

Development of a compact vertical splitting system for the cold neutron beam at JRR-3

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Abstract. In order to efficiently execute neutron beam experiments at JRR-3, the number of beam ports was increased and neutron beam instruments were rearranged in the C2 cold neutron beam line by using a newly developed compact vertical splitting system. Considering the space available for instruments at the downstream region of the cold neutron beam line, the deflection angles of the compact vertical splitting system were set as 10° and 20°. To branch off the cold neutron beam, a bender with characteristic wavelength of 4 Å was developed using Ni/Ti supermirrors coated on both sides of 0.2-mm-thickness silicon substrates. The channel width of the bender is 0.2 mm. The radius of curvature of the compact bender is 938 mm and the lengths of the benders are 160mm and 320 mm, yielding deflection angles of 10° and 20°, respectively. Neutron flux at the end of the neutron guide installed at the bender exit, the deflection angle of which is 20°, was measured to be 1.58×10^7 n·cm⁻²·s⁻¹ with a gold foil activation method. We found that the measured flux agrees with the simulated value.

1. Introduction

The Japan Research Reactor 3 (JRR-3) at the Japan Energy Atomic Agency (JAEA) was designed as a multipurpose reactor for the use of neutron beam experiments and material irradiation tests in various fields of basic research and industrial applications. In order to efficiently supply thermal and cold neutron beams, five neutron guides were installed in the beam hall at JRR-3. The two thermal neutron guides are about 60 m long and the three cold neutron guides are 31-51 m long. The characteristic wavelengths of the cold neutron guides C1, C2 and C3 are 4Å, 4Å and 6Å, respectively. Neutron guides are used to simultaneously supply many instruments with intense neutron beams.

There are great demands for a white neutron beam. The Neutron Spin Echo (NSE) spectrometer was installed at branch port C2-2 by deflecting a monochromatic beam using a multilayer mirror. Great benefits are expected if the NSE is relocated to the end of the C2 guide, because white neutrons increase the incident neutron flux and the large space expands the Q region by increasing the detector area [1]. However, instruments such as the Cold Neutron Radiography Facility (CNRF) [2] and

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Prompt Gamma Activation Analysis (PGAA) [3] are not permanent installations and therefore share the beam time at the end of the cold neutron beam line (C2-3) with only one or two cycles available per year. Thus, in order to construct new white neutron beam ports, a splitting system has been developed using the neutron benders.

Beam line splitting devices

Devices have been introduced in some experimental facilities [4-12]. These devices deflect a neutron beam using a bender, which can be used as not only a branching device but also a wavelength filter [13]. It is common to install these splitting devices close to the neutron source. Splitting devices using the conventional benders can bend the neutron beam by several degrees with a radius of curvature of at least tens of meters. They require a large space to install.

Benders with smaller curvature have also been developed [14, 15]. The production of compact benders with a radius of curvature one-tenth of a conventional device allows relocating instruments to the cold neutron beam hall at JRR-3 because the length of the bender can be shortened.

Since the beam path of the compact multichannel bender is short, it can improve the transmissivity of a neutron by using the silicon substrates for bender mirrors. We carried out simulation calculations that take into account the absorption of the silicon substrate in the bender.

In this paper, we describe the experiments performed to characterize the neutron spectrum and flux and examine the performance of the compact vertical splitting system by using McStas simulation code [16, 17].

2. Design and fabrication of the compact neutron splitting system

The compact vertical splitting system consists of neutron guide tubes and two compact benders as shown in Figure 1. The design specifications of the compact benders are described below. The compact bender is a multichannel micro-bender fabricated with a characteristic wavelength of 4 Å. The channels of a multichannel micro-bender function as curved neutron guides.

The design of the micro-bender is based on the neutron optics as follows. The critical angle for total reflection at a supermirror is defined as

$$\theta_c = \lambda \times m \times \gamma_c^{\text{Ni}},$$

where λ denotes the wavelength of the neutron, γ_c^{Ni} denotes the critical angle of nickel per unit wavelength ($\sim 1.7 \times 10^{-3}$ rad/Å) and m denotes the relative ratio of the critical angle of total reflection of the supermirror to that of natural nickel [18].

The characteristic wavelength λ^* of the bender is a function of the radius of curvature ρ , and the width d of each channel in the bender, and it is defined as

$$\lambda^* = \frac{1}{m \times \gamma_c^{\text{Ni}}} \left(\frac{2d}{\rho} \right)^{1/2}.$$

These supermirrors are stacked with a spacing of 0.2 mm on a pair of curved iron walls as shown in Figure 1. The compact bender yielding deflection angle of 10° consists of a stack of 47 pairs of curved NiC/Ti supermirrors deposited on both sides of silicon-wafer substrates of 0.2 mm thickness. The radius of curvature of the compact bender is 938 mm and the lengths of the benders are 160 mm yielding deflection angles of 10°. In order to fabricate the bender yielding deflection angle of 20°, the two benders, which yield deflection angle of 10°, were arranged in tandem along a neutron beam travelling direction. For such arrangement, the length of the benders yielding deflection angles of 20° become 320 mm.

NiC/Ti supermirrors are fabricated with 403 layers deposited by ion beam sputtering [19] onto silicon substrates with a roughness less than 3 Å r.m.s.. We have fabricated 144 pieces of NiC/Ti neutron supermirrors deposited on the both sides of silicon substrate with $m = 3.0$. The silicon substrate is 40 mm wide, 160 mm long and 0.2 mm thick. Since the substrate is not very thick, the supermirror can be bent to some degree along the curved frame.

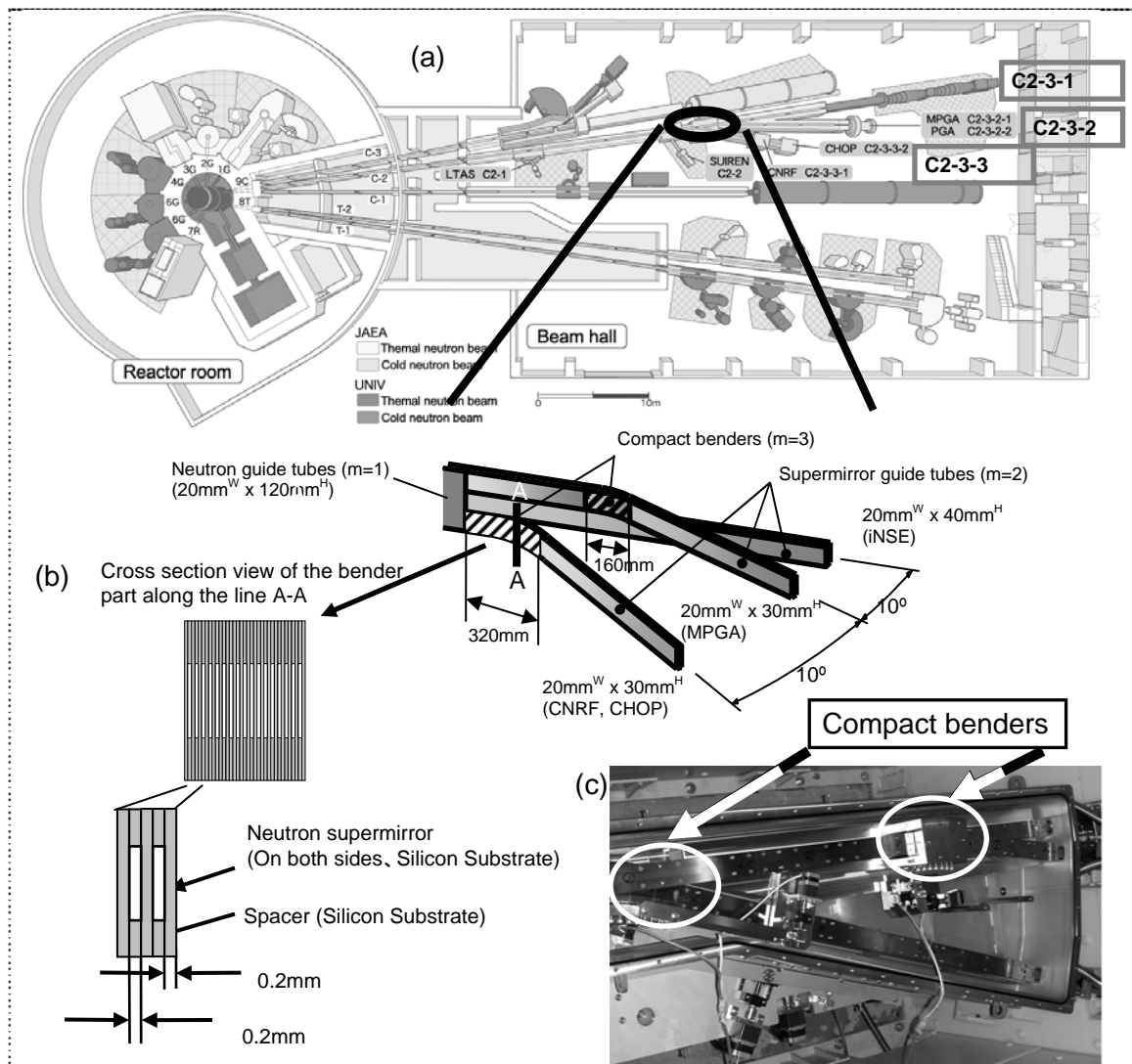


Figure 1. (a) Layout of the instrument and compact vertical splitting system at JRR-3. (b) Cross section view of the compact bender along the line A-A; these supermirrors are stacked with a spacing of 0.2 mm on a pair of curved iron walls. The photograph (c) shows the compact vertical splitting system. Two compact benders and neutron guide tubes are in the vacuum tank.

Figure 2 shows the reflectivity of the supermirror measured using the reflectometer SUIREN [20] at JRR-3. The neutron reflectivity of the front and back surfaces of the supermirrors in the compact bender is 90% at $m = 3$. These data are used in the simulations for evaluating the compact vertical splitting system.

3. Evaluation of the bender

To characterize the neutron beam, the spatial distribution of the neutron beam intensity after branching by the bender was measured using a neutron image plate as the detector. The plate was placed at the CNRF sample position, which is 150 mm downstream from the C2-3-3 beam port. In this position, the neutron beam size was 20 mm in width and 30 mm in height. The distance between the compact bender exit and neutron image plate is 3960 mm. The measured neutron intensity distribution at CNRF

sample position is shown in Figure 3. The distribution of intensity is spatially uniform indicating that the arrangement of bender mirror was successful.

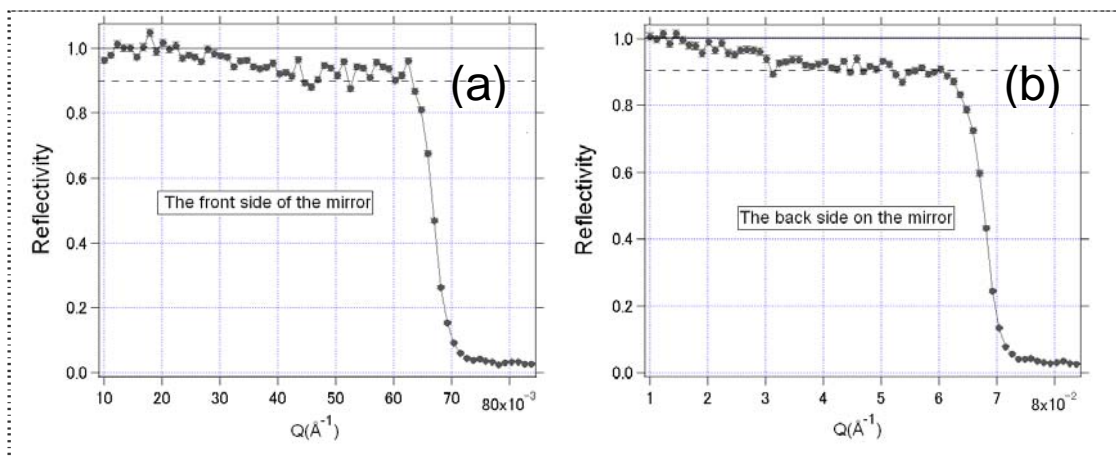


Figure 2. Front surface (a) and back surface (b) reflectivity of a neutron supermirror.

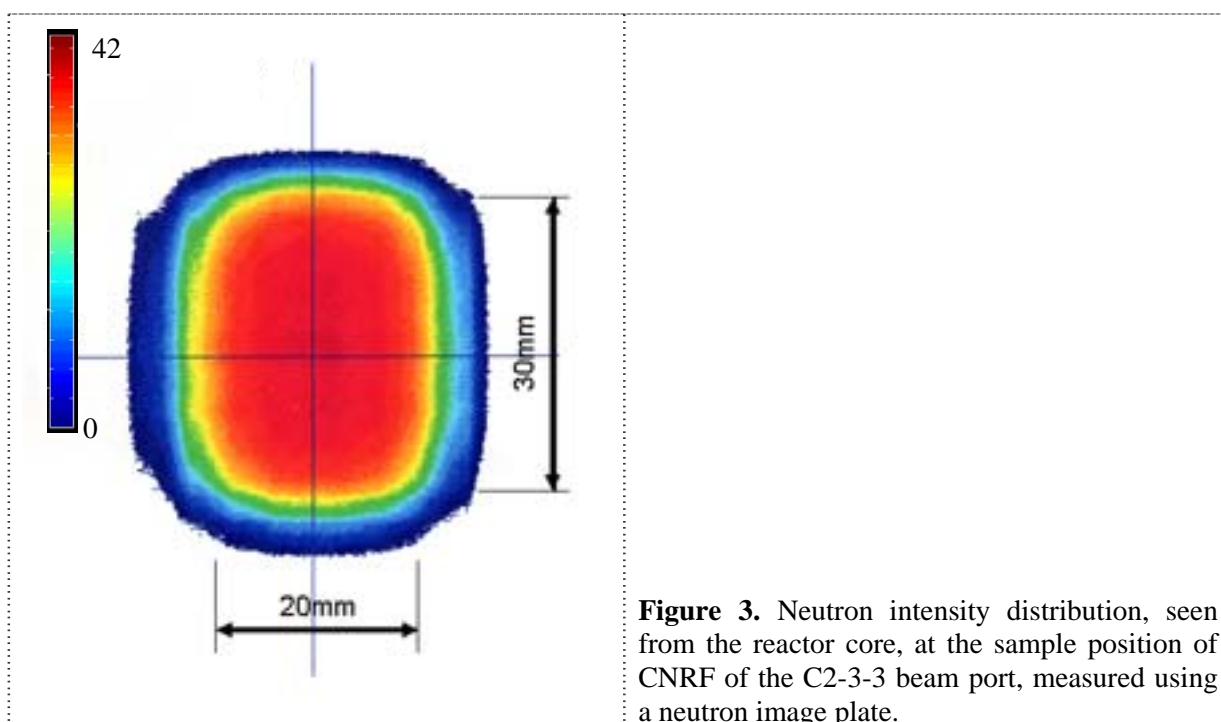
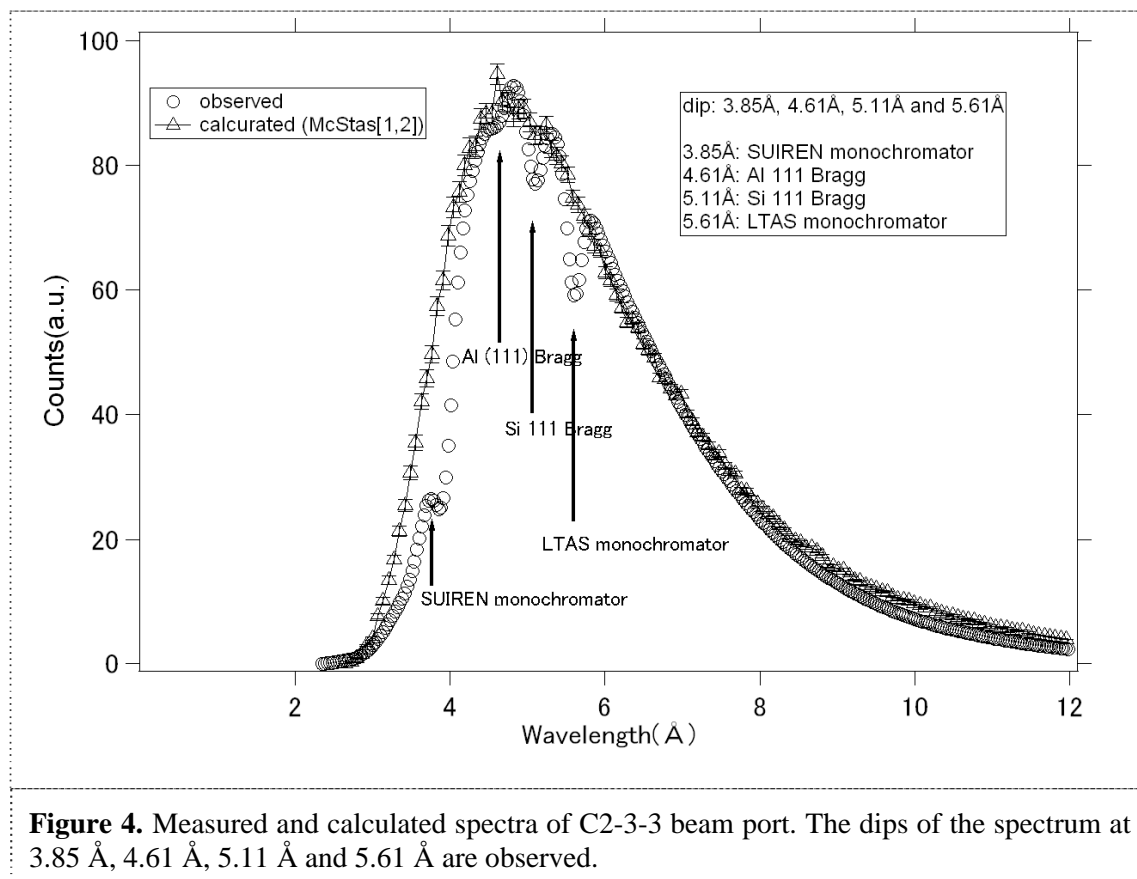


Figure 3. Neutron intensity distribution, seen from the reactor core, at the sample position of CNRF of the C2-3-3 beam port, measured using a neutron image plate.

The neutron spectrum transmitted through the bender was measured using a CHOP (chopper spectrometer) at the cold guide tube. The neutron spectra were measured at the C2-3-3 beam port with the time-of-flight method. A beam collimator in the chopper spectrometer at the neutron guides exit made the neutron beam size of 10 mm in width and 10 mm in height. The neutron chopper has a single slit of 10 mm width and its disk diameter is 700 mm. The chopper rotational speed was 5,000 rpm. The bin width of the multi-channel scale was 1.0×10^{-5} seconds. The flight path between the chopper and the neutron detector was 1.75 m at C2-3-3. The time resolution for 4 \AA neutrons is 1.5%. The reactor power was 20MW.

Figure 4 shows the spectrum of transmitted neutrons and the results of the Monte Carlo simulation for the neutron spectrum. The simulation was executed with the same conditions as the measurements. Open circles and open triangles show the measured spectra and the spectra calculated using McStas code, respectively. In this calculation, Maxwellian energy/wavelength spectrum was chosen for the incident neutron source.

Figure 4 shows that the characteristic wavelength of C2-3-3 beam port is 4.8 Å. The neutron spectra are measured and calculated at the detector position of the chopper spectrometer. Measured spectra were scaled for easier comparison. The dips of the spectrum at 3.85 Å, 4.61 Å, 5.11 Å and 5.61 Å are ascribed to the Bragg reflections of the SUIREN monochromator installed at C2-2, polycrystal Al with index 111, single crystal Si with index 111, and the LTAS (Low energy Triple-Axis Spectrometer) monochromator installed at C2-1, respectively. The agreement between the measured dips and the monochromator angles shows the propriety of our measurement. The measured spectrum almost agrees with the simulated spectrum. This indicates that the compact vertical splitting system achieves the expected performance.



Neutron fluxes at the C2-1, C2-2, C2-3-1, C2-3-2, and C2-3-3 beam ports were measured by the gold foil activation method at a reactor power of 20 MW. The gold foil was of area 5 mm² and thickness 0.05 mm and the irradiation time was 60 minutes.

Because the neutron absorption cross section of gold depends on the neutron energy, the neutron fluxes were obtained using absorption cross sections averaged over the neutron spectra calculated using McStas at the measuring positions. The measured cold neutron fluxes at each beam port are listed in Table 1. Neutron fluxes integrated over energy were measured. The difference in the measured and calculated ratio fluxes is within 15%.

Table 1. Neutron fluxes at C2-1, C2-2, C2-3-1, C2-3-2, and C2-3-3 beam port (calc. & obs.) The ratio of measured fluxes is in good agreement with that of calculation results.

Beam port	Measured neutron flux (n/cm ² /s)	Ratio (measured)	Ratio(calculated)
C2-1	2.66×10^8	1	1
C2-2	1.47×10^8	0.553	0.630
C2-3-1	9.56×10^7	0.359	0.423
C2-3-2	3.13×10^7	0.118	0.130
C2-3-3	1.58×10^7	0.0594	0.0622

4. Conclusion

To meet the demand for a white neutron beam, we have developed a compact splitting system. This has enabled relocating the NSE spectrometer to the guide end, where white neutrons increased the incident neutron flux, and the large space expanded the Q region by increasing the detector area. Furthermore, the CNRF and PGAA instruments became permanent installations.

We evaluated the performance of the compact splitting system through measurements and simulation. The compact splitting system consists of a straight guide tube and two compact multi channel benders. The deflection angles of the compact benders with the same radius of curvature were set as 10° and 20°.

NiC/Ti supermirrors with $m=3$ were deposited on both sides of a silicon substrate by an ion beam sputtering apparatus in JAEA to fabricate the compact bender. The neutron reflectivity of the fabricated supermirrors is 90% at $m = 3$.

Neutron fluxes at the C2-3-1, C2-3-2, and C2-3-3 ports were measured to be 9.56×10^7 n·cm⁻²·s⁻¹, 3.13×10^7 n·cm⁻²·s⁻¹ and 1.58×10^7 n·cm⁻²·s⁻¹, respectively. The neutron spectra were measured at the C2-3-3 beam port by the time-of-flight method and a characteristic wavelength of 4.8 Å was found for the C2-3-3 beam port.

We examined the performance of the compact splitting system with a Monte Carlo simulation. The agreement between the calculation and the experimental measurements is good. Therefore, we succeeded in achieving the desired design performance of the compact splitting system.

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