Next Generation Neutron Sources

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Abstract

The overall theme for this issue of MRS bulletin is New Frontiers in the Application of Neutron Scattering to Materials Science. The present article is devoted to the next generation of neutron sources that will provide an unprecedented jump in performance. The size (~ 50-100 hectares) and cost (1,5 – 2 millions $) of these facilities are such that only 3 of them are envisaged world-wide, the two construction projects, the spallation neutron sources in the US (SNS) and in Japan (J-PARC), and the European proposal for a spallation source (ESS) which is still awaiting a decision to start construction.

Introduction

Neutrons are one of the most powerful probes for making the arrangement of atoms visible and for measuring the forces between them. The potential performance of a neutron source is basically the product of two quantities, the source strength which measures the flux of useful neutrons produced in the source and the instrumentation factor which measures how efficiently we can detect the scattered neutrons.

The first neutron sources were research reactors and a rapid progression in neutron source performance followed the reactor developments in the forties, fifties, and sixties. At the end of the sixties, this technology was fully mature and, from the seventies until the late nineties, advances in the scientific utility of the technique derived mainly from improvements in instrumentation. Neutrons can also be produced by spallation i.e. through bombardment of a heavy atom with intense beams of high energy protons (~ GeV or velocities ~ 90% of the velocity of light). During the nineties, accelerator technology advanced to a state where spallation sources reached parity in scientific performance with the best high flux reactors and the new projects, now under construction or in development, promise significantly improved neutron source performance. The evolution of the performance (peak thermal neutron flux) of neutron sources over time is shown in Figure 1. Coupled with ongoing improvements in instrumentation, there are exciting prospects for new science. These prospects will not be limited to materials science but also cover a wide variety of subjects from earth science to particle physics, from chemistry to engineering and from solid state physics to biology and medicine.

SNS - the US Spallation Neutron Source

The Spallation Neutron Source (SNS) is a next generation neutron source for the United States that was initiated as a construction line item in fall of 1998 by the Office of Basic Energy Sciences which is part of the Department of Energy's Office of Science. SNS is a multilaboratory project being built at Oak Ridge National Laboratory (ORNL) in Tennessee and scheduled for completion in June 2006. An overview of the current status of the project and the key elements of the facility[1] is shown in Figure 2 and Table 1 which summarizes the important machine parameters. In addition to ORNL, the SNS involves Lawrence Berkeley National Laboratory (front end), Los Alamos National Laboratory (warm linac and high power RF), Jefferson Laboratory (cold linac), Brookhaven National Laboratory (ring and transport systems), and Argonne National Laboratory (instruments). ORNL is responsible for the mercury target, conventional facilities, overall management and integration of the project, and eventual operation of the facility.

As of late spring 2003, the SNS is over 63% complete. Adherence to the construction schedule has allowed on-time, and in some cases early, occupancy of the Front-End, Linac, Klystron, and Central Helium Liquefier/Radio-Frequency (RF) buildings. By summer, the only two buildings that will still be under construction are the Target Building and the Central Laboratory and Office (CLO) Building. The Tennessee Valley Authority's electrical transmission line to SNS was completed in January 2003 and energized in June. By the end of 2002, the Berkeley-designed front end (the ion source, low-energy beam transport, and medium-energy beam transport systems) was successfully installed, commissioned, and in operation - three months ahead of the milestone date. Beam current in excess of requirements was demonstrated in an extended commissioning run. Installation of accelerator components is under way in a number of buildings, and installation of RF components for the coupled-cavity and superconducting sections of the linac has begun. Ring and target installation activities are also under way, and cryomodule installation is imminent. Target design was completed in June 2003, leaving instrument systems as the only remaining design activity.

With an initial power specification approximately eight times that of ISIS, currently the world's most powerful pulsed spallation neutron source, and instruments that build on the current state of the art, the SNS will offer scientific performance ranging from ~ 20 to a few hundred times what is now possible. This translates into the capability for faster (time resolved) measurements, smaller samples, more difficult studies of weak cross section, and higher resolution than is currently possible. These capabilities are being realized through the development of a robust instrument suite (shown in Figure 3), which now occupies 16 out of the possible 24 beamlines.

Once the SNS has ramped up to full power, a year or two after project completion, it will outperform any existing neutron facility in the world. The development in accelerator and target technology offers the potential for near term improvements of the source quality by a factor of 2-5, at reasonable cost and could be implemented by early in the next decade. The first target station at SNS is already close to having all beam lines funded and the addition of a second target station is already being discussed. This long range upgrade path to significantly higher power with two separately optimized target stations is shown in Figure 4 and reflects the initial specifications for SNS as laid out prior to the projects conception by the Basic Energy Sciences Advisory Committee.

JSNS at J-PARC - the Japanese Spallation Neutron Source

The Japanese Spallation Neutron Source (JSNS; Materials and Life Science Facility) is to be constructed as a part of the Japan Proton Accelerator Research Complex (J-PARC) in Tokai. Construction started in JFY2001 and is planned to finish in JFY2006. J-PARC is a multi-disciplinary facility and composed from a 400 MeV linac injecting a pulsed beam of H^- into a 3GeV synchrotron, which delivers protons for the neutron-muon science facility (JSNS) and the 50 GeV synchrotron for the nuclear-particle physics facility including a neutrino facility producing neutrinos for SuperKamiokande, which is 300 km away. The 3GeV ring will have 1MW beam power with 25Hz repetition and 1μs in the pulse width. The 50GeV ring accumulates 0.75 MW. JSNS is a short pulse spallation neutron source, whose technology is based on the experience obtained at the KENS facility in KEK, the world's first pulsed spallation neutron user facility, which started operation in 1980. JSNS will be constructed on the Japan Atomic Energy Research Institute (JAERI) site in Tokai village by the Pacific Ocean, where a 20 MW research reactor (JRR3-M) has been in operation since 1990. These two complementary neutron sources will serve a vast range of neutron users world wide. Figure 5 shows the layout of the J-PARC complex.[2]

The accelerator repetition rate of 25Hz for the JSNS facility will secure unique performance of JSNS among the pulsed neutron facilities. The peak intensity will exceed that of present facilities, ISIS(UK), IPNS(USA) and KENS(Japan) substantially, but the slower repetition rate will provide another important advantage, in the form of a wider time band with the time-of-flight method. It enables JSNS to utilize slower neutrons and to realize high resolution with long flight path without reducing the available time frame. It is also a unique feature that all moderators are cryogenic liquid-H_2 moderators, which will give usable intensity for instruments in a very wide energy-band with naturally narrow pulse-width down to low energies (~20meV), and with only a small intensity degradation for thermal neutrons compared to an ambient moderator. Twenty-three beam ports can be fitted within the practical engineering constraint. These are 11 ports for the high intensity coupled moderator, 6 ports for high resolution decoupled moderator and 6 ports for the high resolution poisoned decoupled moderator. So far no budget has been committed for instruments, but, in order to advance the design work of the target station, i.e. moderator performance, number of beam port, etc., and the structure of the experimental hall, a reference instrument suite with 20 typical instruments was determined according to both scientific and user demands. These instruments are two powder diffractometers, a residual stress diffractometer, three single crystal diffractometers, two total scattering instruments, three small angle scattering instruments, two reflectometers, a spin echo instrument, three chopper instruments, three crystal analyzer instruments and a radiography instrument. Ten day-one instruments out of the 20 are now being studied in detail. Figure 6 shows reference instrument arrangements and images of instruments for JSNS.

ESS the European Spallation Source

The ESS facility is from the outset planned with higher beam power and two target stations, a short pulse (SP) target station as SNS and JSNS, and a long pulse (LP) target station (Figure 7).[3,4,5,6,7] The LP target station is a unique feature of the ESS, it receives 5 MW of beam power from 2 ms long proton pulses at a frequency of 16 2/3 Hz (300 kJ/pulse). This is ideal for broad bandwidth applications where the integrated intensity in the pulse is the important parameter. The SP target station also receives 5 MW of beam power but from 1.4 μsec proton pulses arriving at a frequency of 50 Hz (100 kJ/pulse). This is preferable for applications where the peak intensity in the pulse is the key parameter. This design with two optimally optimised complementary target stations allows for a very balanced scientific utilisation, with virtually no compromises for any of the scientific fields that will be using the facility.

The main difference between the ESS accelerator and the accelerators for SNS and J-PARC is the requirement for higher power but more importantly for simultaneously delivering both short and long pulses.[5,7 above] This means that ESS cannot just be a copy or simple scaling of an existing or planned facility. The ESS linac is normal conducting up to 400 MeV and superconducting from 400 MeV to 1.334 GeV.[7]

In order to deliver 5 MW beam power in about 1.4 μsec to the SP target, the ESS facility needs 2 accumulator rings with 35 m mean radius, which are placed in top of each other in a shared tunnel.

The two ESS target stations will apart from minor details –the moderator assembly– be identical. The target stations will as SNS and JSNS use flowing mercury as the target material.[5,8] Each side of the target station is equipped with 11 rotating shutters, which are equidistantly separated by 11°, and will allow vertical insertion of guides or other beam optics without heavy component handling. The rotating shutter concept avoids unshielded caves within the shielding structure and enables high positioning accuracy. The shutters will allow optical elements as close to the moderator as 1.6 m, and the insert plug in the shutter is 23 cm wide and 17 cm tall – allowing for either a guide 'bundle' or complicated optics as a bi-spectral extraction system.[9,10]

For operation of a short pulse target station above approximately 2 MW helium bubbles are required in the flowing mercury to mitigate the pressure pulses created in the mercury by the short intense proton pulses from the ring.[11]

The ESS moderators are based on conventional techniques, cold hydrogen and water at ambient temperature. Each target station will have 2 horizontally inserted moderator assemblies with four viewed faces,[5,10] and provisions for subsequent installation of advanced cold moderators.[12] The average thermal flux will be 3.1 x

10^{14} n/cm^{2}s, and the peak thermal neutron flux 1.3 x 10^{17}n/cm^{2}s and 1.0 x 10^{16}n/cm^{2}s for the SP and LP target station, respectively. A hot source[13] is not yet in the design, but such an option is an important outstanding question to look into. With advanced cold moderators and a hot source there is a potential for an even better performing ESS.

The proposed instrument suite for the ESS is not what will finally be built, rather what we would build if the source was ready today and we had to decide on all instruments immediately. It therefore represents a conservative forecast of how instrumentation at ESS could be. The long pulse target station heavily relies on new developments in beam transport systems, on the ability to transmit neutron beams over large distances with very low loss, [10,14] and on choppers for pulse shaping, repetition rate multiplication, wavelength frame multiplication, etc.[14,15]

By mid-January 2003, it became clear that a decision to build the ESS would not be forthcoming by the end of 2003, and that the project would be delayed. At present, a four to five year delay and a staged approach, starting with the LP target station first, seem to be a realistic option.[16]

Performance of the New Spallation Sources

For a selection of key instruments the predicted source performance of the new MW pulsed spallation sources has been compared to the best existing capability world wide.[17] The predicted source gain is in the range from 5 to 20, this is the biggest jump in source power relative to leading facilities ever experienced and will beyond doubt transform neutron scattering and revolutionise the use of the technique.

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Figure Captions

Figure 1. Historical development of neutron sources starting with the discovery of the neutron sources by Chadwick in 1932. Accelerator based spallation sources have benefited in recent years by the dramatic improvements in accelerator technology.

Figure 2. Overview of the Spallation Neutron Source showing the layout of the facility and construction status as of April 2003.

Figure 3. The instruments planned for the SNS span a wide range of scientific disciplines.

Figure 4. The SNS has been designed from the outset to facilitate operations at significantly higher power than the initial 1.4 MW specification (3-4 MW) and provide for multiplexing across more than one target, enabling a second, long wavelength target station.

Figure 5. Layout of J-PARC (Japan Proton Accelerator Research Complex), a joint project between JAERI and KEK

Figure 6. Reference instrument arrangements and images of instruments being prepared for JSNS

Figure 7. Layout of the ESS facility with the two target stations LP - Long Pulse, and SP - Short Pulse. The size of the facility is approximately 850 m by 1150 m or 98 hectares.