SNS RF SYSTEM PERFORMANCE AND OPERATION*

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Abstract

The Spallation Neutron Source (SNS) Linac and accumulator ring utilize 100 Radio-Frequency (RF) systems for acceleration and bunching of the proton beam. Several different types of gridded tubes and klystrons are operated at 1, 2, 402.5 and 805 MHz, at power levels ranging from a few kilowatts to several megawatts, to drive several types of accelerating cavities, both normal- and super-conducting. The RF systems are standardized, especially in the Linac, to ease operation and maintenance. Phase and amplitude control is achieved with a digital Low-Level RF (LLRF) control system. The RF systems operate reliably and support production of a high-quality low-loss proton beam. Various modifications and upgrades have been made or are in progress to enhance system reliability and performance. Planning is well underway for a power upgrade that will require an additional 36 RF systems.

INTRODUCTION

The SNS Linac and accumulator ring utilize 100 RF systems for acceleration and bunching of the proton beam. The Radio Frequency Quadrupole (RFQ), Medium Energy Beam Transport (MEBT) rebuncher cavities, and Drift Tube Linac (DTL) operate at 402.5 MHz, while the Coupled Cavity Linac (CCL) and Super Conducting Linac (SCL) operate at 805 MHz. The accumulator ring cavities operate at 1 and 2 MHz and are described by Hardek et al. in these proceedings [1]. All of the RF systems are designed for 60 Hz operation with a pulse length up to ~1.4 ms. The layout of the Linac is shown schematically in Figure 1. Note that each cavity is driven by its own RF system, which provides for great operational flexibility. The RF amplifiers include gridded tubes (triodes and tetrodes) and klystrons, as listed in Table 1.

Table 1: RF amplifiers utilized in SNS accelerator.

Type	Application	Frequency (MHz)	Peak Power (MW)	Vendor	Number Installed
Klystron	RFQ, DTL	402.5	2.5	E2V & Thales	7
Klystron	CCL	805	5	Thales	4
Klystron	SCL	805	0.55	CPI & Thales	81
Triode	MEBT Rebunchers	402.5	0.020	CPI	4
Tetrode	Accumulator Ring	1 & 2	0.1	Thales	4

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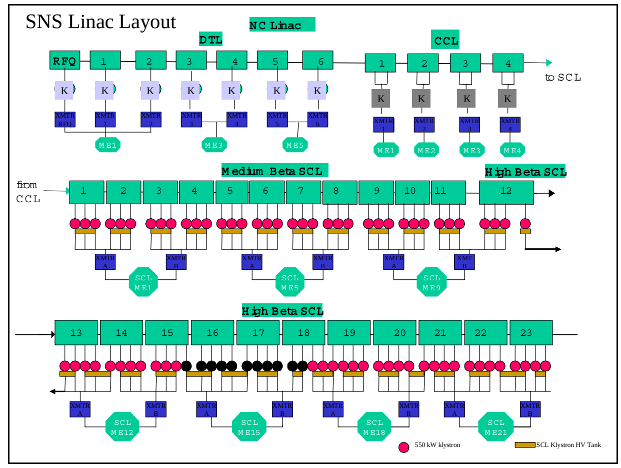

Figure 1: SNS Linac layout. Each cavity is driven by its own klystron-based RF system.

OPERATION

The RF systems are operated via the EPICS control system from the SNS Central Control Room. Only digitized data, both waveforms and scalar values, are available in the control room, i.e., analog signals are not transported from the klystron gallery to the control room. Real time troubleshooting or monitoring of transients must be performed in the klystron gallery. This has not proven to be a hardship thus far.

The EPICS screens used to monitor and control the RF systems are typically divided into two categories: LLRF and High-Level RF (HLRF). Some screens are integrated in this respect. EPICS sequences, i.e., finite state machines, are used to automate various tasks, such as start-up and shut-down of the RF systems. Sequences are used extensively in the LLRF system; it would be very difficult operate the Linac without the automation provided by these programs.

PERFORMANCE

The primary performance metric for the RF systems is the achieved cavity field regulation, typically cited in terms of amplitude and phase. The regulation requirement for the SNS Linac is ±0.5% in amplitude and ±0.5 deg in phase, in order to minimize component activation due to beam loss. Typical performance is shown in Figure 2, where the amplitude and phase errors throughout the Linac are plotted in terms of peak, RMS and average values. The RMS errors are well within the required field regulation requirement. In this case, the Linac was delivering a 65 kW beam. The regulation error is measured at the low-level RF controller, but the real performance proof is seen in beam diagnostics measurements including beam loss, beam phase, and

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energy stability, all of which confirm the high quality of field regulation.

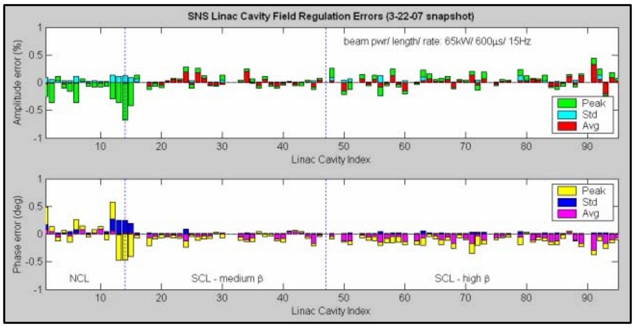

Figure 2: Cavity field regulation achieved in the Linac.

RELIABILITY

The reliability of the RF systems is critical to the overall reliability of the SNS since failure of a single RF system results in lost neutron production time. The Linac can operate with several SCL RF stations disabled, and this is the norm since several superconducting cavities are usually offline at any given time (not due to RF system failures). A semi-automatic procedure is used for rephasing the downstream cavities when a SCL RF station is disabled or enabled. However, in the normal conducting section of the Linac, all RF stations and their associated cavities must be operational in order to accelerate beam through the Linac.

The SNS downtime per technical subsystem during the first half of fiscal year (FY) 2007 is shown in Figure 3. The RF systems are responsible for 7.6% of the total downtime with a ranking of 5th place relative to other subsystems. This is a considerable improvement compared to the past. For example, during the accumulator ring beam commissioning run, the RF systems were responsible for 21% of the downtime and ranked 2nd relative to other subsystems [2].

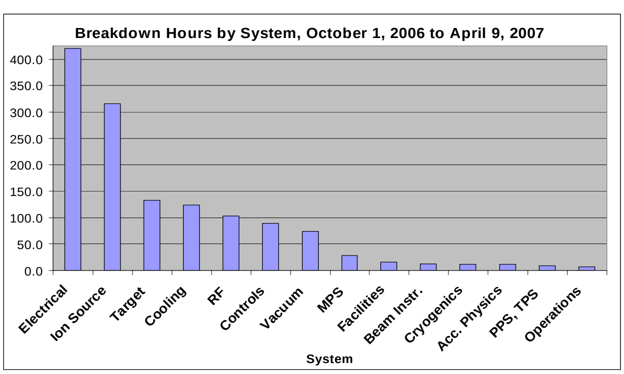

Figure 3: SNS downtime by technical subsystem during first half of FY07. The RF systems were responsible for 7.6% of total downtime.

Klystrons and Gridded Tubes

The SNS Linac utilizes 92 klystrons of three types and four vendors as described in Table 1. The majority of the klystrons are the 805 MHz, 550 kW units used in the SCL. All of the klystrons were specified and procured by Los Alamos National Laboratory (LANL), with the exception of three 402.5 MHz klystrons that were procured later by the SNS RF Group. The klystron reliability has been outstanding to date. There have been no failures attributable to the klystrons themselves. The klystrons have been operated 10,000 to 15,000 hours at this time, depending on their location in the Linac. All of the klystron designs feature relatively low cathode loading, and in principle lifetimes of ~100,000 hours may be expected. Also, the klystrons are generally operated at less than maximum cathode voltages. For example, the SCL klystrons are rated at 550 kW peak power with a cathode voltage of 75 kV, but they are normally operated at 69-71 kV. Spares procurements are based on lifetimes of ~50,000 hours.

The few klystron related failures that have occurred are primarily due to solenoid water leaks. In one case this resulted in arcing and overheating of solenoid wiring. In another, the space between the klystron body and the solenoid partially filled with water, submerging the RF input connection. The only operational symptom was reduced power output. It was somewhat surprising to discover the source of the problem upon removal of the klystron.

The DTL klystrons have a coaxial output followed by a coaxial-to-waveguide transition. Several of these transitions exhibited arcing during testing at Oak Ridge. The cause was out-of-tolerance components in the coaxial output, which resulted in shearing of a thin disk in the waveguide-to-coaxial transition. The vendor subsequently inspected all of the DTL klystrons and made modifications where necessary. This problem has not recurred since making these repairs.

Two of the SCL klystrons exhibited excessive outgassing during vendor testing. This outgassing is RF power level dependent and is apparently not correlated to cathode voltage or solenoid current. One of these klystrons was installed in the SCL and had to be removed from service due to excessive ion pump over current faults. It is planned to further investigate the behavior of these klystrons on a RF test stand at SNS, where they can be operated at maximum power levels in an attempt to vacuum condition them and make them usable spares.

The CCL klystrons are rated at 5 MW peak power, and during acceptance testing at LANL, numerous problems were discovered with auxiliary components such as circulators and loads. The load problems were corrected via a design change (field serviceable), and the circulator issues were mitigated by filling the circulators with Sulfur Hexafluoride (SF6). The klystron output windows are also maintained in an atmosphere of SF6 per vendor specifications.

The aforementioned procurement of three 402.5 MHz klystrons was completed earlier this year. A spares procurement of 38 klystrons for the SCL is in progress. In anticipation of the power upgrade project [3], these klystrons will be rated for 700 kW at a cathode voltage of 83 kV.

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The MEBT rebuncher and accumulator ring RF systems utilize triodes and tetrodes as noted in Table 1. These power tubes have been quite reliable to date, and none have required replacement.

Linac Transmitters and Associated Equipment

The transmitters include power supplies (filament, ion pump, solenoid, and circulator trim coils), equipment protection interlocks, AC power distribution, and PLC-based control and monitoring. Associated equipment includes water distribution racks and instrumentation, waveguide components, and the high-voltage tanks and tube sockets. These systems have proven to be reliable – with a few exceptions – and the PLC-based control and monitoring is very flexible.

The filament power supplies were initially prone to failure at turn on. The vendor provided an upgrade – implemented by SNS RF Group technicians – which effectively eliminated this susceptibility. Other occasional equipment failures include cabinet cooling blowers, solid-state drive amplifiers, and door interlock switches.

The transmitters were designed to switch off the cathode high voltage under most fault conditions, and this feature has contributed to some of the downtime attributed to the transmitters. For example, if the solid-state amplifier is overdriven by the LLRF control system, the high voltage is switched off. In the SCL, this necessitates restarting 11 or 12 RF systems since multiple klystrons are powered by a single high-voltage converter modulator. This particular problem has been alleviated through development of a LLRF feature that clamps the maximum RF drive to a level that prevents overdriving the solid-state amplifier.

MEBT Rebuncher Transmitters

The MEBT rebuncher transmitters support operation of triode-based amplifiers rated at 20 kW maximum power. They were designed and built by industry per SNS specifications. These transmitters have presented numerous operational difficulties including: tripping of AC distribution breakers under certain fault conditions, tuning sensitivity of the amplifier resonator, detuning of the amplifier resonator due to heating when operated at a high duty factor, and unreliable preamplifiers. These problems have been partially mitigated through modifications to the transmitters, but it is planned to eventually replace them as part of an accelerator improvement project. The MEBT rebuncher transmitters, which comprise 4% of the SNS RF systems, were responsible for ~15% of the RF systems downtime during the first half of FY 2007 as shown in Figure 4.

Low-Level RF

The LLRF control system hardware proper has proven very reliable to date. The only notable failures have been the high density RF cable connectors. There are two types of outer conductors used in the connectors: soldered and crimped. In both cases, the attachment of the connector outer shell to the cable outer conductor has failed on several occasions. This failure typically results in increased attenuation rather than complete failure, making detection somewhat difficult.

CONCLUSION

The SNS RF systems have been supporting accelerator operations for more than one year since project completion in the spring of 2006. The RF systems are presently meeting performance and reliability expectations and support the overall SNS program [4]. However, improvements will be needed over the coming years to achieve the high reliability goals.

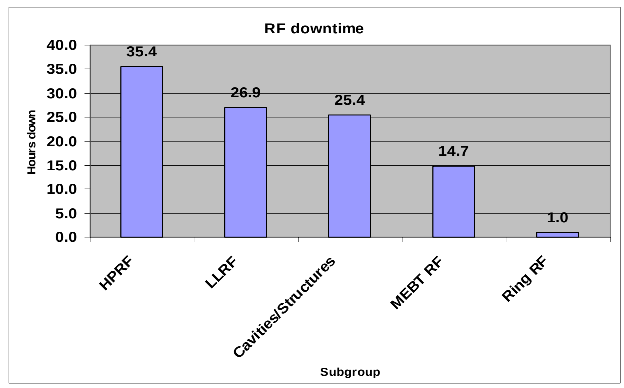

Figure 4: Distribution of RF system downtime during first half of FY07.

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