

What Future in Neutron Imaging?

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Keywords: Neutron Imaging, Neutron Sources, Beam Ports, Neutron Detection, Image Processing

Abstract. We describe the current situation of the neutron imaging technology, based on known “user facilities” and projects at prominent neutron sources world-wide. Although this method has become highly accepted, there is a great potential for further methodical and technical progress. Continued access to most suitable beam ports and future neutron sources are keystones for the future of neutron imaging. Promising new methods and prominent new applications are stimulating this process.

Introduction

Neutron Imaging is today a well-established technique for scientific and technical applications. It is very complementary to similar X-ray methods and can often be used symbiotically [1]. The layout of a dedicated imaging beam line should be based on state-of-the-art technologies and the valuable experience of facility operators. The future of this technique will depend on the continuous access to best suitable beam ports at present and future useful neutron sources.

This paper starts with a “generic neutron imaging facility”, will reflect the situation on neutron sources and their developments, have a look onto new facility projects and upgrades of existing ones, describe options for best facility utilization and highlight the methodical progress and other new options in neutron imaging.

The generic neutron imaging facility

As shown in Fig. 1, a generic neutron imaging (NI) facility consists of four major components: the neutron source, including moderation media and filters, the beam forming equipment (collimation), the sample environment and the neutron imaging detector.

Modern NI stations [2] have become quite complex and sophisticated systems if all modern trends in this technology should be involved. Depending on complexity level and desired performance, the investments required are in the range from some ten thousands to some ten millions of Euros [3].

The technical level of a NI installation depends on the lab strategy, framed by the funding, the major applications and the demands of the user community [4]. The available facilities can be categorized roughly into four classes:

1. Operational user labs, open for an international access by scientific and industrial partners
2. Operational in-house and test facilities, mainly used by own researchers for domestic projects

3. On-going new NI installation projects or facility upgrade activities
4. Projects under considerations for potential new or upgrade facility installations

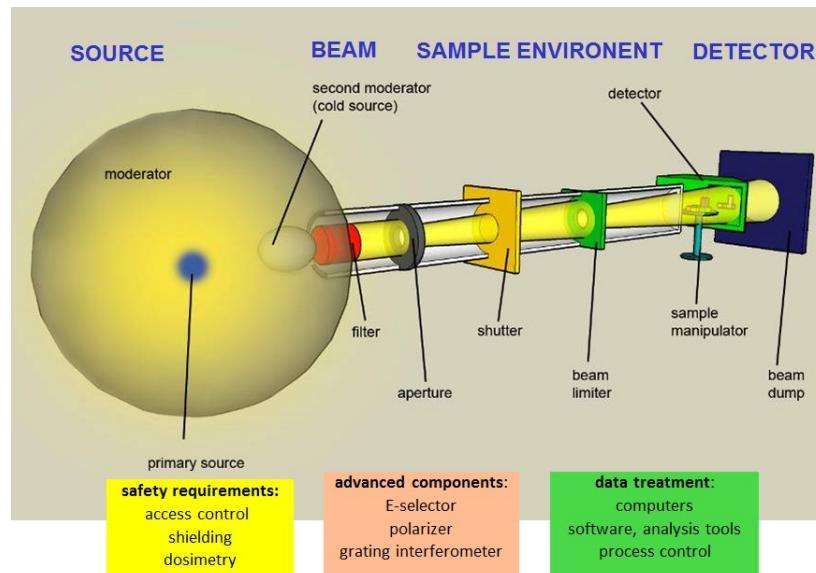


Fig. 1: Layout of a generic neutron imaging facility with the major components and supplementary features

The determining conditions underpinning the most advanced NI systems are:

- Well collimated (high L/D-ratio) neutron beam
- Beam size adequate to the sample dimensions
- High neutron beam intensity
- Narrow energy band (thermal or cold), well-known spectral conditions, necessary for quantification
- Low background from gamma rays or fast neutrons in the primary beam
- Flat beam profile
- No interference from back-scattered neutrons (and process gammas)

In general, a high intensity neutron beam is required to achieve the highest temporal, spatial or spectral resolution in a reasonable acquisition time. In addition, many more sophisticated techniques are possible in reasonable acquisition time when the intensity is suitable.

Neutron source development

From all options for the generation of neutrons, until now the research reactors remain the most common, flexible, powerful and even cost-efficient sources of neutrons. They are also by far the majority of the sources where NI stations are presently located and utilized. There exist a few intensive spallation neutron sources as well as other accelerator based neutron sources with lower output of well collimated beams of moderated neutrons. One notes separately that isotopic neutron sources have by far no chance to compete in NI performance when compared to the above mentioned accelerator or reactor based facilities.

The development of the NI technology has to be seen in a global context. In order to develop, apply and utilize modern techniques, the access to well-suited beam ports is necessary. As a general trend, the number of appropriate neutron sources is decreasing in developed countries, but more are being installed in developing countries. On the other hand, the most advanced NI facilities are still situated in a few labs in developed countries. Therefore, the knowledge transfer towards the newly implemented facilities is essential for the progress in the field and broader access for usage of the technique.

Fig. 2 describes well the world-wide situation of operational research reactors as summarized in the IAEA Research Reactor data base [5]. From the currently running research reactors with a suitable power above 100 kW, 75 facilities declare to perform “neutron radiography”. Since no detailed specification is given in the data base for many facilities, it is difficult to estimate on which technological level these installations are.

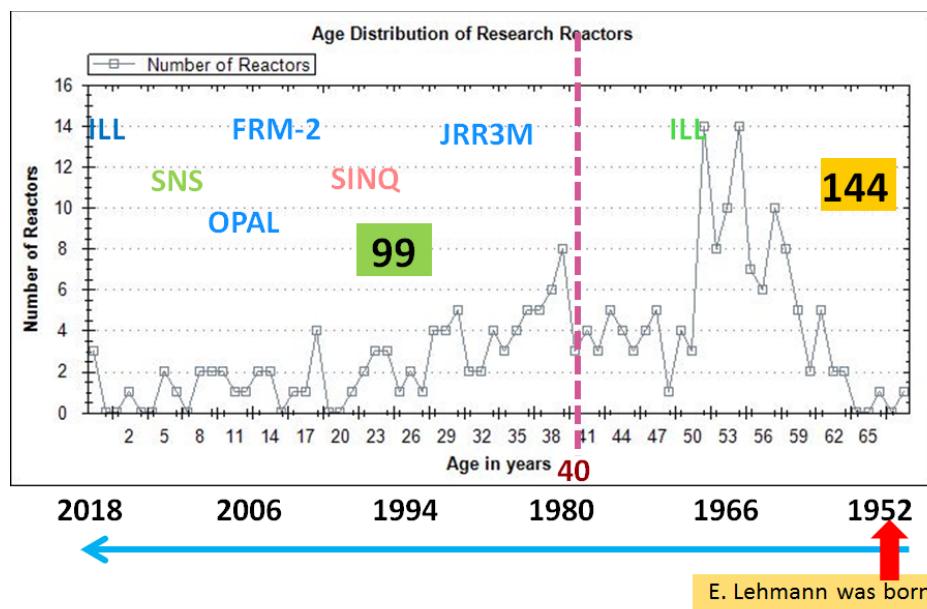


Fig. 2: Number of newly commissioned research reactors per year in an inverse time scale: more than 140 have an age of more than 40 years. Some famous sources are highlighted (ILL is indicated twice since NI started just now – 50 years after its startup); SINQ and SNS are not reactors, but spallation neutron sources – shown for comparison. The data are taken from the IAEA RR data base, see: <https://nucleus.iaea.org/rrdb>.

The show examples are by far not complete, but indicate some milestones for the imaging community.

A more pragmatic way for data achievement about NI facilities has been made by the “International Society for Neutron Radiography (ISNR)” survey as published on their homepage [6]. A list of “user facilities” can be found in [7], but an update will be given in the appendix.

Only few research reactor installations are expected to come to operation in the next years, while aged reactors will continue to shut down for different reasons. On the other hand, all spallation sources (ISIS, JPARC, SNS, ESS) involve NI as a key technology in dedicated projects, while SINQ already operates a few different stations [8] since many years with great success.

The situation within Europe is illustrated by Fig. 3 and the number of NI facilities (running and projected) is added. A similar analysis is not available for the rest of the world in the same quality.

Given the fact that new reactor based sources are not presently being built or planned in the Western world, there are initiatives to evaluate and design accelerator based neutron sources with specific performance, e.g. “high brilliance” [9] customized for specific applications. Also in such cases, NI installations are or could be foreseen from the beginning.

New installations and upgrades of NI facilities

Most of the prominent and powerful neutron sources have been “taken” by the neutron scattering community, by irradiation experiments for nuclear technologies, including isotope production and silicon doping. Therefore, only a few most suitable beam ports remained available and used for NI facilities in the past.

The situation has changed slightly after the development, at the end of last century, of digital imaging detector systems with superior performance compared to film based methods. It was possible to make very competitive installations ready in Japan, Europe and America, and more recently in Australia. Based on that progress, the family of “user facilities” has been established which have a similar operational approach now like neutron scattering instruments.

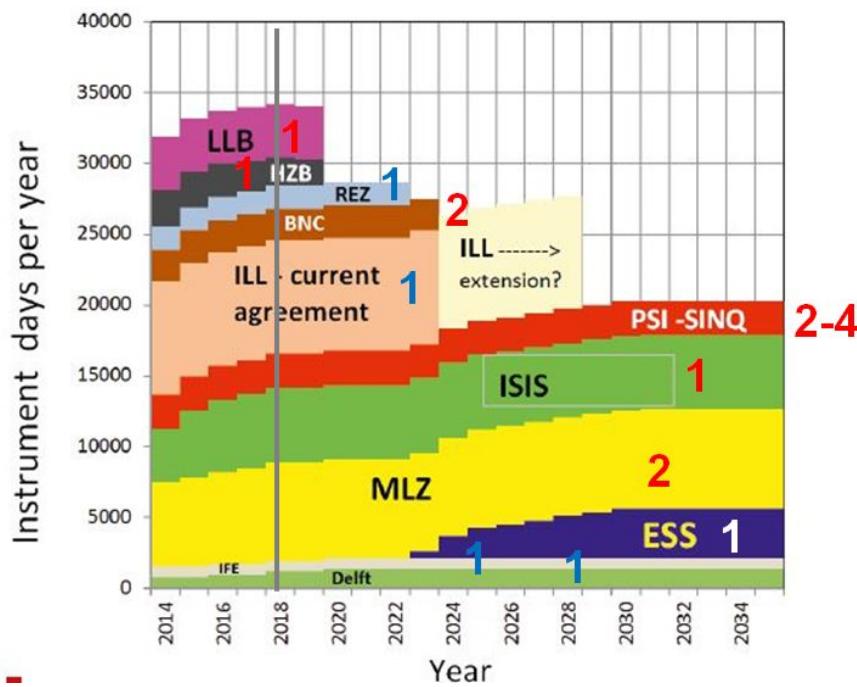


Fig. 3: Neutron sources in Europe (data base: [6]); the numbers indicate existing (red) and planned NI facilities

New sources tried to follow this trend already at the planning stage, including CARR in China, and planned NI facilities in reactors in Argentina, Jordan and Brazil.

Other countries, operating a research reactor for a long time, intend now to rebuild beam ports into NI stations or intend to make a major upgrade, e.g. South Africa and Indonesia. The level of performance these new setups will have depends on the financial situation, the involved

(qualified) manpower and the particular source conditions. Tables 1 to 3 summarize the particular activities where the categories 2-4 as mentioned above are taken.

Table 1: In-house and test facilities, mainly for own projects

country	source	situation
Thailand	reactor TTR-1, 2 MW	NI exists, limited user program
India	reactors at BARC	high potential, but limited communication with NI community
Indonesia	reactor RSG-GAS, 30 MW	NI exists, limited user program
Canada	reactor McMaster, 5MW	commercial activities, limited research
France	reactor Orphee, 14 MW	facility IMAGINE, limited user operation, shutdown after 2019
Europe	reactor @ ILL, 58 MW	a facility at cold beam port D50 under preparation, some users
Egypt	reactor ETRR-2, 22 MW	NI exists, limited user program
Brazil	reactor IEA-R1, 2 MW	NI exists, limited user program
Bangladesh	BAEC TRIGA reactor, 3 MW	NI exists, limited user program
Russia	several research reactors	IR-8, IRT-T, some NI exists
Poland	reactor MARIA	NI exists, limited user program

Table 2: Running NI installation projects and upgrade activities

country	source	situation
Argentina	reactor RA-10, 30 MW	NI facility as day-one installation, completion in 2020
Brazil	new reactor like RA-10	planned and funding provided
Czech Republic	reactor LVR-15, 10 MW	NI facility with limited performance, upgrade intentions
China	reactor CARR, 60 MW	two imaging facilities under preparation
Norway	reactor JEEP-II, 2 MW	NI facility upgrade
Netherlands	reactor HOR, 5 MW	NI facility planned, preliminary setup exists
South Africa	reactor SAFARI, 20 MW	upgrade of the SANRAD facility
South Korea	reactor HANARO, 30 MW	operational again, utilization programme not yet started
USA	Idaho RR, 250 kW	upgrade program for digital NI

Table 3: Potential options and intentions for installations

country	source	situation
Marocco	TRIGA reactor, 2 MW	NI facility planned
Malaysia	TRIGA reactor, 1 MW	NI facility exists, starting with digital system, limited communication
Algeria	reactor NUR, 1 MW	NI facility exists
Chile	reactor RECH 2, 10 MW	reactor out of operation, lack of manpower for NI
Peru	reactor RP-10, 10 MW	NI possible
Slovenia	TRIGA reactor, 250 kW	NI program stopped
Uzbekistan	reactor WWR-SM, 10 MW	NI not existing, but under consideration.
Russia	reactor PIK, 100 MW	operation unclear
Jordan	reactor JTRR, 5 MW	NI facility planned, reactor operational
Mexico	reactor TRIGA, 1 MW	NI considered

Best utilization

With the improvement of the detector technology also the utilization of the beam lines has been increased enormously. This gives the opportunity to perform much more investigations in shorter time while with an increased data volumes (towards the Tera-Byte region already).

In this manner, partners from different research areas can be invited for dedicated studies, with customized infrastructure and equipment. The same is valid for industrial partners on a

commercial basis. Prominent cases are studies for fuel cells, batteries, particulate filters or electronic devices [10].

Since the number of such “user facilities” (see appendix) is still low and there are planned or unplanned shutdowns of these sources, a good communication and coordination between the facility operators will help to serve the increasing user community best.

Methodical developments & new applications

Starting with simple radiography studies many more advanced techniques have been developed and were introduced into the common user program in the meantime. It started with neutron tomography on a competitive level with X-rays and involved the fully quantitative analysis such as for precise water determination.

A very recent approach is “grating interferometry” which enables to study phase contrast and dark image features in samples with structures in the micro-meter range, linking to small-angle scattering studies.

In the dynamic imaging, either high frame rates are possible now (depending on the beam intensity, up to 100 Hz and more) or triggered stroboscopic investigations of repetitive processes. Due to the magnetic moment of neutrons, the separation of one of the two spin states (polarization) enables studies of magnetic properties on the macroscopic scale [11].

The separation of tiny energy bands of the initial beam has many advantages, in particular for crystalline materials with pronounced Bragg scattering behavior. It has been realized to study textures, crystal orientations and even internal stress with energy-resolved options. The use of time-of-flight techniques at pulsed sources will provide even better conditions in this respect.

Conclusions

Neutron imaging has made an enormous progress in the past years, but in limited number of labs only. Now, there is a challenging need to transfer this know-how to other suitable neutron sources and to increase the network within the neutron imaging community. The access to prominent and new installations is mandatory for the progress and strengthening of neutron imaging in the future.

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Appendix: NI user facilities world-wide

country	site	institution	facility	neutron source	spectrum	power [MW]	status
Australia	Sydney	ANSTO	DINGO	OPAL reactor	thermal	20	operational
Germany	Munich-Garching	TU Munich	ANTARES	FRM-2 reactor	cold	25	operational
Germany	Munich-Garching	TU Munich	NECTAR	FRM-2 reactor	fast	25	operational
Germany	Berlin	HZB	CONRAD	BER-2 reactor	cold	10	operational
Hungary	Budapest	KFKI	NORMA	WWS-M reactor	cold	10	operational
Hungary	Budapest	KFKI	NRAD	WWS-M reactor	thermal	10	operational
Japan	Kyoto	Kyoto University	imaging beamline	MTR reactor	thermal	5	standby
Japan	Tokai	JAEA	imaging beamline	JRR-3M reactor	thermal	20	standby
Japan	Tokai	JAEA	RADEN	JPARC spallation	cold	0.5	operational
Korea	Daejon	KAERI	imaging beamline	HANARO reactor	thermal	30	standby
Russia	Dubna	JINR	imaging beamline	IBR-2M pulsed reactor	thermal	2	operational
Switzerland	Villigen	PSI	NEUTRA	SINQ spallation	thermal	1	operational
Switzerland	Villigen	PSI	ICON	SINQ spallation	cold	1	operational
UK	Oxfordshire	Rutherford Lab	IMAT	ISIS spallation	cold	0.3	operational
USA	Gaithersburg	NIST	BT-2	NBSR reactor	thermal	20	operational
USA	Gaithersburg	NIST	NG-6	NBSR reactor	cold	20	operational
USA	Oak Ridge	ORNL	CG-1D	HFIR reactor	cold	85	operational
South Africa	Pelindaba	NECSA	SANRAD	SAFARI reactor	thermal	20	standby