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3. THE US SPALLATION NEUTRON SOURCE (SNS) PROJECT*

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ABSTRACT

The SNS is a 1 MW pulsed spallation neutron source that will be sited at Oak Ridge. It will consist of a high-current, normal-conducting linac accelerating an H^- beam to 1 GeV, an accumulator ring which compresses each 1 ms linac pulse into a 600 ns bunch which is then extracted in a single turn onto a liquid mercury target. Neutron pulses emerge at a 60 Hz rate from the two ambient, and two cryogenic moderators. 18 beam ports surrounding the target station are available for neutron-scattering instrumentation. Funds for ten instruments are included in the construction project; these instruments will provide basic measurement capability for the many and varied research activities at the SNS facility. The new spallation source is being built by a consortium of laboratories; the partners are LBNL, LANL, BNL, ANL and ORNL. The breadth and depth of experience and resources brought by such a wide-spread team offers very significant advantages. Construction will start in October of 1998, operation will begin in October, 2005.

1 INTRODUCTION

A collaboration of five Department of Energy National Laboratories is designing the SNS, a 1 MW pulsed spallation source to serve the neutron-scattering community. An important requirement is a clear upgrade path to "significantly higher powers." Responsibilities for system components are as follows: LBNL will provide the front end, consisting of a high-brightness 35-mA H^- ion source, as well as transport structures and a 2.5-MeV RFQ accelerator; Los Alamos will provide linacs to accelerate the beam to the full energy of 1 GeV; Brookhaven will provide the accumulator ring to compress the linac beam into the sharp pulse delivered to the target ($\approx$1200 turns will be injected, storing $1x10^{14}$ protons, which will be extracted in a single turn); Oak Ridge will provide the mercury target and all conventional facilities; and Argonne and Oak Ridge are coordinating the design and construction of 10 neutron-scattering instruments to be provided as the initial suite of experiment stations.

A well-defined upgrade path has been identified: a) a second target station, operating at a lower frequency (10 Hz) will complement the initial 60-Hz target, and will allow optimization for very low energy neutrons and high-precision, long-flight path instruments; b) two stages of power upgrade, first to 2 MW then to 4 MW are planned that will bring the neutron fluxes up to levels expected for the fully-developed facility. The first stage of power upgrades is accomplished by increasing the ion source current from 35 mA to 70 mA and adding extra rf power to the linac. The second power upgrade, to 4 MW, is accomplished by funneling the front end (two 70 mA ion sources, and two RFQ-DTL systems, each operating at 402.5 MHz combining -- at the 20 MeV point -- into the CCDTL at 805 MHz), and by building a second ring in a separate tunnel, and a complex switchyard capable of extracting both rings simultaneously onto either of the targets. An upgraded target, suitable for 4 MW of power, will also be developed. A key strategy for the upgrade process is that any shutdown will not be greater than six months, in order to minimize the impact on research operations of the facility. This has been an important consideration in selecting the full-energy linac concept, as well as the plan to construct a separate tunnel to house the second ring.

The Conceptual Design Report (CDR) was reviewed by DOE in June 1997, and was accepted as the baseline design. Legislative approval and funding for a construction start is expected for FY99, the construction period will last seven years.

2 BACKGROUND

The SNS Collaboration was formed in late 1995 in response to a request by DOE that Oak Ridge National Laboratory conduct a two-year study of an optimized and upgradable 1 MW spallation neutron source. With ORNL leading the consortium of five laboratories, these studies have resulted in the design published in the SNS Conceptual Design Report [1], and now to the imminent start of the construction of a new world-class facility for neutron sciences.

The CDR underwent an extensive DOE review in June 1997, the favorable outcome of which led to funding in FY98 to continue optimization studies for a potential construction start in FY99. With strong support from within DOE (the SNS is DOE/ER's number one priority for new construction starts for FY99, and $157 M was requested in the President's FY99 budget for the first year of construction), and good support in Congress, a construction start this October is very likely.

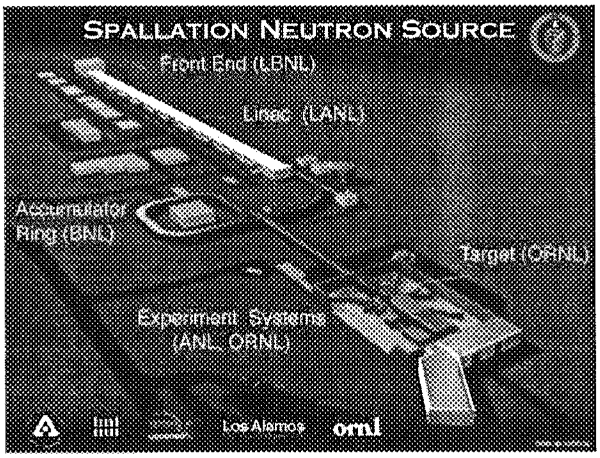

Figure 1: Schematic layout of the SNS.

3 BASELINE DESIGN

Figure 1 shows schematically the layout of the SNS, and Table 1 lists its major parameters. A more complete list of parameters is collected in the formal Parameter List, which is available on the above web-site under "Design Parameters." This Parameter List continues to evolve, with more details added as designs mature, and will eventually be a collection of all of the physics and engineering parameters for the completed facility. This list is one of the major mechanisms for controlling parameters and interfaces for five design teams spanning the North American continent.

Table 1: SNS Baseline Design Parameters

Beam Power	1 MW
Beam Energy	1 GeV
Repetition Rate	60 Hz
Ion Source Current (peak)	35 mA
Source Emittance (rms, norm)	0.14π mm-mrad
Chopping Ratio	0.65
Linac Frequency, RFQ/DTL	402.5 MHz
Linac Frequency, CCDTL/CCL	805 MHz
Linac Beam Duty Cycle	5.8%
Linac Beam Pulse Length	0.974 ms
Linac Length (total, all structures)	503.6 m
Injected Turns	1158
Accumulator Ring Circumference	220.7 m
Ring Revolution Frequency	1.188 MHz
Particles Stored in Ring (ppp)	1×10^{14}
Extracted Pulse Length	591 ns
Beam Spot on Target	7 x 20 cm
Target	Mercury
Target Operating Temperature	80 - 110° C
Moderators, Ambient Temp	2 (water)
Moderators, Cryogenic	2 (Supercritical H_2)
Beam Ports	18
Uncontrolled Beam Loss (@1 GeV)	< 1nA/m

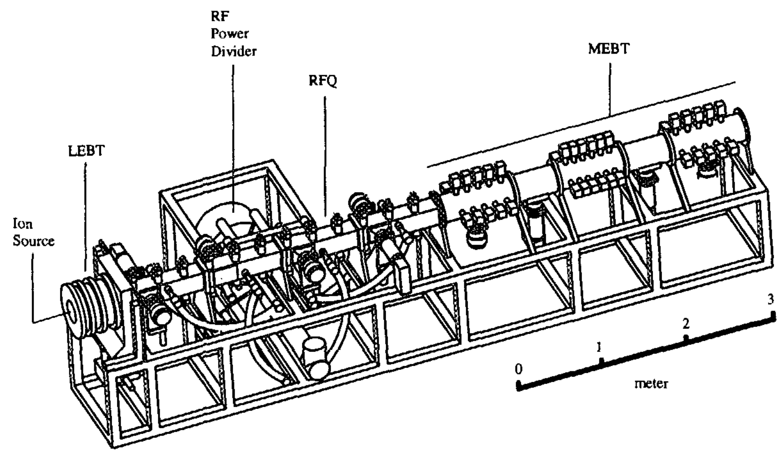

Figure 2: Front End schematic, bringing the beam to 2.5 MeV

3.1 Front End

Figure 2 shows a schematic of the Front End systems; the ion source, producing 35 mA of negative hydrogen ions, and LEBT (Low Energy Beam Transport) are enclosed in the short section at the front with large voltage-grading rings, the RFQ (Radio-Frequency Quadrupole accelerator) occupies the next 3.8 meters of length. The remainder of the Front End consists of the MEBT (Medium-Energy Beam Transport), whose primary function is to provide space for the two main beam choppers and to match the RFQ beam to the following DTL (Drift-Tube Linac) structure. Beam chopping is required to provide the needed beam structure to ensure a suitable gap in the accumulated beam, to allow for switching on of the extraction kicker and avoid beam loss during the kicker excitation time. This is shown schematically in Figure 3. Very fast risetime of the MEBT chopper is needed to switch between the 402.5 MHz beam bunches passing through the chopper structure from the RFQ, coming every 2.5 ns. Partially-deflected bunches are likely to lead to significant beam losses in the linac.

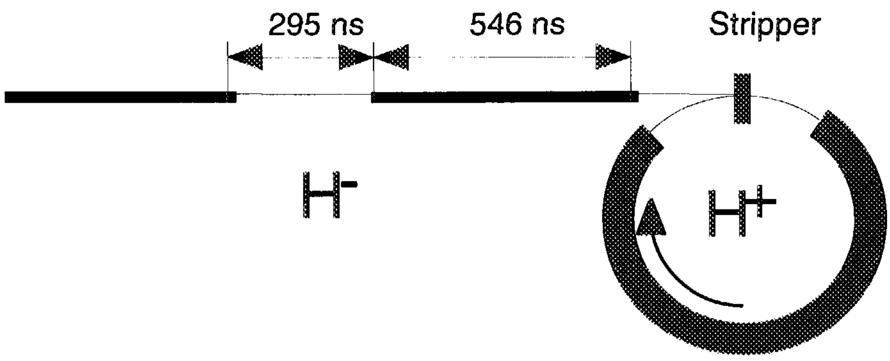

Figure 3: Schematic of beam chopping, required for minimizing beam loss during ring extraction

LBNL's design and R&D activities have made significant progress. A prototype volume H^- source has demonstrated the required 35 mA at 6% duty factor without use of cesium, but requiring a discharge power of about 50 kW. The technique for addition of the appropriate amount of Cs seeding is being developed, allowing the required current to be achieved with about one-third of the power in the source, contributing to significant lifetime extension. A preliminary design for the electrostatic LEBT, only 11 cm in length, has been completed, based on a similar design that has operated successfully at LBNL for positive ions. A cold model of the first section of the 2.5 MeV RFQ has been completed and is undergoing measurements; first results verify the excellent field-stabilization characteristics of the KEK pi-mode stabilizing rod concept [2]. Pulsing supplies for prechopping in both the source and the LEBT have been successfully tested.

3.2 Linacs

Figure 4 shows the configuration of the linac structures that accelerate the beam from 2.5 MeV to 1 GeV. Two DTL (Drift-Tube Linac) tanks operating at 402.5 MHz accelerate the beam to 20 MeV, a CCDTL (Coupled-Cavity Drift-Tube Linac) at 805 MHz accelerates the beam to 93 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. In addition, very large apertures are provided to contain any beam-radius growth. The aperture to rms beam radius is over a factor of 10 at the higher energies.

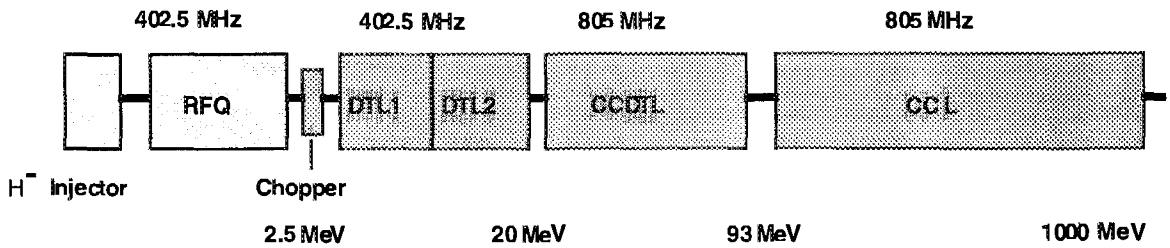

Figure 4: Schematic of linac structures that accelerate beam to 1 GeV. Lengths are not to scale: DTL is 8.7 meters long, CCDTL is 68.8 meters and CCL 417.0 meters.

RF power is provided by 50 2.5-MW klystrons, delivering a conservative 2.02 MV/m real-estate accelerating gradient. E_0T in the cavities averages 2.7 MV/m. A novel pulsed HV power supply concept based on IGBT technology is being incorporated, 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.

3.3 Ring

Figure 5 shows the HEBT (High-Energy Beam Transport) line from the linac exit to the ring, with a straight matching section, 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 straights, for injection, collimation, RF and extraction. The RTBT (Ring-to-Target Beam Transport) line takes the beam, extracted in a single turn by the kicker system, to the target. Beam is focused at the target point into a 7 x 20 cm rectangular shape, of roughly uniform density, to prevent hot-spot power deposition in the window and target.

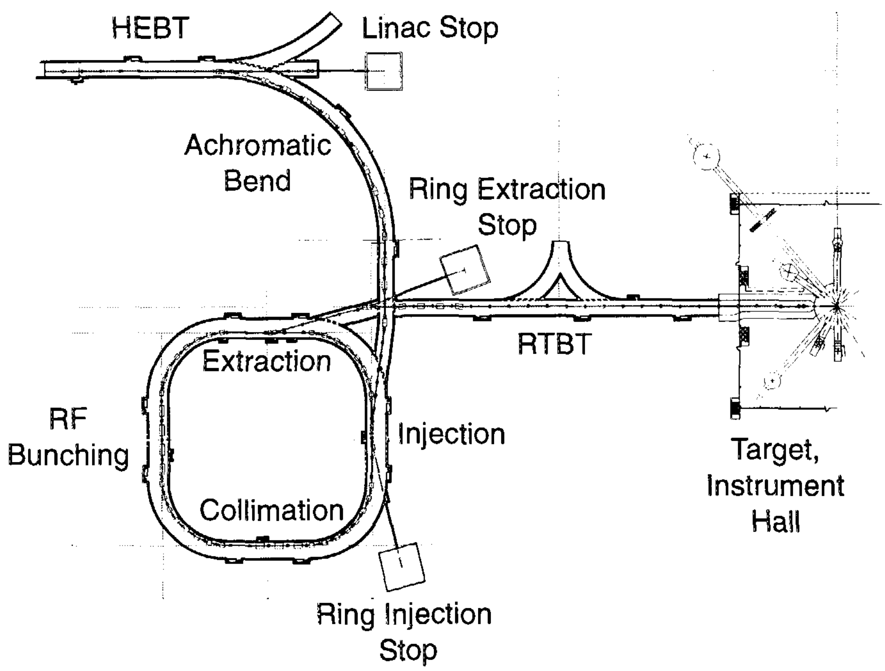

Figure 5: Transport and Accumulator Ring systems

BNL has designed the ring lattice with four-fold symmetry that provides a region in tune-space far from structure resonances. The collimation straight section will provide the principal aperture restriction for the ring in a place where little hands-on maintenance will be required and should limit beam losses in other areas of the ring with more critical requirements for personnel access. The collimators are carefully designed with graded low-Z and high-Z materials, and materials with good neutron-absorbing properties. On average, protons penetrate deeply inside the 3-meter long structures before reacting, and neutrons are largely contained inside the structure. This minimizes activation of external components. Calculations indicate that only one neutron emerges from the collimator for every 100 entering protons.

The injection region has been carefully optimized to prevent beam losses. By placing the stripping foil in the falling fringe-field of the combining dipole, halo in the ring due to Lorentz stripping of excited neutral hydrogens will be avoided. This development is a joint effort between BNL and ORNL [3]. A tracking code has been developed by the ORNL group to model the injection process with proper accounting for space charge buildup in the ring, to optimize the stacking algorithms for proper beam distributions and minimal emittance and halo growth. This tracking code is also reported at this conference [4], [5]. The beam distribution in the ring is a dominant factor in the power density deposited on the target, a tightly regulated parameter for the overall design. One notable result from the tracking simulations has been verification that the FODO lattice of the SNS ring produces less halo for high intensity beams than a doublet lattice ring.

The ring RF is a dual harmonic system, with a peak amplitude of 40 kV per turn in the first harmonic and 20 kV in the second harmonic. This very high voltage, more characteristic of a rapid-cycling accelerator than an accumulator ring, is nonetheless necessary to prevent migration of protons into the extraction gap. Cleanliness to better than 1 part in 10^4 of the 250 ns gap is necessary both for prevention of losses during the rising of the extraction kicker, and to prevent buildup of electrons in the very deep potential well of the circulating beam. This mechanism is considered 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.

3.4 Target

Figure 6 shows the 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.

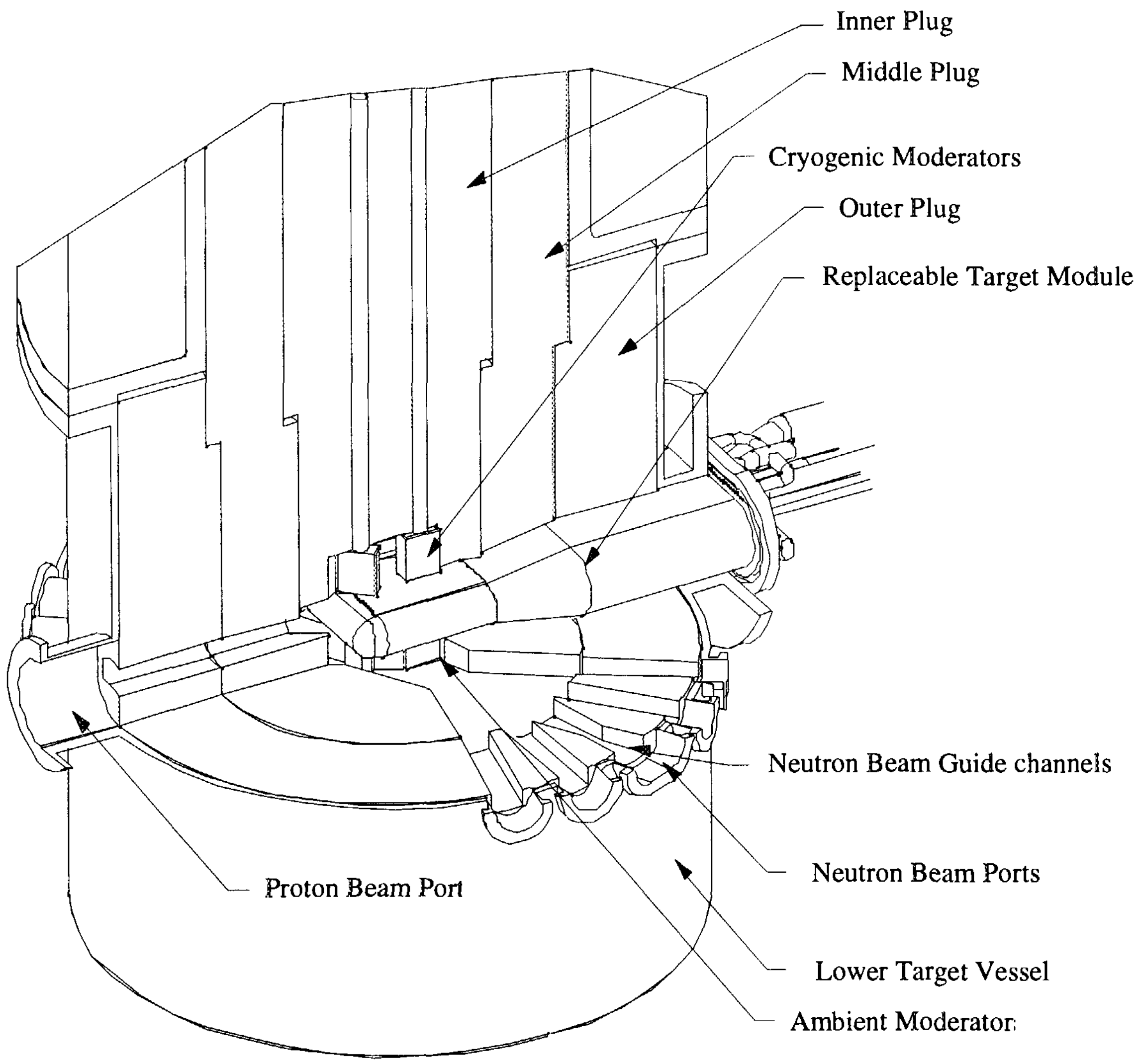

Figure 6: Schematic of target-moderator assemblies

An ongoing R&D program at ORNL is addressing important design issues. Materials irradiation experiments are being conducted at different accelerator facilities to test the impact of radiation in addition to mercury on different containment materials, studying primarily 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.

An international group, known as the ASTE collaboration (KEK, JAERI, PSI, Juelich, ORNL, BNL) [6], is conducting tests on a mercury target at the AGS in Brookhaven. This experiment is aimed at measuring shock and stress experienced by the intense pulse expected from the SNS, and other planned spallation sources of similar power. The SNS pulse will deliver 17 kJ per pulse, at an instantaneous pulse power of around 30 GW, the shock pulse could be expected to have very deleterious effects on the containing vessel. Though at a significantly lower repetition rate, the instantaneous pulse of the 26 GeV proton beam at the AGS is comparable to that expected at the SNS. Strain gauges mounted on the mercury-containing cylinder have registered the pressure pulses from single AGS pulses, and show good agreement with predictions. Future phases of the ASTE experiments are expected to benchmark slow neutron spectra and yield with water moderators placed in close proximity to the mercury cylinder.

3.5 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, it is well-understood that the fluxes from the SNS will be considerably higher than those for which the present-day instruments have been designed. Furthermore, 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 and ORNL, with close contacts to the neutron-scattering community through appropriate oversight and advisory committees.

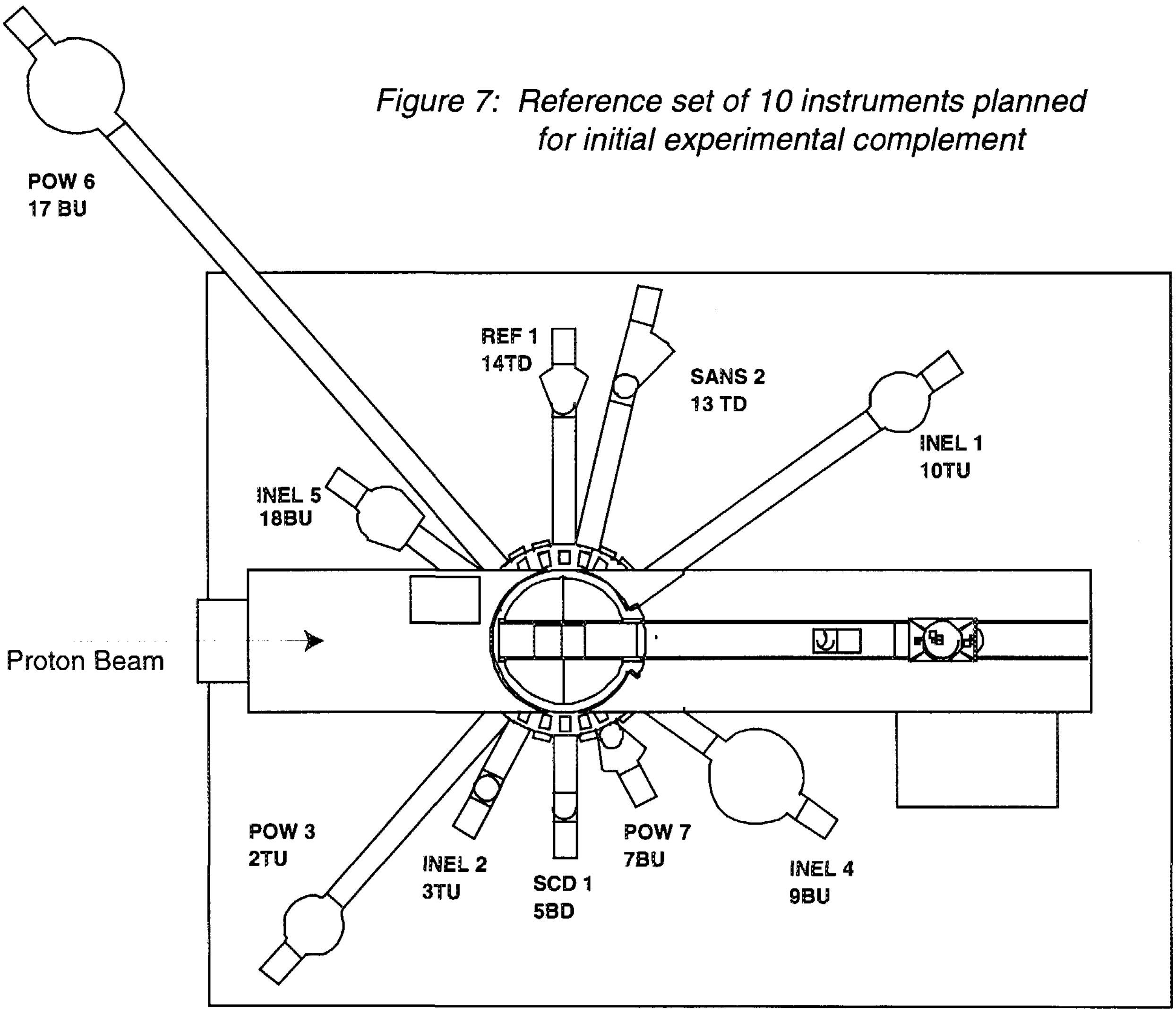

Figure 7: Reference set of 10 instruments planned for initial experimental complement

3.6 Controls

EPICS [7] has been selected as the basis for the controls systems for all elements of the SNS. 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. This group has been working through architectures, naming conventions, interface definitions and general implementation strategies. This Working Group is serving as a cross-cutting model for interfacing in many other technical and managerial areas of the project.

4 SUMMARY

The design concepts for the SNS have reached a very high level of maturity in the short time since the inception of the project, to the point where the collaborative team is confident that technical risks in being able to achieve design performance are very low. The total project cost and the seven-year construction schedule have been validated by two DOE review teams. Requisite project management tools are being put in place; from the Project Office functions and staff to the cost-accounting and schedule tracking systems suitable for working across the full five-laboratory consortium. In summary, the team is in place, the baseline design is complete, and the overall project is ready for the October 1, 1998 construction start.

ACKNOWLEDGEMENTS

Leadership of the SNS teams at ORNL and the collaborating laboratories is listed here. The ORNL senior management team consists of Bill R. Appleton, Associate Laboratory Director for SNS and Project Director, with John Cleaves, Thomas Mason and Jose Alonso as Deputies for engineering, science and accelerators, respectively. The LBNL team is led by Roderich Keller, with Rick Gough, John Staples, Ka-Ngo Leung, Alex Ratti and Ron Yourd contributing technical and managerial expertise. Leadership of the LANL linac team consists of Bob Hardekopf, Senior Team Leader, with principal groups led by Andy Jason, Mike Lynch and John Erickson. BNL's team is led by Bill Weng, with assistance from YY Lee, Andy Soukas and Joe Tuozzolo. Instrument science at ANL is led by Kent Crawford, with input from Jack Carpenter and Bruce Brown. The ORNL Target team is led by Tony Gabriel, with John Haines and Tom McManamy as assistants. The controls group is led by Dave Gurd from LANL, with Bill DeVan from ORNL as his deputy. The conventional facilities team at Oak Ridge is led by Jim Lawson, Jim Schubert is his deputy. Accelerator physics at ORNL is led by David Olsen.

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* This work is supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, of the US Department of Energy under Contract No. DE-AC05-96OR22464.

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[4] "A Particle-in-Cell Model for Space Charge Dynamics in Rings" J. A. Holmes, J. D. Galambos, D. K. Olsen, J. H. Whealton, M. Blaskiewicz, A. Luccio, and J. Beebe-Wang, to be presented at the European Particle Accelerator Conference, Stockholm, June 1998.

[5] "A Particle Core Model for Space Charge Dynamics in Rings" J. A. Holmes, J. D. Galambos, D. K. Olsen and S. Y. Lee, to be presented at the European Particle Accelerator Conference, Stockholm, June 1998.

[6] ASTE (AGS Spallation Target Experiment) is a collaboration formed in 1996 to perform experimental studies at the Brookhaven AGS accelerator on issues associated with high-power targets for pulsed spallation sources. Partners are, Jülich (Germany), PSI (Switzerland), JAERI (Japan), and BNL and ORNL (USA). Chief spokesman is Jerome Hastings, Brookhaven National Laboratory, jhasting@bnl.gov.

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