SNS Accelerator Advisory Committee Review - January 2008

SNS RF Systems

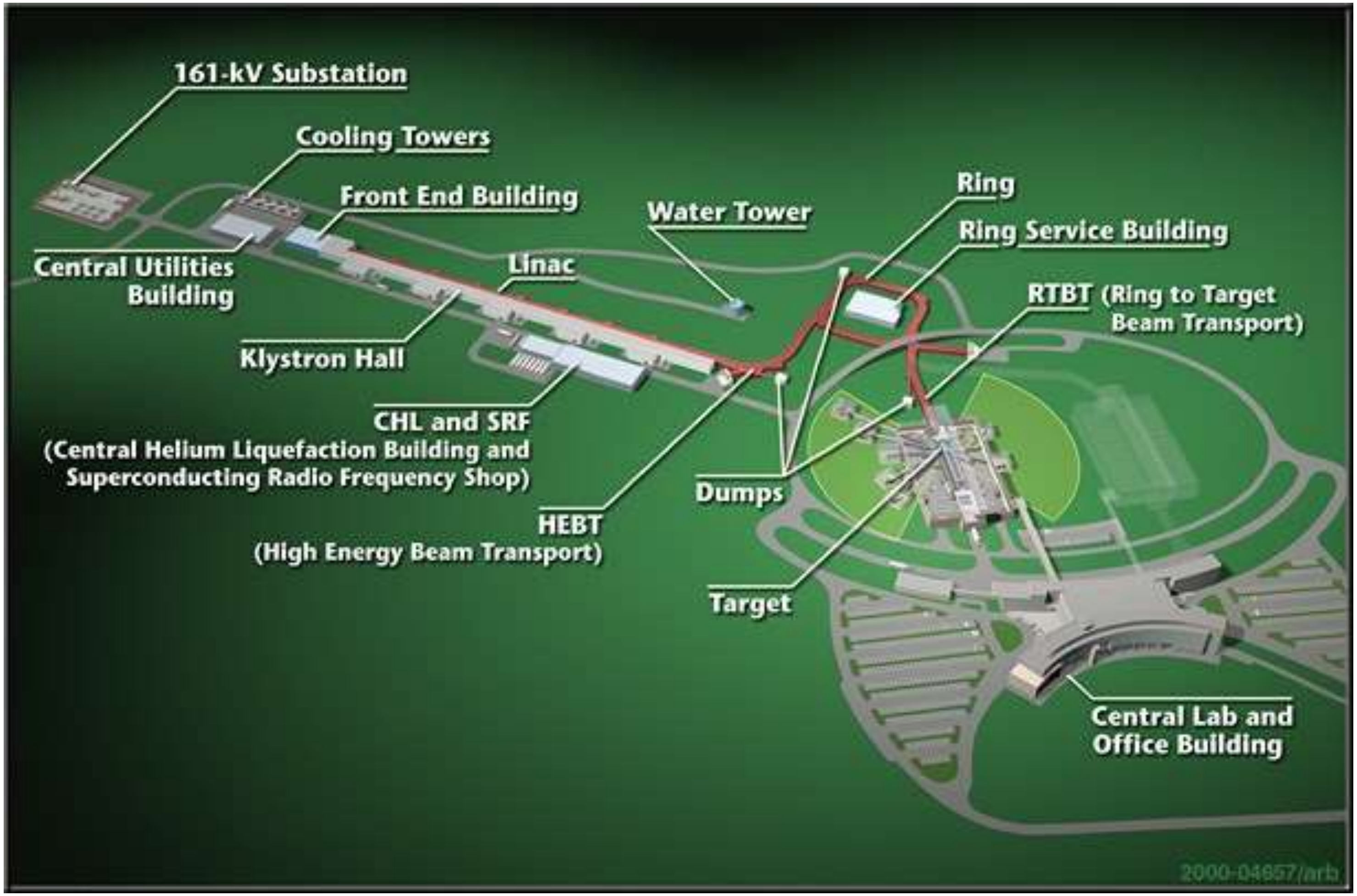
Tom Hardek

RF Systems Group Leader

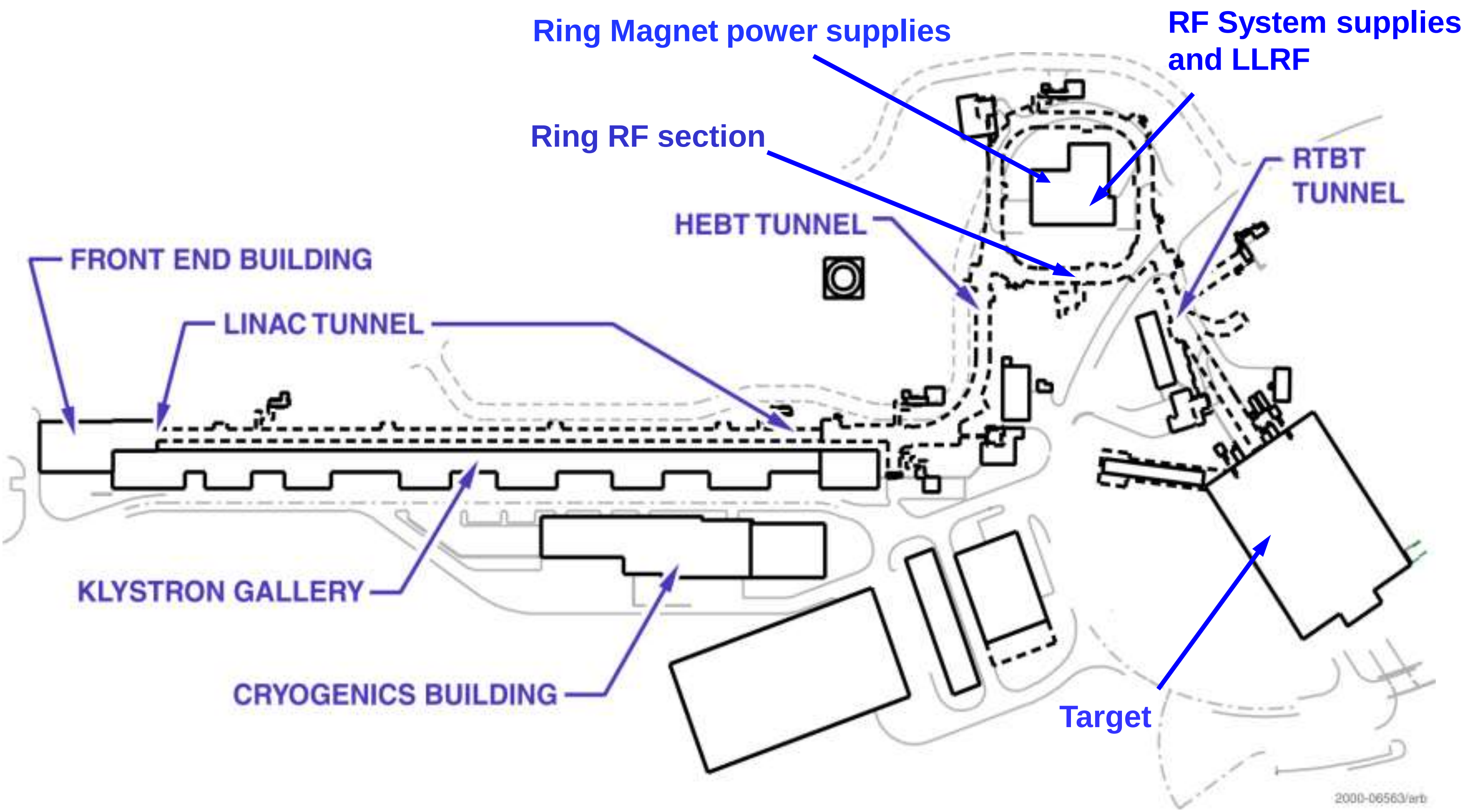
Overview

- General SNS RF Systems Overview
- RF Systems Performance
- Linac RF Systems Issues
  - Present RF System Operational Status
  - Current Operational Results
  - Normal Conducting Linac Klystron Issues
  - Superconducting Linac Klystron Issues
- 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



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**
  - **1st 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

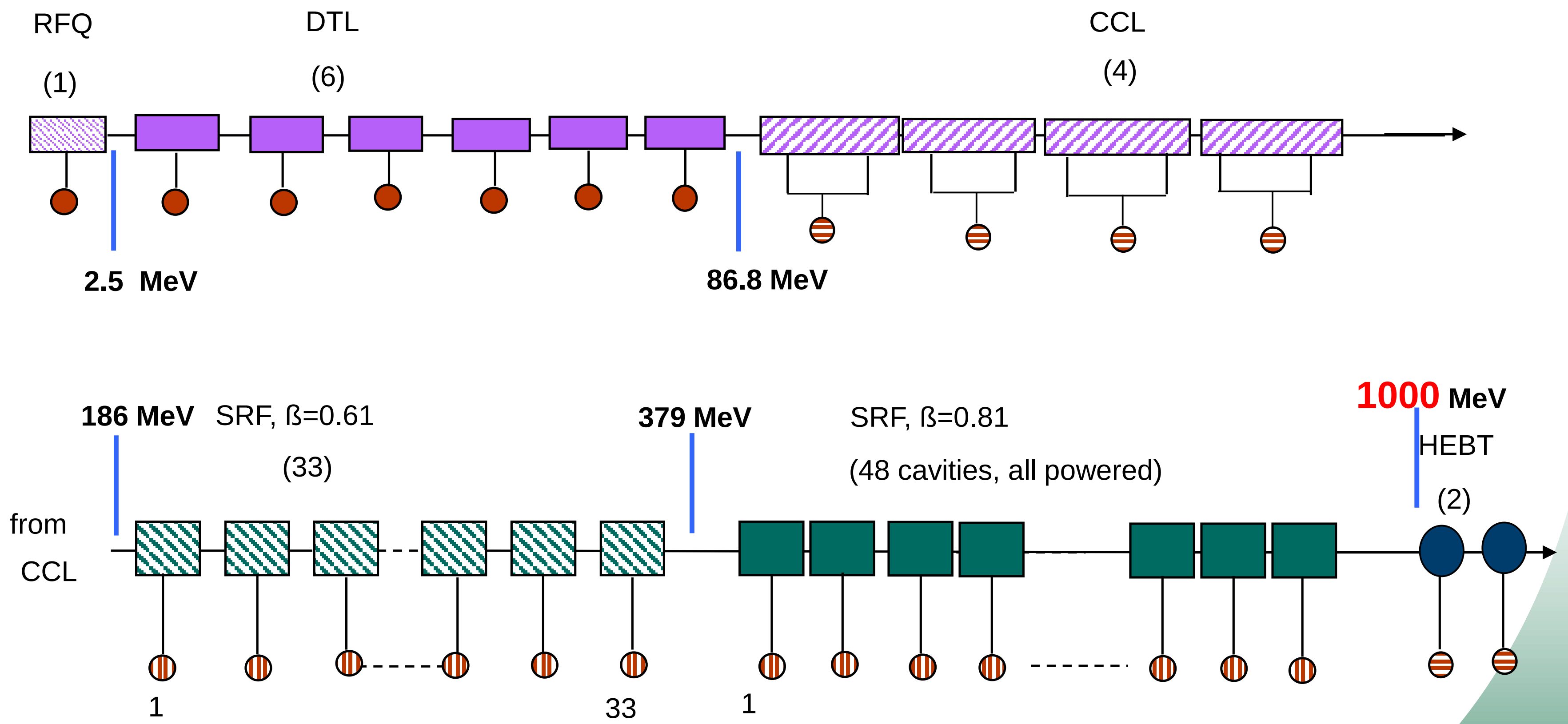
- **CCL**
  - **4 Klystrons power the CCL cavities**
  - **5 MW, 805 MHz Thales Klystrons**
  - **Output window is gas insulated with SF6.**
  - **Circulator is gas insulated with SF6**
  - **Circulator load is conventional water load.**

Klystron Gallery Superconducting Cavity RF

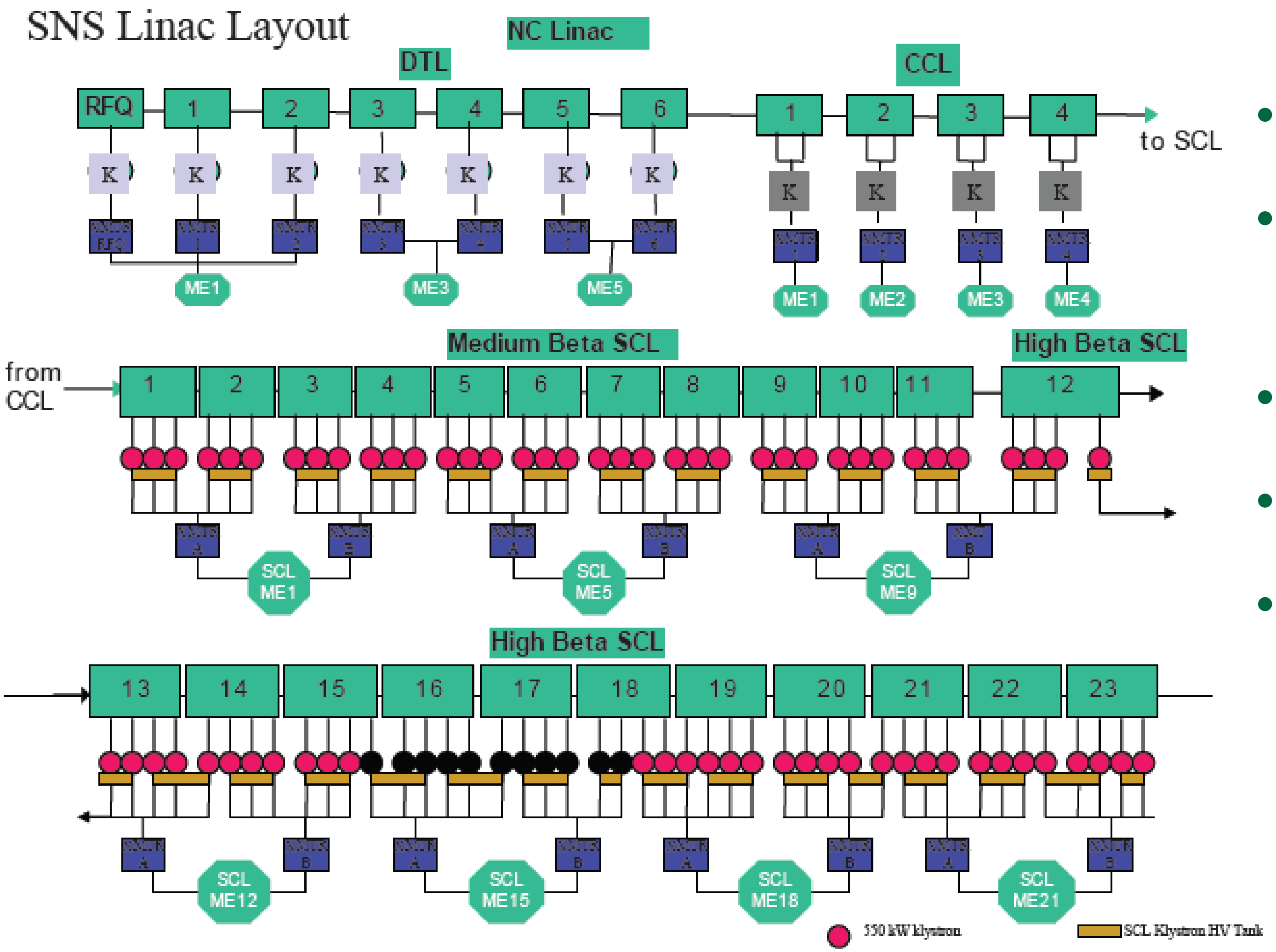
- **SCL RF**
  - **81 Klystrons each powering a separate cavity string,**
  - **550 kW, 805 MHz**
  - **CPI and Thales**

Layout of Linac RF Modules

402.5 MHz, 2.5 MW klystron	3 Transmitter	3 Modulators
805 MHz, 5 MW klystron	4 Transmitter	4 Modulators
805 MHz, 0.55 MW klystron	16 Transmitter	8 Modulators



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

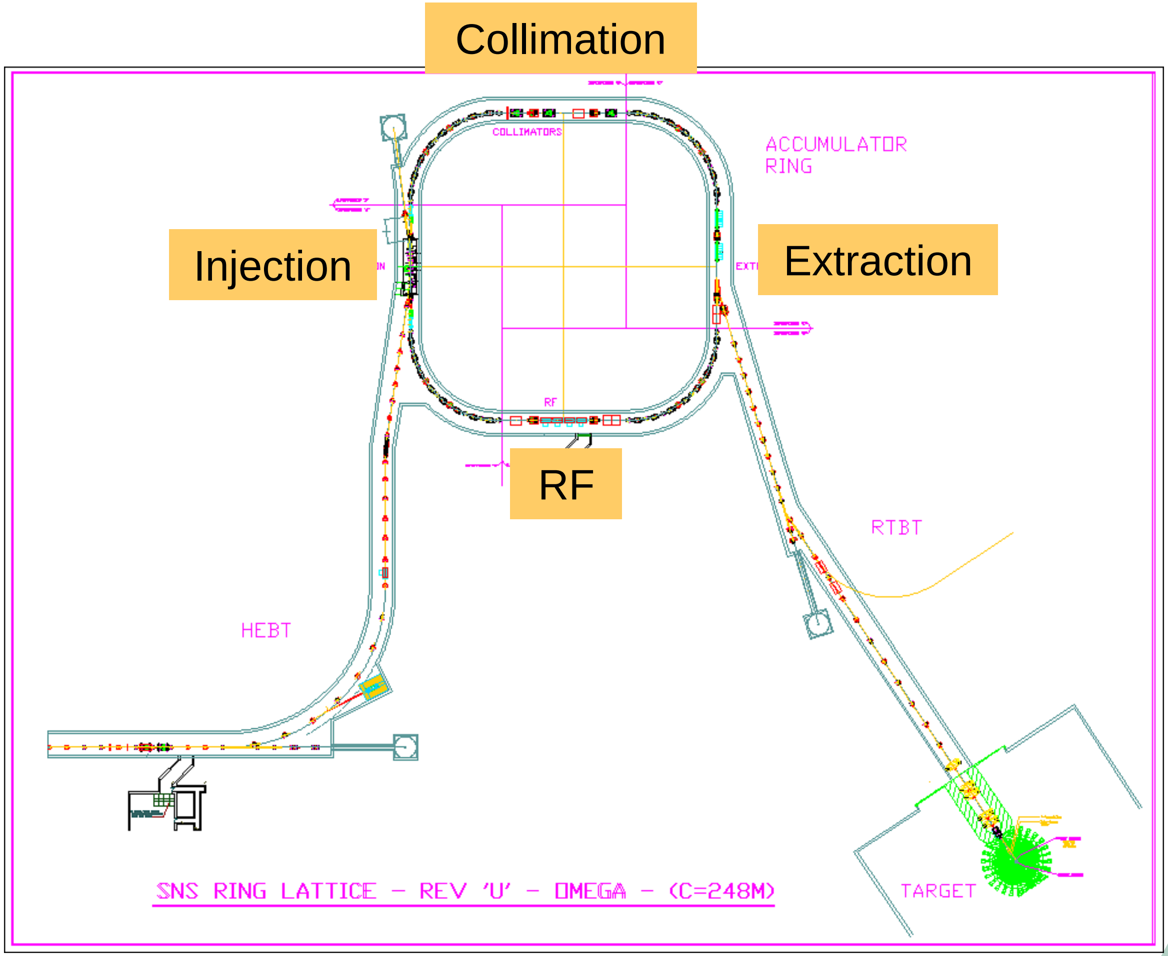
- **Ring RF**
  - **4 Bunching Cavity/Amplifier stations**
    - **Ferrite loaded (Phillips 4M2)**
    - **DC Bias provides dynamic tuning**
    - **Beam pipe and outer housing used for bias.**
  - **2 bunching gaps per cavity**
  - **3 Buncher Cavities operate at the revolution frequency 1.05 MHz**
    - **Maintain a gap to allow the extraction kickers adequate time to reach full field.**
  - **1 Cavity operates at the 2nd 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 2nd harmonic cavity allowing use of the same structure.**

Ring Tunnel

Ring Service Building

Accumulator Ring Parameters

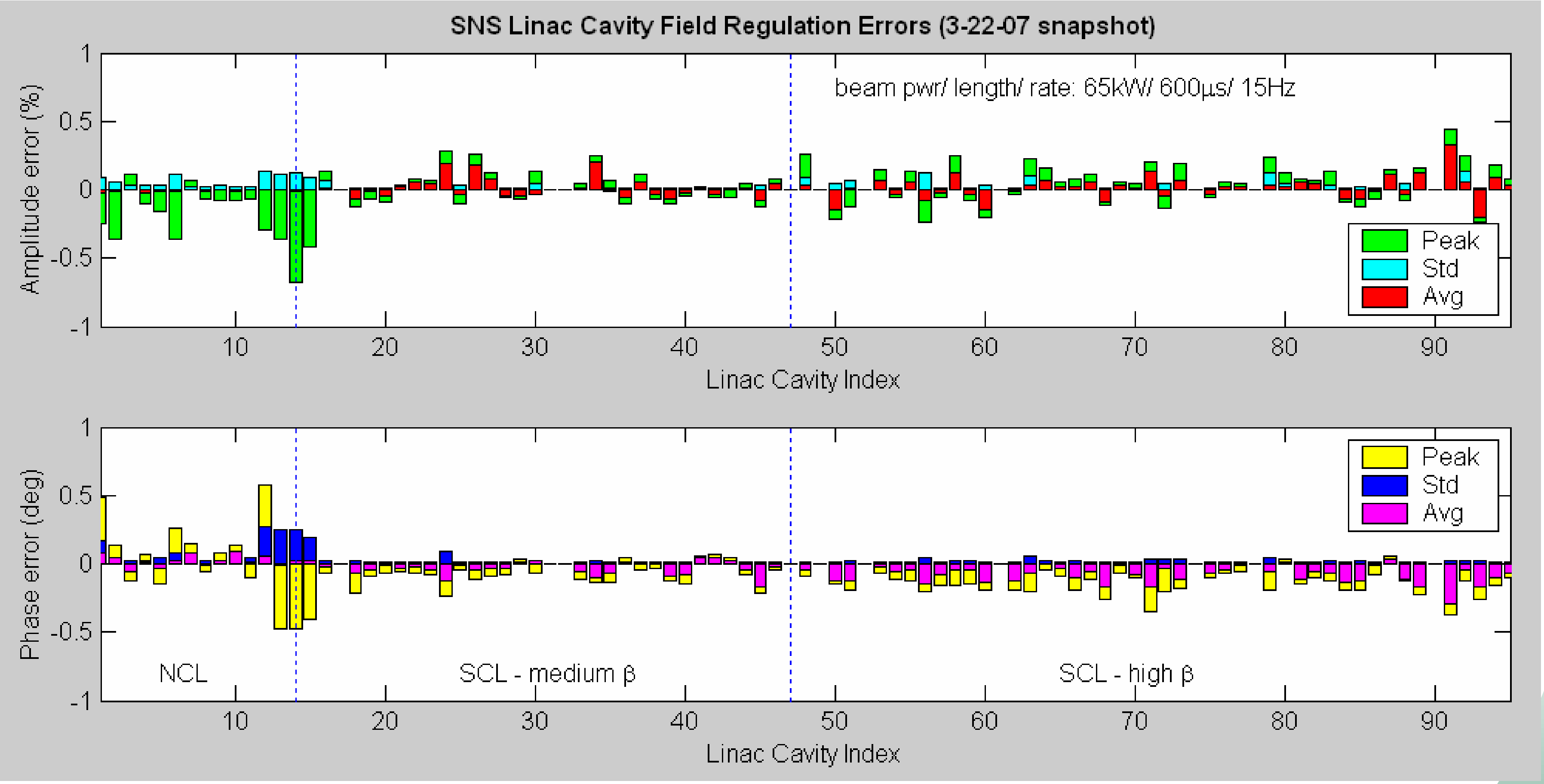
- Circum 248 m
- Energy 1 GeV
- frev 1 MHz
- Accum turns 1060
- Final Intensity 1.5x1014
- Peak Current 52 A
- RF Volts (h=1) 40 kV
- (h=2) 20 kV
- Injected Pulse 645 ns
- Injected Gap 300 ns
- Extracted Pulse 695 ns
- Extracted Gap 250 ns



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



Adaptive Feed-Forward Control is routinely used to improve cavity field regulation throughout the Linac

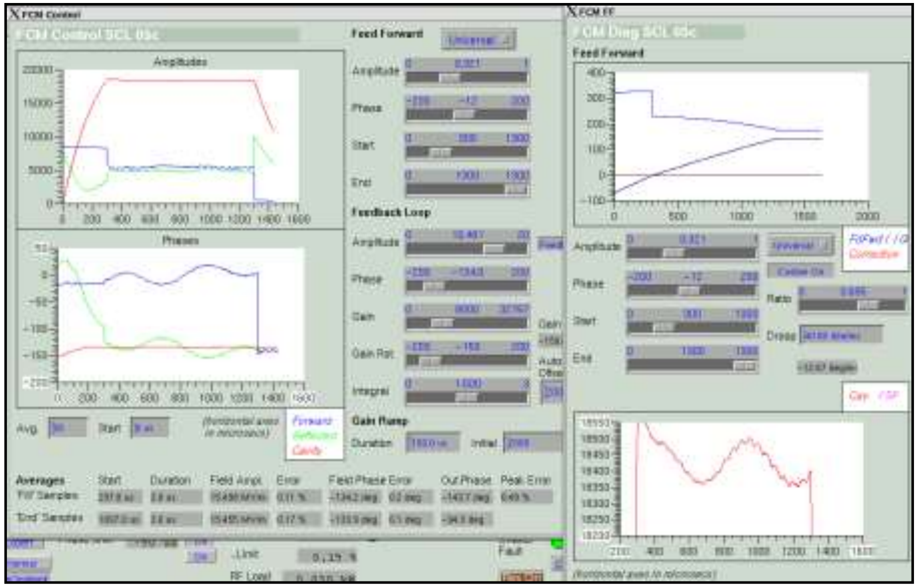


Fig. 1 Adaptive Feed-Forward disabled. Peak field error is 0.5 %.

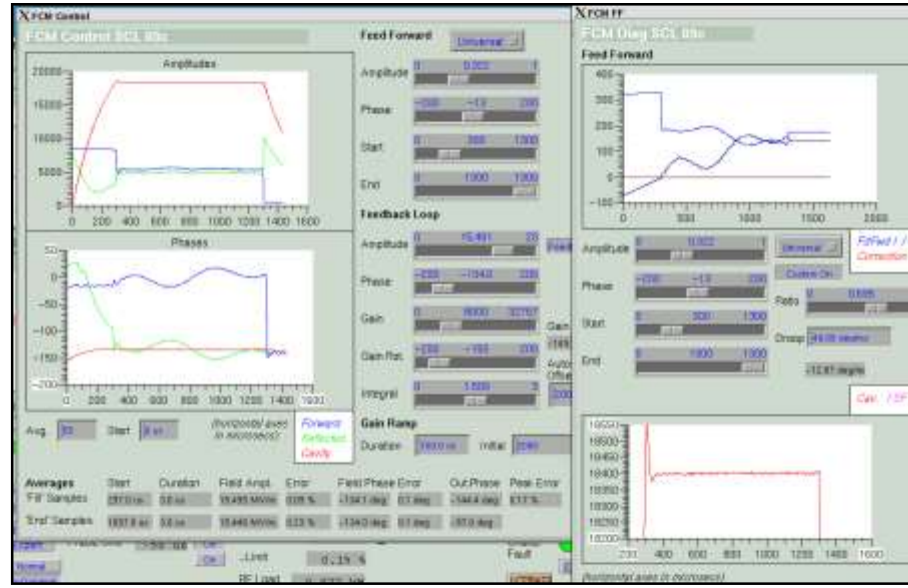
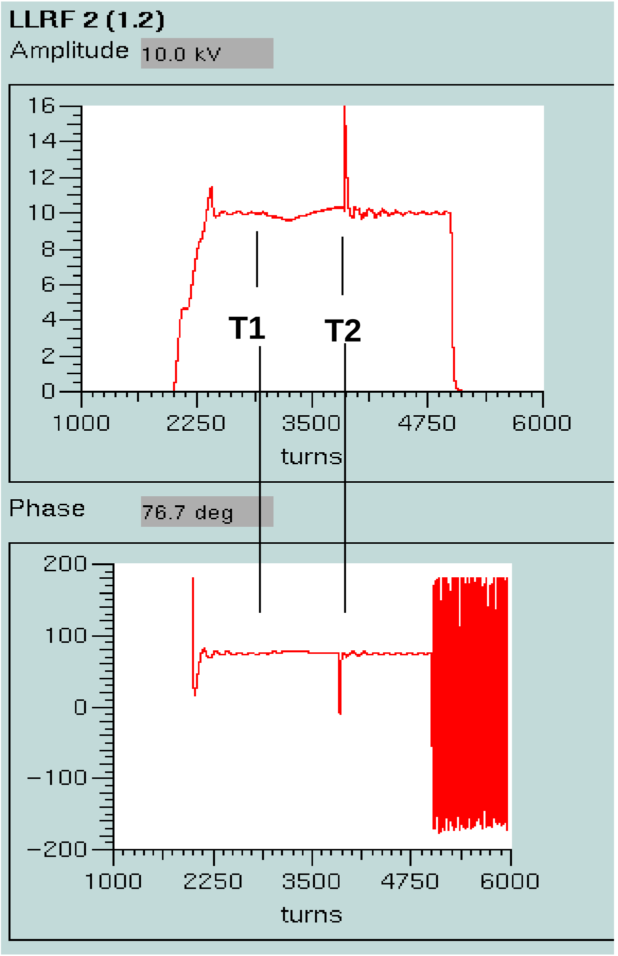


Fig. 2 Adaptive Feed-Forward enabled. Peak field error reduced to < 0.2 % after three iterations using latest version of code under development.

- 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.

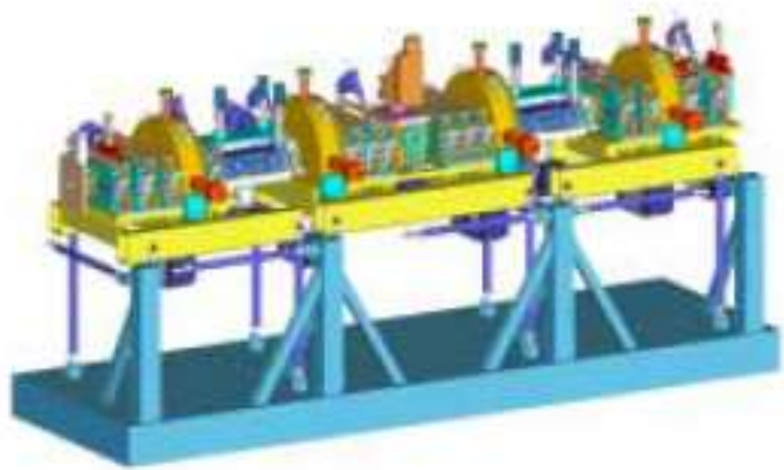
Ring RF System performance with 9e13 Protons



- 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

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 Xray 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.**

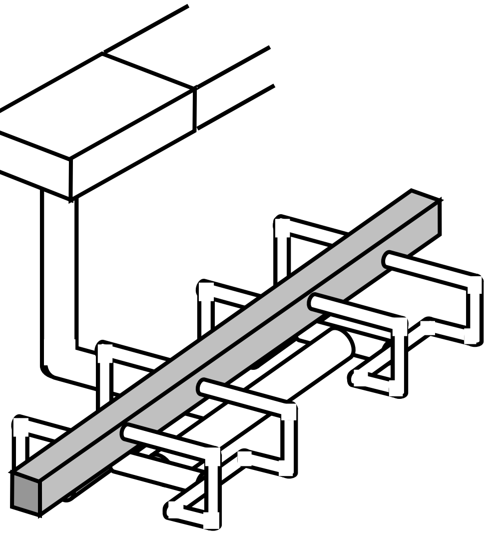
MEBT Rebuncher Solutions

- 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.

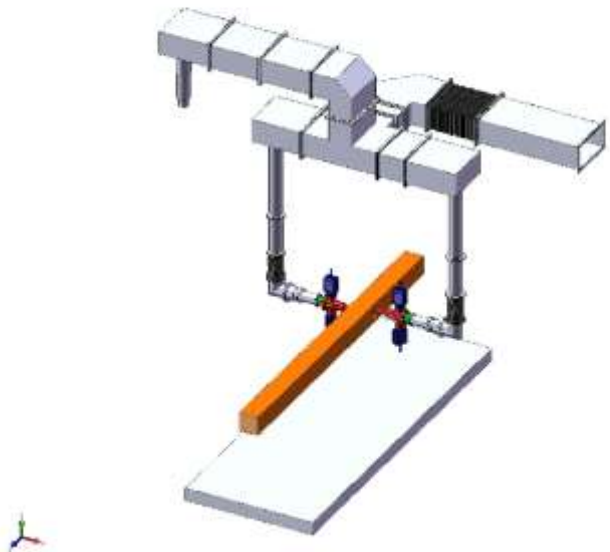
RFQ Issues

- 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



Present Drive System



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

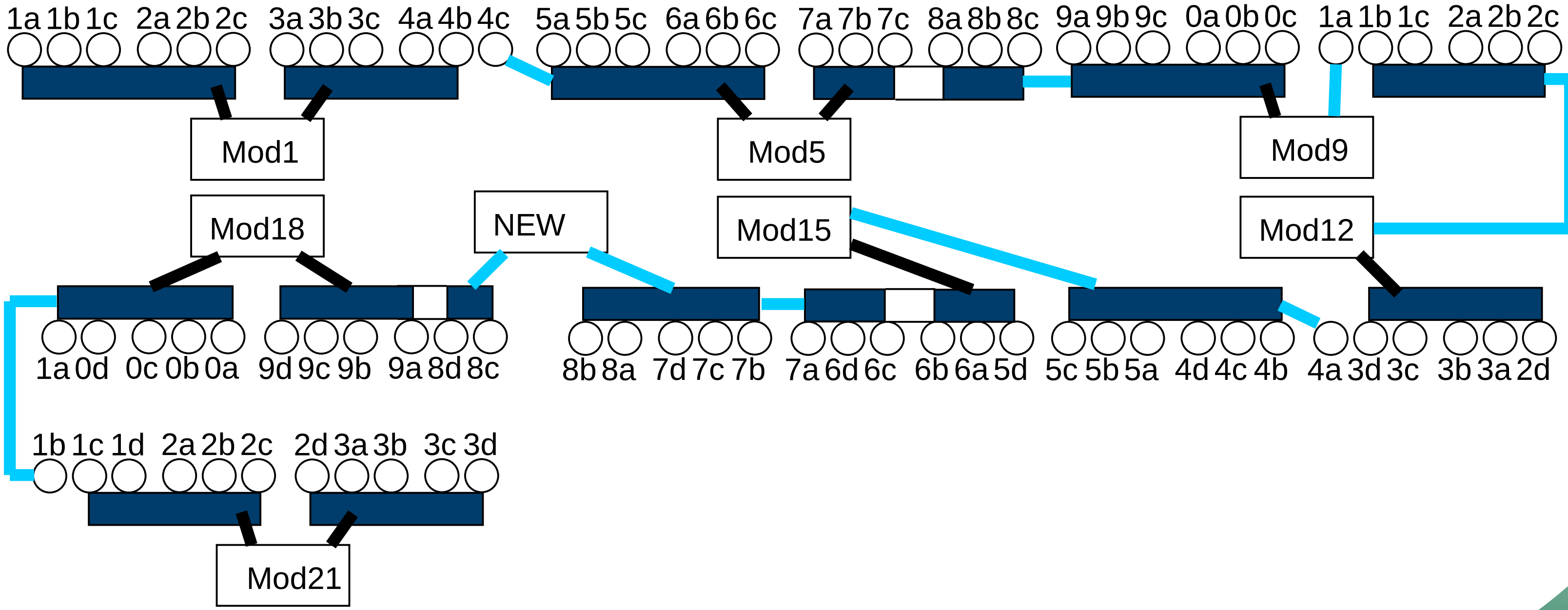
- **2.5 MW, 402.5 MHz DTL klystrons no longer available from E2V.**
  - **Thales has delivered 3 klystrons that meet our specifications.**
- **5 MW, 805 MHz CCL klystrons from Thales have water hose problems.**
  - **Water cooling hoses located inside of the focus magnet show severe degradation that 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.**