Low Level RF Status and Development Activities at the Spallation Neutron Source

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LLRF 2017 Workshop, Barcelona, Spain
SNS Accelerator Availability is Excellent

- Original LLRF systems continue to support reliable operation
- 1.2 MW operation is routine, accelerator is 1.4 MW capable
- During the run completed on September 30th 2017 availability of the accelerator was 96% over 86 days

### Availability For The Past Week

<table>
<thead>
<tr>
<th>Date</th>
<th>Production Beam</th>
<th>Accel Physics</th>
<th>Startup</th>
<th>Planned Shutdown</th>
<th>Availability</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Requested</td>
<td>Delivered</td>
<td>Requested</td>
<td>Delivered</td>
<td>Requested</td>
<td>Delivered</td>
</tr>
<tr>
<td>2017-09-10</td>
<td>24.0 h</td>
<td>23.8 h</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2017-09-09</td>
<td>24.0 h</td>
<td>23.8 h</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2017-09-08</td>
<td>24.0 h</td>
<td>23.5 h</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2017-09-07</td>
<td>24.0 h</td>
<td>21.5 h</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2017-09-06</td>
<td>24.0 h</td>
<td>23.3 h</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2017-09-05</td>
<td>8.6 h</td>
<td>8.6 h</td>
<td>-</td>
<td>5.4 h</td>
<td>5.4 h</td>
<td>10.0 h</td>
</tr>
<tr>
<td>2017-09-04</td>
<td>-</td>
<td>-</td>
<td>22.0 h</td>
<td>22.0 h</td>
<td>2.0 h</td>
<td>2.0 h</td>
</tr>
<tr>
<td>2017-09-03</td>
<td>2.0 h</td>
<td>1.9 h</td>
<td>22.0 h</td>
<td>21.7 h</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The current run started on 2017-07-07. Availability has been 95.87% over the past 66 days.
Accelerator Availability: Monthly Average is 93% During Last 4 Years

- Excludes MEBT water leak & Mercury target failures
- LLRF system failures account for <<1% of accelerator downtime
Since the 2015 LLRF Workshop We Have Been Busy on Development Activities

• System obsolescence continues to be an issue
  – Limited spares for the Ring LLRF

• Desire to add new capabilities to both the Linac and Ring LLRF control systems
  – User friendly interface and controls for the Ring system
  – Faster adaptive feed forward for the Linac system

• Actively working to the Proton Power Upgrade and Second Target Station projects
LLRF Development Platform

• Required a method to quickly test modules that could be used for LLRF projects
  – Reuse of the standard LLRF memory map
    • Artix-7 based system FPGA → VME interface
    • Allows use of existing EPICS screens and tools
  – Support all legacy VME backplane connections
  – Artix-7 (XC7A100T) application FPGA
    • Adequate resources for our development activities

• Planned transition to new μTCA.4 based platform

• Excellent for FMC development

See “Spallation Neutron Source LLRF FMC Module Development” in Poster Session for details on modules
Ring LLRF Hardware Development

- μTCA.4 based system
  - PCIe bus, Linux IOC, EPICS

- Use commercial-off-the-shelf carrier card
  - VadaTech AMC502 carrier card

- Custom 14 bit dual ADC, dual DAC FMC developed by LLRF Team
  - Planned replacement with Quad ADC and Quad DAC to support full ring functionality

- Custom timing receiver FMC module developed by Control Hardware Team

- Development of replacement analog hardware in progress
Ring LLRF Modeling, Firmware & Software

• Joint effort between Controls and LLRF
• Based on the original BNL design
  – Developed a Simulink model to verify the feedback control loop
  – Converted from floating to fixed point implementation
• Migrated from co-simulation using VHDL to FPGA realization
  – Supports open/closed loop operation
  – Turn-by-turn control
  – Waveform capture
• Initial EPICS screens developed
  – Similar look and feel as the Linac screens

Mathematical Model (Dec 2016)
Ring LLRF Initial Test Results

• First test of the system in May 2017
  – Verified open & closed loop operation → 85 kW beam

• Follow on tests
  – Verified operation with 1 MW beam
  – Operated system at both 1\textsuperscript{st} and 2\textsuperscript{nd} harmonic

• System installed for operations in September 2017
  – Basic EPICS screens complete
  – Timing card integrated
  – IOC bootable via network

• Ready for 1\textsuperscript{st} production beam run

• Great collaboration between Controls and LLRF Teams!
**Proton Power Upgrade (PPU) Project**

- Increases power capabilities of existing 60 Hz accelerator from 1.4 MW to 2.8 MW
- Increases power delivered to first target station (FTS) to 2 MW
- Increases neutron flux on existing beam lines
- Provides platform for construction of second target station (STS)
- Requires 7 additional cryomodules (28 cavities)
PPU Overview & High Level Parameters

- 28 additional RF Stations → will require redesign of LLRF systems for second target station (STS)
  - PPU will utilize redesigned LLRF due to obsolete hardware in existing system
  - Original 96 LLRF stations to be retrofitted during STS

- Conceptual design is complete and is awaiting funding

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SNS 1.4 MW</th>
<th>PPU full upgrade capability</th>
<th>PPU FTS 60 Hz operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton beam power capability (MW)</td>
<td>1.4</td>
<td>2.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Beam energy (GeV)</td>
<td>0.97</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>RFQ output peak beam current (mA)</td>
<td>33</td>
<td>46</td>
<td>46</td>
</tr>
<tr>
<td>Average linac chopping fraction (%)</td>
<td>22</td>
<td>18</td>
<td>41</td>
</tr>
<tr>
<td>Average macropulse beam current (mA)</td>
<td>25</td>
<td>38</td>
<td>27</td>
</tr>
<tr>
<td>Energy per pulse (kJ)</td>
<td>23</td>
<td>47</td>
<td>33</td>
</tr>
<tr>
<td>Pulse repetition rate (Hz)</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Macro-pulse length (ms)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>FTS decoupled moderator brightness/pulse (AU)</td>
<td>1</td>
<td>2.04</td>
<td>1.43</td>
</tr>
<tr>
<td>FTS coupled moderator brightness/pulse (AU)</td>
<td>1</td>
<td>2.16</td>
<td>1.51</td>
</tr>
</tbody>
</table>

33% energy increase

50% current increase

No change
Linac LLRF Development

• Replacement Linac LLRF system will be deployed on µTCA.4
  – Leverages development work on Ring LLRF and Data Acquisition Systems (DAS)
  – Solves VME/VXI bandwidth limitation problem
    • Standard VME/VXI data rates are limited to 40 MB/s, PCIe Gen 1 supports 1 GB/s
  – Multiple vendor support
  – Similar system configuration to what is currently installed
    • 1 IOC, 1 timing receiver, & 2 control systems per crate

• Issues
  – Limited board and front panel size
    • Plan to use RTM’s to provide additional panel I/O and increased PCB layout area
  – Investigating COTS carrier card options for cost savings
    • Option to produce custom carrier card in the future
High-power Protection Module (HPM) Development

• The HPM is responsible for the fast shutdown of the RF output signal
  – Detected overpower
  – Quench detection
  – Arcs in the RF distribution system
  – Poor vacuum, water flow, cryo, & high power RF

• New design utilizes improved RF detection
  – Better detectors (ADI ADL5513)
    • 80 dB dynamic range, 20 nSec response time
  – 16 bit ADCs vs. 10 bit
  – Simplified calibration of channels
    • Use of digital potentiometers with plans for automated calibration
    • Use of I²C communication between carrier and FMC module

• Arc detector interface for AFT chassis

• Plan to migrate from FMC format to RTM
  – Solves the front panel issue with µTCA platform
Field Control Module (FCM) Development

- The FCM has been reliable but key parts are now obsolete
- The existing system cannot meet future accelerator upgrades
  - No support for more than one style of beam flavor
- Use of a commercial µTCA carrier card and a custom RTM
  - Initial testing using the Dual ADC/Dual DAC and the Quad ADC FMC modules
- All RF signals will be incorporated in a temperature controlled chassis
  - 50 MHz signals only on the carrier card
- Key design goal is improved diagnostics in both the HPM and FCM replacements

VadaTech AMC523 – supports RTM
Quad ADC FMC
Dual ADC Dual DAC FMC
Summary

• The SNS is a mature facility that has been in operation since 2006
  – Continues to meet the power, availability and reliability goals of 4500 hours/year @ >90% availability.

• The replacement Ring LLRF system is installed and ready to support operations
  – Installed in accelerator in September 2017
  – Development of support hardware is underway

• Actively working on next generation Linac LLRF systems

• Proton Power Upgrade (PPU) project is ready to proceed
  – Adds 28 additional RF stations
  – Increases beam power to 2.8 MW
Acknowledgement

• Thanks to the SNS LLRF Team and Controls Team for their dedication and hard work. None of this would be possible without the help of everyone involved.
  – LLRF Team
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    • Stacey Whaley
  – Controls Team
    • Eric Breeding
    • Doug Curry
    • Xiaosong Geng
    • Alan Justice
    • John Sinclair
    • Michael “Gabe” Trout

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