaneous RRM pulse repetition time on the sample to all neutron wavelengths involved in the RRM set [7]. The right hand side of Figure 2 illustrates the principle by showing a pulse suppression chopper disc designed for thermal neutron spectroscopy at a 50 Hz source.

Combined with a 800 Hz = 16 x 50 Hz chopper #6 as defined on the left hand side of Figure 2 (e.g. a broad band, straight slit Fermi chopper rotating at 400 Hz), it will select a sequence of RRM pulses with times between them given by the series (in ms units) 1.25, 1.25, 2.5, 2.5, 3.75, 3.75 and 5. This sequence fits well the available incoming wavelength range of about 0.5 – 4 Å in the first frame at a typical source to detector distance of 20 m for thermal neutron TOF instruments.

4. Multiplexing chopper systems: elastic scattering and inverted geometry spectroscopy

The principle of the variant of RRM type multiplexing chopper systems for diffraction and inverted geometry spectroscopy [8] (also called Wavelength Frame Multiplication) is illustrated Figure 3. Here subsequent pulses of the pulse shaping fast chopper, placed as close as practically feasible to the source moderator (i.e. some 6 – 8 m = L_M), makes neutrons delivered to the sample and detector in multiple adjacent wavelength bands (i.e. time frames) from well defined neutron pulses emanating from different pulse shaping chopper pulses for each source pulse. These RRM time frames are delimited by the RRM frame overlap choppers, and they correspond to distinct time periods on the detector, separated by regions of half shadow (where adjacent RRM time frames are also allowed to overlap). The half shadow regions are to be excluded from

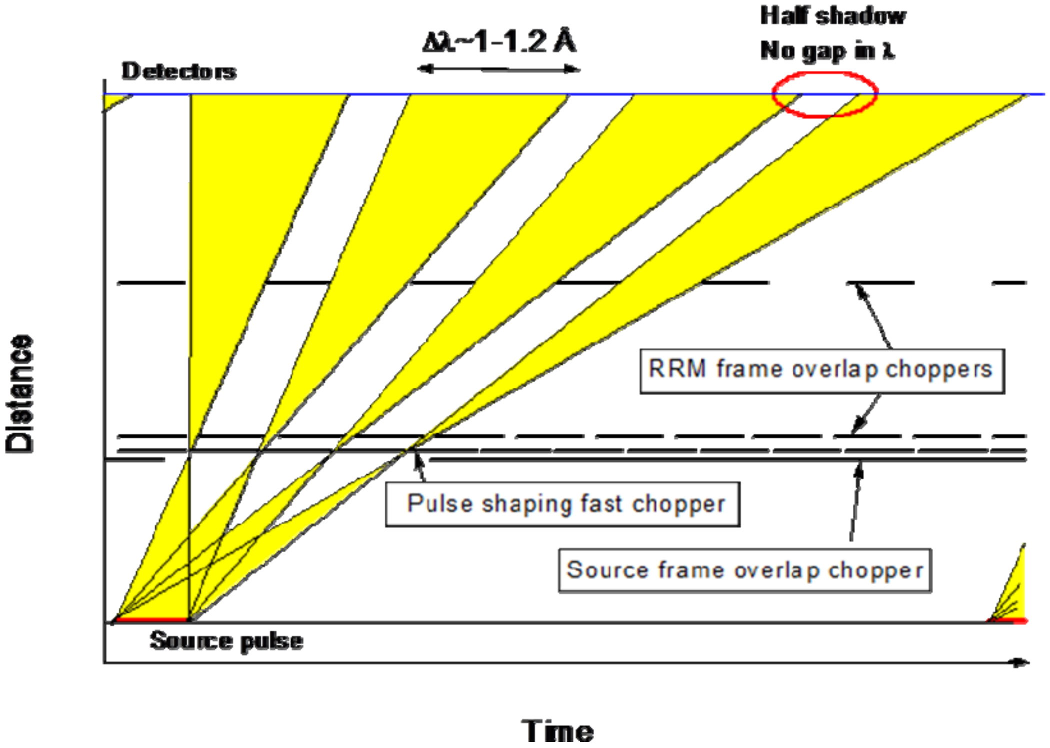

Figure 3. The principle of multiplexing RRM type chopper system for elastic neutron scattering and inverted geometry spectroscopy [8]. It emulates in all respects an enhanced ideal short pulse source with unprecedented features of sharp pulses and individually variable resolution for independently optimizing intensity at each beam line.

data evaluation, and practically they will amount to 5 – 10 % of the total elapsed time. Outside these regions, within the RRM frames the detector fully sees the fast pulse shaping chopper pulses, with no interference from the fully open RRM frame overlap disc choppers. The fast pulse shaping chopper can also be of Fermi type. For T_R RRM time frame lengths (as rather freely selected by the chopper system design), the wavelength band width in one RRM frame is AT_R/L_D, where A is 3956 Åm/s and L_D is the distance between the fast chopper and detector. This chopper system will "look" at neutrons emanating from the moderator within a time period of

$$\tau_M = T_R\,(L_M/L_D) + \tau_C\,(L_D+L_M)/L_D \qquad (1)$$

where τ_C is the total pulse length of the pulse shaping chopper pulse. If the product f_iL_i is a constant for all choppers (where f_i is the frequency of openings – can be several per revolution – and L_i is the distance from the moderator for chopper i), at proper chopper phasing all RRM frames look at the source within the same time period of same duration τ_M. The RRM frame pattern repeats itself for each source pulse, if in addition all f_i are multiples of the source frequency f. The two RRM relations [4]

$$f_iL_i = \text{const}, \qquad f_i/f = \text{integer} \qquad (2)$$

lead to "quantized" possible chopper configurations also in terms of distances L_i.

This multiplexing chopper system, together with the source frame overlap chopper (operating at the source frequency) assures, that a neutron detected at any given time – outside the half-shadow periods – can only come from a single pulse shaping chopper pulse (except for the background, including the fast neutron bursts essentially limited to the duration of the source pulses and, in principle, the inevitable very high wavelength (> 50 Å), fully negligible intensity leakage of choppers system [4]).

It is important to note that the time period τ_M is determined by the chopper system and ideally it can be restricted to the nearly flat part of the source pulse. If τ_M is chosen to be slightly longer than the repetition period of the pulse shaping chopper, the wavelength (neutron velocity) bands of the subsequent RRM frames overlap, so the total source wavelength band $A/f(L_D+L_M)$ is covered by the RRM frames without gaps for each single source pulse.

The duration of τ_M can be chosen rather freely, however, a reasonable lower limit is about 1 ms. The time needed for the RRM frame overlap choppers to go from fully closed to fully open takes typically 100 – 200 μs (note that the shaded areas in Figure 3 indicate the RRM frames corresponding to the unperturbed passage through fully open RRM frame choppers). As τ_M is chosen to be shorter and shorter, this practically makes the number of required RRM frame choppers increase beyond 2 – 5 and ultimately the relative weight of the excluded, half shadow time in data collection (cf. Figure 3) exceeds 10 – 15 % when τ_M gets below 1 ms.

Noting that the peak flux of a long pulse is proportional to the integrated (and not the peak) flux of the short pulse moderator response, the RRM multiplexing chopper system also takes advantage of the appreciated feature of short pulse source diffractometers, that the beam intensity is enhanced by the increasing pulse width with increasing wavelength, i.e. diminishing time resolution need. Here, however, this advantage can be used to the square, by selecting a fast pulse shaping chopper that produces increasing pulse lengths with increasing wavelength, as mentioned in the previous chapter..

Since neutrons with different wavelengths come from different parts of the source neutron pulse, the source pulse shape needs to be taken into account in the data evaluation, e.g. in a single pulse experiment. However, if the phasing of the chopper system is slewed compared to the source firing, we can achieve a full averaging over the selected τ_M long fraction of the source pulse within a measuring time of less than a minute. Thus there is no need to consider the source pulse shape any more, and the effective source brightness will become the average flux over the period τ_M, which is looked at by the chopper system.

This means, that this method also opens up, for the first time, a practical way for shaping neutron pulses at short pulse sources too, with the inconvenience though, that the peak intensity of the pulse will be reduced to this average. The first example for this is the planned DNA spectrometer at J-PARC, for which $\tau_M \sim 700$ μs could be achieved (at half shadow times in the range of 20 %), compared with the ~250 μs FWHM of the coupled cold moderator pulse [9]. Thus, in view of the long tail of these pulses, cf. Figure 1, the average peak intensity of the shaped pulses is about 50 % of that of the peak of coupled moderator pulse itself. This is, however, still close to the peak of the poisoned moderator pulse, while offering the decisive additional advantage of higher resolution capability, more advantageous line shape and tunable resolution, which leads to huge intensity gains, when the best resolution is not required.

This multiplexing chopper scheme has been recently tested [10] at the TOF diffractometer at the continuous reactor source of Budapest Neutron Center. Figure 3 is actually to scale with this setup, with $L_M = 10.4$ m, $L_D = 22$ m, the distances between the pulse shaping fast chopper and the two RRM frame chopper being 0.89 m and 10.4 m, respectively. The fast chopper pulse frequency was $f_1 = 166\ 2/3$ Hz, those of the two RRM frame choppers 153.52 Hz and 83 1/3 Hz = $f_1/2$, respectively. $\tau_M = 6$ ms, and the repetition time of the virtual source pulses 13.8888 Hz = $f_1/12$. With the given chopper positions designed for non-multiplexing use, the frequency ratio $153.52 : 166.667 = 11.053 : 12$ slightly violates the RRM "quantization" rule of simple rational numbers, cf. Eqns. (2). Therefore the 153.52 Hz chopper could not be synchronized to the others. It was operating in an asynchronous mode, and event recording technique [11] was used to factor in its actual time stamped phase at each revolution during data evaluation. With pulse shaping chopper systems the timing with respect to real or virtual source pulses is immaterial for determining the scattering parameters. It is "only" important in order to make sure, that the chopper system "looks" at the source when the source is "on" with the highest brightness.

The results obtained on an Al_2O_3 powder sample are shown in Figure 4. The separation of different RRM frames is visible, since the overlap in neutron wavelength (or lattice parameter d) between these frames included the half shadow regions and in the event recording data evaluation in these regions only neutrons were excluded that could have come from different pulse shaping chopper pulses. The bad statistical accuracy of the data comes from the use of a single, poorly shielded detector, actually at 130° scattering angle.

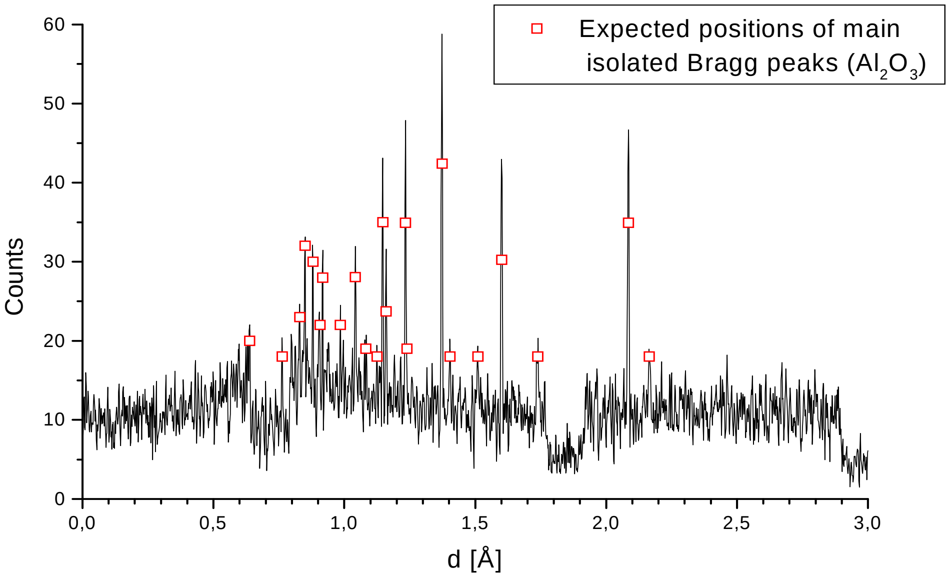

Figure 4. First powder diffraction data obtained by a multiplexing chopper system illustrated in Figure 3. The TOF diffractometer at BNC was used with chopper frequencies and phases set to match RRM conditions, cf. Eqns (2). The coverage in the pertinent neutron TOF (i.e. from the relevant pulse shaping chopper pulse to detection) is continuous, while there are some gaps in the absolute detection times themselves.

5. Summary

In conclusion, the two types of multiplexing chopper system considered can make a long pulse source appear in operation without any restriction as an ideal short pulse source with not only enhanced flux, but sharp, tail free pulses and full flexibility of variable pulse lengths for trading resolution for large gains in intensity, according to the individual needs of each experiment or different scans within the same experiment. Except for minor numerical corrections for data collection cycles lasting less than a few seconds, the instrument designer, simulator or the user will not be able to see or does not even need to be aware of, that the real facility is in reality not a short pulse source with these improved features, but a combination of a long pulse source and a total of about 100 - 150 standard choppers. The costs of installing and operating all of these off-the-shelf choppers together will be a very small fraction of that of a ring accelerator or accumulator ring, and they will offer much enhanced reliability not only for each beam line, but for all beam lines combined. For example, the typically 7 disc chopper systems on current continuous source TOF spectrometers can operate failure free for periods of several years.

In the particular case of a spallation source consisting of a linear accelerator and an accumulator ring (maybe also for CSNS, with an accelerating accumulator ring), neutron intensity gains in the range of 2 – 10 fold can be achieved for all thermal and cold neutron scattering experiments by replacing the accumulator ring by the systematic use of these multiplexing chopper systems and applying the so obtained savings to enhancing the power of the linac. Providing the short neutron pulses by an accumulator ring offers clear advantages for those experiments which need good wavelength resolution in working with epithermal incoming neutrons with energies above 300 meV, but it is largely counterproductive in terms of neutron intensity, resolution capability and source reliability in the whole range of neutron wavelengths > 0.8 Å, where state-of-the-art supermirror based neutron optical beam delivery and sufficiently opaque disc choppers can be efficiently used.

Although proposed and numerically studied in all details several years ago, these multiplexing choppers systems have only been experimentally implemented and tested recently, and their routine use on state-of-the-art instruments recently built at operating spallation sources is just at its beginnings (LET at ISIS TS2, 4SEASONS and AMATERAS at J-PARC). They opened up the opportunity to realize the full potentials of pulsed spallation sources for mainstay neutron scattering research without the serious bottlenecks imposed by ring accelerators. These potentials will first come to complete fruition with the construction of the long pulse European Spallation Source (ESS).

[1] F. Mezei, C.R. Physique 8 (2007) 909

[2] F. Mezei, J. Neutron Res. 6 (1997) 3, and references therein

[3] M. Russina, F. Mezei and F. Trouw, Procedings of ICANS-XV, J.Suzuki and S.Itoh (Eds), (JAERI Conf. 2001-002, 2001) p. 349

[4] M. Russina and F. Mezei, J. Nucl. Instr. and Meth., A604 (2009) 624

[5] M. Nakamura, R. Kajimoto, Y. Inamura, F. Mizono, M. Fujita, T. Yokoo and M. Arai, J. Phys. Soc. Jpn. 78 (2009) 093002

[6] see M. Arai, in these proceedings

[7].M. Russina and F. Mezei, Proceedings of ICNS 2009, Knoxville (in press)

[8] F. Mezei and M, Russina, in: Advances in Neutron Scattering Instrumentation, I.S. Anderson, B. Guerard (Eds.), Proc. of SPIE 4785 (2002) 24

[9] N. Takahashi et. al., in these proceedings

[10] M. Russina, Gy. Kali, Zs. Szanto and F. Mezei, to be published

[11] M. Russina, F. Mezei, T. Kozloski, P. Lewis, S. Pentilla, J. Fuzi, E. David and G. Messing, in: Proceedings of ICANS-XVI, G. Mank, H. Conrad (Eds.), (FZ Jülich, 2003) p. 667