Characterization of SNS Low-Level RF System

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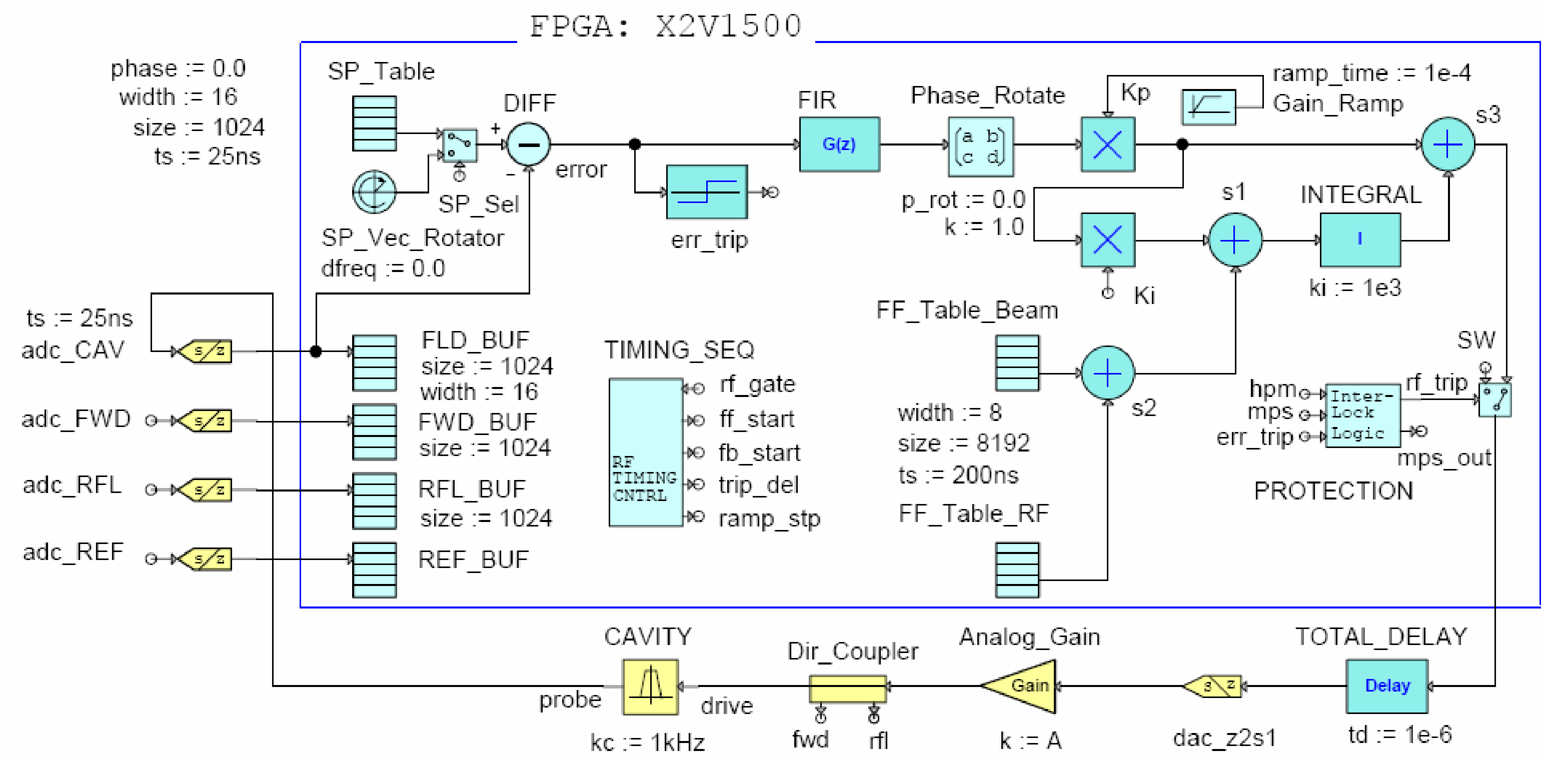
Oct. 10, 2005

- SNS LLRF digital hardware
- System characteristics – frequency / transient response
- Data buffer features - facilitate operations and R&D
- Mode of operations – RF turn-on/cavity filling

Current configuration



chip resources used: 50%

20% of logic slices,

30% of RAMBs, 50% of IOBs,

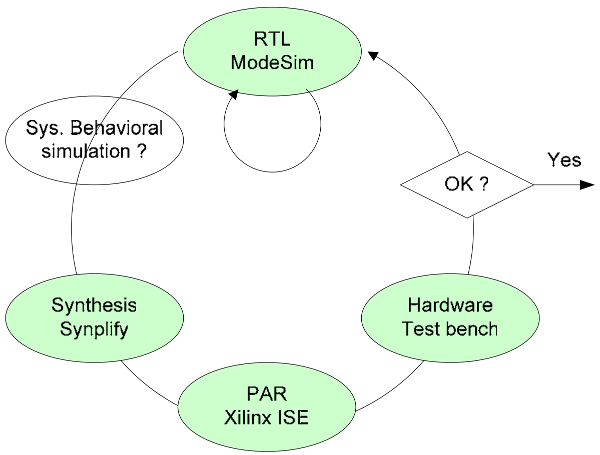
8% of multipliers

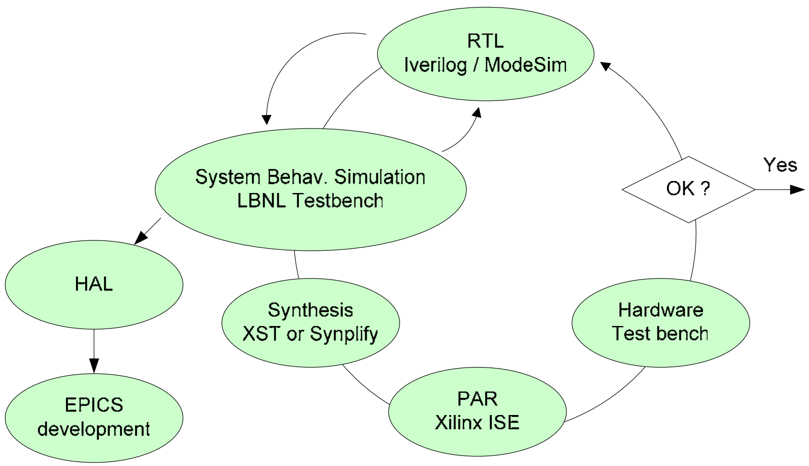
Previous VHDL tool-chain

- A manual process
- Lack of simulation at system level

Present Verilog tool-chain

- Automated code generation
- Integrated development process
- Behavioral simulation of system level





Frequency response

Type I , 2nd + order system

$$G(s) = A \cdot K_p \cdot K_c \cdot \frac{(s + K_i)}{s(s + K_c)} \cdot \frac{K_f}{s + K_f} \cdot \frac{K_k}{s + K_k} \cdot e^{-\tau s}$$

Constraints:

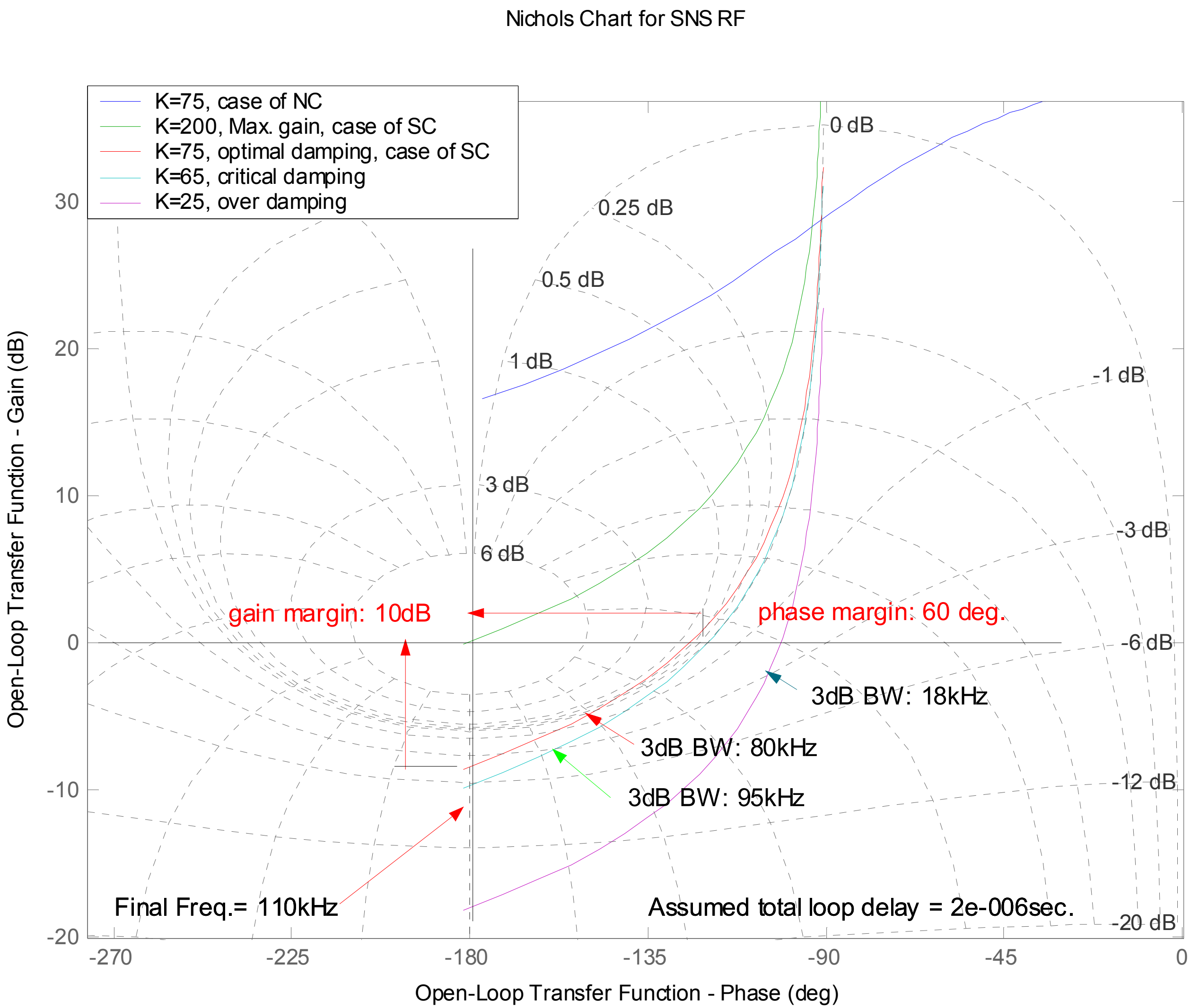
1. Loop delay

- Loop delay limits gain-bandwidth product : $A \cdot K_p \cdot K_c$
- Gain-bandwidth limits the maximum usable loop gain
- Loop gain affects system transient response and control error
- Loop delay term adds more poles and zeros to the system transfer function

2. Quantization errors

- Total loop gain comes mainly from the internal digital gain,
- Quantization error limits the maximum usable digital gain

SNS LLRF: System characteristics



Parameters:

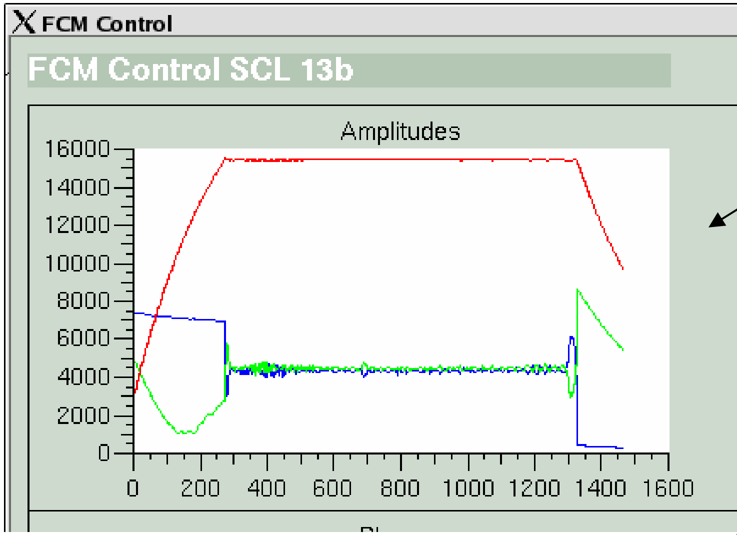
Cav. BW: 0.55kHz

BPF BW: 1MHz

Kly. BW: 1MHz

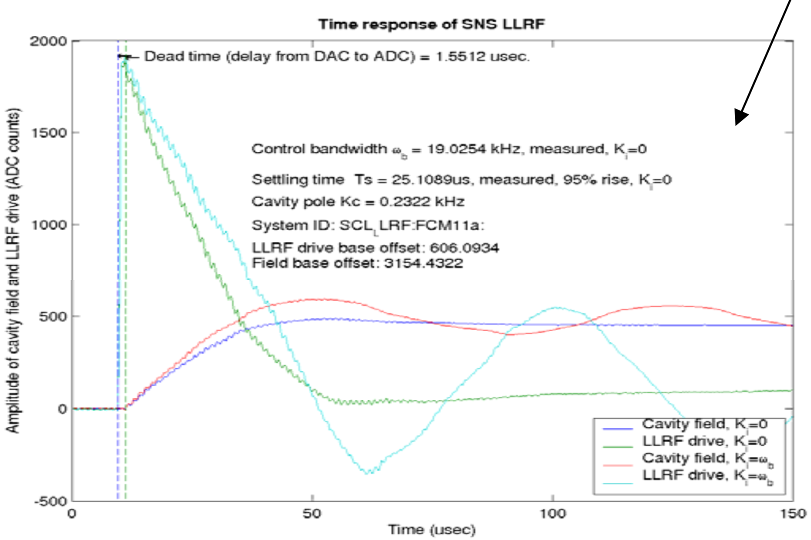
LP Delay: 2us

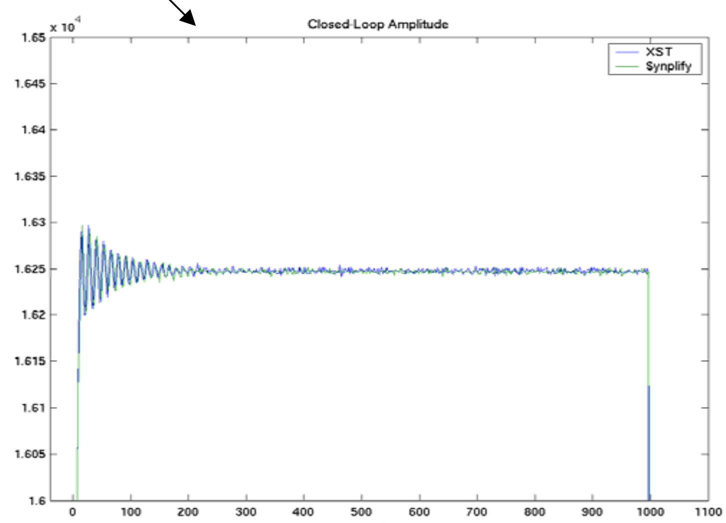
P-I control with integral zero matches cavity pole.



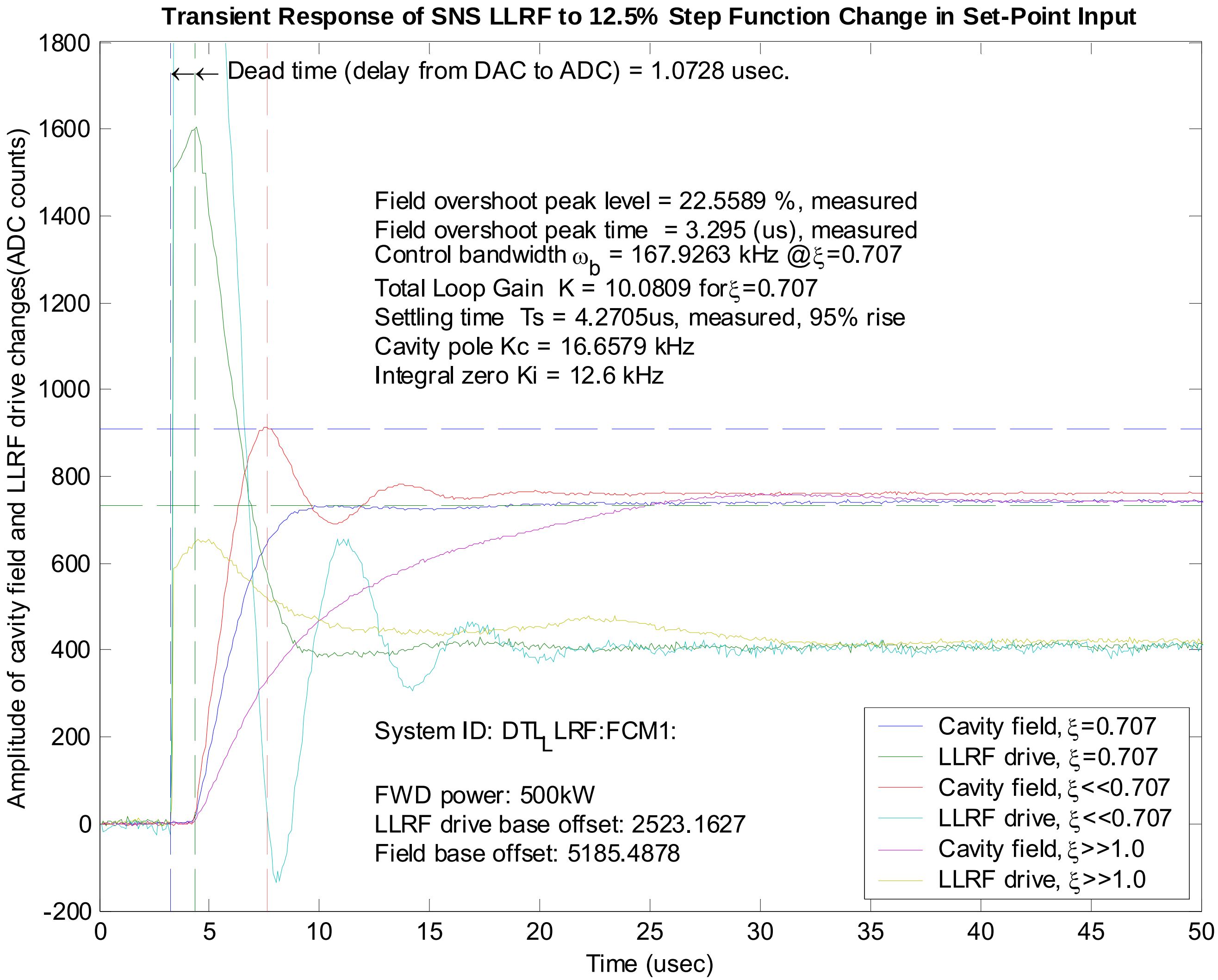
Examples:

- Digital gain <->amplified bit flicking in output - inherent
- Data scaling <->quantization error - mathematical /planning
- HDL synthesis – real life



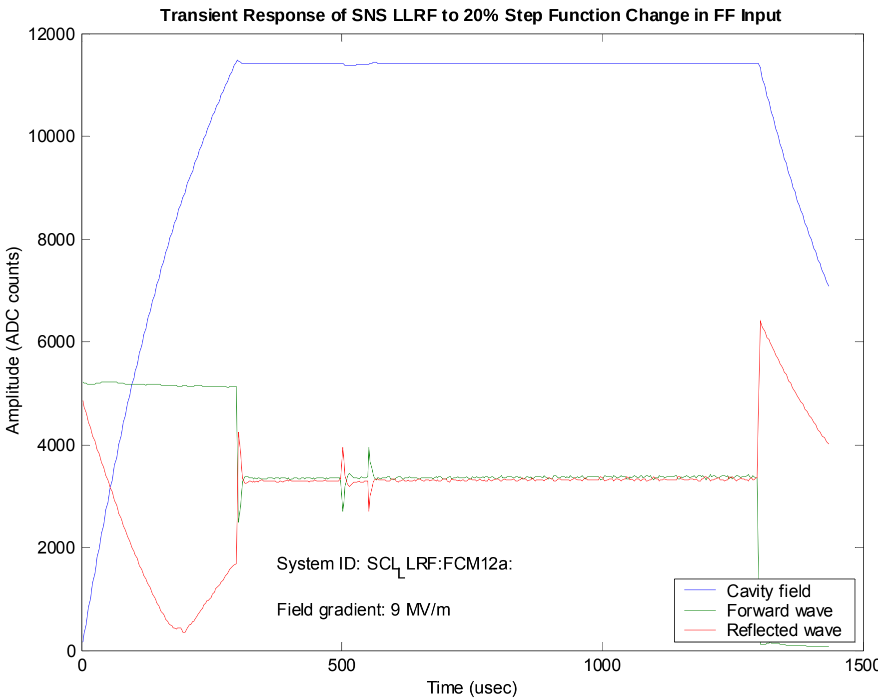


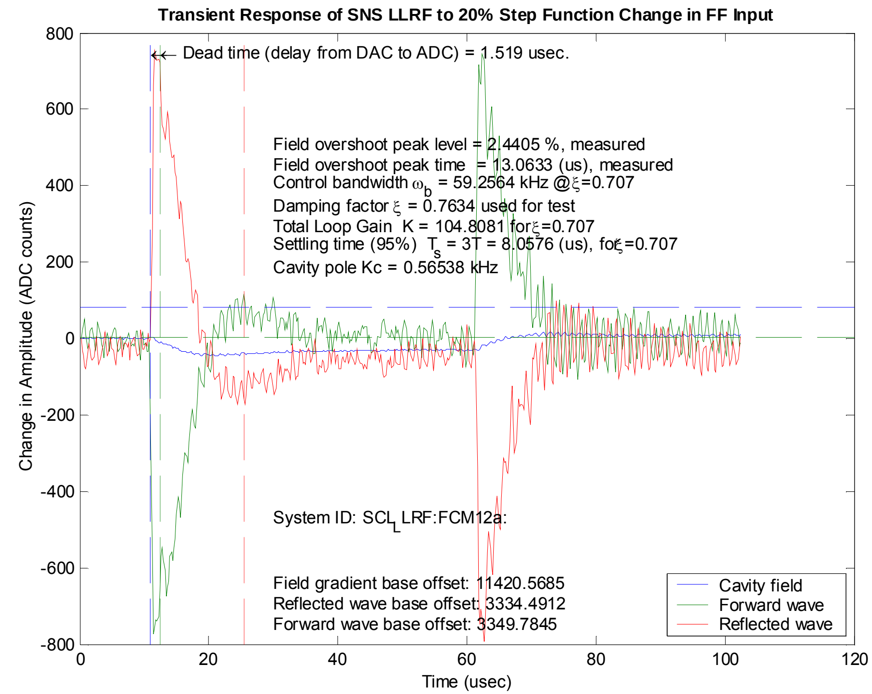
Transient response to step change – NC cavity



- 12.5% Step to SP input
- FWD PWR @ 500kW
- Cavity BW: 16.7kHz
- 3dB Cntrl BW: 167kHz
- Loop gain: 10

Transient response to test pulse - SC cavity

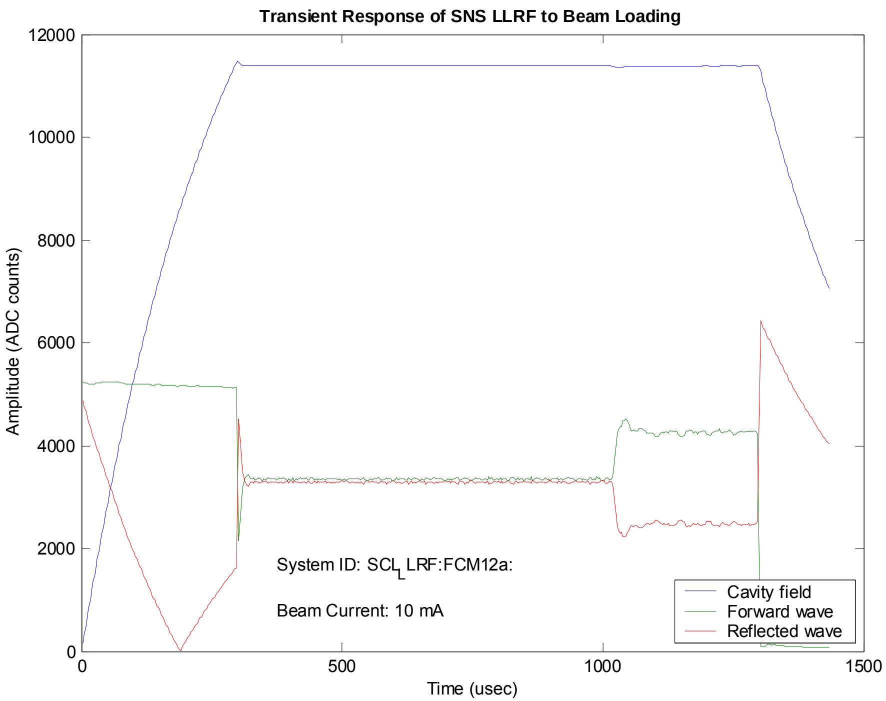


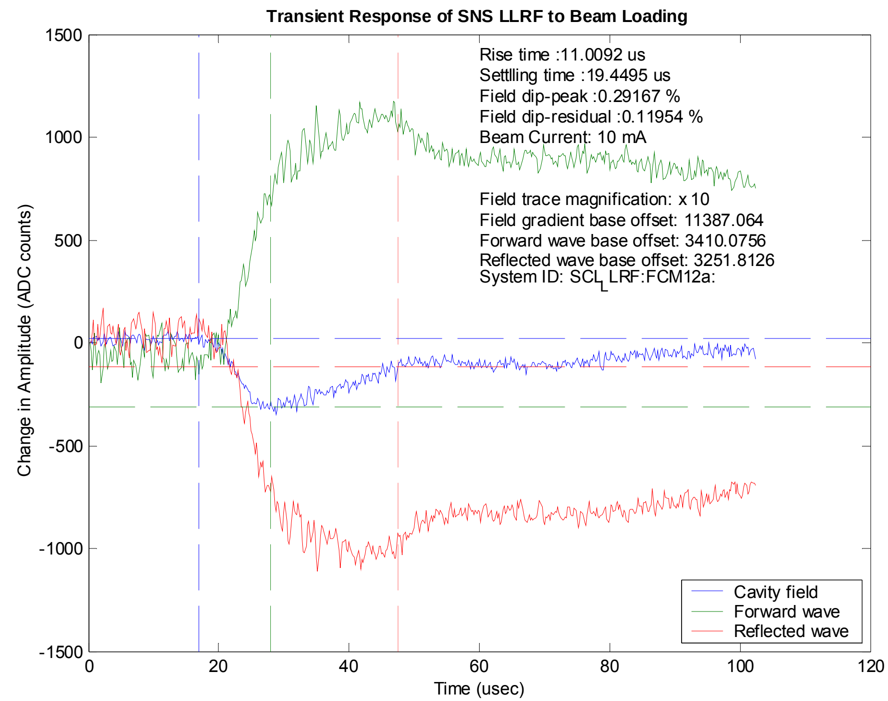


SCL-12a @ 9MV/m response to test rectangular pulse to FF input

- Closed-loop control bandwidth:≈59kHz for critically damped, cavity BW: 0.56kHz
- Total loop gain tested:≈ 89, 104 required for critical damping

Transient response to beam loading





SCL-12a @ 9MV/m response to 10mA/300us beam pulse

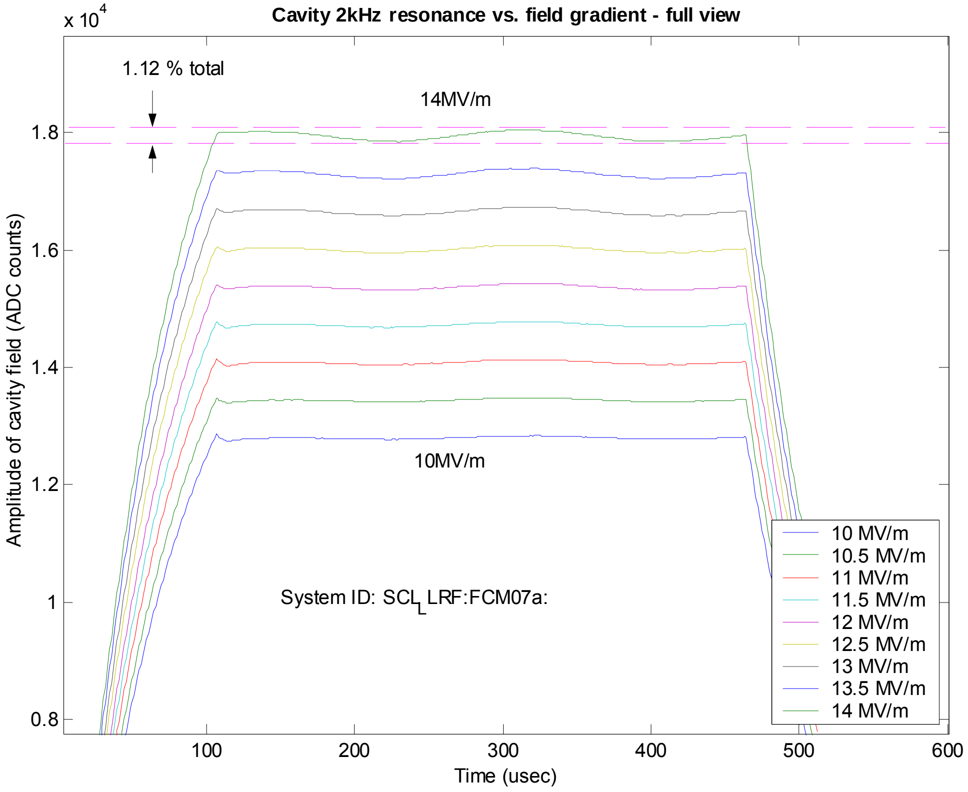
- Beam rise time: ≈ 10us, feedback action delay time: ???
- Settling time of proportional feedback control: ≈19.5us
- Damping ratio: 0.76 ; Peak field error: 0.3% ; Residual error right after settling : 0.12%
- AFF for beam loading compensation ?

SNS LLRF : Data buffers facilitate studies and operations

Example 1:

Scanning field gradient setting to observe the “2kHz” ringing of medium-beta cavities which becomes prominent when the cavity is run at a gradient much beyond the designed 10 MV/m

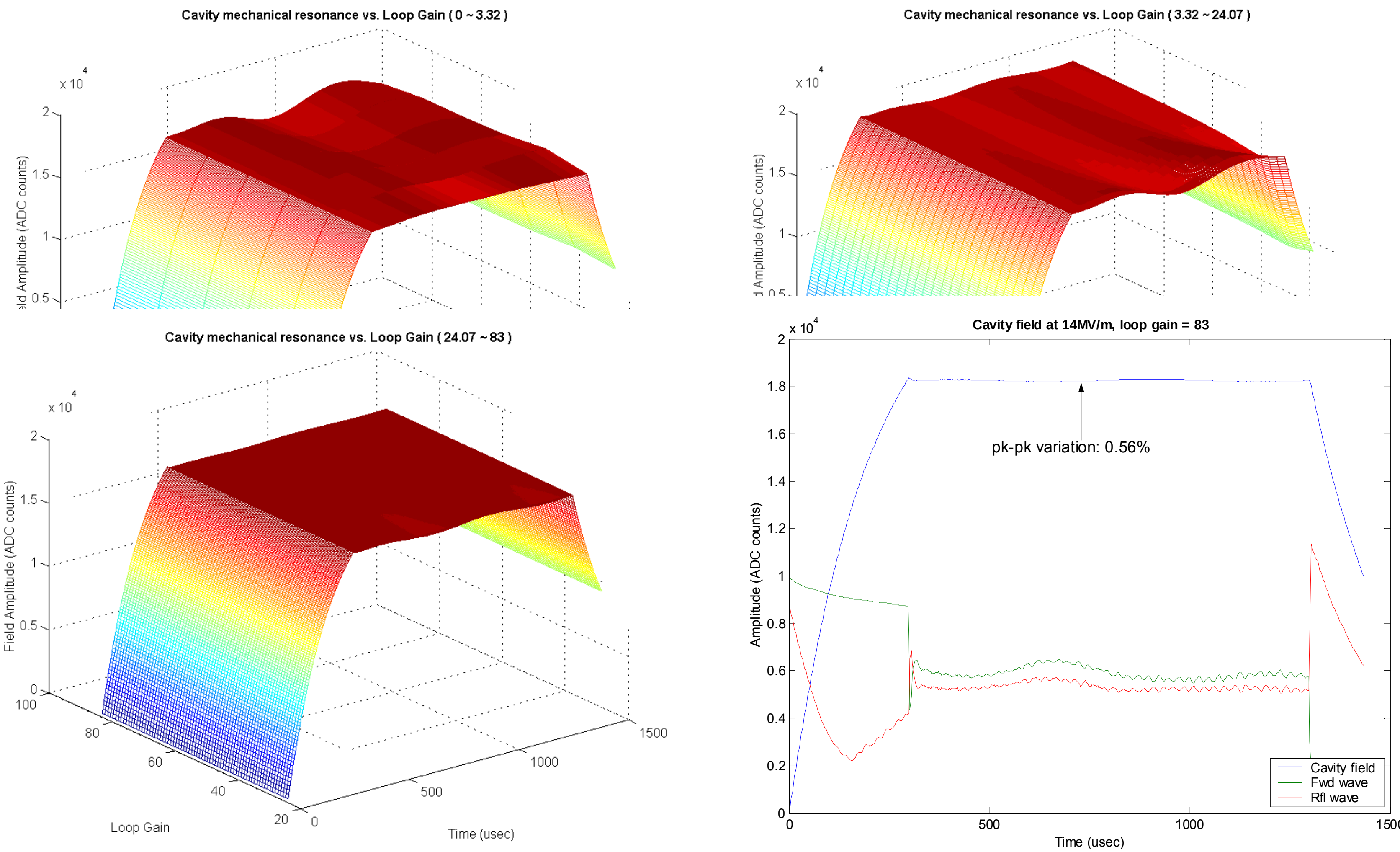
(note: half gain)



SNS LLRF : Data buffers facilitate studies and operations

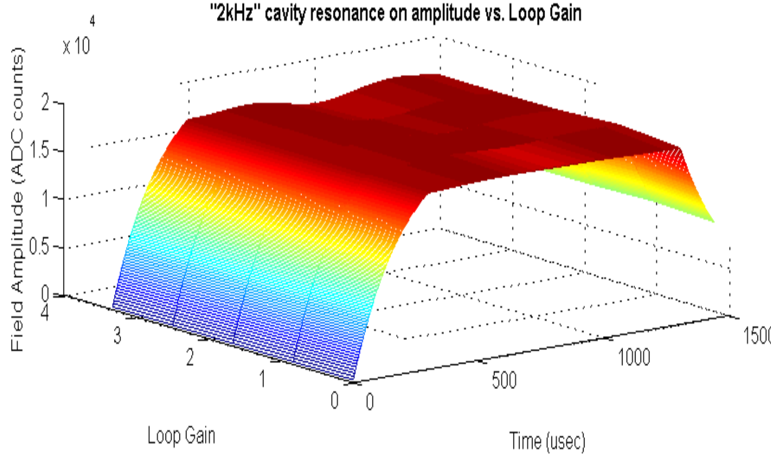
Example 2:

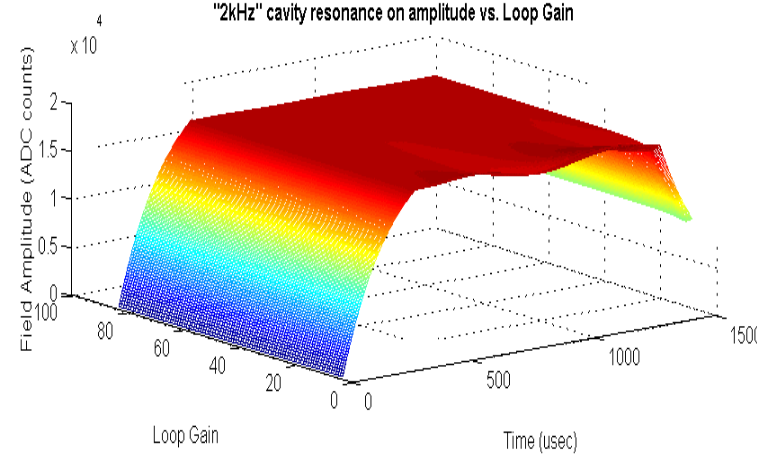
Scanning loop gain to see its effectiveness on controlling “2kHz” cavity ringing

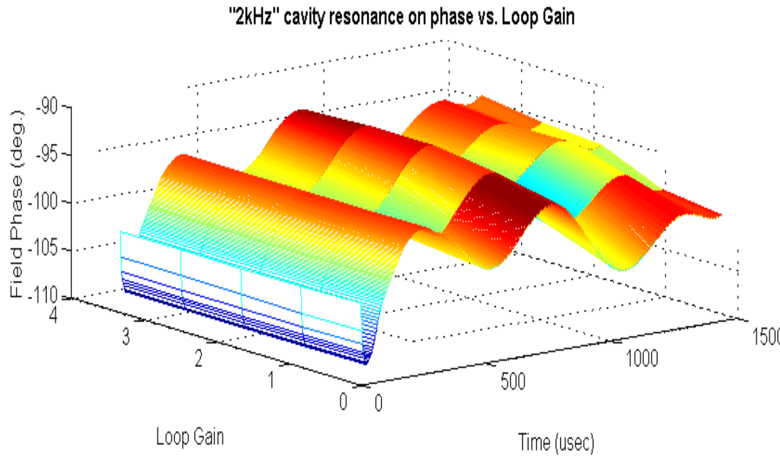


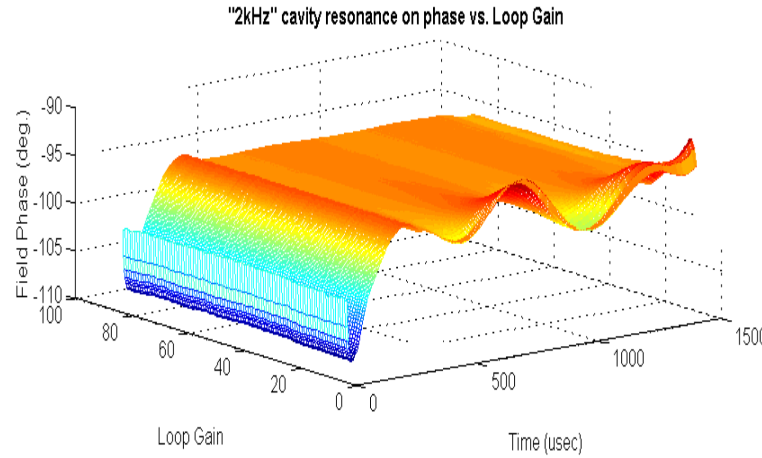
Example 3:

Scanning loop gain to observe the coupling of “2kHz” cavity ringing between field phase and amplitude in association with gain value.





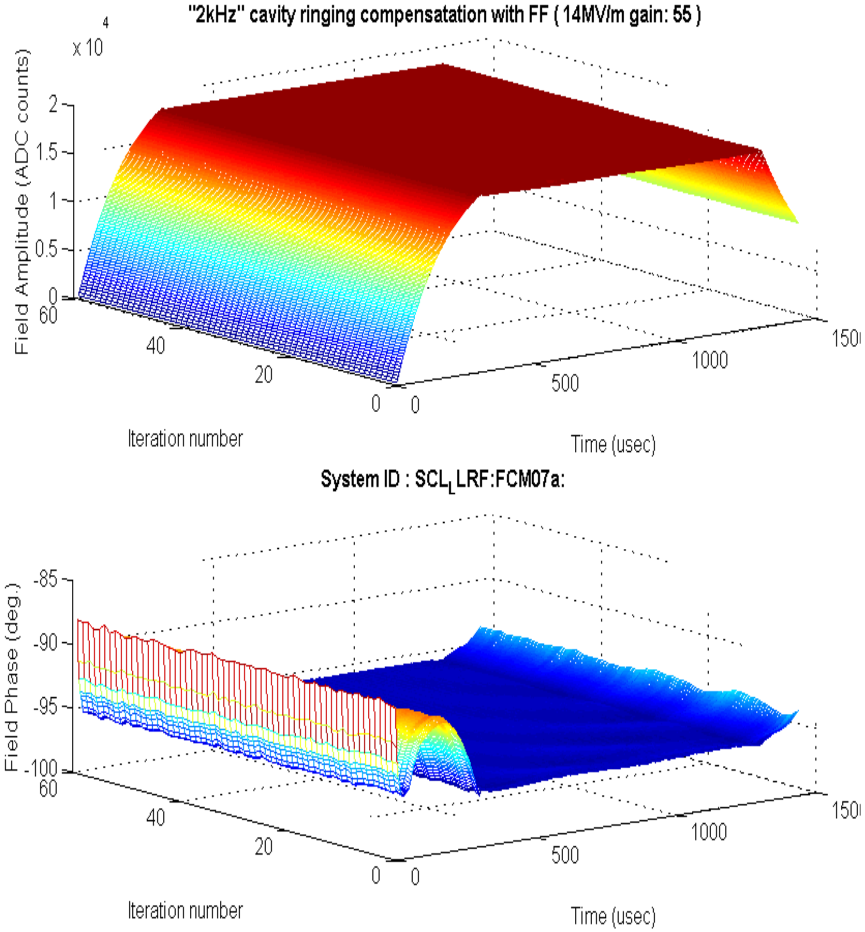


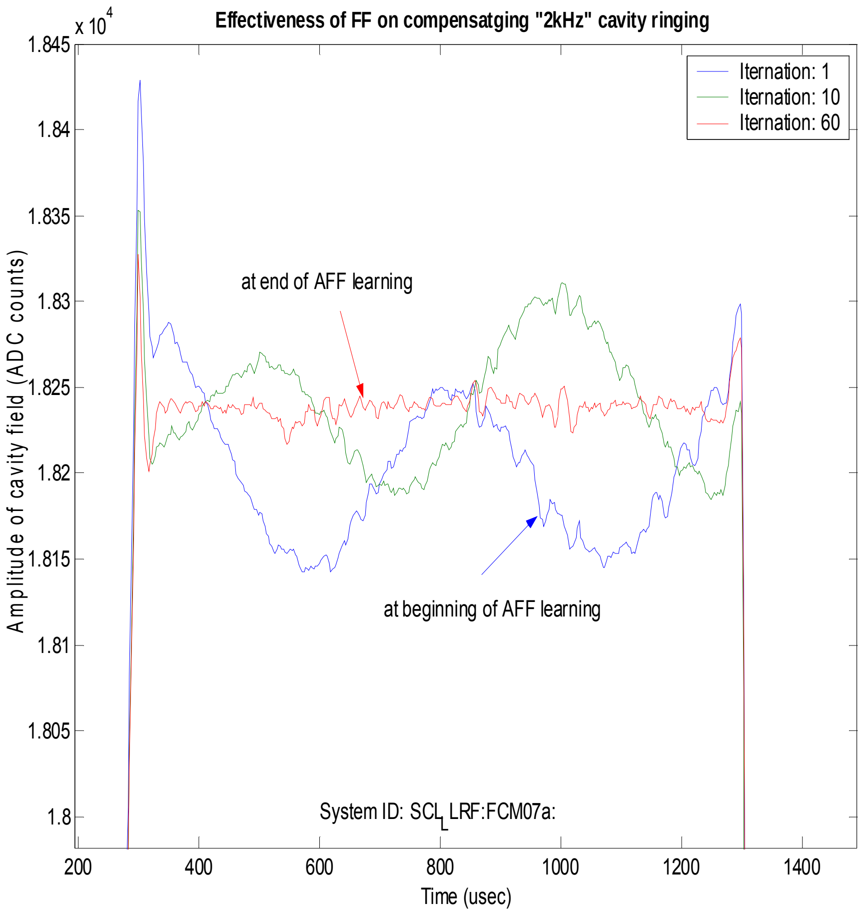


SNS LLRF : Data buffers facilitate studies and operations

Example 4:

Observing effectiveness and learning speed of FF buffer data for compensating "2kHz" cavity ringing.

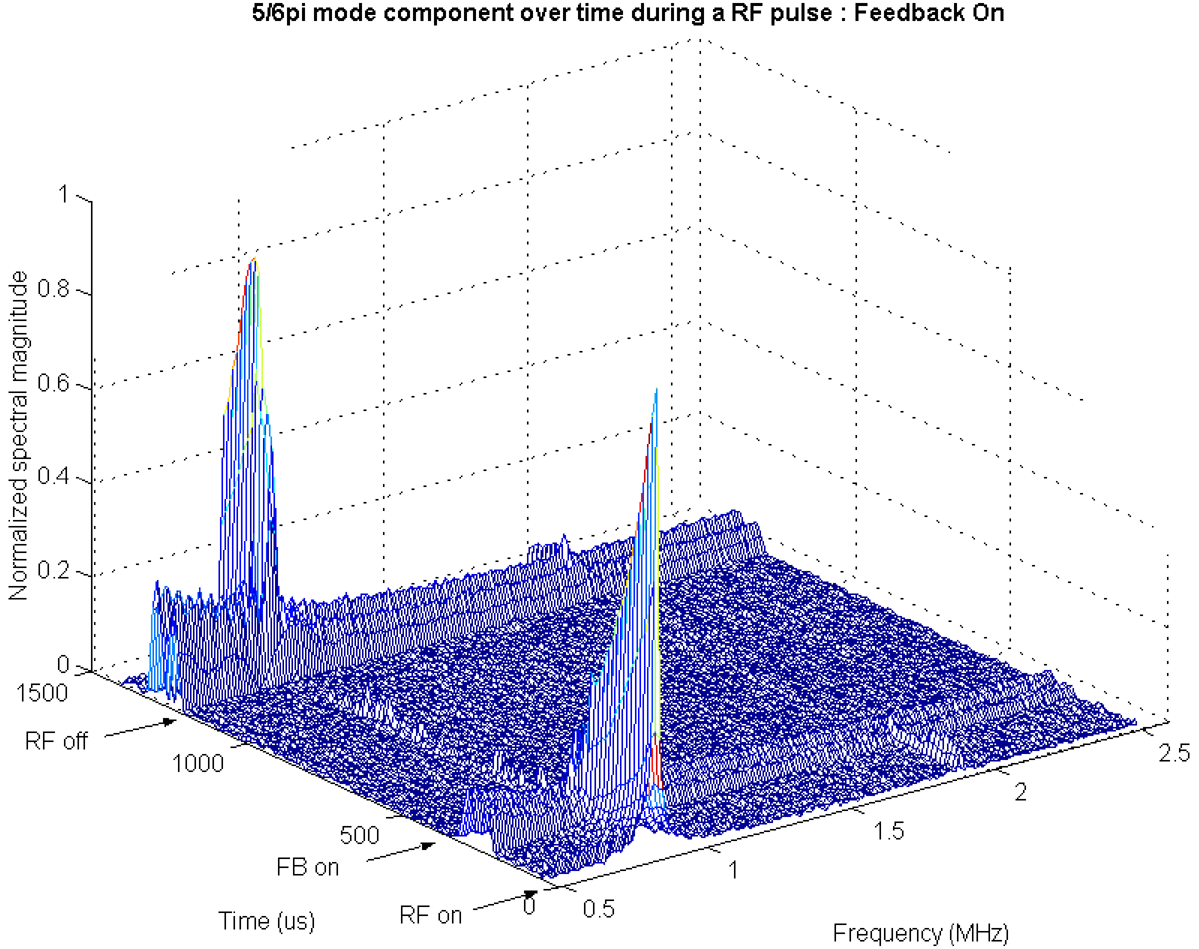




SNS LLRF : Data buffers facilitate studies and operations

Example 5:

Using DSO Zoom/Pan feature of data buffers to observe 5/6pi mode over time in closed-loop.



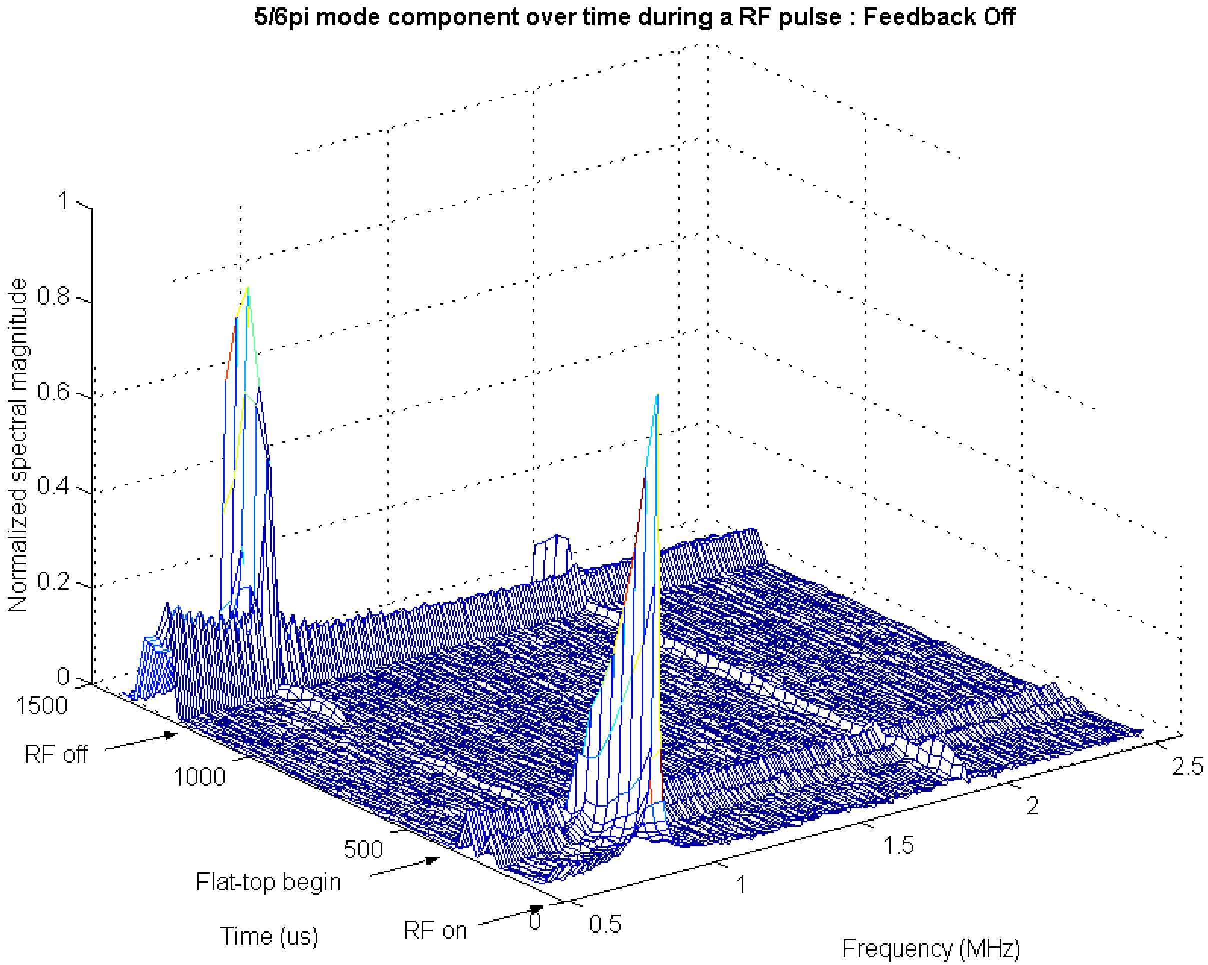
- •Insignificant amount of 5/6 pi mode observed at RF turn-on and off
- •5/6 pi mode decays rapidly and is further significantly reduced during flat-top when feedback is turn on.
- •Moving window =25us,
- •Sampling rate = 5MHz.

SNS LLRF : Data buffers facilitate studies and operations

Example 6:

Using DSO Zoom/Pan feature of data buffers to observe 5/6pi mode over time.

in open loop.



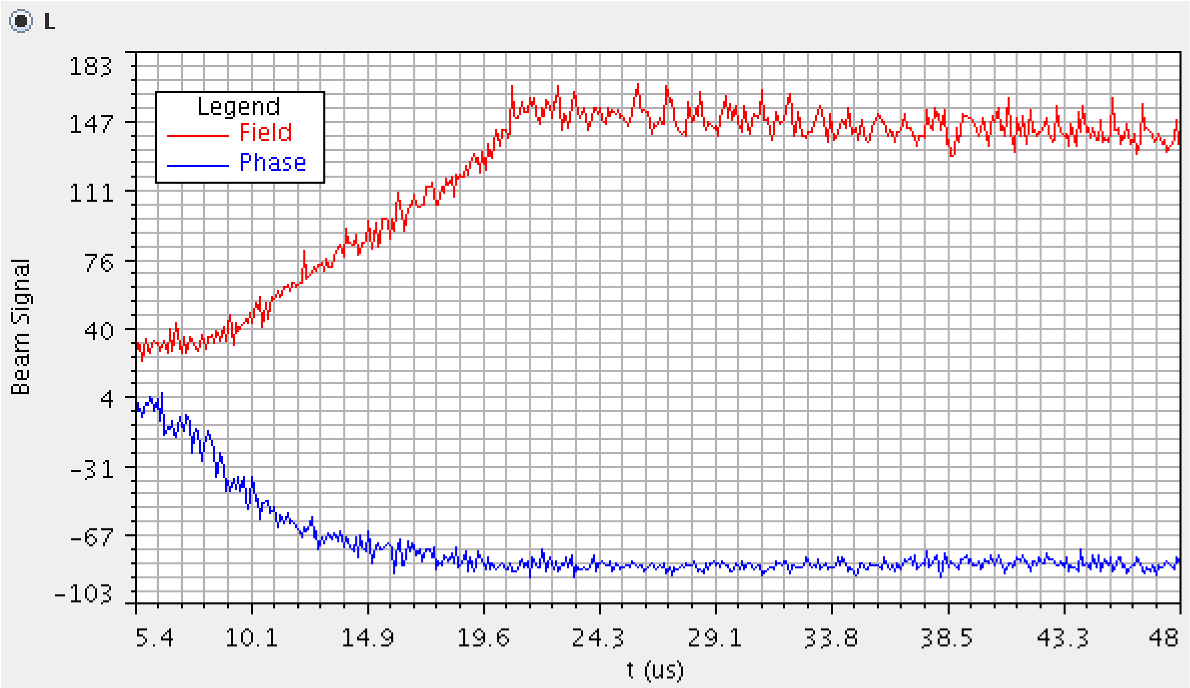
- 5/6 pi mode is also greatly reduced at and during the flat-top time EVEN WHEN FB IS OFF.
- Cancellation effect from FF pattern ?

Example 7:

Accelerator physicists are successfully using LLRF buffer data to implement a new method for calibrating field probe and setting up RF for hi-beta cavities.

Details, see "Calibrate Pickup" Probe of SC Cavity and Set Synchronous Phase with Drifting Beam, " by Y. Zhang*, I. Campisi, P. Chu, J. Galambos, S. D. Henderson.

To be published in *Nuclear Instruments and Methods*.

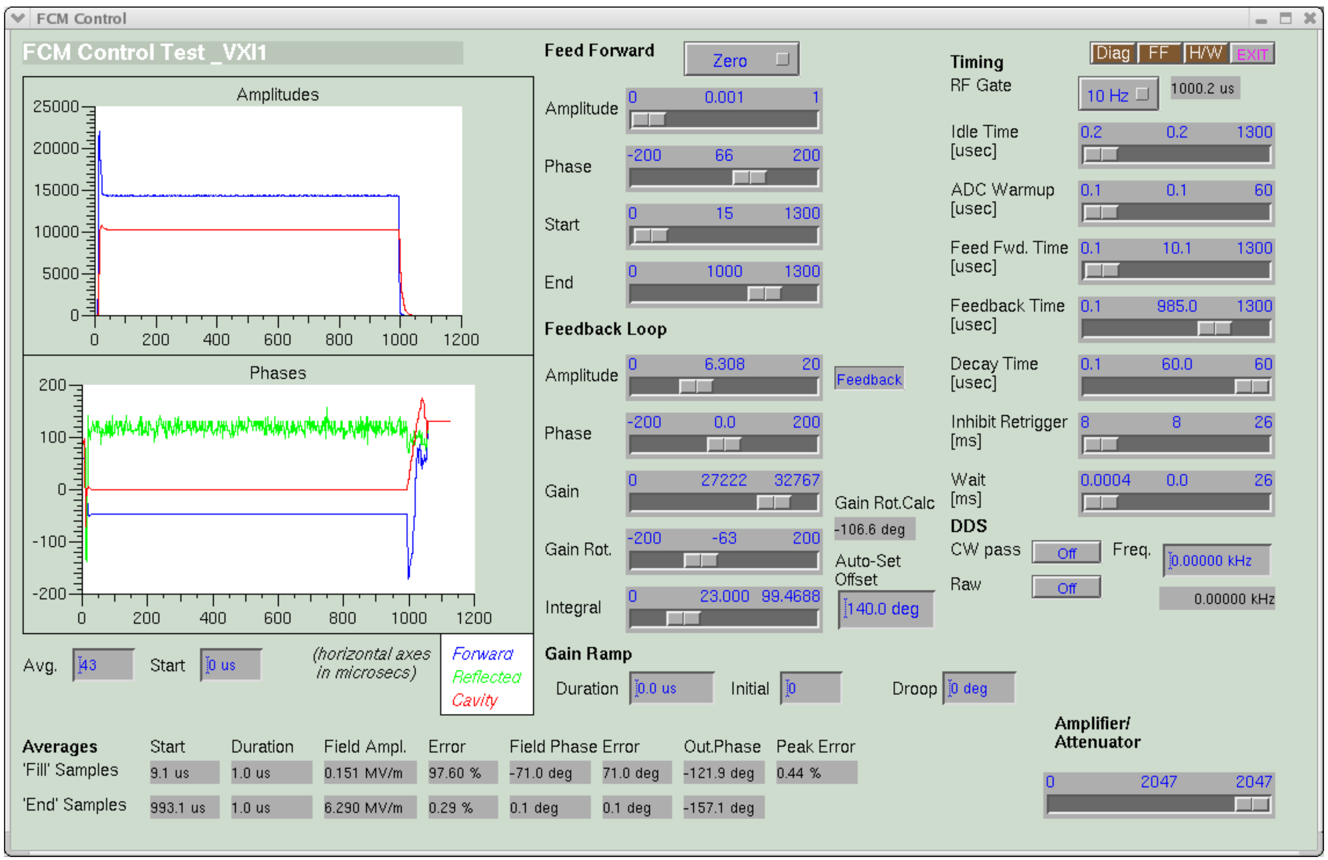


SNS LLRF : Operation modes – RF turn-on & cavity filling

Mode 1: RF turn-on in P-I control only.

Pros – simplest.

Cons – unconstrained overshoot, undesirable large-signal response behavior.

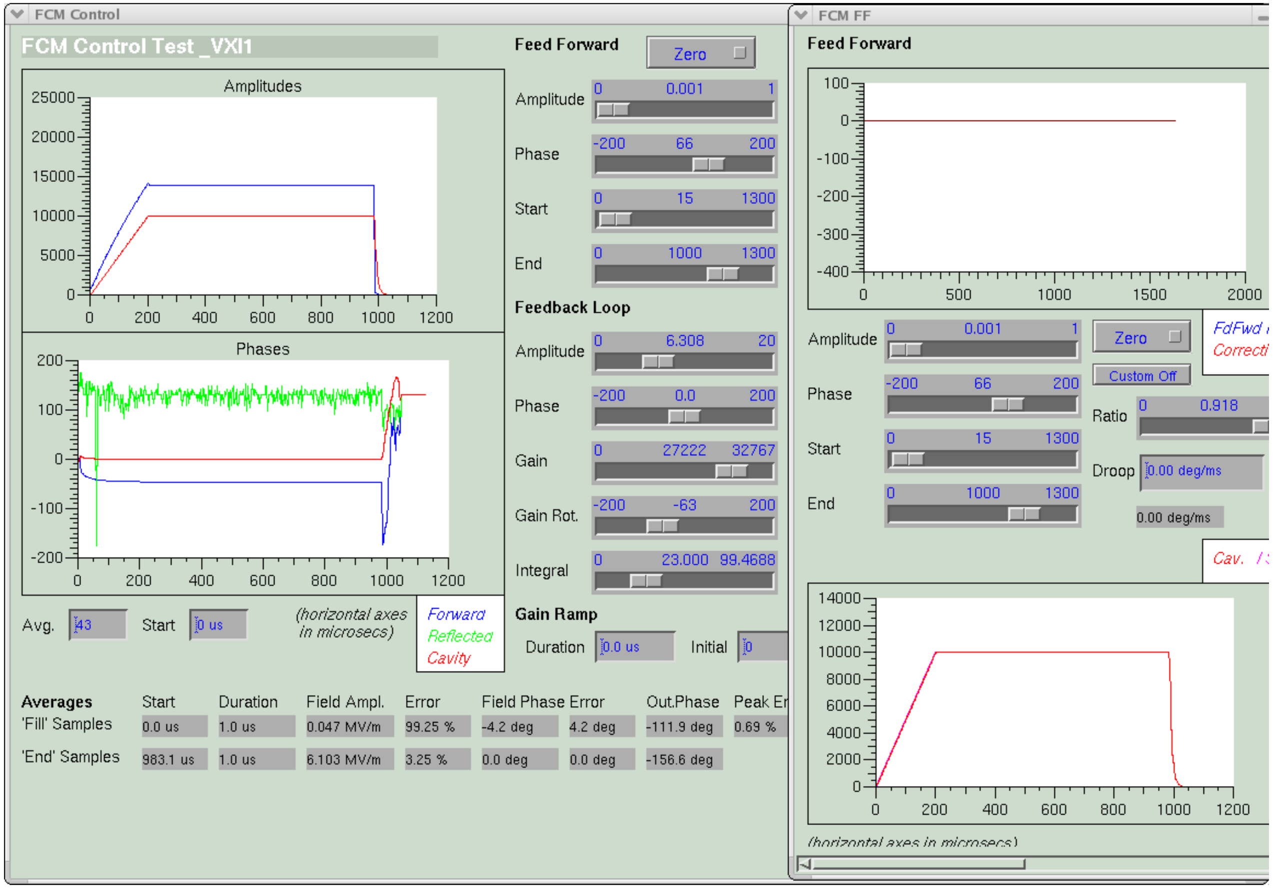


SNS LLRF : Operation modes – RF turn-on & cavity filling

Mode 2: RF turn-on in P-I control only with behavior modified by using a linear set-point ramping.

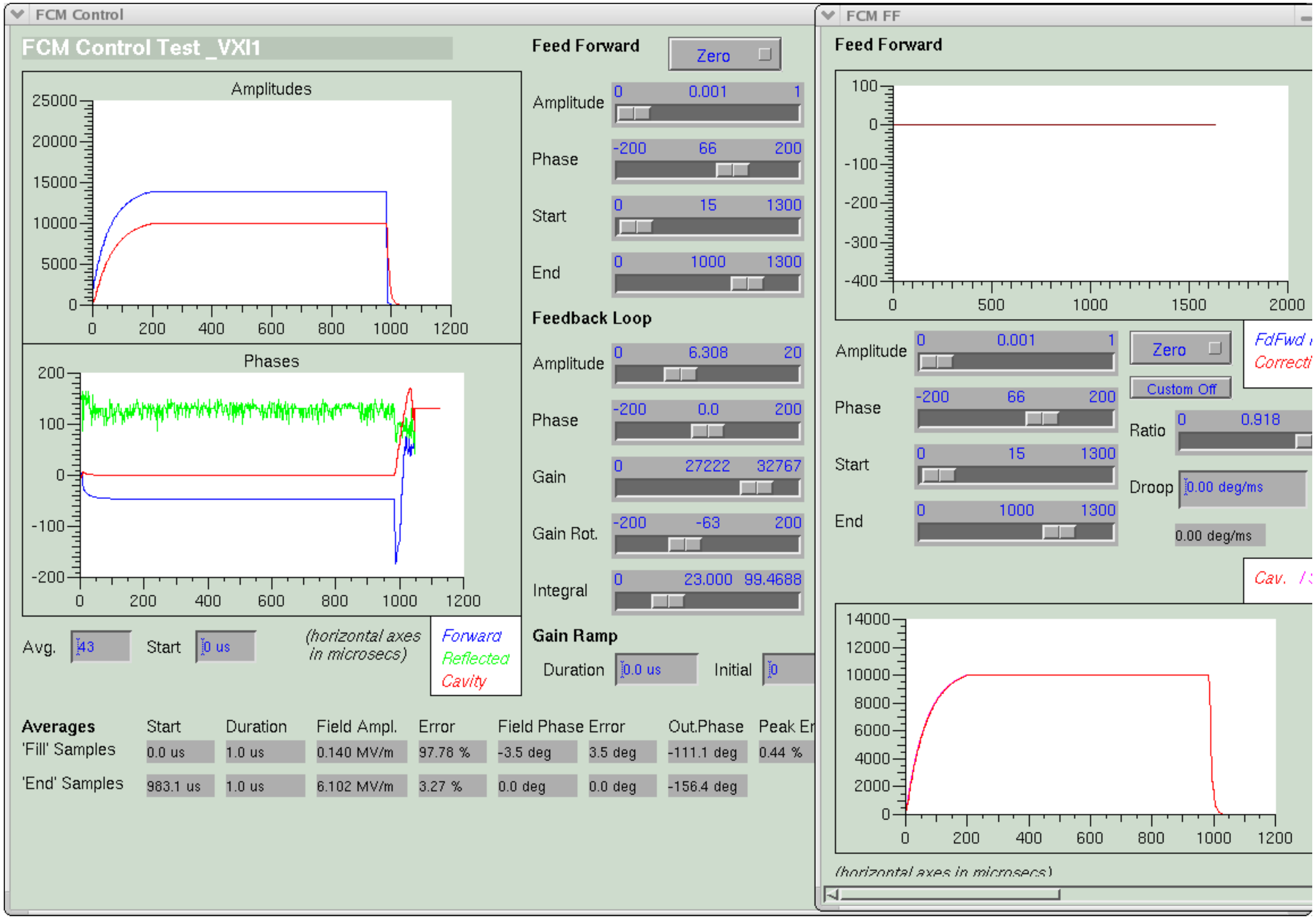
Pros – simple, works well for NC cavities.

Cons – not a solution for SC cavities.



Mode 3: RF turn-on in P-I control only with a set-point curve from SP table.

Pros: flexible.

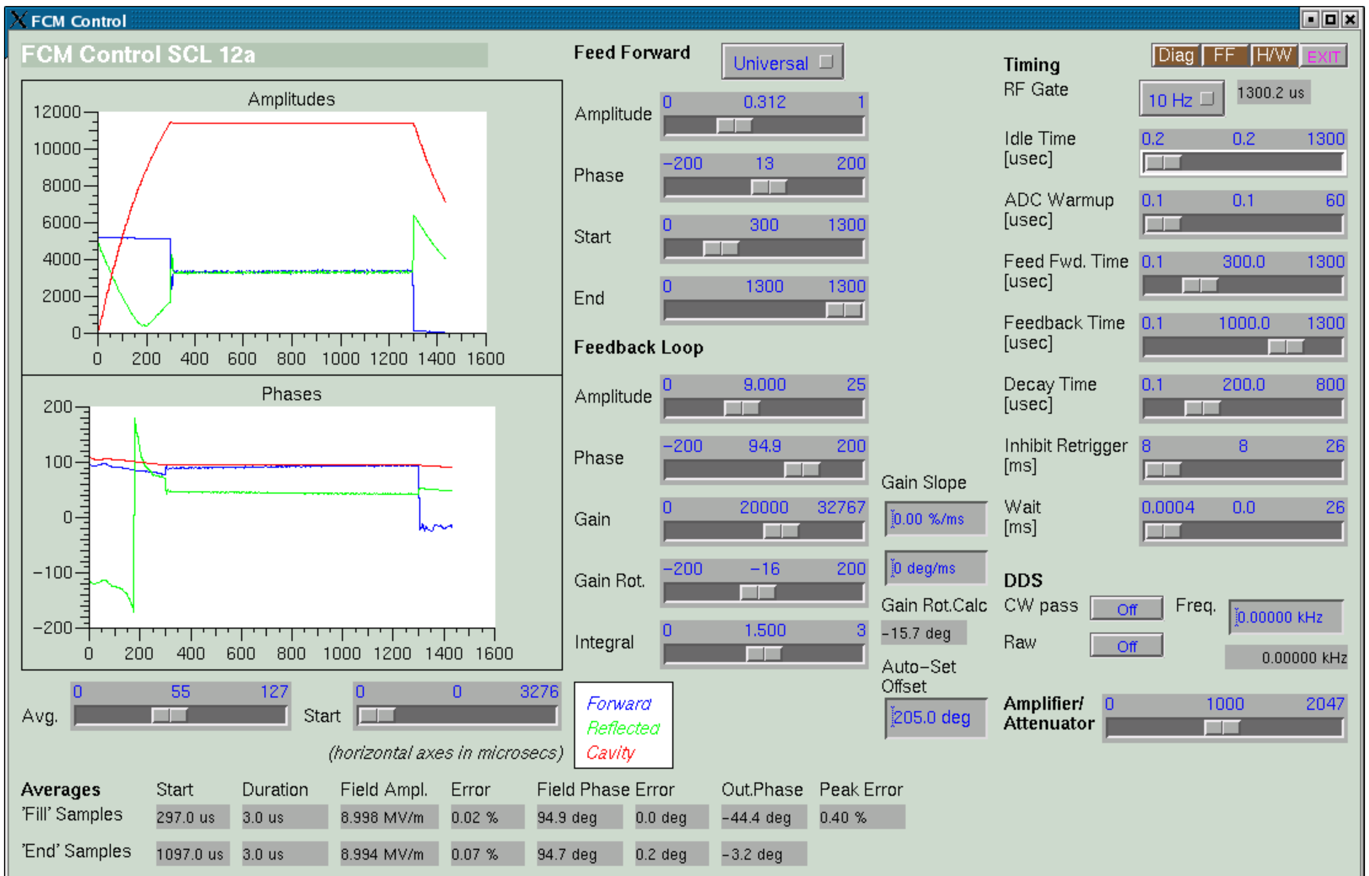


SNS LLRF : Operation modes – RF turn-on & cavity filling

Mode 4: Cavity filling in in open-loop with FF first and then turn on feedback control during flat-top.

Pros – effective for SC cavities. Chance to observe cavity

Cons – Requires a perfect transition from FF to FB.



SNS LLRF : Operation modes – RF turn-on & cavity filling

Mode 5: RF turn-on/cavity filling with FF + SP curve

Mode 6: RF turn-on/cavity filling with FF + SP curve + gain ramping

Currently under testing.

Summary

- System performed well and met the needs during the commissioning runs.
- Hardware platform has flexibility and capacity to allow further expansions.
- Strong software support has offered ease and convenience of operations.
- An immediate focus is on the development of an effective adaptive feed forward for beam loading compensation.