THE SPALLATION NEUTRON SOURCE PROJECT[*]

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Abstract

The SNS is a "joint-venture" project of five DOE National Laboratories, aimed at building the world's most powerful accelerator-based pulse spallation source. At its planned 2 MW operation, it will produce neutron fluxes at least a factor of ten greater than Rutherford Appleton Laboratory's ISIS, currently the world's leading spallation source. The current design of the SNS, shown in Figure 1, calls for 600 ns pulses of 1 GeV protons striking a liquid mercury target at a 60 Hz rate. Room-temperature and cryogenic moderators produce beams of slow neutrons suitable for materials research. Responsibility for system components is as follows: LBNL will provide the high-brightness H^- ion source, transport structures and a 2.5-MeV RFQ accelerator; Los Alamos will build linacs to bring the beam to the full energy of 1 GeV; Brookhaven will build the accumulator ring to compress the 1 ms linac pulse into the sharp pulse delivered to the target; ≈1200 turns will be injected, storing $2x10^{14}$ protons in the ring, which are extracted in a single turn; Oak Ridge will provide the mercury target systems and all conventional facilities; and Argonne and Oak Ridge are coordinating the design of at least 10 neutron-scattering instruments to be provided as the initial suite of experiment stations. The project is formally underway, having been approved and funded by DOE and the US Congress for a construction start in FY99. Neutron beams will be available for users in FY06.

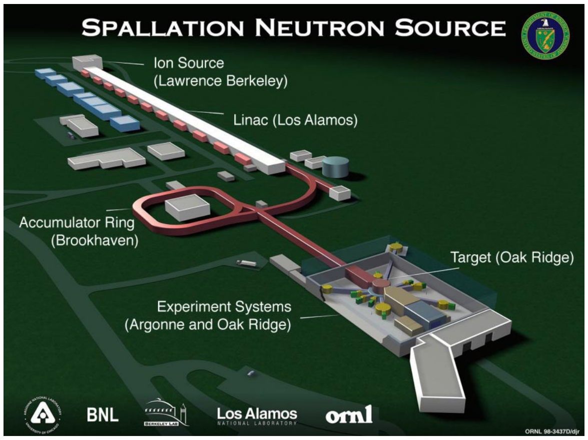

FIGURE 1: Schematic layout of SNS

1 BEAM REQUIREMENTS

Neutron scattering requires low energy (< milli-electron volt) neutrons, to obtain De Broglie wavelengths commensurate with the size of the structures being studied. Of critical importance is the ability to select or measure the wavelength of the neutrons impinging on and scattered from the sample. Accelerator-based sources of these neutrons offer advantages over reactors deriving from the ability to deliver sharp pulses (< 1 μs) of protons to a neutron-producing target. This leads to excellent timing of the neutrons arriving at the sample, as the neutron flight times are considerably greater than 1 μs, thus allowing for an easy determination of the neutron wavelength by a time-of-flight velocity measurement.

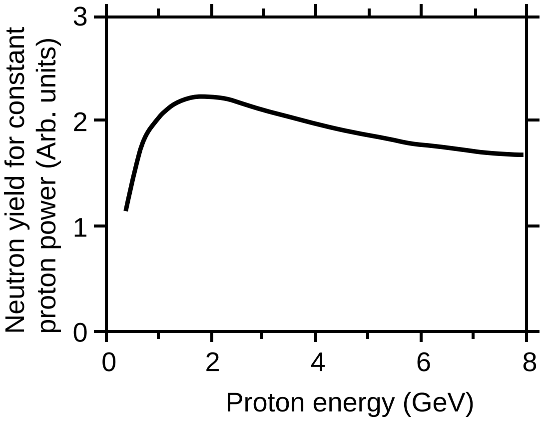

FIGURE 2: Neutron yield as a function of proton energy, for constant proton power deposition on target

Proton energies in the range of 1 to 3 GeV prove optimal for neutron production via spallation reactions in heavy-metal targets, and production rate is directly related to the power deposited on the target[1]. This is illustrated in Fig. 2, where, for instance the requirement of constant proton power means that for 2 MW on target, a 2 mA average beam current at 1 GeV will produce approximately the same neutron yield as would 1 mA of average beam current at 2 GeV.

The sharpness of the "start" signal of a time-of-flight measurement is dominated by the characteristics of the slow neutron pulse emerging from the moderators toward the measurement instruments. Neutrons are produced in the target at energies in the MeV (million-electron-volt) range through nuclear spallation reactions, but for neutron scattering applications the neutron energies must be reduced to the meV (milli-electron-volt) range. This is accomplished through multiple collisions in low-Z moderators, and the velocity distribution is ultimately determined by the temperature of the moderator. Moderators of water at room temperature and liquid methane or liquid hydrogen at cryogenic temperatures are most often used. Figure 3 shows calculated time-distribution widths of neutrons emerging from room-temperature moderators[2], assuming an instantaneous production pulse. The full-width at half-maximum (W) for energies below 10 meV is greater than 10 micro-seconds. Therefore, a proton pulse on target of length 1

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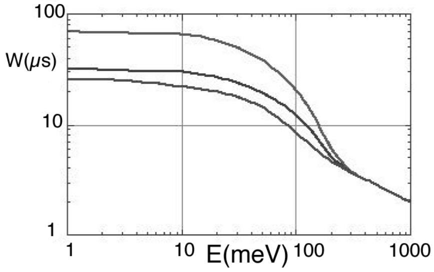

FIGURE 3: Time widths W (FWHM) of neutrons emerging from a room-temperature water moderator, for (top-to-bottom) coupled, decoupled and decoupled-poisoned conditions.

microsecond or less will not appreciably increase the width of the effective start pulse for all but the highest-energy neutrons.

The desired velocity of the neutrons emerging from the face of the moderator is about 1000 meters per second or less. Because typical flight paths from moderator to instrument are 10 to 50 meters, the sensitive time range for neutron measurements will be from a few to a few tens of milliseconds. The requirement of resolving these pulses restricts the pulse-repetition rate for the accelerator to at most a few tens of Hertz. To maximize total power it is desirable to have the highest-possible repetition rate. However for slow neutrons one must deal with the "frame-overlap" problem (Fig. 4) in which slower neutrons from an earlier pulse could arrive at the same time as faster neutrons from a following pulse, thus confusing the interpretation of measurements.

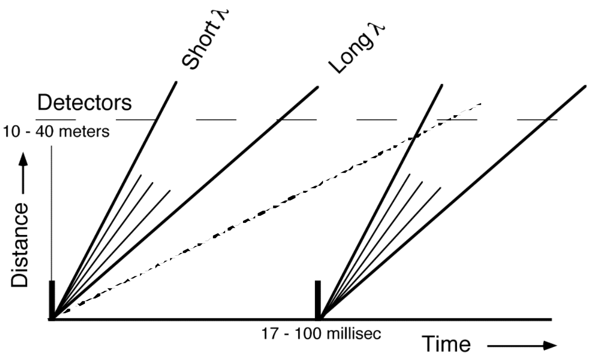

FIGURE 4. Schematic showing arrival time of different neutron wavelengths at a detector located several tens of meters from the source of neutrons. Dotted line shows trajectory of a slow neutron that could be confused with a faster neutron from following pulse.

Optimization of neutron beam lines includes use of mechanical neutron choppers to define time windows in which neutrons are accepted into the line, and also careful selection of the repetition rate of beam on target. The most productive neutron-scattering facility should include at least two target stations receiving beam at different repetition rates to provide optimized neutron fluxes in different wavelength ranges.

2 SPECIFICATIONS FOR THE SNS

The current technical design calls for the linac to produce full-energy (1-GeV) beam at the required current level for an average power of around 2 MW, in the form of 1 millisecond pulses at a 60-Hz rate. An accumulator ring (AR) will effect the current amplification needed to deliver to the target these pulses in the sub-microsecond time frame required. For a 60-Hz cycling rate, approximately 34 kJ per pulse is required; or, a peak-current of about 60 amperes for 600 nanosecond pulses. The current amplification required is about a factor of 1000, using conservatively achievable peak linac currents in the tens-of-milliampere range. The very high instantaneous power levels, close to 60 GW, cause concern about shock loads on the target. Use of liquid metal, specifically mercury, is viewed as the best way of mitigating this problem. Table 1 summarizes the basic parameters for this baseline design.

Table 1. SNS Baseline (AR) Design Parameters

Beam Species on Target	Protons
Proton Beam Energy	1 GeV
Average Beam Power	2 MW
Pulse Repetition Rate	60 Hz
Linac Pulse Length	1 ms
Turns Injected in Ring	1200
Particles Stored in Ring/pulse	2 x 10^{14}
Pulse Width on Target	600 ns
Instantaneous Current on Target	≈60 A
Instantaneous Power on Target	≈60 GW
Target Material	Flowing Mercury
Moderators, Ambient Temp	2 (water)
Moderators, Cryogenic	2 (Supercritical H_2)
Neutron Beamlines	18
Uncontrolled Beam Loss	< 1 watt/meter

An alternate technology approach is to use a lower-energy linac and a rapid-cycling synchrotron (RCS) to raise the beam to the GeV energy range. Linac energy would be between 300 and 500 MeV, the final RCS energy between 2 and 4 GeV. An example of such an approach can be seen in the IPNS-Upgrade Proposal[3]. Optimization studies performed two years for the SNS ago led to selection of the AR as the preferred technology. The somewhat higher cost (≈15%) of this option was offset by the greater flexibility for power-upgrades and perceived lower technical risk. The new management team of the SNS project is considering re-opening the technology choice question, with the possibility of a baseline change. This paper will concentrate on the present AR baseline, and will describe the specific element design choices and progress towards solving physics and engineering issues associated with this technology option.

Note, the last line in Table 1 represents one of the biggest challenges in the design of the SNS. It represents a fractional uncontrolled beam loss of less than 1 x 10^{-4} over the whole length of the accelerator and transport lines. This very low loss is required to ensure that activation and residual-radiation levels in the tunnels are low enough to allow quick access and hands-on maintenance, and is driven by the very high reliability and availability specifications associated with the strong user-orientation of the SNS facility. Areas where unusable beam is diverted (so-called "controlled" beam-loss points), such as collimators, scrapers and dumps, must be designed to collect these particles in a way that does not contribute to background levels in the tunnels where access is required. Normal loss mechanisms must receive particular attention to meet this specification. This implies very tight control over beam emittance, and emittance growth; designing for the largest-possible stay-clear apertures in linac, transport and ring structures; understanding of space-charge and halo effects in linac and ring; ensuring highest-possible vacuum in areas where H^- beam is transported to avoid stripping losses; extremely careful design of ring injection system and painting to ensure minimizing production of, and clean separation of H°*, and the minimum number of foil traversals of the circulating proton beam; understanding potential ring instabilities associated with the very high stored number of protons. In addition, operational issues of stability in power supplies, efficient tuning and feedback algorithms, quick turn-on and rapid tune-up procedures, high-quality diagnostics, and extremely high reliability of all components all add to the challenge of the SNS design.

Rising to these challenges, substantial progress has been made along all fronts of the systems design, this progress is highlighted in the following sections. Numerous papers in this conference cover details of all these systems, this paper summarizes principal features.

3 FRONT END

Figure 5 shows a schematic of LBNL's Front End systems[4] consisting of a volume-production H^- source coupled to the RFQ by a short (≈10 cm) electrostatic einzel-lens LEBT (Low-Energy Beam Transport), the RFQ itself accelerating the beam to 2.5 MeV, and the MEBT (Medium-Energy Beam Transport) that matches the RFQ beam to the following DTL, and houses the primary chopping system.

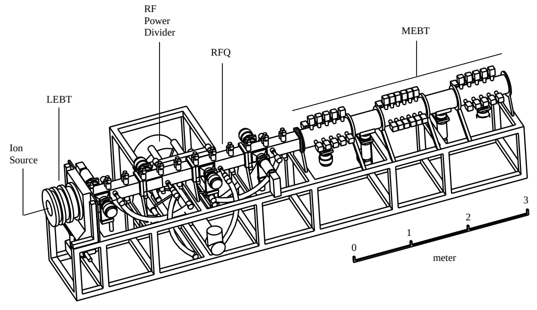

FIGURE 5: Schematic of Front End, showing ion source, LEBT, RFQ and MEBT.

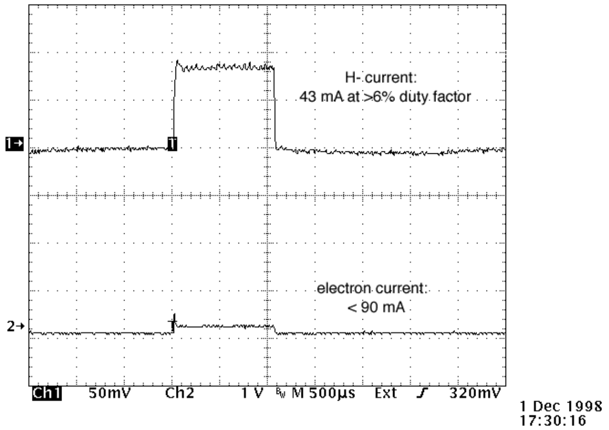

FIGURE 6: Trace from R&D #1 ion source

The source, similar in concept to that delivered by the LBNL group for SSC[5], and which operated at currents over 100 mA (but 10^{-3} duty factor), is being engineered for currents ultimately up to 70 mA at a 6% duty factor. The trace shown in Figure 6 shows the current state of the R&D source, running with Cs, showing a very quiet, reproducible pulse of 43 mA at 12% duty factor. This is well above levels needed for 1-MW operation; and it is expected that this source, with some further development, will reach the 70 mA needed for 2-MW operation[6]. The LEBT concept[7] is based on the successful model built by the same group for transport of positive ions, which demonstrated excellent beam-forming, transmission and emittance characteristics. The RFQ[8], operating at 402.5 MHz, is 3.8 meters long and is built in four roughly equal-length modules. Cold-model tests of this structure, using the pi-mode stabilizer concept developed by Ueno[9], demonstrates excellent field uniformity. A prototype full-power module of the RFQ is under fabrication.

Chopping is an essential part of the beam formation for the SNS. Generating longitudinal holes in the beam, of periodicity corresponding to the ring revolution frequency (1.19 MHz) and of approximately 250 ns length, is critical to minimize losses during the single-turn extraction from the accumulator ring. As this process requires removal of about 35% of the beam, it must be done where the beam energy is below the Coulomb barrier, so no activation will occur. Location of the main chopper is in the MEBT, where beam energy is 2.5 MeV. However, the amount of beam to be removed, and the very tight constraints on space available and small beam size represent an extremely high power density on the MEBT scraper, leading to difficult materials problems. To mitigate this, the beam will be pre-chopped in the LEBT, using the split einzel-lens electrodes to steer the unwanted beam onto slits at the RFQ entrance. Excellent progress is being made with this LEBT pre-chopper[10], good risetime (<20 ns) and extinction factors have been achieved, significantly easing the performance requirements from the MEBT chopper system. The desired risetime for the MEBT chopper should be in the few-nanosecond range, to minimize or better yet to eliminate any partially-chopped rf bunches that would be transported down the linac. At 402.5 MHz, these bunches come every 2.5 ns. A partially-chopped bunch will have its centroid substantially displaced from the central axis of the beam, thus potentially leading to large beam losses in the linac. To mitigate this, an "anti-chopper" is included in the second half of the MEBT, to balance the offset introduced by the first chopper for such partially-chopped bunches. Good progress with these chopper designs, both structure and pulsers, is being made by the LANL team responsible for this hardware.[11,12]

4 LINAC

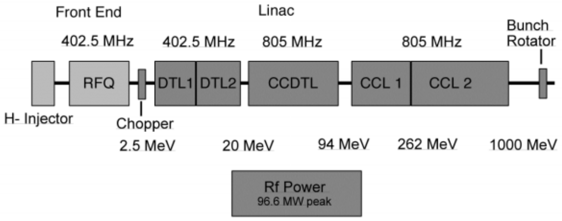

FIGURE 7: Schematic (not to scale) of SNS linac configuration

Figure 7 shows LANL's configuration of the linacs that accelerate the beam from 2.5 MeV to 1 GeV[13,14]. The DTL (Drift-Tube Linac) operating at 402.5 MHz accelerates the beam to 20 MeV, a CCDTL (Coupled-Cavity Drift-Tube Linac) at 805 MHz accelerates the beam to 94 MeV, and CCL (Coupled-Cavity Linac) structures accelerate the beam to 1 GeV. Careful attention is paid to smooth FODO lattice transverse matching at all stages to prevent growth of beam halo. Periodicity is 8 $\beta\lambda$ (at 805 MHz) for the DTL and 12 $\beta\lambda$ for the CCDTL and CCL. CCDTL segments contain two 3/2 $\beta\lambda$ cells, while the CCL is divided into two parts, the first part, to 165 MeV, contains eight cells per segment; the higher energy part has 10 cells per segment. This arrangement allows ample room in the spaces between segments for the quadrupole, plus appropriate diagnostics, correctors and vacuum interfaces. Focusing in the DTL is accomplished with permanent magnet quadrupoles arranged in a FFDD configuration to more closely match the periodicity of the following structures. Very large apertures are provided to contain potential beam-radius or halo growth. The aperture to rms beam radius is over a factor of 10 at the higher energies.

RF power is provided by 66 2.5-MW klystrons, delivering a conservative 2.02 MV/m real-estate accelerating gradient[15]. E_oT in the cavities averages 2.7 MV/m. A novel pulsed HV power supply concept based on IGBT technology is being incorporated[16], which will significantly cut costs for the RF system by combining the HV supply, capacitor bank, crowbar system and modulator into a single pulsed supply.

Physics design is essentially complete, including error studies. Engineering design is commencing, plans for cold and hot models are progressing and these models will be ready by the summer of 1999.

5 RING AND TRANSPORT SYSTEMS

Brookhaven National Laboratory will provide the components shown in Figure 8: the HEBT (High-Energy Beam Transport) between the linac and the ring, the accumulator ring and the Ring-to-Target Beam Transport line, RTBT. The HEBT has a straight matching section, a 90° achromatic momentum analysis section, and a further matching section into the ring injection region. The 4-fold symmetric ring provides achromatic bends to the 4 zero-dispersion straights, for injection, collimation, RF and extraction. Horizontal and vertical tunes are 5.82 and 5.80. The RTBT line[17] takes the beam, extracted in a single turn by the kicker system, to the target. Beam is shaped on the target as a 7 x 20 cm rectangle, of roughly uniform density, to prevent hot-spot power deposition in the window and target.

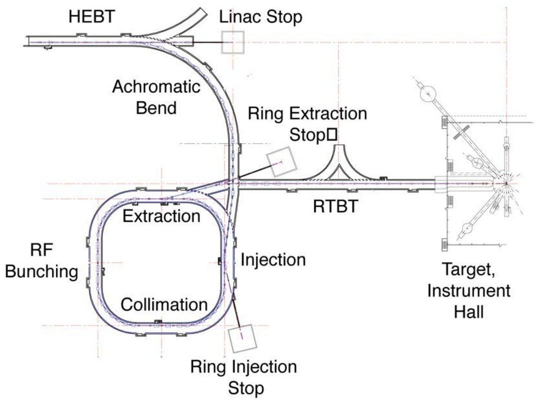

FIGURE 8: Schematic of accumulator ring and transport systems.

The collimation straight section contains the principal aperture restriction for the ring, in a location where little hands-on maintenance will be required. The collimators. are designed[18] with graded low-Z and high-Z materials, so that protons penetrate deeply inside the 3-meter long structures before reacting, and neutrons are largely contained inside the structure. Calculations show that only one neutron emerges from the collimator for every 100 entering protons.

The injection region has been optimized to minimize beam losses[19]. By placing the stripping foil in the falling fringe-field of the combining dipole, halo in the ring due to Lorentz stripping of $H^{\circ *}$ is minimized. A tracking code developed at ORNL models the injection process, that accounts for space charge effects during stacking in the ring, and has been used in analyzing injection to minimize emittance and halo growth[20,21]. Note too that beam stacking in the ring is a dominant factor in the power density distribution on the target.

The ring RF is a dual harmonic system, with a peak amplitudes of 40 kV for first harmonic and 20 kV for second harmonic cavities. These voltage levels will ensure a high bunching factor, and good capture and retention of particles in the bucket. Cleanliness to better than 1 part in 10^4 of the 250 ns gap is necessary both for prevention of losses during the excitation of the extraction kicker, and to prevent buildup of electrons in the very deep potential well of the circulating beam. This has been identified as a potential cause of the observed instability in the Los Alamos PSR ring.

Extraction is performed via an 8-segment full-aperture fast kicker system, providing a vertical offset to the beam. A Lambertson magnet bends the beam into the RTBT channel. Beam shaping onto the target is performed with the last five quadrupoles in the line. However, beam distribution within the rectangular profile on the target is largely determined by the phase-space distribution of the beam just after injection has been completed in the ring, and so will be determined by the bump magnets controlling the stacking of beam into the ring.

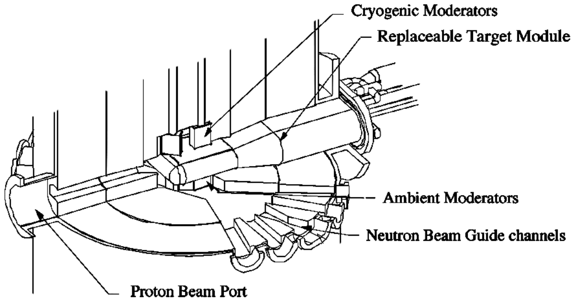

FIGURE 9: Schematic of mercury target and moderator assemblies

6 TARGET

Figure 9 shows ORNL's mercury target, moderator and neutron beam-channel configuration. Mercury flows in from the lateral edges of the stainless vessel and around into the main body of the vessel. Flow rate is such that at full beam power temperature rise is only 30°C. Two room-temperature water moderators, below the target plane, and two super-critical hydrogen (20 K) moderators, above the target plane, deliver neutrons through the 18 beam ports to the experimental floor. Easy replacement of target and moderator assemblies is a design requirement, to assure minimum interruption of experimental programs for maintenance.

An ongoing R&D program is addressing important design issues. Experimental measurements and modeling codes are being used to examine materials effects, testing the impact of radiation in the presence of mercury on different containment materials, studying wetability, embrittlement and ductility. Hydrogen and helium formation is known in spallation processes to be significantly greater than experienced in reactor environments, and can have an adverse effect on target component lifetimes. Various mercury loops are also being built to study thermal hydraulics, flow of mercury through the target head geometry, as well as leaching of materials, such as nickel, from the containing 316 SS vessel. Shock effects and neutronics yields for mercury systems are being studied by an international collaboration[22] through accelerator tests and modeling. All these activities are beginning to yield good understanding of the proposed target design.

7 INSTRUMENTS

Neutron scattering instrumentation will be the heart of the SNS. As a dedicated user facility for the materials-sciences community, of paramount importance will be the ability to measure the detailed interaction of the neutrons produced with the samples brought by the experimenters. While an extensive body of instruments exists today at the various operating spallation sources, the challenge is that the fluxes from the SNS will be considerably higher than those for which the present-day instruments have been designed. It is expected that significant advances will be needed in neutron detectors, guides, neutron choppers and other elements of the instrumentation to make optimum use of the SNS beams. As a result, R&D efforts in all these areas are being planned.

ANL has primary responsibility for instrument development, in collaboration with ORNL. Instruments will be built by SNS neutron scientists at ANL, ORNL and possibly other sites, with close contacts to the neutron-scattering community through appropriate oversight and advisory committees.

8 CONTROLS

EPICS has been selected as the basis for the controls systems for all elements of the SNS, including the conventional facilities. This system now has a proven track record, having been successfully implemented at CEBAF and APS as well as at numerous other smaller installations. Notable in this project is the need to tightly coordinate controls activities across all the laboratory boundaries. To this end a very active Global Controls Working Group has been formed, with LANL taking the lead, and with representatives from all the labs[23]. This group has been working through architectures, naming conventions, interface definitions and general implementation strategies. This Working Group is serving as a model for collaboration and interfacing in many other technical and managerial areas of the project.

9 SUMMARY

The present technical design has reached a sufficient level of maturity to have received endorsement from many internal and external review teams. As stated earlier, a new management team is currently undertaking assessments to decide whether to adopt this design as the project baseline, or to re-open different design options. The project, nonetheless, has received, for FY99, line-item authority and funding to begin Title I work, and is being held to the approved cost of $1.36B and scheduled completion date of December 2005. There are obviously very significant challenges ahead for the project.

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[1] "Los Alamos Next-Generation Spallation Source," LA-UR-95-4300, Dec 1995, Vol 1, Figure 3-12, page 3-20

[2] NSNS Conceptual Design Report, Section 5, p. 5-97, NSNS-CDR-2,V1, ORNL, May 1997.

[3] IPNS-Upgrade Proposal, ANL-95/13, April 1995.

[4] R. Keller, MODR1 this conference

[5] K. Saadatmand et al, PAC93, IEEE 93CH3279-7, p. 2986.

[6] M. Leitner et al, WEA13 this conference

[7] D.W. Cheng et al, WEA34 this conference

[8] A. Ratti et al, MOP92 this conference

[9] A. Ueno et al, LINAC90, LANL Pub, LA-12004-C, P. 57

[10] J.W. Staples et al, WEA32, this conference

[11] S.S. Kurennoy, J.F. Power, TUA139 this conference

[12] J.F. Power, S.S. Kurennoy, TUP7 this conference

[13] N.K. Bultman et al, FRA86 this conference

[14] T.S. Bhatia et al, LANL Preprint LA-UR-98-3595

[15] M. Lynch et al, THBL5 this conference

[16] W.A Reass et al, THAL4 this conference

[17] D. Raparia et al, TUA94 this conference

[18] J. Beebe-Wang et al, THP98 this conference

[19] J. Beebe-Wang, Y.Y. Lee, TUP113 this conference

[20] J.A. Holmes et al, TUAL1 this conference

[21] J.D. Galambos et al, THP81, THP82 this conference

[22] ASTE Collaboration (Jülich, PSI, JAERI, BNL, ORNL) J. Hastings (BNL) spokesman

[23] W.R.Devan, D.P.Gurd, J.P.Hammonds, S.A.Lewis, J.D.Smith, WEDL1 this conference