Spallation Neutron Source

Yanglai Cho
Argonne National Laboratory, Argonne, IL 60439-4800
and
Oak Ridge National Laboratory, Oak Ridge, TN 37831-8218

Editor's Note: Dr. Yanglai Cho is Technical Director of the Spallation Neutron Source at Oak Ridge National Laboratory, and is detailed from Argonne National Laboratory, where he was founding Project Director of the Advanced Photon Source and has been Deputy Associate Laboratory Director. He is an authority on particle accelerator science and technology as well as on construction project management of large-scale scientific facilities. He has served many national and international scientific committees including Machine Advisory Committee of the European Synchrotron Radiation Source in Grenoble France, International Advisory Committee of SPring-8 (an 8-GeV synchrotron radiation source) in Harima, Japan, Accelerator Expert Panel of European Spallation Source in Jǘlich, Germany, Chair of the International Review Committee of the Joint Project of Japan Hadron Facility (KEK) and Neutron Science Project (JAERI), Conference Chair of the 1998 International Conference on Linear Accelerators, and Conference Chair of the 2001 US Particle Accelerator Conference of IEEE/American Physical Society.

Abstract

A 1.36 Billion-dollar research facility is in construction phase at Oak Ridge National Laboratory. It is a Department of Energy multi-laboratory project involving Argonne National Laboratory, Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, Los Alamos National Laboratory and Oak Ridge National Laboratory. When completed, the facility, Spallation Neutron Source (SNS) would be the frontier research facility for neutron scattering to analyze structure of matters and materials. Scientific disciplines in the use of the SNS facility include physics, chemistry, structural biology, pharmacology and others. In this report, a brief description of basic physics involved in generation, use of neutrons, history of pulsed-neutron sources, and description on SNS. The SNS facility being designed consists of negatively charged hydrogen ion source, a 2.5 Million electron Volt (MeV) radio-frequency quadrupole accelerating structure, a 1000 MeV linear accelerator system, a 1000 MeV accumulator ring, neutron generating target system and a suit of the-state-of art scientific instruments.

I. Introduction

For 100 years, x-ray scattering have been used to analyze and study material structures, and last 50 years, neutrons have been also use to do similar studies and analyses. Since x-ray is electromagnetic radiation, x-ray is a very good probe to locate electron cloud and nuclei of high atomic number atoms in the sample. On the other hand, neutron scattering has two advantages, for which x-ray scattering could not do easily. One is that neutron is a very good tool in locating hydrogen atoms in a molecule due to the fact that neutron-proton scattering cross section is large. This is particularly important for study of biological samples. The other advantage is that since neutron has magnetic moment, neutron magnetic scattering enables to study magnetic properties of materials.

I.1 Neutron as Wave Packet

X-ray scattering in material structure analyses uses short enough wavelength x-ray to probe inter-atomic spaces in the material under study. According to particle-wave duality principle, particles have wave properties. The duality principle was one of the most important concepts discovered in the early 20th century. Prince de Broglie postulated the particle-wave duality relationship in form of equation, $\lambda=h/2\pi p$, where λ is the wavelength of particle with momentum, p, and h is the Plank constant. On the other hand, x-ray (electromagnetic wave) has been used to explore crystal structure of matters. Such experimental technique is called x-ray scattering and or x-ray diffraction. Based on particle-wave duality principle, one can use neutrons or electrons to material structure studies. Neutron energy of a few milli-electron-volt (meV) corresponds to wavelength of Angstrom.

1.2 Thermal Neutron Sources

There are two ways to produce neutrons, and one is to use energetic particle beam from accelerators to break-up target nuclei and the other source is nuclear chain reactions. Sir James Chadwick discovered neutron in 1932 by bombardment of nuclei with energetic protons. This process of producing copious number of neutrons by bombardment of high-energy protons is called the spallation process. Typically spallation process produces large number of neutrons with energy range of a few to a few 10s MeV. These energetic neutrons can be slowed down to an ambient temperature in a moderator system. As it turns out that one 1 GeV proton interacting with a heavy element produces about 30 thermal neutrons after moderation. Since a 1 GeV proton produces 30 thermal neutrons, one can states that 30 MeV is required to produce one external thermal neutron.

Neutrons from a steady state reactor have energy of several MeV, and these neutrons also can be moderated to thermal equilibrium. However, in this case, about 270 MeV worth fission energy to produce one external thermal neutron. From the ratio of 270 MeV from reactor consideration and 30 MeV from accelerator consideration, a 5 MW accelerator based source would produce the same average neutrons flux as a 45 MW reactor. Since reactors run in steady state, it peak flux is same as the average flux. However the peak flux of an accelerator source can be higher by several orders of magnitude depending on the accelerator repetition rate and pulse width.

Neutron scattering experiments take advantage of this high peak flux from an accelerator source. As discussed earlier, neutron wavelength is determined from its kinetic energy, which is usually measured with a time-of-flight (TOF) method, i.e. measurement of time required for a neutron to pass point A to Point B.

In kinetic theory of gases, we have learned that when particles are in equilibrium state at temperature T, the kinetic energy of particle is, E=(1/2)kT. Neutrons in an equilibrium state with room temperature of 300^o K have kinetic energy of about meV. The velocity of a meV neutron is about ½ km/sec, and it wavelength is about an Angstrom. This is a typical inter-atomic distance with matters. This is the reason for use of thermal neutrons to prove structures of matters.

Figure 1 shows historical development of effective thermal neutron flux beginning from Chadwick's discovery in 1932. Prior to invention of reactor (Chicago Pile 1) by Fermi in 1942, neutrons were made by accelerators. The figure shows that available thermal neutron flux from reactor sources increased rather rapidly since advent of reactors until 1960s. The saturation of the flux has its origin in the power levels of research reactors, which is in 50 to 100 MW thermal.

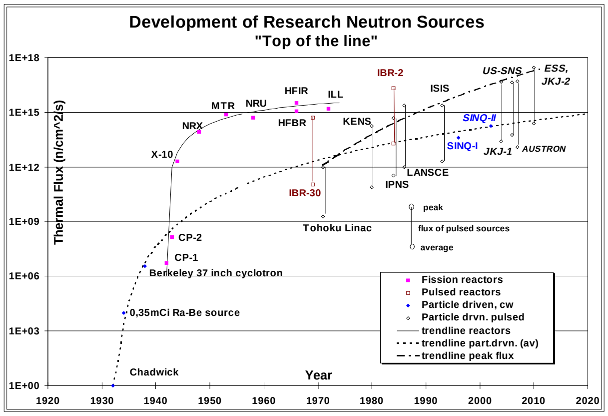

FIG. 1: Historic development of available flux in neutron sources. For pulsed sources peak and average flux are shown; the ratio depending on the pulse repetition rate.

Figure 1 also shows the effective thermal neutron flux from accelerator based source since mid 1970s. In this case the flux plotted is the peak flux of source, which is the figure of merit of time-of-flight applications in neutron scattering research. ZING-P (ZGS intense neutron generator-prototype) was a 200 W accelerator, yet it had demonstrated the principle that low average-power proton accelerator can be used to generate pulsed beam of neutron suitable for the neutron scattering research. Soon after that demonstration, number of high energy physics facilities around the world had converted their booster synchrotrons to pulse sources.

The first of accelerator based pulsed sources for neutron scattering user facilities became operational in early 1980s at KEK, Japan, and Argonne National Laboratory in the US using their booster synchrotrons. These are in power ranges of several kW. During the same period, Rutherford-Appleton Laboratory in UK, built the first dedicated synchrotron based source using the infrastructure of decommissioned high energy physics facility. The ISIS source is the most powerful pulsed source operating today, and its beam power is about 200 kW. An 800 MeV synchrotron occupies a ring enclosure formerly occupied by a 7 GeV synchrotron.

During the past 10 years, several teams from Europe, Japan and US have been put forth construction proposals for multi-MW sources in respective region. The US proposals for 1 to 5 MW sources included plans put forth independently by teams from Argonne, Brookhaven, and Los Alamos in early 1990s. In 1995 the US Department of Energy designated Oak Ridge National Laboratory as the preferred site for the 1-MW accelerator based source, which can be upgraded to 5 MW power level in a later date. Since ORNL lacked experience in large scale accelerator technology, other DOE laboratories with experiences in design/construction of accelerators and scientific instrumentation were asked join the project.

The European proposal is known as European Spallation Source (ESS), and the European group hopes to construct the 5 MW ESS in the second decade of the next century. The proposed source in Japan is called Neutron Science Project (NSP), and the proponent is Japan Atomic Energy Research Institute (JAERI). At the present time there is a plan to combine the NSP with Japan Hadron Facility proposed by KEK, and the joint project is to be constructed at JAERI, and called JAERI-KEK Joint (JKJ) Project. This project has several phases, and the initial beam power is in 1 MW range, and ultimate beam power of 10s MW to do nuclear transmutation study.

I.3 Proton Beam Requirement for a Spallation Source

Experimental measurements have shown that when high energy proton beam bombard a heavy metal target, the neutron yield from such bombardment is proportional to the beam power independent of the beam energy. In another word, a 2 GeV accelerator with 1 mA average beam current produces the same nuetron flux as a 1 GeV, 2 mA accelerator. This is the reason for discussing multi-MW accelerators rather than the machine energy. So one of the requirement of the beam is highest possible beam power within budget.

An additional requirement for the proton beam is the beam pulse length. When neutrons are produced in spallation process, the neutrons have typical energies of 10 MeV or so. These neutrons go through moderator to slow down to reach thermal equilibrium. This moderation process takes some 10 to 20 microseconds. Therefore the pulse length of the incoming proton beam should be much less than 10 microseconds. The typically the proton pulse length should be less than 1 microsecond.

It is a challenge to design, construct and operate a high-power proton accelerator system operating a repetition rate of 60 Hz, and pulse length less than a microsecond. This results a duty factor of 6 10^{-5}, and the peak current of 200 A .

II. The Spallation Neutron Source at Oak Ridge National Laboratory

The accelerator facility under design is to accelerate negatively charged hydrogen ions to 1 GeV with a repetition rate of 60 Hz. Since the designed beam power is 2 MW, the average beam current is 2 mA. The system consists of the ion source and associated front-end equipment, a linear accelerator system, which does all acceleration to attain 1 GeV beam energy, a pulse compressor ring and associated beam transport system. The experimental facility consists of neutron generating target system and a suite of the state-of-the art neutron scatting instruments.

Figure 2 shows a schematic lay out of the facility from ion source and front-end, linear accelerator, high energy beam transport line, accumulator ring, ring to target beam transport line, neutron generating target, and experimental scattering instruments.

Typically the pulse length of a proton linac is about 1 msec. The required beam pulse length at the target is less than a microsecond. Therefore a pulse compression system is required to compress by a factor 1000or more. To facilitate this compression, the system uses the negative hydrogen ions rather than protons and a compressor ring. The ring has its revolution period of about 1 microsecond, and if one can inject into the ring the 1 millisecond long linac pulse in 1000 turns, the pulse length in the ring becomes a microsecond. Then the question is how one can inject a 1000 turn to a ring. To facilitate the 1000 turn injection, negatively charged hydrogen ions and very thin stripper foil are used for the injection process. The stripper foil during the injection process removes two orbital electrons of negatively charged hydrogen ion to make proton. The beam of accumulated proton circulates through the ring, and it may traverse the stripper foil several times. Because the foil is very thin, the beam loss and degradation are negligibly small.

Front End Section of the accelerator system consists of the ion source, a radio frequency quarupole (rfQ) system which bunches and accelerate the ion source beam to 2.5 MeV. The rfQ is followed by a medium energy beam transport system (MEBT). The role of MEBT is to match the rfQ beam to linac system. The 2.5 MeV-beam is injected into linac system. The Front End system is being designed and constructed by a Lawrence Berkeley National Laboratory team.

The Linac System accelerates the 2.5 MeV beam to 1 GeV through three different types of linac. The 2.5 MeV beam is first accelerated to 20 MeV using a drift-tube linac (DTL). This type of linac is also known as Alvarez linac after its inventor. Next section of linac is coupled-cavity-drift-tube linac (CCDTL). The output energy of this section is 79 MeV. The last section is called coupled-cavity linac (CCL). The CCL accelerate the 79 MeV beam to 1 GeV. The linac system is being design by a team from Los Alamos National Laboratory.

Ring System - A team from Brookhaven National Laboratory is responsible for the compressor ring, and its associated beam transport lines. The ring has 220-m circumference, and is capable of handling 2 MW beam power. It accepts 1000 turn injection in a millisecond and eject the compressed beam in a single turn. The repetition rate is 60 Hz. One of the most important design considerations is potential beam loss in the ring. The goal is 10^{-4} for uncontrolled losses.

Target System - Each proton beam pulse bombarding the neutron generating target has 33.3 kJ of energy. Question is whether a heavy element solid target can withstand thermally and mechanically such high-energy shock treatments of 60 Hz repetition rate. To avoid target failure may be caused by the shocks, the design team decided to use mercury as target material. The use of mercury as a neutron-generating target is a new concept requiring a substantial R&D work. There is an international collaboration to development mercury target being carried-out by scientists and engineers from the US, Europe and Japan. A team from Oak Ridge National Laboratory is responsible for the target system design. The baseline contains one target station capable of equipping 18 beam-lines and instruments. However the facility is design to have a second target station in a later date.

Instruments - The most important part of the project is research instruments. The baseline budget contains 10 state-of-the arts instruments. ORNL has hired a number of instrument scientists, and they are currently stationed at Argonne National Laboratory, where there is an operating pulsed source, IPNS. A team of scientists and engineers from ANL is responsible for the instrument development in conjunction with ORNL staff.

The project is scheduled to complete in 2005.

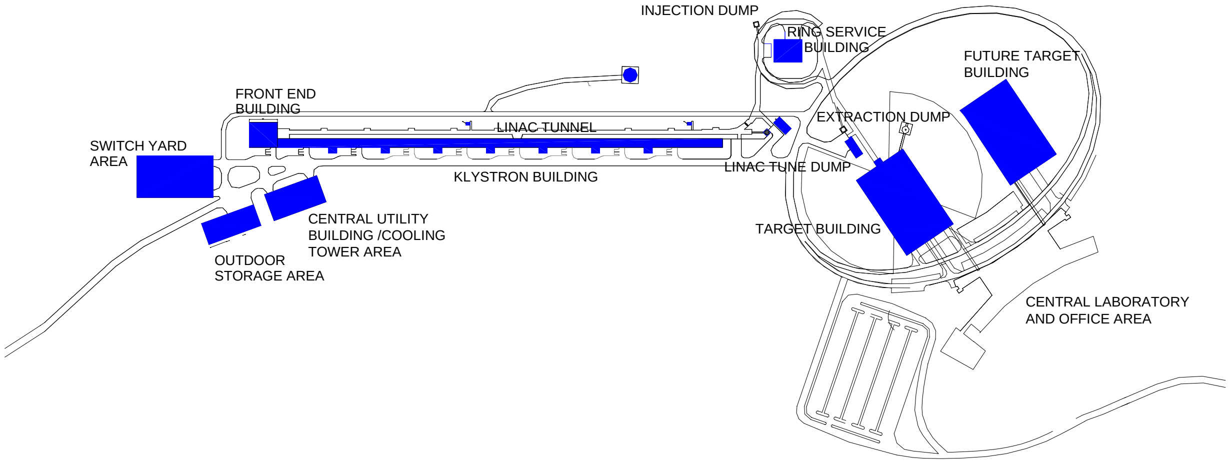

FIG 2: SNS Layout showing Front End, Linac, Accumulator Ring and Target Buildings