THE SNS LINAC AND STORAGE RING: CHALLENGES AND PROGRESS TOWARDS MEETING THEM

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Abstract

The Spallation Neutron Source SNS is a second generation pulsed neutron source and under construction at Oak Ridge National Laboratory. The SNS is funded by the U.S. Department of Energy's Office of Basic energy Sciences and is dedicated to the study of the structure and dynamics of materials by neutron scattering. A collaboration com-posed of six national laboratories (ANL, BNL, TJNAF, LANL, LBNL, ORNL) is responsible for the design and construct-ion of the various subsystems. With the official start in October 1998, the operation of the facility will begin in 2006 and deliver a 1.0 GeV, 1.4 MW proton beam with a pulse length of approximately 700 nanoseconds on a liquid mercury target. The expertise of the different laboratories has been exploited in order to enhance the delivered beam power by almost an order of magnitude compared to existing neutron facilities. The achievable neutron scattering performance will exceed present sources by more than a factor of 20-100. In order to achieve such a big step, the subsystems require substantial improvements compared to existing accelerators. The challenges, the status of the project and potential upgrades will be described in the talk.

Figure 1: Overview of the construction site with accelerator systems, target buildings, the central laboratory office, JINS, CNMS and several support buildings overlaid on a early site photo on top of Chestnut Ridge at Oak Ridge National Laboratory.

1 INTRODUCTION

The Spallation Neutron Source (SNS), authorized for construction in fiscal year 1999 is presently half way through the seven year construction cycle at the Oak Ridge National Laboratory in Oak Ridge, Tennessee. The accelerator, a central laboratory office that will house the central control room, a recently approved Center for Nanophase Material Sciences (CNMS) and the Joint Institute for Neutron Science (JINS) is shown in Figure 1 together with an artistic overlay of the facilities on top of a photo from the actual construction site. JINS will be operated in conjunction with the University of Tennessee supporting the users program. CNMS was recently authorized for construction and is one out of five Nanophase Science Centers under construction in the US right now. The SNS is intended to deliver a proton beam of up to 1.4 MW beam power to a mercury target for neutron spallation. The site layout has possible future upgrades incorporated as for example, the second target station (shown shaded) and space next to the rf building for an SRF facility that will be needed to maintain the existing cryomodules as well as to develop and build new ones at a rate of approximately one per year. Empty spaces in the tunnel allow for installation of an additional nine cryomodules in the tunnel to increase the energy to more than 1.3 GeV. The accelerator systems, basically a full energy injector linac and an accumulator ring, operate at a repetition rate of 60 Hz and an average current of 1.6 mA. It consists of an H^- RF volume source capable of delivering 50 mA peak current, a Low-Energy Beam Transport (LEBT) housing a first-stage beam chopper, a 4-vane Radio-Frequency-Quadrupole (RFQ) for acceleration up to 2.5 MeV, a Medium-Energy Beam Transport (MEBT) housing and a second-stage chopper, a 6-tank Drift-Tube-Linac (DTL) up to 87 MeV, a 4-module Coupled-Cavity-Linac (CCL) up to 186 MeV, a

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Superconducting RF(SRF) linac with eleven medium beta cryomodules (up to 379 MeV) and twelve high beta cryomodules (up to 1000 MeV), a High-Energy Beam Transport (HEBT) for diagnostics and collimation and an accumulator ring compressing the 1 GeV, 1 ms pulse to ≈700 ns for delivery onto the target through a Ring-to-Target Beam Transport beamline (RTBT). The basic parameters of the facility are summarized in Table 1.

Table 1: Baseline parameters for the SNS

Beam energy on target	MeV	1000
Beam current on target	mA	1.4
Power on target	MW	1.4
Pulse repetition rate	Hz	60
Macro pulse duty cycle	%	6
Average current per pulse	mA	26
H- peak current from Front End	mA	38
RFQ output energy	MeV	2.5
DTL output energy	MeV	87
CCL output energy	MeV	186
Med β sc linac output energy	MeV	397
High β sc linac output energy	MeV	1000
Accumulator ring circumference	m	248
Ring fill time	msec	1
Ring beam extraction gap	nsec	250
Protons per pulse on target		1.5×10^{14}
Proton pulse width	nsec	695
Target material		Liq Hg

2 ACCELERATOR SYSTEMS

The design and construction of the accelerator subsystems is the responsibility of the partner laboratories. The integration, testing, installation and commissioning is the responsibility of ORNL SNS staff and will be strongly supported by staff from the partner laboratories with a smooth transition of responsibility to the newly built up Accelerator Systems Division at ORNL. The operation of the facility after finishing the construction project (June ’06) is the sole responsibility of ORNL SNS with approximately 190 people supporting the Accelerator Systems. By then SNS will be a new and at the same time one of the largest accelerator laboratories in the United States.

2.1 Front End Systems (LBNL)

The Front-End Systems (FES) of the (SNS) project comprise an rf-driven H^- ion source, an electrostatic LEBT, a four-vane RFQ and a MEBT. The whole system was designed, constructed, installed and successfully commissioned at LBNL at the end of May ’02 and was sent to Oak Ridge beginning of June.

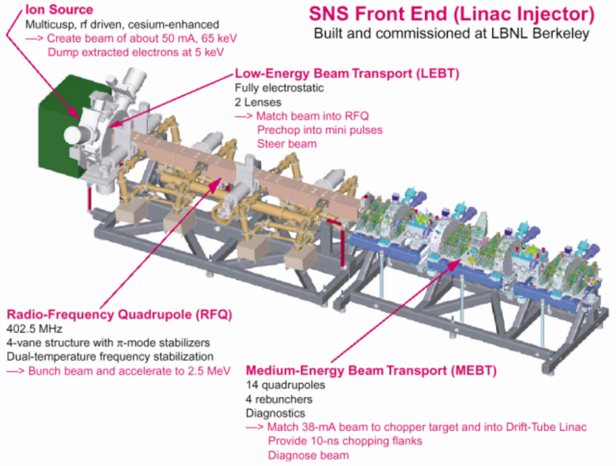

Figure 2: Layout of the Front end systems built at LBNL including an H- Ion source, the RFQ and the Medium Energy Beam Transport system.

The commissioning run, which begun in January ’02 had several highlights that included very stable operation of the Ion Source after implementing a more thickly coated antenna that was developed in collaboration between ORNL Metals and Ceramics Division, the Ion Source Group at SNS and LBNL [1]. Other commissioning highlights include an endurance test with almost 70 hours of continuous operation, peak currents exiting the front end up to 36 mA (design is 38 mA) at 2.5 MeV, the commissioning of the diagnostics and the controls, and finally operating at full 6% duty cycle for an extended period of time. The extracted emittance was measured (emittance with no cuts on the distribution) to be 0.25 π*mm*mrad compared to a design value of 0.27 π*mm*mrad (both rms). With the completion of the commissioning at LBNL the Front End group has successfully completed their subsystem to SNS. Installation on the site will start immediately after delivery and re-commissioning and integration into the SNS complex will start in November ’02.

2.2 The Normal Conducting Linacs and RF Power Systems (LANL)

The DTL [3] is in full production with tank No. 3 being assembled and tuned (compare fig. 3) and five more tanks are to be assembled, tuned and installed by November ’03. The tanks, being designed for a resonance frequency of 402.5 MHz, have permanent magnet quadrupoles (PMQ) integrated into the drift tubes as well as beam position monitors, current monitors and steering dipoles. High duty cycle (>6 %) and beam loss control onto the drift tubes were challenges that had to be met in order to make the design to and the use of PMQ’s feasible.

Figure 3: Picture alongside assembled DTL tank 3 with drift tubes and post couplers installed at LANL ready for shipment to Oak Ridge.

The CCL [3] which accelerates the beam up to 186 MeV moves rapidly into construction in industry (Fig 4). Only the final assembly and tuning will be performed at SNS. First article delivery will begin in autumn this year. A prototype substructure, including one bridge coupler, was tested up to 130% of the design surface field (3.77 MV/m) and an average power of 190% of design values validated very stable operation under extreme conditions.

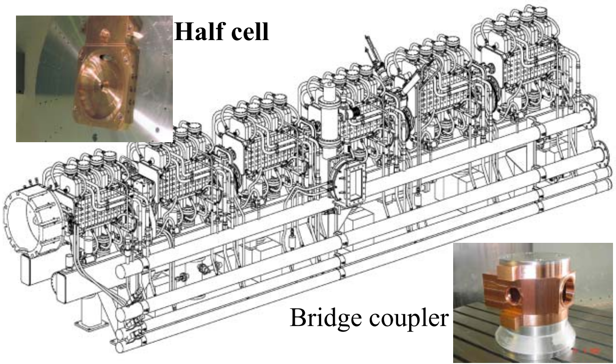

Figure 4: Overview of a CCL linac segment and first article production pieces.

The overall RF installation of the SNS facility includes six 402.5 MHz, 2.5 MW peak power klystrons for the DTL tanks, six 805 MHz, 5 MW klystrons for the CCL and eightyone 805 MHz, 550 kW klystrons with one klystron per cavity in the SC part of the linac. All of the klystrons will be fed by newly developed High Voltage Converter Modulators (HVCM) (fig. 5). This design is based on IGBT fast switching technology and nanocrystalline transformer cores, which compared to older technology allows a much more compact design of rf power stations. Fourteen of these HVCM will be installed in the klystron gallery and deliver approximately 1 MW of average power each to up to 12 klystrons simultaneously. A prototype being built at LANL has been operated at full voltage and ≈ 50% of the design duty cycle. Built to print construction in industry of the modulators is ongoing and installation will begin August this year.

Figure 5: Central piece of the HVCM prototype operating at LANL.

2.3 The Superconducting Linac (JLab) [5]

SNS will be the world's first high beam power superconducting proton linac. The decision to change the design for the main part of the linac to a superconducting structure was made in January '00, well into the project and implemented on a very fast time track. The physics design group headed by LANL concluded that beginning at 186 MeV, two types of structures (33 cavities, medium β=0.61 and 48 cavities high β=0.81) are required to efficiently accelerate the beam to 1 GeV. Optimisation of the geometry and the number of cells per cavity (6 for both types) were based on maximizing acceleration with minimum number of cavity types and making maximum use of the available surface field. In order to cost optimise the design in a second step, the surface fields utilized for the high β cavity design were increased from 27 MV/m to 35 MV/m potentially using elctropolished cavities, which reduced the number of cryomodules that are required to achieve 1 GeV from 15 to 12. The result is shown in Figure 6 where surface fields, on axis fields and effective accelerating fields are shown in one plot with the two types of cavities indicated at the bottom.

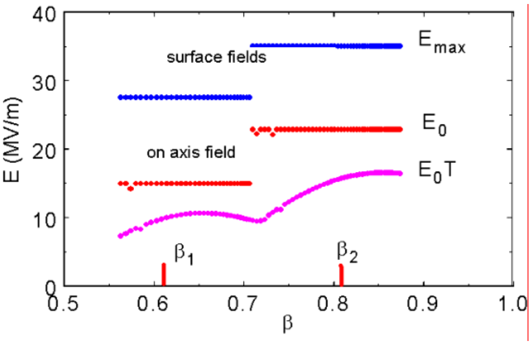

Figure 6: The graph shows surface fields, on axis fields and effective accelerating fields using two fixed geometry structures for acceleration.

The gradient increase in the technical design of the linac is accompanied by an aggressive develoment program led by Jefferson Lab that includes the development of installation procedures for processed cavities under ultraclean conditions as well as the application of electro-polishing techniques (including the set up of the infrastructure). The initial test program has started and a prototype cryomodule has been constructed and installed with rf testing underway (fig 7). Key issues that will be addressed in the test program are the achievable gradient, the Lorentz Force Detuning (LFD) coefficient, vibration issues and integration of the Low Level RF (LLRF) system. Of specific importance is the LFD coefficient, since this is a driver for significant overhead (≈40% at some rf stations) in the design of the rf system, that has to be provided and potentially could be used to generate more beam power. At this point it has been designed to allow for a detuning frequency as high as 470 Hz. Very recently the decision was made to have each cavity equipped with a piezo crystal driven fast tuner to compensate for the LFD (time scale ≈150μsec). The total stroke required is 20μm @4K with a slew rate of ≈0.15μm/μsec. Integrating this system into the LLRF system provided by LANL will allow more stable and higher beam power operations with the baseline installation. A summary of the main parameters is given in table 2.

Figure 7: Three cavities per croymodule prototype (medium β structure of the sc linac) constructed at JLab.

Table 2: Key parameters for the sc linac

Nr of cryomodules med / high β		11 / 12
Nr of cells per cavity		6
Cryomdule length: med / high β	m	4.2 / 6.3
Warm section space between	m	1.6
Microphonics design value (6σ)	Hz	100
Lorentz Force detuning max	Hz	470
Peak fields: med / high β	MV/m	27 / 35
E_{peak} / E_{acc}: med / high β		≈ 2.71 / 2.19
Nr of slots for additional cryomodules in the tunnel	total	9, ⇒ >400 MeV

The construction of the Helium liquifier and the transfer line has begun and first components have been installed on the site. Series production of cryomodules will begin autumn this year, all major contracts are placed and the first medium β cryomodule should arrive in November '02. With approximately one cryomodule per month delivery rate, installation will be finished in October '04.

2.4 Accumulator Ring + Transport Lines (BNL)

The HEBT transports the low emittance H^- beam from the linac to the injection foil of the Accumulator Ring (AR). Transverse jitter tolerances of the beam of ±0.2 mm are almost solely driven by the acceptance area of the H^- stripping foil where approximately 4% of the beam will be lost and directed to an injection beam dump that will have to handle up 200 kW of beam power (including H^0 from inefficiency of stripping). Injection at a dispersion-free region allows independently adjustable painting in the transverse (with orbit bumps) and longitudinal directions (with an energy-spreading phase-modulated RF cavity) for a robust operation. The transverse emittance of the chopped linac beam (0.26 π mm mrad rms) is phase space painted into a maximum acceptance of the AR of 300 πmm mrad (determined by collimators). In addition longitudinal painting into a 19 eVsec bucket generated by the 1.058 MHz rf system and a second harmonic cavity, is controlled by an energy corrector (centroid jitter) and energy spreader cavity (energy tail compression, longitudinal painting). The RTBT transports the extracted beam to the target hall. Some of the main parameters are listed here.

Table 3: Key parameters for the Accumulator Ring

Nr of injected turns		1060
Ring revolution frequency	MHz	1.058
Ring filling fraction	%	68
Ring transverse emittance 99%	πmm mrad	240
Ring transverse acceptance	πmm mrad	480
Space charge Tune shift	$\Delta Q_{x,y}$	0.15
Peak Current	52	A
HEBT / RTBT Length	m	170 / 150
RTBT transverse acceptance	πmm mrad	480
Beam size on target (HxV)	mm x mm	200x70

The optimized SNS ring lattice has a hybrid structure with FODO bending arcs and doublet straight sections. It is crucial that the losses during the accumulation cycle are very well controlled locally with approximately 0.2 % of the beam dumped with ≈90 % efficiency into the 3 collimators. A 12.5 m-long uninterrupted straight section with a flexible phase advance is used to further improve collimation efficiency.

In terms of the ring accelerator physics design, uncertainty still exists in determining the threshold currents for the longitudinal and transverse instabilities. This includes the calculation [6] of the resistive wall impedance, the broadband impedance and the space charge impedance (given the particle distribution in the ring). In order to increase the momentum acceptance chromatic sextupole correction has been added and will further increase flexibility opening up the route to even higher intensity operation. Another area of intense research is the electron cloud instability [7], its correlation to the PSR instability [8] and the determination of threshold currents. In order to avoid secondary electron multiplication from surfaces exposed to the intense proton beam, all vacuum system components will have a titanium nitride coating.

Figure 8: TiN coating facility for vacuum components at BNL.

Stable operation up to 1.0-1.4 MW seems very much reasonable given our present understanding. In an attempt to layout the path to even higher power operation in the future, increasing the injection energy by installing more cryomodules in the linac is certainly most promising. Almost all HEBT, AR and RTBT components have been designed to at least 1.3 GeV and a preliminary study was done to determine the capability of SNS [9].

The construction status shows almost all the design finished and all but one of the large magnet contracts awarded with first article delivery or even series production well underway. Field measurements of solid core magnets showed deviation from specifications, which could be compensated by shimming the magnet cores. Injection and extraction systems, power supplies, diagnostics equipment and vacuum chambers are in construction or procurement. The delivery of AR fully assembled half cells to Oak Ridge will start soon with installation of first components in the ring tunnel in spring ’03. The beamlines and the accumulator ring will be fully commissioned in December ’05 delivering first beam to the target.

2.5 The Accelerator Physics Challenges

A key challenge in linac performance is to minimize beam emittance growth and centroid jitter in both transverse and longitudinal directions upon ring injection, reducing foil traversal there, scattering and especially reduce radio-activation due to beam loss. The general design beam loss criteria of ***1 W/m or less (or one nA at higher energies*** leading to < 100mrem residual activation***)*** was a guideline, to ensure that hands on maintenance is possible. More elaborate studies showed of course that localized losses most likely occur at matching section between accelerator subsystem interfaces (DTL-CCL or CCL-SCL: see example in fig. 9) which is much easier to shield then distributed losses. Especially in this area the SC linac with its very large aperture and excellent vacuum conditions represents a large advantage as compared to the former normal conducting design. Contributions to continuous beam loss stem mainly from beam halo development or beam gas scattering.

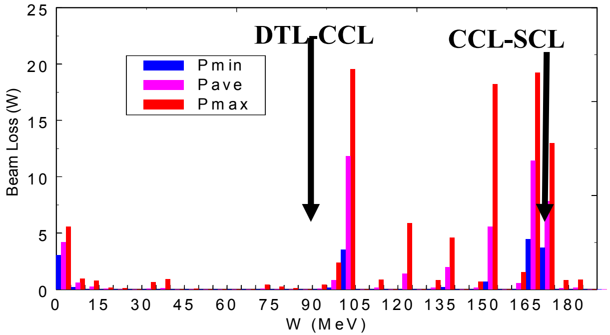

Figure 9: Example for beam loss study in the linac indicating that loss is mainly driven matching between interfaces of linac subsystems.

3 SUMMARY

Over the last year SNS has very rapidly moved from the design stage into construction. This fiscal year’s funding of 291.4 M$ represents the peak in the 1.4 Billion dollar construction project. With all major procurements underway, installation on the site has started and re-commissioning of the Front End Systems by the end of this year will provide the first accelerated H$^-$ ions on the SNS site. Many more details can be found on the web [10].

4 REFERENCES$^{\nabla}$

[1] R.F. Welton et all, “Ion source antenna development for the Spallation Neutron Source”, Rev. Sci. Instrum. 73 (2002) 1008-12.

[2] R. Keller et al, “Commissioning of the SNS Front-End Systems at Berkeley Lab”, this conference.

[3] J. Billen et al, “Room-Temperature Linac Structures For The Spallation Neutron Source”, PAC-2001-MPPH139, Aug 2001.

[4] W. Reass et al, “Operational Results Of The Spallation Neutron Source Polyphase Converter-Modulator For The 140 KV Klystron RF System” PAC-2001.

[5] C. Rode, “The Sns Superconducting Linac System” PAC-2001-ROPB008, Aug 2001. 5pp.

[6] A.V. Fedotov et al, “Exploring Transverse Beam Stability in the SNS in the Presence of Space Charge”, this conference.

[7] M. Blaskiewicz et al, “Calculations Of The Electron Accumulation In The SNS Storage Ring”, PAC-2001, Aug 2001.

[8] K. Harkey et al, “Electron Proton Two-Stream Instability At The PSR”, PAC-2001-FOAB007, 2001.

[9] W.T. Weng, “Upgrading the SNS Compressor Ring to 3 MW”, this conference.

[10] http://www.sns.gov/

$^{\nabla}$ **Acknowledgement**: The reference list is very much incomplete but limited space required to refer to a small subset only. I’m indebted to all contributors from the collaboration for their help.