Final Design Review:
SNS Super Conducting Linac RF Control System

Amy Regan

RF Controls Team:

Irene DeBaca, Sung-il Kwon, Roy Lopez, Mark Prokop, Tony Rohlev, Dave Thomson

August 1, 2001

Agenda

Introduction (Mike Lynch)	**8:30-8:45**
Welcome & Charge to Committee	
Scope of the SRF Linac RFCS FDR	
NC Linac RF Control System Update (Amy Regan)	**8:45-9:00**
NC FDR issues and resolutions	
Board Status	
NC Linac vs SRF Linac RF Controls Requirements (Amy Regan)	**9:00-9:30**
RFCS for SRF Linac Modeling (Sung-il Kwon)	**9:30-10:15**
Control margin: impact of microphonics, Lorentz force detuning	
Break	
CM Interface (Amy Regan)	**10:30-11:30**
Signal Processing (Mark Prokop)	**11:30-12:00**
Lunch	**12:00-12:45**
(provided for committee and RFCS team)	
Global Controls (Kay-Uwe Kasemir)	**12:45-1:00**
Schedule (Amy Regan)	**1:00-1:15**
Wrap-up	**1:15-1:30**
Committee Review Session (Review Committee Only)	**1:30-2:30**
Out Briefing	**2:30-3:00**

Agenda s□tatus

Introduction (Mike Lynch) **8:30-8:45**

Welcome & Charge to Committee

Scope of the SRF Linac RFCS FDR

Charge to the Committee

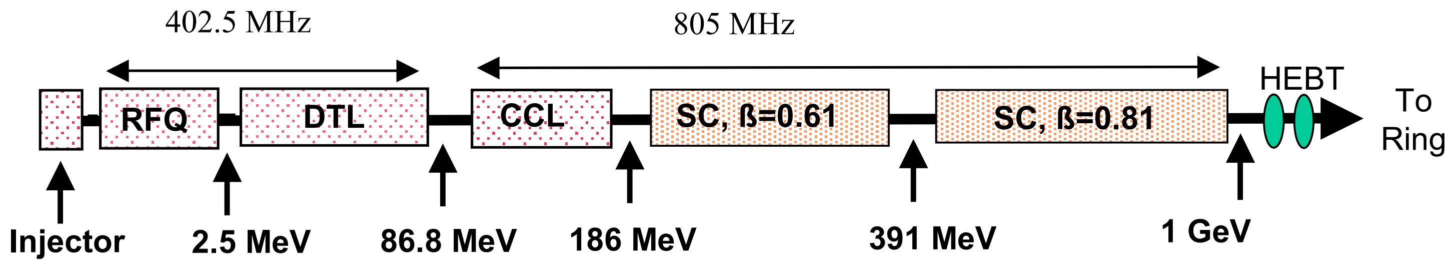
- Does the design meet the requirements?
- Is it consistent with the NC Linac RFCS FDR and its outcome?
- Are interfaces within the RF Control System, as well as external systems, identified?
- Does the fabrication plan and schedule make sense?

Agenda status

NC Linac RF Control System Update (Amy Regan) **8:45-9:00**

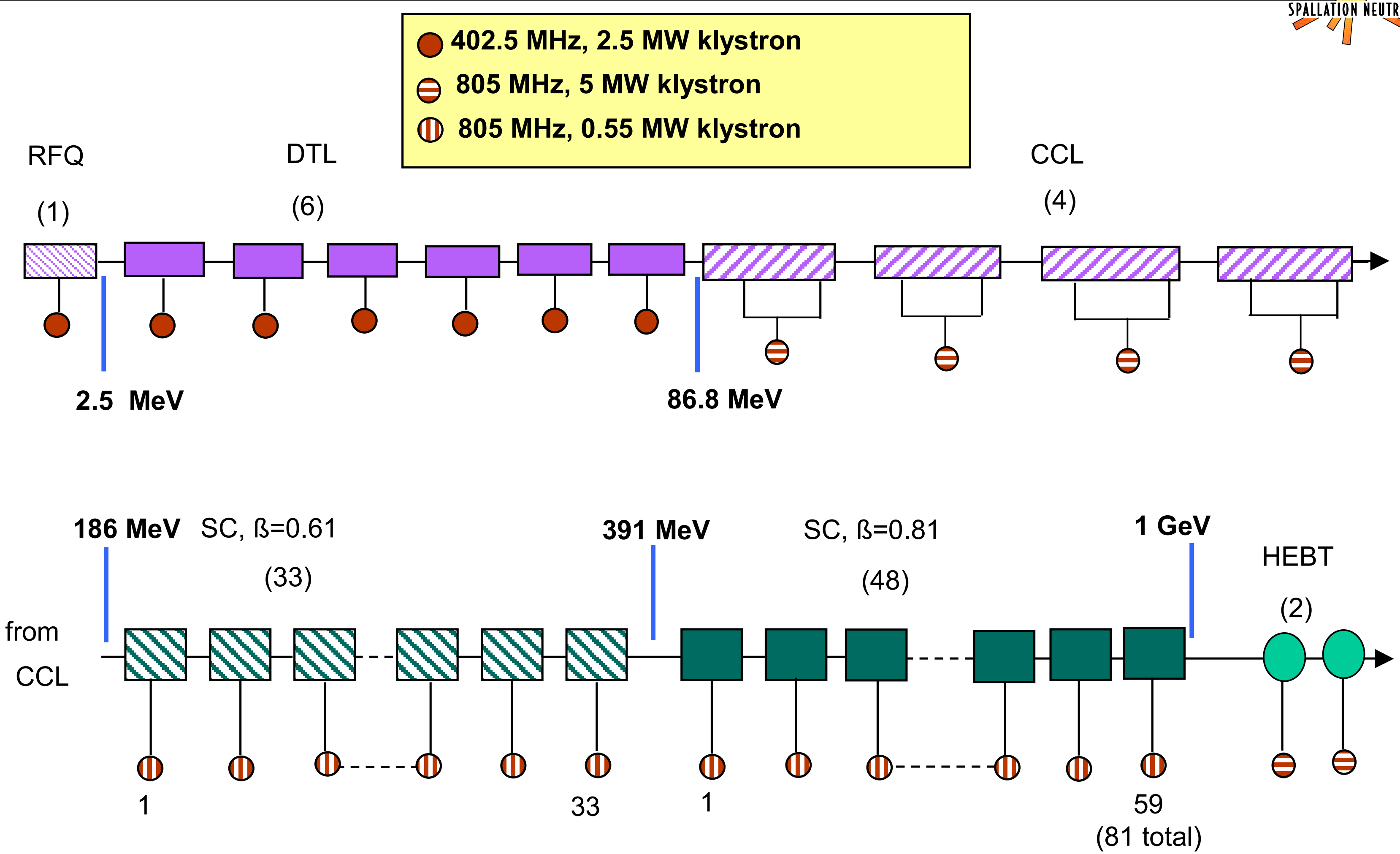
NC FDR issues and resolutions
Board Status

NC/SC Linac for SNS

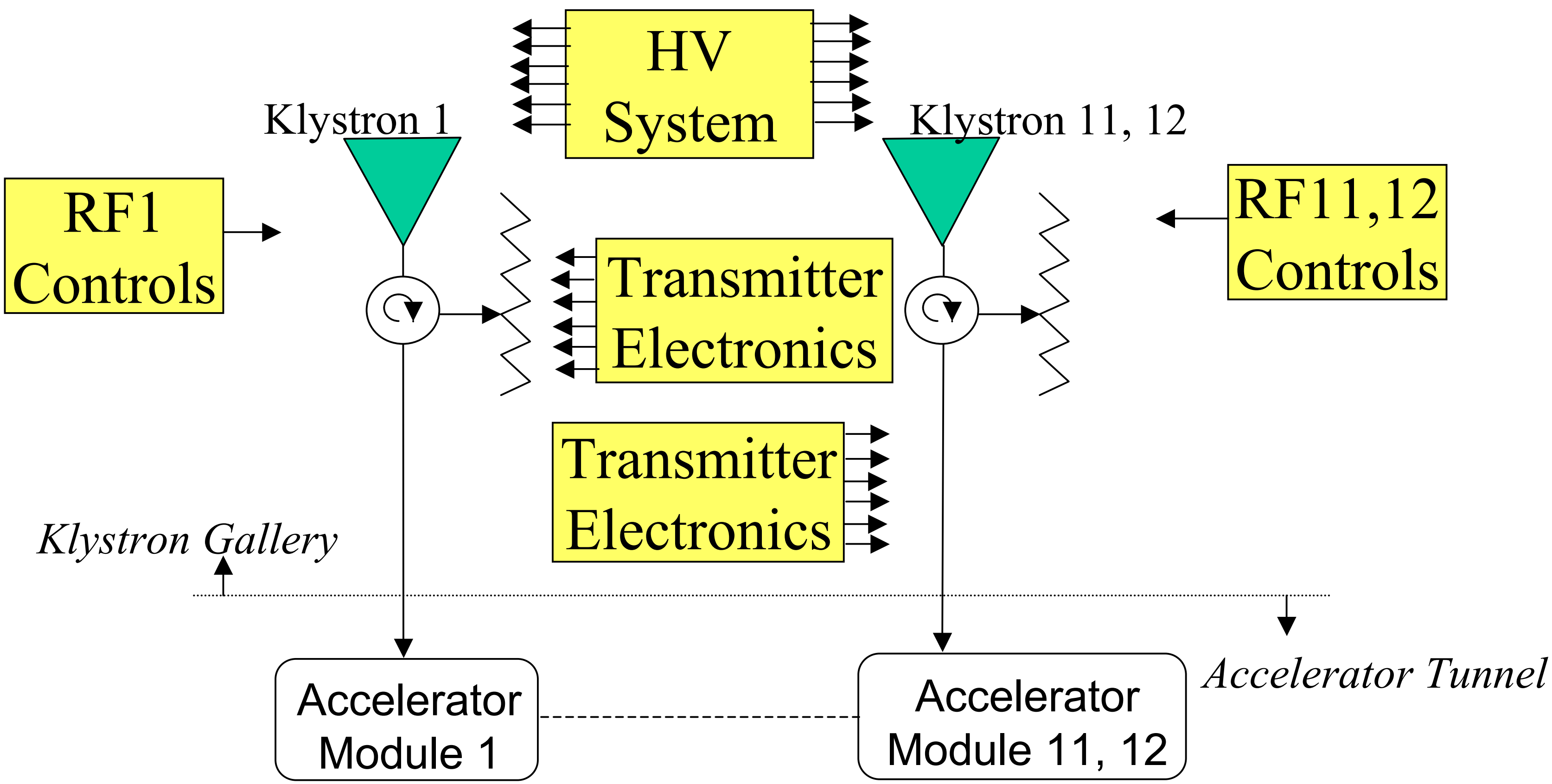


H- energy	**1 GeV**
Beam power	**1.5 MW, avg.**
Pulse Width	**1.04 ms**
Rep Rate	**60 Hz**
Klystrons	
402.5 MHz, 2.5 MW pk	**7**
(includes 1 for RFQ, 6 for DTL)	
805 MHz, 5 MW pk	**6**
(includes 4 for CCL, 2 for HEBT)	
805 MHz, 0.55 MW pk, SC	**81**
HV Converter/Modulator Systems	**1 for each 5 MW klystron or pair of 2.5 MW klystrons** *except 1 for RFQ and first 2 DTL tanks and 1 for 2 HEBT cavities* **1 for 11 or 12 each 0.55 MW klystrons (16 total, plus 2 for test stands)**

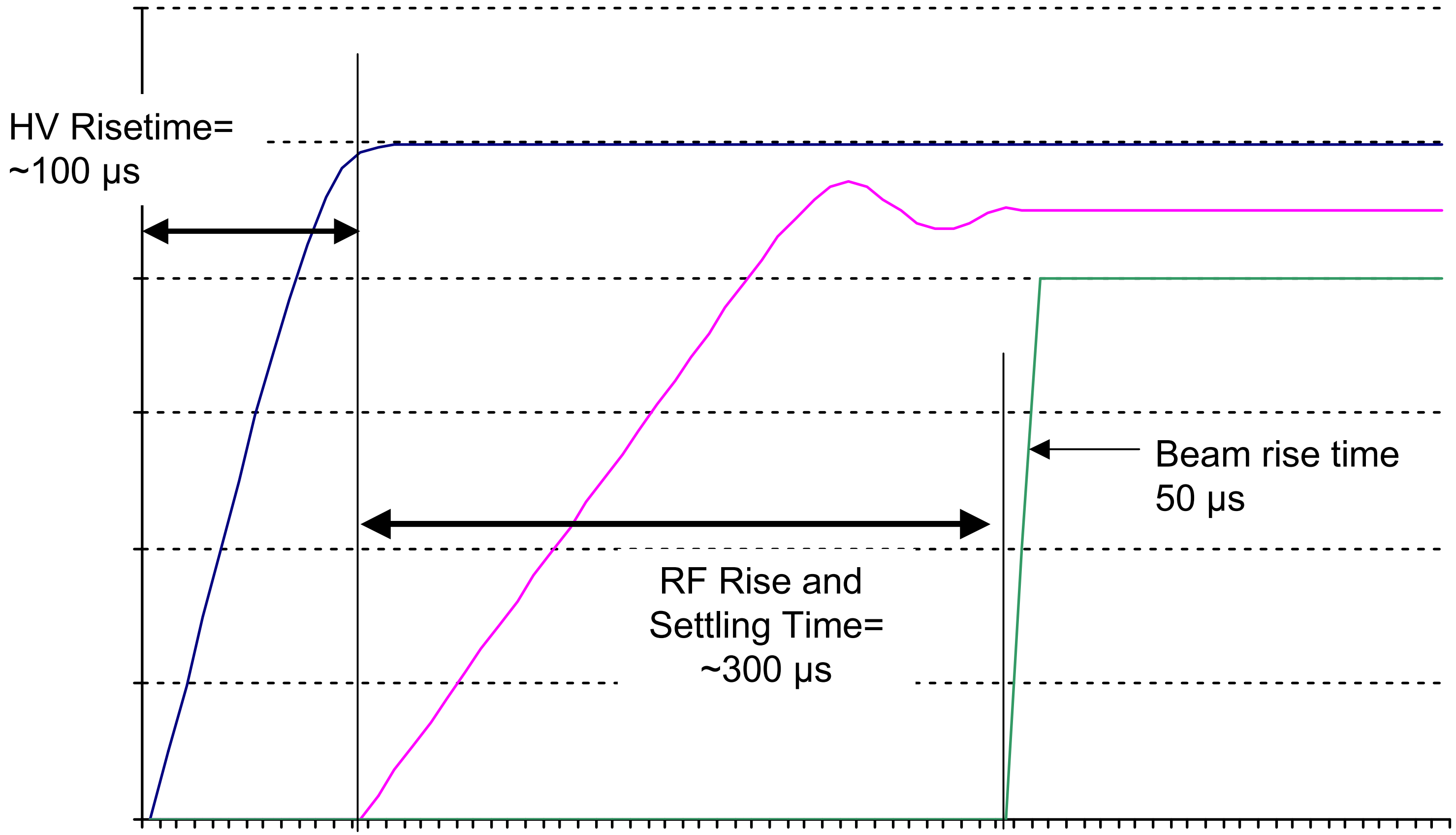
Layout of Linac RF with NC and SC Modules



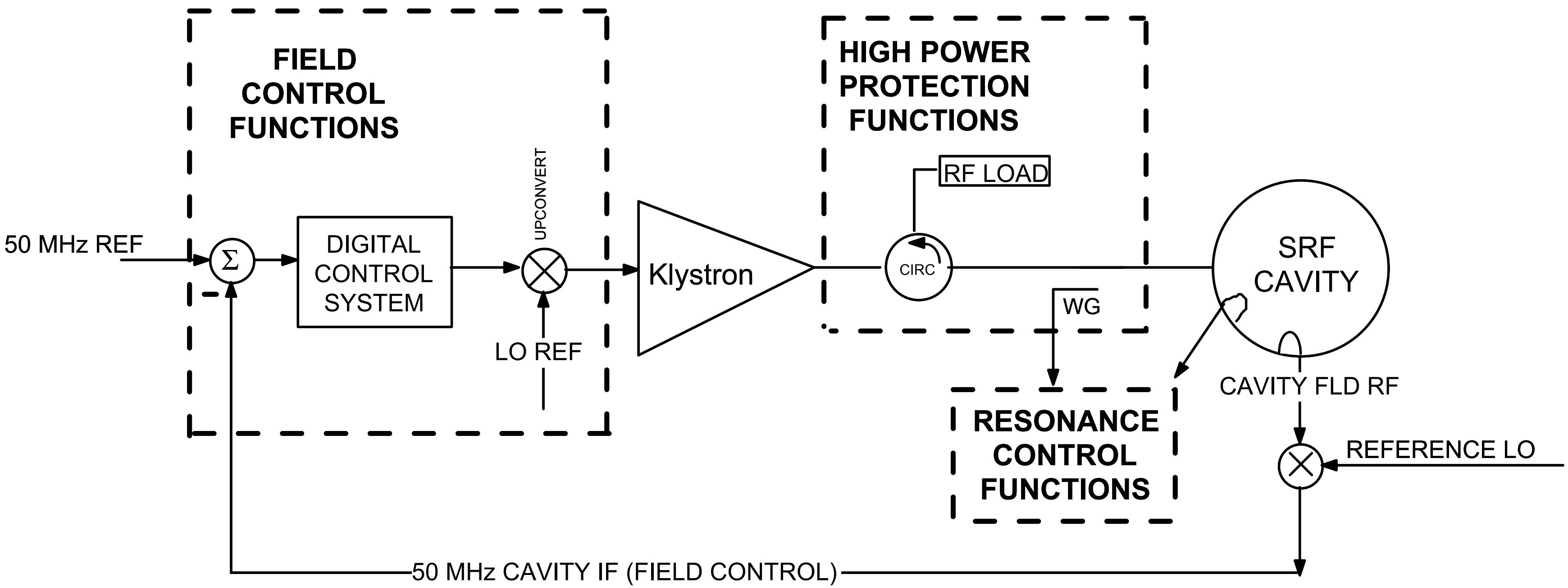
RF System Block Diagram, 0.55 MW klystrons, 805 MHz (SRF cavities)



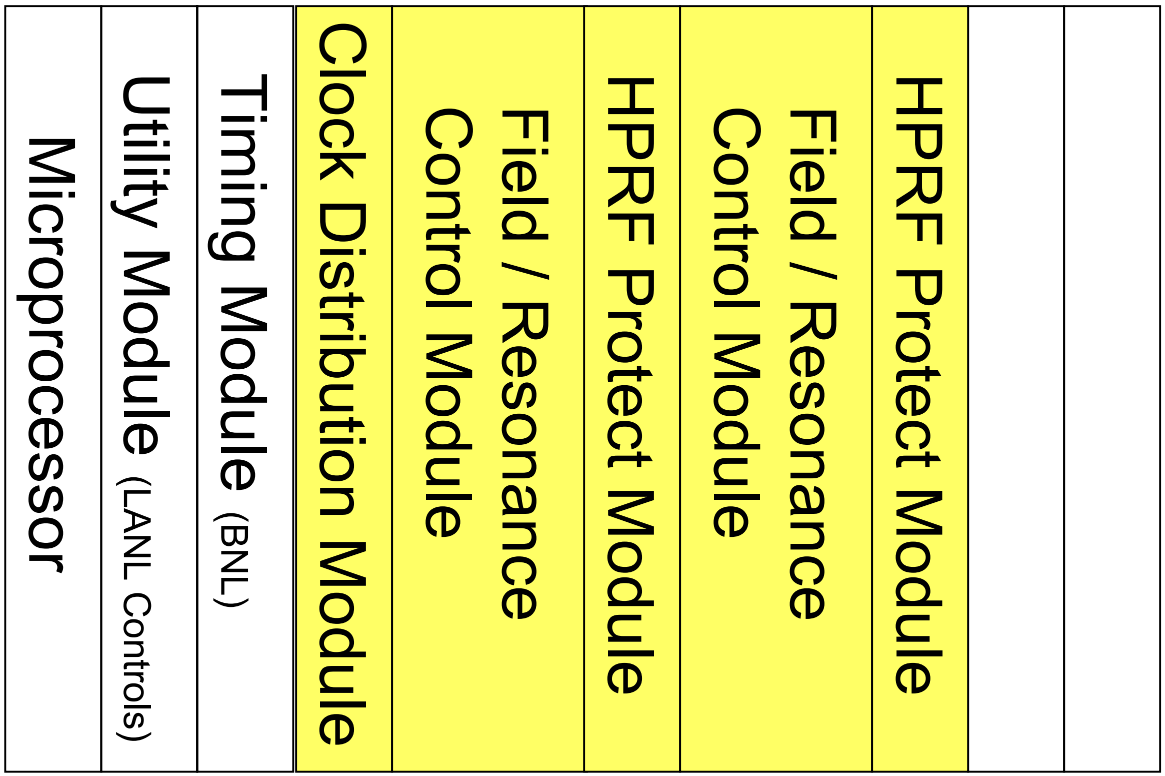
SRF Risetimes and Settling Times



RFCS Functional Block Diagram



SRF RF Control System Architecture
2 systems / VXIbus crate



LANL-designed VXIbus module

NC Linac RFCS FDR Issues & Resolution

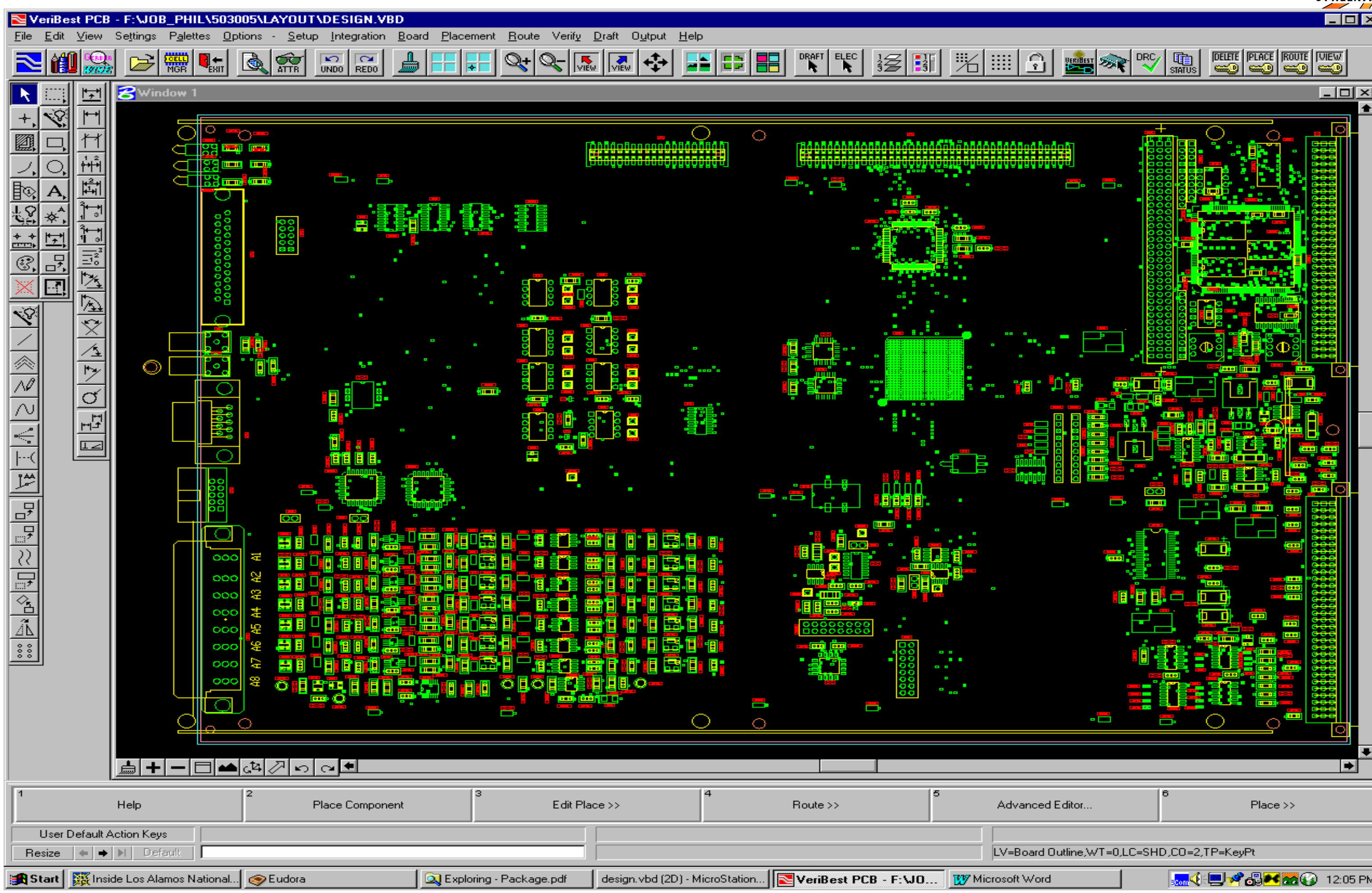
- NEED GOOD SYSTEMS ENGINEERING
  - **We're working on it. Video Conferencing, publication of RF System Description, Modeling continues incorporating top level features,…**
- AGGRESSIVE DEVELOPMENT SCHEDULE
  - **We agree. Yi-Ming's departure hasn't helped. We're in process of changing our WBS schedule to meet project needs and our realistic timeline.**
- ENGINEERING RECOMMENDATIONS ON BOARD DESIGN
  - **Suggestions have been incorporated.**

VXIbus Hardware Status

- FRCM Motherboard in ECAD layout right now
  - Mark will discuss
- RF daughter board built and tested
  - Tony will discuss
- DSP daughter board built
  - We've started testing
- CDM printed circuit board is back from manufacturer.
  - Parts being installed now.
- HPM will go out for PCB manufacture and assembly next week.

High Power Protect Module Layout

SPALLATION NEUTRON SOURCE



Agenda Status

NC Linac vs SRF Linac RF Controls Requirements (Amy Regan)9:00-9:30

RF control system requirements drive design

REQUIRED FUNCTIONS

- Cavity Field Control
- Cavity Resonance Control
- RF Reference generation and distribution
- HPRF protection

SYSTEM CONFIGURATIONS

- NC: Single 2.5 MW klystron driving single cavity (402.5 MHz; RFQ, DTL)
- NC: Single 5 MW klystron driving single cavity through a split (805 MHz; CCL)
- SRF: 550 kW klystrons driving single cavities (medium and high β)

OPERATIONS

- Pulsed beam, Pulsed RF
  - 60 Hz rep rate
  - 68% chopping, 26 mA avg

CONDITIONING & COMMISSIONING

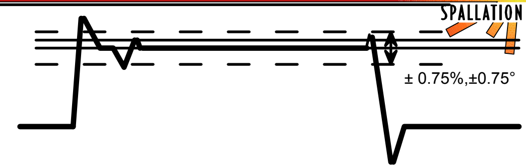
May occur with different rep rates and current

- varying pulse rate
- varying pulse width

RF Control System Requirements

FIELD CONTROL

± 0.5% amplitude, ± 0.5° phase per cavity

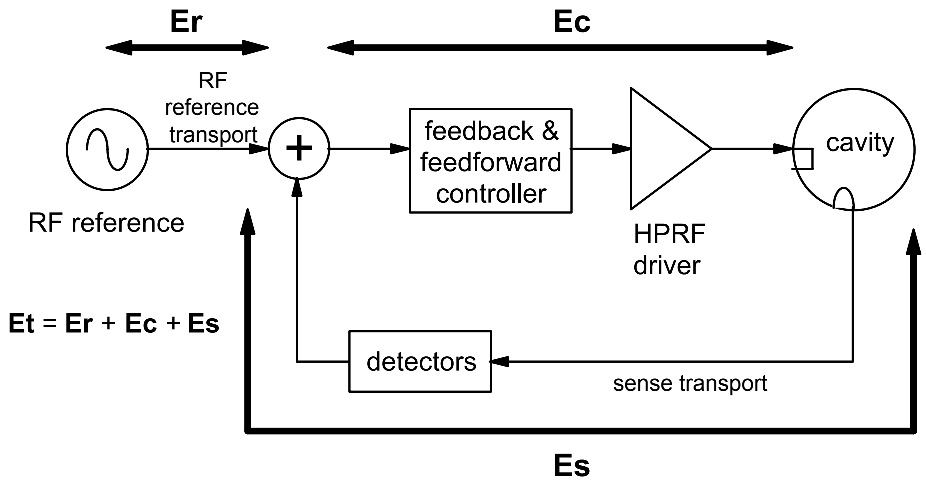


RESONANCE CONTROL

Maintain cavity resonance

NC	SRF
402.5 MHz: RFQ f_0 ± 15 kHz (Q_L = 3300 BW = 122 kHz)	
402.5 MHz: DTL f_0 ± 2 kHz (Q_L = 25,000 BW = 16 kHz)	805 MHz: med. β f_0 ± 50 Hz (Q_L = 733,000 BW = 1 kHz)
805 MHz: CCL f_0 ± 10 kHz (Q_L = 10,000 (smallest bandwidth case) BW = 80 kHz)	805 MHz: high β f_0 ± 50 Hz (Q_L = 699,000 BW = 1.1 kHz)

Error Allocation



Er = reference line transport error
Ec = residual control loop error
Es = sense line and detection error
Et = total system error

PERFORMANCE OBJECTIVES
PEAK AMPLITUDE ERROR: ≤0.5%
PEAK PHASE ERROR: ≤0.5°

TOLERANCE BUDGET

	AMPLITUDE (%)	PHASE
Er	N/A	±0.15
Es	±0.2	±0.15
Ec	±0.3	±0.2

Required Functions: NC vs SRF

Required Function	NC	SRF	NC/SRF Differences
Field Control			
Beam loading	X	X	cavity loop gains, feedforward constants
Beam noise	X	X	cavity loop gains, feedforward constants
Klystron Performance	X	X	amplifier loop gains
Microphonics		X	cavity loop gains
Lorentz Force Detuning		X	cavity loop and feedforward, tuner preset
Resonance Control			
1st Determine Res. f	X	X	sweep, find, tune (NC-water, SRF-motor)
Setup Coarse	X	X	NC - calc. admittance; SRF - freq. sweep
Fine tune (w/in Hz)		X	cavity phase ring down measurement
Provide Tuner info.	X	X	same - error signal via EPICS

Required Functions: NC vs SRF

Required Function	NC	SRF	NC/SRF Differences
HPRF Protection			# of monitors differs per cavity type
High Reflected Power	X	X	none
Waveguide Arc (f/o)	X	X	none
Cavity Arc	X	X	same algorithm in HPM
Cavity Quench		X	algorithm in FRCM
Interact with EPICS	X	X	# of channels differs per cavity type
Interact with MPS	X	X	none
Interact w/ Timing Sys.	X	X	none
Provide RF Reference	X	X	none
Cavity Calibration		X	signals available from FRCM

Agenda Status

RFCS for SRF Linac Modeling (Sung-il Kwon) 9:30-10:15

Control margin: impact of microphonics, Lorentz force detuning

MODELING OF SNS SRF CONTROL SYSTEM AND POWER CONTROL MARGIN ANALYSIS

Sung-Il Kwon

August 1, 2001

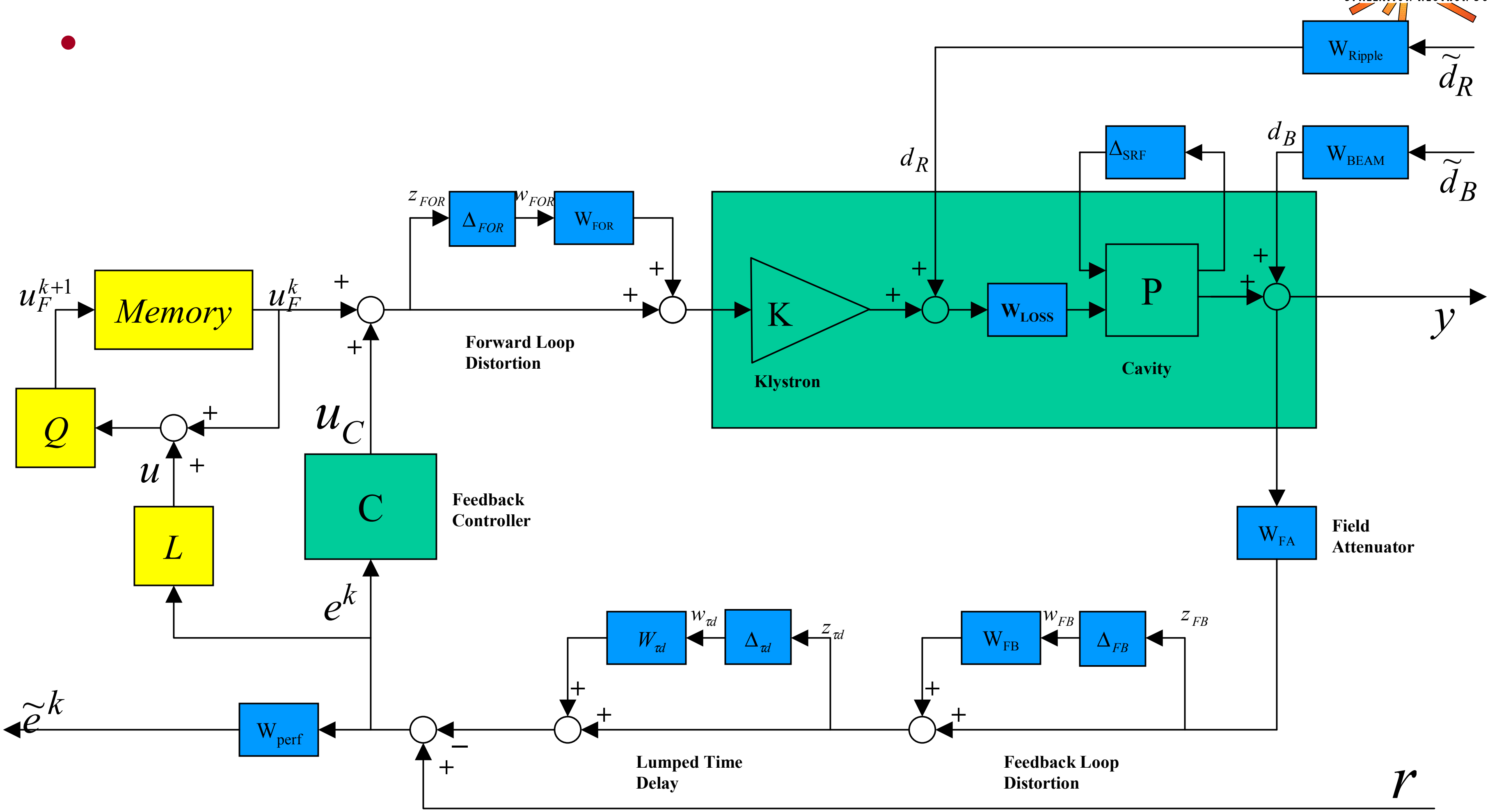
Modeling Issues

Approaches

- Two Approaches are Considered
  - Nonlinear Simulation Model :Time Domain Model
    - MATLAB/SIMULINK Block Model
    - Time Domain Simulation
    - Nonlinearities in System
    - Disturbances, Noises effects are Verified through Simulation
  - Linearized Uncertainty Model : Frequency/Time Domain Model
    - Enjoy the Frequency Domain System Parameters
      - Open/Closed Loop System Bandwidths
      - Determined Feedback, Feedforward Controller Parameters
    - Analytic Check of Nonlinear Time Domain Simulation
      - Disturbances, Noises effects are Analyzed in Frequency Domain

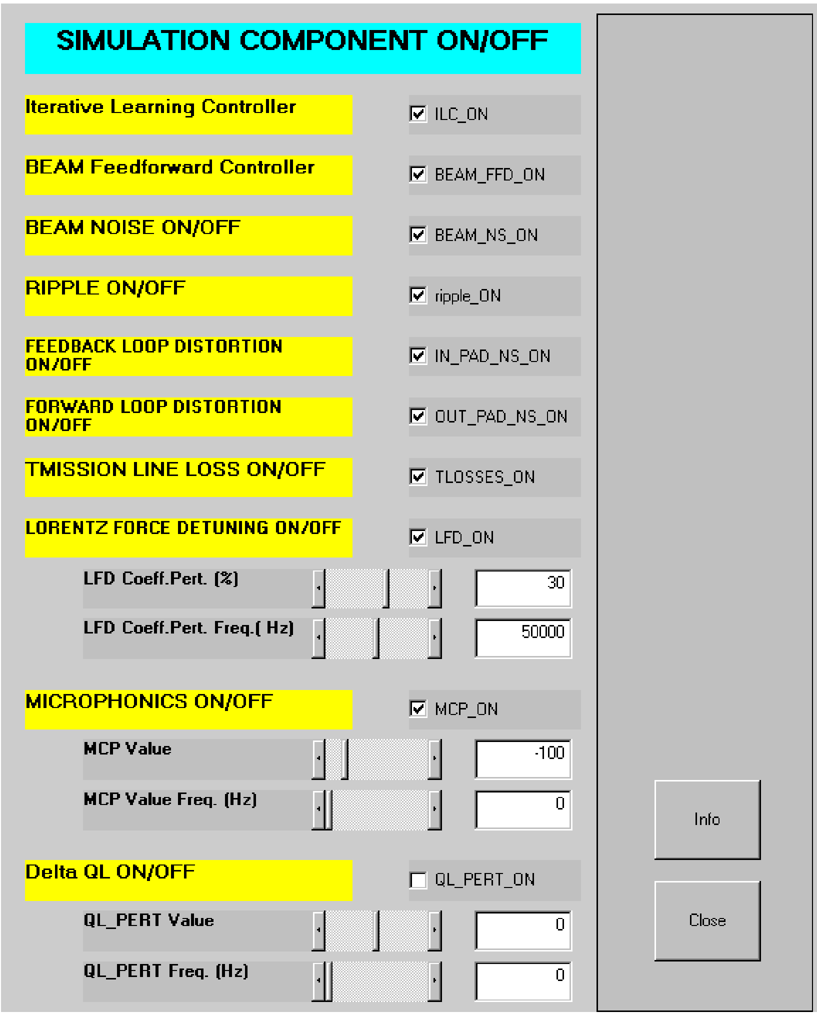
- Graphical User Inteface (GUI) in MATLAB

Feedback and Feedforward Control
(PI Control and Plug-in Type Iterative Learning Control)



Modeling Issues

System Components : Klystron, Disturbances, Noises, Time Delays



- Nonlinearities : Klystron
  - Make it difficult to use modern linear system theory for analysis and synthesis
  - Need to be linearized around operating point sacrificing the transient behavior
- Noises, Disturbances, Distortions
  - **HVPS ripple**
  - **Forward Loop Distortions due to RF components**
  - **Feedback Loop Distortions due to RF components, cable noises**
  - **Beam Noise : 1.2 % in amplitude, dominant frequency 30 kHz**
  - **Chopped Beam**
  - **Higher order modes in passband**

Modeling Issues

System Components : Klystron, Disturbances, Noises, Time Delays

- Noises, Disturbances, Distortions
  - Time Delays : High Frequency Uncertainty
    - Klystron : 150 nsec
    - Waveguide : 116.5 nsec ----- 100ft
    - Feedback cable : 121.0 nsec ---- 100ft
    - DSP, FIR filter, computation time : ~1.0 usec
  - Lorentz Force Detuning : $\Delta f_L \propto E^2$
    - Medium beta : K_L=-2.0±1.0 Hz/(MV/m)^2
    - High beta : K_L=-1.2±0.6 Hz/(MV/m)^2
    - Mechanical Time Constant : τ_m=1.0 msec

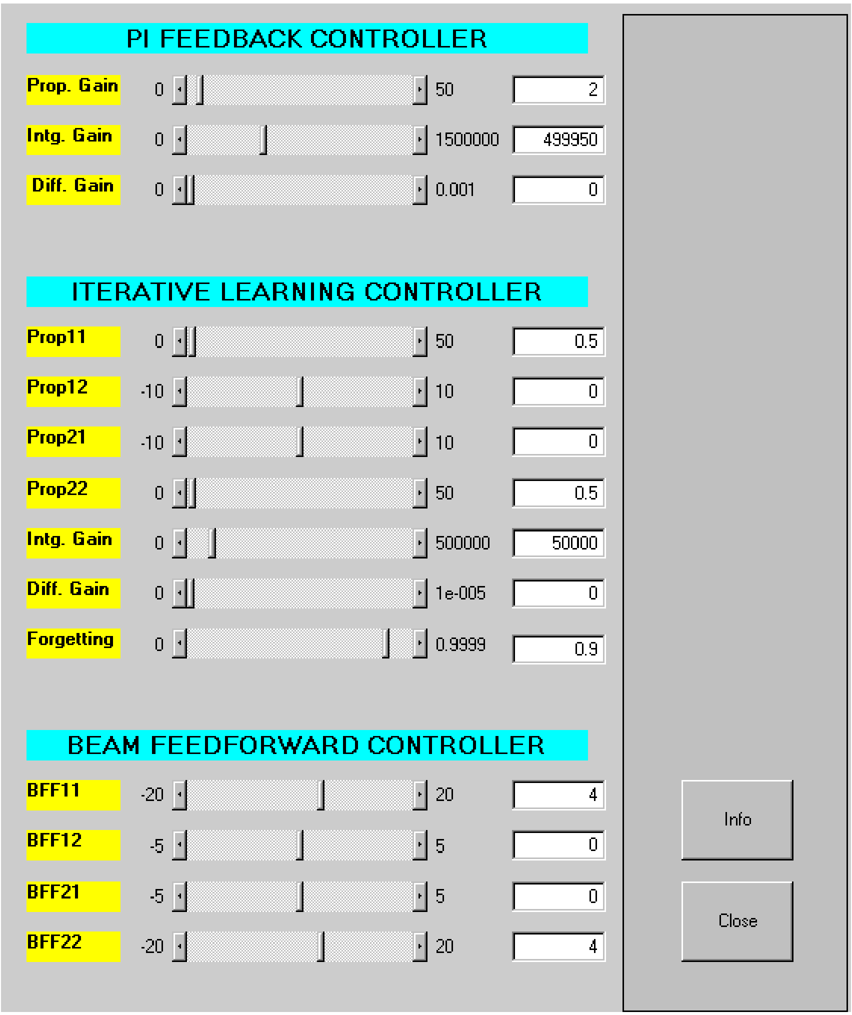
$$\Delta\dot{\omega}_L = -\frac{1}{\tau_m}\Delta\omega_L - \frac{2\pi}{\tau_m} K E_{acc}^2$$

$$\Delta\dot{\omega}_L = -\frac{1}{\tau_m}\Delta\omega_L - \frac{2\pi}{\tau_m} K_{LFD} \frac{E_{acc}^2}{V_o^2}(V_I^2 + V_Q^2)$$

  - Microphonics
    - rms value : 9 Hz
    - Worst peak-to-peak : ±100 Hz

Modeling Issues

System Components : Controllers



- Controllers
  - **Transient : ±0.75 %, ±0.75°**
  - **Steady State : ±0.50 %, ±0.50°**
  - **Feedback Controller**
    - **PI Controller C(s)**
  - **Feedforward Controller**
    - **Iterative Learning Controller**
    - **(Beam Feedforward Controller)**

Feedback+Feedforward Controller

Nonlinear Model Simulation

- Feedback Control : PI Feedback
  - Kp=35*I
  - Ki=800,000*I
- Feedforward Control : Iterative Learning Control
  - $K_P^{LFD} = 10I$
  - $K_I^{LFD} = 200{,}000I$
  - Robustness Gain, α=0.6*I
  - forgetting matrix, *f*=0.9*I

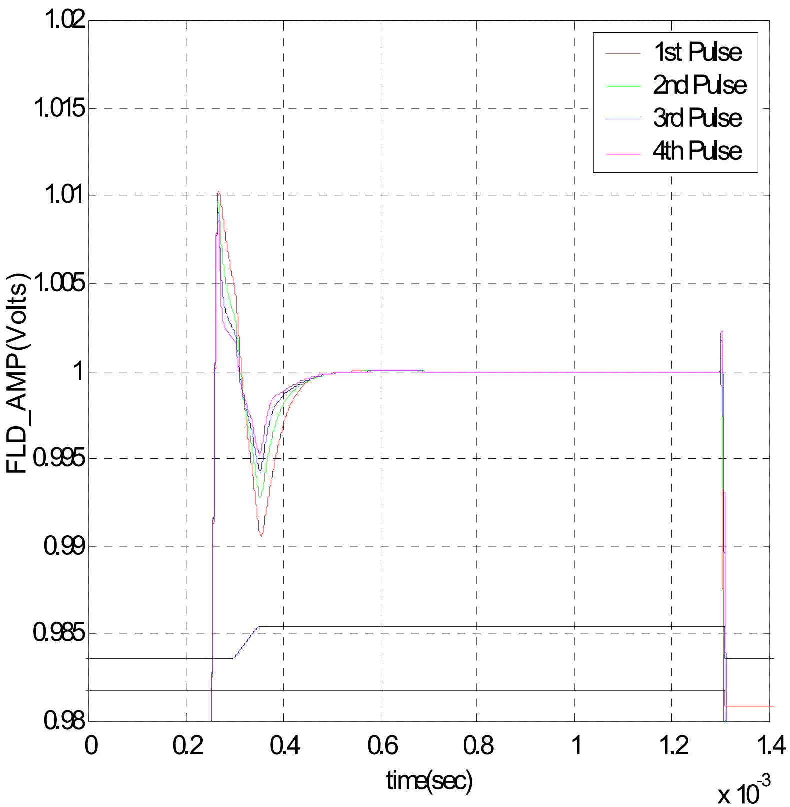
$$U_F^{k+1} = Q\left(f \cdot U_F^{k} + \alpha \cdot LE^{k}\right)$$

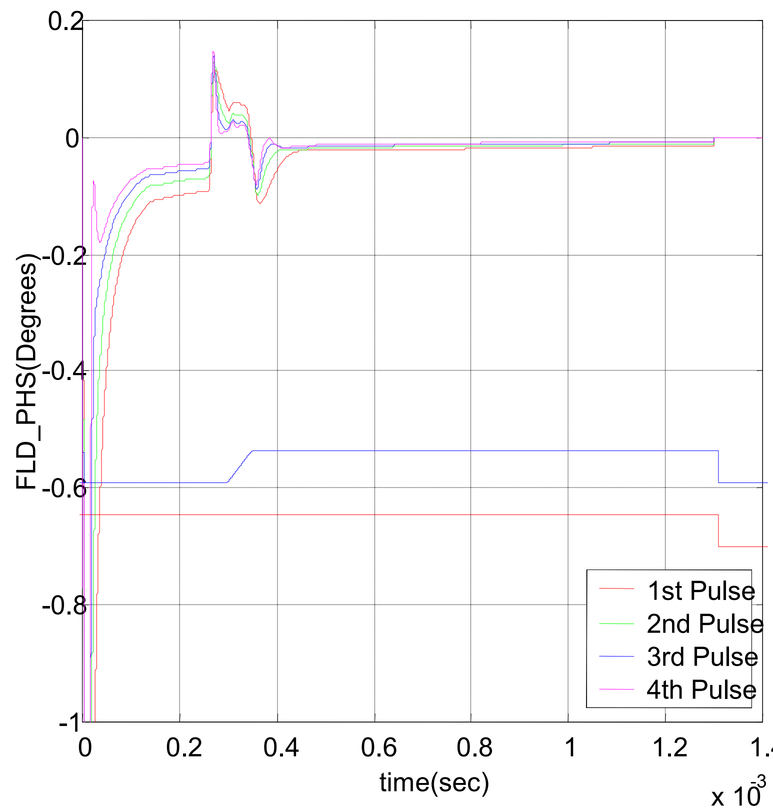
$$L(s) = K_P^{LFD} + \frac{1}{s} K_I^{LFD}$$

Feedback+Feedforward Controller

Nonlinear Model Simulation

- Field Amplitude — Field Phase





Power Control Margin Calculation

Power Control Margin Calculation

$$P_g = P_C \frac{1}{4\beta}\left\{(1+\beta+b)^2 + \left[\frac{2\Delta f_b}{f_{odB}} + \frac{2\Delta f_m}{f_{odB}} + \frac{2\Delta f_L}{f_{odB}} + b\tan\phi_b\right]^2\right\}$$

$$b = \frac{I_b (r/Q) Q_o}{V_C}\cos(\phi_b) \qquad f_{odB} = \frac{f_o}{Q_o}$$

Δf_m :Microphonics Δ f_L : Lorentz Force Detuning

Δ fb : **Synchronous Detuning Against Beam Loading,**

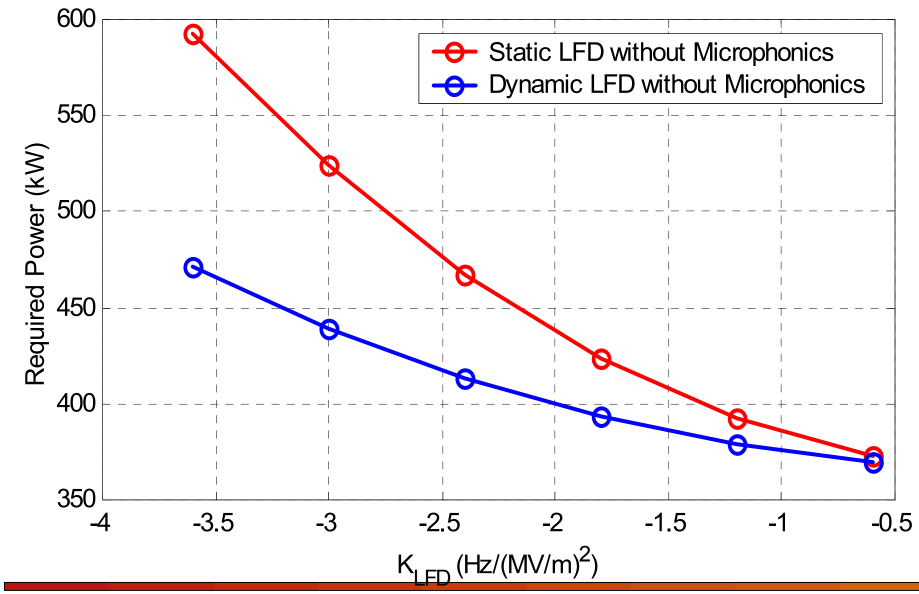
$$\Delta f_b = -\frac{f_{odB}}{2} b \tan\phi_b = -\frac{f_o}{2Q_L}\tan\phi_b$$

$$\Rightarrow \quad P_g = P_C \frac{1}{4\beta}\left\{(1+\beta+b)^2 + \left[\frac{2\Delta f_m}{f_{odB}} + \frac{2\Delta f_L}{f_{odB}}\right]^2\right\}$$

Power Control Margin Calculation

High Beta SRF #70 : Lorentz Force Detuning

K_{LFD} ($Hz/(MV/m)^2$)	Static			Dynamic, 68% at the end of 1.3 msec RF pulse		
	Lorentz Force Detuning (Hz)	Required Power Increase(%)	Total Power (kW)	Lorentz Force Detuning (Hz)	Required Power Increase(%)	Total Power (kW)
-0.6000	-150.6253	1.7083	373.3214	-102.4252	0.7899	369.9506
-1.2000	-301.2505	6.8330	392.1320	-204.8504	3.1596	378.6486
-1.8000	-451.8758	15.3743	423.4828	-307.2755	7.1091	393.1452



* The table does not consider the worst case microphonics -100 Hz $\Delta f = \delta f_L$

* When -100 Hz microphonics is considered together, the frequency sihft Δf is the sum of Lorentz Force Detuning and Microphonics. The Required power is obtained by referring the figure in the previous slide with the data Δf $\Delta f = \delta f_m + \delta f_L$

Pb=367 kW

E_{acc}=15.8443 MV/m

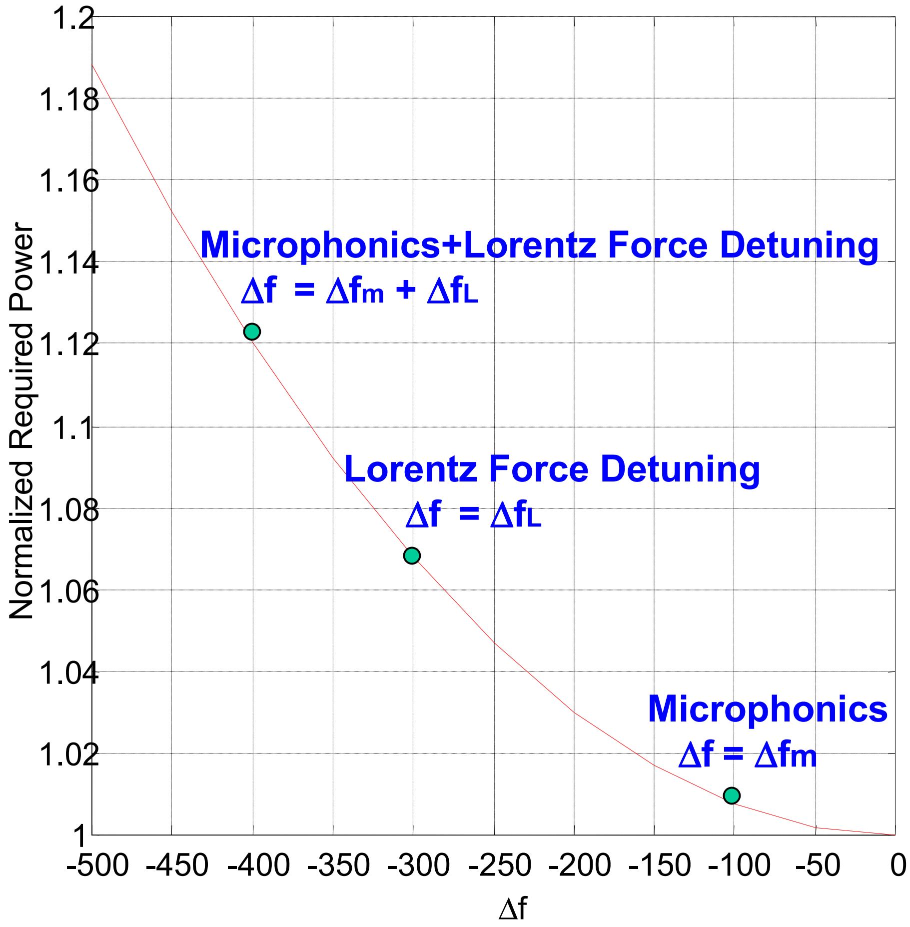
τ_{mech}=1.0 msec

Static $\Delta f_L = -K_{LFD}(Eacc)^2$

Dynamic $\Delta f_L = -0.68 K_{LFD}(Eacc)^2$

Power Control Margin Calculation

High Beta SRF #70



Δf(Hz)	Normalized Required Forward Power when $Q_L=Q_{opt}$
0	1.0000
-50.00	1.0019
-100.00	1.0075
-150.00	1.0169
-200.00	1.0301
-250.00	1.0471
-300.00	1.0678
-350.00	1.0922
-400.00	1.1205
-450.00	1.1525
-500.00	1.1882

Pb=367 kW

E_{acc}=15.8443 MV/m

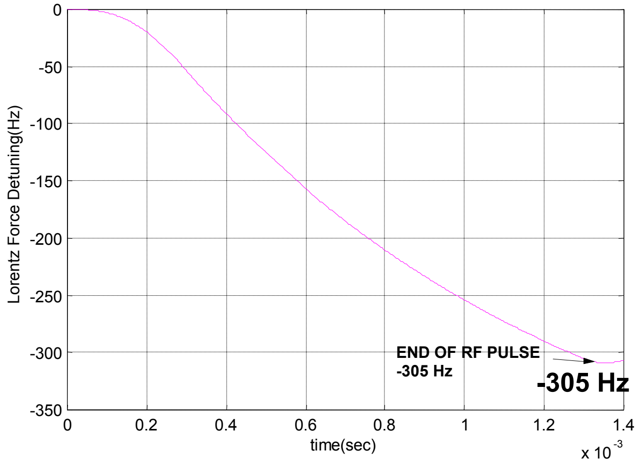
K_{LFD}=-1.2±0.6 Hz/(MV/m)^2

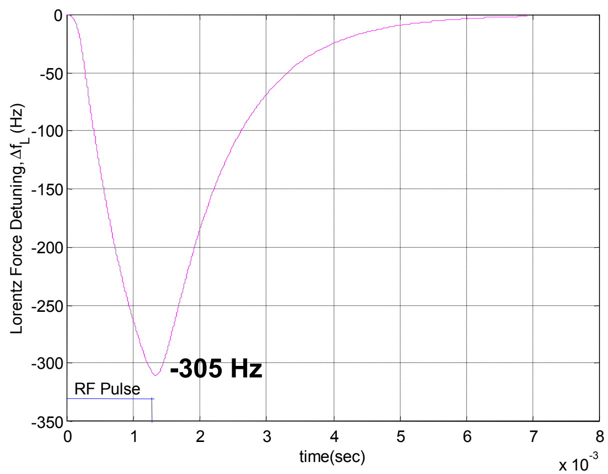
τ_{mech}=1.0 msec

Microphonics=-100 Hz

High Beta SRF #70

SRF Cavity-Nonlinear Model Simulation





Pb=367 kW

E_{acc}=15.8443 MV/m

K_{LFD}=-1.8 Hz/(MV/m)^2

τ_{mech}=1.0 msec

Decay Time =5.8 msec

Microphonics=-100 Hz

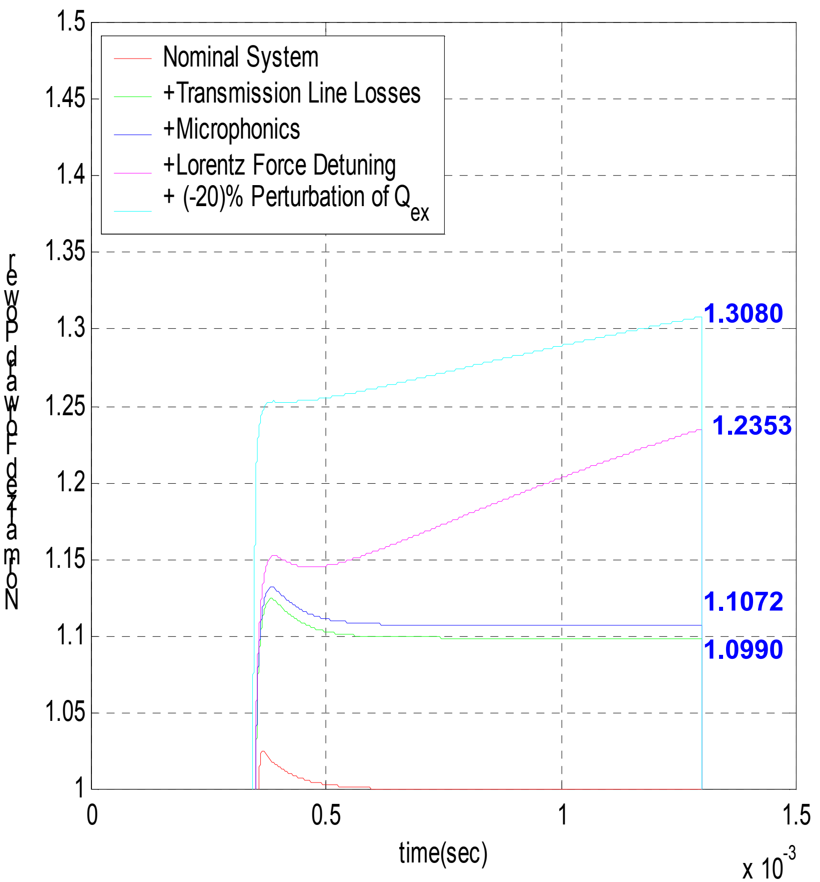
$$\dot{\Delta\omega}_L = -\frac{1}{\tau_m}\Delta\omega_L - \frac{2\pi}{\tau_m}K_{LFD}\frac{E_{acc}^2}{V_o^2}(V_I^2+V_Q^2)$$

High Beta SRF #70

SRF Cavity-Nonlinear Model Simulation

Accumulated Power Margin : + 30.8%

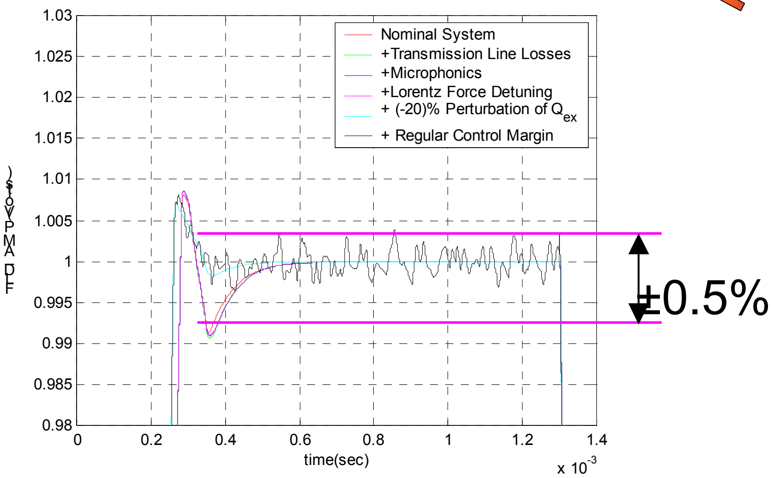
1. For Transmission Line Losses, +9.9% (36.333 kW)
2. For Transmission Line Losses and Microphonics, +10.72% (+39.342 kW)
3. For transmission Line Losses and for Frequency Shift Δf=-405 Hz sum of Lorentz Force Detuning -305 Hz and -100 Hz Microphonics , +23.52% (+86.32 kW)
4. For transmission Line Losses, for Frequency Shift Δf=-405 Hz sum of Lorentz Force Detuning -305 Hz and -100 Hz Microphonics , and for -20% Qext perturbation, +30.80% (+113.04 kW)

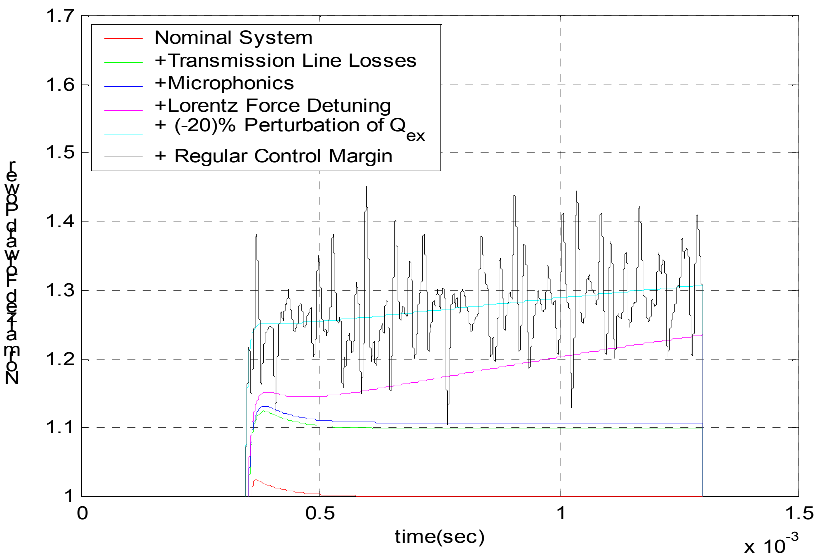


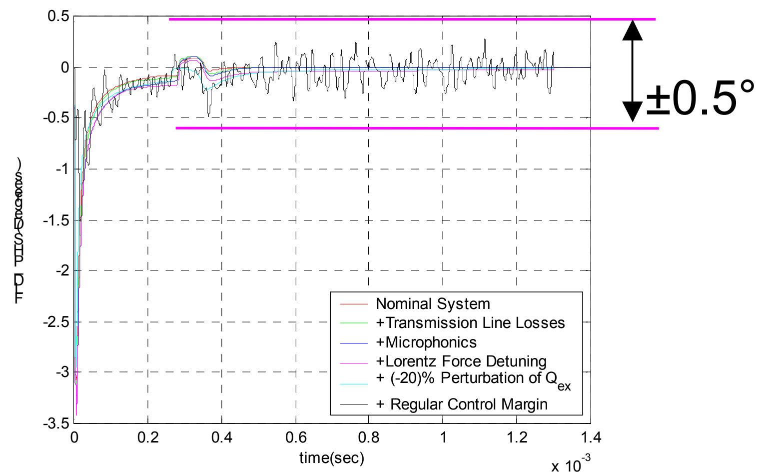
P_b=367 kW
E_{acc}=15.8443 MV/m
K_{LFD}=-1.8 Hz/(MV/m)^2
τ_{mech}=1.0 msec
Microphonics=-100 Hz

The addition of Colored noise at a higher level than expected is still within control limits

- **Assumed Colored noise level is probably high.**
  •Some 'Colored' noise will be 60 Hz related, and therefore repetitive. Feedforward can remove most repetitive noise
  Additional Power Margin for Disturbance and Noise: ~ +9.0%

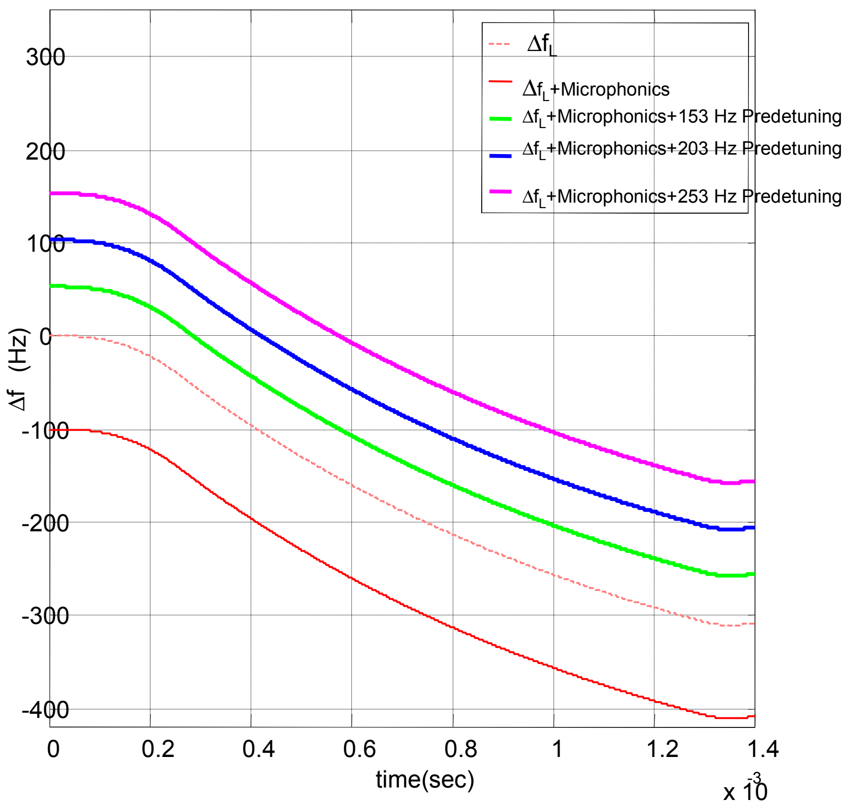


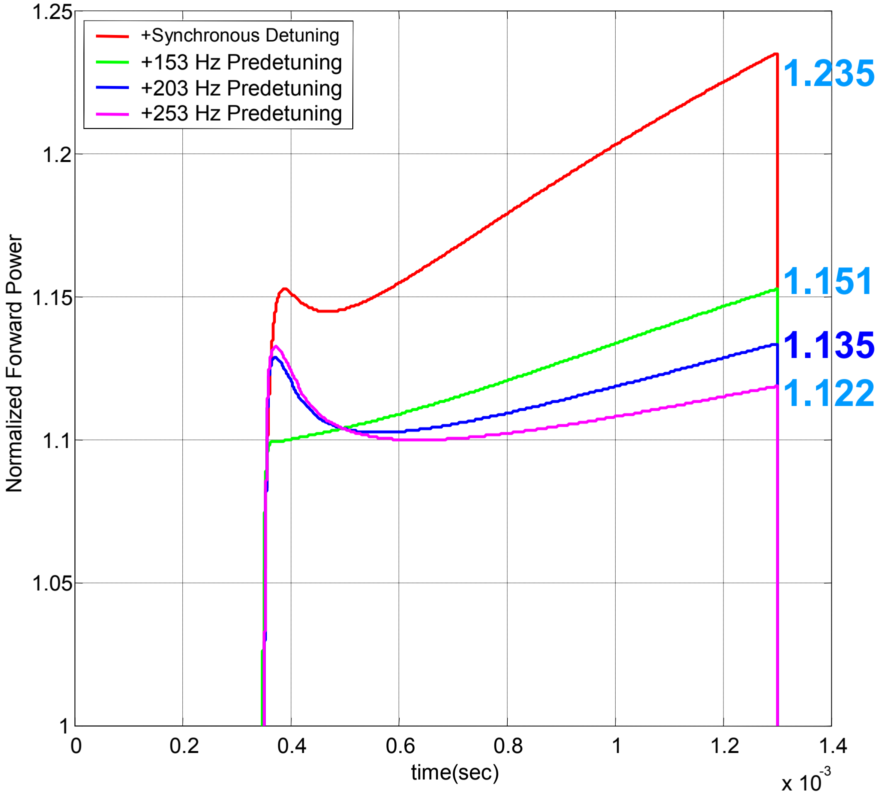




Power Control Margin Calculation

SRF Cavity-Nonlinear Model Simulation With Predetunings for SRF #70





$$\Delta f = (\Delta f_m + \Delta f_L) + \Delta f_{predetuning}$$

Summary

- Modeling
  - PI Feedback Control
  - Feedforward Control : Improve transient Behavior
- Power Control Margin :

	β-0.61	β-0.81
E_{acc} (MV/m)	10.3924	15.8443
K_{LFD} (Hz/(MV/m)^2)	-3.0	-1.8
Dynamic Lorentz Force Detuning (Hz)	-220 Hz (-324 Hz)	-307 Hz (-452 Hz)
Tranission Line Losses	+9.9%	+9.9%
Tranission Line Losses +Microphonics +Lorentz Force Detuning	+18.41 % (Additional 8.51 %)	+23.52 % (Additional 13.62 %)
Tranission Line Losses +Microphonics +Lorentz Force Detuning +(-20)% Q_{ext}	+23.90 % (Additional 5.49 %)	+30.80 % (Additional 7.28 %)
Tranission Line Losses +Microphonics +Lorentz Force Detuning +(-20)% Q_{ext} +Other disturbances and Noises	+32.90 % (Additional 9.0 %)	+39.80 % (Additional 9.0 %)

Agenda Status

CM Interface (Amy Regan) **10:30-11:30**

Cryomodule Interfaces/Interlocks from JLAB assigned to LANL have changed

• Original SNS Interface Parameter List	January 13, 2000
• "Orphan" Signals identified	July 21, 2000
• Meeting at LANL to resolve orphans	November 28, 2000
• Latest Cryomodule Interlock list	January, 2001
• Official Orphan resolution from ORNL	February 15, 2001

Cryomodule Interface/Interlock list from JLAB individually addressed

- 5. Coupling, Qext. ($5 * 10^5 \pm 20\%$) Used to determine the cavity bandwidth associated with the superconducting cavity.
  - **Our modeling shows we can deal with this. However the 20% spread has an impact on the amount of margin we have and hence we cannot push the beam current any higher.**
- 12. Cavity field probe signal and tolerance. (1 ± 2 dB mW/(MV/m)^2)
  - an electric antenna, mounted on the beam pipe adjacent to the end cell at the end opposite to the fundamental power coupler.
    - probe has to be removed from the cavity and remounted after final cleaning, the accuracy with which its coupling can be controlled is limited to ± 2 dB. However, once finally installed and lowered to 2.1 degrees K, this probe is extremely stable in coupling coefficient and phase.
  - **This will be calibrated out.**

= JLAB-provided values and tolerance

= RFCS response/implementation

Cryomodule Interlock list from JLAB individually addressed. Cont'd.

- 13. Interface connector type and location. (SMA-F)

  connector provided on the surface of the cryomodule, and is the connector to which you connect your Heliax cable that goes to your mixer.

  - actual feedthrough is vacuum tight
    - Possible problems: connecting a cable can break the vacuum seal if the center pin does not engage properly; adapter becomes worn through repeated cable connections and disconnections, it can be replaced, whereas replacing the hermetic feedthrough would be a major repair job.
  - **Make sure an adapter is on the connector and provide strain relief.**

Cryomodule Interlock list from JLAB individually addressed. Cont'd.

- 14. Lorentz detuning coefficient, DC (2 ± 1_{max} Hz/(MV/m)^2)
  - coefficient which determines how much the cavity frequency changes between off and on in a continuous wave condition.
- 15. Lorentz time response curve
  - still being calculated, will first be measured when a 1 MW RF source is available to test a CM.
  - It specifies how the resonant frequency of the cavity changes with time for a particular cavity field vs. time profile.
  - RF feed-forward will used to offset this effect, since it is reproducible from pulse to pulse.
  - **Static response - we will preset tuner (by sending it a "DC offset" signal) to offset the Lorentz Force detuning effect. The Lorentz Detuning value has changed over the course of the project. This affects how efficiently we provide power to the cavity, and hence how much beam current we can support.**

Cryomodule Interlock list from JLAB individually addressed. Cont'd.

- 16. Microphonic amplitude limit. (±100 Hz)
  - ± 6 sigma limit on excursions of the cavity frequency associated with externally driven microphonics.
  - essentially random, so dealt with by the feedback circuit. Very high gain here so should be no problem.
  - **This has also been included in our modeling. We will handle it with the feedback control loop, as we have high gain here. Again, however, this eats into our control margin.**

Tuner Implementation

- Mechanical tuner (accordion-like. Directly squeezes the cavities)
  - Motor must be energized. If the motor is turned off, the tuner will expand into a relaxed position.
- ORNL Global Controls (Bob DaLesio, *et al*) responsible for Tuner interface (motor itself is being provided by JLAB (Tom Powers) - "a rather standard 5V stepper motor probably on the order of a few Amps").
- RFCS provides signal via EPICS that indicates f_{Δ} - they translate that to N steps of movement.
- Tuner resolution - each step = **X** Hz
  - Spec right now is 60 Hz, Physicists say we need to get to f_{res} within 50 Hz, so we need resolution of 10 Hz.

Cryomodule Interlock list from JLAB individually addressed. Cont'd.

- 17. Tuner resolution and backlash. (60 Hz, 400 Hz max) The resolution and backlash determine conditions under which the tuner could end up hunting (which is interlocked to inhibit the tuner so it doesn't wear it out mechanically), and will also determine how accurately the resonant frequency can be set.
  - **We need 10 Hz resolution in order to meet $f_{resonance}$ ±50 Hz for commissioning, preloaded for no backlash. Still waiting to hear from JLAB (John Hogan).**
- 18. Tuner tuning rate. (3000 Hz/s minimum)
  - highest rate at which the tuner will respond if it is asked to change frequency. The low level controls should not ask for a higher rate than this.
  - **EPICS will filter/integrate this.**
- 20. Tuner position readback. There is no tuner position readback, so the control circuit that controls the tuner has no way of telling what the cavity resonant frequency is. Hence LLRF simply makes sequential frequency change requests, with iterations depending on differences between the change requested and the change achieved.
  - **We continually send $f\Delta$ information to EPICS on a pulse-to-pulse basis and let them filter it and drive tuner as necessary.**

Cryomodule Interlock list from JLAB individually addressed. Cont'd.

- 23. Inter-cell coupling through beam pipe. (0.30%max, (table)) Just as the coupling between adjacent cells in a cavity is around 1.5%, the coupling between the two end cells in different but adjacent cavities is 0.0016% (note from Ron).
  - This determines the extent to which the field in one cavity is affected by the field in the adjacent cavity.
  - **This could lead to phase error. A work-around may be to commission an entire cryomodule at a time (3 or 4 cavities). Lloyd Young discussed commissioning plans in his PAC'01 paper "A Procedure to Set Phase and Amplitude of the RF in the SNS Linac's Superconducting Cavities."**

Cryomodule Interlock list from JLAB individually addressed. Cont'd.

- 26. Frequencies of non-pi members of fundamental passband. The 5/6 pi mode is close enough to the pi mode in frequency that it can cause control circuit oscillations if not appropriately dealt with in the design of the low level RF system.
- 27. Loaded Qs of non-pi members of fundamental passband. The value for the 5/6 pi mode, along with the frequency, determines how difficult it is for the low level control circuit to avoid problems with this mode.
  - **We filter the data coming in and average over that period of time (in effect we filter out that 800 kHz nearest mode).**

Cryomodule Interlock list from JLAB individually addressed. Cont'd.

- 28. Thermal attenuation stability of ref. probe cable. (±0.04 dB)
- 29. Thermal phase shift stability of ref. probe cable. (±0.25°)
  - cable inside the cryomodule which connects the field probe (parameter 12) to the connector on the surface of the cryomodule (parameter 13). at 2.1 degrees K where it attaches to the cavity (very stable T)
  - cable is thermally connected to the thermal shield (which prevents thermal radiation from the outer wall of the cryomodule from reaching the 2.1 K surfaces). The cable then continues to the outer wall of the cryomodule, which is at room temperature. If the shield and outer wall temperatures were held constant, the attenuation of this cable would be quite stable.
    - present facility specifications: tunnel temperature: ±2.5°F
    - **According to Joe Preble at JLAB, the thermal phase drift of the cable is due to very slowly changing conditions. This should not be a problem. Run cycle to run cycle drift will be calibrated out.**

Cryomodule Interlock list from JLAB individually addressed. Cont'd.

- 119. HOM frequencies. This parameter is relevant to the low level RF system because the field probe couples to beam-induced HOMs as well as to the fundamental frequency. Although the amplitudes of these are small compared to the fundamental mode, the cut-off rate in the beam pipe is lower, and some devices (such as directional couplers) commonly have much stronger couplings than their rated couplings for frequencies above their rated band. The low level RF system needs to avoid being adversely affected by these modes. If necessary, a low pass filter can be used to keep them out of the mixer.
  - **Filtering within the feedback control loop will minimize their effects.**

Cryomodule Interlock list from JLAB individually addressed. Cont'd.

- 137. Transmitted to incident power ratio RF and beam inhibit.

  (if ratio below 10% of nominal for greater than 100 μs, interrupt RF & beam)
- 138. Excess incident power inhibit of beam. (if incident power greater than power transferred to beam plus nominal reflected power by more than 10%, inhibit RF & beam)
  - Goal for both: determine if cavity is going into a thermomagnetic quench condition.
  - **Cavity quenches take 10s of milliseconds to propagate, so inhibiting the RF and beam after the end of a pulse in which it is detected is fine. The RF and beam can generally be turned back on after about 2 seconds, as the quench will have recovered by then. If the quench keeps reoccurring, operator intervention will be needed (e.g., reducing the gradient or processing the cavity).**
  - **Because we run off crest, we have no way of knowing how much power we are putting into the beam (function of cos φ_{beam} and gradient). We will do quench detection in the FRCM DSP based on the difference of the forward and reflected power.**

Agenda Status

Signal Processing (Mark Prokop) 11:30-12:00

SRF Cavity Signal Processing

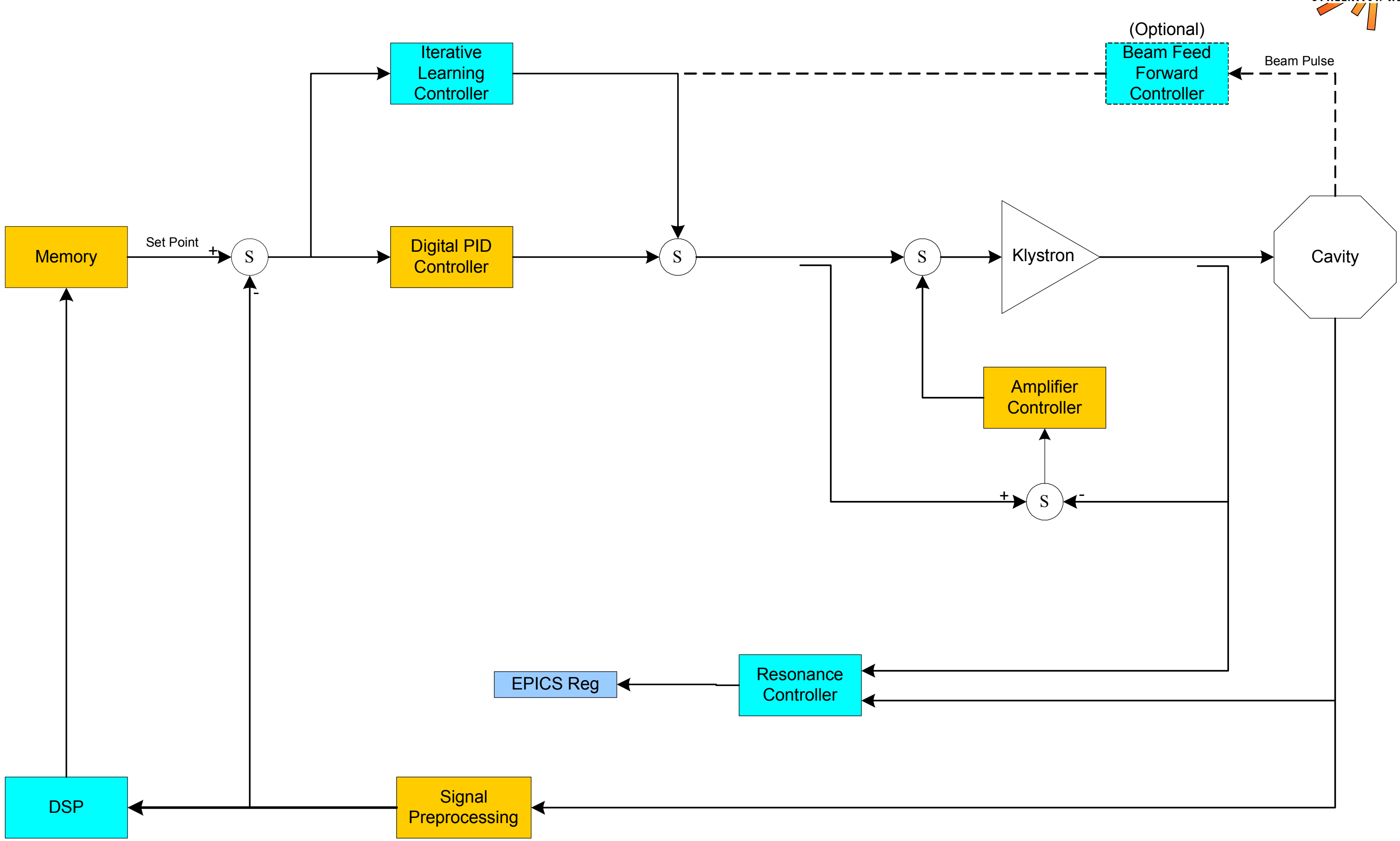
Mark Prokop
Los Alamos National Laboratory, Los Alamos, NM 87545, USA

August 1, 2001

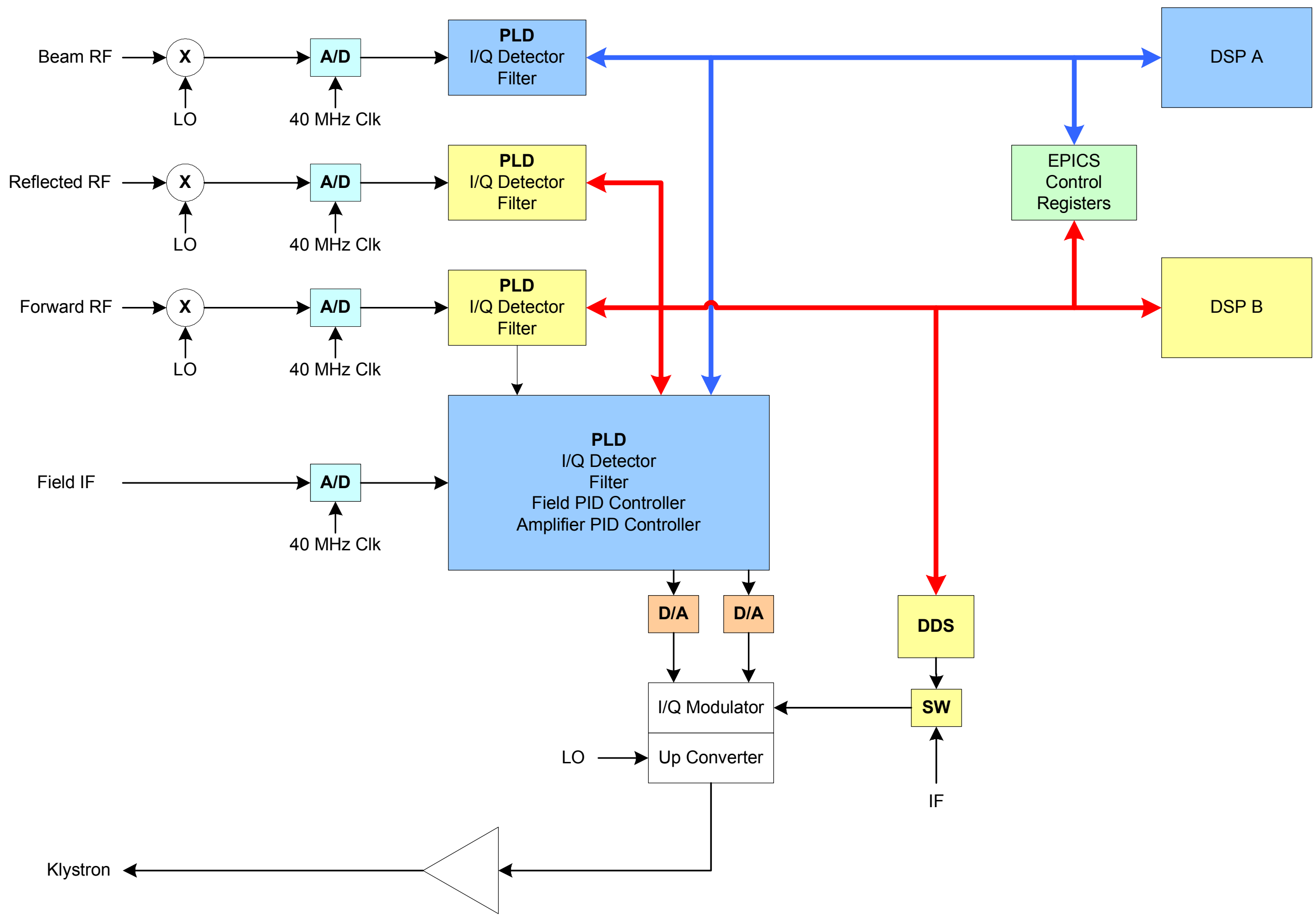
Control System Requirements

• Control Bandwidth:	200 kHz
• Latency of the signal path:	<2 μs
• Controllers:	Digital PID controller Digital Feed-Forward.
• I/Q detector dynamic range:	> 60dB
• I/Q detector accuracy:	< .1%
• History buffers:	Available along the signal paths

Functional Block Diagram of the Digital Control System



Frequency/Resonance Control Module Block Diagram



FRCM Changes Since NC FDR

Functionality Placement

Module	NC FDR	SRF FDR
RF	RF, A/D, D/A, DDS, PLD, Data Memory, History Buffers	RF, A/D, D/A, DDS
DSP	DSP, Processor Memory	DSP, Processor Memory
Motherboard	VXI Interface, Processor Interface, Diagnostics, External Interfaces, Power supplies	VXI Interface, Processor Interface, Diagnostics, External Interfaces, Power supplies, PLD, Data Memory, History Buffers

FRCM Layout – RF and DSP

FRCM Layout – Mother Board

LLRF Signal Processing

Function	NC	SRF
Data Preprocessing •I/Q Extraction •Filtering •Rotation	 •Fixed I, Q, -I, -Q •34-tap FIR •2x2 Arbitrary	 •Fixed I, Q, -I, -Q •34-tap FIR •2x2 Arbitrary
Field Control •Set Point Mode •PID Controller •Rotation •*Field Protection* •Feed Forward Controller •Mode Control	 •Fixed or Adaptive Trajectory •Programmable Gains •2x2 Arbitrary •Loop Saturation, Hard & Soft Limits •Iterative Learning (Beam or Error) •8 modes	 •Fixed or Adaptive Trajectory •Programmable Gains •2x2 Arbitrary •Quench, Loop Saturation, Hard & Soft Limits •Iterative Learning (Beam or Error) •8 modes
Amplifier Control •Filtering •PID Controller •Protection	 •68-tap FIR •Programmable Gains •Loop Saturation	 •68-tap FIR •Programmable Gains •Loop Saturation
Resonance Control •*Coarse Tuning* •*Fine Tuning* •*Verification* •Control Output	 •FWD Max/REFL Min Phase •Admittance •Admittance •EPICS Register, Analog output	 •Frequency Sweep •Phase RF Only Tune / Calibrate Beam Only •Cavity Decay •EPICS Register, Analog output

SRF Resonance Control Requirements

- Tuning: $F_0 \pm 50$ Hz
- Provide Error via EPICS register

SRF Resonance Coarse Tuning Algorithm (Commissioning)

- Set RF Power to 50% Field Strength
- Frequency Sweep with adaptive step size
- Tune Cavity to within 1 kHz of F_0

SRF Resonance Fine Tuning Algorithm (Commissioning)

- Full RF power
- Measure Phase shift wrt Reference
- Tune Cavity within ±50 Hz (1° of Cavity field phase shift)
- Measure Beam only response of Cavity
- Measure phase of cavity
- Calculate amplitude calibration factors

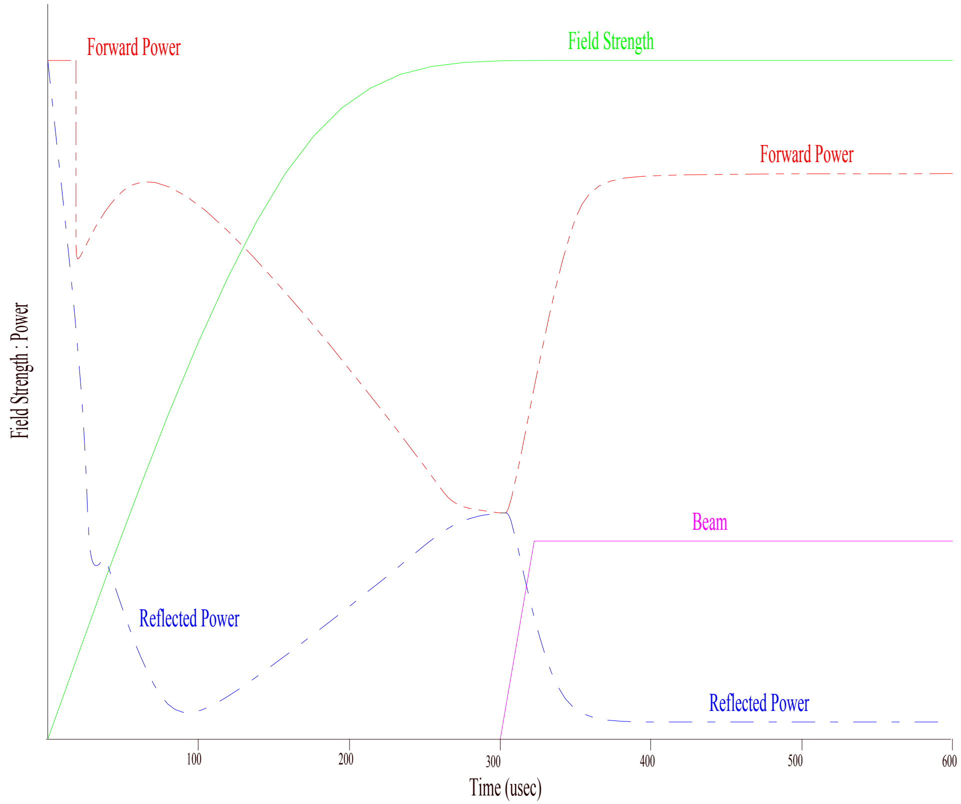
SRF Resonance Verification Algorithm (Operation)

- Calculated on an individual pulse basis
- No special modes required
- Measure Cavity response after RF is turned off
- Calculate phase shift

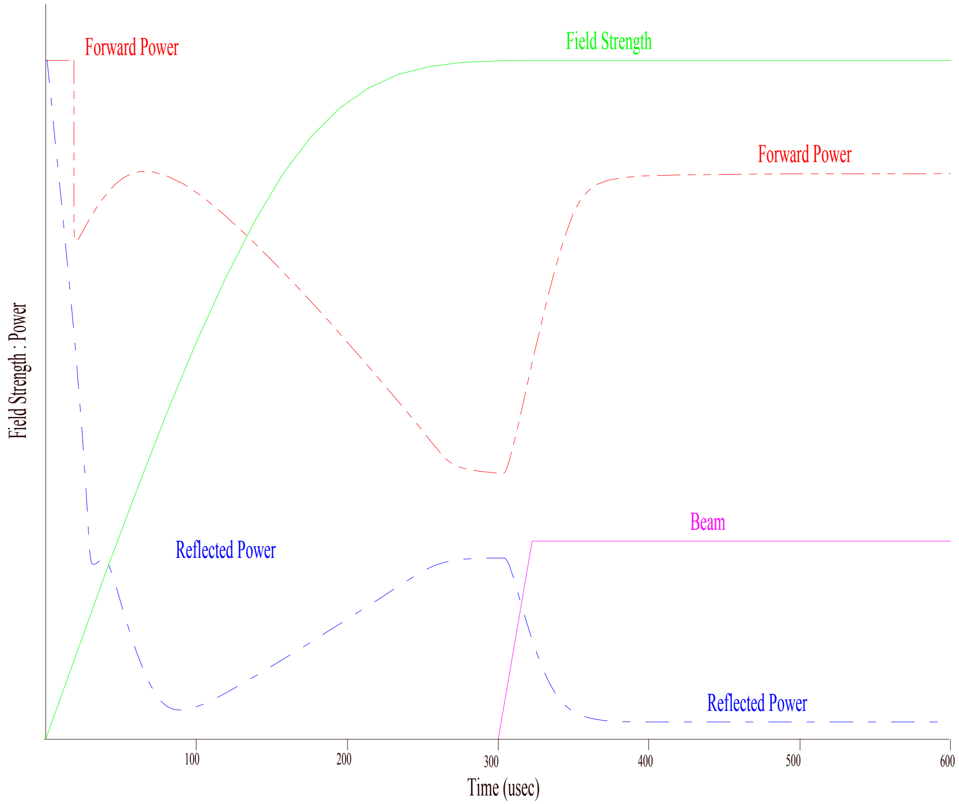
SRF Field Control Requirements

- Field Control
- Operational Modes: 8
- Operational modes are updated through IOC
- Quench Protection

SRF Quench Protection - Normal



SRF Quench Protection - Quench



SRF Quench Protection Algorithm

- Implemented in PLD
- Comparison of Forward to Reflected Power levels prior to Beam
- EPICS programmable threshold
- Set Quench Error
- Terminate Beam and RF

SRF Cavity Signal Processing Summary

- Hardware is the same for both NC and SRF
- EPICS programmable constants control system performance
- Cavity-type specific resonance algorithms implemented in combination of programmable logic and DSP software
- Quench detection implemented in programmable logic
- Maintainability enhanced with common hardware
- Reliability enhanced by built-in test and calibration functions

Agenda Status

Global Controls (Kay-Uwe Kasemir)	12:45-1:00

SNS LLRF Control System
(Superconducting)

August 2001

Kay-Uwe Kasemir

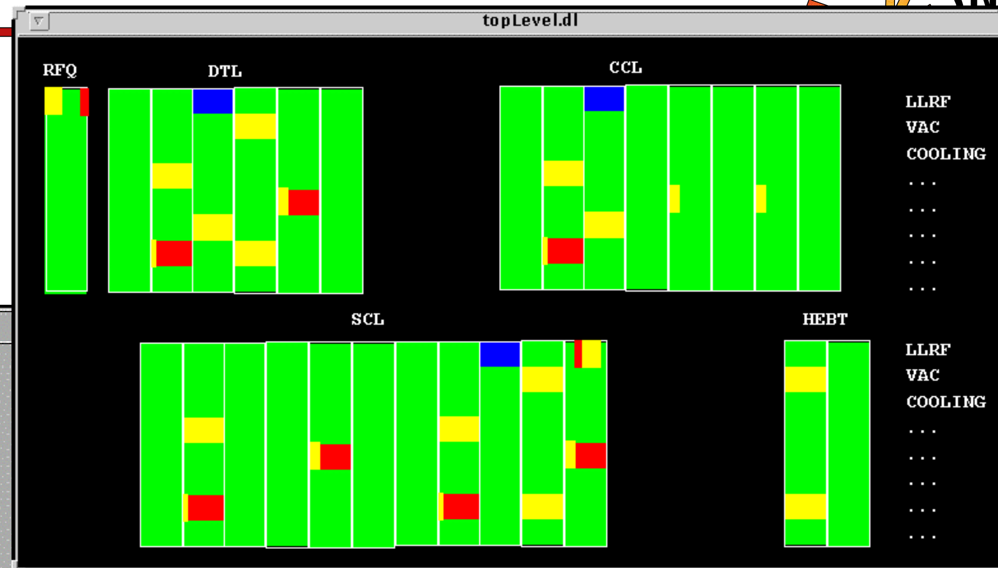
SNS-4

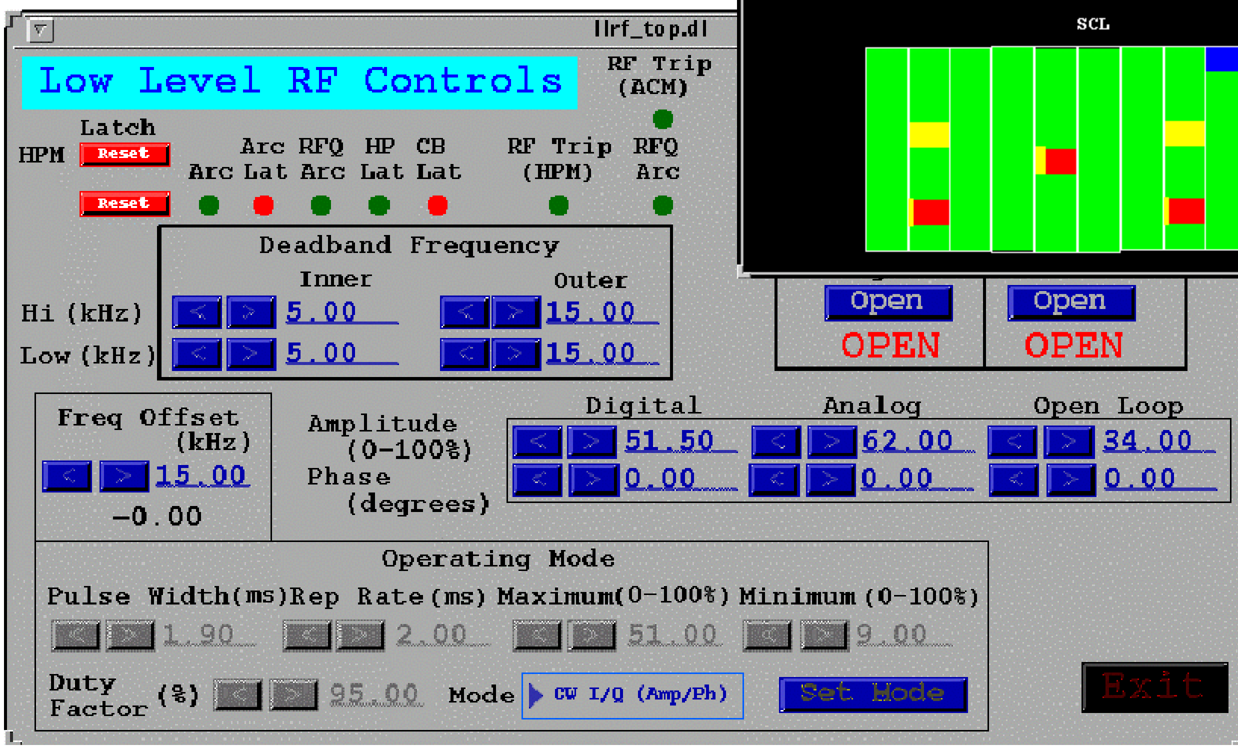
LLRF IOC & Operator Interface

- IOC
  - SNS Standard CPU on VXI adapter (MVME2100, PPC)
  - EPICS base software:
    periodic scanning (60Hz), sequential automation
  - Custom software for LLRF modules: HPM, CDM, FRCM
- Operator Interface
  - Edm, StripTool, Alarm Handler: operator displays
  - Archiver
  - Matlab, …

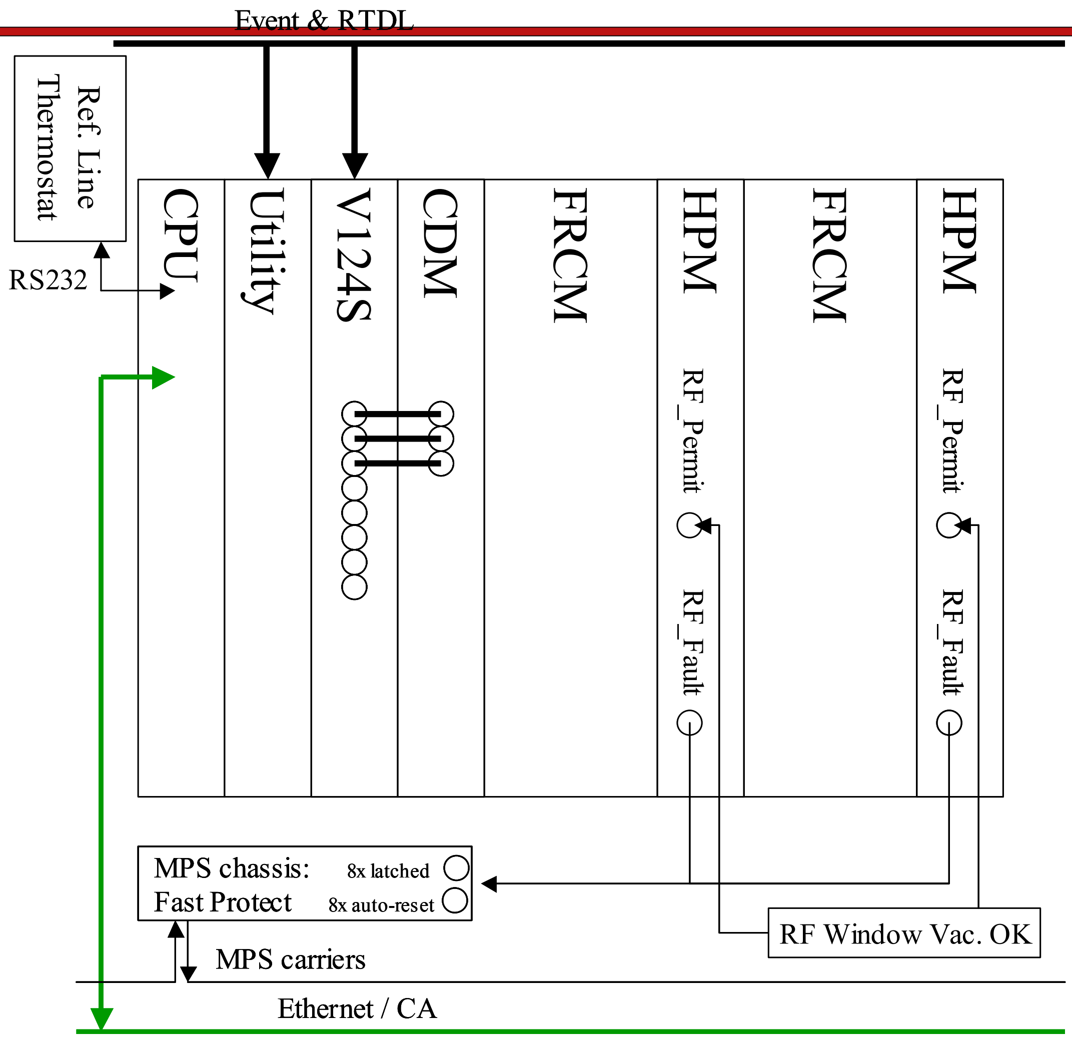
Operator Screens

- Top level
- …
- Detail





LLRF IOC



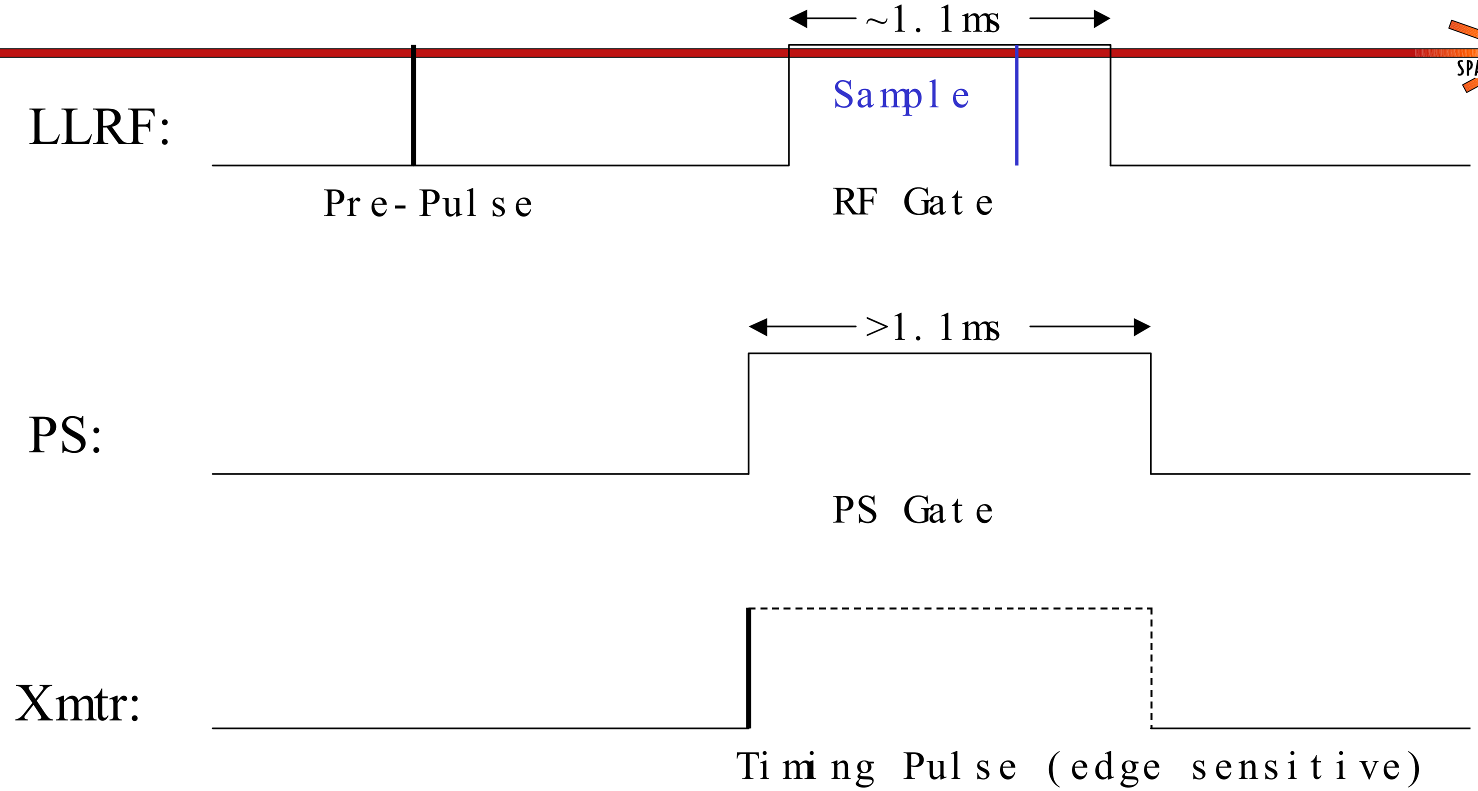
Event & RTDL
Ref. Line Thermostat
RS232
CPU
Utility
V124S
CDM
FRCM
HPM
RF_Permit
RF_Fault
FRCM
HPM
RF_Permit
RF_Fault
MPS chassis:
Fast Protect
8x latched
8x auto-reset
RF Window Vac. OK
MPS carriers
Ethernet / CA

Interfaces

From	Description
Controls	Ethernet to controls subnet
RTDL/event link	Time & date for IOC
	last pulse good/bad, mode (aka Pulse ID) for FRCM
	timing signals for CDM
Vacuum	Hardware RF Permit (TTL line) into HPM
HPRF	Arc detect inputs: HPM reacts to arcs, Xmtr group builds detection unit.
Diagnostics	Beam feed forward data (coax)
RCCS, HPRF, Cryo.	Signals that combine into Software RF permit: RF Window cooling OK, coupler inner conductor flow & temp, coupler DC Bias OK, cryo. status, …
Internal to LLRF	RS232 for reference line's temperature control box

To	Description
MPS (in HPRF)	RF Fault into Fast Protect/Beam Permit
RCCS (NC), HPRF (SC)	Cavity resonance freq. Error (CA)
HPRF	"Drive" for Transmitters (coax)
Cryogenics (SC)	Computed RF power sent to the cavity
Diagnostics	2.5 MHz RF Reference line
Internal to LLRF	Internals of LLRF to control room displays

Timing



- V124S generates programmable TTL pulses from SNS event link
- LLRF IOC provides FRCM with "Pulse ID" and "Previous Pulse Status" from RTDL @ 60Hz.

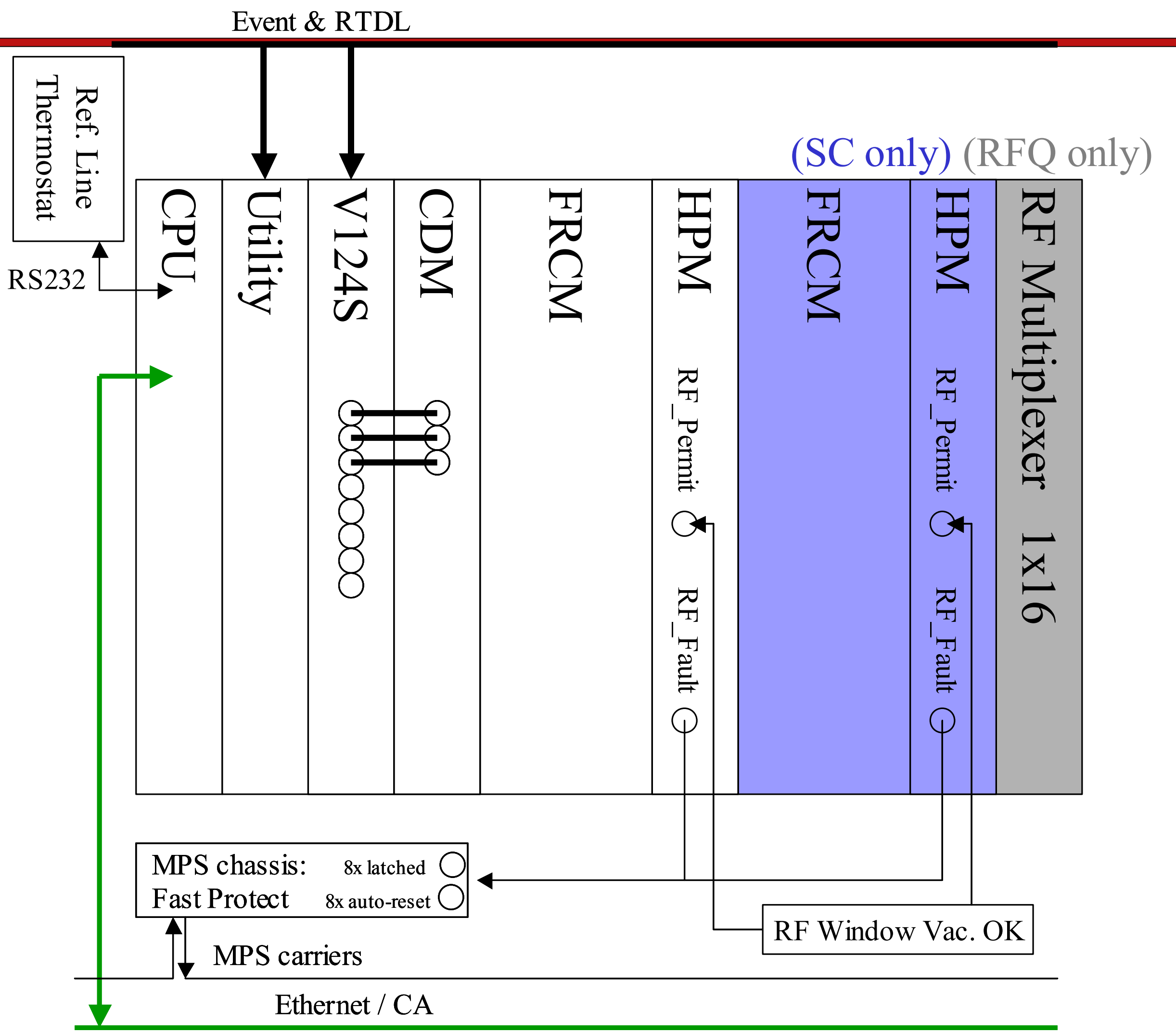
Issues

- RTDL/Event Link, MPS
  - Will be programmable, details still vary
- Software requirements follow module design and testing
  - Attempt to e.g. settle register maps while boards being built
- Requirements for sampling & viewing waveforms
  - Which ones?
  - Not continuously but “armed” for next or given beam pulse?
- Other issues?

- End –

Reserve slides follow

LLRF IOC: NC vs. SC



RF Permit

RF Permit Input	Quality	Details
RF Window Vac.	HW/TTL	Uses the RF Permit hardware input? Unclear: Is there a 10 msec response time from the vacuum gauges?
RF Window cooling	Soft	Slow enough to use software: Signals are combined into “Soft RF Permit”
Coupler inner conductor flow, in/out temperature		
Coupler DC Bias		
Cryo. status		
Waveguide pressure		
… more		
RF Fault Output		**Details**
HPM “RF Fault”	HW/TTL	Wired into MPS “Fast Protect”, latching input (maybe later to auto-rest). MPS programming can mask it out or use it to cut beam

PPC CPU Performance

- Time critical task:
  - For each beam pulse, get this from the utility board into the FRCM:
    - Pulse ID (8 possible values)
    - Last Pulse OK/aborted
  - This is to happen within ~4ms at 60hz/120hz

- Provided by Noboru Yamamoto (KEK, Japan):
  - Interrupt latency, including simple ISR: <10 μs
  - EPICS record processing: ~20 μs

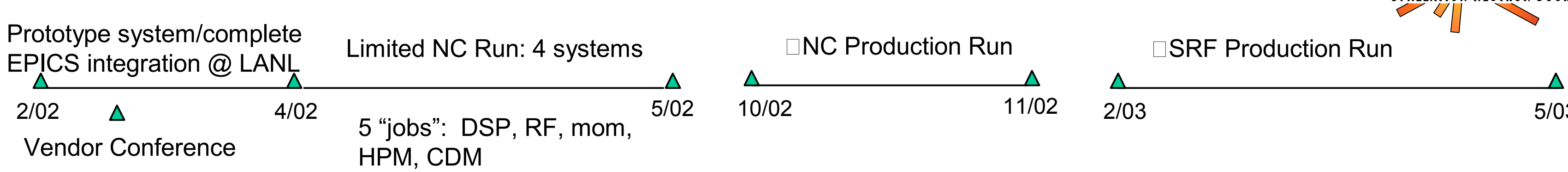
Orphan Signals Inherited by HPRF IOC

- Per SC Klystron (~81)
  - Stepper motors for tuning the cavity
  - Window IR Detector, 24mA Thermocouple and IR test source
  - Coupler inner conductor in, out temp, 0..24V
    - Two thermocouple inputs, one 0..10V flow readback, calculate T_{out}-T_{in} and P_{diss}
(Nobody is pumping the water, so there is no flow!)
  - Coupler Window Heater: "Output", "Power", "On/Off", "Status"
  - Coupler DC bias:
HV power supply: 0..10V setpoint, 0..10V voltage readback, 0..10V current readback, 1 binary in for PS status.
(No one is providing the power supply!)
- Plan: handle all but motors via Beckhoff I/O.

Agenda Status

Schedule (Amy Regan)	**1:00-1:15**

Preliminary Schedule



- RFQ system integrated at LANL then delivered to ORNL
  - Ready to go 6/02 at ORNL (install in May)
- DTL-3 ready to go at ORNL 6/02
- JLAB Test Stand Proto 9/02
- DTL-1 ready at ORNL 12/02
- CCL-2 1/03
- CCL-3 3/03
- CCL-4 5/03
- CCL-1 7/03
- DTL-2 5/03
- DTL-4-6 10/03

33 Medium Beta SRF 2/04
24 High Beta SRF 5/04
24 High Beta SRF 5/04

VXIbus Module Manufacturing Details

NC: 1 RFQ, 6 DTL, 4 CCL, 2 HEBT, 1 test stand, no spares ⇒ 3 modules/sys.
SRF: 81 cavities, 1 test stand, no spares ⇒ 2.6 modules/system

1. INITIAL FABRICATION & TESTING RF Control System

Prototype Designs & Fabrication at LANL
Complete documentation for external manufacture and test

<u>CONTRACT MANUFACTURER SELECTION</u>

Specifications

100% Inspection
IPC 610 CLASS 3

Capabilities Required

Surface Mount Technologies
Ball Grid Array Application & Inspection with x-ray camera
Purchasing Components / Kitting
Cable Assemblies
Full Functional Testing

Resources (Albuquerque)

Sparton	L & L
Delta Group	MPC Technologies

2. LIMITED PRODUCTION RUN NC Linac RF Control Systems
3. PRODUCTION RUN NC Linac RF Control Systems
4. PRODUCTION RUN SRF Linac RF Control Systems

VXIbus Production Module Testing Details

Module Manufacturer will perform Bed of Nails test (continuity, voltages, etc.)

Same, or other, Contract Manufacturers with RF/Digital Testing capabilities exist in Albuquerque. (as we select vendor for PCB manufacture we will weigh their ability to perform follow-on full-functional testing as well. More efficient than going to different test vendor).

Our plan - Have Contract Manufacturer perform full-functional test.

We will provide detailed Test Procedures.

Tested modules will be shipped directly to ORNL.

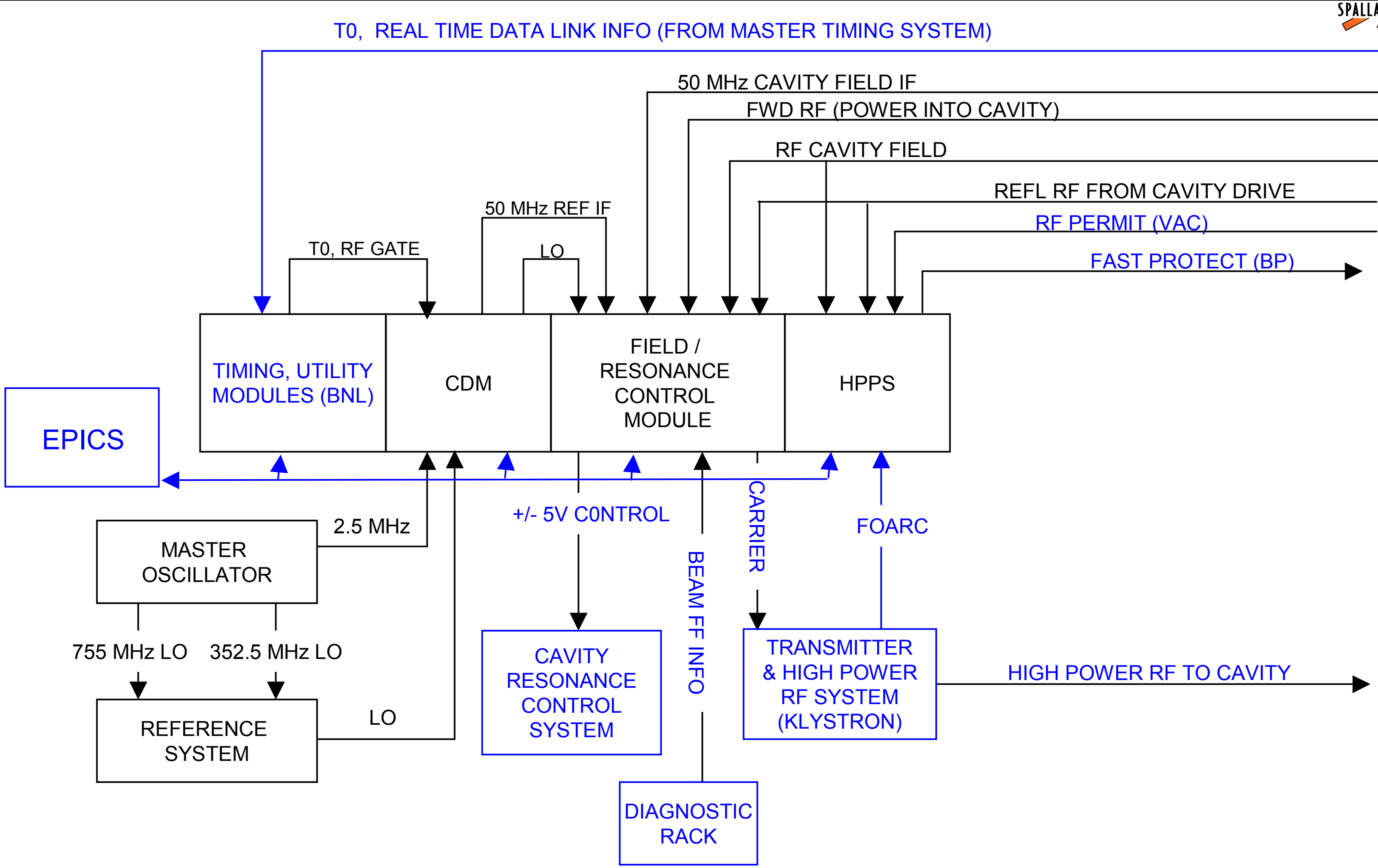
Backup plan - we perform testing at LANL, with support from ORNL. However, this is more time-intensive, and not nearly as cost-effective.

Agenda Status

Wrap-up	**1:15-1:30**

RFCS interfaces with a variety of external systems.

This implies much more involvement of RFCS personnel over other RF people during beam startup.



Summary

- SRF Linac RFCS hardware designs same as those for NC Linac RFCS.
  - Printed Circuit Boards almost 100% complete
  - Same design means large quantity parts cost discounts
- SRF/NC differences in software and firmware
- CM Interfaces - we're aware of and incorporating into our system
- Modeling continues. Cavity parameters not completely settled. So far impact has not affected our design.