Experts Meeting on Fast Neutron Imaging

Sunday 20 October 2019 - Wednesday 23 October 2019

MLZ Garching

Book of Abstracts

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Detectors / **1**

An Efficient, Compact and Versatile Camera for Fast Neutrons

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With the support of an international agency, NeutronOptics Grenoble has developed a compact neutron camera for fast neutron tomography using a PSI/RC-TriTec PP scintillator. This scintillator can be exchanged in-situ for thermal neutron or gamma scintillators to test for these beam components. The FOV with a cooled 16-bit 1" Sony CCD is 125x100 mm or 85x70 mm with 2750x2200 pixels and up to 8x8 binning. Newport Micro-Controle (France) mechanics for tomography are synchronised with the camera using simple *.bat Windows scripts. The L-shaped periscope design allows good radiation protection, and simplicity and low repair cost mean that inexperienced students can use the camera with minimal supervision.

Welcome Session / **2**

Imaging with Fast Neutrons (and Gamma Radiation) –State of the Art and Challenges

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Neutron imaging has matured towards a powerful tool for non-destructive testing, but also for many other kinds for research domains.
Majority of facilities for neutron imaging are using neutrons in the thermal and cold spectrum (similar to neutron scattering devices) because of their availability at the large-scale facilities,. The advantage of using thermal and cold neutrons is the wide range of interaction probabilities between different materials (even isotopes) with wavelength in the order of the atomic distances, enabling contrast features which are complementary to X-ray interactions.
Even if all the nuclear reactions for neutron extraction start with high-energy neutrons in the MeV region, the imaging with fast neutrons is less developed (in comparison to thermal and cold neutrons) and there are only a few facilities around the world with useful performance. One of them is the fission neutron facility at FRM-2, NECTAR, equipped already with a camera based detector and the capability for neutron tomography. In some respect, NECTAR can be taken as benchmark although its performance is not yet characterized completely and a potential for upgrade should be exploited.
On the other hand, neutron sources on the basis of the interaction of accelerated particles or even electrons are available, again starting with fast neutrons (e.g. D-D: 2 MeV; D-T: 14 MeV). Their source strength is limited to less than 1010 s-1 and the collimated beam has much less intensity than NECTAR can deliver. However, the accelerator sources are transportable and not part of a large-scale facility.
Fast neutron imaging has the advantage of very high penetration of large objects even of high-Z materials. The most probable interaction process is neutron scattering where the microscopic cross-sections are very similar for most of the materials. Therefore, it is the difference in the nuclear density of the involved materials which can be distinguished in the imaging process with fast neutrons.
Starting from a fast neutron spectrum, it can be shifted by the slowing-down process in a moderator and neutrons in the thermal and epi-thermal region can be used for imaging purposes. Here, an optimization process is needed, what moderator and which detector are the best combinations for the particular object to be investigated. This can be done either in an experimental way, but also with the help of simulations. Such kind of simulations are very important anyway in order to understand

the processes in the sample and the detector in comparison to the available nuclear data. A data base for attenuation coefficients for the particular setup has to be created and its dependency on the sample thickness has to be studied either experimentally or on the way of simulations.
Modern neutron imaging detectors are mostly based on camera systems with high sensitivity for the light from a scintillation converter. Therefore, the scintillator is the key component for the detection process, defining the efficiency and the spatial resolution. Both have to be optimized for the most efficient use of fast neutrons for imaging purpose.
Because nearly all nuclear processes are accompanied by gamma radiation emission, their use for imaging purposes should also be considered as complementary tool to the neutron options.

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Status of Fast Neutron Imaging Research at ETH/PSI

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In collaboration between ETH Zurich (Laboratory of Nuclear Energy Systems) and the Paul Scherrer Institute in Switzerland, fast neutron imaging techniques are actively developed. This includes a custom D-D fast neutron generator with a small emitting spot (~2 mm) and an output of about 3E7 neutrons/s. It is equipped with a rotating beam target in order to manage high power density at the emitting spot. Ongoing source upgrades include changing from an RF-driven to a microwave-driven ion source in order to reduce operating pressure and enable higher acceleration voltage. This is expected to bring the output to about 3E8 neutrons/s. A custom array of plastic scintillator detectors is used for fan-beam tomography, including research on energy-selective techniques where tomography data is collected at different source emission angles, corresponding to a quasi-monoenergetic range of about 2.2-2.8 MeV. By combining images at multiple angles, because elements have uniquely energy-dependent cross-sections in the case of neutrons (unlike X-rays), element sensitivity can be achieved. Feasibility studies using homogeneous samples were successful, and the technique is now being tested with more realistic, heterogeneous samples. Development of a gamma-blind, high efficiency, high-resolution 2D fast neutron imaging detector is also ongoing. The concept uses wavelength shifting fibers embedded in a ZnS(Ag)-epoxy mixture with SiPM readout of the light collected. A single channel prototype was developed and tested for characterization of spent nuclear fuel, and by segmenting the fiber readout it is expected that roughly 0.5 mm resolution can be achieved. That status and outlook of all of these efforts will be presented.

Scintillators 2 / **4**

Neutron Scintillation Screens for Imaging with Fast Neutrons from RC Tritec AG. (Actual situation and forecast of planned developments)

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By the use of fast neutrons dense or large materials can be analysed by Radiography and computed tomography. Motivated by James F. Hunter from Los Alamos National Laboratory, we (RC Tritec AG) evaluated in 2016 in cooperation with the Fraunhofer Institute (Germany) a production process for manufacturing large sized (450 x 450 mm) ZnS filled PP-plates for conversion of fast neutrons into visible light. Detection could be done either by a large flat panel or by standard CCD-camera systems. For adjustment of the emission color to the corresponding detector ZnS:Cu (green emission) or ZnS:Ag (blue emission) filled PP-plates are provided. An overview about the typical features, like light output, resolution or gamma sensitivity is published by Malgorzata G. Makowska in 2017. 1 A comparative measurement regarding resolution and noise performance has been done by Nicola M. Winch et al. from LANL. 2 A disadvantage of the plates provided by RC Tritec is the lower resolution reachable, but show in contrast to other products a significantly better noise performance. We (RC Tritec AG) are going to launch end 2019 or latest beginning of 2020 in cooperation with the Paul Scherrer Institute a development project to evaluate different possibilities to improve the resolution of the scintillation screens for Imaging with fast neutrons. We would like to present within this meeting our actual state of the art in production, adjustment possibilities and a rough plan how we would follow up to improve the performance of the scintillation screens.

1 Malgorzata G. Makowska, Bernhard Walfort, Albert Zeller, Christian Grünzweig and Thomas Bücherl J. Imaging 2017, 3, 60.
2 Nicola M. Winch, Amanda C. Madden, James F. Hunter and Ronald O. Nelson 2017 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)

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A New Fast Neutron Imaging System at the Phoenix Neutron Imaging Center –Current Status and Initial Results

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Phoenix LLC has designed and is currently constructing the Phoenix Neutron Imaging Center (PNIC) in Fitchburg, WI. Phoenix has a well-established history of developing and deploying the world's strongest deuterium-deuterium accelerator-based compact neutron sources with continuous operation measured at over 5×10^11 n/s for over 100 consecutive hours. The new facility, which will house a newly developed ion source, provides 10 thermal neutron beamlines, one dedicated fast neutron beamline, as well as a 450 kV X-ray CT system for complimentary radiography studies. The fast neutron beamline will provide a source of up to 16 MeV neutrons with a yield of approximately 3×10^13 n/s. The spot size will be variable between a few millimeters up to several centimeters to change the effective L/D ratio as required for the specimen under interrogation. The samples will be mounted on a high-precision turntable to enable fast neutron CT and the initial detector will be an amorphous silicon DDA coupled to a fast neutron scintillator, likely PP/ZnS. This presentation will show the facility in its current state, the neutron beamlines, detector options and future upgrades, and shielding against neutron activation, facility dose, and scatter contributions to the images. Initial experiments that show the measured neutron flux and resolution will be presented as will 2D and 3D fast neutron images captured on the new PNIC system. Efforts toward X-ray and fast neutron CT fusion will also be discussed and presented as applicable.

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Parametric Evaluation of New Fast Neutron Scintillator Designs

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Experiments conducted at Idaho National Laboratory (INL) measured the performance of prototype fast neutron scintillator screens with various scintillator materials deposited in a range of thicknesses on high density polyethylene (HDPE) of varying thickness. The HDPE acts as a converter for the fast neutrons, utilizing a proton recoil reaction to cause the scintillator material to emit photons. INL's Neutron Radiography (NRAD) Reactor's North Radiography Station (NRS) beamline has a fast neutron flux (above 1 MeV) greater than 1.5×107 n/cm2s. This study determined which combination of scintillator material and thickness, as well as which HDPE thickness, exhibited the best screen performance for fast neutron imaging based on light output and spatial resolution. The results of these measurements inform development of higher detection quantum efficiency screens for fast neutron imaging.

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Fast Neutron Beam Line at The Ohio State University Research Reactor

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The Ohio State University Research Reactor (OSURR) is a pool type, light water moderated, uranium silicide fueled research reactor licensed for steady-state operating powers up to 500kWth. It provides a variety of functional testing facilities including near-core and in-core irradiation locations. A thermal neutron beam facility is available at OSURR, providing a small neutron beam (30 mm diameter) to a working bench where various device testing can be set up for neutron radiograph, tomography, or device evaluation. The size of the neutron beam can be refined to mm level with neutron apertures, which enables electrical characterization and functional testing of devices during spatially controlled neutron irradiation. Although it is designed as a thermal beam, the residual 1-MeV fast neutron flux is still at 104 cm-2s-1, which has been used to evaluate fast neutron scintillators developed by Lawrence Livermore National Lab. To meet the increasing demands for fast neutron imaging applications, we have built a dedicated fast neutron beam line that consist of two collimators for shaping the neutron beam, a beam shutter for switching the beam on/off, and a beam-stop for reducing the dose rate in the environment. The 58" (147.3 cm) long collimation features a 6" (15.24 cm) thick graphite block with an aperture of 40 mm and a 4" (10.16 mm) thick solid polycrystalline bismuth, which are positioned near the core for slowing down neutrons and filtering gamma-rays, respectively. A cylindrically shaped beam shutter located between the two collimators utilizes high-density polyethylene and lead to attenuate fast neutrons and gamma rays, respectively. The collimators accommodate several lead, borated aluminum and borated polyethylene blocks with same aperture size but varying thicknesses to shape the 40-mm diameter beam. An MCNP simulation executed with 2.0 MeV neutrons with the beam shutter open, estimated a neutron flux of ~1.8×108 neutrons/cm2s at the exit of the collimator. Furthermore, calculations revealed that the gamma ray content in the beam is reduced to less than 0.01 % of its near core value. The project is at the final testing stage and the fast neuron energy spectrum is being measured with foils activation method, unfolded by STAYSL code and a Bonner sphere neutron spectrometer.

Detection and Applications / **8**

Fast-neutron imaging with broad and quasi-monoenergetic sources

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Lawrence Livermore National Laboratory (LLNL) is near-completion of a quasi-monoenergetic neutron source for fast-neutron imaging. The source is expected to produce 10-MeV neutrons with an on-axis flux of ~1011 per second per steradian through a collimated aperture with a ~7-degree opening angle. The application for this source is imaging of low-Z materials heavily shielded by high-Z materials. We have tested the feasibility of the system at Ohio University. We have recently used the spallation source at the Los Alamos Neutron Science Center (LANSCE) to generate radiographic images. We will discuss our recent imaging data from LANSCE and compare them with prior data obtained using a quasi-monoenergetic source. We will also discuss our results as they relate to our expectations of the near-complete neutron source at LLNL.

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Radiography with Fast DD and DT Neutron Generator, Associated Particle Imaging with DT Neutron Generator, and Grating Optics Applied to Fast Neutron Radiography

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Presented are fast neutron radiography, based on fast (2.5 MeV DD and 14 MeV DT) fusion-based, Adelphi neutron generators. Radiography experiments at LLNL with Adelphi 14 MeV source under a DARPA program are presented. Also reported are experiments Associated Particle Imaging (API) using a 14 MeV DT neutron generator, which provide a spatial map of the isotope composition of the fast neutron interrogated sample. Example of API presented is mapping carbon content within top 30 cm of soil. Also discussed is the prompt gamma neutron activation analysis, which can be applied to 14 MeV neutron interrogation of samples. Finally presented, is the potential use of grating optics developed by Refined Imaging for fast neutron radiography to improve resolution and contrast.

Scintillators 1 / 11

Investigation of PVT Scintillators for Fast Neutron Imaging

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Three Polyvinyltoluene (PVT) scintillators, provided by Lawrence Livermore National Laboratory (LLNL), with different dimensions and doped with 2% Flrpic (an Iridium complex flour) have been characterized in terms of spatial resolution and relative light output using the North Radiography Station (NRS) beamline of Neutron Radiography (NRAD) Reactor at the Idaho National Laboratory (INL). The beamline provides above 1-MeV fast neutrons with a flux higher than 1.5 x 1e7 n/cm2s. The mechanism that causes energy deposition, and eventually scintillation, in PVT material, is the recoil of a proton from n-p elastic scattering. In this study, radiography and tomography images of a phantom made of HDPE and structures containing various neutron absorbing and scattering materials such as paraffin wax, Aluminum, cement, and stainless steel were also acquired. All images were obtained using a camera-based system along with a rotating stage for obtaining different projections of the phantom. This study focused on evaluating of PVT scintillators for fast neutron imaging applications.

Detectors / 12

On the Possibility to Count Fast Neutrons with High Spatial and Timing Resolution

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Various technologies have been developed to this date for the detection of fast neutrons, each having certain advantages and limitations at the same time. There is no one single device, which meets all the requirements of various experiments where fast neutrons have to be detected. Detectors with microchannel plates (MCPs), which were initially developed for the applications with very low input photon fluxes, have been recently extended for thermal and epithermal neutron imaging experiments. The fact that event multiplication within the MCP is localized within a pore, has low transit time spread and can be encoded with virtually no readout noise provide the possibility to detect both time and position for every neutron registered with relatively high detection efficiency. Conventional glass MCP manufacturing technology has been recently modified to contain neutron-absorbing atoms (e.g. B, Gd) for thermal and cold neutron counting. Detection of fast neutrons with MCPs has been also demonstrated by novel MCPs manufactured from plastic material (PMMA), where proton recoil is used for fast neutron detection. In this paper we will review the characteristics of plastic MCPs for fast neutron detection and discuss possible readout options. Although such devices will not outperform or replace widely used scintillator-based detectors, where incoming neutron flux is converted into light subsequently detected by a CCD or CMOS sensor, the detectors with plastic MCPs can still provide some unique capabilities in some applications, where high resolution neutron counting with low readout noise is required.

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High Resolution High Energy Neutron Computed Tomography at LANSCE-WNR

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It has long been recognized that neutrons can compliment x-rays for imaging. This is due to their very different attenuation characteristics based on nuclear cross-section, which allows imaging of low Z materials through higher Z materials. Additionally one can use energy dependent Time of Flight
(ToF) imaging to exploit phenomenon like nuclear resonances for isotope and element specific imaging. The Los Alamos Neutron Science Center (LANSCE) accelerator is an 800 MeV proton linear accelerator which supplies protons to a range of missions including two spallation neutron targets, one moderated (water and liquid hydrogen) and one unmoderated. This combination of targets provides flight paths which have cold, thermal to epi-thermal and fast neutron energy ranges. In addition the proton pulse structure of the LANSCE accelerator provides neutron pulse lengths of < 270ns for the thermal/cold flight paths and < 1ns for the fast flight paths. These pulse lengths allow for energy discrimination from eV to ~100 MeV.

Detection and Applications / 16

A Multi-Pixel Camera for Fast Neutron Radiography

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The neutron radiography group at the Physics Institute III B, RWTH Aachen University, develops a multi-pixel camera for fast neutron radiography using an AmBe neutron source or a neutron generator.
So far, two camera prototypes were built: A single-pixel prototype and a 16-pixel camera. Both prototypes use stilbene scintillator cuboids of size 5x5x25 mm³ for neutron detection. The created scintillation light is detected via silicon photomultipliers.
In detailed test measurements and Geant4 simulations, the detector response to neutrons and gamma rays, the material discrimination capability and the spatial resolution are studied. In the near future, an improved version of the neutron camera using the obtained results shall be constructed.
In this talk, the most important results from the measurements and simulations are shown, focusing especially on the material discrimination in radiography applications, and design concepts for the improved camera are discussed.

Reactor Facilities / 17

First Steps in Neutron Imaging at the Very Low Flux Facility AKR-2

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In 1990, seven research reactors (FRM I, RFR, FRG-1, FRJ2, FRG 2, FMRB, BER II) have been in operation for the field of neutron science in Germany. Since that time, five facilities have been decommissioned with one more (BER II) to be shut down by the end of 2019. Because of this trend of neutron sources going offline in Germany, it is becoming more and more difficult to train staff, to optimize instruments as well as methods, and to provide user beam time for both fundamental

and non-fundamental research applications. With the neutron imaging system at the training and research reactor AKR-2 the TU Dresden offers a low flux neutron source so far with the capability of neutron imaging utilizing the thermal neutron spectrum. It will also counter the aforementioned negative development induced by the loss of neutron sources in Germany.

In order to provide a basic platform for training and first contact research in the field of neutron science, (very) low flux facilities represent a sufficient solution. The AKR-2 with a maximum continuous power of two Watts can be categorized as such a facility, where students and the next generation of neutron scientists gain their first experience. In this context, the experimental field of the AKR-2 has been extended by a thermal neutron imaging radioscopy system in the course of the last year. Currently, this setup utilizes thermal neutrons with a 200 µm LiF/ZnS(Ag) scintillator, but with the prospect to be able to switch to the fast neutron spectrum in a later setup. So far, the characterization is in progress through an L/D study, which is the subject of this presentation. This study builds upon a previous investigation with a less advanced imaging system and is intended to demonstrate the limits in neutron imaging at AKR-2.

A two-way cadmium knife-edge with integrated reproduction scale will be used for signal-to-noise analysis. As part of the common procedure, the knife-edges will be tilted against the pixel grid of the deep-cooled camera system known as slanted-edge method. In order to find the best imaging configuration, the collimation setup will be modified and the distance in front of the experimental channel will be varied with respect to the source.

Aside from the limits in neutron imaging at AKR-2, the complete setup will provide prove-of-concept insights for other facilities considering the construction of similar neutron imaging systems. Furthermore, upon familiarizing new generations of scientists with thermal neutron imaging techniques, additional methods shall be applied one after another known as fast imaging and laminography. Finally, experiments not ranked sufficiently high enough for the limited beam time at high flux facilities but with their experimental needs fulfilled by the AKR-2 can be conducted.

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The Low Flux Neutron Source AKR-2

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The low flux neutron source AKR-2

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Abstract
In 1990, 7 research reactors have been in operation in Germany for the field of neutron science (FRM I, RFR, FRG-1, FRJ2, FRG-2, FMRB, BER II). Since that time, five facilities have been decommissioned with one more to be closed by the end of 2019 (BER II). In 2020, only 1 research reactor (FRM II) will be in operation in Germany to produce neutrons for neutron science. Because of this radical reduction of neutron sources in Germany it becomes more and more difficult to train staff and to optimize instruments and methods employed in neutron science. The same applies for finding motivated students. To guarantee competence in Germany in the field of neutron science for the future, it is indispensable to get in touch with students and to raise the awareness of neutron sources close to universities. The zero-power campus reactor AKR-2 at the TU Dresden fulfills this task.

The training and research reactor AKR-2 is a thermal, homogeneous, solid material moderated zero power reactor with maximum permanent power of 2 Watt. AKR-2 was completely refurbished in 2005 and is actually the most advanced zero power training reactor in Germany. The facility is equipped with a state-of-the-art digital I&C control system Teleperm XS (see also http://tu-dresden.de/mw/akr). The main purpose of AKR-2 and its design basis was and is the education of students in nuclear and reactor physics, in nuclear engineering as well as to teach fundamental knowledge in radiation protection. Due to the physical characteristics of AKR-2, research is limited to projects where low neutron fluxes are desirable and variable operational conditions as well as low costs are requested. The access to AKR-2 is uncomplicated and there is no proposal reviewing system. While at high flux facilities high level and well recognized research is carried out, AKR-2 is ideal for idea, test and quick trial experiments. There are a couple of experimental channels enabling flexible access to the neutron field. In the presentation, we will give a detailed description of the AKR-2's design and its physical properties. Some selected results of neutron imaging with thermal neutrons which was performed for the first time at AKR-2 will be shown. Furthermore, we would like to discuss the question how the AKR-2 can contribute in the education of scientists dealing with neutron scattering methods in future?

Pulsed Neutrons / 19

Short-Pulse Laser-Driven Moderated Neutron Source

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Los Alamos National Laboratory (LANL) and collaborators have pioneered a novel short duration yet extremely intense neutron source using the short-pulse laser at LANL's Trident laser facility [1-5]. The Trident laser facility was until it's closure in 2016 one of the most intense and powerful short-pulse lasers in the world, providing a very high contrast laser pulse of ~600 fs in duration, ~80 J energy with a wavelength of 1053 nm. The laser beam can be concentrated to a peak intensity up to 1021 W/cm2, that, when interacting with a sub-micron ultrathin CD (or CD2) foil target, drives a high-energy deuteron beam. That intense beam converts into a neutron flux in a beryllium target that acts as catcher of deuterons and converter of deuterons to neutrons. The Trident laser-driven neutron source featured high intensity and directionality, ~1010 fast neutrons per shot in a ~1 sr cone and with an extremely short neutron pulse of <1 ns in time. The source has been already used effectively towards the development of a new generation of active interrogation concepts to detect clandestine nuclear material [6]. In order to enable other applications, such as nuclear resonance spectroscopy for isotopic identification of (irradiated) nuclear fuel [7], temperature measurement in shock–driven dynamic material experiments [8], and pulsed neutron diffraction and scattering, we have developed a bright moderated short-pulse laser-driven neutron source. Beryllium and high density polyethylene were used to realize this aim. The single pulse moderated neutron source was fully characterized in its energy spectral components by a set of neutron time-of-flight detectors, including the fast neutron component (~1 MeV-~50 MeV) coming from the neutron production, as well as the epithermal, thermal, and cold (few meV) components subsequent to the moderation of the neutrons. The presentation reports and discusses the measured features of the moderated single-pulse neutron source that we have just demonstrated and preliminary results in the detection of nuclear resonances with a view towards spectroscopy.
Moreover, the presentation compares the laser-driven short pulse neutron source with the spallation neutron source at the LANSCE facility, and the prospects of such novel laser-driven compact neutron sources based on available or proposed laser systems for medium and large scale neutron user facilities. The precedence of high-powered lasers in rugged environments for military or industrial (e.g. welding) applications may even provide a pathway to mobile compact short-pulse neutron sources.
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Scintillators 1 / 20

Development of Novel Scintillation Materials for Fast Neutron Detection

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Neutrons are/can be used in several applications such as material science, medical science, non-destructive investigation, security, neutron radiography and maintenance of social infrastructures such as bridge and tunnel. To detect the fast neutrons, gaseous detectors (³He, ¹⁰B) and neutron scintillators (H, ⁶Li, ¹⁰B) can be used in such fields. Since gaseous detectors contain expensive gas or toxic gas like ³He and BF₃, scintillators are expected to be next generation neutron detector.
We focused on organic crystal scintillators, with no toxic material no hygroscopicity and low detection efficiency for gamma rays. scintillation properties of some organic scintillators such as trans-stilbene were investigated, and we have developed novel martials with higher light outputs or/and fast decay/rise time. In this paper, we show some novel organic scintillation materials prepared by the self-seeding vertical Bridgeman technique. For example, Benzoic-acid and benzoic-acid-based materials such as Sodium benzoate were prepared by the self-seeding vertical Bridgeman technique, and some samples were found to have shorter decay time than trans-stilbene have.

Pulsed Neutrons / 23

Repetitive Laser Driven Neutron Source and Organic Scintillation Crystal for Fast Neutron Detection

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We are carrying out a project of development of laser driven neutron source under the support of Japan Science and Technology agency (JST). We will introduce about the present status of the project,

especially focused on repetitive neutron pulse generation system and 2D fast neutron imaging system using our original organic scintillation crystal for fast neutron detection.
We are investigating a possibility to develop a compact neutron source with ion beams driven by high-intensity short-pulse laser. The laser driven neutron source (LDNS) has the potential to be a unique compact neutron source because of some features such as; (a) realization of a compact neutron source by closely locating a laser-driven particle source and a neutron generating target, (b) a small size neutron source which is advantageous for high resolution radiography, and (c) neutrons with short pulse duration leading to a possibility for time-of-flight measurements in material analyses and imaging. However, neutron flux per laser pulse energy is relatively small in comparison with that in the accelerator driven neutron source. There are several ways to compensate the lack of flux. One is increasing the energy conversion efficiency of laser energy into ion beam energy. Another is increasing repetition rate. Modern ultra-intense laser systems which are adopted as the driver laser can be operated in 10Hz or more. We use the diode pumped ultra-intense laser system of Hamamatsu photonics as the driver laser. It can be operated in 10 Hz of repetition rate. The irradiation target supplying system is also important for realizing repetitive neutron generation.
Our neutron generation scheme is so-called pitcher-catcher system. There are two targets. The first "pitcher"target is laser irradiation target. The target material is deuterated polystyrene. The ultra-intense laser pulse is focused on to the target. Then the deuteron beam is generated by laser driven ion acceleration such as TNSA (target normal sheath acceleration) mechanism. The generated deuteron beam hits the second "catcher"target. The material is also deuterated polystyrene. At the second target D-D nuclear reaction is occurred. Then fast neutron beam is generated. The energy is 2.45MeV. We are constructing target supplying system for 10Hz operation. For realizing 10Hz operation, we adopted tape-shaped target. The target tape is loaded on the target drive mechanism like a movie projector. However thin deuterate polystyrene tape is too week to drive by such a mechanism. Therefor we developed composite tape consisting of thin deuterate polystyrene tape and tape with sufficient strength. Currently the performance is evaluating.
We also developing 2D fast neutron imaging system. The imaging system consist of scintillators with grid structure and multi-anode phot multiplier tube. We developed organic scintillation crystal for fast neutron detection. The melting point of the crystal is more than 200 degrees Celsius. The decay time is less than 6nsec. The light output is more than twice of trans-stilbene. We succeeded in growing a large diameter crystal of over 1 inch. Currently we are dicing and polishing crystal to constructing 2D imaging system.
We will introduce the current status of our project in the presentation.

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Testing New Fast Neutron Scintillators with a D-T Neutron Generator

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Prototype scintillator screens were fabricated in various formats and variations, and tested with fast neutrons from a D-T neutron generator at Adelphi Technology in Redwood City, CA. The scintillators were designed with combinations of plastics+scintillator in which the hydrogen in the plastic acts as a converter for the fast neutrons producing a proton recoil reaction to yield photons within the scintillator. Both mixed and layered plastic/scintillators were tested. Mixed scintillators were made with polystyrene and ZnS:Cu, and layered scintillators included polystyrene, HDPE (high density polyethylene), coated with a layer of ZnS:Cu scintillator. The various scintillator samples were lens-coupled to an Andor EMCCD detector for imaging with the D-T neutron source that produces 14.1 MeV neutrons with a neutron output of 10^8 neutrons/second.
The mixed scintillator screens of polystyrene/ ZnS:Cu produced the best results and images could be acquired on the time scale of minutes with scintillators on the order of 3 mm thick. Imaging performance was similar to Tritec PP/ZnS screens that were included for comparison. Of the layered scintillators, 3 mm polystyrene and 100 micron ZnS:Cu produced the best results. The complete imaging results will be presented. GEANT 4 simulations were also performed to optimize the thickness of conversion and scintillator layers.

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Excursion

Meeting-Point is the front gate of FRMII.
Link to Meeting-Point:
https://goo.gl/maps/wSArxwLp8JqKVuxcA

From there we will head to the U-Bahn station.
Bring comfortable shoes for a short hike.
Our destination will depend on the weather.

Information on the destination can be found under the following link:
Information on the planned excursion can be found at:
https://translate.google.com/translate?hl=de&sl=auto&tl=en&u=https%3A%2F%2Fwww.auf-den-berg.de%2Fwandern
herrsching-zum-kloster-andechs%2F

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Director's Welcome

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The MLZ Neutron Imaging Group and Facilities

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Introductory Presentation

Detectors / 30

Fast Neutron Imaging Capability at NOBORU and RADEN of J-PARC

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Neutron beamlines of the Materials and Life science experimental Facility (MLF) utilizes short-pulsed neutrons produced by 3-GeV proton beam irradiation at the Japan Proton Accelerator Research Complex (J-PARC). The most probable energy of neutrons produced in spallation reactions is around ~ MeV although high energy neutrons up to ~ GeV are also produced. Two beamlines, NOBORU and

RADEN, are available to utilize such fast neutrons for imaging experiments. Massive steel collimators, filters to reduce the prompt gamma-ray produced at the moment of proton pulse injection, and thick shields of sample room are equipped to utilize wide neutron-energy-range. The neutron's penetration power, generally increases with its energy, is expected to provide a unique capability for non-destructive inspection of large objects or high neutron absorbing materials: architectural and civil engineering structures, simulated melted core material containing boron, etc.

In this presentation the characteristics of NOBORU and RADEN are discussed from a viewpoint of neutron imaging with higher energy neutrons. Then some results of imaging with neutrons between 0.5 eV and ~MeV are presented. The authors also introduce an activity of developing a neutron imaging detector based on a lithium glass scintillator and a multi-anode photomultiplier tube to obtain a high efficiency at higher energies.

Reactor Facilities / 31

Multiprobe Imaging using Neutrons and Gammas at the NECTAR Beam-Line

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NECTAR is a superior beam-line 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 1, as well as neutrons interacting with beamline geometry, such as the collimator, gamma rays are produced in the process. The production of these gamma rays is inevitable as they are inherent with the principles of collimating or stopping the neutrons. Furthermore, these gamma rays are highly directional due to their constraint to the same beam-line 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 and swapped-out in-situ.

Here we present the advantages of combining the information gained from neutron imaging in conjunction with gamma imaging at the NECTAR beam-line, providing a unique probe with unparalleled isotope identification capabilities. Initial results were produced from data measured in the 2019 run-cycle, performed at and supported by the Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRMII). Furthermore, future improvements and advancements for the development of this technique will be discussed.

1 T. Bücherl and S. Söllradl, "NECTAR: Radiography and tomography station using fission neutrons" , Journal of large-scale research facilities JLSRF (2015) 1 p.19.

Detection and Applications / 32

The Combination of Chemical Analysis and Imaging with Neutrons

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At MLZ, we have three different methods using cold, thermal, and fast neutrons for the determination of the elemental composition in various samples. (1) Cold neutrons are guided to the Prompt Gamma Activation Analysis (PGAA) facility in the Neutron Guide Hall West. The PGAA method is based on the measurement of the prompt gamma radiation released during the de-excitation of the compound nucleus formed in neutron capture. (2) In classic Neutron Activation Analysis (NAA), the delayed gamma radiation is used instead. Taking into account the different half-lives of the activation products, a variation of irradiation, cooling and measurement times enables an optimized detection for each element. (3) The Fast Neutron-induced Gamma Spectrometry (FaNGaS) is a unique instrument built by Jülich Centre for Neutron Science (JCNS). It applies the gamma radiation of the (n,n') reactions induced by reactor neutrons. The FaNGaS instrument shares a beam port with the instruments NECTAR and MEDAPP. Originally, these complementary methods are suitable for bulk analysis. For PGAA, we have already implemented an add-on which provides spatially resolved information of the elemental composition. The results from PGAA sub-volume measurements are combined with the absorption coefficients from Neutron Tomography. This is called Prompt Gamma Neutron Activation Imaging + Neutron Tomography (PGAI/NT). As a next step, we discuss a possible combination of the capabilities of FaNGaS and NECTAR in order to offer spatial resolved measurements also with fast neutrons. Single-event mode will play a key role in this context.

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New Developments in the "Event-by-Event" Fast Neutron Radiography

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A new generation of the Lintech's neutron imaging device is under development, extending the capabilities of the previously patented solution 1. Our device implements general design of the fast neutron imager, previously demonstrated spatial resolution just under 0.5 mm 2. It operates in the event-by-event readout mode, acquiring energy, timing, and pulse shape information for all detected radiation events, and achieving good separation from backgrounds. New hardware includes the next generation of Hamamatsu position sensitive photomultiplier tubes (PSPMT) with enhanced characteristics, an improved readout electronics, and a new fast data acquisition module that is capable of acquiring of up to 20-50 MHz of neutron interaction events. The design of the readout and DAQ allows to build detectors either with a single PSPMT or with an array of PSPMTs in various configurations (such 2x2, 3x3, 2x4, etc.). The new version of the hardware may be used, with an appropriate scintillator, for imaging with thermal and ultra-cold neutrons, in neutron scattering and interferometry. Using pulse shape discrimination, it is also suitable for joint multimodal imaging of neutrons and photons.

1 V. Popov, P. Degtiarenko and I. Musatov, "Fast neutron imaging device and method" U.S. Patent No. 8,648,314, (2014).
2 V. Popov, P. Degtiarenko and I. Musatov, "New detector for use in fast neutron radiography", doi:10.1088/1748-0221/6/01/C01029, (2011).

Scintillators 2 / 34

Nanostructured Scintillators 'Nanoguide'for Improved Fast Neutron Radiography

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