

STATUS OF THE OAK RIDGE SPALLATION NEUTRON SOURCE (SNS) RF SYSTEMS *

T. Hardek, M. Crofford, Y. Kang, S-W. Lee, M. Middendorf, M. Piller, A. Vassioutchenko,
ORNL, Oak Ridge, TN 37831, U.S.A.

Abstract

The SNS has been delivering production neutrons for five years with first beam delivered to the neutron target at the end of April 2006. On September 18, 2009 SNS officially reached 1 megawatt of beam on target marking the achievement of a decades-old dream of providing a U.S. megawatt-class pulsed spallation source. The SNS is now routinely delivering 1 megawatt of beam power to the neutron target at over 85 percent of the scheduled beam time. The present effort is aimed at eventually increasing availability to 95 percent and gradually increasing the intensity to the 1.4 megawatt design level. While the RF systems have performed well since initial installation some improvements have been implemented. This paper provides a review of the SNS RF Systems, an overview of the performance of the various components and a detailed review of RF-related issues addressed over the past several years.

INTRODUCTION

On September 18, 2009 the SNS officially reached 1 megawatt of proton beam on target marking the achievement of a decades-old dream of providing a U.S. megawatt-class pulsed spallation neutron source. The present effort is aimed at increasing the availability by improving the reliability of the various sub-systems. Over the past 5 years some fairly major changes have been introduced into the Radio Frequency accelerating systems. This paper describes the various issues addressed along with the changes incorporated to redress these issues.

RF SYSTEM LAYOUT

Figure 1 gives the Linac structure and RF configuration. The Linac consists of a Radio Frequency Quadrupole (RFQ) powered by a single 402.5 MHz, 2.5 MW klystron supplying about 700 kW, six Drift Tube Linac (DTL) sections also powered by 402.5 MHz, 2.5 MW klystrons, four Coupled Cavity Linac (CCL) sections powered by 805 MHz, 5 MW klystrons, 33 medium-Beta superconducting cavities and 48 high-Beta superconducting cavities powered by 805 MHz, 550 kW klystrons [1],[2].

An Accumulator Ring is used to redistribute the 1 msec linac macro-pulse beam by stacking a thousand chopped linac mini-pulses into a single high intensity ~645 nsec bunch that is extracted and sent to the target. The ring RF operates on the fundamental revolution frequency of 1.05 MHz. Three dual-gap ferrite cavities provide 30 kV of

fundamental mode bunching voltage and a fourth cavity provides 10 kV of 2.1 MHz second harmonic bunching voltage to control the peak current within the beam bunch.

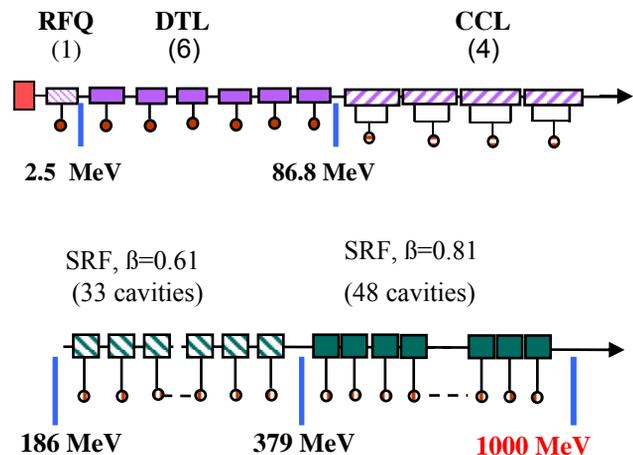


Figure 1: SNS Linac Structure and RF Configuration

PERFORMANCE OVERVIEW

The SNS has been delivering production neutrons since April 2006. On September 18, 2009 it reached a design goal of delivering 1 megawatt pulses of protons to the mercury target at a pulse repetition rate of 60 pulses per second. Availability has increased to greater than 85% with some extended periods over 90%.

During the power ramp up period the RF systems have experienced several significant weaknesses.

- Ion source 2 MHz amplifier not easily accessible. Troubleshooting failures difficult. Components not readily available.
- The RFQ has twice shifted tune; we believe in response to cooling water pressure surges.
- Medium Energy Beam Transport (MEBT) RF amplifiers unreliable.
- Two CCL RF vacuum windows have failed due to cracked ceramic. One window failed during excessively aggressive conditioning. The second failed window is still being analysed as to cause.
- One DTL RF vacuum window has failed due to a leaky braze joint.
- Converter-Modulator design would not support 75 kV cathode voltage required for full power output from klystrons supplying the superconducting accelerator section.
- SCL cold cathode gauges not always reliable

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- Non-functional Quench detection
- Small variations in beam loss have been correlated to klystron gallery temperature.

ION SOURCE

SNS uses a radio frequency-driven multi-cusp ion source design [3]. A low power continuous plasma is generated by ~300 watts of 13 MHz RF power. The high current beam pulses are generated by superimposing 30 – 70 kW pulses at 2 MHz onto the same antenna to which the 13 MHz was applied. The 2 MHz power amplifier and its driver stage along with a pulsed RF generator was initially located within the ion source high voltage enclosure elevated to the -65 kV ion source accelerating voltage. An RF isolation transformer has been developed to allow operation of this amplifier at ground potential and the amplifier has been relocated outside the high voltage enclosure. Solid state versions of the 2 MHz amplifier have been acquired to replace the vacuum tube-based original amplifier.

RADIO FREQUENCY QUADRUPOLE

The original power feed design for the RFQ included eight couplers along with a coaxial power distribution system. Each power coupler was rated at 100 kW for a total of 800 kW. As long as the couplers are well balanced this is adequate. Obtaining a good balance with 8 couplers is difficult and there were indications of unequal coupling. A redesigned feed system [4] was based on the proven high power coupler design utilized in the SCL section. These couplers use Toshiba ceramic and routinely operate in the 500 kW range. The number of couplers was reduced to two and installed with a waveguide power splitter.

To address the issue of RFQ detuning SNS has contracted for the mechanical redesign and manufacture of a spare RFQ and is well along the way to having it manufactured. The spare RFQ design replaces the original brazed cooling passages with gun-drilled passages and improves the stability of the vanes. The spare will have the same physics parameters and vane undulations as the present RFQ.

MEDIUM ENERGY BEAM TRANSPORT RF AMPLIFIERS

The original triode vacuum tube-based power amplifiers utilized for rebuncher cavities along the MEBT proved to be a major source of accelerator downtime. These are not very high power amplifiers, 20 kW each at 402 MHz, but reliable, consistent operation was difficult to maintain. The amplifiers suffered from frequent output cavity and power supply arcing resulting in frequent AC circuit breaker trips. While the breaker trips were ultimately eliminated by replacing the brute force anode supplies with capacitor charging-type supplies the performance of these amplifiers remained marginal. The original amplifiers have now been replaced with four solid state units and one spare [5].

ADDED CONVERTER MODULATOR

The original Superconducting Linac (SCL) transmitter design was configured to support six klystrons per transmitter with a single converter-modulator powering twelve klystrons [6]. Some locations utilized only eleven klystrons. In practice the converter modulator design allowed eleven klystron sets to operate at 72 kV while the twelve klystron sets operated at 69 kV. The klystrons were designed to output 550 kW at 75 kV and with the reduced cathode voltage the superconducting section was RF power-limited to less than the design beam power level of 1 MW.

An extra converter modulator has been added allowing for operation with ten klystrons per modulator. The first section of the medium-beta superconducting Linac still uses eleven klystrons powered from one modulator but this section is not RF power limited.

LOW LEVEL RF IMPROVEMENTS [7]

Eight Channel Pulsed Power Meter

The Spallation Neutron Source Low Level RF (LLRF) Control System currently utilizes a High-Power Protection Module (HPM) to monitor RF power levels, arc faults, and associated signals for the protection of the RF systems and accelerating cavities. The HPM is limited to seven RF channels for monitoring signals which in some instances leaves signals of interest unmonitored. In addition, the HPM does not support monitoring of RF frequencies below 10 MHz, which makes it unusable for our Ring and Ion Source systems that operate at 1 and 2 MHz respectively. To alleviate this problem, the SNS RF Systems team has developed a microprocessor-based eight channel pulsed RF power meter that allows for monitoring additional channels between the frequency range of 1 MHz to 2.5 GHz [8]. In addition, the power meter design includes four analog channels intended for monitoring klystron cathode voltage and current and providing perveance data throughout the converter-modulator pulse. Since the converter-modulators have considerable droop and the pulse length has been increasing throughout the past operating periods good archived perveance data has been difficult to obtain. The power meters will be phased into operation as time and funding permit.

Pico-Ammeters

Superconducting cavity protection from vacuum issues was originally performed with cold cathode gauges. These devices tend to be unreliable. The cavity design included electron probes that can be monitored with pico-ammeters. The SCL has been instrumented with these meters which input into a spare channel in the (HPM). Each cavity can be independently monitored through the protect module and some cavities currently utilize the protect feature as an additional interlock.

Quench Detection

Quench detection was originally included in the LLRF package but it failed to function properly. A more robust version has been implemented in hardware within the HPM module and a software-based version now detects the onset of a quench and shuts off the RF power preventing the quench over a full pulse.

Field Control Module Upgrade

Small increases in beam loss were correlated to changes in the klystron gallery temperature. A subsequent study of the LLRF field control module showed that small changes in phase occur as the module temperature is changed. The phase changes, while well within the original specification, can be significantly reduced by moving the Analog Front End (AFE) and Analog Output hardware into the temperature controlled down converter module. A redesign of the field control module and down converter has been completed and as time and funding permit the updated versions will be manufactured and incorporated into the overall system.

SCL Heater Control

Heaters are provided to keep the thermal load on the cryogenic system constant. The LLRF system enables these heaters when the RF power is disabled.

Beam Blanking

During tuning sessions the downstream RF is disabled while amplitude and phase is adjusted on each cavity. Tuning was initially accomplished by time shifting to allow the RF systems to continue to operate. This works but is limited by the available pulse width and is still fairly time consuming. Since tuning is done at low pulse repetition rate it is possible, with the inclusion of the beam blanking feature, to simply blank the downstream RF power during a beam pulse. This allows the physics team the ability to turn on the entire Linac RF and quickly step through each cavity in sequence.

RFQ Control

As the SNS pulse length was increased toward full beam power the RFQ began experiencing tuning issues. With the RFQ operating in a stable condition some event would disturb the operation, requiring much time and effort to recover. The event is related to an earlier change in gas flow to the ion source. It is believed that hydrogen gas from the Ion Source is absorbed in the copper of the RFQ. Heating resulting from RF power and some beam loss releases the hydrogen and reduces the cavity Q. The gas flow is now more closely regulated to reduce the likelihood of this factor initiating the loss of stable operation.

Somewhat marginal structure cooling is also involved in the control issue. The structure is cooled by a pair of fixed-temperature chillers with one chiller cooling the vanes and a second the structure body. The chillers have been replaced with others that have higher cooling capacity.

Finally it was observed that small changes in the pulse length at the onset of unstable operation would provide the necessary control. A slow pulse-length adjusting feedback loop was incorporated into the LLRF control software. Slow control loops for chiller temperature control are also implemented within the LLRF control software.

Arc Detection

Fiber-Optic arc detectors are installed throughout the High Power RF System. They monitor klystron windows, circulators, water load windows and both the air side and the vacuum side of structure windows. The arc detectors input to the LLRF system and truncate the RF pulse and blank the next RF pulse. There is a mode that allows the system to recover after a single or a selected small number of sensed arc faults, which is referred to as a chatter fault.

During initial RF system operation several of the structure-monitoring optical fibers became darkened due to x-ray radiation. The sections exposed to x-ray radiation were replaced with jumpers of plastic optical fiber. The plastic fiber has performed well over the years. In addition to installing the plastic fiber jumpers a fiber test system was implemented to ensure that the fibers will transmit light. Light-emitting diodes are installed at the structure, both on the air and the vacuum side, that are automatically flashed daily and report the number of tries and failures on a LLRF screen.

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