Final design of the Energy-Resolved Neutron Imaging System “RADEN” at J-PARC

T. Shinohara1, T. Kai1, K. Oikawa1, M. Segawa1, M. Harada1, T. Nakatani1, M. Ooi1, K. Aizawa1, H. Sato2, T. Kamiyama2, H. Yokota3, T. Sera4, K. Mochiki5, Y. Kiyanagi6

1J-PARC Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan
2Faculty of Engineering, Hokkaido University, Sapporo 060-8628, Japan
3Center for Advanced Photonics, RIKEN, Wako 351-0198, Japan
4Faculty of Engineering, Kyushu University, Fukuoka 819-0395, Japan
5Faculty of Engineering, Tokyo City University, Tokyo 319-1195, Japan
6Graduate School of Engineering, Nagoya University, Nagoya 464-8603, Japan

Abstract. A new pulsed-neutron instrument, named the Energy-Resolved Neutron Imaging System “RADEN”, has been constructed at the beam line of BL22 in the Materials and Life Science Experimental Facility (MLF) of J-PARC. The primary purpose of this instrument is to perform energy-resolved neutron imaging experiments through the effective utilization of the pulsed nature of the neutron beam, making this the world’s first instrument dedicated to pulsed neutron imaging experiments. RADEN was designed to cover a broad energy range: from cold neutrons with energy down to 1.05 meV (or wavelength up to 8.8 Å) with a good wavelength resolution of 0.20% to high-energy neutrons with energy of several tens keV (or wavelength of 10-3 Å). In addition, this instrument is intended to perform state-of-the-art neutron radiography and tomography experiments in Japan. Hence, a maximum beam size of 300 mm square and a high L/D value of up to 7500 are provided.

1. Introduction

Neutron imaging is a fundamental technique for visualizing the internal structure of objects and is regarded as an indispensable tool for non-destructive inspection, especially in the field of industry. Recently, a new neutron imaging technique, which utilizes neutron energy-dependent transmission, called “energy-resolved neutron imaging”, has become a very attractive technique because of its capability to not only visualize but also to quantify physical quantities and elemental distribution or composition with spatial resolution [1]. Therefore, this technique is expected to provide a chance for neutron imaging to develop into a new scientific method, one which is not a simple inspection of internal structure but a quantitative characterization of many properties inside objects with spatial resolution. Following recent development work, several energy-resolved imaging techniques have been successfully performed, i.e. Bragg-edge imaging for crystallographic information [2], resonance absorption imaging for elemental composition and thermal information [3], and polarized neutron imaging for magnetic field information [4]. For conducting these imaging experiments, a pulsed
neutron beam has several advantages, owing to its pulsed nature, as compared to a monochromatic neutron beam from a continuous source. For example, it is possible to measure energy dependent phenomena efficiently by means of the Time-of-Flight (TOF) method. Additionally, the energy or wavelength resolution is intrinsically fine in the case of the short-pulsed neutron source (better than 1%). Thus, a wide range of neutron energies, from epithermal to cold neutrons, is available simultaneously. Until now, the low intensity of pulsed neutron beams from low-power spallation neutron sources has been a limiting factor for the application of this imaging technique. However, the construction of MW-class spallation neutron sources at J-PARC and SNS has changed this situation.

In Japan, intensive technical development of pulsed neutron imaging has been done using the small accelerator-driven neutron source at Hokkaido University (HUNS) and the pulsed neutron facility (Materials and Life Science Experimental Facility, MLF) at J-PARC. Furthermore, in the Japanese pulsed neutron imaging project, a new beam line dedicated to pulsed neutron imaging, named "RADEN", has been proposed so as to bring the pulsed neutron imaging technique into the operational phase, and its construction was started from 2012 at beam line BL22 of the MLF. In addition to the main purpose of this instrument, namely, to perform energy-resolved neutron imaging experiments, it has a role as the state-of-the-art neutron imaging instrument in Japan with sufficient neutron flux, selectable L/D values up to several thousands, and monochromatic neutron imaging capability, achieving a performance comparable to the world's several-tens MW-class reactor sources. In this paper, we report the final design of the instrument and discuss the expected performance.

2. Beam line design

The requirements for the instrument, which have been discussed at the initial design stage in our previous report [5, 6], are briefly described here. The necessary performance for each energy-resolved neutron imaging technique was considered in terms of the wavelength resolution and the wavelength/energy coverage. On the other hand, for conventional neutron radiography and tomography experiments, other aspects, such as available beam flux, size and L/D value, which is directly coupled with the accessible spatial resolution, becomes important. A minimum wavelength resolution of 0.2% and high neutron energies up to several tens of keV are required for Bragg-edge and resonance absorption imaging techniques, respectively. In addition, because the availability of longer neutron wavelengths is preferable for conducting experiments using the neutron’s optical properties, the wavelength range was expanded to around 9 Å within the first frame. These requirements are achieved by viewing a decoupled moderator, which possesses the best balance in the performance of the pulse width and neutron intensity from among the three types of hydrogen moderators at the J-PARC MLF, and by setting two sample positions. At the near sample position, located at a distance of 18 m from the source, a high time-averaged beam flux of less than $9.8 \times 10^7$ n/sec/cm² and broad wavelength coverage are expected, while a large beam size up to 300 mm square and a fine wavelength resolution of 0.2% will be available at the far sample position at 23 m from the source.

The resulting beam line layout of RADEN is shown in Figure 1 and the expected parameters are summarized in Table 1.

![Figure 1. Layout of the RADEN instrument.](image-url)
Table 1. Basic parameters of RADEN.

|                         | Beam line | BL22 |
|-------------------------|-----------|------|
| Moderator type          | Supercritical hydrogen decoupled moderator |      |
| Sample position         | 18 m      | 23 m |
| Beam Size               | < 221 x 221 mm² | < 300 x 300 mm² |
| L/D ratio               | 180 ~ 5000 | 230 ~ 7500 |
| Wavelength resolution (cold) | 0.26% | 0.20% |
| Energy resolution (epithermal) | 1.6% | 1.2% |
| Longest wavelength (first frame) | 8.8 Å | 6.9 Å |

Figure 2. Typical calculation result of the dose rate using PHITS code. The sum of neutron and gamma ray doses is shown.

2.1. Shielding design
To conduct neutron imaging experiments, the capability to accommodate large objects and sufficient flexibility in the experimental arrangement are quite important. Therefore, the shielding should be designed as thin as possible to provide a wide experimental area. However, as RADEN utilizes the biggest beam and sample size in the MLF along with high-energy neutrons, massive shielding is necessary to attenuate the radiation efficiently. To design and optimize the shielding structure, we have performed dose rate calculations and evaluated the performance using PHITS code [7] (Figure 2). As a result, it was decided to use a shielding wall consisting of 4 layers, i.e., from the inside out, boron-included mortar, polyethylene, steel and concrete. Moreover, because the neutron imaging detectors are placed directly in the beam line, scattered neutrons and radiated gamma rays from the beam stop directly irradiate the detectors from the rear and cause a huge background. To suppress such background, the beam stop was placed as far as possible from the detector position. Finally, two heavy doors, which are driven electrically, are used to intercept the radiation at the gateway to the experimental area. While most of the other instruments at the MLF adopt a labyrinth structure with a light, unshielded door, the unique two-door configuration for RADEN was chosen to provide good accessibility to the experimental area.

2.2. Optical devices
Upstream of the experimental area, several optical devices are installed as shown in Figure 3. The optical devices of RADEN are divided into two groups: the beam collimation and shaping device group and the energy selection device group. The beam collimation and shaping device group is composed of a heavy shutter, rotary collimators and slits. In addition, a light shutter, referred to as a blocker, is included to suppress undesired sample activation. To enlarge the beam size at the sample position, an aperture must be placed as close as possible to the source. Thus, a heavy shutter containing three collimator insertion devices, with hole sizes 100 mm x 100 mm, 50 mm-φ and 26 mm-φ, was installed near the source [8]. Using these collimators, beam sizes ranging from 100 x 100 mm² to 300 x 300 mm² will be achieved at the far sample position (23 m from the neutron source), with the smallest L/D value producing the highest neutron flux. Inside the forward section of the shielding, two rotary collimators with four aperture slots are installed. The upstream rotary collimator uses small apertures to make higher L/D values for experiments requiring high spatial resolution, while the downstream one is used to limit the beam size as adequate for a given sample size. Because RADEN uses high-energy neutrons with energies over 1 keV, these collimators are made of thick steel and polyethylene and have an artifice on the inner wall to reduce neutron reflection.

The energy selection device group is composed of filters, a low-speed double disk chopper and a T0 chopper. Five kinds of filters, namely, Bi (25 mm, 25mm, 50 mm thicknesses), Pb (25 mm, 50 mm thicknesses), Cd (1 mm thickness), acrylic resin (5 mm thickness), and borosilicate glass (2 mm thickness), are placed upstream of the first rotary collimator and can be remotely moved in or out of the beam depending on experimental requirements. The Bi and Pb filters are used for gamma ray attenuation, especially in the case of resonance absorption imaging experiments, for which the T0 chopper is stopped to allow access to the high-energy neutron range. The Cd filter is also used in resonance absorption experiments to cut thermal and cold neutrons. The acrylic resin and borosilicate glass are used for neutron intensity attenuation. The double disk chopper, which can be operated at 25 Hz and 12.5 Hz, defines the available wavelength range in one frame. Changing the opening angle by adjusting the delay of each disk enables us to fine-tune the bandwidth at the different sample positions. Additionally, a quasi-monochromatic neutron beam with a wavelength resolution of around 10% can be provided when the opening angle is adjusted to its smallest value. The T0 chopper is installed to eliminate the prompt neutron pulse and flash gamma rays produced at the instant of neutron generation. This chopper has one heavy hammer made of Inconel alloy, whose rotation is synchronized with the accelerator, only bringing the hammer into the beam at T = 0. By means of the T0 chopper, the neutron background caused by fast neutrons is decreased effectively, and the shortest neutron wavelength accessible becomes 0.43 Å (or an energy of 0.44 eV).

![Figure 3. Arrangement of optical devices located upstream of the experimental area.](image)

2.3. Sample environment
Inside the experimental area, several stages are installed for sample mounting and detector positioning. Also, exchangers for optional equipment are provided (Figure 4). Three sample stages are provided for mounting and positioning samples, and their topmost movable axis is rotational to easily allow for
computed tomography (CT) measurements. The basic specifications of each sample stage are shown in Table 2. The stages are controlled remotely from outside of the shielding using device control software. The top table of each stage conforms to the MLF standard for sample environments so as to facilitate the mounting of various devices such as cryostats, electromagnets, furnaces, etc. A large sample stage placed at a distance of 23 m from the neutron source can be equipped with mechanical test devices developed at the engineering materials diffractometer TAKUMI [9] for use in Bragg-edge imaging experiments. A medium sample stage sits on the optical bench located at the near sample position. When the medium sample stage is removed, optical tables for polarized neutron experiments or other experiments using special devices can be slid into the beam path by an automated exchanger. Finally, a small rotation stage for CT measurements can be placed on top of the large and medium sample stages.

Flight tubes, which are filled with He gas and whose inner walls are covered with a neutron absorber, are placed in the gaps of the beam line to suppress neutron beam attenuation due to scattering in air. Additionally, a lift located upstream of the near sample position is used to exchange the flight tube with equipment for polarization analysis. With this lift, we can easily switch the setup from an unpolarized to a polarized neutron beam.

Optionally, RADEN can be equipped with an apparatus for neutron diffraction measurements consisting of $^3$He position sensitive detector tubes and a Soller collimator (complementary to Bragg-edge imaging) and with a gamma ray detector to provide precise analysis for resonance absorption.

![Figure 4. Arrangement of stages and exchangers in the experimental area.](image)

**Table 2. Specifications of the sample stages.**

| Stage  | Position | Movable axis  | Max. load | Table size                      |
|--------|----------|---------------|-----------|---------------------------------|
|        |          | $\theta$    | $X, Y, Z$ | $R_x, R_y$ | $R_z$ | 1.0 ton | 700 mm-$\phi$ / 750 mm x 750 mm |
| Large  | L=23m    | $\pm 173^\circ$ | $\pm 300$ mm | - | 1.0 ton | 700 mm-$\phi$ / 750 mm x 750 mm |
| Medium | L=18m    | $\pm 175^\circ$ | $\pm 100$ mm | $\pm 5^\circ$ | 600 kg | 300 mm-$\phi$ / 750 mm-$\phi$ |
| Small  | Portable | $360^\circ$ | - | $\pm 5^\circ$ | 10 kg | 150 mm-$\phi$ |

### 2.4. Detectors

To conduct energy-resolved neutron imaging using pulsed neutrons, precise TOF information is essential, requiring neutron detectors with fine time resolution. Counting-type imaging detectors are promising, owing to their sub-microsecond time resolution, while their spatial resolution is relatively coarse. Of these detectors, we selected three candidates for RADEN: the $\mu$NID detector [10], the GEM detector [11] and a pixel detector composed of an array of small rectangular Li-glass scintillators coupled to a multi-anode photomultiplier. On the other hand, for conventional neutron imaging, fine
spatial resolution is desirable. Hence, a cooled CCD camera system with a thin $^6\text{LiF/ZnS}$ scintillator screen and a CMOS camera combined with a neutron image intensifier are prepared in conjunction with the counting-type detectors.

3. Conclusion

Construction of the Energy-Resolved Neutron Imaging System RADEN began from 2012 at beam line BL22 of the J-PARC MLF. Because this system is designed to fully utilize the short-pulsed neutron beam of the MLF, all types of energy-resolved neutron imaging experiments can be carried out with fine energy resolution. RADEN also has an important role as the state-of-the-art neutron radiography and tomography instrument in Japan. Therefore, RADEN was designed with the flexibility to satisfy the requirements for both of these imaging techniques. After completion of the construction phase, the first neutron beam was delivered to this beam line in November 2014, and following an initial commissioning study, RADEN began to accept user programs from April 2015.

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