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High-Power Linac for the Spallation Neutron Source*

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Abstract. The Spallation Neutron Source (SNS) will be the world's most intense source of neutrons for fundamental science and industrial applications. In this paper, we review the physics requirements, design, construction, installation, and first commissioning results of the 1-GeV, 1.4-MW average power RF linac for SNS. The overall project is 82% complete, with most of the linac hardware manufactured and delivered to the SNS site. Commissioning of the first drift tube linac tanks was a success. Approximately 100% of the beam was transmitted at full average current while achieving the emittance goal of less than 0.3 π mm-mrad.

Neutron scattering is a powerful tool to study material structure and dynamics. The relatively deep penetration by neutrons into matter enables *in-situ* studies of macroscopic samples and a broad range of scale lengths ranging from 0.01 to 10^4 nm. Interdisciplinary uses include materials science, chemistry, biology, and engineering. At 1.4 MW average power, the Spallation Neutron Source (SNS) will be the world's leading facility for neutron scattering. SNS is being built at Oak Ridge National Laboratory in a $1.4B project for the U.S. Dept. of Energy. Design and construction is a joint venture between six DOE laboratories. Construction began in 1999 and is currently ahead of the scheduled 2006 completion date.

SNS is designed to deliver a proton beam of up to 1.4 MW average beam power to a mercury target for neutron spallation. The accelerator system consists of a 1-GeV linac injecting an accumulator ring (Fig. 1). The system operates with a 1-ms macropulse width, a repetition rate of 60 Hz (6% duty factor), and an average current of 1.4 mA. It consists of: (1) an inductively-coupled RF H^- ion source capable of delivering 50 mA peak current; (2) a low-energy beam transport housing a first stage beam chopper; (3) a 4-vane radio-frequency-quadrupole (RFQ) for acceleration up to 2.5 MeV; (4) a medium-energy beam transport housing a second-stage chopper; (5) a 37-m-long, 6-tank drift-tube linac (DTL) up to 87 MeV; (6) a 55-m-long, 4-module coupled-cavity linac (CCL) up to 186 MeV; (7) a 157-m-long superconducting-RF linac (SCL) with eleven medium-beta ($\beta = 0.61$) cryomodules (up to 379 MeV) and twelve high-beta ($\beta = 0.81$) cryomodules (up to 1000 MeV); (8) a high-energy beam transport for diagnostics and collimation; (9) a 170-m-circumference accumulator ring compressing the 1-GeV, 1-ms pulse to 695 ns for delivery of 1.5E14 protons onto the target through a ring-to-target beam transport. Three-dimensional particle-in-cell simulations of beam dynamics were performed to maximize output energy while minimizing emittance growth. The accelerator utilizes approximately 100 MW of pulsed power operating at 60-Hz with an 8% duty factor. Ninety-four 402.5 or 805-MHz klystrons, with outputs between 0.55 and 5 MW, are used.

The Los Alamos role on SNS is to design, procure, and help install/commission the DTL and CCL, to provide beam physics analyses for the entire linac, and to provide RF power, diagnostics, and controls for the entire linac. The resonant RF frequency of the DTL is 402.5 MHz, and 805 MHz for the CCL and SCL. The linac physics design is inherently stable, meeting the performance requirements (Table I). Phase and quadrupole settings are designed to avoid structure and parametric resonances, while coherent resonances pose minimal risk for emittance growth. 3-D particle-in-cell simulations of beam dynamics have been performed to validate performance. Expected errors have small effect on the beam distribution at the ring injection foil. Beam diagnostics include position, phase, profile, and current monitors. They are designed to enable accurate beam steering and matching, and to minimize beam loss that would lead to activation and prevent hands-on maintenance.

The drift tube linac (DTL) is designed in six tank assemblies. Permanent-magnet quadrupoles, steering dipoles, and beam diagnostics are integrated inside the drift tubes. Each tank has a single high-power RF feed. The entire system has been delivered and is installed in the SNS beamline. Commissioning of Tank-1 successfully concluded in Nov. 2003. Approximately 100% beam transmission was observed at emittance $\varepsilon_{RMS} < 0.3\ \pi$ mm-mrad and average current > 1 mA. (Figs. 2 and 3). Commissioning of Tanks 1, 2, and 3 successfully concluded in Apr. 2004. Within the first two days of this commissioning run, approximately 100% beam transmission was observed at the design energy.

The coupled-cavity linac (CCL) is designed in four modules. Each module is powered by two 805-MHz RF feeds and is composed of twelve segments. Each CCL segment consists of eight accelerating cells. The entire system has been delivered and installed in the SNS beamline. Module 1 was successfully RF conditioned to 2.5 MW RF (~ 120% of nominal power) @ 20 Hz and 1 ms, after five 12-hour shifts. Modules 2 and 3 are tuned and under vacuum. Beam commissioning will begin on schedule in Sept. 2004.

FIGURE 1: Spallation Neutron Source

TABLE I: Linac performance requirements

Final Energy, W	1 GeV ±15 MeVrms
Emittance at foil	$< 0.34\ \pi$ mm-mrad
Energy stability	± 0.2 MeV
Energy spread	± 0.85 MeV (rms)
Transverse stability	± 0.2 mm
Beam loss	< 1 W/m
Uncontrolled loss at ring injection foil	2%

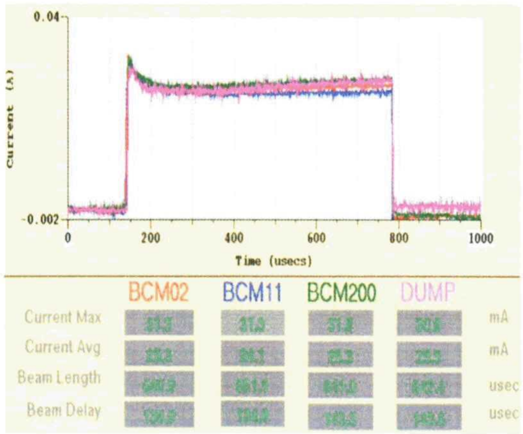

FIGURE 2: Overlays of output beam currents measured from RFQ, RFQ-DTL transfer line, DTL Tank-1, & beam dump. Operational Parameters: 60 Hz, 640 μs, 26 mA, & 7.5 kW average H^- beam power

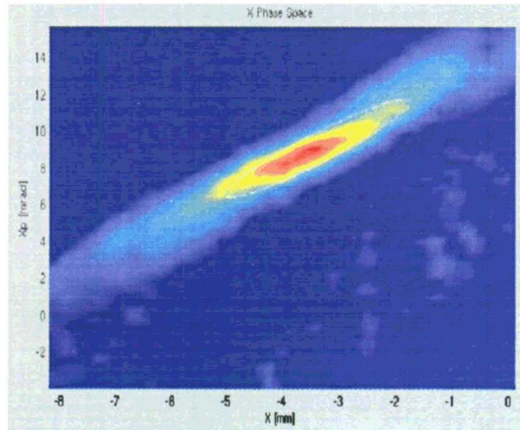

FIGURE 3: Transverse phase space profile from measurements with slit and retractable wire scanner on beam from SNS DTL Tank-1. Emittance requirement of 0.3 π mm-mrad was achieved.

Los Alamos designed, developed, and delivered the 100-MW pulsed power (7-MW average) RF system for the entire linac, front-end RFQ, and linac-to-ring transfer line. All RF systems for the RFQ, DTL, and CCL have been installed and operated. Klystron quantities and parameters are included in Fig. 4. Over half of the 81 SCL systems are installed. Beam energy in the SCL is limited by cavity quality. Beam current is limited by klystron power. The 1-GeV final energy and 1.4-MW average power were optimized for fixed accelerator cost. SCL klystron power is fixed at 550 kW per cavity with 40% control margin (*e.g.,* for microphonics and Lorentz detuning). Beam current is matched with fields & klystron parameters. Energy or current may be increased by adding cryomodules and RF systems.

Klystrons are powered by fifteen, 11-MW pulsed power (1-MW average) dc-to-dc high-voltage converter modulators (HVCMs). The modulators are compact, efficient (measured efficiency up to 94%), and based on the following new technologies and concepts: (1) insulated-gate bipolar transistors and low-inductance, self-clearing capacitors developed for the traction motor industry; (2) efficient nanocrystalline amorphous transformer cores developed for the power supply industry; and (3) 20-kHz resonant power conversion. The production systems were built by industry, while prototype tests were conducted at ≤ 140 kV pulses over 1.3-ms pulsewidth and 60-Hz repetition rate, 11-MW peak power, and 1-MW average input power (Fig. 5).

All HVCM production units have been manufactured by industry and delivered. Ten units are installed and eight are operating, some at high average power. Units have logged over 7000 hours of successful operation (Table II). While HVCMs operate at good availability, several upgrades have been identified. Effort is underway to further reduce mean time to repair and increase mean time between failures; goals are to (1) accumulate additional hours of operation at near-full average power independent of accelerator operational needs and characterize thermal

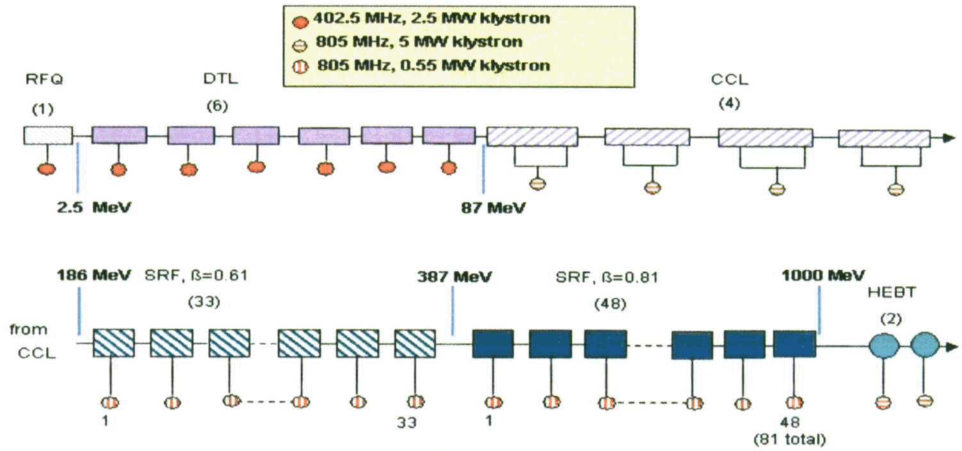

FIGURE 4: RF System schematic

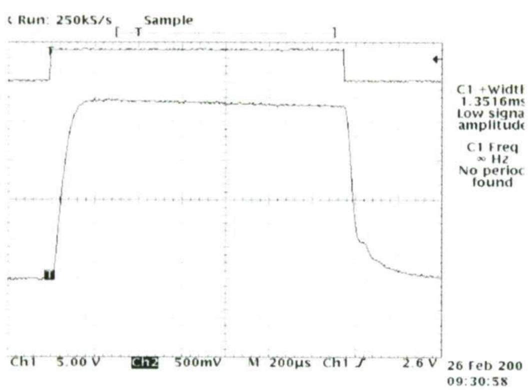

FIGURE 5: HVCM voltage waveform. Prototype operated at full spec: 9.5 MW, ~800 kW avg (135 kV, 70A, 1.35ms gate, 60Hz), ~94% efficiency .

Table II: Operational hours on HVCMs

SYSTEM	*HOURS*
DTL-UNIT #:	
Low average power (<5 Hz, single klystron)	1500
Single klystron @ 30 Hz, 1.4 ms, 107 kV	120
Dual klystron to above parameters	1700
DTL-UNIT #2: Single klystron to 60 Hz)	1030
DTL-UNIT #3: Dual klystron full average power	500
RF Test Lab: Single klystron to full duty	200
LANL units: almost all at 50% or 100% maximum design average power	2000
TOTAL	**7050**

issues; (2) reduce 20 kHz harmonics, especially in SCL units, by implementing 20 and 40 kHz harmonic traps; (3) optimize pulse generation scheme for SCL units, varying pulse width durations to minimize switching losses, including phase shift modulation; (4) close feedback / adaptive feed-forward loops and refine DSP and FPGA algorithms; and (5) evaluate bypass capacitor performance.

The overall SNS project is 82% complete, and within the total project cost of $1,411.7 M, and is on schedule for a Mar. 2006 early completion date. The longest path item is the target system hot cell installation with 22 days of positive schedule float. The budget to complete is $140.1M, the remaining contingency is $28.2M, while the remaining contingency based on estimate at complete is $25.3M (21.4%).

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