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Design of a TOF-SANS instrument for the Proposed Long Wavelength Target Station at the Spallation Neutron Source

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Abstract

We have designed a versatile high-throughput SANS instrument [Broad Range Intense Multipurpose SANS (BRIMS)] for the proposed Long Wavelength Target Station at the SNS by using acceptance diagrams and the Los Alamos NISP Monte Carlo simulation package. This instrument has been fully optimized to take advantage of the 10 Hz source frequency (broad wavelength bandwidth) and the cold neutron spectrum from a tall coupled solid methane moderator (12 cm x 20 cm). BRIMS has been designed to produce data in a Q range spanning from 0.001 to 0.7 Å^{-1} in a single measurement by simultaneously using neutrons with wavelengths ranging from 1 to 14.5 Å in a time of flight mode. A supermirror guide and bender assembly is employed to separate and redirect the useful portion of the neutron spectrum with $\lambda > 1$ Å, by 2.3° away from the direct beam containing high energy neutrons and γ rays. The effects of the supermirror coating of the guide, the location of the bender assembly with respect to the source, the bend angle, and various collimation choices on the flux, resolution and Q_{min} have been characterized using spherical particle and delta function scatterers. The overall performance of BRIMS has been compared with that of the best existing reactor-based SANS instrument D22 at ILL.

Introduction

Small angle neutron scattering (SANS) is being extensively used for the characterization of materials in the fields of polymers, biology, ceramics, metallurgy, porous materials, magnetism, etc. SANS has high sensitivity in the size range of 1 to 100 nm and thus can be used to probe complex hierarchical structures containing individual particles, aggregates, and large agglomerates with distinct length scales. Although electron microscopy (EM) is a direct probe for the studies in this length scale it is impossible to use EM for *in situ* studies. SAXS also has high sensitivity in the above length scale, but the unique contrasts available with neutrons provide additional advantages for the study of multi-component systems as well as magnetic materials. To probe the above length scales one requires data in a wide Q ($4\pi\sin\theta/\lambda$, where 2θ is the scattering angle and λ is the wavelength of neutrons) range, 0.001 to 0.7 Å^{-1}. In our experience in running a productive SANS user program at the Intense Pulsed Neutron Source we have seen that more than 50% of the experiments take advantage of the data available at the SAND instrument reaching a Q_{max} around 0.8 Å^{-1}.

DISCLAIMER

At present, a Q_{min} of 0.001 $Å^{-1}$ can be reached reliably only by select reactor-based instruments, such as D11 and D22 at ILL at Grenoble, France, and it is not possible for the time-of-flight SANS instruments at the pulsed neutron sources to measure at $Q < 0.005$ $Å^{-1}$ reliably. Furthermore, the quality and density of the data in the low Q region (0.005 to 0.01 $Å^{-1}$) is inadequate for the determination of radius of gyration (Rg) for larger particles (Rg > 100 Å) using the conventional method, Guinier analysis. On the other hand, the time-of-flight SANS instruments such as SAND provided data in a wide Q range, 0.005 to 0.8 $Å^{-1}$, in a single measurement. To cover such a wide Q range at the reactor-based SANS instruments, experiments have to be repeated 3 to 4 times, changing the geometry and the wavelength of the instrument. This is a big disadvantage of the reactor-based SANS instruments. To sum up, the reactor-based SANS instruments are superior for measuring the scattering data in the low Q region while pulsed-source SANS instruments are excellent for measuring high quality data in a wide Q region in a single measurement.

What is needed in the near future for the wide SANS community is a hybrid SANS instrument that combines the best features of the reactor-based and present TOF SANS instruments, capable of measuring data in a Q range of 0.001 to 0.7 $Å^{-1}$ in a single measurement. This will become a reality with the advent of the proposed Long Lavelength Target Station (LWTS) at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. This source will deliver a high flux of cold neutrons useful for SANS (λ=1 to 15 Å) at a source frequency of 10 Hz. The cold moderators are large and directly view the target thus producing a large cold neutron flux for each proton pulse. This source will offer unprecedented opportunities to study time-dependent phenomena and systems at low concentration and low contrast levels. For example it will become possible to study pressure-dependent protein folding kinetics (Woenckaus et al., 2000) and the temperature dependent phase separation and crystallization kinetics in polymers and metallic alloys using time-resolved SANS. At present, such biological experiments are done using time-resolved SAXS at synchrotrons where effects such as radiation induced aggregation is a concern and contrast variation is not feasible.

Design Criteria

The scientific community would greatly benefit by a versatile SANS instrument that can provide the highest flux and cover a Q range of 0.0022 to 0.4 $Å^{-1}$ in a single measurement and this instrument is designed to meet such a need. Options are available to extend the Q ranges on both ends by selecting the collimation and beam stop size as well as the position of the area detector. One important consideration in this design is to separate the neutrons useful for SANS (λ =1 to 15 Å) efficiently from the high-energy and gamma ray components of the direct beam.

The Q_{min} and Q_{max} in this instrument are determined by

$$Q_{min} = 4\pi \sin \theta_{min}/\lambda_{max} \quad (1)$$
$$Q_{max} = 4\pi \sin \theta_{max}/\lambda_{min} \quad (2).$$

The available bandwidth ($\Delta\lambda$) or the maximum wavelength (λ_{max}) useful in a given frame can be calculated using

$$\Delta\lambda = \lambda_{max} = 3955/f\,L \qquad (3)$$

where f is the repetition rate and L is the length of the instrument. While designing this instrument, we set the maximum length of the instrument to be 31 m with the sample being at the 23 m and the entrance aperture at 15 m from the source. The area detector can be placed either at 27 m (λ_{max}=14.6 Å) or at 31 m (λ_{max}=12.75 Å) from the source, each providing unique advantages in flux and Q resolution depending on the experiment. For example, the longer sample to detector distance gives slightly higher resolution and higher point density at each Q while shorter sample to detector distance allows higher flux on sample and a broader Q range. Horizontally offsetting the detector will increase Q_{max} and improve the resolution and statistical quality of the data at middle and high Q regions. Since the multiple scattering effects vary as λ^2, we restrict the λ_{max} to be < 15 Å.

Instrument Layout

The schematic of BRIMS is shown in Figure 1. This instrument will be situated on the long wavelength target station wherein the neutrons are produced by bombarding a heavy

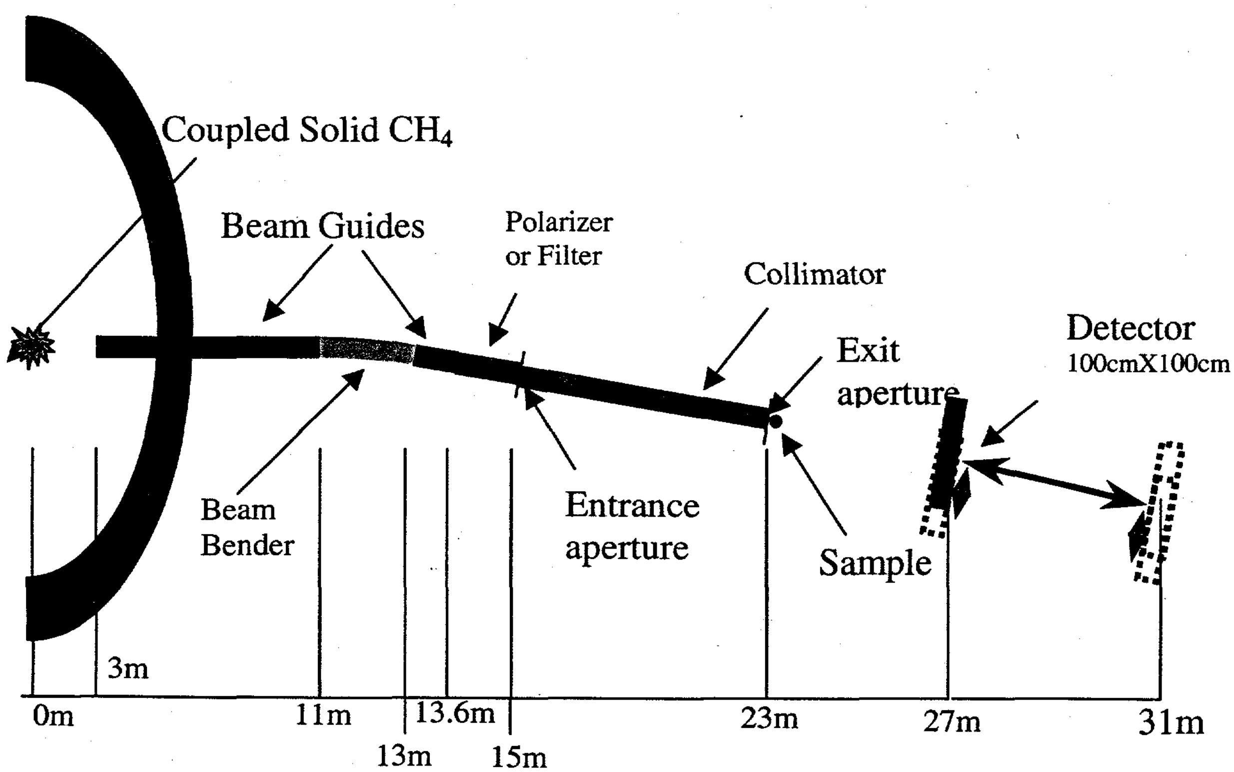

Fig.1 Schematic of the Broad Range Intense Multipurpose SANS instrument for the proposed Long Wavelength Target Station at SNS.

metal target with 1 GeV proton pulses with 0.1 μs pulse width at 10 Hz. High energy neutrons thus generated will be thermalized by a 12 cm x 20 cm coupled solid methane moderator to produce a large cold neutron flux. Key features of this instrument are as follows: It will use a supermirror coated guide and bender assembly to separate the useful cold neutrons away from the fast neutrons and the γ rays so that neither the sample nor the area detector will view them. A space of 1.4 m space between beam bender and collimation is allocated for spectral filters or polarizer elements. It will provide a choice of various pinholes and multiplexed pinholes that can be selected by the user depending on the experimental requirements. It will employ a moveable, 100 x 100 cm^2 position sensitive area detector with small pixels and a high data rate. Frame definition choppers or mirror filterss will be used to eliminate neutrons with wavelength greater than 15 Å. We describe the properties of individual components used in the simulations below.

Bender and Guide Assembly

The prompt neutron spectrum from the target and moderator system contains a large amount of fast neutrons and γ rays which must be prevented from entering the collimation system. Currently, four different techniques are in use to reduce or eliminate the fast neutrons at different pulsed neutron sources. The SANS instrument at the KENS pulsed source at KEK in Japan uses a long reflecting bent neutron guide to make the detector out of sight of the source (Ishikawa et al., 1986). The LOQ instrument at the ISIS pulsed source in the UK (Heenan and King, 1993) employs a beam bender (an array of short narrow curved guides placed side by side) for this purpose. The two SANS instruments at IPNS utilize cold MgO filters (Thiyagarajan et al., 1997, 1998a, 1998b), and the LQD instrument at LANSCE (Seeger et al. 1990) uses a T_0 chopper to attenuate the fast neutrons.

For BRIMS, our choice is a guide and bender assembly to separate the cold neutrons from the direct beam so that the area detector is completely out of the line-of-sight of the source. To improve the flux at short wavelengths, we have used high index supermirrors to accept the short wavelength neutrons at higher angles. The 8 m long input snout consists of two 20 cm tall vertical blades which are separated by 44.625 mm. The inner surfaces are coated with 5 μm thick m=3 supermirror (high angle reflectivity index=0.8). A 2 m long bender consisting of several 15 cm tall vertical blades follows the input snout. The number of blades within the total width of 44.625 cm depends on the required bend angle. For example, a 11.95 mR bender has 15 channels while 40 mR bender has 50 channels. Each blade that gets inserted in the bender consists of a 0.2 mm SiO2 substrate on which 3.5 μm thick m=3.5 supermirror (high angle reflectivity index =0.7) is coated on the reflecting side. The 0.6 m long output guide following the bender has a similar width and is coated on its horizontal inner surfaces with 3.5 μm thick m=3.5 supermirror.

Collimation System

BRIMS will have various choices of collimation that can be selected by the user to match the Q range and flux to the requirements of the experiment. Table 1 compiles the pinhole collimators along with the geometrical parameters and the expected relative flux for each combination of slits. The collimation system consists of two circular slits with the entrance slit at 15 m and the exit slit at 23 m from the source. Via computer control, various different size pinholes can be inserted at the entrance and sample slit positions and corresponding beam stop can be selected. Different combinations of pinholes and beam stops can be used to determine on the Q range and resolution according to experimental requirement.

Detectors

A 100 cm x100 cm position sensitive small pixel, high data rate area detector will be used for the scattering measurements. This detector will be mounted on rails so that it can be moved from 27 m to 31 m from the moderator as well as offset horizontally to increase the solid angle as required. The condition L_1=L_2, where L_1 is the entrance slit to sample slit distance and L_2 is the distance between the sample and the detector, is the symmetric case that is typically used at the reactor-based instruments. This is the instrument geometry when the detector is placed at 31 m position. In this geometry, a higher density of points can be measured at the lower values of Q , increasing the quality of the data at low Q and the number of points available for the Guinier analysis. In the asymmetric configuration, where L_1=2L_2, the instrument has higher flux and a wider Q range at the same Q_{min} as the symmetric configuration. The asymmetric configuration (detector at 27 m from the source) is the highest throughput mode for this instrument (see Table 1). The resolution of the instrument at a given value of Q is comparable for both configurations.

Supplementary Detector Banks

The BRIMS instrument can be augmented to extend the Q range up to 10 $Å^{-1}$ by the addition of supplementary detectors as has been done at the SAND instrument at IPNS and the LOQ at ISIS. These banks will be placed at angles as near to the transmitted beam as possible to minimize geometrical effects arising from the typical plane geometry of the sample for SANS. We plan to incorporate an high angle LPSD area bank to extend the Q range to ~ 3 $Å^{-1}$ along with a back scattering detector cluster to extend to Q ~ 10 $Å^{-1}$. The detector sizes will be selected such that Q ranges from the supplementary detectors overlap substantially with each other as well as with that from the area detector, allowing for the data to be merged easily.

Polarizer

Space has been allocated for a multilayer-based or other transmission polarizer to polarize the neutron beam for the studies of magnetic materials. At the V4 instrument at BERII reactor of HMI, Berlin, a high efficiency spin flipper is being used for polarizing cold neutrons (Keller et al., 1999) with wide range of wavelengths above 4 Å. We believe this technology will continue to improve and high efficiency polarizers and spin flippers for neutrons of nearly the full wavelength range of interest will be available when this instrument is ready to be built.

Frame Definition Mirror

The cold moderators will produce significant amounts of long wavelength neutrons that can arrive at the detector coincident with neutrons from subsequent pulses. Thus, their presence will cause frame overlap contamination. Hence, we plan to introduce a mirror whose critical angle is set to remove neutrons with $\lambda > 15$ Å to combat this problem. This can be installed upstream to the entrance aperture.

Methods

We used acceptance diagrams (Carpenter and Mildner, 1982) to determine the appropriate collimation and beam stop dimensions to maximize the flux at the detector for our choice of Q range. Table 1 shows the settings that were considered along with the Q ranges and the fluxes at the detector. Evaluation of the instrument performance in terms of flux and Q resolution for various instrument parameters was carried out by using the Los Alamos NISP Monte Carlo package. This software package has a number of features that was required as per Kent Crawford's report (ICANS XIV). This package utilizes correct physics modules for the interaction of neutrons with a given component in the instrument. This allows for generating the geometry of the instrument including the position and orientation of the different components, surfaces, regions, and the materials involved in each. In addition, the Monte Carlo engine that moves neutrons between components and handles statistics also allows the saving of histories to identify the sources of problems. It is capable of realistically tracking neutrons through an instrument from moderator to detector and it simulates scattering from spherical particles of any size and delta function scatterers. Furthermore, this package handles the effects of gravitation, neutron polarization and multiple scattering. We believe that all these features are extremely important in the evaluation of the instrument performance. We used the neutron spectrum (λ=1 to 14.5 Å) from the decoupled solid methane wing moderator viewed by SAND as the source for the BRIMS instrument evaluation. Prior to carrying out the simulation of BRIMS we validated the simulation results by simulating the SAND instrument and comparing the simulated results with the experimental data.

In order to compare the performance of BRIMS with what is generally acknowledged as the World's best SANS instrument, D22 at ILL, France, we simulated the D22 instrument with the appropriate neutron guides and the actual neutron spectrum (published at www. Ill.fr). Upon our request Dr. Roland May kindly provided the following 3 settings that would be useful to cover a Q range of 0.001 to 0.5 Å^{-1} at D22. The Q range of 0.001 to 0.012 Å^{-1} can be measured using 18 Å neutrons and a sample-to-detector distance of 18 m and the Q range of 0.0052 to 0.063 Å^{-1} can be covered using 7.5 Å neutrons and a sample-to-detector distance of 8 m. The high Q region 0.026 to 0.5 Å^{-1} can be accessed with 7.5 Å neutrons and a sample-to-detector distance of 1.4m along with a detector offset of 0.39 m. We carried out simulations for these settings and compared the normalized scattered neutrons per second and the resolution in the whole Q range.

Table I

Instrument Settings considered for the full simulation of BRIMS

Entrance aperture diameter (cm)	Sample aperture diameter (cm)	Beam stop Diameter (cm)	Entrance aperture to Sample aperture (m)	Sample to detector distance (m)	Relative Intensity from Acceptance diagrams	λ_{max} (Å)	Q_{min} ($Å^{-1}$)	Q_{max} for 1Å neutrons ($Å^{-1}$)
4*	1.33	4	8	4	1.00	14.5	0.00217	0.785
3*	1.5	6	8	8	0.72	12.75	0.00185	0.393
3	1	3	8	4	0.32	14.5	0.00163	0.785
2*	1	4	4	4	0.57	14.5	0.00217	0.785
2	1	4	8	8	0.141	12.75	0.00123	0.393
2	0.67	2	8	4	0.063	14.5	0.00108	0.785
1.35	0.67	2.67	8	8	0.029	12.75	0.00082	0.393
1.35*	0.45	1.35	8	4	0.0130	14.5	0.00073	0.785
0.9	0.45	2	8	8	0.0058	12.75	0.00062	0.393

Parameters in blue and black correspond to 4m and 8m sample-to-detector distances, respectively. Parameters in red was studied and found to be less preferable. The configuration marked with an (*) were extensively modeled using NISP.

Results and Discussion

We have carried out our Monte Carlo simulations for BRIMS using the settings indicated in Table 1 assuming delta scatterers at Q = 0.002 $Å^{-1}$, 0.005 $Å^{-1}$, 0.01 $Å^{-1}$, 0.02 $Å^{-1}$, 0.05 $Å^{-1}$, 0.1 $Å^{-1}$, 0.2 $Å^{-1}$, 0.5 $Å^{-1}$ as well as spherical particles. The scattering from the delta function scatterers provide both the normalized intensity of scattered neutrons per second and the ΔQ at each Q value studied. We carried out similar calculations for the 3 settings for D22 described above. The normalized scattered neutron count rates for each Q for both BRIMS and D22 are shown in Fig.2. The simulation of the delta function scatterers at different Q values provides the resolution over the whole Q range. The solid lines in Fig.3 correspond to BRIMS while the dotted lines correspond to the two sample to detector distances of 8 m and 1.4 m for D22. As expected, there exists a discontinuity in the ΔQ values for the D22, while it continuously varies for BRIMS. The gravitation effects for 18 Å neutrons with the18m sample to detector distance can be seen in the simulations where the beam drops about 7 cm from the direct view, but the ΔQ values for this configuration is about half of that for BRIMS at $Q < 0.002$ $Å^{-1}$. The lines in the figure are the ΔQ values calculated using equation 4 (Mildner and Carpenter, 1984) for the two instrument configurations.

$$(\Delta Q)^2 = \frac{1}{12}\left(\frac{2\pi}{\lambda}\right)^2\left[3\frac{R_1^2}{2L_1^2} + \frac{3}{2}R_2^2\left(\frac{1}{L_1^2} + \frac{1}{L_2^2}\right) + \frac{(\Delta R)^2}{L_2^2} + \frac{R^2}{L_2^2}\left(\frac{\Delta\lambda}{\lambda}\right)^2\right] \quad (4)$$

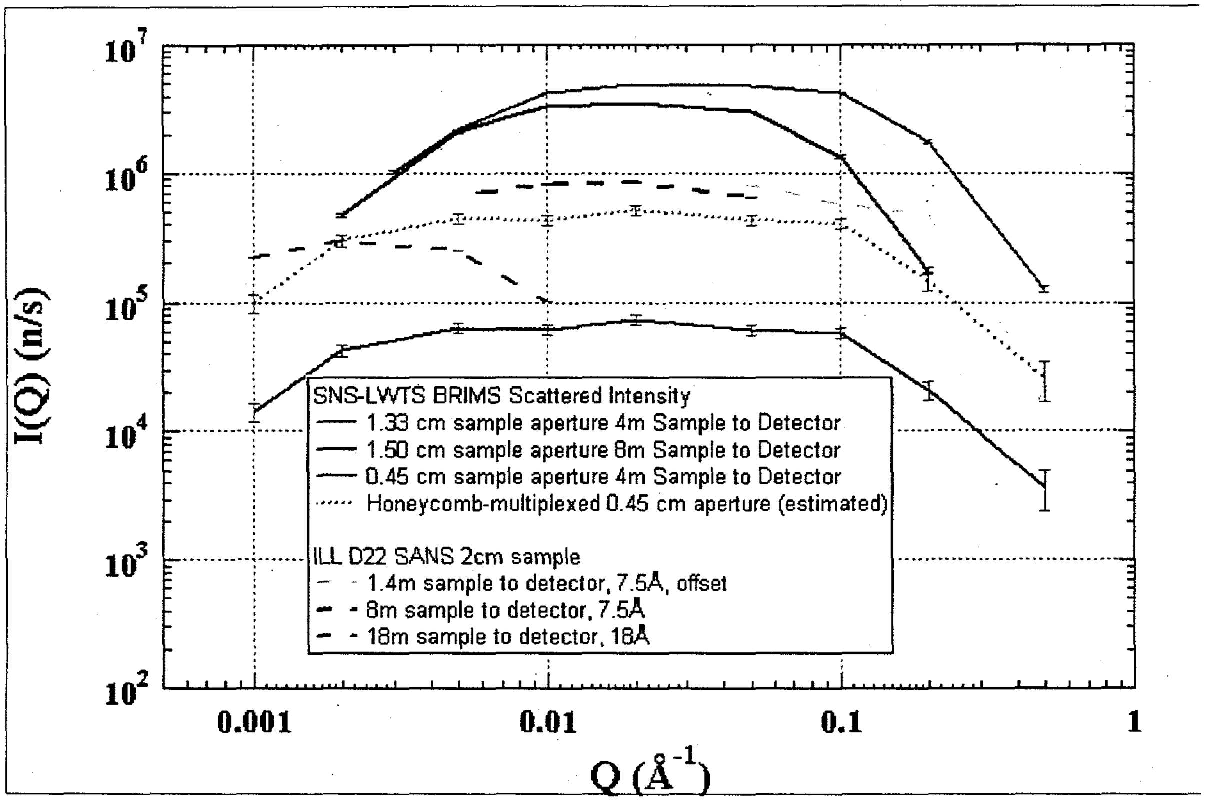

Fig.2. The flux at different Q values for BRIMS and D22 as obtained from the Monte Carlo simulations.

In equation 4, L_1 is the entrance slit to sample slit distance and L_2 is the sample to detector distance, R_1 and R_2 are the radii of the entrance and sample slits and $\Delta\lambda/\lambda$ is the wavelength dispersion, R is the radius of the annulus and ΔR is the width. It is important to note in Fig. 3 that the calculated ΔQ values for D22 at the 3 settings agree quite well with those determined from the simulation with the delta function scatterers using NISP. Such agreement inspires confidence in the simulation results regarding both the flux of the scattered neutrons and the resolution for BRIMS. In fact this is one of the better ways to determine the relative flux and resolution of instruments which simultaneously employ multiple wavelengths.

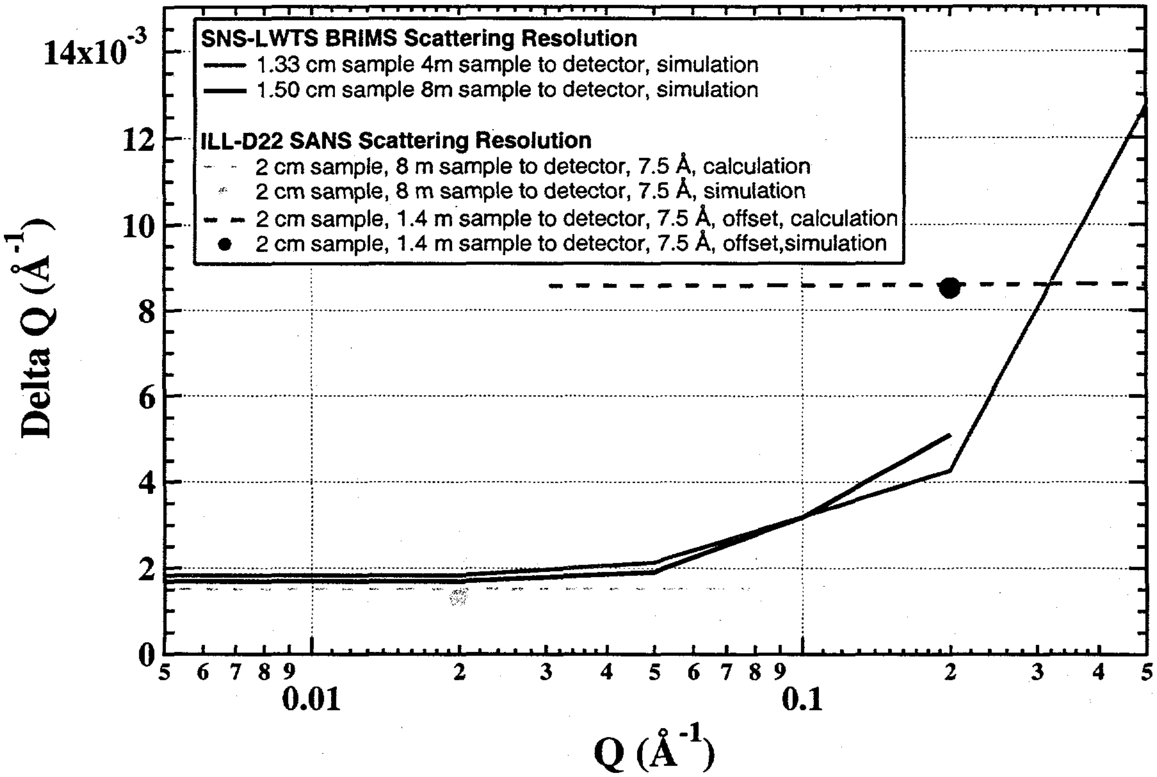

Fig.3. ΔQ values obtained from the simulation using the delta function scatterers for BRIMS and D22. The points in the figure are those calculated using equation 4 which agree quite well with those obtained from the simulated data.

Bender performance

In order to assess the effect of the bender and MgO filter on fast neutrons ($\lambda < 0.5$ Å) we have carried out simulations using the ISIS water moderator that has neutrons with a wavelength down to 0.1 Å . The 11 mR bender, the minimum to separate the useful portion of the spectrum from the direct beam, seems to cause a 15% reduction in transmitted intensity at useable wavelengths when compared to a straight guide. This bender permits significant amount of fast neutrons through the instrument. The preferred 40 mR (50 channel) bender, which completely avoids the line-of-sight of the source for the area detector regardless of in-line shielding, reduced the transmitted flux at useable wavelengths by 28%. Both benders outperformed the MgO filter (Thiyagarajan et al., 1998b) in both transmission of the useful flux and reduction of high energy neutron background.

Performance of Soller Collimators

We also simulated BRIMS using the conventional crossed pair of Soller collimators similar to those used at SAD and SAND (Thiyagarajan et al., 1997, 1998a).

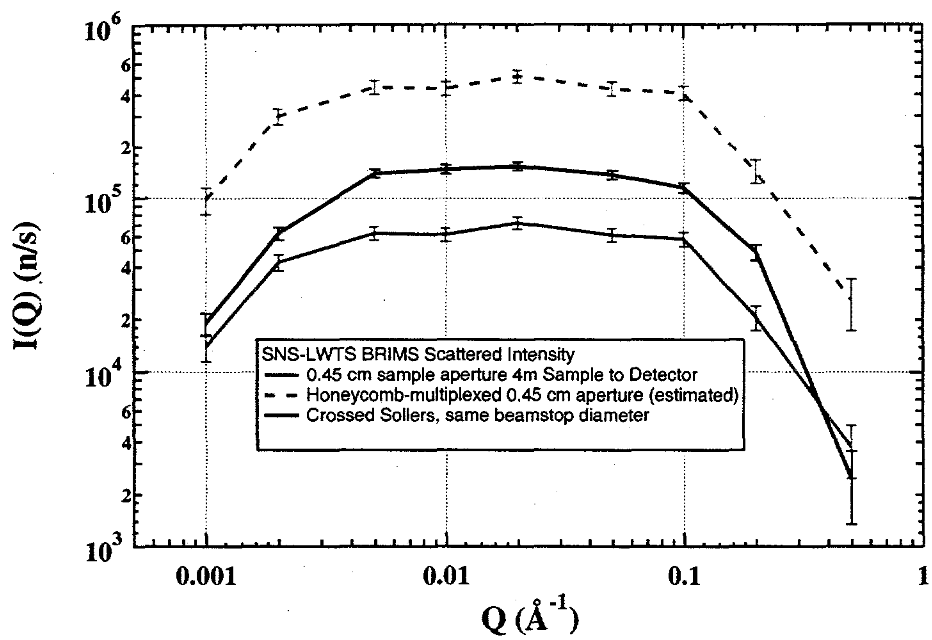

Fig.4. Comparison of the scattered neutrons/s determined from the simulations for the small pinhole with the crossed pair of Soller collimators. The curve for the multiplexed pinholes has been estimated using the results from the simulation for the single pinhole.

The Soller collimators considered here consist of a horizontal set (length = 1.177 m) with a total entrance and exit widths of 22.74 mm and 18.63 mm divided into 21 channels followed by a vertical set (length = 0.813 m) with a total entrance and exit widths of 20.36 mm and 17.25 mm divided into 23 channels. Fig. 4 shows the comparison of the scattered intensity with a small pinhole and a crossed pair of Soller collimators. For a given Q resolution the flux with Sollers is only marginally higher. Based on our experience with these type of Soller collimators the marginal gains in intensity is not advantageous as the surfaces in the Sollers do produce background that will compromise the low Q measurements. We strongly believe that the multiplexed small pinholes would prove more advantageous than crossed Soller collimators.

Neutron Spectrum at LWTS

Erik Iversen and Brad Miklich have carried out careful Monte Carlo simulations of the neutron spectrum expected from different solid methane moderators at LWTS. Fig. 5 shows the normalized neutron spectra for three of the cases studied. We plan to place BRIMS on the coupled slab moderator which provides the maximum flux for the neutrons useful for SANS applications (λ=1 to 15 Å). We would like to point out that all the simulations that were described above were performed assuming the neutron the simulations that were described above were performed assuming the neutron spectrum from a decoupled solid methane wing moderator that is viewed by SAND. On per pulse basis, the cold neutron flux from the coupled slab moderator proposed at LWTS

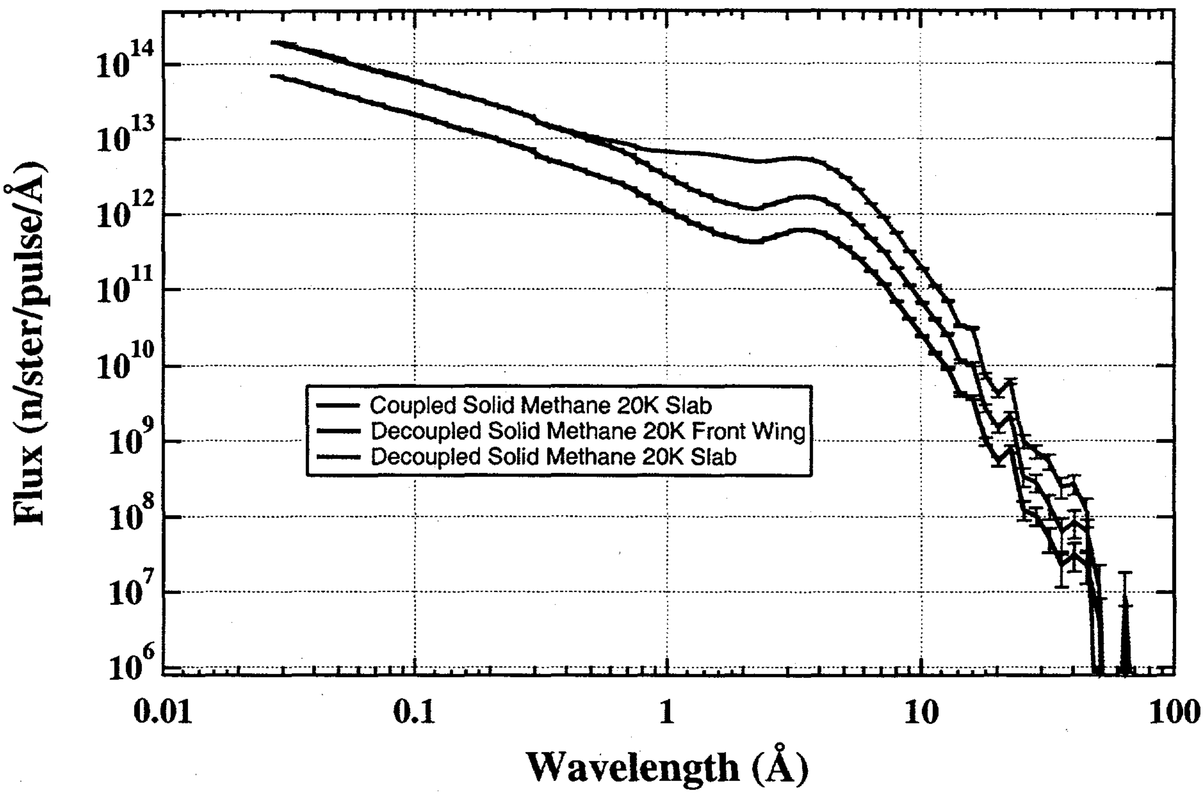

Fig.5. Simulated neutron spectra from the proposed moderators at the Long Wavelength Target Station at the SNS.

will be roughly 6 times higher than that from a decoupled wing moderator for the wavelengths of interest, including a factor of 3 at all wavelengths coming from the slab geometry that was included in the normalization. Therefore, we strongly believe that the count rate expected from BRIMS will be higher than that predicted by our Monte Carlo simulations as shown in Fig. 2.

Summary

We have described the design of a versatile TOF-SANS instrument (BRIMS) for the proposed long wavelength target station at SNS designed using acceptance diagrams and evaluated using NISP Monte Carlo simulations. This instrument combines features from the best reactor-based and the pulsed source SANS instruments. Our simulations show that the BRIMS in its high-throughput configuration (entry #1 in Table 1) should have a few times higher scattered intensity and comparable resolution when compared to the D22 at ILL. In the symmetric configuration it will produce high resolution data in the low Q region just like the reactor instruments. The D22 is noticeably better than BRIMS in terms of flux and resolution only at $Q < 0.002$ Å^{-1} when it employs 18 Å neutrons at a sample to detector distance of 18 m. In our estimate, using honeycomb or bottle-case type multiplexed narrow pinholes on BRIMS will narrow that gap substantially with regard to flux in that low Q region although a penalty in resolution will inevitably remain due to a shorter instrument and shorter operating wavelength.

Acknowledgments

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References

Carpenter, J. M., & Mildner, D.F.R., (1982). Nucl. Inst. Meth. A 196, 341.

Heenan, R. K.& King, S.M. Proc. International Seminar on Structural Investigations at Pulsed Neutron Sources, Dubna, (1993). 176-184.

Ishikawa, Y., Furusaka, M., Nimura, N., Arai, M. & Hasegawa, K. (1986). J. Appl. Cryst. **19**, 229-242.

Keller, Th., Wiedenmann, A., Krist, Th., Mezei,F. (1999). Nuc Inst. Methods (In Press).

Mildner, D.F.R. and Carpenter, J.M.(1984). J. Appl. Cryst., **17**, 249-256.

Seeger, P. A., Hjelm, R. P., & Nutter, M. J. (1990). Mol Cryst. Liq. Cryst **18A,** 101-117.

Thiyagarajan, P., Epperson, J.E., Crawford, R.K., Carpenter, J.M., Klippert, T.E., & Wozniak, D.G., J. Appl. Cryst. 30, (1997). 280-293.

Thiyagarajan, P., Urban, V., Littrell, K., Ku, C., Wozniak, D.G., Belch, H., Vitt, R., Toeller, J., Leach, D., Haumann, J.R., Ostrowski, G.E., Donley, L.L., Hammonds, J., Carpenter, J.M., & Crawford, R.K. (1998a), Proceedings of ICANS XIV - The XIV Meeting of the ICANS, June 14-19, 1998, Starved Rock Lodge, Utica, Illinois, edited by Carpenter, J.M., & Tobin, C. Volume **2**, 864-878. Springfield, VA: National Technical Information Service.

Thiyagarajan, P., Crawford, R.K., & Mildner, D.F.R., J. Appl. Cryst. (1998b). 31, 835-840.

Woenkhaus, J., Kohling, R., Thiyagarajan, P., Littrell, K., Seifert, S., Royer, C.A., & Winter, R. (2000). Biophysical J. (In Press).