SNS Accelerator Advisory Committee Review - January 2008

SNS RF Systems

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Overview

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- Linac RF Systems Issues
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- Accumulator Ring RF System Issues
  - Present RF System Operational Status
  - Current Operational Results
- Low Level RF Systems Issues
  - Present Status
- Conclusions
SNS Facility – Artists View
Overall Site Layout

- Ring RF section
- Ring Magnet power supplies
- RF System supplies and LLRF
- Target
- FRONT END BUILDING
- LINAC TUNNEL
- KLYSTRON GALLERY
- CRYOGENICS BUILDING
- HEBT TUNNEL
RF Systems in the Front End Building

- **Ion Source**
  - 2 MHz 80 kW amplifier to ionize the hydrogen gas.
  - 13 MHz 2 kW amplifier aids in ionization.

- **MEBT Rebuncher**
  - 4 Cavities used to match the beam from out RFQ into the DTL section.
  - 20 kW, 402 MHz amplifiers
Klystron Gallery Normal Conducting RF

- **RFQ**
  - 1\textsuperscript{st} klystron powers the RFQ structure.
  - 800 kW, 402.5 MHz
  - E2V klystrons
  - The klystron can provide 2.5 MW so this klystron has excess power.

- **DTL**
  - 6 Klystrons power the DTL
  - 2.5 MW, 402.5 MHz
  - E2V klystrons
  - Circulator Loads use a Water – Glycol mix.
Klystron Gallery Normal Conducting RF

- **CCL**
  - 4 Klystrons power the CCL cavities
  - 5 MW, 805 MHz Thales Klystrons
  - Output window is gas insulated with SF6.
  - Circulator is gas insulated with SF6
  - Circulator load is conventional water load.
Klystron Gallery Superconducting Cavity RF

- **SCL RF**
  - 81 Klystrons each powering a separate cavity string,
  - 550 kW, 805 MHz
  - CPI and Thales
Layout of Linac RF Modules

- **RFQ** (1) 2.5 MeV
- **DTL** (6) 86.8 MeV
- **CCL** (4)

- **186 MeV** SRF, $\beta=0.61$ (33) from CCL
- **379 MeV** SRF, $\beta=0.81$ (48 cavities, all powered)
- **1000 MeV** HEBT (2)
SNS Linac RF Configuration

- One cavity per klystron
- Multiple klystrons per high-voltage power supply
- 402.5 MHz RFQ, MEBT, & DTL
- 805 MHz CCL & SCL
- 96 Linac RF systems
Accumulator Ring RF

- **Ring RF**
  - 4 Bunching Cavity/Amplifier stations
    - Ferrite loaded (Phillips 4M2)
    - DC Bias provides dynamic tuning
    - Beam pipe and outer housing used for bias.
  - 2 bunching gaps per cavity
  - 3 Buncher Cavities operate at the revolution frequency 1.05 MHz
    - Maintain a gap to allow the extraction kickers adequate time to reach full field.
  - 1 Cavity operates at the 2\(^{nd}\) harmonic 2.1 MHz
    - Reduce the peak beam current to minimize the possibility of exciting instabilities.
  - All cavities and amplifiers are the same.
    - Resonating capacity reduced for the 2\(^{nd}\) harmonic cavity allowing use of the same structure.
Accumulator Ring Parameters

- Circum: 248 m
- Energy: 1 GeV
- frev: 1 MHz
- Accum turns: 1060
- Final Intensity: 1.5x10^14
- Peak Current: 52 A
- RF Volts (h=1): 40 kV
  (h=2): 20 kV
- Injected Pulse: 645 ns
- Injected Gap: 300 ns
- Extracted Pulse: 695 ns
- Extracted Gap: 250 ns
Performance of the SNS RF System

- One major performance metric for the RF systems is the achieved cavity field regulation.
- The regulation requirement for the SNS Linac is ±0.5% in amplitude and ±0.5 deg in phase, in order to minimize component activation due to beam loss.
  - This requirement is readily achieved as shown on next slide
- Beam loss and energy stability measurements confirm quality of field regulation.
Amplitude and Phase Regulation in the SNS Linac exceeds requirements

SNS Linac Cavity Field Regulation Errors (3-22-07 snapshot)

beam pwr/ length/ rate: 65kW/ 600μs/ 15Hz

NCL  SCL - medium β  SCL - high β
Adaptive Feed-Forward Control is routinely used to improve cavity field regulation throughout the Linac.

![Fig. 1 Adaptive Feed-Forward disabled. Peak field error is 0.5 %.

- Adaptive Feed-Forward (AFF) is useful for compensating repetitive field errors caused by beam loading and Lorentz force detuning.
- AFF development is ongoing with goals of greater robustness and reduced learning time.
- Collaborative effort between SNS and DESY-Hamburg.

![Fig. 2 Adaptive Feed-Forward enabled. Peak field error reduced to < 0.2 % after three iterations using latest version of code under development.](image-url)
Ring RF System performance with 9e13 Protons

- Upper trace is cavity voltage for station RF-12
- Beam is injected at T1
- Feedback corrects for beam loading.
- Voltage excursion is about 500 volts.
- No real effort went into adjusting the feedback parameters.
- Beam is extracted at T2
- Transient at extraction can be removed by gating RF drive off at extraction
- Lower trace shows phase with respect to the beam

T1  T2
MEBT Rebuncher Issues

- 4 Cavities
- Peak Integrated Gradient ranges from 45 to 106 kV
- Design power for Cavity 4, the highest power required, is 22 kW
- 6 Power Amplifiers are available.
  - 4 operational
  - 2 spare
- Amplifiers have reliability and power issues.
- Cavities generate X-ray radiation
MEBT Rebuncher Issues

- **Reliability**
  - Amplifiers suffer from arcing issues within their output cavities.
    - Cavity arcing results in an amplifier protection trip resulting in an equipment circuit break trip, and often a main circuit breaker trip, that can not be reset from the control room.
  - Amplifiers tend to drift away from their optimum output power settings.
  - Amplifiers show sensitivity to repetition rate and pulse length.
MEBT Rebuncher Issues

- Amplifiers not able to operate at required power levels.
  - Cavity 4 design power level is 22 kW
  - Some amplifiers, with careful adjustment, can reach 20 kW at the beginning of the RF pulse.

- Cavities produce excessive Xray radiation
  - Running well below the design power levels all cavities generate Xray radiation.
  - Lead shields are incorporated but do not completely shield the cavities.
MEBT Rebuncher Solutions

- We made extensive improvements on the existing amplifiers.
  - We can now operate at 60 Hz
  - We are not currently limited by power
  - As we increase the beam power we will require higher output power from the MEBT Amplifiers

- We have an Accelerator Improvement Project in place to replace the existing amplifiers.
  - Purchase a single, IOT based, 120 kW amplifier
    - Existing IOT’s do not operate as low as our required 402 MHz.
    - Many IOT’s do not operate above the 80 kW level
    - Working with E2V and CPI on both issues
    - At least one Gridded Tube solution exists
    - Could use extra power from RFQ klystron
  - Split the power 4 ways
  - Perform Amplitude and Phase control at high level
    - We have operated the components of a Vector Modulator at power levels well beyond MEBT Rebuncher required power levels

- Working on improving the shielding to allow cavity operation at higher power levels.
RFQ Issues

- Present Drive system uses 8 couplers.
  - Difficult to properly balance.
  - Not properly balanced now.
    - Couplers are limited to 100 kW each
    - With some couplers providing 60 kW others show only 30 kW.
  - Probably can not operate at 60 Hz with a 1 msec pulse length.
RFQ Improved Drive System

- New drive system utilizes the same windows as our SCL couplers
  - Windows have been conditioned to 400 kW
  - 2 couplers instead of 8 used in the present system
  - Easier to balance than present system

- Planning to install the improved drive system during the February shutdown.
DTL/CCL Klystron Issues

- 2.5 MW, 402.5 MHz DTL klystrons no longer available from E2V.
  - Thales has delivered 3 klystrons that meet our specifications.

- 5 MW, 805 MHz CCL klystrons from Thales have water hose problems.
  - Water cooling hoses located inside of the focus magnet show severe degradation that we believe is radiation damage.
  - We have rad-hard hose to replace the existing hose.
  - We plan to replace the hoses on all 4 operational klystrons during the February shutdown.

- 5 MW 800 MHz CCL klystrons require SF6 gas insulation at their output windows.
  - We have experienced gas leaks
    - Some leaks were obvious assembly issues
    - Remaining leaks are minor but will require more effort to properly seal.
    - We have added pressure sensors to monitor the gas pressure

- CCL Circulators also have SF6 gas leaks
SCL Klystron Issues

- Klystron available power is well below the 550 kW design level
  - We are currently limited by converter-modulator constraints to 69 kV rather than the klystron design voltage of 75 kV
  - Reduced klystron power lengthens cavity fill time
    • Intended fill time is 300 usec.
    • We typically require 400 usec with our reduced klystron output power.
  - To achieve full beam power we will need to resolve this power issue.
    • We are developing a plan to reconfigure the modulator loading and allow for 75 kV operation.
Reliable 75kV Operation in SCL - Option

- Add one additional modulator (NEW)
- Reconfigure most klystron stations to allow modulators to power 10 klystrons each.
- At first medium beta station (SCL- Mod1) we configure the klystron stations to allow the modulator to power 11 klystrons.
  - There is adequate power available in the medium Beta section to allow for the reduced klystron power.
Accumulator Ring RF - Issues

- Major power components are operational and adequate to achieve full beam power.

- LLRF Needs Attention
  - The Ring LLRF system is not easily compatible with the remainder of SNS control system.
  - Little software support.
    - People who know about the system are no longer available.
  - We are working toward utilizing much of the Linac hardware and software to perform the needed Ring LLRF tasks.
Beam Loading - A Major Issue

- **Our Options**
  - **I&Q Feedback**
    - Basic feedback that samples cavity field and corrects for deviations from a programmed function.
  - **Cavity Dynamic Tuning**
    - Cavity bias is dynamically adjusted to compensate for the apparent cavity detuning resulting from beam current (180 Hz Sinusoidal function is used).
  - **Programmed Feed Forward**
    - Provide RF drive to the amplifier chain based on predicted beam loading effects.
    - The system can learn from previous beam cycles.
  - **Beam Derived Feed Forward**
    - Sample beam current and feed an inverted beam current signal into the amplifier chain.
LLRF Issues

• We currently operate with Adaptive Feed Forward (AFF) beam loading control.
  – As we increase the beam current we will need to fine tune the AFF control.
    • Require software modifications.

• Current LLRF control modules utilize components that are becoming obsolete.
  – We have purchased components to complete 50 additional module sets and are proceeding to complete the modules.

• Ring LLRF different than the remaining accelerator systems.
  – Working on developing a system that utilizes much of our existing Linac hardware and software.
Conclusions

- The SNS RF systems have been supporting accelerator operations for more than one year since project completion in the spring of 2006.

- The RF systems are presently meeting performance and reliability expectations and support the overall SNS program.

- Improvements will be implemented over the coming years to achieve the high reliability goals.