Neutron scattering instrumentation at the Spallation Neutron Source

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ABSTRACT

The Spallation Neutron Source (SNS) is an accelerator-based short-pulse neutron scattering facility designed to provide an order of magnitude more power than the most powerful existing facility of this type. The SNS is being constructed at Oak Ridge National Laboratory and is on schedule for completion in 2006. The unprecedented power of this facility brings many new opportunities and challenges for neutron scattering instrumentation. This instrumentation will cover a broad spectrum of science, with every instrument designed to be best-in-class. The SNS has provisions to accommodate up to 24 neutron beam instruments, and design and construction of a number of these instruments are already underway. Some of these instruments are funded within the SNS construction project and some from external sources. This paper will discuss the status of these funded instrumentation activities and of some other instrumentation activities in the planning stage, and will also discuss the process for providing additional instruments. The paper will also indicate the performance expected from many of these instruments and will address some of the challenges and opportunities faced in instrumenting a new spallation source of this unprecedented intensity.

Keywords: Neutron scattering, instrumentation, Spallation Neutron Source

1. SPALLATION NEUTRON SOURCE OVERVIEW

The Spallation Neutron Source (SNS) is an accelerator-based short-pulse neutron scattering facility designed to meet the needs of the neutron scattering community in the United States well into the 21st century. The SNS is a U.S. Department of Energy (DOE) construction project under construction at Oak Ridge National Laboratory, with planned completion in mid-2006. The SNS is being designed and constructed by a 6-laboratory partnership including Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Lawrence Berkeley National Laboratory (LBNL), Los Alamos National Laboratory (LANL), Oak Ridge National Laboratory (ORNL), and Thomas Jefferson National Accelerator Facility (TJNAF). Construction began in 1999 and is now well along. Installation of the initial parts of the accelerator system has already begun, with commissioning of the first accelerator stages to begin in the fall of 2002.

In operation, the SNS accelerator system will produce very short (less than 1 microsecond) intense pulses of protons at a 60 Hz rate. These proton pulses bombard a mercury target, producing large quantities of fast neutrons by the spallation process. One ambient temperature water moderator and three cryogenic moderators slow the neutrons from the target to produce beams of thermal and cold neutrons optimized for neutron scattering experiments.

The baseline SNS design will provide a proton beam power of 1.4 MW, with the potential for future enhancement to 2 MW or more. Initially there will be one target station having 18 beam ports including 6 wide ports, so that approximately 24 neutron beams can be accommodated for neutron scattering experiments, but the facility has been designed to accommodate inclusion of an anticipated second target station in the future.

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From the beginning, the SNS has been planned as a dedicated user facility for neutron scattering research. As such, it is expected to eventually accommodate 1000-2000 national and international users per year, carrying out research in such diverse fields as materials science, condensed matter physics, chemistry, mineralogy and geology, and biology. Argonne National Laboratory, working with scientists from Oak Ridge National Laboratory, is responsible for the neutron scattering instrument R&D activities and for the design, construction, and installation of the initial set of neutron scattering instruments at the SNS.

Figure 1 shows an artist's rendition of the SNS facility, superimposed on an aerial photo of the site taken just after completion of site preparation.

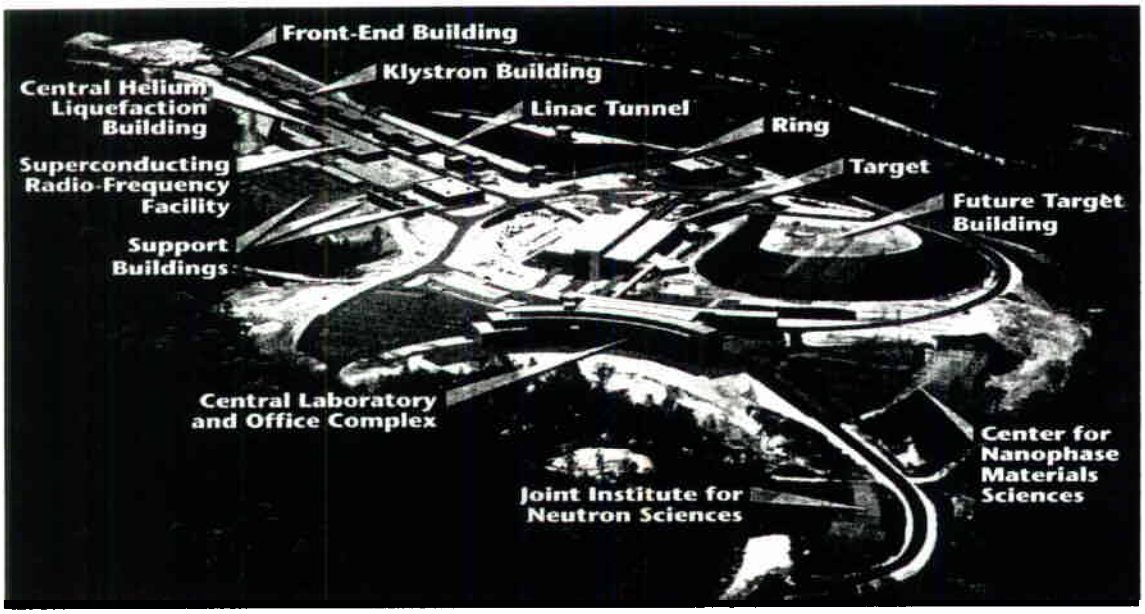

Figure 1. Overview of the SNS facility showing the locations of the various buildings.

2. SNS INSTRUMENTS

2.1 Instrument overview

The guiding philosophy for selection, design and construction of the neutron scattering instruments at SNS is that every instrument should be best-in-its-class. This means that the instrument itself should provide performance gains beyond those that will naturally arise from the order of magnitude increase in source flux. In addition, where possible, upgrade paths have been designed into each of the initial instruments to enable the instrument ultimately to reach the full potential performance practical with available technology.

It is assumed that instruments will continue to be added or upgraded with SNS funds or with external funds throughout the lifetime of the facility. Planning for and coordination with such other instruments, some as yet undefined, has been incorporated into all SNS instrument designs to the extent practical. Standard component designs are being developed and are being used for all instruments as appropriate in order to minimize duplication of design effort from instrument to instrument and to greatly facilitate maintenance and operation of the instruments.

Five instruments in the initial instrument suite are being funded within the SNS construction project, and several additional instruments are being provided by external groups with additional sources of funding. The SNS instrument development team is responsible for the design and construction of the five SNS-funded instruments, development of standardized designs for components common to these and other instruments, and interfacing with external groups to ensure that the instruments they provide can be integrated with the other SNS instruments and meet SNS standards for performance, reliability, maintainability, and ease of operation. This SNS team is also responsible for instrumentation R&D efforts to develop conceptual designs for instruments and to advance the state-of-the-art for neutron detectors, sample environment equipment, and neutron optical components.

2.2 Instrument selection and user involvement

Instruments to be included at SNS are being selected through a well-defined peer-reviewed process. Central to this process is the SNS Experimental Facilities Advisory Committee (EFAC). Instrument ideas are first presented to the EFAC as a brief Letter of Intent (LOI) from a group of interested scientists from inside or outside the SNS organization. If the EFAC responds favorably to the LOI, the submitting group is requested to produce a full conceptual design and performance evaluation for the instrument, along with the scientific case and an indication of the extent of user community support for such an instrument. If the EFAC approves the instrument on the basis of this scientific case, conceptual design, and performance, a beamline is assigned to the instrument and the group then proceeds to obtain funding. The SNS is funding five instruments that first went through this process, and a number of additional instruments have completed this process with a few of these already having acquired funding.

The SNS user community has been and continues to be consulted throughout the process of selection and design of the instruments. In addition to the peer review provided by the EFAC, two other formal mechanisms have been set up for user groups to participate in the selection and development of neutron scattering instrumentation at SNS. These are via participation in an Instrument Advisory Team (IAT) or an Instrument Development Team (IDT). IATs have been formed for each of the instruments funded within the SNS project. Since the funding for these instruments is already available, these teams primarily serve as discussion forums to ensure that the instrument designs reflect the scientific requirements of a broad set of prospective users. Any additional instruments require external funding, so IDTs are formed for each such instrument. The IDT must take on a greater degree of responsibility for its instrument. It must first provide the conceptual design and receive EFAC approval. Then it must acquire the funding and manage the design, construction, and installation of the instrument. In return for this greater degree of effort and responsibility, the IDT is allocated a fraction of the beam time on this instrument for a set period after operation begins.

2.3 Instrument specifics

To date, twelve instruments have been approved by the EFAC. Of these, five are being funded, designed, and constructed entirely within the SNS project. Design is well along on each of these, and procurement of components has started.

- High-resolution backscattering spectrometer
- Vertical surface (magnetism) reflectometer
- Horizontal surface (liquids) reflectometer
- Extended Q-range small-angle diffractometer
- Third generation high-resolution powder diffractometer

So far two more instruments have been funded by IDTs. Design is partially done on each of these.

- Wide-angle thermal chopper spectrometer
- Cold neutron chopper spectrometer

Funding has not yet been secured for the remaining approved instruments.

- Engineering materials diffractometer
- High pressure diffractometer
- Disordered materials diffractometer
- High resolution thermal chopper spectrometer
- Single crystal diffractometer

In addition to these approved neutron scattering instruments, it is anticipated there will soon be approval for the use of one neutron beamline for fundamental physics measurements. There are also a number of other instruments that have started the process toward approval but are not yet approved at this time.

Figure 2 shows a layout of the target building indicating positions currently allocated to the approved instruments.

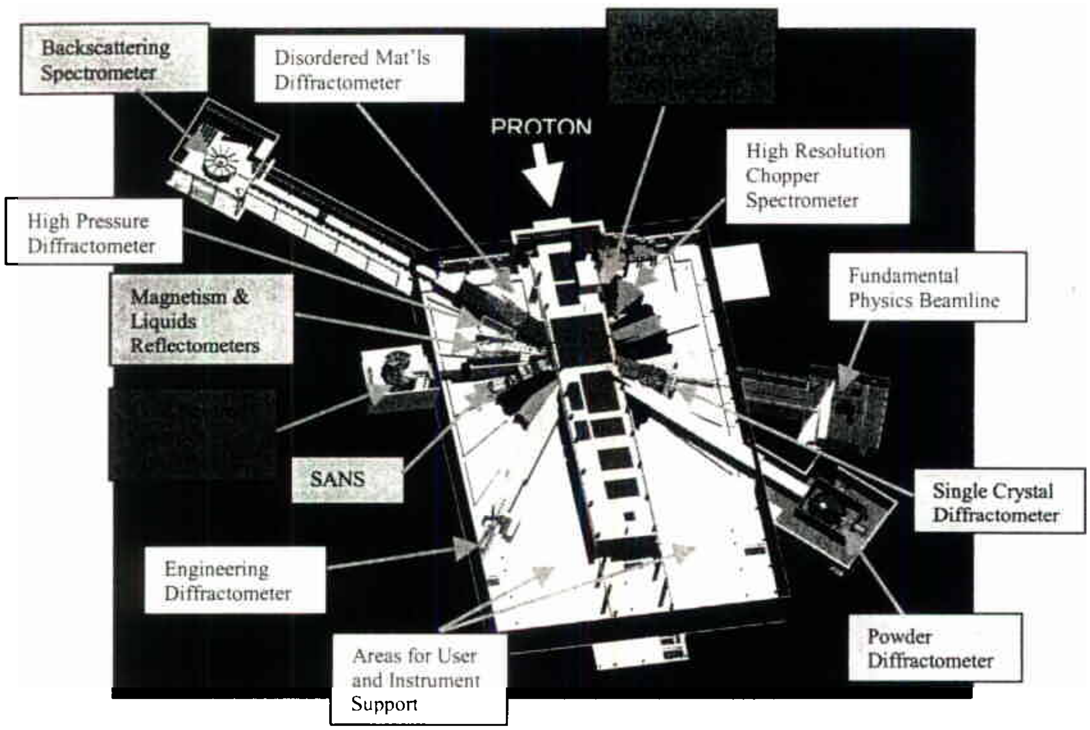

Figure 2. Layout of the target building showing locations for approved instruments.

2.4 Details of SNS-funded instruments

This section contains some of the design and performance details for the five instruments being provided by the SNS project. It is expected that the designs for other instruments will be of similar scale, involve similar challenges, and show similar performance gains to those described here.

2.4.1 Backscattering Spectrometer

The backscattering spectrometer is intended for study of atomic scale dynamics at high resolution, and is well optimized for diffusive and vibrational motions of adsorbed molecules or large molecules. This instrument is designed to provide extremely high energy resolution (2.2 μeV) near the elastic peak, enabling studies of the diffusive dynamics of slow molecular processes (quasielastic scattering). This instrument features very high flux and a dynamic range in energy transfer that is approximately 5 times greater than available on comparable instruments today. In addition, the instrument provides the unique capability of shifting the incident neutron bandwidth enabling inelastic scattering at up to 18 meV of energy transfer with a resolution of 0.1% of the energy transfer. No existing instrument provides all these capabilities, and this instrument will be a factor of 30-100 faster than existing instruments where capabilities overlap.

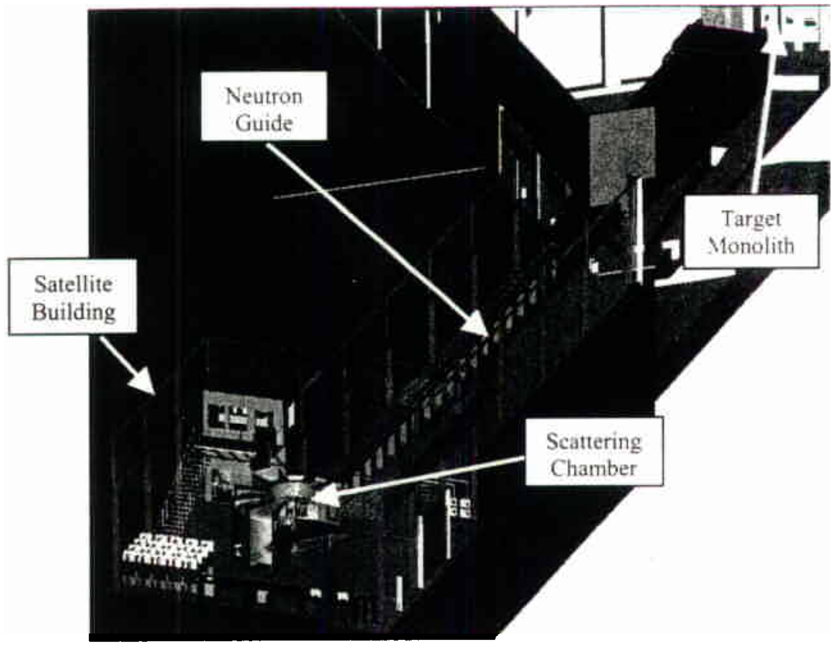

Figure 3. Overview of the Backscattering Spectrometer.

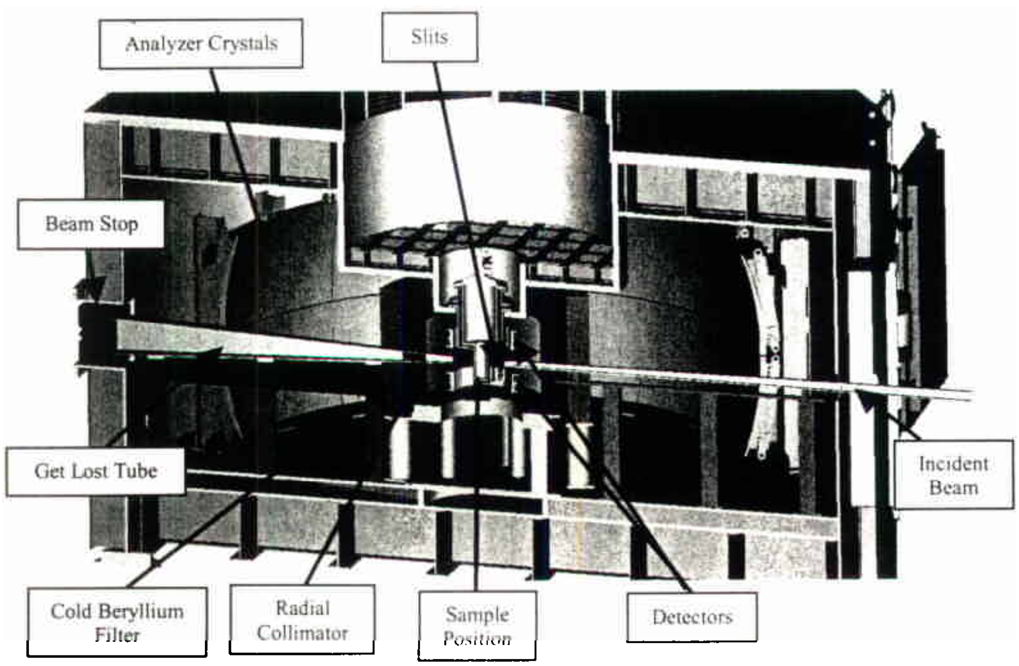

Figure 4. Internal details of the evacuated scattering chamber for the backscattering spectrometer.

Moderator	decoupled poisoned supercritical hydrogen
Beam line	2
Source-sample distance	84 m
Sample-analyzer crystal distance	2.5 m
Analyzer crystal-detector distance	2.2 m
Elastic energy	2.08 meV
Band width	±258 μeV
Resolution (elastic)	2.2 μeV
Q-range (elastic)	$0.1 < Q < 2.0$ Å^{-1}
Solid angle coverage	1.45 steradians

The decoupled poisoned supercritical hydrogen moderator produces relatively short pulses (~45 microsec fwhm at 6.267 Å, the wavelength selected by the Si 111 analyzer crystals). The incident neutron wavelengths are determined by time of flight on this instrument, and the long incident flight path translates this good timing resolution into an excellent wavelength resolution. A curved neutron guide coupled with a guide funnel before the sample transports the neutrons with usable energies and divergences and directs these optimally onto the sample. The guide extends to ~1 m from the moderator to maximize the number of useful neutrons captured and transported. The sample is surrounded by arrays of curved perfect Si crystals oriented to provide near-backscattering for the 111 reflection. Scattered neutrons having wavelengths of 6.267 Å are Bragg reflected back to an arrays of detectors located above and below the nominal scattering plane near the sample. The scattering flight path must be fairly large in order to match the energy resolution for scattered neutron to that for the incident neutrons. Thus the sample-analyzer distance is 2.5 m, and the detectors are at a radius of 30 cm. The use of position sensitive detectors and radial collimators ensures relatively good angular resolution for the scattered neutrons, so this instrument will have good Q resolution. Because of its long incident flight path, the backscattering spectrometer requires a satellite building to house portions of the instrument as is evident in Figure 2. Figures 3 shows an overview of this instrument in its satellite building, and Figure 4 shows some of the details of the secondary flight path for this instrument.

This instrument is optimized for quasielastic scattering to study translational diffusion with self diffusion coefficients as low as 10^{-7} cm^2/sec, and rotational motions with correlation times to hundreds of psec. The high intensity enables parametric studies (~ 15 minutes/data set), studies of very small samples (< 10^{-4} moles H-atoms), and studies of dilute systems and weakly scattering isotopes. The ability to study small samples opens up access to many specialized sample environments, including high pressure, high temperature, and shear (down to 1 micron thick for hydrogenous samples). The unique dynamic range of this instrument enables detailed lineshape analysis, which permits more sophisticated modeling of the diffusive dynamics. In addition to the quasielastic capabilities the instrument can also be used for high-resolution inelastic scattering. Here as well the unique dynamic range, high resolution, and high intensity will provide similar benefits. Areas of science expected to benefit from this instrument include the dynamics of biomolecules and polymers, solvent dynamics such as occur in nanometer scale reverse micelles, H-diffusion in metallic nanoparticles, ion diffusion in ionic conductors, quantum tunneling, and the dynamics of interfacial films including lubricating molecules.

2.4.2 Magnetism (vertical surface) reflectometer

Two reflectometers share one of the wide beam ports at SNS, but are quite differently optimized. Together they cover a very wide range of surface, thin film, and multilayer science.

The SNS magnetism reflectometer is focused on investigations of nanostructures. It is optimized for the characterization of magnetic interfaces and magnetic in-plane structures such as domains. The polarized beam capability is also an important means for investigations of non-magnetic systems. The instrument will have in-situ thin film preparation/manipulation capabilities to explore atomic engineering by design, one of the most promising areas in nanotechnology. This instrument will have data rates 10-100 times faster than those of the best existing instruments, providing access to many areas of science that were previously inaccessible.

Moderator	coupled supercritical hydrogen	
Beam line	4a	
Source-sample distance	17.5	m
Sample-detector distance	0.5 - 2	m
Detector size	20×20	cm^2
Detector resolution	1.5	mm
Polarized beam and polarization analysis		
Bandwidth	$\Delta\lambda = 3.5$	Å
Wavelength range	$1.8 < \lambda < 14.0$	Å
Q range	$0 < Q < 7.0$	$Å^{-1}$
Minimum reflectivity	$\approx 10^{-10}$	

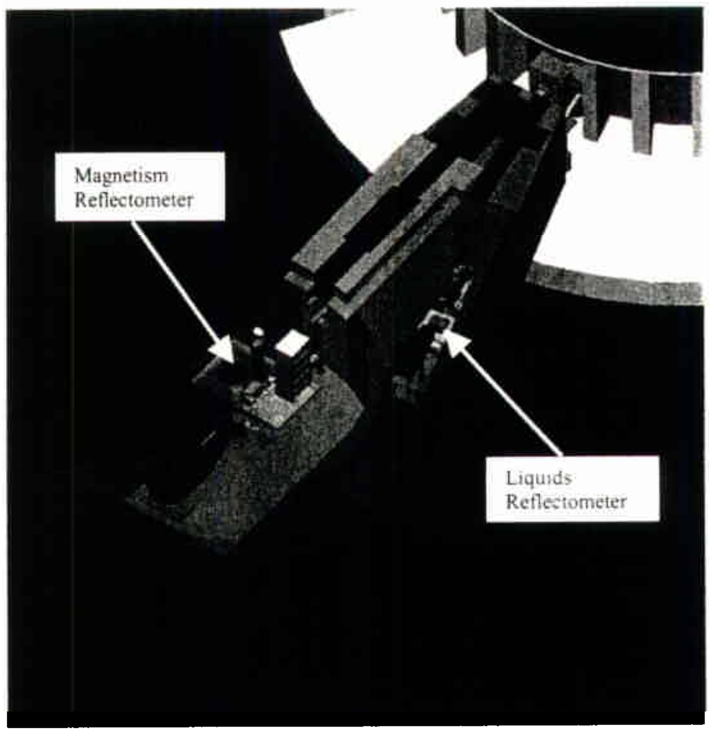

Figure 5. Layout of the magnetism and liquids reflectometers, showing most of the shielding in place.

The geometry for this reflectometer utilizes samples with the surface oriented vertically. This geometry is optimum for the use of large magnets when studying magnetic behavior, but can also be used for most other applications except for unconstrained liquid surfaces. The coupled supercritical hydrogen moderator produces a high flux of long-wavelength neutrons with modest pulse widths. The incident neutron wavelengths are determined by time of flight on this instrument, and the incident flight path, although relatively short, is still adequate to translate this timing resolution into wavelength resolution appropriate for the intended science. A neutron beam bender is used to eliminate fast neutrons and a tapered guide after this bender is optimized to provide maximum flux on the sample. Sets of adjustable slits allow the beam from the funnel to be tailored to match the divergence requirements of the particular experiment. A position sensitive area detector is used to detect both the specular and off-specular scattering. This detector can be rotated about the sample position so that high-angle measurements can be used in the study of multilayered systems. Figure 5 shows both this reflectometer and the liquids reflectometer within their respective shielding enclosures, and Figure 6 shows some details of these two reflectometers.

The high intensity of this instrument will make possible studies down to lower reflectivity values than possible elsewhere, and will also facilitate parametric and time-dependent studies and studies of very weakly scattering processes. This instrument will be particularly good for obtaining layer-averaged chemical and magnetic depth profiles for thicknesses of 5 Å -10,000 Å. Specific areas of science expected to benefit from these capabilities of this reflectometer include studies of magnetic moment formation in thin films, interface polarization, interfacial coupling and quantum confinement, characterization of prototypes of new hard and soft magnetic materials to improve the efficiency of energy delivery systems (e.g., motors, transformers, etc.) or to improve magnetic recording media and magnetic sensors, studies of giant and colossal magnetoresistance, and flux penetration and flux-lattice ordering in superconductors and molecular magnets. In addition, the high intensity should make possible depth-dependent studies of chemical and magnetic lateral structures using grazing-incidence small-angle scattering (GISANS) and in-plane diffraction. This will open up many new areas including nucleation and growth of structured surfaces, structures of magnetic domains, and patterned structures of magnetic dots for potential storage technologies. Unique capabilities of this instrument include the combination of reflectometry and high-angle diffraction, and the ultra-high intensity for in-plane diffraction and off-specular GISANS measurements, time-dependent studies (pulsed magnetic, electric, light or other fields), in-situ structural or magnetic phase-diagram determinations, and structural and magnetic in-situ studies on ultrathin films in an ultrahigh vacuum environment.

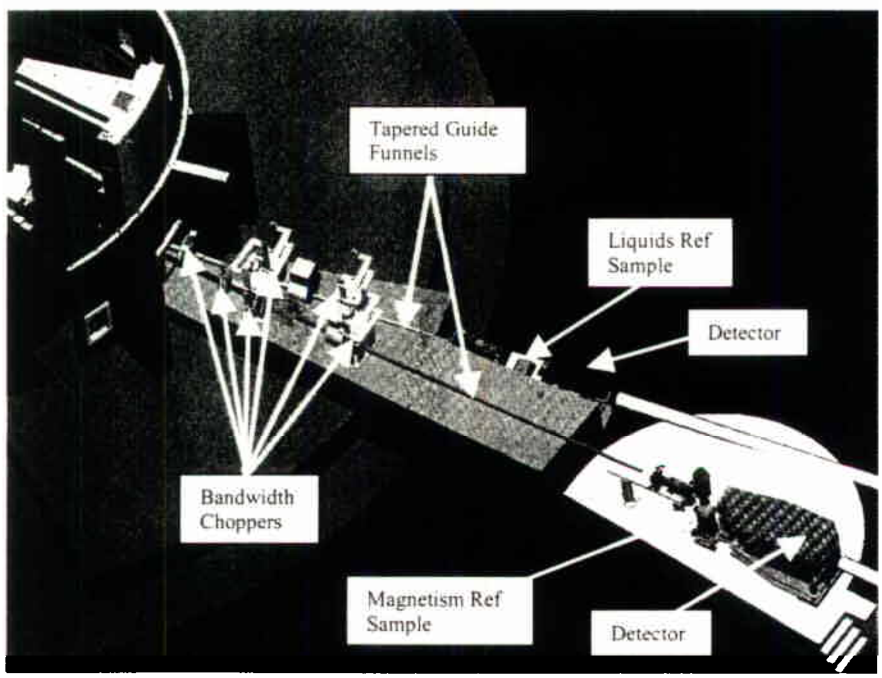

Figure 6. Details of the two reflectometers.

2.4.3 Liquids (horizontal surface) reflectometer

The SNS liquids reflectometer is optimized for the study of interfaces where gravity plays an essential part. A primary focus is the study of interfacial behavior at liquid surfaces, so the instrument is optimized to study samples where the surface must be horizontal. Because of the focus on liquid interfaces, careful attention is also paid to vibration isolation to prevent surface ripples from interfering with the measurements. This instrument will also have data rates 10-100 times faster than those of the best existing instruments, providing access to many areas of science that were previously inaccessible.

Moderator	coupled supercritical hydrogen	
Beam line	4b	
Source-sample distance	13	m
Sample-detector distance	1.5	m
Detector size	25×25	cm^2
Detector resolution	1.5	mm
Bandwidth	$\Delta\lambda = 4.5$	Å
Wavelength range	$1.8 < \lambda < 13.6$	Å
Q range (air/liquid)	$0 < Q < 0.5$	$Å^{-1}$
Q range (air/solid)	$0 < Q < 2$	$Å^{-1}$

This reflectometer geometry utilizes samples with the surface oriented horizontally. This geometry is required for the study of free-standing liquid interfaces or other systems where gravity plays an important role, and can also be used for other applications when desired. The incident beamline is inclined downward at an angle of 4° to permit reflection from these horizontal surfaces. Operation of this instrument is very similar to that of the magnetism reflectometer. The coupled supercritical hydrogen moderator produces a high flux of long-wavelength neutrons with modest pulse widths. The incident neutron wavelengths are determined by time of flight on this instrument, and the relatively short incident flight path is still adequate to translate this timing resolution into wavelength resolution adequate for the intended science. A neutron bender is used to eliminate fast neutrons and a tapered guide after this bender is optimized to provide maximum flux on the sample. The bender is inclined downward at 4°, but bends the beam in the horizontal direction, and the funnel is also inclined downward at 4°. Sets of adjustable slits allow the beam from the funnel to be tailored to match the divergence requirements of the particular experiment. On this instrument, the slits also serve to select the angle of incidence of the beam onto the sample surface. A position sensitive area detector is used to detect both the specular and off-specular scattering.

As with the magnetism reflectometer, the high intensity will make possible studies to lower reflectivity values than possible elsewhere, and will also facilitate parametric and time-dependent studies and studies of very weakly scattering processes. This instrument will be particularly good for obtaining layer-averaged chemical depth profiles for thicknesses of 5 Å -10,000 Å at liquid-liquid and liquid-gas interfaces. Specific areas of science expected to benefit from the capabilities of this reflectometer include, complex fluids under flow, reaction kinetics, interfacial structure in drug delivery systems, diffusion of complex molecules, critical phenomena in fluid systems, and catalytic surfaces and electrochemistry. As with the magnetism reflectometer, the high intensity should make possible depth-dependent studies of lateral structures using grazing-incidence small-angle scattering (GISANS) and in-plane diffraction. This will open up many new areas including phase separation in polymer films, inorganic templating at air/water interfaces, vesicles and gels, surfactants at interfaces, membranes and their intermolecular interaction, protein adsorption, and self-assembled monolayers. Unique capabilities of this instrument include high intensity for off-specular/GISANS measurements, time-dependent studies (e.g. pulsed electric fields, pressure, temperature, kinetics), and parametric studies (e.g. temperature, pressure, pH) for phase-diagram mapping.

2.4.4 Extended-Q SANS

The Extended Q-range small angle neutron scattering (SANS) instrument is designed to cover an unprecedented range in Q space. It will also have very high intensity and good wavelength resolution. The instrument is optimized for studying complex systems that require data collection at low and high Q simultaneously. It will be especially good for simultaneous measurement of both small and large-scale structures in a variety of materials, including biological molecules, polymers, and colloidal systems. No existing instrument spans this full Q range, and this instrument will be a factor of at least 10 times faster than existing instruments at the same Q and Q-resolution.

Moderator	coupled supercritical hydrogen	
Beam line	6	
Source-sample distance	14	m
Low-angle detector		
Sample-detector distance	1-4	m
Detector size	1 × 1	m
Detector resolution	5	mm
High-angle detector		
Sample-detector distance	1	m
Angular coverage	~35°-150°	
Detector resolution	5	mm
Bandwidth	3.5-4.3	Å
Q Range	$0.004 < Q < 12$	$Å^{-1}$
Integrated flux on sample	$\sim 10^8 - 10^9$	$n/cm^2/s$

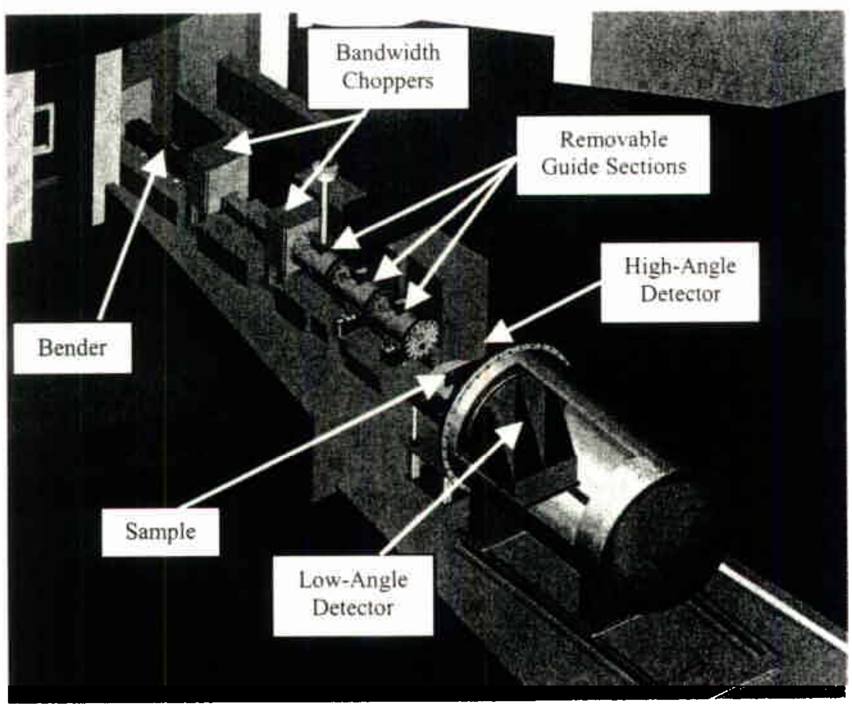

Figure 7. Some of the details of the SNS Extended-Q SANS instrument

Operation of this instrument is very similar to that of the reflectometers. The coupled supercritical hydrogen moderator produces a high flux of long-wavelength neutrons with modest pulse widths. The incident neutron wavelengths are determined by time of flight on this instrument, and the incident flight path translate this timing resolution into wavelength resolution adequate for the intended science. A neutron beam bender is used to eliminate fast neutrons, and removable guide sections downstream from this bender allow the tradeoff between resolution and intensity on sample to be optimized for each experiment. A large position sensitive area detector is used to detect the scattering at low angles, while an array of position sensitive detectors at higher angles extend the measurement range to very high values of Q. Figure 7 shows some details of this SANS instrument.This instrument will be particularly good for the study of such diverse systems as solution structures of protein, DNA and other biological molecules and molecular complexes; protein-protein, protein-ligand interactions, kinase regulation, protein-membrane interaction, block copolymers, micelles, micro emulsions, polyelectrolytes, electric double layer and ion distribution at solid-liquid interface, dendrimers, aerosols, simultaneous study of domain and crystalline structures, crystallization and precipitation, nanoparticles, pore structure in soil, mechanism of absorbing contaminants by soil, and fractal structure of rocks.

2.4.5 Powder diffractometer

The SNS powder diffractometer will be an extremely flexible and versatile general purpose diffractometer useful for a wide range of structural studies. It can cover d-spacings from ~0.5 Å or less to well over 40 Å in a single measurement, and is capable of collecting typical Rietveld statistics in ~20 minutes from a 0.6 cm^3 sample with a < 0.1% resolution at short d-spacings and < 1% resolution for nearly all d-spacings of interest. Alternatively, much of this resolution can be traded for intensity, making it possible to make measurements in ~1 minute. Instrument features allow the users great latitude to optimize the data range, resolution, and statistical precision for each particular experiment.

Moderator	decoupled poisoned supercritical hydrogen	
Beam line	11a	
Source-sample distance	60	m
Sample-detector distance	1-6	m
Detector angular coverage	$6 < 2\theta < 170$	deg
Wavelength bandwidth	~1	Å
Frame 1	0.3 Å < d < 10	Å
Frame 6	3 Å < d < 66	Å
Resolution	$0.001 < \delta d/d < 0.016$	
Resolution at 90°	$\delta d/d = 0.0015$	

The decoupled poisoned supercritical hydrogen moderator produces relatively short pulses (~10 microsec fwhm at 1 Å). The incident neutron wavelengths are determined by time of flight on this instrument, and as on the backscattering spectrometer the long incident flight path translates this good timing resolution into an excellent wavelength resolution. A straight neutron guide transports the neutrons with usable energies and divergences to the sample. A straight guide is used because relatively short wavelength neutrons are needed for many experiments. Since there is no guide curvature to eliminate the fast neutrons, a T_0 chopper is used for this purpose. At 60 m the bandwidth available from a single frame (single period between pulses for 60 Hz operation) is ~1 Å. A set of bandwidth-limiting choppers prevents overlap of neutrons from adjacent pulses, and while allowing this bandwidth range to be adjusted to utilize neutrons of different wavelengths. The full range of adjustment permits operation with neutrons from the first 6 frames, or up to ~6 Å. The sample is surrounded by arrays of detectors on a locus chosen to optimize the resolution of the instrument. The sample-detector distance is fairly large in order to match the angular resolution for scattered neutron to that for the incident neutrons. The detector arrays are divided into pixels to optimize both the in-plane and out-of-plane angular resolution. Figure 8 shows some details of the secondary flight path for this instrument, including the end of the incident beamline.

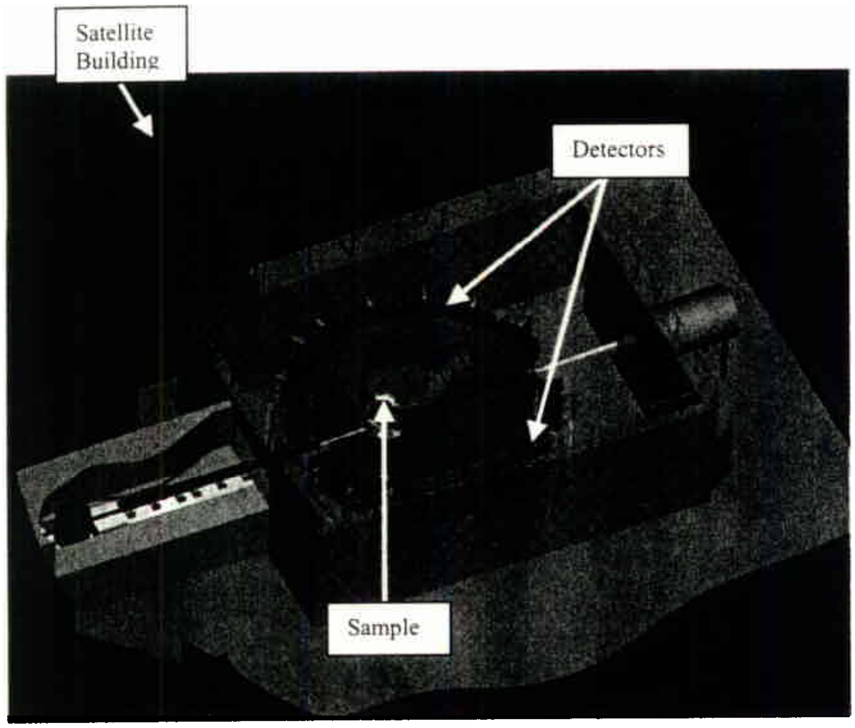

Figure 8. Secondary flight path of the SNS powder diffractometer. The end of the incident flight path is also shown.

Experiments performed on this diffractometer will be able to investigate structural response of materials to changing applied conditions and to elucidate magnetic and non-magnetic crystal structures with unprecedented precision and speed. The areas of interest include high-Tc superconductors, colossal magnetoresistive perovskites, metal-insulator transitions, charge and orbital ordering transitions, molecular magnets, frustrated and spin-glass magnets, heavy fermions, spin fluctuators, permanent (large and fine particle) magnets, zeolite and AlPO frameworks, ionic conductors, fuel cell, battery and sensor materials, gas-hydrates, metals and semiconductors, dielectrics and ferroelectrics, negative thermal expansion, complex dehydroxylation mechanisms, cements, pharmaceuticals, and minerals.

3. NEW TECHNIQUES AND CHALLENGES

The SNS instruments are pushing the frontiers of instrumentation for pulsed source neutron scattering in a number of areas. The design of these instruments makes extensive use of advanced instrument simulation techniques. This begins with the detailed neutronic simulation of the moderator performance to provide wavelength-dependent intensities and pulse shapes. Other simulation codes then propagate this source information through the instrument, and the process is iterated until all the relevant portions of instrument and source parameter space have been explored and the instrument performance has been optimized. Extensive use of advanced calculational techniques has also been applied to the determination of neutron beamline shielding requirements and optimization of the shielding composition and thickness.

All of the instruments make extensive use of neutron guide systems optimized to enhance the useful flux on sample. In most cases these are not just simple straight or curved guides – many of the guide systems also include beam benders and/or converging guide funnels. Guide coatings up to m=3.6 have been specified for some of the guide sections. Inserts have been designed to allow guide sections to penetrate inside the core vessel containment area to permit the guides to extend to within ~1 m of the moderator faces where desired. Inserts have also been designed to allow the guides or benders to extend through the neutron shutters and to be reproducibly positioned when the shutters are opened and closed. This is a challenge since the shutters are massive devices designed to stop fast neutrons, and the inserts themselves weigh up to

2 tons. Great care has been taken in the design of the guide systems to provide steel shielding as close to the neutron channel as practical, in order to prevent streaming of fast neutrons along the sides of the guides. In most cases the guides are curved or else beam benders are used in order to prevent direct lines of sight for the fast neutrons from the moderators. One particularly innovative guide system is that for the liquids reflectometer, which has been designed to provide ±4° of divergence. That guide system is also inclined downward at 4°, so that the angle of incidence on the horizontal sample surface varies between 0° and 8°. A set of slits is then used to select both the desired incidence angle and divergence to match the needs of the measurement.

Another area in which the SNS instruments have extended the frontiers is in the extensive use of bandwidth limiting choppers to provide the flexibility to select the wavelength bands optimized for particular measurements. This flexibility to shift the wavelength band around at will means that much of the time these instruments might be using a frame higher than the first, so that the neutrons of interest might have originated at the moderator several pulses earlier. In order to provide the correct time-of-flight for the neutrons with this type of operation, the data acquisition system must be capable of tracking the frame information in addition to just the time since the last prompt pulse from the source. Flexibility in rephrasing the bandwidth-limiting choppers and/or changing their speeds also provides the option of rejecting some of the pulses in order to work with a larger bandwidth when desired.

The SNS instruments have all been optimized to maximize the counting rates for the science intended. This has been done by using the guide systems and other optimizations to maximize the useful flux on sample. In most cases the collection of the scattered neutrons is also optimized by covering a large solid angle with arrays of detectors. Because of the need for angular resolution, these detector arrays are usually divided into a number of rather small pixels. A given instrument may have several thousand detector pixels. These efforts to maximize counting rates have produced two significant challenges. One is in the massive amounts of data generated and the rates at which this is generated. The other is the need for detectors or detector arrays capable of providing the desired spatial resolution, time-of-flight resolution, and counting speed at a reasonable cost.

Consider as an example an instrument with 1000 detector pixels, each being encoded into 5000 time-of-flight values (typical of some of the instruments). This will provide 5,000,000 channels of data. If a measurement takes an hour or less (typical) then this instrument may generate in excess of 100 million channels of data a day. Each channel will require several bytes to describe its contents, so the data handling problem will be significant. Fortunately, the current speed of electronics is adequate for the collection and storage of the raw data from the SNS instruments. Design and prototyping of the SNS data acquisition system is well along, and it appears that there will be no fundamental problems in providing a very flexible system capable of acquiring data at the rates and quantities envisioned. However, there is still a formidable challenge in the management and analysis of these vast amounts of data, and this challenge is sure to occupy the attention of the SNS staff and users for some time to come.

The situation for detectors is less optimistic. Detectors are certainly one of the major contributors to the costs of the SNS instruments, and in at least a few cases currently available detector technologies are also the limiting factor on instrument performance. Several of the SNS instruments are capable of producing data at instantaneous rates that exceed the capabilities of current detector technologies (e.g., instantaneous rates of up to 10^8 counts/sec in a few pixels in the worst case encountered so far). So far work-arounds have been found for all of the SNS instruments where this is a problem, but these work-arounds are less than satisfactory and better detector performance would be highly desirable. Also, the higher flux on sample makes it practical to use smaller samples and correspondingly smaller pixel sizes on the detectors, so in some cases detector spatial resolution can also be a limiting factor. It is likely that detectors will continue to limit the performance of some SNS instruments well into the future, and this will become even more of an issue since even more powerful pulsed neutron facilities are in the planning stage. Thus it is imperative that significant sustained efforts be devoted to the development of neutron detectors if the full potential of SNS and other pulsed spallation sources is to be reached.

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