RF Control in SNS Linac

Implementation and what has been learned

Hengjie Ma

1-2007

Outline

- **SNS LLRF System Overview**
  - Configuration
  - Phase reference schemes
  - Mechanical construction
- **Implementations**
  - Chosen controller type
  - Performance analysis
  - Digital implementation
- **Test & Operation Results**
  - Control bandwidth, error
  - Linac-wise performance
- **Some Observations**
  - Lorentz Force detuning.
  - 5/6pi mode excitation.
- **Issues & Improvements**
  - Control stability
  - Cavity filling techniques.
  - Feed forward control algorithms

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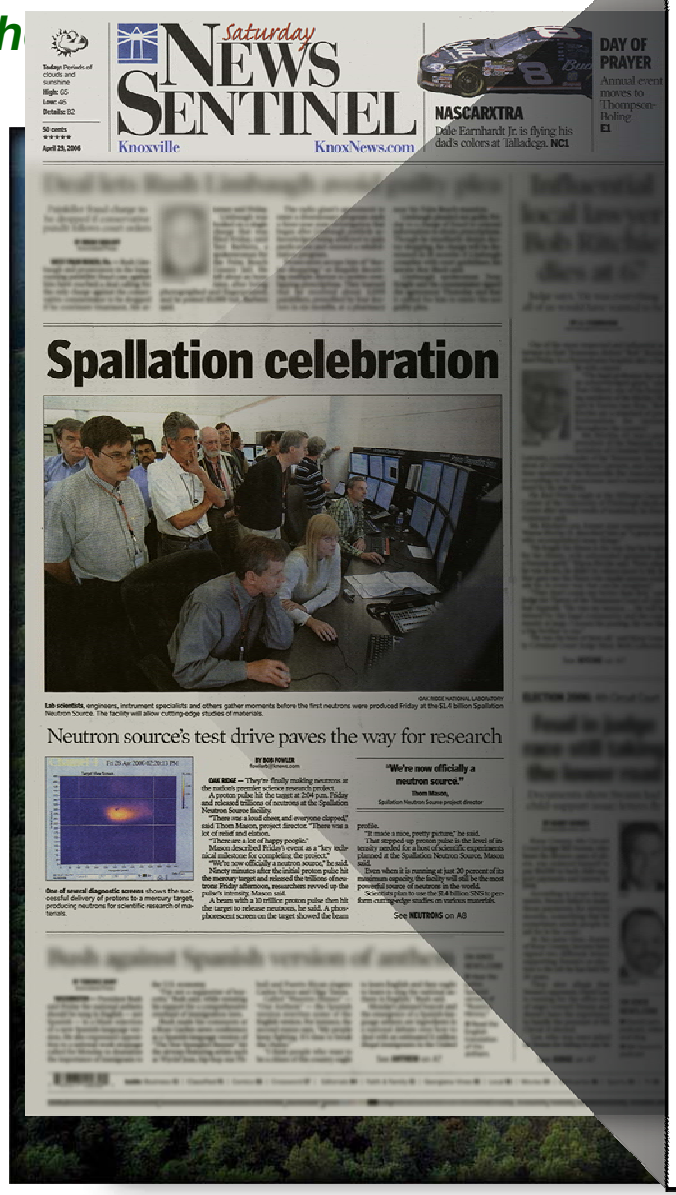

Saturday NEWS SENTINEL
Knoxville
KnoxNews.com
April 23, 2006

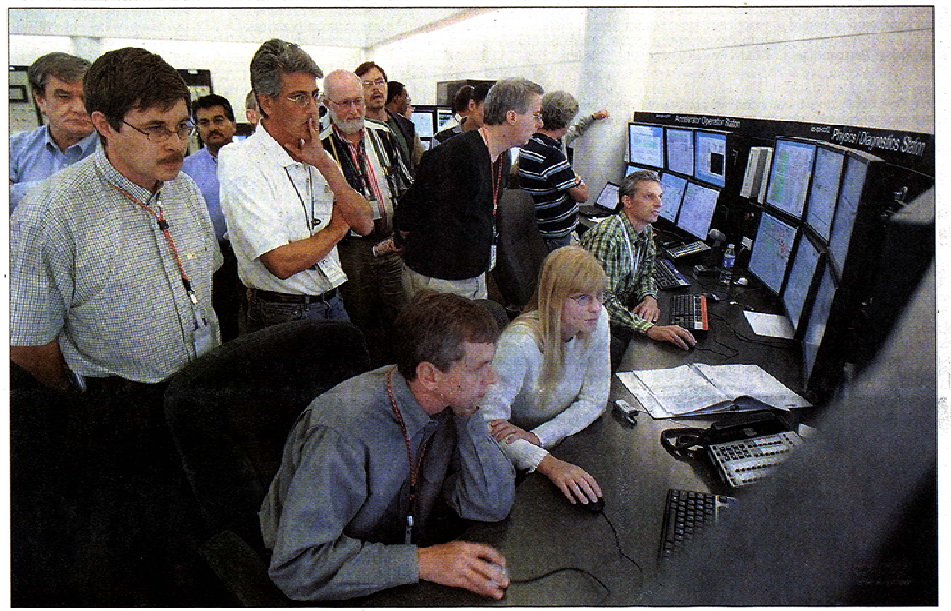
NASCAR XTRA
Dale Earnhardt Jr. is flying his dad's colors at Talladega. NC1

DAY OF PRAYER
Annual event moves to Thompson-Boling E1

Spallation celebration

Neutron source's test drive paves the way for research

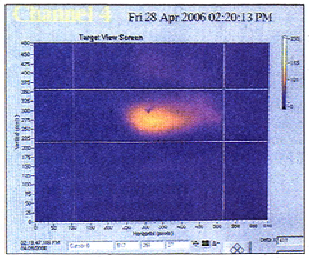
Spallation celebration



OAK RIDGE NATIONAL LABORATORY

Lab scientists, engineers, instrument specialists and others gather moments before the first neutrons were produced Friday at the $1.4 billion Spallation Neutron Source. The facility will allow cutting-edge studies of materials.

Neutron source's test drive paves the way for research



One of several diagnostic screens shows the successful delivery of protons to a mercury target, producing neutrons for scientific research of materials.

BY BOB FOWLER
fowlerb@knews.com

OAK RIDGE — They're finally making neutrons at the nation's premier science research project.

A proton pulse hit the target at 2:04 p.m. Friday and released trillions of neutrons at the Spallation Neutron Source facility.

"There was a loud cheer, and everyone clapped," said Thom Mason, project director. "There was a lot of relief and elation.

"There are a lot of happy people."

Mason described Friday's event as a "key technical milestone for completing the project."

"We're now officially a neutron source," he said.

Ninety minutes after the initial proton pulse hit the mercury target and released the trillions of neutrons Friday afternoon, researchers revved up the pulse's intensity, Mason said.

A beam with a 10 trillion proton pulse then hit the target to release neutrons, he said. A phosphorescent screen on the target showed the beam profile.

"It made a nice, pretty picture," he said.

That stepped-up proton pulse is the level of intensity needed for a host of scientific experiments planned at the Spallation Neutron Source, Mason said.

Even when it is running at just 20 percent of its maximum capacity, the facility will still be the most powerful source of neutrons in the world.

Scientists plan to use the $1.4 billion SNS to perform cutting-edge studies on various materials.

"We're now officially a neutron source."
Thom Mason,
Spallation Neutron Source project director

See **NEUTRONS** on A8

Summary of Beam Parameters Achieved in Commissioning

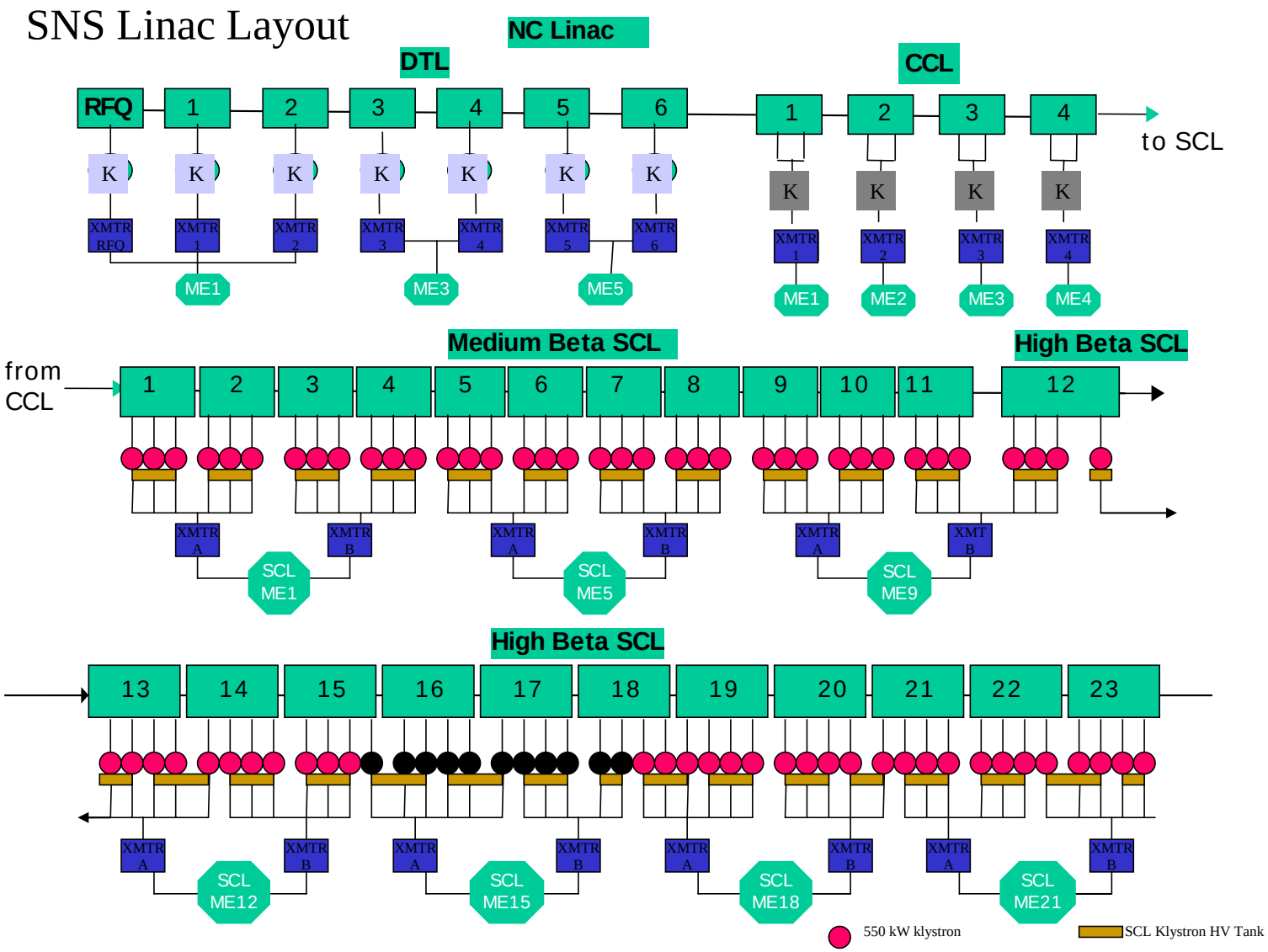
Parameter	Baseline/ Design	Achieved	Units
Linac Transverse Output Emittance	0.4	0.3 (H), 0.3 (V)	π mm-mrad (rms,norm)
CCL1 bunch length	3	4	degrees rms
Linac Peak Current	38	> 38	mA
Linac Output Energy	1000	952	MeV
Linac Average Current	1.6	1.05 (DTL1 run) 0.003 (SCL run)	mA
Linac H-/pulse	1.6×10^{14}	1.3×10^{14} (DTL run) 1.0×10^{13} (CCL run) 8.0×10^{13} (SCL run) 1.0×10^{14} (Ring run)	Ions/pulse
Linac Pulse length/Rep-rate/Duty Factor	1.0/60/6.0	1.0/60/3.8 (DTL1 run) .050/1/.005 (CCL run) 0.85/0.2/0.017 (SCL)	msec/Hz/%
Extracted protons/pulse	1.5×10^{14}	5×10^{13}	Protons/pulse

SNS Site Layout (Start of RF Equipment in Gallery)

The SNS utilizes 100 RF systems for acceleration and bunching

Type	Application	Frequency	Peak Power	Vendor	Installed	Spare
Klystron	RFQ, DTL	402.5 MHz	2.5 MW	E2V & Thales	7	5
Klystron	CCL	805 MHz	5 MW	Thales	4	5
Klystron	SCL	805 MHz	550 kW	CPI & Thales	81	14
Triode	MEBT Rebunchers	402.5 MHz	20 kW	CPI	4	3
Tetrode	Accumulator Ring	1 & 2 MHz	100 kW	Thales	4	1

SNS HPRF Configuration

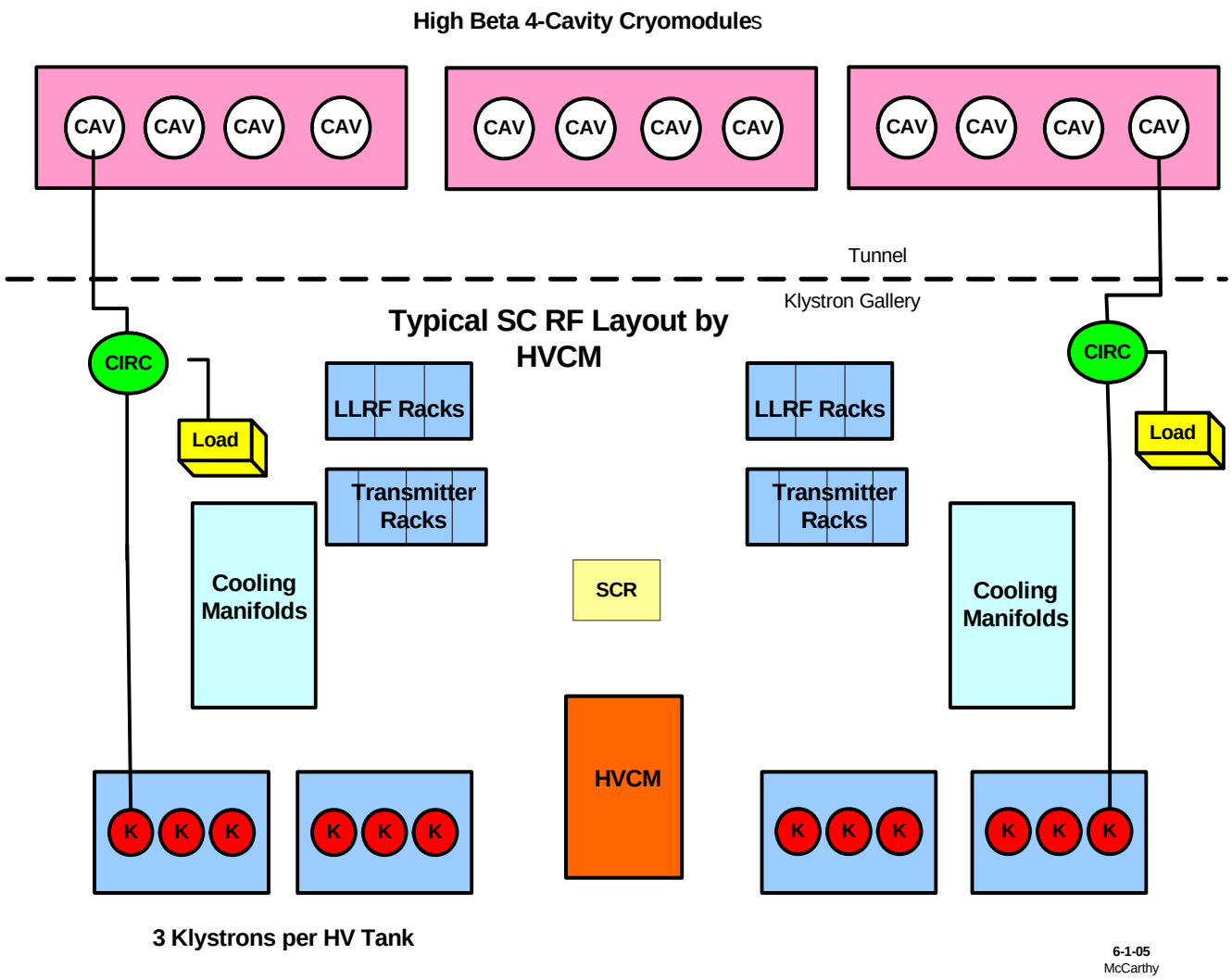


RFQ, DTL and CCL RF Systems

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.

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

Hengjie Ma, 1/18/2007, JLab

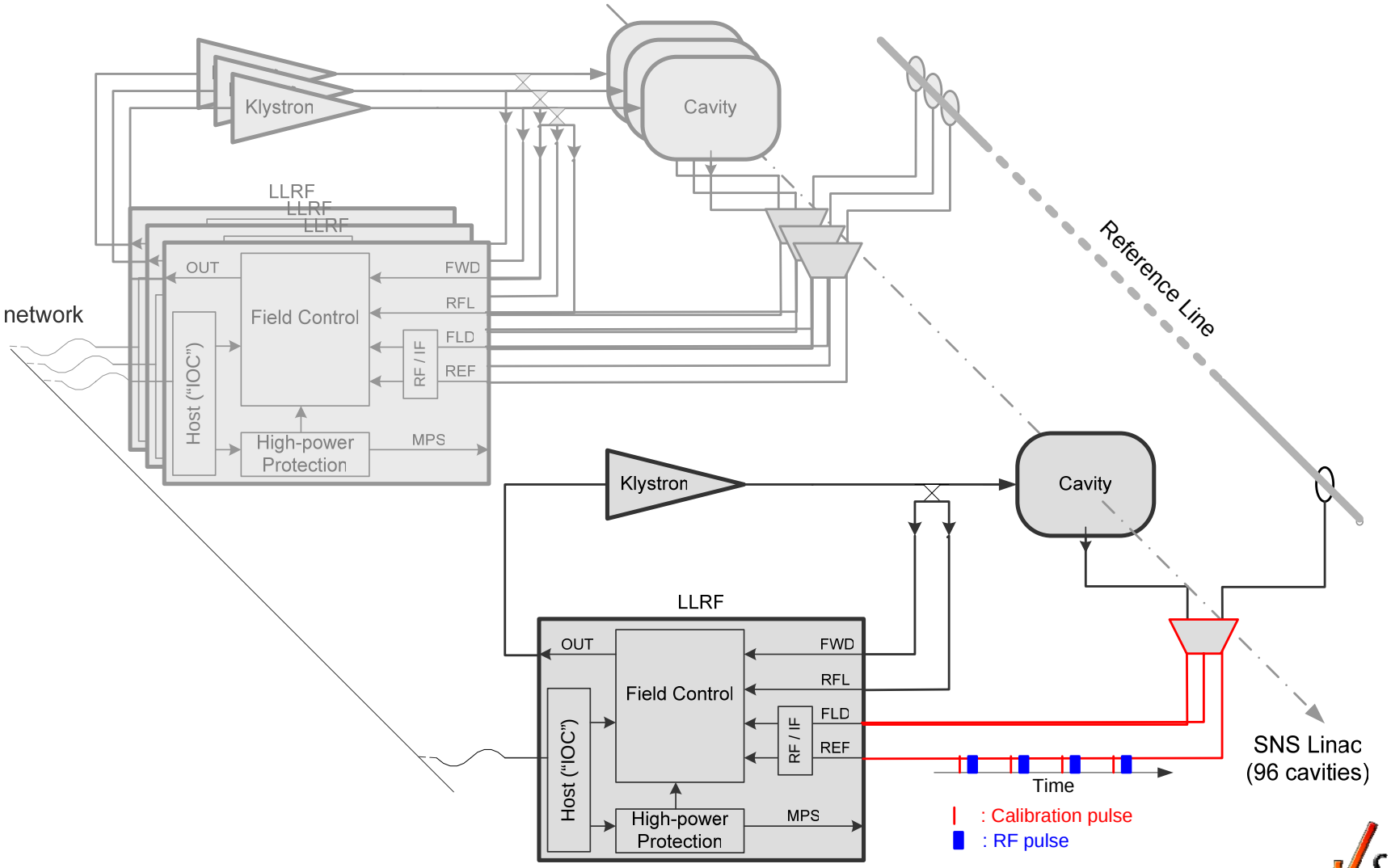
Typical LLRF control rack installation in the superconducting Linac.

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 Control – system overview

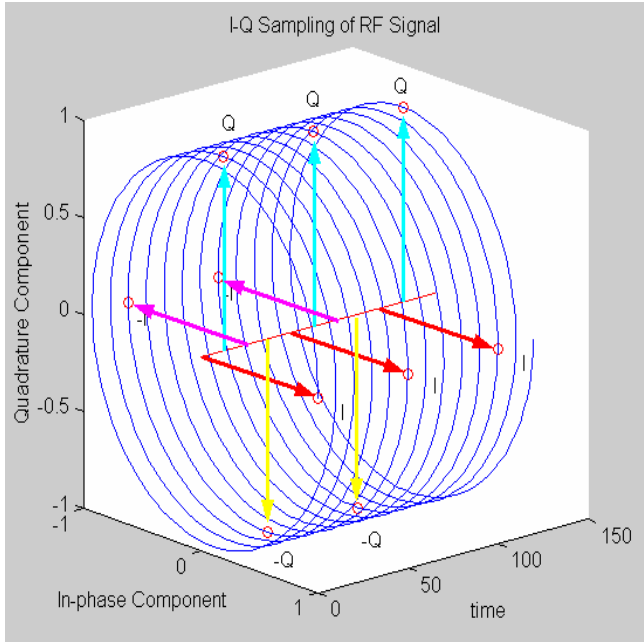
System configuration and phase reference scheme



SNS Linac RF Control – system overview

FCM Electrical Specs.

- I-Q sampling interval:(1+1/4)*2pi (Fs=40MHz)
- IF inputs: 2, 50MHz
- IF ADC resolution: 14-bit



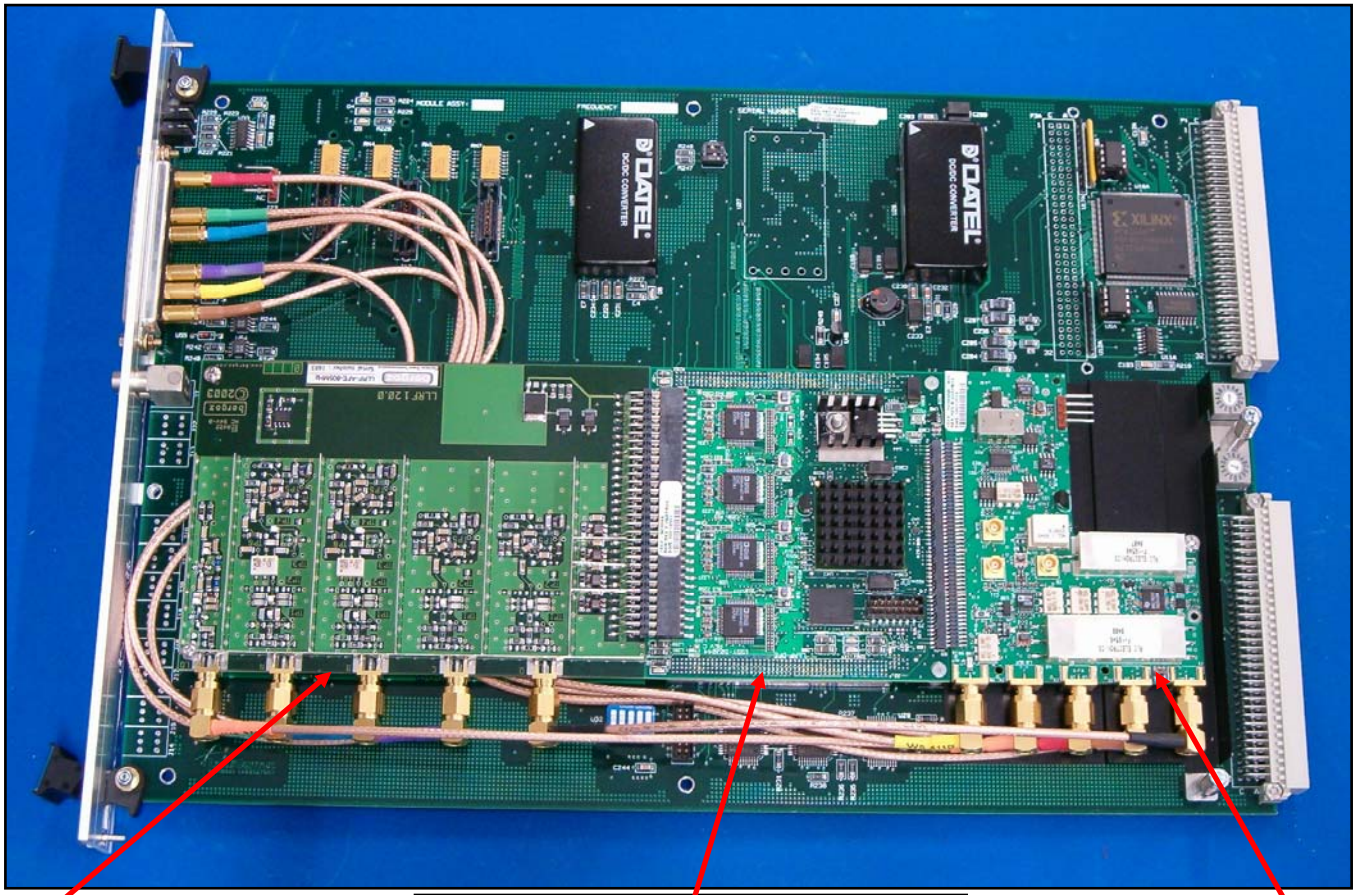
- RF inputs: 2, 805/402.5MHz
- Channel analog bandwidth:1MHz

- High-speed output DAC:1
- DAC resolution: 14-bit
- Output Frequency shift range:+/-645kHz

- FPGA: XC2V1500, SDRAM: 128Mb

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

Hengjie Ma, 1/18/2007, JLab



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

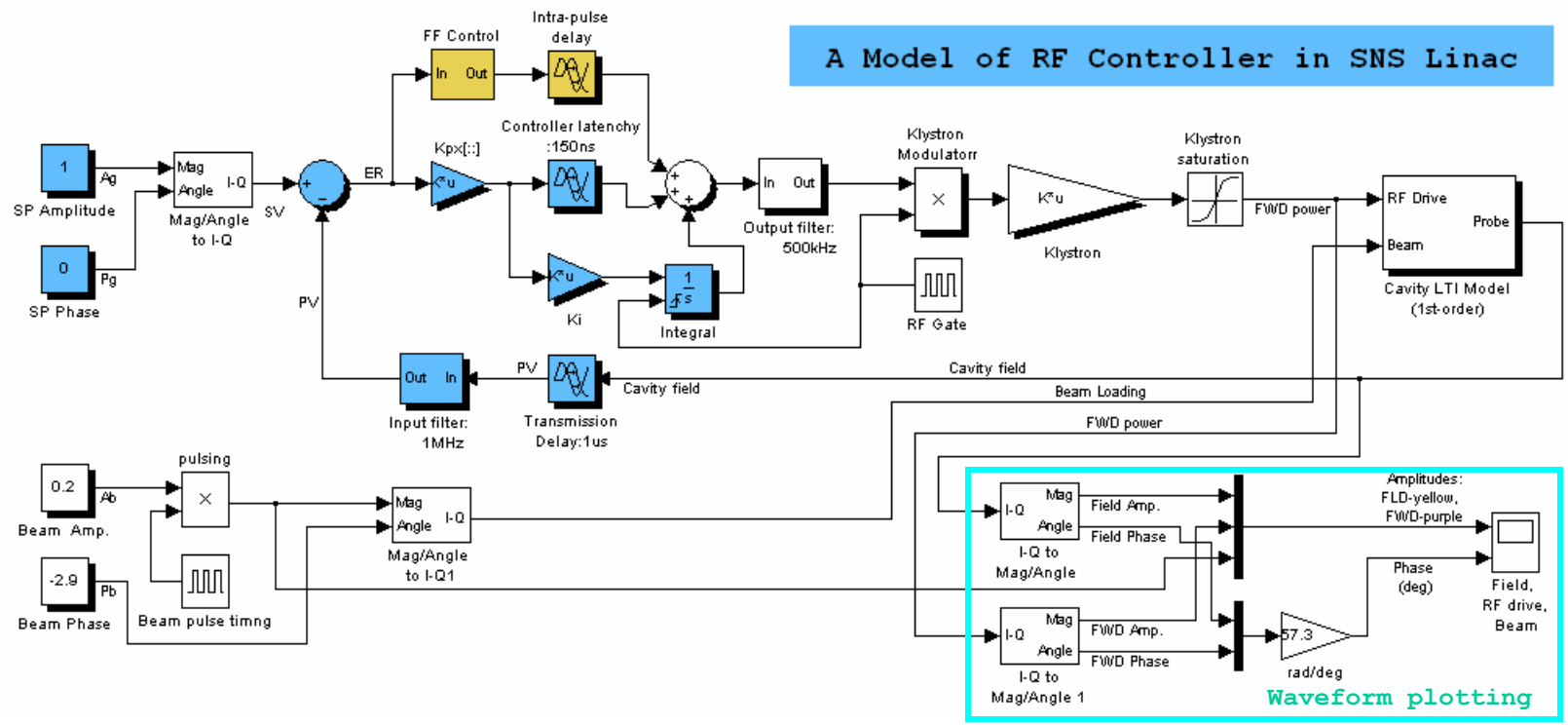
Digital Front End (DFE)
Four 14 bit, 40 MHz ADC channels
One Virtex II FPGA
(XC2V1500 – 1.5M gates)

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

SNS Linac RF Control – implementations

Field Control Module (FCM):

P-I feedback + AFF control



SNS Linac RF Control – implementations

Digital implementation:

from continuous

$$\mathbf{G_c(S) = H_f(S) \cdot R \cdot K_p \cdot \left(1 + \frac{K_i}{S}\right)} \qquad \textbf{(1)}$$

to discrete time

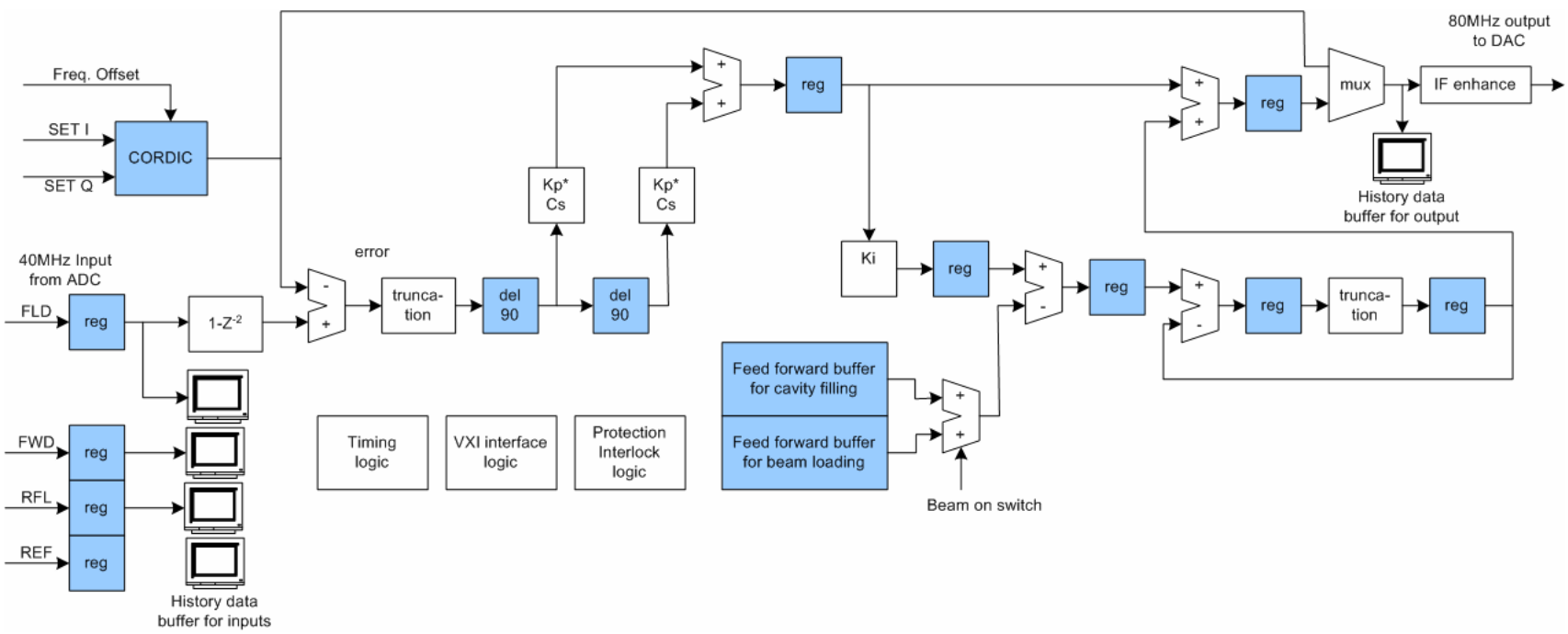
$$\mathbf{G_c(Z) = (1 - Z^{-2}) \cdot (1 - S) \cdot \left(C_c \cdot Z^{-1} + C_s \cdot Z^{-2}\right) \cdot \left\{K_p \cdot \left(1 + K_i T_s \cdot \frac{Z^{-1}}{1 - Z^{-1}}\right)\right\}} \qquad \textbf{(2)}$$

$$\Updownarrow$$

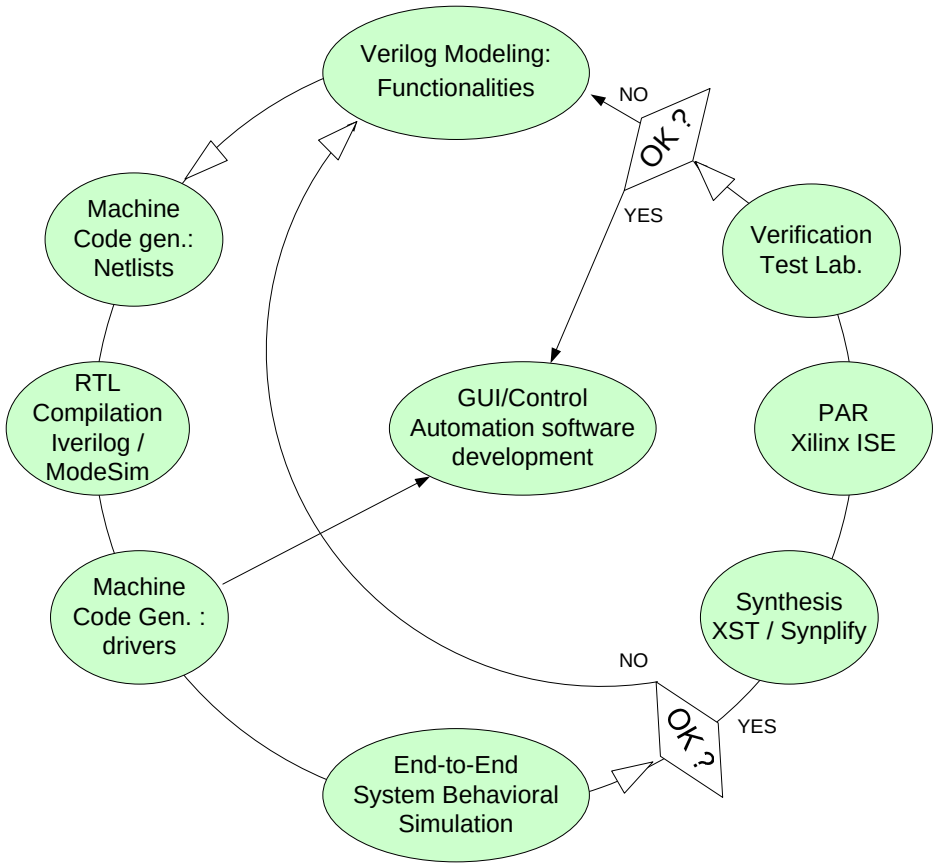
$$\left\{\mathbf{K_p} \cdot \left(\mathbf{1} + \sum_{n=0}^{N} a_n \cdot \mathbf{Z}^{-n}\right)\right\}$$

SNS Linac RF Control – implementations

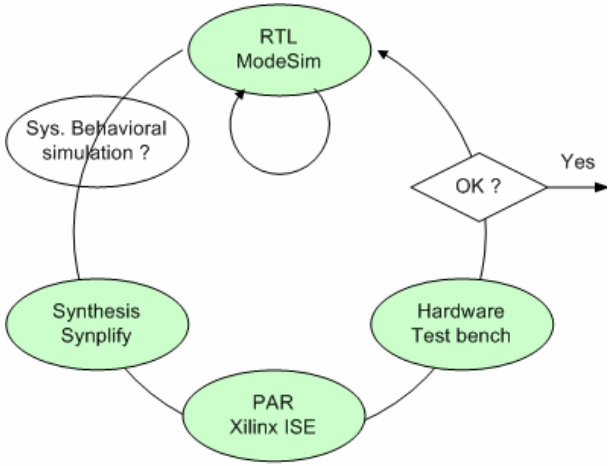
Digital implementation: data flow



Digital implementation: Development system



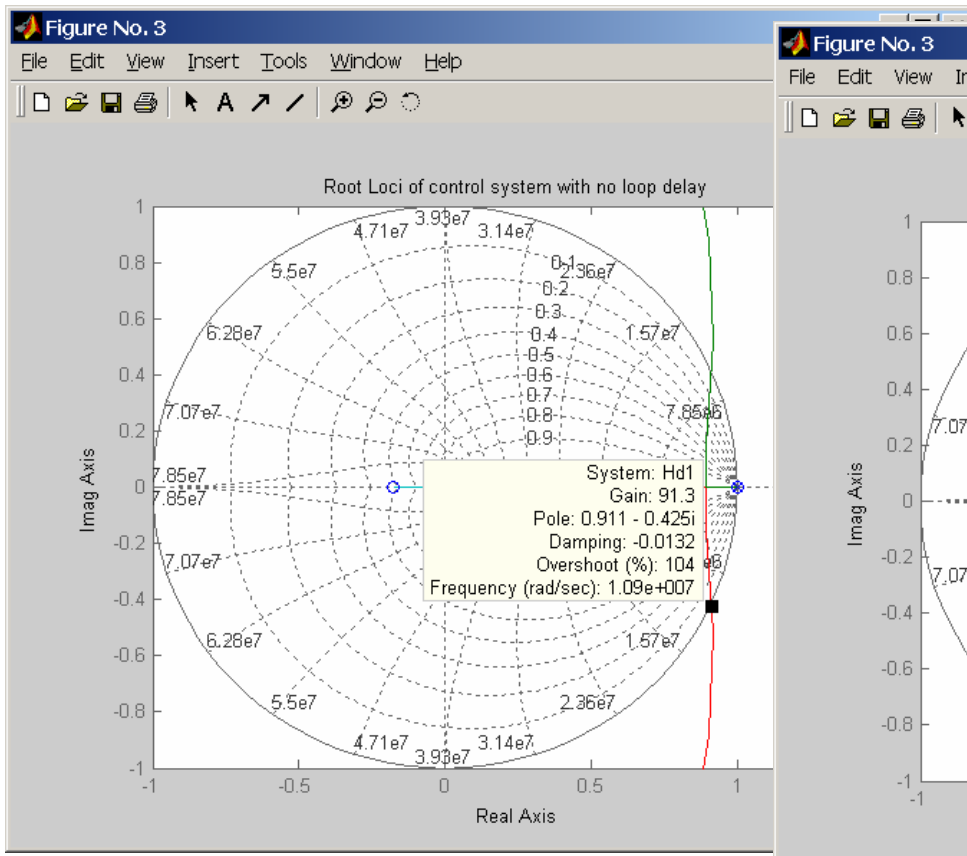
current llc system

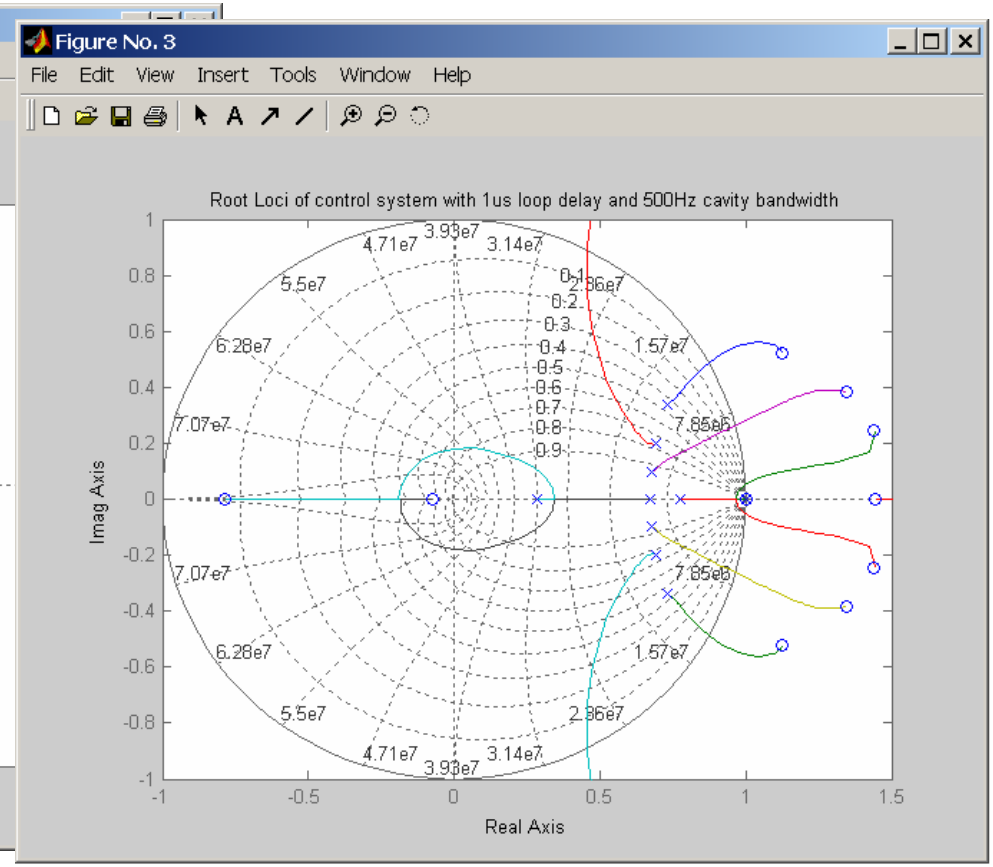


Previous VHDL flow

Controller Performance: Stability

Effect of loop delay





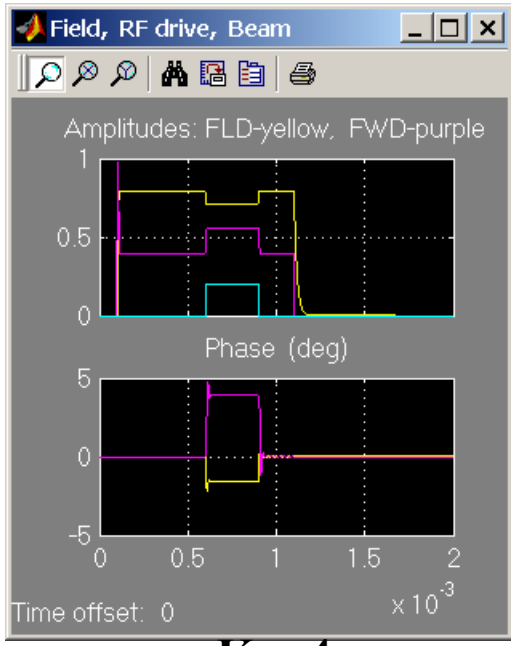
With no loop delay **With 1us loop delay**

SNS Linac RF Control – implementations

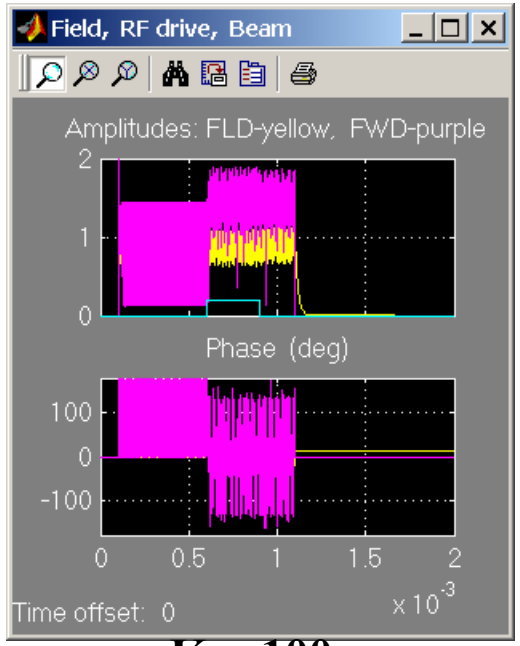
Controller performance: Steady-state error

Constraints between control gain, stability and steady-state error.

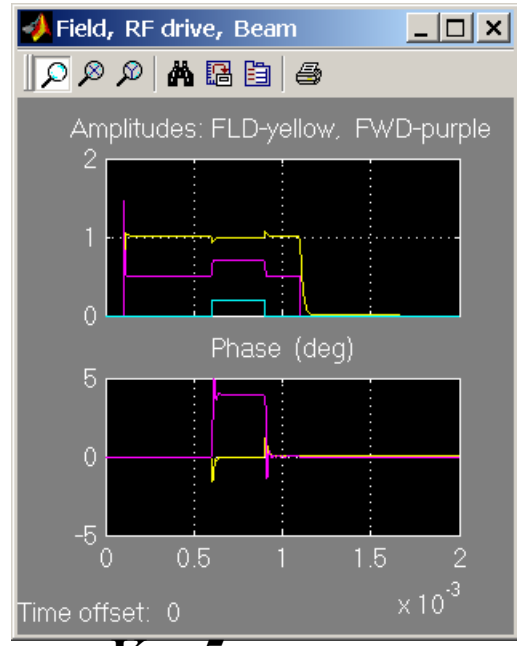
Example 1: 1us delay, cavity BW=10kHz (NC)



Kp=4,
Ki=0
stable
Er=20%



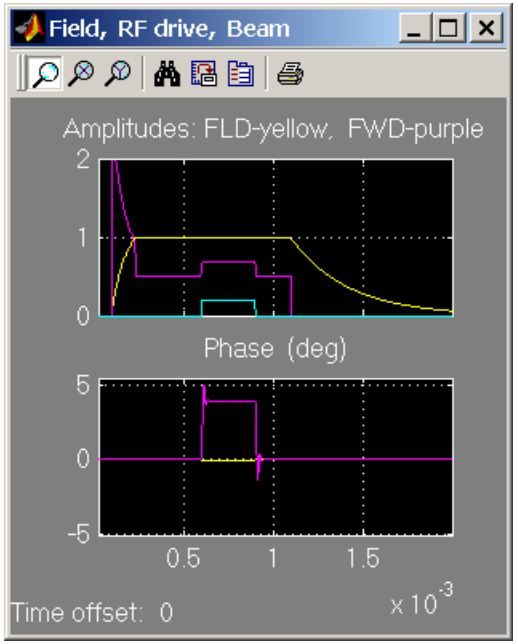
Kp=100
Ki=0
unstable

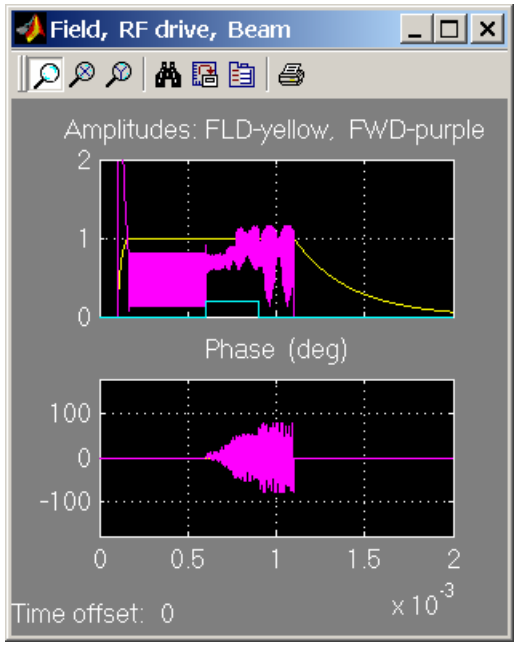


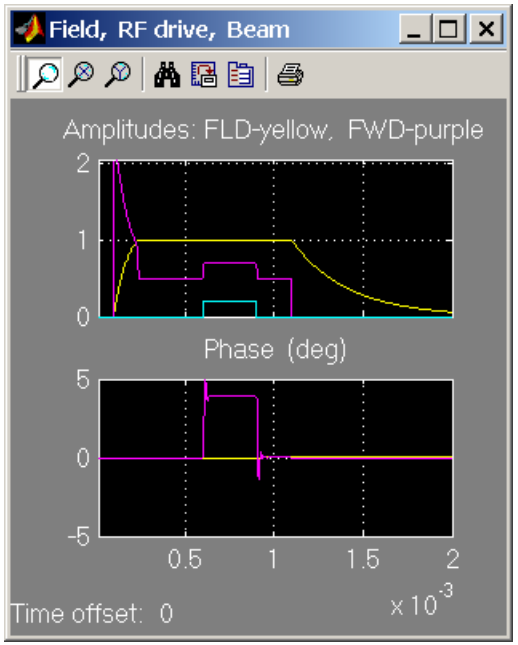
Kp=5
Ki/Ts=10kHz
stable
Error=0

Controller performance: Steady-state error

Example 2: 1us delay, cavity BW=500Hz (SC)







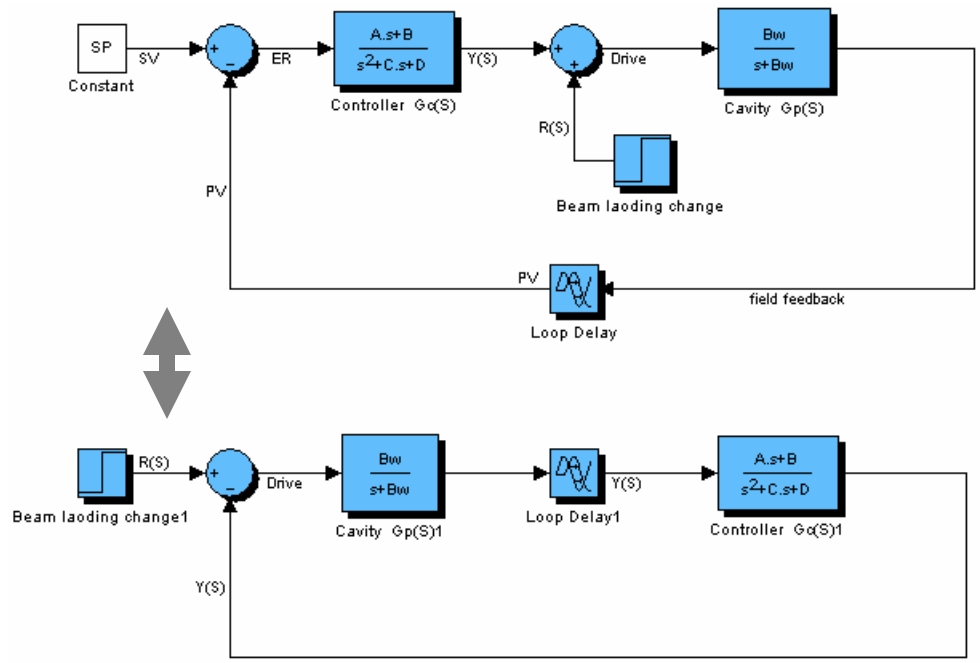
Kp=100,
Ki=0
stable
Er=1%

Kp=400
Ki=0
unstable

Kp=100
Ki/Ts=150Hz
stable
Error=0

Controller performance: Transient response

Exam the response of a P-I controller to a step disturbance (beam loading) at the input of the plant (cavity).

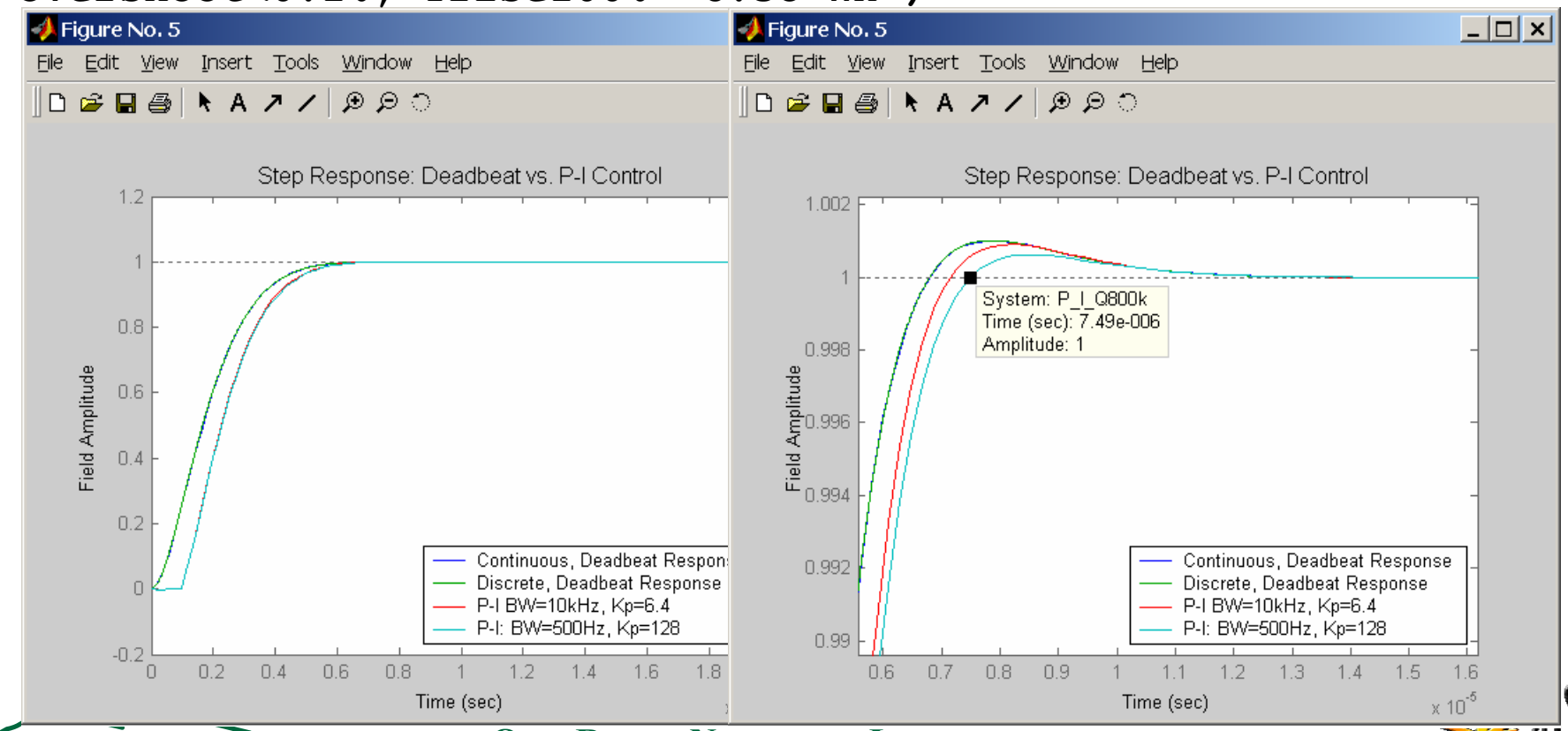


Rearrange so that the disturbance Becomes the input.

Controller performance: Transient response

Comparison: P-I control (dipole tune, delay=1us) vs. performance benchmark : a 2nd-order deadbeat tune,

(Ts=5us, Wn*Ts =4.82, alpha = 1.82, undershoot 0%, overshoot<0.1%, Trise100% =6.58*Wn)



SNS Linac RF Control – implementations

Basic cavity model:

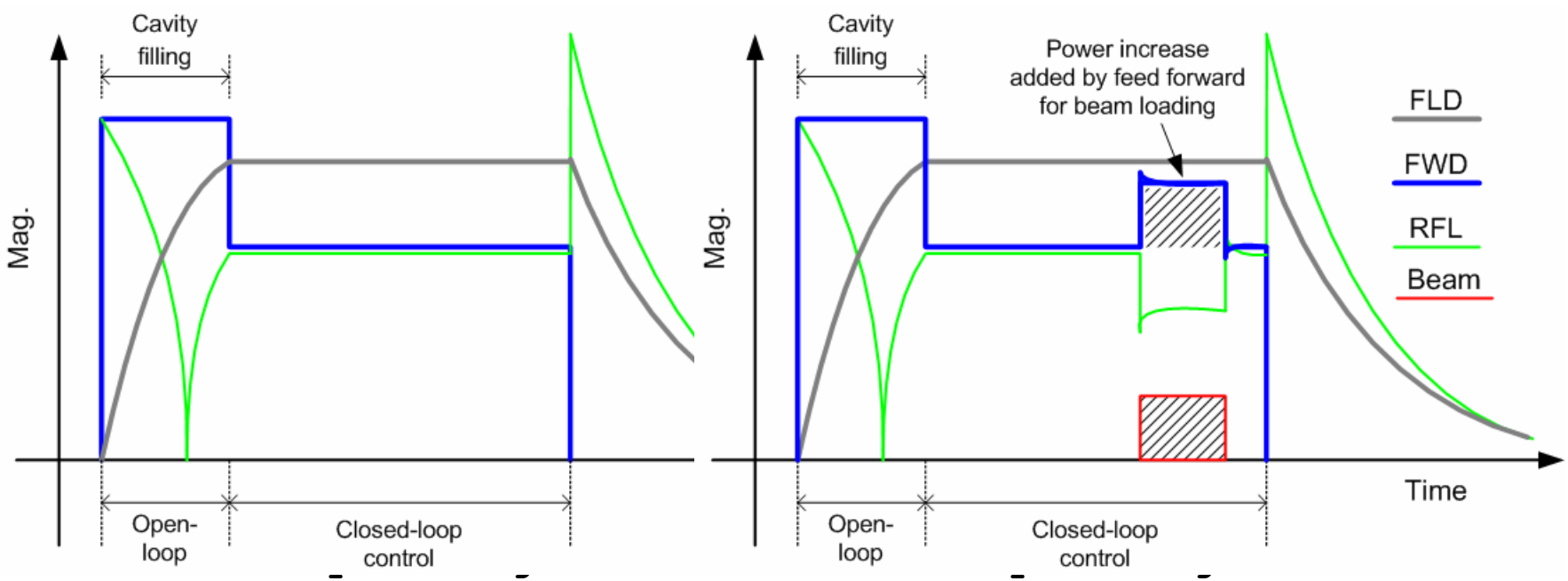
$$\begin{bmatrix} \omega_{1/2} & -\Delta\omega \\ \Delta\omega & \omega_{1/2} \end{bmatrix} \cdot \begin{bmatrix} V_r \\ V_i \end{bmatrix} = \omega_{1/2} \cdot R_L \cdot \begin{bmatrix} I_r \\ I_i \end{bmatrix}$$

Is it reasonable to use a simplistic P-I controller of LTI design in a nonlinear application ?

Yes, provided in a linearized operating condition.

SNS Linac RF Control – implementations

Operating feedback control with assistance of cavity filling and adaptive feedforward.



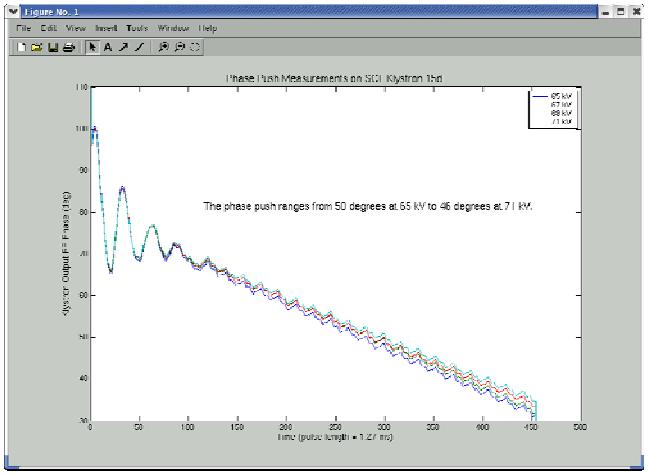
(with no beam) **(with beam)**

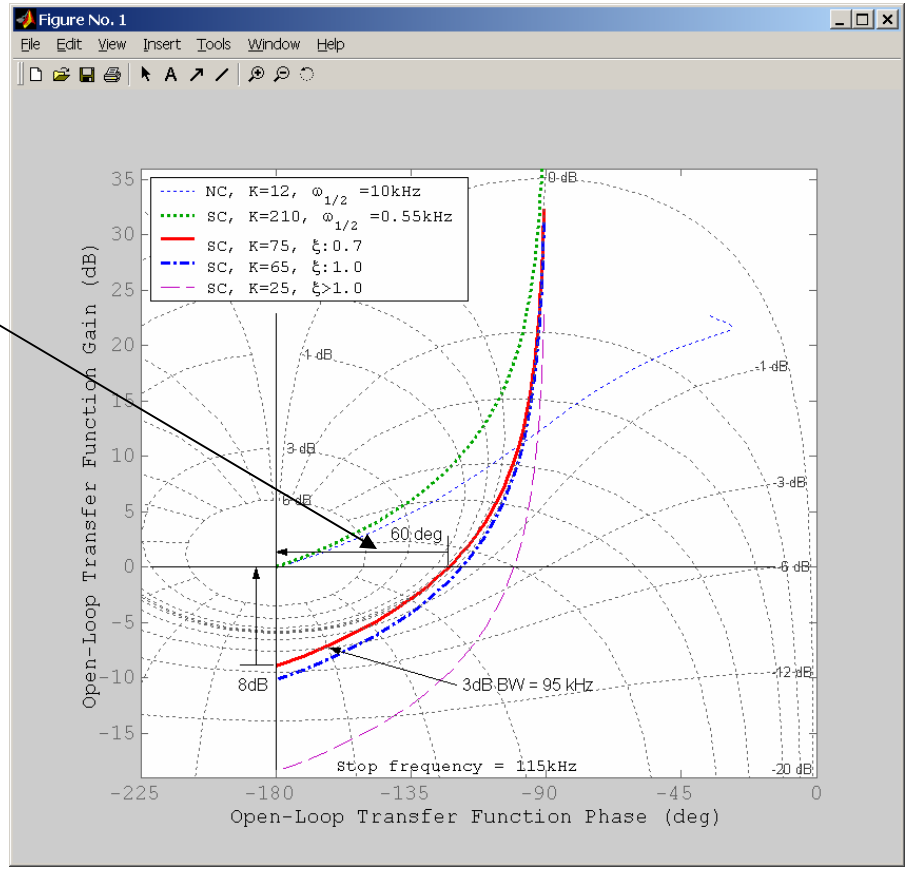
SNS Linac RF Control – implementations

The Issue of loop phase change in system

LFD and Klystron phase change

Availability of 60 degree phase margin under LTI assumption

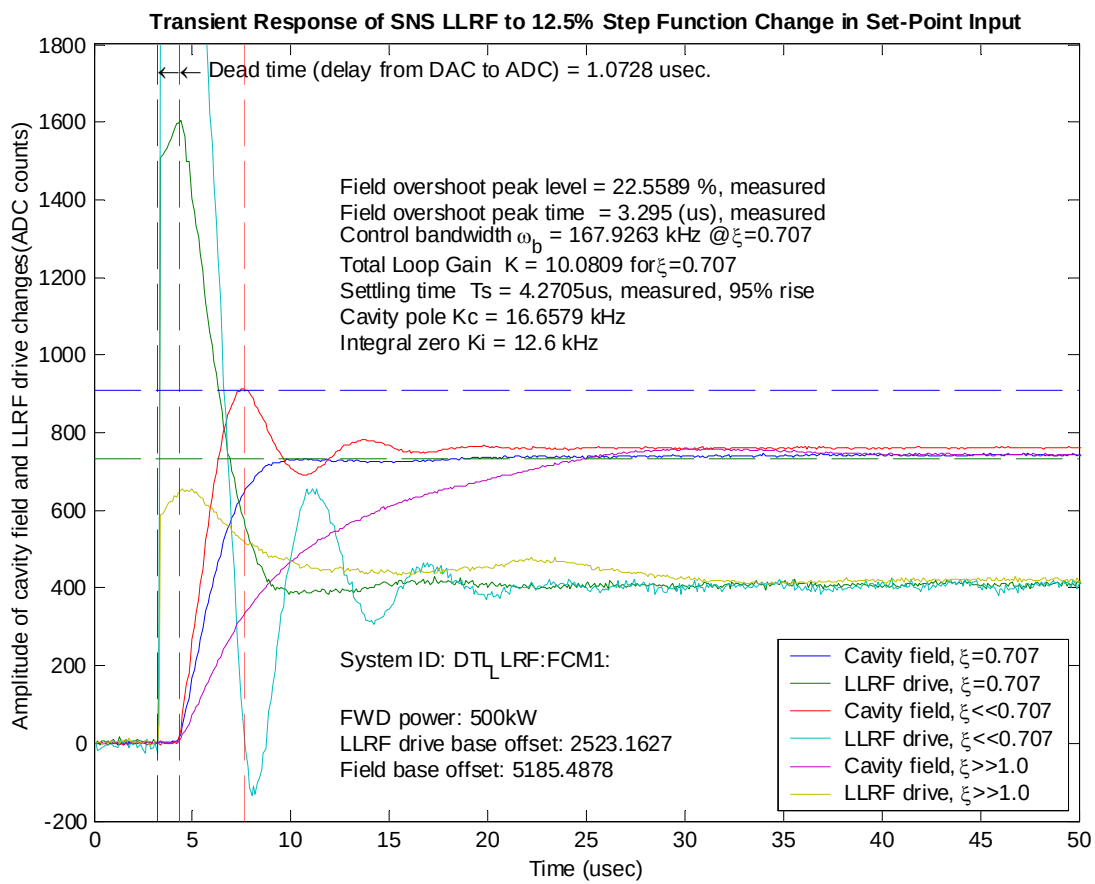




SNS Linac RF Control – Some test and operation results

Control Bandwidth measurement:

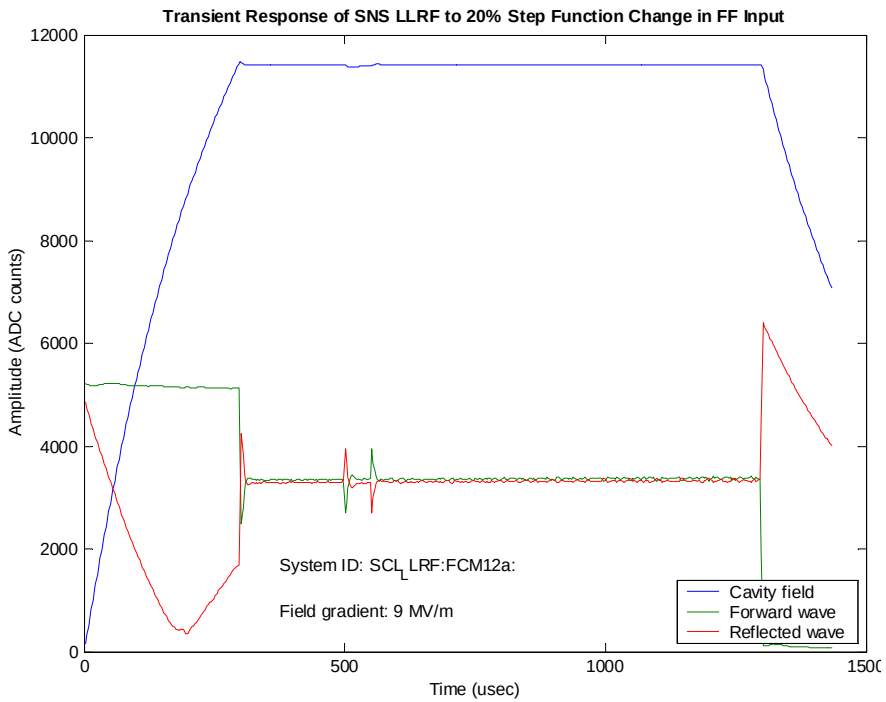
By the step response (set-point as the input)

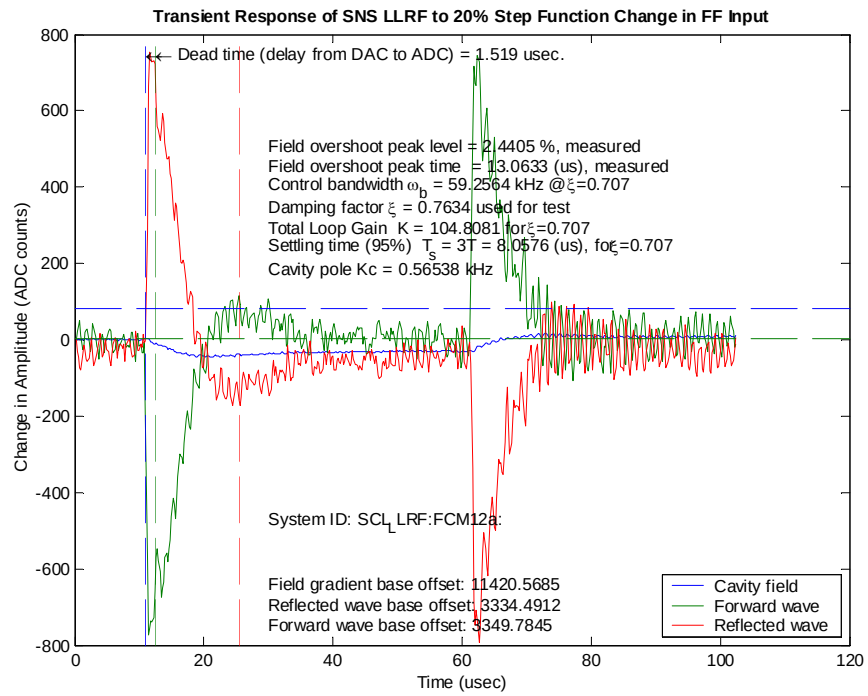


SNS Linac RF Control – Some test and operation results

Control Bandwidth Measurement:

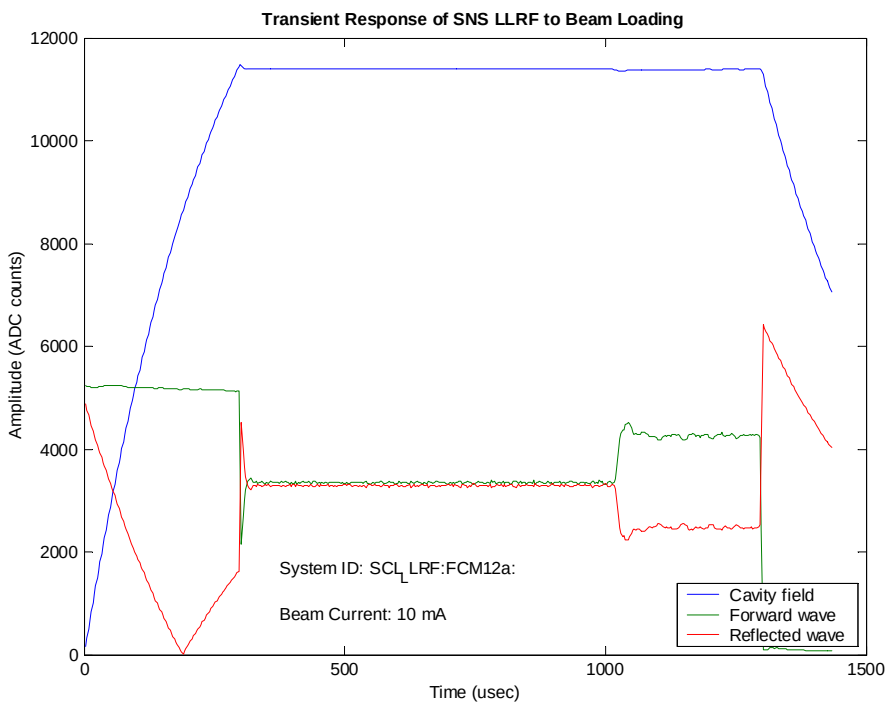
By transient response to a step in FF waveform.

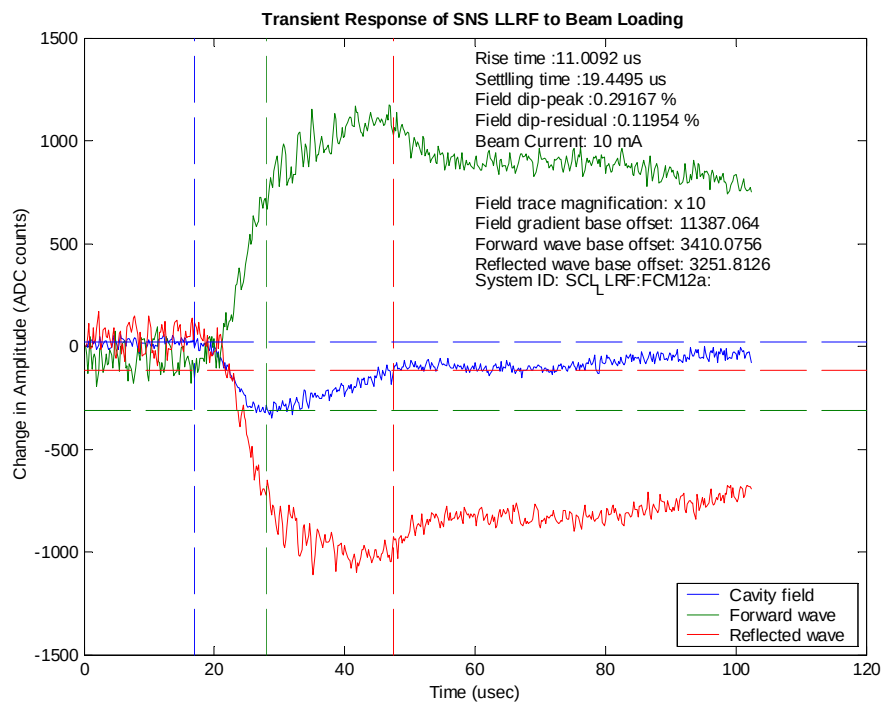




SNS Linac RF Control – Some test and operation results

Transient Response to Beam Loading

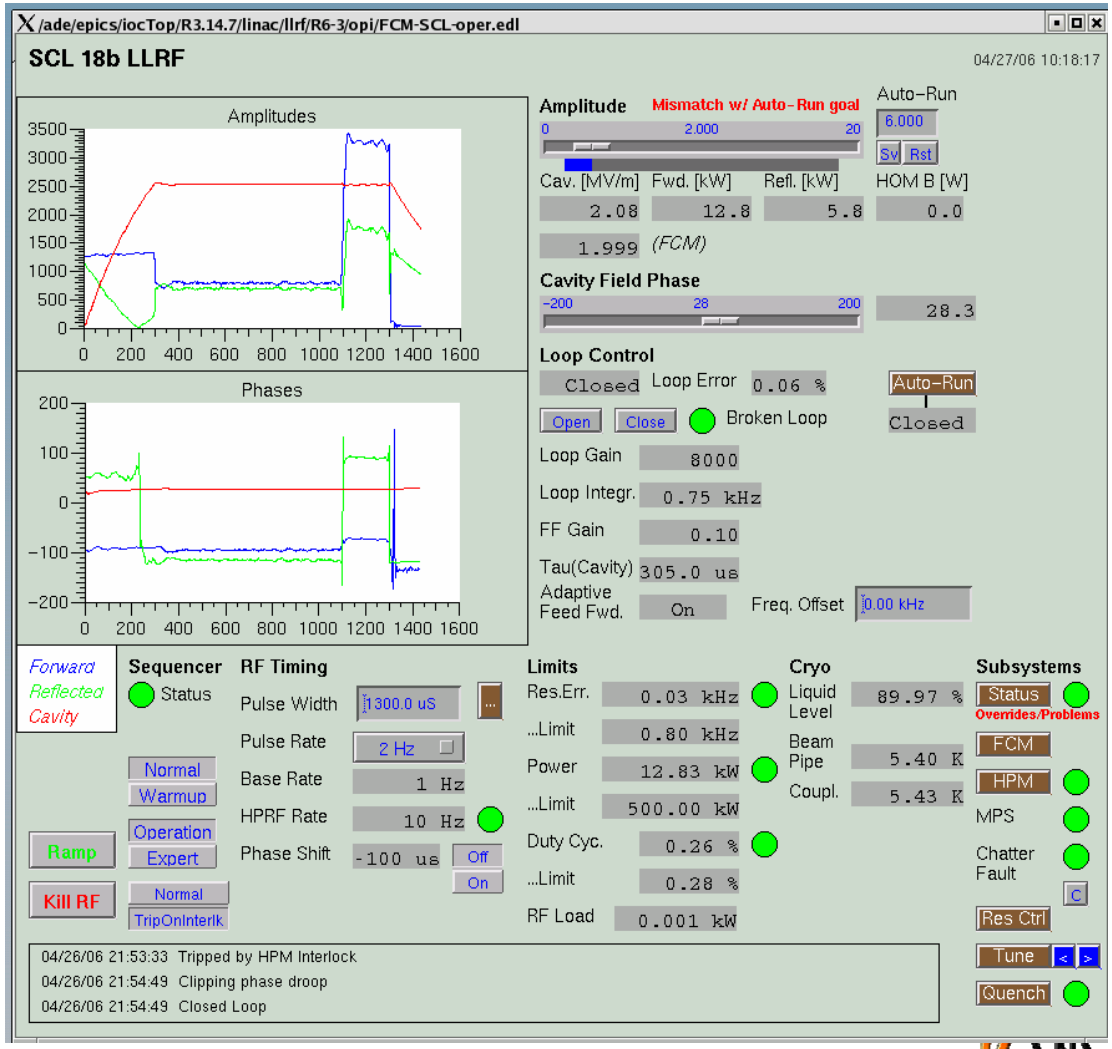




SNS Linac RF Control – Some test and operation results

A demo of FCM's stability and dynamic range

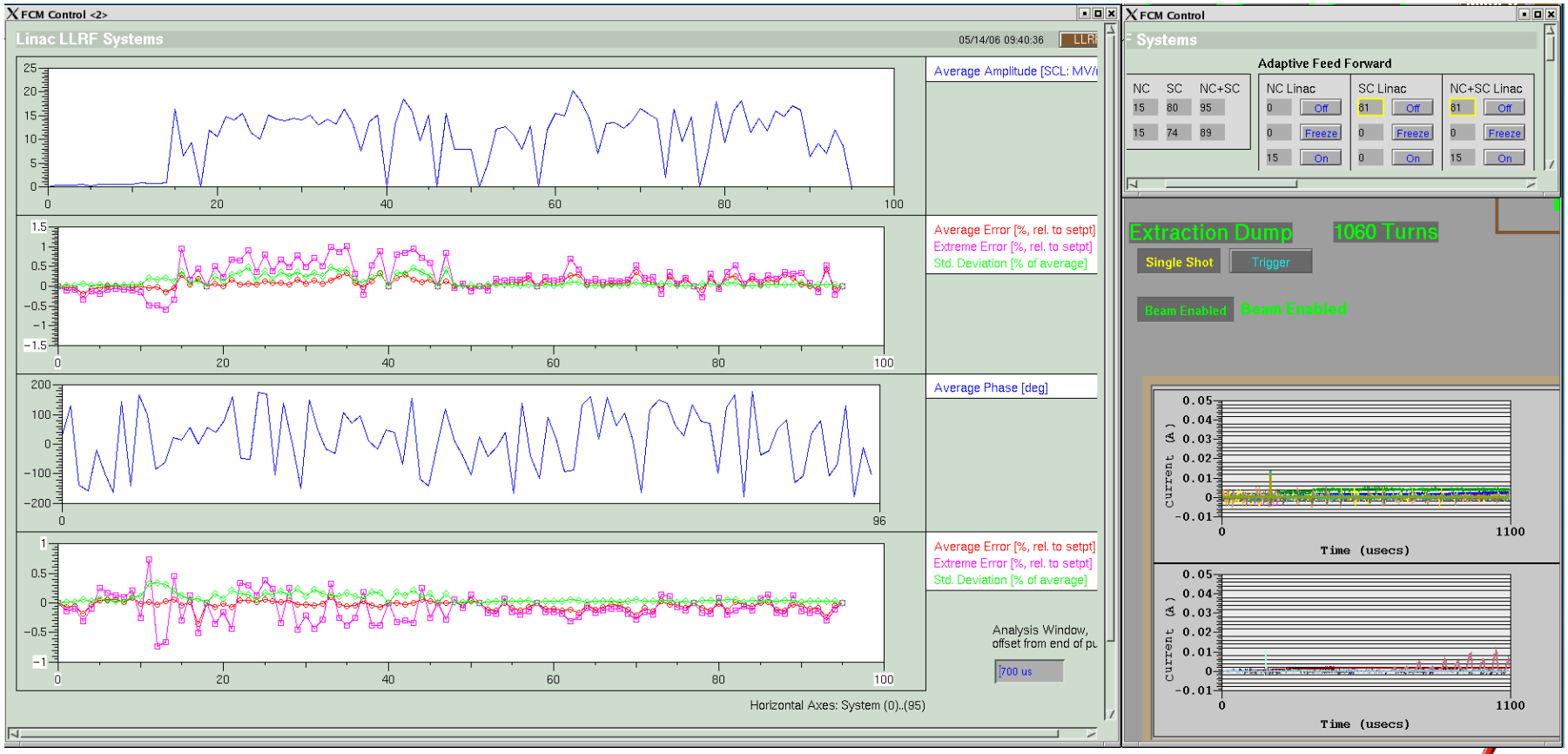
- Operating point: 2M V/m (13% of the nominal value)
- Relatively heavy beam loading, >900% rf power increase.



SNS Linac RF Control – Some test and operation results

A snapshot of RF errors throughout Linac

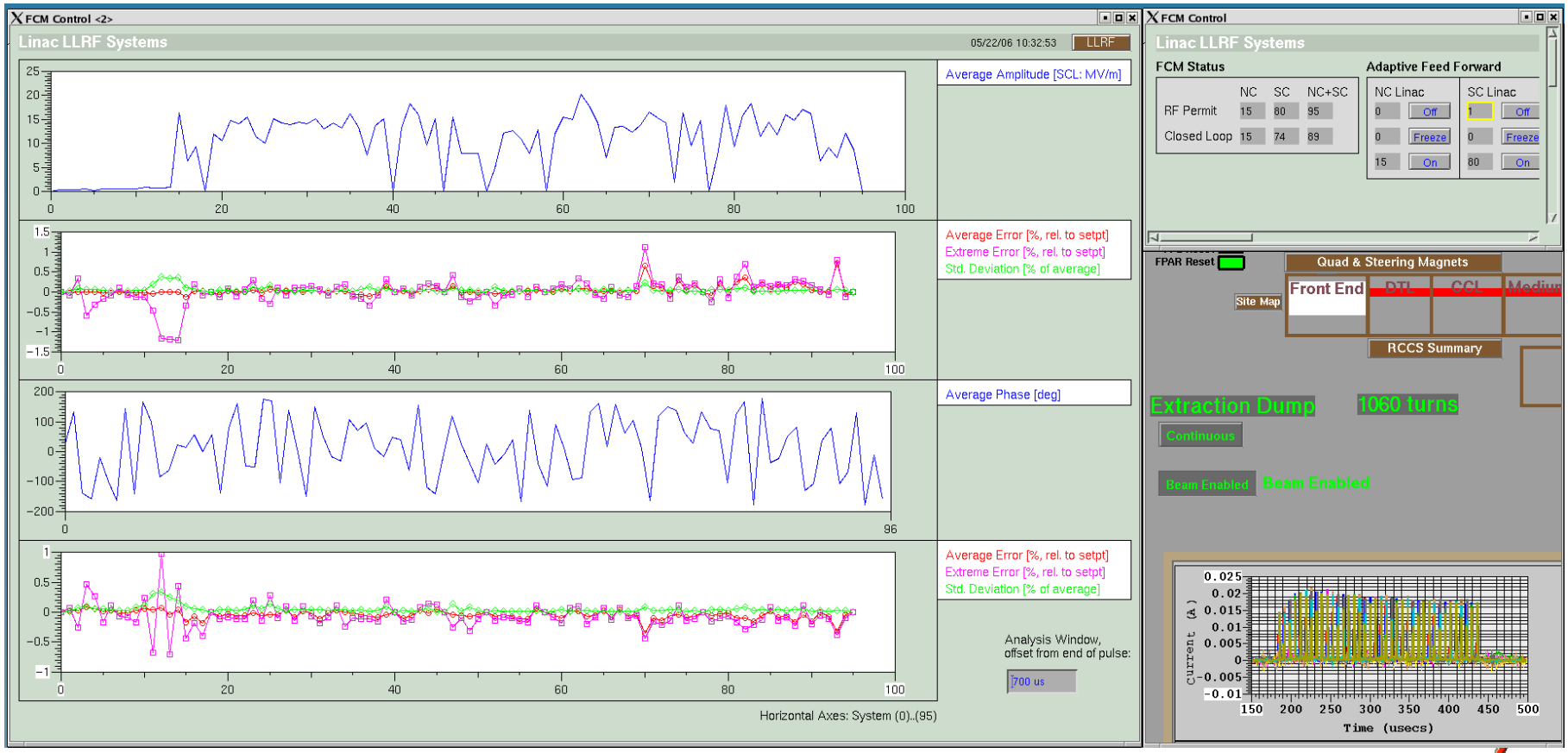
No beam, AFF turned off, field error is maintained under 1%, 1 deg.



SNS Linac RF Control – Some test and operation results

A snapshot of RF errors throughout Linac

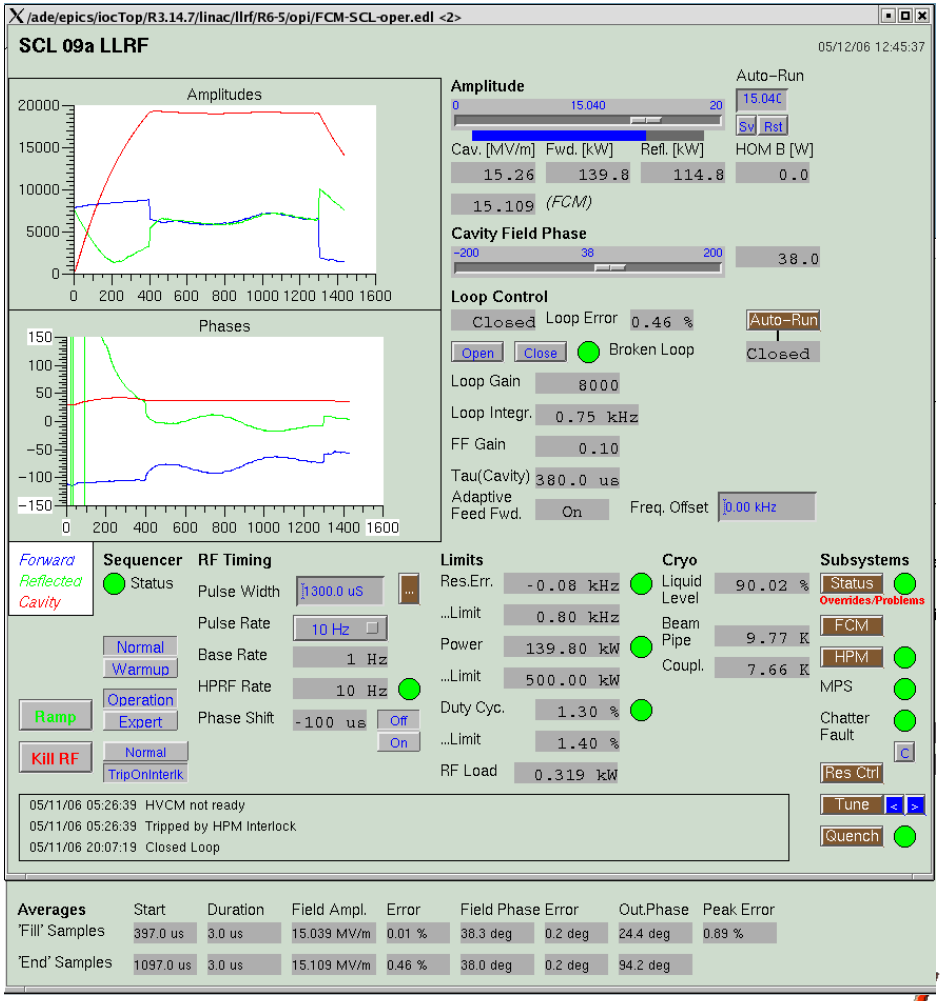
With 25mA beam, AFF turned ON, the RF control is still able to keep the field error under 1%, 1 deg.



SNS Linac RF Control – Some observations

Interaction between rf and cavity vibrations

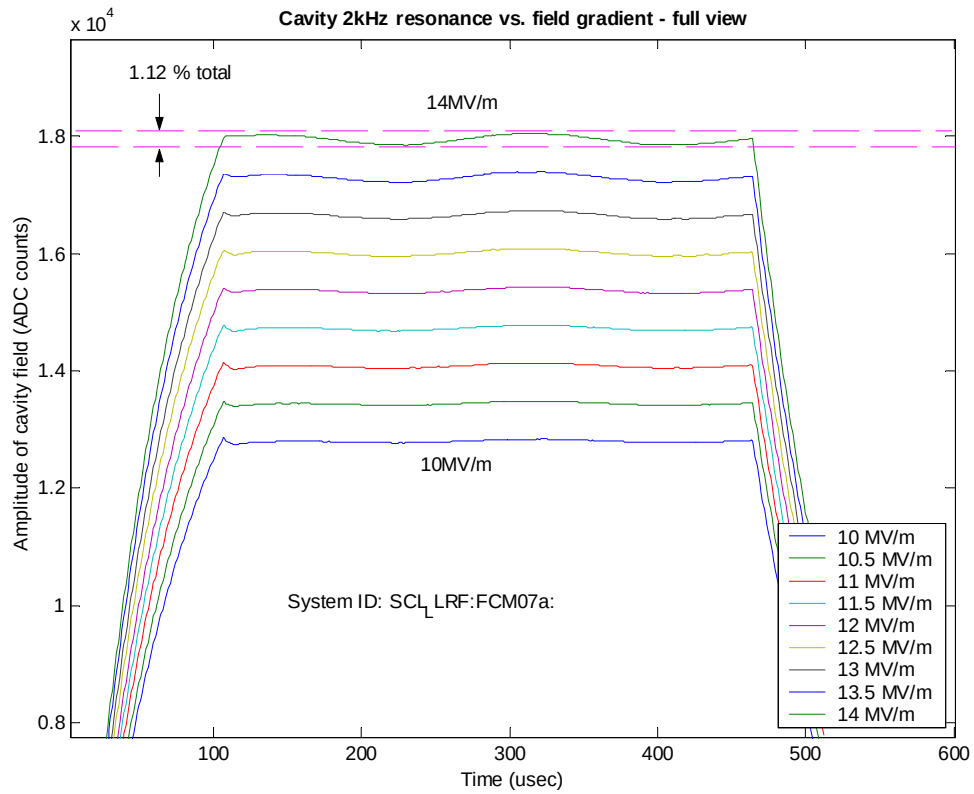
A resonance of ~2kHz has being seen on many medium-beta cavities, which has created some difficulty to the rf control, mainly in the choice between the control error and gain setting.



SNS Linac RF Control – Some observations

Interaction between rf and cavity vibrations

The magnitude of the resonance grows as the gradient increase.



SNS Linac RF Control – Some observations

Interaction between rf and cavity vibrations

Measured Lorentz force detuning of all running cavities

- ***The 2kHz oscillating shows up on all MB cavities, but not HB ones.***
- ***The peak of LFD is only one half of the cavity BW.***

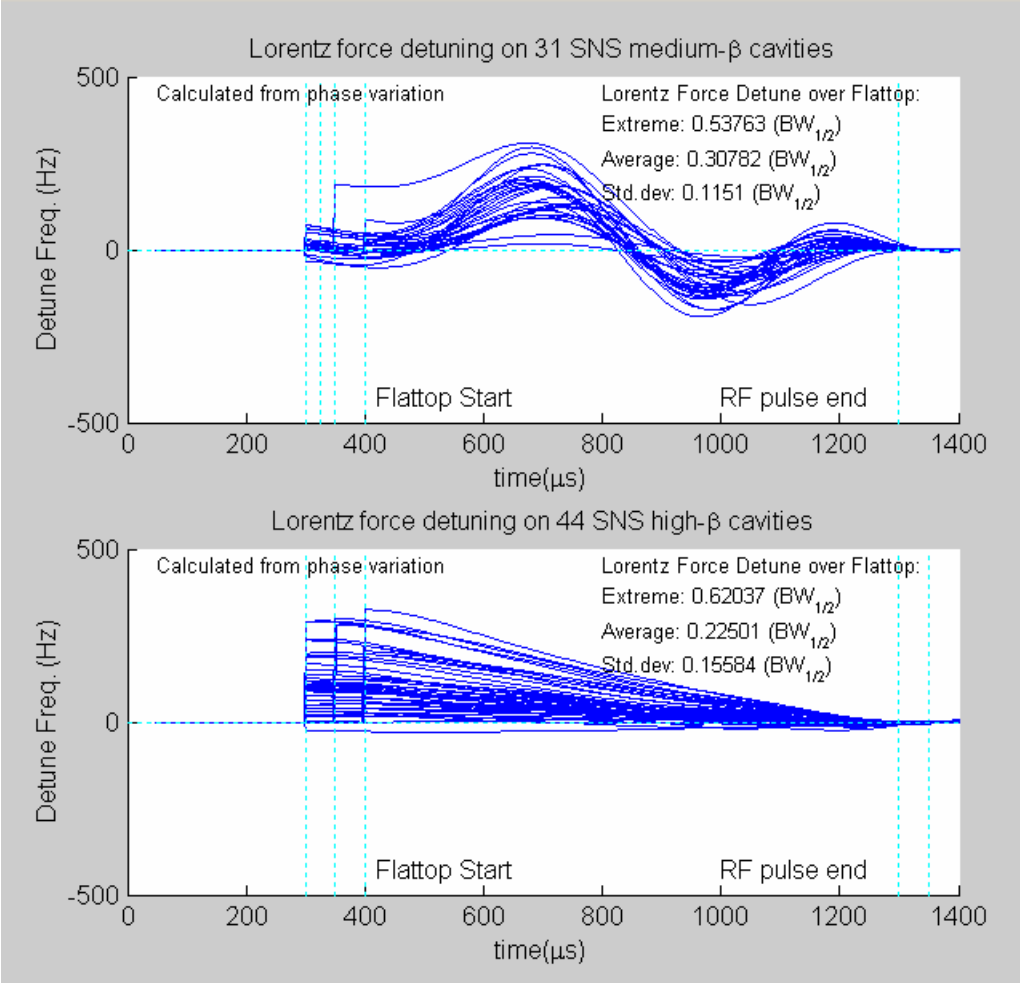
(Calculation using

$$\dot{\mathbf{x}} + \left(\omega_{1/2} - \mathbf{j}\cdot\Delta\omega\right)\cdot\mathbf{x} = \omega_{1/2}\cdot\mathbf{y}$$

$$r\dot{\Phi} - r\cdot\Delta\omega = \omega_{1/2}\cdot\rho\cdot\sin\left(\Psi - \Phi\right)$$

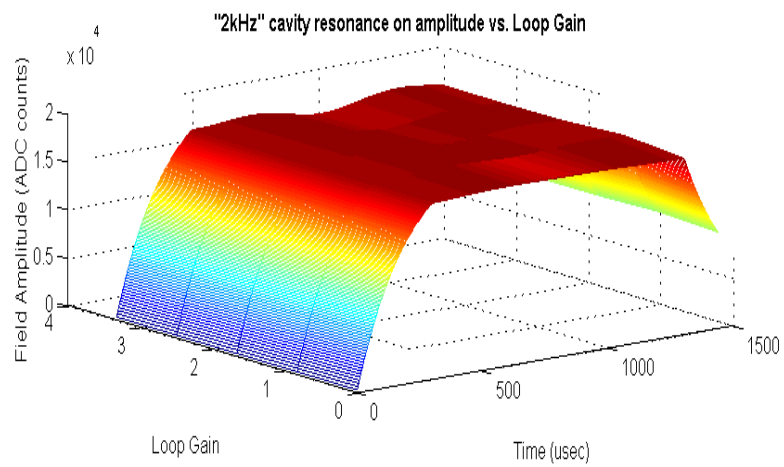
$$\dot{r} - r\cdot\omega_{1/2} = \omega_{1/2}\cdot\rho\cdot\sin\left(\Psi - \Phi\right)$$

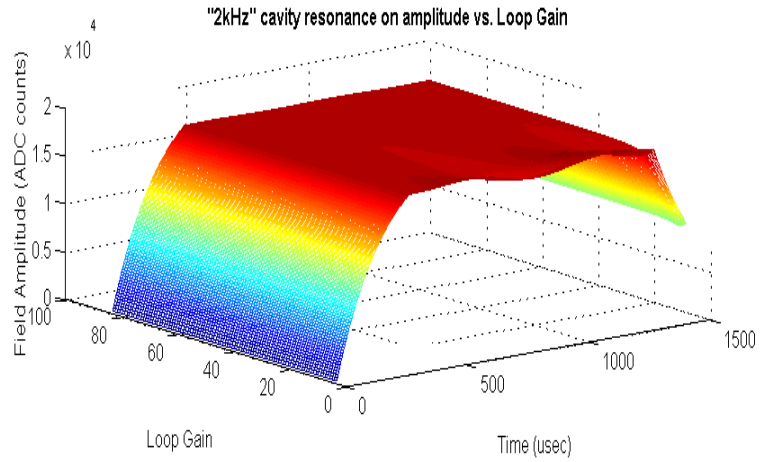
in closed-loop control condition.)

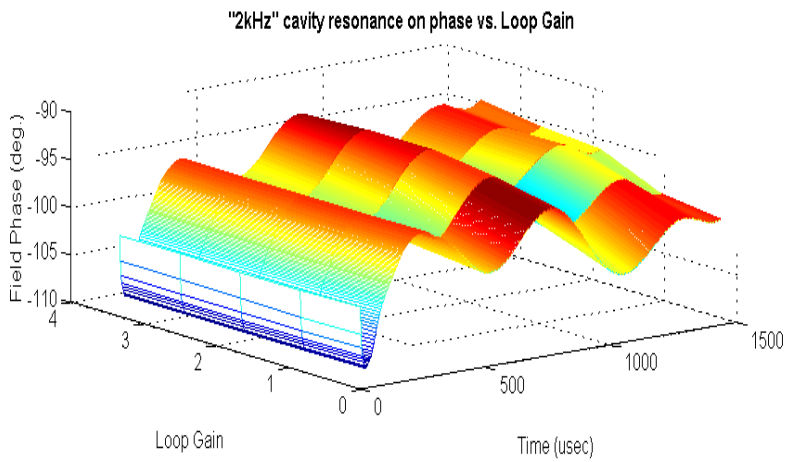


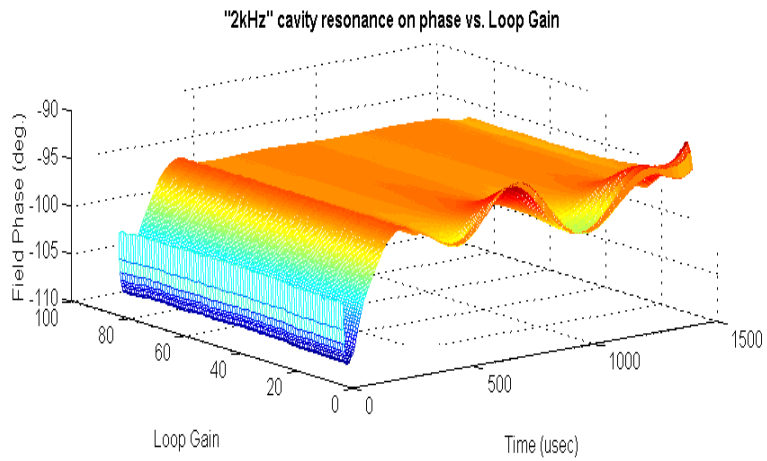
SNS Linac RF Control – Some observations

Interaction between rf feedback control and 2kHz resonance. Oscillation coupled from phase to amplitude.



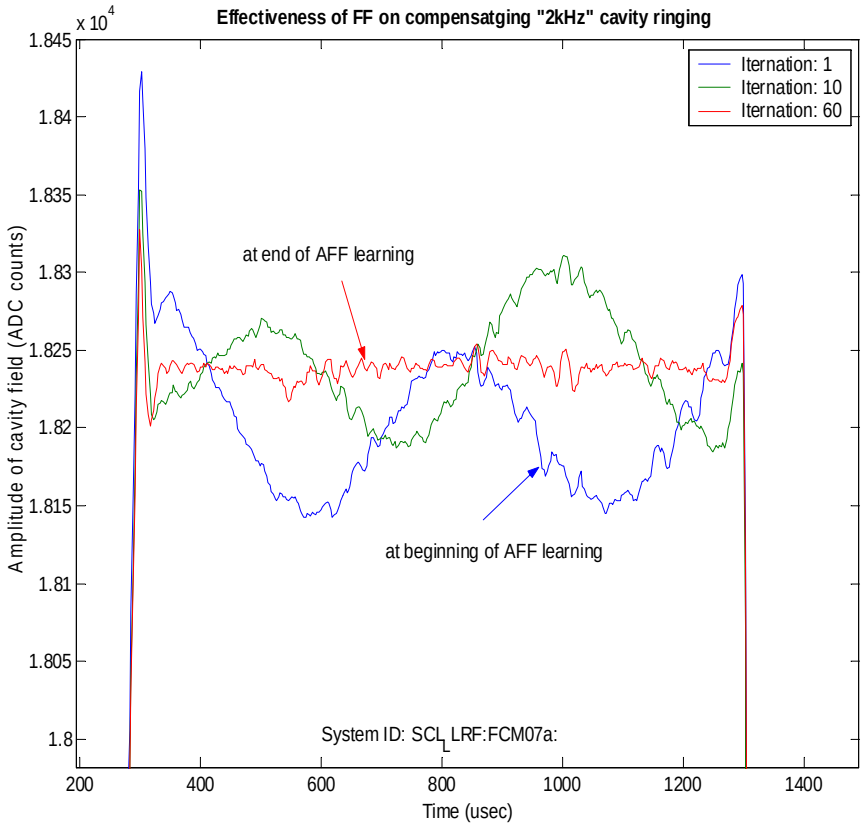






SNS Linac RF Control – Some observations

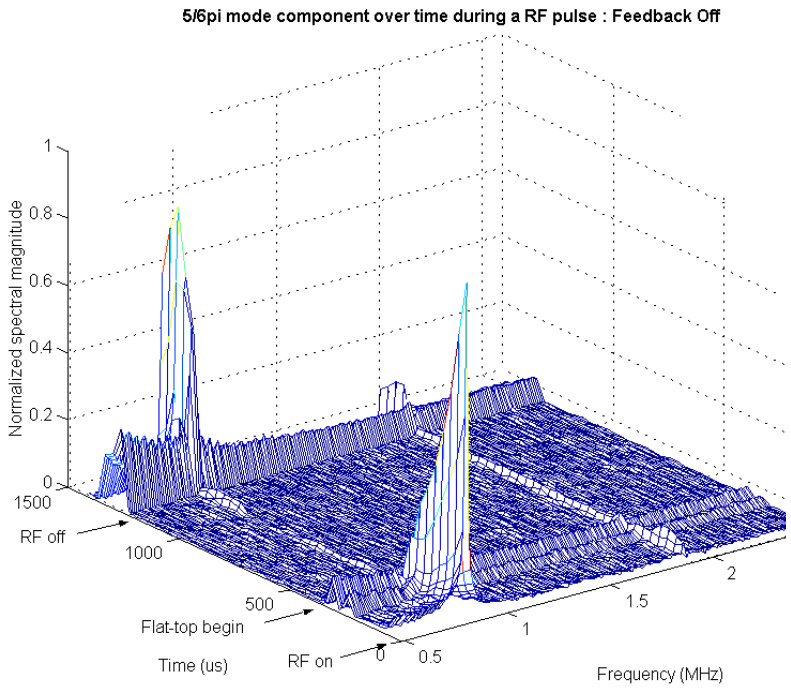
Adaptive feed forward control not only compensates the beam loading, but also effectively damps the 2kHz resonance.



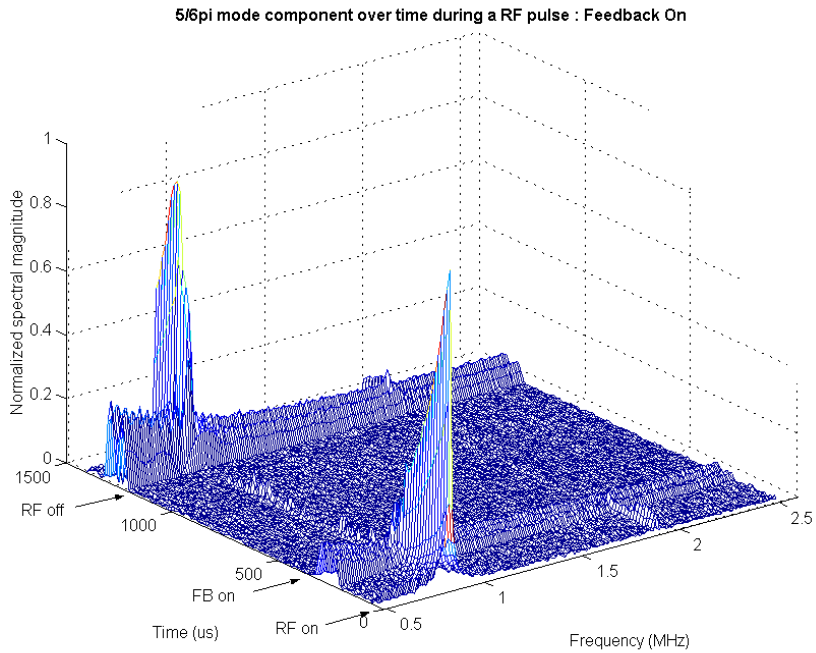
SNS Linac RF Control – Some observations

5/6π mode sideband excitation

Exists in both open-loop and closed-loop control condition, but is contained. Normally, the peak magnitude is under 3% of the field level.



Feedback OFF



Feedback ON

SNS Linac RF Control – Issues and improvements

Issues & Improvements

- Control stability
- Cavity filling schemes
- Feed forward algorithms.

SNS Linac RF Control – Summary

- System performed well and met the needs during the commissioning and recent operation runs.
- Hardware platform has flexibility and capacity to allow further expansions.
- Strong software support has offered ease and convenience of operations.
- Further development is necessary in the aforementioned areas.

SNS LLRF project is a collaborative effort among ORNL, LBNL, and LANL.

Power Upgrade Project

Power Upgrade Project requires increased RF power
- 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 requires
→ more cryomodules

Additional beam loading requires
→ increased RF power everywhere

Design Goal
- maximize re-use of existing systems
- maintain compatibility with existing systems

SNS Linac RF Control – Looking ahead

Power Upgrade Project

- The RF Systems Upgrades include:
- Installation of 36 additional Linac RF stations
- Installation of 2 HEBT RF stations including cavities
- Upgrades to 4 existing Ring RF stations

SNS Linac RF Control – Looking ahead

Power Upgrade Project

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)

Milestones for RF Systems, Power Upgrade Project

Milestone	Early Dates
Begin design activities	Oct 06
Award klystron contract	Apr 08
Receive 1st klystron	Oct 08
Complete klystron installation	Oct 10
Award transmitter contract	Aug 08
Receive 1st transmitter	May 09
Complete transmitter installation	Feb 10
Begin waveguide installation	Apr 08
Complete waveguide installation	Mar 09
Begin HEBT RF system installation	Jun 08
Complete HEBT RF system installation	Dec 09
Award HEBT cavities contract	Feb 08
Begin HEBT cavities installation	Jun 09
Complete HEBT Cavities installation	Dec 09
Decide extent of Ring RF upgrade	Oct 08
Complete Ring RF upgrade	Oct 10
Commissioning	Mar 11