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COMPLEMTARITY OF LONG PULSE AND SHORT PULSE SPALLATION SOURCES

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ABSTRACT

The complementarity of short pulse spallation sources (SPSS) and steady state (CW) reactors is a widely accepted concept. SPSS and long pulse spallation sources (LPSS) are complementary in two ways: a) in their performance in neutron scattering experiments LPSS closely emulate CW reactors. In this respect two facets of the time–of–flight (TOF) monochromator method adequate for LPSS will be discussed: the superiority of the TOF approach to the crystal monochromator method in high resolution powder diffraction, and the novel technique of repetition rate multiplication in TOF spectroscopy. b) LPSS combined with adequate chopper systems can also emulate SPSS in a number of applications. It will be shown that the LPSS method of producing short neutron pulses is more efficient for cold and thermal neutrons (below an energy of about 100 meV), while SPSS is the more favourable approach for hot, epithermal neutrons, i.e. in the slowing down regime in contrast to the moderated regime. These two aspects of complementarity of LPSS and SPSS lead to the conclusions that for about 75% of the spectrum of neutron scattering experiments as known of today the LPSS approach is the most advantageous one with a feasible neutron intensity exceeding that available at ILL by a factor of about 30, while for the remaining 25% of applications the SPSS technique is superior with a well–known potential of a similar gain over present day performances.

1. Introduction and Overview

The complementarity of SPSS and CW reactor sources can be illustrated by comparing two facilities of roughly the same costs. The FRM-II 20 MW reactor project (Munich) and the AUSTRON 200 kW spallation source project (see report given at this meeting) happen to represent such a pair. The projected time averaged flux in the epithermal (slowing down) neutron range is equal for both facilities, while FRM-II should provide

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a moderated thermal and cold average flux which is an order of magnitude higher than that of longest pulse length moderators (some 150 μs for thermal and 1 ms for cold neutrons) at AUSTRON. On the other hand, AUSTRON at a repetition rate of 25 Hz and with a pulse width of less than 10 μs in the slowing down regime should outperform FRM-II in respect of the peak flux by a factor of more than 4000, while for thermal and cold neutrons independently of the moderator type the gain "only" amounts to a factor of 30 and 4, respectively. These flux relations, as well known from several studies (cf. Abingdon workshop on ESS), make AUSTRON about an order of magnitude inferior for white beam irridiation and fixed wavelengths experiments (such as interferometry) and comparable or vastly superior to FRM–II in the rest of neutron scattering work (e.g. small angle scattering and short wavelength powder diffraction, respectively). This complementary performance in various utilizations is primarily due to the huge variation of the ratio of the peak fluxes of both facilities with the neutron energy.

In contrast, for a LPSS facility, due to the fact that the pulse length (which is in the ms range) is constant, the neutron wavelength dependence of the peak flux follows that of the average flux, i.e. it is rather similar to a reactor (with an enhanced slowing down range though). The difference between a CW and long pulse source resides in the potential for *more efficient utilization* of the average flux of the latter. The clue to this efficiency is to use a neutron monochromatization technique which only needs the source to be on for a limited time, i.e. some 10% of the total time. By the TOF wavelength band monochromatization technique a quasi–continuous monochromatic beam can be produced on the sample, which has about the same time averaged intensity as that on a CW source with a flux equal to the peak ("on") flux of the LPSS. However, there is one major difference: At the CW source we have a constant wavelength all the time, while on a LPSS we will have a well defined wavelength at any given time, which changes periodically within a more or less narrow band. The width of the wavelength band can be adapted to the various types of experiments, but it has to be at least $\delta\lambda/c$, where $\delta\lambda$ is the wavelength resolution aimed at, and c the duty factor of the source. The efficiency of the use of LPPS is thus determined by the relative merits of performing a given experiment with a series of adjacent wavelengths for the same total period of time instead of using a single wavelength all the time. If several different wavelengths, i.e. different intensities and resolutions, are used the experimental procedure requires an adequate combination of the information obtained at various wavelengths, and not only the simple summation of raw spectra. This kind of *information processing*, as opposed to *input data processing*, is usual in high energy physics experiments, and it is getting more and more common in the work at SPSS facilities, but it is still quite unusual at CW sources. The two examples of employing TOF monochromator techniques instead of the usual single wavelength approach at CW sources discussed below show, that the multiple wavelength approach can a) be largely superior in some, rather obvious cases or b) still be favourable or competitive in other cases, where this would not be expected on the basis of conventional wisdom.

The example for a) is high resolution powder diffraction, where the larger acceptable solid angle of the detector in the TOF approach is clearly advantageous. The case study for b) concerns TOF spectroscopy. The straightforward transfer of CW source TOF spectroscopy to pulsed sources is known to be disadvantaged by being tied to the repetition rate of the source, which is too low in most cases. If one accepts to use more than one wavelength (repetition rate multiplication), the same freedom of choice as on a CW source is regained in respect to the choice of the repetition rate. It will be shown below for a specific example that the multiple wavelength approach can offer a competitive (and actually better) information collection rate than the conventional single wavelength method. In most cases this new proposal of multiplying the repetition rate removes one last technical disadvantage that pulsed sources (short or long) were perceived to have in comparison to CW sources. Thus, with LPSS sources with an average power of 10 to 20 MW now appearing well within reach (cf. the 135 MW "on" linac power without proton beam chopping of the ESS reference design) the LPSS approach offers a capability to achieve average neutron intensities on the sample, which are 20 to 40 times higher than that of ILL for all neutron scattering applications.

Beyond the complementarity between LPSS and SPSS, which is due to the similarity of LPSS and CW reactors, there also is a technical complementarity in another respect: It turns out that it is more efficient to produce short pulses of cold and thermal neutrons by fast choppers on a LPSS than by a SPSS. The fundamental reason for this are the long moderation times for maximum time averaged flux moderator–reflector ensembles. Quite similarly to mechanical choppers the pulse length can only be shortened by taylored, short pulse moderators at the expense of the total neutron flux and to some extend also at the expense of the peak flux. If we thus consider a pair of a SPSS and a LPSS, which represent about the same investment, the technically less demanding LPSS will display some four times higher average power, mainly due to the higher "on" power of the linac operating without beam chopping and eventually with H^+. Beyond substantially higher peak fluxes for cold neutrons and comparable ones for thermal neutrons, the LPSS approach with choppers also offers more flexibility in the choice of pulse lengths, leading to improved resolution for cold neutrons in view of the shortest SPSS moderator pulse of 100 μs. Furthermore, present instrumentation concepts for SPSS favour short target to sample distances, and thus lead to the necessity to split the accelerator power between two target stations, which amounts to a flux reduction on all instruments. The TOF monochromator approach for LPSS instrumentation often calls for the use of neutron guides of substantial length (20–100 m), so that there is room for many instrument positions on a single target station. In sum, SPSS offer the most efficient way to produce short neutron pulses in the epithermal neutron energy range via the slowing down mechanism. (On a cold moderator the slowing down regime extends somewhat into the thermal energy range.) This mechanism provides pulse lengths $\lesssim$ 10 μs. LPSS complement SPSS performances by providing the most efficient way of producing variable length thermal and cold neutron pulses with pulse lengths ranging from 20 μs to several hundreds of μs using state of the art chopper technology.

In what follows various points mentioned in this chapter will be discussed in more detail.

2. Neutron monochromators and the principle of time-of-flight wavelength band monochromatization

In all neutron scattering experiments on a CW source a small, more or less precisely monochromatic fraction of the Maxwellian spectrum of the moderator is selected by eliminating the rest. Actually the precision of this monochromatization determines in nearly all cases the resolution of the experiment. The exceptions are Neutron Spin Echo (NSE) and TOF Fourier Diffraction. The clue of these Fourier methods is exactly the intensity gain achieved by the poor monochromatization required compared to the resolution offered. Unfortunately, such "simultaneous" methods, in which the signal from various wavelengths is detected at the same time and sorted out by signal processing methods standard in other modern experimental techniques (such as Fourier transformation e.g. in pulsed NMR) can only be used in a few special cases with neutrons, due to the inherent quantum noise of neutron signals. Namely neutron scattering spectra contain a very small number of quanta (neutrons) compared to microwave or light signals, for instance, so that the statistical Poisson noise is inevitably large. In simultaneous data processing this leads to masking the low intensity part of the spectra, which contain the hard-to-observe pieces of the information. (This was the reason of the practical abandoning of neutron correlation spectroscopy, a promising idea from the 1960's).

There are basically three types of successful monochromator devices used on CW sources, none of them without substantial drawbacks though. Crystals transmit not only the desired wavelength λ, but higher orders $\lambda/2$ and/or $\lambda/3$ etc. too, which has to be most often removed by a filter. Furthermore, the reflectivity of many crystal monochromators is considerably lower than 100% and the resolution curve shows up long tails. The optimal adjustment of the resolution, requiring a set of exchangeable crystals, is of limited flexibility. Last but not least, crystals also display other scattering processes than Bragg reflection. This often leads to "spurion" signals, which are time consuming and not always easy to be sorted out. Helical slot velocity selectors suffer from none of these drawbacks of crystal monochromators, but they cannot provide comparable resolution due to mechanical limitations of the speed of rotation. They are actually limited to some 5% best resolution and this holds for cold neutrons only. In contrast to these two continuous beam, (CW) monochromators, disc chopper systems of the type of IN5 at ILL provide a clean, tunable beam and to crystals comparable resolution, but only for a fraction of the time with duty factors around 1% or less.

In a neutron scattering experiment on a CW source one starts with choosing an optimal incoming neutron wavelength. This choice is never a unique, single value, it is rather one of many equivalent ones within a given more or less broad wavelength band. Conventionally a single wavelength within this "useful band" is selected for extended data collection periods. In many cases the best compromise between intensity,

resolution and dynamic range requirements is, however, achieved by dividing the beam time between runs with several incoming wavelengths within the useful range.

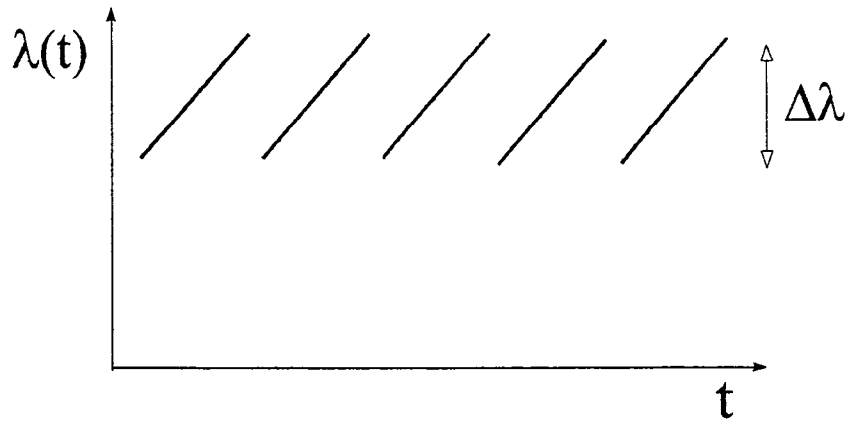

Fig. 1: Time dependence of the wavelength of the monchromatic beam in a TOF monochromator.

The basic idea of the approach of time-of-flight wavelength band monochromatization (TOF-monochromators) is to produce a set of monochromatic wavelengths (within a suitable range) one after the other with an appropriate periodic repetition. A TOF-monochromator provides a monochromatic beam at any instant of time t with a wavelength $\lambda(t)$ and a resolution $\delta\lambda(t)$, with $\lambda(t)$ and $\delta\lambda(t)$ periodically changing in time. Actually $\lambda(t)$ follows a sawtooth pattern within a band $\lambda_{max} - \lambda_{min} = \Delta\lambda$ (Fig. 1). Thus instead of using one single wavelength the measurement is performed with a set of wavelengths stretching over a range $\Delta\lambda$ which is chosen to be fully within the "useful range" so that each wavelength $\lambda(t)$ provides roughly equally useful information. Fig. 2 illustrates how this can be realized with a set of disc choppers [1].On this distance vs. time TOF-diagram the trajectory of an incoming neutron is a straight line with the slope corresponding to the velocity $v = h/m\lambda$.

The essential point is that the TOF monochromator delivers useful neutrons for nearly all the time onto the sample and maintains all the advantages of chopper systems compared to crystals (no higher orders, clean, well defined lineshape without tails, tunable resolution, 100% transmission at the center of the line). The price to be paid for is the more complex data collection (i.e. adding the additional parameter t which labels the various wavelengths $\lambda(t)$ used and combining the information content of data sets corresponding to a set of single wavelength bins $\lambda_1, \lambda_2, ...\lambda_n$). This complexity is, however, rather small compared to state-of-the-art methods in e.g. nuclear physics, and to a large extent well under control on existing spallation souces.

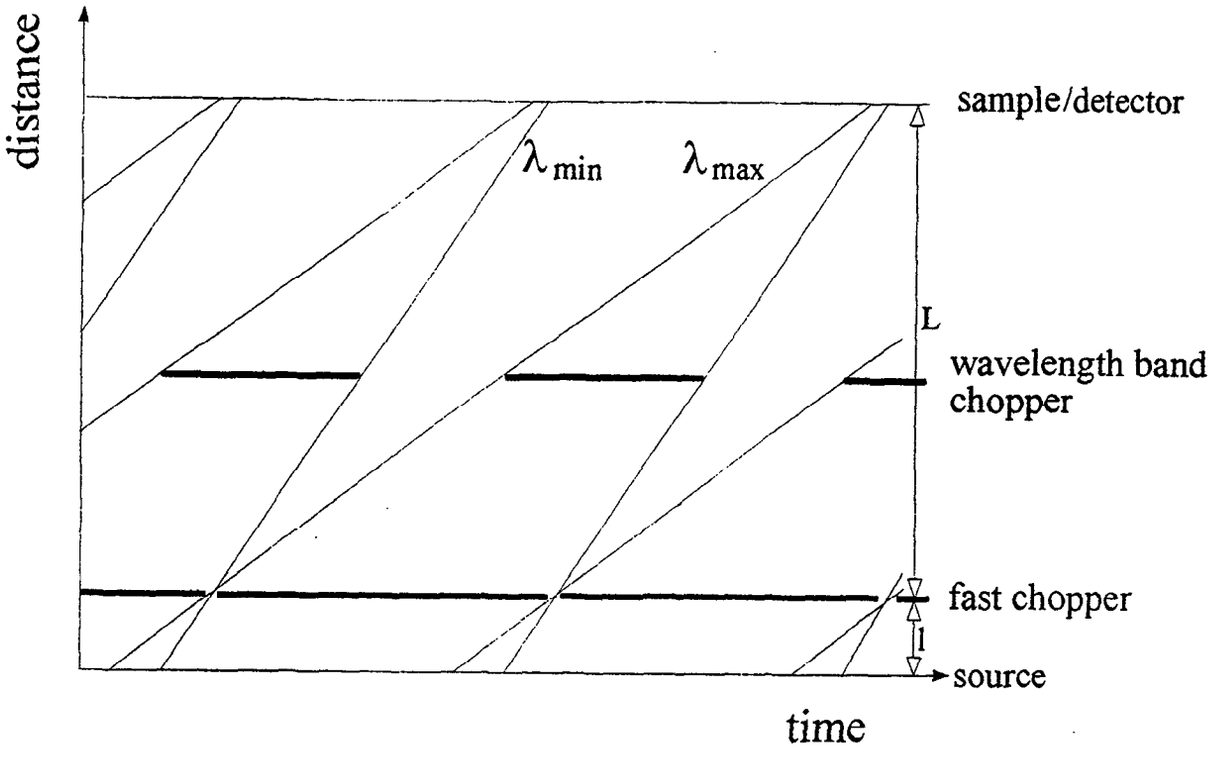

Fig. 2: The principle of TOF monchromators after Ref.[1].

The clue to making the whole wavelength band of a TOF-monochromator uniformly useful is to make it narrow enough. In some cases, e.g. TOF-diffraction as suggested long time ago by Buras [2], this restriction is rather mild since the relevant intensity parameter $\lambda^4\phi(\lambda)$ is flat over a large range of λ (where $\phi(\lambda)$ is the quasi-Maxwellian neutron flux distribution of the moderator). In other cases, such as triple-axis spectroscopy, where one wants to concentrate on a small range of momentum and energy transfer $\vec{q}$ and ω, $\Delta\lambda/\lambda$ might be chosen as small as 10–20%. We will show now, that under the condition of selecting an uniformly useful wavelength band $(\lambda_{min}, \lambda_{max})$ the time averaged flux produced by the TOF monochromator at the sample is equal to that of the CW-monochromator (assuming equal resolution and beam collimations, and neglecting losses such as finite crystal reflectivities, filter absorption etc.) [3]. Indeed:

$$\Phi_{CW} \simeq \phi(\lambda)\delta\lambda \tag{1}$$

and

$$\Phi_{TOF} \simeq c\phi(\lambda)\Delta\lambda \tag{2}$$

where c is the duty factor of the fast chopper in Fig. 2, and it is given as c = δt/t, i.e. the ratio of the chopper opening time δt to the pulse repetition time Δt. On the other hand

$$\delta\lambda = \frac{h}{m}\frac{\delta t}{L}, \qquad \Delta\lambda = \frac{h}{m}\frac{\Delta t}{L} \tag{3}$$

where L is the neutron flight path from the fast chopper to the detector or – in inverted geometry inelastic experiments – to the sample. Thus we find that

$$c = \frac{\delta t}{\Delta t} = \frac{\delta\lambda}{\Delta\lambda} \tag{4}$$

Substituting (4) into (2) and comparing to (1) we get the mean flux (MF) theorem:

$$\Phi_{TOF} = \Phi_{CW} \tag{5}$$

i.e., that the time averaged flux on the sample for the TOF monochromator is the same as that for the conventional CW monochromator of equal resolution (for equal beam collimatimations and neutron transmission efficiencies) if the wavelength band $\Delta\lambda$ is narrow enough.

The second half of the previous sentence is the crux of the matter. Without making the band $\Delta\lambda$ narrow enough, i.e. working with just one fast chopper and making the repetition rate small enough so that there is no frame overlap between the fastest and slowest neutrons from contiguous pulses (as originally proposed by Buras or actually done on short pulse spallation souces) $\delta\lambda$ is not uniformly useful. One reason for this is the strong wavelength dependence of the Maxwellian distribution $\phi(\lambda)$ with eventually the low intensity parts contributing little to the information gathered. Also the strongly λ dependent resolution might limit the usable range. Thus a narrow enough $\Delta\lambda$ is a guarantee to make all of it fully useful, which can be achieved by making L long enough and/or $\Delta\lambda$ short enough. (This latter choice applies to a CW source, where the chopper system can have any repetition rate mechanically feasible.)

The TOF wavelength band monochromator method can also be applied to generalize conventional TOF-inelastic spectroscopy. Here the difference between CW and pulsed operation is that in the first case the repetition rate is freely chosen as required by the secondary (sample to detector) flight-path. In the spirit of the present approach, however, we can run the monochromator system at a lower repetition rate than that of the analyser TOF system, so that we use instead of one a number of wavelengths in the $(\lambda_{min}, \lambda_{max})$ range, cf. Fig. 2. Thus eq. (5) also holds for this case, meaning that in this approach the flux of a chopper spectrometer is independent of the monochromator/source repetition rate. This solves a longstanding problem in spectroscopy on existing short pulse spallation sources, where the TOF spectrometers are running at the same repetition rate as the source, which is much lower than ideal for this kind of work, e.g. 50 Hz instead of 300 Hz. We will discuss this subject in more detail in chapter 4.

In connection with eq.(5) we used the expression "time averaged flux on the sample". Indeed, what matters for the experiments is the number of neutrons actually hitting the sample at a given angular and wavelength resolution within a given beam time, and not the number of neutrons in the core, target, or moderators. Thus this flux is the relevant number for comparing sources and instruments. In applying these arguments to actual SPSS instruments, we usually observe time averaged fluxes on the sample which are in contrast to LPSS much lower than those corresponding to the peak flux of the source as given by eq.(1), because $\Delta\lambda$ (i.e. L is too small cf. eq.(3)) is much too large. In addition with $\delta\lambda$ determined by the source and moderator ensemble, we sometimes have to work with better than necessary wavelength resolution (e.g. in small angle scattering), which can be avoided on CW and LPSS sources.

3. TOF–monochromator for high resolution powder diffraction on CW sources

High resolution powder diffractometry (HRPD) is one of the most successful ways of utilizing short pulse neutron sources. This is partially due to the excellent peak flux and short duration of the epithermal neutron pulses in the slowing down regime. Although the hot neutron flux on the hot source at ILL is proportionally higher with respect to the thermal flux than on a SPSS, no high resolution monochromatization method is known for hot neutrons on a CW source with a comparable efficiency to the shorter than 10 μs pulses of the SPSS. On the other hand, for thermal and cold neutrons both crystal monochromators and disc choppers give quite satisfactory resolutions on CW sources.

The other clue of the success of HRPD on SPSS has nothing to do with the source: It is due to the advantages of the TOF method itself, as early recognized by Buras [2]. In order to illustrate this point, we consider a detailed quantitative comparison of a crystal monochromator and a TOF monochromator instrument on the same thermal moderator of a CW reactor source. The scheme of the two instruments are shown in Fig. 3.

The crystal monochromator HRPD set–up is assumed to work at a fixed wavelength of 1.5 Å at the monchromator take–off angle of 90°, i.e. giving best resolution due to focussing for the lattice spacing d=1.06 Å. The in–pile collimation is 6' FWHM and the 62 detectors span 7.5°–150° scattering angle in steps of 2.5° with a 6' FWHM collimator infront of each detector. The width of each collimator was assumed to be sufficient to see the whole sample volume. The detectors are 20 cm high and installed at a distance of 1.5 m from the sample. The monochromator has a Gaussian mosaic distribution of 10' FWHM. A natural collimation of 40' FWHM was assumed between monochromator and sample as defined by the beam width and the distance. No losses have been assumed, i.e. the peak transmission of the collimator, the peak reflectivity of the monochromator, the transmission of the higher order filter and the efficiency of the detectors have been taken as 100%. The vertical collimation of the beam impinging on the sample was assumed to be the same as that of the neutron guide of the

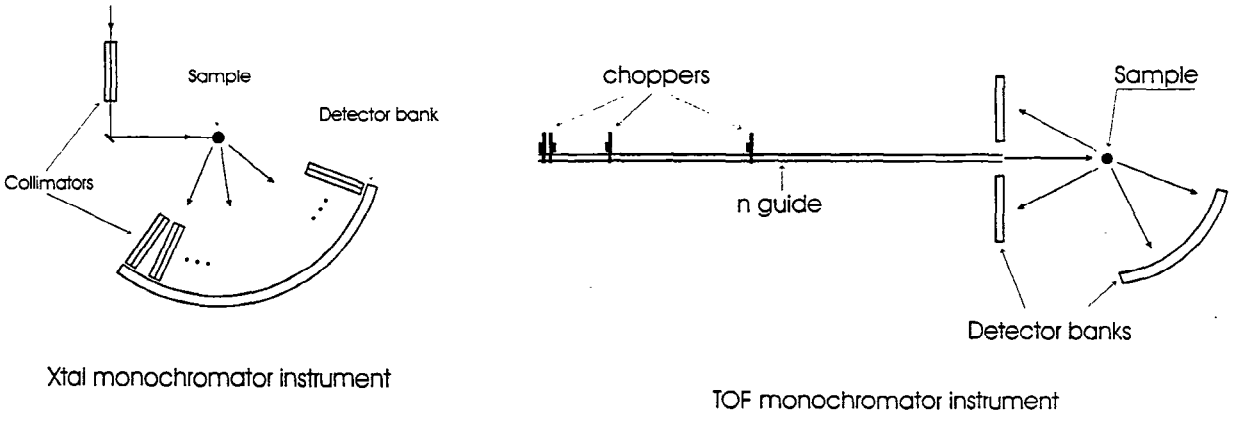

Fig. 3: Layout of a crystal (left) and a TOF monochromator high resolution powder diffractometer.

TOF instrument specified below, i.e. no vertically curved monochromator assembly has been assumed. We shall discuss this point later.

The TOF monochromator instrument has the following parameters: The pulse length of the counterrotating pair of choppers is 10 μsec, which is achievable for a beam width of 1 cm. The neutron guide follows the "eye–of–the–needle" principle [1] with a beam width of 1 cm at the the entrance and a width of 2 cm towards the sample and for most of its length. The length of the guide is 16 m and it stops 2 m before the sample position. The two single choppers determine the wavelength band which has been choosen to be 1.5–5 Å. At a repetition rate of 50 Hz this implies 12% dead time between successive frames. The detectors are 1.25 cm thick, with an efficiency of 70% at 1 Å. They form banks with a horizontal resolution of 1.25 cm and a hight of 20 cm. (Low resolution banana detectors could be an alternative.) Two banks on top of each other are placed on both sides of the incoming beam in order to cover the scattering angle range of 157°–175°. A third bank covers the low angle range from 15° to 60°. The sample is contained in a flat slab perpendicular to the incoming beam, 0.4 mm thick, 2 mm wide and 10 cm high. No collimators are used, the precision of the scattering angles is determined by the geometry of the set–up.

In Fig. 4 the resolutions for the determination of lattice spacings d and the relative intensities of the two instruments are compared as functions of d. The results were obtained by a complete Monte–Carlo simulation using the above instrumental parameters and the Maxwellian spectrum of thermal neutrons. The dashed lines for the TOF instrument indicate the behaviour for other wavelength bands obtained by shifting the phasing of the third and fourth chopper, e.g. 6.5–10 Å in order to explore

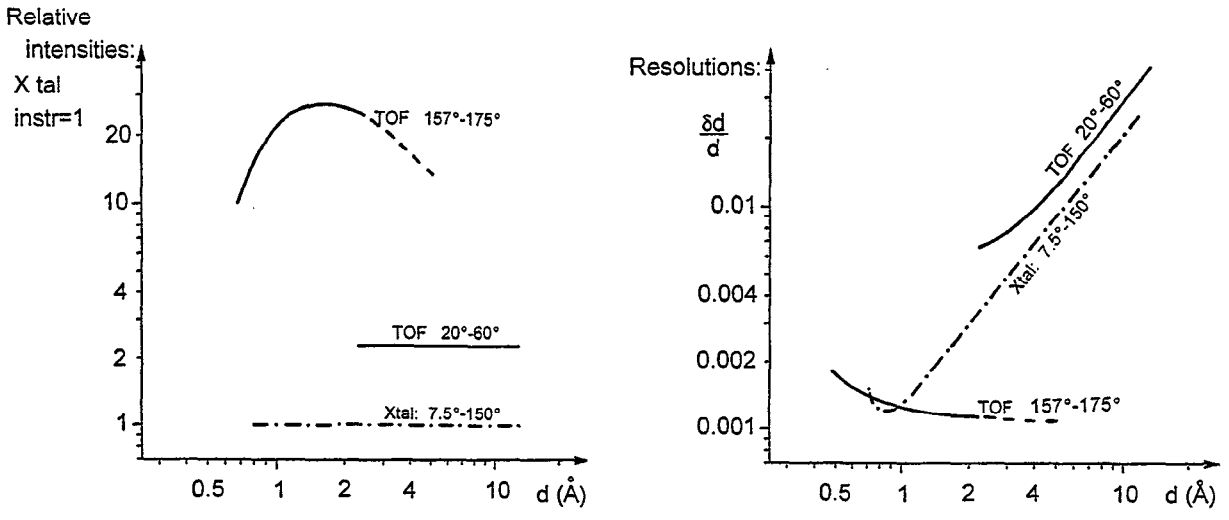

Fig. 4: Comparison of the intensity of the reflections (left) and the resolution as a function of the d–spacing for the crystal and TOF monochromator instruments described in the text.

d spacings in the range of 3.25–5 Å with high resolution. (On the Xtal instrument this would require a change of the monochromator in order to obtain an incoming wavelength of about 5 Å.)

The reason why the intensity offered by the TOF monochromator approach is about an order of magnitude superior can be understood by the following simplified reasoning: The same resolution requires a cruder beam collimation at both, higher scattering angles and longer neutron wavelengths. Therefore it is advantageous to use several wavelengths, since for all reflections data are collected under the best conditions, as opposed to the single wavelength monochromator method which would only allow for the use of the nearly backscattering geometry for an extremely narrow d range (some 2%), compared to 0.75–2.5 Å for TOF. For a given Bragg reflection we have a detector solid angle of 0.16 sterad with a duty factor of $10\mu s/20ms = 0.5 \times 10^{-3}$ with TOF, while the crystal instrument only offers a detector solid angle of 2×10^{-4} sterad with a duty factor of 4% (due to the necessity to scan the detector bank over the 2.5° gap between neighbouring detectors covering 0.1° each).

The intensity offered by the monochromator instrument can normally be improved by using a curved monochromator focussed to the sample. Compared to a flat monochromator without a guide the gain in incoming flux for a small sample (not higher than 2-3 cm) can optimally amount to a factor of 5. However, compared with a TOF monochromator, this gain is largely offset by the finite transmission of the collimators and the higher order filter and the finite reflectivity of the monochromator crystal. In addition by using guides coated with supermirrors on the top and on the bottom or with a vertically converging section in front of the sample some vertical focussing can also be achieved with TOF monochromators, which reach namely some 1° vertical divergence at 2 Å and more at higher wavelengths. Thus, the more

efficient vertical beam focussing capability of crystal monochromators on the whole compensates for the higher instrumental losses in this approach compared to the TOF method. This is why in the above comparison both vertical focussing and beam losses were ignored.

4. Repetition rate multiplication and constant $\vec{q}$ TOF spectroscopy

We will now consider in some detail how the main aspects of the TOF monochromator concept can also be applied to IN5 type multichopper TOF spectrometers [4]. The key idea of the TOF-monochromator approach is that the same information can be obtained by using not only a single incoming wavelength, but a set of eventually close wavelengths $\lambda_2 ... \lambda_n$ and combining the information obtained afterwards. Adding a fast chopper to the TOF monochromator set-up just infront of the sample with a repetition rate properly chosen for the TOF energy analysis in the secondary spectrometer and running synchronously with the TOF-monochromator, (i.e. with a frequency being an integer multiple of the that of the monochromator system) we get a set of short pulses with wavelengths $\lambda_1, \lambda_2, ... \lambda_n$, cf. Fig. 5. With each of these wavelengths we obtain a complete TOF spectrum of the sample, and the n spectra will carry essentially identical information if the total wavelength band $\lambda_n - \lambda_1$ is narrow, or eventually – and actually quite often – an improved data collection rate by extending the dynamic range of the data if $\lambda_n - \lambda_1$ is chosen to be substantial. Thus we can also formulate the mean-flux theorem eq. (5) for this case as follows: the mean flux on the sample in a TOF spectrometer of any repetion rate ν installed on a TOF monochromator with a repetition rate ν/n (where n is an integer) is independent of n as long as the wavelength band $\lambda_n - \lambda_1$ is narrow enough

$$\Phi^{(\nu)} = \Phi_{TOF}^{(\nu/n)} \tag{6}$$

This TOF-monochromator – TOF secondary spectrometer combination also offers another new possibility: constant $\vec{q}$ scans on single crystal samples in a single run using TOF technique only, a problem which was deemed to be unsolvable. Instead of phasing the fast chopper in front of the sample to the TOF monochromator system we let it run asynchronously, so that we get TOF spectra with a quasi continuous set of incoming wavelengths (reasonably binned according to the resolution) within the $\Delta\lambda$ wavelength band. The thus obtained 2 dimensional data set $I(\lambda_{in}, \lambda_{out})$ contains many constant $\vec{q}$ energy spectra in an exended 2 dimensional (with detectors covering a large vertical angular range, as usual, 3 dimensional) $\vec{q}$ domain (cf. Fig. 6). The method is mechanically simpler than the TOF monochromator TAS approach described elsewhere [5], although in principle it provides inferior data rates if a single or a small number a constant $\vec{q}$ scans are required due to the additional duty factor loss by the sample-end chopper. This disadvantage could be partially compensated for by the larger solid angles attainable with TOF and by having no reflectivity losses and higher order reflections in the analyser system.

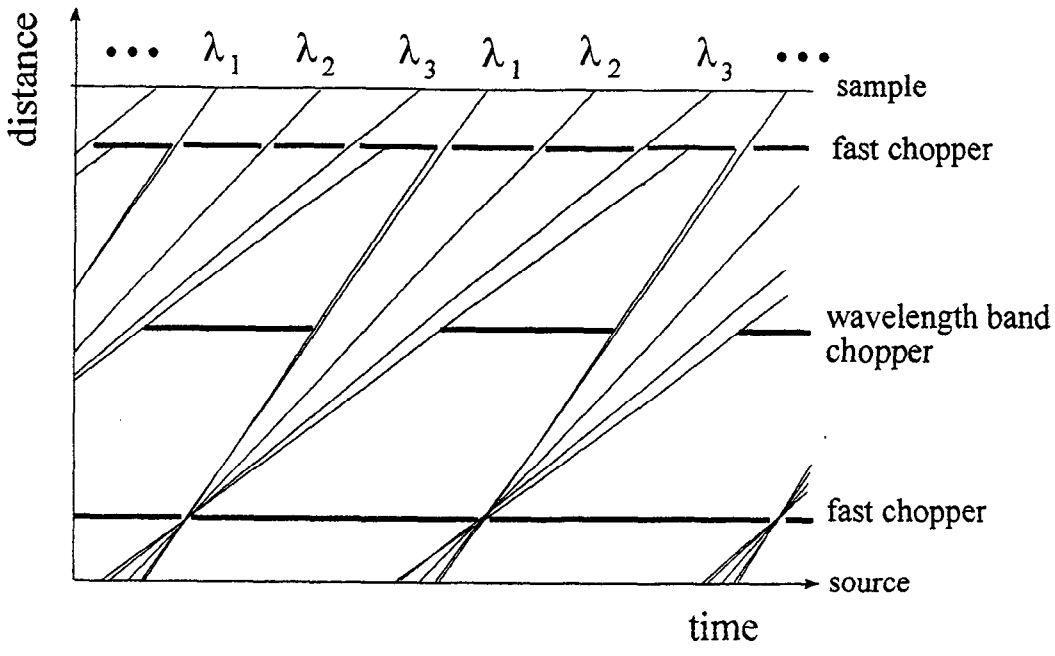

Fig. 5: Principle of TOF monochromator – TOF analyser inelastic spectroscopy with repetition rate multiplication [4].

In order to illustrate the main point of the present approach, i.e. the efficient combination of information obtained with different incoming wavelengths, a model example has been numerically evaluated and the results are shown in Fig. 7. A TOF spectrometer is considered here with a chopper system of the type shown in Fig. 5. The goal of the assumed experiment is to determine the linewidth Γ of quasielastic Lorentzian lines. The continuous line in the Fig. 7. shows the relative statistical error of the determination of Γ obtained in a given measuring time as a function of the ratio of Γ and the width Δ of the triangular resolution function of the chopper system at a chosen reference wavelength λ=2.5 Å, assuming that the two fast choppers in Fig. 5. run at the same repetition rate, i.e. single wavelength conventional operation. The best precision within a given measuring time is obtained at around $\Gamma \simeq 2.7\Delta$, an understandable conclusion. The two dashed curves shows the relative error of Γ obtained by combining (taking the error weighted average of) the Γ values obtained during the same measuring time with the fast chopper near to the source operating at 5 times lower repetition rate (but with the same pulse length), i.e. by taking 5 TOF spectra at 5 different wavelengths. Explicitely these 5 wavelengths were assumed to be 1.5, 2, 2.5, 3 and 3.5 Å. The intensity distribution across these wavelengths was assumed to correspond to a thermal moderator with the peak at 1 Å. The $\delta\Theta$ = const case corresponds to using equal collimations for all wavelengths, in which case the incoming beam intensity changes by a factor of 26 between 1.5 and 3.5 Å. Note, that the information obtained at 3.5 Å is still relevant at small Γ values. In contrast, if

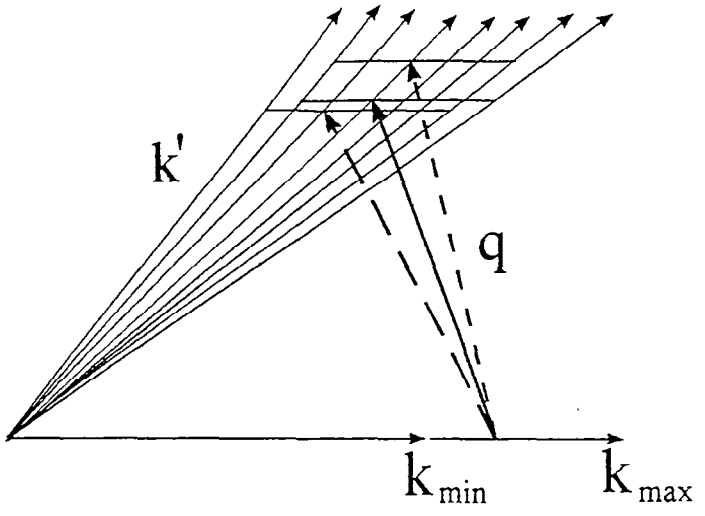

Fig. 6. Constant q scans on a TOF monochromator – TOF analyser inelastic spectrometer. The horizontal bars at the end of the q vectors and equal to the incoming k band represent the constant q cuts across the quasi–continuous set of TOF data at various fixed angle detectors.

constant q resolution is aimed at, a supermirror neutron guide can be envisaged for the incoming beam, and the a matching horizontal angular resolution can be achieved on the detector side by adding the spectra of more or less individual detectors. In this δq = const case (cf. Fig. 7) the incoming flux ratio between 1.5 and 3.5 Å is only 2. The spectrometer resolution in both cases, however, varies by a factor of 13 between the two extreme wavelengths, assuming constant chopper pulse lengths. The results in Fig. 7 clearly show, that the data collection rate on the whole is the same for all 3 cases and that, in contrast to the conventional wisdom, data taken for the same time with very different intensities and resolutions can in a very meaningful way be combined by using proper information processing. (Actually the δq = const curve shows the best characteristics in view of the smaller variation of the precision over a broad range of Γ values.) From the point of view of the time-of-flight wavelength band monochromator concept the fundamental conclusion from Fig. 7. is that quite different wavelengths can be included in a "useful" wavelengths band, which leaves us with a substantial flexibility.

This kind of repetition rate multiplying TOF-spectroscopy offers a new opportunity for the usual short pulse spallation sources too. It allows one to make optimal use of the source flux by being able to use a pulse repetition rate on the sample corresponding to the one optimal for the secondary spectromter, i.e. to the flight path

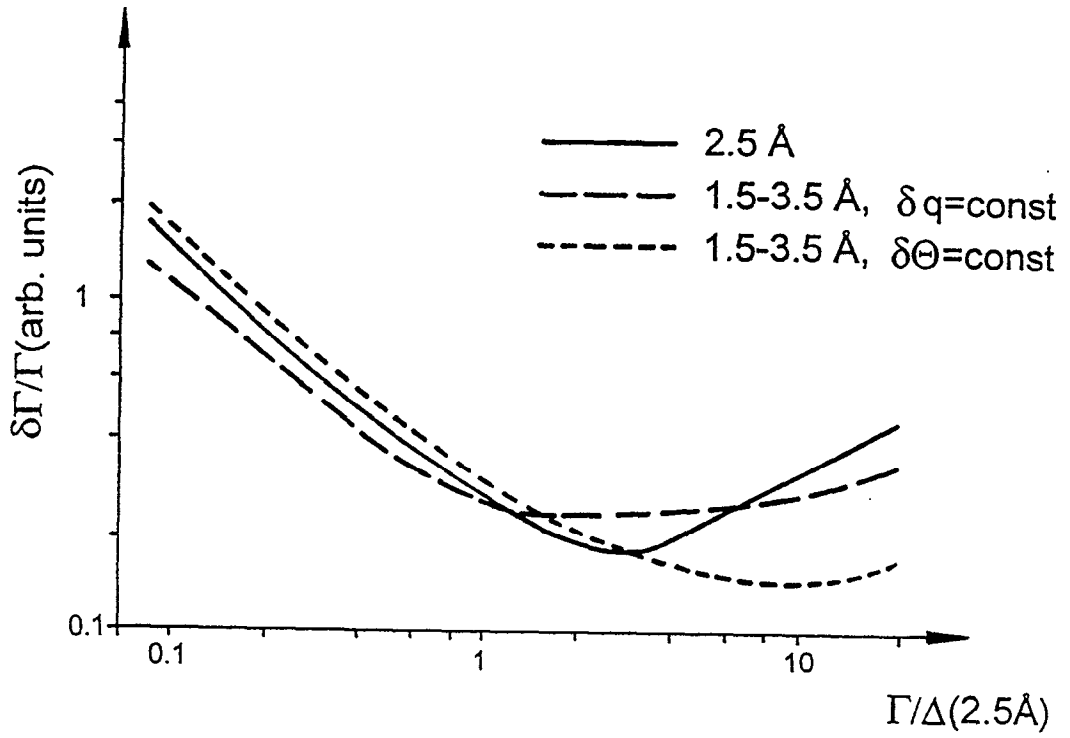

Fig. 7. Comparison of the data collection rates — as characterized by the error of the determination of quasielastic linewidts within a given measuring time — by the use of a single wavelength (continuous line) and five different wavelengths within the limits shown (see text).

of the scattered neutron, as usual on a CW source. The flux gain compared to the conventional use of TOF spectroscopy on SPSS will reach a factor of 5 - 10 in many cases, e.g. by running a spectrometer at 300 Hz on a 30 Hz source.

5. Producing short pulses: SPSS vs. choppers on LPSS

In the slowing down regime, i.e. for hot neutrons the time averaged luminosity of the moderators is to a large extent independent of the type of monochromator: coupled or decoupled, poisoned or not etc. [6]. In this regime the integrated intensity per pulse only depends on the energy per pulse. Thus typical neutron pulse lengths of 10 μs (or less) for sub μs proton pulses mean some 100 times higher peak flux than for an equal energy 1 ms proton pulse. We have to take into account however, that if one works with a linac and a proton storage ring for pulse compression from about 1 ms to 1 μsec, the linac beam chopping necessary for the injection and the injection losses themselves lead to an energy per pulse for the storage ring of about 1.5–1.8 smaller than the one the same linac would produce. Furthermore, if the additional costs for a

H^- source (also necessary for injection) instead of H^+, for the beam chopping device, for the beam preparation for injection, for the ring accelerators and for the two target stations instead of the one sufficient on an LPSS (due to the longer source to instrument distances) are used to build a linac and a long pulse target station of higher power, we will end up with a LPSS of about 4 times higher average power than the more powerful target station of a SPSS of equal costs. This would likely also apply for a 5 MW SPSS vs. a 20 MW LPSS. Thus we can conclude that for a pair of cost–equivalent SPSS and LPSS the peak flux of the epithermal neutron pulses of the SPSS exceeds by a factor of about 25 at low epithermal energies (and more at higher ones) the peak flux of the LPSS. In addition 10 μs FWHM is about the shortest pulse length choppers can produce, so for this neutron energy range the SPSS is clearly superior with respect to both flux and resolution.

The situation is drastically different for moderated (cold or thermal) neutrons. In this range the neutron pulse length on a SPSS becomes dramatically longer due to the moderation time, and the average brightness becomes strongly dependent on the type of moderator and reflector choosen [6]. The integrated neutron flux per pulse increases with the moderator pulse length in a way similar to variable pulse length choppers, and for slow (high intensity) moderators it is typically an order of magnitude higher than for fast (high resolution) ones. With moderation times for high intensity moderators being around 0.5 ms, or more, the peak flux gain achieved by compressing the proton pulse length fom 1 ms to a 1 μs is marginal, and more than off–set by the lower power available at the same costs. Thus the investment in making the proton pulses shorter is counterproductive for cold neutrons, it is more cost effective to produce short cold neutron pulses by choppers on LPSS than by SPSS. In addition, choppers can produce considerable shorter long wavelength pulses than the about 100 μs minimum achievable with tailored moderators. Thus for cold neutrons a LPSS source provides pulses with both superior peak intensity and superior resolution compared to a cost equivalent SPSS.

For thermal neutrons (10 to 100meV) the situation is basically similar to that of cold neutrons, but somewhat more favourable for the SPSS in view of the shorter moderation times. The difference might however be rather small, since time constants in efficient reflectors for thermal neutron production are not much shorter than those for cold neutrons [6]. Although this case has to be studied more in detail, one can expect the peak thermal fluxes to come out about equal for the above defined cost–equivalent LPSS and SPSS sources. The greater flexibility of disc chopper systems, their more favourable lineshape and the higher resolution (shorter pulse lengths) they offer are, however, a clear advantage for the LPSS approach in the production of short thermal neutron pulses, too. (Note that with the exception of TOF inelastic spectroscopy without repetition rate multiplication, chopper systems cannot efficiently be used on SPSS for reducing the neutron pulse lengths).

6. Conlcusion

In comparing the performance of a long pulse spallation source (LPSS) to a complementary pair a CW reactor and a usual short pulse spallation source (SPSS) one finds that: a) LPSS reproduce the utilization characteristics of CW reactors in neutron scattering applications with a LPSS providing time averaged fluxes on the sample which is about 4–8 times superior to that of a cost–equivalent reactor. This opens up the way to emulate by LPSS reactor sources with a flux 20–40 times superior to that of ILL. b) For the production of short neutron pulses a LPSS equipped with disc chopper systems (TOF monochromators) offers both superior peak flux and better resolution for cold neutrons, and equivalent peak flux and superior resolution for thermal neutrons compared to a cost–equivalent SPSS. In contrast in the slowing down regime (hot neutrons) the SPSS is clearly superior to the LPSS in both peak flux and resolution. Points a) and b) amount to conclude that for some 75 % of the neutron scattering work as practiced today the LPSS approach provides the most efficient source and the remaining 25 % is best served by SPSS.

7. References

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