THE NOVEL METHOD OF FOCUSING-SANS WITH ROTATING MAGNETIC SEXTUPOLE LENS AND VERY COLD NEUTRONS*

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Abstract

We are developing a high-resolution small angle neutron scattering (SANS) instrument utilizing pulsed white very cold neutrons (VCN) and modulating magnetic lens for focusing in time of flight (ToF) mode.

The magnetic lens adopted new modulation method for focusing pulsed neutron beams over some wavelength range without chromatic aberration; the lens is composed of two concentric permanent magnet arrays in sextupole geometry and the rotation of outer array about fixed inner array provides sinusoidal field gradient modulation. We named this lens as rotating-Permanent Magnet Sextupole lens (rot-PMSx). We have fabricated the prototype of rot-PMSx with the bore diameter ø15 mm and the magnetic length 66 mm. The modulation range of magnetic field strength g' inside the bore $1.5\text{x}10^4$ T/m$^2 \leq$ g' $\leq 5.9\text{x}10^4$ T/m^2 and the repetition rate ≤ 25 Hz [1, 2].

We proved the focusing principle with it at PF2-VCN beam line in Institut Laue Langevin (ILL), France [3]. The focused beam image size was kept constant at the same beam size as the source (≈ 3 mm) over wavelength range of 30 Å ≤ λ ≤ 48 Å in focal length of ≈ 1.14 mm while the depth of focus was quite large. These results showed good performance of the rot-PMSx and we moved on to the demonstration of its performance as high-resolution VCN-f-SANS in this compact geometry of just 5 meters.

We chose a tri-block copolymer poly(oxyeheylen-oxypropylene- oxyeheylen)(PEO_{100}-PPO_{65}-PEO_{100}) called Pluronic F127 as a sample, which has been well studied since 1990' [4]. The measureable q range of this system were 0.009 Å^{-1} ≤ q ≤ 0.3 Å^{-1} or 0.004 Å^{-1} ≤ q ≤ 0.08 Å^{-1} depending on the distances between the sample to detector 100 mm or 465 mm. The results of fitting these data to reasonable models were well consistent with one of same experiments carried out in the past.

These results in two experiments are presented together.

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INTRODUCTION

In this few years, several spallation neutron source based on a accelerator are constructed and start use program. We are developing a focusing SANS (f-SANS) instrument called VCN-f-SANS utilizing VCN beam (~40Å, ~50μeV) and magnetic lens, which are used in ToF mode experiments. Small angle scattering using neutron (SANS) or X-ray (SAXS) beams are the method to study nano-scale structures or dynamics in reciprocal space and have contributed in various science domains. The scattering vector q is represented as

$$q = 4\pi \sin\theta / \lambda \qquad (1),$$

where 2θ and λ are the scattering angle and the de Broglie wavelength of neutrons, respectively. Performance of SANS instrument is generally indicated by these four parameters; neutrons per second per unit area (beam current) at the sample position, measureable minimum q (q_{min}), dynamic q range q_{min}/q_{max}, and q-resolution dq. Our novel method is to utilize longer wavelength neutrons for measurements with smaller q_{min}, while SANS instruments so far have been constructed aiming for approaching smaller 2θ for smaller q_{min}. In our system, 2θ is no longer small and then sample could be placed at the focus point. Then smaller size samples are measurable. Magnetic lens makes the total system size very compact and furthermore, the focal length becomes relatively shorter for such slow neutrons.

On the other hand, ToF method allows us to use poly-chromatic beams to extend dynamic q range drastically and carry out a measurement with better q-resolution. Moreover, ToF method distinguishes the background from signal.

MAGNETIC LENS FOR F-SANS

The source of focusing power is an interaction between neutron's magnetic dipole moment and the magnitude of sextupole magnetic field [5] described as;

$$B = (1/2)g' r^2 \qquad (2)$$

The sextupole magnetic field strength corresponds to positive constant value g'. In sextupole magnetic field, neutrons which have spin parallel to the field are focused to the focal point and the others are defocused. We fabricated the prototype of rot-PMSx with double rotating array structure [2]. In order to generate stronger magnetic field, the magnetic lens is composed of permanent magnet in so-called extended-Halbach configuration [1, 6-9]. Our compact prototype of rot-PMSx has the bore ø15 mm, the magnet length 66 mm, the modulation of g' over range 1.5×10^4 T/m$^2 \leq$ g' $\leq 5.9 \times 10^4$, and the repetition rate of g' modulation ≤ 25 Hz. The strongest magnetic filed at the inner surface of the bore almost saturates and is 1.6 T. The outer array is driven by a 1.5 kW electric motor, through a belt drive.

When we synchronize the g' modulation and beam pulse, beam is focused without significant chromatic aberration. We carried out the focusing experiment with the outer array rotating and continuous modulation at PF2-VCN beam line in ILL. To find the optimum delay between g' modulation and beam pulse for this setup, we carried out the synchronization delay scan first. We varied the detector position at the optimum delay to measure the depth of focus as well.

Experimental Setup

The setup is shown in the FIG.1. The continuous white VCN beam from the reactor is pulsed and polarized by the disc chopper with 60 ms period located just after the exit of the neutron guide and a magnetic supermirror that has m = 2.3 with incident angle 6.8º, respectively. At this moment, only the neutrons which have parallel spin to the mirror's field are reflected and others go through the mirror to an absorber layer. We selected the wavelength range of 30 Å ≤ λ ≤ 48 Å for this experiment. The source and the second collimator are ø1=3 mm and ø2=14 mm pinholes, respectively, both are made of Cd plate. The second aperture is fixed on the front surface of rot-PMSx. Beam profiles focused by rot-PMSx are observed by two-dimensional position sensitive detector (measured horizontal and vertical spatial resolution were 3.3 mm and 2.0 mm, respectively) called bidim80 [9]. FIG.3 shows the VCN beam spectrum that we measured at the detection position with the same setup as the delay scan measurement and with optimum delay 14 ms. The peak wavelength was 36 Å. The significant distances between each apparatus are shown in Table 1. As can be seen in Table 1, the magnification of this optical arrangement is 1.

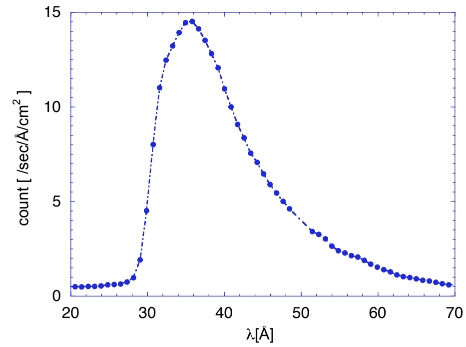

Figure 2: The VCN beam spectrum at the sample position.

Table 1: The distance on focusing measurements

chopper to pinhole through pol. mirror	325 mm
pinhole to magnetic lens centre	2275 mm
magnetic lens centre to detector surface	2275 mm
the focal distance (30 Å ≤ λ ≤ 48 Å)	1138 mm
ToF length	4875 mm

Results

The observed beam profile was fitted by two-dimensional Gaussian distribution function and we equated the beam size (FWHM) to $2\times\sqrt{2\ln(2)\sigma^2}$, where σ^2 is the variance of the Gaussian.

Through series of the delay scan, we determined the optimum delay as 14ms. With the rot-PMSx in position and synchronized with the chopper the image size reduced from ø25 mm to and was kept at ø3.0 ± 0.4 mm over wavelength range of 30 Å ≤ λ ≤ 48 Å in focal length of ≈ 1.14 m, which consistent with the source size (ø3 mm). The flux gain factor comparing with the optics without lens is 35.

We also carried out the detector position scan; the variance was up to 175 mm forward and 150 mm backward at optimum delay 14 ms (see FIG. 3). The beam sizes coincide each other remarkably well in our measurements, although we note a small increase in beam size with wavelength. This may indicate a slight mismatch between slope of g' and the neutron time of flight.

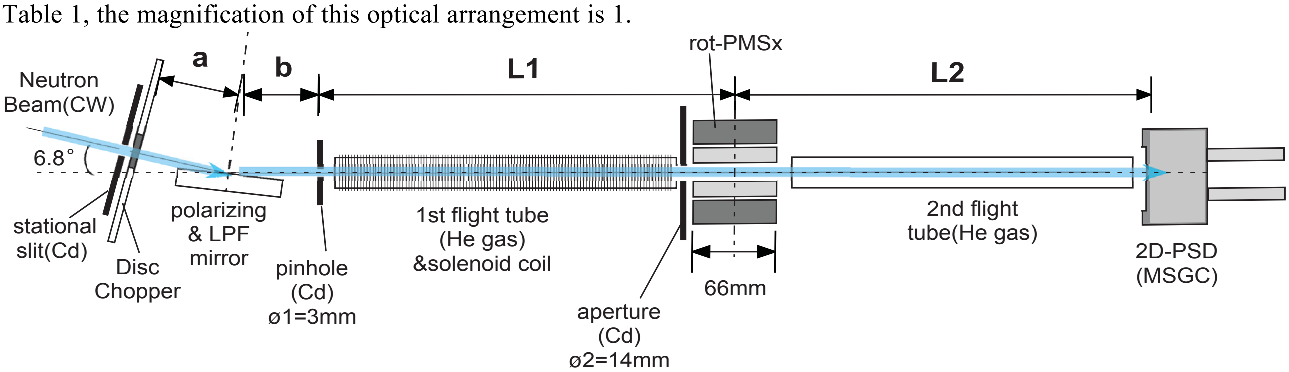

Figure 1: Setup of the focusing experiment. The continuous beam from the reactor is pulsed and polarized. The source beam size is φ3 mm and we observe the focused beam size at the magnification of one.

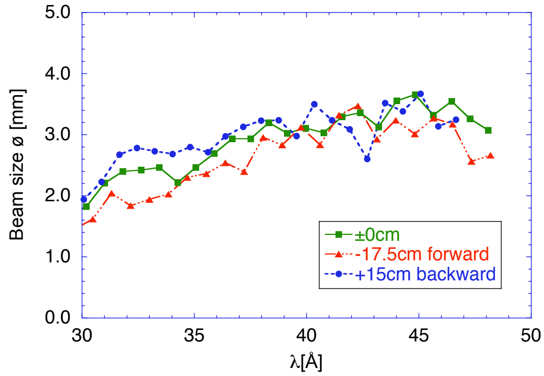

Figure 3: The beam size at optimum delay detector position scan.

THE DEMONSTRATION OF THE PERFORMANCE OF VCN-F-SANS

Sample ; Pluronic F127

To determine the performance of this SANS instrument, we selected a well studied tri-block copolymer Pluronic F127, $(PEO)_{100}(PPO)_{65}(PEO)_{100}$. This polymer have been the subject of intense research because of its diverse phase transitions depending on both temperature and solution concentration [4, 11].

At temperatures less than ~13 Cº, critical temperature of micellization for its 15wt% D_2O solution, the unimers are isolated each other. On the other hand, at temperatures above the critical temperature, the unimers aggregate and compose spherical micelles; a core and a corona are dominated by PPO and hydrated PEO, respectively.

Experiments

The measurements were performed in ToF mode and the sample-to-detector distance was just 100 mm. The sample was mounted in sealed quartz cell with 1 mm flight path.

The measured SANS profiles are shown in FIG. 4. The profile taken at 4 Cº is fitted with a Debye function of a randomly distributed coil model. On the other hand, the profile taken at 28 Cº is fitted by the model composed of the structure factor assuming Pedersen and Gerstenberg model [12, 13] and the micelle form factor assuming a sharp interface of dense spherical objects.

The first order peak around 0.3 $Å^{-1}$ and shoulder around 0.65 $Å^{-1}$ corresponding to inter-particle and intra-particle interference, respectively, were observed at latter measurement. The fitted parameters are consistent with the preceding experiments [12, 13] well. Reliable data are acquired between $0.009\ Å^{-1} \leq q \leq 0.27\ Å^{-1}$. Meanwhile, it will be $0.004\ Å^{-1} \leq q \leq 0.08\ Å^{-1}$ when we extend the sample to detector distance 465mm. More detail total results will be published soon.

CONCLUDING REMARKS

We are developing VCN-f-SANS instrument, which is applicable to ToF mode experiments, for high resolution SANS even for smaller size samples utilizing the combination of poly-chromatic VCN beam and modulating magnetic lens.

We proved the principle of rot-PMSx's focusing performance for wide wavelength range of VCN beam and the beam size was same in-between 175mm forward and 150mm backward, where the origin is the detector position in the delay scan at PF2-VCN in ILL. This system provided special SANS setup; the beam focused at both points the sample and the detector as long as they are placed at both position in-between above range. The special set up allows user to measure smaller size samples at smaller q-region and with better resolution.

The results of the demonstrations of the VCN-f-SANS for the tri-block copolymer Pluronic F127 in a compact geometry of just 5m encouraged us to move on the design of competitive SANS instruments with this concept. Then we demonstrated the performance of high-resolution VCN-f-SANS with this system.

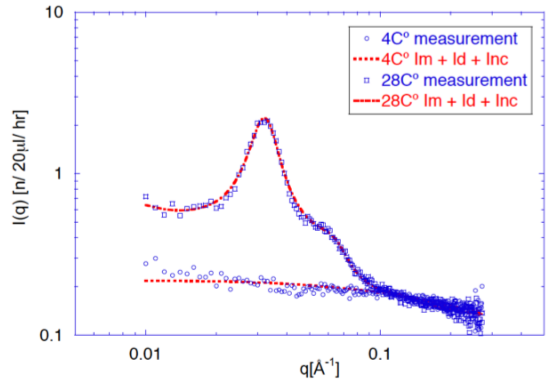

Figure 4: The SANS plot for Pluronic at 4Cº and 28Cº. The model fittings are also showed together.

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