Future prospects of imaging at spallation neutron sources

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Abstract

The advent of state-of-the-art spallation neutron sources is a major step forward in efficient neutron production for most neutron scattering techniques. Although they provide lower time-averaged neutron flux than high flux reactor sources, advantage for different instrumental techniques can be derived from the pulsed time structure of the available flux, which can be translated into energy, respectively, wavelength resolution. Conventional neutron imaging on the other hand relies on an intense continuous beam flux and hence falls short in profiting from the new development. Nevertheless, some recently developed novel imaging techniques require and some can benefit from energy resolution. The impact of the emerging spallation sources on different imaging techniques has been investigated, ways to benefit will be identified (where possible) and prospects of future imaging instruments and possible options and layouts at a spallation neutron source will be discussed and outlined.

1. Introduction

Since the efficiency of producing fission neutrons seems to have reached its maximum with state-of-the-art high flux reactors such as HFIR (US), FRM2 (D) and at the ILL (F), spallation neutron sources have been favoured in order to improve the performance of neutron scattering instruments. Although the production of neutrons is about an order of magnitude more efficient in spallation targets (for a given amount of energy deposition), the available time-integrated flux reaches a maximum of only fractions of the above-mentioned reactor sources in state-of-the-art spallation sources (e.g. approximately 30% J-SNS [1] compared with FRMII [2]). This is due to current technical implications concerning the target and accumulator rings, which limit the power of short pulse sources like SNS (US) and J-SNS (J) to around 1 MW. This drawback, which indeed has different implications for specific instrumental needs, might – to a certain degree – be overcome by the 5 MW ESS long-pulse spallation source concept [3]. Despite the limited time-averaged flux, most scattering techniques profit substantially from the pulsed sources and increase their efficiency by orders of magnitude due to the efficient use of the time-structured flux by spectroscopic methods. The figure-of-merit (FOM) for such techniques depends strongly on the duty cycle $c = t/T$ of the source, where $t$ is the source pulse width and $T$ the repetition time, in relation to the wavelength resolution requirements $(\delta \lambda/\lambda)_{\text{required}}$ of the instrument. Given that the full wavelength band $\Delta \lambda$ available for a desired resolution (i.e. source to detector distance) is required for a measurement the efficiency in terms of the FOM has been derived by Schober et al. [4] for specific (spectroscopic) scattering techniques as

$$ F = \Phi \min\{1, (\delta \lambda/\lambda)_{\text{required}}\} $$

(1)

with $\Phi(\lambda)$ being the source peak brilliance [4,5]. The min-function is the smaller of 1 and the product of the duty cycle $c$ and the required wavelength resolution in terms of $(\delta \lambda/\lambda)_{\text{required}}$. In Fig. 1, which corresponds to a figure published by Mezei in [5], the FOM is represented for the planned ESS in comparison to SNS thermal and coupled cold moderators and the available ILL moderators. The figure takes into account only techniques that can benefit from a pulsed source, i.e. which can use a spectroscopic mode. The lowest limit of wavelength resolution requirements considered in the figure is $(\delta \lambda/\lambda) \sim 10\%$ like typical for e.g. small angle scattering investigations.

However, in addition to instruments requiring neutrons of a certain single wavelength, observing a single Bragg peak at a time (e.g. three-axis spectrometers), conventional neutron imaging, which requires a constant continuous flux on the sample has never really been considered to benefit from pulsed spallation sources. The FOM as defined above does not apply, because either a single wavelength or no wavelength resolution are required (i.e. these are no spectroscopic methods) and hence only the time-averaged flux matters.

Nevertheless, recently the option of imaging at spallation neutron sources has been discussed and initiatives to investigate and advertise this option against the background of growing...
interest and a number of outstanding developments in the field have been launched [6,7]. The most prominent neutron imaging techniques that have been envisaged are energy-dispersive imaging [8–10], mainly in order to take advantage of Bragg techniques that have been envisaged are energy-dispersive imaging at Bragg edges in the transmission spectrum [8–10] because these imaging methods have been discussed as the most promising at spallation neutron sources. Nevertheless, no detailed and elaborated considerations or discussions have been reported. The requirements of the latter method depend strongly on the features of a sample that are intended to be addressed. Therefore, special attention has to be paid to this technique, which is being investigated extensively. Another method that shall be discussed, but has not been taken into account yet in detail with respect to opportunities offered by the new sources is polarized neutron imaging [18]. In most of the current approaches, it requires a monochromatic beam but it can profit from multiple wavelength measurements as will be discussed. Other methods like propagation-based inline phase contrast [19], and the grating interferometer-based methods of differential phase contrast and dark field imaging [20], which require a fixed wavelength with low resolution ($\delta \lambda / \lambda = 15–30\%$) will be mentioned only shortly with respect to necessary considerations for effective implementation. Otherwise their benefit from a pulsed source has to be considered equal to that of conventional imaging.

3. Special imaging methods

Moreover, during the last decade neutron imaging has seen a rapid and outstanding development concerning technical as well as methodical aspects. With the advent of several new methods, all of which require different beam conditions, the benefit of different sources to neutron imaging cannot any longer be defined straightforwardly as a single figure as it is possible to do for most highly specialized scattering techniques. Rather, a FOM has to be determined separately for different methods. An outstanding challenge might be keeping in mind to combine as many of the methods within one instrumental set-up, best without negatively affecting the performance of each of them. Several (of the most promising) methods and their needs with regard to the source shall be discussed.

First, some detailed considerations shall focus on fast, respectively, stroboscopic imaging [11–13] of dynamic and repetitive processes and energy-dispersive imaging at Bragg edges in the transmission spectrum [8–10] because these imaging methods have been discussed as the most promising at spallation neutron sources. Nevertheless, no detailed and elaborated considerations or discussions have been reported. The requirements of the latter method depend strongly on the features of a sample that are intended to be addressed. Therefore, special attention has to be paid to this technique, which is being investigated extensively. Another method that shall be discussed, but has not been taken into account yet in detail with respect to opportunities offered by the new sources is polarized neutron imaging [18]. In most of the current approaches, it requires a monochromatic beam but it can profit from multiple wavelength measurements as will be discussed. Other methods like propagation-based inline phase contrast [19], and the grating interferometer-based methods of differential phase contrast and dark field imaging [20], which require a fixed wavelength with low resolution ($\delta \lambda / \lambda = 15–30\%$) will be mentioned only shortly with respect to necessary considerations for effective implementation. Otherwise their benefit from a pulsed source has to be considered equal to that of conventional imaging.

3.1. Fast and stroboscopic imaging

Both fast and stroboscopic imaging [11–13] require the highest possible neutron flux density within the shortest time intervals of exposure. It has been argued that the pulsed beam of a spallation source may enable very short exposure times and hence time-focused images, i.e. good time resolution. However, the beam pulses spread in time until at the nearest possible sample position at about 10–12 m from the target (due to shielding requirements) the advantage of a small time window of a highly intense beam has nearly vanished. A rough comparison for an envisaged exposure time of 1 ms between a beam extracted from a J-SNS coupled cold moderator and the ANTARES facility at FRMII based on published material [1,2] results in a gain factor of only $\sim 1.3$ at comparable collimation. In a time frame of 1 ms only a wavelength bandwidth of approximately 0.33 Å representing in the maximum (at around 3 Å) about 10% of the total intensity of a pulse can be used (at 12 m distance). For shorter exposure times, the intensities for both sources scale similarly, when the moderated spectrum is considered approximately flat in the given wavelength range. For longer exposure times, the situation gets
worse for the spallation source until the limit of the relation between time-averaged flux values has been reached. Hence, no considerable gain is to be expected. On the other hand, the quasi-monochromatization in the case of a short time exposure might yield improved contrast and transmission values for correspondingly selected wavelengths. Similarly, a limited gain is to be expected for the SNS. For the ESS LPTS, an estimate has to account for a time-integrated flux considered to be a factor 3–5 higher, but is delivered by a lower number of pulses (factors 1.5–4). Consequently, a conservative estimate of at least a factor of 5 in a time window of 1 ms seems to be realistic. The fact that the considered exposure time of 1 ms is shorter than the source pulse of 2 ms is counterbalanced by a lower monochromatization in the case of the LPTS. However, for both fast and stroboscopic imaging also the repetition time has to be considered. The gain in comparison to a high flux reactor vanishes, if images with a frequency higher than the pulse repetition rate of the spallation source can be taken. With ready available detectors (see Section 5) at ILL exposure times of 10 ms have proved to be feasible [13].

Taking into account read-out times of the order of 5 ms and the given pulse frequencies at the SPTSs, a comparable performance for a fast measurement of a dynamic process might be expected in the best case. However, the pulsed sources fall short, if an expansion of the exposure is necessary. The LPTS on the other hand enables shorter exposure times or improved images, however, images can be taken every 60 ms only. These facts complicate the task to define a real gain. However, it becomes even more sophisticated for stroboscopic imaging. In the stroboscopic case images taken in phase with the repetitive process can be accumulated. At a continuous source, the exposure frequency can be adapted to the one of the investigated repetitive process and the single exposures are accumulated “on-chip”, i.e. without intermediate read-out, until sufficient count rates have been achieved for the corresponding process phase. Although chances are slim that a repetitive process addressed by stroboscopic imaging has the same frequency as the source, images taken at different source pulses can be sorted with respect to the phase of the process at a given time. Images with corresponding phase can be accumulated and accumulated images at different process phases can be added together in time series i.e. movies of the process. However, such procedure requires a read-out of the chip for every single exposure, which introduces significant additional noise, and still the repetition of the source defines the image frequency. Consequently, the signal-to-noise ratio will limit the feasibility of this approach for short exposure times even in the case of flux gains expected at the LPTS. Additionally, a new generation of imaging detectors (Section 5), which is needed for efficient energy-dispersive imaging at pulsed sources, will – if available – allow for a continuous time-resolved detection. In this case, pulsed sources must fall short significantly in efficiency for fast and stroboscopic imaging.

3.2. Energy-dispersive imaging

In the neutron attenuation spectrum of materials scattering contributions are superposed to the absorption contributions. Most significant in the thermal and cold energy region, where the wavelengths of the neutrons match the lattice spacing dimensions d of crystalline materials are the Bragg edges. They result from decreased transmission due to Bragg scattering in the crystalline material described by Bragg’s law $n \lambda = 2d \sin \theta$ with $d$ being the lattice spacing of the $(hkl)$ planes and $\theta$ is half the scattering angle $2\theta$. While in conventional scattering experiments the scattered intensities are measured in order to determine the size and geometry of the unit cell, respectively, distortions due to stress and strain, in transmission the signal increases significantly when the wavelength exceeds $\lambda = 2d_{\text{hl}}$ $(2\theta = \pi)$ and hence no more Bragg scattering can take place at the corresponding lattice planes. Consequently, the spectral position of a Bragg edge measured in transmission is a reliable measure of the particular lattice spacing $d_{\text{hl}}$ along the incoming beam direction.

Already in the 1980s, transmission measurements on Bragg edges and their application to the determination of internal strain have been proposed. However, only in the 1990s has the technique been pioneered in time-of-flight (TOF) mode at LANSCE (US) and ISIS (GB) – both pulsed sources – in order to study the potential of the technique for time-resolved investigations of the kinetics of phase transitions by means of the decomposition of austenite to bainite, respectively, for strain determination in steel plates [21,22]. Nowadays even programs for the Rietveld refinement for transmission data are available [23]. Within the current decade first but limited approaches to utilize Bragg edge transmission for imaging have been undertaken at pulsed (ISIS) [8,9] as well as at continuous sources (SINQ, BERII) [10]. Although the technique seems promising and spatially resolved structure and phase determination are highly desirable, the technique yet suffers from limited feasibility. This is mainly due to low available flux densities, respectively, resolution (either spatial or time/energy).

Indeed the advent of state-of-the-art spallation sources like SNS and J-SNS and to some extent even TS2 at ISIS may change this picture significantly, given that the development of a detector combining sufficiently high spatial and time resolution for this purpose succeeds. This topic will be dealt with later in this article (Section 5).

The instrument requirements are, however, different for e.g. the purpose of spatially resolved stress and strain measurements [8,9] on the one hand and the identification of different crystalline phases and textures by imaging on the other hand [9,10]. The first intention requires a resolution in terms of crystal lattice spacing $d$, respectively, flight time $t$ and wavelength $\lambda$ of

$$\frac{\Delta d}{d} = \frac{\Delta t}{t} = \frac{\Delta \lambda}{\lambda} \approx 10^{-3}.$$  \hspace{1cm} (2)

In the latter case, as realized (in different quality) at both pulsed and continuous sources [9,10], a corresponding resolution of some $10^{-2}$ is sufficient. This is indeed a significant difference with a clear impact on instrumentation needs when keeping in mind that excessive resolution may cause severe drawbacks in efficiency. Hence it has to be considered, if either both resolutions can be realized in a satisfactory manner in a single instrument, e.g. by taking into account separated sample positions, or one option, i.e. the high-resolution transmission set-up, should better be implemented in another instrument like e.g. an engineering diffractometer. In a TOF experiment, the wavelength resolution is given by

$$\frac{\Delta \lambda}{\lambda} = \frac{\tau}{\tau} = \frac{h \tau}{L m \lambda}.$$  \hspace{1cm} (3)

where $t = L m \lambda / h$ is the flight time of the neutron with the wavelength $\lambda$ and the mass $m$ for the distance $L$ from source to detector and $h$ being the Planck constant. At a SPTS, the pulse width $\tau$ depends strongly on the used moderator and the wavelength [1,5]. However, because conventional imaging and most other imaging methods (see above) require a maximum available time-integrated flux a coupled moderator has to be favoured. A coupled moderator on the other hand causes the longest wavelength-dependent pulse FWHM of the order of $10^4 \mu s$ in the range of the wavelength band of the highest interest for the given task, i.e. between 2 and 7 Å. Consequently, a flight path of the order of 10 m would already satisfy the resolution requirements for the one task in contrast to about 100 m for e.g. stress.
and strain measurements. Such distance does not only imply the use of frame overlap chopper(s) and a guide system but also a significant reduction of the useable wavelength bandwidth depending on the source repetition rate (at 60 Hz $\Delta \lambda < 0.8 \text{Å}$, at 25 Hz $\Delta \lambda < 2 \text{Å}$, see Fig. 2). In the given cases of wavelength-resolved imaging, the FOM like defined above for scattering instruments applies straightforwardly. However, the FOM is reduced when the available wavelength band exceeds the one useful for the measurement. In such cases the efficiency decreases by a factor $\Delta \lambda_{\text{required}}/\Delta \lambda_{\text{available}}$. Consequently, no further efficiency loss has to be taken into account when increasing the resolution (i.e. source to detector distance) as long as $\Delta \lambda_{\text{required}} \leq \Delta \lambda_{\text{available}}$ and the same measurement position for both above methods could be considered. Due to the fact that the described methods are new developments a well-founded prediction of requirements seems difficult and will depend strongly on feasible applications.

At the planned LPTS of a future ESS the situation looks different. Here, the time of the proton pulse of the order of 1–2 ms defines the burst time. Already a resolution of the order of $10^{-2}$ would require a distance of up to hundred meters from the source, for which in turn neutron guides – for certain disadvantages not usual standard in neutron imaging – have to be considered. For the high-resolution option, however, a pulse shaping chopper system in a frame multiplication mode \cite{24,25} is unavoidable but could eventually be implemented in the same instrument (see Fig. 3). Further relevant instrumentation considerations will be discussed later.

### 3.3. Polarized neutron imaging

Imaging with polarized neutrons is a novel approach to address magnetic fields and structures inside of massive samples for spatially resolved investigations. It is based on the position-sensitive analysis of the final spin precession angle due to the magnetic field integral along a defined path of a polarized monochromatic neutron beam through the sample \cite{18}. Neglecting other effects like attenuation, for increasing field integrals a sinusoidal response function

$$I(x,y) = I_0(x,y) \frac{1}{2} (1 + \cos \phi_s(x,y)) \quad \text{with} \quad \phi_s = \frac{\gamma J m}{2 \pi h} \int \limits_{\text{path}} B \, ds$$

is measured with $I_0(x,y)$ being the incident intensity (spatially resolved in $x,y$), $\gamma$ is the gyromagnetic ratio of the neutron and $\phi_s$ is unknown due to the cosine of the final spin precession angle $\phi_s$ (i.e. spin phase). Wavelength-resolved measurements can obviously solve this problem. Although the spallation source-dependent gain factor in such cases has to be considered moderate because in most cases – depending on the field in the sample and the choice of wavelengths – 2–4 measurements at distinguished wavelengths would be sufficient to determine the field integral quantitatively also benefits for the data evaluation may be expected. A wavelength resolution of the order of $10^{-2}$ will meet the actual needs of such measurements. However, even more profit could be taken if different wavelength-dependent polarization directions in the incoming beam are used to probe arbitrary magnetic fields in polarimetric measurements \cite{26,27}. A correspondingly prepared incoming beam could simply be

\[ -1.8324 \times 10^8 \text{rad s}^{-1} \text{T}^{-1} \] and $B$ is a magnetic field perpendicular to the polarization. This function hinders a quantitative determination of the field integral if the number of full spin revolutions is unknown due to the cosine of the final spin precession angle $\phi_s$ (i.e. spin phase). Wavelength-resolved measurements can obviously solve this problem. Although the spallation source-dependent gain factor in such cases has to be considered moderate because in most cases – depending on the field in the sample and the choice of wavelengths – 2–4 measurements at distinguished wavelengths would be sufficient to determine the field integral quantitatively also benefits for the data evaluation may be expected. A wavelength resolution of the order of $10^{-2}$ will meet the actual needs of such measurements. However, even more profit could be taken if different wavelength-dependent polarization directions in the incoming beam are used to probe arbitrary magnetic fields in polarimetric measurements \cite{26,27}.
achieved by the wavelength-dependent precession of the spins of a polarized beam in a well-defined field upstream the sample position. It will depend on developments of the subsequent data analyses, if either only wavelengths with spins initially parallel to the main axis of the coordinate system will be evaluated or a more continuous approach can be found. (Details will be given elsewhere.) The potential of wavelength dependent, i.e. time-dependent polarization analyses, on the other side for different polarization directions might be investigated as well and might be found a potential further efficiency gain for pulsed sources.

3.4. Other imaging methods

For other imaging methods that require moderate or low-resolution monochromatic radiation ($\Delta\lambda/\lambda \geq 5\%$), but where multiple wavelength solutions are not feasible, imaging facilities at SPTS must fall short compared with steady-state high flux sources and an ESS LPTS. Such techniques are monochromatic imaging [28], inline phase contrast [19] and differential phase and dark field contrast imaging using a shearing interferometer [20]. The shearing interferometer requires a wavelength resolution of only $>1\%$, where a wavelength selector or filters are sufficient. Additionally, it has to be kept in mind that for tomographic investigations of crystalline phase distributions in bulk samples a monochromatic approach may be considered sufficient in some cases, once the most useful wavelength has been identified by an initially measured attenuation spectrum.

Propagation-based inline phase contrast imaging has been demonstrated on the other hand to work well with a broad energy spectrum (white beam) [19]. However, a wavelength-dependent approach could be envisaged instead of multiple distance measurements for holotomographic phase contrast imaging like explored with X-rays but not yet realized with neutrons. This potential is given due to the fact that the addressed real part of the refractive index is strongly wavelength dependent ($\lambda^2$-dependence). An advantage of a corresponding approach would be the constant geometric conditions, while a drawback is the wavelength-dependent attenuation, which complicates data evaluation. However, no real efficiency gains may be expected by such approaches.

4. Instrumentation considerations

It is obvious that a future imaging instrument at a spallation source – especially if full benefit of the source properties shall be taken – has to use components and instrumentation concepts not yet considered/utilized in state-of-the-art imaging facilities at continuous sources. This includes mainly chopper systems and (eventually partly removable) neutron guides. Another challenging task is the development of a detector system for high spatial and temporal resolution which is a precondition for efficient energy-resolved imaging experiments at a spallation neutron source. However, the first question is how to realise an instrument optimized for methods with different requirements.

At a SPTS, the choice of the moderator is the first decision to be taken. For most of the applications envisaged and discussed above a cold moderator has to be preferred, because cold neutrons provide better contrast in many cases and phase and scattering effects utilized for imaging are more distinct. All imaging methods requiring a moderate or no wavelength resolution, i.e. most except e.g. stress and strain imaging should clearly be placed at a coupled moderator offering the highest neutron flux. For all these methods, the instrument can be kept short and might be constructed similar to a state-of-the-art facility at a continuous source. Different sample positions can be implemented depending on flux and resolution needs. Fast and stroboscopic imaging positions can be placed as close as approximately 12 m from the source while at total length of 25 m could be envisaged for other applications like high spatial resolution imaging, energy-resolved imaging and to utilize large fields of view. However, the wavelength resolution at 25 m on the other hand can be considered to be too good for most applications already (Eq. (2)) and it has to be kept in mind that at 25 m the useful wavelength band might be limited already depending on the source frequency ($<3\AA$ for 60 Hz, see Fig. 2). The necessity of a wavelength band chopper for certain applications has to be taken into account.

For stress and strain imaging, where a higher wavelength resolution has to be envisaged, a factor of at least three in length is required (Eqs. (2) and (3), Fig. 2), if realized at the same moderator. For a resulting length of the order of 70–80 m, a neutron guide has to be used. Modern neutron guide techniques utilizing ballistic guides [29] combined with nowadays available high $m$ coatings [30] guarantee for a nearly loss free transport of the required divergence (even for small wavelengths, i.e. down to approximately 0.9 Å) for neutron imaging, i.e. even for large fields of view in a final pinhole geometry. Bandwidth choppers (frame overlap choppers) are indispensable in such a set-up where generally relatively small wavelength bands are available. For cases where a broader bandwidth is desirable a pulse suppression chopper should be provided. The different length required and the necessity of a guide hinder or at least complicate a combination with the scenario described above for other imaging methods, when a significant pay off concerning either (wavelength) resolution or efficiency is to be avoided. If an independent instrument for stress and strain imaging is considered – which can benefit the most from the SPTS – a different moderator, e.g. a decoupled moderator might be taken into account. Decoupled moderators provide shorter pulses and improved pulse shapes at the price of lower flux densities. While the shorter pulses enable a shorter instrument for the same required resolution and consequently a broader wavelength band that can be utilized, the need of an improved pulse shape for high resolution has to be considered carefully. Potential shorter instruments at decoupled moderators with lower flux density (a factor of 5 in terms of time-averaged flux for the decoupled moderator at J-SNS [11]) but broader available wavelength bandwidth and the long instrument described above at a coupled moderator and an optimized neutron guide have to be compared carefully before definite conclusions are possible. Long instruments utilizing neutron guides are capable to suppressing extensive epithermal neutron and gamma background efficiently, when introducing bent guides. At short moderator to sample distances, the alternative use of such radiation might on the other hand be considered [31], but background effects for conventional imaging have to be minimized ($T_{0\text{-chopper}}, filters$).

The situation at a LPTS is a bit different (Fig. 3). Due to the long pulse times the moderation time is negligible. Besides the choice between a thermal and cold moderator for imaging a combined solution is feasible [17]. Due to the necessarily longer instrument even for moderate wavelength resolution, i.e. approximately 50–70 m, the corresponding extraction section does not impose a problem, because a neutron guide has to be considered anyway. At 60 m, the wavelength resolution increases from 2.2% to 6.6% with decreasing wavelength from 6 to 2 Å for a source pulse width of 2 m s$^{-1}$ (Eq. (3)). This dependence is stronger than at SPTS moderators where the pulse width increases with the wavelength [1]. Using a frame multiplication approach [24,25] even high wavelength resolution for stress and strain imaging can be realised for the same instrument length (Fig. 3). Such a solution would not necessarily fall short in efficiency as compared with a dedicated instrument at a SPTS [4,25]. To avoid losses a longer
instrument for such investigations is necessary when a narrower wavelength band is sufficient. However, the frame multiplication technique additionally enables to achieve a constant but variable wavelength resolution over the whole bandwidth, if a double chopper with variable distance is used [4,32]. For other imaging methods, the LPTS has to be considered superior.

Figs. 2 and 3 are time-of-flight diagrams for draft potential imaging configurations at different spallation sources. They are based on considerations of different resolution requirements for different techniques and the resulting instrument lengths as outlined above. For the short pulse sources, the main position for conventional imaging and similar methods was taken to be at 25 m in order to allow an instrument geometry optimized for high spatial resolution. The spectroscopic resolution at 25 m exceeds that required for many measurements and thus is not comparable in resolution to the one considered for the LPTS at 60 m. At the outlined LPTS, the resolution at 60 m, which allow for an optimized imaging geometry, is moderate (between $10^{-2}$ and $10^{-1}$) but optimized for many spectroscopic imaging applications. If no additional (longer) instrument for high spectroscopic resolution is envisaged, the implementation of the frame multiplication technique [24,25] combined with the double chopper approach [32] might be considered to be rather schematic as included in Fig. 3 (i.e. chopper configurations are not optimized). Additionally, the TOF diagrams provide an overview of which wavelength bandwidths would be available for certain distances (i.e. wavelength resolutions) without pulse suppression.

5. Detector requirements

All recently published results utilizing the TOF approach for energy-resolved imaging could either not use the inherent strength/advantage of the method [9], or have been limited severely in spatial resolution [8]. Conventional detectors for TOF are limited to spatial resolutions of the order of $10^{-3}$ m. This is at least an order of magnitude worse than the state-of-the-art in neutron imaging and the aim of current developments. Conventional imaging detectors on the other hand lack sufficient time resolution of the order of $\mu$s. Even if exposure times of the order of $<10^{-1}$ ms – by e.g. an electronically triggered amplifier [11,12] – are feasible with available detectors the specific read-out process hinders fast repetition, i.e. no continuous time-resolved data recording is possible. Additionally, the signal-to-noise ratio of such short single exposures would disable evaluation. Consequently, up to now such detectors allowed only for accumulations of single short time exposures per source pulse from a big number of subsequent pulses. The efficiency of such data recording equals and in fact is analogue to a beam monochromatization and hence not a progress yet. Nevertheless, the corresponding experiments have at least been a proof of principle [9].

However, promising detector developments are ongoing and especially the development of micro-channel plate MCP detectors [33,34] have already proved to display outstanding characteristics for spatial (<40 μm) and temporal (<1 μs) resolution. Results from a prototype proving that sufficient time resolution for the envisaged imaging applications has been or can be achieved are expected soon [35,36]. Silicon active pixel sensors including monolithic active pixel sensors might be promising candidates as detectors that could eventually satisfy the requirements for position sensitivity, timing resolution and count rate capabilities for time-resolved imaging as well [37], although the read-out times seem to be not yet of a useful order of magnitude. Another challenge might be the availability of such detectors with a satisfactory active area (field of view) and such appropriate for the expected count rates. However, any efficient exploitation of spectroscopic sources for imaging (beyond utilizing the high time-averaged flux) depends on the availability of such detectors.

6. Expected gain factors

Summarizing the above considerations about different imaging methods, Fig. 4 is intended to provide an idea of what potential gain factors in performance might be expected at the upcoming sources as compared with a high flux reactor source (ILL). Depending on uncertainties concerning new methods and potential compromise in optimization maximum and minimum gain factors are provided. An optimum transport and detection of neutrons is on the other hand considered, if not stated explicitly in the following discussion. For conventional imaging obviously the expected time-averaged flux densities in comparison to ILL ranging between 0.3 and 0.5 for SPTS and 1–1.5 for the projected ESS are presumed. For fast and stroboscopic imaging at a SPTS no gain and hence a maximum of 1 has been considered. For the LPTS, a maximum flux gain of 6 for a short time exposure has been opposed to the consideration, that at a high flux reactor about 3 images can be recorded within 60 ms. This results in a final maximum gain factor of 2. Both estimates take into account, that no detectors with high time resolution, like being a precondition for TOF spectroscopic imaging, were available, i.e. using conventional detectors [11,12]. With the availability of detectors with high spatial and temporal resolution pulsed sources must fall short because the time-wavelength correlation hinders exposure repetition faster than with the source frequency. For exposure times of 1 ms, the efficiency falls below 1/8 already, which has been set the minimum. For spectroscopic i.e. energy-dispersive imaging separate considerations have been taken into account for high and low wavelength resolution according to the corresponding section above. In the case of high-resolution requirements (Δλ/Δλ_{required}=10^{-3}, Eq. (2)) the FOM equals the peak flux for all considered sources (Eq. (1)). A coupled cold moderator is taken into account for the maximum figure at the SPTS, considering that the pulse shape would not hinder the envisaged resolution. With respect to the wavelength dependence of the FOM (Fig. 1) a gain

\[ \frac{dI}{d\lambda} = \left(\frac{\lambda}{\lambda_{0}}\right)^{-n} \]

\[ \text{FOM} = \frac{\langle I \rangle}{\langle \Delta I \rangle} \]

\[ \text{ILL} \]

\[ \text{SPTS max} \]

\[ \text{SPTS min} \]

\[ \text{LPTS max} \]

\[ \text{LPTS min} \]

\[ \text{pol} \]

\[ \text{fast} \]

\[ \text{strobosc.} \]

\[ \text{low res. spec.} \]

\[ \text{high res. spectroscopic} \]

\[ \text{conventional} \]

\[ \text{others} \]

Fig. 4. Potential gain factors for spallation sources compared with a high flux reactor are shown for different imaging methods. In order to take into account uncertainties of both the requirements for potential new applications and the actual performance of different sources when reaching their nominal power, maximum and minimum gains have been defined based on the considerations above. Maxima are defined for instruments optimized for the specific method assuming that the necessary technical requirements can be met e.g. by corresponding detectors for high spatial and temporal resolution (see Section 5). Minima include compromise and requirements deviating from what an instrument may be optimized for. More details will be provided in the text.
factor of approximately 45 represents a mean value for wavelengths between 2 and 6 Å in comparison to the ILL cold source. However, to achieve such resolution at a LPTS would require an extremely long instrument which is not considered realistic (of the order of 500 m, Eq. (3)). Therefore, the frame multiplication mode is considered at the LPTS. Simulations performed by Schober et al. [4] and Lieutenant et al. [25] as well as some simple estimates based on the chopper set-up in Fig. 3 allow to consider that such set-up at the ESS LPTS would perform approximately equal to the considered SPTS. The minimum gain provided for the sources in this place account for the case that approximately a wavelength band of Δλ = 1 Å would be required for a measurement with an instrument corresponding to Fig. 3, respectively, that a decoupled moderator has to be used at the SPTS. Hence, the gain decreases by a factor of about 4 at the LPTS and by 5, due to the reduced moderated flux, times 1.5, which accounts for the broader available wavelength band according to a shorter instrument at a SPTS. These figures change significantly for resolutions of the order of some percent. Here for the LPTS, the FOM still corresponds to the peak brilliance (up to about 3.3% resolution, compare Eq. (1)), while it drops significantly for a SPTS even if a coupled moderator is used (e.g. 0.2% at 3.3% for the SNS for τ = 100 μs). For the minima, the above considerations with respect to the required wavelength band apply for both target stations. This results in a reduction of the gain factor by a factor of about 4 for instruments corresponding to Figs. 2a and 3. Additionally for the SPTS, the use of a decoupled moderator might be considered (in order to enable high resolution at the same instrument). However, in such case a SPTS could already fall short as compared with an ILL class source. For polarized imaging maxima 8-fold multiple wavelength measurements have been taken into account (considering 2 perpendicular polarization directions at 4 wavelengths each) while for the minima 3-fold multiple wavelength measurements for a single polarization direction are considered. The corresponding gains are therefore products of the relative time-averaged flux (as compared with a continuous source) and the number of wavelength fractions that can be utilized per pulse. As outlined earlier for other methods no efficiency gain other than related to the time-integrated flux at the projected LPTS could be identified.

7. Conclusion

In conclusion, a cutting edge imaging instrument is clearly feasible at state-of-the-art short pulse target stations but will be outperformed by a comparable instrument at a LPTS like planned for ESS with respect to most imaging applications. However, even an instrument at a SPTS can compete with and will in many cases be superior to existing state-of-the-art imaging instruments. With regard to detail, an instrument at a LPTS can be expected to have an at least equal performance in comparison with high flux reactor sources with respect to imaging techniques requiring high time-averaged flux. Methods that require energy resolution will benefit significantly, but only under the precondition that imaging detector developments for high time resolution succeed. Under the same precondition fast and stroboscopic imaging must – in contrast to widespread expectations – fall significantly short at pulsed sources. At a SPTS moderate drawbacks for conventional methods and purely monochromatic techniques contrast massive benefits for energy-resolved methods. However, the SPTS cannot compete with the LPTS especially when a moderate energy resolution is required. In addition especially at a SPTS an effective implementation of energy-resolved imaging with high wavelength resolution into an imaging instrument optimized for other imaging methods seems to be not feasible without significant compromise. Therefore, a separate instrumental solution has ideally to be envisaged. Polarized imaging has a high potential to benefit from the new sources, if novel multiple wavelength and polarization approaches are developed and implemented.

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References