HIGH INTENSITY BEAM PERFORMANCE OF THE SNS ACCUMULATOR RING LLRF CONTROL SYSTEM*

M. Piller, M. Crofford, T. Hardek, ORNL, Oak Ridge, TN 37831, U.S.A.

Abstract

Four ferrite loaded resonant radio frequency (RF) cavity structures and one resistive wall current monitor (WCM) located in the South leg of the Spallation Neutron Source (SNS) accumulator ring provide a 250+ ns beam extraction gap. Three ring RF cavities operate at the fundamental accumulator ring revolution frequency (~1.05 MHz) to bunch the beam while the fourth cavity operates at the second harmonic (~2.10 MHz) to suppress the peak beam current. The SNS ring low-level RF (LLRF) control system utilizes dynamic cavity tuning and proportional, integral, and derivative (PID) feedback to regulate the amplitude and phase of the fields in the ring RF cavities. In April 2009 the SNS accelerator delivered 835 kW of beam power (928 MeV, 60 Hz, 15 μC/pulse) to the target during a neutron production run. This paper discusses operation and performance of the SNS ring LLRF system with high intensity beam loading.

INTRODUCTION

A negatively charged chopped hydrogen ion beam generated in the SNS front-end (FE) is accelerated to ~1 GeV in the linear accelerator (LINAC), converted to protons upon injection into the ring, accumulated for up to 1060 turns (~1 ms), extracted from the ring and transported to a liquid mercury target. The SNS delivered first beam to target in April 2006. Beam power to target reached 835 kW in April 2009. SNS full design beam power is 1.4 MW (see Table 1).

Six national laboratories [1] were involved in the SNS collaboration: Argonne, Brookhaven, Jefferson, Lawrence Berkeley, Los Alamos, and Oak Ridge. The SNS Accumulator Ring RF systems were developed at Brookhaven.

OPERATION

Ring RF Cavities

Four ferrite loaded resonant RF cavity structures located in the South leg of the SNS accumulator ring provide a 250+ ns beam extraction gap. Three ring RF cavities operate at the fundamental accumulator ring revolution frequency (~1.05 MHz) to bunch the beam while the fourth cavity operates at the second harmonic (~2.10 MHz) to suppress the peak beam current. Each ring RF cavity has two accelerating gaps. The Ring RF cavity accelerating gaps can be shorted remotely when the station is not in use to protect equipment and to prevent the development of beam induced cavity fields [3].

Table 1: SNS Parameters

Parameter	April 2009 Run	SNS Design
Proton beam power on target	835 kW	1.4 MW
Proton beam energy	928 MeV	1.0 GeV
Ring revolution frequency	1.045 MHz	1.058 MHz
Protons per pulse on target	9.57×10^{13}	1.5×10^{14}
Charge per pulse on target	15 μC	24 μC
Repetition Rate	60 Hz	60 Hz
Number of injected turns	690	1060
Beam extraction gap	250 ns	250 ns
Proton pulse length on target	695 ns	695 ns
Maximum uncontrolled beam loss	1 W/m	1 W/m

Timing

The SNS accelerator is a pulsed machine operating at a nominal 60 Hz pulse repetition rate. During the course of a 1 ms pulse up to 1060 mini-pulses (turns) of beam are injected into and accumulated in the 248 meter circumference SNS ring. The ring revolution frequency (F_rev) is ~1.05 MHz which corresponds to a revolution period of about 1 us. The ring RF systems maintain a proton beam pulse length of 695 ns throughout accumulation and provide the clean 250+ ns gap necessary for low loss extraction of beam from the ring.

The digital ring LLRF systems utilize an external timing master 32 * F_rev clock signal as a phase and frequency reference. A four channel 14 bit ADC board clocked at 64 * F_rev is used to digitize the Cavity RF signal, the anode vs. grid signal, and the WCM signal (one unused channel). A four channel 14 bit DAC board clocked at 64 * F_rev outputs a grid boost signal, a cavity tuning signal, a window comparator reference signal, and the RF drive signal. FPGA's on the ADC and DAC boards handle most of the required functionality however each system also uses a commercial DSP board running at 80 MHz to perform I/Q feedback loop signal processing.

The ring RF systems are typically operated with a 2500 turn (~2.5 ms) flat top closed loop constant amplitude and phase RF waveform. Enable and inhibit timing trigger events are used to modify the start and stop time of the RF pulse. The ring RF pulse width can be extended to a maximum of 3.5 ms for long beam store instability studies.

Cavity Tuning

Resonance control [2] for each ferrite loaded ring RF cavity structure is accomplished by a tuning current provided by a 1000 A current supply. The LLRF cavity tuning system drives the current supply with a tuning signal comprised of both a feed-forward 180 Hz dynamic component and a slow feedback static offset component. The dynamic component feed-forward waveform amplitude and phase settings are adjusted to compensate for the significant beam induced cavity detuning experienced during accumulation. The static offset tuning component is regulated by an Experimental Physics and Industrial Control System (EPICS) sequencer which uses the ring high power RF (HPRF) tetrode power amplifier anode vs. grid phase detector readback signal to provide slow feedback control.

Fundamental ring RF stations require both static and dynamic cavity tuning signal components whereas the second harmonic ring RF station has been found to operate best with only a static tuning signal component (dynamic tuning signal amplitude component set to zero). The falling zero crossing of the dynamic tuning signal phase waveform is set near the middle of accumulation to provide a linear control region with correct slope. The amplitude component of the dynamic tuning signal on fundamental ring RF stations is roughly proportional to accumulated beam charge however this relationship is skewed by non-linear ferrite behaviour at higher accumulated beam charge levels.

Ring RF Cavity Phasing

The fundamental Ring RF stations are used to bunch the beam with the centroid of the beam coincident with the falling zero crossing of the cavity field phase. The second harmonic Ring RF station is used to suppress the high peak beam current (produced by the fundamental Ring RF stations) with the centroid of the beam coincident with the rising zero crossing of the cavity field phase.

PERFORMANCE

Wall Current Monitor

A resistive WCM cavity structure located adjacent to the Ring RF cavities in the South leg of the SNS accumulator ring provides a high bandwidth signal of the beam current during accumulation and storage. The WCM output signal is captured by an oscilloscope and processed by the SNS control system (see Fig. 1). The lower traces shown in Fig. 1 are slices taken from the WCM signal early in the accumulation cycle while the upper traces are slices taken later in the accumulation cycle (near extraction). The lower traces in the display show that the second harmonic ring RF station is operating and that the phase appears to be correct as can be seen by the amplitude dip (peak suppression) in the center of the bunches. The clean gap between bunches in

the upper traces and the symmetric bunch shape shows that the fundamental ring RF stations are operating with proper amplitude and phase.
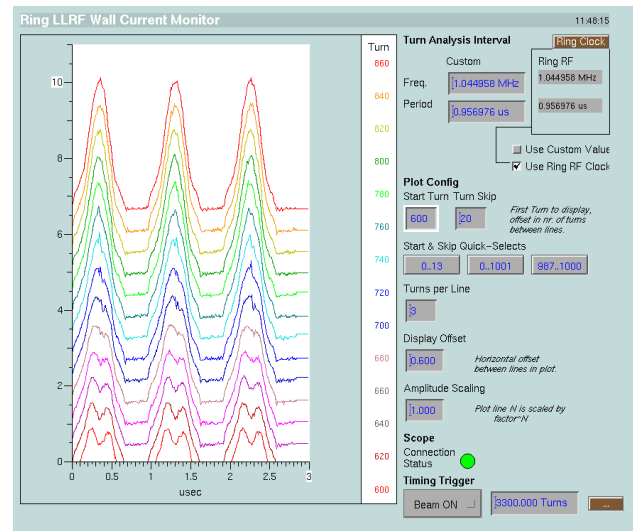

Figure 1: WCM output for 835 kW beam.

Cavity Field Regulation

The digital ring LLRF systems [4] use PID feedback control to regulate the amplitude and phase of the fields in the ring RF cavities to +/-1 percent and +/-1 degree. During the 835 kW production run two of the three fundamental ring RF stations were each operated at 10 kV (20 kV total fundamental component) and the second harmonic ring RF station was also operated at 10 kV. The ring RF cavities experienced an average RF beam loading of 21.6 A (15 µC/695 ns) during the 835 kW production run however the peak beam loading currents were in excess of 30 A due to the uneven charge distribution in the bucket. The LLRF feedback loops for a fundamental ring RF station responded to this level of beam loading by increasing the output drive signal amplitude component by a factor of 5 and by swinging the output drive signal phase component 125 degrees during the accumulation cycle (see Fig. 2).

The drive signal amplitude component trace in Figure 2 decreases to a minimum after approximately 100 turns of accumulation and then increases steadily until extraction (~690 turns). The amplitude dip at 100 turns is caused by the ring RF cavity tuning system which was operating with a 25 A feed-forward 180 Hz dynamic tuning component during the 835 kW production run. The static offset slow feedback tuning component is typically about 250 A on a fundamental station and 400 A for the second harmonic station. The slope of the phase trace in Fig. 2 is a maximum while the cavity swings through resonance at 100 turns.
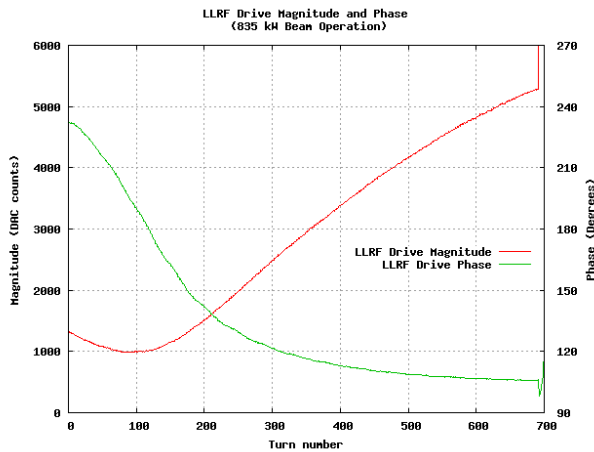
Figure 2: Fundamental ring RF station feedback loop response during 15 μC beam charge accumulation.

Ring RF Issues

The SNS ring LLRF user interface software controls include a combination of EPICS and TCL/TK applications. A transition to an all EPICS system is planned.

Ring LLRF window comparator protection systems have been problematic. Beam loss monitors provide necessary protection however the long term solution will be to implement window comparator functionality in the ring LLRF control system software as was done with the SNS linac LLRF control system.

Water cooled solid state ring RF driver amplifiers have been unreliable. Recent test results of a new air cooled solid state RF driver amplifier during the 835 kW production run are encouraging.

Noise in the 20 - 50 kHz frequency range originating in the 1000 A cavity tuning supplies is visible on several ring RF waveforms.

None of these ring RF issues are show stoppers however they will all need to be addressed in order to achieve high availability operation at the full 1.4 MW SNS design beam power level.

SUMMARY

The SNS ring LLRF systems performed well in regulating cavity field amplitude and phase to about +/- 1 percent and +/- 1 degree during the recent production run with 15 μC/pulse accumulated beam charge. Ring operation is not beam loss limited and the ring has been able to handle all beam power levels produced by the SNS accelerator to date [5]. Experience gained operating the ring RF systems with 15 μC/pulse of accumulated beam charge suggests that sufficient reserves exist in terms of ring RF station Voltage and cavity tuning capacity for future operation with 24 μC/pulse of accumulated beam charge at the full 1.4 MW SNS design beam power level.

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REFERENCES

[1] N. Holtkamp, "Status of the SNS Project," Proc. 2003 PAC
[2] M. Blaskiewicz, et al., "RF System for the SNS Accumulator Ring," Proc. 2001 PAC
[3] T. Hardek, et al, "The Spallation Neutron Source Accumulator Ring RF System", Proc. 2007
[4] K. Smith, et al, "Progress on the SNS Ring LLRF Control System", Proc. 2003 PAC
[5] M. Plum, contributed oral talk, these proceedings