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Status and perspectives of neutron imaging facilities

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Abstract

The methodology and the application range of neutron imaging techniques have been significantly improved at numerous facilities worldwide in the last decades. This progress has been achieved by new detector systems, the setup of dedicated, optimized and flexible beam lines and the much better understanding of the complete imaging process thanks to complementary simulations. Furthermore, new applications and research topics were found and implemented.

However, since the quality and the number of neutron imaging facilities depend much on the access to suitable beam ports, there is still an enormous potential to implement state-of-the-art neutron imaging techniques at many more facilities. On the one hand, there are prominent and powerful sources which do not intend/accept the implementation of neutron imaging techniques due to the priorities set for neutron scattering and irradiation techniques exclusively. On the other hand, there are modern and useful devices which remain under-utilized and have either not the capacity or not the know-how to develop attractive user programs and/or industrial partnerships. In this overview of the international status of neutron imaging facilities, we will specify details about the current situation.

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1. Introduction: history & relation to X-ray imaging

With respect to the approach in transmission imaging and the abilities for non-destructive testing, neutron imaging is closely linked to the developments in the X-ray field. Historically, the neutron aspects were handled much later than those in the X-ray case, as indicated by the milestones in Fig. 1.

Roughly, the period between the availability of free neutrons, in particular thermalized and well collimated ones, and about 1990 is dominated by the application of film methods in various configurations (different converters, films, direct-indirect, track-etch foils, …). Mostly, the radiography mode was applied and the inherent resolution was more limited by the beam properties than by the detection system itself. Films have inherently a high spatial resolution capability but other disadvantages (non-linearity, limited dynamic range, gamma-sensitivity and low efficiency).

A few beam lines were made available at research reactors for specific investigations of technical relevant components (explosives, turbine blades, nuclear fuel, aircraft wings, …), some of them with a clear commercial or safety/security background.

Since the 90ies, several new detector systems have been developed and introduced into the routine work in both X-ray and neutron imaging. Whereas the reduction of the dose to the human body during medical inspections was the major aspect for more efficient detection system for X-rays, the needed long exposure with film (accompanied with high sample activation) at relatively weak neutron sources motivated the developments for higher efficiency in neutron imaging. In several cases, the already established systems for X-ray imaging were adapted to the neutron conditions best possibly.

Fig. 1: Time line with the developments in the field of X-ray and neutron research with particular emphasis to the imaging aspects (with examples of relevance for the Swiss authors)

Since these early days, we have now the following digital imaging systems available:

- Imaging plates: seen to be a replacement to films, but are more efficient, have linear response, are re-usable after erasure, have high spatial resolution (e.g. 25 µm pixel size) and high dynamic range [1].
• Image intensifier tubes coupled to video camera systems, mainly used in the radioscopy mode for time-dependent studies [2].
• CCD or CMOS cameras optically coupled to scintillator screens with variable field-of-view (FOV); this is the most common, flexible and very sensitive system for the moment, available in different configurations and versions [3] (see the example in Fig. 2).
• Amorphous silicon flat panels with scintillation converter screens on top of the active sensor [4], placed into the direct beam.
• Pixelated detectors with micro-channel plate structured converters or just neutron-to-radiation converter layers (B-10, Li-6 or Gd) in front of the active semi-conductor matrix, direct exposure [5].

Based on this new generation of neutron imaging devices a process for more advanced and sophisticated imaging method was initiated. The aims are a better quantification of the sample content, the access to the third dimension of objects (tomography), the use the information from the scattered beam component, the better tuning of the beam conditions (spectrum, collimation, coherence) and the understanding of the whole transmission process by using simulation tools – in comparison to experiments under well-defined conditions. In this digital era the whole power of image processing tools can now be applied best for the extraction of most suitable information from the neutron interaction process.

Fig. 2: The PSI-MIDI box as example for a setup with moderate FOV (6 cm … 15 cm) usable with different camera configurations with the standard setup: scintillator screen, mirror, lens, sensor)

2. Neutron Sources

The neutron source is the essential (and most expensive) component of a neutron imaging setup. Commonly, a most intense and well-collimated beam of thermal or cold neutrons is required to perform state-of-the-art neutron imaging today. This spectral range delivers the most interesting contrast variation, complementary to the X-rays in many cases.

Because the spatial and the time resolution depend much on the beam intensity, the beam ports have to be placed at the strongest neutron source possible. If narrow energy bands have to be selected from the beam, the demands for high beam intensity are further increased.

Such strong sources are either reactor based or spallation neutron sources. Unfortunately, the sources for scientific use do not all accept the access to the most suitable beam ports yet for imaging purposes. However, in several recent cases it was possible to build an imaging facility from scratch along with the installation of the source itself as a “day one” instrument. Such a positive case can be found at the FRM-2 reactor
(München/Garching/Germany) with the facilities ANTARES (cold neutrons) and NECTAR (fast neutrons) (Fig. 3) which were designed and built in the very early stage of this reactor project. It is the perfect way to go since the performance is tuned already very close to the initial source itself.

Fig. 3: Layout of the instruments at the FRM-2 research reactor with the two imaging facility highlighted (ANTARES=cold, NECTAR=fast neutrons); source: MLZ homepage

Apart from the beam intensity, the collimation, the most suitable spectral range, the reduction of background from gamma-radiation and from higher neutron energy contributions has to be chosen efficiently in the design. Although there are experiences gained over the years, each neutron imaging facility has been built individually and can only be compared in an evaluation process (see chapter 5).

There are other cases of beam lines in use for imaging which were just taken while available and tuned as good as possible [6]. In such cases, several compromises have to be taken into account and the outcome of the neutron image data acquisition cannot be optimal, but acceptable in some cases.

Tremendous developments been done in the X-ray field by the implementation of synchrotron sources. Their intensities are far above what the neutron sources will ever reach. Even the X-ray tube technology has been developed further much. Therefore, it is a real challenge and need to get access to the most powerful and modern neutron sources (see chapter 4) to be competitive to the X-ray imaging community.

In the framework of an IAEA/ISNR initiated survey, 48 neutron imaging facilities were identified and characterized, but only about 15 can be considered to be “state-of-the-art” today [7]. Contrary, the IAEA “Research Reactor Data Base” [8] counts 246 operating research reactors, from which 74 declare to perform neutron radiography. The distribution in regions is shown in Fig. 4. “Eastern Europe” facilities does not reflect at all their participation and contribution to the neutron imaging community. Although 160 reactors have an age of more than 40 years and non-negligible risk to stop their operation in the short future, we see a potential in the order of 100 research reactors where neutron imaging facilities could be implemented. Indeed, it has been shown in several cases that the reactor power is not the only limiting factor to perform neutron imaging, although high neutron fluxes enable fast, high resolution and high quality data acquisition.

In several cases the reactors are not efficiently used and the implementation of a neutron imaging facility would enhance the whole performance and can also be used as a trainings tool very easily.
3. Design & characteristics of neutron imaging facilities

The design goal for a neutron imaging facility is the illumination of a sample with a well collimated (nearly parallel) beam of suitable dimension (just a little larger than the sample) with neutrons of well-defined energies, equally distributed over the field-of-view (FOV) of the detector which is closely placed behind the sample. A strongly divergent intense beam generated by X-ray micro-focus tubes and very useful for a magnifying illumination, is unfortunately not feasible for neutron sources due to the missing local neutron intensities.

Until now, almost all of the beam lines have a stationary continuous neutron delivery. A dedicated time structure of the beam can be useful for a separation of different neutron energies according to the “time-of-flight” (TOF) principle: the early arriving fast neutrons are separated from the later arriving slow neutrons in the time-dependent neutron detector. This beam structure can be managed with the help of chopper devices, but the intensity in the beam drops down by orders of magnitude. Therefore, the approach with a pulsed neutron source is much more attractive and relevant since the source provides already the pulse structure and the intensity in the pulse is huge. Such sources are already operational in UK (ISIS), USA (SNS), Japan (JPARC) and Russia (IBR-2) and under construction in Lund, Sweden (ESS). While the Russian source is reactor based, the other ones are spallation neutron sources. Most of them are already equipped with neutron imaging beam lines, at the others we have projects running (see chapter 4).

Although the individual design of neutron imaging facilities can be quite different, they contain most of the components sketched in Fig. 5. The main structure can be divided into: source, beam and detector parts, with the sample in close contact.

The optimization of all components can be done on the basis of the knowhow of experienced facility builders or operators. Compared to older established beam lines with a reasonable but fixed collimation there are new aspects with variable apertures. New beam tuning devices are energy selectors, polarizers and grating interferometers which enable advanced imaging procedures.

Another new aspect is the use of additional X-ray systems aligned along or perpendicular to the neutron beam direction for the principle of “data fusion” with the neutron image data (pixel/voxel wise) [9]. The major effort is given to the detection system and the experimental infrastructure. All the detector options mentioned in chapter 1 have to be considered and adapted in the most suitable configuration under the respective beam conditions.
4. New approaches, installations and upgrades

All attempts for the implementation of new neutron imaging capabilities have to be seen in a global context due to the limited number of sources spread over the world. In the best case, new facilities are organized as “user lab” and accessible by the world-wide community.

The above mentioned installation process of pulsed spallation sources was taken as a reason for a workshop series on energy-selective neutron imaging taking place yearly since 2008 (NEUWAVE workshops 1-8 [10]). This initiative resulted now in the construction and inauguration of the facilities RADEN (JPARC, Japan) [11] and IMAT (ISIS-TS2, UK) [12]. There are projects running for VENUS (SNS, USA) and ODIN (ESS, Sweden) with the time line to be finished before 2020.

New research reactor based projects are on the way in Argentina and in Jordan, where neutron imaging will be a “day-one” installation. Other initiatives, upgrade measures and projects are summarized in Table 1 and 2. Some information was gained during a dedicated experts meeting in Vienna in March 2016 [13].

A very positive example of a straightforward and promising installation for neutron imaging is the new beam line at the pulsed reactor IBR-2 in Dubna, Russia (see Fig. 6). It was realized within the period of several month only with limited but pragmatic inhouse effort. Already in integrating mode (white beam), interesting and convincing results were obtained. The further development at that beamline should be to use the full capability for time-of-flight-studies in neutron imaging mode. Some neutron imaging detector developments and beam tuning devices (choppers) are required for this purpose.
Fig. 6: Layout of the IBR-2 pulsed reactor (Dubna, Russia) with the NRT facility indicated by an arrow (source: private communication)

Table 1: Overview of spallation neutron source based neutron imaging activities and installations

| name     | source | country | status            | readiness |
|----------|--------|---------|-------------------|-----------|
| NEUTRA   | SINQ   | CH      | user operation    | 1997      |
| ICON     | SINQ   | CH      | user operation    | 2008      |
| BOA      | SINQ   | CH      | shared operation  | 2013      |
| RADEN    | JPARC  | Japan   | user operation    | 2015      |
| IMAT     | ISIS-TS2 | UK     | facility test     | 2016      |
| VENUS    | SNS    | USA     | project           | 2018?     |
| ODIN     | ESS    | Europe  | project           | 2019?     |

Table 2: New approaches for neutron imaging at reactor based neutron sources

| reactor based projects for neutron imaging facilities |
|-----------------------------|-----------------|-----------------|-----------------|
| **country** | **source** | **facility** | **site** | **status** |
| Argentina   | RA10           | NI              | Boenos Aires  | project      |
| Czech Republic | LVR-15       | NI              | Rez near Prague | considerations |
| PR China    | CARR           | 2 NI            | Beijing       | project      |
| France      | ORPHEE         | IMAGINE         | Saclay        | operational  |
| Europe      | ILL            | D50             | Grenoble      | shared with reflectometer |
| Norway      | JEEP-II        | NI              | Kjeller       | upgrade project |
| Netherlands | Delft RR       | FISH            | Delft         | project      |
| Jordan      | new reactor    | NI              | Jordan        | "day one" project |
| South Africa | SAFARI        | SANRAD-II       | Pelindaba     | upgrade project |
| Russia      | IBR-2          | NI              | Dubna         | improvements |
| South Korea | HANARO RR      | NI              | Daejon        | upgrade project |
5. Outlook

It is the intention to develop neutron imaging techniques further, to implement them at as many as possible suitable sites and to apply them for many more practical and scientific cases. There are many positive trends already seen, but some more efforts are needed to succeed in this process.

On the other hand, it is time for evaluation and certification procedures in order to compare the performance of different facilities and of the resulting image quality. Previous such attempts in the framework of ASTM [e.g. 14] where exclusively based on film technology and have to be updated to digital detection systems. For the evaluation of spatial resolution there are already some test devices available [15]. IAEA initiated Specialist’s Meetings for the continuation of the standardization process and round robin samples have been developed [16]. They are under further improvements and suited for also tomography applications.

The International Society for Neutron Radiology (ISNR) is the current and future platform for exchange of knowledge in the field of neutron imaging, in particular by organizing the major conferences (series WCNR, ITMNR, NEUWAVE) [17].

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