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Construction of the energy-resolved neutron imaging system "RADEN" in J-PARC MLF

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Abstract. Construction of the Energy-Resolved Neutron Imaging System (RADEN) has started in 2012 at the beam line of BL22 in the Materials & Life Science Experimental Facility (MLF) of J-PARC. This is the first instrument dedicated to the pulsed neutron imaging experiments in the world. The primary purpose of this instrument is to perform the energy-resolved neutron imaging experiments effectively utilizing the pulsed neutron nature. Therefore, this instrument is designed to cover a broad energy range at the same time: not only cold neutrons up to 8.8 Å with a good wavelength resolution of 0.20% but also high energy neutrons with the energy of several tens keV. In addition, this instrument is intended to perform a state-of-the-art neutron radiography and tomography experiments in Japan. Hence, the maximum beam size of 300 mm square, and the highest L/D value of 7500 are provided.

1. Introduction

Neutron imaging is a very fundamental technique to visualize the internal structure of objects, and is regarded as an indispensable 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", becomes a very attractive technique because of its capability not only to visualize but also to quantify the physical or chemical quantities with spatial resolution [1]. Therefore, this technique is expected to provide a chance for the neutron imaging to develop into a new scientific method, which is not a simple inspection of intra-structure of objects but a characterization of many properties inside objects with spatial resolution. Owing to recent developments, several imaging techniques regarding it are 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]. Conducting these imaging experiments, usage of the pulsed neutron beam brings several advantages due to its pulsed nature compared to those using monochromatic neutron beam from continuous sources. For example, at first, it is possible to measure the energy dependent phenomena efficiently by means of Time-of-Flight (TOF) method. Second, energy or wavelength resolution is intrinsically fine in the case of using the short-pulsed neutron source, which is better than 1 %. Then, wide energy range neutrons from epithermal to cold neutrons are available simultaneously. So far, the low intensity of pulsed neutron beam from the low-power spallation neutron sources has set a limitation to the application of this imaging technique. However the construction of MW-class spallation neutron sources at J-PARC and SNS makes a change of such situation.

In Japan, technical developments of the pulsed neutron imaging have been intensively done using small accelerator driven neutron source at Hokkaido University (HUNS) and the pulsed neutron facility (Materials and Life science experimental Facility, MLF) in J-PARC. And also, in the Japanese pulsed neutron imaging project, a new beam line dedicated to the pulsed neutron imaging, named "RADEN" has proposed so as to make the pulsed neutron imaging technique operational phase, and its construction has started from 2012 at the beam line of BL22 of MLF. The main purpose of this instrument is, of course, fully performing the energy-resolved neutron imaging experiments by effectively utilizing the pulsed neutron's nature as a pioneering facility for the pulsed neutron imaging. In addition, it also has a role for 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, which has a comparable performance with those at 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

At first, we mention the requirements for the instrument, which has been discussed as the initial stage of the instrument design in our previous report [5, 6]. 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, concerning the conventional neutron radiography and tomography experiments, another aspect, such as available beam flux, size and L/D value, which is directly coupled with the accessible spatial resolution, becomes important. Then, the minimum wavelength resolution of 0.2% and high energy neutrons with the energy of up to several tens of keV were settled based on the requirements from Bragg-edge and resonance absorption imaging techniques. In addition, because availability of longer wavelength neutrons is preferable to conduct experiments using neutron's optical properties, wavelength range was expanded into around 9 Å within the first frame. These requirements is achieved by viewing a decoupled moderator which possesses balanced performance of the pulse width and the neutron intensity as well among three types of hydrogen moderators of J-PARC MLF, and by setting two sample positions. At the near sample position located at the distance of 18 m from the source, a high time averaged beam flux less than 9.8×10^7 n/sec/cm^2 and coverage of a broad wavelength range are expected, while a large beam size up to 300 mm square and fine wavelength resolution of 0.2% are done at the far sample position of 23 m.

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

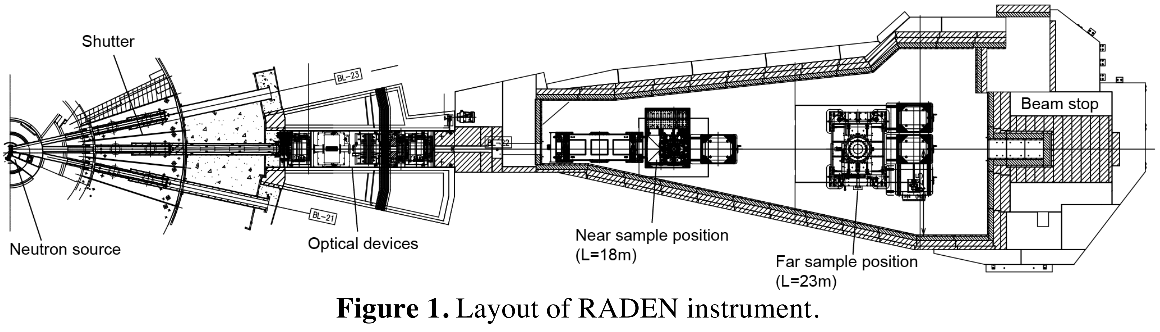

Figure 1. Layout of RADEN instrument.

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 mm^2	< 300 x 300 mm^2
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

2.1 Shielding design

At first, the shielding is one of the essential components of this instrument. To conduct neutron imaging experiments, handling large objects and arranging the experimental setup freely are quite important. Therefore, designing the shielding as thin as possible is quite important to secure a wide experimental area. However, as RADEN utilizes most biggest beam and sample size in the MLF and high-energy neutrons, massive shield is necessary to attenuate radiation outside of the shielding efficiently. To design and optimize the shielding structure, we have performed dose rate calculation and evaluated its performance using PHITS code [7] (Figure 2). As the results, the shielding wall was decided to consist of 4 layers, i.e., boron included mortar, polyethylene, steel and concrete from the inside. Moreover, because the neutron imaging detectors are put in the direct beam line, scattered neutrons and radiated gamma ray from the beam stop directly irradiate 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. Two heavy doors, which are driven electrically, are used to intercept the radiation at the gateway, while most of the instruments adopt a labyrinth structure with a light door without any shielding performance. This is because accessibility to the experimental area takes precedence for RADEN.

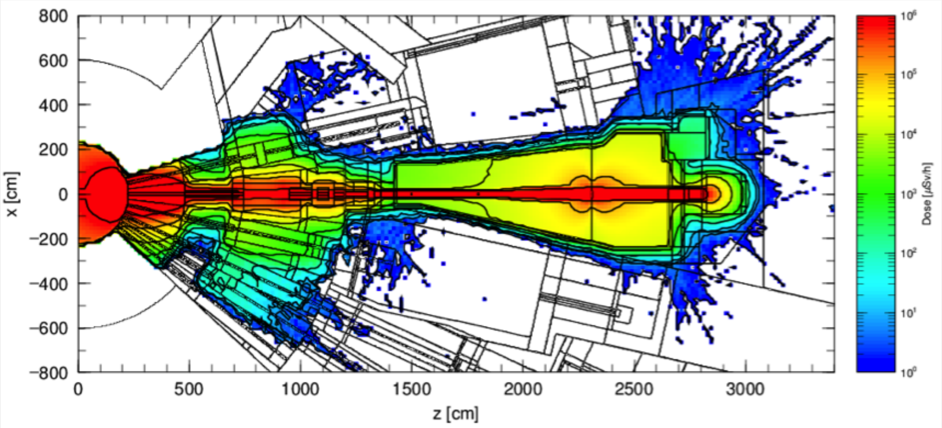

Figure 2. Typical calculation result of the dose rate using PHITS code. The sum of neutron and gamma ray doses is shown.

2.2 Optical devices

In the 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. One is beam collimation and shaping device group and another is energy selection device one. The former group is composed of a shutter, rotary collimators and slits. In addition, this beam line is equipped with a light shutter, named blocker, to suppress undesired sample activation. To make the beam size at the sample position enlarged, an aperture is needed to be placed as close as possible to the source. Then, the existing heavy shutter was replaced into new one with three collimator insertion devices, whose hole sizes are 100 mm x 100 mm, 50 mm- ϕ and 26 mm-ϕ. Using these collimators, beam size ranging from 100 x 100 mm^2 to 300 x 300 mm^2 will be achieved at the far sample position (23 m away from the neutron source), and the smallest L/D value producing highest neutron flux is provided. Inside the preposition shield, two rotary collimators with 4 aperture slots are installed (Figure 4 (a)). The front rotary collimator is used to make higher L/D value for high spatial resolution experiments by small apertures, and the rear one is to limit the beam size as adequate to the object size. Because RADEN uses high energy neutrons with the energy of over keV, these collimators are made of thick steel and polyethylene and have an artifice to reduce neutron reflection at the inner wall of them.

The latter optics group is composed of filters, a double disk low-speed chopper and a T0 chopper (Figure 4 (b), (c)). Five kinds of filters, that is, Bi (25 mm, 25mm, 50 mm), Pb (25 mm, 50 mm), Cd (1 mm), acrylic resin (5 mm), and borosilicate glass (2 mm), are placed in front of the first rotary collimator. Bi and Pb filters are used for gamma ray attenuation especially in the case of resonance absorption imaging experiment, at which the T0 chopper is stopped to access high energy range. Cd filter is also used in resonance absorption experiments to cut off thermal and cold neutrons. The acrylic resin and the borosilicate glass are for neutron intensity attenuation. The double disk chopper, which can be operated in 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 properly enable us to suit the bandwidth at different sample position. The quasi-monochromatic neutron beam with the wavelength resolution of around 10% can be served when the opening angle is adjusted to smallest value. The T0 chopper is installed to eliminate the prompt neutron pulse and flush gamma ray produced at the instance of neutron generation. This chopper has one heavy hammer made of Inconel alloy, which rotates synchronized with the accelerator, and the hammer only comes in the beam at T = 0. By means of the T0 chopper, the neutron background caused by the fast neutrons decreases effectively.

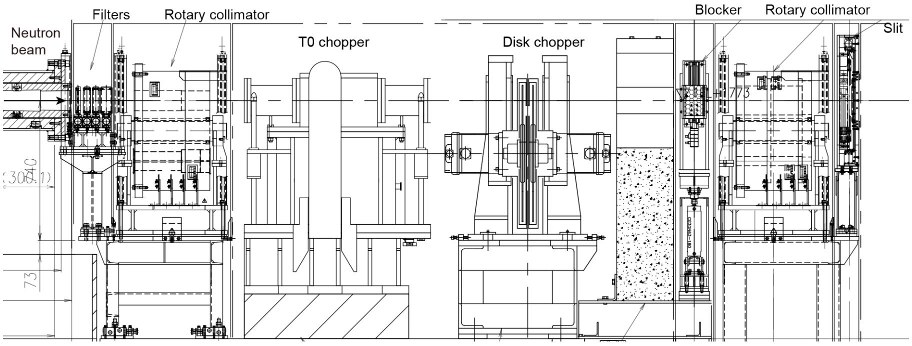

Figure 3. Arrangement of optical devices for beam shaping inside the preposition shield.

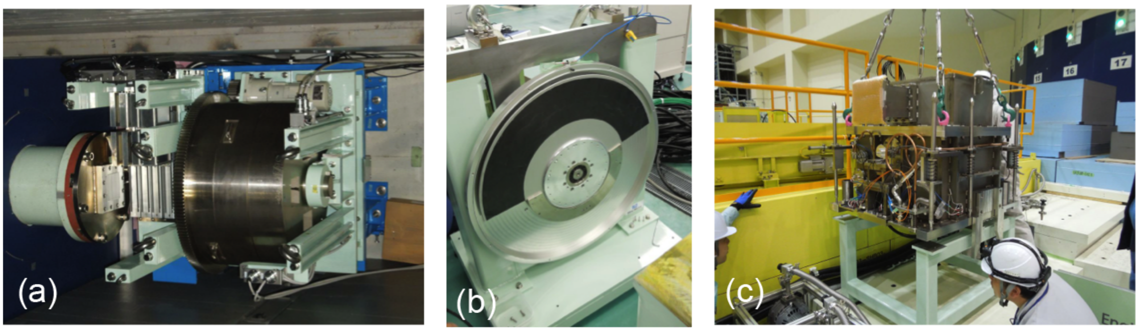

Figure 4. Photographs of some optical devices. (a) Rotary collimator, (b) Disk chopper, and (c) T0 chopper.

2.3 Sample environment

Inside the measurement area, there installed some stages for sample mounting and detector. And also, exchangers for optional equipment are settled (Figure 5). Three sample stages are prepared for mounting and positioning the sample, and their topmost movable axis are rotational considering the computerized tomography experiment. Basic specifications of each sample stages are shown in table 2. They are remotely controlled from outside of the shielding using the device control software. The top table of each stage conforms to the MLF standard for sample environment so as to mount various devices such as a cryostat, an electromagnet, a furnace, and so on. Especially the large sample stage placed at the distance of 23 m from the neutron source is designed to equip with mechanical test devices developed at the engineering materials diffractometer TAKUMI [8] for Bragg edge imaging experiments.

The medium sample stage sits on the optical bench located at the near sample position. When the medium sample stage is removed, optical tables for the polarized neutron experiment or other experiments using special devices can be slide into the beam position by an automated exchanger. The small rotation stage for CT measurements is available by putting on the top of those sample stages. Flight tubes, which are filled with He gas and inner walls are covered with neutron absorber, are placed in the gap of beam line to suppress the possible neutron beam attenuation due to the air scattering. In front of the near sample position, there is a lift to exchange the flight tube and the equipment for the polarization analysis. With this lift, we can easily switch the setup from the unpolarized neutron beam to the polarized one.

Optionally RADEN is equipped with the apparatuses for neutron diffraction measurements composed of ^{3}He position sensitive detector tubes and a soller collimator complementary to the Bragg edge imaging and for gamma ray detector to support precise analysis of the resonance absorption.

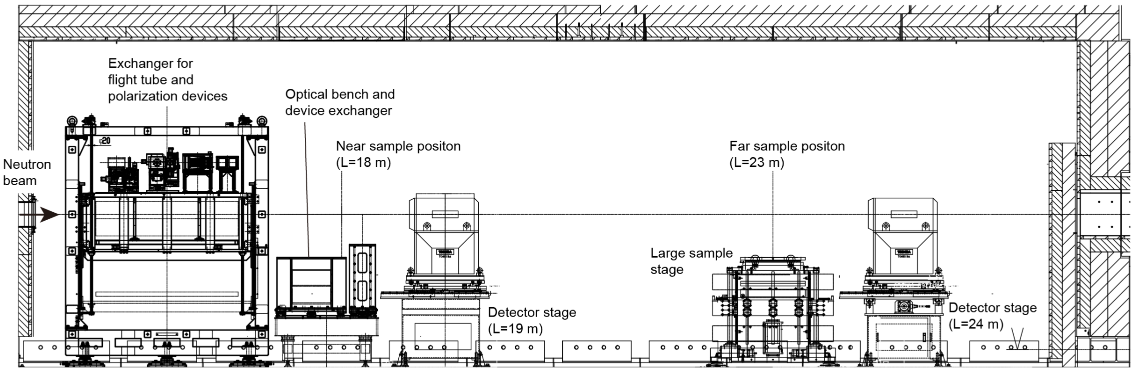

Figure 5. Arrangement of stages and exchangers in the measurement area.

Table 2. Specifications of sample stages.

Stage	Position	Movable axis			Max. load	Table size
		θ	X, Y, Z	R_X, R_Y		
Large	L=23m	±173°	±300 mm	-	1.0 ton	700 mm-ϕ / 750 mm x 750 mm
Medium	L=18m	±175°	±100 mm	±5 °	600 kg	300 mm-ϕ / 700 mm-ϕ
Small	Portable	360°	-	±5 °	10 kg	150 mm-ϕ

2.4 Detectors

To conduct the energy resolved neutron imaging using pulsed neutrons, precise TOF information is essential and the neutron detectors required to have fine time resolution. The counting type imaging detector is promising owing to their sub micro second time resolution while their spatial resolution is relatively course. Then, we selected three candidates, that is, μNID detector [9], GEM detector [10] and pixel detector composed of pieces of small Li glass scintillators and a multi-anode photo multiplier. On the other hand, regarding the conventional neutron imaging fine spatial resolution is desirable. Hence, a cooled CCD camera system with a ^{6}LiF/ZnS scintillator screen and a CMOS camera combined with neutron image intensifier are prepared together with the counting type detectors.

3. Conclusion

We have been constructing the energy-resolved neutron imaging system RADEN from 2012 at the beam line of BL22 in J-PARC MLF. Because this is designed to utilize the good nature of the short-pulsed neutron beam, every energy-resolved neutron imaging experiment becomes possible with fine energy resolution. And also it has an important role as the state-of-the-art neutron radiography and tomography instrument in Japan. It was designed to satisfy the requirements from both of these imaging techniques and several devices have been installed. In Nov. 2014, the first neutron beam was delivered to this beam line and the commissioning study started after that. We are going to start user programs from 2015.

Acknowledgement

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