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

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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].

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.

Table 1: SNS Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>April 2009 Run</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton beam power on target</td>
<td>835 kW</td>
<td>1.4 MW</td>
</tr>
<tr>
<td>Proton beam energy</td>
<td>928 MeV</td>
<td>1.0 GeV</td>
</tr>
<tr>
<td>Ring revolution frequency</td>
<td>1.045 MHz</td>
<td>1.058 MHz</td>
</tr>
<tr>
<td>Protons per pulse on target</td>
<td>9.57 x 10^{11}</td>
<td>1.5 x 10^{14}</td>
</tr>
<tr>
<td>Charge per pulse on target</td>
<td>15 µC</td>
<td>24 µC</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>60 Hz</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Number of injected turns</td>
<td>690</td>
<td>1060</td>
</tr>
<tr>
<td>Beam extraction gap</td>
<td>250 ns</td>
<td>250 ns</td>
</tr>
<tr>
<td>Proton pulse length on target</td>
<td>695 ns</td>
<td>695 ns</td>
</tr>
<tr>
<td>Maximum uncontrolled beam loss</td>
<td>1 W/m</td>
<td>1 W/m</td>
</tr>
</tbody>
</table>

*SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy.


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.

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 1: WCM output for 835 kW beam.

Figure 2: LLRF drive signal traces for 835 kW beam.

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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.

**REFERENCES**

[5] M. Plum, contributed oral talk, these proceedings