A REVIEW OF SPALLATION NEUTRON SOURCE ACCELERATORS

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Abstract

The operational performance of the current Spallation Neutron Sources and their possible upgrades are described. The new sources proposed, including the European Spallation Source, the Oak Ridge SNS and the Japanese proposals are reviewed. The differences in the designs of the accelerators and the methods used to control beam loss are highlighted.

1 INTRODUCTION

Accelerator driven pulsed spallation neutron sources have now been in operation for about two decades and are making significant contributions to forefront topics in neutron scattering science. Most of the sources have upgrade plans that will enhance their performance and some of the upgrades that involve accelerator developments are described.

The next generation of pulsed spallation neutron sources have significantly higher proton beam power and are now being researched, designed, and in some cases, funded. The proton beam powers of 10 - 200 kW achieved with the present sources will be increased to 0.5 - 5 MW in the new sources. In addition to the short pulsed sources, where the proton beam pulse length is about 1µs, long pulse sources with a pulse length of a few hundred micro-seconds are being considered and the CW source, SINQ at PSI, has started operation with a proton beam power of 1 MW at 590 MeV.

One of the most important factors in the design of all spallation neutron sources is the control of beam loss that may lead to activation of, or thermal damage to, the accelerator components. It is interesting to compare the beam loss control methods developed on the current generation of sources with the proposed methods for the new sources.

2 SOME EXISTING SOURCES AND THEIR UPGRADES

2.1 Existing Sources

Table 1 shows the main parameters of existing spallation sources.

2.2 Argonne National Laboratory, US. IPNS

IPNS operates with availability of over 95% for 25 weeks each year and has now been in operation for over 15 years. Although the beam power is only 7 kW the low PRF of 30 Hz, the Uranium Target enhancement factor of 2, and the use of solid methane moderators, provide a very competitive facility. An Enriched Uranium Booster Target has been used in the past to give a factor of 2 to 3 increase in neutron intensity. IPNS decided not to use another Booster Target due to the changes in operation required to deal with the increase in the delayed neutron

Table 1: The main parameters of some existing sources.

	IPNS Argonne USA	KENS KEK Japan	MLNSCE Los Alamos USA	ISIS RAL UK	SINQ PSI Switzerland
Accelerator	50 MeV Linac & Synchrotron	40 MeV Linac & Synchrotron	800 MeV Linac & Storage Ring	70 MeV Linac & Synchrotron	72 MeV Cyclotron & Cyclotron
p Energy (MeV)	450	500	800	800	590
Beam Current (µA)	15	4.6	70	200	1500
Repetition Rate (Hz)	30	20	20	50	Continuous
Beam Power (kW)	6.8	2.3	56	160	885
Injection System	H^- to p Foil	H^- to p Foil	H^- to H^0 Grad Mag H^0 to p Foil	H^- to p Foil	Direct p
Target Material	U^{238}	Tantalum	Tungsten	Tantalum	Zircaloy
No. of n Instruments	15	16	6	17	15
Last year’s beam for n production (mA.hr)	63	4.5	144	672	~500

background and the requirements for dealing with enriched uranium.

An Enhancement Project will increase the productivity by improving the instruments, the accelerator, and the target/moderator/reflector systems. The proposed accelerator improvement will consist of the addition to the synchrotron of an rf system of twice the frequency of the present system. Although this project is not yet funded it is estimated that it will increase the proton beam intensity by 30-50%.

2.3 KEK National Laboratory, Japan. KENS

The KENS facility has been in operation since 1979 and has made a good improvement in beam intensity from 1.10^{12} to 2.10^{12} ppp over the last few years. The Booster Synchrotron produced 14.9 mA.hr of beam last year but the beam is shared with the 12 GeV Synchrotron, a Medical Facility and a Meson Laboratory leaving 4.5 mA.hrs for neutron production. Further work will cover non-intercepting beam profile monitors for the beam transport line, injection painting studies and development of a stripping foil with a single support edge. The main thrust is, however, now directed at the neutron source design for the JHF[1].

2.4 Los Alamos National Laboratory, US. MLNSCE

The MLNSCE Facility operated for 2060 hrs last year and produced 144 mA.hrs of beam. The facility is in the middle of a major improvement programme that is planned to take it to 200 µA beam current at 30 Hz, almost tripling the beam power, and making it one of the most powerful spallation sources available. This is coupled with an increase in the number of neutron scattering instruments from 6 to 14, and modifications of the Target/Moderator/Reflector systems for improved performance and greater ease of maintenance.

Great interest is shown in the performance of MLNSCE as it is based on an 800 MeV linac, capable of operation with a proton beam power of 1 MW, and a storage ring that employs H^- charge exchange injection, and this is the basis of design of several of the proposed, new Short Pulse Spallation Sources.

The present operation is limited to 70 µA beam current at 20 Hz by beam losses. Injection into the compressor ring uses 2 stage charge exchange with 1700 turns. H^- is stripped to H^0 via Stark effect in a high field magnet followed by H^0 to proton stripping in a carbon stripper foil. Studies have elucidated that the beam loss is attributable to “First Turn” losses (0.2 - 0.3 %) where excited H^0 states produced in the stripping foil strip to protons in the downstream dipole and are outside the acceptance of the ring, and to “Stored Beam” losses (0.3 - 0.5 %) from nuclear and large-angle Coulomb scattering produced as the protons in the stored beam pass repeatedly through the foil. The stripper magnet produces a factor of 3 emittance growth in the bend plane due to the statistical spread in the point where the stripping occurs, and this is followed by a large mismatch in the horizontal plane as the beam enters the ring. The H^0 beam, which enters the ring through a hole in one of the main dipoles, Figure 1, cannot be manipulated for painting the beam emittance into the ring.

A new injection scheme using direct H^- injection is being installed and will be commissioned during the summer of 1998, Figure 2. A merging dipole combines the incoming H^- beam with the circulating proton beam and the replacement of the ring window frame dipole downstream of the foil with two C-magnet dipoles allows improved handling of the “First Turn” losses. It is estimated that the stored beam foil hits will be reduced by a factor of 10 and that the overall loss rate will be reduced by a factor of 4 to 5 after optimisation of the foil thickness to reduce the excited H^0 states.

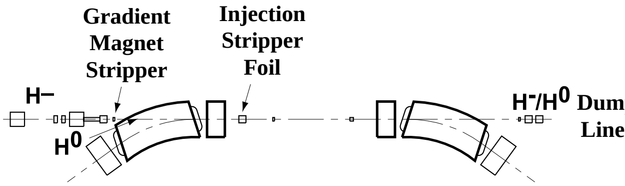

Figure 1. MLNSCE H^- to H^0 to p injection scheme

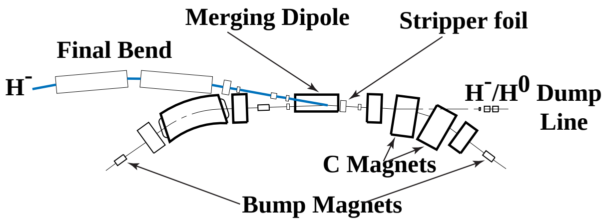

Figure 2. MLNSCE direct H^- injection scheme

A programme to double the Linac current, with a new H^- ion source, will allow shorter ring filling times and thus lower ring losses. This improvement will bring the PSR closer to its high intensity limit, set by sudden, substantial loss of the circulating beam. Interesting measurements show that the threshold for this effect can be altered by the amplitude of the ring rf, by the amount of beam in the gap between the beam bunches, and by the use of an inductive insert in the ring. The effect is thought to be due to an e-p instability, and while the effect will be studied further, it is expected that the introduction of a new ring rf system will allow 30 Hz operation at 200 µA.

Table 2: The main parameters of some proposed sources.

	SNS Oak Ridge USA	JHF KEK Japan	NSP JAERI Japan	ESS Europe	AUSTRON 11 Austria
Injector	1 GeV Linac	0.2 GeV Linac	1.5 GeV SC Linac	1.33 GeV Linac	130 MeV Linac
Ring	1 (2) Storage Rings	Synchrotron	1 (2) Storage Rings	2 Storage Rings	Synchrotron
p Energy (GeV)	1.0	3.0	1.5	1.334	1.6
Beam Current (mA)	1.0 (4.4)	0.2	1 (3.2)	3.7	0.13
Repetition Rate (Hz)	60	25	50	50	25
Beam Power (MW)	1.0 (4.4)	0.6	1.5 (5)	5	0.2
Linac I_{peak} (mA)	130	30	17 (30)	107	33
Linac Pulse (μs)	1000	<500	2000 (3720)	1200	187
Injection System	H^- to p Foil	H^- to p Foil	H^- to p Foil See text	H^- to p Foil	H^- to p Foil
No. Injected Turns per Ring	1200	250	1500 (2777)	1000	126

2.5 Rutherford Appleton Laboratory, UK. ISIS

The ISIS facility operates for 25 weeks a year and averages 90% availability for the accelerator and Target Moderator systems with a beam power of ~160 kW. The operating current is limited by the beam losses, but this limit is very close to the maximum intensity that can be achieved in the synchrotron at present. With the low injection energy of 70 MeV and direct H^- charge exchange injection, the losses associated with the injection process (~1%) are easily catered for with the H^0 and unstripped H^- beam picked up on a collector downstream of the 0.5 μm thick aluminium oxide foil. Up to 10% of the circulating injected beam is then lost in the trapping process and this beam is lost over the first 2.5 ms of the 10 ms acceleration period. The horizontal and vertical closed orbits of the synchrotron are minimised and adjusted to ensure that this lost beam is picked up on the 3 horizontal and 3 vertical, adjustable beam collectors, placed in the long straight section one superperiod downstream of the injection superperiod. A limit of 10 nA is set for the loss that occurs at the extraction septum magnet during beam extraction. Operation of the synchrotron can be limited by this loss. The rf trapping and the extraction loss are under study and this has highlighted the need for improved beam diagnostics for high intensity machines, to enable the behaviour of the small amounts of beam at the edges of the beam distributions to be studied.

Possible upgrades for ISIS include the addition of a second synchrotron rf system operating at twice the frequency of the present system and the addition of a second low frequency Target Station. Studies indicate that the new rf system will increase the beam current by up to 50% and the low frequency Target Station will enable increased neutron instrumentation specialising in the use of cold neutrons.

3 A COMPARISON OF PROPOSED SOURCES

3.1 General Design Considerations

Several new sources are under consideration and Table 2 lists some parameters of some of the proposed new sources. The high power spallation source designs include a linac and storage ring(s) as in ESS, ORNL SNS and JAERI NSP or a linac and synchrotron as in JHF and AUSTRON ll. For the ESS a two synchrotron option was considered and would have been selected if the higher proton beam energy of 3 GeV had been needed for the target design. However, the synchrotron option was discarded because of its greater complexity and the higher space charge levels at low energies. The complexity is partly due to the large rf systems required and this was not considered to be offset by the benefits of less severe heat related problems for the H^- stripping foils and for the 50 Hz target.

The proton beam pulse length at the target must be of the order of 1μs to retain a sharp enough neutron pulse and this sets the total circumference of the synchrotron or compressor rings. Transverse stability criteria set the maximum circulating current in the rings. H^- charge exchange injection must be used for low enough losses from the necessary multi-turn injection process. The proton energy must be greater than 1 GeV to reach the plateau for neutron production per watt of beam power and to achieve acceptable energy density in the target. The loss mechanisms associated with the stripping foil, the peak foil temperature, and the need to move the circulating beam off the foil limit the number of injected turns to about 1000 per ring, thus setting the peak linac current required. This current is further increased by ~65% by the need to retain a gap in the circulating beam in the compressor rings for the rise time of the fast extraction kicker magnets. The gap is produced by a beam chopper, at the ring rf frequency, in the low energy end of the linac. For the Oak Ridge SNS and the ESS this means peak linac H^- currents in excess of 100 mA. The achievement of such high currents, with low enough emittance to be transmitted through the linacs and with losses of less than 1 nA/m, infers the use of linac funnelling. The use of a funnel also allows twice the number of rf cycles to be filled with beam where the linac high energy section operates at a higher harmonic of the low energy sections.

3.2 Injection Schemes

The reference design for the ESS is described in [2]. Injection features simultaneous painting in all three phase planes of the two compressor rings to achieve low loss. A momentum ramp is produced by a cavity at the end of a 100m drift section following the linac. The beam then enters a 180° achromatic bend. The parameters of the drift section and the achromatic bend enable the beam to be scraped by stripping foils in the horizontal, vertical and momentum planes, ensuring that only beam of the specified parameters is delivered to the rings. The beam from the scrapers is taken to substantial, shielded beam dumps.

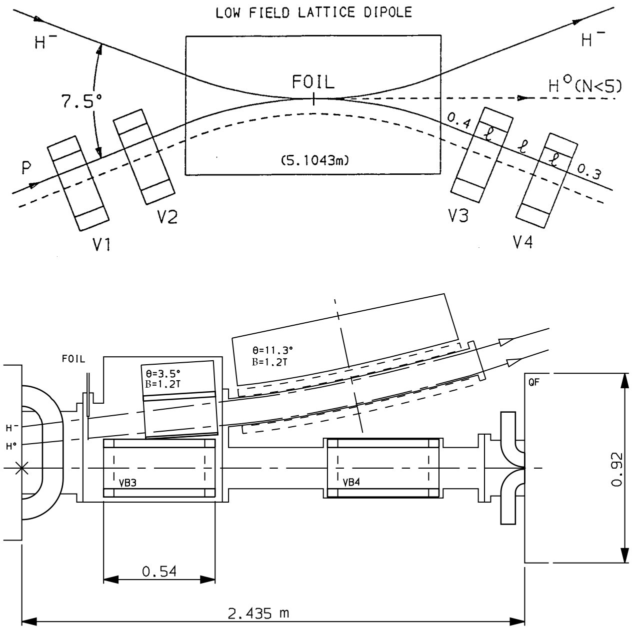

Figure 3. The ESS ring injection scheme.

Injection takes place in a low field bending magnet, Figure 3, to ensure that the unstripped H^- beam, and the H^0 beam and its excited states, are brought out of the ring to beam dumps or are accepted within the ring. Beam that is scattered by Coulomb interactions and nuclear interactions in the foil and the generated momentum tail is caught by downstream collectors [3]. A foil with two free edges is used and the circulating beam is moved progressively away from the foil by programmed currents in vertical orbit bump magnets and by changes to the frequency of the dual harmonic ring rf systems. Foil hits are estimated at less than seven per circulating proton, by the computations carried out allowing for full space charge effects [4]. However, foil temperature estimates are still seen to be near the limit and larger circumference rings are now being considered allowing the use of foil stripping or the new JAERI laser stripping mentioned below.

The Oak Ridge SNS is described in [5] and the injection scheme differs from that proposed for the ESS in that the H^- beam is merged with the circulating proton beam at a foil between a horizontal orbit bump magnet and a ring quadrupole. No momentum ramping is proposed and the pre-ring scraping is carried out in a 90° achromatic beam transport line. Figure 4 shows the layout of the low dispersion injection straight.

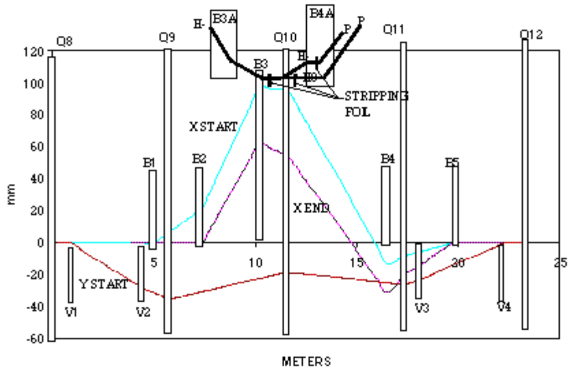

Figure 4. The Oak Ridge SNS ring injection scheme.

The JAERI NSP [6] considers foil stripping for the reference design but also studies a new concept of Laser stripping [7]. A section of an undulator magnet provides Stark stripping of the incoming H^- beam to H^0. The H^0 beam then drifts into the ring straight section where it is repeatedly excited to $H^0(3)$ by a laser and then stripped at the peak fields in a 7 period undulator magnet. It is estimated that each undulator half period will convert just under 50% of the H^0 beam present to $H^0(3)$ for high stripping efficiency. A pulsed laser of 1.5 kW power in conjunction with an optical resonator is assumed. The laser frequency and bandwidth must be matched to the energy and momentum spread of the incoming H^- beam.

A compressor ring lattice that includes both the JAERI Laser stripping scheme or the ESS foil stripping is being studied for the ESS, a section of which is shown in Figure 5.

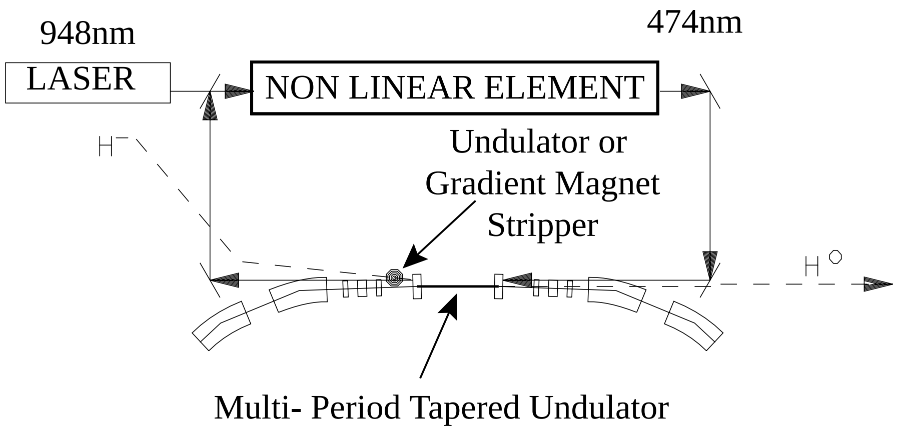

Figure 5. Elements of the JAERI Laser stripping scheme with Laser frequencies suited to ESS

Table 3. High current linac accelerating sections and frequencies

	RFQ		**DTL**		**CCDTL**	**CC Linac or Superconducting Linac**	
ORNL SNS	402.5		402.5	Funnel	805	805	MHz
APT US, France	350		350			700	MHz
JHF	324		324		-	972	MHz
ESSA	280		280	Funnel	560	560	MHz
ESS	175	Funnel	350		-	700	MHz
JAERI	200		200		-	600	MHz

3.3 Funnels and Choppers

Continuing studies on the ESS predict a 30 % emittance growth in the reference design beam chopper and angular dispersion in the funnel section. An alternative linac design (ESSA) is being considered and tests will also be made on a Funnelling RFQ at Frankfurt JWG University. The result of the studies and tests may be applicable to other high current linacs. The rf frequencies and linac accelerator sections for proposed high current linacs are shown in Table 3.

4 TIME SCALES

Of the new sources the ORNL SNS has the most clearly defined programme and is aiming for a phased approach that will deliver 1MW operation with one ring by 2006. The subsequent upgrades will take it to 4.4 MW with two rings.

The ESS has now entered a three year R&D phase which is a collaborative effort with several European Institutes. It is anticipated that this phase will be followed by a seven year construction period making the earliest operation at least ten years from now.

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