SNS RF System Performance and Operation

Mark Champion

June 29, 2007

UT-BATTELLE

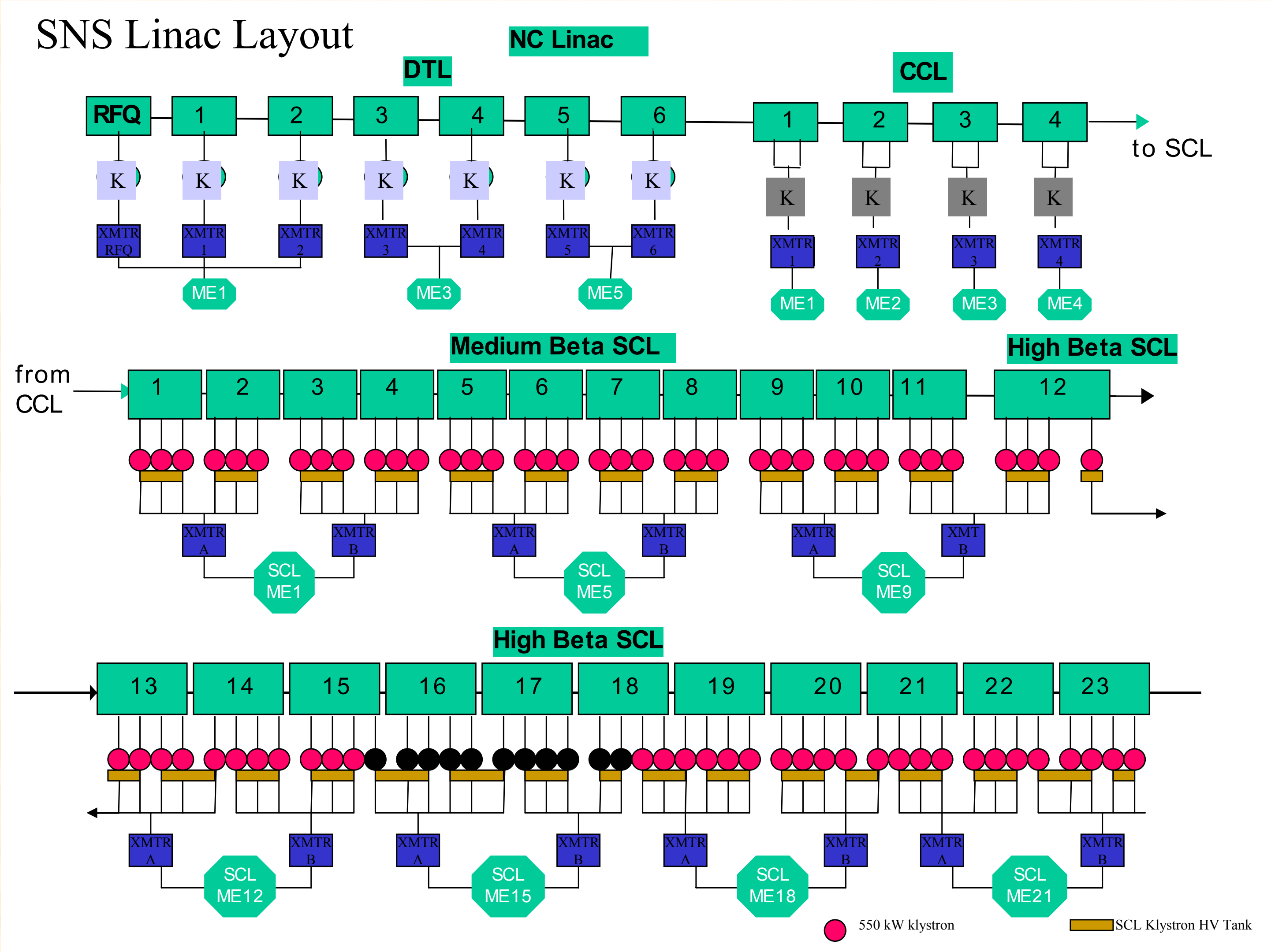
SNS
SPALLATION NEUTRON SOURCE

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

RF Systems Overview

- 100 RF systems are installed and operational
- The RF Group is staffed with 18 people
  - 7 engineers, 9 technicians, secretary and group leader
- The RF Group is responsible for operation, maintenance and upgrades of all SNS RF systems.

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

The SNS utilizes 100 RF systems for acceleration and bunching. Five types of power tubes are in service.

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

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

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

Transmitter racks & LLRF for support of six klystrons.

Each high-voltage power supply supports 11-12 klystrons.

Three klystrons are mounted to each oil tank.

Each LLRF Rack in the Linac Contains Hardware for one or two RF Systems

Typical LLRF control rack installation in the superconducting linac.

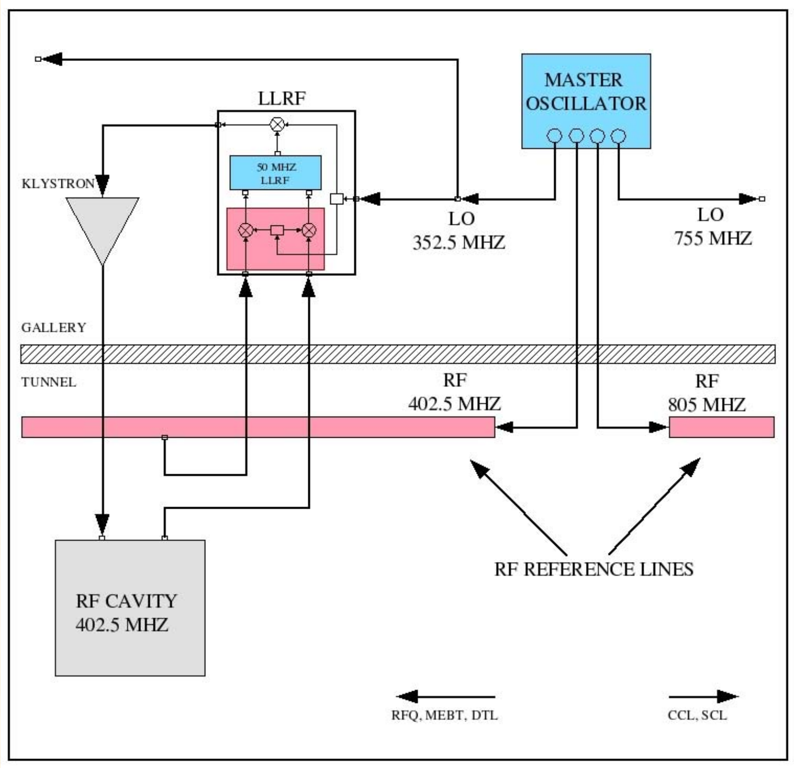
The VXI crate contains:

- 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

SNS Linac RF Reference System

- 402.5 MHz section serves 11 systems: RFQ, MEBT Rebunchers, and DTL
- 805 MHz section serves 85 systems: CCL and SCL
- 805 MHz section extends to end of Linac tunnel and is ready to support additional RF systems to be installed for the power upgrade project

Master oscillator rack located at DTL/CCL transition



Schematic of RF reference system

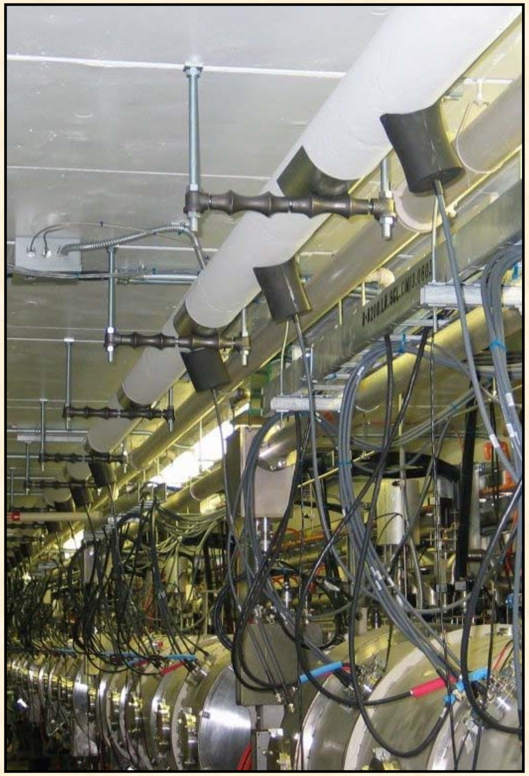
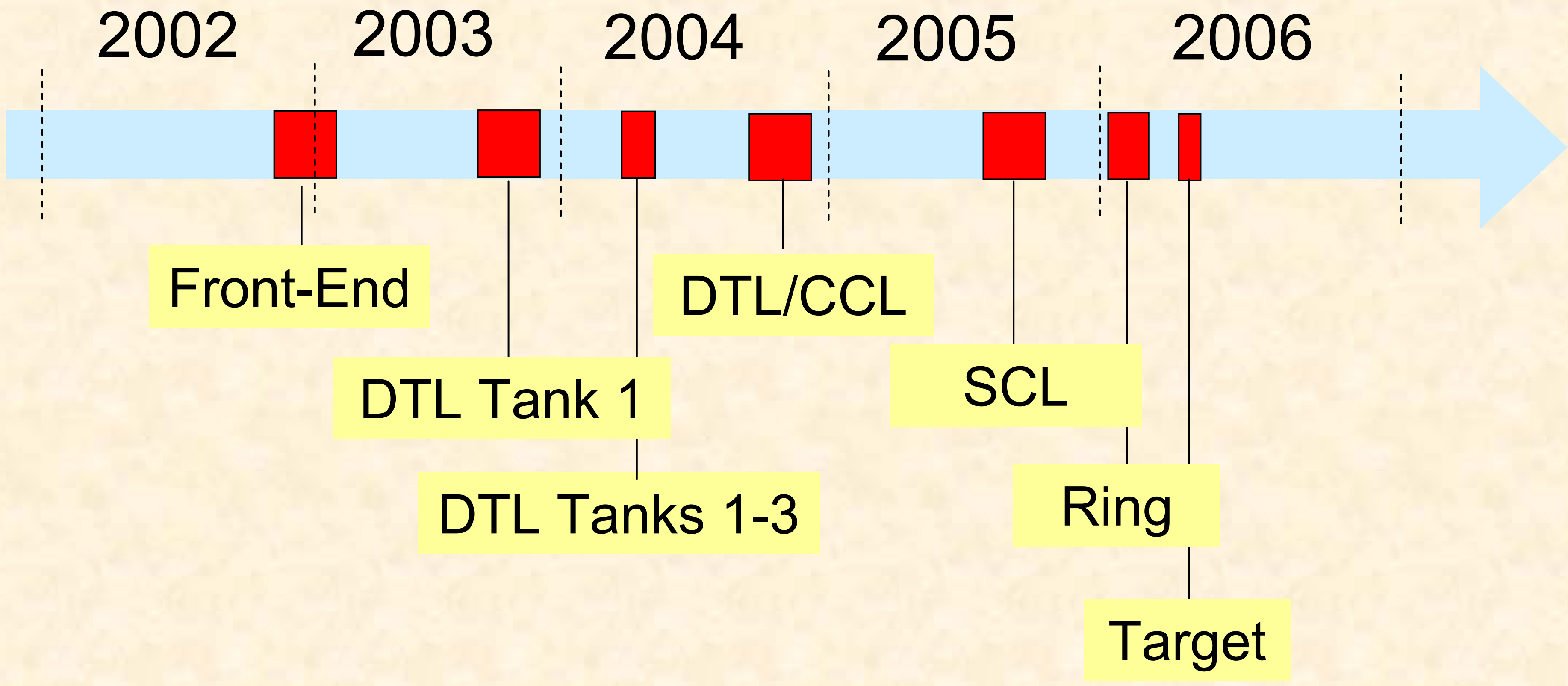


Photo of reference line in SCL

Commissioning Timeline

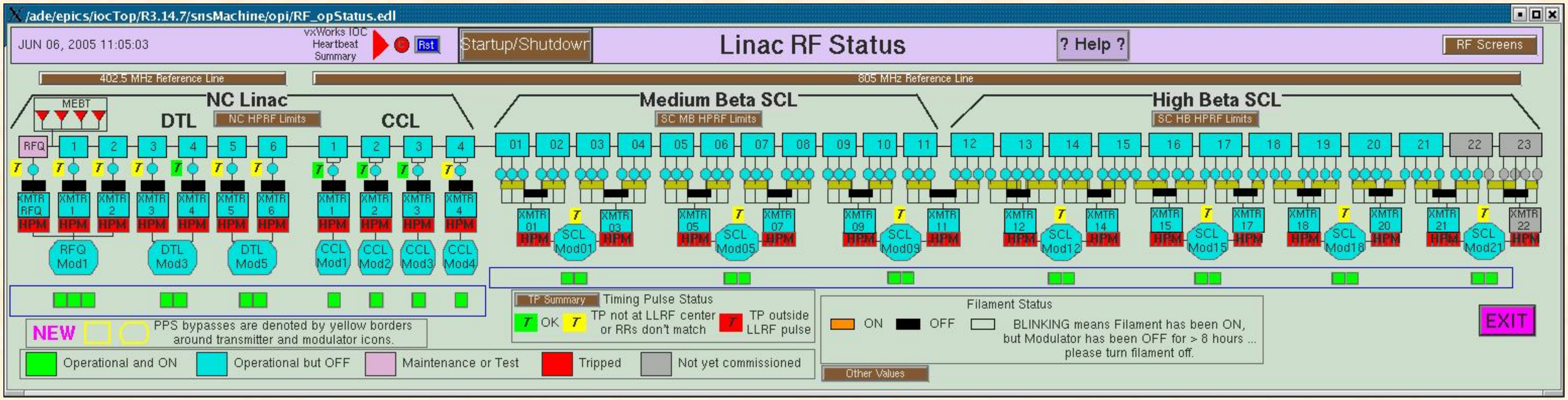


- Installation and testing of the RF systems took place over several years
- Commissioning experiences were valuable and prompted changes:
  - improved controls interfaces
  - modified LLRF functionality

Operations

- The RF systems are operated from the central control room via the EPICS control system.
- Remote consoles available in klystron gallery for maintenance and troubleshooting.
- Only digitized data available; no analog links between RF systems and control room
  - Real-time / transient troubleshooting and investigation must take place in klystron gallery
- Operation of the RF systems, especially the LLRF control system, depends heavily on EPICS sequences (finite state machines) executing on the LLRF IOCs (input/output controllers)
- Goal is to have four basic control actions:
  - Start-up, shut-down, amplitude, and phase

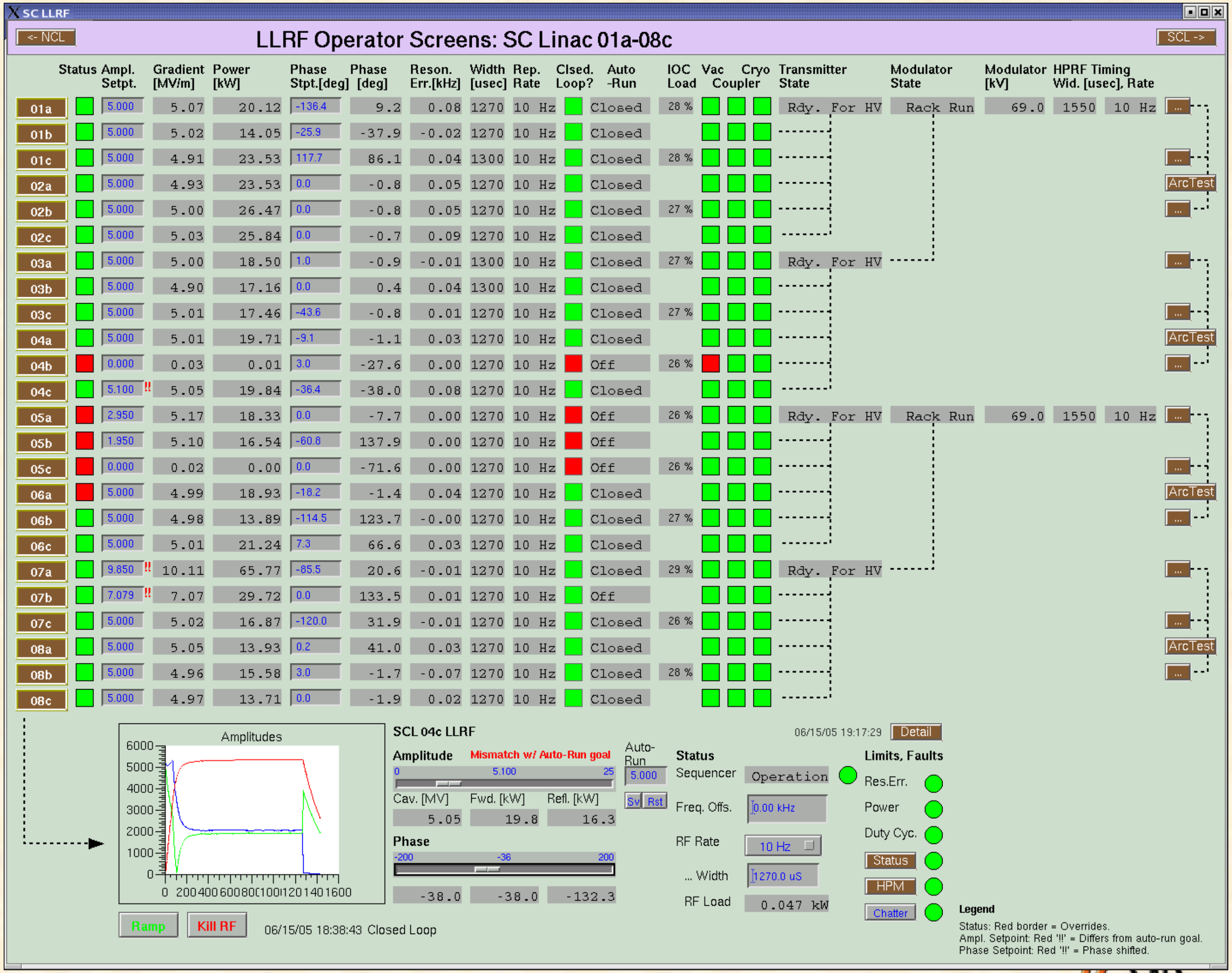
RF System overview screen gives status of entire Linac



- **Status of entire Linac RF system is presented**
- **Provides links to more detailed RF system screens**
- **Provides for automated start-up and shut-down of high-power RF system via EPICS sequencers**

EPICS sequencers provide for one-button start-up of LLRF systems

- **Auto-Run sequencer ramps up cavity field under open-loop conditions.**
- **Auto-Tune sequencer maintains correct cavity frequency.**
- **Upon reaching the desired gradient, the feedback control loop is engaged.**

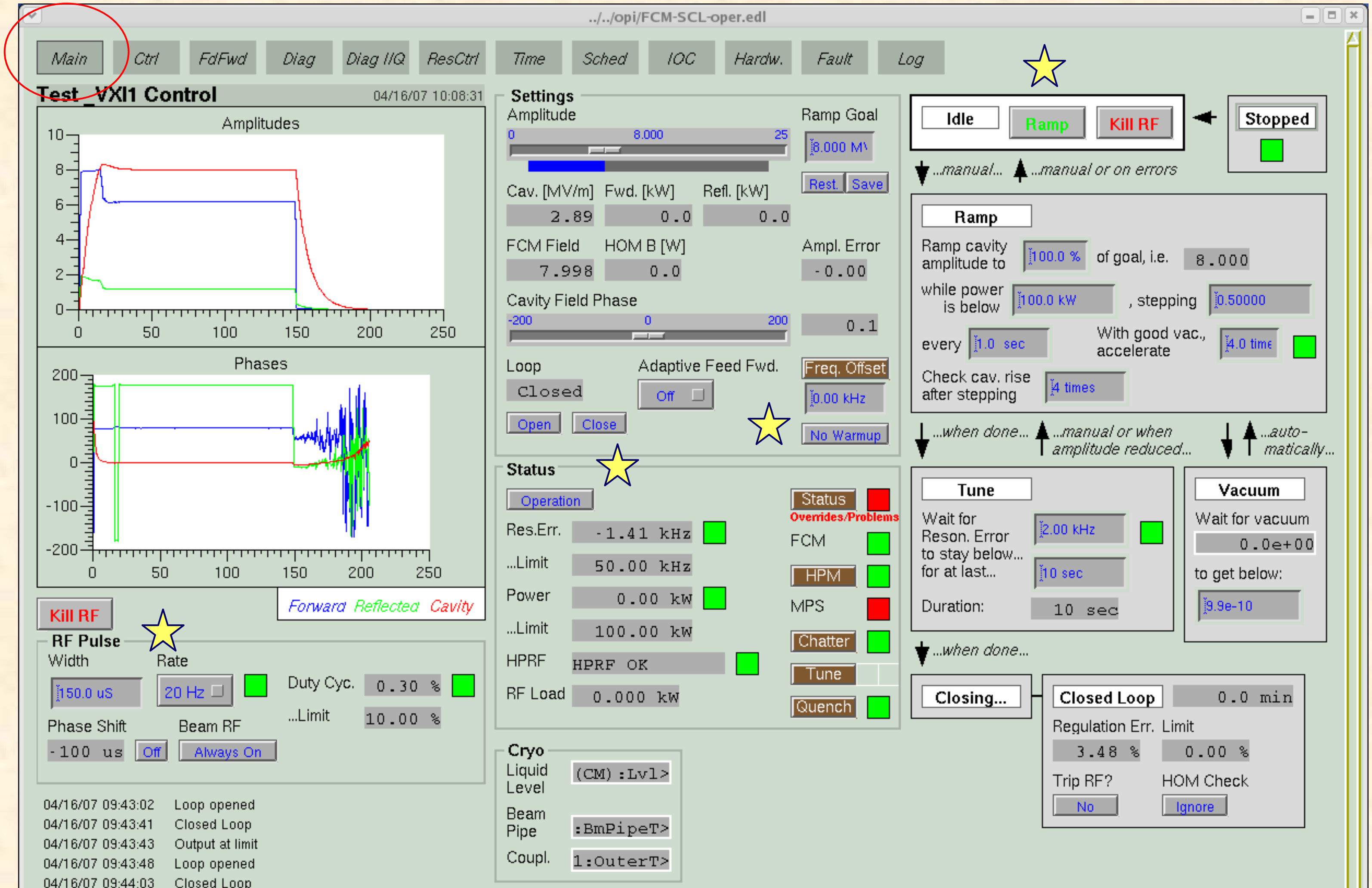


Hengjie Ma, 05/2007

LLRF Graphic Users-Interface / Operators Screen, (“Main”)

Operators screen displays all the control and administrative information important to the operation, and hosts some of the automated operation sequences ☆ Such as

- Auto-run
- Loop close/open
- Warm-up mode
- rf pulse width setting
- Etc.



UT-BATTELLE

SNS SPALLATION NEUTRON SOURCE

LLRF GUI / Expert Control Screen ("Ctrl")

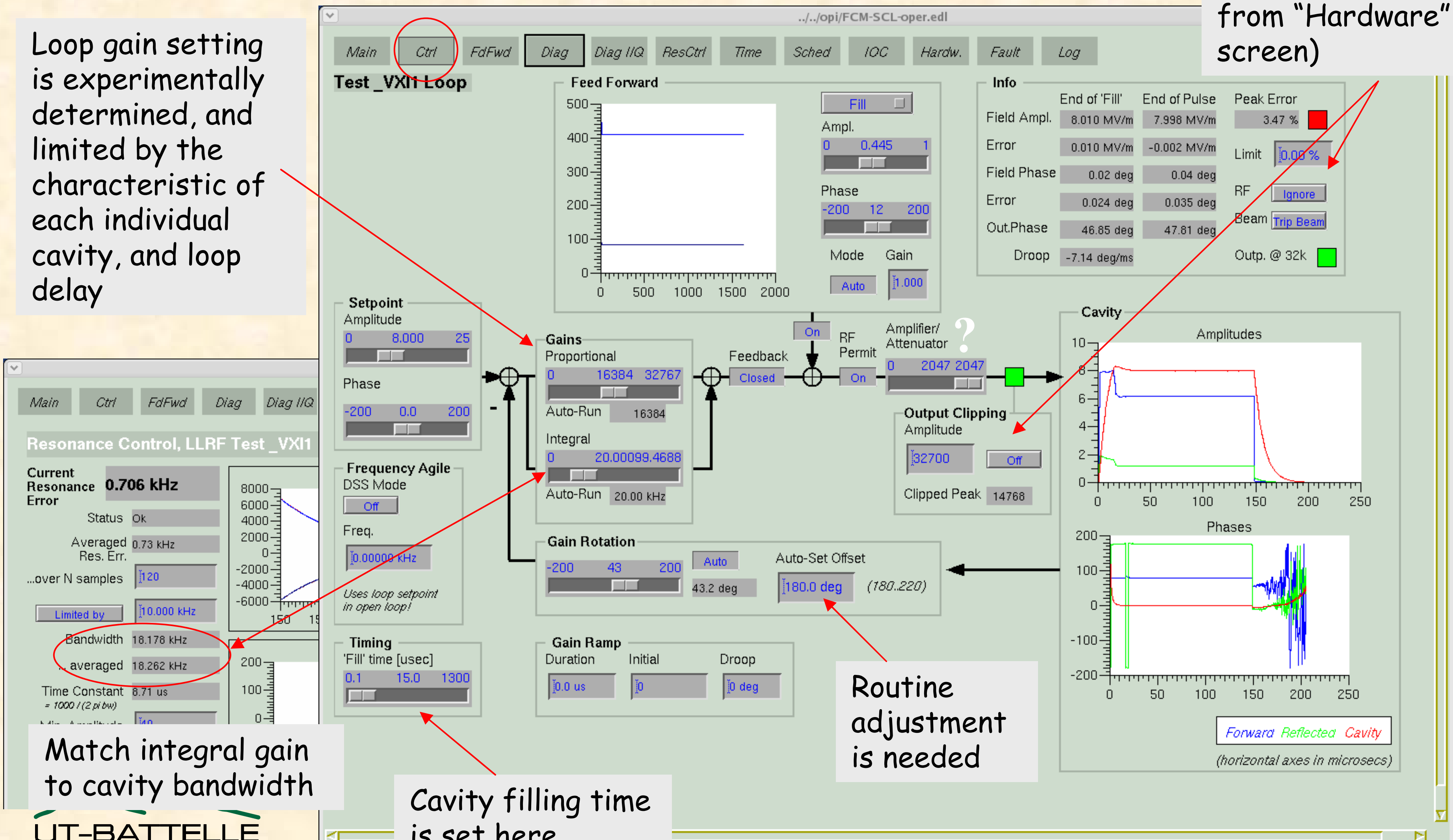
Hengjie Ma, 05/2007

Expert control screen allows manual changes on every control PV for study purposes, and the displayed control diagram depicts the relationships between the control parameters.

Interlock configuration

(duplicated info from "Hardware" screen)

Loop gain setting is experimentally determined, and limited by the characteristic of each individual cavity, and loop delay



Match integral gain to cavity bandwidth

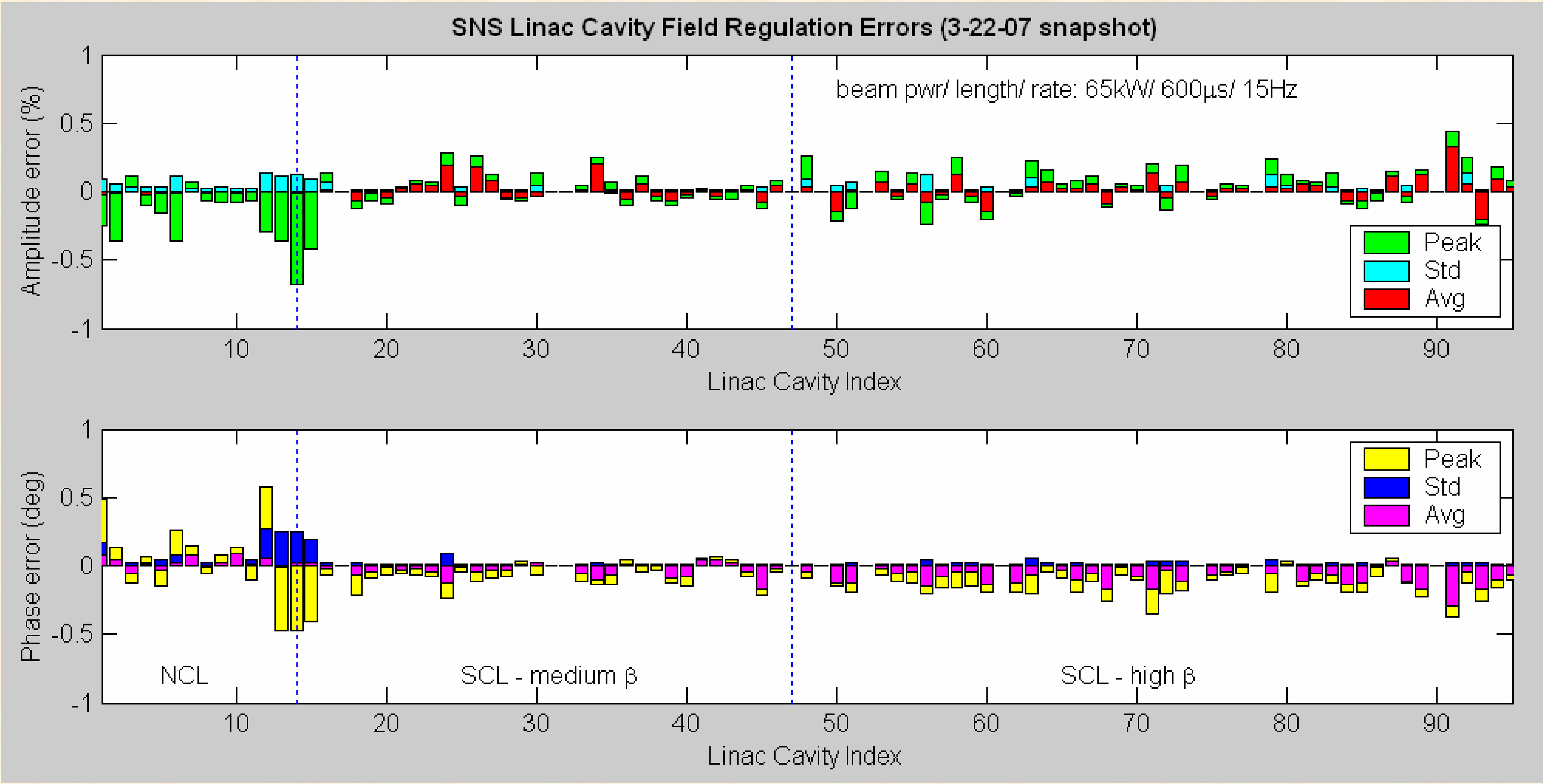
Cavity filling time is set here

Routine adjustment is needed

Performance of the SNS RF System

- The primary 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

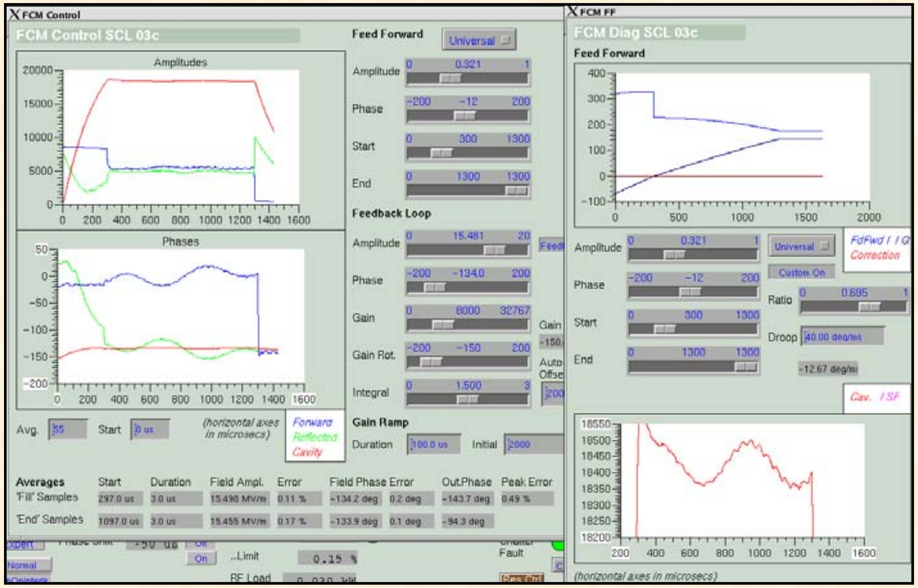


Fig. 1 Adaptive Feed-Forward disabled. Peak field error is 0.5 %.

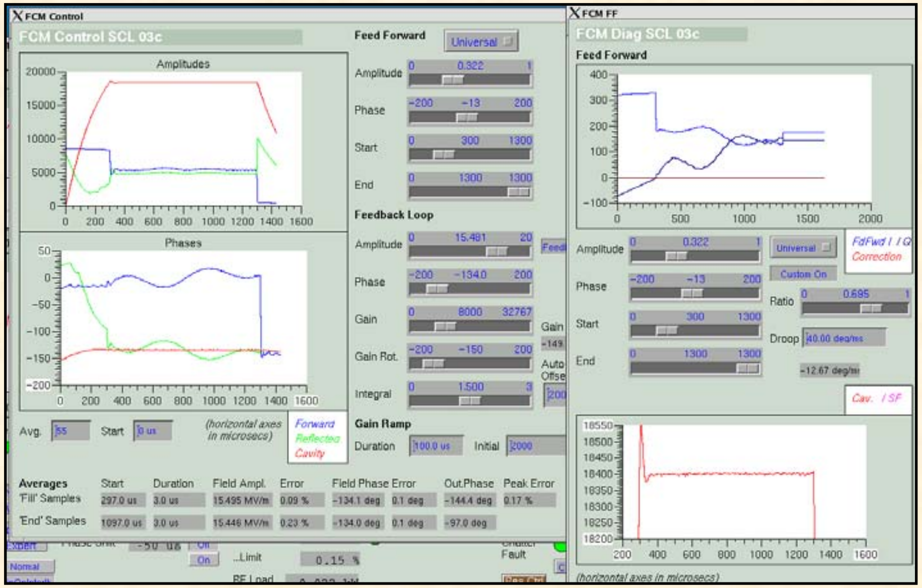


Fig. 2 Adaptive Feed-Forward enabled. Peak field error reduced to < 0.2 % after three iterations using latest version of code under development.

- 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.

Adaptive FeedForward Beam Compensation was developed during the Warm Linac Commissioning in 2004

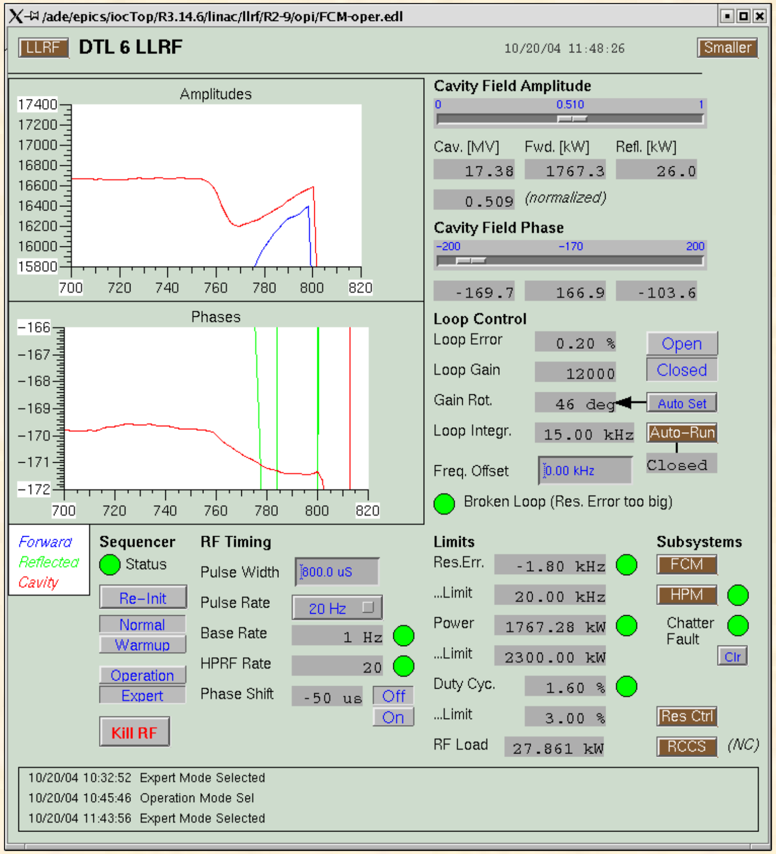


Fig. 1 Beam loading in DTL6 with ~40 us, 20 mA beam induced error of 2.7% and 2 deg in amplitude and phase.

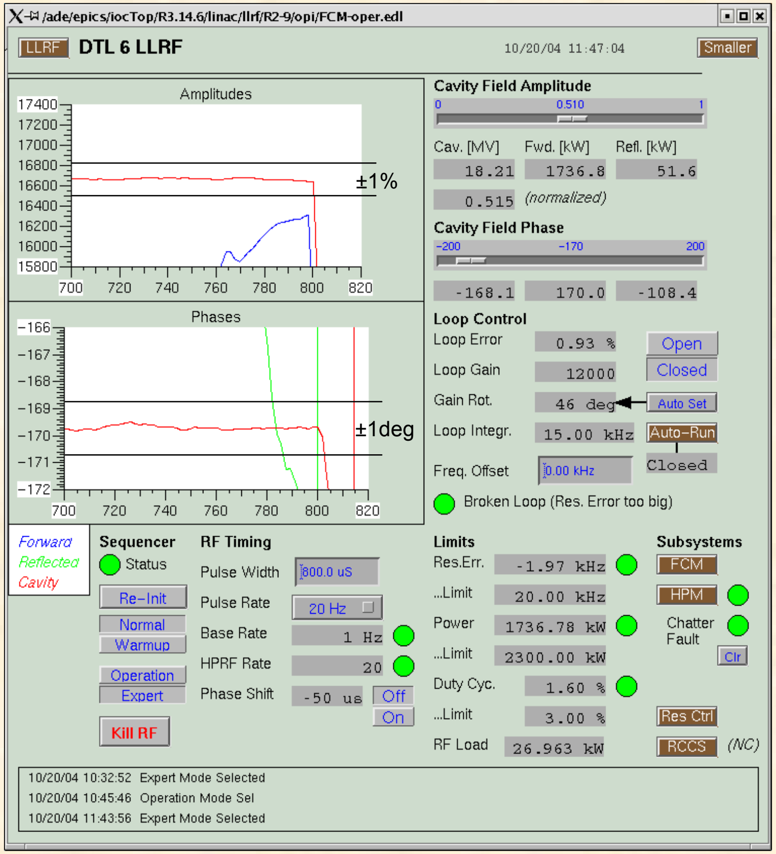
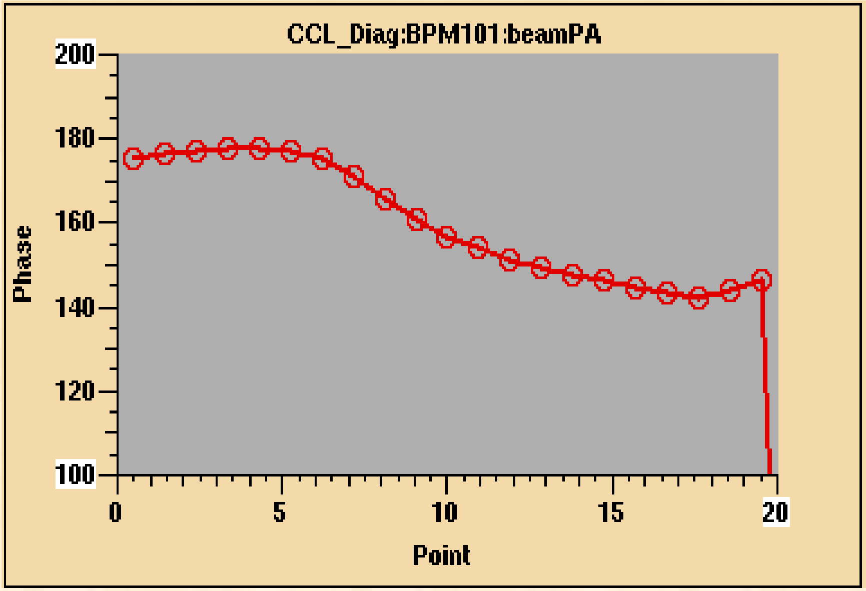
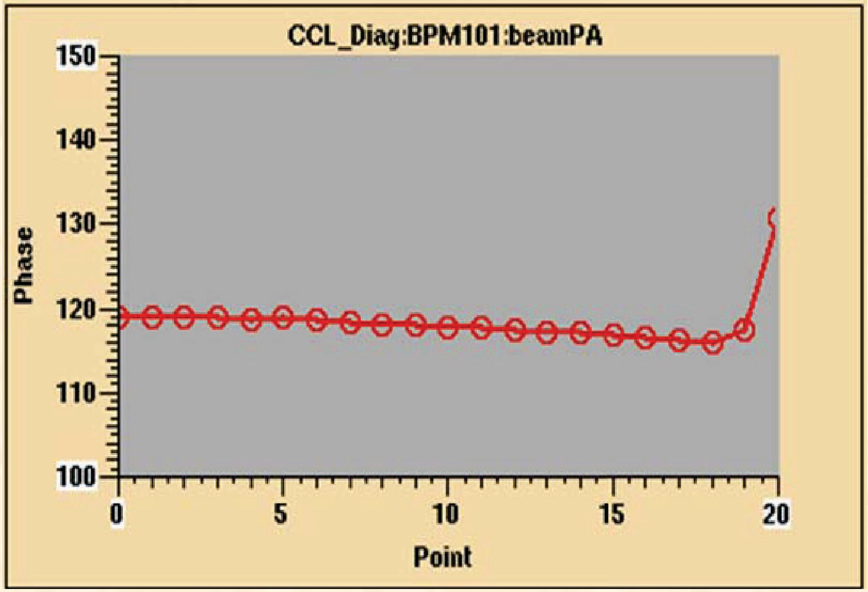


Fig. 2 Beam loading eliminated by means of Adaptive FeedForward.

Beam measurements show the effectiveness of Adaptive FeedForward beam loading compensation



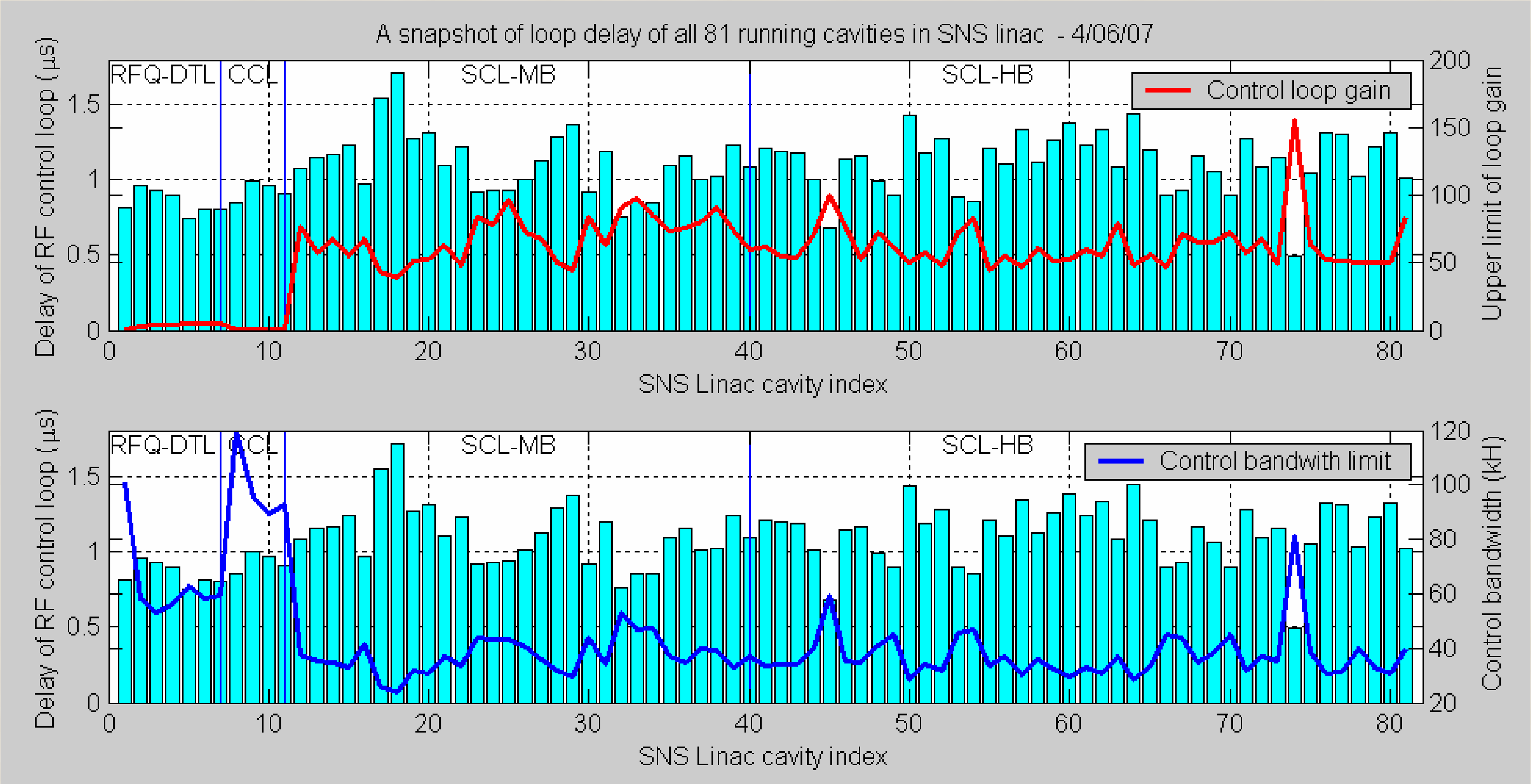
Beam phase vs. time at the entrance to CCL1 with Adaptive FeedForward disabled. Beam current is 40 mA. Beam pulse length is 40 us.



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

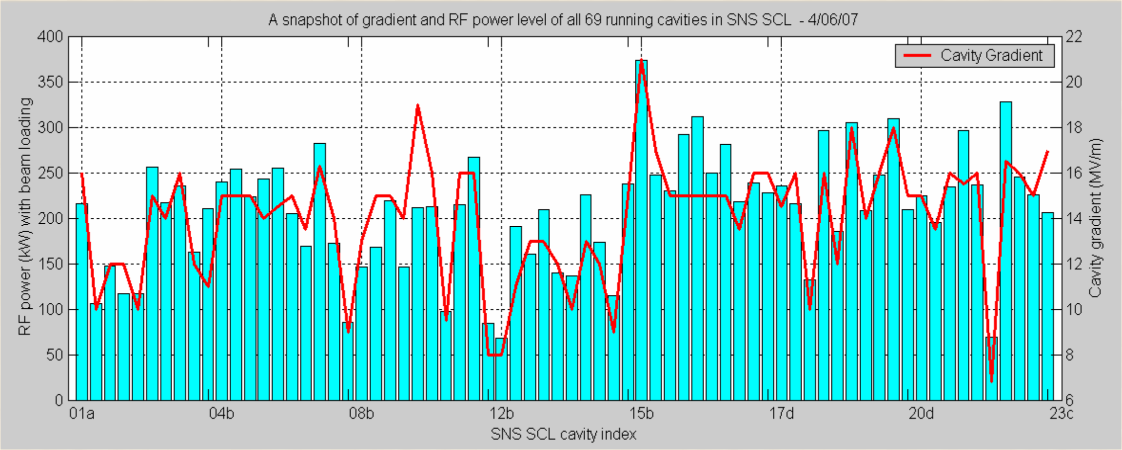
Commissioning / issues / loop delay / gain limiting

Measured loop delay of all systems in SNS Linac, and calculated limit of usable loop gain, and maximum control bandwidth

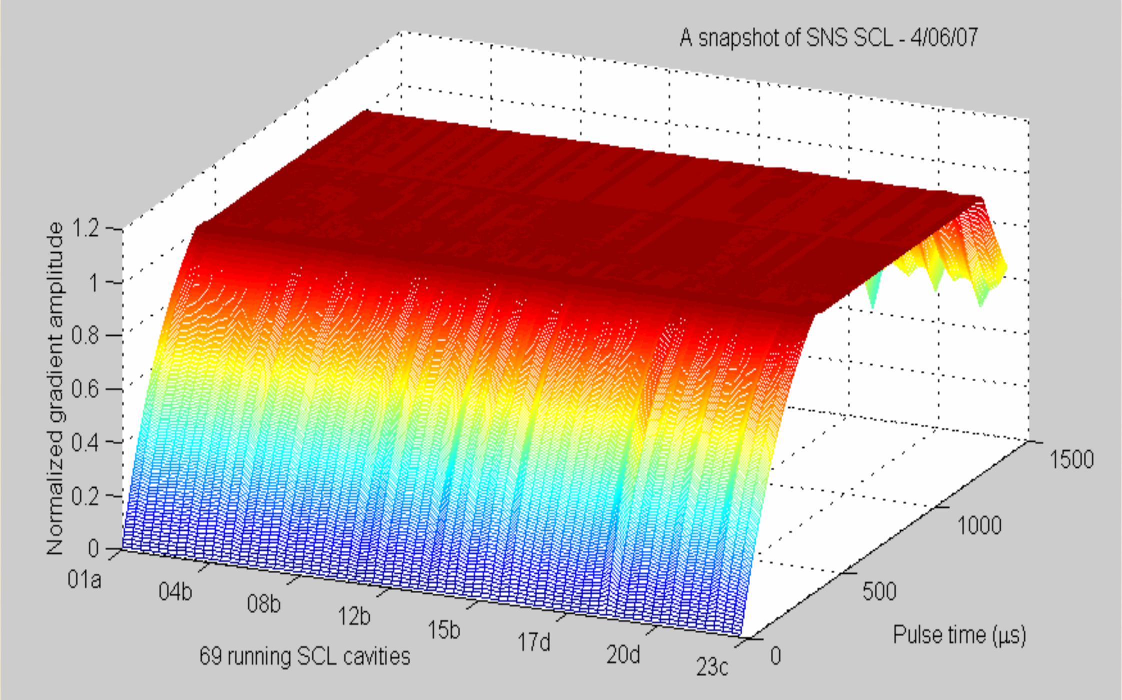


Commissioning results/ SCL cavity field control

- The running gradient and power across SNS Linac in April 2007



- Actual result of the cavity filling scheme in operation (with 400us, 12mA avg. beam current running)

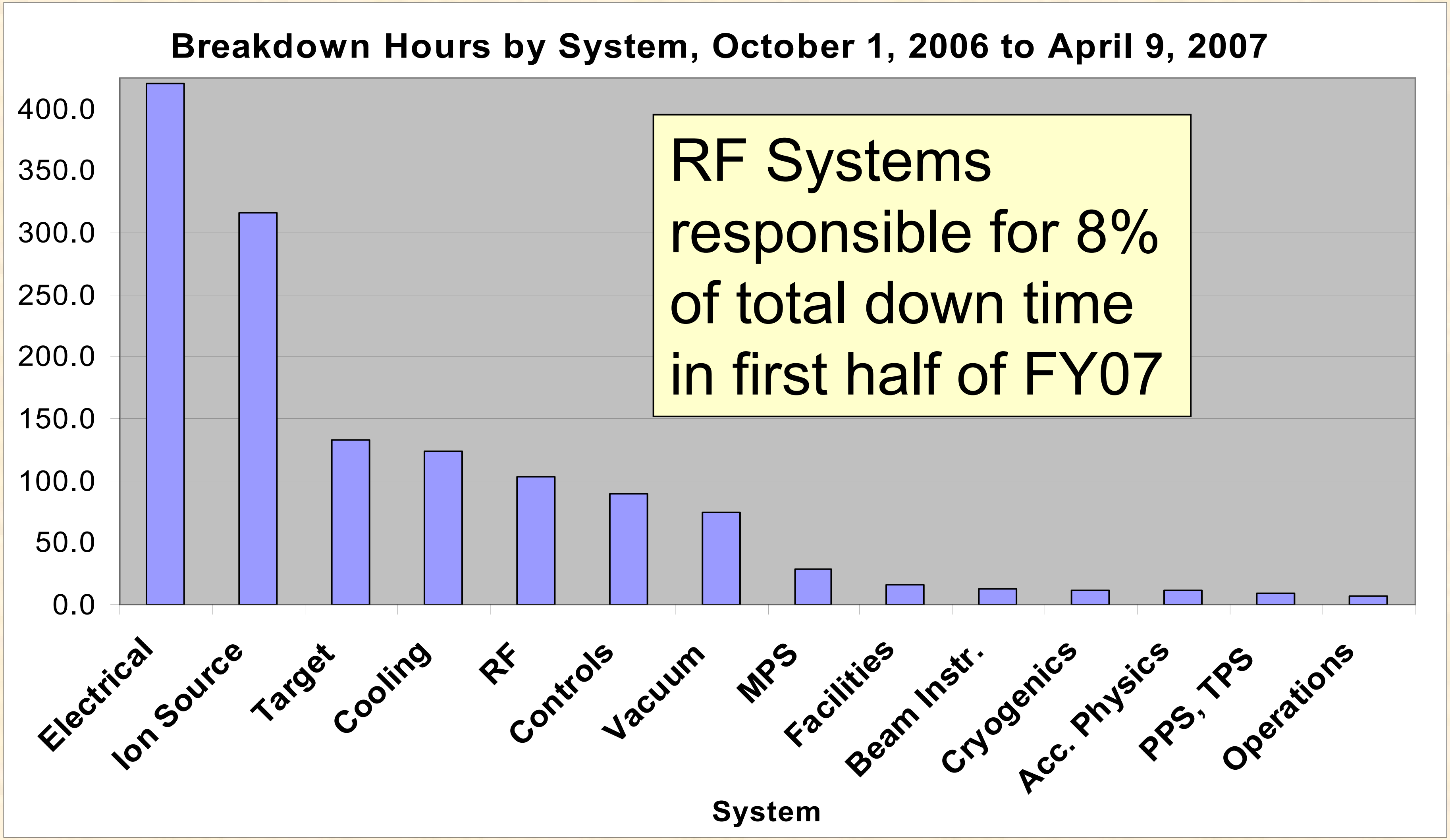


- Achieved a consistent field profile in all cavities across SCL

Reliability

- The reliability of the RF systems is critical to the overall reliability of the SNS since failure of a single RF system results in lost neutron production time.
- The Linac can operate with several SCL RF stations disabled, and this is the norm since several superconducting cavities are usually offline at any given time.
- A semi-automatic procedure is used for adjusting the downstream cavity setpoints when a SCL RF station is disabled or enabled.
- In the normal conducting section of the Linac, all RF stations and their associated cavities must be operational in order to accelerate beam through the Linac.

System breakdowns for Runs 2007-1 and 2007-2



Operational Statistics for SNS Commissioning Runs

Commissioning Run	Front End	DTL1	DTL 1-3	to CCL3 15/Dec/04 thru 18/Jan/05	CCL4 and SCL		Ring Commissioning	
	Percent	Percent	Percent	Percent	Hours	Percent	Hours	Percent
Total					1176.9		575.95	100%
Planned Shutdown	1.6%	0.5%	3.6%	0.1%	102.5	8.7%	77	13%
Planned Uptime				56.9%	1074.4	91.3%	498.95	87%
Machine On Time	53.6%	62.5%	75.0%	84.2%	718.1	61.1%	319.2	55%
Machine Start_Up	0.8%	0.9%	0.0%	2.2%	41.5	3.5%	14	2%
Rad Monitoring/Tunnel Sweep/PPS	0.0%	0.4%	2.6%	1.8%	11.0	0.9%	0	0%
Equipment Breakdown	45.3%	35.7%	18.8%	11.8%	302.9	29.7%	165.75	34%
Breakdown								
RF	33.6%	27.9%	15.4%	68.1%	81.1	26.8%	34.7	20.94%
Magnets							12.4	7.48%
Power Supplies	4.2%	22.3%	0.0%	11.8%	63.0	20.9%	17	10.26%
Ion Source	31.7%	21.0%	5.6%	0.0%	0.5	0.2%	1.5	0.90%
Facilities	9.7%	2.7%	0.0%	0.0%	39.8	13.2%	3	1.81%
Cryogenics				0.0%	0.0	0.0%	1	0.60%
Diagnostics	6.9%	5.8%	0.0%	0.0%	3.6	1.2%	1	0.60%
Protection Systems	0.0%	0.0%	0.9%	3.5%	1.5	0.5%	4	2.41%
Controls	12.0%	17.2%	3.7%	4.4%	35.9	11.9%	16.45	9.92%
Vacuum	2.0%	2.9%	0.0%	12.2%	37.5	12.4%	11.2	6.76%
Water	0.0%	0.0%	74.4%		29.8	9.8%	63.5	38.31%

Klystron & Gridded Tube Performance

- 92 klystrons and 8 gridded power tubes in service
- No tube failures so far (cathodes, windows, vacuum integrity)
- Klystron high-voltage operating hours 10,000 to 15,000 hours depending on location in Linac
- Gridded tubes:
  - No problems
- 402.5 MHz, 2.5 MW klystrons:
  - Arcing occurred at waveguide-to-coaxial transition due to out-of-tolerance components in the coaxial output.
    - Vendor inspected all klystrons and made repairs as needed
    - Problem solved
  - Several water leaks at copper water fittings on solenoids

Klystron & Gridded Tube Performance

- **805 MHz, 5 MW klystrons:**
  - Occasional loss of SF6 at klystron output window or circulator
  - Occasional Ion Pump connector arcing
- **805 MHz, 550 kW klystrons:**
  - One klystron exchanged due to excessive outgassing during RF operation
    - Plan to RF condition on test stand
    - Another klystron (not installed) showed similar symptoms at factory – will be tested at SNS
  - A few water leaks
- **Most klystrons, especially in SCL, are operated at less than rated voltage**
  - For example 69-71 kV compared to 75 kV in SCL

Water Leaks

Example of typical water leak on 402.5 MHz klystron.

This 805 MHz, 550 kW klystron would not make full power. Upon removal we discovered it was full of water and the input RF connection was submerged!

DTL3 Klystron exchanged in March 2006 due to water leak

Preparation for lifting of spare klystron.

Water leaking onto this solenoid connector caused a short circuit and subsequent arcing and overheating.

Linac Transmitter Reliability

- **The transmitters include power supplies (filament, ion pump, solenoid, and circulator trim coils), solid-state drive amplifiers, equipment protection interlocks, AC power distribution, and PLC-based control and monitoring.**
- **Associated equipment includes water distribution racks and instrumentation, waveguide components, and the high-voltage tanks and tube sockets.**
- **These systems have proven to be reliable – with a few exceptions – and the PLC-based control and monitoring is very flexible.**

Linac Transmitter Reliability

- **The filament power supplies were initially prone to failure at turn on.**
  - The vendor provided an upgrade which eliminated this susceptibility
- **Other occasional equipment failures & faults include:**
  - cabinet cooling blowers
  - cathode over-current faults
  - solid-state drive amplifiers
  - solenoid power supply current drift
  - solenoid power supplies
  - door interlock switches
  - AC distribution breakers
  - water flow faults
  - excessive reflected power at klystron
    - TCU breaker tripped or TCU out of adjustment

MEBT Rebuncher Transmitter Reliability

- The MEBT rebuncher transmitters support operation of triode-based amplifiers rated at 20 kW maximum power.
- Numerous operational difficulties include:
  - tripping of AC distribution breakers under certain fault conditions
  - tuning sensitivity of the amplifier resonator
  - detuning of the amplifier resonator due to heating when operated at a high duty factor
  - preamplifier failures
- Problems have been partially mitigated through modifications to the transmitters, but it is planned to eventually replace them as part of an accelerator improvement project.
- The MEBT rebuncher transmitters, which comprise 4% of the SNS RF systems, were responsible for ~15% of the RF systems downtime during the first half of FY 2007.

LLRF Control System Reliability

- The LLRF control system hardware has been extremely reliable
  - Essentially no failures to date
- The high-density RF connectors have been somewhat problematic due to quality of outer conductor connection between connector and braid
  - Both crimped and soldered connectors have occasionally failed

Unintended Consequences

- Down time is very often not due to equipment failures
- Instead it is the unintended consequence of:
  - systems operating as designed
  - sporadic EMI or instrumentation noise
  - attempts to improve the systems, e.g., firmware & software upgrades
  - unanticipated interactions between technical subsystems
  - human error, sometimes facilitated by poorly implemented human/machine interfaces
- Some examples follow:
- The klystron transmitter solid-state amplifier has user-defined operating limits. If these limits are exceeded, the high-voltage modulator is shut down. This requires restarting 11-12 stations in the SCL.
- The DTL6 area of the klystron gallery is the "Bermuda Triangle" of LLRF EMI problems.
- First-Fault annunciation: If a high-voltage modulator shuts down unexpectedly, the LLRF control system attempts to maintain the cavity field and may overdrive the transmitter, resulting in a transmitter fault.

Unintended Consequences

- There have been instances of "missing" high-voltage pulses due to timing problems at the modulators. Again, this results in a transmitter fault due to overdrive of the solid-state amplifier. Diagnosis is difficult.
- Maintenance activities sometime result in crossed or disconnected cables.
- Network problems can result in loss of communication with the IOCs, which can render a system uncontrollable, i.e., it continues to run, but it cannot be stopped nor can its operating parameters be changed.
- Phase margin of LLRF control system is reduced due to voltage droop on the high-voltage modulators. This makes operation of the LLRF systems more difficult and is sometimes causes down time.
- In the SCL, six klystrons share an ion pump controller. In case of ion pump overcurrent faults, the source of the fault is not immediately obvious.
- Transmitter doors are interlocked. On occasion the doors have been opened by mistake during operations, which brings down the transmitter and associated high-voltage modulator.
- Water flow faults are sometimes caused by operation near the limit combined with instrumentation noise.

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.**

Acknowledgements

- Thanks the members of the SNS RF Group and Research Accelerator Division for their efforts in making a success of the SNS RF systems.
- Thanks our partners at Lawrence Berkeley, Los Alamos, and Brookhaven National Laboratories.
- Special thanks to Mark Crofford, George Dodson, Kay Kasemir, Hengjie Ma and Tom Hardek for their contributions to this report.

Jeff Ball
Mark Cardinal
Mike Clemmer
Mark Crofford
Taylor Davidson
Ray Fuja
Pam Gurd
Tom Hardek
Dale Heidenreich
Stacey Jones
Yoon Kang
Kay Kasemir
Pam Kite
Hengjie Ma
Mike McCarthy
Rob Peglow
Curtis Phibbs
Chip Piller
John Reed
Craig Swanson
Bob Wilson
Sasha Vassioutchenko