Neutron Optics Requirements for Neutron Imaging Techniques

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Abstract. The utilization of X-rays for material research is common in many respects since their discovery at the end of the 19th century. New sources as electron synchrotrons or free-electron lasers push the methodology and the application ranges further. A similar approach started 50 years later with neutrons when sources with reasonable high intensity became available. Today, there are many similarities and complementarities visible between X-ray and neutron studies and the involved techniques. Therefore, it is worth to compare and to adapt from the advanced X-ray techniques and to translate it into the neutron world. Despite of the lack of neutron intensities compared to the most brilliant X-ray beams, the specific properties of neutrons (contrast, spin, magnetic moment, penetration power) are utilized and they will further play an important role in non-invasive studies on the micro- and macro scale. This paper wants to encourage to “look over the fence” into activities of the X-ray community as currently running in the COST action MP-1203.

1. Introduction
Today’s neutron research is mainly focused onto two areas: neutron scattering and neutron imaging. Other applications from the past like neutron activation analysis (NAA and PGAA), depth profiling, and boron capture therapy gained much less importance and practical usage. The most prominent neutron sources for research purposes are equipped with advanced and sophisticated diffractometers, spectrometers and other scattering research facilities while imaging beam lines are still a minority there. However, there are initiatives and strong signals to build and to implement newly developed facilities for neutron imaging too. A list for existing and future facilities is provided in the appendix. As sketched in a historical review in some details below, there are many similarities and synergies in neutron research in comparison to X-ray studies. This holds in particular with respect to neutron optical components, detector options and scientific techniques and their application. There are advantages and drawbacks when neutron and X-ray investigations are compared. On atomic level, both kinds of radiation can perform diffraction studies because the wavelengths are in the order of magnitude of the lattice distances. As the best suitable X-ray energies are in the keV range, the transmission into bulk metals is much less than in the case of thermal neutrons. On the other hand, the intensity of the synchrotron light sources is orders of magnitude higher than neutron sources can provide. This result in much shorter acquisition time and the options for studying very fast dynamic processes with highest spatial resolution, sometimes just during the sample destruction by the applied radiation. With respect to imaging in transmission mode (radiography or tomography) both kinds of radiation can provide similar image quality but with different contrasts, given by the attenuation behavior of the involved materials for the particular kind of radiation. As shown in the Figure 1, a complementary approach is feasible to gain best possible information about the observed object.
Figure 1: Comparing the neutron and X-ray imaging performance for the case of a Swiss army knife, where the plastic cover is enhanced by neutrons (lower left) and the metallic parts by the X-rays (lower right); the transparency for the two material categories is vice versa. The image on top is the result of a neutron tomography run, not photography.

This paper intends to gain attention for new developments in the field of optics for X-rays with the idea how to translate them for neutrons, in particular for neutron imaging. The considerations are based on existing literature, our own experiences and are linked to the recently started COST action MP-1203, dealing with the study of “Advanced X-ray spatial and temporal metrology” [1].

2. COST MP-1203
Initiated by a group in France (action chair: P. Zeitoun, CNRS), the COST action MP-1203 was started in November 2012 administratively and in April 2013 scientifically [1]. The action is structured into the following Working Groups:

Working Group 1: X-ray spatial metrology of optics
Working Group 2: Spatial and temporal metrology of X-ray sources
Working Group 3: X-ray coherent and incoherent imaging diagnostic
Working Group 4: Damage on X-ray optics
Working Group 5: High brightness and coherent X-ray sources for advanced spatial and temporal metrology
Working Group 6: Dissemination and technology transfer

The topics are mainly based on the work at the leading synchrotron sources, but experiences at free-electron lasers and at common lab sources are also involved. Since the action will last 4 years at least, progress will be reported on-line during the different meetings and mutual exchange opportunities in the COST framework.

Although neutrons are not explicitly mentioned and involved in this action, communications with the X-ray experts will become important and interesting in different respect. As it will be explained and outlined in detail below, there are common fields and synergies between neutron and X-ray physics which should be highlighted and exploited.
3. Historical observation: neutrons vs. X-rays
Looking back into the history of the developments in X-ray and neutron research, a scheme of highlights as shown in Figure 2 can be derived.
While X-ray imaging was the very first application of this newly discovered radiation, neutron images (film radiographs) with the same quality were produced much later. Single event neutron counting was preferentially been done in the first days of neutron research.

Figure 2. Time scale for important events and developments in the field of X-ray and neutron research, respectively.

From this overview, the following statements can be made:
- Free neutrons were discovered 37 years after the X-rays were found. First detection of the X-rays was done with imaging techniques (using film).
- Neutron imaging started 50 years after first X-ray images were made
- Neutron diffraction comes 30 years later than X-ray diffraction
- Neutron tomography comes 25 years later than X-ray tomography in hospitals
- Phase contrast imaging with neutrons comes 10 years later than with X-rays
- Neutron imaging is now a competitive and complementary method compared to the X-ray techniques

However, there are new approaches and opportunities available at the high intense X-ray sources which are based on coherence, where neutrons have not yet the chance to compete.
The clear challenge for future neutron research will be to use the existing and the few sources under construction with their limited intensity most efficiently in several respects. The improvement of the
detector techniques, the use of focusing devices and to narrow energy bands more efficiently are approaches with high importance for future neutron applications.

On the one hand, there are different contrast mechanisms of the neutrons compared to X-rays resulting in alternative and complementary information about the object under investigation. The approach to combine the two beams into one imaging facility is described in [2]. On the other hand, neutrons have unique properties like a spin and magnetic moment that can be used for polarization studies [10] describing magnetic phenomena on the macro-scale.

The COST-action P7 “X-ray and neutron optics” was running from 2002 until 2006 [12, 16] with the aim to understand better the interaction of X-rays and neutrons at flat surfaces and interfaces and to apply this knowledge to create advanced optical elements, mainly to guide neutrons and to enhance the intensities in neutron scattering experiments. Since this time some progress happens, and we focus here more on the neutron imaging aspects.

4. Neutron beams

Neutron sources with the needed high intensity are either reactor based (power 10 to 70 MW) or using the spallation principle at intense particle (mostly protons) accelerators (beam power in the order of 1 MW presently). The initial (fast) flux density cannot be higher than $10^{15}$ cm$^{-2}$ s$^{-1}$, mainly for cooling reasons. As the most suitable neutrons for research are in the thermal or cold region, the moderation process is needed before a beam is formed. However, neutrons cannot be manipulated by guiding fields and therefore neutron beams just consist of the neutrons with the right directions. In this respect, a dramatic loss of intensity has to be taken into account and a neutron flux on the order of $10^{7}$ cm$^{-2}$ s$^{-1}$ to $10^{10}$ cm$^{-2}$ s$^{-1}$ will arrive at the sample.

This order of magnitude has to be compared to photon values (e.g. at the SLS, PSI, CH) where $10^{18}$ photons/s/mm$^{2}$/mrad$^{2}$/0.1% band width are common.

A major issue under such circumstances is to use the beam most efficiently by sending the “useful” neutrons to the sample and to collect the neutrons after interaction in the right manner to form a signal which can be analyzed.

Compared to the pioneering time in neutron research, there are many developments done to enable the above mentioned strategy. Neutron guides, other neutron optical elements, analyzing devices, including new detectors have been developed and will be improved further. As an example, the development and implementation of digital imaging detectors replacing the traditional film techniques gave a performance gain by orders of magnitude (30 minutes $\rightarrow$ some milli-seconds in exposure time).

5. Neutron optics

There are several options for manipulating neutron beams, as summarized in Table 1.

The attempts for understanding of the wave properties of neutrons has started very early after the discovery of the neutron and the availability of suitable beams. Papers like [17] and later overview articles [19, 20] which are recently complemented [18] indicate the high standard of knowledge about neutron optical phenomena from fundamental aspects towards applications in neutron scattering. However, the usage for practical applications in neutron imaging aspects (beam tuning, increase in performance) is still quite limited.

The development of neutron guides on the basis of total reflection of (preferentially cold) neutrons and their installation at many prominent sources raised the opportunities for the beam extraction dramatically. Instead of only one or two instruments per beam port, we can now deliver the beams to many facilities at the same time. Compared to the initial Ni based cladding, the “super-mirrors” as multi-layers of Ni-Ti provide higher reflectivity over much wider energy bands now (at the expense of divergence).
Table 1. Neutron interaction options for tuning beams (taken from [3])

| Interaction | Applications                                      |
|-------------|---------------------------------------------------|
| Reflection  | Mirrors, capillaries, reflecting lenses            |
| Diffraction | Bragg scattering, monochromators, zone plates     |
| Refraction  | Refracting lenses, energy analysers               |
| Absorption  | Collimators, filters                              |
| Magnetic    | Larmor precession                                 |

On the other hand, the reflection properties can be used to build focusing devices in order to increase the intensity at the sample position. With a parabolic shape in one or two directions a gain by a factor of 10 to 20 was demonstrated with a focal spot in the order of less than a millimeter. Fig. 3 shows an example where adaptive neutron optics devices were used to focus the beam at BOA [4] in one direction.

Figure 3. Intensity distributions of a neutron beam at BOA (without focusing device – left) and after focusing with an adaptive optical device in one dimension (right) (see [5]). The gain in the spot was about 12 times the peak intensity of the initial beam.

For cutting out narrow energy bands around the wavelength $\lambda$ from the “white” spectrum in the beam, there are options available with single crystals (C, Si) where the Bragg condition

$$n\lambda = 2d \sin \theta$$  \hspace{1cm} (1)

is used to separates a specific wavelength. Unfortunately, the beam direction is changed too by $\theta$. Either the experiment is arranged into this direction or a second crystal with same properties is aligned in the manner to bring the scattered beam back into the initial direction (double-crystal mono-chromatizer). The
field-of-view and the homogeneity of the beam depend much on the crystal quality. Second order reflections from the crystals can disturb the beam properties. For neutron imaging applications these parameters are essential.

Neutrons can perform refraction, but the corresponding refraction index deviates from 1 only very little (about by $10^{-6}$, depending on the refracting material and the wavelength $\lambda$ of the neutrons):

$$n = 1 - \delta = 1 - N \cdot \sigma_{\text{coh}} \cdot \frac{\lambda^2}{2 \cdot \pi}$$

(2)

As the coherent scattering cross-section $\sigma_{\text{coh}}$ plays a major role in this relation, preferentially the crystalline solids carry the properties for refraction.

The refraction can be used to build “concave alligator” type lenses to focus or to enable magnification of neutrons afterwards. Such lens systems have to be extended along the flight direction due to the small refraction impact per single lens. In this way, the neutron absorption becomes a competing process which will reduce the intensity accordingly. This is the major reason why the concept has not been implemented. For practical neutron imaging, the FOV is too little and the focal spot too large.

Using neutron diffraction, the concept of “zone plates” can be considered in similarity to the X-ray world. However, the dimensions for suitable such plates are very small, given by the wavelength conditions. Furthermore, a high energy resolution and a degree of coherence are required. This limits the applicability of such a concept to neutron applications due to the intensity driven performance.

Grating interferometry is a method to study phase contrast phenomena [13] – described by the parameter $\delta$ in (2). It represents also material properties and can be taken to perform a complementary “phase contrast imaging”. In the case of neutrons with their magnetic moment, a magnetic phase contribution can be added: $\delta_{\text{mag}} = 2 \cdot \mu_n \cdot B \cdot \text{m} \cdot \lambda^2 / h^2$.

In the meantime, neutron grating interferometry devices have been found useful to visualize USANS and SANS properties of macroscopic samples by deriving the “dark field” signal from the interference patterns. In this way, large magnetic domains have been visualized in bulk samples [14].

6. Neutron detection

Most of the X-ray detection concepts (starting with films – ending now with digital semi-conductor driven systems) can be transferred from X-rays to neutrons – with some drawback: a conversion nuclear reaction is required before a measurable signal is created. The major reason is the missing charge of the neutrons for a direct excitation.

Common conversion reactions are based on strong neutron absorbers for efficiency reasons; $^3$He, $^{10}$B, $^6$Li, Gd or U-235 are the mostly used detection materials. The secondary processes for the detection are light emission (scintillation), ionization and charge transfer or chemical excitation which can be used for signal readout.

In respect to neutron imaging, this transfer process hinders highest spatial resolution as the distance between the neutron impact and the detection point provides a spread.

Most promising detectors today are based on semiconductor pixel devices [6] with single event counting readout which can be used for imaging and also diffractometer devices in the future. Such detectors have the potential to achieve a 2 to 5$\mu$m resolution.

7. Neutron imaging

The usage of neutrons for non-invasive and non-destructive studies of material distributions gained more and more attention in the last years as the performance and the application range has extended in several respects. Depending on the transparency of the object under investigation, the field-of-view can be tuned
to the relevant size. Accordingly, the spatial resolution (pixel size of a digital detector) is adapted. As shown in Figure 4, a wide range of objects dimensions can be covered because a beam diameter of 30 cm is quite common at dedicated imaging facilities.

Presently, the highest spatial resolution is on the order of about 10 micro-meters [7]. There are initiatives to improve the spatial resolution further in order to come into the region of a few micro-meters. Than a competition and complement to X-rays is possible while the high contrast for e.g. hydrogen, lithium or boron can be exploited.

Initiatives to create focusing neutron devices on the basis of Wolter optics [15] or mirror capillary (Chumakov) are in the design stage and have not yet proven useful for practical neutron imaging applications.

Figure 4. Three detection concepts in use at the PSI’s beam lines NEUTRA and ICON [8] with camera based systems covering the sample size of up to 40 cm and the lowest pixel size of 13.5 μm.

Other aspects in the field of neutron imaging (similarly to X-ray imaging where these methods have been set already before) are the implementation of grating interferometers where the phase-contrast is derived simultaneously to the so-called “dark field” image (see above). Both are based on the wave properties of the neutrons and their coherence behavior. One important application is the visualization and study of magnetic domain structures in bulk metal components on the macro-scale.

Because the energy selection plays an important role for some neutron imaging techniques like diffractive imaging [9], polarized neutron imaging [10] and the precise quantification of transmission data [11] the use of pulsed beam in time-of-flight (TOF) mode becomes very important. Therefore, the installations and projects at pulsed sources (IMAT at ISIS (UK), ERNIS at JPARC (Japan), VENUS at SNS (USA)) and ODIN at ESS (Sweden) will provide essential steps forward to establish neutron imaging as a modern research tool.

8. Summary & outlook
As demonstrated at the most advanced X-ray sources, where imaging facilities are well accepted installations next to the spectroscopy and diffraction devices, there is also a trend visible for neutron imaging activities at several places. It is very important, to have a permanent look to the activities in the X-ray community because similarities and complementarities with neutrons can be exploited for our own
purpose. Some limitations in respect to the missing brightness, coherence and resolution can partly be
compensated by the specific neutron properties. The direct link and comparison between neutron and X-
ray data can be used for data fusion on a higher level of knowledge about matter.

9. Appendix
Facilities for neutron imaging around the globe (status 2013):

| Country    | Site     | Institution | Neutron Source | Facility name | Spectrum | Status     |
|------------|----------|-------------|----------------|---------------|----------|------------|
| Australia  | Sydney   | ANSTO       | OPAL 20 MW     | DINGO         | thermal  | operational|
| Austria    | Vienna   | Atominstitut| TRIGA 250 kW   | imaging beam line | thermal | operational|
| Brazil     | Sao Paulo| IPEN        | IEA-R1M 5MW    | imaging beam line | thermal | operational|
| Germany    | Munich   | MLZ Garching| FRM-2 20 MW    | ANARES         | cold     | user lab   |
| Germany    | Munich   | MLZ Garching| FRM-2 20 MW    | NECTAR         | fast     | user lab   |
| Germany    | Berlin   | HZB         | BER-2 10 MW    | CONRAD         | cold     | user lab   |
| Hungary    | Budapest | KFKI        | WRS-M 10 MW    | imaging beam line | thermal | operational|
| Japan      | Kyoto    | Kyoto University | MTR 5 MW   | imaging beam line | thermal | user lab   |
| Japan      | Tokai    | JAER        | JRR3M 20 MW    | imaging beam line | thermal | user lab   |
| Japan      | Tokai    | JAER        | JPARC spallation | ERNIS     | pulsed   | project    |
| South Korea| Daegu    | KAERI       | HANARO 30 MW   | imaging beam line | thermal | operational|
| South Korea| Daegu    | KAERI       | HANARO 30 MW   | imaging beam line | thermal | operational|
| South Africa| Pelindaba| NECSA      | SAFARI 10 MW   | SANRAD       | thermal  | user lab   |
| Switzerland| Villigen| PSI         | SINQ 1MW spallation | NEUTRA   | thermal  | user lab   |
| Switzerland| Villigen| PSI         | SINQ 1MW spallation | ICON     | cold     | user lab   |
| United Kingdom| Didcot | Rutherford Lab. | ISIS-TS2 | ISIMAT       | pulsed   | project    |
| USA        | PennState| P S University | TRIGA 2MW    | imaging beam line | thermal | operational|
| USA        | Sacramento| Mc Cleallan RC | TRIGA 2MW    | imaging beam line | thermal | operational|
| USA        | Gaithersburg| NIST       | NBSR 20 MW    | imaging beam line | thermal | user lab   |
| USA        | Oak Ridge| ORNL        | HFIR 70 MW    | CG-TD         | cold     | user lab   |
| USA        | Oak Ridge| ORNL        | SNS spallation | VENUS       | pulsed   | project    |

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