Operational Experience of a Superconducting Cavity Fault Recovery System At the Spallation Neutron Source

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Outline

- The SNS Linac
- Commissioning and Operational experience With the SCL Linac
- Why does SNS need a cavity fault recovery system?
- A Cavity Fault Recovery System and Use Cases
The SNS Linac

- SNS is a pulsed, accelerator driven spallation neutron source
- It is driven by a high power linac - 1.5 MW baseline (constructed device) - 3 MW upgrade power  (CD-0 approved)
- It is the first high power or high energy superconducting proton linac - 80% of the acceleration is provided by superconducting cavities
- Did not come with an operating manual
- 1st beam to target April 28, 2006
- 1st “neutron production” Oct. 2006
Normal Conducting Linac

- CCL Systems designed and built by Los Alamos
- 805 MHz CCL accelerates beam to 186 MeV
- System consists of 48 accelerating segments, 48 quadrupoles, 32 steering magnets and diagnostics

- 402.5 MHz DTL was designed and built by Los Alamos
- Six tanks accelerate beam to 87 MeV
- System includes 210 drift tubes, transverse focusing via PM quads, 24 dipole correctors, and associated beam diagnostics
Superconducting Linac

- Designed an built by Jefferson Laboratory
- SCL accelerates beam from 186 to 1000 MeV
- SCL consists of 81 cavities in 23 cryomodules
- Two cavities geometries are used to cover broad range in particle velocities
- Cavities are operated at 2.1 K with He supplied by Cryogenic Plant
- Most operation has been at 4.2 K
Linac RF Systems

- Designed and procured by LANL
- All systems 8% duty factor: 1.3 ms, 60 Hz
- 7 DTL Klystrons: 2.5 MW 402.5 MHz
- 4 CCL Klystrons: 5 MW 805 MHz
- 81 SCL Klystrons: 550 kW, 805 MHz
- 14 IGBT-based modulators

- 2nd largest klystron and modulator installation in the world!
Beam Power Progress

- Power has ramped up from 8 kW to 60 kW over the last two run periods (since Oct. 2006)

- Machine setup and beam state recovery is more repeatable
The Beam Power Ramp Up Goal

- We need to ramp to full design power, at full final reliability with decreasing beam study time by Oct. 2009
SNS Availability Is Important

- SNS is a user facility – many users only scheduled for a few days
- Target availability is 95%
- RF systems are a major focus of availability

PSI Availability (ICFA High Brightness Workshop, 2006)

A short overview over the last 8 years shows that it is very hard to achieve availability values above the magic limit of 90%.

<table>
<thead>
<tr>
<th>Year</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
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<td>Hours with beam on target</td>
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<td>5200</td>
<td>4250</td>
<td>5030</td>
<td>4790</td>
<td>4710</td>
<td>5420</td>
<td>5520</td>
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<tr>
<td>Availability</td>
<td>91.0%</td>
<td>86.0%</td>
<td>86.0%</td>
<td>88.6%</td>
<td>89.2%</td>
<td>84.2%</td>
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<td>86.0%</td>
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<tr>
<td>Min avail./week</td>
<td>52.0</td>
<td>30.0</td>
<td>27.3</td>
<td>53.5</td>
<td>71.1</td>
<td>29.3</td>
<td>0.2</td>
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<td>Max avail./week</td>
<td>98.0</td>
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<td>97.8</td>
<td>96.4</td>
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**Layout of Linac RF with NC and SRF Modules**

- **Warm Linac**
  - RFQ (1)
  - DTL (6)
  - 2.5 MeV
  - 86.8 MeV
  - 186 MeV SRF, $\beta=0.61$, 33 cavities

- **SCL Linac**
  - from CCL
  - 379 MeV SRF, $\beta=0.81$, 48 cavities
  - 1000 MeV

- **CCL** (4)
  - 402.5 MHz, 2.5 MW klystron
  - 805 MHz, 5 MW klystron
  - 805 MHz, 0.55 MW klystron

- **SCL has 81 independently powered cavities**
  - Many parts to keep running
  - Many values to set w.r.t. the beam
SCL Cavity Amplitudes

- Strategy is to run cavities at their maximum safe amplitude limit
- Need to be flexible – SRF capabilities change, not near the design
- Linac output energy is a moving target
Cavity Fault Impact on Beam Arrival Times for a Proton Linac

- Proton beams for high power applications (< 10 GeV) are not fully relativistic and the velocity is energy dependent.
- If a cavity fails, the beam arrives at downstream cavities later.
- For SNS if an upstream cavity fails, the arrival time at downstream cavities can be delayed up to 5 nsec.
  - This is over 1000 degrees phase setting of an 805 MHz RF cavity.
  - Our goal is to set the cavity to within ~ 1 degree.
Longitudinal Acceleration Modeling (Application Programs – Online Model)

- Drift-kick-drift method
- Assume design field profiles throughout the cavity
- Transit Time Factor is calculated at each gap, based on a fit of Superfish calculations
- The beam sees a large phase slip from gap to gap as it traverses the cavity

Medium-Beta ($\beta_g=0.61$)

Beam-RF Phase (deg)

Parmila  OLM
Setting the Phase of the SCL Cavities

A beam based measurement must be done to initially set each cavity RF phase setpoint. Scan the cavity phase of a cavity 360, and observe the resultant change in the Time of Flight (TOF) between 2 downstream detectors. Compare this difference with model calculations. Need good relative phase measurements from the detectors (~1 degree!).

Example SCL Phase Scan

Black line = measurement fit
Dot = model
Red = cosine fit

RF Cavity Phase vs. BPM Phase Difference
**SCL Cavity Phase Setup Times are Getting Shorter**

- **August 2005:** 48 hrs  
  - 560 MeV, initial run, >20 cavities off

- **Dec. 2005:** 101 hrs  
  - 925 MeV, turned on all planned cavities

- **July 2006:** 57 hrs  
  - 855 MeV

- **Oct 2006:** 30 hrs  
  - 905 MeV, used established cavity turn on procedure

- **Jan. 2007:** 6 hrs  
  - 905 MeV, beam blanking used, which allowed all cavities to be on during the tuning process

- **The procedures used to setup the superconducting linac have matured, and the setup time is now minimal**

- **Still exists a need for fast recovery from changes in the SCL setup**

\[\text{Power cavities on sequentially}\]
SCL Tune-up – Linac Energy Gain is Understood and Predictable

- Energy gain per cavity is predictable to a few 100 keV and distributed about 0.
- Final energy is predictable to within a few MeV
Scaling Method for Cavity Fault Recovery

A new technique has been developed to recover from cavity faults. The method involves:

- Using beam measurements for original beam arrival times.
- User inputs changes to the SCL RF setup.
- A model predicts changes in the beam arrival times (RF phase setpoint changes), sends them to the machine, and predicts the new beam energy.
- It takes less than 1 second to calculate and apply the new SCL setup.

However, this technique has been applied to recover from “events” that take hours or days to evaluate and proceed.

### Table: Cavity Fault Recovery

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Amplitude 0</th>
<th>Amplitude New</th>
<th>Avg Phase 0</th>
<th>Start Phase 0</th>
<th>Manual Phase 0</th>
<th>Start Phase New</th>
<th>( W_0 ) (MeV)</th>
<th>( W_{\text{New}} )</th>
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<tr>
<td>SCL_RF:Cav01a</td>
<td>23.964</td>
<td>23.964</td>
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<td>193.45</td>
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<td>198.258</td>
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<td>15.006</td>
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<td>0</td>
<td>63.529</td>
<td>419.914</td>
<td>413.044</td>
</tr>
</tbody>
</table>
Expected Errors from the Scaling Method (I)

- Uncertainty in the cavity positions leads to errors in the predicted change in phase

- Relative cavity positions are known to a few mm, so < 1 degree error is expected from this uncertainty
Expected Errors from the Scaling Method (II)

- Uncertainty in the energy gain/cavity results in errors in the predicted change in cavity phase
- Energy gain is known to within a few hundred keV, so the error from this uncertainty is 1-2 degrees
Test of the Cavity Recovery Method – Single Cavity “Failure”

- Turned off cavity 7, rescaled the downstream cavity phase setpoints
- Downstream cavity phase setpoints changed > 1000 degrees
- A beam measurement check with the last cavity showed it was within 1 degree of the scaled prediction
Application of the Cavity Fault Recovery Scheme (I)

- In the spring 2006, 11 cavities had to be either turned off or have their amplitudes reduced for safe operation, 1 cavity was returned to operation
- The fault recovery scheme was applied “all at once”
- Phase scan spot checks indicate the scaling was within 4 degrees
- No detectable change in beam loss
Application of the Cavity Fault Recovery Scheme (II)

- In April 2007 the SCL was lowered from 4.2K to 2 K to facilitate 30 Hz operation.
- About 20 cavity amplitudes changed.
- The fault recovery scheme restored beam to the previous loss state.
Cavity Fault Recovery Scheme at SNS

- Additional applications of the cavity recovery scheme
  - Missing cryo-module tests to evaluate the impact on beam loss from removing entire cryo-modules from service for repairs.
  - Recovery from a control system failure that resulted in 3 broken cavity tuners.

- While intended for use in recovering from a single cavity failure, the scheme has been used more often to recover from more severe situations
  - Usually takes days to assess the situation, minutes to apply the recovery scheme
  - Previously took days to setup the cavities (now ~ 1 shift) with beam based measurement techniques

- This technique is considered a “standard practice” by now at SNS
  - Future improvements may include a more automated invocation
Summary

- High availability will be a strong driver at SNS
- A fault recovery scheme for superconducting cavity failure has been developed
- To date, its primary application has been for quick recovery from events involving multiple cavities
- It works!