# The SNS Linac RF System


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# Outline

- Introduction to the SNS project
- RF System overview
- Linac HPRF details
- Linac LLRF details
- Operational status
- Upgrade plans

# The Spallation Neutron Source

- The SNS will begin operation in 2006
- At 1.4 MW it will be ~8x ISIS, the world's leading pulsed spallation source
- The peak neutron flux will be ~20-100x ILL
- SNS will be the world's leading facility for neutron scattering
- It will be a short drive from HFIR, a reactor source with a flux comparable to the ILL

# SNS Site Layout (Start of RF Equipment in Gallery)

# Spallation Neutron Source Primary Parameters

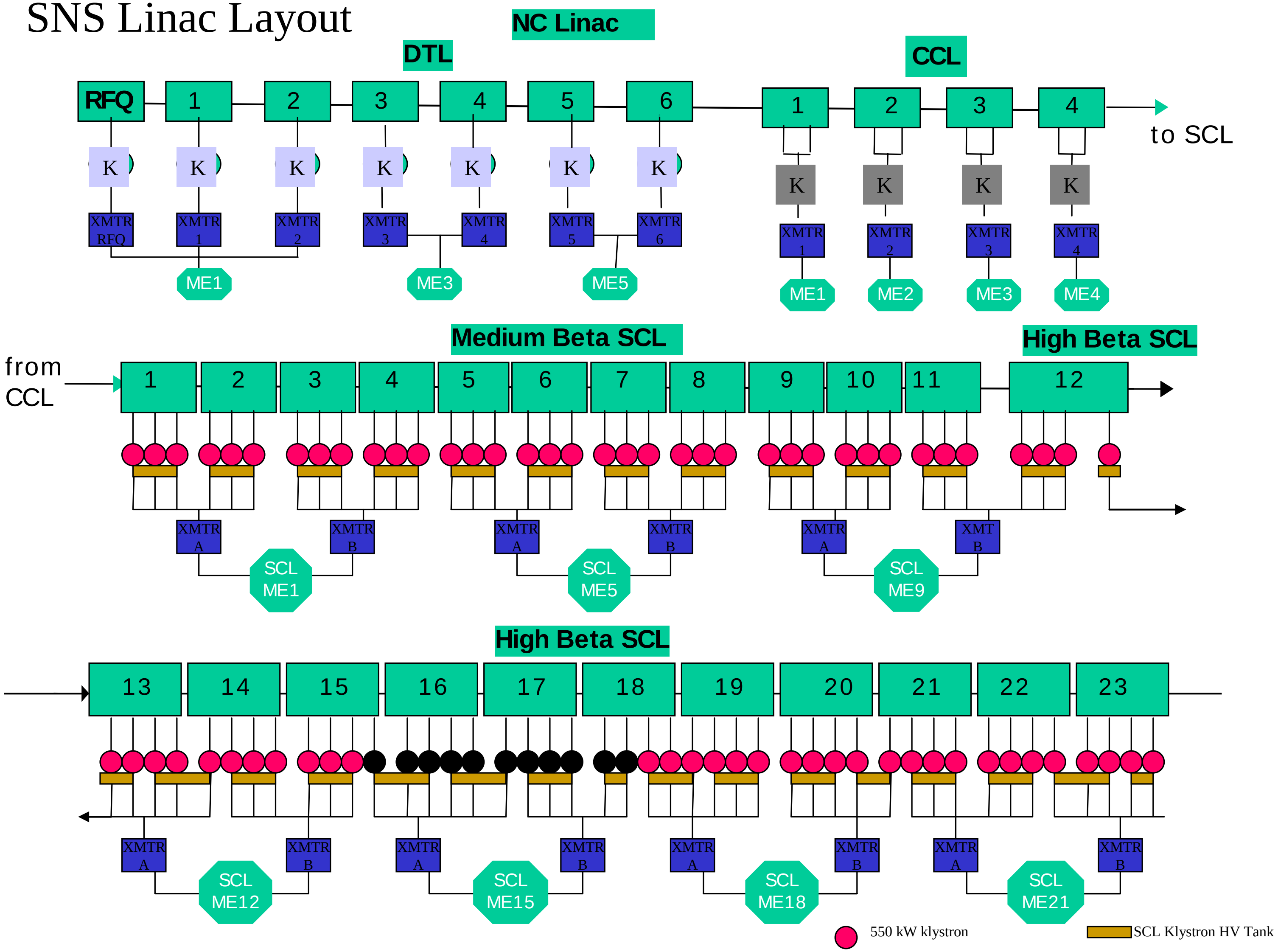
- Proton beam power on target 1.4 MW
- Proton beam kinetic energy on target 1.0 GeV
- Average beam current on target 1.4 mA
- Pulse repetition rate 60 Hz
- Protons per pulse on target $1.5\times10^{14}$ protons
- Charge per pulse on target 24 C
- Energy per pulse on target 24 kJ
- Proton pulse length on target 695 ns
- Ion type (Front end, Linac, HEBT) H minus
- Average linac macropulse H- current 26 mA
- Linac beam macropulse duty factor 6 %
- Front end length 7.5 m
- Linac length 331 m
- HEBT length 170 m
- Ring circumference 248 m
- RTBT length 150 m
- Ion type (Ring, RTBT, Target) proton
- Ring filling time 1.0 ms
- Ring revolution frequency 1.058 MHz
- Number of injected turns 1060
- Ring filling fraction 68 %
- Ring extraction beam gap 250 ns
- Maximum uncontrolled beam loss 1 W/m
- Target material Hg
- Number of ambient / cold moderators 1/3
- Number of neutron beam shutters 18
- Initial number of instruments 5

# The SNS utilizes 100 RF systems for acceleration and bunching

| Type | Quantity | Frequency | Peak Power | Application |
|---|---|---|---|---|
| Klystron | 7 | 402.5 MHz | 2.5 MW | RFQ, DTL |
| Klystron | 4 | 805 MHz | 5 MW | CCL |
| Klystron | 81 | 805 MHz | 550 kW | SCL |
| Tetrode | 4 | 402.5 MHz | 20 kW | MEBT Rebunchers |
| Tetrode | 4 | 1 & 2 MHz | 100 kW | Accumulator Ring |

# SNS HPRF Configuration

## SNS Linac Layout

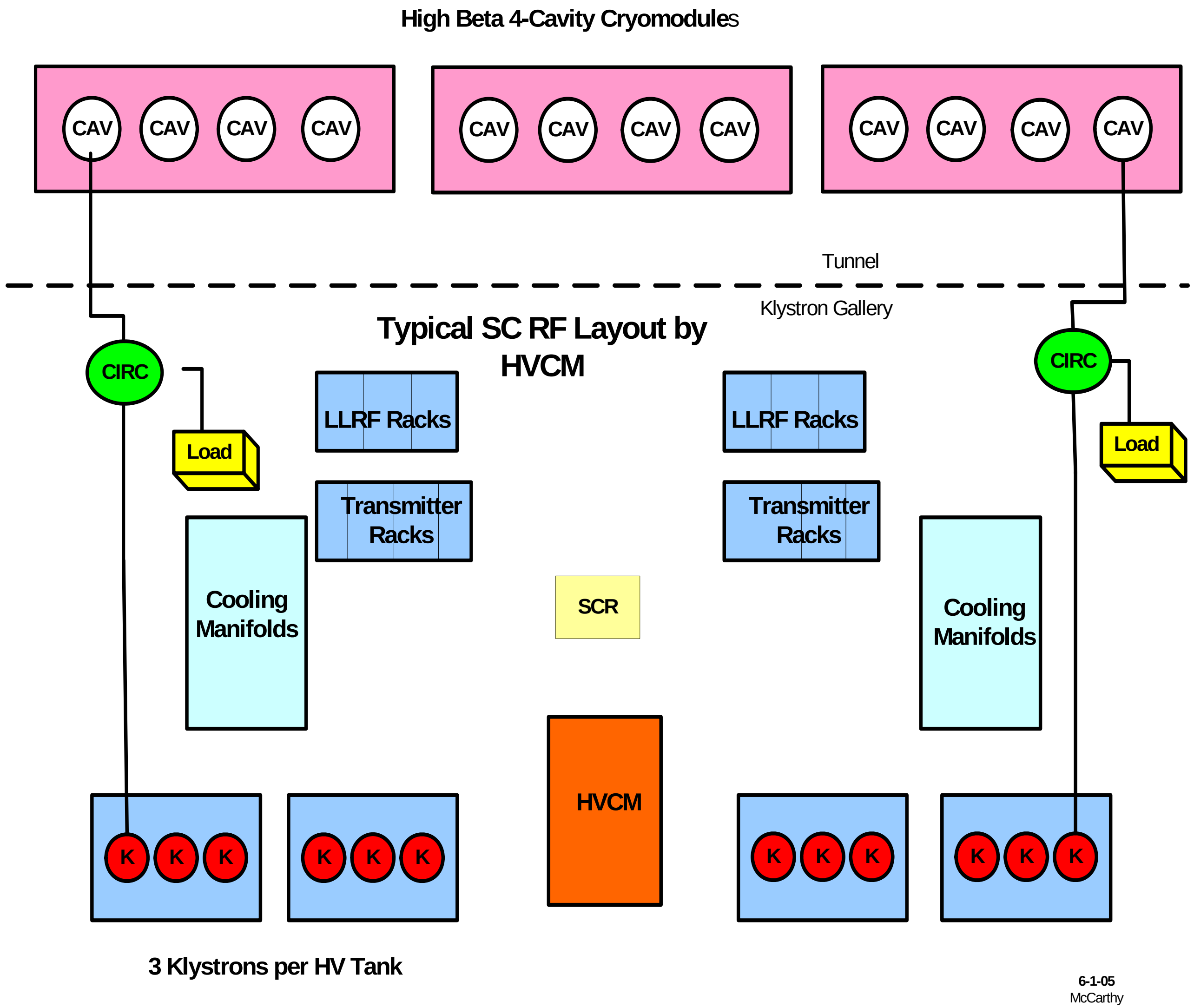


# RFQ, DTL and CCL RF Systems


Seven 402.5 MHz, 2.5 MW klystrons power the RFQ and DTL


Four 805 MHz, 5 MW klystrons power the CCL

# SC Linac RF System Layout

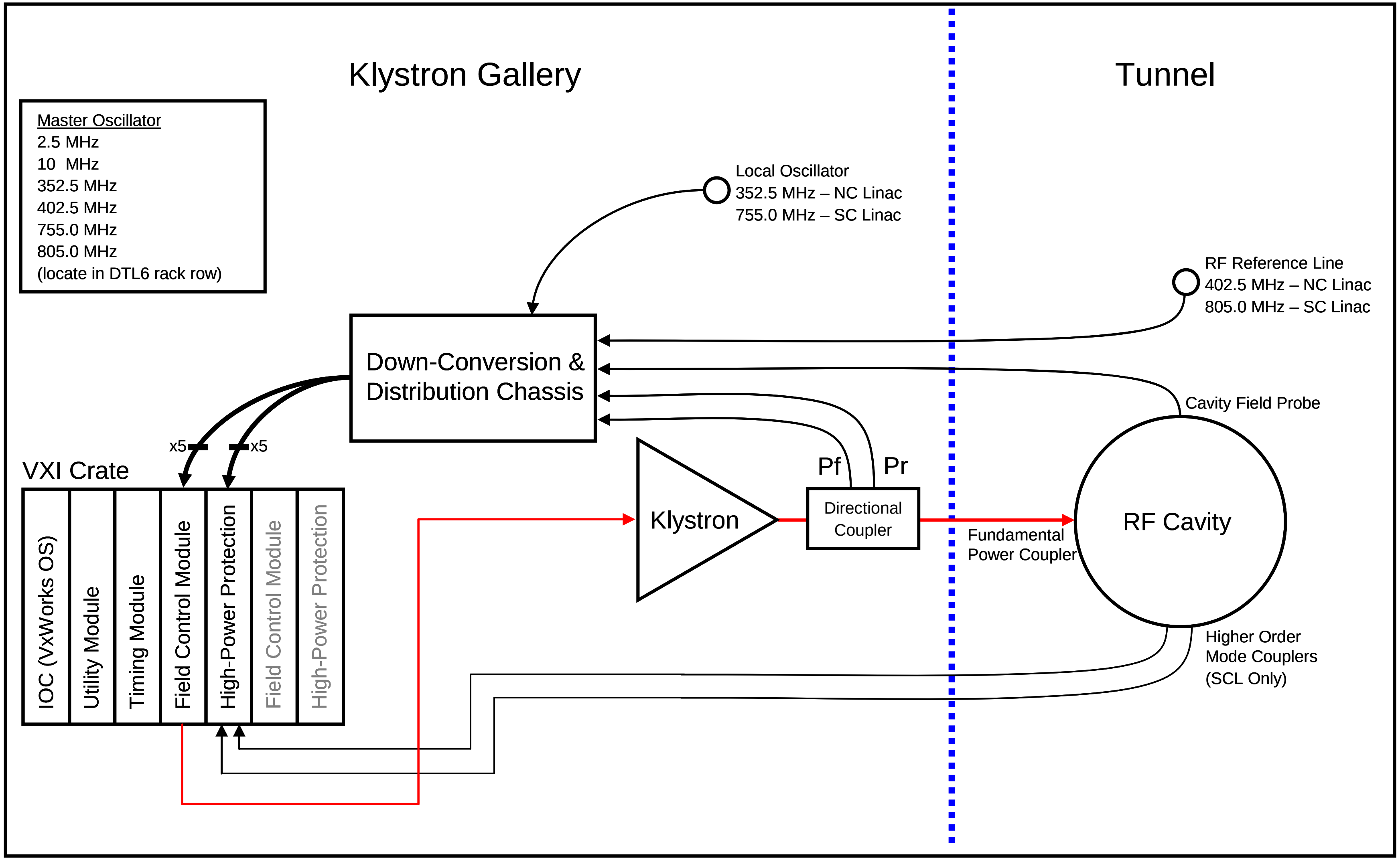


# Eighty-One 805 MHz, 550 kW klystrons power the superconducting Linac


Transmitter racks & LLRF for support of six klystrons.


Three klystrons mount to a single oil tank.

# Block Diagram of the SNS Linac LLRF Control System



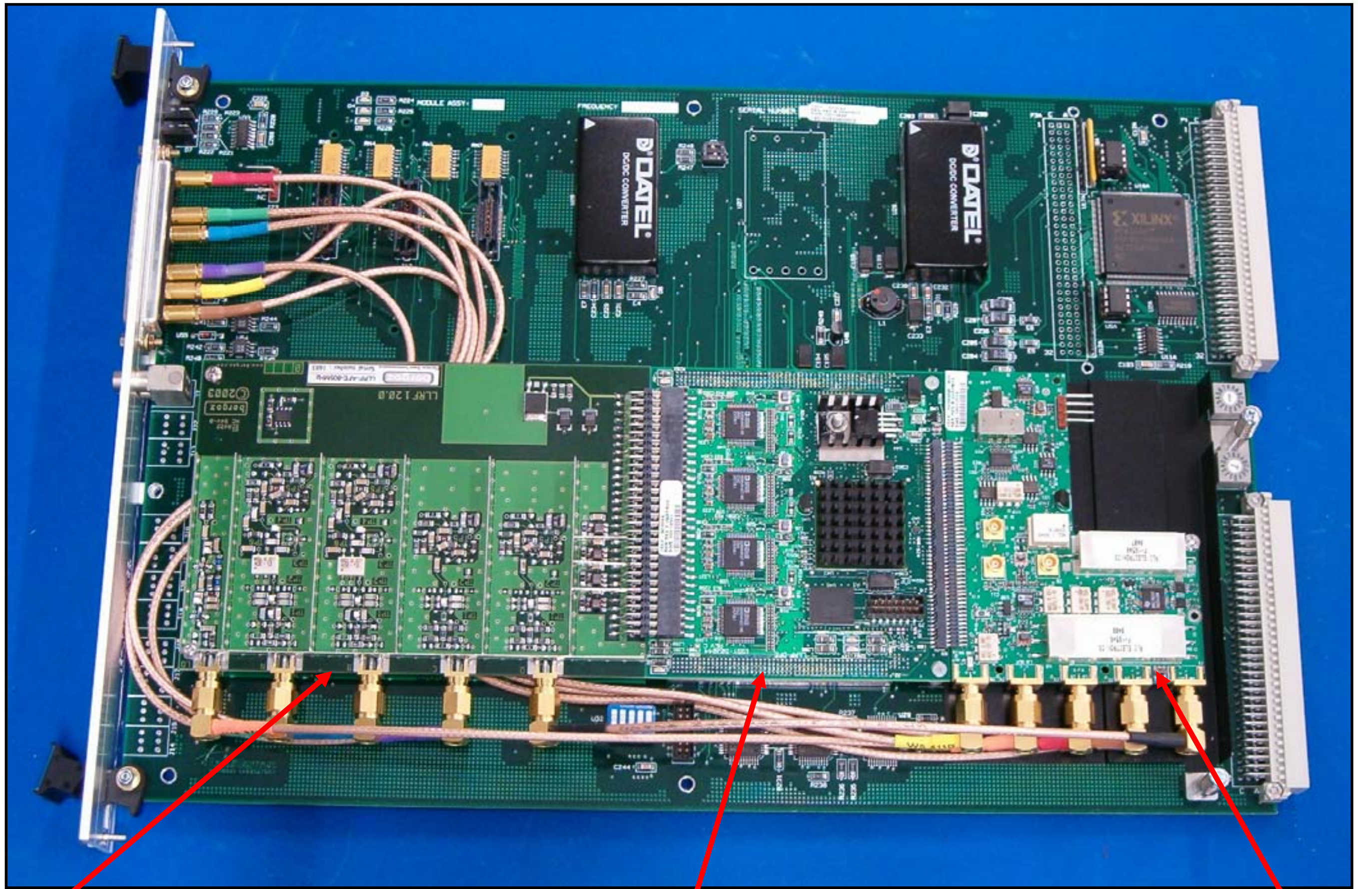
# Each Rack in the Superconducting Linac Contains LLRF Hardware for Two RF Systems


Typical LLRF control rack installation in the superconducting linac.


The VXI crate contains:

- Input/Output Controller:  PowerPC running VxWorks
- Utility Module:  Decodes events from Real Time Data Link
- Timing Module:  Generates RF Gate timing signal
- Two FCM/HPM pairs

# The Field Control Module (FCM) consists of a motherboard and three daughterboards

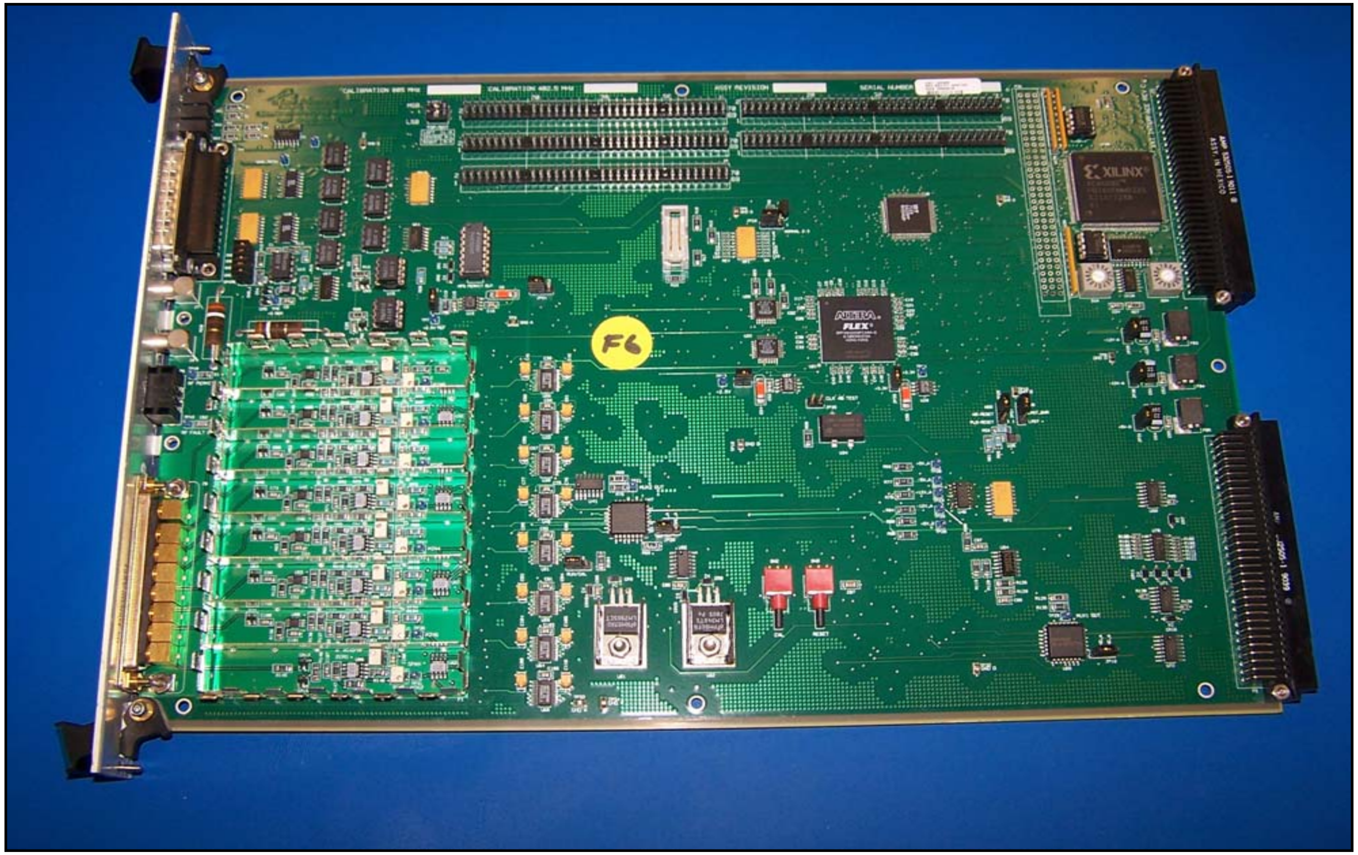


Analog Front End (AFE)
Down-converting channels:
Incident and Reflected RF
(402.5 or 805 MHz)
IF channels:
Cavity and Reference (50 MHz)

Digital Front End (DFE)
Four 14 bit, 40 MHz ADC channels
One Virtex II FPGA
(XC2V1500 – 1.5M gates)

RF Output (RFO)
Clock & PLL circuitry
One 14 bit, 80 MHz DAC
Up-Conversion to 402.5/805 MHz
Filtering

# The High-Power Protection Module (HPM) protects the RF system from RF-driven damage by inhibiting RF drive



- RF channels (7)
- Arc detector channels (14)
- Vacuum permit
- Cryo, Coupler and HPRF permits (software)

# LLRF Control Functions

- Proportional Integral (PI) controller implemented on FPGA for fast feedback control of cavity field
  - Basic requirement is ±1%, ±1deg on amplitude and phase.
- FeedForward is used for canceling repeatable errors, such as transient beam loading.
- The LLRF Finite State Machine is implemented as EPICS Sequencers executing on the IOC.
  - Auto-Run startup sequence
  - Resonance error computation and correction
  - Timing parameter adjustment
  - Warm-Up mode
  - Adaptive FeedForward control setup
  - Sanity checks

# Adaptive FeedForward Beam Compensation was developed during the Warm Linac Commissioning

- Development started in early October using Matlab scripts to test concepts
- Proof-of-principle completed Oct 20; IOC implementation completed Oct 25
- Turned over to Operations on Oct 26

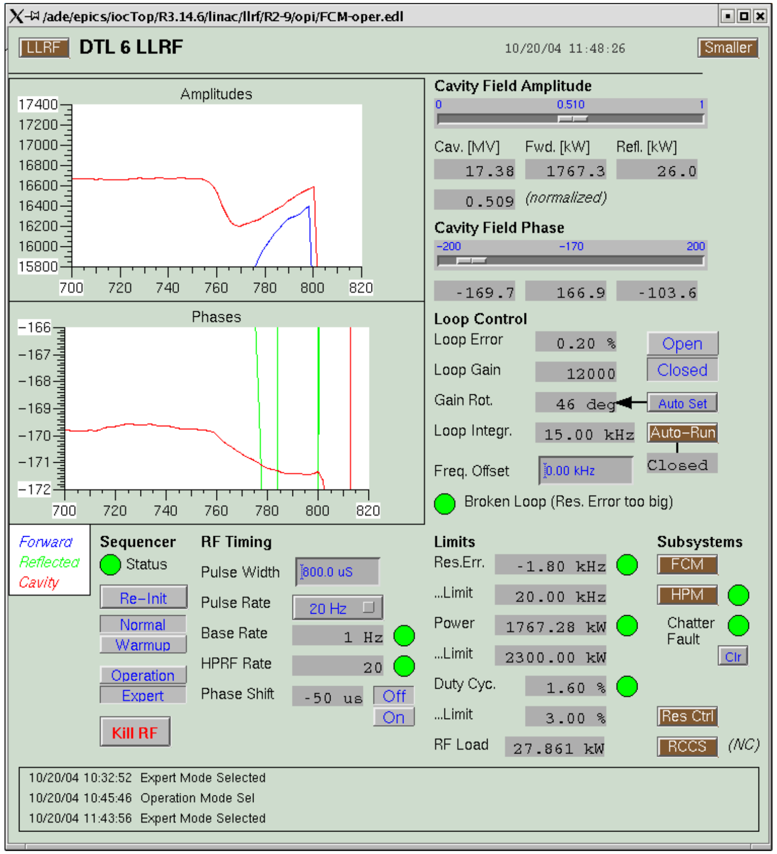



Fig. 1 Beam loading in DTL6 with ~40 us, 20 mA beam induced error of 2.7% and 2 deg in amplitude and phase.

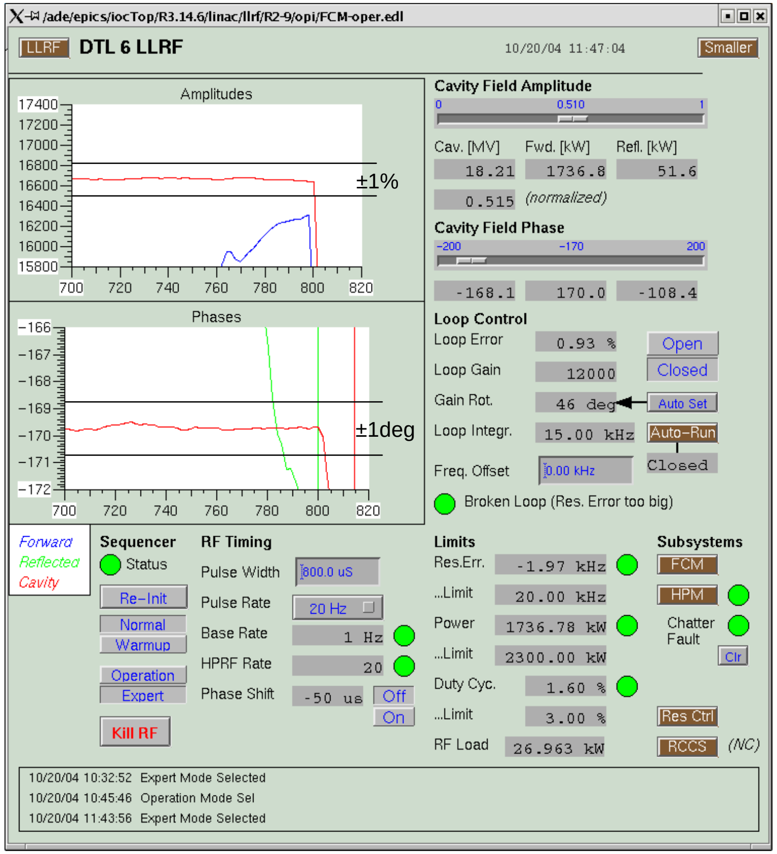
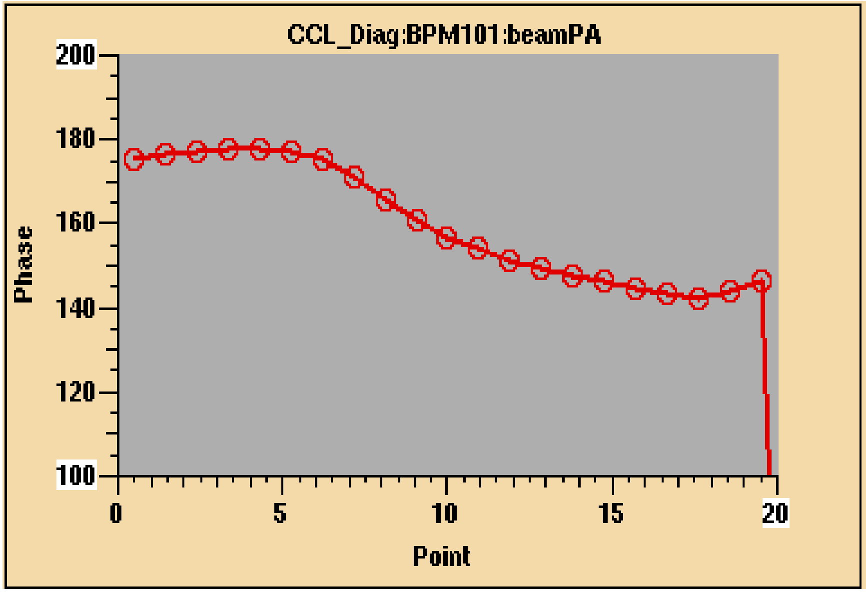
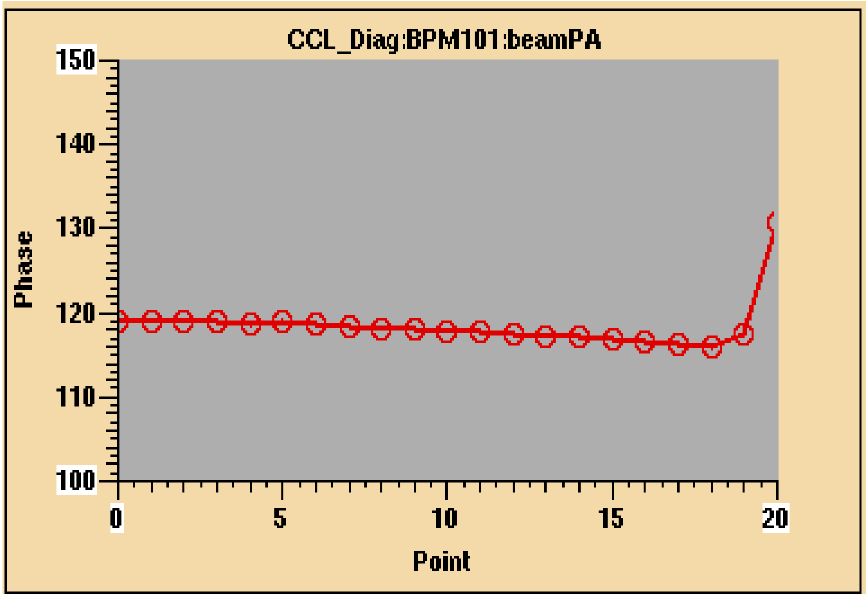



Fig. 2 Beam loading eliminated by means of Adaptive FeedForward.

# Beam measurements show the effectiveness of Adaptive FeedForward beam loading compensation




Beam phase vs. time at the entrance to CCL1 with Adaptive FeedForward disabled. Beam current is 40 mA. Beam pulse length is 40 us.




Beam phase vs. time with Adaptive FeedForward enabled. The variation in beam phase is reduced by a factor of ~20. Beam parameters are unchanged.

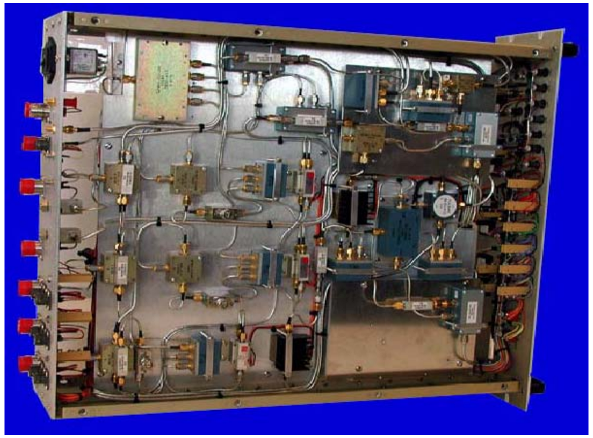
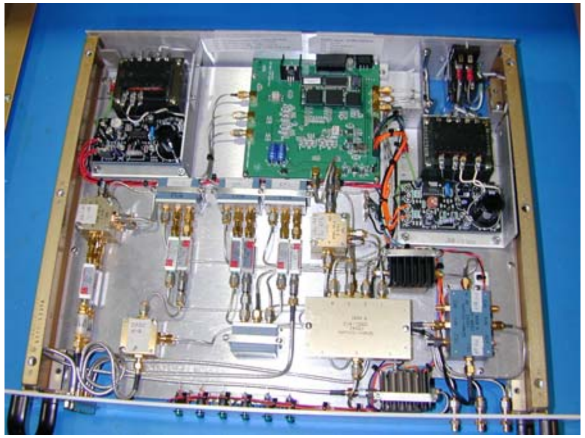
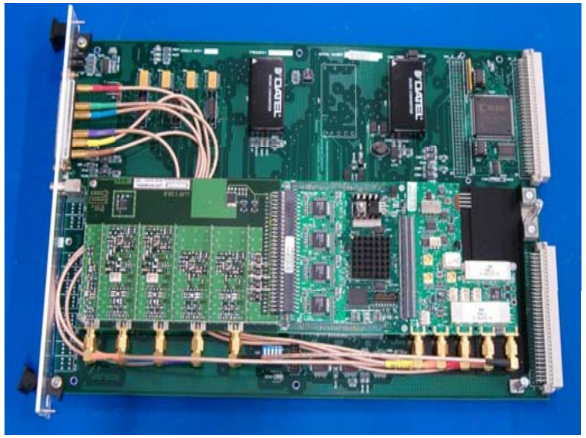
## How did we get here?

- In the beginning, one laboratory was responsible for the development and delivery of the Linac LLRF control system.
- LLRF delivery milestones were missed in the summer of 2002, and SNS beam commissioning milestones were at risk.
- A backup plan was formulated whereby LBNL provided LLRF control systems to support early commissioning of the RFQ and DTL.
- A special review of the LLRF control system was held in September 2002.
- Result: reorganize the LLRF control system development with leadership at ORNL and in collaboration with LBNL and LANL.

# Highlights of the Reorganization

- Reviewed and documented the LLRF control system requirements.
  - Goal was to define the minimum set of requirements necessary to successfully commission and operate the SNS accelerator
  - Regulation requirements relaxed from ±0.5%, ±0.5deg to ±1%, ±1deg.
- Created a development and production plan.
  - New team combined expertise at ORNL, LANL and LBNL
  - Designed, tested, produced & commissioned 96 systems plus spares over 2-1/2 years
  - Used existing assets for near term goals:
    - MEBT Rebuncher RF Control System (LBNL)
    - High Power Protect module (LANL)
  - Built on these to develop the final system, which began deployment in Feb 2004
  - New delivery schedule based on Integrated Project Schedule

# Overview of Linac LLRF Control System

| 1st Generation Control Chassis | 2nd Generation Control Chassis | 3rd Generation Field Control Module |
|---|---|---|
|  |  |  |
| MEBT Rebunchers | RFQ & DTL | CCL, SCL & HEBT |
| 4 installed, 1 spare | 7 installed, 3 spares | Retrofit to MEBT, RFQ & DTL |
| Retrofitted with FCM Nov 04 | Retrofitted with FCM Jul 04 | 98 systems + spares |

Evolutionary Development: build on proven concepts, hardware and software

# FCM development progess followed original schedule of October 2002

| | |
|---|---|
| 1. Complete the conceptual design of the final system. | Nov 02 |
| 2. Demonstrate amplitude and phase control at JLab. | Jan 03 |
| 3. Complete the detailed design of the final Field Control Module (FCM). | Feb 03 |
| 4. Produce FCM prototype and demonstrate its performance in the lab. | Mar-May 03 |
| 5. Test the FCM with DTL and/or SCL. (RFQ and DTL actually) | Jun-Jul 03 |
| 7. Revise the design of the final control board if necessary. | Aug 03 |
| 8. Begin production of the final system. | Sep 03 |
| 9. LLRF Advisory Board issues final report and disbands. | Sep 03 |
| 10. Install first production FCM in CCL1. | Apr 04 |
| 11. Test production FCM with cryomodule at Jefferson Lab. | Apr 04 |
| 12. Approve Phase II production of FCM (105 systems). | May 04 |
| 13. Complete installation of Linac LLRF control systems | May 05 |

# Lessons Learned & Advice for the Future

- Document the system requirements.
  - Avoid feature creep.
- Document the development plan.
- Make a resource-loaded schedule and budget.
- Use proven solutions. Don't reinvent the wheel. Resist the "not invented here" syndrome.
- Keep it simple.
- If your schedule is at risk, ask for help.
- Your team must "take ownership" of the system.
- Software support and development is an integral and essential part of the process.
- Be willing to cross functional and subsystem boundaries.
- Avoid dictating the choice of software tools and languages if possible.

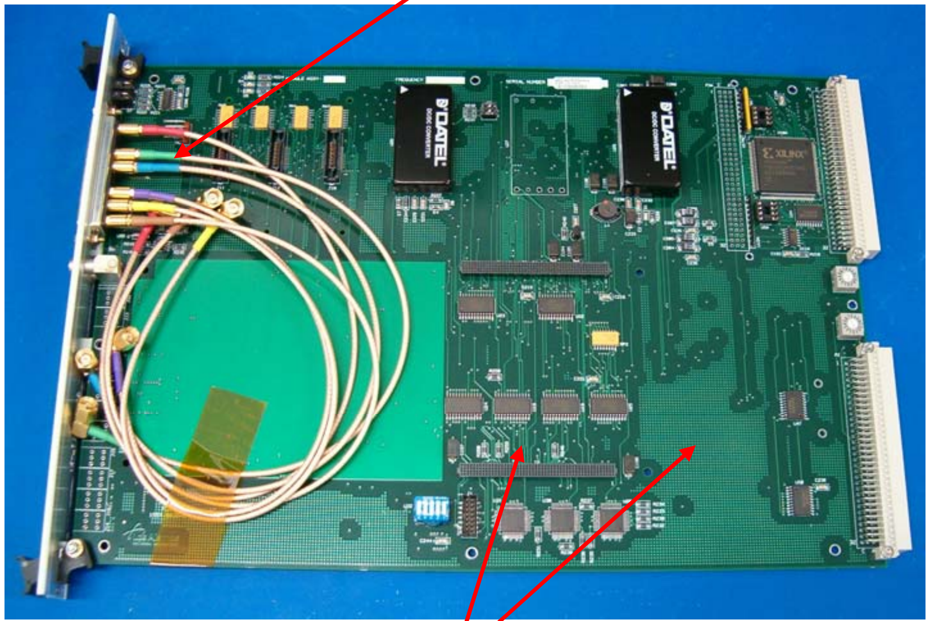
# Hardware Design Advice

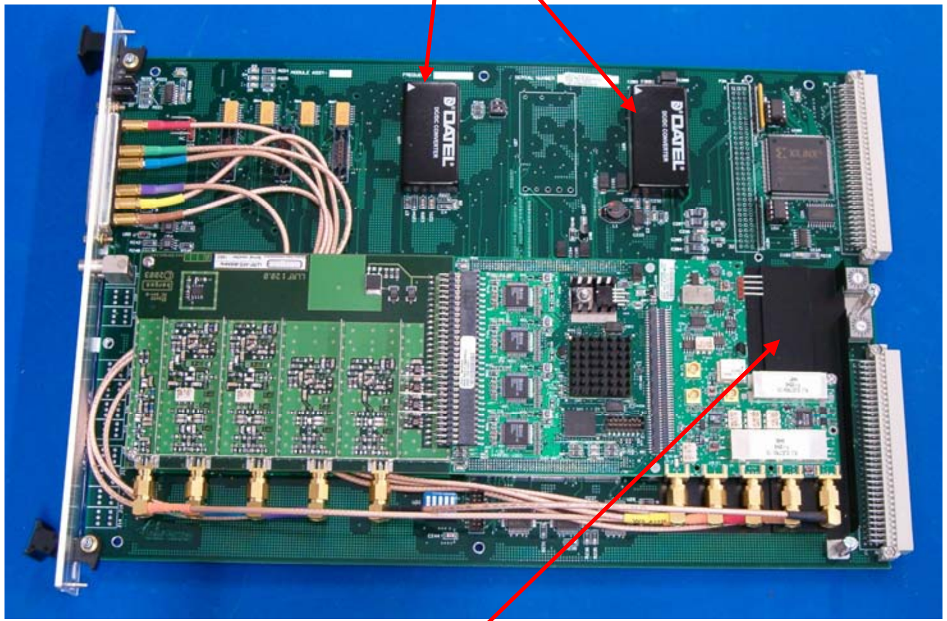
- Avoid early parts obsolescence.
- Install a RF PIN switch diode on your RF output.
- Install extra channels – you will need them later!
- Verify your parts can withstand a wet wash process following SMT assembly.
- Do not use epoxy-mount components (difficult to replace)
- Provide adequate shielding between motherboard and daughterboard.
- Provide “clean” DC power to your circuits.
  - Beware of DC-to-DC switching supplies.  The switching frequency (usually 200 kHz) will find its way into your system!
- Don’t waste your time building cables.  Let a vendor do it.
- Use a symmetric layout for your ADC clock distribution and pay attention to impedance matching.
- Think about how you will test, troubleshoot and repair your circuit boards when you do your board design and layout (not after you receive the circuit boards)

# FCM Hardware Design Issues

Note color-coded vendor-supplied cables. They are very convenient and inexpensive.

Switching DC/DC converters are a source of 200 kHz noise.





Note the absence of a ground plane beneath the DFE and RFO daughterboards.

A ground plane was added to reduce crosstalk between the motherboard and daughterboards.

# Low-Level RF Conclusions

- The development of the SNS Linac LLRF control system was accomplished on schedule despite serious problems and a reorganization in 2002.
- The development process was constrained by schedule, budget, personnel, overall linac design requirements, and in-progress or complete procurements and developments.
- The process was not ideal, but it produced a solid platform that will meet the needs of the SNS linac for many years.
- Many lessons were learned and are still being learned.
- The performance of the system has been verified during beam commissioning of entire Linac
- The installation of the system is complete.  IOC and FPGA code development is ongoing.

# SNS Linac Low-Level RF References

M. Champion et al, “Overview of the Spallation Neutron Source Linac Low-Level RF Control System, PAC05.

M. Crofford et al, “Operational Experience with the Spallation Neutron Source High Power Protection Module,” PAC05.

K. Kasemir et al, “Adaptive Feed Forward Beam Loading Compensation Experience at the Spallation Neutron Source Linac,” PAC05.

H. Ma et al, “SNS Low-Level RF Control System: Design and Performance,” PAC05.

M. Piller et al, “The Spallation Neutron Source RF Reference System,” PAC05.

M. Champion et al, “The Spallation Neutron Source Accelerator Low Level RF Control System,” PAC03.

A. Regan et al, “Newly Designed Field Control Module for the SNS,” PAC03.

L. Doolittle et al, “The SNS Front End LLRF System,” LINAC2002.

# The SNS Power Upgrade Project will double the beam power on target

- Mission need statement (CD-0) approved Nov 2004
- CD-1 DOE review scheduled for Feb 2006
- CD-4 Project Completion scheduled for Sep 2011
- Beam energy increases from 1000 to 1300 MeV
- Average macropulse current increases from 26 to 42 mA
- Total peak RF power requirement (structure + beam)
  - 42.8 MW baseline
  - 71.5 MW upgrade
- Additional voltage and beam loading requires
  - → more cryomodules and
  - → increased RF power everywhere
- Design Goal
  - maximize re-use of existing systems
  - maintain compatibility with existing systems
- Scope
  - Installation of 36 additional Linac RF stations
  - Installation of 2 HEBT RF stations including cavities
  - Upgrades to 4 existing Ring RF stations

# Scope – Superconducting Linac RF

- The 36 additional RF systems will essentially be duplicates of the 81 systems already installed.
- Layout:
  - 36 klystrons
  - 6 transmitters
  - 3 high-voltage converter-modulators (HVCM)
  - 36 low-level RF control systems
- Klystrons: Baseline Parameters
  - Baseline klystrons rated for 550 kW peak RF power with 9% duty factor at 75 kV cathode voltage
  - Stations 1-48 limited to 69 kV (445 kW) due to 12 klystrons per HVCM
  - Stations 49-81 may operate at full power due to 11 klystrons per HVCM
- Klystrons: Upgrade Parameters
  - Cathode voltages will increase to 83 kV for high-beta stations (37-117)

    → Peak RF power increases to 708 kW

    → Provides minimum margin of 37% (need 517 kW max without margin)
  - Similar to baseline klystrons, which are very robust and have been factory tested to 105 kV, 1.3 MW (one test)

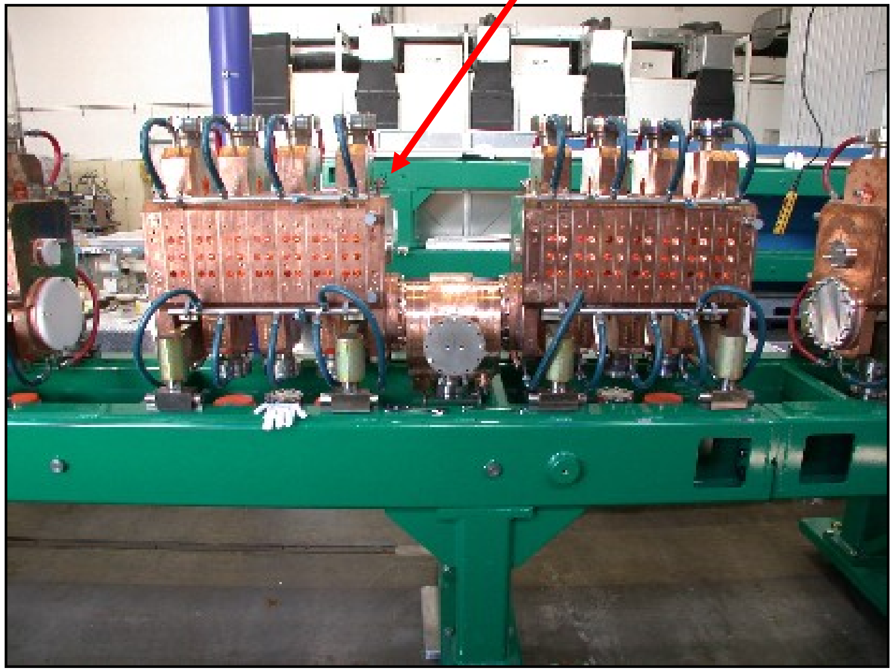
# Scope – Superconducting Linac RF

- Transmitters: support for six klystrons
  - Solenoid, vacuum and filament power supplies
  - Solid-state driver amplifiers
  - Klystron protection interlocks
  - PLC-based controls, interlocks and monitoring
- Waveguide runs
- Water skids

Linac klystron gallery during installation of baseline RF systems

# Scope – HEBT RF

- Energy spreader and energy corrector cavities
  - Two copper 805 MHz cavities similar to CCL segment
- Two complete RF systems
  - Transmitters and klystrons (805 MHz, 708 kW)
  - RCCS (resonance control cooling system)
  - LLRF control systems
  - Waveguide runs
  - Water skids



# Scope – Ring RF

- The Ring RF system will be upgraded to meet the demands of higher beam loading
  - Additional high-voltage charging supplies will be installed
  - Cavity tuning supplies may be replaced or upgraded


Ring RF equipment in Ring service building


Ring RF cavities and amplifiers in Ring tunnel

# Conclusions

- The Linac RF system installation and testing is complete.
- The entire Linac has recently been very successfully commissioned with beam.
- The Ring RF system is under test and will be ready to support Ring beam commissioning in Jan 2006.
- The project is on track for completion by Jun 2006.
- A power upgrade is planned to double the beam power by 2011.