International NR Newsletter

No. 16 December 2020

International Society for Neutron Radiography

(www.isnr.de)

Content

Early evening in Munich downtown, December 2020

Editorial

Dear members of the ISNR, dear colleagues and friends,

originally an image of our ITMNR-9 meeting in Buenos Aires, Argentina, to take place in autumn 2020, was planned for the front cover of this NR Newsletter. But everything turned out differently. As you all know, ITMNR-9 had to be postponed, based on intense discussions by the organizers and the Board of Members in July. The uncertainties concerning organization of the meeting, already existing and upcoming possible travel and contact restrictions etc. were too large to be neglected. The actual situation has finally confirmed the decision. Meanwhile I have participated several virtual, hybrid and physical presence meetings, the latter by keeping personal distances and hygiene regulations, by wearing masks, by regular ventilation of meeting rooms and drastical reduction of the number of participants. Yes, these forms of meetings are working, but to my opinion a very important part of a meeting is lost: the direct and personal communication (even in the aforementioned face to face meetings due to the limitations). This is - at least for me - in most cases the essential and most valuable part of a meeting. Based on the presentations, where subsequently usually only a few short questions are possible, in the breaks, at lunch or dinner, in the evening or during conference walks new ideas and/or questions on details can be discussed, new (international) projects or collaborations may be initiated etc. Particularly for colleagues new to the field of neutron imaging, these face to face meetings give them the nearly unique chance to establish their personal networks and to contact experienced persons in neutron imaging directly for help and/or advise.

Despite the missing face to face meetings, several members of the ISNR contributed again in the preparation of this NR Newsletter. This time we have a large section with articles from industrial companies, often created in cooperation with scientific partners from research centers, demonstrating the working(!) transfer of information from research to application. Together with the contributions “Out of the Lab” I am convinced to present you an interesting overview on the actual situation in neutron imaging.

Coming back to the cover image. I selected a photo of the Munich townhall with the Christmas tree. The photo was taken on the 20. December 2020 at about 19:00 o’clock, a time the Marienplatz (place in front of the townhall) usually is quite crowded. If you look on the upper part of the tower you see a chime, showing dancing coopers. Their dance, called the Münchner Schäfflertanz, is proven first in the year 1702. The legend says, that the dance was first performed in 1517 during an epidemic plague to soothe the population, that rarely dare to leave their homes due to the plague, and to revitalize public life.

With the hope that the coopers will start dancing in the streets all over the world soon, I wish you all the best for 2021 and hope to have the chance to meet you at one or another place again.

Best regards

Thomas Bücherl

Words from the ISNR President

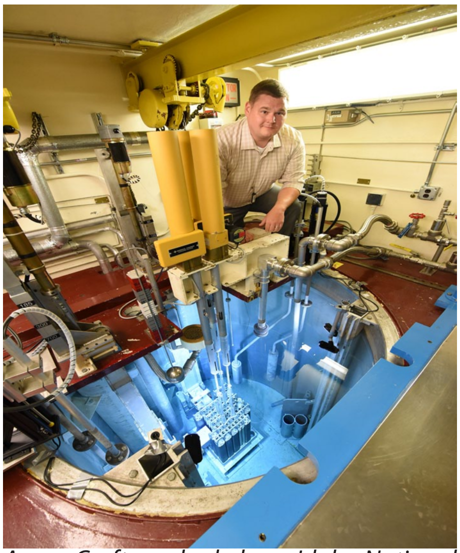
"May you live in interesting times," they said. Interesting times, indeed!

I hope that you all escape hardships and remain healthy during this Covid pandemic.

For some, neutron sources are unavailable, and work has slowed or even stopped. For many of us, work continues despite the times, interesting though they may be.

Large research facilities continue performing experiments, some even still accepting users in person. Many of you have been very productive in publishing your work, presumably an ironic benefit of time available during lockdowns. Many of you who have experienced a shortage of neutrons have focused on developing new and improved instrumentation. Commercial providers of neutron radiography for industrial applications are seemingly busier than ever before. Students are continuing to perform their research and graduate. All this despite the Covid pandemic. The world-wide neutron community appreciates your individual resilience and continued efforts.

The IAEA has launched a new e-learning course aimed at young specialists, technicians and analysts on neutron imaging to help increase the use of research reactors, and to preserve the skills of an aging workforce. A link to this new E-Learning course is available on the ISNR website (www.isnr.de).


Aaron Craft perched above Idaho National Laboratory's Neutron Radiography Reactor (NRAD).

The ISNR's primary mission is to facilitate communications and interactions among our growing worldwide community, which is primarily accomplished through our international conferences, including the International Topical Meeting on Neutron Radiography (ITMNR) and World Conference on Neutron Radiography (WCNR), and workshops such as the workshop series on NEUtron WAVElength Dependent Imaging (NEUWAVE).

The ISNR is not immune to the same scheduling issues that have caused virtually every other organization to reschedule meetings and conferences. Due to the Covid pandemic, the ITMNR-9 Organizing and Scientific Committees together with ISNR have decided to postpone the meeting to sometime in 2022. We will follow the evolution of events and will announce the new date for the meeting as plans develop. Planning for NEUWAVE-11 is ongoing, to be held in Mito Japan with tentative dates in October 2021. The WCNR-12 will be held in 2024 in the United States.

In addition to the ISNR meetings, there are occasionally special issues of journals and conference sessions specifically related to our field that can enable us to exchange ideas and collaborate. Please let the ISNR Board know about such venues as you discover them so we can distribute this information to the rest of the ISNR Community. In lieu of in-person meetings, the ISNR Board is considering approaches to facilitate electronic communications, which may include webinars and/or recorded presentations being made available on the ISNR website (www.isnr.de).

This 16th edition of the ISNR Newsletter includes interesting news from around the world, including summaries about new instruments, new imaging hardware, scientific outputs, and new beamline facilities. This Newsletter includes contributions from some vendors that produce instrumentation and hardware for neutron imaging, which I hope many of you will find useful in the development of your own neutron imaging capabilities. For neutron imaging users, I hope you find the scientific outputs summarized in this Newsletter to be inspiring for your own future applications.

Wishing you all continued health, and with best regards,

Aaron E Craft

Aaron Craft
ISNR President

NI in Industry

How to find your best-suited scintillator screen for imaging applications?

Neutron imaging detectors based on a very light-sensitive camera, which observes the emitted light from a scintillator screen have become a standard tool at many facilities. Meanwhile, there are systems available for very large field-of-view (FOV), very high spatial resolution, high frame rate and those for sophisticated new methods. Each of them has specific requirements in particular related to the scintillator screen - one of the key components.

Looking back into the history of neutron imaging, it was until about 1995 that neutron radiography was performed with film methods exclusively. Besides the long exposure and development time needed per image, there were no real options for post-processing, data transfer and quantification. After some digitalization with through-light scanners, only 8 Bit dynamic ranges were available. The data were by far not linearly related to the exposure.

By the availability of cooled CCD cameras from the astrophysics community, an option to make exposures lasting for many seconds to minutes, with low noise background became available. However, these devices have to be cooled – in the beginning with liquid nitrogen. The pixel number was 512*512 or even less.

At these times, only basic, non-optimized scintillator screens were available, because neutron imaging was rather exotic and never a “big thing” for the supporting industry. The disadvantages of these early screens were not only their large thickness (0.3 … 0.5 mm), limited homogeneity, unsatisfactory light output but also their gamma-sensitivity.

Because other neutron imaging detection systems were developed at the same time (Imaging Plates by Fuji, a-Si flat panels by several X-ray companies), there was competition at least for the radiography mode. Although it was hard to compete in spatial resolution, the other advantages with the camera based setups, as the immediate digital output and its flexibility were obvious.

One driving force to improve scintillators and the camera-based detector systems in general, was the introduction of neutron tomography, which required a locally fixed detection system under all conditions while the sample was rotated. Since all big companies denied requests to improve their scintillator products, PSI took over the initiative to develop and to produce their own screens with better performance. They found a small company in

Switzerland (RC Tritec Ltd., Teufen) with experience in light emitting materials and with equipment to produce small layers with good homogeneity of the scintillation material.

Over the years, this development and production was improved and expanded. The manufactured screens are exported all over the world. Now the costumer can choose among different scintillator materials, their thickness, the size and shape of the panel. Therefore it is important to give a guideline to the users which screen is the best possible choice for a specific setup and its application.

The requirements for scintillator screens are mainly about high sensitivity (in order to use the neutrons most efficiently), high spatial resolution, the spectrum of the emitted light (to fit the maximum detection efficiency of the camera sensor). In long-term use it is also important to keep the stability in the light emission high (low burnup) and to have short decay times (afterglow) after exposure.

With respect to the used neutron spectra, thermal and cold neutrons are most important and dominate in the applications. However, for larger objects and specific applications, also epi-thermal neutrons and fast neutrons have advantages. For these applications, another class of scintillators has had to be developed and introduced into the practical use.

Because neutrons are uncharged particles, they do not induce ionization processes directly. Therefore, a primary nuclear reaction is needed to initiate countable events. In the thermal and epi-thermal spectral range, the capture of the neutrons by strong absorbers is the dominating conversation reaction. It has been found, that either Li-6 or Gd are the most promising absorber materials for scintillators. B-10 or Cd were lacking in efficiency and were found so far to provide only insufficient performance.

It has been demonstrated in several tests, that the combination of Li-6F with specially doped ZnS enables the highest neutron-to-light conversion. Therefore, such screens are used for high frame rates, relaxed spatial resolution and large FOV (10 to 40 cm). Depending on the layer thickness (practically between 50 and 300 µm) either a higher light output or a higher spatial resolution can be achieved. However, the inherent spatial resolution is limited by the migration path of the reaction products from the capture in Li-6 (alpha and triton) of several tens of µm.

Therefore, when pushing the resolution limits, another material became important: Gd oxysulfide, which is neutron absorber and light emitter in only one material. On the one side, Gd is absorbing neutrons very efficiently due to the high capture cross-section. On the other side, the light emission is much less than that of ZnS.

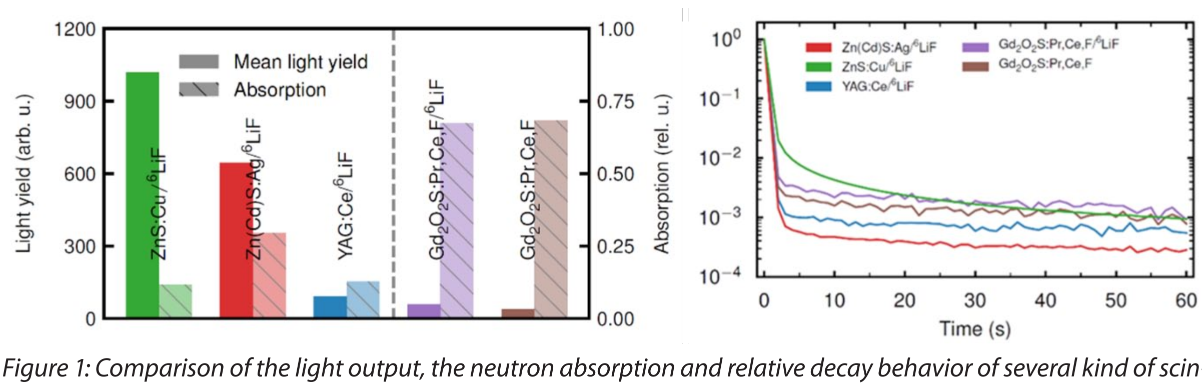


Figure 1: Comparison of the light output, the neutron absorption and relative decay behavior of several kind of scintillation screens supplied by RC Tritec Ltd. The measurements have been performed by T. Neuwirth et al. at FRM II (Garching) [2] and demonstrate very nicely the emission behavior of different scintillation screens during and immediately after neutron irradiation.

A final step in the optimization with regards to spatial resolution was the utilization of the isotope Gd-157, which is one of the strongest neutron absorbers overall. Due to its dense packing, layers of a few µm (~5 µm) are sufficient to absorb most of the cold or thermal neutrons. Tuned for highest spatial resolution, such screens are generally only a few square-centimeters in size as the number of pixels of the used camera limit the possible field of view significantly, when effective pixel sizes are of micrometer size [1].

A viable candidate for high frame rate imaging is the Zn(Cd)S:Ag/6-LiF-scintillation screen due to its fast decay (see figure 1). It is not only the fast decay, this screen also shows high light output and a high radiation hardness, i.e. a limited decay of efficiency with dose.

Table 1: Comparative listing of different scintillation screens (available from RC Tritec Ltd.) regarding their most relevant features for selection for best suitability. The data has been measured at PSI or FRM II with thermal neutrons. By adjusting the thickness of the applied material, the light output, resolution or absorption can be varied. The most promising candidates per feature have been highlighted.

Luminous Material	Absorber material (ratio)	Thickness	Relative light output	Resolution	Absorption	UV-illuminated decay time (10%)	Neutron irradiated I(rel) after 1 sec.	Radiation hardness	Emission (Max.)
ZnS:Cu	6-LiF (2 / 1)	100 µm	**~100 %**	~100 µm	~20 %	2.6 ms	8 %	limited	540 nm
ZnS:Ag	6-LiF (2 / 1)	100 µm	**~80 %**	~100 µm	~20 %	2.6 ms	not measured	limited	445 nm
$^{157}Gd_2O_2S$:Tb	none	5 µm	~6% %	**~ 5 µm**	**~70 %**	not measured	not measured	not measured	540 nm
Gd_2O_2S:Tb	none or 6-LiF (4 / 1)	10 µm	~10% %	**~ 10 µm**	**~70 %**	1.5 ms	not measured	**very good**	540 nm
Y_2O_2S:Eu	6-LiF (2 / 1)	100 µm	~20 %	~100 µm	~20 %	1.3 ms	not measured	not measured	625 nm
Zn(Cd)S:Ag	6-LiF (3 / 1)	100 µm	**> 80% %**	~100 µm	~30 %	**0.5 ms**	**0.1 %**	**very good**	605 nm
$Gd_3Al_2Ga_3O_{12}$:Ce	6-LiF (2 / 1)	50 µm	~2 %	~ 50 µm	~50 %	**30 µs**	not measured	not measured	530 nm
ZnO:Ga	6-LiF (2 / 1)	125 µm	very low	not measured	~30 %	**20 µs**	~8 %	not measured	386 nm
Gd_2O_2S:Pr,Ce,F	none or 6-LiF (4 / 1)	25 µm	~6 %	**> 10 µm**	**~68 %**	**17 µs**	5 %	**very good**	513 nm
$Y_3Al_5O_{12}$:Ce	6-LiF (2 / 1)	125 µm	~10 %	~100 µm	~13 %	**10 µs**	**2 %**	limited	555 nm
Y_2O_3:Eu	6-LiF (2 / 1)	100 µm	~40 %	~100 µm	~20 %	2.7 ms	not measured	not measured	610 nm

One disadvantage of the 6LiF/ZnS:Cu scintillation screens is the relative low absorption of 20% within a layer of 100 µm, resulting in a relative low neutron statistic. By use of a Gd-based scintillation screen, with an absorption of ~70%, the neutron statistic can be significantly improved. Unfortunately this is to the detriment of the resulting light output (~10% in comparison to the ^{6}LiF/ZnS:Cu scintillation screens). A good compromise is the use of 10B doped scintillation screens with intermediate absorption and light output. An overview about general properties of 10B doped scintillation screens is given by W. Chuirazzi et al. [3].

In the case of epi-thermal neutrons, the use of strong resonance absorbers is necessary and has been demonstrated already. Here, In, Au or Dy are key candidates, which have to be combined with a light emitting material, preferentially ZnS. The advantage of epithermal neutron imaging is the higher transmission (i.e. less attenuation) and, thus, the option to penetrate very thick layers of material or highly attenuating materials like Cd, Gd or In.

Because there are no strong neutron absorbers for fast neutrons available, another nuclear process has to be utilized – the recoil of neutrons at hydrogen, which ends in the kick of a proton able to make excitations. The combination of a hydrogenous material with a scintillation component has been used as homogenous mixture until now. Due to the low collision rate, the material layer has to be quite thick – on the order of a few millimeters. This, of course, reduced the probability to get as sharp images as with thermal or cold neutrons. Typically, a poly-propylene (PP) plate with ~30% of ZnS:Cu or Ag embedded in the matrix is used as the scintillation screen. Recently, a new setup (ZnS:Ag or Cu was

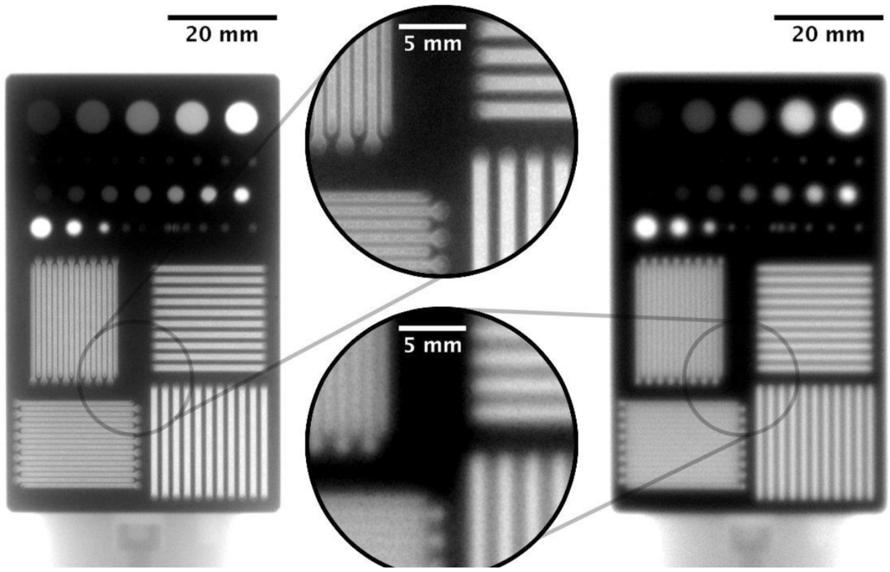


Figure2: Comparison of the radiograph of an iron block with the two different type of scintillation screens (right side: 30% of ZnS:Cu embedded in a 2.4 mm thick PP-Plate; left side: 2 layer system of 60 µm ZnS:Ag applied on a 3 mm PE plate).

applied on a PE plate) for higher resolution was developed and tested successfully, where a resolution of about 0.2 mm was reached [4]. However, this is achieved by a trade off with the detection efficiency and therefore the need of longer exposures.

A promising alternative way of imaging with fast neutrons was demonstrated by the use of colloidal nano-crystals diluted in organic proton rich solvents. The publication from K. McCall et al. [5] gives a good overview about the first tests done in this direction.

With the introduction of time-of-flight methods and the use of pulsed sources, other aspects of scintillator performance have to be taken into account. Here, the afterglow, the sensitivity for accompanying gamma radiation and the resistance against highest beam intensities play a more important role. Currently, novel neutron imaging detectors, largely operating without scintillator screens are dominating this imaging regime. However, developments enabling scintillator based imaging detectors also in time-of-flight mode are ongoing, in order to enable the strengths, like the unparalleled flexibility in trading resolution and field-of-view, to be exploited also in such applications.

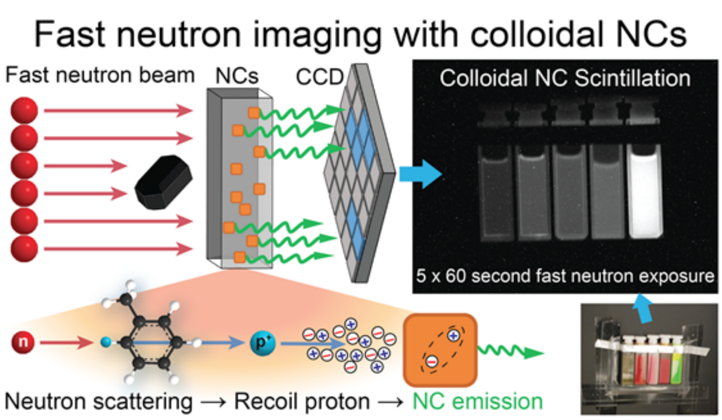


Figure 3: Scheme illustrating imaging with fast neutrons with Colloidal Nano-Crystals diluted in organic proton rich solvents.

Whatever your measurement conditions, (beamline properties) or your intentions to measure (application) are, please do not hesitate to contact us (www.rctritec.com) and we will help to find the best-suited scintillation screen for you. If your desired screen is not already an existing standard product, we are open to produce customized scintillation screens on your demand or, if needed, even to start a new development project!

References:

[1] *P. Trtik et al., Improving the spatial resolution of neutron imaging at Paul Scherrer Institut – The Neutron Microscope Project; Physics Procedia 2015, 69, 169ff.*
[2] *T. Neuwirth et al., Light Yield Response of Neutron Scintillation Screens to Sudden Flux Changes; J. Imaging 2020, 6, 134ff.*
[3] *W. Chuirazzi et al., Boron-Based Neutron Scintillator Screens for Neutron Imaging; J. Imaging 2020, 6, 124ff.*
[4] *E. Lehmann et al., Improvement in the spatial resolution for imaging with fast neutrons; Nuc. Inst. and Meth., Phys. A 2021, 987, 164809ff.*
[5] *K. M. McCall et al., Fast Neutron Imaging with Semiconductor Nanocrystal Scintillators; ACS Nano 2020, 14, 11, 14686ff.*

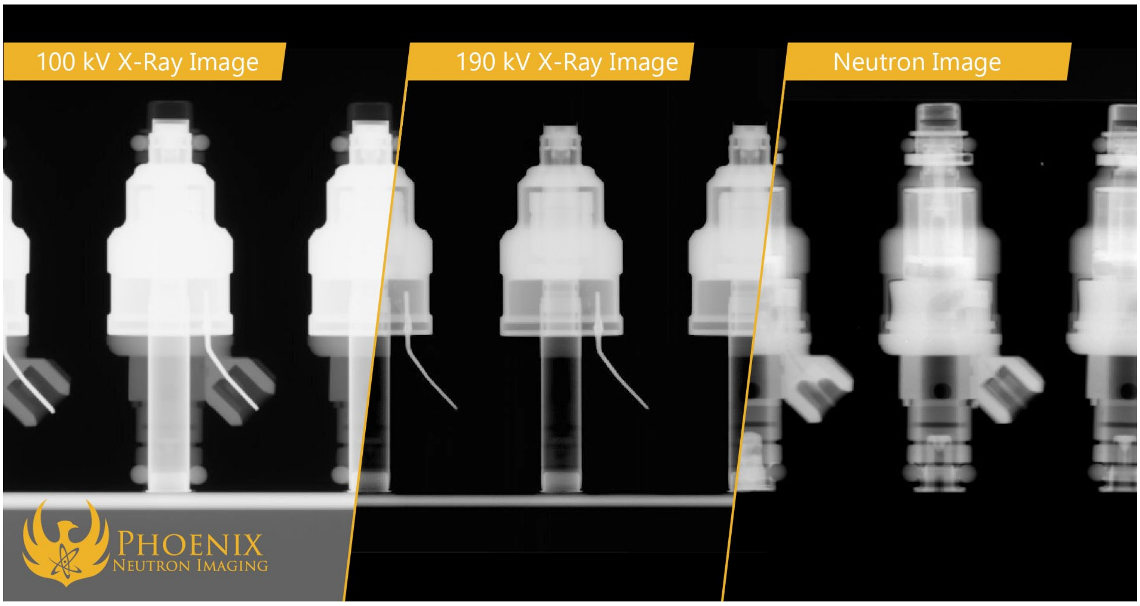
Eberhard Lehmann, Bernhard Walfort, Markus Strobl

A Bright Future for Neutron Radiography

Since the discovery of the neutron in the 1930s by James Chadwick and its utility for industrial radiography soon thereafter, neutron radiography has lagged decades behind X-ray radiography. Over the past few decades, reactor facilities which offer neutron radiography for commercial use have been decreasing in number and becoming less accessible, which has been a significant pain point for entities who rely on neutron radiography for quality assurance and failure analysis, such as the manufacturers of turbine blades and energetic materials such as ejection and payload separation mechanisms. National labs across the world have been working hard to reverse this trend of decreasing reactor sources over the past few years, and together with recent advancements in alternative, accelerator-driven neutron sources, the future for the world of neutron radiography is looking very bright.

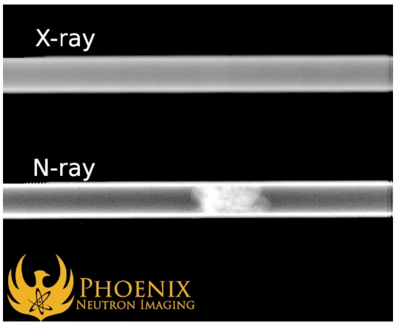
Founded in 2005 by alumni of the University of Wisconsin-Madison's nuclear engineering program, nuclear technology company Phoenix, LLC. works to realize near-term applications of nuclear fusion, one of which is neutron radiography. Phoenix found itself poised to occupy a critical niche in the world of nondestructive testing in which it could supplement the shrinking number of commercial neutron radiography facilities available. From the very beginning, Phoenix's fusion neutron generators, which use a compact particle accelerator to cause nuclear fusion and produce neutron radiation, represented a promising alternative to reactors, which at the time were one of the only neutron sources powerful enough to produce a sufficient neutron flux for high-quality industrial imaging.

With a new headquarters and imaging facility in Fitchburg, Wisconsin, Phoenix has made leaps and bounds in the world of neutron radiography over the past year. In 2019, in a joint test with its sister company SHINE Medical Technologies, Phoenix's neutron genera-



tors broke a thirty-five year-old record for sustained neutron flux from a fusion source. In the same year, it cut the ribbon on the brand-new Phoenix Neutron Imaging Center (PNIC), one of the first facilities with the capability to produce ASTM Category I neutron images in a timely fashion without the use of a fission reactor as a neutron source. Phoenix's engineers are hard at work advancing neutron radiography, helping to devise official global standards for digital neutron imaging with the ASTM, developing the capability to fuse neutron and X-ray radiographic data into hybrid images, researching neutron CT, and examining the usage of boron and other neutron absorbers as radiographic contrast images.

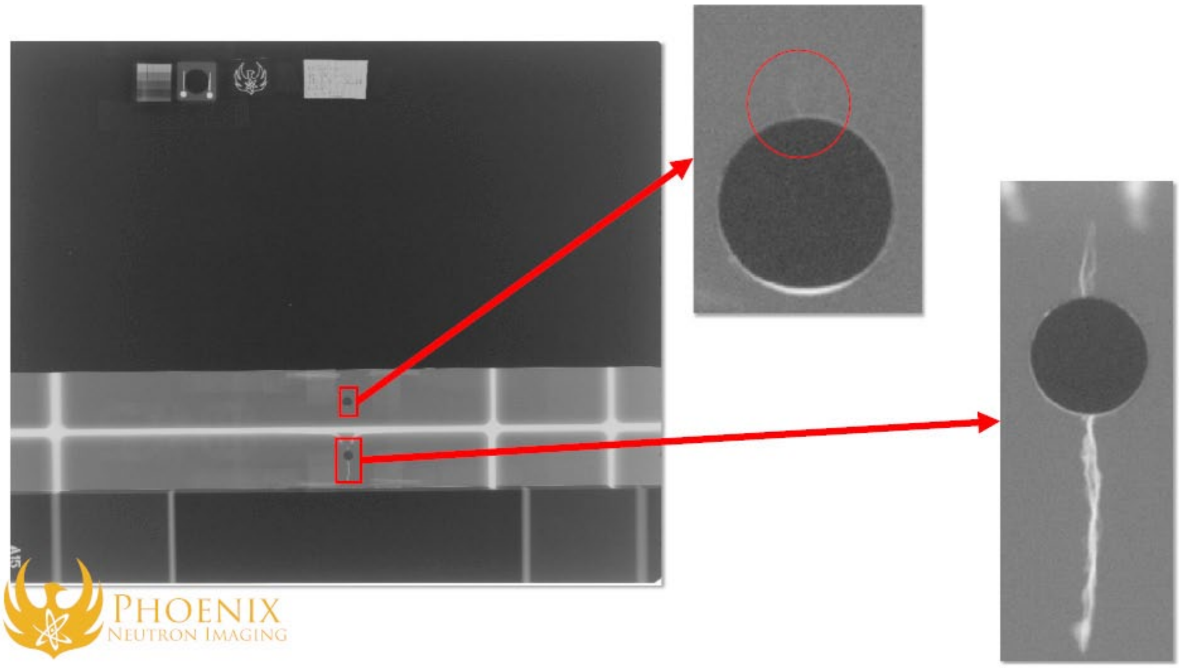
PNIC's facilities make comparing and contrasting X-ray and neutron images simple and convenient. In the case of these fuel injectors, neither the high nor low-energy X-ray images can capture details such as O-rings and blockages which show up clearly on the neutron image.



By placing a wad of cotton in an aluminum pipe, Phoenix was able to loosely replicate the clogged fuel line that almost brought down the AEHF-1 communications satellite in 2010 and demonstrate how neutron radiography could have detected this flaw in quality assurance testing even though X-ray imaging could not.

Gadolinium tagging and neutron imaging is a vital tool for detecting potentially dangerous flaws in aircraft turbine blades, but has less thoroughly investigated uses as well. Phoenix, along with INL, has been looking into the use of gadolinium penetrant dye as a contrast agent to make flaws and discontinuities more visible in planar neutron images and three-dimensional neutron CT models.

Plans are currently underway for Phoenix to build a new neutron imaging facility on the United States West Coast, tentatively dubbed "PNIC West" and located in the San Francisco area. The facility is expected to add an additional ten to twenty full time, high tech professionals to Phoenix's growing employee base and will support the growing US space sector by providing critical on-site radiographic inspection capabilities to aerospace man-



ufacturers on the west coast, especially the manufacturers of energetic devices. In addition to providing commercial and research clients with neutron radiography services in the Midwest and west coast, respectively, both PNIC Wisconsin and PNIC West will have the capability to train the next generation of NDT professionals on its X-ray and N-ray systems. This is a promising step forward for the accessibility of neutron radiography to the NDT community.

Phoenix LLC
katie.rittenhouse@phoenixwi.com

Inexpensive Neutron Imaging Cameras

It's often said that neutron sources are expensive, so there is no point in saving money on a neutron camera. As responsible for the Diffraction group budget for 20+ years at the world's most expensive neutron source, ILL Grenoble, I don't agree. It's different money! Even for a rich laboratory, the annual budget for investment is a small fraction of the total budget. And there are many small research reactors that could do useful neutron imaging, but have even less money.

Neutron cameras improve faster than neutron sources, and indeed neutron cameras are damaged by neutron sources. There is no point in extreme camera cooling, if after a year in the beam the noise is largely due to radiation damage. Cleaner images can be obtained by replacing a less expensive camera more frequently.

In fact the neutron camera is not the limiting factor to obtaining good images. The neutron beam - its collimation, shielding and intensity optimisation - are much more important [1]. Otherwise the neutron scintillators, front-surfaced mirrors, lenses etc are the same for inexpensive cameras as for the most expensive. Money is saved on the CCD/CMOS detector and on simplified design.

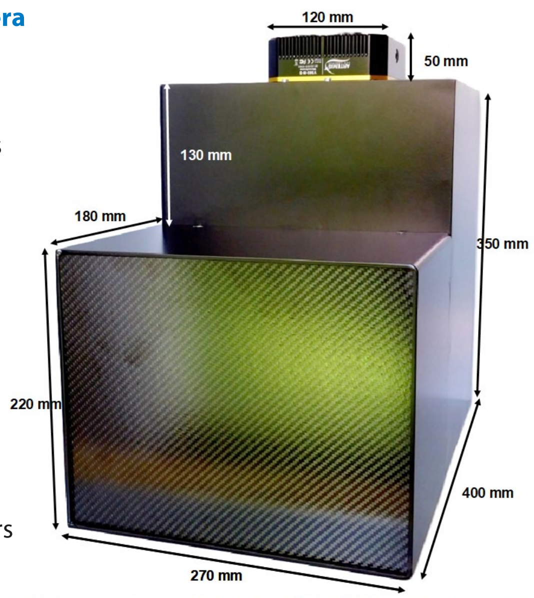
Simplicity also reduces mistakes by inexperienced users. If there are no moving parts, there is less to go wrong,. Cameras where the detector position and focus are computer controlled are open to inexperienced user error, and require the detector to be enclosed in the camera body, where it is more difficult to shield and cool.

Since 2007 NeutronOptics Grenoble [2] have used CCD/CMOS detectors designed for amateur astronomers [3]. They require the same low-light performance, yet are relatively inexpensive. Mass market. CCD technology is highly developed, and has effectively reached the limits imposed by physics. The amount of light that can be captured depends on the area of the detector, and whether it is “front” or “back” illuminated doesn’t change much when the “quantum efficiency” is already >70%. Photon or electron multiplication doesn’t improve the signal statistics for a thermal neutron scintillator that already multiplies a single captured neutron to 160,000 photons. The detector area is also constrained by the camera lens. A 1” chip is the largest that can be used with a C-mount lens, and a 35mm chip the largest for commonly available “full frame” lenses. The latter are not necessarily an advantage because they usually focus less closely, with a larger Field-of-View (FOV), and the camera efficiency decreases with the FOV.

There are exceptions to these limitations, but none relevant to inexpensive cameras. Detectors that cost an order of magnitude more are not even 10% more effective for neutron imaging. They are usually designed for biological imaging, where there is no radiation background, no damage to the detector, and no problem in extreme cooling because there is no shielding to get in the way. Their cost is driven up by the medical market they appeal to, and partly due to the expensive advertising associated with that market. The amateur astronomy market is a mass consumer market using components from the even larger amateur photography market. These market forces explain why 90% of the performance can be obtained for 10% of the price. Even leading German neutron labs, now accept such inexpensive design principles [4].

What does an Inexpensive Neutron Camera Look Like ?

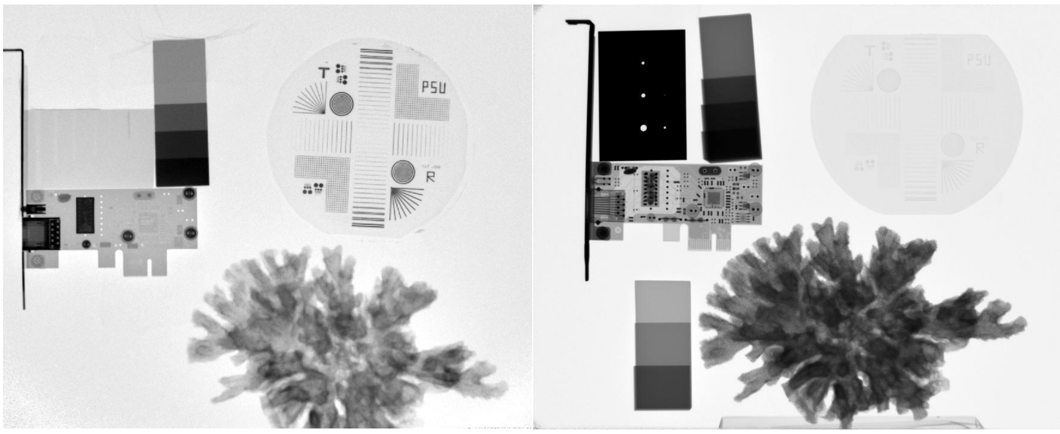
- For simplicity, there are no moving parts
- The CCD/CMOS unit is on the outside
- It is then easy to cool and shield
- Uses Peltier plus dual fan air cooling
- The periscope shape helps shielding
- Scintillators on interchangeable frames
- So it can be used for x-rays or neutrons
- Variable length section to change FOV
- Either 1” or 35mm CCD/CMOS detector
- Either C-mount or 35mm F-mount lens
- Same mirrors as for expensive cameras
- RC-TriTec [5] & Scintacor [6] scintillators
- Resolution limited by beam & scintillators
- Efficiency equal to expensive cameras
- Tomography motor synchronisation
- Remote control via USB or µ-computer.



250x200mm at 530mm with f=25mm & ICX694ALG 12.49x9.99mm CCD
175x140mm at 380mm without front-end extension (high intensity config.)

- Sensor: 1" Sony EXview HAD CCD II
- Optics: High resolution f/1.4 1" lens
- Resolution: 2750 x 2200 pixels
- High sensitivity: (QE~75%), low smear
- Dark current: 0.0004 e/pix/s @-10 °C
- Cooling: Regulated Peltier ΔT = -35°C
- Digital Output: 16-bit 65536 levels
- Readout Speed: 6-12 MPixels/s
- Binning and Region-of-Interest
- External Trigger: GPIO synchronisation
- SDK: C++, VB, .net, ImageJ, LabView

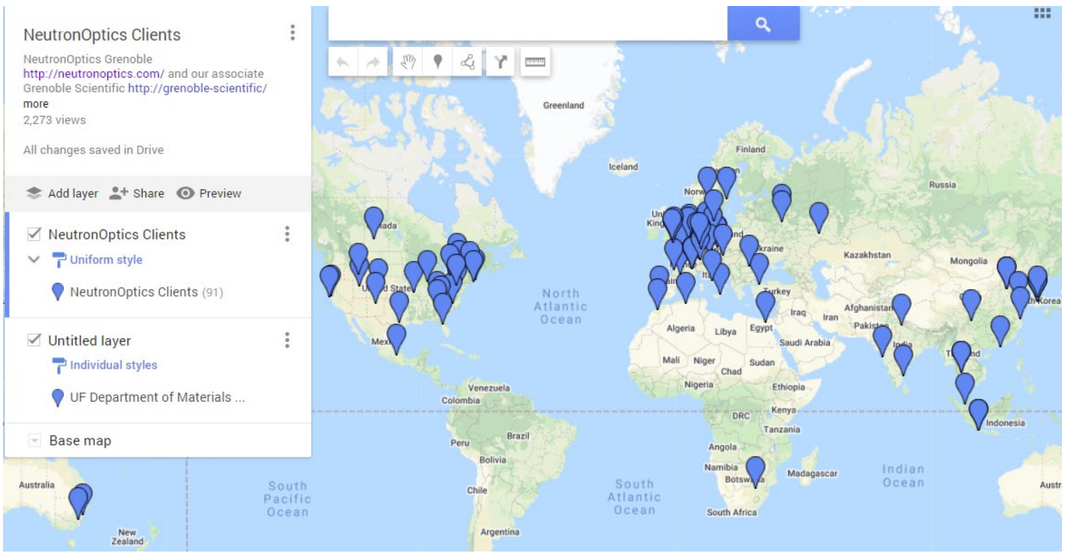
Examples of Neutron and X-ray Images on very low flux sources



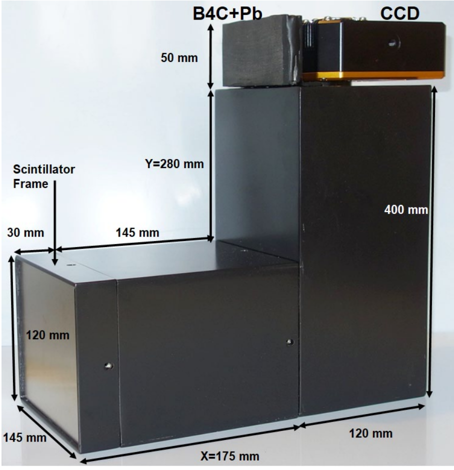
Left: Neutron image on 100 kW Triga reactor. Right: X-ray image on a 60kV/3ma/10s x-ray source Dr Robert Zboray (Penn. State Uni.) [7]

Our classic high resolution x-ray or neutron camera is made from laser cut, folded and welded aluminium plate, with aluminium screws to reduce radiation activation. The main body has the detector bolted on top, with the lens inside. A trap door allows access to the lens for focussing, but re-focussing is only necessary when the FOV changes.

Who uses our Inexpensive Neutron and X-ray Cameras ?



Optimisation of the camera for efficiency in fast neutron imaging



At the 2019 Munich Experts Meeting on Fast Neutron Imaging [8] we discussed the optimisation of a camera for maximum efficiency in fast neutron imaging. We proposed to maximise the ratio of the CCD area to the FOV area with An efficient camera for fast neutrons using a very low-noise 1" Sony CCD and a bright close focus C-mount lens. We showed that using a larger CCD did not help because larger lenses could not focus so closely, requiring a larger FOV. There are exceptions to this rule, using macro-focussing techniques, but then the FOV becomes very small. The 125mm x 100mm or 90mm x 70mm FOV of this camera is a good compromise.

A 125x100mm FOV is also sufficient for most thermal neutron imaging according to user demand at FRM2 Munich. This smaller camera is easier to shield as well as being more efficient, and with 2750 x 2200 pixels is capable of higher resolution with a well collimated beam and a high resolution scintillator; the optical resolution is better than 50 µm.

Very high resolution neutron imaging

If small FOV are acceptable, macro imaging techniques give both very high resolution and high efficiency. PCO have claims that a front-to-front lens macro is almost as efficient as direct fibre optic coupling of the scintillator to the CCD [9]

We have constructed various 1:1 macro imaging cameras using different 90-degree mirrors and the latest Gd neutron scintillators from RC-TriTec [5], or YAG:Ce single crystal x-ray scintillators from CRYTUR [10].

The simplest on the left, is a 100mm f/2.8 Tokina 1:1 macro lens coupled to a 90o mirror with a 40mm diameter carbon fibre window that can be unscrewed to exchange the scintillator.

The brighter version on the right uses a Rodenstock 90o lens-mirror, in a front-to-front 1:1 macro configuration with a Nikon 50mm f/1.2 lens, again with a 40mm diameter carbon fibre window to achieve resolution better than 5 µ [11].

The resolution of these 1:1 cameras is equal to the pixel size of the CCD, and in fact limited only by the scintillator.

Simpler, Less Expensive Neutron Cameras for Beam Alignment

A variety of compact cameras have been designed for neutron-sample beam alignment. These cameras permit exposures of seconds with ~100 µ resolution.

- Sensor: 2/3" Sony EXview HAD CCD II
- Optics: High resolution f/1.4 2/3" lens
- Resolution: 1392 x 1040 pixels
- High sensitivity: (QE~70%), low smear
- Dark current: 0.001 e/pix/s @-10 °C
- Cooling: none
- Digital Output: 16-bit 65536 levels
- Readout Speed: 6-12 MPixels/s
- Binning and Region-of-Interest
- SDK: C++, VB, .net, ImageJ, LabView

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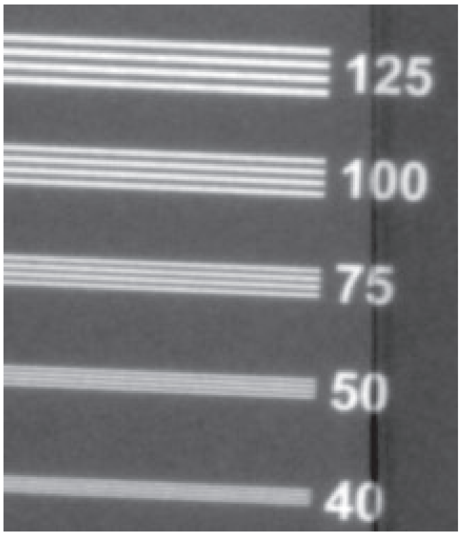
Alan Hewat

Neutron Imaging Systems from Photek

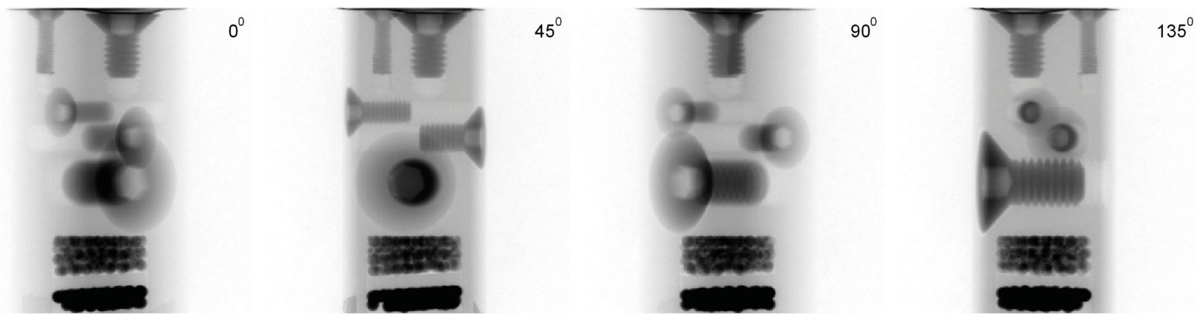
Since our beginning, Photek has been in the business of making vacuum tube photodetectors and we are always looking for new applications that would benefit from their low noise light amplification. We recently tested a prototype neutron imaging camera at ISIS-IMAT based on a large format image intensifier with a GADOX scintillator applied to the input fiber optic window. The idea is to amplify the light generated in a thin layer of GADOX before imaging it onto a cooled sCMOS camera. This amplification helps overcome the poor light collection between the scintillator and image sensor to significantly increase sensitivity and enable the use of thinner GADOX scintillators for higher resolution imaging. The prototype system, now commercially available as N-Cam, uses a 75 mm diameter image intensifier to provide better than 10 lp/mm resolution over the full imaging area with simultaneous high detective quantum efficiency. The attached Paul Scherrer Institute resolution chart shows 10 lp/mm resolution with the resolved 50 µm lines, consistent with the predicted resolution in this configuration. Shown below are four views of a tomography sample consisting of various Titanium screws, copper ball bearings and borosilicate glass balls. The 4 Mega-pixel camera provides dynamic imaging greater than 30 frames per second. Energy selective imaging can be obtained by gating the image intensifier on and off on timescales as fast as 100 ns.



Radiograph of a PSI resolution chart. The lines adjacent to "50" on the chart are 50 µm wide on 100 µm pitch.

There are a number of possible camera configurations including: larger fields of view using intensifiers up to 150 mm in diameter or fiber optic reducers coupled to the input of the 75 mm intensifier, different scintillator types and thickness, sCMOS camera formats, an optical zoom for higher resolution over a smaller central FOV, and user swappable scintillator screens. For fast neutrons, a thin scintillator plate or a scintillating fiber block can be used.

Other vacuum tubes manufactured by Photek and suitable for use in neutron imaging include magnetic focus image intensifiers having up to 90 lp/mm resolution, demagni-



Radiographs of Aluminium block with M3 to M8 titanium screws, copper balls, and borosilicate balls.

fying image intensifiers for lossless image reduction, electronic readout devices such as neutron counting imagers, and multi-anode PMTs. A white paper with detailed analysis of our N-Cam prototype test at ISIS-IMAT is available on our website at www.photek.com/products/n-cam-neutron-imaging. Photek is excited to provide new detection options for the neutron imaging community and is interested in finding new applications for N-Cam and our other vacuum photodetectors.

Paul Hink

New ^{6}Li Based Scintillators for Neutron Detection and Imaging

RMD has developed novel scintillators for thermal neutron detection and imaging which include

(1) $^6Li_{0.47}Na_{0.47}I$ (LNI),

(2) ^{6}LiI:Ce, a new composition that demonstrates rapid decay, enabling high count rates, and

(3) the well-known ^{6}LiI:Eu in a novel microcolumnar structure form.

These materials are fabricated either in crystalline form or in a large area format using thermal vapor deposition. All these compositions are bright, have high thermal neutron detection efficiency, and show excellent neutron/gamma discrimination based on pulse height discrimination and/or pulse shape discrimination. As such these materials are well suited for neutron diffraction imaging using SiPM or other pixelated sensor-based anger cameras, for thermal neutron radiography using commercial a Si:H flat panels or CCD/CMOS high resolution readouts, and numerous other applications including homeland security. In one variation, ^{6}LiI:Ce, the scintillator doping is altered from conventional Eu doping to Ce doping to achieve fast response. Consequently, this material has a potential to achieve high count rates desired for such applications as neutron reflectometry.

$^6Li_{0.47}Na_{0.47}I$ (LNI) Crystals and Films

LNI is a solid solution, so ^{6}Li content can be varied while growing crystals or thin films. In film form, LNI is a microcolumnar scintillation screen that enables high efficiency neutron detection and imaging (Figure 1). LNI films have a 45% concentration of 95% enriched 6Li by atomic fraction, allowing for high efficiency neutron detection. At the same time, due to the microcolumnar structure of LNI scintillator, the intrinsic spatial resolution is high ranging from 50 µm to 250 µm depending on the film thickness. In crystalline form the material has demonstrated more than 70,000 photons/thermal neutron interaction with a gamma equivalent energy (GEE) of greater than 3.5. Microcolumnar films are also bright

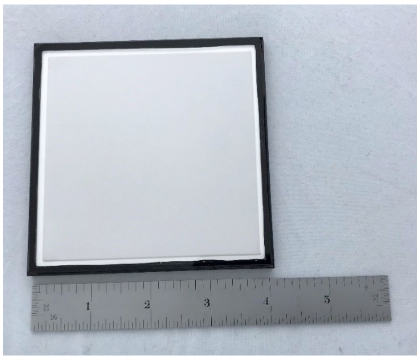


Figure 1: A packaged 4″×4″ sample of microcolumnar LNI film.

and have demonstrated up to 60,000 photons/neutron, which is ~10× brighter than GS20 glass. The scintillator exhibits excellent neutron-gamma discrimination based on pulse height discrimination and pulse shape discrimination. Key features include:

- Up to 1.5-inch diameter crystals have been grown.
- Films are ideal for neutron radiography, tomography, diffraction, and homeland security applications.
- Films available in sizes up to 8 inch in diameter, 1 mm in thickness. Significantly larger sizes possible.
- Up to 70% efficiency for thermal neutrons using only 1 mm thick LNI film.
- Neutron-gamma discrimination using pulse height (PHD) and pulse shape (PSD).

High brightness of LNI films have enabled excellent spatial resolution, estimated to be ~350 µm using SiPM Anger Logic, and neutron/gamma discrimination better than 10-6. Corresponding data using an SiPM Anger camera for a 500 µm thick, 4″×4″ active area LNI film is shown in Figure 2.

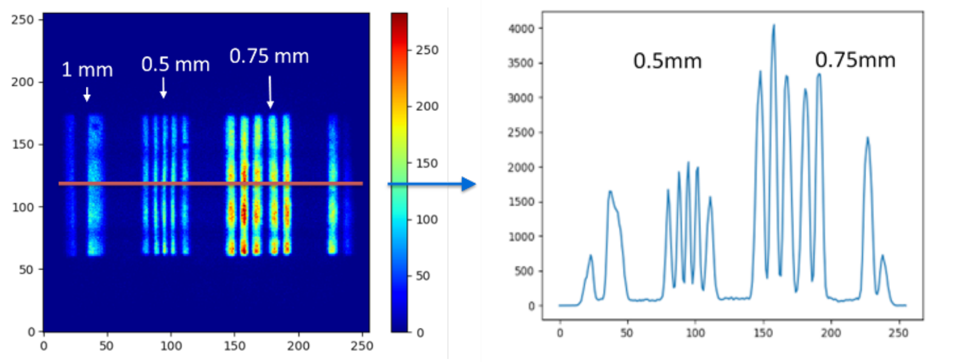


Figure 2: (Left) Resolution mask image acquired using a 4″×4″, 500µm thick, LNI film to an SiPM Anger camera. (Right) Line profile demonstrating a high degree of modulation even for a 0.5 mm pattern. Estimated resolution is ~350 µm.

^{6}LiI:Ce Crystals and Films

The LiI crystals doped with Ce3+ are grown by the vertical Bridgman technique using 95%-enriched ^{6}Li (Figure 3 Top). The decay kinetics are well described by two distinct exponential components, the primary being ~43-50 ns (93%) and the secondary some 300 ns (7%), which is significantly faster than Eu^{2+}-doped ^{6}LiI decay of ~1 µs. Light yield for thermal neutron interactions is measured to be ~18,500 photons/interaction, which is a factor of three higher than GS20 (Figure 3 Bottom). The X-ray excited radioluminescence spectrum of Ce^{3+}-activated LiI at room temperature shows three well-defined emissions in the visible range, peaking at 430, 474, and 590 nm, which are due to 4f-5d transitions of Ce. The crystals also demonstrate high GEE of nearly 3 MeVee, thereby permitting effective neutron/gamma PHD. The films demonstrate brighter emission than GS20 and neutron gamma discrimination of 2×10^{-6}.

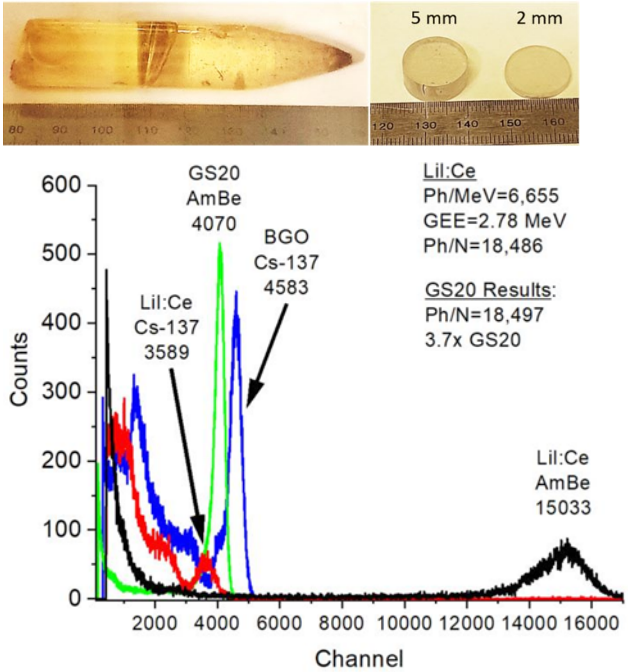


Figure 3: (Top) Photograph showing ^{6}LiI:Ce crystal with 0.5 mole% Ce^{3+} grown at RMD. (Bottom) This crystal demonstrated ~18,500 photons/thermal neutron interaction and ~6,650 photons/MeV for γ response.

- Up to 1-inch diameter crystals have been grown.
- The material is ideal for neutron reflectometry applications where desired count rates exceed 10 MHz.
- Microcolumnar ^{6}LiI:Ce films are well suited for radiography, tomography, diffraction, and homeland security applications. Up to 15×15 cm^2 films are possible at this stage.
- Neutron-gamma discrimination PHD.

^{6}LiI:Eu Films

The well-known ^{6}LiI:Eu scintillator has been grown in a microcolumnar form (Figure 4) which has demonstrated up to ~30,000 photons/neutron, which is six times the brightness of GS20 glass, while exhibiting ~60% absorption of thermal neutron for 1 mm thick scintillator. Recent studies have demonstrated neutron gamma discrimination on the order of 4×10^{-7} using PHD, showing excellent performance for neutron diffraction imaging. The scintillator can be grown in large formats of up to 8" in diameter. We anticipate significant increase in the material brightness once the dopant concentrations in the evaporated film are optimized.

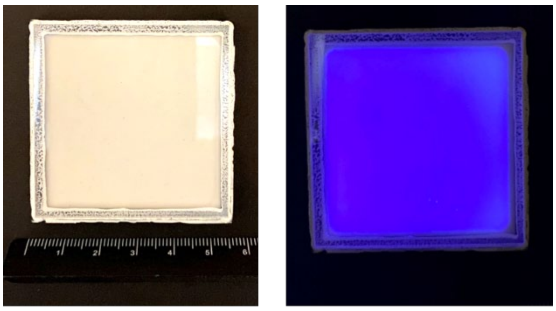


Figure 4: A packaged ^{6}LiI:Eu scintillator under visible illumination (Left), and under UV light (Right).

Vivek V. Nagarkar
vnagarkar@rmdinc.com

Custom Sensor and Materials Development at DMI / Reading Imaging

DMI / Reading Imaging (DMI) specializes in creating customized sensor and detector solutions for our customers for use in a wide variety of applications. Our customers include national laboratories, universities, the military, commercial companies, and others. Our expertise includes prompt-emitting scintillator phosphors, storage phosphors, converters and other materials manufactured to our specifications by our suppliers or ourselves, for use in the detection, measurement and imaging of ionizing and non-ionizing radiation.

We particularly enjoy the experience of working with researchers and other customers who wish to image slow or fast, transient or repeating or triggered phenomena, and who need to image objects that are stationary, or rotating, or in motion traveling at thousands of meters per second, or being detonated or imploded, or being propelled into each other, or are being deformed until they calmly or catastrophically fail. Many fast-moving objects, flying debris and object internals are notoriously difficult or impossible to image optically, whereas X-rays and neutrons can yield clear images through smoke, dense particulate fields, solids, and other optically opaque conditions. Our sensors may be installed and used for years in quiet laboratories, or brought to the field to be used once and sacrificed in the process.

Our experience in radiation detection, measurement and imaging dates back to the early days of nuclear medicine (imaging the presence, absence or movement of injected, inhaled or swallowed gamma-emitting radiopharmaceuticals and radioactive materials in the human body and in animals, via gamma cameras), the early days of X-ray CT, and the adolescence of modern radiation therapy. Since then, we have developed and refined scintillator materials, detector technology, systems, imaging techniques, algorithms, and software from operating systems to clinical, scientific, industrial, security and other applications.

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Several years ago DMI began working with neutron researchers such as Dr. Aaron Craft of Idaho National Laboratory (INL) and Dr. Michael Taylor of Phoenix LLC, and with users of neutron facilities. Drs. Craft and Taylor, in particular, tasked us with creating customized sensors that would allow them to explore new concepts in neutron sensing and imaging.

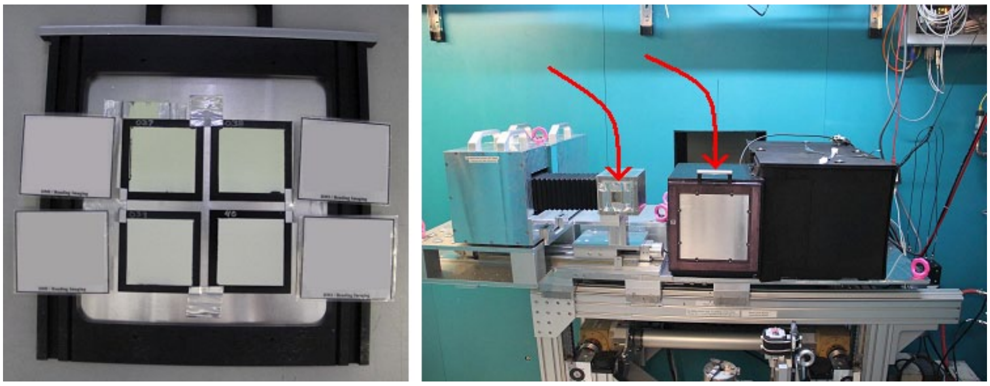
Doing so required that we locate or formulate specialized scintillator and converter materials, assess and develop unusual substrates and moderators, and fabricate unique, custom sensors, often using new fabrication techniques. Much of what we developed was quite different from what we used in the detection of ionizing radiation (X-rays, gamma rays and charged particles), where we already had decades of experience.

We have now fabricated hundreds of sensors for use in neutron imaging, that have enabled the investigation of boron-based and other converters combined with a wide variety of scintillators and scintillator formulations [1,2], including commonly used and recognized phosphors such as ZnS:Cu, CsI:Tl and GOS:Pr (Gd_2O_2S:Pr), plus others that show promise and some that are proprietary to DMI. These sensors have been used in neutron radiography and tomography both in the US and abroad [2,3].

We've developed unusual approaches to meet the needs of our customers and collaborators, such as INL researchers' requirement for sensors with a monotonic thickness gradient in one or in each of two layers on a substrate [3]. A single layer was a mix of a scintillator and a converter material such as $^{10}B_2O_3$, while two layers included separate scintillator and converter layers, where both might be wedged perpendicularly to the other's gradient. These sensors are complex in their construction, and require that their thicknesses be controlled and carefully measured. INL researchers found that by X-raying the wedged sensors, they could exactly determine their relative coating thicknesses, instead of depending upon DMI's potentially inaccurate (and, I can tell you, tedious) micrometer and thickness gauge measurements. They also found that neutron detection efficiency could be measured by taking a neutron radiograph of the prototype screens themselves [3].

Cross sections of gradient sensor coatings on aluminum substrates.

Since materials such as ^{10}B-enriched anhydrous boron trioxide ($^{10}B_2O_3$) and ^{10}B-enriched anhydrous sodium pentaborate ($Na^{10}B_5O_8$) were not available, DMI fabricated the missing required materials.

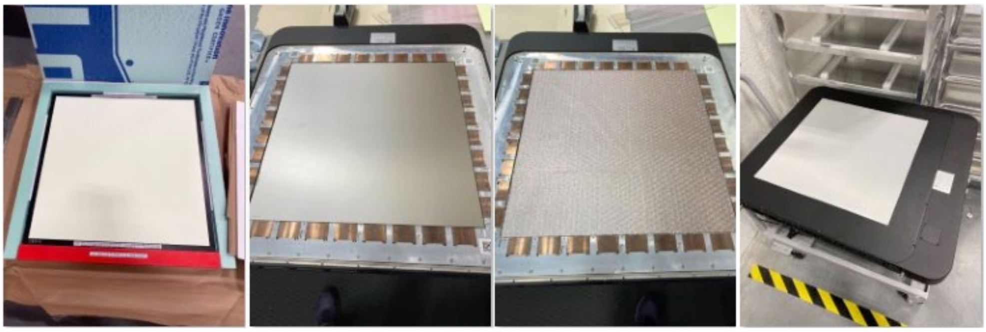


Four DMI high-resolution gradient ZnS:Cu sensors mounted by Dr. William Chuirazzi (INL) on the imaging system's right-hand, larger sensor holder. Another sensor could be mounted on the smaller left-hand holder. The entire assembly can slide left-right along the visible rails into place with respect to the neutron beam, depending on which sensor holder should be exposed. This view is from the neutron beam's perspective; the beam originates from behind the viewer of the photo.

To test layered fast neutron imaging screens, INL researchers required plastic substrates precisely machined into flat or wedged slabs, with scintillator coatings of different thicknesses (some with multiple strips of different thicknesses, oriented perpendicularly to the wedge gradient), in order to determine optimal thicknesses of the plastic and the scintillator. We researched and determined which plastic, and then which variety of that plastic, has the highest hydrogen density. Next we worked with our machinist to fabricate flat slabs or wedged (gradient) slabs of that plastic of exact thicknesses ranging from under 1 mm to over 3 mm, and then finished the surfaces to provide the desired type and degree of reflection or absorption of scintillator light.

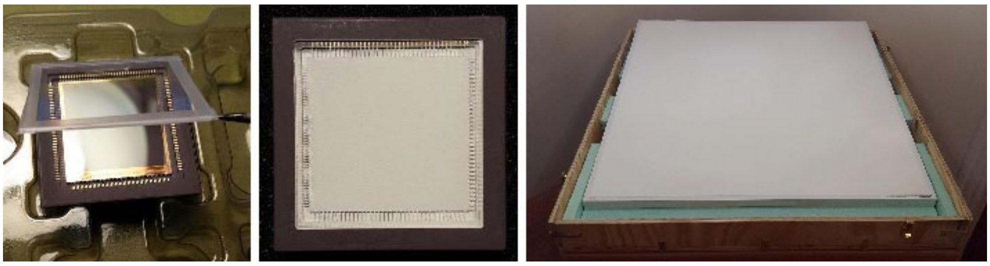
Coatings can typically be any required thickness. At the extreme, we've deposited uniform, ultra-thin layers of scintillator onto clear plastic substrates, where the layer thicknesses were just a little greater than the phosphor particle sizes.

Control plates (under room and UV light) made by DMI for INL, on aluminum only, without a plastic substrate, used in conjunction with corresponding scintillator-coated wedged plastic slabs (described) to help determine the light output of each different scintillator and scintillator formulation alone, without the plastic substrate.



41 cm x 41 cm sensor DMI fabricated for Phoenix LLC for neutron radiography experiments. L-R: As received by Phoenix; coupled face down to a PerkinElmer 1621 flat-panel detector; compression cushioning added; flat panel cover attached.

Our sensors typically range from the size of a fingernail up to about a meter square (without tiling), using a wide variety of scintillators and storage phosphors, coating thicknesses, substrates and treatments.



2.54 cm x 2.54 cm CMOS chip before and after coating by DMI. DMI 84 cm x 84 cm seamless sensor crated for shipment.

Substrates we use include aluminum (plain to white/black anodized), steel, tantalum, plastics/polymers, glass/fused quartz, fiberoptic plates, front surface mirrors, dysprosium foil (custom made for us in desired sizes and thicknesses), and graphite, with surfaces from flat/matte black (highest resolution) to mirror finish (highest light output). DMI also has the capability to directly coat sensors (e.g., CMOS/CCD chips to flat panels) to provide the best optical coupling, has the capability to cast sensors (scintillator phosphor in epoxy or resin), and can fabricate curved sensors or coat curved surfaces.

We run extended tests to better understand material responses and behaviors, such as the long-term response of ZnS:Cu/ZnS:Ag to ambient and UV light, the rate at which anhydrous B2O3 will absorb moisture from the ambient atmosphere, and the reactivity of materials used together in sensors, such as scintillators, metals, and coating binder formulations.

DMI's focus is on customization, flexibility, fast turnaround, and design refinement, which we believe has served our collaborators and customers well.

These efforts are challenging and instructive, and working with the talented people mentioned here and many others has made it all both enjoyable and worthwhile.

11 cm diameter, 1 cm thick, coherent fiberoptic plate coated by DMI with LSO:Ce scintillator (40-45 ns decay time to 1/e).

DMI flexible sensor (scintillator coating on aluminized Mylar); DMI storage phosphor paint; DMI ~ 8 cm x 8 cm cast sensors.

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Steven Cool
DMI / Reading Imaging
DMIReadingImaging@gmail.com

Out of the Lab

Multimodal imaging using neutrons and gammas at NECTAR applied to ancient Roman concrete

NECTAR is a unique beamline with access to fission neutrons for non-destructive inspection of large and dense objects, where thermal neutrons or X-rays face limitations due to their comparatively low penetration. With the production of fission neutrons at the instrument, gamma rays are produced in the same process. The production of these gamma rays is inevitable as they are inherent with the production of fission neutrons and the principles of collimating or stopping them. Furthermore, the gamma rays are highly directional due to their constraint to the same beamline geometry and come with similar divergence as the neutrons. While difficult to shield, it is possible to utilize them by using gamma sensitive scintillator screens in place of the neutron scintillators viewed by the same camera, enabling multimodal imaging using thermal and fast neutrons, as well as gammas at the NECTAR instrument.

The first measurements utilizing this technique were performed in spring of 2020 on ancient Roman concrete specimens. The pozzolanic concretes of the monuments of ancient Rome and the seawater harbor constructions that Romans built in the Mediterranean Sea are some of the most durable cementitious materials on the planet. They remain resistant to decay, even after 2000 years exposure to groundwater saturation, strong variations in relative humidity, and submersion in seawater. Modern production of Portland cement is an energy intensive process responsible for a staggering 5-8 % of the annual global CO2 emissions. The concretes of ancient Roman monuments and seawater harbors, produced from volcanic rocks and hydrated lime, have a far smaller CO2 footprint

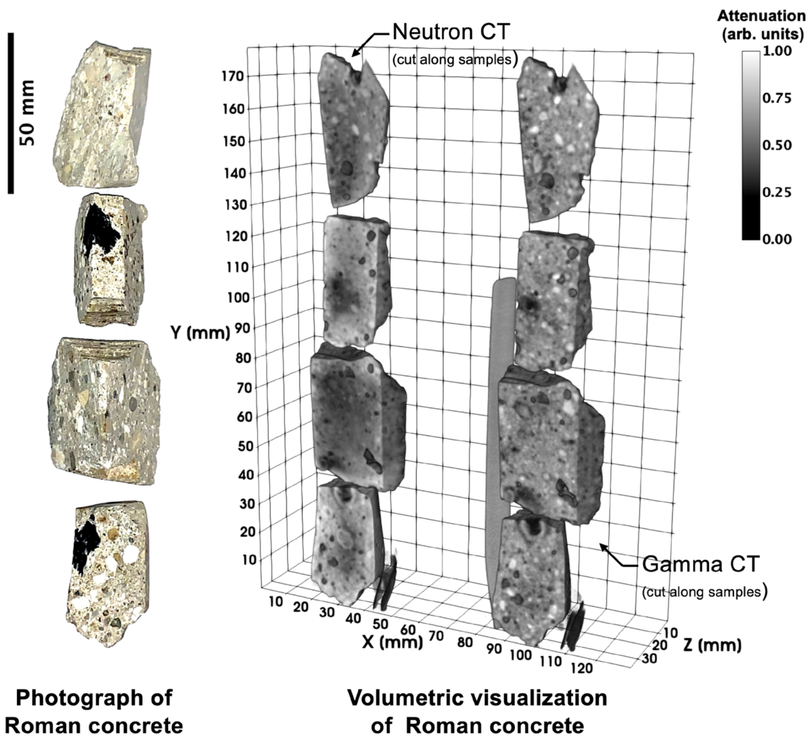

Figure 1: Photograph of Roman concrete specimens on the left. Volumetric reconstruction of the specimens using simultaneously recorded neutron and gamma CT on the right. The two modalities show different contrast of the various features within the concrete samples.

than conventional Portland cement concretes, far greater chemical and mechanical resistance to decay, and a smaller energy budget to produce.

The goal of this investigation is to gain a fundamental understanding of the cracking mechanism of ancient Roman concrete: the interaction of large lightweight rocks with the matrix and the pozzolanic reaction be- tween calcium hydroxide and amorphous alumino-silicate that the Roman engineers used. The measurements at NECTAR provide information complementary to other non-destructive studies conducted with X-rays and Scanning Electron Microscopy, with the possibility to visualize and to quantify water distributions. Furthermore, the dual modality, as shown in figure 1, provided by neutrons and gammas adds elemental sensitivity on cm length scales, not accessible with other techniques. With the recent upgrades at NECTAR, both modalities can be measured combined. The in- sight gained by these measurements is crucial in developing a new generation of high-performance concrete that may last centuries.

A. Losko, M. Schulz, R. Schütz (MLZ),
A. Tremsin, Paulo J.M. Monteiro, K. Xu, J. Li (UC-Berkeley)

Magnetic flux guidance in electrical steel employing stress induced by embossing

High energy efficiency is a key component to combat global warming. In electric drives, especially in reluctance and permanent magnet synchronous machines, this can be achieved by optimizing the magnetic flux guidance in their magnetic core. Conventionally, cutouts in the electrical steel sheets comprising the magnetic core are used for magnetic flux guidance. Accordingly, the mechanical strength of the rotating magnetic core is compromised. As a result, the maximum angular velocity is limited.

In the DFG priority program SPP2013 the MLZ researches, in collaboration with the utg (TUM) and the IEM (RWTH), the use of embossing the electrical steel to guide the magnetic flux. The stress induced by embossing changes the local magnetic properties and decreases the local magnetic permeability. By guiding the magnetic flux by embossing, we intend to increase the mechanical stability of the electric steel and consequently the angular velocity as well as the power density of electric drives.

The neutron grating interferometry (nGI) setup installed at the ANTARES beamline allows to probe the local magnetic properties of the embossed electrical steel. In particular, nGI maps the ultra-small-angle scattering of neutrons off magnetic domain walls. The combination of local magnetic properties (MLZ), global magnetic properties (IEM) and mechanical simulations (utg) enable a deeper understanding of the influence of embossing induced stress on the local magnetic properties of electrical steel sheets.

During the first phase of the priority program we have used electrical steel sheets with a single large embossing acting as a magnetic flux barrier. Fig. 1 shows the variation in the signal arising from different punch geometries. Our results show that ideally the deformation of the electrical steel sheet is kept localized, which is achieved with a flat punch, as used in sample C. This also provides the highest stability of the flux barrier with respect to the applied magnetic field.

Building on these results we have recently begun to study flux barriers comprised of finely distributed small embossing points. This change allows to reduce the deformation of the electrical steel necessary to form a flux barrier. Examples for such embossing patterns are

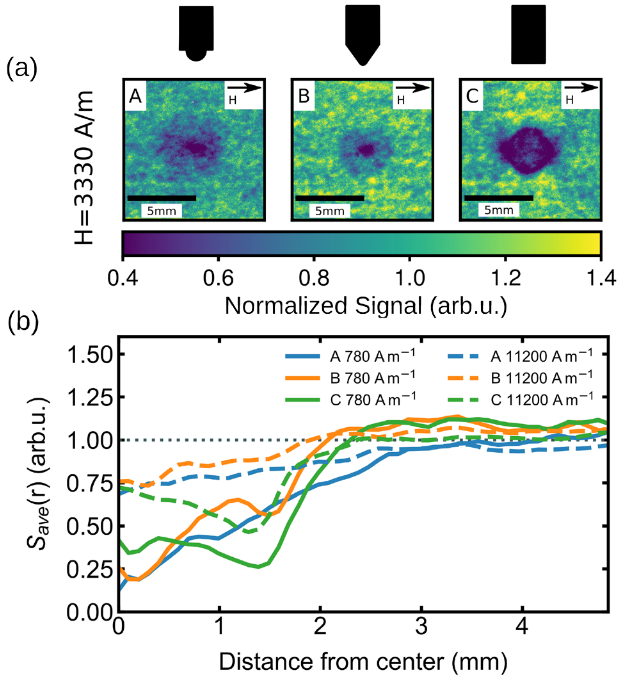

Fig. 1: Analysis of the influence of embossing on the scattering contrast. (a) DFI-signal of samples A, B and C in an applied magnetic field H = 3330Am^{-1}. The data is normalized using the reference sample also exposed to H. A signal smaller than S = 1 indicates more scattering in the embossed sample than in the non-embossed reference. (b) Normalized signal Save (r) as obtained by radially averaging the images of samples A (blue), B(orange), and C (green) exposed to two different magnetic fields. Figure taken from [1].

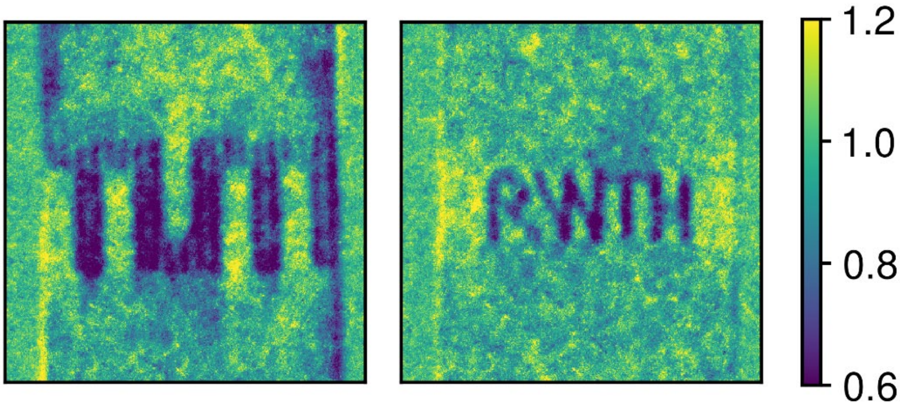

Fig. 2: Examples of finely distributed embossing points acting as magnetic flux barriers

shown in Fig. 2. Using these results, we plan to develop an electric drive using embossing to guide the magnetic flux, resulting in increased angular velocity.

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Tobias Neuwirth (MLZ)
Ines Moll (TUM),Benedikt Schauerte (IEM RWTH)
Simon Sebold (MLZ), Alex Gustschin (TUM) ,Alexander Backs (MLZ)
Simon Vogt Hannes, Alois Weiss, Nora Leuning (IEM RWTH)
Franz Pfeiffer (TUM) , Kay Hameyer (IEM RWTH), Wolfram Volk (TUM)
Peter Böni (TUM), Michael Schulz (MLZ)

3D-printable shielding for thermal and cold neutrons

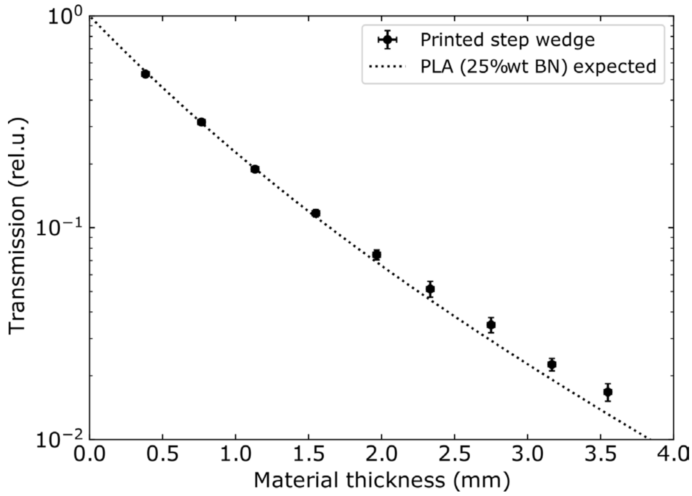
Effective neutron shielding is key to prevent the unnecessary irradiation of samples and instrument components or protect electronic components from radiation damage. This is especially important for neutron imaging instruments, which usually feature an intense neutron beam with a broad thermal or cold spectrum.

To provide an option for custom-made quick and cost-effective shielding of thermal and cold neutrons we developed a borated 3D-printing filament in cooperation with a commercial filament manufacturer. By using a Polylactic Acid (PLA) polymer and adding Boron nitride (BN) particles, it was possible to create a new filament that is easily printable with all common fused-filament-fabrication (FFF) printers. By choosing non-abrasive BN particles with hexagonal crystal structure, the default brass nozzles can be used for printing and printed parts can be machined. As a first iteration, a mass ratio of approximately 25%wt BN was achieved and trials for higher concentrations are currently being performed. The cost of our new filament is on the same order of magnitude as for standard high quality PLA filament.

The mechanical and shielding properties of the filament are currently being investigated in detail. Initial tests of the transmission for different thicknesses performed at the Institute Laue-Langevin (ILL) are shown in Fig. 1 and are compared to the expected transmission of the material. The measurement was performed for a step wedge printed with a Prusa i3 MK3 FFF-printer, requiring only small changes to the default print settings for PLA based filaments. The expected transmission curve is based on the chemical composition of PLA and BN, assuming typical densities and natural isotopic abundances. The transmission was corrected for beam hardening with respect to the spectrum of the NeXT beamline at ILL [1].

The transmission of the printed part shows good agreement with the expected curve for small thicknesses. For a thickness higher than 1.5mm a slight deviation towards higher transmission values is visible. The higher transmission indicates a generally lower Boron concentration than expected. This can be explained as printing with the FFF method tends to reduce the density of the material by layering thin lines of plastic and thereby introducing small air gaps. This lowers the total amount of Boron per volume of shielding material and thus increases the transmission.

With a transmission of 1.7% for a thickness of only 3.6mm and an expected thickness of approximately 7mm to reach a transmission of 10^{-3} we expect this new filament to be a



valuable addition to the available shielding options for thermal and cold neutrons. The option to rapidly manufacture almost arbitrarily shaped shielding without the need of a workshop allows for more custom shielding applications throughout the neutron research community.

We would like to thank the scientists of NeXT at ILL and SNAP at Oak Ridge National Lab (ORNL) for kindly providing beam time for this project.

If you are interested in the material, please contact us at: imaging@frm2.tum.de

References:

[1] Tengattini et al., Nuclear Instruments and Methods in Physics, Volume 968 (2020)

Simon Sebold, Tobias Neuwirth
Alessandro Tengattini, Michael Schulz

International Neutron Grating Interferometry Software collaboration

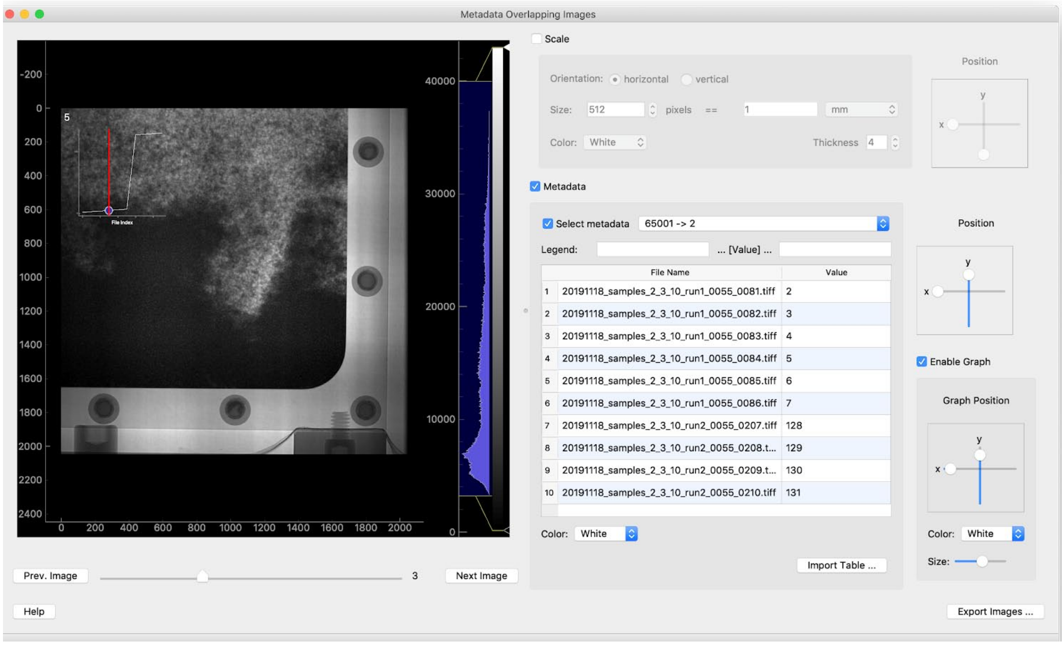
FRM II, PSI, ILL and ORNL started a collaboration regarding the development of a grating interferometry software package that will be facility independent. The software development currently in progress is based on the python program initially developed by Tobias Neuwirth and now mostly maintained by Simon Sebold under the lead of Michael Schulz (FRM II). Others, Jean Bilheux (ORNL), Alessandro Tengattini (ILL) and Anders Kaestner (PSI) are now contributing to the refactoring phase of the code in order to easily adapt the code to other institutions. The goal being to produce an open source python project that anyone can easily adapt and use on their instrument.

Jean Bilheux, Tobias Neuwirth, Simon Sebold
Alessandro Tengattini, Anders Kaestner, Michael Schulz

ORNL imaging python Jupyter notebooks now available as open source software

A series of imaging python Jupyter notebooks developed in collaboration with the ORNL neutron imaging user community is now available as open source code and is fully compatible with all operating systems (OS). Tutorials explaining how to install and utilize the notebooks can be found here, https://neutronimaging.pages.ornl.gov/tutorial/notebooks/. The community is welcome to modify and contribute to the repository. Please contact me (bilheuxjm@ornl.gov) if you want me to share your changes or even add new notebooks on our github website (https://github.com/neutronimaging/python_notebooks).

Jean Bilheux



Example of a user interface launched from a notebook. This particular notebook/UI has been requested by users to allow display of metadata (value, plot) on top of projections measured.

Semi-automatic panoramic stitching of radiographs using a Jupyter notebook

When a sample is larger than the field-of-view (FOV), multiple radiographs are measured sequentially. This step is repeated as needed when time-dependent studies, such as water uptake in roots, are required.

After normalization, the radiographs must be stitched together before moving to data analysis. ImageJ, an NIH-developed software tool (imagej.net) is capable of automatically stitching data in some cases but not all. Hence, we developed a couple of notebooks that perform automated stitching of multiple radiographs. A first notebook sorts all the images into cycles, starting at the top left radiograph then moving to the bottom right by row and then columns. The images are also renamed in order to follow ImageJ convention. One can try ImageJ stitching plugin at this stage, but if this step fails, a second notebook we developed allows the semi-automated stitching of the radiographs. First, one needs to manually position the radiographs to form the first panoramic image. Then, The program automatically uses metadata such as motor positions to stitch the first radiographs and applies the same logic to the subsequent cycles. Vertical and horizontal profiles are also displayed to provide a more precise stitching. The full tutorial can be found on our web site at neutronimaging.pages.ornl.gov/tutorial/notebooks/panoramic_stitching.

Jean Bilheux

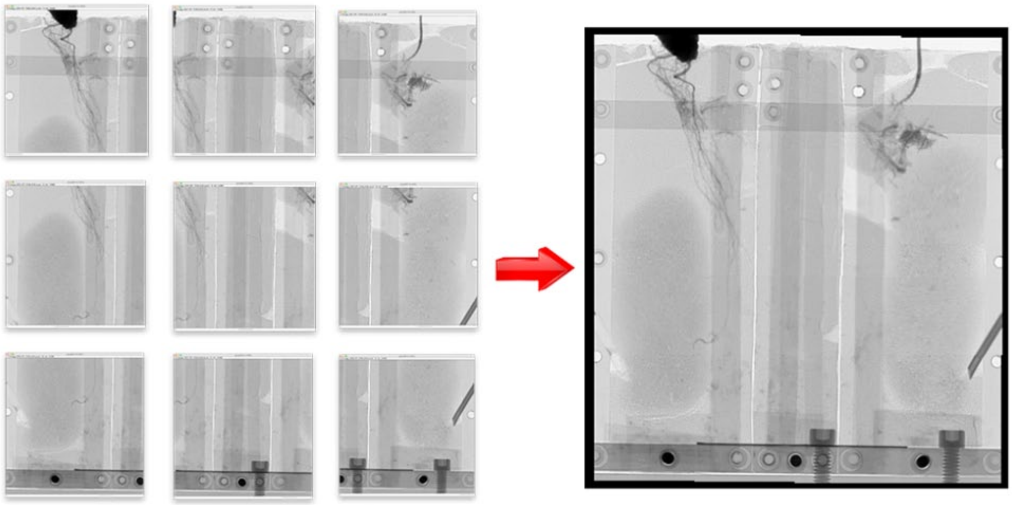


Figure 1: Before and after stitching using the panoramic stitching notebook (courtesy of Profs Kathryn Morris and Jonathan Morris, Xavier University).

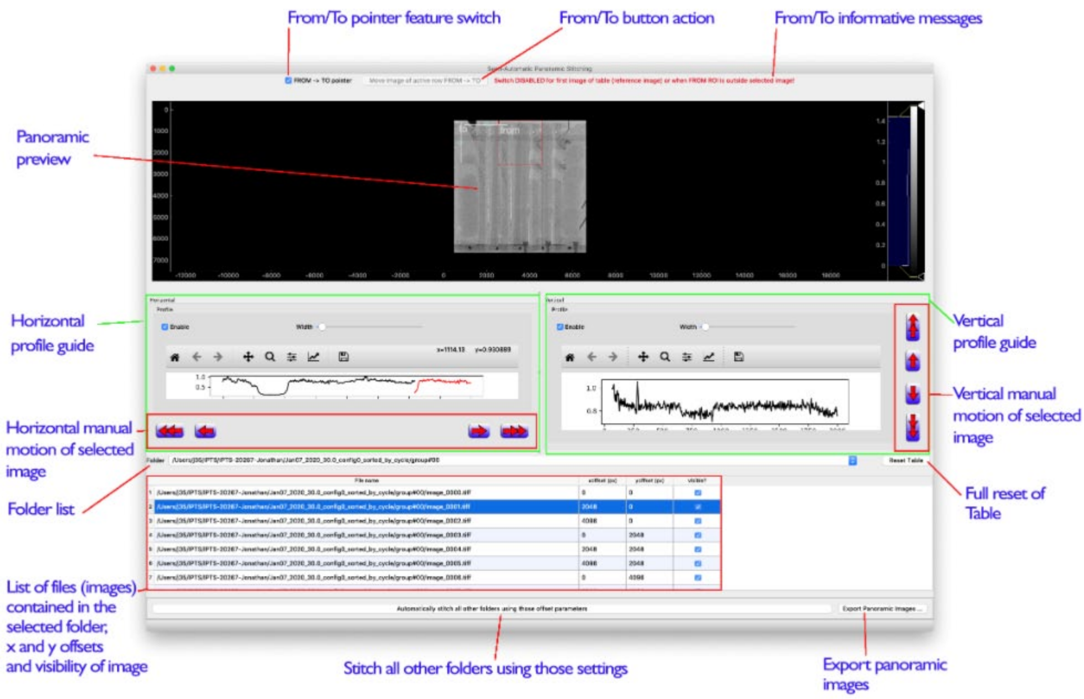


Figure 2: Intuitive General User Interface (GUI) launched by the notebook to facilitate the stitching of the radiographs.

MCP detector correction script now available in python

Anton Tremsin's MCP detector correction code is now available in python and can be executed on any OS. The code takes 2 mandatory arguments, an input and an output directory. The input directory is the raw data produced by the MCP detector where the time spectra, shutter counts and shutter time must be present in addition to all the FITS files. The output directory is the location where the corrected data will be created. The code is open source and is available in the ORNL imaging repository:https://github.com/ornlneutronimaging/NeutronImagingScripts/blob/main/scripts/mcp_detector_correction.py

Jean Bilheux, Anton Tremsin

The role of the Computer Instrument Scientist at Oak Ridge National Laboratory

Neutron imaging instruments often require computer intensive tools for data normalization, analysis and visualization. At the Oak Ridge National Laboratory, a new and unique position was created to allow a dedicated scientist, called a computer instrument scientist or CIS, to focus on software, from integration of software tools to data acquisition system (DAS), to advanced algorithms for data processing and analysis. At ORNL, dedicated CIS positions were filled for several techniques such as imaging, diffraction, SANS and spectroscopy. The advantage of focused CISs is the ability to keep up with the community's software efforts but also the ability to collaborate on a worldwide scale and develop tools for ORNL and other worldwide facilities alike.

In June 2020, I started a CIS role for neutron imaging capabilities at ORNL. This role is key in enabling successful experimental planning but also ensures advanced software tools are available to the scientific community after their experiments. Similarly to the optimization of an experiment, optimization of data processing/analysis is essential to the success of an experiment at neutron imaging (and scattering) beamlines.

In a few words, the CIS is the intermediate between the instrument scientist (IS) and the software development team (i.e. the dedicated programmers who are not verse in neutron techniques but are experts in creating intuitive, user-friendly, and reliable software tools). Since the CIS is an expert in specific neutron technique, he or she does thorough literature search, links with international collaborators, develops a logical plan to develop the algorithms, test the algorithms on a sampling of data, before interacting with the software developmen team. At ORNL, the latter team is called the Research and Software Engineering (RSE) team.

An example of such effort has been the automation of the micro-channel plate (MCP) detector count rate correction or work in progress regarding the automated fitting of Bragg-edges. The CIS and the IS work hand-in-hand to define the requirements for the software tool, then the CIS develops the prototype that he/she tests on data provided by the IS. Once ready, the IS tests the software, and then the CIS works closely with the RSE team to provide/deploy an optimized and reliable to the user community.

Jean Bilheux

Update on the Bragg edge analysis round robin

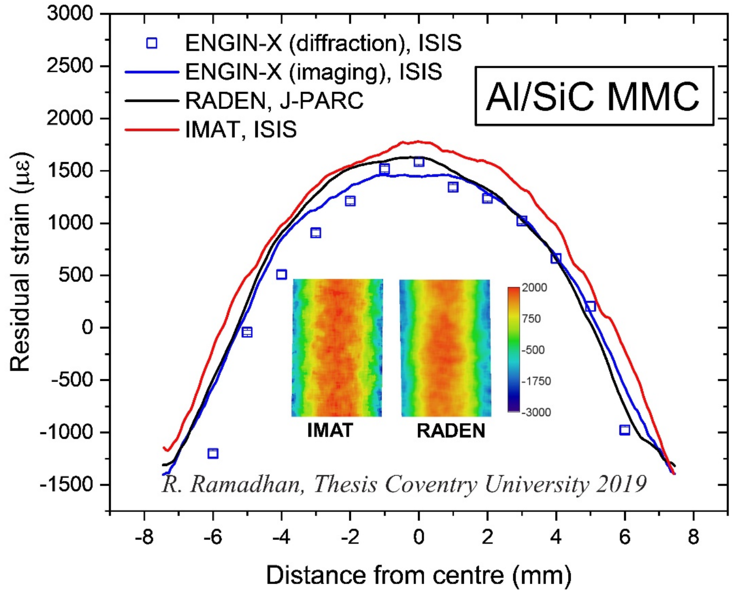
In last year's ISNR newsletter we had proposed a Bragg edge round robin and we give a brief update here. We hope to be able to raise interest for this round robin among facilities and universities who are engaged in neutron strain imaging. Although the number of studies is increasing steadily Bragg edge analyses are far from being routine, and there is a need for standardized collection and analysis procedures, and for developing software to raise confidence of academic and industrial users in the new Bragg edge methods. At the same time, we consider participation of existing and new diffraction strain scanners as immensely useful as this will help to increase acceptance of the imaging methods by academic and industrial users.

My turn! My turn!

Therefore, the round robin exercise will include imaging instruments and diffraction strain scanners, with emphasis on Bragg edge analysis on time-of-flight or steady state sources with energy selection. The aim is to benchmark the known and new capabilities on all types of instruments, to assess levels of accuracy, precision, and detection limits of Bragg edge transmission and neutron diffraction for residual strain and phase composition analysis.

The round robin is at an early stage and will probably not start before early 2022. We have preselected samples for use in the round robin, mostly metals considering the targeted engineering science user community. The round robin will include several samples, even though some participants may choose running a subset of samples, and we will limit the round robin to quantitative analysis of strains and phase amounts in 2D. Sample candidates include: the VAMAS aluminium ring&plug; a Fe/Cu ring&plug; a near-surface-strain sample; a two-phase Al/SiC metal matrix composite with a simple strain profile; a dissimilar weld. During 2021 we will determine strain components and characterise the texture of the samples using neutron diffractometers, and perform some initial analyses on imaging beamlines. This will help us identify weak and large strain components, select samples with no or weak preferred orientation, and come up with a reasonable analysis protocol. We will also try to perform complementary characterisation methods if opportunities arise.

We believe the round robin will come up with recommendations and good practices for data collection and analysis, provide opportunities to produce data to download for users and software developers to work on. Last but not least, one aim of the round robin is to encourage collaborations between facilities.



Winfried Kockelmann, Ranggi Ramadhan
Markus Strobl, Aaron Craft

Neutron Imaging at Oak Ridge National Laboratory: Update on construction of VENUS and a vision for a comprehensive instrument suite

VENUS construction

VENUS is a dedicated time-of-flight neutron imaging facility currently under construction at the Spallation Neutron Source first target station (SNS-FTS) with a projected completion date of Spring 2023. The current Winter (2020/21) maintenance outage at SNS is facilitating installation of some of VENUS's major front-end components including the core vessel insert (CVI, see figure below), the beamline shutter and the shutter insert (SI, see figure below), which contains the beam defining fixed aperture. The CVI is the first component of the instrument and sits closest to the target monolith and requires cooling using He gas. The SI resides in the shutter gate itself and contains the first optical component of the beamline, a ~ 95% isotope-enriched $^{10}B_4C$ aperture designed such that at the 25-m detector position, the maximum available field-of-view is 20 cm x 20 cm.

Hassina Bilheux

Neutron Imaging at ORNL: what the future might hold

The long-term strategy for neutron imaging at Oak Ridge National Laboratory focuses on the optimization of imaging capabilities across multiple sources - current and planned - or the most impactful science portfolio. For time-of-flight imaging, in addition to VENUS on SNS-FTS the imaging user community is currently championing a proposal for CUPI^{2}D (CUPI2D is an acronym for Complex, Unique and Powerful Imaging Instrument for Dynam-

Core vessel (top) and shutter inserts (left) to be installed at VENUS during the SNS Winter outage, 2020/21.

ics) as part of the initial instrument suite for the planned SNS second target station. At the High Flux Isotope Reactor (HFIR) an upgrade (tentatively named ARES) is being considered for the current instrument in the cold guide hall (CG-1D) as part of a wholescale refurbishment of the neutron guide network during the extended outage in 2024 to replace the reactor's beryllium reflector. For the longer term, a case is also being developed for MERCURY an epithermal imaging beamline at the reactor.

These beamlines, taking names from Roman and Greek mythology, will complement each other in terms of capabilities such that scientific areas can employ one or more of the facilities. For example, while VENUS is optimized for a large field-of-view (20 cm x 20 cm) semi-static and slow kinetics Bragg edge and resonance imaging, CUPI^{2}D will be optimized for fast kinetics and characterization over the broadest length and time scales using Bragg edge imaging and neutron grating interferometry. Its maximum field-of-view will be limited to 10 cm x 10 cm. ARES will be capable of providing an intense flux of cold neutrons (without wavelength resolution comparable to VENUS or CUPI^{2}D) and will be home of the highest achievable spatial resolution radiography and tomography beamline with a field-of-view on the order of a few mm^2 (in high resolution mode). Finally, MERCURY will provide unprecedented penetration power as it will be exclusively using epithermal and fast neutrons. It is anticipated that large objects will be measured at VENUS and at the future MERCURY.

Hassina Bilheux

The Future Neutron Imaging Beamline at the Oak Ridge National Laboratory's High Flux Isotope Reactor

In 2024, the High Flux Isotope Reactor will go through major upgrade activities such as the replacement of the Be reflector and the guides in the cold guide hall. The replacement of the Be reflector is replaced every 20 years, approximately, due to radiation damage. The upcoming presents an opportunity to upgrade the cold guide hall guide systems and optimize the instrument suite for significant performance improvements. The beam port at CG-1D, where the Cold Neutron Imaging Beamline is currently located (as of 2020), will be reconfigured to host a new cold neutron triple-axis spectrometer (MANTA). Therefore, the existing neutron imaging capability at HFIR will be relocated to the new beam position (NB-4) between the Bio-SANS and GP-SANS instruments (as shown in Figure 1), where the area is made available by the cold guide hall expansion. Current efforts are focused on the imaging instrument conceptual design, neutronic simulation and engineering feasibility. The goals are to ensure the neutron guide system is optimized for a cold neutron imaging instrument and to improve the current imaging capabilities at the future NB-4 location. The new instrument will be optimized for high spatial resolution white beam imaging (on the order of a few μm) over a few mm^2 field-of-view, while still maintaining the capability to reconfigure the instrument to measure samples with a field-of-view of 10 cm x 10 cm. The modeled integrated intensity (at the 10 cm x 10 cm sample location) is expected to be comparable to the existing CG-1D neutron imaging beamline.

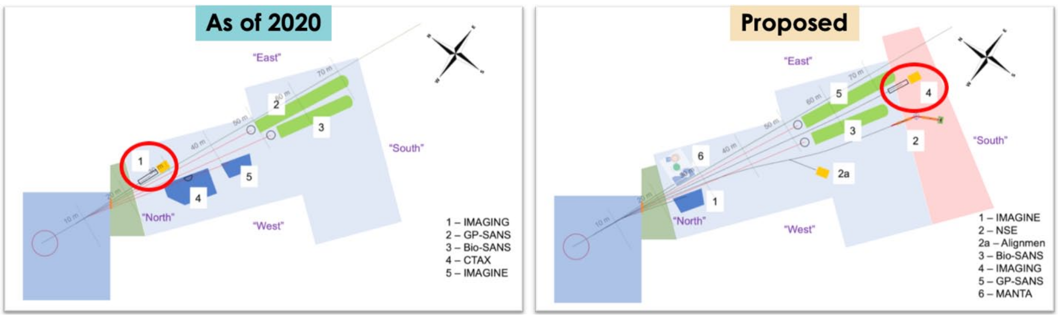


Figure 1 (Left) current instrument position circled and (right) proposed instrument position circled after the building extension post Beryllium changeout (figure curtesy of Dr. Georg Ehlers, ORNL).

Yuxuan Zhang

New high-pressure sample environment available at the imaging beamlines at PSI

Neutrons are well known for their capability to transmit through many structural materials while being highly sensitive to hydrogenous materials. Consequently, neutron imaging is well suited for investigations of processes occurring in liquids under high gas pressures. A new sample environment device has been recently developed for this purpose.

The measuring cells of this sample environment device are made from Titanium Grade 5 and thus allow for the in-situ investigation of liquids exposed up to several hundreds of bars of gas pressure. The device can be used for different types of gases and liquids, the sample temperature is regulated using a water circulator and the entire device can be continuously purged with an inert gas. Thus, the device routinely allows for the investigations of samples maintained at 5 to 50 °C.

The device has been used in the pilot investigation (Vopicka et al., PLoS One, 2020 https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0238470) which was focused on methane (CH4) diffusion into perdeuterated liquid ethanol (C2D6O) and perdeuterated n-decane (n-C10D22). These substances are directly relevant for the societally relevant though currently rather unpopular topics of production, refining and transportation of natural gas and crude oil.

It is demonstrated that the diffusion of the pressurized methane, liquid swelling and the liquid surface tension can be measured simultaneously in a one-pot experiment. A particular highlight is the non-tactile measurement of the liquid surface tension necessitating no assumptions imposed on the properties of the liquid. The axial symmetry of the samples allows for the provision of the tomographic reconstructions based on single neutron radiographies. Figure 1 shows examples of the tomographic reconstructions of the menisci shapes in the titanium cells under various gas pressures from which the surface tensions of the liquid can be directly derived.

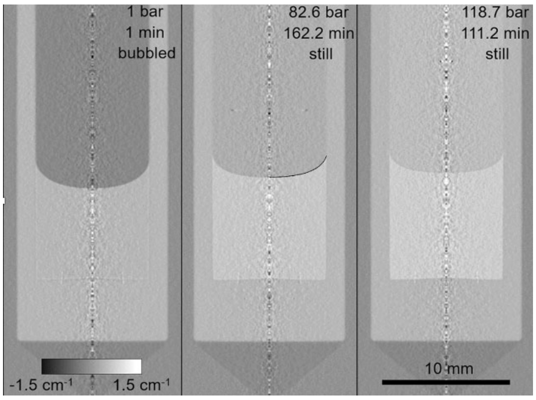


Figure 1 - Tomographic reconstructions of the titanium cell high pressure with the liquid body and methane phase for 1 bar (left), 82.6 bar with shown model of meniscus (middle) and 118.7 bar (right) .

In case of an interest in using this device please do not hesitate to contact Ondřej Vopička (ondrej.vopicka@vscht.cz) and Pavel Trtik (pavel.trtik@psi.ch).

Ondřej Vopička, Petr Číhal, Martina Klepić, Vladimír Hynek (VSCHT, Prague, Czech Republic)
Vladimír Hynek, Karel Trtík (U3V-CVUT, Prague, Czech Republic)
Jan Crha, Pierre Boillat, Pavel Trtik (PSI)

E-learning Course on Neutron IMaging

The IAEA e-learning course on neutron imaging is now on-line and accessible for self-enrolment:

https://elearning.iaea.org/m2/course/view.php?id=633

and

https://www.iaea.org/newscenter/news/iaea-launches-new-neutron-imaging-e-learning-course-to-preserve-knowledge-improve-services-and-promote-the-use-of-research-reactors

News from the Board

Retirement of Frikkie de Beer

A letter by Frikkie

Dear colleagues, friends, co-workers, fellow neutron radiography scientists,

I am a little sad to say goodbye to you as colleague and fellow scientist who has also became long life friends during my international career as NRAD scientist and who I have encountered frequently at conferences but also performed research together. After 32 years of service with Necsa, I will retire on early pension on May 31, 2020 - last day May 29. I have no plans to join another company but can assure you that it is a well calculated and rational decision.

Over the past 32 years at Necsa, I have lived out my calling at Necsa to be creative and created opportunities for fellow colleagues and researchers in South Africa that did not exist before. The situation at Necsa is currently such that I do not receive support (Financial, career development, national and international conference attendance, engineering support, etc.) in my calling to also complete the upgrading of the NRAD facility as well as being more scientifically creative. However, I completed my calling at Necsa with the creation and use of a well-functioning micro-focus XCT facility (9 years now) linked to a USER OFFICE management system similar to what I used in BERII, PSI, FRMII, NIST and IMAT - but not yet online. With 24 peer-reviewed publications only for 2019 and many postgraduate students who have improved their qualifications at Necsa through the use of the Necsa facilities, I leave a legacy that my colleagues (Kobus, Lunga and Robert) can only expand to higher heights. In the short term, two NRAD research projects are currently underway at international facilities (NIST and ISIS) showing the need of SA researchers to continue using neutrons in the hydrogen economy and in the geosciences respectively.

With my departure from Necsa, I will unfortunately , as pensioner, not be able to travel so frequently to attend the ITMNR and WCNR gatherings organized and scheduled by the ISNR-board. The only plan is that I might partly attend the next WCNR in USA in 2022 as back to back visit to my son who is currently playing rugby football for the Utah Warriors (Jan - June) and for the Chicago Rugby Lions (July - Dec)

I hereby officially submit my resignation as a member of the ISNR board because I cannot guarantee that I will be able to attend any conference of the ITMNR or WCNR series. I also cannot guarantee that I will remain involved in NRAD related research but also not be able to make significant contributions to the activities of the board without attending its meetings.

During my international career starting in WCNR-6 in Osaka, Japan in 1999, I was privileged to be accepted by the international neutron radiography community, to serve on the ISNR board since 2004 (WCNR-7 in Rome), to work with you and other professional neutron radiography scientists at high profile international organizations (e.g., IAEA, PSI, FRMII, ISIS, Helmholtz, ANSTO, KAERI, NIST, Oak-Ridge and others) as well as sharing research projects together, publish and having a meeting with a beer around a table. I was able to travel the world in my interaction with you and other NRAD scientists at vari-

ous levels and this is something that will always stay with me. It is practically impossible to meet with you individually to confirm our longstanding friendship and scientific relationship before I retire - therefor this email and message from my heart.

The initiative to complete the upgrade of the Nrad facility at Necsa will continue with my fellow colleague, Mr Robert Nshimirimana heading the project. Hopefully he will be able to attend the ITMNR during Oct 2020 in Argentina if he obtain the necessary funding support.

Nevertheless, I hope we will meet or communicate again in the distant future - God bless and good bye.

My contact email address from 1st June 2020 will be: 1958Frik@gmail.com

Kind regards

Frikkie de Beer

09.03.2020

About the retirement of Frikkie de Beer, South Africa

Recently, we got the message from F. de Beer that he will quit his affiliation at NECSA, the South-African institute for nuclear research in his country at the end of May 2020. This is a remarkable step, because it takes place before he reached the official retirement age. In his message, he pointed out that the support for his projects and the funding for the participation in meetings of the world-wide organized neutron imaging (NI) community is not provided by his institute in the future.

With this retirement step, the neutron imagers, organize in ISNR, will lose a prominent member, representing not only his institute, but also his whole country and the continent.

Former Presidents of ISNR (from left to right): John Barton, Muhammad Arif, Frikkie de Beeer, Eberhard Lehmann, Ulf Garbe

Therefore, we want to recover some memories to him with the aim to highlight his merits for the development of neutron imaging facilities and methods in South Africa.

Frikkie has a long record of work at NECSA for more than 32 years. He joined the international NI community about 20 years ago by a conference visit in Osaka (Japan). Based on the opportunities at the SAFARI-1 reactor (20 MW) for applied neutron research, he intended to establish a state-of-the-art NI facility there. First trial with film methods were overcome by the idea to establish a digital system, which enables also advanced methods like neutron tomography and real-time imaging. Next to the needed fund raising, he established contacts to leading NI teams with the aim to take over their know-how and to install copies of their equipment on commercial basis.

In addition to his technical approach, he continued to network by visiting other relevant meetings and created a fruitful interaction with IAEA in Vienna. This culminated with the proposal to host the 9th World Conference on Neutron Radiography (WCNR-9) in South Africa in 2010.

It was certainly a highlight for him, but also for the NI community to hold the conference in South Africa (and for the participants to stay for a week or more in this beautiful country). Aside to this important meeting he created a team of young researchers, including PhD students and technicians for his new neutron tomography facility at SAFRI-1.

Based on this obvious success, further installations like X-ray tomography, were done at NECSA and an user program was established with very interesting topics like the study of natural cultural heritage objects, of porous media and facilities for hydrogen storage.

After his election as president of ISNR in course of the chairmanship of WCNR-9 he became an active and motivated member of the societies board within different meetings, partly funded by IAEA. He contributed to publications of this organization and helped to clarify the terminology for NI. By means of scientific visits at different other NI facilities he extended his knowledge in the field and performed many interesting experiments, leading to remarkable publications.

It was his dream to improve the NI performance in South Africa by an upgrade of the NRAD facility and install NI also at a possible SAFARI-2 reactor to be build in near future.

His retirement will cast a shadow over the situation at NECSA. It is still to hope that his successors will continue his engaged work with similar effort and output.

To him, we want to deliver a great "thank you, Frikkie" for the wonderful spirit in all the past years, your enthusiasm and team work. We cannot believe to be out of the field completely after May 2020 and hope for some continuation and communication with you in the future.

Eberhard Lehmann

The List of Members

on the ISNR-website is now password protected, as some members received an email about "ISNR LOGISTICS SUPPORT REQUEST." This is a phishing email seeking to elicit a response, then it will reply asking for money as was the case for some colleagues whose auto-reply elicited the response from the scammer.

Please always check the address of the email and in no case response to the scam email.

To make the access to your email addresses given in the list of members on the ISNR website more difficult, it is now password protected. The password is now required for each single access to the data.

Amazingly, I only received one request for the password! If you want to access the database you have to unravel the following mystery: what's the probe, we are using for our investigations? Take the first two letters in lower case. Add the number that sounds like "for" followed by the first two letters for a synonym for "picturing" in lower case letters.

Upcoming conferences and workshops

The International Society for Neutron Radiography (ISNR) is not immune to the same scheduling issues that have caused virtually every other organization to reschedule meetings and conferences. The 9th International Topical Meeting on Neutron Radiography, ITMNR-9, would have been held this year but was postponed back in April 2021 due to the pandemic. World events have not calmed down much since then. However, the ISNR Board has adjusted the schedule for our Society's upcoming meetings.

2021: NEUWAVE-10 Workshop in Japan.

2022: ITMNR-9 in Argentina.

2024: WCNR-12 in the United States.

We, the Board of Members, are following the evolution of events and will announce new dates and details as plans progress.

... and finally

Please review your data on the website (*www.isnr.de/index.php/about-us/list-of-members*) and inform me on errors and / or changes.

Editor

Thomas Bücherl
TU München
Walther-Meissner-Str. 3
85748 Garching
Germany
thomas.buecherl@tum.de
secretary@isnr.de

Advances in Neutron Imaging

Guest Editor:

Prof. Dr. Wolfgang Treimer
Department Mathematics, Physics & Chemistry, University of Applied Sciences Berlin, Luxemburger Str 10, 13353 Berlin, Germany

Wolfgang.Treimer@ beuth-hochschule.de

Deadline for manuscript submissions:
31 May 2021

Message from the Guest Editor

This special issue on “Advances in Neutron Imaging” of *Applied Sciences* shall publish a wide range of scientific research activities for a broad audience. It presents new and important findings using neutron imaging, reflecting many important areas of research activities in different scientific fields. Welcome are review articles, results of interdisciplinary research, as well as the latest research results from various disciplines, carried out with neutron imaging, which appeal to a broad audience.

Topics of interest include (but are not limited to):

- neutron imaging in physics research
- material sciences
- non-destructive investigations
- interdisciplinary sciences
- neutron imaging of quantum phenomena

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Special Issue