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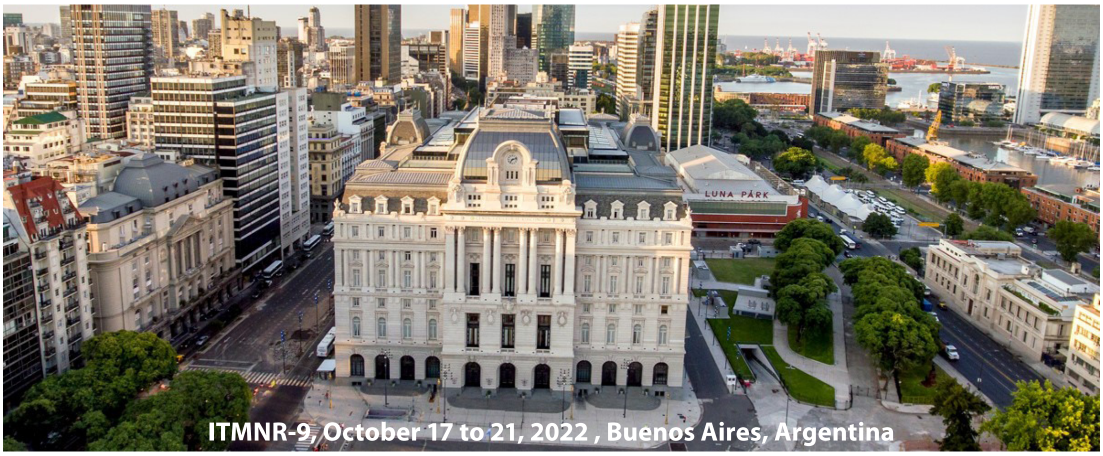


https://itmnr-9.sciencesconf.org/

Content

Editorial

Dear colleagues,

with the present issue of the NR Newsletter we once again want to inform you on ongoing topics in the field of Neutron Imaging. But wait! Did you realize the vague formulations in this first sentence? Who is meant by the word "we"? What do "we" understand by the term "information"?

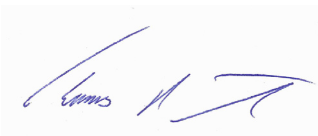
With this, I want to focus your attention on one of the basic features of our (scientific) work: be clear and precise in your statements! Use references whenever possible and validate that the content you refer to is reliable. Unfortunately, even in science the same procedures take place like in our daily environment: statements and "facts" are presented without any proof and are repeated ingenuously by others until nearly anybody accepts them as real facts. This is accelerated by electronic communication more than ever before. Therefore, I can only advise you to verify the references you are referring too at least by reading them critically and not only citing to have enough references.

Realizing the increasing number of publishers in the scientific field and others advertising that the time until a submitted paper is published is as short as 14 days or even less I'm really wondering how this works keeping quality at least at a certain minimum level. From time to time, I am reviewing papers, but from the first request until it is finished it takes much longer, especially if you are doing this in addition to your regular profession. To present an actual result of a measurement a short notice might be fine and no extensive review is necessary. In this case, the corresponding data must be available to verify the conclusions. I personally had a publication with some colleagues, which lasts nearly one year until publication. The referees put many efforts in correcting and improving our paper giving us many valuable suggestions. This improved the quality of our paper drastically (which wasn't that bad originally, at least to my opinion). Finally, we, the authors, got many new ideas for continuation of our work and a paper we are extremely satisfied with.

Why I am writing this in my editorial? I want to draw attention, especially of the young generation, to keep quality high and avoid harming your reputation by using only "facts". Errors can happen but sloppily work can be avoided. Before asking, all contributions in this NR Newsletter are not reviewed, but presented by members of the ISNR for members of the ISNR. You can contact the authors directly if some clarification is needed.

… and keep in mind: “facts” are not always facts! Especially outside our community!

Enjoy reading this new issue and keep healthy



Thomas Bücherl
ISNR secretary

Words from the ISNR President

I hope that this 17th ISNR Newsletter finds you well, that you are all in good health.

We appear to be coming out of the pandemic and the world is opening back up. Though the international situation continues to be challenging, many of you have continued publishing fantastic work. I personally try to keep informed about your work by reading your papers, using online resources to notify me of newly published papers. There are many promising developments in our field and ever-higher impact applications being addressed. Honestly, it is difficult to keep up, which is a good problem to have. Thank you to all of you for continuing to push the state of the art. The world-wide neutron imaging community appreciates your efforts.

The ISNR conferences have been disrupted by the recent pandemic, of course. However, we have been actively working towards the time when we could all meet in person again at an ISNR conference, and we are finally close to meeting once again at the 9th International Topical Meeting on Neutron Radiography (ITMNR-9).

I am excited for ITMNR-9 this October 17-21, 2022 in Buenos Aires, Argentina. The Organizing Committee, led by our colleague Javier Santisteban, together with the Scientific Program Committee have produced a high-quality technical program. I earnestly hope that you can all attend and share your work with our world-wide community.

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 inform the ISNR Board about such opportunities as you discover them so we can distribute this information to the rest of the Neutron Imaging community.

One such upcoming non-ISNR conference is the 12th International Conference on Methods and Applications of Radioanalytical Chemistry (MARC XII), which is meeting 3-8 April, 2022 in Kona, Hawaii, USA. The conference organizers invited some colleagues and me to organize a new session specifically on Neutron Imaging. Our session garnered more submitted abstracts from around the world than almost every other section of the conference, which was quite promising for a first session on neutron imaging at this conference.

I would like to briefly report here that a notable addition has been made one of our community's standards: The term "Neutron Imaging" is now officially a technical term included in ASTM E1316-22, Standard Terminology for Nondestruuctive Examinations, Section H: Neutron Radiologic Testing Terms. This effort was first formalized by a Terminology Committee within the ISNR Board led by Markus Strobl before my tenure as President. Their report can be found on the ISNR website (isnr.de). I brought this effort to the ASTM E07.05 Committee for incorporation into the glossary (E1316). Notice that the definition approved by ASTM bares a striking resemblance to the definition in the ISNR terminology report. You may notice other new terms in E1316-22, but that is a topic for another day.

> **neutron imaging**, n—the process, science, and application of producing images (physically or in the form of data) of objects and phenomena by the means of neutron radiation.

This 17th edition of the ISNR Newsletter includes encouraging and interesting news from around the world. I hope that you find this newsletter inspires new ideas with each of you.

Looking forward to seeing you in person at ITMNR-9.

With best regards,

Aaron Craft
ISNR President

Neutron Imaging in the World

Launch of Space Telescope: a historical NR Perspective

On December 25, 2021, after twenty years and ten billion US Dollars in development, a planned new Space Telescope was launched by the Ariane 5 flight VA256.

The reliability of this Ariane launch derives from experience with 255 prior launches, each having used Neutron Radiography to make up to 500 NR Tests of pyrotechnic devices.

The launch of the new Space Telescope from French Guiana using the Ariane 5 launcher was reported to be so nearly perfect that fuel was conserved which could extend the life of the telescope from 10 years to 20 years.

A detailed introduction to the qualitative and quantitative uses of neutron radiography applied to the Ariane launcher series is by J. P Bouloumie of the Centre National d'Etudes Spatial, Toulouse, France where the rockets have been developed [1]. Later reports by G. Bayon of Saclay also give valuable details on Ariane 5 neutron radiography applications using the Orphee reactor cold beam at Saclay [2]. Recent reporting includes that by C Grunzweig at The Paul Scherrer Institute in Switzerland [3].

After launch there are many more ways in which things could fail. But by February 1 2022 the Telescope had successfully reached its intended permanent orbit L2, with balanced gravity between the earth and sun. Other critical steps included unfolding the large reflective mirror and preparing the infra-red sensors. The Space Agencies of USA (NASA) Europe (ESA) and Canada (CSA) are each involved, and authorities have projected that some first images may be made public by June 2022 if all continues well.

The new James Webb Space Telescope is designed to provide about seven times more sensitivity than the previous Hubble Space Telescope. Thanks in part to the support of neutron radiography, the now successfully launched new telescope should provide images dating back 13.7 billion years to just before the big bang.

A winner of the 2020 Nobel Prize in Physics, Roger Penrose, has claimed with colleagues that there is evidence of existence preceding the "big bang" [4]. However, imaging with the new space telescope, if achieved back about 14.7 billion years, would be historic imaging indeed, all thanks in part to neutron radiography!

[1] *J P Bouloumie. Aspects Qualitatifs Et Quantitatifs Du Controle Neutronographique Applique Aux Chaines Pyrotechniques Du Lanceur Ariane Second World Conference on Neutron Radiography 1986 https://link.springer.com/chapter/10.1007/978-94-009-3871-7_36*

[2] *Guy Bayon. REVIEW ON USE OF NEUTRON RADIOGRAPHY AT SACLAY NUCLEAR RESEARCH CENTRE https://inis.iaea.org/collection/NCLCollectionStore/_Public/28/024/28024567.pdf or https://www.osti.gov/etdeweb/biblio/475560*

[3] *Paul Scherrer Institute 21 June 2019. PSI imaging helps with rocket launches. https://www.psi.ch/en/media/our-research/psi-imaging-helps-with-rocket-launches*

[4] *Roger Penrose, 2018. https://physicsworld.com/a/new-evidence-for-cyclic-universe-claimed-by-roger-penrose-and-colleagues/ and https://futurism.com/sir-roger-penrose-alternate-theory-of-the-big-bang-2*

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Could Growing Demand for Nuclear Power also Grow Demand for Neutron Tests?

Growing Debates about Next Generation Nuclear Power

Following recent climate change meetings, more than 50 nations have pledged to achieve "net-zero" greenhouse gas emissions by 2050. The Energy Information Administration forecasts non-transportation electricity demand will rise 30% above 2019 levels by that date, and electric vehicles would increase demand further.

Renewables, such as solar and wind, alone cannot meet replacements of coal, oil and gas on a timeline consistent with climate goals. Nuclear is the only proven non-fossil fuel alternative to provide baseload supply shortfall. Critics have raised the issue of long-term nuclear waste management. A response is that in the USA, where Nuclear Power has been in use since the 1950s and where over 90 power reactors currently are operating, all the nuclear waste produced is under 90,000 tons, equivalent to one football field size covered only 10 meters high. This can be better managed than the billions of tons of carbon dioxide gas that would be the waste product of equivalent coal, oil or gas burning.

In February 2022 French President Macron pledged to construct six mammoth, next-generation, pressurized water reactors starting 2028, with an option for eight more by 2050. France also announced plans for small modular reactors by 2030, joining the many other countries in that field. In France there are 56 nuclear power reactors that have produced 70% of electricity reliably since the 1980s.

In neighboring Germany nuclear power plants have been recently closed, which makes a striking contrast. The debates about the future of nuclear power in countries around the world seem likely to continue for reasons of both national energy security and climate change. The European Union on behalf of its 27 nations agreed recently to classify nuclear energy as a green investment.

China has announced plans to build over 150 new full scale power reactors in the next 15 years.

In the USA in November 2021 a major $1.2 trillion infrastructure spending bill signed into law included $6 billion to keep existing nuclear power reactors in service longer and $2.5 billion for research and development of new nuclear power technologies.

Worldwide 450 nuclear power reactor reactors currently produce about ten percent of total electricity. The increasing level of debates about possible next generation nuclear power can be followed in The International Atomic Energy Weekly News [1].

History of Neutron Radiography in Earlier Generation Nuclear Power

Neutron Radiography played important roles in the earlier development of nuclear power programs and it might behoove those involved with future neutron test technologies to be aware of those earlier lessons learned.

For example, over half of the 140 papers presented at The First World Conference on Neutron Radiography were on nuclear power applications. A helpful introductory paper with 38 references is that by J. Domanus et al. [2].

The proceedings of The Second World Conference on Neutron Radiography, which is also available online, provides many more papers on Neutron Radiography applied to the first-generation nuclear power needs. A paper by J. Bakker et al on light water reactor fuel NR is particularly drawn to the attention of those concerned with second generation nuclear power reactor options [3].

Conclusion

There is recent news of increasing debates about the pros and cons of nuclear power and increasing funding for research and development of next generation nuclear power technologies. The history shows numerous important roles for neutron testing. Awareness of the above could help find future roles for neutron testing capabilities.

[1] *International Atomic Energy Agency Weekly News. https://mail.google.com/mail/u/0/#search/iaea+weekly/FMfcgzGmtNcXfzWfqKxHNcPpWknnftdM*

[2] *J.C Domanus and P. von der Hardt. Nuclear Industry Application of Neutron Radiography in Europe. Proceedings of the First World Conference. J. P. Barton et al. eds. 1981 https://link.springer.com/book/10.1007/978-94-009-3871-7*

[3] *J. Bakker et al. Neutron Radiography of Light Water Reactor Fuel Rods at the High Flux Reactor Petten. Proceedings of the Second World Conference on Neutron Radiography. J. P Barton et al eds. 1987. https://link.springer.com/chapter/10.1007/978-94-009-3871-7_49*

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Neutron Supply

Contribution of PSI's Applied Materials Group to Mitigate International Shortage of Neutron Imaging Beamtime

Apart from the Corona pandemic and its detrimental effects on experimental work at large scale neutron facilities, recent years have seen a shortage of neutrons in particular in Europe, which was also strongly affecting the neutron imaging community. The planned ultimate shut-downs of the BER-2 neutron source at Helmholtz Zentrum Berlin (HZB) and the reactor of LLB at Saclay were accompanied by the unforeseen shut-down of IFE's neutron source in Norway and longstanding issues hindering operation of FRM-2 for extended periods lingering into 2022, with cold neutrons for ANTARES not expected within the next two years to come. In addition, IMAT at RAL in the UK was affected by a planned shutdown in 2021 for maintenance works at the accelerators, which lingers on till spring 2022 and ILL, now running a powerful cold neutron imaging instrument entered a shutdown spanning close to the full year 2022.

On the other hand, the pandemic forbid access to overseas facilities and instruments such as in the US and Japan and also American facilities struggled with unforeseen issues, like the NIST neutron source and for short term also the spallation source at LANL.

The resulting shortage of neutrons and beamtime for neutron imaging posed an enormous strain in the form of beamtime requests and overloads on instruments at PSI and in particular also on the instruments of the Applied Materials Group (AMG, former NIAG) at PSI. The neutron source at PSI, SINQ came out of a shutdown period related to upgrading the guide systems and instruments in the guide hall in the wake of the pandemic in spring 2020. Overload factors of the AMG imaging instruments NEUTRA and ICON boosted from already relatively high normal levels of 2 to 4 to up to 6 and beyond. This led to cut-off values affecting very well rated proposals. AMG responded with attempts to serve the community flexibly also with shares of in-house beamtime and in particular by supporting a significant amount of imaging user beamtimes through AMG at the testbeamline BOA (Fig. 1) [1,2], operated by the Neutron Optics Group of PSI (LIN).

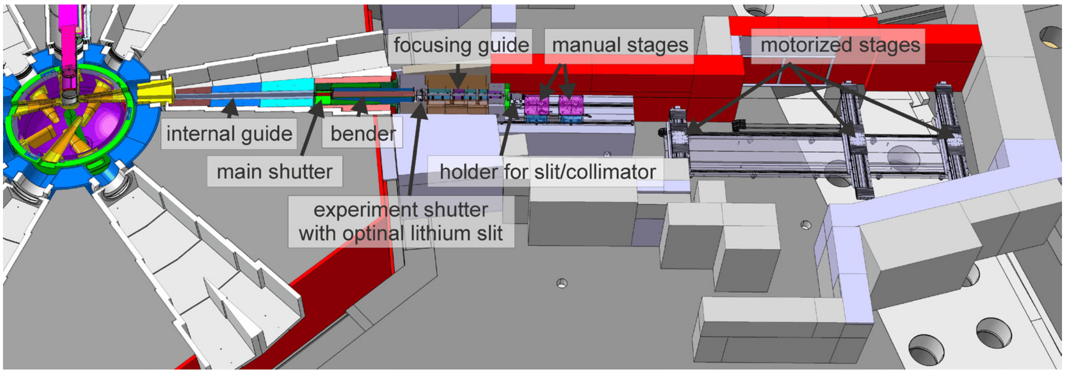

Fig. 1 BOA beamline layout [1,2]

With remaining and even increasing pressure of enormous overload factors in the 2nd call of 2021 AMG took action and achieved an in-house agreement to take responsibility of 75% of beamtime at BOA including the possibility to include BOA in the official user program. Consequently, BOA was included in the proposal call 2022-I for the first time and achieved an overbooking factor of 4 immediately, while the overload factor of ICON could be reduced this way to around 4.5, on bar with NEUTRA in this call.

BOA enables a wide range of neutron imaging modalities [3], offers flux conditions similar to these at ICON with a somewhat colder spectrum. BOA provides very flexible set-ups and can serve conventional attenuation contrast imaging from medium size (field of view 15 x15 cm^2) and resolution (200 µm) down to smallest sizes (5 x 5 mm^2) and highest resolution (<5µm)[4] just as much as advanced methods, in particular grating interferometry [5], polarized neutron imaging [6] and diffraction contrast imaging, i.e. Bragg edge imaging (Fig. 2)[7], in both time-of-flight and monochromatic modes, as well as combinations of these contrast modalities [8].

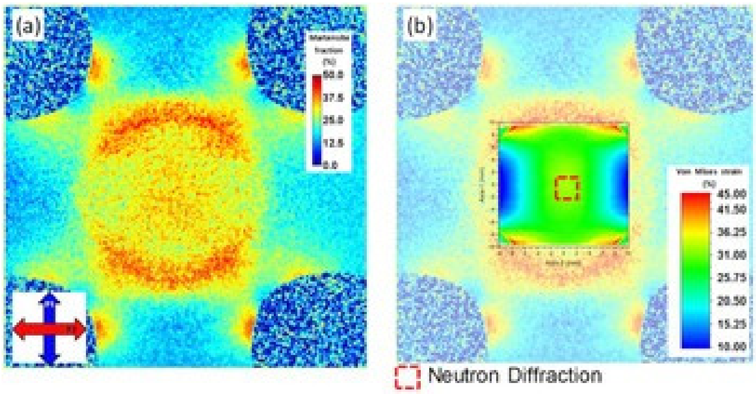

Fig. 2 Bragg edge imaging of phase distribution in TRIP steel samples after bi-axial loading [7]; left: phase distribution image from diffraction contrast neutron imaging, right: overlayed by FE simulation and indication of typical in-situ diffraction target area;

In addition, AMG has initiated an agreement of PSI's Laboratory for Neutron Scattering and Imaging (LNS) with IFE, providing Norwegian users with neutron beamtime while receiving funding for instrument support and upgrades. Accordingly, AMG has started its instrument upgrade project AM-UP [9] which of the imaging instruments concerns foremost NEUTRA, a day-1 imaging instrument at the Swiss Spallation Neutron Source SINQ and thus already in service since more than 20 years. NEUTRA will see a complete re-build, which will foremost generate more space in the instrument bunker and will thus allow access to higher flux positions and the implementation of advanced imaging techniques (Fig. 3). This will allow in the future to better share the load between the imaging instruments ICON, BOA and NEUTRA, and shall therefore also allow to better cope with the high levels of request for imaging beamtime at PSI. Also, ICON and BOA will see upgrades to extend their methodical capabilities and be fit to host the most advanced techniques developed at PSI.

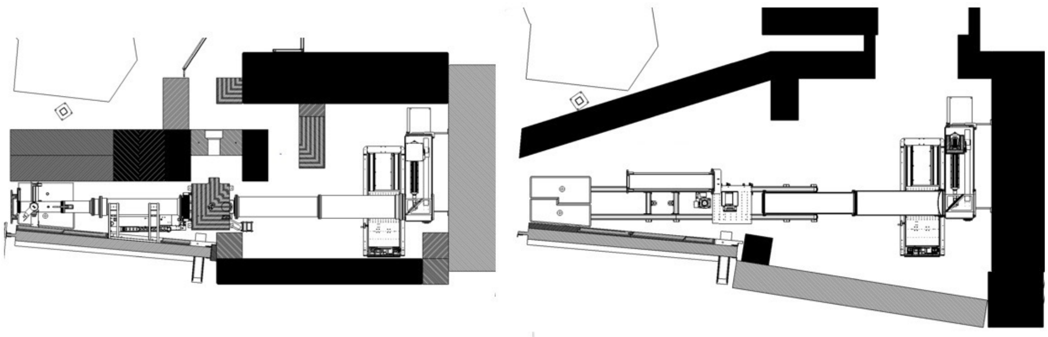

Fig. 3 NEUTRA shielding bunker before (left) and after (right) upgrade – preliminary sketch of increased interior space for access all along the beamline;

A detailed outline of the upgrade project, where construction works are planned to affect our user program at a minimum, will be provided in one of the next ISNR Newsletters.

[1] *https://www.psi.ch/en/sinq/boa/description*
[2] *Morgano M, Peetermans S, Lehmann EH, Panzner T, Filges U, Neutron imaging options at the BOA beamline at Paul Scherrer Institut, NIM A 754 (2014) 46*
[3] *https://www.psi.ch/en/sinq/boa/imaging-modalities*
[4] *Gong W, Trtik P, Valance S, Bertsch J, Hydrogen diffusion under stress in Zircaloy: high-resolution neutron radiography and finite element modeling, J. Nucl. Mat. 508 (2018) 459*

[5] *Kim Y et al., Quantitative neutron dark-field imaging of milk: a feasibility study Appl. Sci. 12(2) (2022) 833*
[6] *Valsecchi J et al., Visualization of compensating currents in type-II/1 superconductor via high field cooling, APL 116(19) (2020) 192602*
[7] *Polatidis, Efthymios, et al. "Neutron diffraction and diffraction contrast imaging for mapping the trip effect under load path change." Materials 13, 6 (2020) 1450*
[8] *Valsecchi J et al. Decomposing magnetic dark-field contrast in spin analyzed Talbot-Lau interferometry: a Stern-Gerlach experiment without spatial beam splitting, PRL 126(7) (2021) 070401*
[9] *https://www.psi.ch/en/lns/am-up-project*

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The New NICHE Imaging Station at the TRIGA-Reactor in Pavia

A new neutron imaging station has been established at Laboratorio di Energia Nucleare Applicata (LENA) in Pavia (Italy) at the 250 kW TRIGA reactor. The station is the result of the CHNet-NICHE applied physics project, financed by Istituto Nazionale di Fisica Nucleare (INFN), as part of the developing activity of the INFN Cultural Heritage Network (CHNet).

The NICHE imaging station is located on the TRIGA thermal beam port B, the one available with the highest ratio between thermal and epithermal + fast neutrons so that it is the one with the best potential for imaging applications with thermal neutrons. The flight tube contains 70 mm bismuth and 100 mm sapphire filters to lower epithermal and gamma flux. According to MCNP simulation and target activation measurements, the thermal flux at the sample area is of the order $2x10^5$ $cm^{-2}s^{-1}$.

The main instrumental components are the following:

- experimental hutch, main area size: 2500 mm length, 600 mm width, 2100 mm height, entrance area with maze double corner;
- remotely controlled beam shutter;
- pin-hole selector made of interchangeable ceramix cartridges 8 mm thick (10 or 20 mm diameter aperture);
- ample manipulation: x-z-ω motorized movement (typical working sample-to-detector distance: 40 mm);
- acquisition system: Cu doped 300 µm thickness LiF/ZnS scintillator screen coupled with CMOS digital camera (14 bit), 20 mm optic lens on a remotely controlled translation stage for focusing; camera pixel size corresponds on the scintillator to 50 µm x 50 µm area;
- LabVIEW based remote control interface allowing to perform script sequence of commands (motor movement and acquisition).

A picture of the experimental hutch of beam port B containing the scheme of the NICHE component and a 3D technical view of the camera box and sample manipulation set-up are shown in Fig. 1.

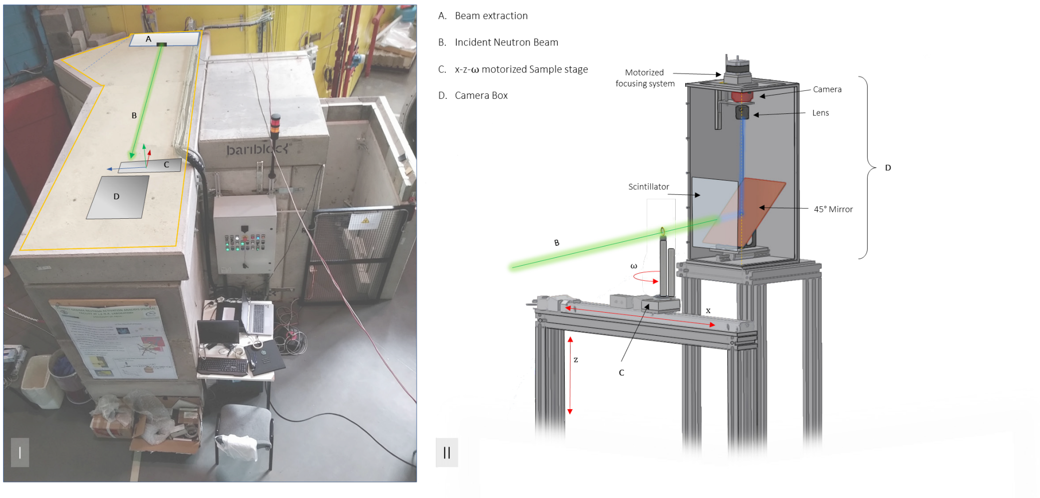

Fig. 1 I. picture of the thermal beam port B experimental hutch with, included, a scheme of the NICHE station components: A) beam shutter and pin-hole; B) neutron beam; C) sample stage; D) neutron camera box. II. Graphical scheme of the sample area (C) and neutron camera box (D) showing the available x-z-ω sample movements and the components of the camera box.

Due to the limited size of the experimental hutch, two working configurations were established.

Configuration 1:

- shutter to detector distance 141 cm;
- L/D=140;
- field of view: diameter 65 mm (rounded), max square 45 mm side;
- standard spatial resolution (PSI bar pattern at 40 mm sample-scintillator working distance): 180 µm;
- best spatial resolution (PSI bar pattern sticked to the scintillator): 150 µm;
- acquisition time: 600 s (optimal), 300 s (typical), 120 s (tomography mode).

Configuration 2

- shutter to detector distance: 192 cm;
- L/D=190;
- field of view: diameter 95 mm (rounded), max square 65 mm side;
- standard spatial resolution (PSI bar pattern at 40 mm sample-scintillator working distance): 150 µm;
- best resolution (PSI bar pattern sticked to the scintillator): 125 µm;
- acquisition time: 1200 s (optimal), 600 s (typical), 240 s (tomography mode);

Resolution was determined by direct observation of bar pattern lines and by Modulation Transfer Function analysis.

The station is operational since May 2021 in sharing with other experimental activities. Working duty cycle of the reactor is 6 hours per day from Monday to Friday so a typical time for performing a tomography is 2 days in configuration 1 and 4 days in configuration 2, performing about 300 projections.

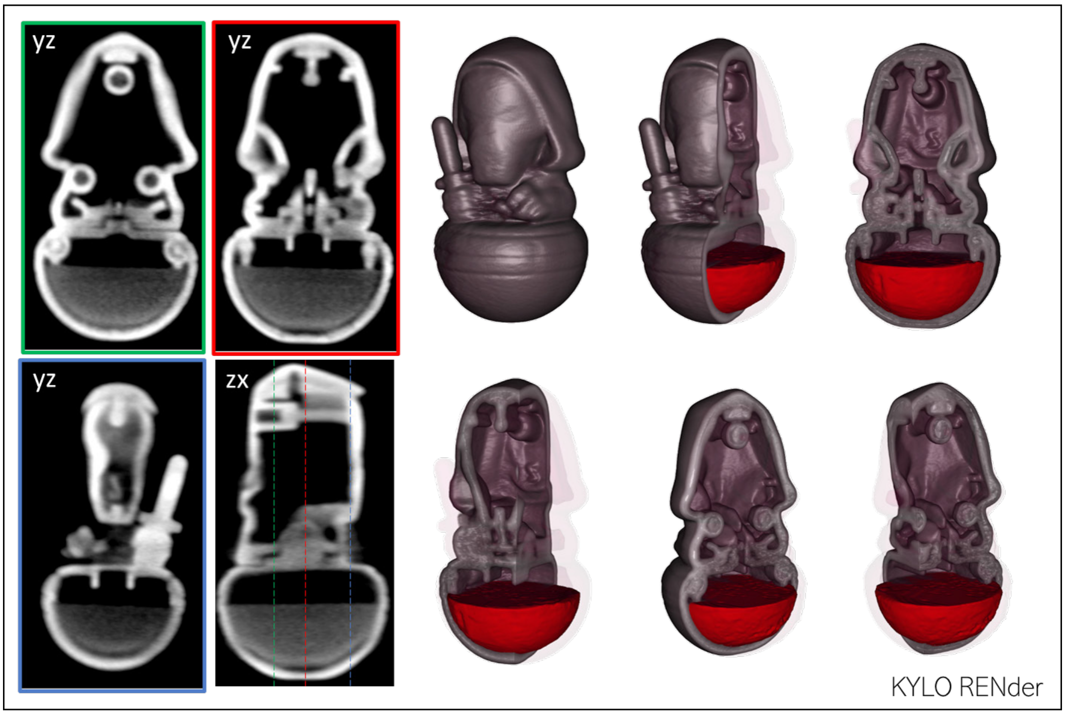

Fig. 2 Left: set of selected tomography slices of a plastic figure (30 mm height), showing construction details. Voxel size 100 µm, projection integration time 120 s, number of projections 301. Right: set of selected 3D rendering images showing volume segmentation in false color of the plastic material composing the main body respect to the magnetite half-hemisphere basement and the empty inner volume. The level of details on such a figurine is good enough to read compositional details.

We show in Fig. 2 the results of a test tomography measurement performed on a composite set of different samples, here we show reconstruction slices and 3D volume rendering of a plastic composite figure.

The instrument will be available from 2023 to external users through the CHNet website for applications in the field of cultural heritage and material science.

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The Future Combined Neutron Imaging Beamline to PGAA Instrument at the Maamora TRIGA Research Reactor

A neutron radiography/tomography instrument was designed and will soon undergo construction at Maamora TRIGA MarkII (2MW) Research Reactor (CNESTEN Research Center, Rabat-Morocco). The whole system will be mounted on the tangential channel (NB-1) as shown in Fig. 1.

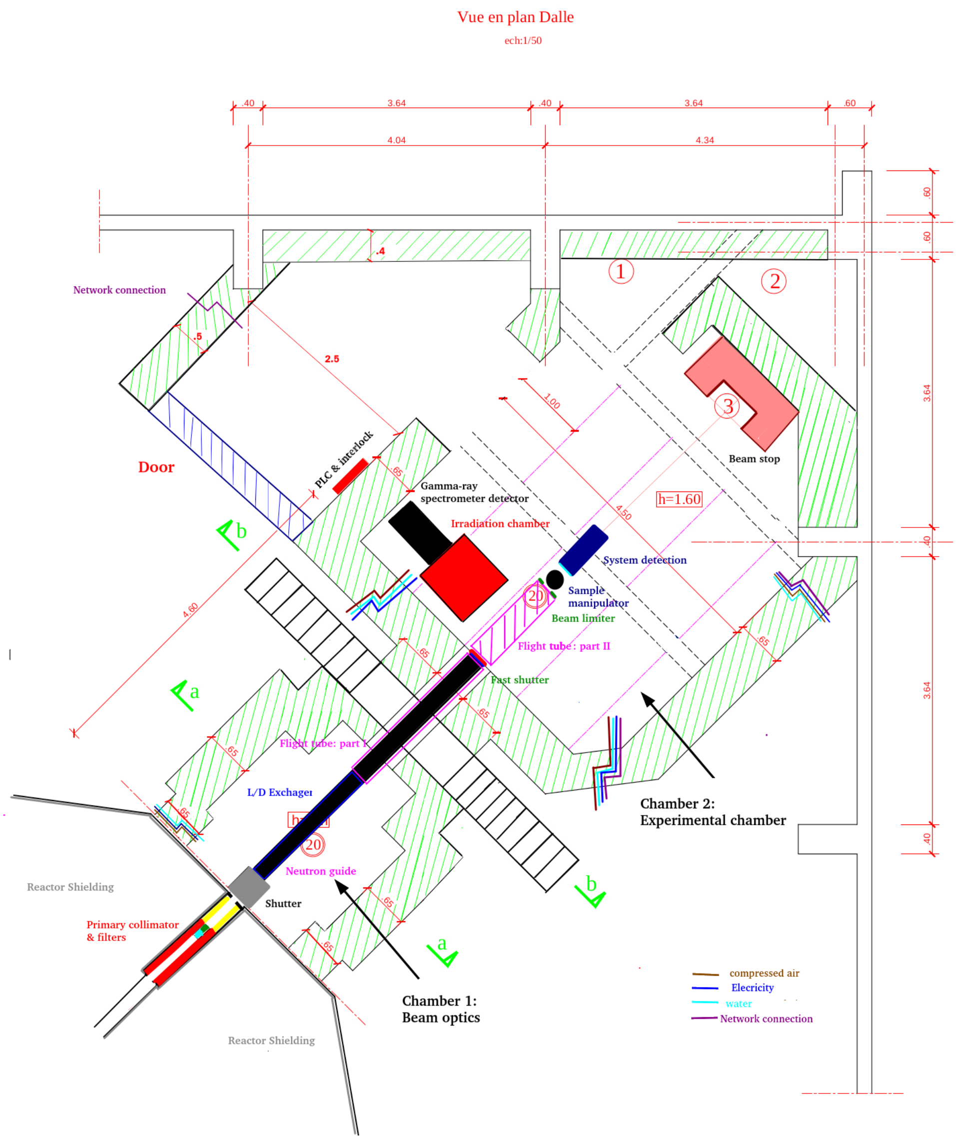

Fig.1 The design of the biological shielding of combined PGAA and NRAD instruments

This instrument is designed for research community and for routine quality control for industrial, mining, automotive and aircraft applications. Neutron imaging is usually used to visualize and study spatial distribution of various elements within a homogeneous object. This combined system also offers the possibility to make prompt gamma activation imaging (PGAI) to analyse the bulk concentration and 3D distribution for a specific elements in the composition of studied objects.

The project is scheduled with 3 phases :

- Phase I : Installing the primary collimator and primary Shutter with provisional shielding
- Phase II: Installation of the PGAA system.
- Phase III : Installation of neutron imaging system (NRAD) & shielding around the combined facilities.

The system when in NRAD imaging mode will be designed as shown in Fig.2. The neutron optical components immediately downstream of the primary shutter are placed on a neutron optics exchanger. For reasons of space, a vertical design is chosen. The exchanger would switch between (1) the guide for PGAA and (2) the primary flight tube and the L/D exchanger for NRAD. It is shown in Fig. 2 as a vertical translator.

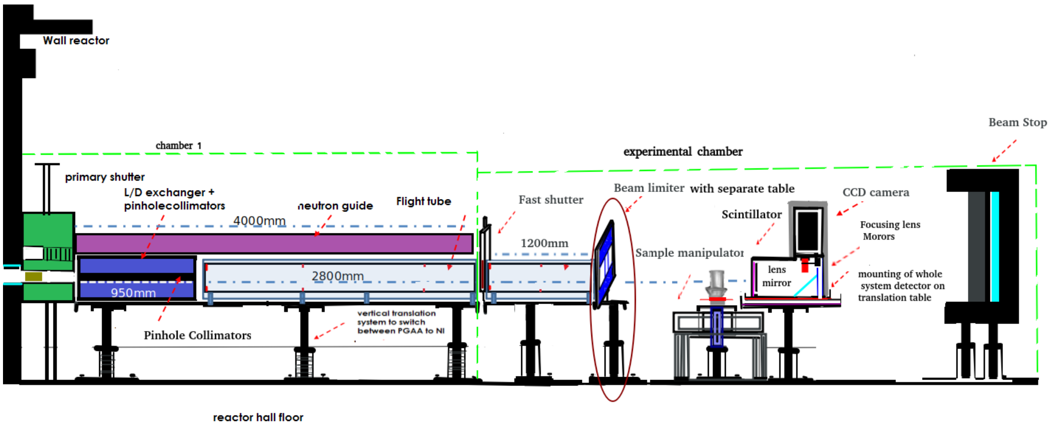

Fig. 2 The System in the NRAD setup showing the placement of the components within the two chambers (dashed green lines) of the bunker

According to neutronic simulation, several parameters were defined related to the design conception (filters dimensions, shielding material etc.), but current efforts are focused more on the NI/PGAA instruments engineering feasibility.

The filtered beam is collimated with a simple thermal neutron pinhole located downstream of the sapphire and cooled bismuth filters. The maximum diameter of this pinhole is 2.5 cm and the minimum size is 1.5 cm. Using this apertures produces an effective L/D ratio ranging from 240 to 420. Each inner (upstream) collimator accepts neutrons within the convergent angle (as defined in Tab. 1) to travel to the aperture. It suppresses undesired radiation components coming from the primary collimator within the NB-1 tangential beam tube and the shutter.

Tab. 1 The convergences and divergences and apertures for each collimator.

Collimator L/D	100	240	300	430
Convergent angle (α)	4°	0,37°	0,34°	0,40°
Divergent angle(β)	4°	1,12°	0,80°	0,61°
Radius of Gd aperture (mm)	open	25	20	10

The L/D drum exchanging is housing 4 pinhole collimator with apertures of 1cm, 2cm, and 2,5cm and will reduce the beam size to 8 cm x 8 cm, 12 cm x 12 cm and 20 cm x 20 cm at the detector position respectively. The whole instrument will operated in 3 different positions, one for high resolution and the other for high speed.

The collimated beam spread out of the drum pass through a sealed, evacuated aluminum flight tube. The flight tube ends right before the sample position (Fig. 2). Two sample positions are planned where the object to be radiographed sits on a sample manipulator (with 3-axis translation and 2-axis rotation). A digital detection system based on CCD camera-scintillator combinations is used to digitize the 2-dimensional neutron distribution. Finally, the beam is stopped by a "beam stop". Additional equipment at the facility includes the fast shutter used to protect the detector and the beam limiter capable of totally closing and opening up a beam of 25 cm by 25 cm (Fig. 2).

ACKNOWLEDGMENTS

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Neutron Tomography at the Very Low Power Training Reactor VR-1

In November 2021, the first three-dimensional neutron computed tomography of a technical object was performed at the near-zero power training reactor VR-1. The training reactor VR-1 is operated by the Czech Technical University in Prague, and it is mainly used for education and training. The nominal thermal power of the reactor is 100 W which can increase up to 500 W up to 70 hours annually.

Neutron imaging has been developed at the VR-1 reactor since the beginning of 2020. Thanks to the collaboration with Dr. Burkhard Schillinger from FRM II reactor at Heinz Maier-Leibnitz Zentrum (MLZ) of Technische Universität München (TUM), who downscaled the ANTARES imaging system at FRM II to a small portable detector, the first neutron radiography measurements at VR-1 reactor were made in the spring of 2021.

The small portable system is based on a CMOS camera with a scintillator screen. The CMOS camera is placed inside the special camera box with a lens, additional cooling for the camera and lead shielding. The camera model is the cooled QHY 178m with 14-bit digitization. The scintillator screen is made of ^{6}LiF/ZnS:Cu and is placed on the scintillator box, which also contains a mirror positioned at an angle of 45°. A simple neutron tomography setup was also built for this system. This set up consists of small rotation and linear stages, a tiny and affordable computer (Raspberry Pi) and an expansion board for Raspberry Pi (Gertbot). For neutron imaging experiments, the radial channel of the VR-1 reactor also had to be modified. The original diameter of the radial channel is 25 cm, but can be reduced to 9 cm, but it is still too much for the needs of neutron imaging. For this reason, a pinhole made of 5 cm lead with an inside diameter of 3 cm and 5 cm borated polyethylene with an inside diameter of 2 cm, was placed in the radial channel.

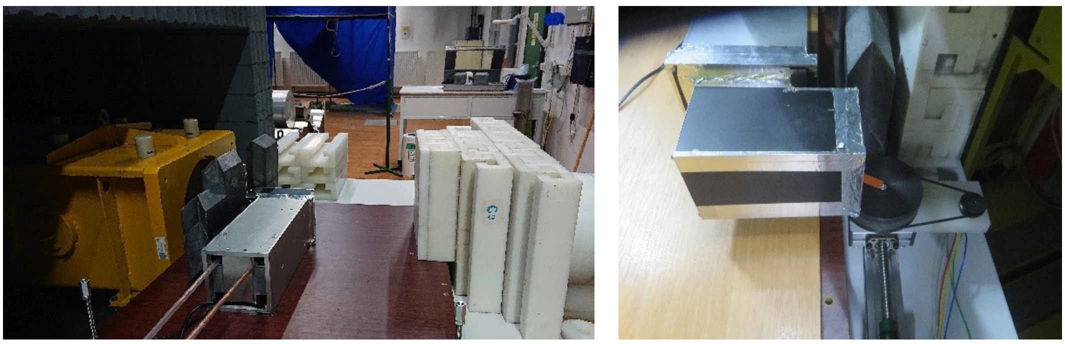

Fig. 1 Neutron radiography and tomography setup at the VR-1 reactor

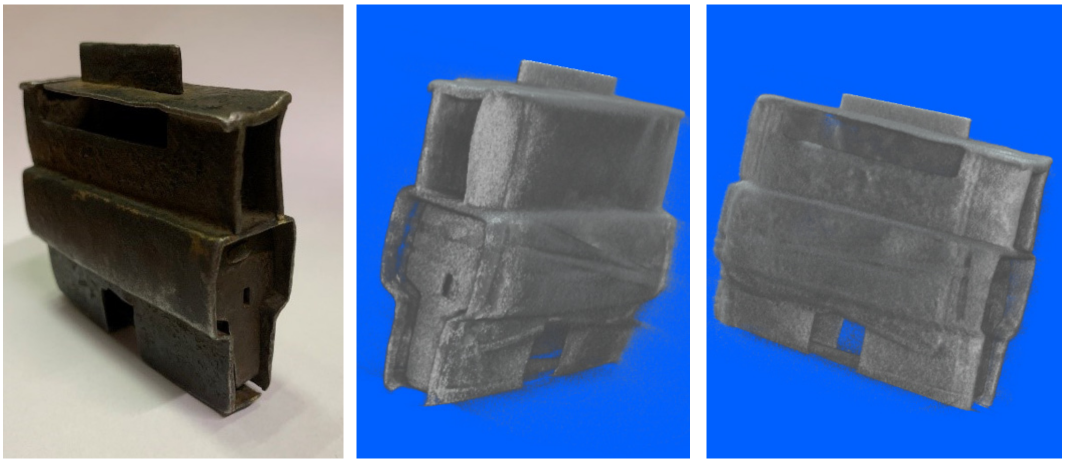

Fig. 2 Photo and 3D reconstruction of Tibetan lock

In autumn 2021, the worldwide first computed neutron tomography at a low power reactor was measured at the training reactor VR-1 at reactor power 500 Watts. A historical object, a Tibetan lock, was used as a sample for this measurement. The L/D for this measurement was 80, the exposure time was 4 minutes, and neutron flux at the sample position was $2.5 \cdot 10^5$ $cm^{-2}s^{-1}$.

The neutron imaging system at the reactor VR-1 will be further characterized and improved, and together with MLZ/TUM, it may be copied for other low power reactors in the world. The results to date have shown that although neutron imaging in low power reactors is associated with several challenges, it is possible to operate a neutron imaging system there successfully. In the future, the neutron imaging at the training reactor VR-1 should be used not only for the education of students at CTU but also for other research activities.

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Operation Resume of Research Reactor Called JRR-3 and Introduction to Neutron Radiography Facility in JRR-3

Japan Research Reactor-3 (JRR-3) owned by Japan Atomic Energy Agency (JAEA) is a research reactor with thermal power of 20 MW (Fig. 1). JRR-3 had been used for a number of academic research and industrial applications since its criticality in 1990. However, the facility operation had been shutdown for 10 years since a periodic inspection in November 2010. The reason was to comply with the regulatory standards about research reactors which was revised following the Great East Japan Earthquake in March 2011. Thus, although JRR-3 itself was not fatally damaged by the earthquake, it was necessary to perform various antiseismic reinforcements, such as preventing the exhaust tower from tipping over and reinforcing the reactor building of JRR-3. After the reinforcements were completed, JRR-3 operation resumed on February 26, 2021, following a periodic inspection. In addition, shared use of JRR-3 was also restarted in July, 2021, and the shared use operation were performed for 100 days (4 cycles). After

Fig. 1 External appearance of JRR-3

2022, JRR-3 is scheduled to shared use operation for seven cycles (approximately 170 days) from May to December.

JRR-3 has two neutron radiography facilities, TNRF (Thermal Neutron Radiography Facility) and CNRF (Cold Neutron Radiography Facility), and this newsletter briefly introduces mainly TNRF. TNRF is a radiography system using thermal neutrons installed in the 7R port of the JRR-3 reactor room [1]. Tab. 1 shows the TNRF specifications. The facility has a large irradiation field (W255 mm × H305 mm) and a high neutron flux (approximately 1.0×10^8 n/cm²/s). By utilizing these performances, it is capable of not only two-dimensional radiography and three-dimensional CT with the large field of view (FOV), but also dynamic imaging of fluids. L/D is 176 and the spatial resolution is not very high. The available camera systems for user experiments using TNRF are shown in Table 2. The cooled CCD camera is used for 2D radiography and 3D CT. The EM-CCD camera or the high-speed camera are used for obtaining moving images. Figure 2 shows a result of imaging a PSI indicator using the cooled CCD camera and a 200-mm lens (F=4.0). The FOV of image was about 70 mm × 70 mm. From the result, the resolution was determined by an edge spread function to be approximately 140 µm.

Tab. 1 TNRF specifications.

Neutron Flux [n/cm^2/s]	1.0×10^8
Radiographic Field Size [W× H mm]	255 × 305
Collimator Ratio [L/D]	176

Tab. 2 Outline of available camera systems at TNRF.

	Cooled CCD Camera	EM-CCD Camera	High-Speed Digital Video Camera
	Andor, iKon-L 936	Andor, iXon Ultra 897	Photron, FASTCAM SA5
Image size [pixel]	2048 × 2048	512 × 512	1024 × 1024 (Maximum)
Pixel Size [µm]	13.5 × 13.5	16 × 16	20 × 20
A/D converter [bit]	16	16	12
Frame Rate [fps]	0.95 (Maximum)	56 (Maximum)	1M (Maximum)

Prior to the shutdown of JRR-3, TNRF had been used to image various things such as water distributions in a fuel cell and concrete blocks, an oil flow in a running car engine [2-4]. After the resumption of operation, radiography of batteries, CT imaging of reinforced concrete blocks, and dynamics imaging of water and liquid metals, etc. have been performed. In 2021, 17 research proposals were implemented using TNRF, 4 of which were by companies. After 2022, the number of research proposals to be implemented is expected to increase as the number of shared use operation days of JRR-3 per year is going to increase.

In the future, TNRF will focus not only on conventional radiography and CT imaging, but also on high frame rate video imaging that takes advantage of the strong continuous beam. In addition, to make the facility more user-friendly, we plan to improve the sensitivity and spatial resolution of TNRF. We are collaborating with members of an energy resolved neutron imaging system called "RADEN" at J-PARC [5], which is located on the same site, and we are working together to make complementary use of each other's facility. Finally, we introduce how to apply for research proposals using JRR-3. JRR-3 calls for proposals in around November and May each year. Users can basically apply for the next

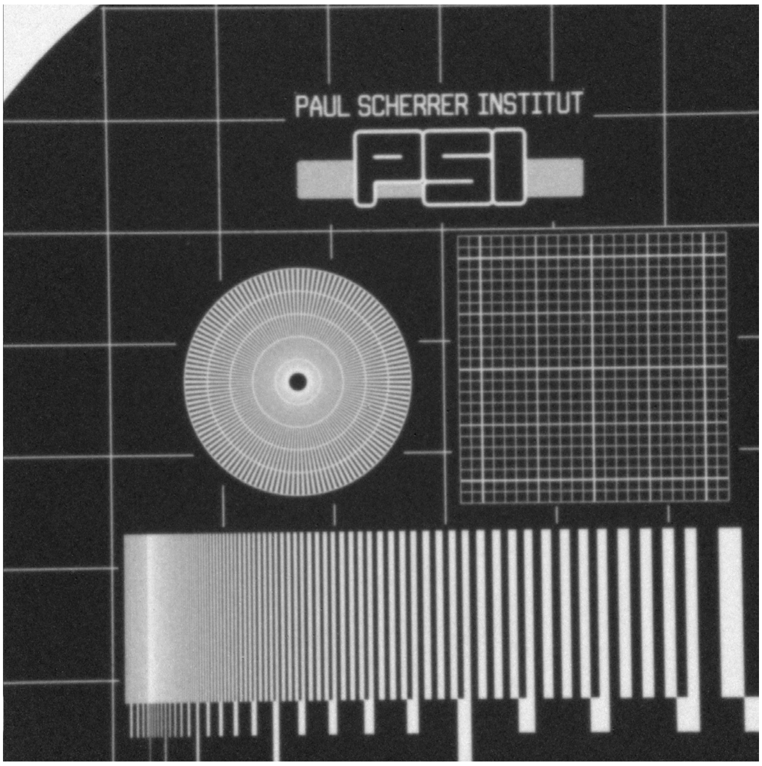

Fig. 2 Radiogram of a PSI indicator with the cooled CCD camera and a 200-mm lens.

year's assignments in November. The May recruitment is additional and users can only apply for the second half of the shared use operation period. A system called JRR-3 RING (URL: https://jrr3ring.jaea.go.jp/index.php) is used for the application, but the system does not currently support English. Therefore, international researchers considering applying the experiments with TNRF should contact us directly.

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Out of the Lab

Neutron Imaging Study of a Thermochemical Heat Storage Reactor

Strontium chloride octammine $Sr(NH_3)_8Cl_2$ offers high volumetric and gravimetric NH_3 densities and can store and release heat upon exo-/endothermal absorption and desorption of NH_3. Thus, it is a promising material for thermochemical heat storage (THS) applications. To study mass transfer and heat distribution effects in a THS prototype reactor (Figure 1A), we performed in-situ neutron imaging during NH_3 uptake and release in the $SrCl_2$/$Sr(NH_3)_8Cl_2$ system. The THS prototype reactor contained $SrCl_2$ embedded in a stainless-steel honeycomb structure to promote thermal conduction [1]. The high neutron scattering cross-section of hydrogen present in ammonia molecules allowed the observation of the NH_3 sorption kinetics and distribution within $SrCl_2$. The higher the NH_3 content in the salt, the darker the corresponding area in the image.

The imaging experiments were performed at MLZ and at ILL. At MLZ, the NECTAR instrument was employed using thermal neutrons (collimation ratio L/D~230), a ZnS/^{6}LiF scintillator screen and an Andor iKon-L-BV CCD camera with 2048 × 2048 pixels. At ILL, experiments were performed at the NeXT beamline using a cold neutron beam (L/D ~ 435), a LiF:ZnS scintillator screen with a field of view 10cm x 10cm and a thickness of 50 µm, and Hamamatsu Orca 4V2 CMOS camera providing images with a time resolution of 1s.

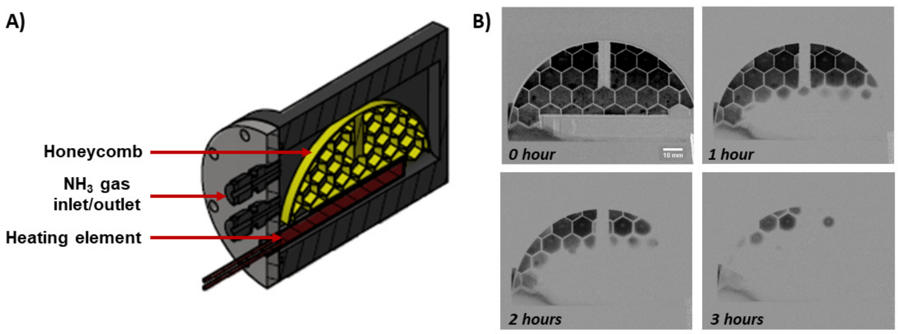

Fig. 1 (A) Schematic representation of the THS reactor prototype and its main components. (B) Normalized neutron radiography images acquired at NECTAR during the NH_3 desorption at 100 °C. The figure is adapted from [1].

In-situ neutron radiography at NECTAR showed that a stainless-steel honeycomb structure is not ideal for transferring the heat from the heating element to the edges of the honeycomb during the NH_3 desorption processes. The desorption of NH_3 from $Sr(NH_3)_8Cl_2$ happens from the heat transfer through the powder rather than from the honeycomb and slower desorption kinetics are observed in the regions farthest away from the heater (Fig. 1B). Along with the images collected perpendicular to the cell, longitudinal images revealed the $SrCl_2$ volume changes during the ammonia cycling.

Subsequent experiments using the same THS prototype reactor allowed testing different solutions for improving the heat transfer within the reactor. At the NeXT instrument, it was shown that embedding and confining $SrCl_2$/$Sr(NH_3)_8Cl_2$ in an Expanded Natural Graphite (ENG) matrix resulted in faster absorption and desorption. For instance, the desorption of 7 moles of NH_3 from $Sr(NH_3)_8Cl_2$ powder was complete within 4 hours at 100 °C [1], while it was completed within 2.5 hours in $Sr(NH_3)_8Cl_2$-ENG composite at similar conditions [2], since the increased porosity and thermal conductivity of ENG allowed for better heat and mass transfer. Furthermore, neutron tomography at NeXT (Figure 2) demonstrated that the ENG matrix in the composite acts as a buffer during NH_3 cycling, limiting the expansion and contraction of $SrCl_2$-ENG during NH_3 uptake and release, respectively [2].

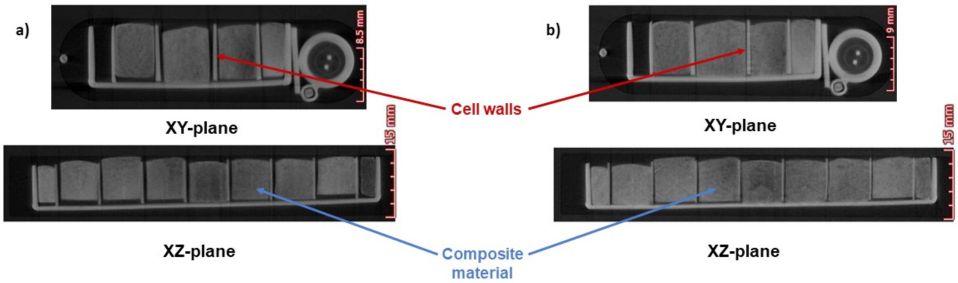

Fig. 2 Orthogonal view of the sample in the XY and XZ-planes after tomographic reconstruction of neutron tomography data acquired at NeXT a) before and b) after NH_3 cycling in SrCl2-ENG composites [2].

Finally, it was demonstrated that a much better heat transfer can be achieved by using a honeycomb structure made of aluminum, which has a higher thermal conductivity than stainless steel. Fig. 3 shows how NH_3 desorption from $Sr(NH_3)_8Cl_2$ starts at the edge of each cell of the aluminum honeycomb, indicating that the heat within the reactor is transferred through the honeycomb rather than the powders, as observed in the case of stainless-steel.

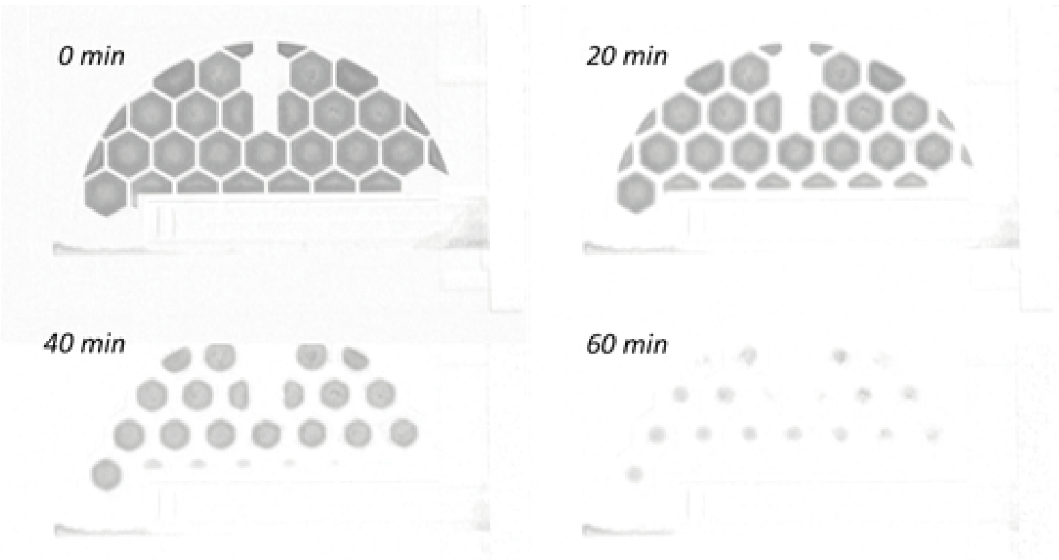

Fig. 3 Normalized neutron radiography images acquired at NECTAR during the NH_3 desorption at 200 °C.

These results demonstrate that neutron imaging techniques are ideal and powerful tools for investigating NH_3-based thermochemical heat storage prototype systems and provide critical information on SrC_{l2} powder behavior upon NH_3 absorption and desorption reactions. More importantly, they provide crucial data for developing and validating numerical models which can be applied for the optimization of novel THS reactor designs [3].

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New Perspectives for Neutron Imaging through Advanced Event-Mode Data Acquisition

Recently developed event-driven detectors are capable of observing and time-stamping spots of light induced by particle interactions on scintillator materials. Reconstructing the Center-of-Mass (CoM) of the light emitted can provide a precise location of the interaction. This principle provides a pathway to overcome the blurring introduced by integration of the light emission that often limits the highest possible spatial and time resolution for imaging techniques using scintillators. Implementation of this concept with real-time data acquisition paves the road for a new era of event-based detectors for various types of radiation.

Utilizing the CoM principle with a detector concept based on the Timepix3 sensor, it was shown that spatial resolution can be improved beyond the classical boundaries of "regular" neutron imaging with a camera concept capable of time-of-flight imaging of light emission, a flexible Field-of-View (FoV), ad-hoc binning and re-binning of data based on the requirements of the experiment including the possibility of particle discrimination via the analysis of the event shape in space and time. An example of a super-resolution neutron radiograph is shown in Fig. 1, whereby Fig. 1 A) shows a radiograph using the native pixel resolution of the Timepix3 sensor at a spatial resolution close to the intrinsic resolution of the sensor for that FoV with ~3 lp/mm or ~166.7 µm, and Fig. 1 B) shows a reconstructed event-based neutron image that shows an improved resolution of ~12 lp/mm or ~42 µm [1].

Aside from improvements in spatial-resolution for such measurements, luminescent afterglow of scintillators can be eliminated using the proposed technique, improving the temporal resolution of scintillator detectors similar to concepts used in wavelength shifting fiber detectors. Temporal improvements were initially demonstrated for Bragg-edge

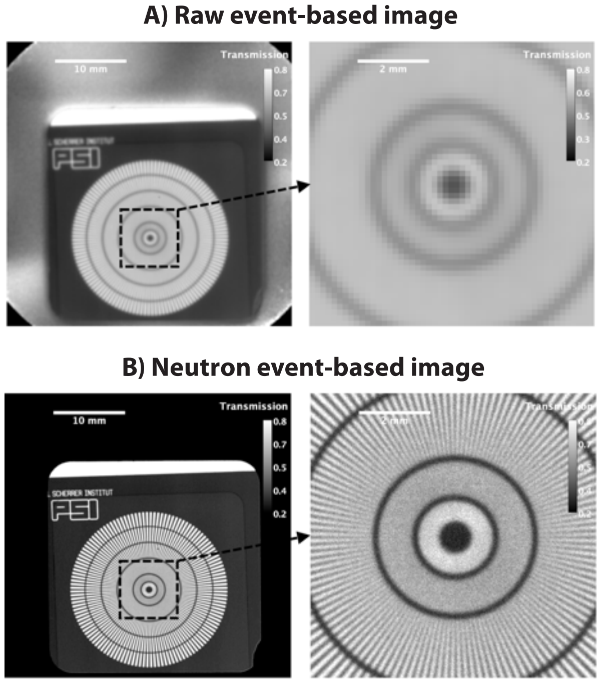

Fig. 1 Thermal neutron radiographs of a resolution pattern. Raw event-based image using native detector resolution in A. Neutron CoM event-based image at sub-pixel resolution of ¼ pixel-pitch in B.

imaging measurements with ongoing efforts to extrapolate this advancement to diffraction techniques, providing a competitive solution to existing ^3He detectors for diffraction measurements.

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Realization of Bimodal Imaging with a Single-Electron Linear Accelerator

Bimodal imaging requires that both the neutron and X-ray be present within the system to inspect the object. The conventional approach [1], which provides the two radiation sources separately, inherently suffers from the spatial interference between the two sources. Because the imaging geometry for X-rays and thermalized neutrons can hardly

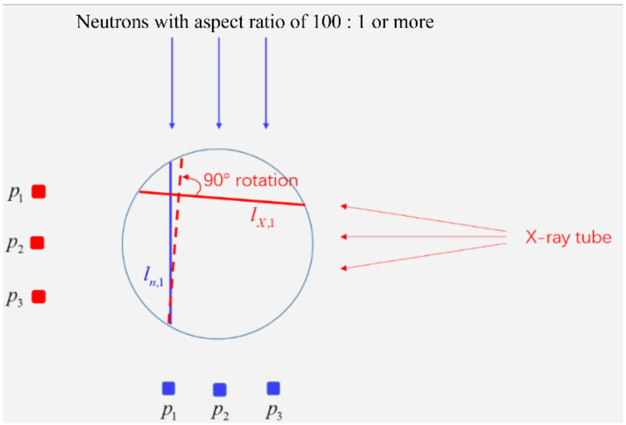

Fig. 1 Spatial interference occurs between the two radiation sources in a conventional bimodal imaging system. The imaging geometries of X-rays and neutrons are not the same even when rotation at a proper angle is realized.

be the same (Fig. 1), pixel-wise fusion of the neutron and X-ray images is quite difficult. Therefore, time-consuming computerized tomography should usually be conducted in advance for both neutron and X-ray imaging to align the two images via linear translation, rotation, scaling, or skewing to achieve fusion.

A new method of realizing bimodal imaging driven by a single radiation source was proposed and realized by the Tsinghua Group in 2021 [2]. The underlying principles of electron-linear-accelerator- (e-LINAC-) driven bimodal imaging is shown in Fig. 2. The energetic electrons delivered by the e-LINAC first bombard the "e→γ convertor," typically made of tungsten or tantalum, to produce bremsstrahlung photons. The forward-emitted photons then undergo photonuclear reactions to liberate the confined neutrons from the target nuclei of the "γ→n convertor." Depending on the energy of bremsstrahlung photons, the γ→n convertor could be the same as the e→γ convertor. For an e-LINAC delivering electrons with energies smaller than 10 MeV, the γ→n convertor should use low-(γ,n)-threshold materials, such as beryllium or heavy water, which differ from the materials of the e→γ convertor. If the e-LINAC can deliver high-energy electrons, i.e., 20 MeV or higher, which energy is significantly larger than the (γ,n) reaction thresholds of all the nuclides, the materials comprising the γ→n convertor can also be tungsten or tantalum to take advantage of the large (γ,n) cross-section, the maximum value of which is approximately proportional to Z. In this case, the γ→n and e→γ convertors are, in fact, the same convertor. A moderator can be placed adjacent to the γ→n convertor to slow the fast photoneutrons. Polyethylene is typically chosen as the moderator due to its large macroscopic cross-sections of neutrons that can slow neutrons over a short distance. The moderator also acts to scatter the bremsstrahlung photons to lower energy. When the direction of extracting the imaging neutrons and X-rays is 90° with respect to the direction of incident electrons, the energy of the imaging X-rays will be approximately within the region of 511 keV. Photons with energies in this region mainly interact with matter via Compton scattering. Therefore, by measuring the attenuation of imaging X-rays, the mass thickness of the inspected object can be easily acquired, which would be helpful for further identifying the materials by fusing the neutron and X-ray images. As the imaging neutrons and X-rays are, in fact, finally scattered by the same atoms of the moderator, from the point of view of the detector, which is located 3–10 m from the moderator, the image geometries of the two radiation sources would be the same. A neutron-sensitive micro-channel plate (nMCP) detector with a complementary metal-oxide semiconductor (CMOS) readout is suitable for registering both neutrons and X-rays. The separation between the neutrons and X-rays can be easily realized due to the pulsed working mode of the e-LINAC, the typical pulse duration of which is several microseconds. The moderation of neutrons within the moderator will provide a sufficiently long time for the influences of X-rays inside the nMCP to dissipate. The challenge posed by the low intrinsic detection efficiency of an nMCP to 511-keV photons can be addressed by the large number of photons contained in each X-ray pulse.

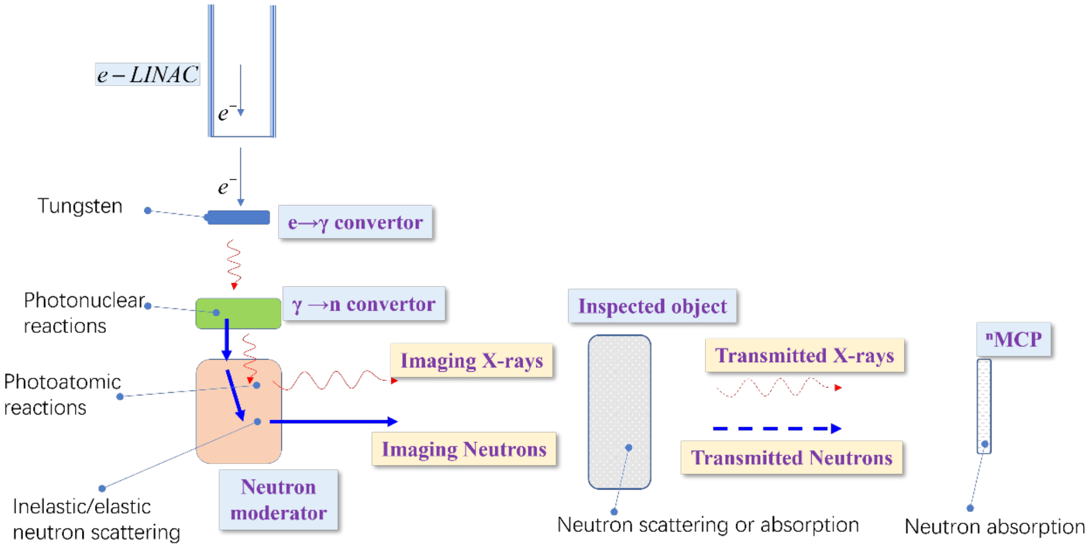

Fig. 2 Principles of e-LINAC-driven bimodal imaging.

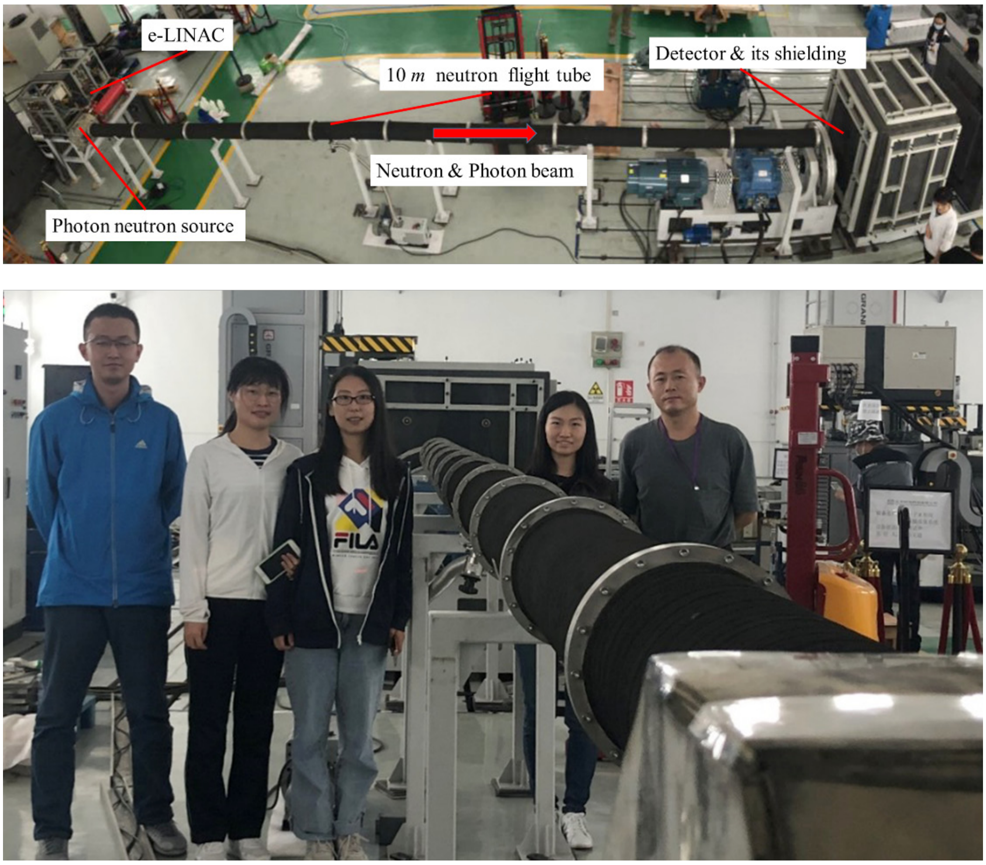

Fig. 3 upper: Photograph of 9-MeV/900-W e-LINAC-driven bimodal imaging system. lower: Group members, from left to right: Yangyi Yu (Ph. D. student in charge of physics, detector, and algorithm for fusion); Nana Pei (engineer in charge of mechanical design); Ruiqin Zhang (Master's student in charge of shielding design); Lu Lu (Ph. D. student in charge of convertor and moderator design); Yigang Yang (principal investigator).

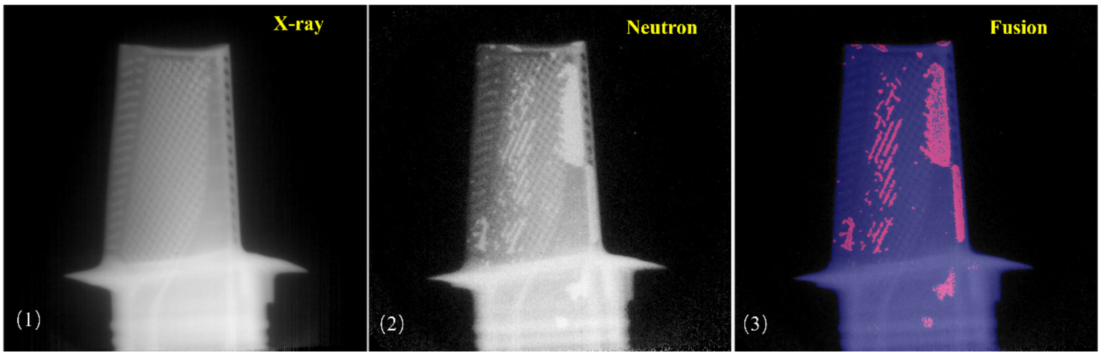

Fig. 4 (1) X-ray image of turbine blade with gadolinium tracer; (2) photoneutron image of the same turbine blade; (3) fusion of both images.

A 9-MeV/900-W e-LINAC-driven bimodal imaging facility was constructed by the Tsinghua Group headed by Dr. Yigang Yang. The total neutron yield is 2×10^{11} n/s and the thermal neutron flux 10 m from the convertor is 2.5×10^{3} n/cm^2/s.

Figs. 4(1) and 4(2) show the X-ray image and photoneutron image of a turbine blade with gadolinium tracers inside, respectively. The gadolinium tracer cannot be seen in the X-ray image, but can be easily seen in the photoneutron image. Figure 4(3) is the fused image of the two radiation sources, in which the material property, which is reflected by the ratio of the neutrons' attenuation cross-section versus that of the X-rays, is shown using different colors to facilitate material identification. The experimental results shown in Fig. 5 demonstrate the system's sensitivity to hydrogen, even with a lead background, and its ability to separate isotopes [the color difference between a) and b) in the figure is caused by the different neutron attenuation coefficients of ^{1}H and ^{2}H.

An upgrade, namely enhancing the neutron yield to 1×10^{12} n/s, is nearly achieved by increasing the e-LINAC's energy/power from 9 MeV/900 W to 15 MeV/3.75 kW. Thus, the acquisition time for bimodal imaging, which is limited by the acquisition time of neutrons, can be reduced to 10 min. The inspection time can be further expected to be reduced to be less than 1 min when the construction of a 50-MeV/50-kW e-LINAC-driven bimodal imaging system, supported by 60 M¥ of funding, is completed to deliver neutrons with a yield of ~1×10^{14} n/s.

This study is the first time, to the best of our knowledge, that bimodal imaging has been applied in a one-source–one-detector system for both neutrons and photons. Benefitting from the small footprint and working robustness of the e-LINAC, this technology is promising for in situ industrial applications.

Acknowledgments

We thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript.

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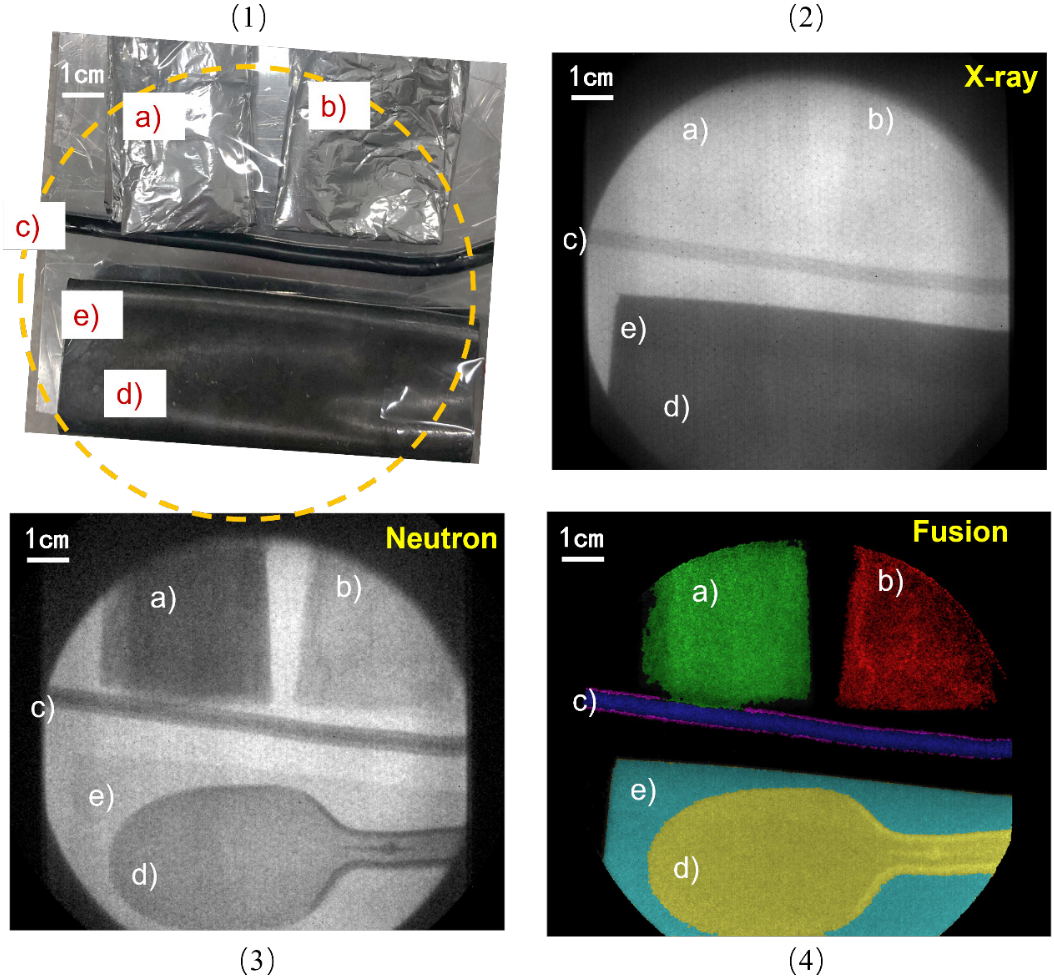


Figure 5 (1) Various objects inspected by the bimodal imaging system: a) tissue containing 7.5 ml of light water with an average mass thickness of ~0.2 g/cm², covered with aluminum foil; b) tissue containing 7.5 ml of heavy water with an average mass thickness of ~0.22 g/cm², covered with aluminum foil; c) a cable, comprising, from inside to outside, copper inner conductor, dielectric, copper braid, outer jacket; d) plastic spoon covered by 2-mm-thick lead foil; e) 2-mm-thick lead foil. (2) X-ray image. Only the copper inner conductor and braid of c) and the lead of d) can be observed. (3) Photoneutron image; the light water of a), heavy water of b), outer jacket of c). and plastic spoon of d) can be easily observed. (4) Fused image of photoneutron and X-ray images. The color of each object is determined by $\ln(I_n/I_{n,0})/\ln(I_{X\text{-}ray}/I_{X\text{-}ray,0})$, which, in fact, is the ratio of $\sigma_n/\sigma_{X\text{-}ray}$, because the unknown mass thickness of the inspected object is removed in this calculation.

Neutron Grating Interferometry to Detect Defects in Additively Manufactured Components

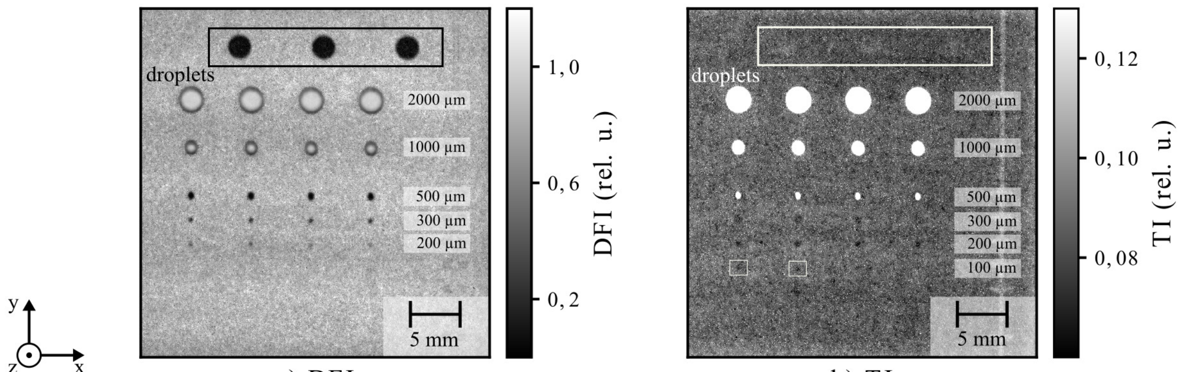
Additive manufacturing (AM) has been used a long time to rapidly produce models and prototypes. In recent years, AM has been used more to complement conventional machining techniques when creating complex and curved components, where conventional machining often reaches its limits with respect to cost effectiveness. While the cause for defects in conventionally machined parts is generally well understood, defect formation and detection in AM is not yet as well understood.

A common AM process is laser beam melting. During this process, a laser melts a thin layer of metal powder in predefined areas. Layer by layer, the component forms in a bed of powder. Process instabilities can lead to defects and reduce the strength of the component. Typical defects are pores and cracks. Moreover, even partial or total separation of individual layers can occur. Various testing methods are in use to locate such defects inside components.

In cooperation with the Institute for Machine Tools and Industrial Management (iwb) of the Technical University of Munich (TUM) we have used various non-destructive testing methods such as active infrared thermography (aIRT), ultrasonic testing (UT), X-ray computed tomography (CT) and neutron grating interferometry (nGI) to detect predefined defects in an additively manufactured Inconel 718 specimen.

Neutron grating interferometry as an add-on to classical neutron imaging allows to simultaneously probe the transmission (TI) and ultra-small-angle-scattering (DFI) of a sample. This allows to both detect changes in density of the sample due to missing material, as well as changes in the microstructure due to e.g. unmelted powder (lack of fusion).

In our tests we were able to show that nGI is able to detect defects typically not visible with other techniques. In particular, lack of fusion can be easily visualized using nGI while remaining invisible in the other non-destructive testing methods including neutron radiography. In Fig.1 the DFI and TI of the evaluated specimen are shown. The specimen was a rectangular cuboid with an edge length of 50 mm and an in-beam depth of 25 mm. In which artificial blind holes with varying diameter (20 – 2000 µm) and depth below the surface (20 – 80 µm) were introduced during manufacture. Additionally, in the upper area of the specimen lack of fusion droplets were introduced.



a) DFI b) TI

[1] *C. G. Kolb, K. Zier, J.-C. Grager, A. Bachmann, T. Neuwirth, S. Schmid, M. Haag, M. Axtner, F. Bayerlein, C. U. Grosse, M. F. Zaeh An investigation on the suitability of modern nondestructive testing methods for the inspection of specimens manufactured by laser powder bed fusion SN Appl. Sci., 3, 713 (2021) – DOI: https://doi.org/10.1007/s42452-021-04685-3*

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MANTID Develops Neutron Tomography GUI

IMAT users have been using Octopus for tomographic reconstruction, as well as Muhrec [1] and NeutomPy [2]. Motivated by the demise of Octopus, and inspired by the three packages above the Mantid software development team at ISIS has produced a graphical toolkit for processing neutron tomography data. "Mantid Imaging" [3] builds on algorithms provided by libraries including Astra Toolbox and Tomopy to offer noise reduction, artifact removal, alignment, filtered backprojection and iterative reconstruction methods. Extra functionality was added by using algorithms from Algotom [4] for ring removal and from the Core Imaging Library [5] for regularized 3D reconstruction.

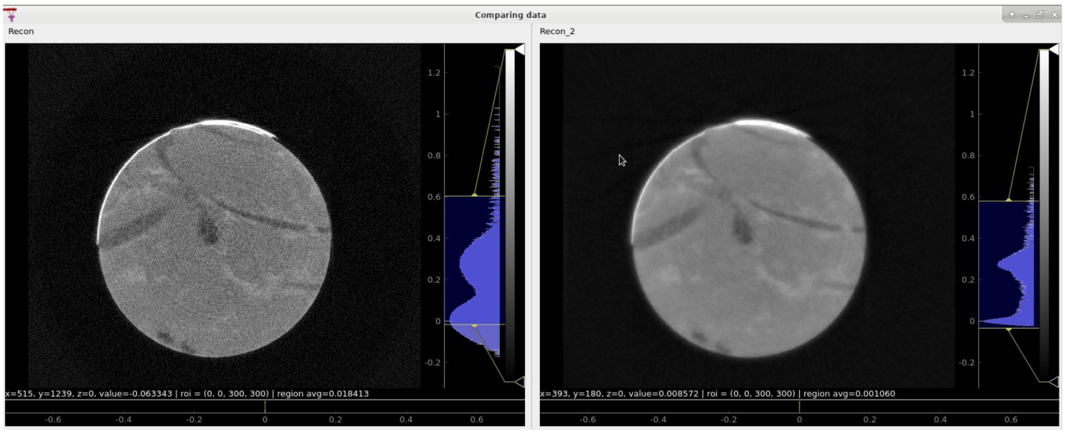

Fig. 1 Reconstructed slices using Mantid Imaging of a rock sample using filtered backprojection (AstraToolbox) and regularized iterative reconstruction (CIL)

Mantid Imaging 2.3.0 has just been released (25 February 2022). It is an open source python GUI, runs under Linux and can easily be installed on end user systems. Mantid Imaging is aimed at users with no programming background and with little image processing experience. At ISIS Mantid Imaging runs on the ISIS-Data-Analysis-as-a-Service (iDAaaS) platform, which is remotely accessible by a browser and which gives users access to sufficient hardware resources to handle large datasets. Extensions of Mantid Imaging for energy-resolved neutron imaging are planned for the future.

[1] Muhrec: A Kaestner, NIMA 651 (2011) 156
[2] NeuTomPy: D Micieli, et al, SoftwareX 9 (2019) 260
[3] https://github.com/mantidproject/mantidimaging
[4] AlgoTom: N. Vo, https://github.com/algotom/algotom
[5] https://github.com/TomographicImaging/CIL

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Corresponding author: winfried.kockelmann@stfc.ac.uk

Radial Delayed Hydride Cracking in Unirradiated and Irradiated Zircaloy-2 Claddings

Neutron interactions with hydrogenous matter and zirconium are well known primarily because of their use in nuclear reactors as neutron moderators and neutron transparent cladding material, respectively. As the neutron scattering cross-sections of hydrogen and zirconium differ greatly, neutron imaging is a well-suited analytical technique for hydrogenated zirconium alloys especially when hydrogen concentration gradients occur. Adapted testing techniques, including three-point bending on thin walled specimen (see Fig. 1a), have been employed to study certain hydrogen-induced failure mechanisms in zirconium alloys, where stress gradients lead to extreme variations in hydrogen concentration gradients.

Delayed hydride cracking (DHC) has been an extensively studied failure mechanism of zirconium alloys used as pressure tubes and nuclear fuel cladding materials. During DHC, hydrogen diffuses towards locations of high tensile stresses, where it precipitates subsequent to exceeding the local solvus limit. Once the hydride precipitate reaches a critical size, it fractures under the local tensile stress, and continues to propagate in repeated steps by the same mechanism [1], [2]. It is important to deepen the understanding of the DHC mechanisms to ensure the mechanical integrity of spent nuclear fuel cladding during transportation and dry storage when DHC conditions are greatly enhanced.

Recently, multi-physics models of the hydride volume fractions have shown the trend of hydrogen diffusion and precipitation around the DHC crack tip [3]. In order to validate such models, experiments with the given conditions, as well as applicable analytical techniques are required. Until now, the measurement of hydrogen concentration has only been accurately achieved through completely destructive methods, known as hot gas vacuum extraction (HVE). Certain studies have also attempted to quantify and characterize hydrogen concentrations and hydride formation through metallography and image processing methods [4]–[6], but is also destructive and highly dependent on the hydride rate of formation. However, recent studies have shown the attraction of hydrogen towards a liner within lined-cladding materials through neutron radiography [7]–[9]. In the study described here, neutron radiography achieves hydrogen quantification results capable of validating aforementioned multi-physics models without destructive methods. In addition, this method allows localized investigations of DHC cracks within lined-cladding and highly radioactive material, using proven encapsulating containers [10], with significantly less effort and without any destructive techniques.

Hydrogen diffusion and precipitation patterns of DHC in irradiated and unirradiated Zircaloy-2 within a spectrum of test temperatures from 160°C to 410°C have been investigated using high-resolution neutron radiography using PSI Neutron Microscope detector. As the radiography experiments are ex-situ analysis techniques, the hydrogen diffusion patterns during DHC cracking are inferred through the hydride precipitation patterns. The DHC cracks were propagated through the wall thickness (0.4 – 0.6 mm) and imaged with neutrons perpendicular to the cracking direction. The combination of thin (2.0 mm, see Fig. 1b) sections of cladding encompassing the deepest location of the hydride crack together with the high-resolution capability of the detector resulted in an effective image spatial resolution of 8.1 µm. With a thorough calibration study using hydrogenated Zircaloy-2 standards ranging from 10 to 2700+ wppm H, a transmission versus hydrogen concentration reference curve was established [9], [11]. With a radial averaging tool, the average radial transmission was obtained and subsequently converted to hydrogen concentration (see Figures 1c and 1d). Selected samples are presented in the Figure 1 showing respective neutron radiographs (n-rad) and either light optical micrographs (LOM) or back-scattered electron micrographs (BSE).

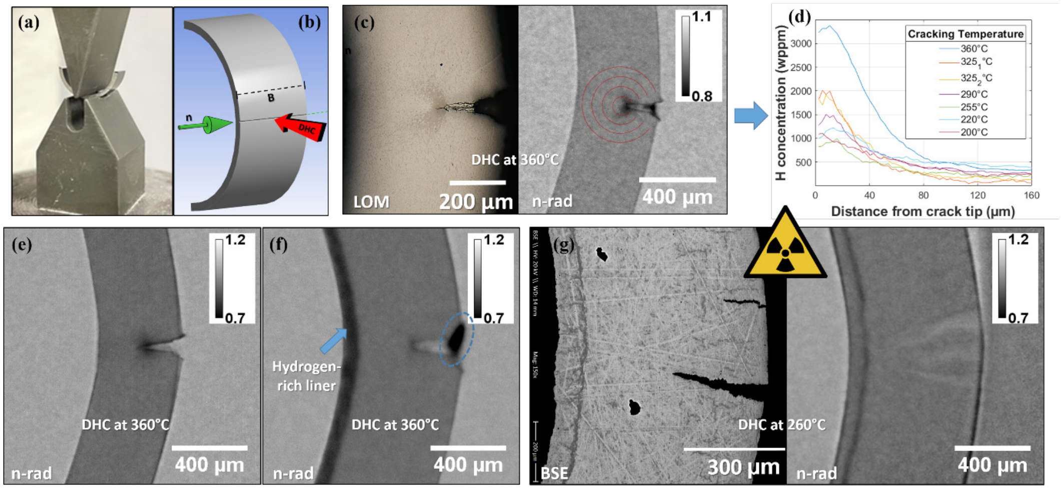

Fig. 1 (a) The three-point bending test setup with Zircaloy cladding sample in place. (b) Visualization of neutron beam and DHC crack propagation (c) Unirratiated cladding (200 wppm H), hydride precipitation around the crack tip indicates the stress field shape and subsequent hydrogen diffusion patterns (LOM and n-rad). (d) Averaged transmission profiles about the crack tip (example paths shown by red arcs) converted to average radial hydrogen concentrations. (e) Cladding (320wppm H) without inner liner with hydrogen rich DHC crack tip. (f) Cladding (300wppm H) with hydrogen rich inner liner (indicated with the blue arrow) showing less hydrogen at the DHC crack tip. A sample artifact (glue) is encircled by the blue dotted line. (g) irradiated cladding (120 wppm H), not all cracks in BSE images visible where n-rad image unveils all major cracks.

The implication of the findings from this analytical technique open new possibilities for non-destructive testing of irradiated and unirradiated zirconium alloy claddings. High-resolution neutron radiography has unveiled the following –otherwise difficult to obtain– information about DHC:

1. There is a strong correlation of DHC cracking temperature and resulting hydrogen concentration around the crack tip (see Figure 1d [9])

2. Despite the liner depleting the matrix of hydrogen, sufficient hydrogen diffusion occurs to enable DHC propagation (see Figure 1f and quantification results [11])

3. Complex cracks can be observed, especially in highly radioactive material where multiple non-uniform cracking occurs (see Figure 1g and [11])

The PSI Neutron Microscope detector will continue to investigate irradiated zirconium alloys to better understand hydrogen kinetics and the effect of irradiation damage under various thermomechanical loads.

This extended abstract is presented on behalf of all the co-authors of the recently published paper [9] and the recently submitted manuscript [11] by Aaron Colldeweih and Pavel Trtik.

[1] R. Dutton, et al., Met. Trans 1977
[2] D. O. Northwood et al., Int. Met. Rev., 1983
[3] Z. Xia, et al., J. Mech. Phys. Solids, 2019
[4] S. Valance et al., J. Nucl. Mater., 2015
[5] M. Maric et al., J. Nucl. Mater., 2022
[6] S. Valance, et al., ASTM Int., 2011
[7] W. Gong et al., J. Nucl. Mater., 2019

[8] *L. I. Duarte, et al., J. Nucl. Mater., 2021*
[9] *A. W. Colldeweih, et al., J. Nucl. Mater., 2022,*
[10] *P. Trtik, et al., Rev. Sci. Instrum., 2020*
[11] *A. W. Colldeweih, et al., Zircon. Nucl. Ind. 20th Int. Symp., 2022 (STP: Accepted).*

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News from the Board

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

12.-18. June 2022: Advanced school on neutron diffraction and neutron imaging principles and analytical methods , San Giovanni in Valle Aurina (BZ), Italy

17.-21. October 2022: **ITMNR-9** Buenos Aires, Argentina

2024: WCNR-12 in the United States.

After a long period without in person meetings, and nearly two years after its originally planned dates, we invite the neutron imaging community to the 9th International Topical Meeting on Neutron Radiography (ITMNR-9), which will take place in Buenos Aires, Argentina, from October 17 to 21, 2022. This will be the 9th conference in the ITMNR series being coordinated by the International Society for Neutron Radiography (ISNR), and follows the eight conference held in China in 2016. In this occasion it will be organized by the Atomic Energy Commission of Argentina (CNEA) and it will be focused on Neutron Imaging for "Applications of Neutron Imaging for Science, Industry and Heritage".

As in previous occasions, the meeting will be a forum for scientists working with neutron imaging techniques to share their experiences and expertise, and learn about the latest advances on the application of neutron imaging techniques to an ever increase number of problems in science and technology, that include:

Materials science and engineering
Cultural heritage, Art and Conservation
Solid state physics and magnetism
Paleontology
Botanic and wood science and technology
Materials degradation
Nuclear materials and fuels
Archaeometry
Electrochemistry
Hydrogen and processes
Concrete technology

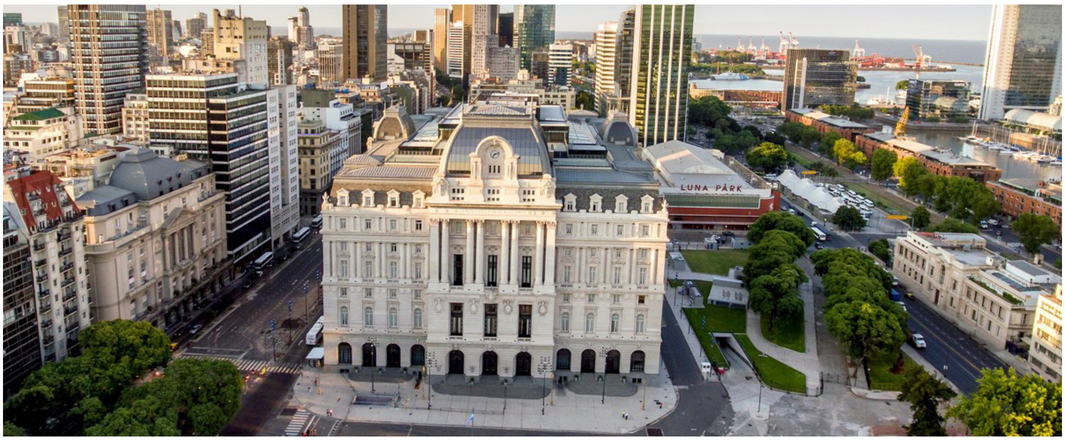
Some of these applications are made possible by the latest technical developments on neutron imaging, to be presented in the following areas:

New imaging instruments
New techniques and analyses
Tomography
Novel Software

The aim of the meeting is for participants to be able to network in person, by engaging in fruitful discussions and collaborations, and to return home with new ideas for their work.

The meeting will take place at Centro Cultural Kirchner (cck.gob.ar), a landmark building of Buenos Aires, with multiple accommodation options within walking distance or a short Metro ride.

View of Puerto Madero quarters in Buenos Aires



View of Centro Cultural Kirchner

For those interested, there will be the possibility to visit the site of RA-10, a 30 MW multi-purpose research reactor being built by CNEA near Buenos Aires, which will host the Argentine Neutron Beam Laboratory (LAHN, www.lahn.cnea.gov.ar). Among the first instruments to be commissioned will be ASTOR, a state-of-the-art neutron imaging instrument for cold neutron.

The ITMNR-9 Conference proceedings will be published Open Access in Journal of Physics: Conference Series (JPCS), published by IOP Publishing, and the paper will need to be submitted before December 1st.

We hope this conference will further promote the applications of neutron imaging technology around the world.

Looking forward to seeing you in Buenos Aires,

Dr. Javier Santisteban Chair of ITMNR-9 Scientific Committee

ITMNR-9 SCIENTIFIC PROGRAMME COMMITTEE

Javier Santisteban, Comisión Nacional de Energía Atómica, Argentina (Chair)
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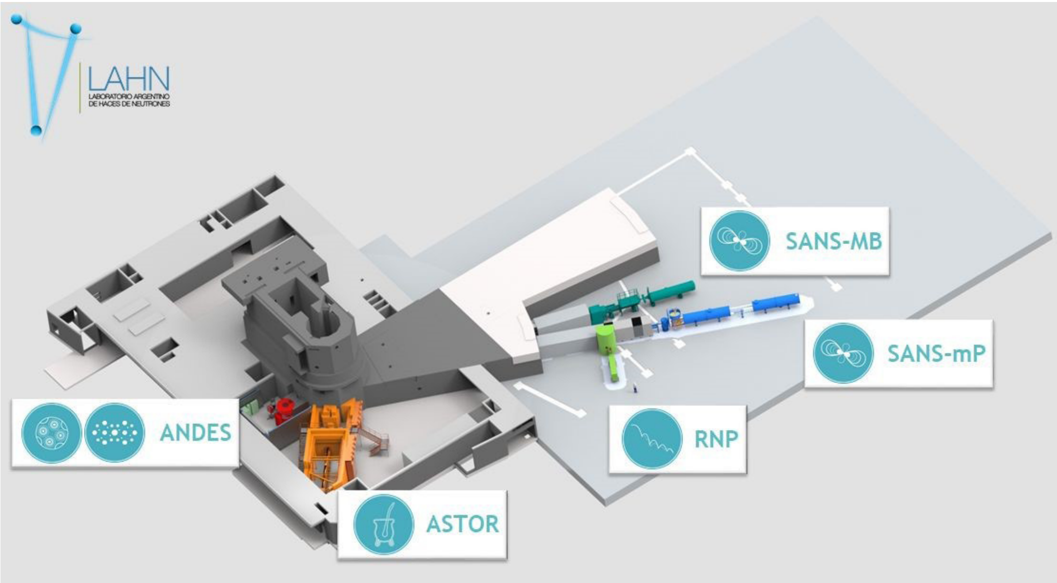
Anton Tremsin, University of California at Berkeley, USA
Pavel Trtik, Paul Scherrer Institut, Switzerland

COVID-19 REGULATIONS

Argentina is one of the countries with higher percentage of vaccination (February 2022): 78% with two doses, 88% with one dose (link to data).

At present, universities in Argentina work at "full presence", but with compulsory use of face masks and ventilation of indoor spaces.



Artistic view of CNEA RA-10 reactor complex in Centro Atómico Ezeiza, near Buenos Aires.

IMPORTANT DATES AND CONTACTS

15/12/2021 to 30/03/2022: CALL FOR ABSTRACTS
06/05/2022: NOTIFICATION OF ABSTRACT ACCEPTANCE
14/05/2022 to 10/08/2022: EARLY REGISTRATION
31/08/2022: Final Program
11/08/2022 to 09/09/2022: NORMAL REGISTRATION
17/10/2022 to 21/10/2022: ITMNR-9, Buenos Aires
01/12/2022: Full-paper submission deadline

Email: itmnr-9@sciencesconf.org
Website: https://itmnr-9.sciencesconf.org/

... 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.

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