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INTENSE PULSED NEUTRON SOURCES*

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Abstract

Accelerator requirements for pulsed spallation neutron sources are stated. Brief descriptions of the Argonne IPNS-I, the Japanese KENS, Los Alamos Scientific Laboratory WNR/PSR, the Rutherford Laboratory SNS, and the West German SNQ facilities are presented.

I. Introduction

Slow neutrons have unique properties that make them excellent probes into the microscopic nature of a broad range of physical, chemical, and biological phenomena. They have the ability to penetrate bulk matter. Their low energy and short wavelength are well-matched to the ranges of interest in condensed matter. They couple to magnetic systems through their magnetic moment. They have relatively strong interaction with light atoms like hydrogen and carbon and have particularly strong isotope-dependent interactions with the light atoms.[1]

The study of condensed matter using neutrons has been centered at nuclear reactor centers where special provisions have been made to allow neutron beam tubes and experimental areas for research. These sources have provided neutron scattering scientists with the opportunity to do some excellent research.

Inelastic neutron scattering studies, processes in which the neutron exchanges both energy and momentum, are used to study the spectrum of excitations of a condensed matter system at a microscopic level. Such techniques have led to the intricate knowledge of the existence and spectrum of phonons, enabling the construction of sophisticated theories of bonding and cohesion of metals, semiconductors, and insulators. Electron-phonon interactions, vital to the understanding of transport and superconducting processes of metals, have been probed by inelastic neutron scattering.[1]

Neutron diffraction is concerned with the structural arrangement of the atomic particles in a material, and the relation of this arrangement to its physical and chemical properties. Neutron diffraction has had a major impact on the study of homogeneous catalysts, metal hydrides, hydrogen-bonded materials, solid electrolytes, ferroelectrics, antiferroelectrics, organic compounds, ferro-, antiferro-, and ferri-magnetic materials, and polymers. These techniques are starting to play a major role in the study of biological systems like viruses, proteins, and enzymes.[1]

Neutron scattering science has always been a severely intensity-limited field. The highest flux research reactors in the world are HIFR at Oak Ridge National Laboratory, HFBR at Brookhaven National Laboratory, and the High-Flux Reactor at the Institut Laue-Langevin (ILL), France. ILL is at present considered the world's most advanced research reactor. The desire for a "super high-flux" reactor beyond these exists; but for technological, political, and economic reasons, it is highly unlikely one will ever be built. Carpenter and Price[2] suggested the possibility of using proton accelerators for producing intense bursts of neutrons to produce both more intense sources and time-structured beams that could make use of time-of-flight techniques. The use of pulsed sources allows performance of real time experiments and provides low background noise because the source is off most of the time.

The first spallation source was tested at Argonne in 1974 using the 200 MeV proton accelerator, Booster-I, with a prototype target station, ZING-P'.[3] This prototype was operated infrequently and only at very low intensity; yet, it did provide confidence to proceed with the ZING-P' facility at Argonne. ZING-P' was built as the second stage in the development of pulsed spallation sources with the goals to act as a test bed for source, target, and moderator development; instrument development; and to produce preliminary scientific results. These goals were successfully achieved before ZING-P' was shut down in August 1980. At that time, the conversion to the new IPNS-I facility began.

In December 1975, the Japanese government gave approval to construct a Booster Utilization Facility (BSF), which included a neutron scattering target at the National Laboratory for High Energy Physics at Tsukuba. The facility uses the 500 MeV, 20 Hz booster of the 12 GeV KEK accelerator in a time-sharing mode. That facility came on-line on June 18, 1980. Five spectrometers are installed on this facility. It has a room temperature and a cold methane moderator. It will be used for neutron scattering physics approximately 30% of the time that the BSF operates.

The Weapons Neutron Research Facility (WNR) at LASL is another pulsed spallation source that started operation in the 1970's. Beam from the 800 MeV LAMPF accelerator has been directed onto the WNR target since 1977. The system was built for weapons-related research, but is available part time for neutron scattering studies. The main shortcoming of the present WNR facility is the long beam pulse (~10 μs) which deleteriously impacts on the resolution of time-of-flight measurements. This shortcoming will be overcome when a new storage ring currently starting construction will be completed. This facility, with the addition of the storage ring, will have the potential to increase the peak flux as much as a factor of 4 or 5 over the projections of the IPNS-I facility at Argonne. The funds for construction of the PSR have now been released.

In June 1977, the British government announced the decision to fund construction of the Spallation Neutron Source (SNS) at the Rutherford Laboratory. Construction has started and major procurements are in process. This facility will be the largest pulsed spallation source in the world when it becomes operational in the mid-80's. The design goal is a time-averaged proton current of 200 μA on target at 800 MeV. The pulse repetition rate will be 50 Hz.

A reference design for an advanced pulsed spallation neutron source is presently being jointly developed by groups at the Kernforschungszentrum at Karlsruhe and the Kernforschungsanlage at Jülich in

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Germany; known as the German spallation source project (SNQ). This reference design was started after a recommendation to pursue a spallation source was delivered by a special panel appointed by the German minister for research and technology. The reference design is based on an 1100 MeV proton linac with an average current of 5 mA on target. A compressor ring is considered for producing narrow pulses for time-of-flight measurements.

II. Accelerator Requirements for Pulsed Spallation Sources

The four important parameters that establish the requirements for the accelerator are the intensity, energy, pulse length, and repetition rate.[1] The intensity is a parameter that is naturally maximized within the economic and scientific constraints of the system.

The energy of the accelerator is determined from target and moderator considerations. The yield of neutrons from the target is roughly proportional to E-120 where E is the proton energy in megavolts. The energy of the neutrons emitted from the target surface is reduced by several orders of magnitude by using polyethylene, liquid hydrogen, or liquid methane moderators in close coupling to the target. Reflectors are added to increase the low energy neutron flux. The optimal proton energies are in the range of a few hundred megavolts to a couple of gigaelectronvolts. The moderators are limited in size to avoid excessive time spreading of the neutron pulse. The yield tends to be linear with E-120 for energies up to 2 GeV, but levels off at higher energies because of range and moderator effects.

The energy resolution of neutron diffractometers is affected by the pulse width of proton beam. Calculations performed by Carpenter[1] indicate that this effect doesn't alter precision much if the extracted pulse is about 500 μs or less.

The repetition rate between pulses is defined by minimum and maximum energies that are to be measured in a given spectrometer and the distance from the source. Typically, the desired repetition rates are in the range of 10 to 100 Hz, which allow an energy bandwidth of about 10 in typical spectrometers without the high energy neutrons overlapping with the low energy neutrons from the previous pulse.

III. Accelerators For Pulsed Spallation Neutron Sources

A. IPNS-I, ANL, USA

An overview of the IPNS-I facility is shown in Fig. 1. The facility consists of a 750 kV preaccelerator, a 50 MeV linac, a 30 Hz, 500 MeV rapid-cycling synchrotron, two target stations inside one shield, and the experimental hall containing the neutron beam lines and instruments. The preaccelerator and the linac were originally part of the ZGS facility. The synchrotron was first operated in late 1977. It was used from April 1978 until August 1980 as a proton source for the ZING target, shown in the tunnel above the synchrotron in Fig. 1. The IPNS-I target station and experimental hall shown to the right of the synchrotron are in the final stages of construction and should be in operation by this summer or early fall. The major characteristics of the IPNS-I accelerator are listed in Table 1.

The operation of the accelerator has improved significantly in intensity, pulse rate, and reliability in the three years of operation for the ZING-P' facility. Before the shutdown for the IPNS-I conversion in August 1980, the accelerator delivered 188 million pulses to the ZING-P' target in the 1980 calendar year. This compares to 43 million pulses in 1978 and 113 million in 1979. Reliability increased from 67% in 1979 to 85% in 1980.[4]

The intensity improvements were, in part, the result of programmable power supplies for the sextupole correction magnets. The chromaticity was observed, changing from negative to positive in the region of 14-15 ms after injection. In addition, split electrode measurements indicated time variations of the charge distribution within the RF bucket.[5] Other contributions to the intensity improvement were due to injection and RF capture studies.

Programmable octupole magnets and an improved extraction kicker magnet system are presently being installed. Reliable operation with over 8 μA and efficient extraction at 500 MeV is anticipated after the initial commissioning period with the new IPNS-I target facility.

The IPNS-I target consists of a zirconium-clad uranium target with fifteen horizontal beam tubes for neutron scattering research and a tantalum or uranium neutron irradiation target with four vertical beam tubes for neutron damage research. A prototype for the uranium target was developed on the ZING-P' facility. A liquid hydrogen moderator was tested on ZING-P' and a similar one will be included in IPNS-I.

Table 1. Characteristics of the IPNS-I Accelerator System

Source Current (H^-)	12 mA
Preaccelerator Voltage	750 kV
Linac Energy (200 MHz Alvarez)	200 MeV
H^- Current @ 50 MeV	6-8 mA
Synchrotron	
Type - Strong focussing, combined function	DOFDFO
Average Radius	6.84 m
Number of Periods	6
Magnetic Field (injection/extraction)	0.281/0.98 T
RF Frequency (injection/extraction)	2.91/5.3 MHz
Harmonic Number	Single Bunch
Betatron Tune (ν_x/ν_y) (nominal)	2.2/2.32
Extraction Energy, one turn (nominal)	500 MeV
Pulse Length (nominal)	100 ns
Protons per Pulse (Present Long-Term Average)	$1\text{-}2 \times 10^{12}$
Pulses per Second	30
Average Beam Current (Present Long-Term Average)	6 μA
Peak Beam Current (600 pulse Average)	8 μA

B. KENS National Laboratory for High Energy Physics, Japan

The pulsed neutron source facility (KENS) came on-line on June 18, 1980, at the National Laboratory for High Energy Physics in Japan. The KENS target operates with the 500 MeV proton beam from the KEK booster. The KEK booster is a 20 Hz synchrotron that is shared as the injector for the 12 GeV high energy accelerator and the Booster Synchrotron Utilization Facility (BSF).[6] The effective repetition rate is 16 Hz for the BSF. The KENS target is the only one of the three target stations in the BSF.

The booster presently operates with an accelerated beam of 6×10^{11} protons per pulse, which at 16 Hz is equivalent to about 1.5 μA of time-averaged beam current on target. Neutron beams are provided by a tungsten target and moderators of polyethylene at room temperature and solid methane at 20°K.[7] Thirteen neutron beam holes are installed in the biological shield. Nine of the beam ports are used for neutron scattering studies. The remaining ports are used for the cold neutron experimental area. Major parameters of the KEK booster are provided in Table 2. Figure 2 is a photograph of the main experimental area A at KENS.

An H^- injection scheme is currently under consideration. If implemented, 150 turns at 15 mA of H^- could result in about 5.6 μA of average proton current on target.

Table 2. Characteristics of the KEK/KENS Booster Facility

Injection Energy	20 MeV
Type--Strong Focussing, Combined Function	FDFO
Average Radius	6 m
Number of Periods	8
Magnetic Field (injection/extraction)	0.197/1.102 T
RF Frequency (injection/extraction	1.62/6.03 MHz
Harmonic Number	1
Betatron Tune (ν_x/ν_y) (nominal)	2.2/2.3
Extraction Energy; One Turn	500 MeV
Pulse Length	50 ns
Protons per Pulse (present)	6×10^{11}
Pulses per Second (effective at BSF)	16
Average Beam Current	∿1.5 μA

C. WNR/PSR, LASL, USA

The Weapons Neutron Research facility at LASL has been in operation since 1977. It uses protons at 800 MeV from the LAMPF linear accelerator. The present beam pulse widths are typically around 10 μs. A proton storage ring (PSR) currently under construction will act as an accumulator ring to convert the 100 to 750 μs pulses into submicrosecond pulses.[8] Two different operating modes are under consideration. The long-bunch low-frequency (LBLF) mode is the one most applicable to neutron scattering physics. The proposed LBLF mode would accumulate an entire linac macropulse, bunch it into a single 270 ns bunch and extract it in one turn. The pulse repetition rate would be 12 Hz. The time-averaged current on target would be 100 μA.

The PSR will be a separated function storage ring with an average radius of 14.4 m. It will have ten periods with horizontal and vertical tunes of 3.25 and 2.25, respectively. The injection technique will use an H^- to H^o to H^+ scheme where H^- to H^o transition will be accomplished magnetically and the H^o to H^+ transition will be accomplished with a thin foil. A 2.795 MHz RF cavity will be used for beam bunching in the LBLF mode. One-turn extraction will be accomplished by a TEM transmission-line type ferrite kicker system.

The basic PSR parameters are listed in Table 3. Figure 3 is an artist's conception of the PSR.

The funds for the PSR construction have been released. The expected operational date is 1985.

Table 3. Characteristics of the WNR/PSR Booster Facility

Injection Energy	800 MeV
Type--Strong Focussing, Separated Function	FODO
Average Radius	14.4 m
Number of Periods	10
RF Frequency ∿ LBLF Buncher	2.795 MHz
Harmonic Number	1
Betatron Tune (ν_x, ν_y) (nominal)	3.25/2.25
Extraction Energy; One Turn	800 MeV
Pulse Length (LBLF Mode)	270 ns
Protons per Pulse (estimated)	5.2×10^{13}
Pulses per Second	12
Average Beam Current (estimated)	100 μA

D. SNS, Rutherford Laboratory, England

The largest pulsed spallation neutron project is currently under construction at the Rutherford Laboratory in England.[9] The accelerator is a 50 Hz, high intensity, 800 MeV proton synchrotron. The design intensity is 2.5×10^{13} protons per pulse. Injection will be with H^- ions at 70 MeV. The RF harmonic number will be 1 and the extracted pulse beam width will be 200 ns. It is planned to have a target with two moderators, one at ambient temperature and the other at sub-ambient temperature. Each moderator is expected to serve seven beam tubes and 14 or 15 time-of-flight instruments.

The mean radius of the synchrotron will be 26 m. The synchrotron components are arranged in five superperiods with horizontal and vertical betatron tunes of 4.2 and 3.9, respectively. The maximum RF voltage amplitude is 135 kV with a frequency range of 0.672 - 1.545 MHz.

The linac drift tubes are now being aligned and new modulators for the linac RF system are under test. Twenty of the main quadrupoles and twenty of the trim quadrupoles have been delivered. A prototype bending magnet is expected shortly. The dc portion of the power supply has been delivered and the ac portion is out for tender. Prototype ceramic vacuum chambers with glazed joints have been delivered and assembled on site. The ferrite material for the RF cavities has been delivered and the first RF cavities and first high power RF amplifier will be

Table 4. Characteristics of the SNS Accelerator System

Injection Energy	70 MeV
Type--Strong Focussing	5 Superperiod
Average Radius	26 m
RF Frequency (injection/extraction)	0.672/1.545 MHz
Harmonic Number	1
Betatron Tune (ν_x, ν_y) (nominal)	4.2/3.9 (or 3.4)
Extraction Energy	800 MeV
Pulse Length	200 ns
Protons per Pulse (estimated)	2.5×10^{13}
Pulses per Second	50
Average Beam Current (estimated)	250 μA

completed shortly. An extraction system kicker prototype is under test. Present plans project commissioning of the linac in early 1982 and the first neutron beams in mid-1984, if the funding rate remains adequate.

A photograph of one of the doublet magnets with a trim quadrupole on concrete support base is shown in Fig. 4.

E. SNQ, Karlsruhe and Jülich, West Germany

The most ambitious spallation source project currently under active study is in West Germany. The design teams are from research establishments at Jülich (KFA) and at Karlsruhe (KFK). The design is based on a 1.1 MeV linac capable of producing a peak neutron current of 100 mA in a 0.5 ms on, 9.5 ms off cycle. The time-averaged current on target would be 5 mA.[10] The preaccelerator voltage for the study is 450 keV. The linac design consists of two stages, an Alvarez structure up to 105 MeV and a disk-and-washer structure up to 1100 MeV. Beam can be extracted at 350 MeV.

About 20 MW at 108 MHz of RF peak power would be needed to feed the Alvarez tanks, and about 260 MW at 324 MHZ would be needed to feed the disk-and-washer structures.

A compressor ring is also included as part of the study. The extraction pulse width would be 0.7 μs from the compression ring.

Heat dissipation in spallation targets is a major problem. The SNQ target represents a major challenge, since it must be designed for 5.5 MW of time-averaged beam power. A rotating target system has been conceived for this purpose. The target diameter of the design is 2.5 m and it would rotate at 0.5 Hz. The system uses an H_2O moderator with lead reflector. A photograph of the design concept is shown in Fig. 5.

Table 5. Characteristics of the SNQ Linac System

Alvarez Accelerator	
Injection Energy	0.45 MeV
Extraction Energy	105 MeV
RF Frequency	108 MHz
Length	85 m
Number of Tanks	7
RF Peak Power (during pulse)	21 MW
Disk-and-Washer Accelerator	
Extraction Energies	350,1100 MeV
RF Frequency	324 MHz
Length	405 m
Number of Tanks	57
RF Peak Power	267 MW
Duty Cycle	5%
Pulse Width	500 μs
Repetition Rate	100 Hz

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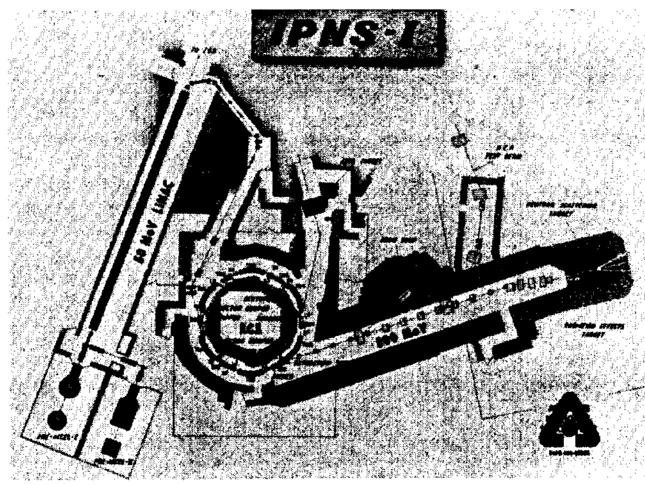

Fig. 1. Overview of the IPNS-I Facility.

Fig. 2. Photograph of Main Experimental Area A at KENS (courtesy of H. Sasaki).

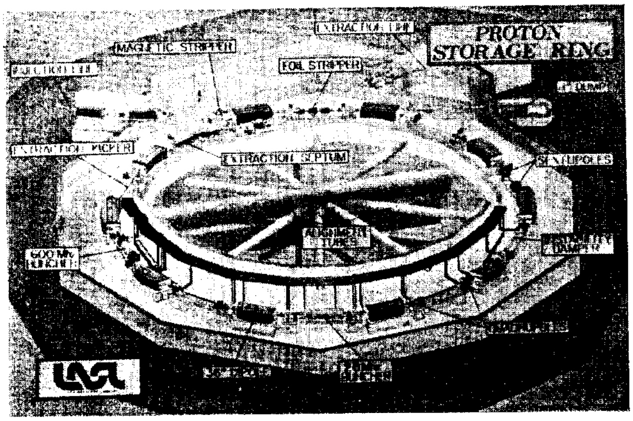

Fig. 3. Artist's Conception of the Proton Storage Ring at LASL (courtesy of R. Cooper).

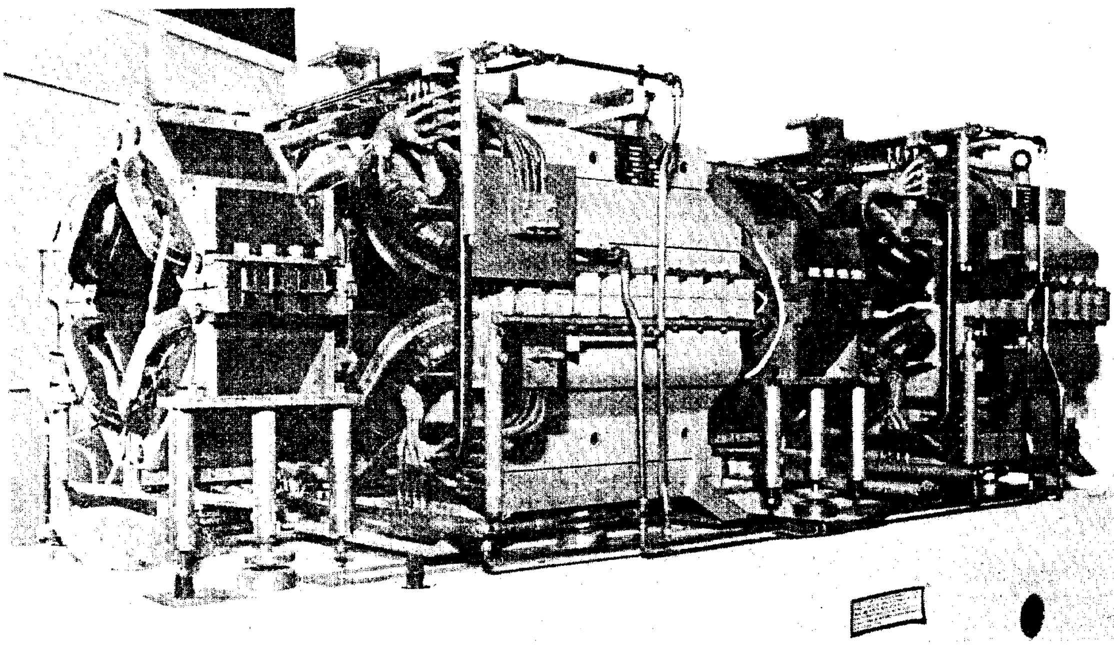

Fig. 4. Photograph of one of the SNS Doublet Magnets with a Trim Quadrupole on a Concrete Base (courtesy of G. Rees).

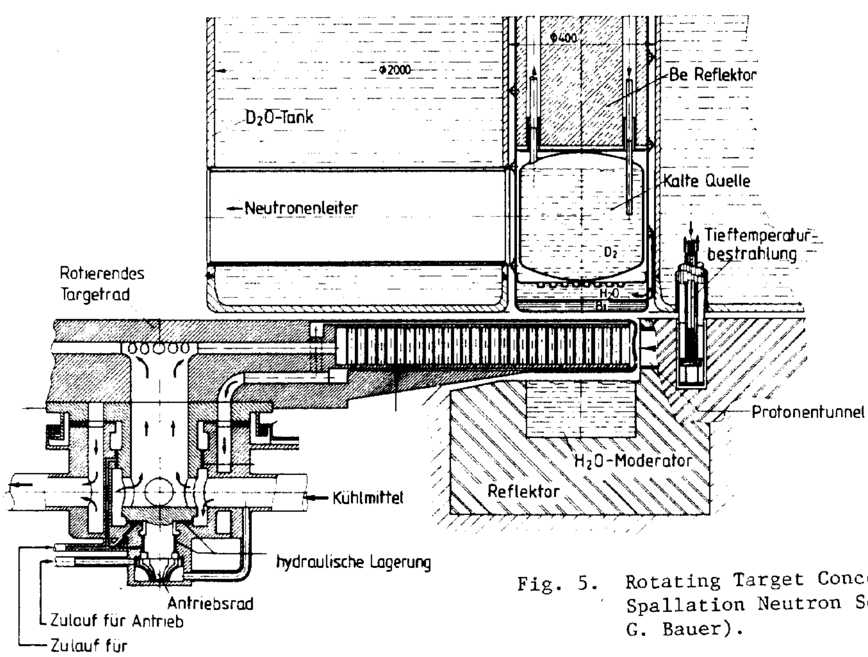

Fig. 5. Rotating Target Concept for the West German Spallation Neutron Source (courtesy of G. Bauer).