THE SPALLATION NEUTRON SOURCE RF REFERENCE SYSTEM*

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Abstract

The Spallation Neutron Source (SNS) RF Reference System includes the master oscillator (MO), local oscillator(LO) distribution, and Reference RF distribution systems. Coherent low noise Reference RF signals provide the ability to control the phase relationships between the fields in the front-end and linear accelerator (linac) RF cavity structures. The SNS RF Reference System requirements, implementation details, and performance are discussed.

INTRODUCTION

Construction of the SNS facility in Oak Ridge, TN is scheduled for completion in 2006. A pulsed ∼40 mA 1 GeV H^- ion beam produced by the front-end and linac systems is extracted from a 1000 turn accumulator ring and delivered to a liquid mercury target to produce neutrons.

The ∼40 mA H^- beam generated by the SNS front-end ion source is first bunched and accelerated to an energy of 87 MeV over a distance of 44 meters by 11 RF systems operating at 402.5 MHz. The H^- beam is then accelerated to 1 GeV over a distance of 210 meters by 85 RF systems operating at 805 MHz. All 96 RF systems operate in pulsed mode with a maximum repetition rate of 60 Hz and pulse width of 1.3 ms.

The SNS RF Reference System includes the MO, LO distribution, and Reference RF distribution systems. The MO generates six coherent low noise output signals at 2.5, 10, 352.5, 402.5, 755, and 805 MHz. All Reference System signals are continuous wave (CW) sinusoids and the distribution systems are multi-point grounded.

The Reference System provides a 352.5 MHz LO signal and a 402.5 MHz Reference RF signal to each of the 11 LLRF control systems in the 402.5 MHz section. The 402.5 MHz section contains the radio frequency quadrupole (RFQ), 4 medium energy beam transport (MEBT) rebuncher, and 6 drift tube linac (DTL) RF systems.

The Reference System provides a 755 MHz LO signal and an 805 MHz Reference RF signal to each of the 85 LLRF control systems in the 805 MHz section. The 805 MHz section contains 4 coupled-cavity linac (CCL) and 81 super conducting linac (SCL) RF systems.

The MO is located in the klystron gallery in between the DTL (402.5 MHz) and CCL (805 MHz) sections. The 352.5 MHz LO and 402.5 MHz RF signals are distributed upstream towards the RFQ while the 755 MHz LO and 805 MHz RF signals are distributed downstream towards the SCL.

Table 1: Reference System Logistics

	RFQ, MEBT, DTL	CCL, SCL
RF Frequency	402.5 MHz	805 MHz
LO Frequency	352.5 MHz	755 MHz
Systems	11	85
Section Length	44 m	210 m

The LO signals are used to perform frequency translation for the 50 MHz intermediate frequency (IF) based digital LLRF control systems[1]. Reference RF signals provide the RF frequency used to operate the RF systems and make it possible to accurately control the phase relationships between the fields in the RFQ, MEBT, DTL, CCL, and SCL RF cavity structures.

Installation of the SNS RF Reference System in the front-end and linac sections is complete. The 755 MHz LO and 805 MHz RF Reference distribution systems were designed and built to support a planned SNS energy upgrade[2]. The SNS RF Reference System has demonstrated excellent reliability and performance during testing and commissioning of the front-end and linac RF systems.

REQUIREMENTS

A two stage process[3] is used to transport the Reference RF signals to the LLRF systems. The Reference RF signals are first distributed by one of the two RF Reference Lines (402.5 or 805 MHz) and are then delivered to the LLRF systems via the Reference/Cavity Signal Transport system.

The RF Reference Lines are 3-1/8” rigid copper coaxial transmission lines that run parallel to and ∼1.5 meters above the beam line. The RF Reference Lines are temperature controlled, pressure regulated, and include one directional coupler for each RF cavity structure. The directional couplers are positioned directly above the cavity field probe connector for each RF cavity structure. The RF Reference Line phase error stability requirement is specified at ±0.1 degrees between adjacent cavities and is not to exceed ±2.0 degrees between any two points in the linac.

The Reference/Cavity Signal Transport system takes the Reference RF signal from the RF Reference Line directional coupler and the Cavity RF signal from the cavity field probe connector and sends the two signals to the LLRF rack via a pair of phase stabilized and phase matched 3/8” Heliax cables. The two cables experience little phase drift

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Table 2: RF Reference Line Requirements

	Phase Error
Between Adjacent Cavities	$\pm$ 0.1 degrees
Between Any Two Linac Points	$\pm$ 2.0 degrees

and the phase drift that does occur is largely cancelled. At the LLRF rack the Reference RF and Cavity RF signals are down-converted by the reference LO signal to 50 MHz Reference IF and Cavity IF signals in a temperature controlled dual down-converter chassis. The Reference IF and Cavity IF signals are then provided to the LLRF system for processing. The phase error specification for both the Reference Signal Transport and the Cavity Signal Transport is $\pm$0.3 degrees. The LLRF control system phase error requirement is $\pm$0.4 degrees.

Table 3: LLRF Requirements

	Phase Error
Cavity RF Transport	$\pm$ 0.3 degrees
Reference RF Transport	$\pm$ 0.3 degrees
Control System	$\pm$ 0.4 degrees
Total	$\pm$ 1.0 degrees

IMPLEMENTATION

Master Oscillator

The SNS Reference system master oscillator (MO) is an ultra low noise multiple frequency source which provides six outputs at 2.5, 10, 352.5, 402.5, 755, and 805 MHz. All six outputs are coherent and are directly synthesized from a single 10 MHz low noise oscillator. The MO was produced for the SNS by Wenzel Associates in Austin, TX, USA.

Frequency synthesis begins with a single 10 MHz ovenized ultra low noise SC-cut quartz crystal oscillator. A low noise divide-by-four module produces the 2.5 MHz signal. The 2.5 MHz and 10 MHz signals are then processed by low noise multiplier and mixer modules to produce 352.5, 402.5, 755, and 805 MHz signals. Other components including a low noise linear power supply, cavity bandpass filters, and low noise amplifiers are essential to production of the MO output signals.

The MO is packaged in a sealed 5.25" high 19" rack mount chassis. An SMA tuning input connector located on the front panel is useful for phase locking to another source. The output signal power levels are +20 dBm.

LO Distribution

Reference System LO signal distribution is performed in a simple and cost effective manner. Phase drift errors in the LO distribution are acceptable because the LO signal is used to down-convert the Reference RF and Cavity RF signals and also to up-convert the LLRF output drive IF signal.

LO signals are amplified to +40 dBm in the MO rack and distributed using 3/8" Heliax cables. The 352.5 MHz LO signal is sent to an 8-way splitter in the DTL3 LLRF rack. Outputs from the splitter are sent to the RFQ, MEBT, and DTL LLRF racks.

The 755 MHz LO signal is transported from the MO rack to the East end of the klystron gallery using 3/8" Heliax cable. Directional couplers are periodically installed in this cable, bringing the 755 MHz LO signal out to 1 central location for every 4 LLRF rack groups. The coupled signal goes into a 20 Watt 40dB gain low noise power amplifier with 4 outputs. One output goes to the LLRF rack containing the LO amplifier, the other 3 outputs are sent to nearby LLRF racks. The LLRF systems use level 17 mixers in the temperature controlled LLRF dual down-converter chassis. LO power levels are +21 dBm going to the RFQ, MEBT, DTL, and CCL racks. LO power levels are $\sim$+30 dBm going to each group of 3 adjacent SCL LLRF racks.

Reference RF Distribution

The Reference RF signals are amplified in the MO rack and transported to the linac tunnel RF Reference Lines in a pair of phase stabilized and phase matched 7/8" Cellflex coaxial cables. The 402.5 MHz signal level is +42 dBm and the 805 MHz signal level is +50 dBm at the 7/8" coaxial cable inputs. The S11 input Voltage standing wave ratio (VSWR) is 1.05:1 for the 402.5 MHz 7/8" line and the input VSWR is 1.15:1 for the 805 MHz 7/8" line.

The RF Reference Lines are 3-1/8" rigid copper coaxial transmission lines. The 402.5 MHz RF Reference Line is 140 feet long with 10 directional couplers. Coupling values are fixed at -22 dB on the 402.5 MHz RF Reference Line. The 805 MHz RF Reference Line is 941 feet long and has 123 adjustable directional couplers. The 805 MHz coupler settings are typically adjusted to a coupling value of -34 dB.

The RF Reference distribution system contains no teflon due to the linac tunnel radiation environment. Custom center conductor insulators, bullet connectors, and 3/8" Heliax type N connectors using polyethylene dielectric material were produced with good RF properties that will hold up to total integrated dose rates two to three orders of magnitude greater than teflon.

The RF Reference Lines are pressurized at 2 psig with clean dry instrument air (dew point = - 40$\circ$C) and a precision regulator. The RF Reference Lines are temperature controlled with 4 temperature zones on the 402.5 MHz RF Reference Line and 24 temperature zones on the 805 MHz RF Reference Line. Each temperature zone is independently controlled using 4 wire RTD sensors and PID temperature controllers. RF Reference Line temperature zones are maintained at 100.0 $\pm$0.1 degrees F. An 8 W/ft kapton insulated heat tape is run the length of each temperature zone (35 feet for 402.5 MHz section, 39 feet for 805 MHz section). The RF Reference Lines are insulated with 1.5" thick fiberglass.

PERFORMANCE

The RF Reference Line temperature control and pressure regulation systems are fully operational. Measurements between several 805 MHz RF Reference Line couplers did not show any phase drifts. Calculations support this result, in fact if one assumes a ± 0.1 degree C temperature error over the entire length of the 805 MHz RF Reference Line from CCL1 to CM12d, then the worst case phase error would be <0.7 degrees of phase at 805 MHz. This would require that 18 separate PID controlled temperature zones all move together over a range of 0.2 degrees C which is very unlikely. Even if this unlikely worst case scenario were to occur the phase error is still well within the requirement of ± 2.0 degrees between any two points in the linac.

Another measurement however has shown slow phase drifts of ± 3.5 ps between the 402.5 and 805 MHz RF Reference lines, over a time period of several days. This is equal to ± 1 degree of phase at 805 MHz, so some additional investigation/control here is warranted.

Table 4: MO Phase Noise $dBc/\sqrt{Hz}$

	352.5	402.5	755	805
10 Hz	-115	-108	-107	-104
100 Hz	-118	-111	-107	-103
1 kHz	–135	-133	-128	-123
10 kHz	-152	-148	-139	-136

Frequency stability of the MO has been impressive[4]. The MO 10 MHz oscillator aging characteristics were measured using a GPS receiver over a period of 610 days. The 10 MHz output frequency increased by 0.10 Hz for an aging rate of <2e-11/day. MO phase noise was also measured using the SNS MO and the spare MO, with both units installed in the klystron gallery MO rack. The phase noise measurements were found to be within the specifications for the unit.

REFERENCES

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