LLRF for ILC

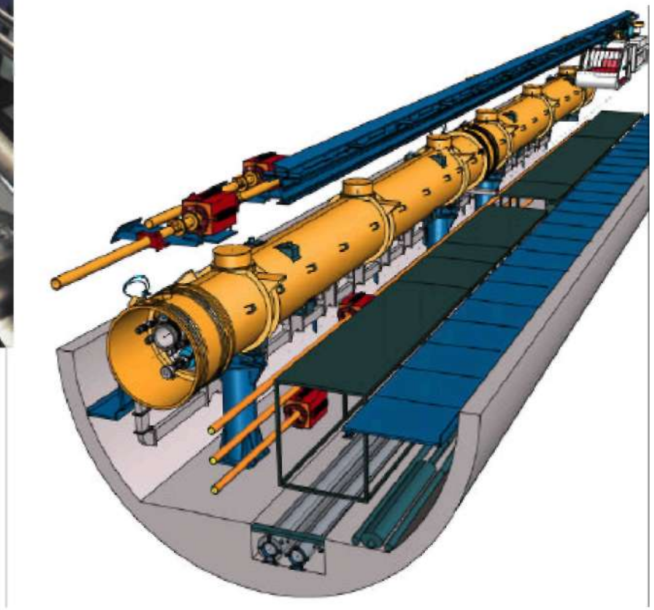
S. Simrock, B. Chase
GDE

Requirements for ILC

- CM energy: 500 GeV. Range 200 - 500 MeV. Upgradeability to 800 GeV
- Luminosity and reliability of the machine should allow L_{eq} = 500 fb^{-1} four years
- Energy scans between 200 GeV and 500 GeV. Energy change should take less than 10% of data taking time.
- Beam energy stability and precision should be below the tenth of percent level

RF Systems for ILC

- e^- and e^+ source
- Injectors
- Damping Rings
- Main Linacs
- Crab cavities at IP



LLRF Requirements

- Maintain Phase and Amplitude of the accelerating field within given tolerances to accelerate a charged particle beam to given parameters
  - up to 0.5% for amplitude and 0.03 deg. for phase

- Minimimize Power needed for control
  - RF system must be reproducible, reliable, operable, and well understood.

- Other performance goals
  - build-in diagnostics for calibration of gradient and phase, cavity detuning, etc.
  - provide exception handling capabilities
  - meet performance goals over wide range of operating parameters

Amplitude and Phase Stability

- Specification for LLRF Stability derived from Beam properties
  - Energy spread (intra-bunch, bunch-to bunch, long-term)
  - Intra-bunch 5e-4 => desired bunch-to-bunch same order (5e-4) to limit chromatic effects (=> emittance growth)
  - Long term (usually time scale for thermal drift => beam based feedback
  - Emittance (can increase as result of chromatic effects)
  - Arrival time jitter (will reduce luminosity)

Requirements for Main Linac

	phase tolerance limiting luminosity loss (deg)	phase tol. limiting incr. in energy spread (deg)	amplitude tolerance limiting luminosity loss (%)	amplitude tolerance limiting increase in energy spread (%)
correlated BC phase errors	.24	.35		
uncorrelated BC phase errors	.48	.59		
correlated BC amplitude errors			0.5	1.8
uncorrelated BC amplitude errors			1.6	2.8
correlated linac phase errors	large	.36		
uncorrelated linac phase errors	large	5.6		
correlated linac amplitude errors			large	.07
Uncorr. linac amplitude errors			large	1.05

Summary of tolerances for phase and amplitude control. These tolerances limit the average luminosity loss to <2% and limit the increase in RMS center-of-mass energy spread to <10% of the nominal energy spread.

Ref. Mike Church

Requirements for Crab Cavity

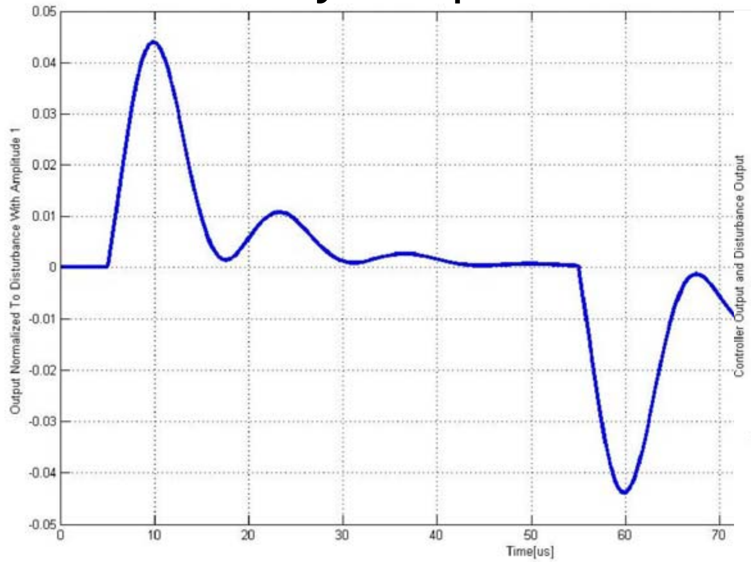
	timing tolerance limiting luminosity loss to < 2% (ps)	amplitude tolerance limiting luminosity loss to <2% (%)
RMS beam timing jitter	0.67	
RMS beam energy jitter		0.29
RMS cavity timing jitter (uncorrelated)	0.043	
RMS cavity timing jitter (anticorrelated)	0.032	
RMS cavity amplitude jitter		4.3

Summary of tolerances for crab cavity timing and amplitude control, and beam timing and energy for 20 mrad crossing angle. Considered separately, each of these tolerances will limit the average luminosity loss to <2%.

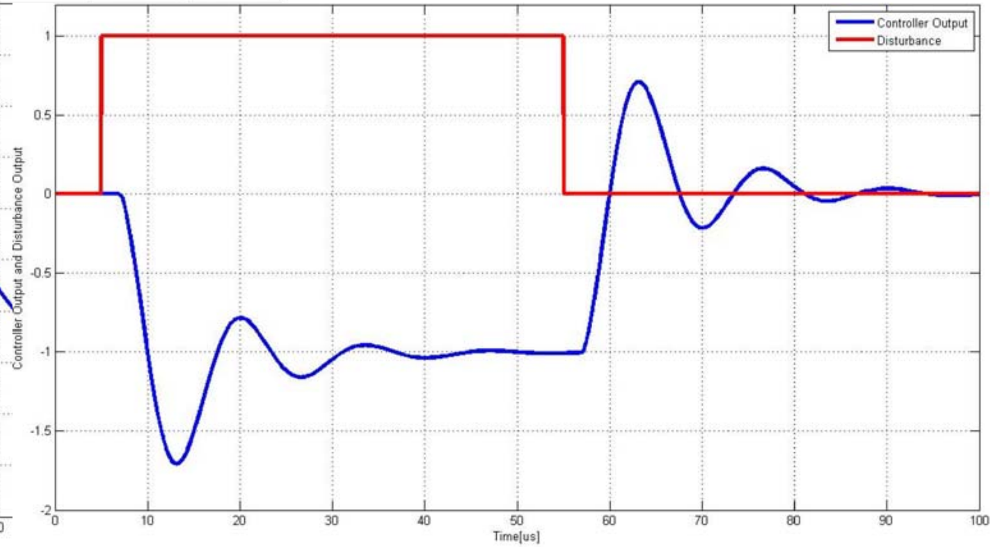
Ref. Mike Church

Crab Cavity Control Simulation

Cavity Response



Disturbance and Controller Response



Cavity response to beam loading
Klystron in linear region
Voltage error: 4.5% of disturbance

Cavity BW : 2kHz

System Group Delay: 2 us

Proportional gain : 31

Integral gain : 2500000

CL Bandwidth: 62kHz

Scope of Main Linac LLRF

total number of klystrons / cavities per linac	~ 350/ 8,400
per rf station (klystron):	
# cavities / 10 MW klystron	~ 24
# of precision vector receivers (probe, forward, reflected power, reference line, beam)	~90
# piezo actuator drivers / motor tuners	~ 24/24
# waveguide tuner motor controllers	~ 24
# vector-modulators for klystron drive	1
Total # of meas. / control channels per linac	~30,000 / ~30,000

Requirements

- Reliability
  - not more than 1 LLRF system failure / week
  - minimize LLRF induced accelerator downtime
  - Redundancy of LLRF subsystems
  - ...
- Operability
  - “One Button” operation (State Machine)
  - Momentum Management system
  - Automated calibration of vector-sum
  - ...
- Reproducible
  - Restore beam parameters after shutdown or interlock trip
  - Recover LLRF state after maintenance work
  - ...

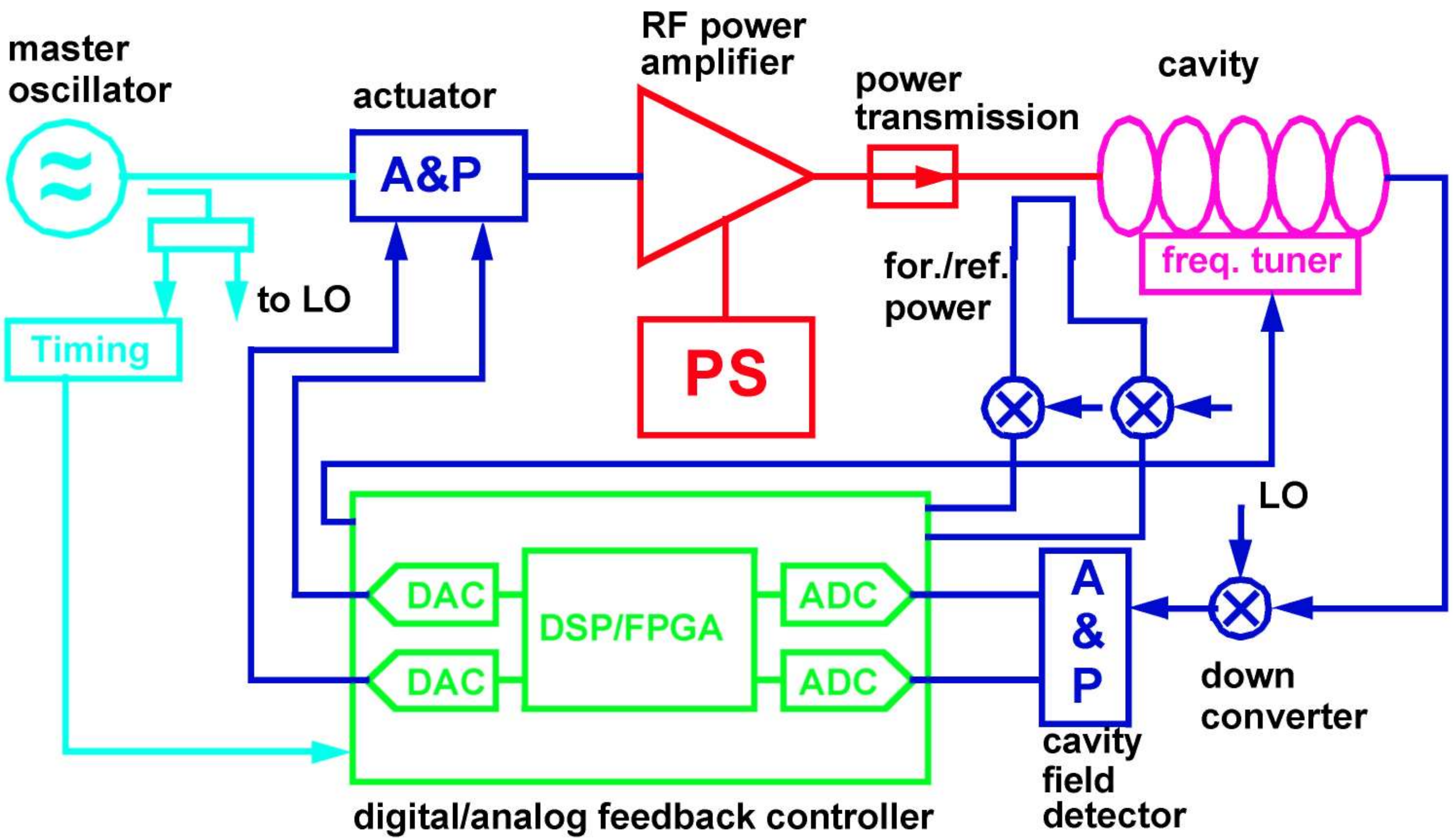
Requirements

- Maintainable
  - Remote diagnostics of subsystem failure
  - “Hot Swap” Capability
  - Accessible Hardware
  - ...
- Well Understood
  - Performance limitations of LLRF fully modelled
  - No unexpected “features”
  - ...
- Meet (technical) performance goals
  - Maintain accelerating fields - defined as vector-sum of 24 cavities - within given tolerances
  - Minimize peak power requirements
  - ...

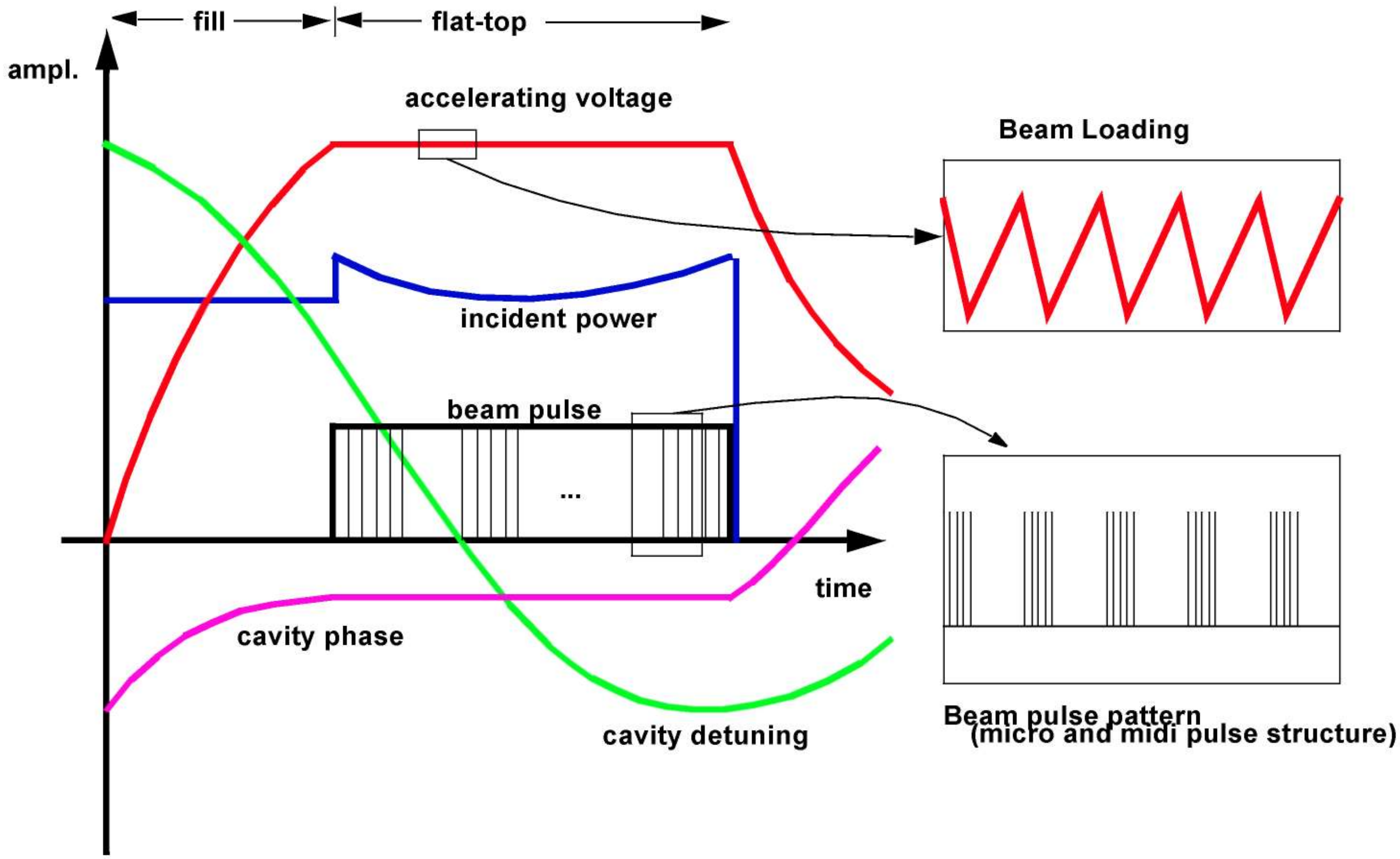
Sources of Perturbations

o <u>Beam loading</u>	o <u>Cavity dynamics</u>
- Beam current fluctuations	- cavity filling
- Pulsed beam transients	- settling time of field
- Multipacting and field emission	
- Excitation of HOMs	o <u>Cavity resonance frequency change</u>
- Excitation of other passband modes	- thermal effects (power dependent)
- Wake fields	- Microphonics
	- Lorentz force detuning
o <u>Cavity drive signal</u>	
- HV- Pulse flatness	o <u>Other</u>
- HV PS ripple	- Response of feedback system
- Phase noise from master oscillator	- Interlock trips
- Timing signal jitter	- Thermal drifts (electronics, power
- Mismatch in power distribution	amplifiers, cables, power
	transmission system)

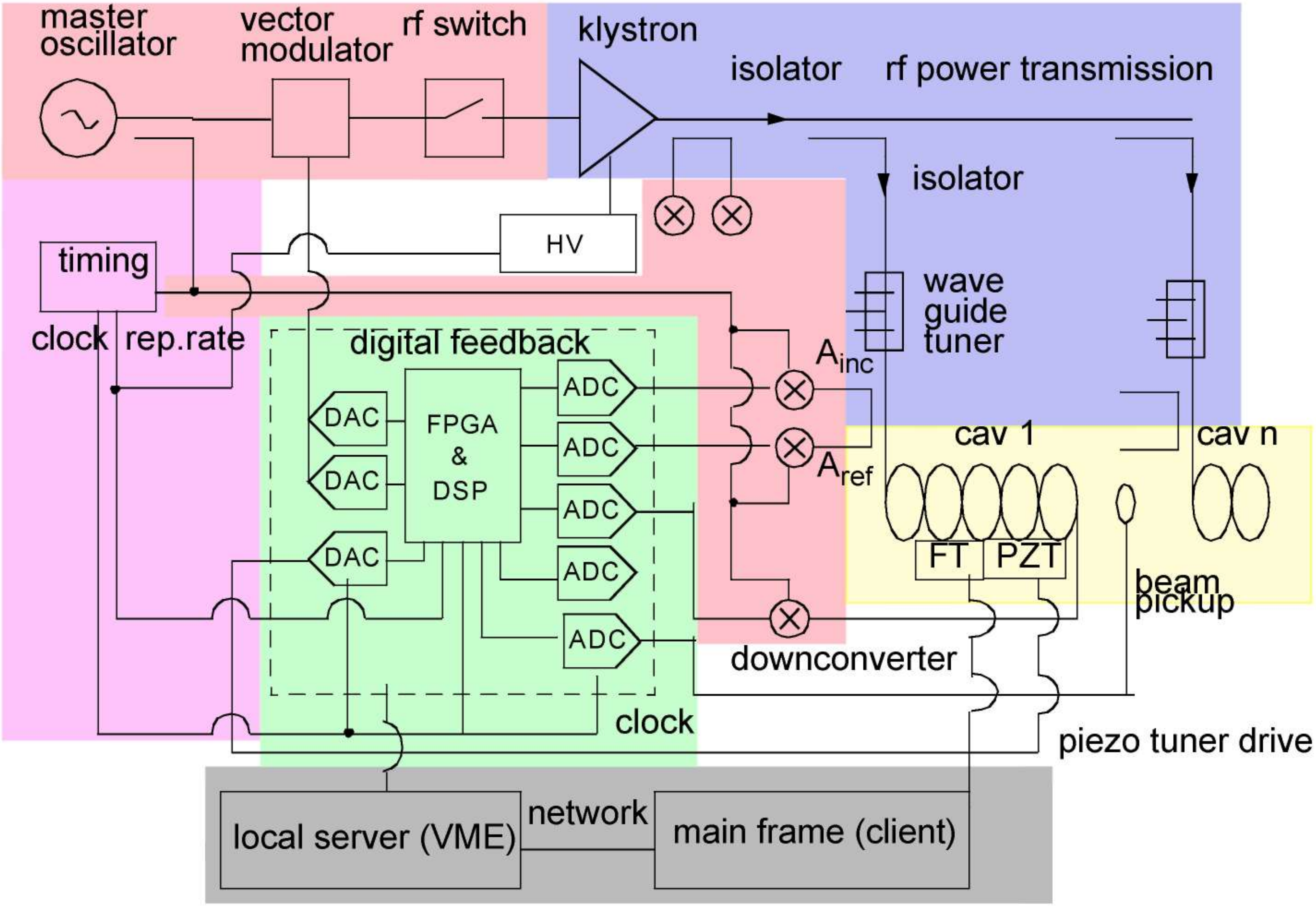
RF System Architecture (Simplified)



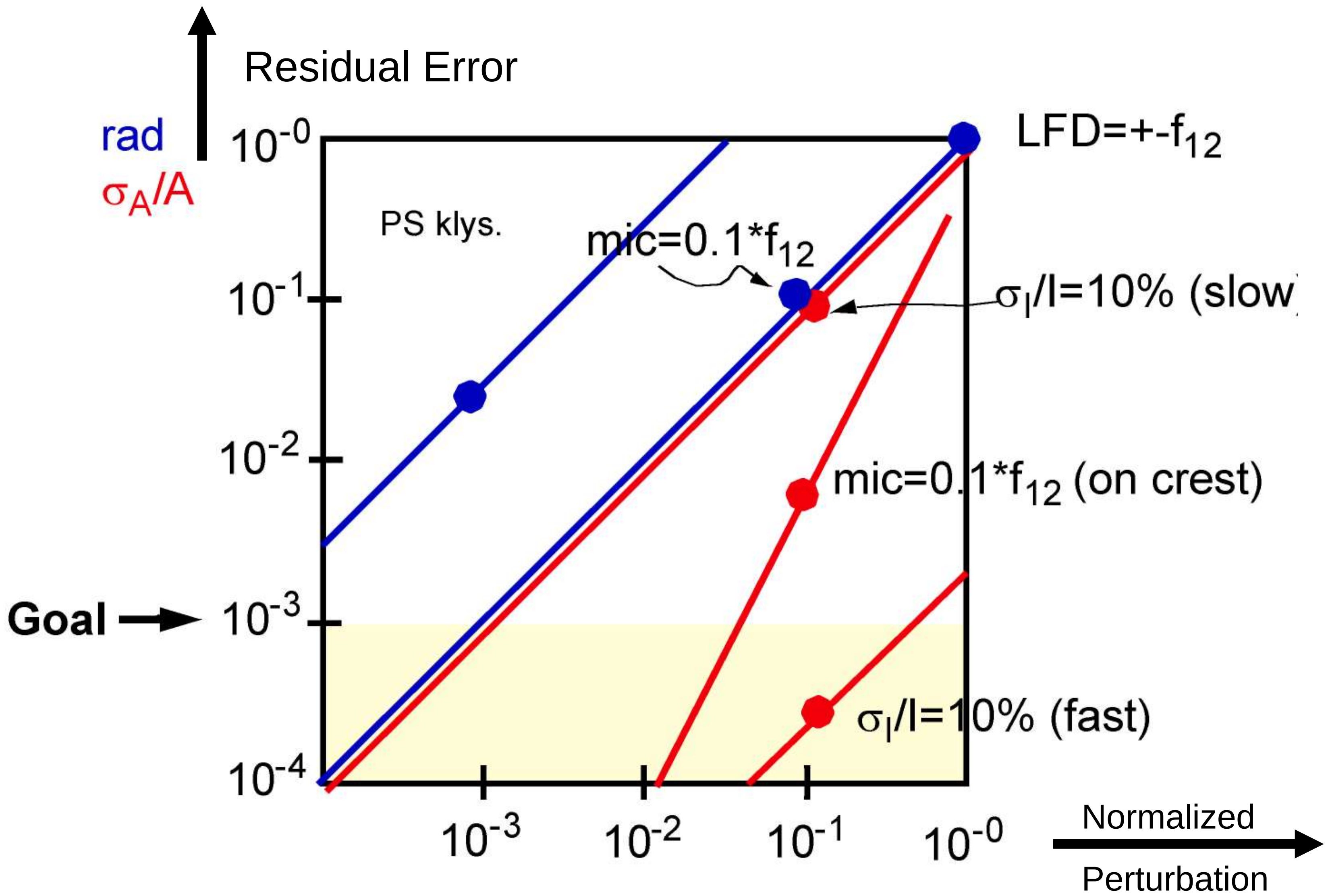
Typical Parameters in a Pulsed RF System



Architecture of Digital RF Control

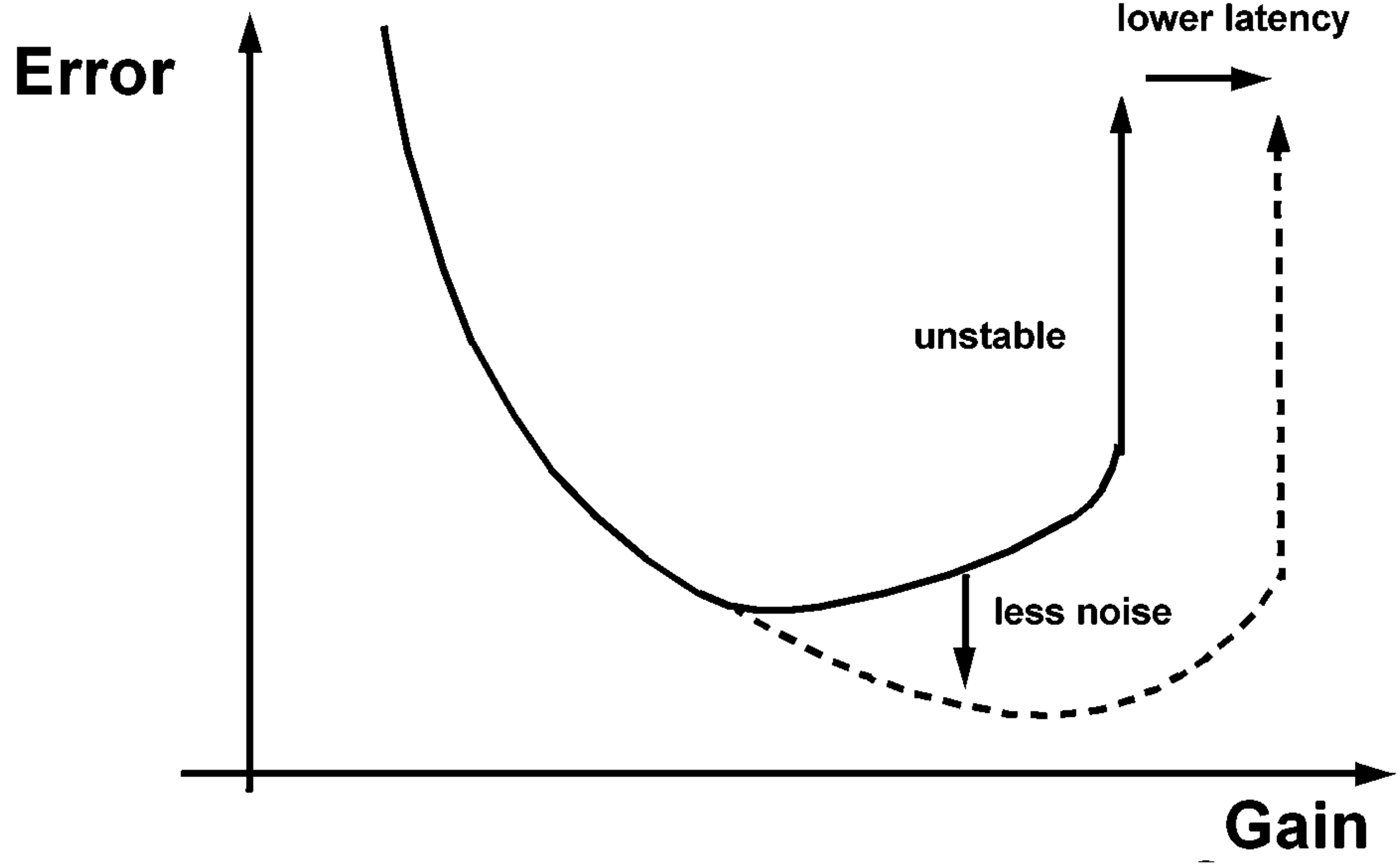


Error Map

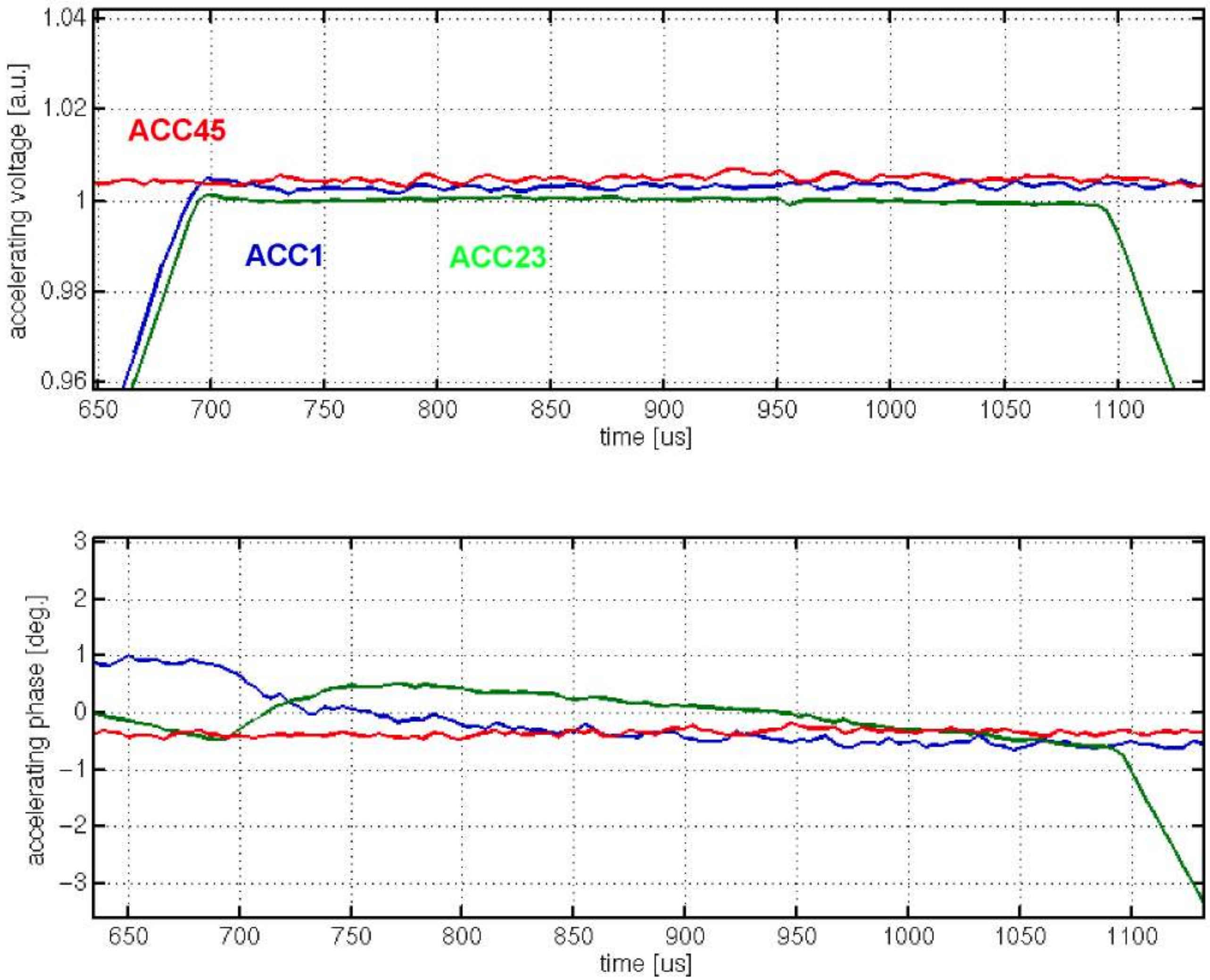


Residual Error
rad
σA/A
Goal
10-0
10-1
10-2
10-3
10-4
PS klys.
mic=0.1*f12
LFD=+-f12
σI/I=10% (slow)
mic=0.1*f12 (on crest)
σI/I=10% (fast)
10-3
10-2
10-1
10-0
Normalized
Perturbation

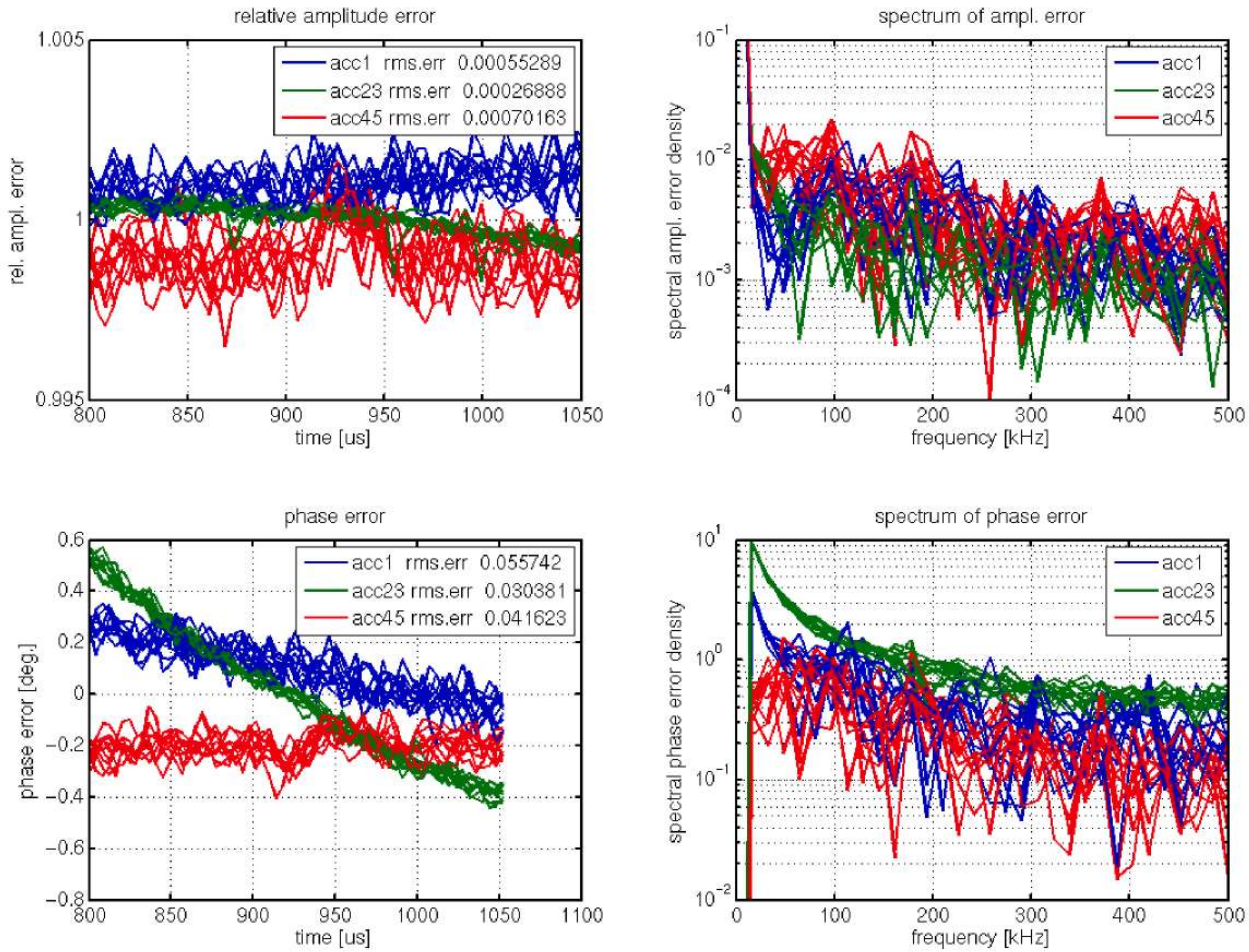
RMS Error as Function of Gain



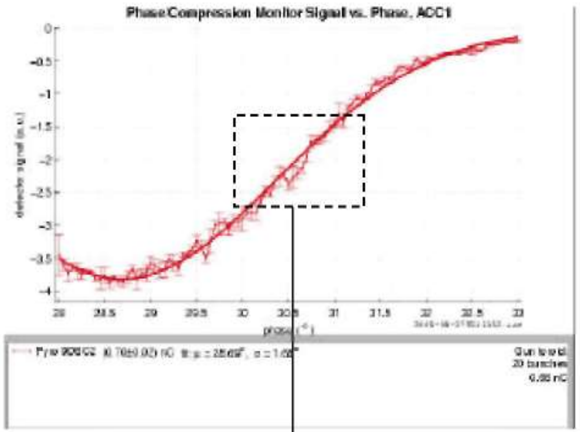
Field Regulation at FLASH

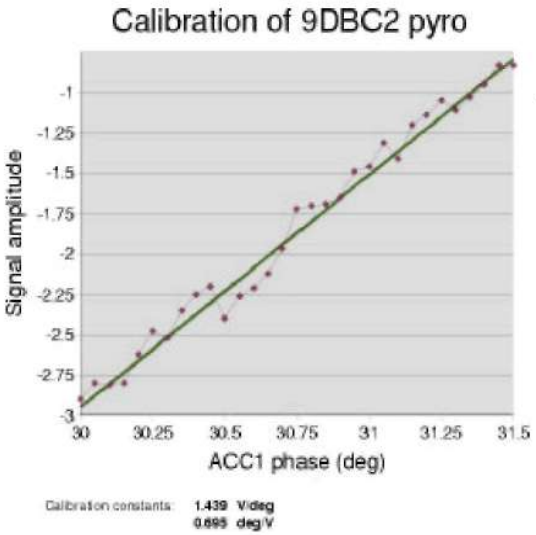


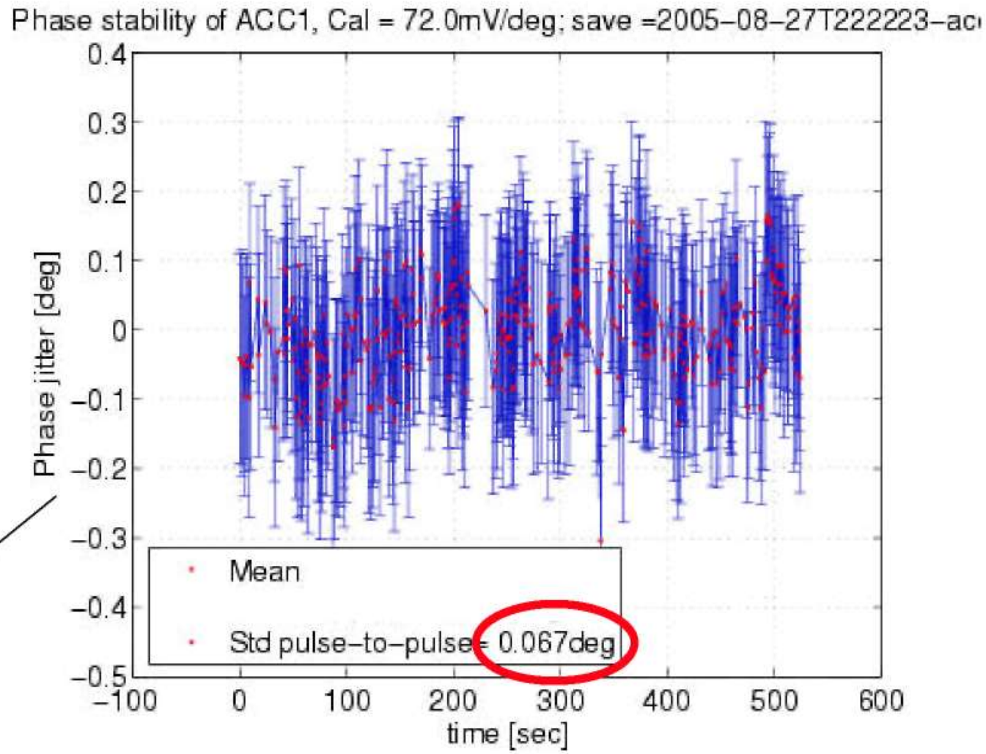
Field Regulation at FLASH



Field Regulation at FLASH







But! This is the phase stability between the beam arrival into the acceleration module relative to the RF phase!!!

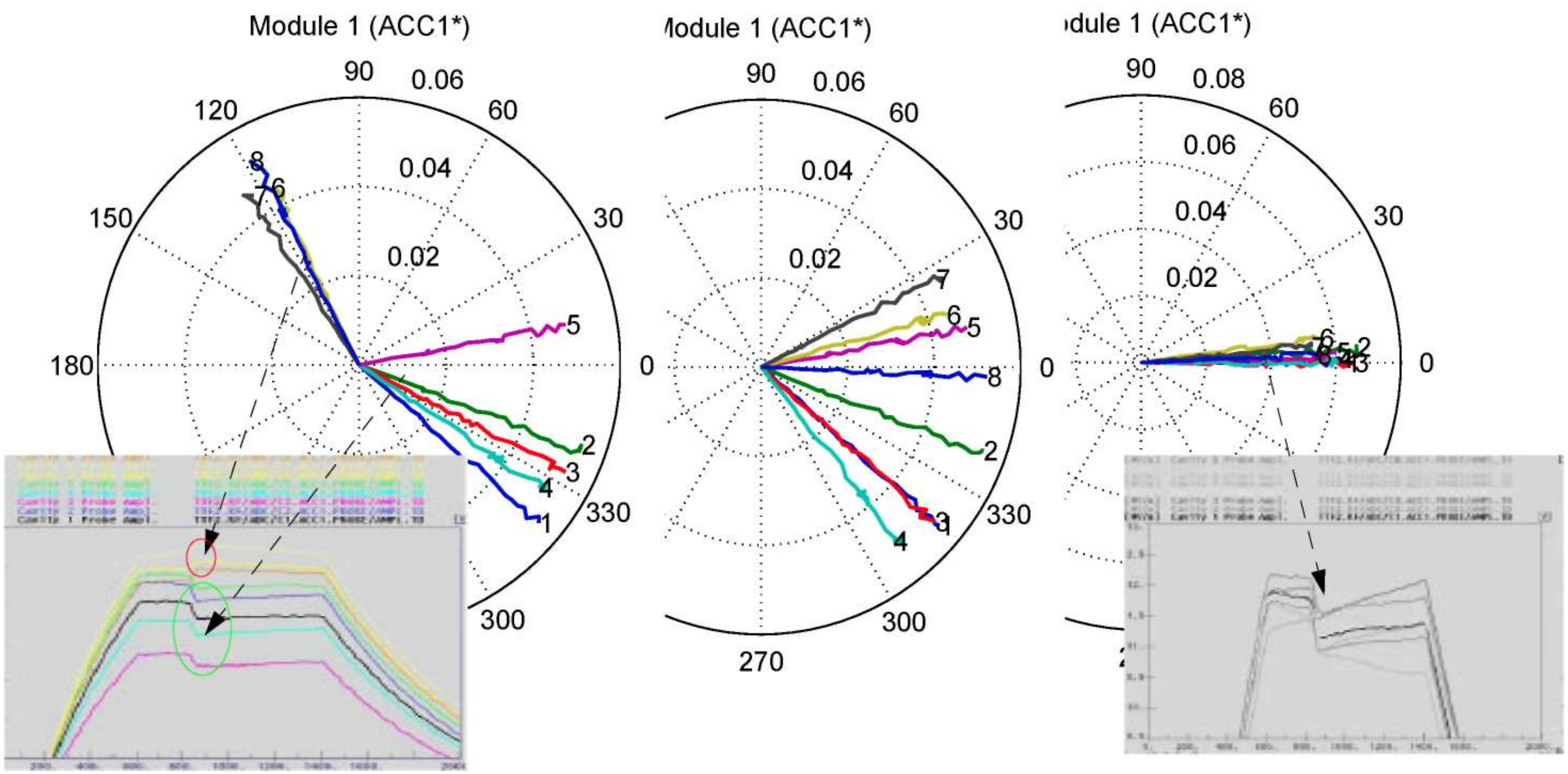
=> Major contribution is likely from laser

Challenges for RF Control

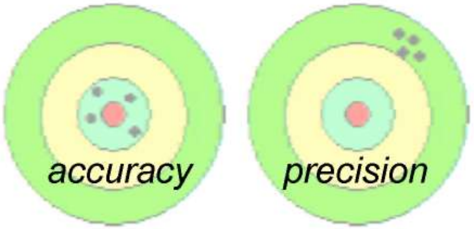
- Topics
  - **Vector-Sum Calibration (Ampl. & Phase)**
  - **Operation close to performance limits**
  - **Exception Handling**
  - **Automation of operation**
  - **Piezo tuner lifetime and dynamic range**
  - **Optimal field detection and controller (robust)**
  - **Operation at different gradients**
  - **Defining stándards for electronics (such as ATCA)**
  - **Interfaces to other subsystems**
  - **Reliability**

Beam Based Calibration

- Minimum Beam loading required (240 nC, 30us)
- Phase calibration to 3 deg.
- Gradient calibration 3-5%

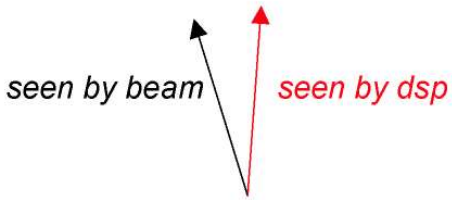


Vector Sum Calibration



How precise can we measure the vectorsum seen by the beam (not: how good can we control the vectorsum...). We are not interested in *accuracy* but in *precision*!

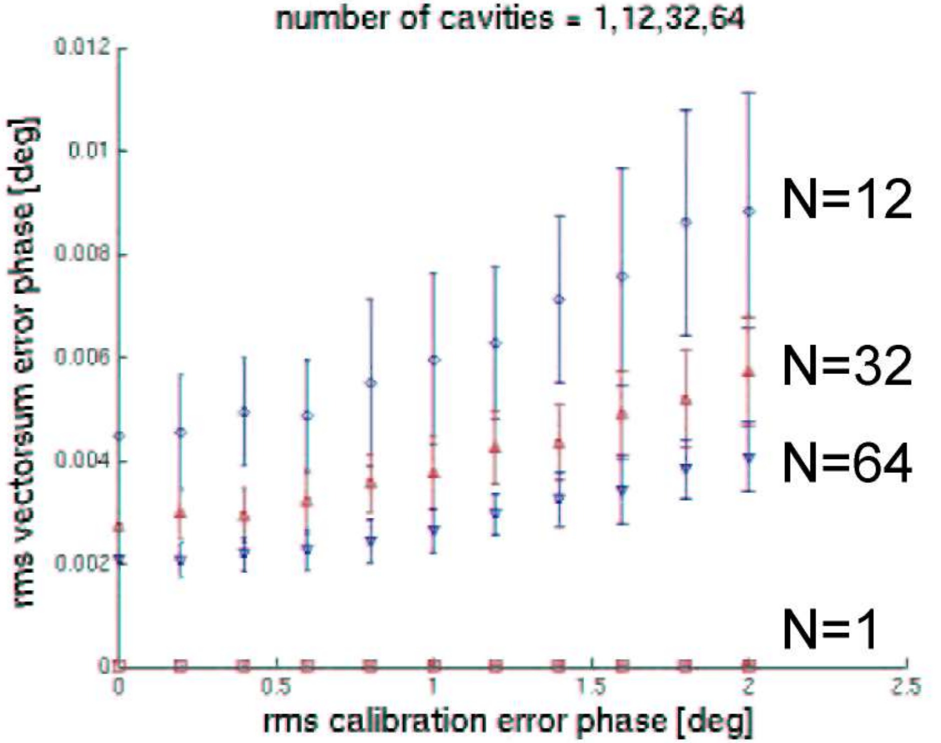
Every vector carries an error that is assumed to be constant:



Two extreme configuration: the dsp sees identical vectorsums but the beam does not!

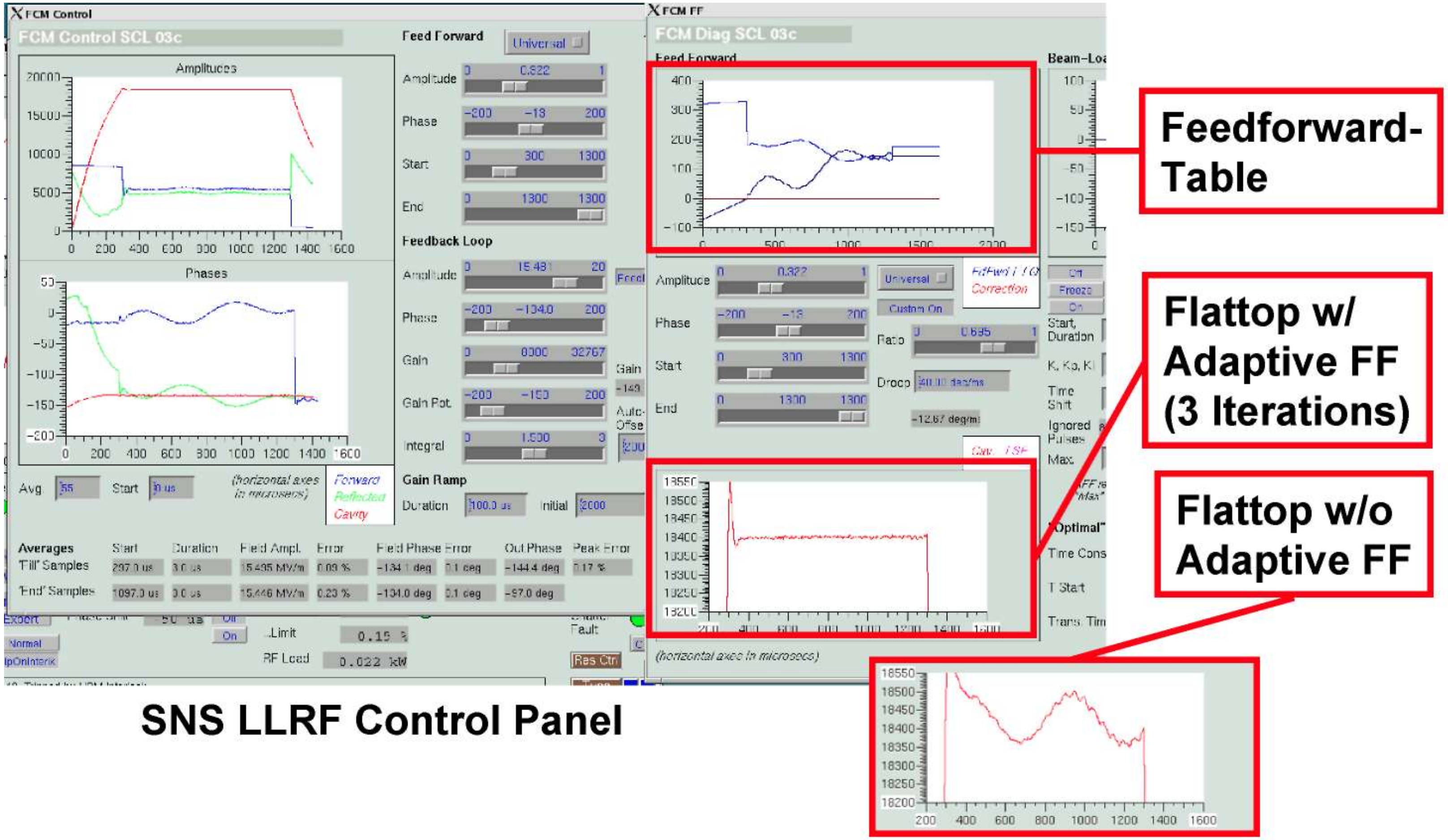
Vector Sum Calibration

Number of cavities: 1,12,32,64, Predetuning: 50 Hz, Detuning-Spread: 11 Hz, Amplitude cal. error: 0.01



Surprising result: the more we measure, the better we get!

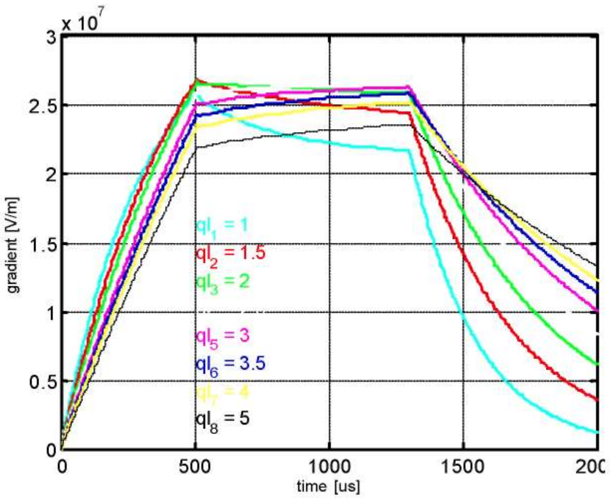
Automation ex.: Adapt. Feedforward



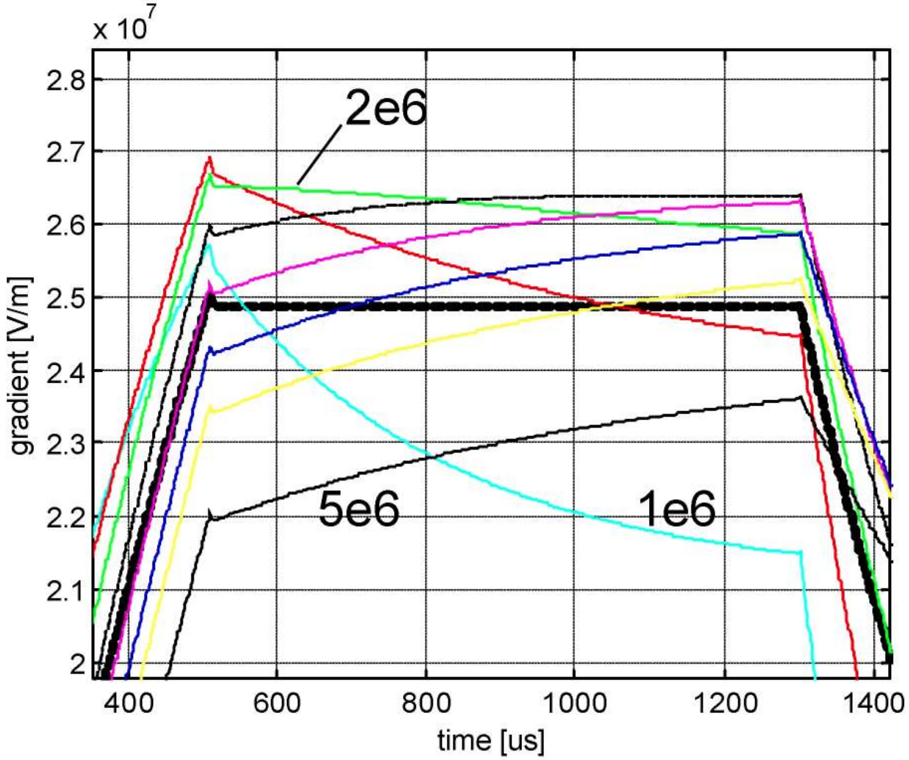
SNS LLRF Control Panel

Operation at Different Gradients

Variations in Loaded Q



8 cavities



Subsystems Susceptible to Failure

o RF phase reference - from main driveline - LO for downconverter o Timing System o Vector modulator o Downconverter o Digital Control (Fdbck + FF) - ADC, DSP, DAC - includes exception handling - Redundant simple feedforward - Redundant monitoring system o Transient detection o Interfaces to other subsystems - includes interlocks	o Waveguide tuner and controls o Cavity resonance control - slow (motor) tuner - fast (piezo) tuner o CPU in VME crate o Network to local controls o Cabels and connectors o Power supply for electronics o Airconditioning in racks o Software - DSP (FPGA) code - Server programs - Client programs - LLRF Parameters - Finite State Machine

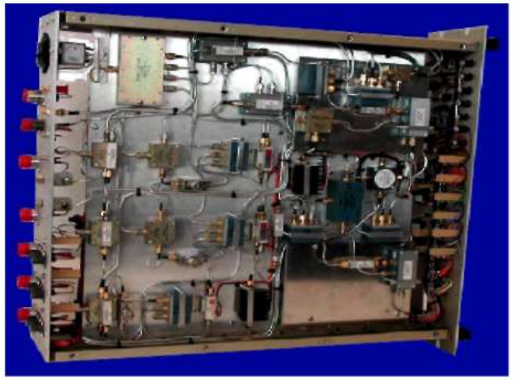
Reliability

- Some examples (rough numbers)

PC motherboard	50 kh
VME CPU	180 kh
Fan	60 kh
Power supply	50 kh .. 400 kh
SCSI disk	1 000 kh
IDE	300 kh

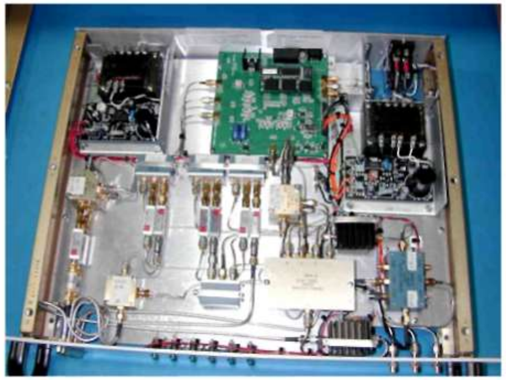
Evolution of Hardware at SNS

1st Generation
Control Chassis



MEBT Rebunchers
4 installed, 1 spare
Retrofitted with FCM
Nov 04

2nd Generation
Control Chassis



RFQ & DTL
7 installed, 3 spares
Retrofitted with FCM
Jul 04

3rd Generation
Field Control Module

CCL, SCL & HEBT
Retrofit to MEBT, RFQ & DTL
98 systems + spares

Evolutionary Development: build on proven concepts, hardware and software

October 10, 2005

Lesson Learned

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

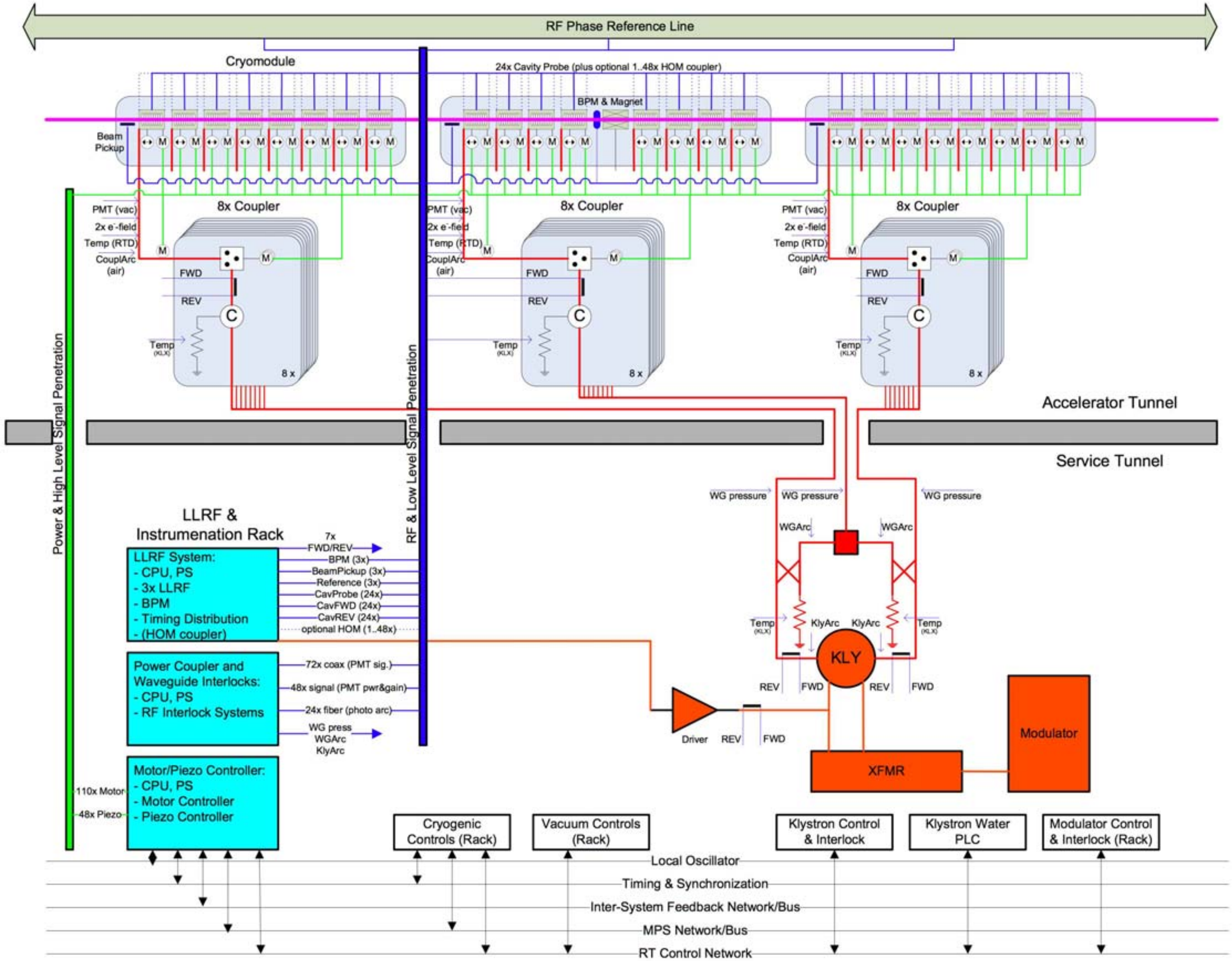
Ref. M. Champion

Advice for Hardware Development

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

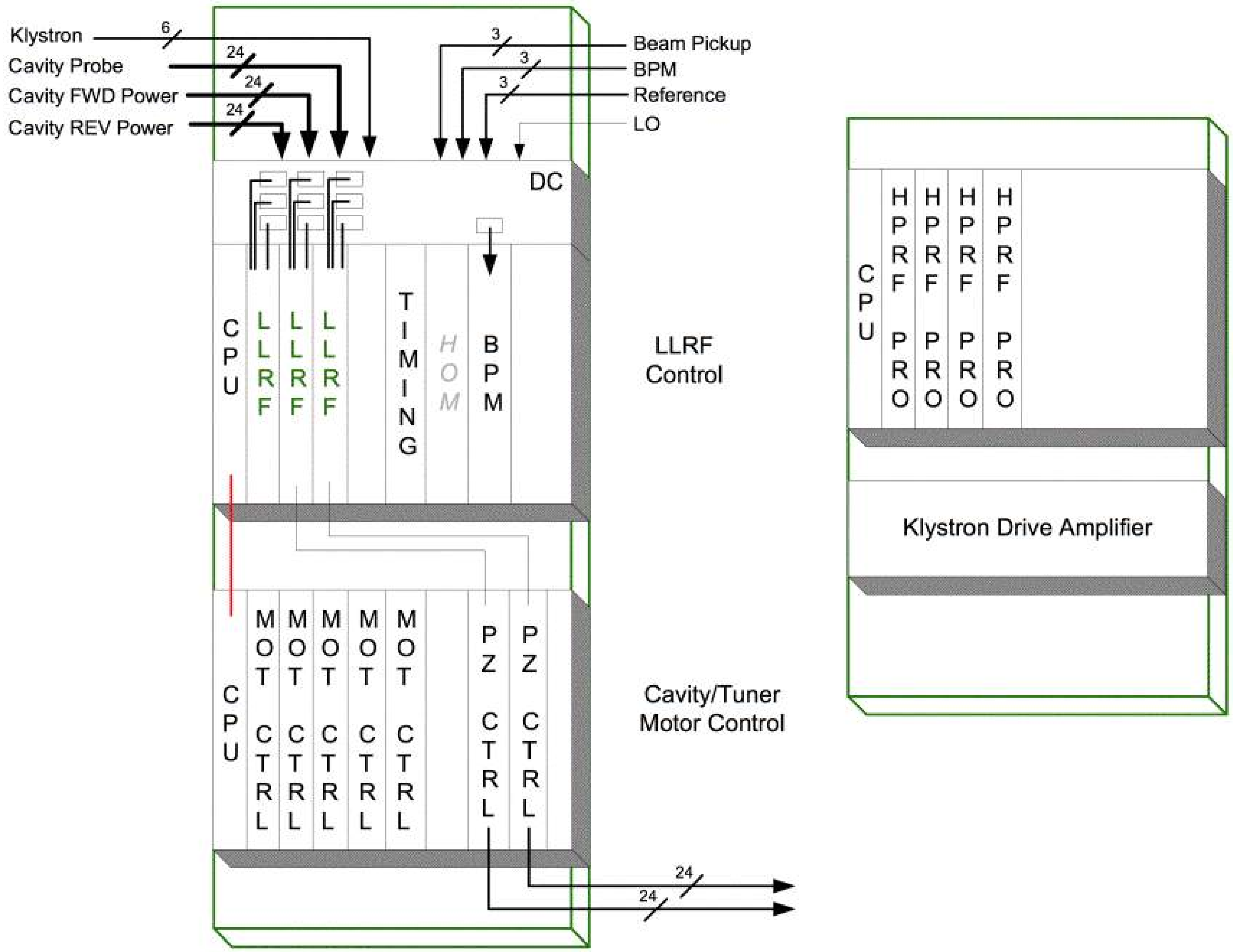
Ref.: M. Champion

RF Station with 3 Cryo-modules

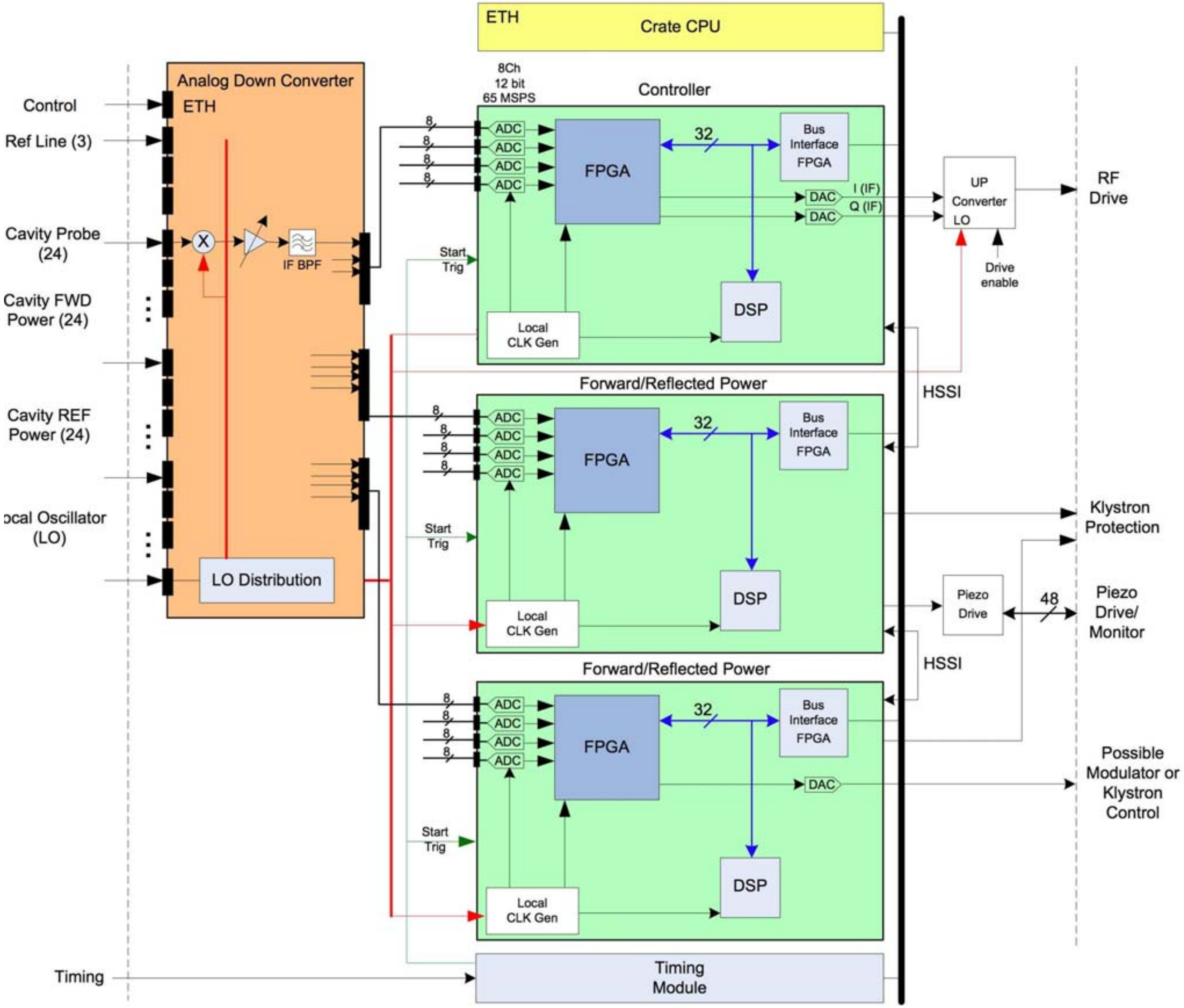


Rack Layout

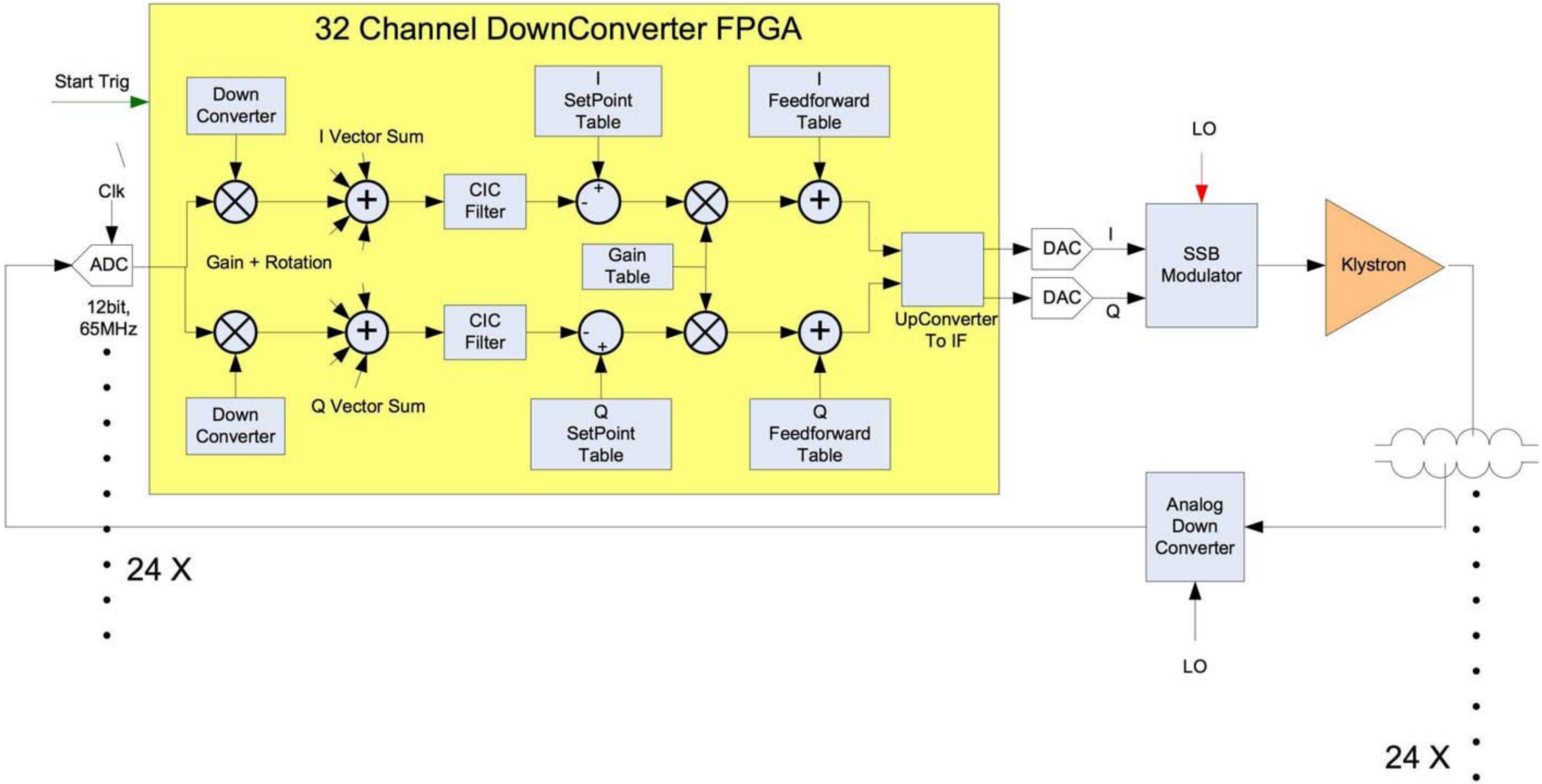
LLRF/Instrumentation Racks



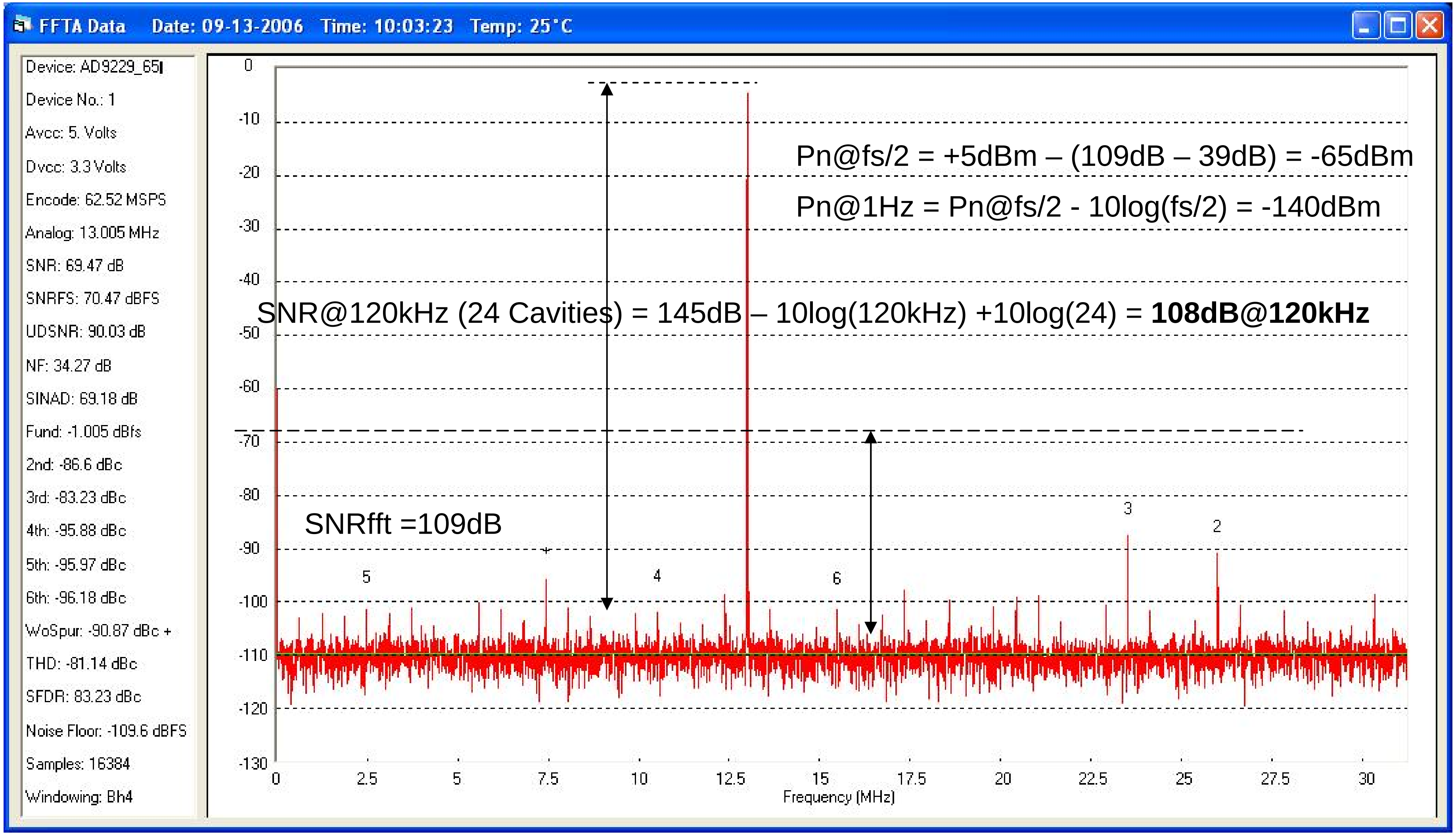
LLRF Rack Detail



3 Cryomodule Field Controller

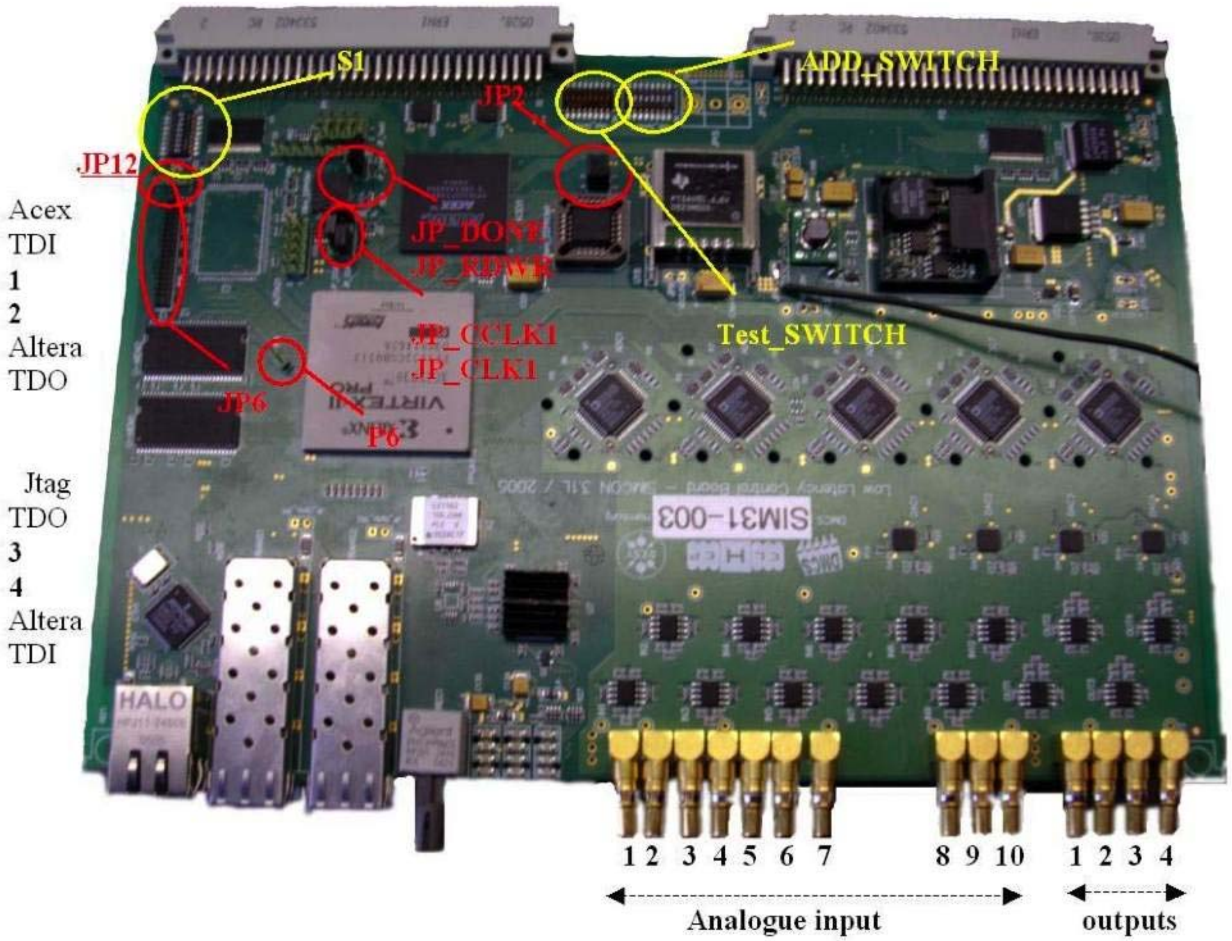


Receiver SNR Calculations



DESY SIMCON3.1 Controller

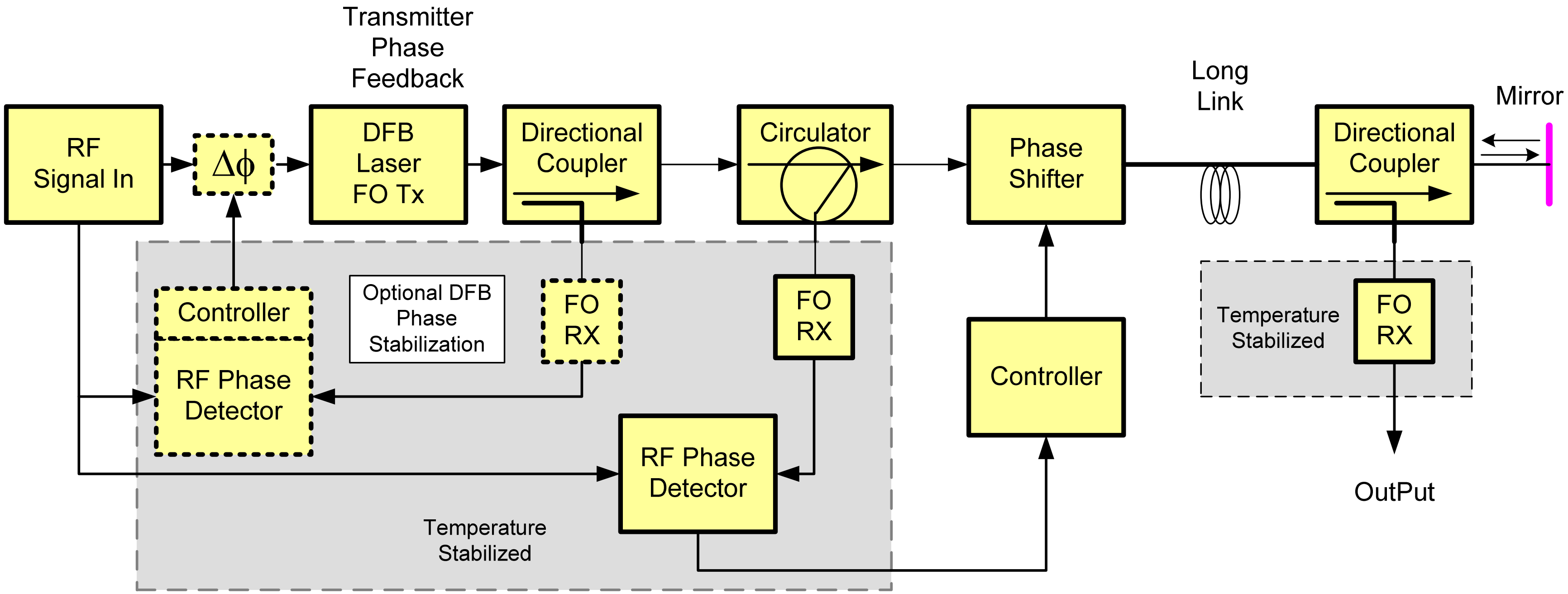
2.SIMCON3.1 board description and schematics.



Phase Reference Chain

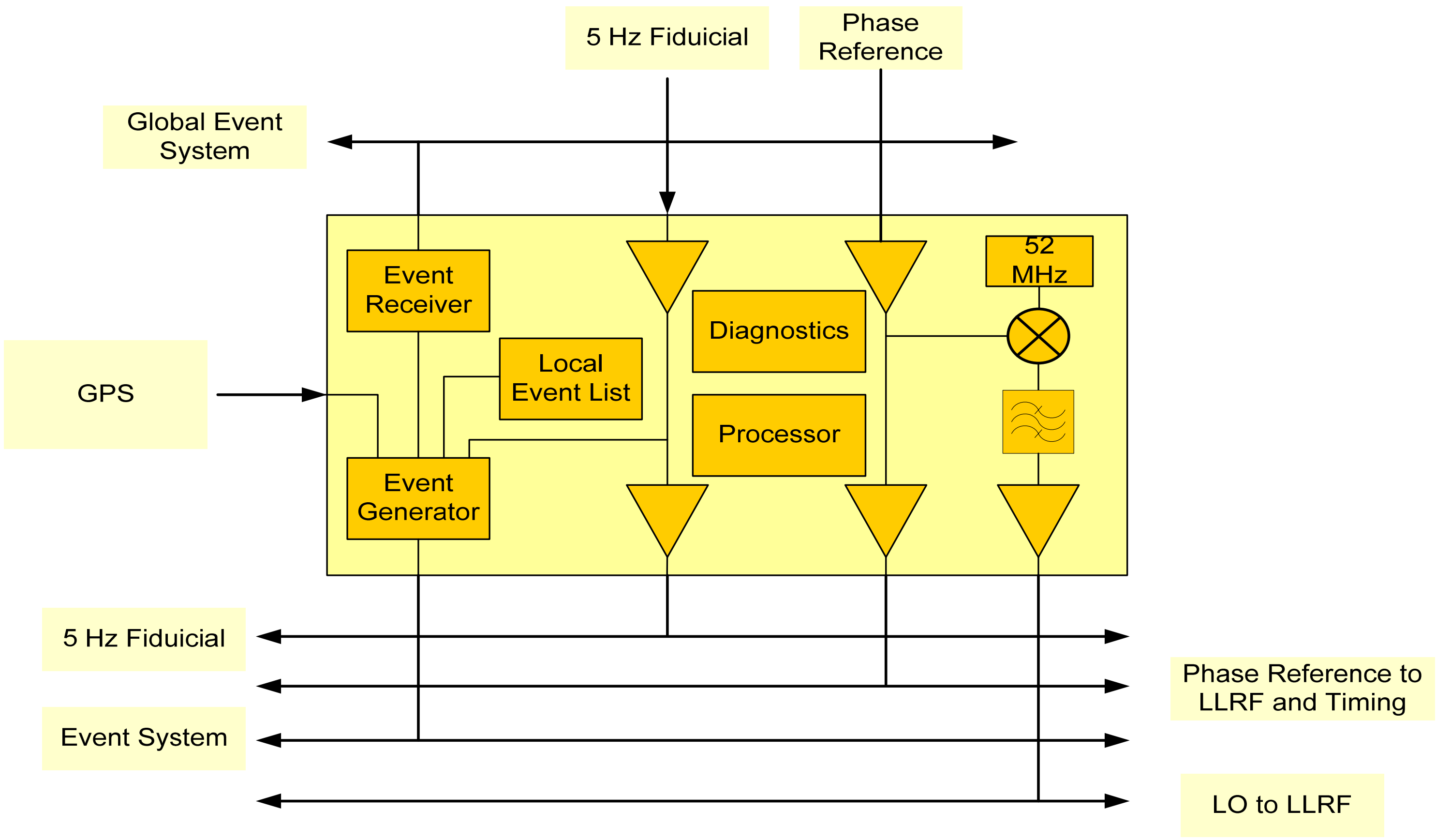
- Master Oscillator drives fiber reference(650,1300,3900MHz)
  - **Close in phase noise from MO is coherent across all systems and does not matter to first order**
  - **Relative phase is critical!**
- Local phase distribution repeats fiber signal without narrow band filters
  - **Filtering is done in the phase measurement process in the LLRF receiver**
  - **Narrow filters have problems with drift and microphonics**
- Narrow band PLL filtering is used in the generation of the LO which is phase locked to the reference RF
  - **LO noise will be driven to the cavities by the LLRF system**
- Absolute phase of the reference line relative to the LO is measured over 1 ms before the RF pulse
  - **Absolute phase in the LO is not important as long as it is stable over the time frame of phase measurement and the RF waveform ~ 5 ms.**

Active Phase Stabilized Link



From Frank Lenkszus APS

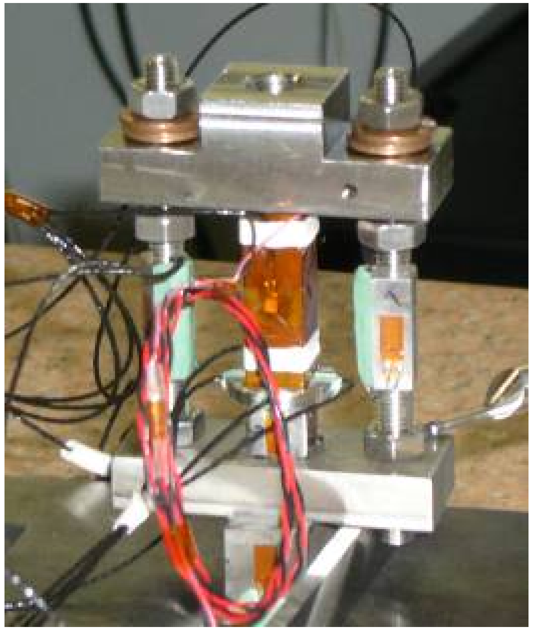
Sector Timing Controller



From Frank Lenkszus APS

CC2 Piezo Tuner

Calibrated "Bullet" Strain Gauge Sensor to measure preload changes during cooldown and stepping motor operation

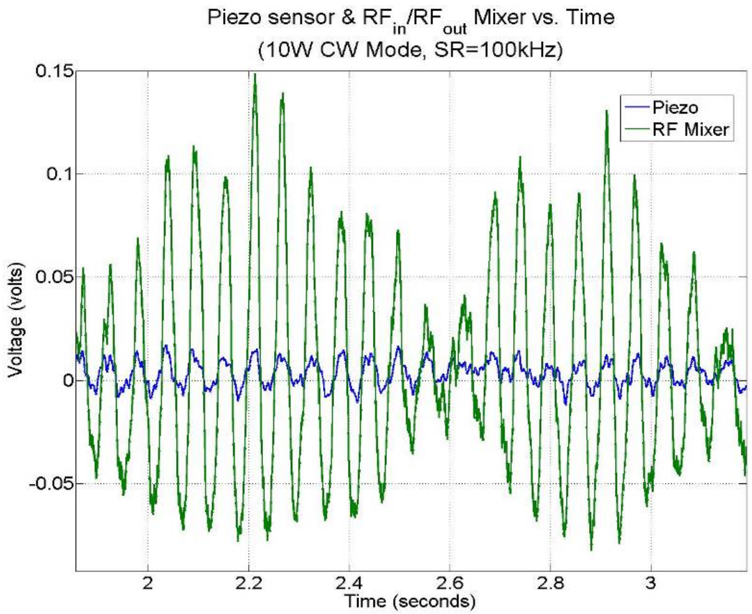


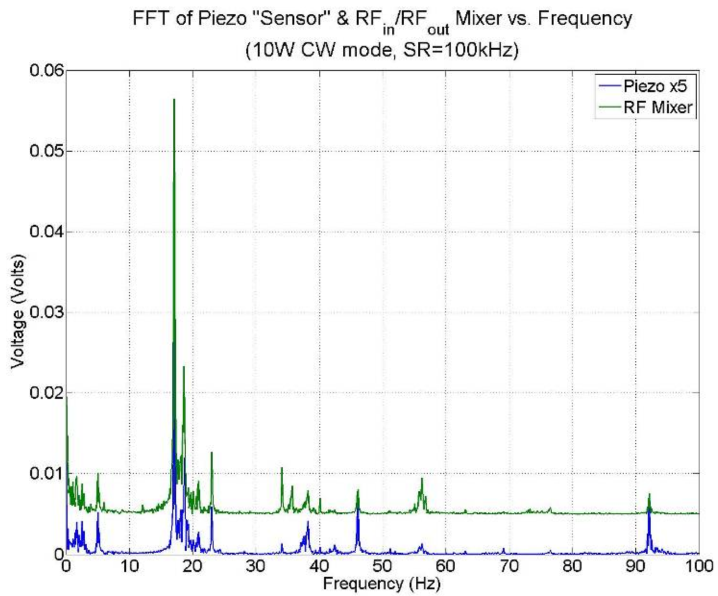
CC2 Piezo assembly instrumentation:

- **11 strain gauges**
- **2 RTDs**

Piezo Test as a Vibration Sensor – CW mode

Piezo Tuner & RF Mixer Measurement of CC2 @10W CW Mode





There is a good correlation between the Piezo Tuner and the RF Mixer in the time domain.

An FFT of the Piezo Tuner and the RF Mixer signals show close agreement in the frequency domain.

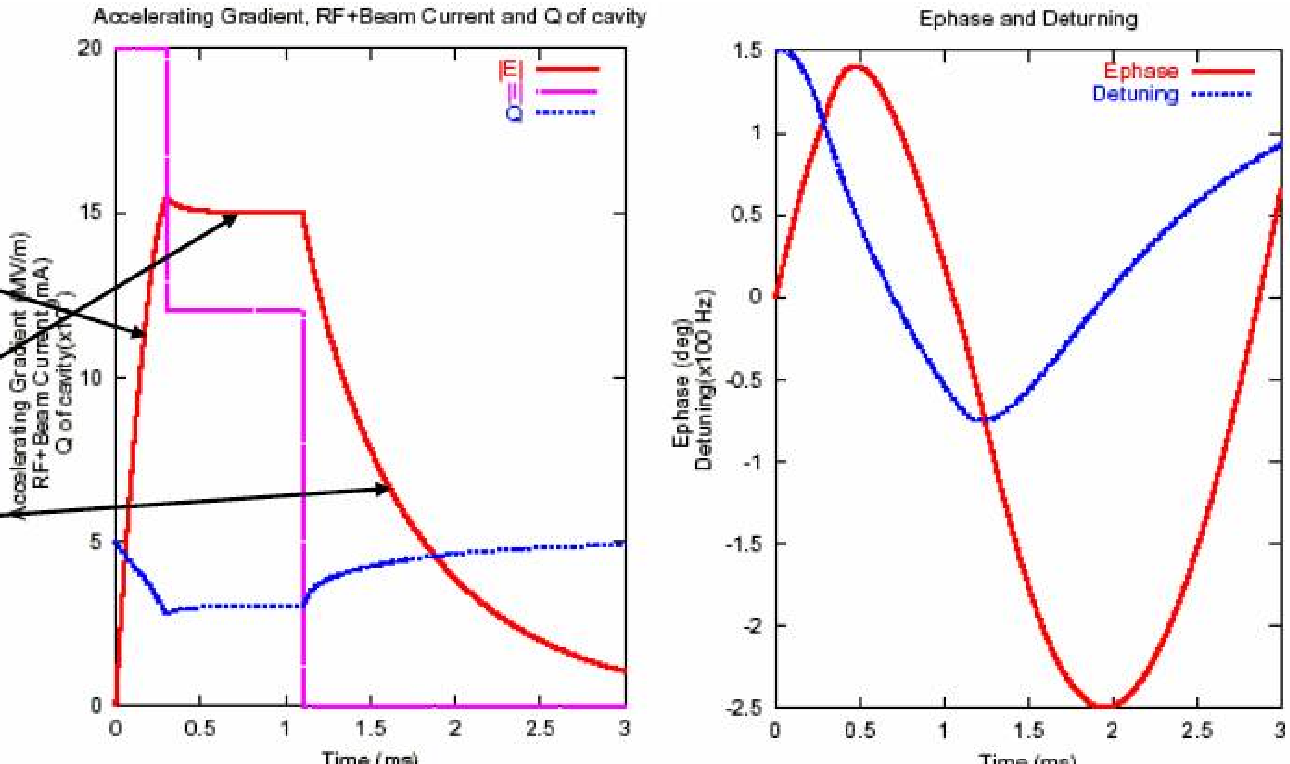
Real Time Cavity Simulator

<u>Test run of ILC Cavity Simulator (no beam)</u>

1)fill: 0 - 0.3 ms at 20 mA (full power)

2)flat-top: 0.3 -1.1 ms at 12 mA

3)cavity emptying, decay curve shows high Q of cavity.



(a) Amplitude response

(b) Phase response

Compare with TESLA cavity measurements:
Shapes are similar, model is working.

IF in these simulations is 50 MHz.

Justin Keung, UPenn

Automation

- Large number of stations require-
  - **System diagnostics must be mostly automated**
  - **Expert diagnostics must be carried out remotely through the control system**
  - **Error and fault detection and failure prediction**
    - Track klystron gain
  - **Self test**
    - On reboot and schedule
  - **Auto Calibration**
    - Built in “Network Analyzer” receiver calibration
    - Klystron linearizer calibration
    - Beam based cavity vector calibration

Software Modules

1. Control Algorithms (Fdbck/ Feedforward)
2. Meas. QL and detuning
3. Cavity Frequency Control (Fast and Slow)
4. Amplitude/Phase Calibration
5. Vector-Sum Calibration
6. Loop phase and loop gain
7. Adaptive Feedforward
8. Exception Handling
9. Klystron Linearization
10. Lorentz Force Compensation

LLRF Collaboration

- DESY, Warsaw ELHEP, KEK, FNAL(CD,AD,TD), LBL,SNS, SLAC, JLAB,University of Pennsylvania
- Weekly telecom for LLRF
- Weekly telecom for Controls
- Weekly telecom for HLRF
- Major design efforts underway for XFEL and test string at FNAL
  - **Several high performance controllers being developed**
  - **Master Oscillator and distribution**
  - **Real time Cavity Simulator**

Uncharted Waters(what looks tough)

- Large system scale
  - **All the issues of automation and getting it done right the first time**
  - **Phase reference and distribution over long paths**
- Identifying single point failures and adding redundancy where needed
  - **Example -LO and reference distribution**
- Vector sum calibration
  - **Accuracy - each system wide calibration will introduce a systematic error.**
- Beam based feedback
  - **Phase and energy at IP**
  - **Feedback to Crab Cavity vector control**

References

- “ILC Timing”, ILC-doc-158-V1, Lenkszus, APS
- “Status of the Penn C-based ILC Cavity Simulator”, Justin Keung, University of Pennsylvania
- “Recent Developments and Layout of the Master Laser System for the VUV-FEL”, A. Winter, F. Ö. Ilday, H. Schlarb, F. X. Kaertner, DESY Hamburg, Bilkent University, MIT 16.05.2006
- “Digital Low-Level RF Control for Future Superconducting Linear Colliders”, S. Simrock, PAC 2005
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- “LLRF of Low Level RF System for the J-PARC LINAC”. S. Michizono, LINAC 2004