Chapter

Basics of Neutron Imaging

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Abstract

Neutron imaging is established at many neutron sources around the world as a method for noninvasive investigations of samples and object on the macroscopic scale. Similarly to X-ray imaging, it provides the possibility to "look through" materials and allows one to "see" the inner, hidden content. However, owing to the complete different interaction mechanism, neutron imaging provides very different and complementary contrasts compared to X-rays, even if the image quality often is about the same. We report about the method's principles, describe the state of the art, and give an outlook for new trends and developments.

Keywords: neutron source, research reactor, neutron tomography, nondestructive testing, neutron detection, neutron moderation, thermal neutrons, cold neutrons

1. Introduction

The discovery of neutron in 1932 and afterward the process to initiate nuclear fission in a chain reaction provided the opportunity to set free an enormous amount of energy for two purposes: nuclear weapons and nuclear power plants. However, there is a third aspect in using fission reactions: the generation of fields of free neutrons.

For this purpose, the erection of specialized strong neutron sources, the so-called research reactors, which have been designed and built in many countries all over the world, has started just after World War II. Their principle is the fission of U-235 in a compact nuclear core with the purpose of highest possible neutron output, but minimal energy production. In this case, the energy release is seen to be more disturbing than useful. In the end, the necessity to remove the resulting energy from the reactor core limits the strength of such neutron sources to about 100 MW and the corresponding neutron flux level of about 10^{15} cm^{-2} s^{-1}.

Such strong neutron sources have been used for many scientific and also practical purposes until today. Next to the training of specialists in the reactor technology for power plants and the test of nuclear fuel in the compact cores with its high power density, the neutrons themselves are the target and tool of research.

In the interaction of neutrons with matter, nuclear reactions are initiated with the result of new isotopes, often not existing in nature due to their limited lifetime during decay. Many of such isotopes can be used in medicine for diagnostics and therapy and as gamma sources for several practical applications. On the other hand, neutrons are scattered at atomic nuclei and provide in this way important information about the investigated materials, not accessible by other scientific methods.

Neutron imaging, the topic of this chapter, is a method on the macroscopic scale, performed with the aim to study materials, too. Similarly to common X-ray diagnostics, the material under investigation is illuminated by a directed beam of neutrons, and the detector behind registers the remaining neutron intensity. By comparison to the beam intensity without sample, the amount of missing (captured, scattered out) neutrons can be determined and related to the attenuating properties of the investigated material.

In order to perform neutron imaging experiments, next to the neutron source, a dedicated and well-designed facility has to be built. Such neutron imaging stations are part of the suite of experimental devices around the neutron source (up to now mainly research reactors).

In this chapter, we will describe how the best conditions for neutron imaging are provided: from the initial fission reaction, the tuning of the suitable neutron energy in the moderation process, via the beam extraction toward the best detector design. We will show some of the best installations for neutron imaging, describe the principles of the interaction of neutrons with matter, and demonstrate with examples how neutron imaging can be used for scientific and technical purposes. In the outlook, we will sketch how neutron imaging is developed further by methodical improvements and new neutron sources next to the still existing research reactors.

2. Reactor-based neutron sources for neutron imaging

As described above, none of the research reactors have been built exclusively for neutron imaging. Other applications like isotope production, neutron scattering, or fuel development have higher priorities and importance. Therefore, not all neutron sources are able to perform neutron imaging on an up-to-date level yet. The main aspect is the access to a suitable beam port, where the most useful neutrons can be extracted and a beam is formed for the imaging process.

While the neutrons, resulting from the fission reaction, are very fast (energies on the order of MeV), the most useful and interesting neutrons are very slow (in the range of meV). The reason to use slow neutrons is their specific interaction properties with matter (neutron's wavelength are about the atomic distances in solids), high detection probability, and high diversity in the cross-sectional data, which allows one to distinguish even individual isotopes very precisely.

In order to slow down fission neutrons over such a high energy range (nine orders of magnitude), a moderation process is necessary. It has been found out that the elastic collision with very light materials, which do not absorb neutrons much, enables a stepwise reduction of the neutron energy. The lower the mass of the moderator material, the less nuclear collisions are needed to reach the intended "thermal energy"—the equilibrium with the thermal movements of the moderator's molecules. Hydrogen is the ideal material to provide such moderation performance. However, the natural hydrogen ^{1}H also absorbs neutrons. This reduces the amount of the resulting slow neutrons. Much better is the hydrogen isotope deuterium ^{2}H = the nucleus with a proton and an additional neutron. It absorbs nearly no neutrons, but needs some more collisions to arrive at the required thermal equilibrium.

About 2.4 fast neutrons are emitted with each fission reaction of U-235, of which already one neutron is needed to continue the chain reaction. From the remaining 1.4 neutrons, a part is lost by parasitic capture in the moderator or in structural materials in the reactor core. However, there are still enough neutrons remaining, forming a cloud around the reactor core. Because neutrons are neutral particles without a charge, there are no methods available to guide them with electromagnetic fields into a desired direction. Therefore, neutrons can only be extracted from the source region by a selection of useful ones, which fly into the dedicated direction of an experimental facility. Neutron flux intensities of only about 10^7 cm^{-2} s^{-1} are common at imaging stations.

Despite the success of research reactors, spallation neutron sources have been built as replacements and complements, useful in particular with their pulsing option for time-of-flight (TOF) investigations.

3. Principles and options in neutron imaging

Indeed, right with the availability of neutron sources, several attempts were made to use neutrons for imaging purposes. It was quickly found out that such transmission images look similar to X-ray and gamma images, however with alternative contrast features [1, 2].

As sketched in **Figure 1**, neutron images are obtained employing a two-dimensional area detector behind an object when a collimated neutron beam is sent through it. In the beginning of such investigations, photographic film methods were applied. However, as neutrons cannot directly activate the film, a neutron-to-radiation converter has to be used. There are some materials with high absorption probability as Gd, Dy, In, or Au, converting the captured neutrons into another kind of radiation, which then excites the film.

The film techniques were used until the 1990s of the last century (and even today for special certified applications) before some "revolution" happened: the introduction of digital neutron imaging detection systems. In this way, the previous limitations with film were overcome, and new techniques in neutron imaging have been developed and established. **Figure 2** provides an overview on which kind of methods are available today, all based on the advantages of the digital imaging option.

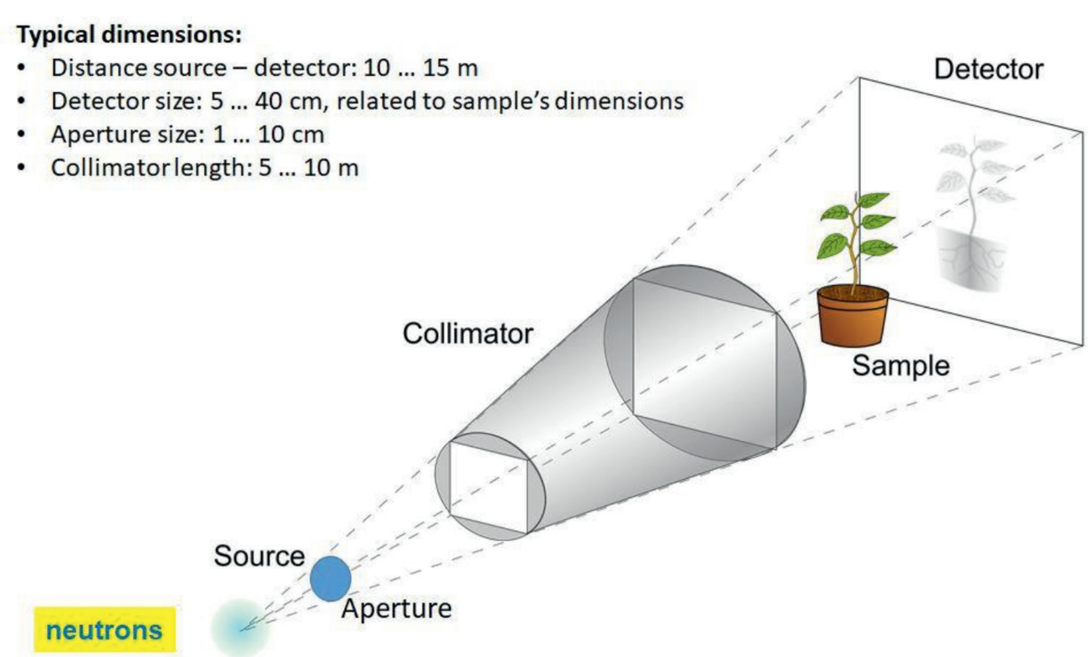

Figure 1.
Sketch of a neutron imaging experiment (not to scale), where an aperture and the collimator define the beam properties.

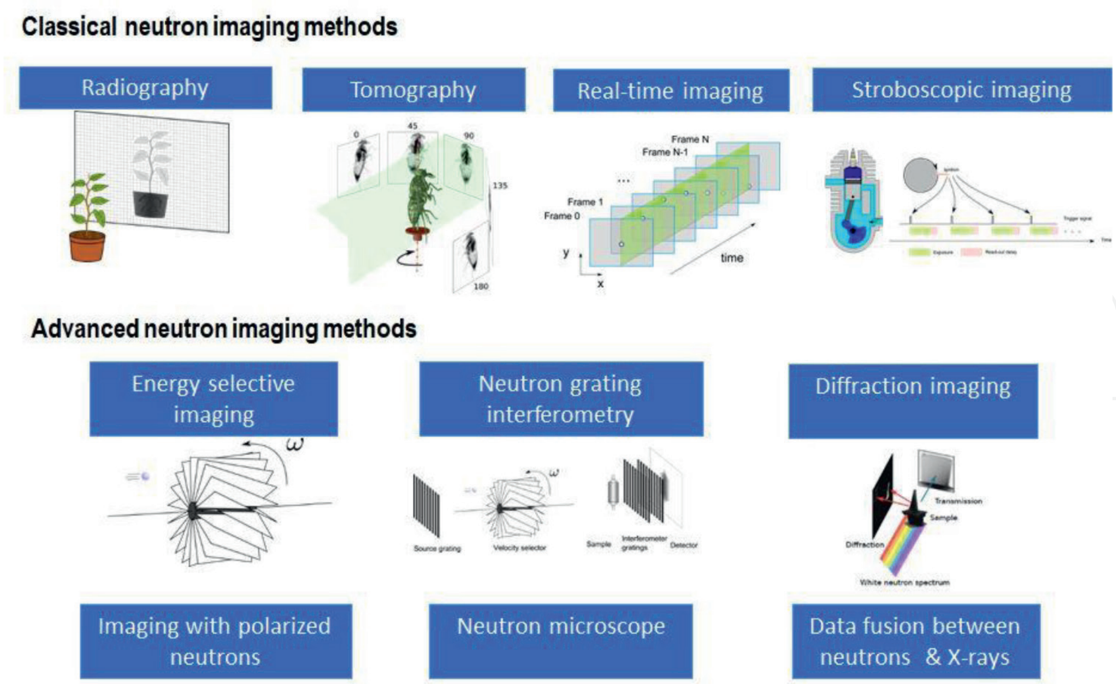

Figure 2.
Overview of neutron imaging techniques, available in several user facilities (see the list in the appendix).

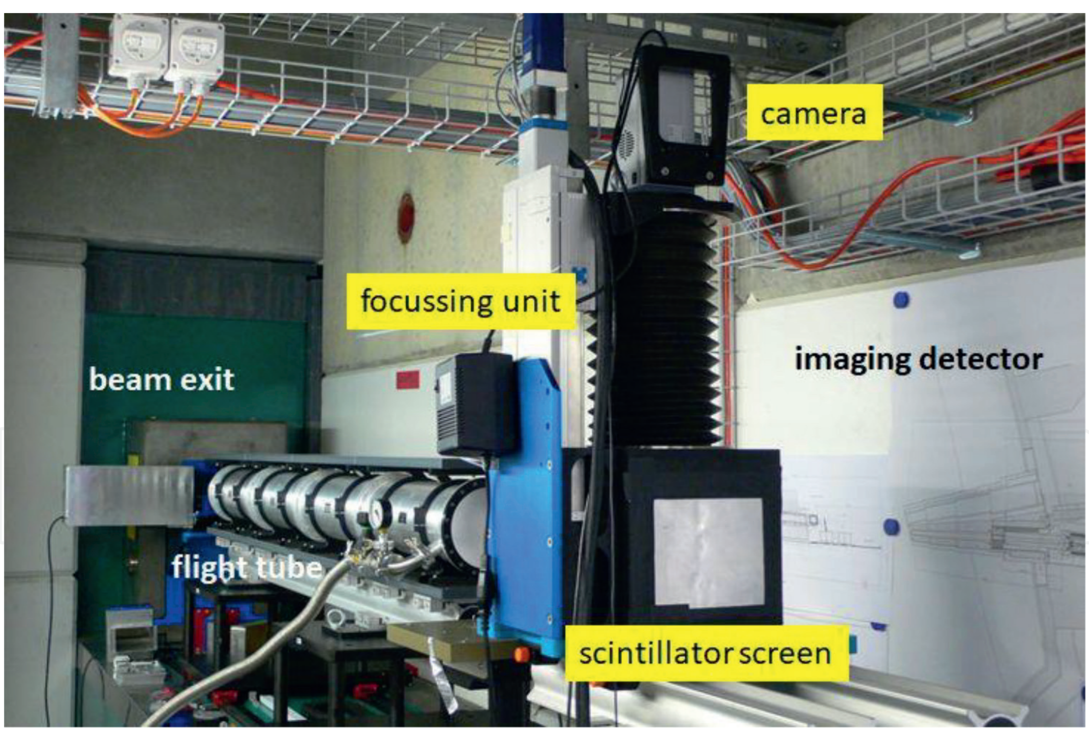

Figure 3.
Setup of a camera-based neutron detector with its major components; the induced light emission from the neutron-sensitive scintillator screen is sent to the camera via a mirror arranged in 45° inside a light-tight box with permission by the IAEA [3].

In particular, the acquisition time for a "valid" neutron image is now on the order of seconds and below, enabling the sampling high amounts of data—to be treated accordingly and stored efficiently.

From the various digital methods, the setup with a highly sensitive digital camera has been found most flexible and efficient. The principle construction is shown in **Figure 3**. Next to the (often expensive) high-performance camera (CCD or CMOS), the neutron-sensitive scintillator screen is of importance. It converts the capture of neutrons into visible light, registered pixelwise in the camera detector. It depends on the particular application if high spatial resolution, high frame rate, or highest quantitative accuracy has to be obtained in the experiments. Accordingly, the composition, layer thickness, and converter material of the scintillator have to be chosen well.

Based on the digital imaging data, neutron tomography is established as a routine method, providing access to the 3D volume of an object, as shown in the example in **Figure 4**. In time sequences, a current image can be compared to a previous one, while the precision to derive values of changes is much enhanced. This is shown in

Figure 4.
Results of radiography (middle) and tomography (right) measurements with thermal neutrons, when a bronze sculpture from Tibet (seventeenth century) has been investigated concerning its hidden organic content (wood, paper, and dry flowers).

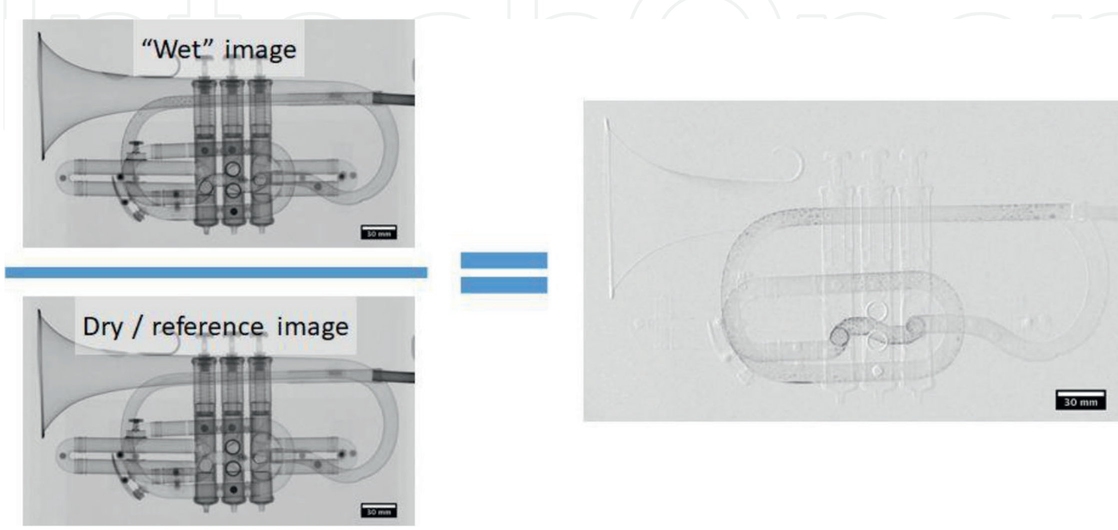

Figure 5.
Using a pixelwise referencing image procedure, it is possible to visualize the moisture accumulation inside the trumpet (online during "playing").

an example in **Figure 5**, where the moisture accumulation during trumpet play is determined very locally and with high sensitivity for water deposits.

4. Generic setup of a neutron imaging facility

Although no neutron imaging facility is constructed identical to another one, the most important components of it can be specified, as shown in **Figure 6**. Starting with the primary source of fast neutrons, the moderators define the neutron energy and the best point for the neutron extraction. Because a high amount of gamma radiation is emitted during the fission process in addition to the neutrons, a direct view on the fission region should be avoided. It is better to look toward the peak of moderated neutrons next to the nuclear core. Remaining gamma radiation can be reduced in its intensity with suitable filters.

The beam for the neutron imaging facility is formed in the collimators in a way to get a quasi-parallel flat neutron distribution at the end of the flight path. Because neutrons interact also with the moisture in the air, the whole neutron flight path should be empty, which means evacuated. A He-filled tube is also acceptable when vacuum is not possible.

To get a beam with low divergence, the aperture close to the source should be small and the distance to the detector long. Both the features are reducing the beam intensity much, and a compromise has to be found between collimation and resulting neutron flux. The so-called L/D-ratio (L = collimator length, D = aperture diameter) should be on the order of 200 or even higher. A useful neutron flux level is on the order of 10^6 cm^{-2} s^{-1}.

To handle the samples in the beam, it is very useful to install remotely driven manipulators, which enable precise motions in all three directions and additionally

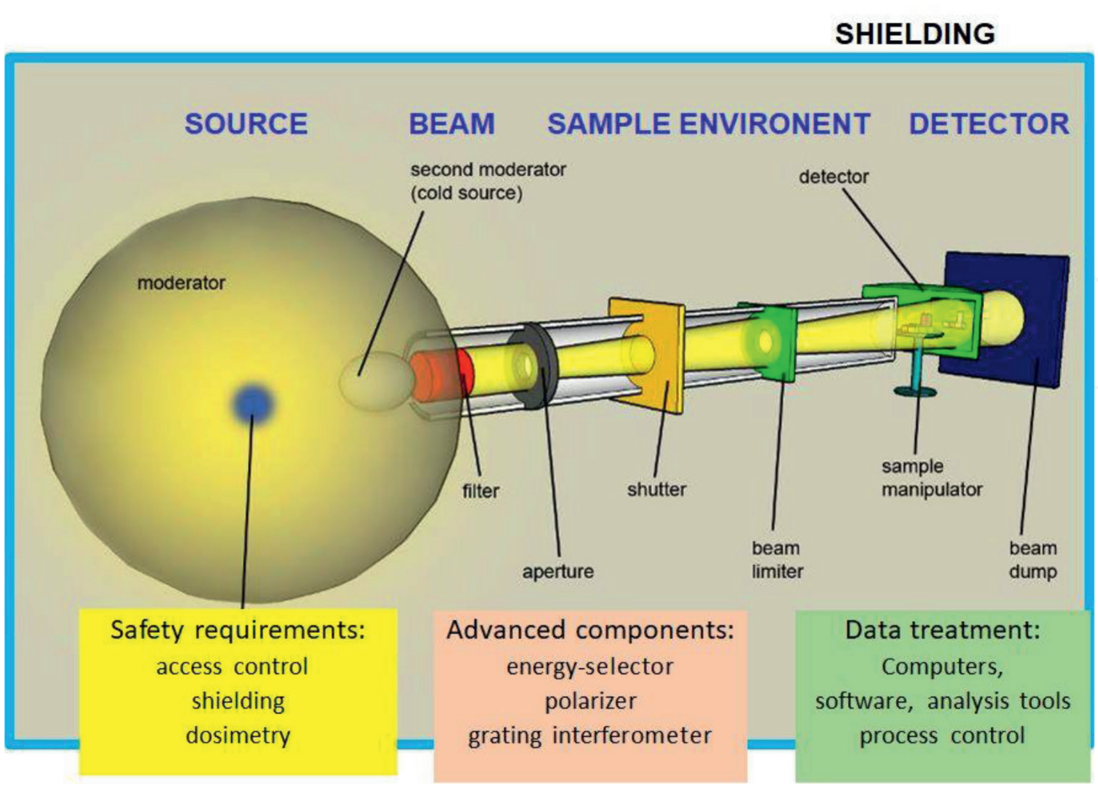

Figure 6.
Generic neutron imaging facility (not to scale); the whole system is surrounded by a radiation tight shielding (mostly concrete) with permission by the IAEA [3].

a rotation stage, mainly used in tomography experiments. The precision in sample manipulation should be better than 0.1 mm depending on the detailed requirements.

The detection system (see below for more details) is the most important component in an experiment, but not necessarily the most expensive. Here, the requirement to surround the whole setup with a tight shielding comes in. Because not only the direct beam, but also scattered radiation has to be enveloped safely during beam applications, the demands for shielding are high. With the common flux level mentioned before, concrete walls of about 1-m thickness in all directions are required. In the forward beam direction, a neutron-absorbing beam catcher is additionally needed behind sample and detector.

Many other installation components are added according to the methodical requirements on demand (see Section 7).

5. Detector options

As mentioned before, camera-based detection systems are quite common in neutron imaging today. The outdated film technology with a neutron-absorbing converter was used for nearly half the twentieth century. Its advantage was high spatial resolution (about 50 μm) for relative large fields of view (FOVs) (about 30 ×30 cm). However, the acquisition time per image is on the order of 30 minutes (exposure, handling, development, fixation, and drying) at usual flux levels. This is not competitive today at all. Furthermore, film methods are not linear in their response, have low dynamic range, and cannot be used for precise quantification.

The abovementioned camera detector technology has several degrees of freedom: number of pixels, spectral range, efficiency, pixel size, and dynamic, noise behavior. In

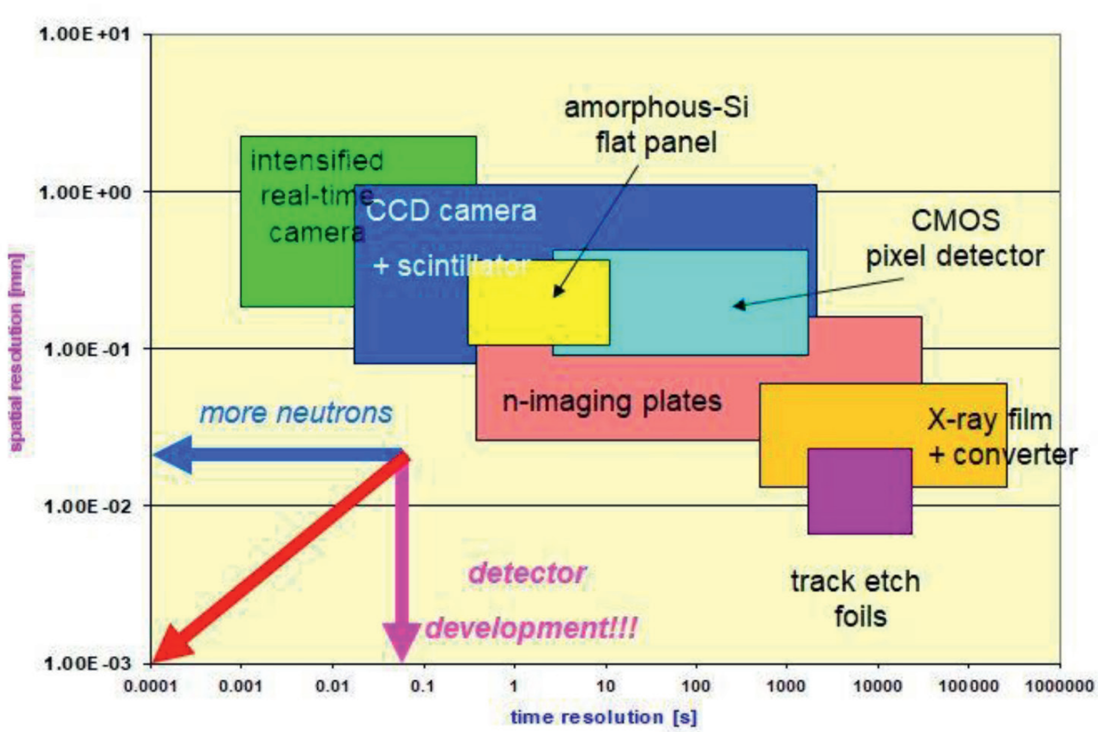

Figure 7.
Detectors for neutron imaging with their approximate working range w.r.t. spatial and time resolution, covering several orders of magnitude with permission by the IAEA [3].

addition, also the optical coupling system is relevant for the performance. Because the number of photons from the scintillator is all times limited, lenses with small f-numbers are preferred, which makes a trade-off with geometric aberrations necessary.

Some more detector options are given in **Figure 7**: flat panels based on amorphous silicon or CMOS technology, pixel sensors with absorber doped microchannels, and intensified camera systems. Recent developments with camera sensors of highest readout capability allow already counting the neutrons event by event [4].

With this high flexibility and variability, the operators of neutron imaging facilities (and their users) have to decide what are the most useful setups for their specific study. Generally, neutron imaging is limited by the number of neutrons. More neutrons would allow for higher frame rates or higher spatial resolution or better counting statistics—but never all these things at the same moment.

6. User lab function in a global context

Large-scale neutron sources (research reactors and spallation neutron sources) have been built as "user labs" with a worldwide access to beam time at high-level performing neutron research instruments, mainly for neutron scattering. Because the counting statistics at such devices is often limited in the neutron beam intensity, high source power is required.

The reactor at the Laue-Langevin Institute (ILL) in Grenoble, France, can be seen as a template for such kind of neutron source facilities. It has been functional since 1971; it is financed by 14 European countries and provides 40 neutron research instruments. The access to these instruments is organized and formalized with research proposals and supervised by scientific boards. Recently, also a neutron imaging facility (NEXT) has been installed—about 50 years after the reactor's start, indicating the increasing importance of neutron imaging techniques in "neutrons for society" (according to ILL marketing).

In the meantime, many other institutes followed the ILL scheme with their sources, often nationally operated and organized. A list of currently available user lab sources (with options for neutron imaging) is given in the Appendix.

For a while, until about 2005, neutron imaging was seen to be a simple technique without high scientific value. However, using modern imaging detection systems on the basis of digital and highly efficient methods, neutron imaging is now widely considered an important tool for many scientific, but also industrial relevant applications in various fields, where other methods are limited and often fail.

Because the experimental infrastructure for neutron imaging on high technical level can become quite expensive, it is a clever approach to share these devices also in the user lab scheme, following that for neutron scattering, and including the access rules.

High-performance neutron sources are unique with respect to their specific layout and particular performance at diverse beam lines. For neutron imaging, however, thermal and cold neutrons are the most common options; only a few facilities employing fast or epithermal neutrons are in use. No wonder, also the respective beam lines for neutron imaging have been built individually. Owing to the user lab function, a high flexibility in the infrastructure with respect to beam size, collimations, intensity, and spectrum is required. The facility ICON at the spallation neutron source SINQ, Paul Scherrer Institut (PSI), Switzerland, is shown in **Figure 8** as an example. The neutron spectrum at ICON is given in

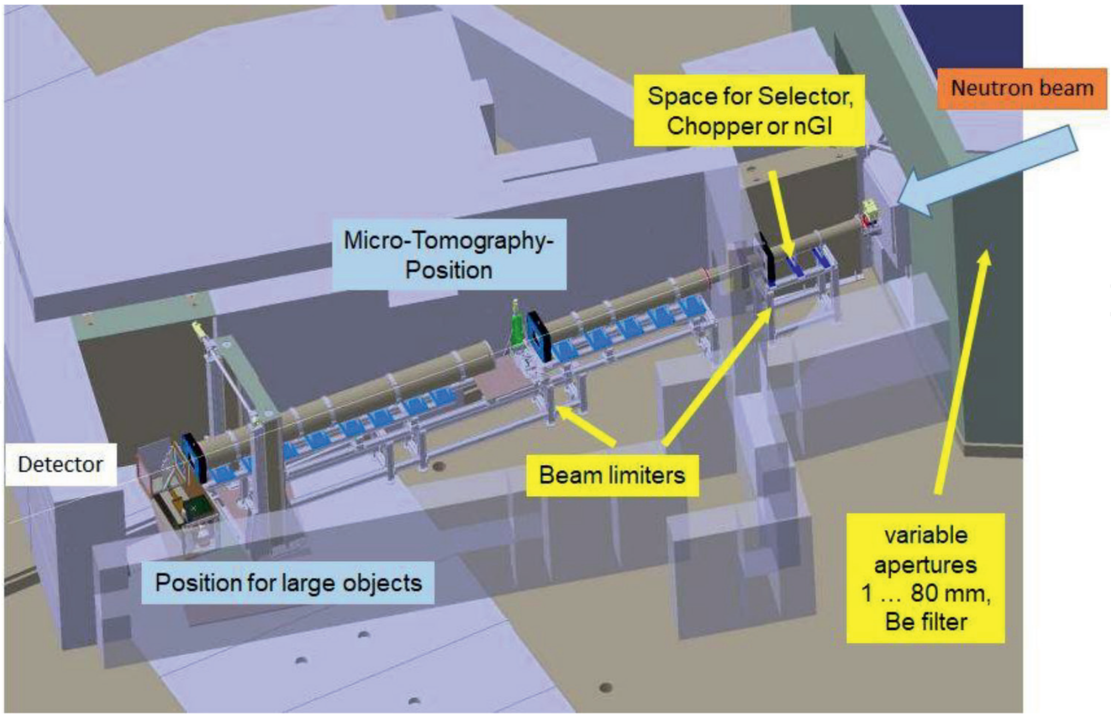

Figure 8.
Layout of the ICON neutron imaging facility for cold neutrons at PSI with the description of major installation features.

Figure 9 in comparison to the other two beams at SINQ in use for neutron imaging—demonstrating the overall high flexibility with respect to penetration power and detection sensitivity.

An overview of the current neutron imaging options and modalities was already given in **Figure 2**—accordingly, special devices and setups need to be available. However, not all sources provide the full set of options or the same conditions. Any potential applicants have to check, which facility fits best to their demands. A pretest at one or more facilities might be useful for developing a perfect setup for a specific request.

7. Methodical features in neutron imaging

The overview of "standard" and "advanced" methods has been already given by **Figure 2**. Here, we want to spend some more effort on describing particular features and their advantages for the research with neutrons.

Most of the different methods are based on the transmission image as sketched in **Figure 1**. Already this "radiography" setup has the degree of freedom for larger or smaller fields of view (FOVs), depending on the sample size, or higher or coarser spatial resolution. Because camera-based detection systems are coupled to the primary sensor (scintillator screen), the relation between FOV and pixel size can be managed by variable lens systems. The moment best layout with respect to high spatial resolution [5] enables a pixel size of 2 μm, FOV = 5×5 mm. On the other hand, the large FOV is limited by the neutron beam dimensions to about 40 ×40 cm. Even larger (but flat, e.g., paintings) objects can be studied in a scanning mode, taking images at different position by moving the sample and composing them together.

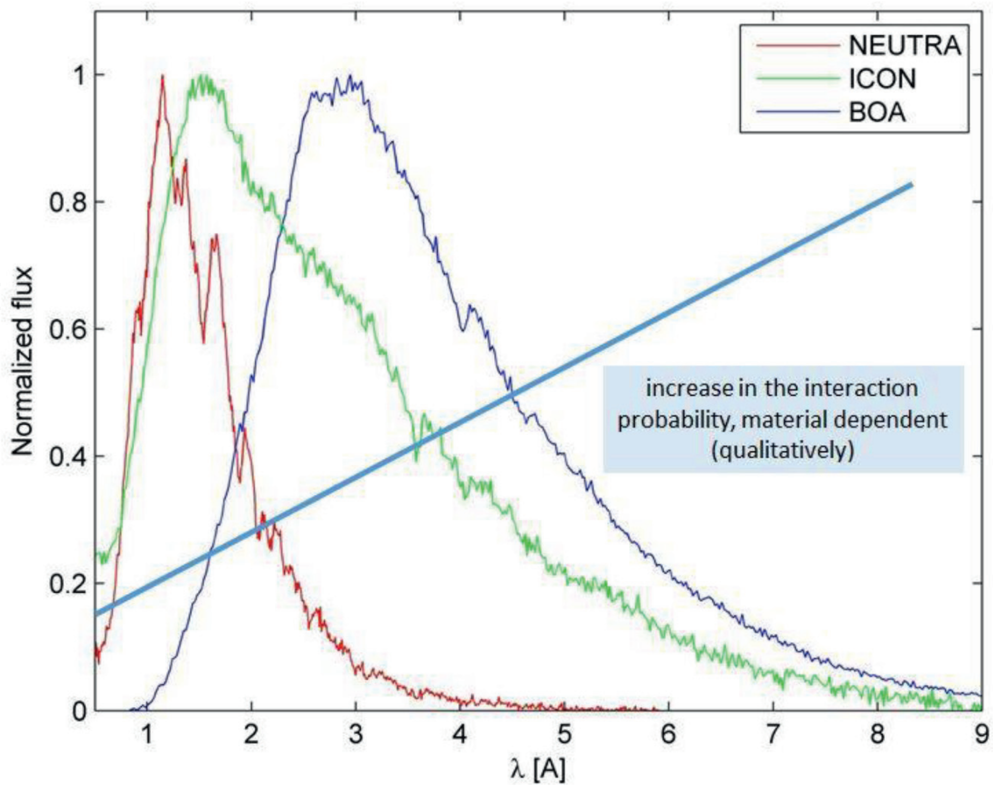

Figure 9.
Normalized neutron spectra at the PSI imaging facilities NEUTRA, ICON, and BOA and the slope of the interaction probability with Al, rising toward longer wavelengths (lower neutron energies) with permission by the IAEA [3].

Neutron tomography allows one to study samples also in their third dimension. The method works similarly to X-ray tomography in hospitals. However, neutron sources cannot be moved around the object: the scanning from different directions has to be done by sample rotation around a vertical (or horizontal) axis. A number of "projections" are taken over an angular range of at least 180° in sequential steps. They are used for the volume reconstruction harnessing mathematical procedures like "filtered back-projection" in the inverse Fourier space. The 3D neutron image of the investigated object is built from a voxel matrix of attenuation coefficients. With the help of visualization tools, slices through the object at arbitrary positions can be calculated and displayed. Regions with the same voxel value can be segmented and measured. The example in **Figure 4** compares one two-dimensional neutron radiography image of a Tibetan bronze sculpture with its 3D tomography reconstruction, for this image, cut in the middle.

Real-time image sequences can be obtained when the detector is able to provide high frame rates and corresponding read-out features. It is the advantage of modern detector options (see Section 5) to have such capabilities, at least at facilities with the required beam intensity.

Stroboscopic imaging is most useful for the observation of repetitive processes like engines. In this way, even fast motions can be investigated by a synchronization of the detection system with the process itself. Snapshots with durations of milliseconds are obtained and stacked to a valid image with good statistical accuracy. A frequency of about 800 rpm has been studied successfully [6].

Energy-selective neutron imaging has its relevance in particular for the study of crystalline solid materials like metals. Their elastic scattering behavior with neutrons is given via the Bragg condition:

$$\mathbf{n} \cdot \lambda = \mathbf{2d} \cdot \sin\Theta \qquad (1)$$

with the neutron's wavelength λ, the lattice distance d, and the scattering angle θ. By choosing the right neutron wavelength λ (corresponding to the neutron energy via the de Broglie relation), crystallites with the same orientation θ can be visualized on the macroscale. In this way, textures and their modifications can be seen and analyzed even for large structures. The example in **Figure 10** shows the texture of an Al sample near a polycrystalline weld.

Because the initial beam at a neutron imaging facility is spread over a wide energy range (Maxwellian distribution around the mean thermal (25 meV) or cold (3 meV) energy), such investigations are only possible with narrowed energy bands. There are three techniques in use to select neutrons for specific energies: turbines with tilted absorber blades, double-crystal settings, and choppers for time-of-flight (TOF) options. In all the cases, the amount of the usable neutrons is strongly reduced, and the acquisition time has to be extended accordingly.

Neutron grating interferometry is based on the coherence properties in the interaction of neutrons with matter. In the understanding of neutrons as waves according to the de Broglie's relation, next to their amplitude, a phase can also be attributed [7]. If coherent neutrons with the same phase interact with samples of suitable structure, a phase shift in different regions of the sample occurs, which can be analyzed with a grating setup [8]. With this technique, magnetic domain walls can be studied online during the magnetization process [9]. An extension of this method is the determination of the "dark field image" of a sample with structures in the μm to nm range, where small-angle scattering happens [10].

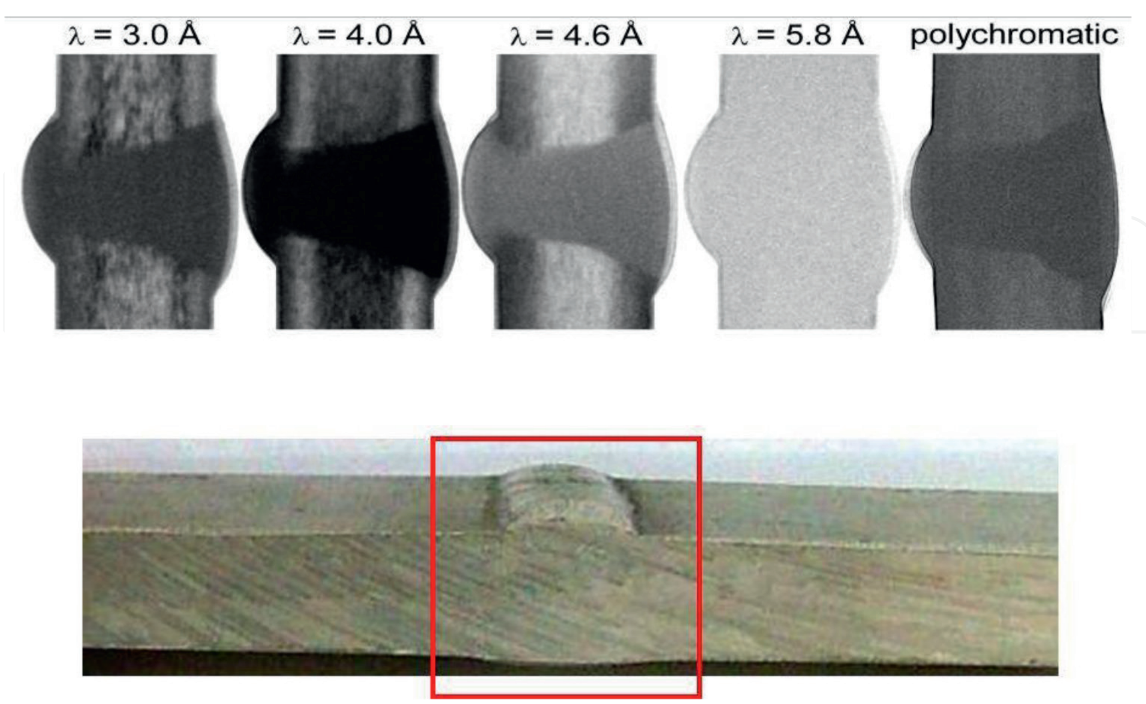

Figure 10.
Structural analysis by neutron imaging of a rolled Al sample near a weld using neutrons with different wavelength; at long wavelengths (5.8 Å) and in the polychromatic beam, no texture is visible, contrary to at other wavelengths.

Diffraction imaging is based on the detection of scattered neutrons to the side of a sample by means of detection systems around it. The transmitted beam is only used as a monitor to see where the initial beam hits the sample. This method is useful mainly for samples with large grain structures and for the characterization of single crystals.

A simple setup consists of a second imaging detector perpendicularly arranged to the transmission detector at the side of the sample. During sample rotation, regions of the single crystal are illuminated with neutrons, which fulfill the condition (1) and the out-scattered signal is registered [11]. As a practical case, turbine blades of high-performance engines can be studied for their homogeneity in the structure nondestructively. For samples with smaller crystallites, multiple spots are detected by a setup covering the forward and backward regions around the sample. If the sample is rotated, many diffraction patterns can be used to derive crystalline orientation and crystallite size [12].

Imaging with polarized neutrons is based on the neutron's property to carry a magnetic moment as particle. It is oriented antiparallel to the spin vector and has a value of about $-1.9\ \mu_n$, the nuclear magneton. Because of the spin value ½, two states (up and down) are possible. In a nonpolarized beam, the two states exist equally. However, it is possible to sort out one of the states with special absorbing filters [13], and the remaining state yields a "polarized beam."

When this beam hits samples with magnetic properties, the polarization of the neutrons can be changed. An analyzer device behind the sample can observe how many polarized neutrons have changed their orientation by the sample or by the magnetic fields on their way to the detector. Therefore, imaging with polarized neutrons is very useful to investigate magnets (e.g., under superconducting conditions at low temperatures) and also magnetic fields in a certain strength range.

Data fusion with X-ray images becomes possible because common digital detection systems are able to detect both radiations in pixelwise precision. However, since the interaction with matter of neutrons and X-rays, respectively, are different in principle, two independent image data sets are produced. While X-rays only interact with the electrons in the atomic shell, neutrons "ignore" all electrons and interact with only the atomic nuclei. The higher the mass number of the atoms and the number of electrons, the higher is the X-ray contrast. This is not the case for neutrons at all—the contrast of neutron interactions depends on the peculiarities of the structure of the involved atomic nuclei. Even very light isotopes like ^{1}H, ^{10}B, or ^{6}Li have a high attenuation power, cases in which additional neutrons can readily be incorporated in the respective nuclei; in addition, in simple billiard-ball physics, energy transfer is much higher when neutrons scatter with light nuclei.

Now, it is a question how to combine the two independently obtained data sets in order to enhance features and structures. A symbolic case is the study of moisture migration in porous media (stone, concrete, wood, soil, etc.). Here, the X-rays can probe the empty structure, while the neutron image is dominated by the water contrast [13].

8. Applications in neutron imaging

Because neutrons can penetrate heavy materials, in particular metals, better than X-rays, technical applications have a high importance. This enables many industrially relevant studies like of the fuel injection in running engines, the oil distribution in combustion motors, soot accumulation in particulate filters, water distributions in electrical fuel cells, and ion migration in batteries.

The quality assurance of explosives for civil applications (initiators in rockets and detonators in mining fields) can only be done with neutron imaging.

Also, the investigation of cultural heritage objects can take advantage of neutron imaging techniques, in particular when metallic samples cover some hidden organic material—see **Figure 4** [14]. This holds also for checking the corrosion status of old samples, including the monitoring of the success of anticorrosion treatments.

Scientific usage of neutron imaging methods is widely spread. It covers different fields, listed here without going into much detail. This chapter should only give an impression how powerful and important these techniques are.

- Geoscience: structural details, porosity, organic inclusions, and water permeability [15]
- Archaeology: status of find objects, conservation, and corrosion status
- Material testing: crack analysis, connections by welding, soldering, or gluing
- Nuclear materials: fuel integrity, cladding behavior, and hydrogen uptake
- Soil and plant physics: growing of roots, water uptake, and poison analysis
- Wood research: water absorption, annual ring density, and gluing connections
- Agriculture and Food studies: fertilizer distribution, freeze drying, and moisture
- Electrochemistry: fuel cells, batteries, electrolyzes, and agent distribution
- Liquid metal behavior: bubble motion, impact of magnetic fields, and freezing
- Paleontology: bone reconstruction, specific organs, and their development
- Building material studies: moisture uptake, water isolation, and corrosion of steel

9. Conclusions: future trend and outlook

Neutron imaging depends strongly on the access to suitable neutron sources. This method alone does not justify the construction and operation of large-scale facilities as spallation sources. However, in the "concert" with other important techniques like neutron scattering and fundamental research of the neutron itself (lifetime, electrical moment), neutron imaging with all its versatile features can play an important role.

In particular, the pulsed beam option of spallation neutron sources will enable a flexible and very efficient resolution of the neutron energy in the TOF operation of beam and detection systems. The direct combination with a diffractometer device is already considered at some places [16].

However, with lower beam intensities, we can perform some neutron imaging experiments. This has been demonstrated at weak sources operating in the few watts power range [17]. New sources on the basis of proton or deuteron accelerators are under consideration and are designed in countries where a renovation of research reactors is nearly impossible, mainly for political and ideological reasons [18].

Because of their uniqueness, neutrons will be used for investigations also in near, maybe also far future, as long as the neutron sources are available. In the meantime, further methodical progress is expected, and improvements in the detection methods, like single event counting, become available.

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A. Appendix

Neutron imaging facilities at large-scale neutron sources (Status Jan. 2023).

Institution	Country	Neutron source	Source type	Operation mode	Name of the facility	Neutron spectrum
TU Munich	D	FRM-2	reactor	stationary	ANTARES	cold/thermal
TU Munich	D	FRM-2	reactor	stationary	NECTAR	Fast/gamma
PSI	CH	SINQ	Spallation source	stationary	NEUTRA	Thermal
PSI	CH	SINQ	Spallation source	stationary	ICON	cold/thermal
PSI	CH	SINQ	Spallation source	stationary	BOA	Cold
JPARC	JP	MLF	Spallation source	Pulsed 25 Hz	RADEN	Cold
NIST	USA	NCNR	reactor	stationary	BT-2	Thermal
NIST	USA	NCNR	reactor	stationary	NG-6	Cold
ILL	EU, F	ILL reactor	reactor	stationary	NEXT	Cold
ANSTO	AUS	OPAL	reactor	stationary	DINGO	Thermal
ESS	SWE, EU	ESS	Spallation source	Pulsed 14 Hz	ODIN	Cold
ORNL	USA	HFIR	reactor	stationary	CG-9	Cold
ORNL	USA	SNS	Spallation source	Pulsed 60 Hz	VENUS	Cold
Rutherford Lab	UK	ISIS	Spallation source	Pulsed 10 Hz	IMAT	Cold
KFKI	H	WWS-M	reactor	Stationary	NORMA	Cold
KFKI	H	WWS-M	reactor	Stationary	NRAD	Thermal
JINR	RUS	IBR-2	Pulsed reactor	Pulsed 5 Hz	NR	Thermal
NECSA	ZA	SAFARI-1	reactor	stationary	SANRAD	Thermal

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