Nuclear Instruments and Methods in Physics Research A 769 (2015) 97–104

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

# Development of a pulsed neutron three-dimensional imaging system using a highly sensitive image-intensifier at J-PARC

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ARTICLE INFO

*Article history:*
Received 25 April 2014
Received in revised form
25 August 2014
Accepted 10 September 2014
Available online 19 September 2014

*Keywords:*
J-PARC
MLF
Pulsed neutron imaging
TOF
Resonance imaging
CT

ABSTRACT

To realize neutron energy resolved three-dimensional (3D) imaging in the resonance neutron energy region, a camera system coupled with a high sensitivity and high frame-rate gating image-intensifier was developed. The resonance absorption 3D imaging was successfully demonstrated at the pulsed neutron source of the Japan Proton Accelerator Research Complex (J-PARC). The camera system allowed us to obtain a time-of-flight (TOF) image of 2352 (W) × 1726 (H) pixels resolved into a narrow energy range. 3D images with enhanced contrast at corresponding resonance energy regions for cylindrical Au, Ta, and In samples were reconstructed by convolution filtered back-projection (FBP) and maximum likelihood expectation maximization (MLEM) methods. The spatial resolution in the depth direction was evaluated experimentally to be approximately 1 mm. Our results show that the system could have applications in industrial fields.

## 1. Introduction

It is well known that several elements have large resonances of neutron total cross-sections in the energy region from a few eV to a few hundred keV. The metals including these elements, mostly heavy metals, are often used for industrial commodities or as nuclear engineering materials. Thus, a technique is required to make use of these resonances to visualize and analyze the elements three-dimensionally for investigations and evaluations in concerned fields. Here the realization of the technique was achieved using an intense pulsed neutron beam, including the neutron resonance energy region, to resolve these neutrons into narrow energy ranges corresponding to the resonance width of the elements.

Energy-selective tomography experiments have been performed previously using reactor-based neutrons in the Bragg-edge energy region, rather than in the resonance energy region [1–4]. The development of high-intensity pulsed neutron sources permitted an intense neutron beam can be generated with wider energy spectrum, including resonance neutron energies, increasing the efficiency to enable the investigation of the energy dependence of total cross-sections. Energy-selective radiography using wider neutron spectrum in combination with TOF method has been studied by several groups using two kinds of neutron detectors: two-dimensional neutron counters [5–7] and camera-type devices [8–10]. Energy-selective radiography at the pulsed neutron source was formed on a Micro-Channel Type (MCP) detector developed by Anton Tremsin [7] and on a gated, intensified, and cooled CCD camera [8,9]. Resonance radiography with a high-speed video camera was successfully demonstrated in the neutron energy region from a few eV to a few hundred eV at J-PARC [10]. While two-dimensional neutron counters have a time resolution of less than 1 μs, it is still difficult to achieve both a spatial resolution of less than 0.1 mm and to adjust the field-of-view (FOV).

In this study, we focused on camera-type devices. However, there were several problems in adapting radiographic techniques of camera-type devices to tomography at the resonance neutron energy. Tomography requires a high neutron flux to perform the object inspection in a reasonable beam time. For example, the neutron flux in the resonance energy region is only a small percentage of that of the thermal energy region of the short pulse neutron source at J-PARC. In the resonance neutron energy range, very fast imaging with high-speed video cameras or gated, intensified, and cooled CCD cameras requires more than 100k frame/s. With this high frame-rate, the *signal/noise* ratio at any time window becomes very low. In preliminary experiments using an image intensifier with a typical multiplying function of $10^4$ the obtained image at the resonance energy region was too dark to enhance the resonance elements, even if a few hundred images were accumulated. Furthermore, it is difficult to achieve a high pixel number in high frame-rate recording with existing

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http://dx.doi.org/10.1016/j.nima.2014.09.030
0168-9002/

high-speed video cameras. To obtain a resonance 3D image with high-speed video cameras, sufficient examination may be required to select samples adjusted for the reduced pixel numbers or a new type of high-speed camera, providing unchanged pixel numbers in high frame-rate recording.

Thus, to realize neutron energy-resolved 3D imaging in the resonance neutron energy region, a camera system coupled with a high-sensitivity image-intensifier with the capacity to amplify incident light by more than $10^5$ was developed. The system allows us to obtain a TOF image of 2352 (W) × 1726 (H) pixels resolved into a narrow neutron energy range in the resonance energy region with improved frame-rate gating and sensitivity. Using this system, resonance absorption 3D imaging techniques were demonstrated using the pulsed neutrons at J-PARC. 3D images with enhanced contrast at corresponding resonance energy regions for cylindrical Au, Ta, and In samples were obtained by FBP and MLEM, and the spatial resolution in the depth direction was evaluated.

This paper is organized as follows: Section 2 describes the present system at J-PARC and experimental details; the results are summarized in Section 3, and the conclusion is given in Section 4.

## 2. Experiments

### 2.1. Experimental setup

The present experimental system was developed at Beam Line 10 (NOBORU) at J-PARC [11,12]. The accelerator at J-PARC consists of a 180-MeV linear accelerator (linac), a 3-GeV rapid-cycling proton synchrotron (RCS), and a 50-GeV proton synchrotron. The linac will be able to accelerate up to 400 MeV in the future. These accelerators provided a proton beam at a frequency of 25 Hz to produce the spallation neutrons. The spallation neutrons were slowed to the thermal and cold energy region by a super-critical hydrogen moderator. The present experiments were performed at a proton beam power of 200 kW. Fig. 1 shows a schematic view of the present system set 13.7 m downstream from the neutron source. The system consists of a turntable, a neutron scintillator incorporating mixtures of $^{10}B_2O_3/ZnS$ powder, an optical macro-lens, an image intensifier (I.I.), an industrial CMOS camera, and a control computer. To protect the system from neutron irradiation, it was placed at 45° to the neutron beam line. The raw images obtained by the present system were vertically enlarged by a factor of $\sqrt{2}$ compared with the aspect ratio of original objects. If CT images were reconstructed using these raw images, this vertical enlargements hardly affect the three-dimensional spatial resolution in depth direction discussed in Section 3. The details of the instruments in the system are listed in Table 1.

The transmitted neutrons were converted to visible light by a neutron-to-fluorescence scintillator, where the intensity of the emitted light was proportional to the intensity of the entering neutron beam. The 0.3-mm $^{10}B_2O_3/ZnS$ scintillator was selected because it has a faster decay than that of $^6LiF/ZnS$ scintillators. The afterglow of lights emitted from the $^{10}B_2O_3/ZnS$ scintillator decreased exponentially and its decay time was approximately 10 μs at half maximum. In this experiment the time width of one frame was a few μs, which was narrower or almost equivalent to the time width ($\Delta T$) corresponding to the width of the resonance energy (Er), e.g., In (Er=1.5 eV, $\Delta T$=33 μs ), Au (Er=4.9 eV, $\Delta T$=18 μs), and Ta (Er=4.1 eV, $\Delta T$=18 μs) as shown in Fig. 2 discussed below. Thus, the decay time of the $^{10}B_2O_3/ZnS$ scintillator was sufficient to enhance resonance elements in the corresponding energy regions. This scintillator was made by Dr. Katagiri, J-PARC Center. After this experiment, the $^{10}B_2O_3/ZnS$ scintillator having similar characteristics was commercialized by Chichibu Fuji. Co., Ltd.

The industrial camera sensor comprised 2352 (W) × 1726 (H) pixels. The pixel resolution was 60 μm/pixel. The FOV was about 98 mm ∅ in diameter. The present system could visualize one TOF image per 40 ms neutron beam cycle. A high frame-rate gating type I.I., with amplification factor $4.7 \times 10^6$, allowed us to select the neutron energy with a narrow energy band width of a few μs. The time resolution of a high frame-rate gating type I.I. was 5 ns. Technically, the neutron energy resolution of the system was limitted by the time resolution. Fig. 2 shows the incident neutron TOF spectrum at NOBORU, together with the region visualized by the present system. The region corresponds to resonances of Au, Ta and In used as samples. The gate was triggered by a TTL signal synchronized with the proton bombarding timing. The width of the gate signal was equal to the exposure time. The images from the industrial camera were visualized by a frame grabber board within the control computer via two camera link cables. The data was continuously stored within the control computer. The neutron intensity data was caluculated by J-PARC Center assuming

**Table 1**
The model of instruments in the system.

| Instruments | Model |
|---|---|
| Image intensifier (I.I.) | C9547 (Hamamatsu Photonics K.K.)<br>Time resolution: 5 ns<br>Amplification factor: $4.7 \times 10^6$ $(l\,m/m^2)/lx$ |
| Industrial camera | A403k (Basler AG)<br>Resolution: 2352 × 1726 pixels<br>Sensor: Progressive Scan CMOS<br>Pixel size: 7 μm × 7 μm |
| Frame grabber board | Solios eV-CL (Matrox Electronic System Ltd.) |

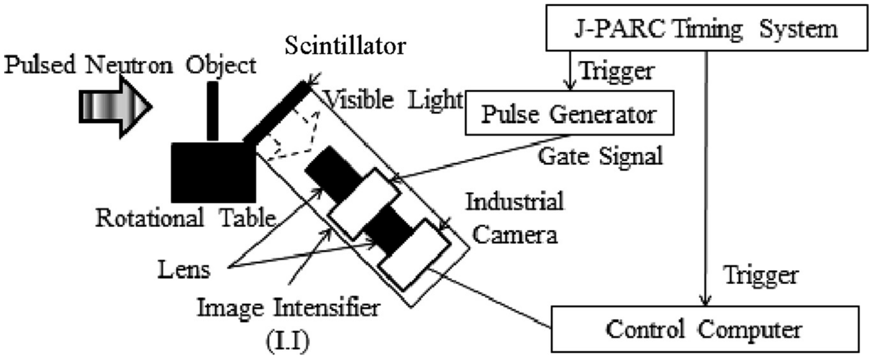

**Fig. 1.** Schematic view of the neutron beam and experimental setup at NOBORU. The present system was at a 45° angle to the beam and set 13.7 m downstream from the neutron moderator.