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Development of Carbon Neutron Mirror for High Irradiation Field

Yuji KAWABATA, Masahiro HINO, Hironobu UNESAKI, Seiji TASAKI, Masatoshi SUZUKI[1] and Atsushi WAKATA[2]

Research Reactor Institute, Kyoto university, Kumatori-cho, Sennan-gun, Osaka 590-0494, Japan
[1]*Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan*
[2]*Gunma R&D Center, Mitsubishi Pencil Co., Tateishi, Fujioka, Gunma 375-8501, Japan*

A carbon mirror has been developed as a component of a neutron guide tube which adjointed a cold neutron source in order to extract very cold neutron(VCN) beam as much as possible. The mirror has been fabricated by polishing a glassy carbon plate which is very strong against neutron irradiation dose. Surface roughness of the mirror is less than 1.0 nm and the neutron reflectivity is 0.998±0.004. We have calculated the disturbance of neutron flux distribution in a reflector area of neutron source inserted the carbon guide tube. The calculated results show that the use of carbon guide tube gains 20 percents increment of the source flux in comparison with the case of a usual neutron guide tube, when the distance between entrance of the guide and the reactor core is 30 cm.

KEYWORDS: neutron mirror, carbon, very cold neutron(VCN), irradiation

§1. Introduction

Most of neutron scattering facilities have neutron guide tubes to extract thermal and cold neutron beam. The irradiation damage of neutron mirrors in guide tubes for extraction of thermal and cold neutron beam is not severe because they are not placed in high irradiation field. To extract very low energy neutrons, i.e. very cold neutron(VCN) and ultracold neutron(UCN), the neutron mirrors have to be placed into the high irradiation field and the mirrors are endured with the high irradiation dose and heat cycle. Soda-lime and borosilicate glasses are used as substrates for neutron mirrors due to the following advantages; small surface roughness, good surface flatness, availability for large size and low cost. They are not strong against high neutron irradiation though they are commonly adopted in thermal and cold neutron guide tubes.[1)] Aluminum is used in the high neutron irradiation field due to the small neutron activation cross-section and the short decay life time. It is easy to make large size plate and process it to a complicated shapes, and then Utsuro *et al.* polished aluminum plate mechanically and covered with nickel using vacuum evaporation method for use of VCN guide tube.[2)] Though Stainless steel is difficult to eliminate cobalt which has big neutron activation cross-section and long decay life time, polished stainless is used for UCN guide[3)] . Because the surface roughness of polished stainless steel is, in general, smother than that of aluminum one. In our knowledge, surface roughness of polished stainless steel with a large size is above 4 nm, it is still not enough smooth to use as a VCN guide tube. It is necessary for high transmission efficiency of UCN to fabricate surface of the guide as smooth as possible. Steyerl *et al.*[4)] developed quite smooth neutron mirrors called replica-mirrors and Kawabata *et al.*[5)] have improved them to be supermirrors. They are fabricated as the following process; 1) Nickel thin film or Ni-Ti supermirror is deposited on a float glass using sputter or vacuum evaporation method, 2) Copper metal is deposited on the Nickel thin film or the Ni-Ti supermirror using electroplating method, 3) Remove Cu thin plate from the float glass. The roughness of the surface of Ni film or Ni-Ti supermirror is quite smooth because they are the replica of the float glass surface whose roughness is almost below 1.0 nm. The thickness of Cu plate is usually less than 1 mm. Then it easily warps and it is very difficult to handle due to the thin thickness. In case of installing a neutron guide tube near to a reactor core, effects of the installing should be as small as possible, i.e. the effects must not decrease neutron flux in the neutron source. To cope with these requirements, we have developed a polished carbon mirror as a new substrate for VCN guide tube.

§2. Neutron Reflectivity

The source material of carbon mirrors is a blended polymer of furan and phenol resin. By baknig the source material in an atmosphere of nitrogen at two kinds of temperature, 1000 and 2000 degrees, it becomes a glassy carbon of which the grain size is less than about 5nm. The sample disk is 77mm in diameter and 0.8mm in thickness. The surface is polished mechanically by abrasive grains of tiny diamonds in three stages. The sizes of grains in each stage are 2, 0.5 and 0.1m. The surface roughness of a carbon mirror was measured by the scanning optical interferometor. The measured rectangular area of surface roughness was 0.14mm by 0.11mm. The profile of surface roughness showed that there were two types of waviness due to polishing scratches. We prepared four samples, and average PV value which indicate distance between maximum peak and valley height for these samples was almost within 10 nm. The average surface roughness (rms) was within 1.0 nm. We measured another elements in these carbon mirrors up to lower limit of an inductively coupled plasma atomic emission spectroscopy. Total impurity for all elements was less than 5ppm, and then neutron absorption materials (B, Cd and Gd) were less than 1ppm. Therefore reduction of neutron intensity due to the carbon mirror is negligible.

We measured neutron reflectivity by the carbon mirror with the neutron reflectometer in C3-1-2 beam port of JRR-3M in JAERI.[6] The experimental configuration is shown in Fig.1. The wavelength of the incident neutron was 1.26 nm and the wavelength resolution ($\delta\lambda/\lambda$) was 3.5%. The horizontal divergence angle of the incident beam is decided by the first and third slits, and which is estimated to be 0.92 mrad. The vertical one is decided by the second and the third, and it is 72mrad.

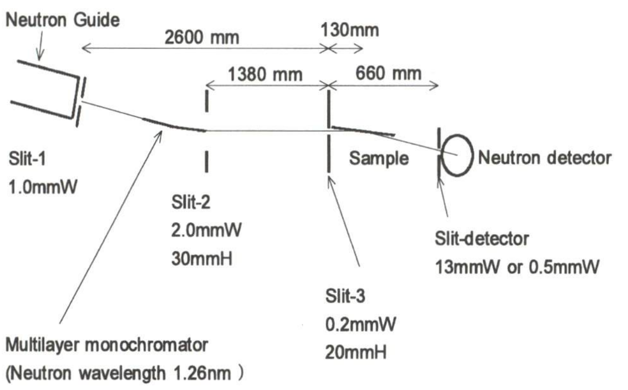

Fig. 1. Experimental configuration of the neutron reflectivity measurement by the reflectometer in C3-1-2, JRR-3M, JAERI.

The ^{3}He neutron detector was placed 660mm from the goniometer for the mirror sample. The slit width in front of the neutron detector was 13mm to detect all reflected neutrons. It was narrowed to be 0.5mm when the spread of the reflected beam was measured. The intensity of the direct beam with this narrow slit was 26.5 counts/sec. The full width at half maximum of the divergent beam angle reflected by Si wafer as the standard was 4×10^{-4} rad and was equal to that of the incident beam. That of a carbon mirror became a little larger to be 5.4×10^{-4} rad by surface waveness and roughness of scratches by the polishing process. The increment of the divergence is small enough to neglect the effect on the neutron reflectivity.

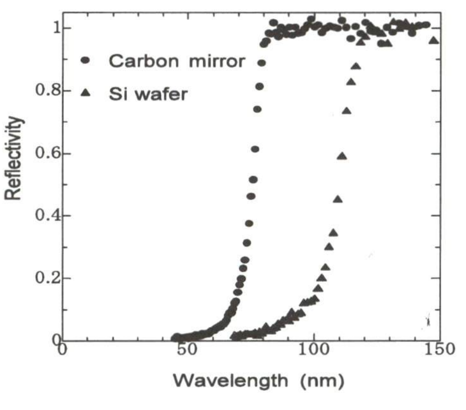

Fig. 2. Neutron reflectivities of a carbon mirror and a silicon wafer.

The measured neutron reflectivities of a carbon mirror and a silicon wafer are shown in Fig.2. The critical wavelength of Si was 123nm. It corresponded to the known potential of 54neV[7] and showed the reliability of this measurement. The reflectivity of a carbon mirror was 0.998±0.004 in the total reflection range (90 - 145 nm) and the critical wavelength was 79 nm. It also corresponded to the potential of 130neV and the carbon density of 1.50 g/cm^3. This density was exactly same with the measured value of this carbon mirror. The high reflectivity shows that this carbon mirror has a good performance as the neutron mirror.

§3. Benefits of Guide Tubes with Carbon Mirrors

The cell size of a cold neutron source (CNS) should be smaller because of the heat load, but it also should be large enough to illuminate the inlet of neutron guide tubes. It is decided by the geometry of CNS and guide tubes. When the distance between CNS cell and a inlet of a guide tube with natural nickel mirrors is 1m, the size decided by the critical angle of the total reflection will be 34cm for the wavelength of 10nm, and 69cm for 20nm, respectively. These sizes are very hard to construct in a high flux area of a neutron source. When a guide tube with carbon mirrors is used, it can be connected directly to CNS cell. Therefore, the size of CNS cell can be only the beam size of a guide tube, for instance 5cm x 10cm typically. This is a great benefit for CNS engineering.

Usually an installed horizontal beam tube makes a large cavity in the heavy water reflector of the research reactor. This inevitably brings a disturbance of the thermal neutron flux distribution because beam tubes are installed in the neutron flux peak to extract neutron as much as possible. Then this makes the thermal neutron flux lower. It is possible that the size of the cavity for the ejection is minimized, when the neutron guide tube is installed into this position. It makes the source thermal neutron to CNS increase and the total cold neutron flux higher. The material of mirrors in the core region should be irradiation resistant and reliable to the reactor safety. Carbon is used for a long time as a good neutron reflector in the nuclear reactor core because it has small absorption cross section. Carbon makes it possible to minimize the disturbance of the neutron flux distribution in the core, and it substantially increases the neutron flux and the utilization efficiency of the neutron source. The great store of experience using carbon as a core structure material gives us reliability for the safety of the nuclear reactor.

The perturbation effects of inserting a carbon guide on the neutron flux are numerically calculated using TWOTRAN[8] with 4 energy groups. Core configurations are shown in Fig.3. Fuels are low-enriched uranium (LEU) using 19.75% enriched U_2Si_2. The fuel meat is 4.8gU/cm^3 and cadmium wire is used as the burnable poison. The heavy water reflector surrounds the fuel area. In the calculation, the coordinate is the R-Z cylindrical system. The beam ejection hole is installed on the rotational axis. Its diameter is 10cm. The graphite is installed in this beam hole with a vacant channel for

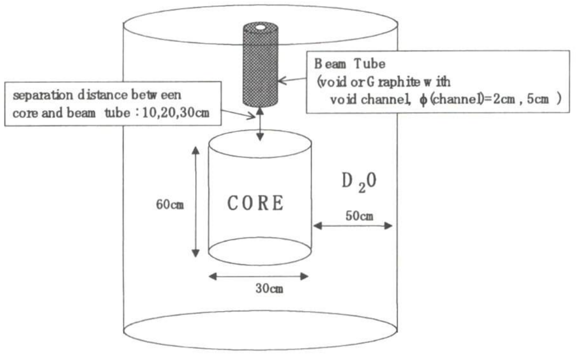

Fig. 3. Core configuration of TWOTRAN calculation for the perturbation effects of inserting a carbon guide on the neutron flux.

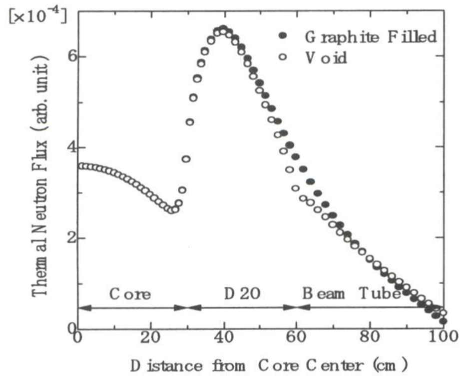

Fig. 4. Neutron flux distributions. A beam tube is void or filled by graphite. The distance between the core and the beam tube is 30cm.

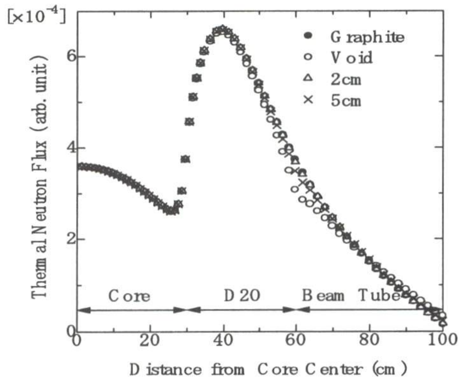

Fig. 5. Neutron flux distributions with different center hole sizes in a carbon of a beam tube. Void, graphite filled , 2 or 5cm holes. The distance between the core and the beam tube is 30cm.

the neutron extraction. The change of the neutron flux with the different size and distance are calculated. These calculations show the estimated effect of upgrading a present vacant beam tube with carbon mirrors and reflectors.

The effects of the graphite filled beam tube and that of the void are shown in Fig.4. The distance between the core and the beam tube is 30cm. The fluxes of the graphite filled are almost same with that of no beam tube though it is not shown here. The difference from these results is about 20%. It shows the flux can be increased up to 20%. The results with void for extracting neutrons are shown in Fig.5. The diameters are 2 and 5cm with the distance of 30cm. The flux with 2cm decreases slightly and that with 5cm does about 7%. It shows that the size of the beam extraction hole can be 2cm with a small neutron loss.

§4. Concluding Remarks

A carbon mirror with good surface quality was fabricated and its neutron reflectivity was measured. The average surface roughness (rms) was below 1.0 nm. The critical potential for total reflection of this carbon mirror was 130nm which was consistent with the measured carbon density of 1.5g/cm^3. The neutron reflectivity of the total reflection was 0.998±0.004. These results show that it has the good performance as a neutron mirror. Carbon mirror has the irradiation resistance, since it is made of pure carbon which has small neutron absorption cross section. A carbon neutron guide tube can be inserted into the reflector of the reactor core or the accelerator target area because carbon materials have been used as the reflectors in the nuclear reactor core for a long time. A void in the reflector area will be minimized with a carbon neutron guide, because the void will be limited only to the beam extraction size. It also could be minimize the disturbance of the neutron flux. The calculation results shows the neutron flux increases about 20%, when the distance between the inlet of the guide tube and the reactor core is 30cm in the reference core using low enrichment fuel and heavy water reflector.

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