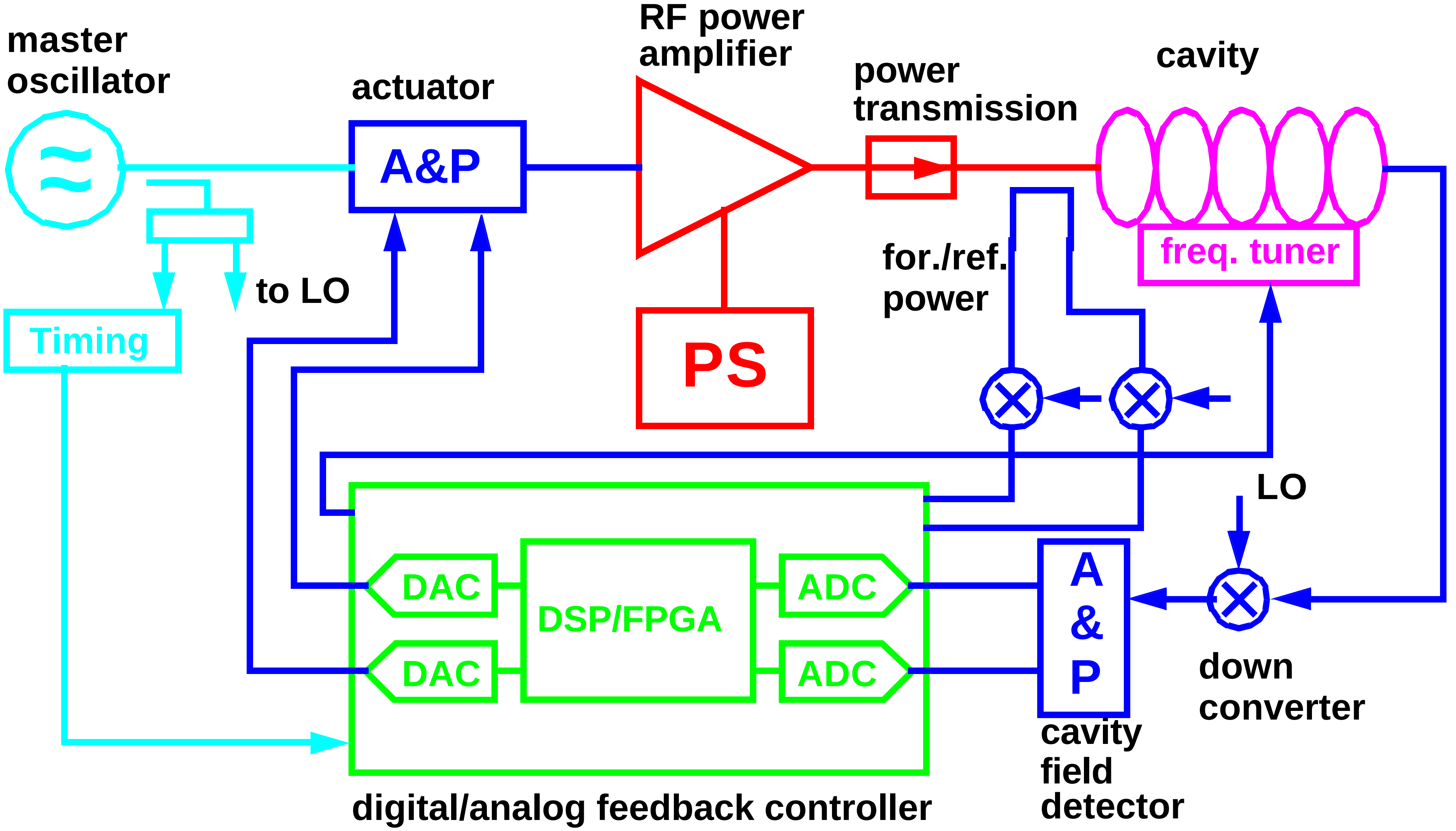
State of the Art in RF Control

S. Simrock, DESY

Outline

- RF System Architecture
- Requirements for RF Control
- RF Control Design Considerations
- Design Efforts Worldwide
- Measured and Predicted Performance
- Conclusion

RF System Architecture



RF Subsystems

A. Frequency generation
   (1) Phase stable reference frequency oscillator
   (2) Phase locked Oscillators (various frequencies)
   (3) Power supply
   (4) Diagnostics
   (5) Control system interface
   (6) Phase stability monitoring and correction

B. Frequency and Reference Phase Distribution
   (1) Phase stable transmission line
   (2) Temperature stabilization
   (3) Power distribution (directional couplers)

C. Cavity Field Control (LLRF)
   (1) Detectors for accelerating field
      (a) amplitude detector
      (b) phase detector
      (c) I/Q detector
   (2) Actuators for amplitude and phase of incident wave
      (a) pin-attenuator
      (b) multiplier
      (c) phase-shifter
      (d) vector-modulator
   (3) Field error detection
   (4) Cavity field controller with Feedback and Feedforward
   (5) Interlock system
   (6) Diagnostics
   (7) Interface to control system

D. High Power Amplifier
   (1) RF power source
   (2) Power supply
   (3) Interlocks
   (4) Diagnostics
   (5) Interface to control system

E. Power Transmission System
   (1) Transmission line (coaxial, waveguide)
   (2) Circulator, Isolator
   (3) Power dividers
   (4) Directional couplers (Monitor)
   (5) Waveguide (coaxial) window
   (6) Pressurisation system

F. Accelerating System
   (1) Cavity
   (2) Fundamental Coupler
   (3) Higher Order Mode Coupler

G. Cavity Frequency Tuning System
   (1) Cavity tuner (fast and/or slow)
      (a) Ferrite loaded
      (b) Motor tuner
      (c) Magnetostrictive
      (d) piezoelectric
      (e) coupled variable reactance (VCX tuner)

RF Control Requirements

- Maintain Phase and Amplitude of the accelerating field within given tolerances to accelerate a charged particle beam
- 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

Requirements RF Control

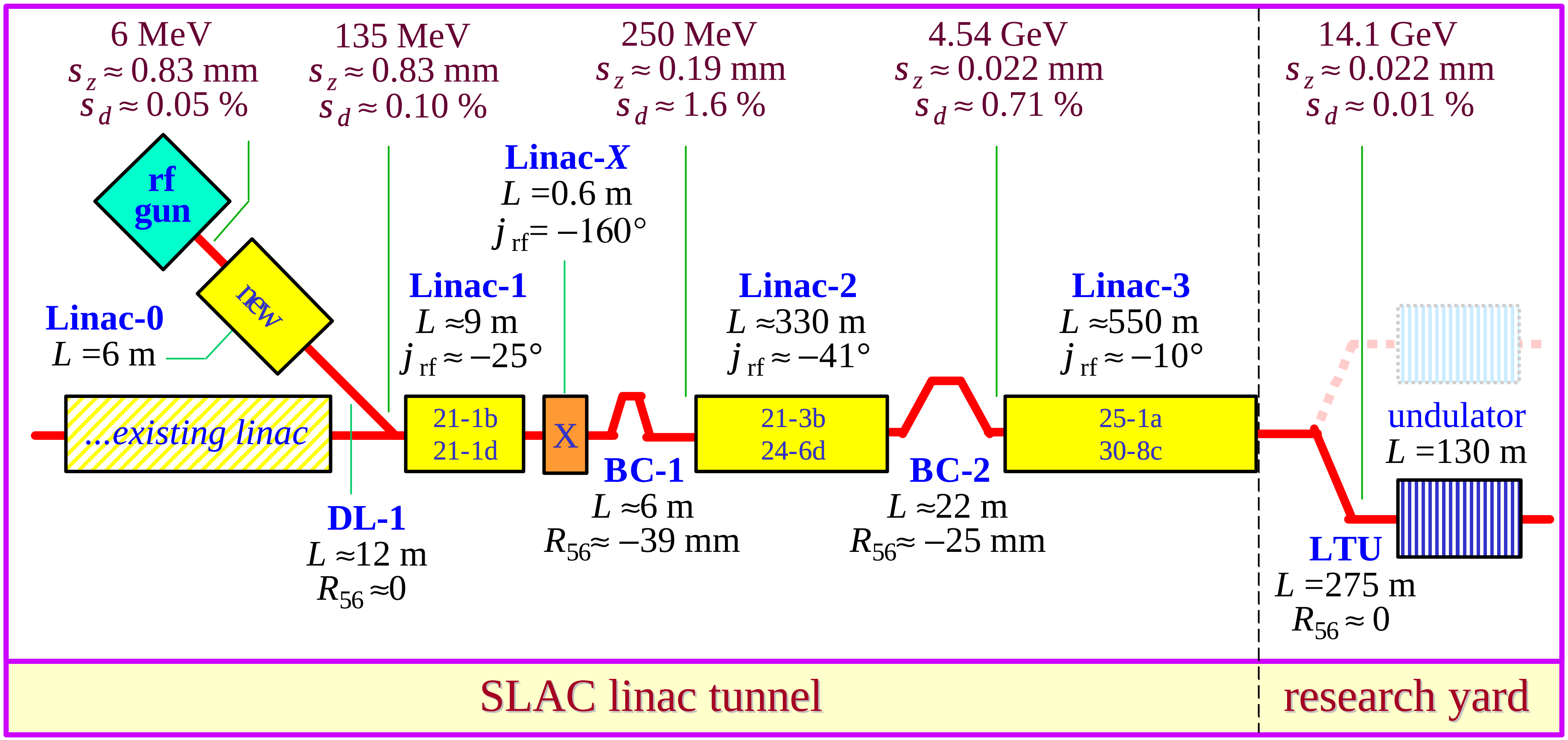
- Derived from beam properties
  - energy spread
  - emittance
  - bunch length (bunch compressor)
  - arrival time

- Different accelerators have different requirements for field stability (approximate RMS requirements
  - 1% for amplitude and 1 deg. for phase (example: SNS)
  - 0.1% for amplitude and 0.1deg.for phase (linear collider)
  - up to 0.01% for amplitude and 0.01 deg. for phase (XFEL)

Note: Distinguish between correlated and uncorrelated error

Nominal *LCLS* Linac Parameters for 1.5-Å FEL

Single bunch, 1-nC charge, 1.2-*mm slice* emittance, 120-Hz repetition rate…



(RF phase: f_{rf} = 0 is at accelerating crest)

P. Emma, SLAC

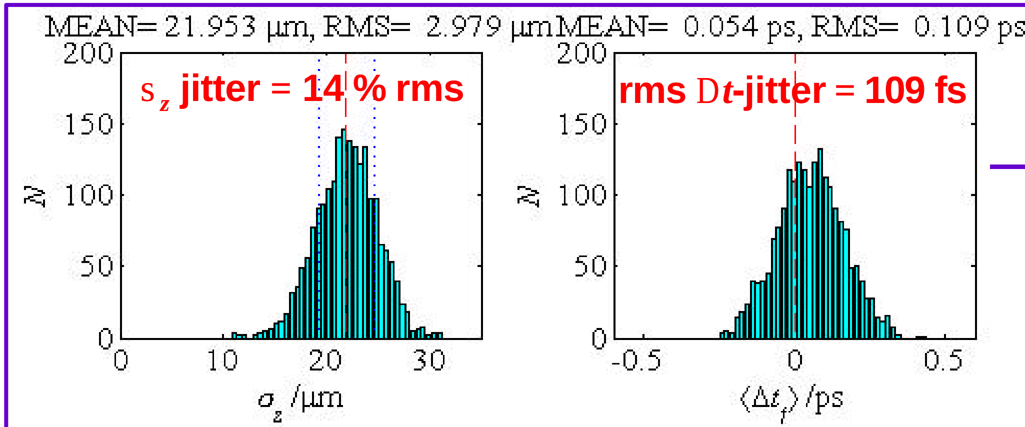
Jitter Tolerance Levels in the *LCLS*

$|\langle \Delta E/E_0 \rangle| < 0.1\%$ **and** $|\Delta I/I_0| < 12\%$

Parameter	Symbol	LCLS	Unit
Gun timing jitter	Δt_0	0.80	psec
Initial bunch charge	$\Delta Q/Q_0$	2.0	%
mean L0 rf phase X-band	φ_0 X-	0.10	deg
mean L1 rf phase	φ_1	0.10	deg
mean L*h* rf phase	φ_h	0.50	deg
mean L2 rf phase	φ_2	0.07	deg
mean L3 rf phase	φ_3	0.15	deg
mean L0 rf voltage	$\Delta V_0/V_0$	0.10	%
mean L1 rf voltage	$\Delta V_1/V_1$	0.10	%
mean L*h* rf voltage	$\Delta V_h/V_h$	0.25	%
mean L2 rf voltage	$\Delta V_2/V_2$	0.10	%
mean L3 rf voltage	$\Delta V_3/V_3$	0.08	%

Jitter tolerance budget for *LCLS* based on the many sensitivities

…and test the budget with jitter simulations



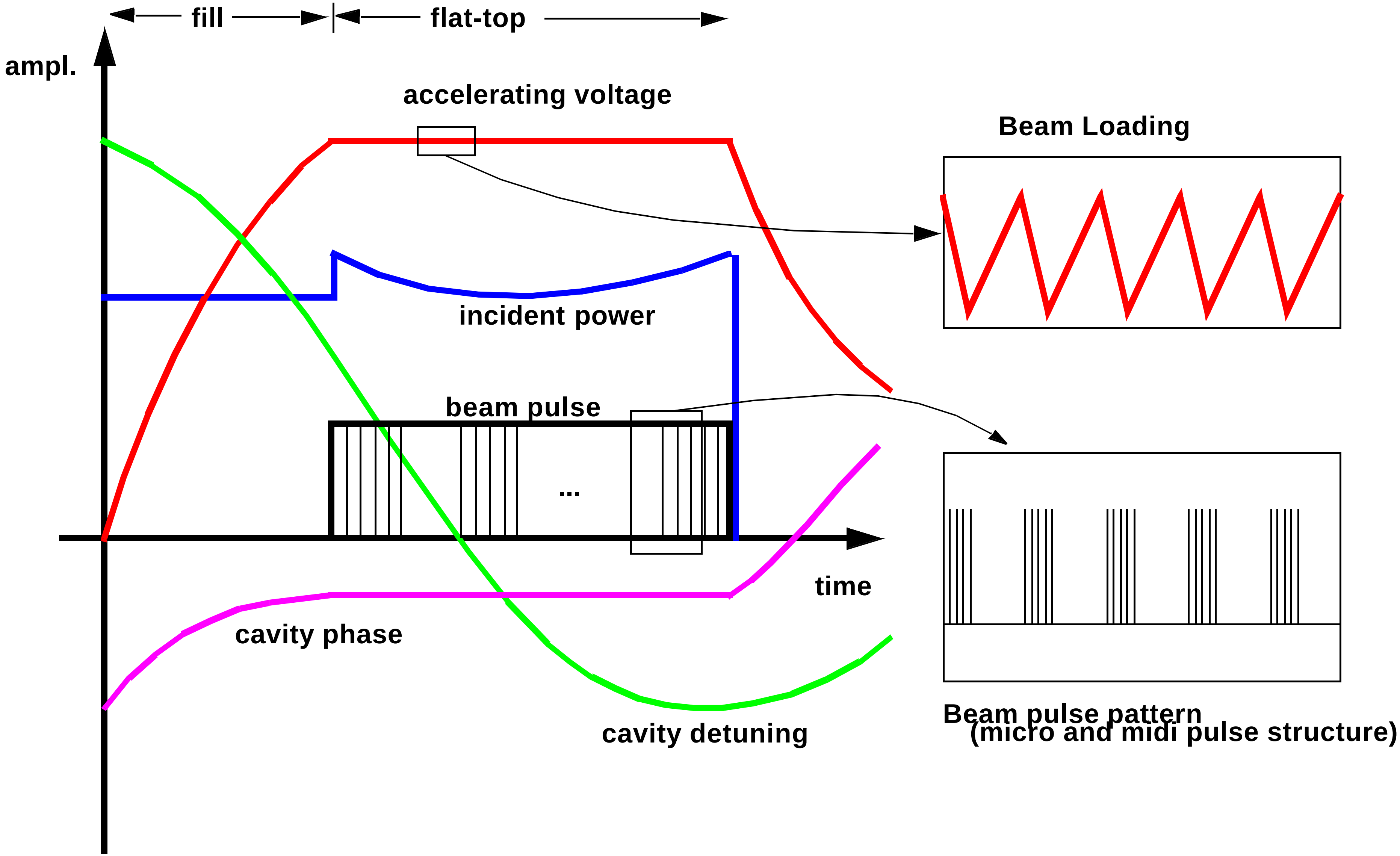
Jitter simulation, tracking 10^5 particles 2000 times, where each run is randomized in its 12 main rf-parameters according to the tolerance budget

- **P. Emma, SLAC**

Parameters and Requirements

	CESR-c	ERL buncher cavity	ERL s.c. inject. cavities	ERL s..c. main linac cavities
frequency [MHz]	500	1300	1300	1300
number of cavities	4	1	5	7
cells per cavity	1	1	2	7
R/Q / cavity (circuit def.) [W]	44	105	109	392
Q_0	1.2 to 1.6 $\cdot 10^9$	20,000	> $5 \cdot 10^9$	> 10^{10}
Q_{ext}	$2 \cdot 10^5$ to $1 \cdot 10^6$	9,900	> $4.6 \cdot 10^4$ ($4.1 \cdot 10^5$)	$2.6 \cdot 10^7$ for 25 Hz peak detuning
acc. voltage per cavity [MV]	1.9 to 3	0.12	1 (3)	» 16
required klystron power per cavity [kW]	up to 180	7	130	11
required relative amplitude stability (rms)	< 1 %	$8 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	$3 \cdot 10^{-4}$
required phase stability (rms)	< 0.5°	0.1°	0.1°	0.06°

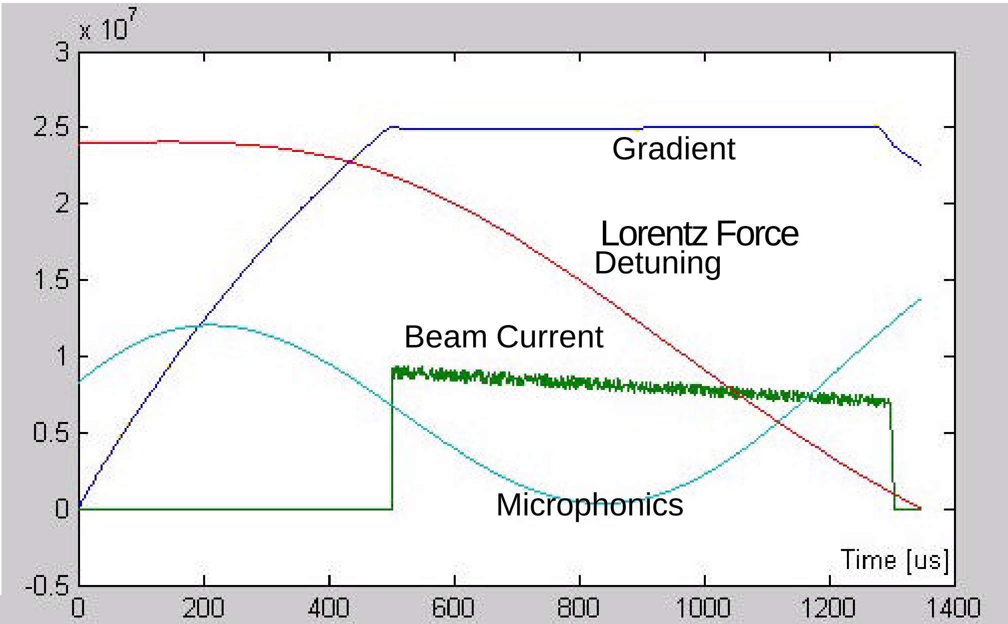
Typical Parameters in a Pulsed RF System

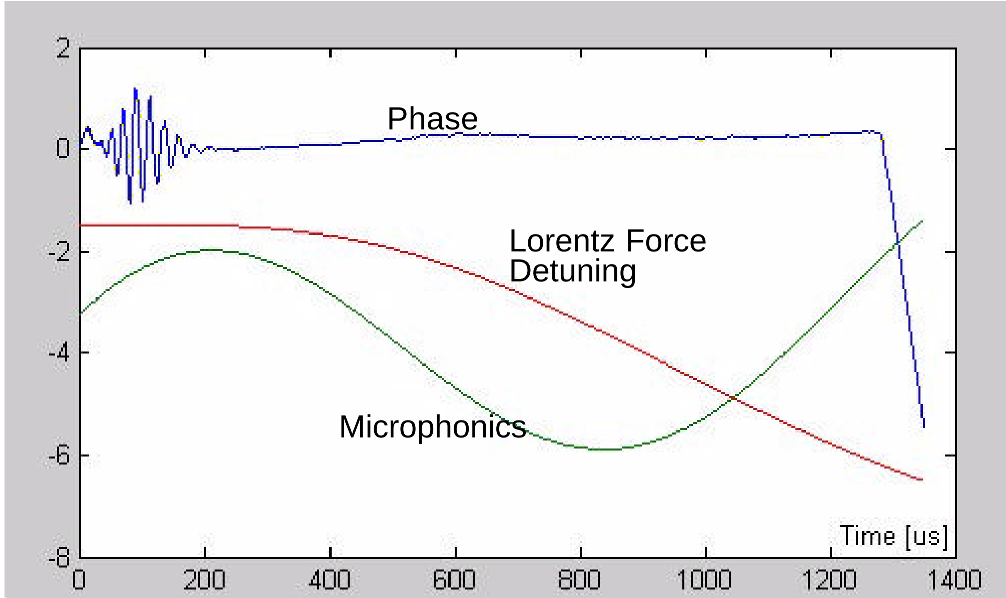


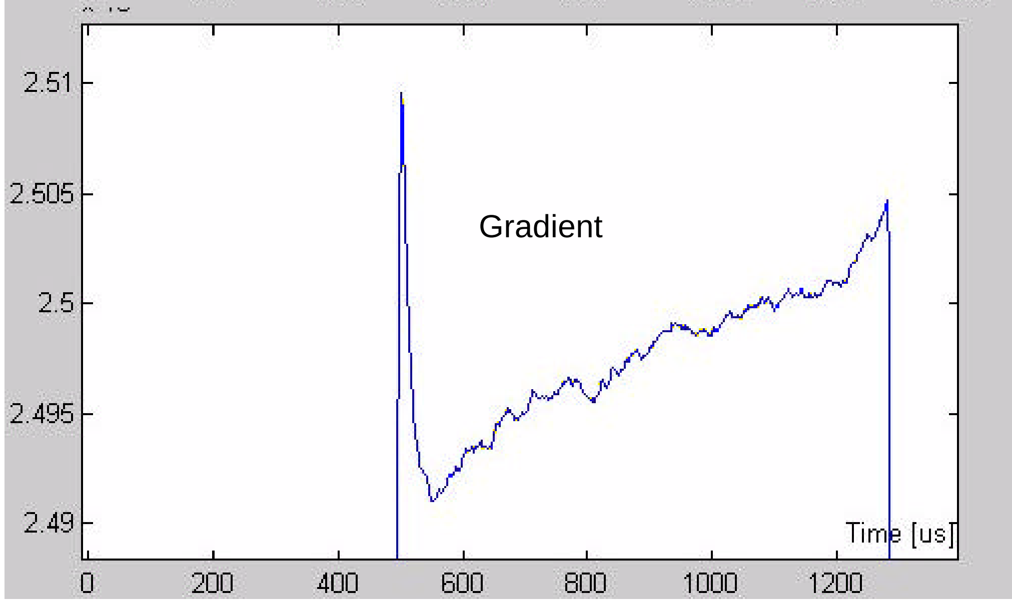
Sources of Perturbations

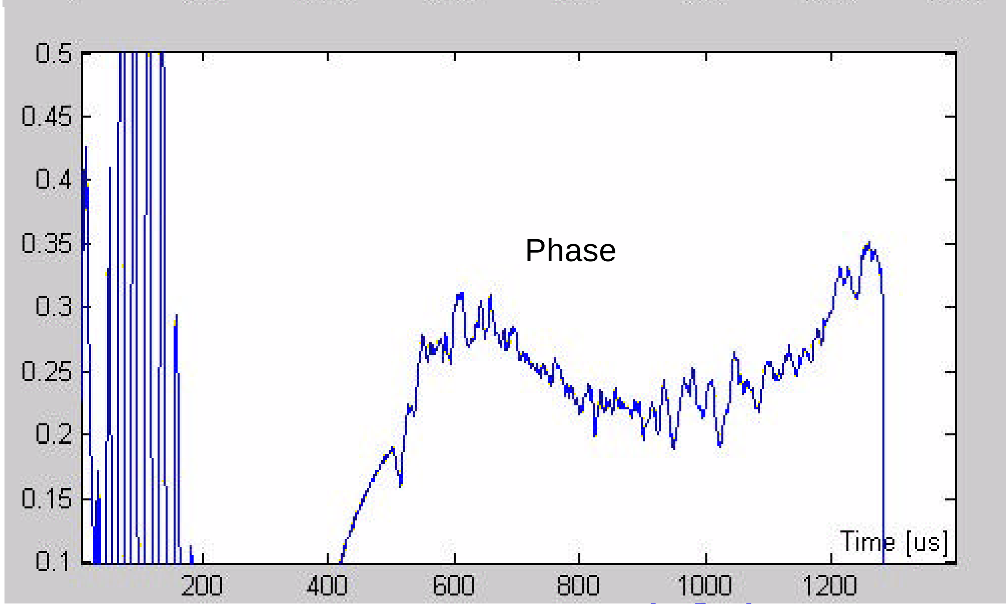
o Beam loading - Beam current fluctuations - Pulsed beam transients - Multipacting and field emission - Excitation of HOMs - Excitation of other passband modes - Wake fields o Cavity drive signal - HV- Pulse flatness - HV PS ripple - Phase noise from master oscillator - Timing signal jitter - Mismatch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

RF Regulation TESLA Cavity (Simulation)

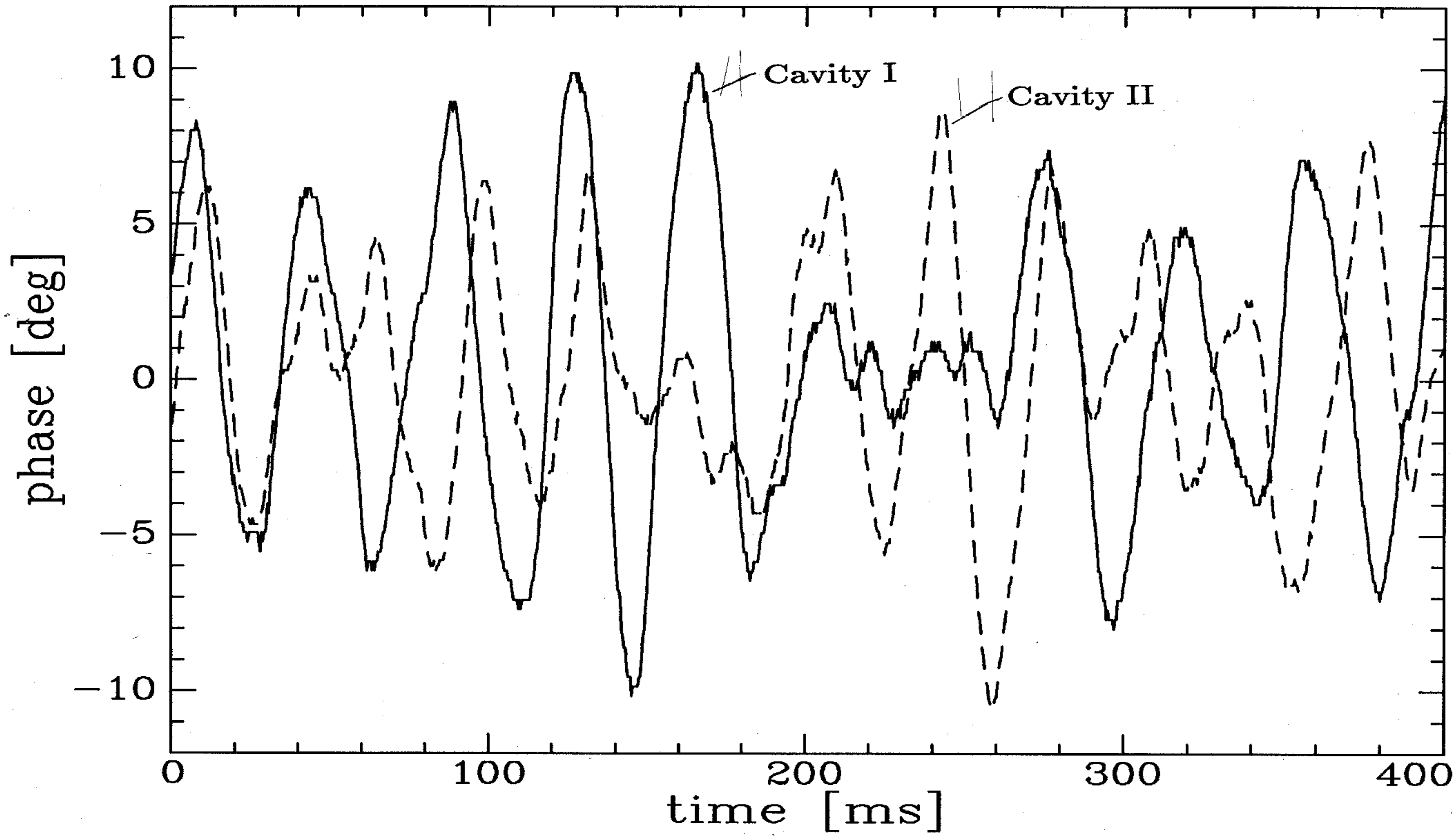








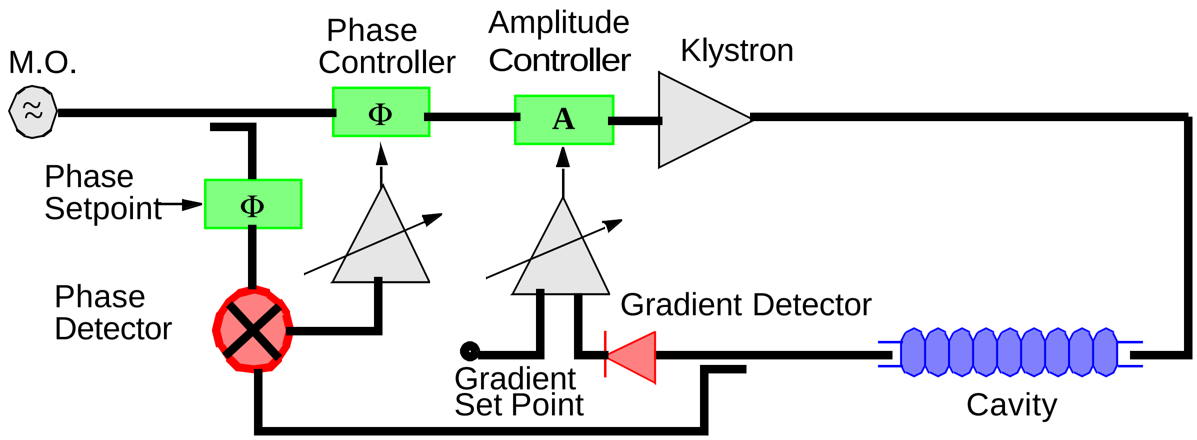
Microphonics at JLAB



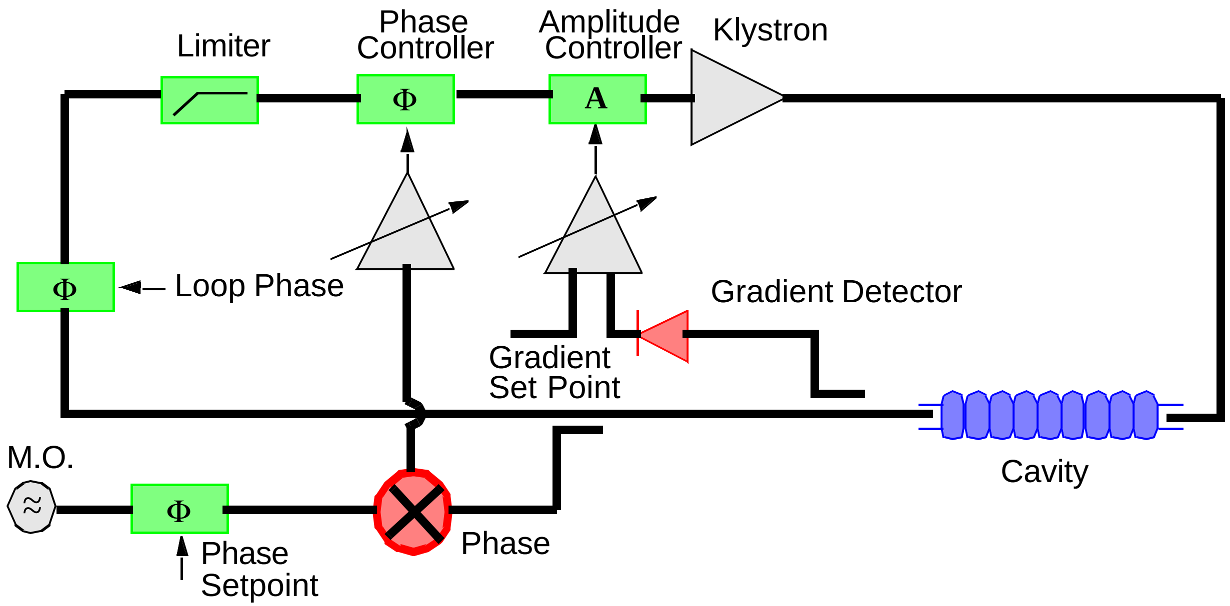
Control Choices (1)

- Self-excited Loop (SEL) vs
  Generator Driven System (GDR)
- Vector-sum (VS) vs individual cavity control
- Analog vs Digital Control Design
- Amplitude and Phase (A&P) vs
  In-phase and Quadrature (I/Q) detector and controller

Control Choices (2)

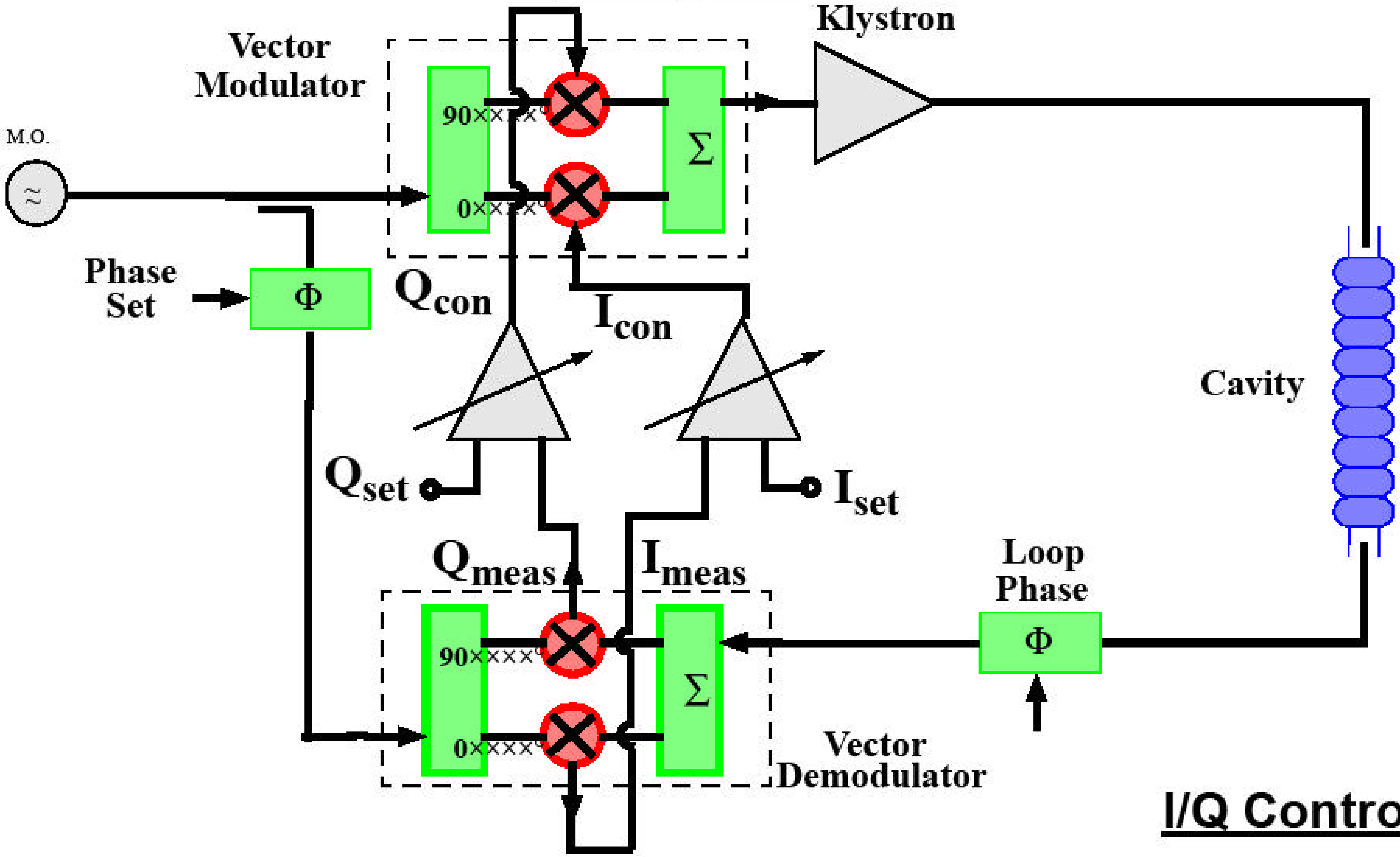


Generator Driven Resonator



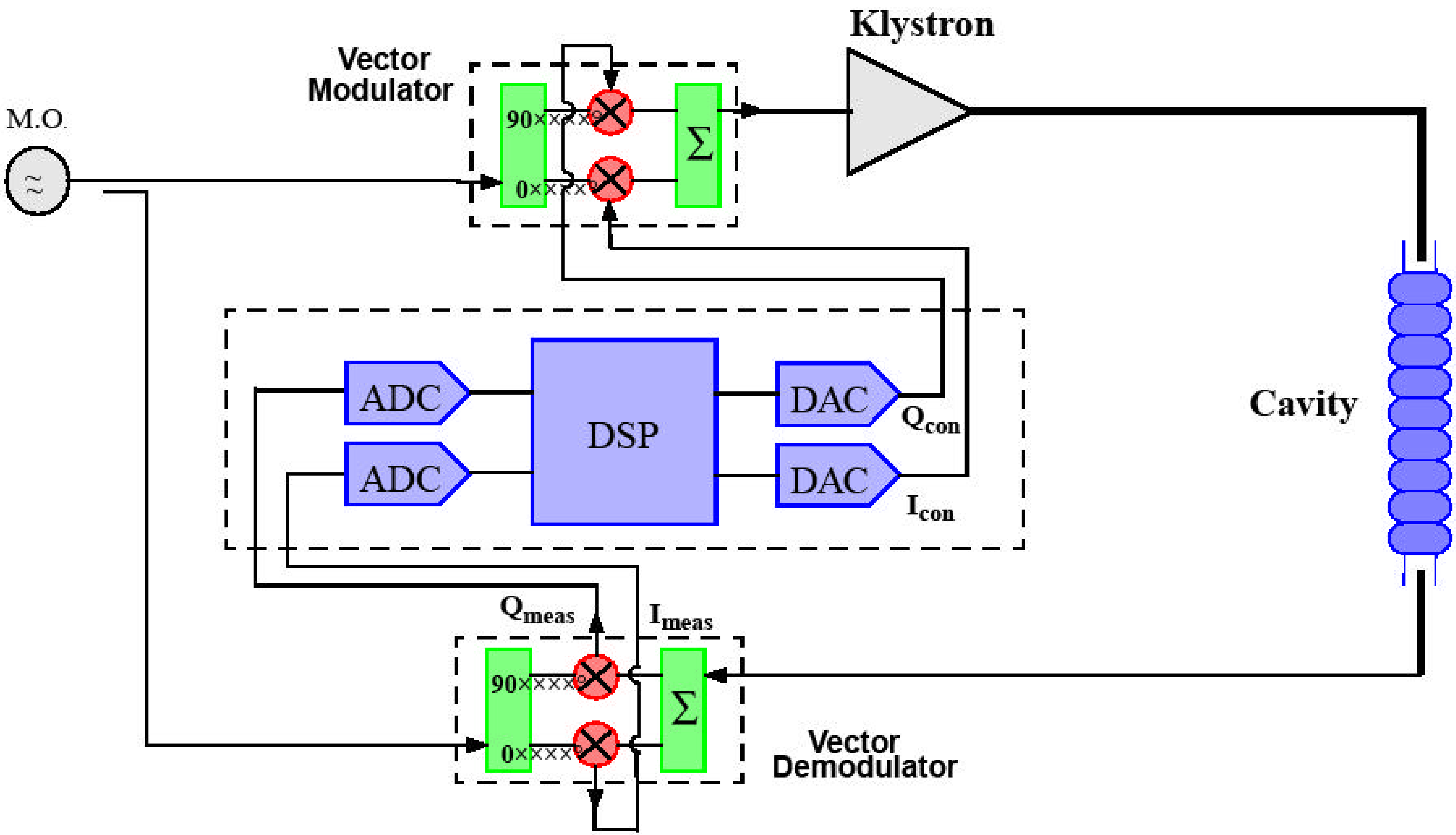
Self Excited Loop

Analog IQ Control

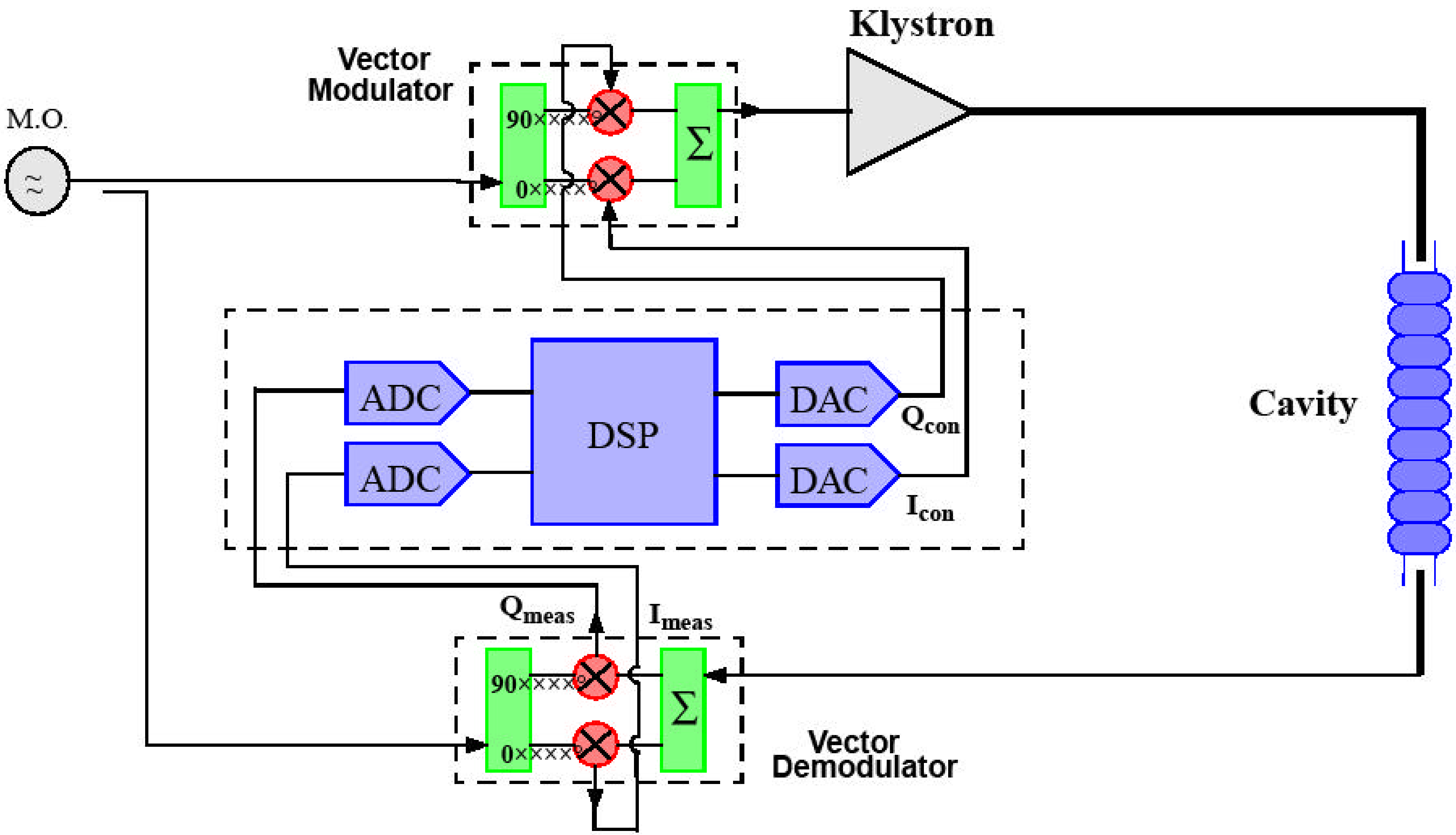


I/Q Control

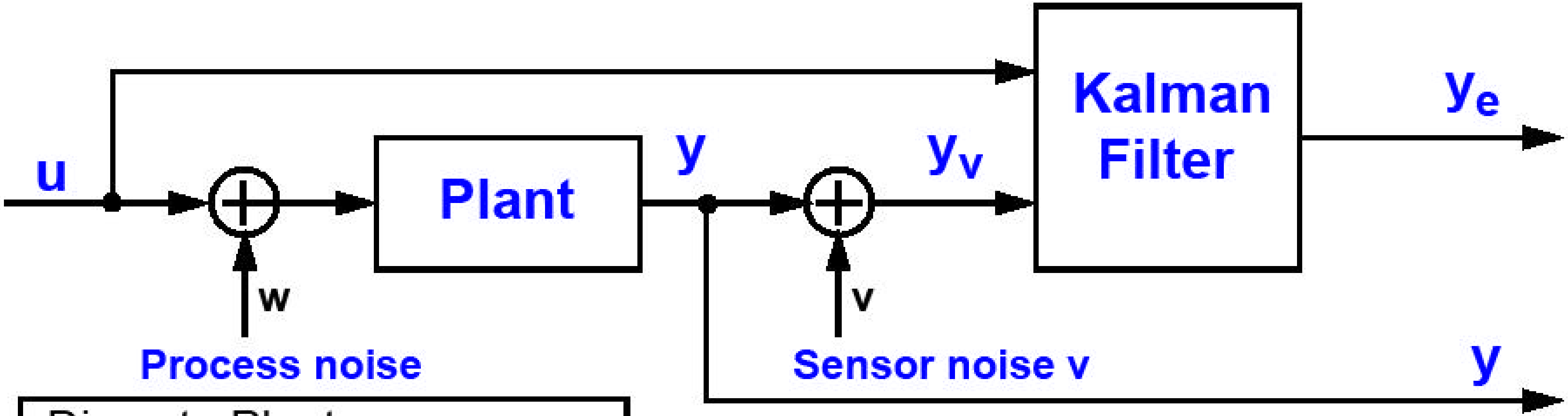
Digital IQ Control



Digital IQ Control



Principle Kalman Filter (steady state)



Discrete Plant:

$x[n+1]=Ax[n]+B(u[n]+w[n])$

$y[n]=Cx[n]$

Noisy output measurement: $y_v[n]=Cx[n]+v[n]$

Measurement update:

$$\hat{x}[n|n]=\hat{x}[n|n-1]+M(y_v[n]-C\hat{x}[n|n-1])$$

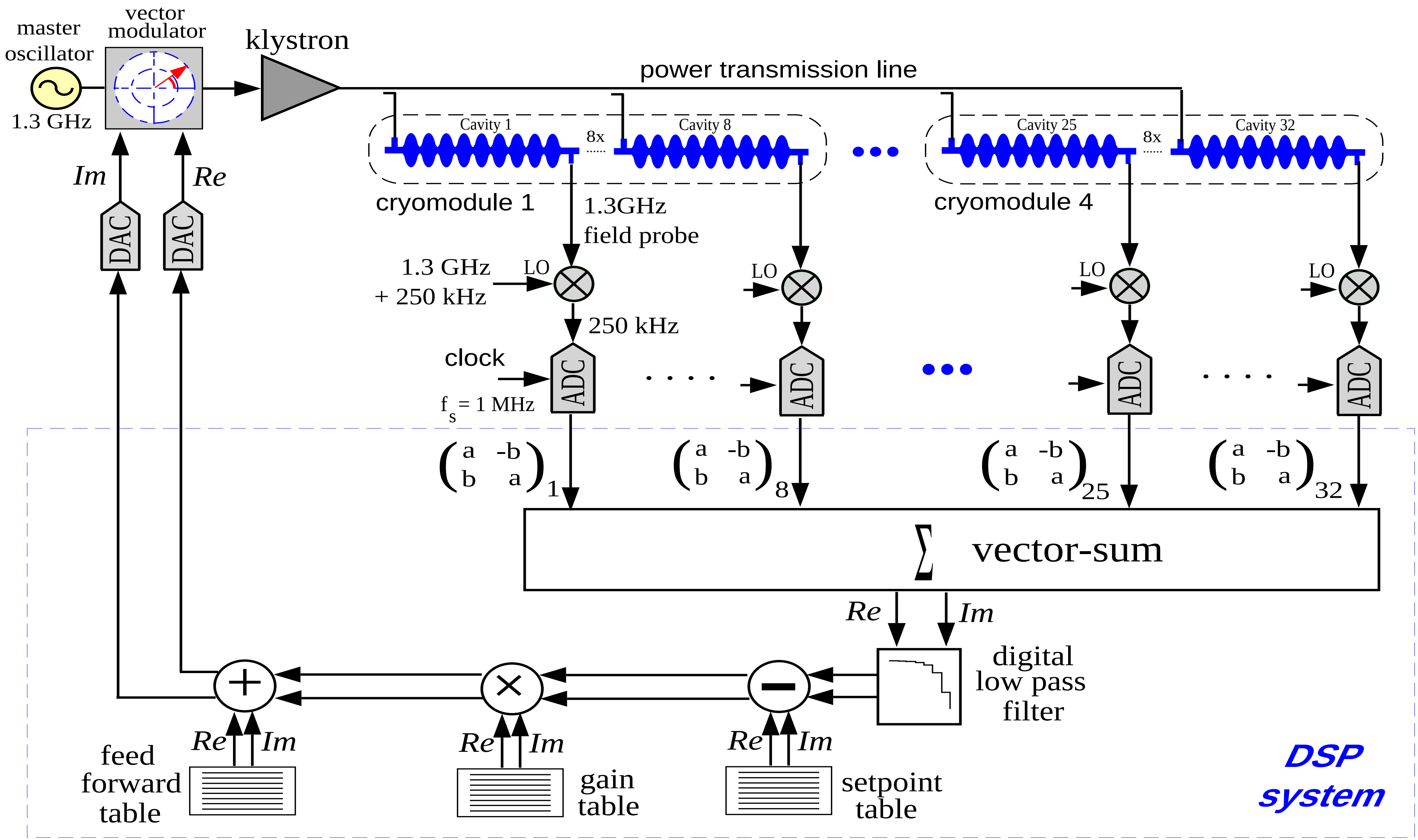
Time update: $\hat{x}[n+1|n]=A\hat{x}[n|n]+Bu[n]$

The correction term is a function of the innovation, i.e. the discrepancy

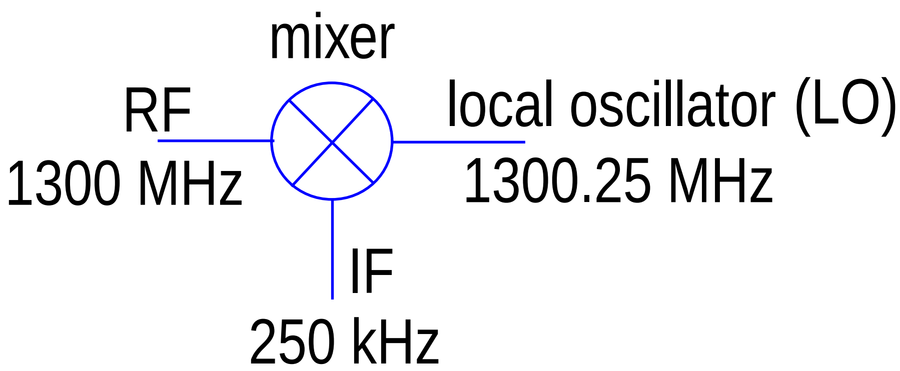
$$y_v[n+1]-C\hat{x}[n+1|n]=C(x[n+1]-\hat{x}[n+1|n])$$

The innovation gain matrix M is chosen to minimize steady-state covariance of the estimation error given the noise covariances $E(w[n]w[n]^T)=Q$ and $E(v[n]v[n]^T)=R$

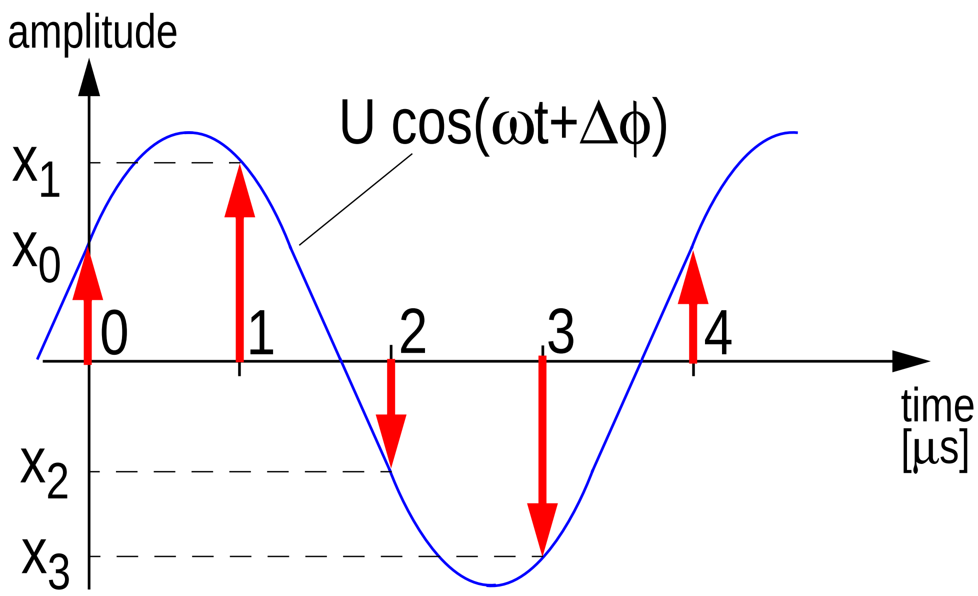
Digital Control at the TTF



Digital I/Q Detection

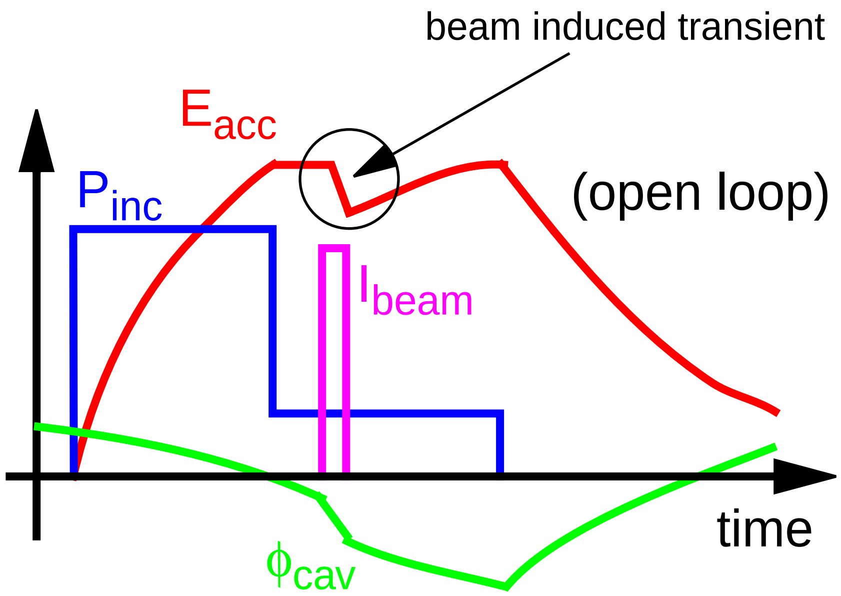


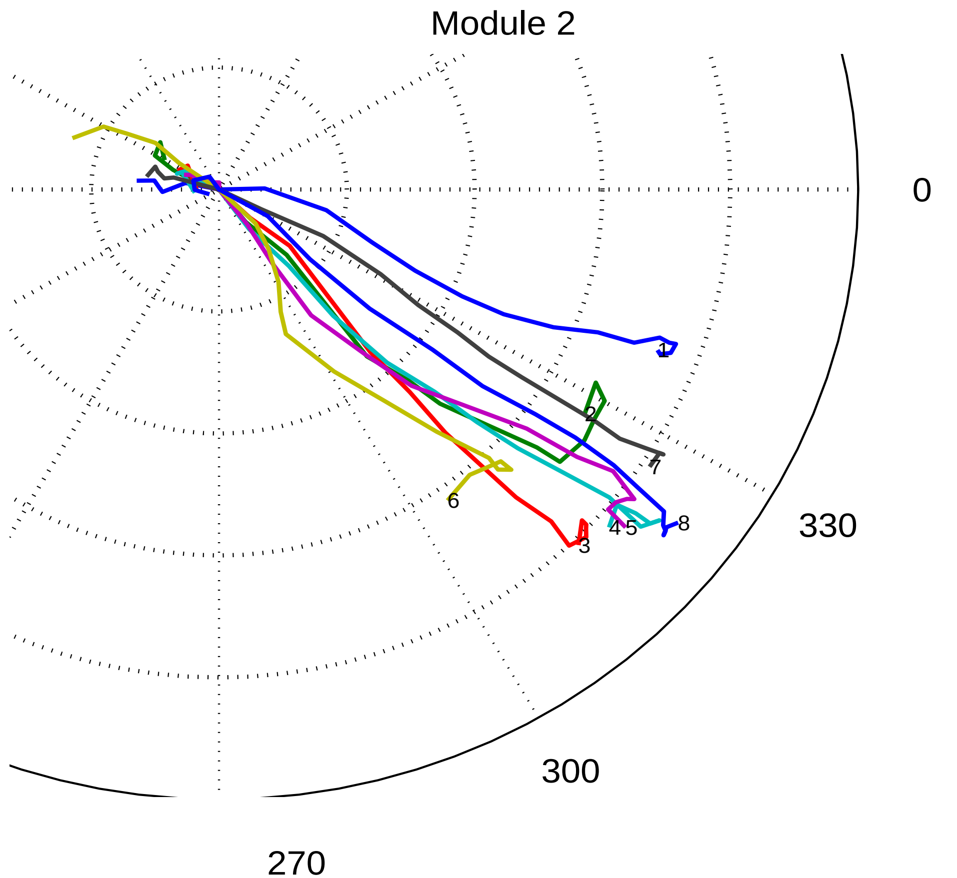
- downconversion of cavity field to IF frequency at 250 kHz
- complete phase and amplitude information of the accelerating field is preserved.

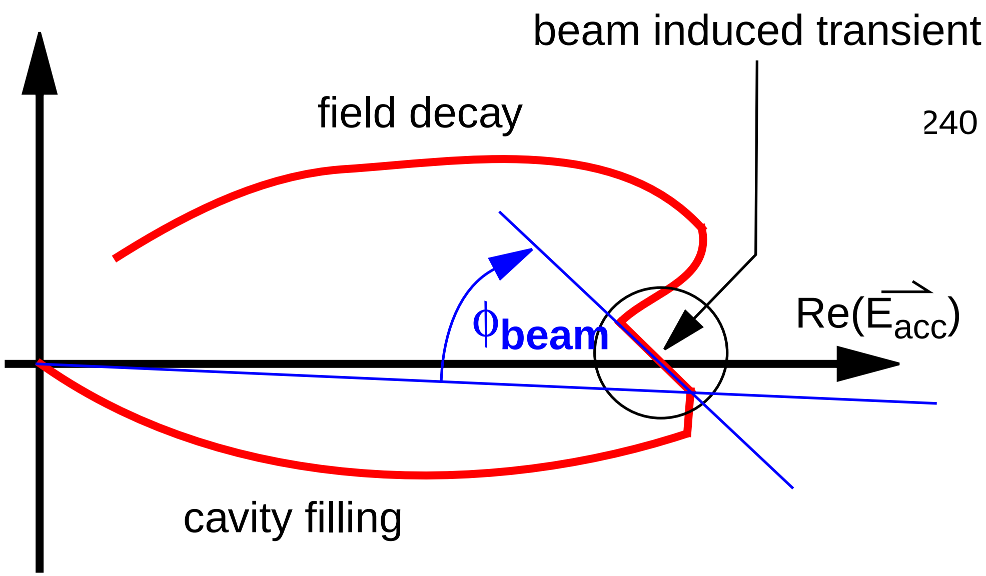


- sample IF signal at 1MHz rate
- subsequent samples describe real and imaginary component of the cavity field.

Beam Transient based Phase and Gradient Calibration



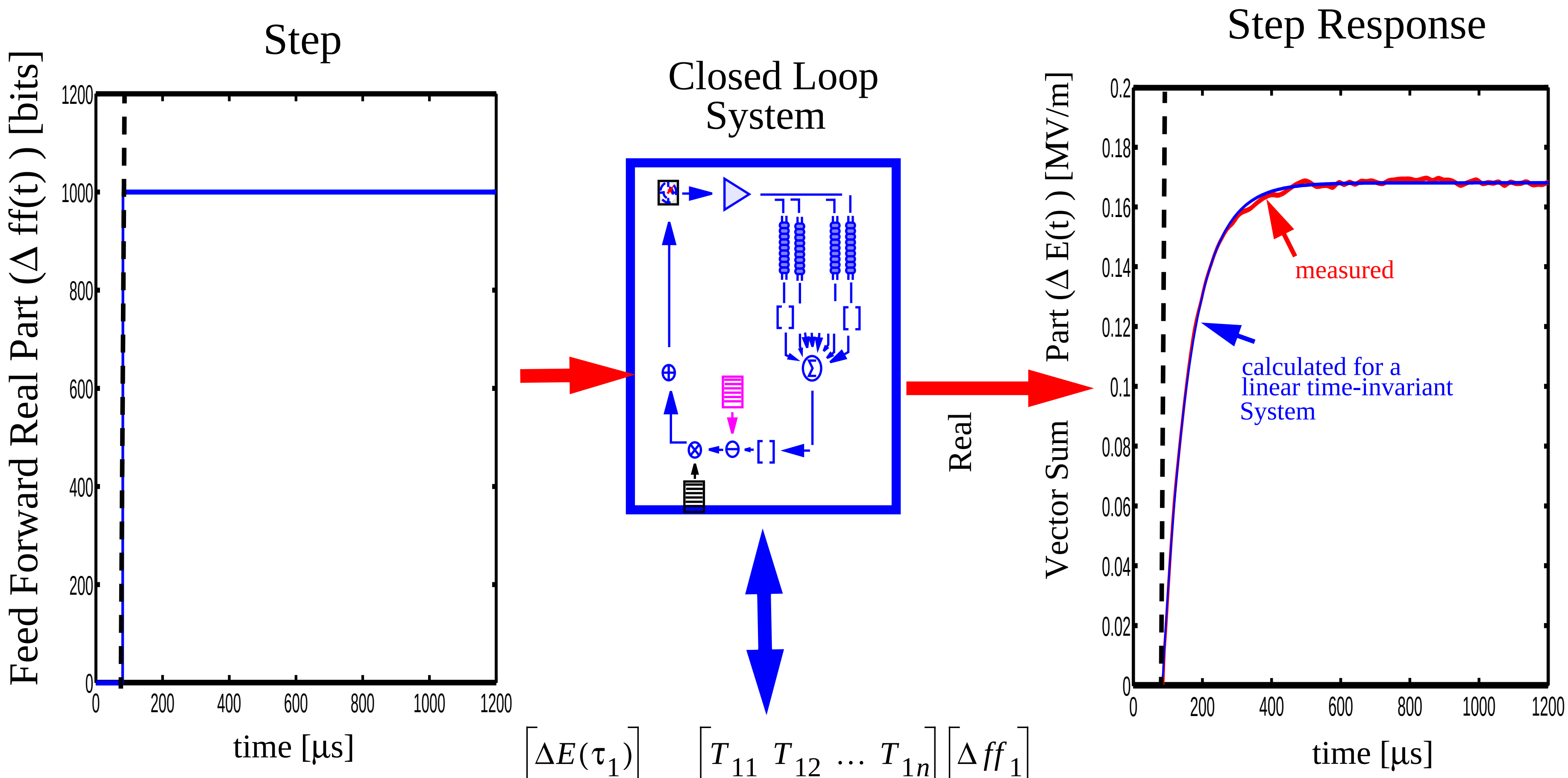




for $\Delta t << \tau_{cav}$:

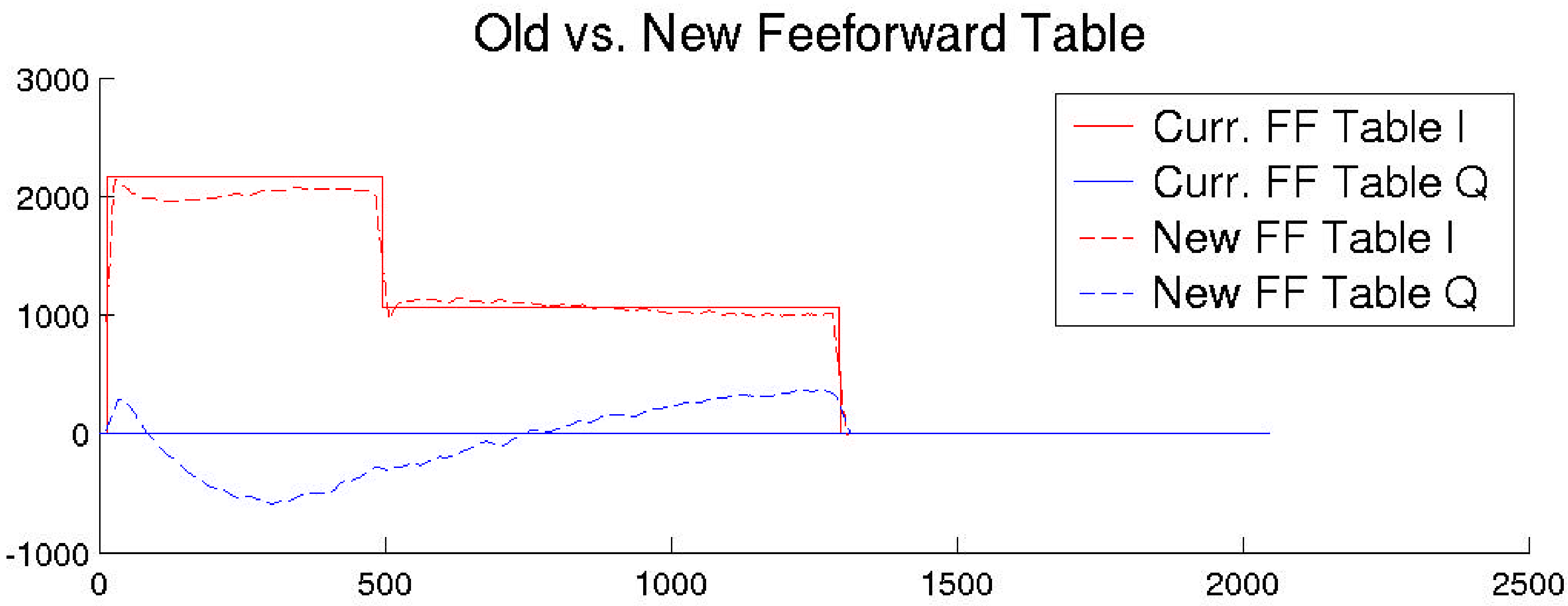
$$\Delta V_{ind} = I \cdot \Delta t \cdot \left(\frac{r}{Q}\right) \cdot \pi \cdot f$$

Adaptive Feedforward

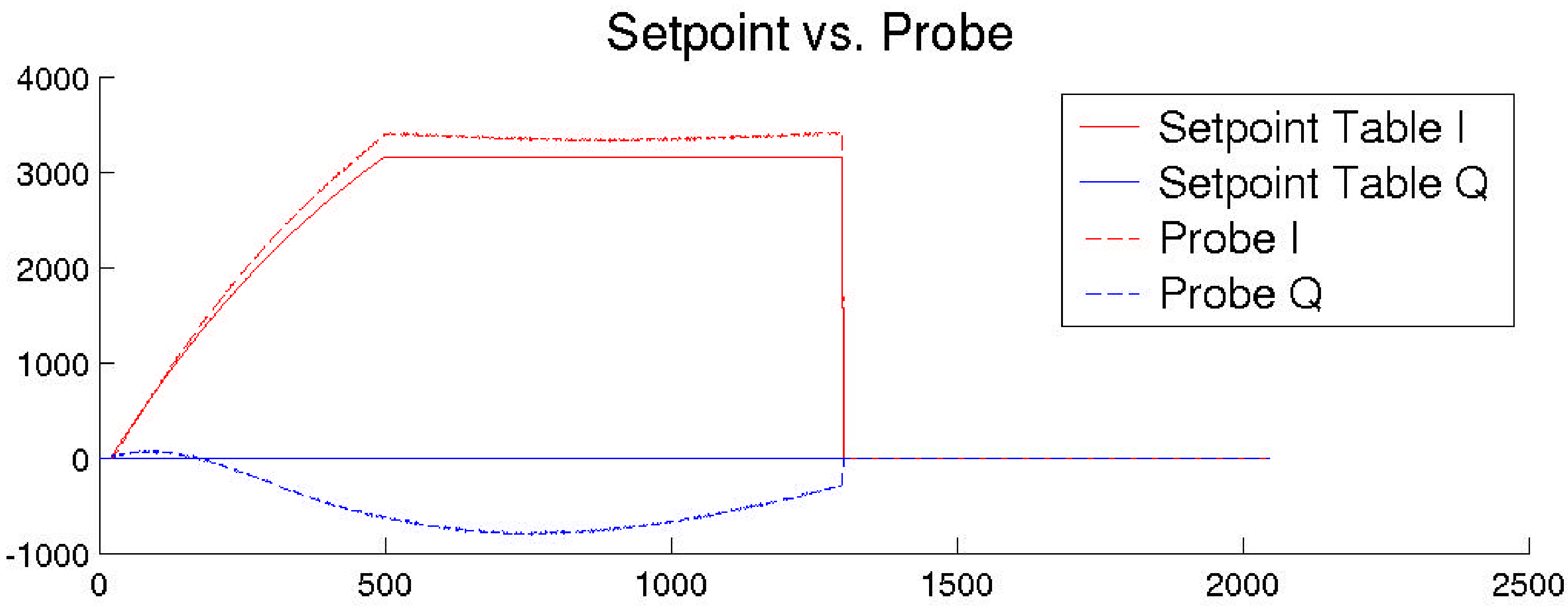


$$\begin{bmatrix} \Delta E(\tau_1) \\ \Delta E(\tau_2) \\ \dots \\ \Delta E(\tau_n) \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & \dots & T_{1n} \\ T_{21} & T_{22} & \dots & T_{2n} \\ \dots & \dots & \dots & \dots \\ T_{n1} & T_{n2} & \dots & T_{nn} \end{bmatrix} \begin{bmatrix} \Delta ff_1 \\ \Delta ff_n \\ \dots \\ \Delta ff_n \end{bmatrix}$$

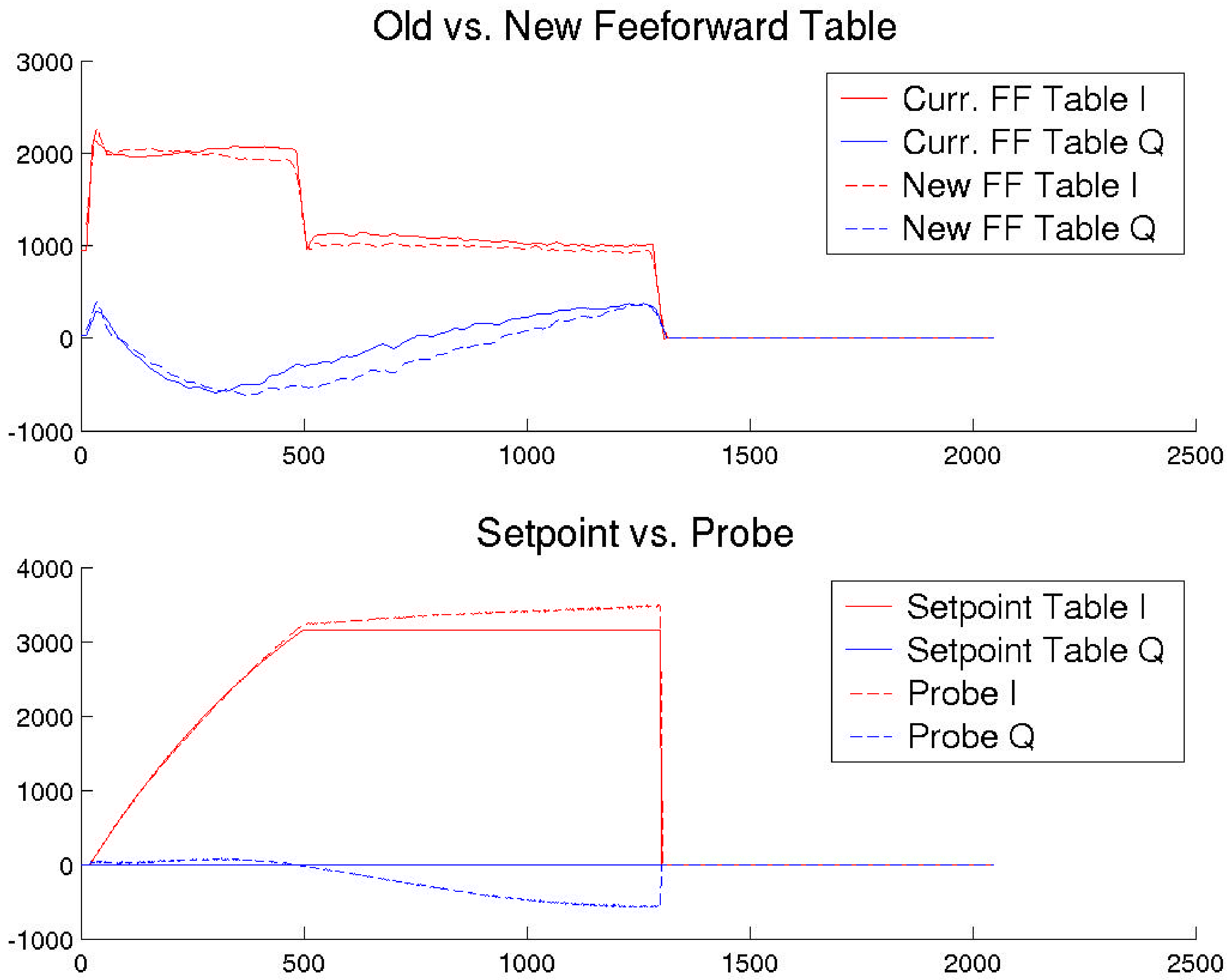
$$\Delta ff(t) = \sum_j \Delta ff_j \Theta(t - t_j).$$

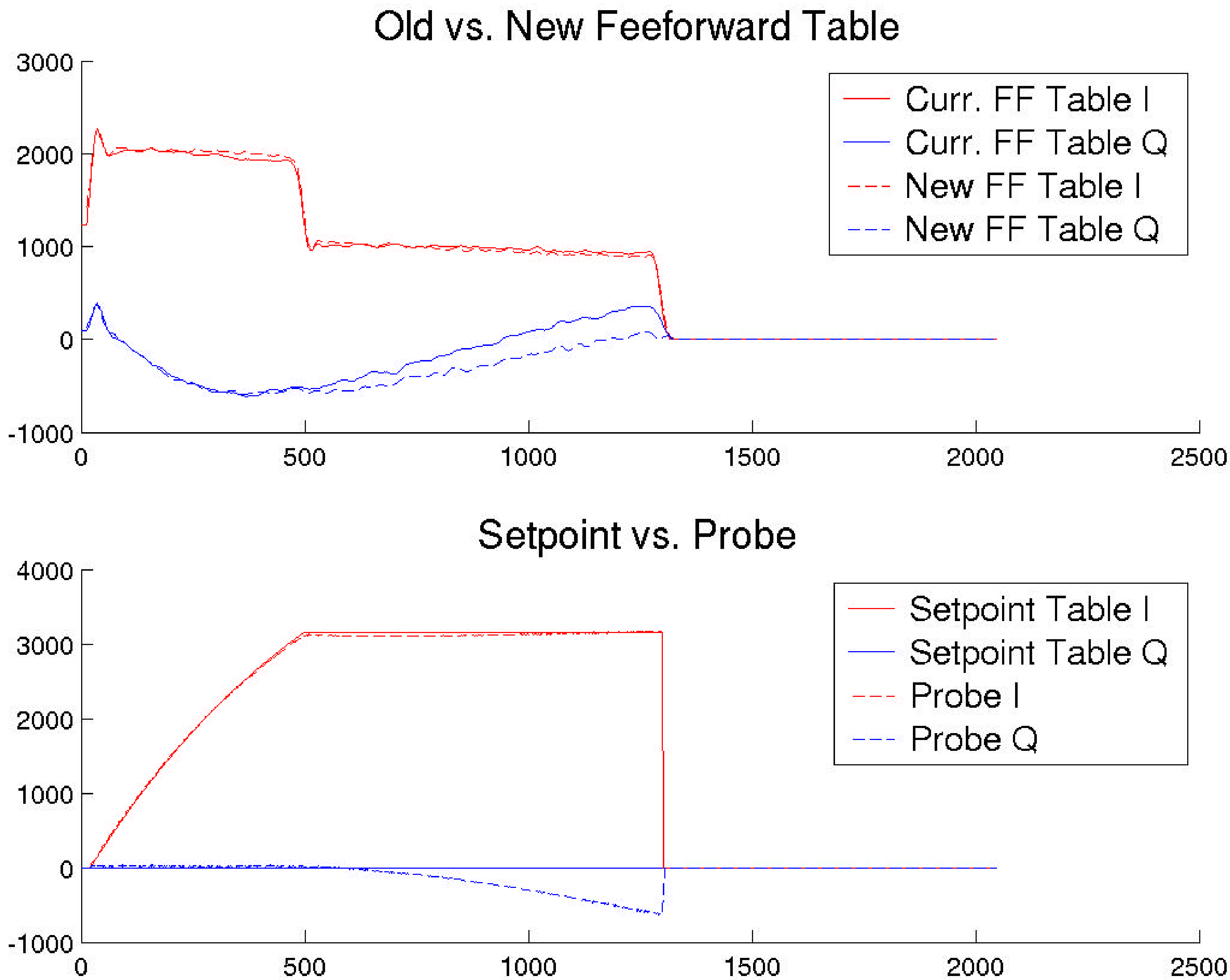


Old vs. New Feeforward Table
Curr. FF Table I
Curr. FF Table Q
New FF Table I
New FF Table Q
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500

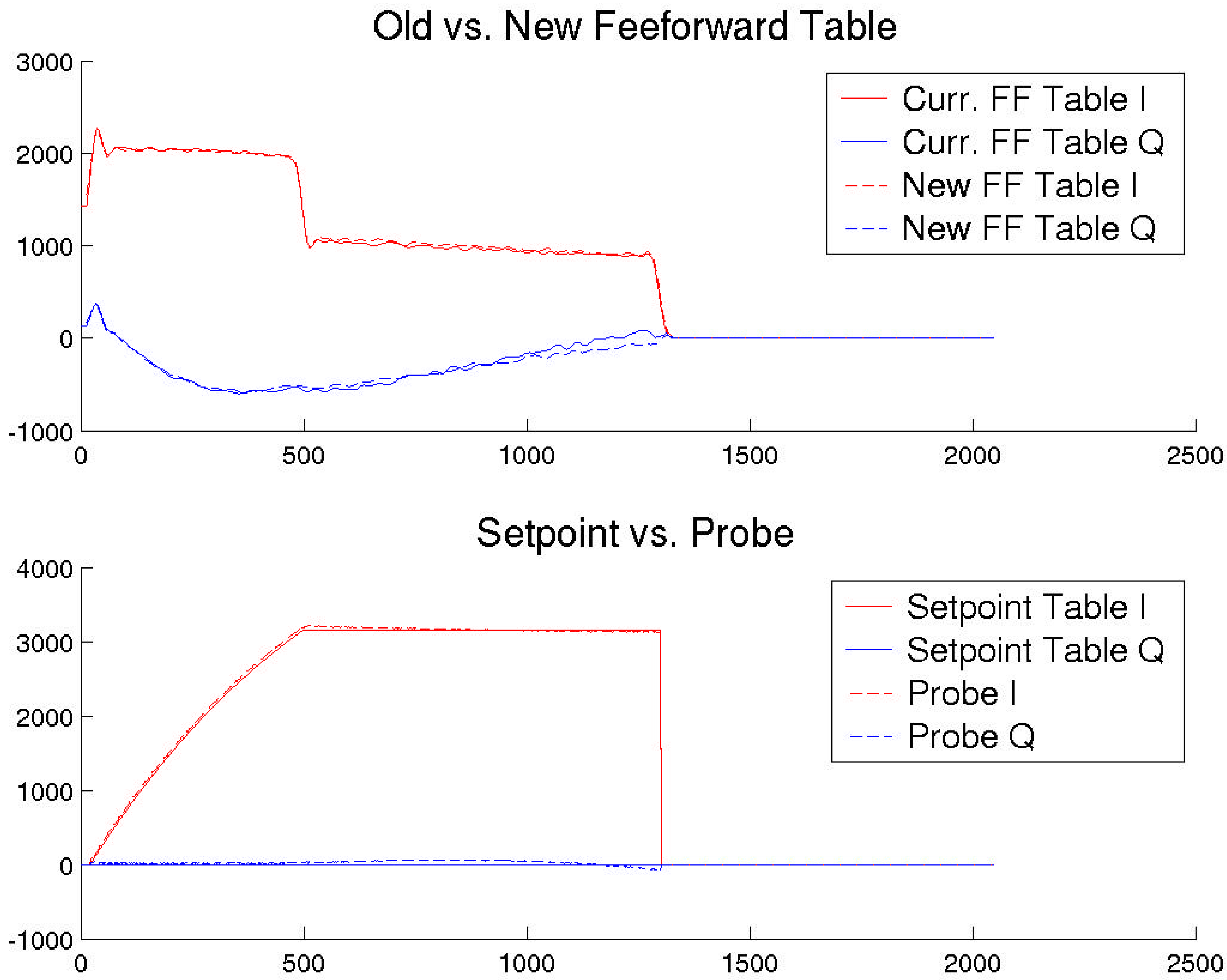


Setpoint vs. Probe
Setpoint Table I
Setpoint Table Q
Probe I
Probe Q
4000
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500

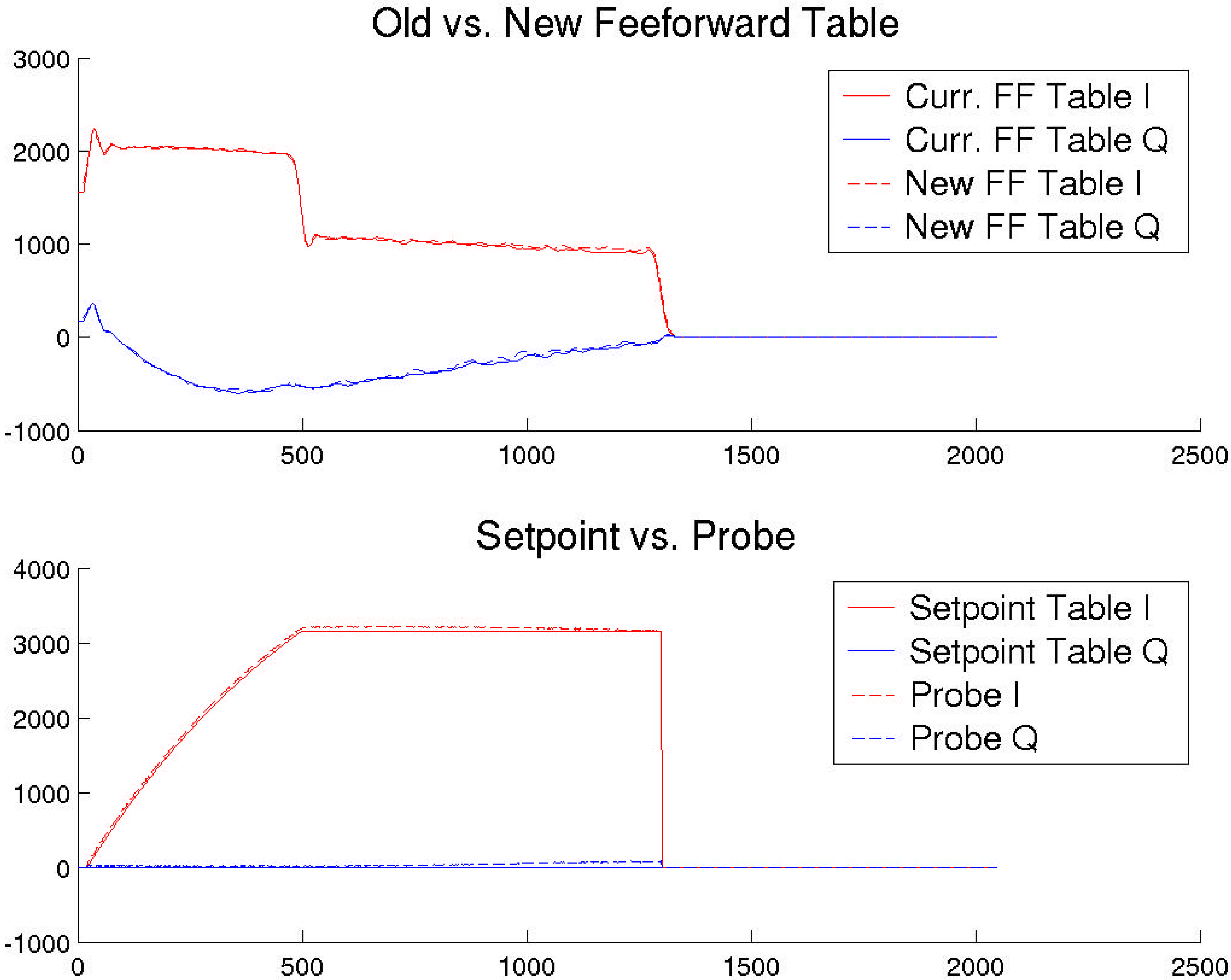

Old vs. New Feeforward Table
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500
Curr. FF Table I
Curr. FF Table Q
New FF Table I
New FF Table Q
Setpoint vs. Probe
4000
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500
Setpoint Table I
Setpoint Table Q
Probe I
Probe Q



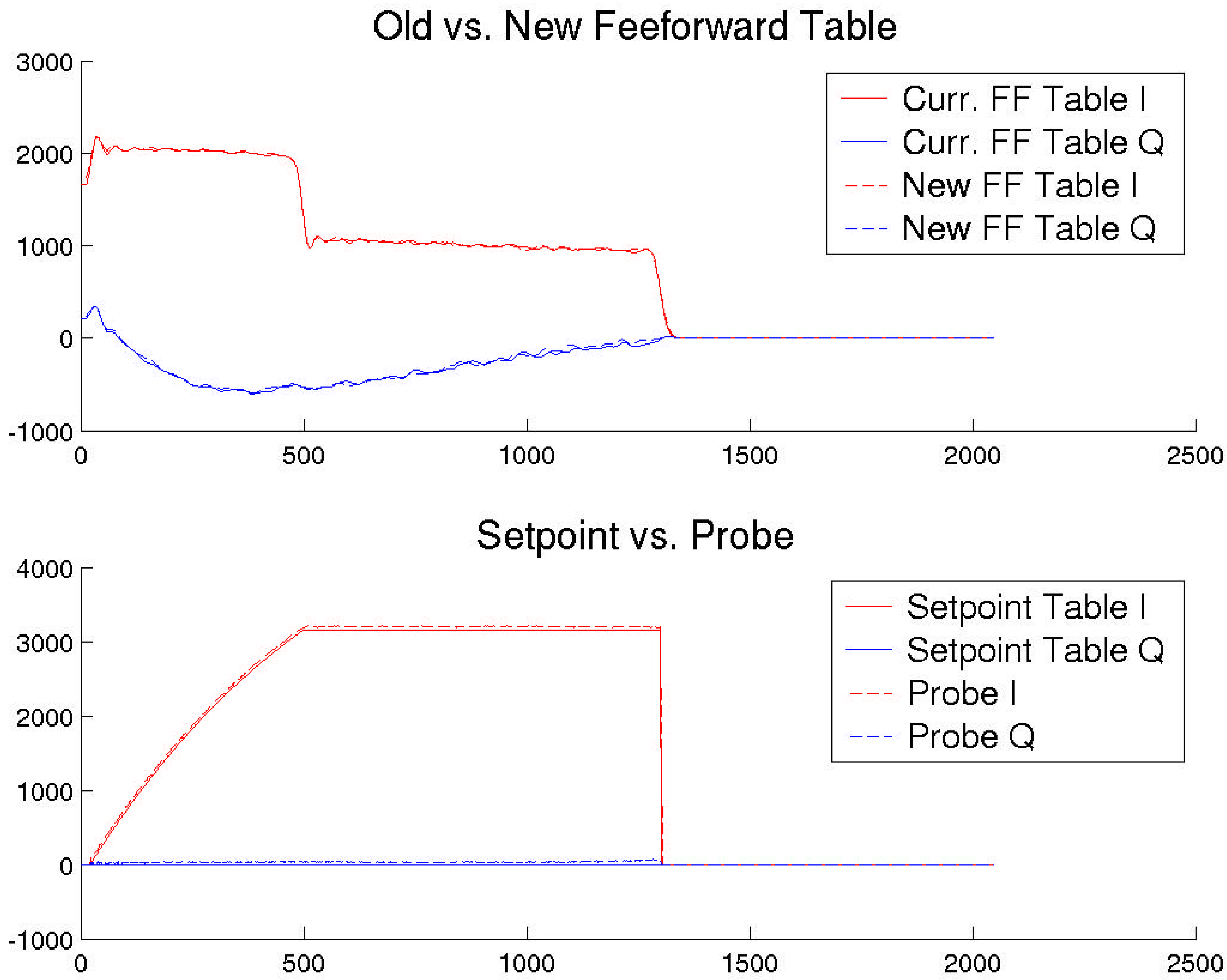
Old vs. New Feeforward Table
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500
Curr. FF Table I
Curr. FF Table Q
New FF Table I
New FF Table Q
Setpoint vs. Probe
4000
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500
Setpoint Table I
Setpoint Table Q
Probe I
Probe Q

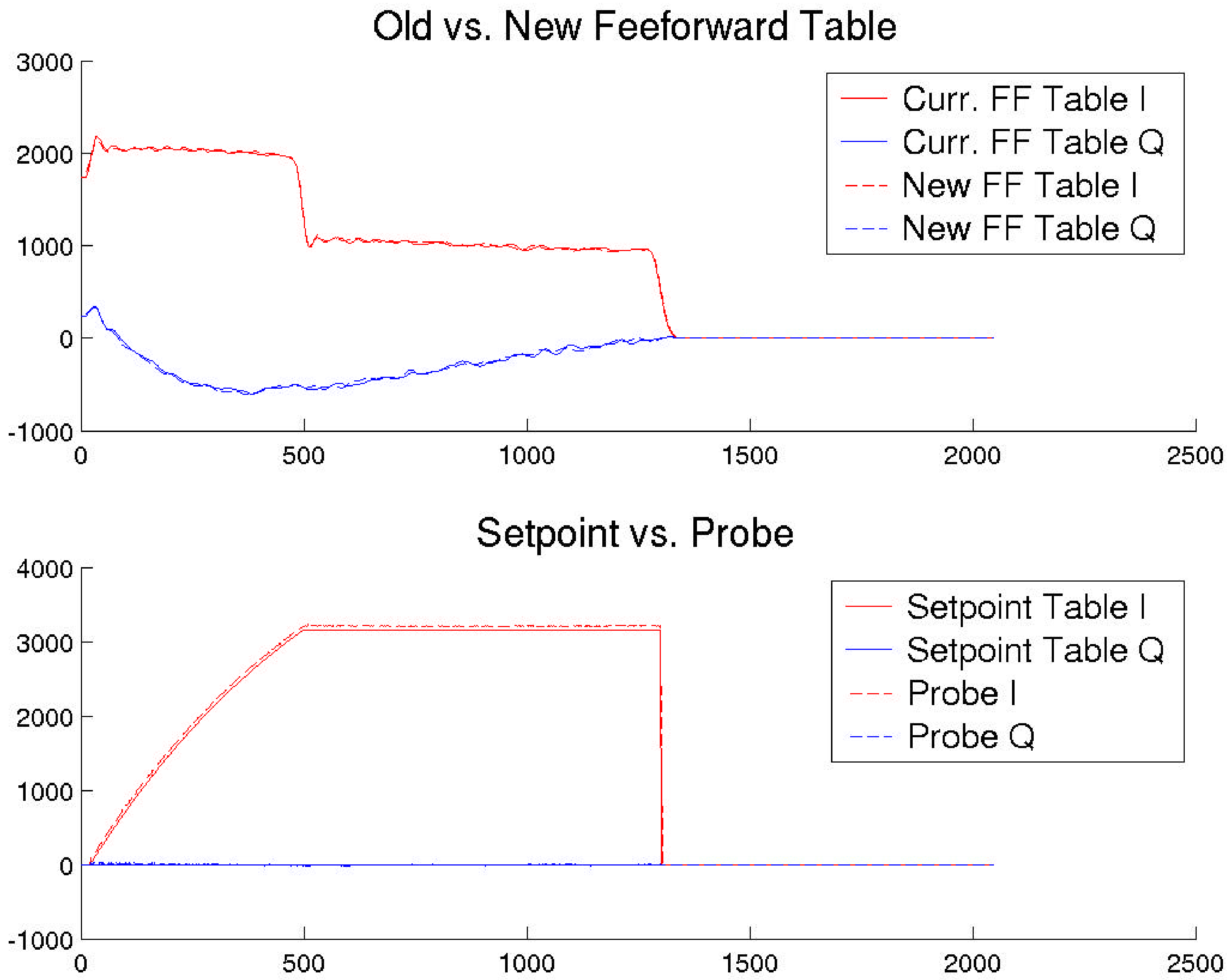


Old vs. New Feeforward Table
Curr. FF Table I
Curr. FF Table Q
New FF Table I
New FF Table Q
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500
Setpoint vs. Probe
Setpoint Table I
Setpoint Table Q
Probe I
Probe Q
4000
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500



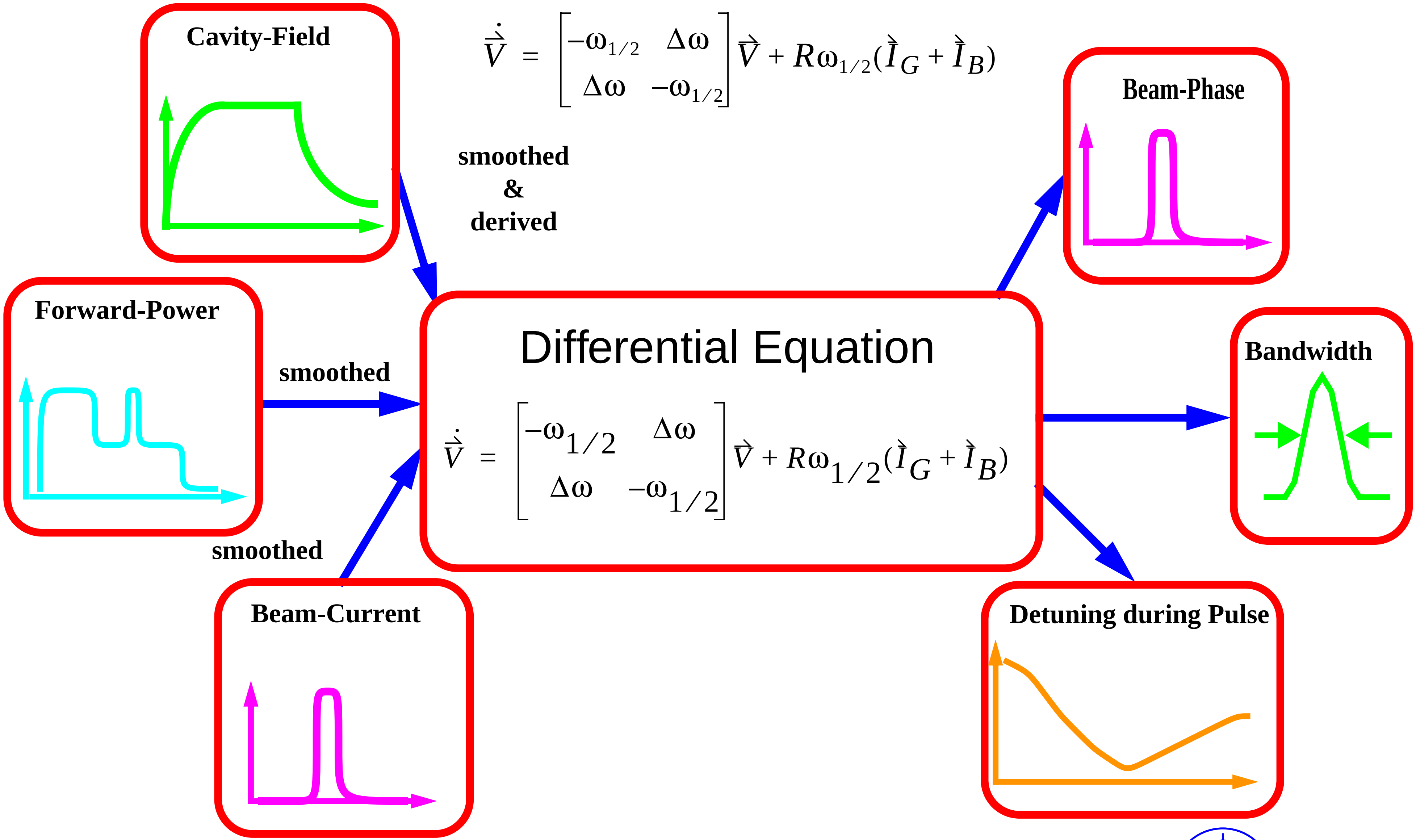
Old vs. New Feeforward Table
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500
Curr. FF Table I
Curr. FF Table Q
New FF Table I
New FF Table Q
Setpoint vs. Probe
4000
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500
Setpoint Table I
Setpoint Table Q
Probe I
Probe Q


Old vs. New Feeforward Table
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500
Curr. FF Table I
Curr. FF Table Q
New FF Table I
New FF Table Q
Setpoint vs. Probe
4000
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500
Setpoint Table I
Setpoint Table Q
Probe I
Probe Q

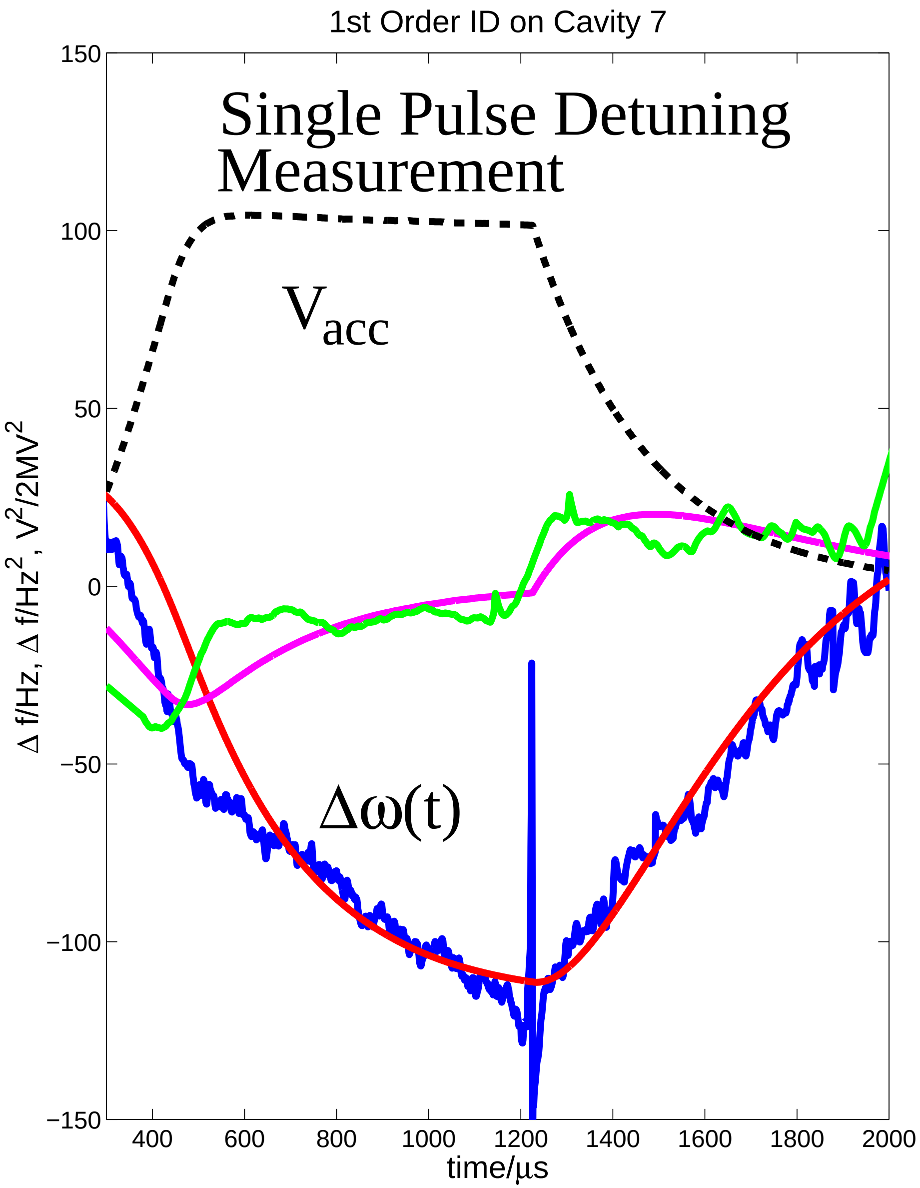


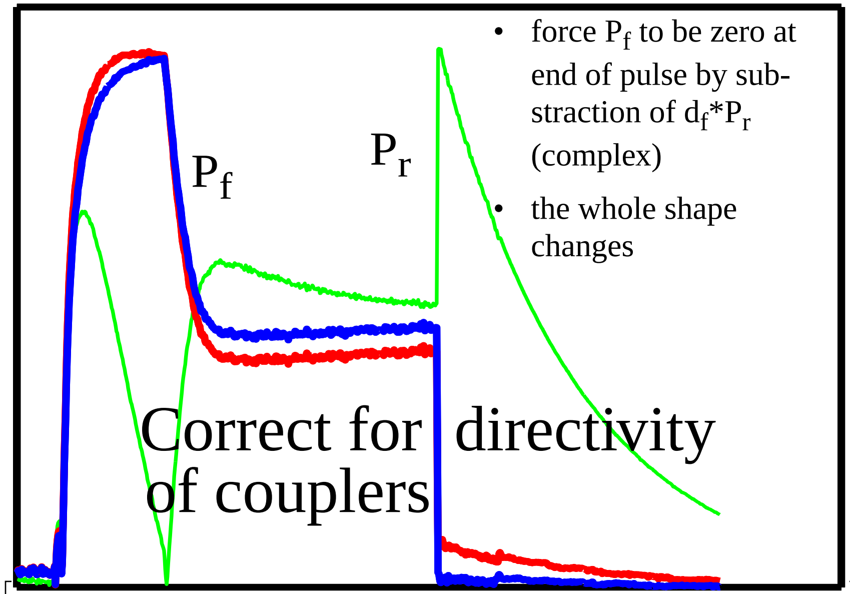
Old vs. New Feeforward Table
Curr. FF Table I
Curr. FF Table Q
New FF Table I
New FF Table Q
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500
Setpoint vs. Probe
Setpoint Table I
Setpoint Table Q
Probe I
Probe Q
4000
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500

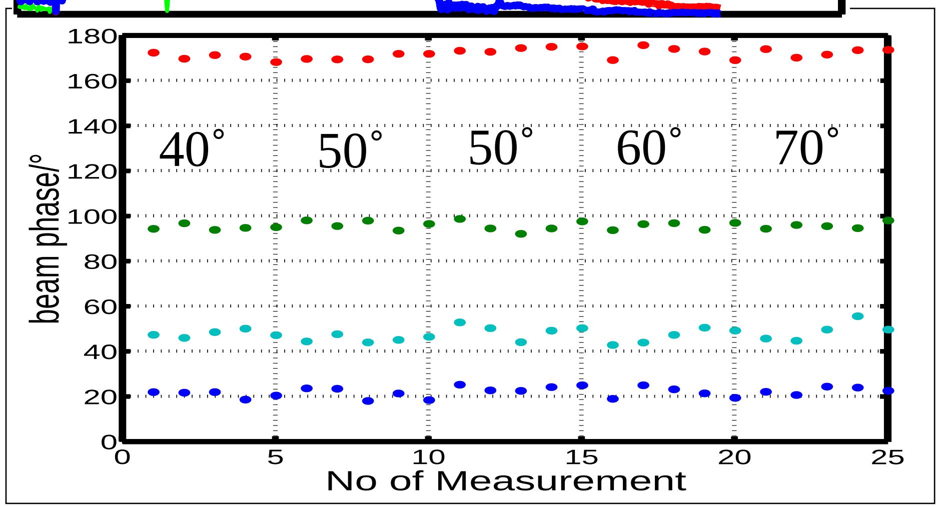
System Identification (1)



System Identification (2)

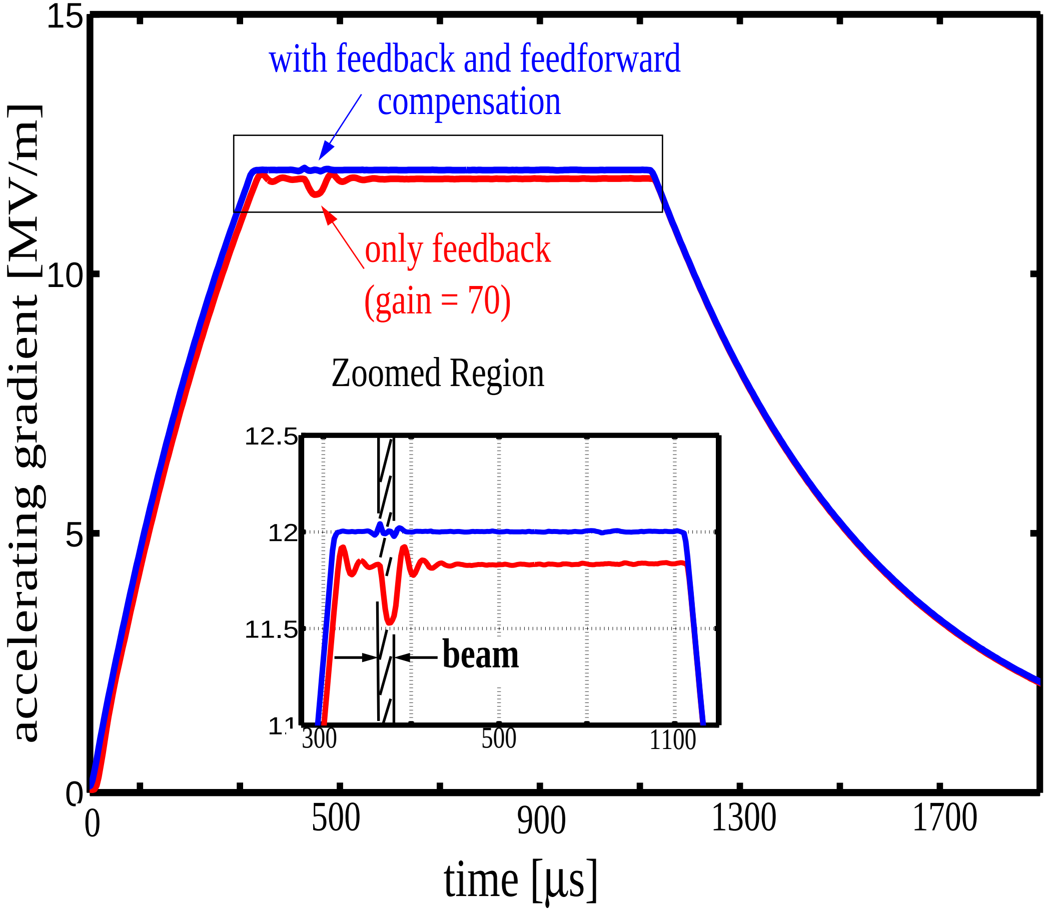


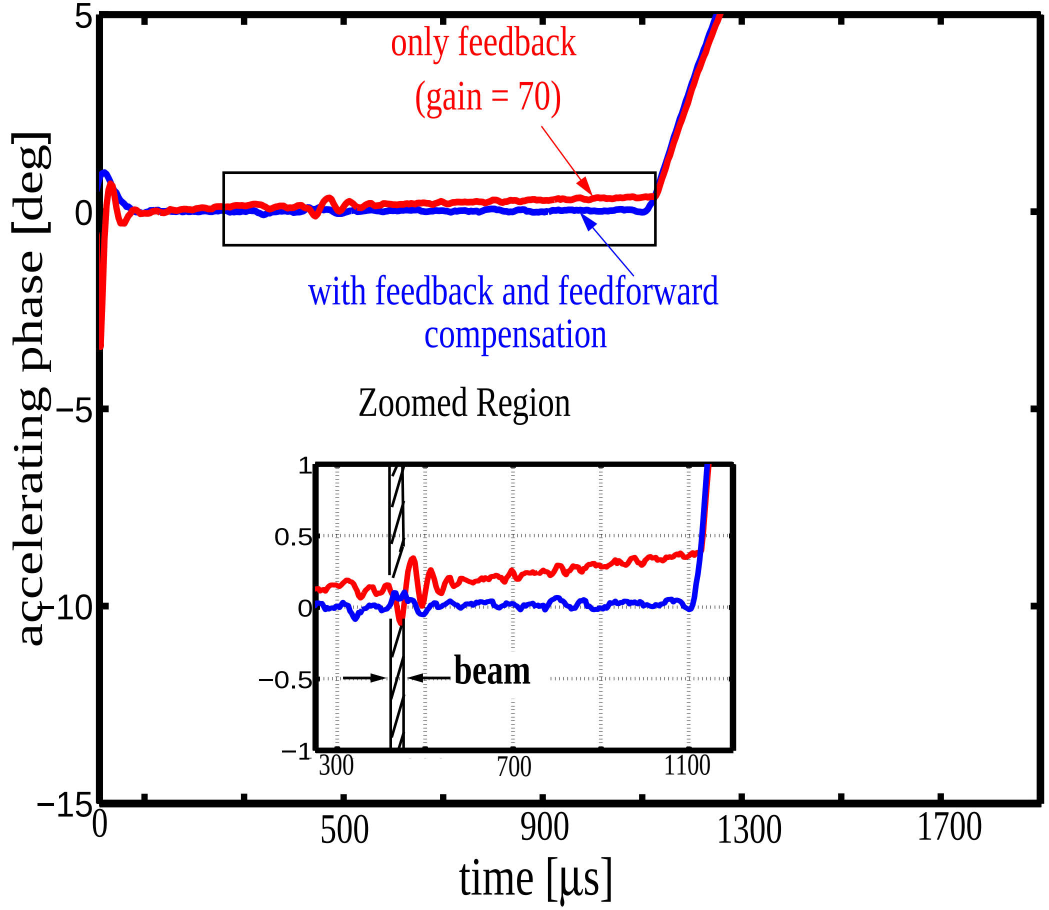




Beam phase of 4 cavities for different phase of V_{acc}

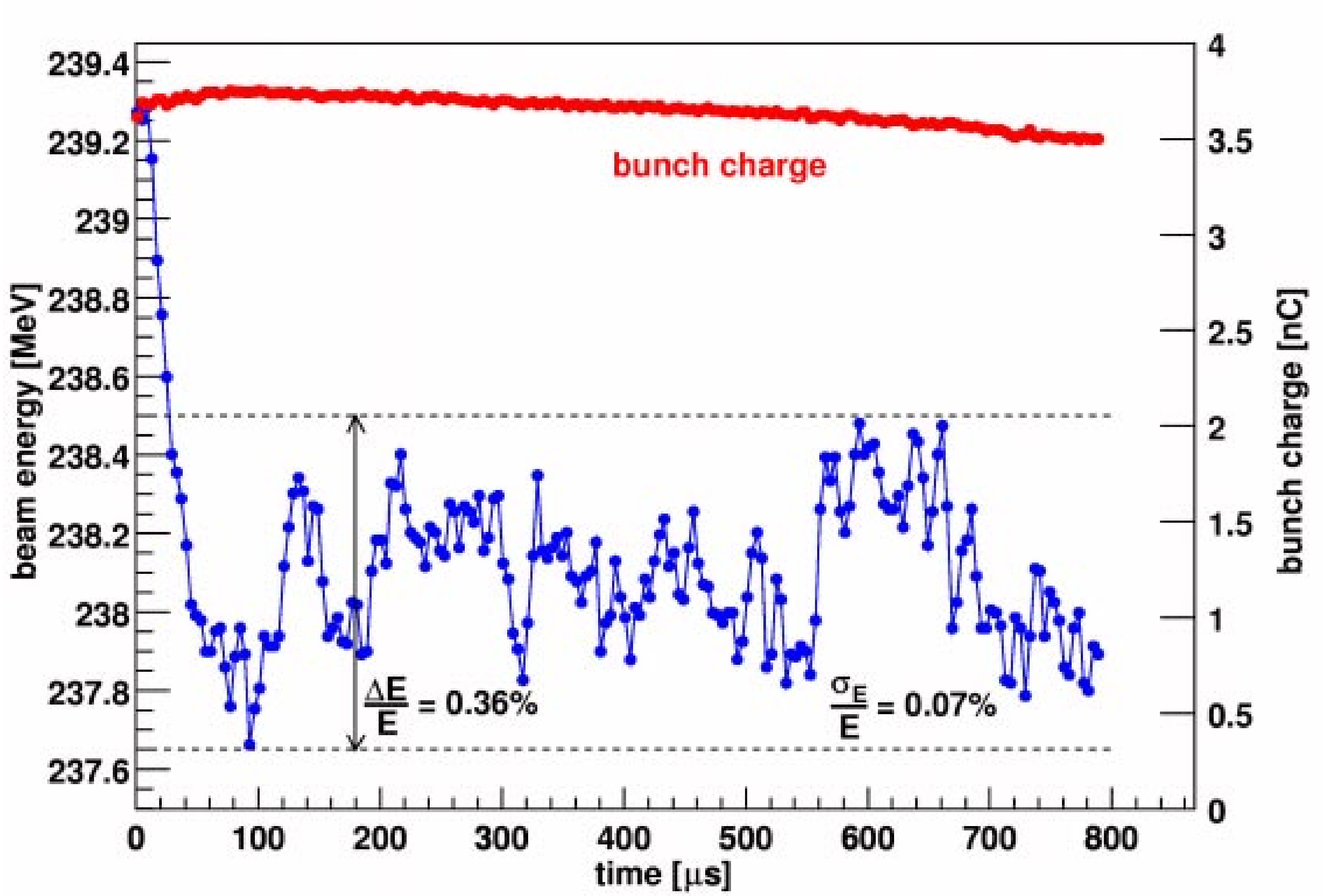
Performance at TTF (1)





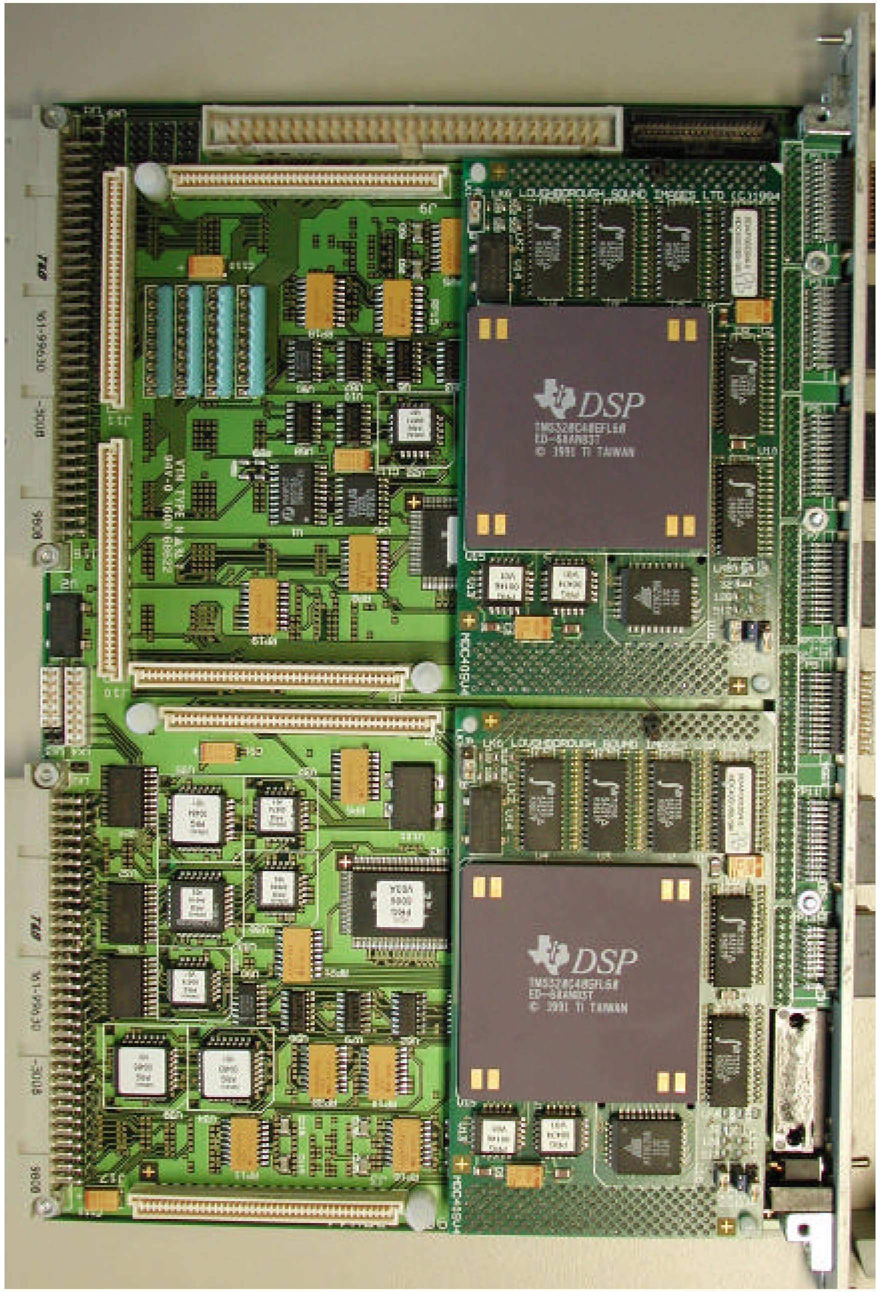
Amplitude **Phase**

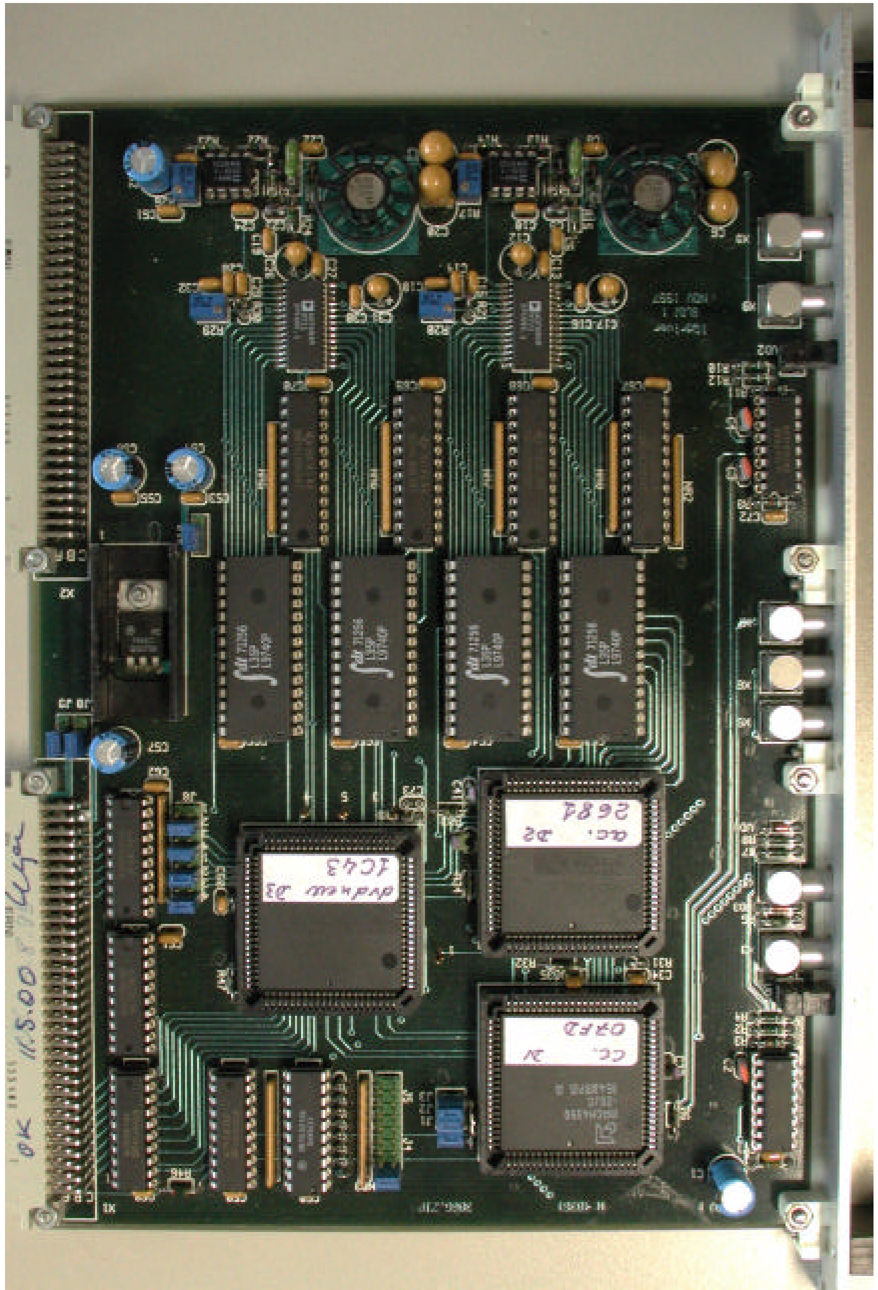
Performance at TTF (2)



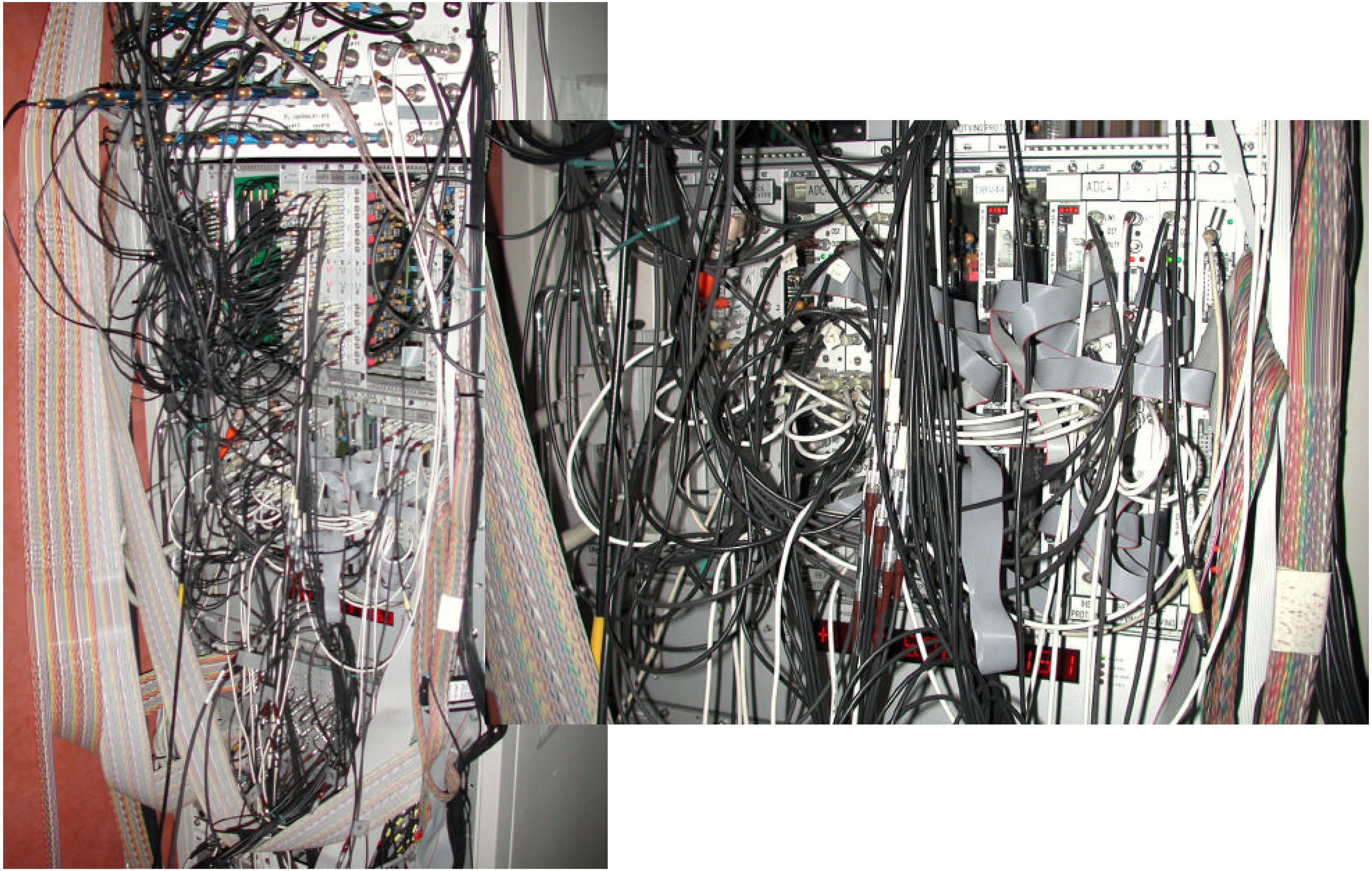
Operation with long beam pulses

DSP and ADC board LLRF for TTF I

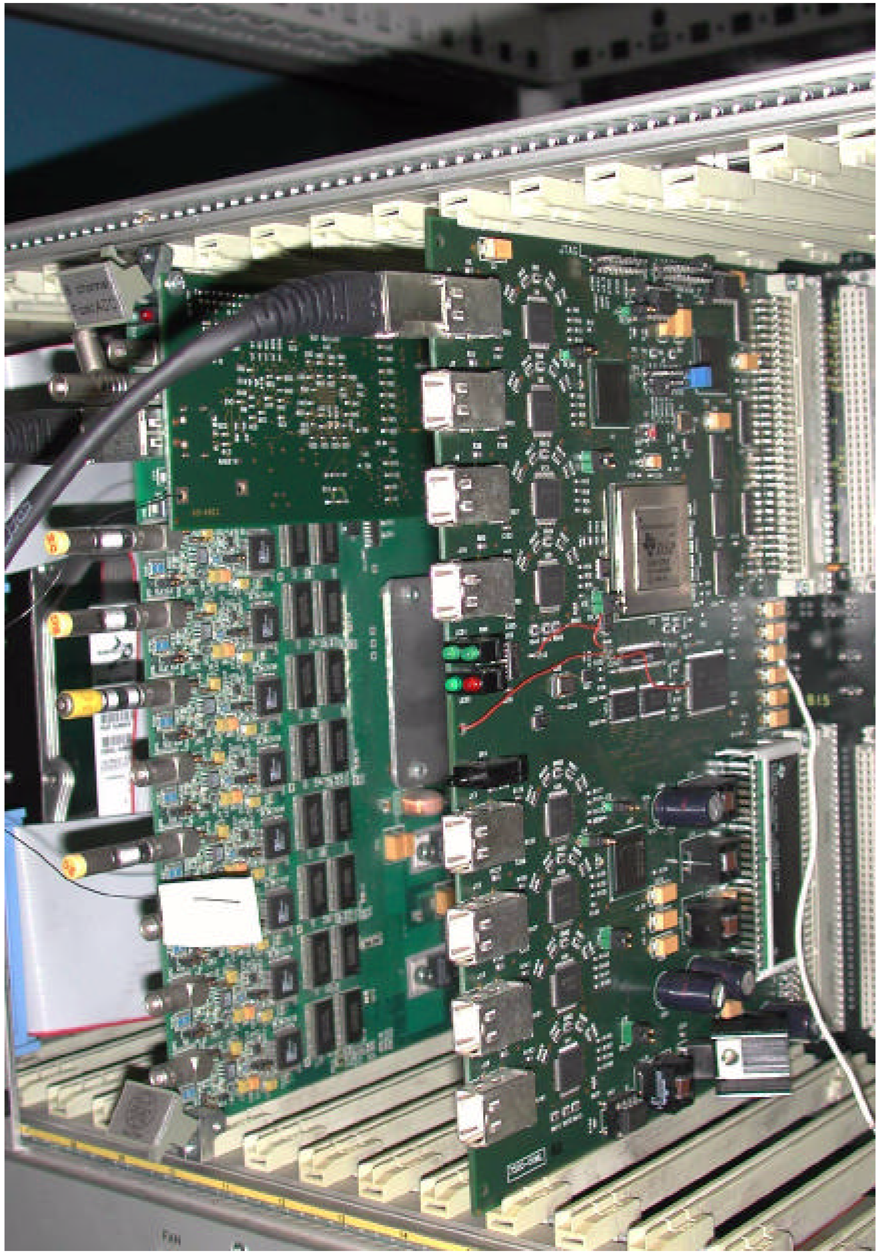




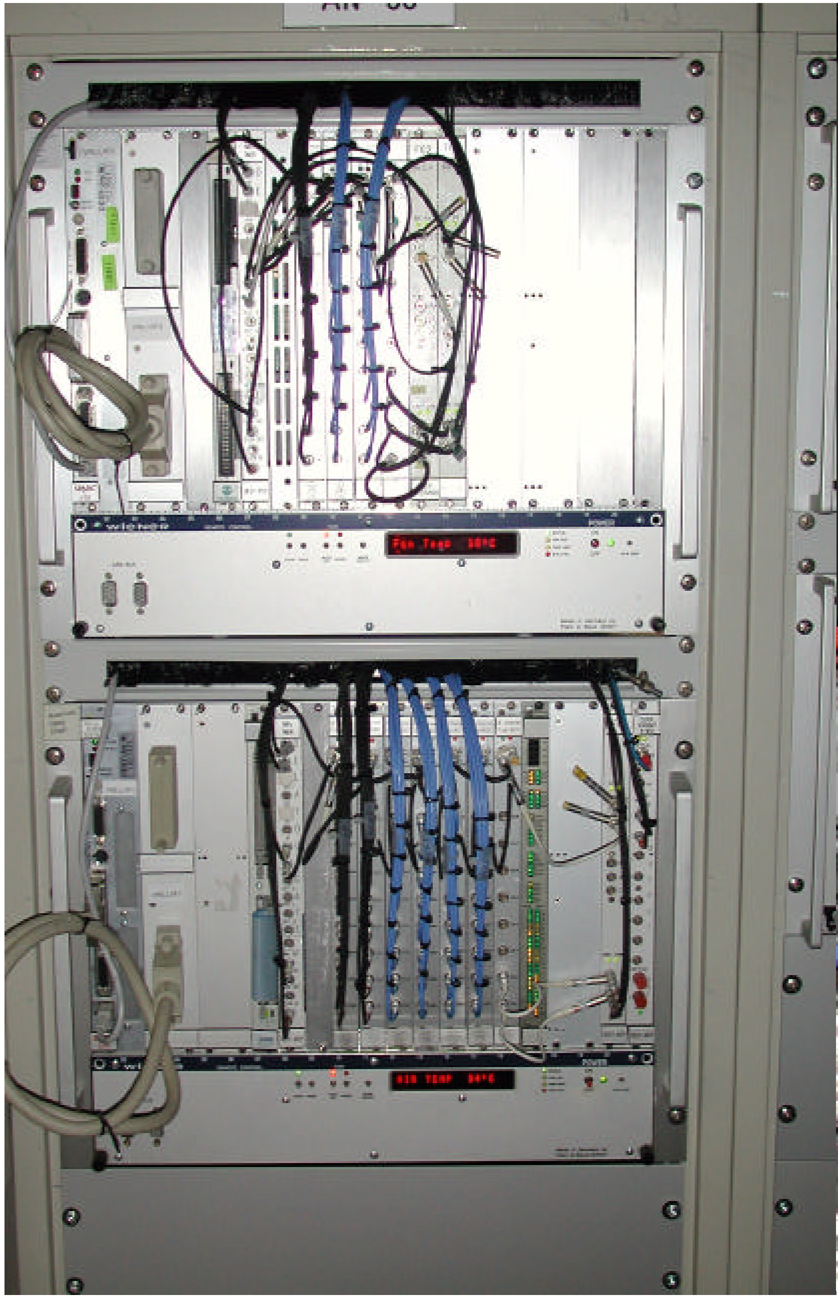
Rack Layout and Cabling for TTF I

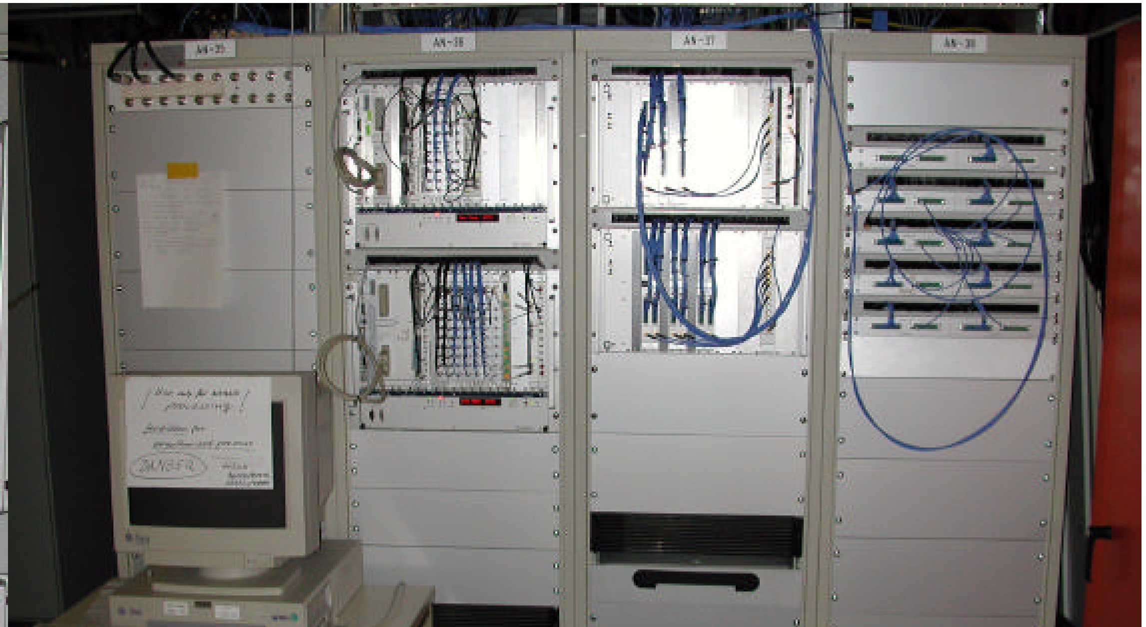


C67 DSP board

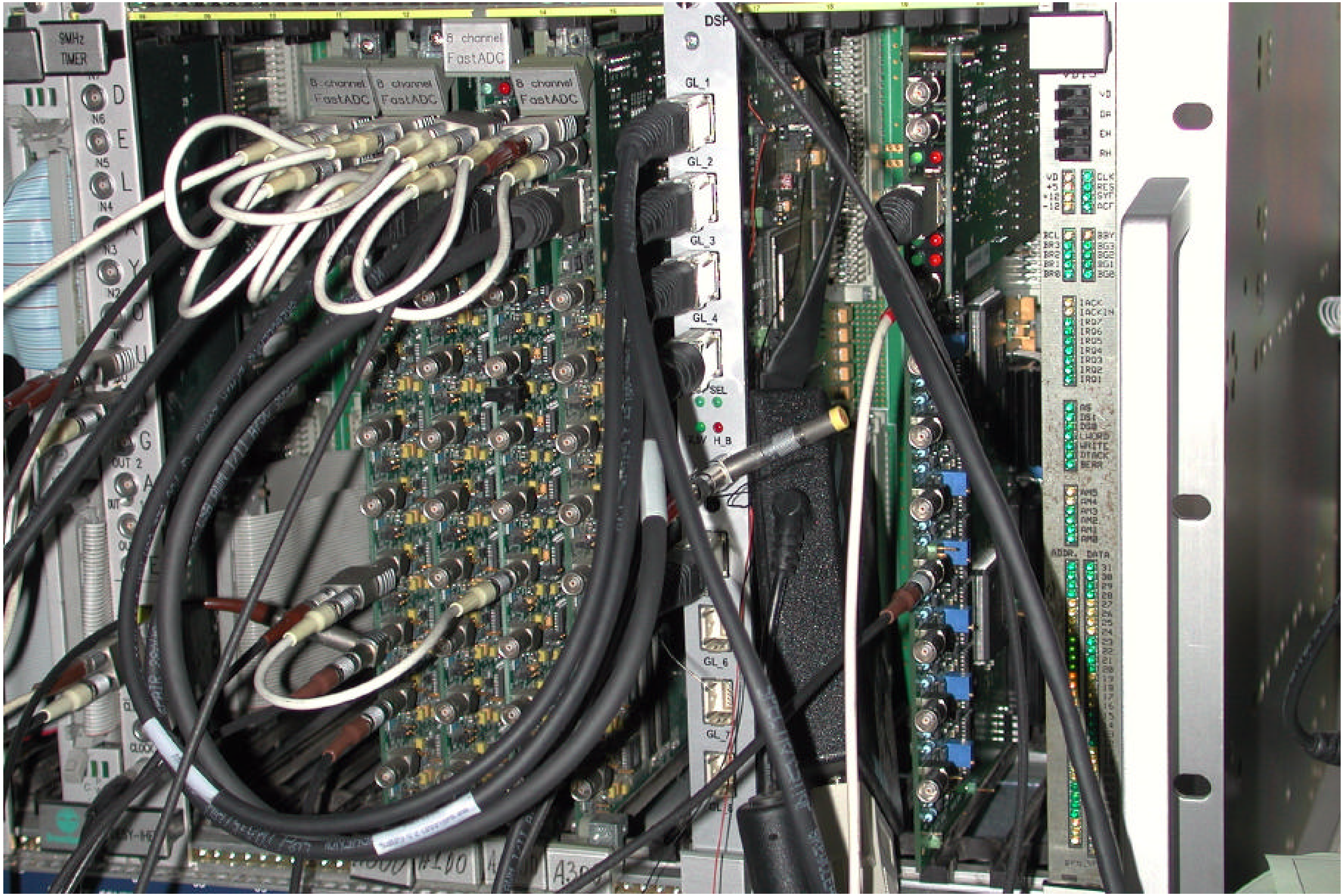


Installation Status of LLRF for ACC 2-6

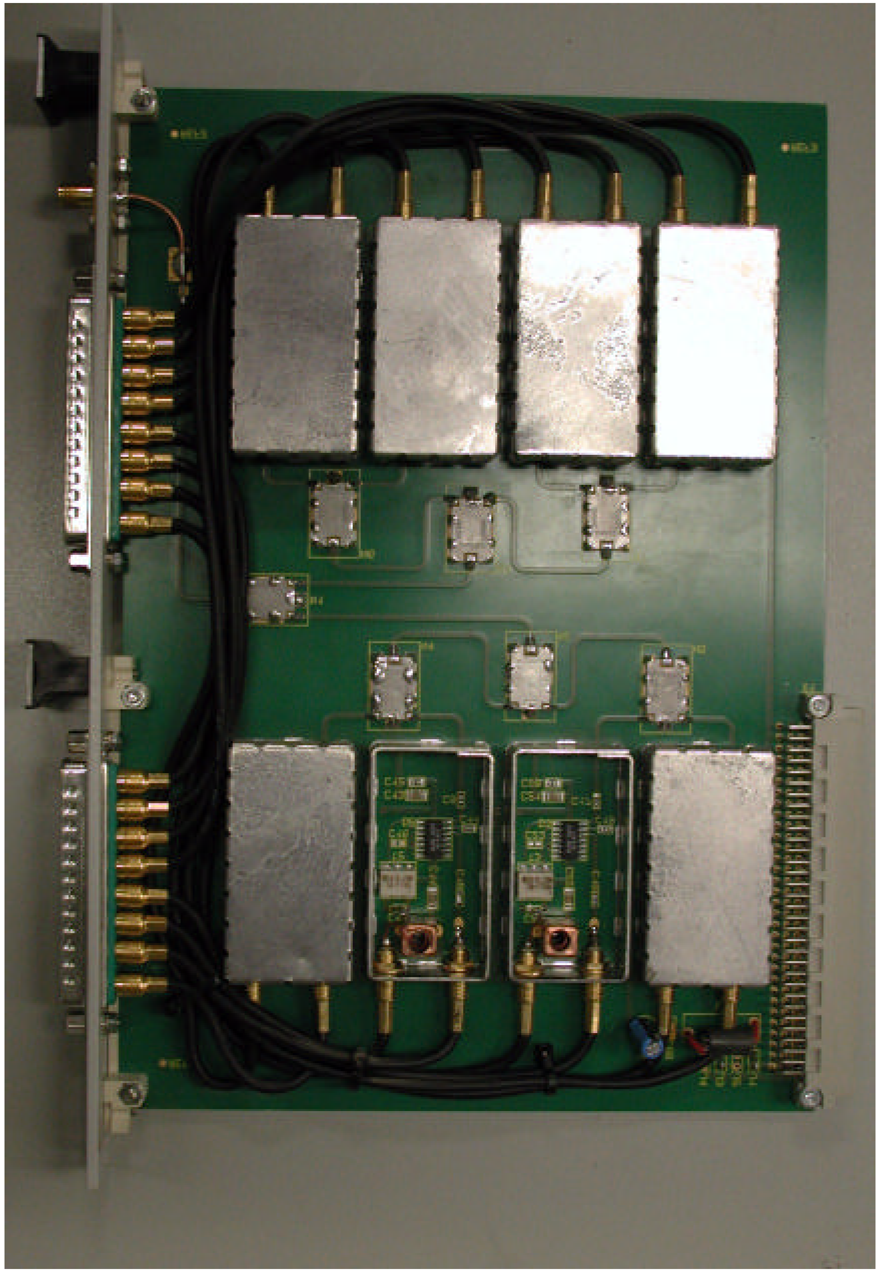


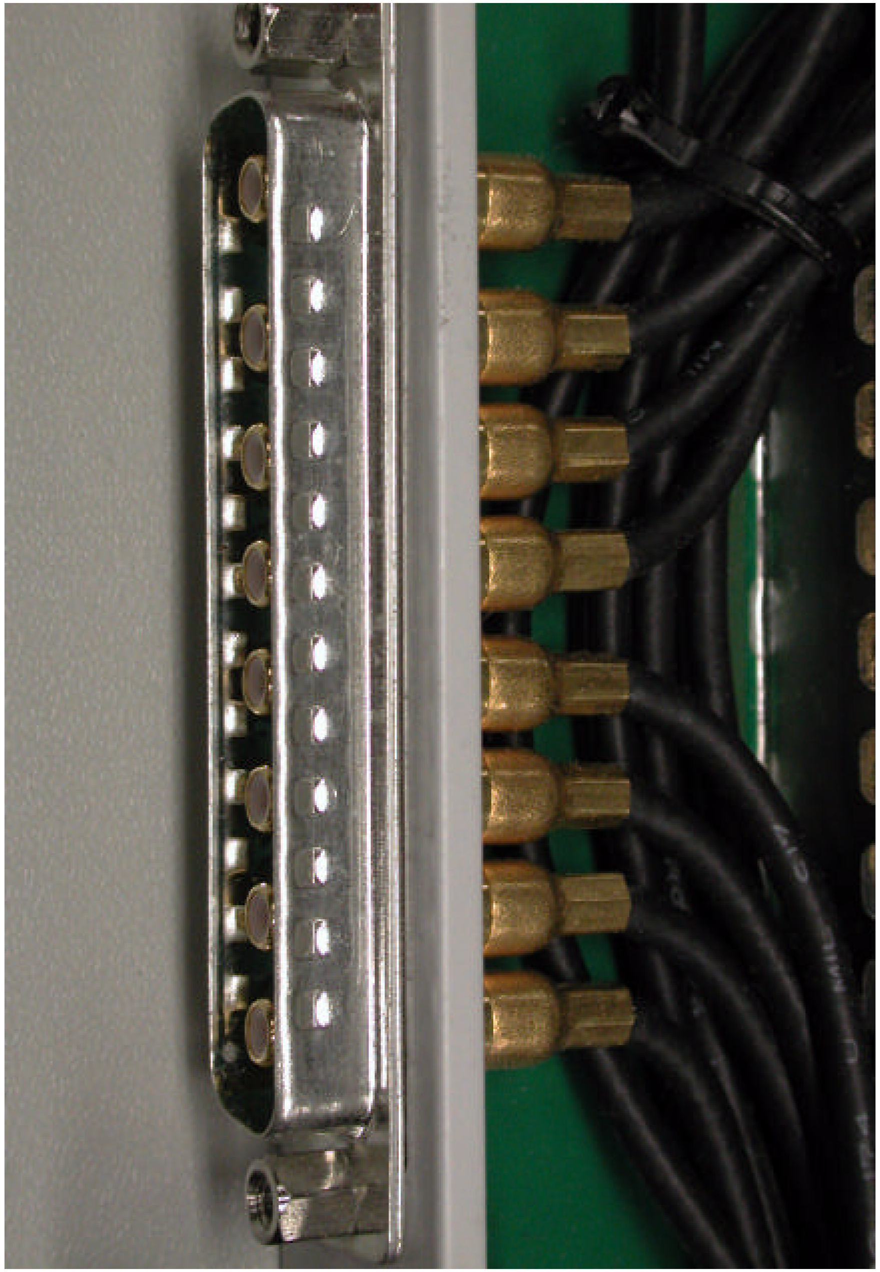


C67 DSP board

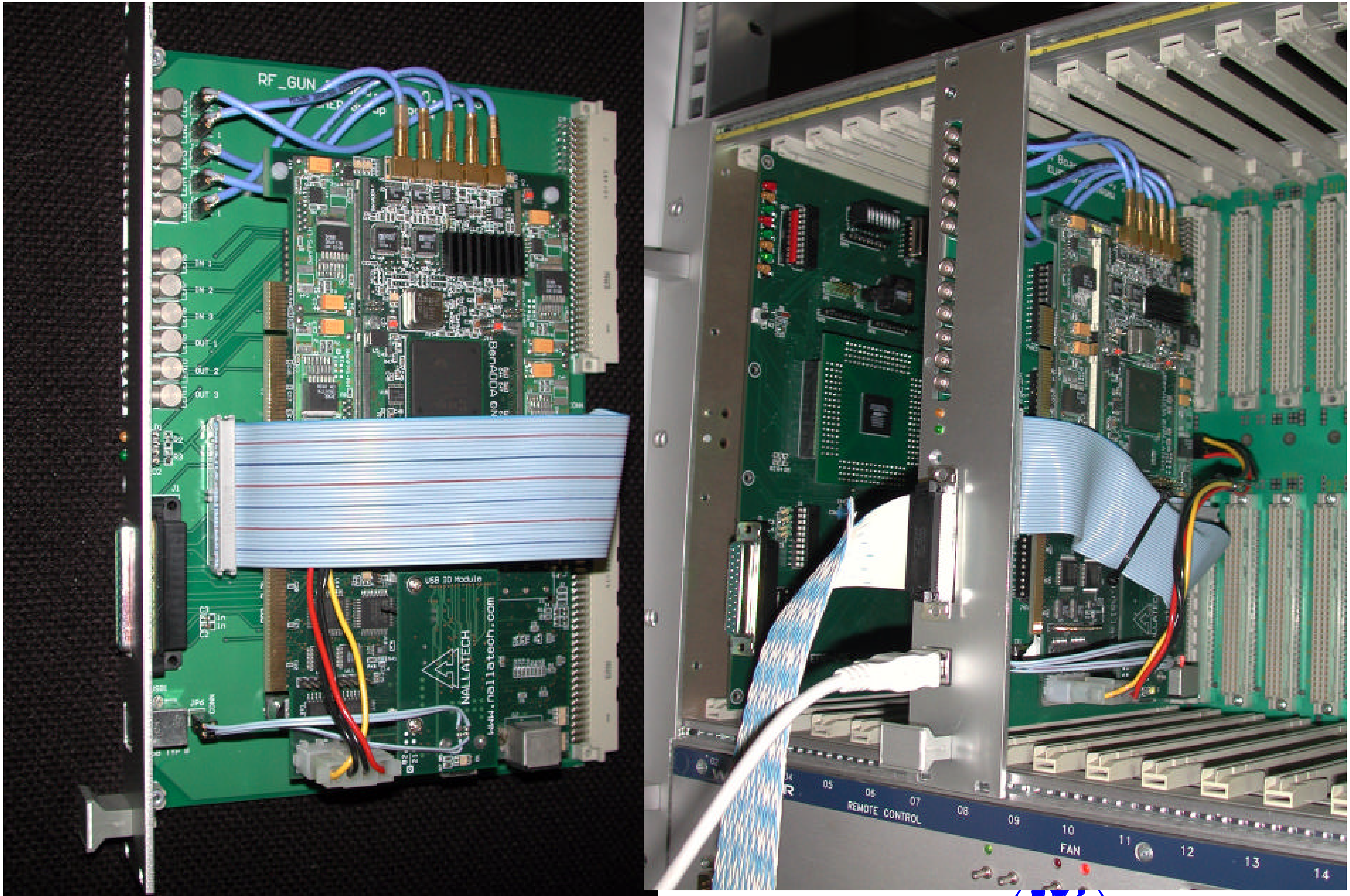


Downconverter

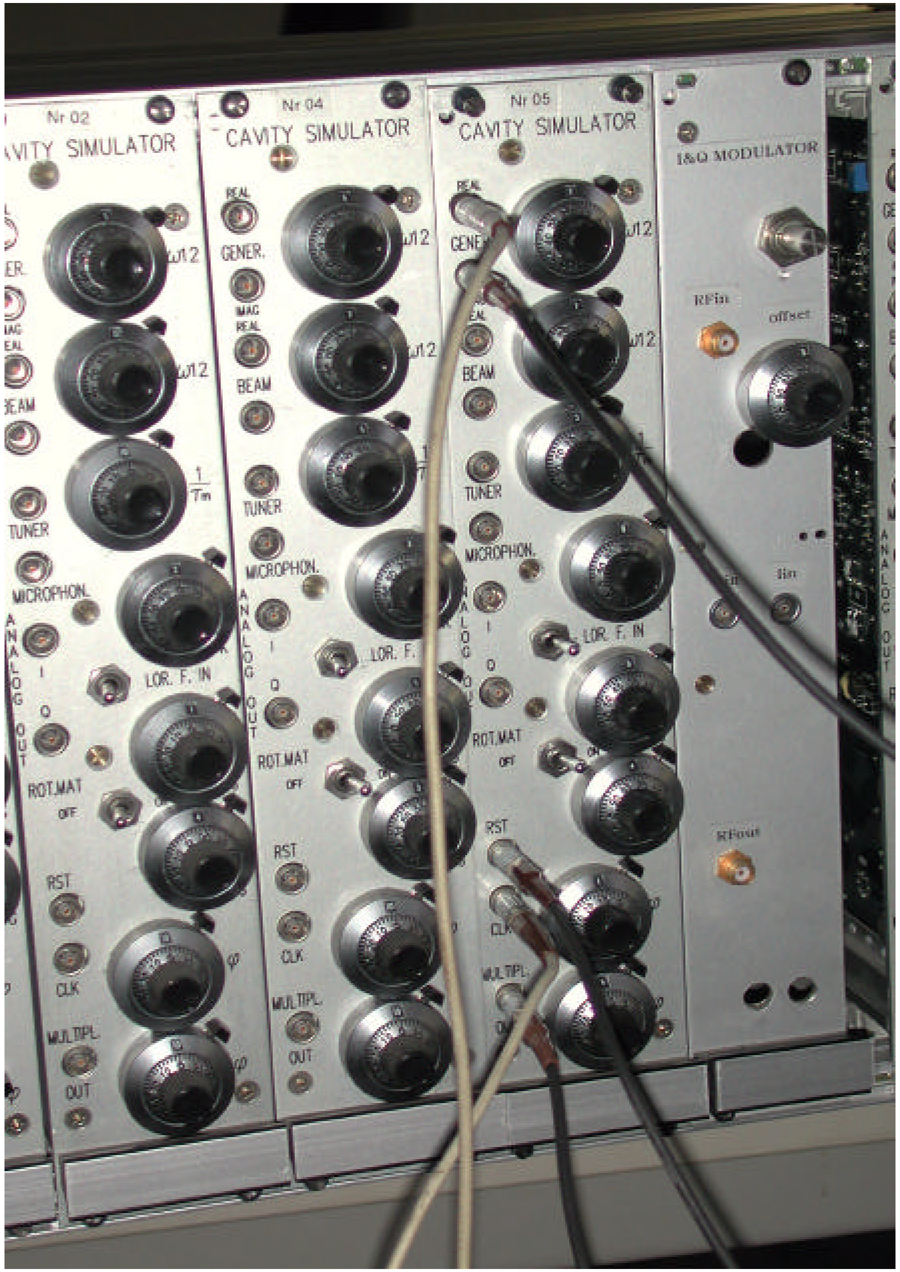




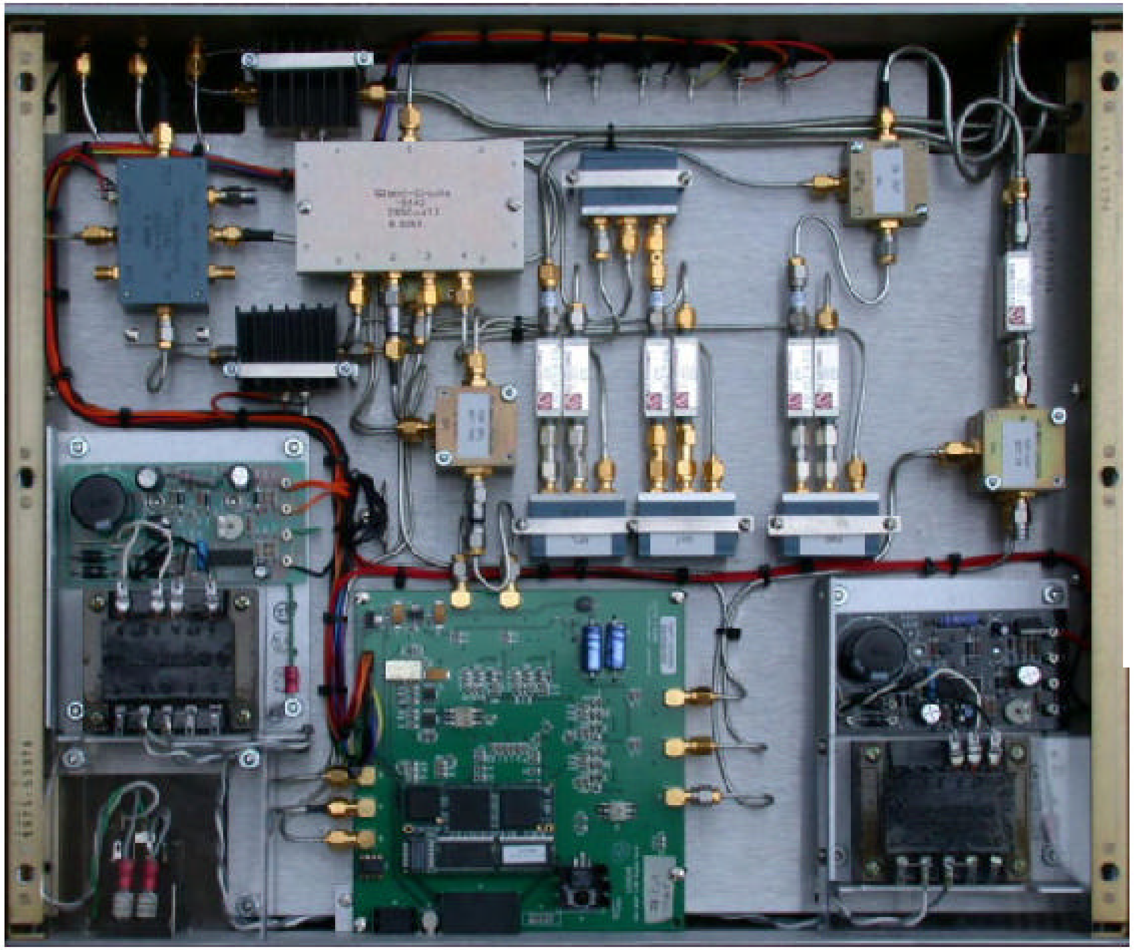
FPGA based RF Gun Controller



Cavity Simulator

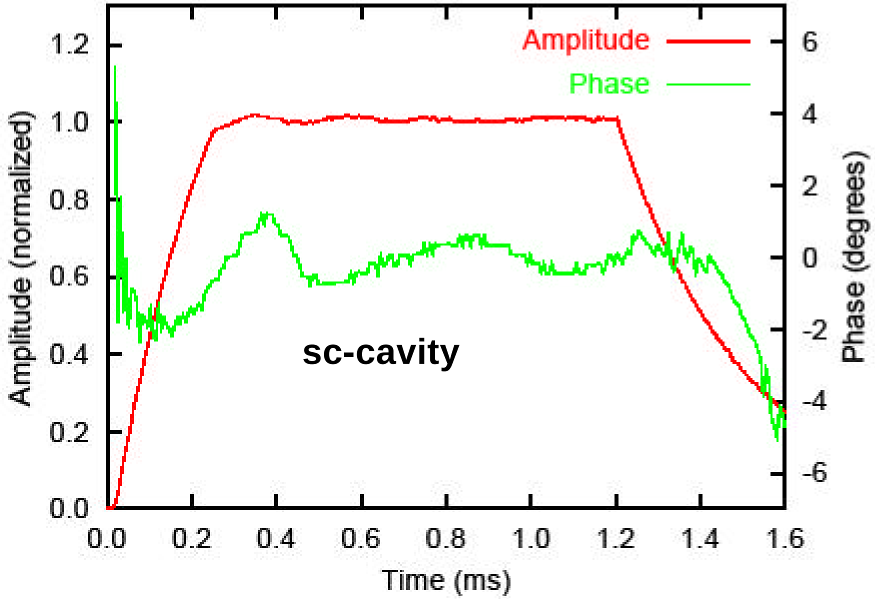


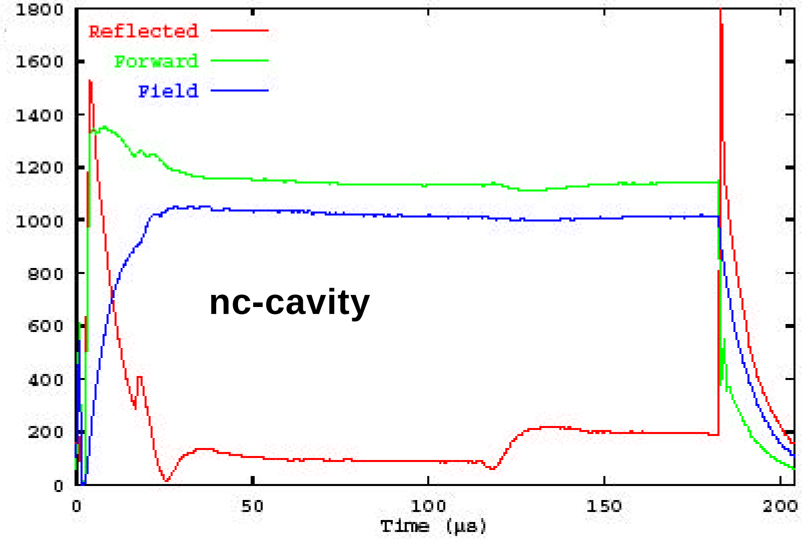
SNS Controller and Initial Performance Test



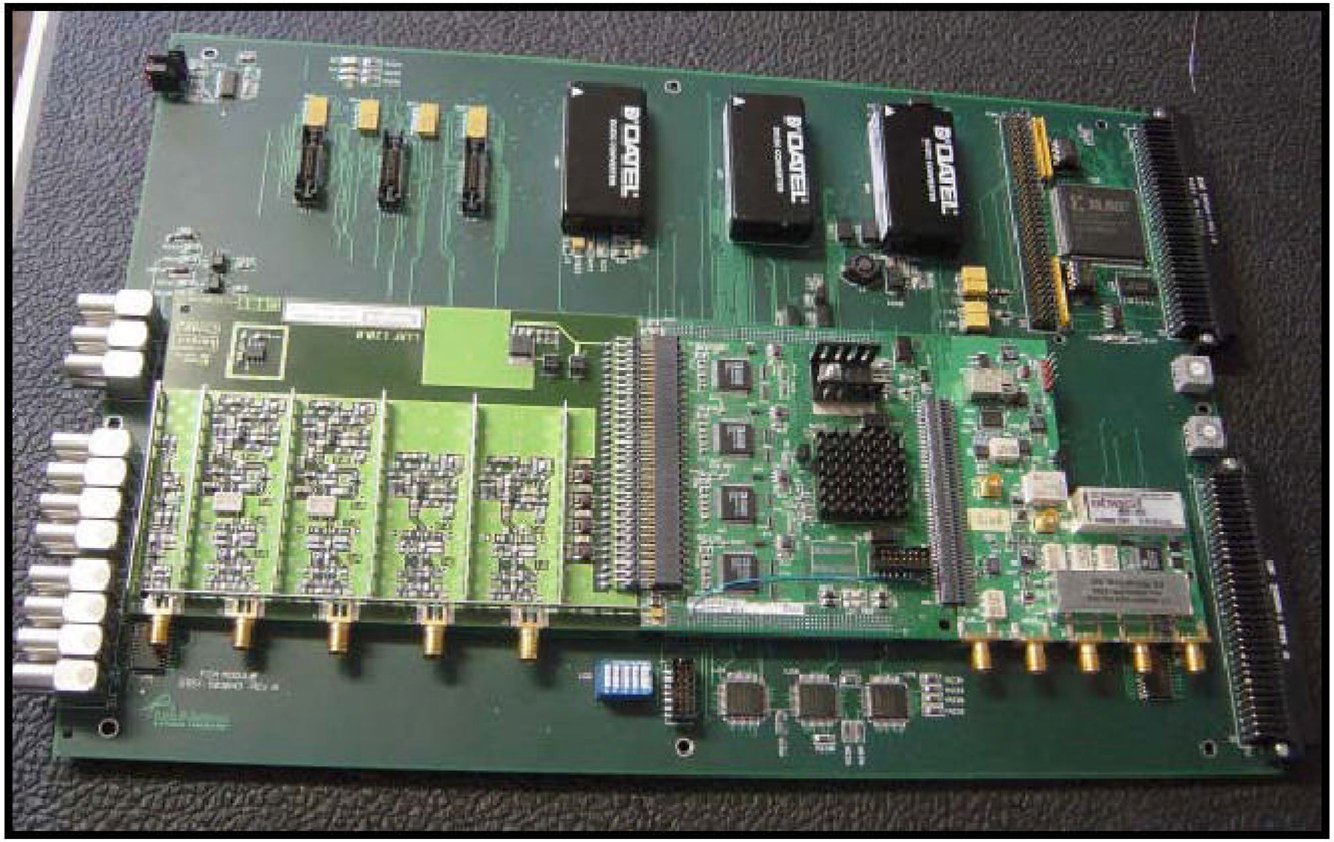
Chassis photograph.

L. Doolittle





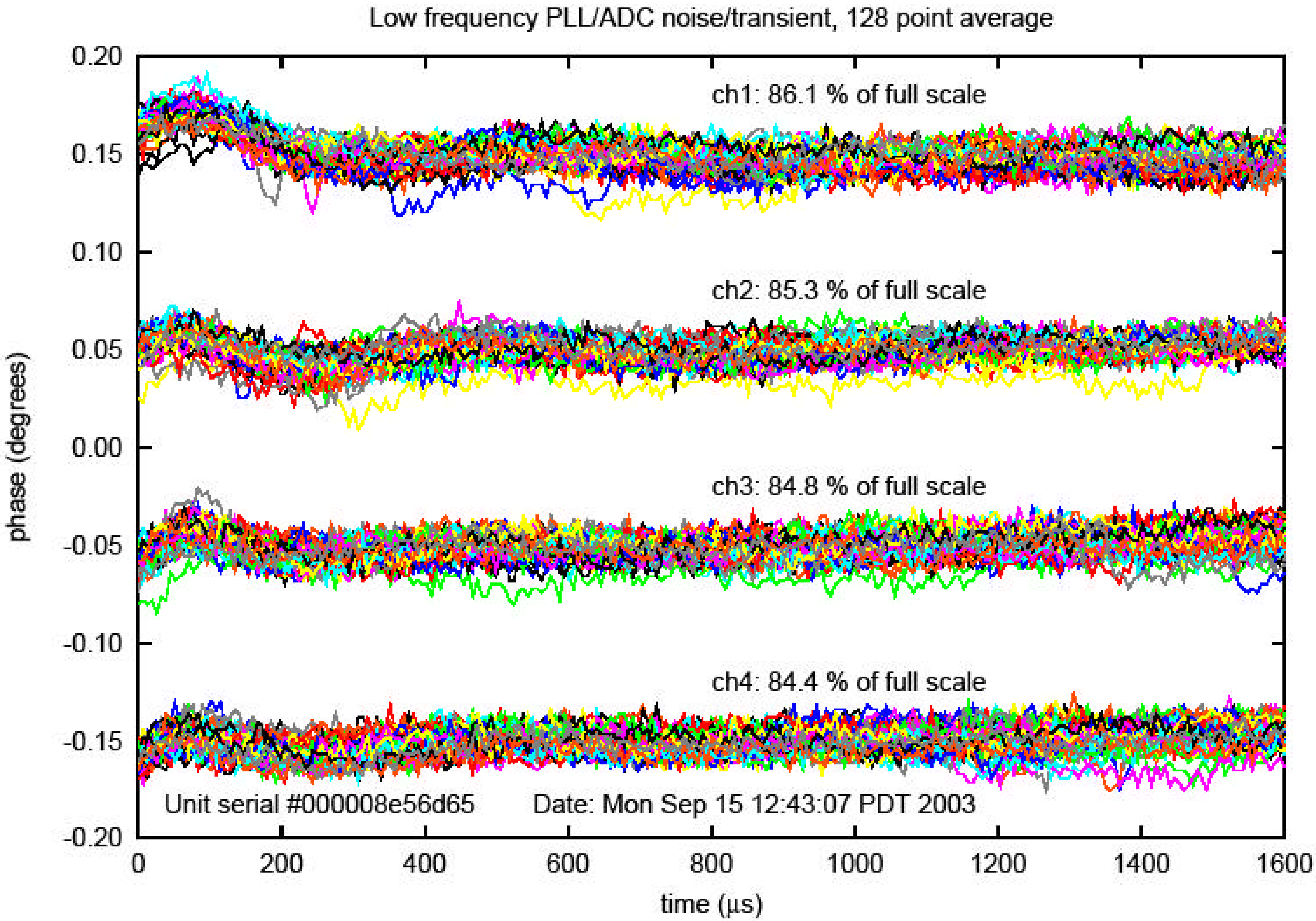
New Field Control Module for SNS



The prototype Field Control Module. The Analog Front End, Digital Front End, and RF Output daughtercards (left to right) are mounted on the VXI motherboard .

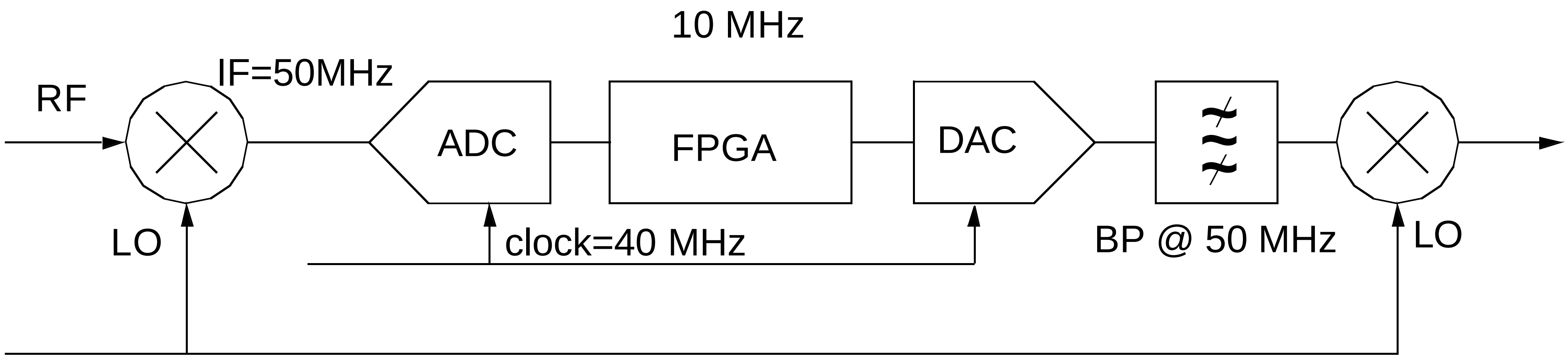
L. Doolittle

Measurement Phase Noise



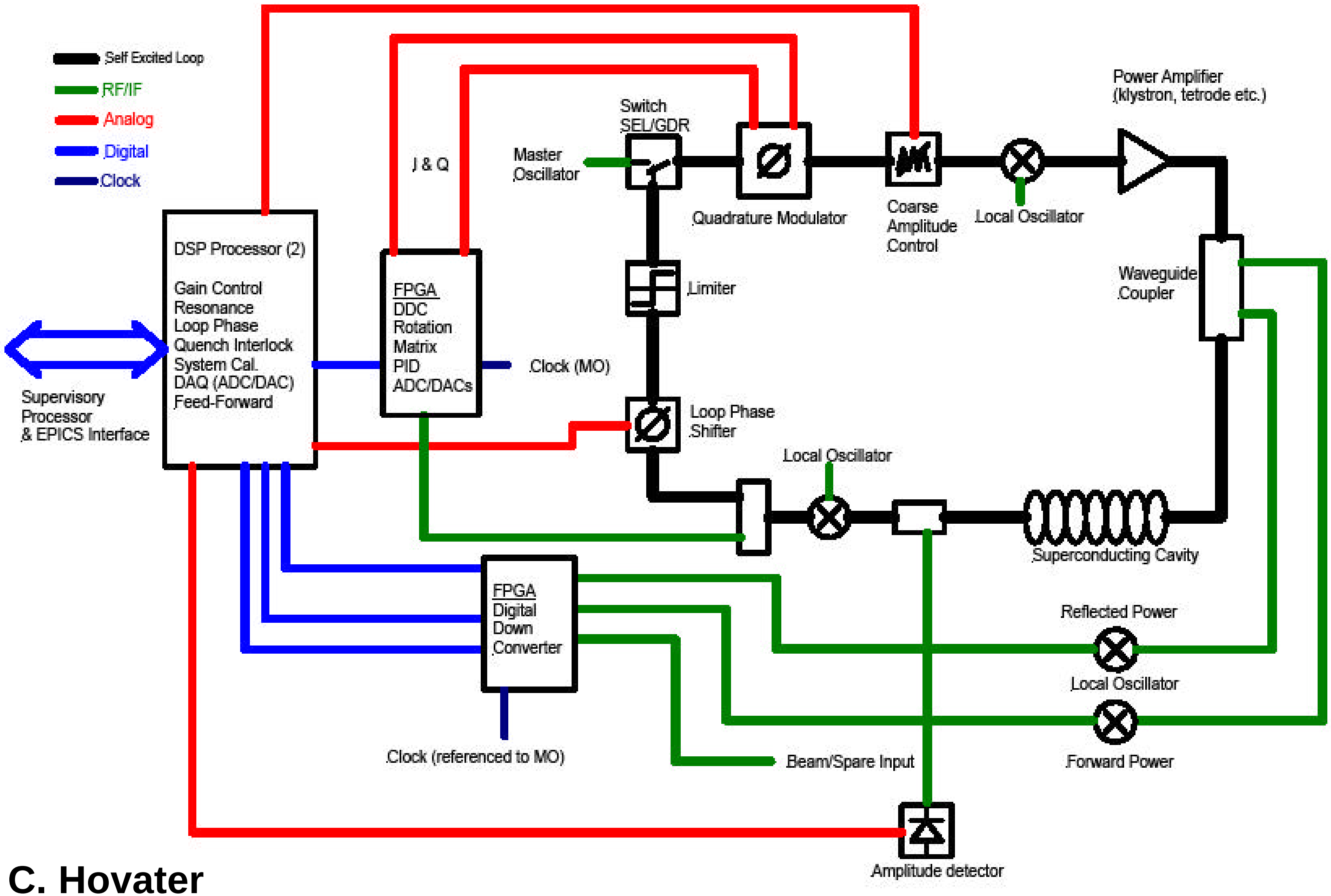
L. Doolittle

RF Vector Control Scheme



L. Doolittle

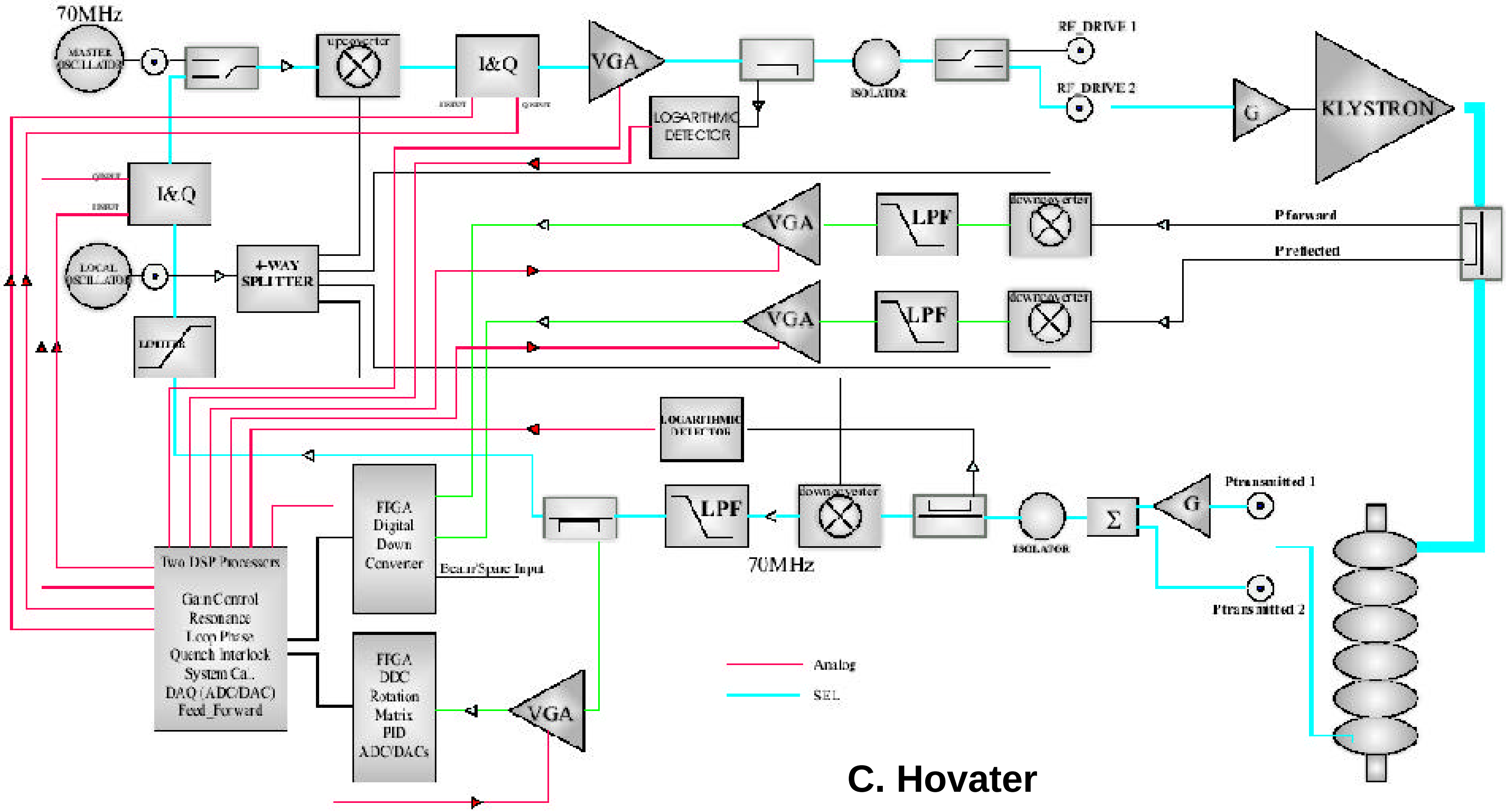
LLRF Proposal for CEBAF Upgrade



C. Hovater

Low Level RF Block Diagram

Proposal for RIA LLRF



C. Hovater

Conceptual block diagram of the LLRF control system for lightly beam loaded superconducting cavities

ANALOG DEVICES

LF–2.7 GHz RF/IF Gain and Phase Detector

AD8302

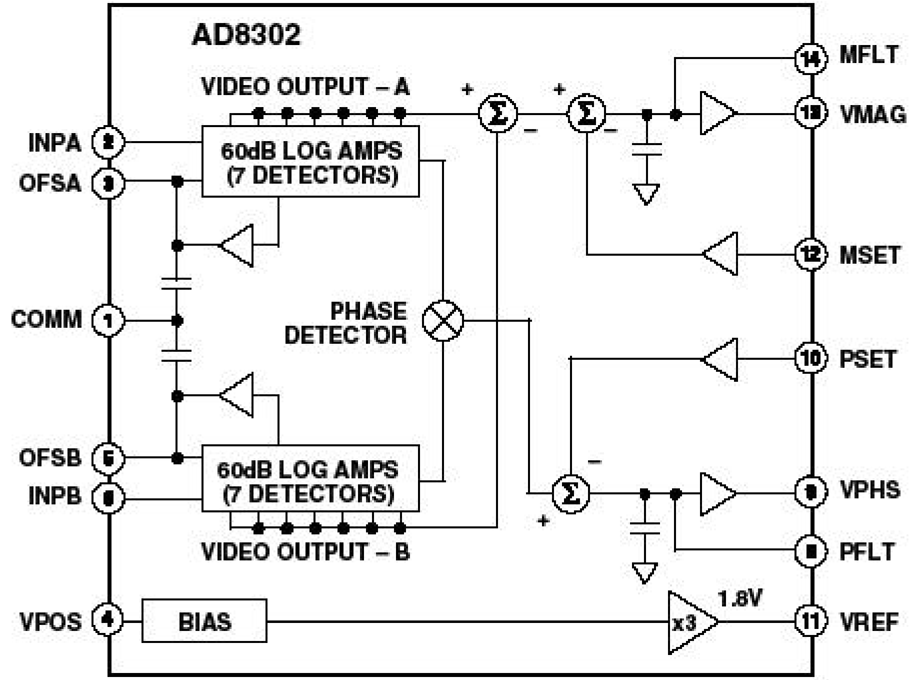
FEATURES

- Measures Gain/Loss and Phase up to 2.7 GHz
- Dual Demodulating Log Amps and Phase Detector
- Input Range –60 dBm to 0 dBm in a 50 Ω System
- Accurate Gain Measurement Scaling (30 mV/dB)
  - Typical Nonlinearity < 0.5 dB
- Accurate Phase Measurement Scaling (10 mV/Degree)
  - Typical Nonlinearity < 1 Degree
- Measurement/Controller/Level Comparator Modes
- Operates from Supply Voltages of 2.7 V–5.5 V
- Stable 1.8 V Reference Voltage Output
- Small Signal Envelope Bandwidth from DC to 30 MHz

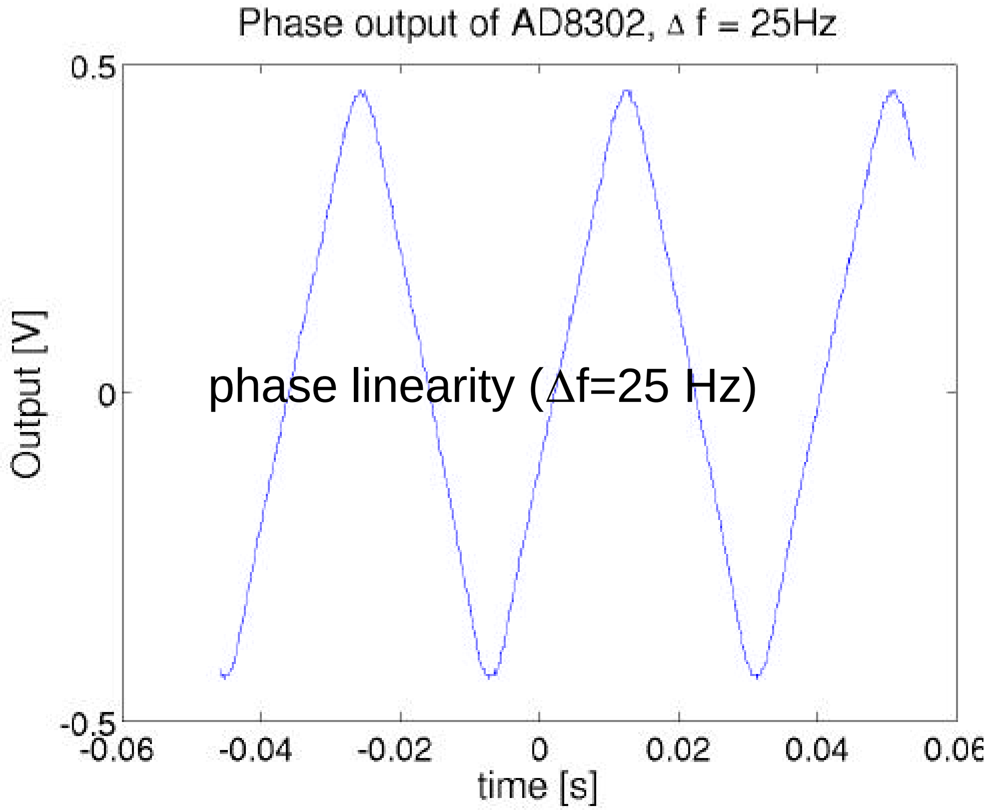
APPLICATIONS

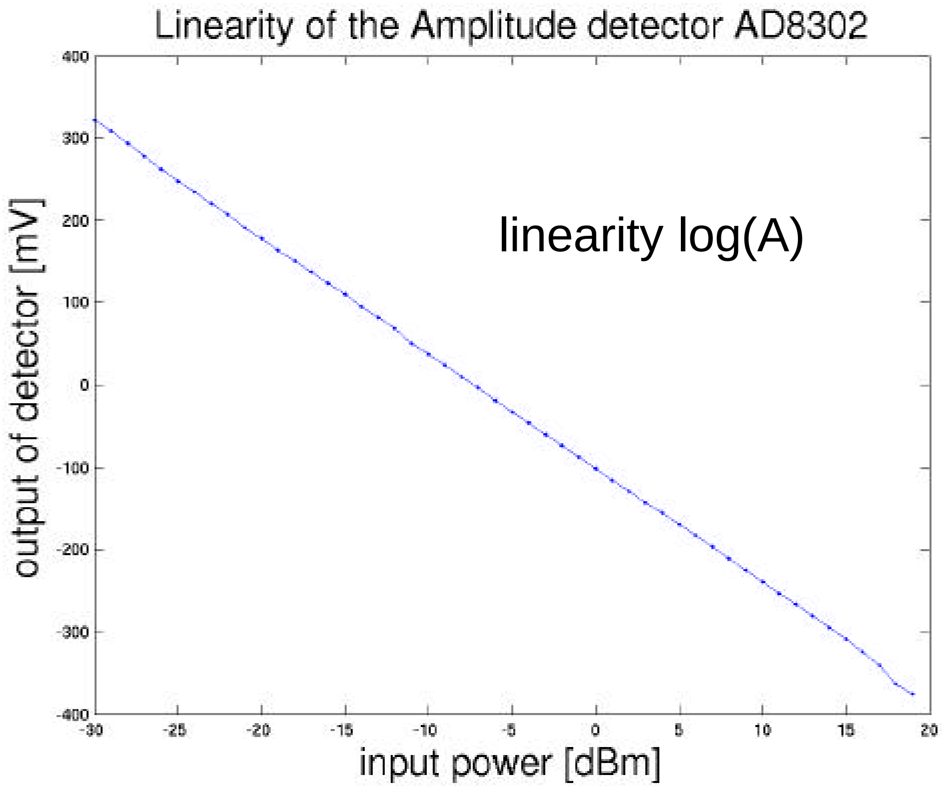
- RF/IF PA Linearization
- Precise RF Power Control
- Remote System Monitoring and Diagnostics
- Return Loss/VSWR Measurements
- Log Ratio Function for AC Signals

FUNCTIONAL BLOCK DIAGRAM

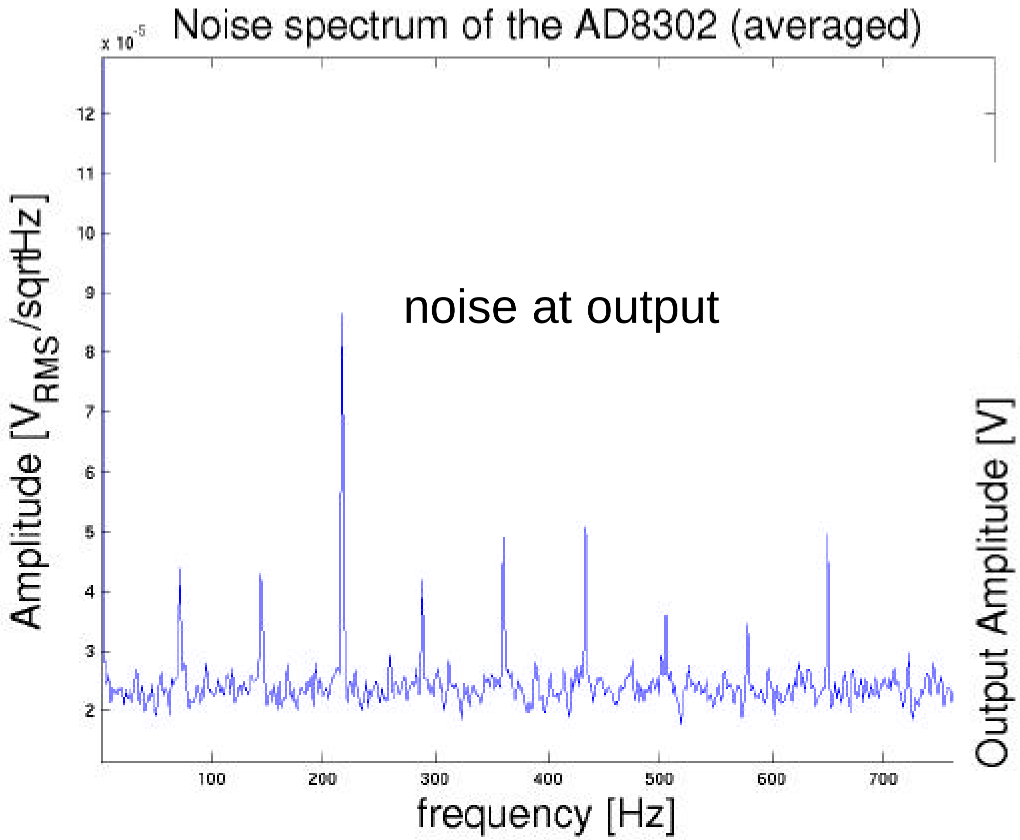


AD 8302

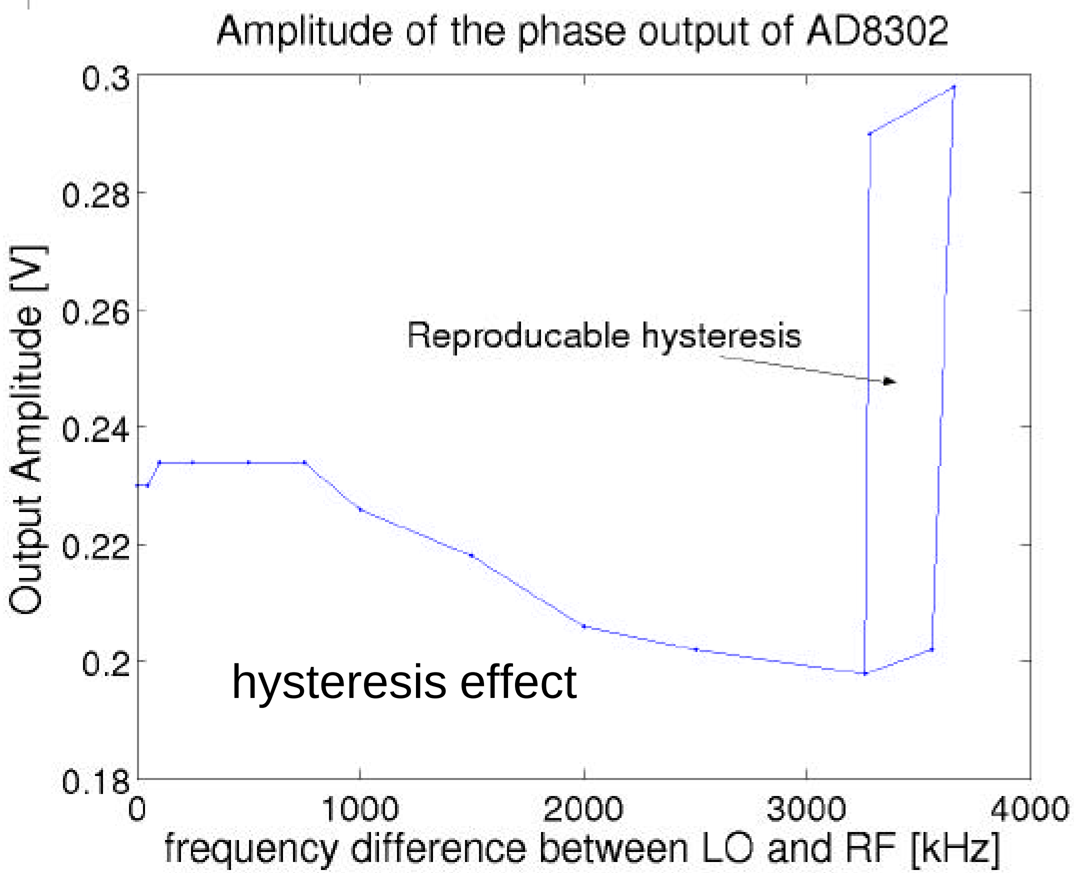

Phase output of AD8302, Δ f = 25Hz
Output [V]
0.5
0
-0.5
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
time [s]
phase linearity (Δf=25 Hz)


Linearity of the Amplitude detector AD8302
output of detector [mV]
input power [dBm]
400
300
200
100
0
-100
-200
-300
-400
-30
-25
-20
-15
-10
-5
0
5
10
15
20
linearity log(A)

AD 8302 (Cnt´d)



Noise spectrum of the AD8302 (averaged)
x 10^-5
noise at output
Amplitude [V_RMS/sqrtHz]
frequency [Hz]



Amplitude of the phase output of AD8302
Reproducable hysteresis
hysteresis effect
Output Amplitude [V]
frequency difference between LO and RF [kHz]

LF to 2.5 GHz TruPwr™ Detector

AD8361

FEATURES

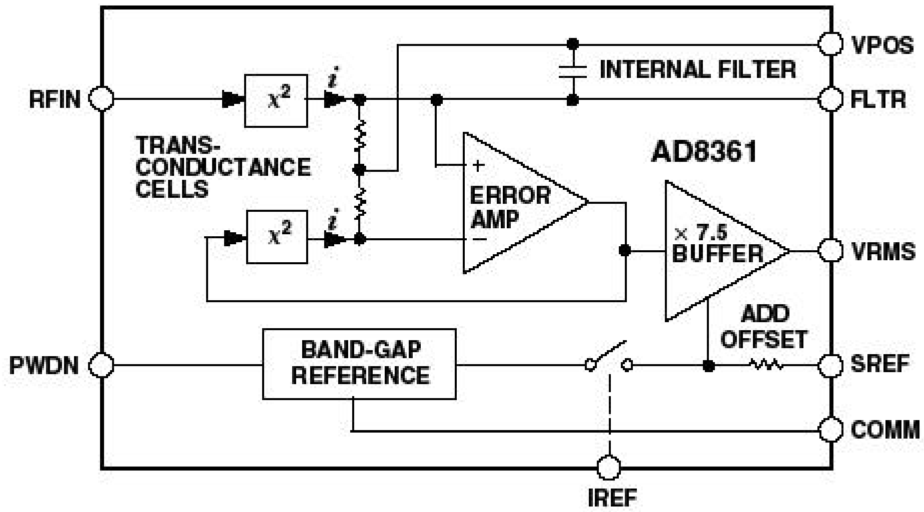
Calibrated RMS Response
Excellent Temperature Stability
Up to 30 dB Input Range at 2.5 GHz
700 mV rms, 10 dBm re 50 Ω Maximum Input
±0.25 dB Linear Response Up to 2.5 GHz
Single Supply Operation: 2.7 V to 5.5 V
Low Power: 3.3 mW at 3 V Supply
Rapid Power-Down to Less than 1 μA

APPLICATIONS

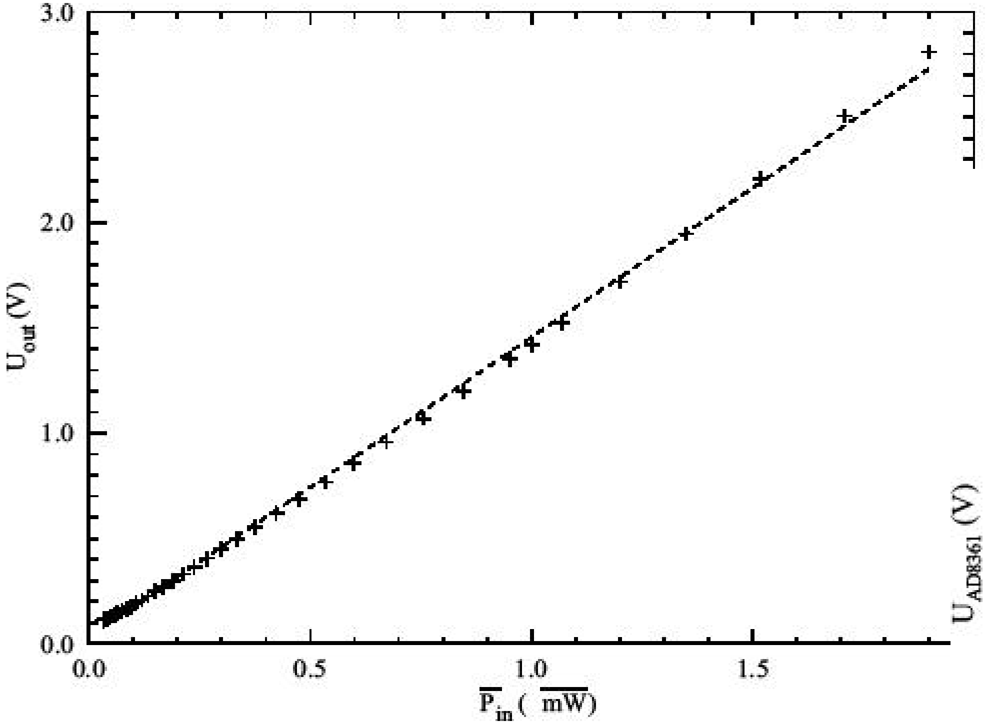
Measurement of CDMA, W-CDMA, QAM, Other Complex Modulation Waveforms
RF Transmitter or Receiver Power Measurement

FUNCTIONAL BLOCK DIAGRAMS

micro_SOIC

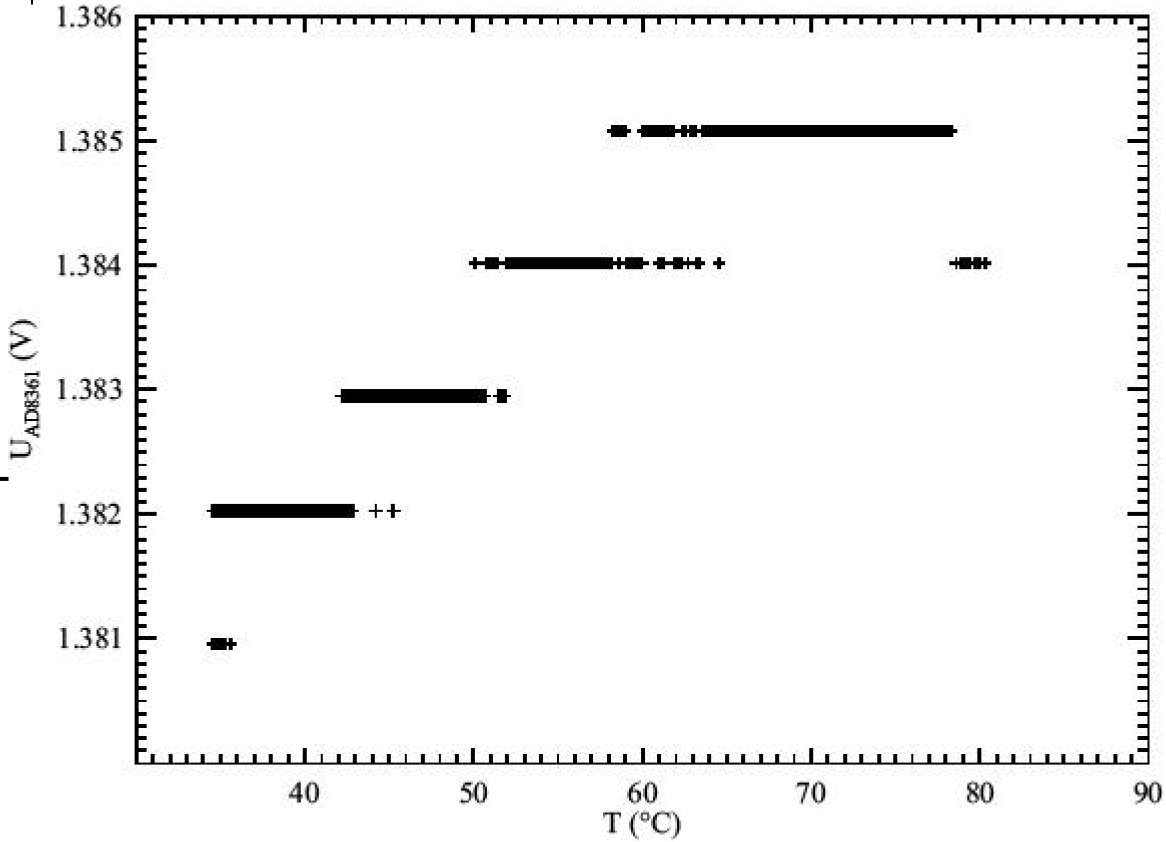


AD8361



Linearity

Temperature Stability



ANALOG DEVICES

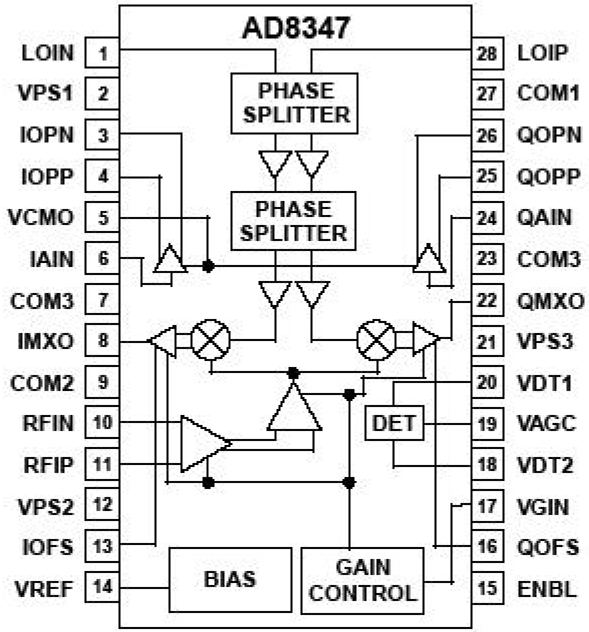
0.8 GHz–2.7 GHz Direct Conversion Quadrature Demodulator

AD8347*

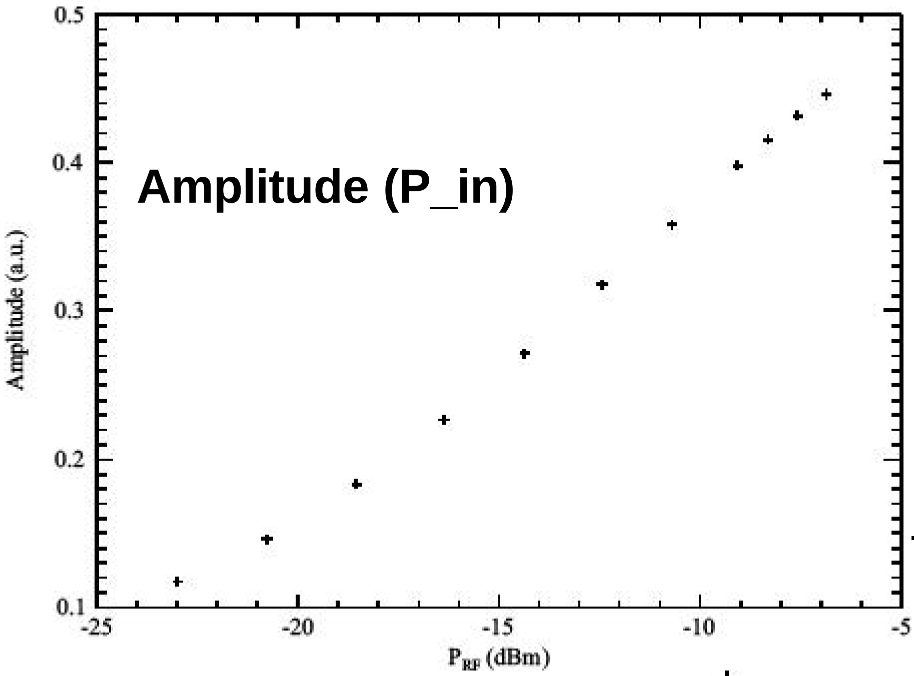
FEATURES
Integrated RF and Baseband AGC Amplifiers
Quadrature Phase Accuracy 1° Typ
I/Q Amplitude Balance 0.3 dB Typ
Third Order Intercept (IIP3) +11.5 dBm @ Min Gain
Noise Figure 11 dB @ Max Gain
AGC Range 69.5 dB
Baseband Level Control Circuit
Low LO Drive –8 dBm
ADC Compatible I/Q Outputs
Single Supply 2.7 V–5.5 V
Power-Down Mode
Package 28-Lead TSSOP

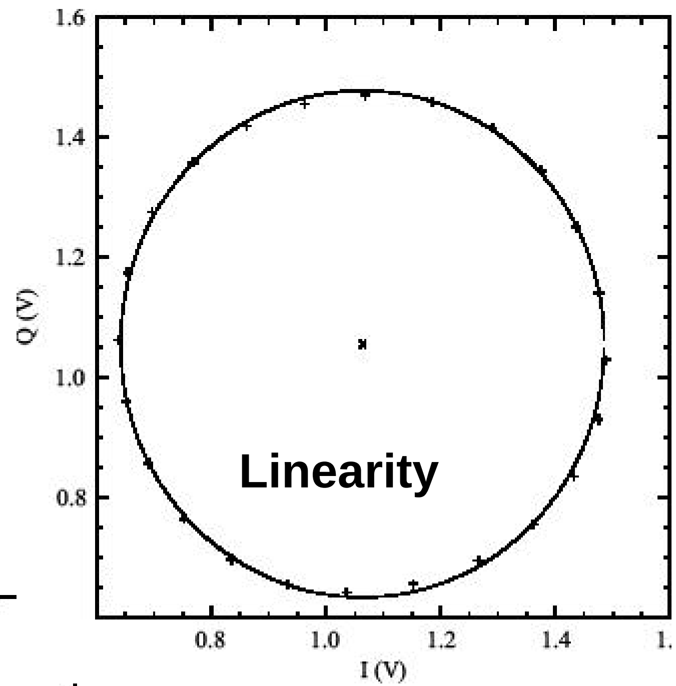
APPLICATIONS
Cellular Basestations
Radio Links
Wireless Local Loop
IF Broadband Demodulator
RF Instrumentation
Satellite Modems

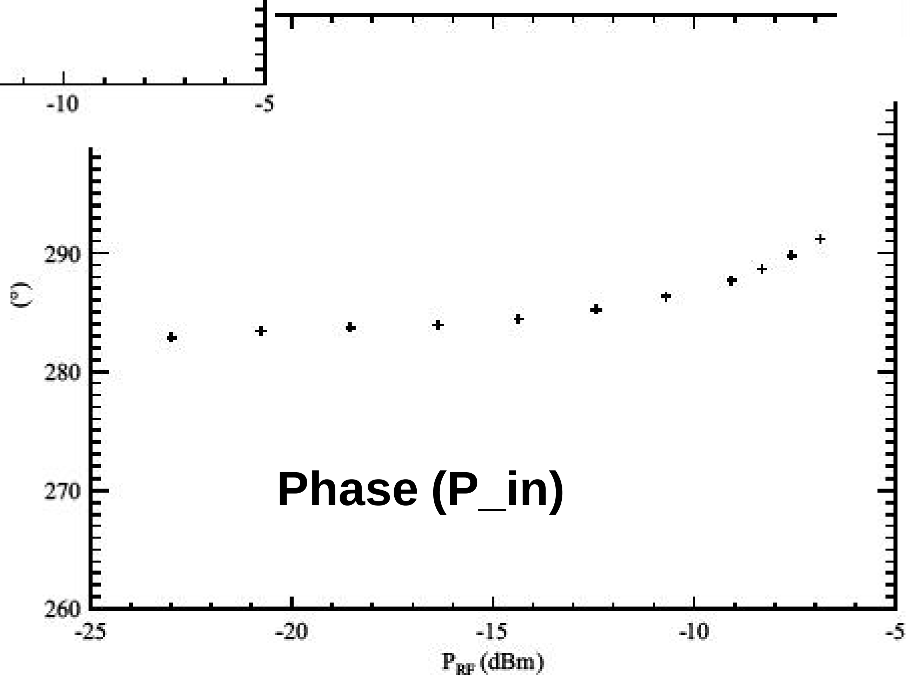
FUNCTIONAL BLOCK DIAGRAM



AD 8347


Amplitude (P_in)
Amplitude (a.u.)
0.1
0.2
0.3
0.4
0.5
-25
-20
-15
-10
-5
P_{RF} (dBm)


Linearity
Q (V)
I (V)
0.8
1.0
1.2
1.4
1.6
0.8
1.0
1.2
1.4


Phase (P_in)
(°)
260
270
280
290
-25
-20
-15
-10
-5
P_{RF} (dBm)

Hittite MICROWAVE CORPORATION v01.0503

HMC439QS16G

HBT DIGITAL PHASE-FREQUENCY DETECTOR, 10 - 1300 MHz

Typical Applications

This Phase Frequency Detector is a key component in low phase noise frequency synthesis applications such as:

- Pt - Pt Radios
- Satellite Communication Systems
- Military Applications
- Sonet Clock Generation

Features

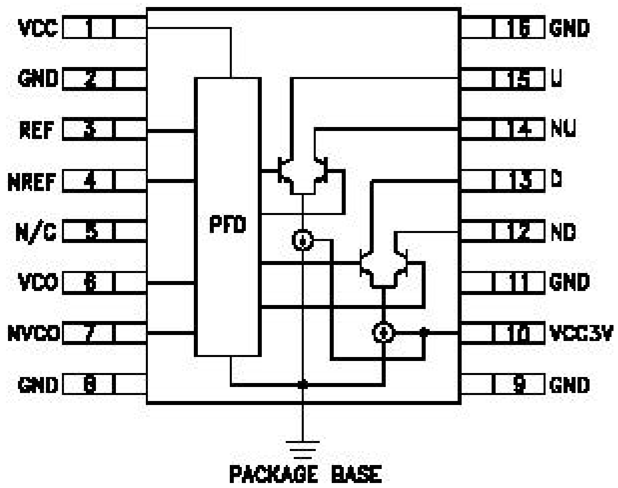
Ultra Low SSB Phase Noise Floor:
-153 dBc/Hz@10 kHz offset @ 100 MHz
Input up to 1300 MHz Fin.

Differential Input/Single Ended Output

Open Collector Output Buffer Amplifiers

QSOP16G SMT Package: 29.4 mm²

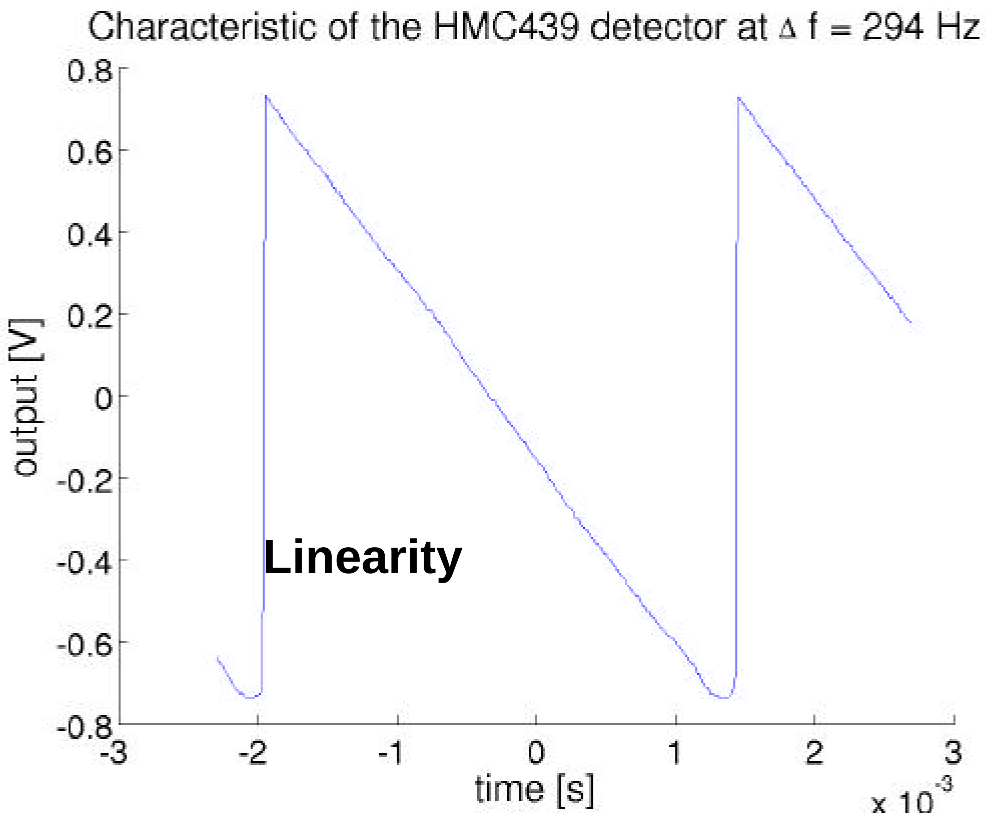
Functional Diagram



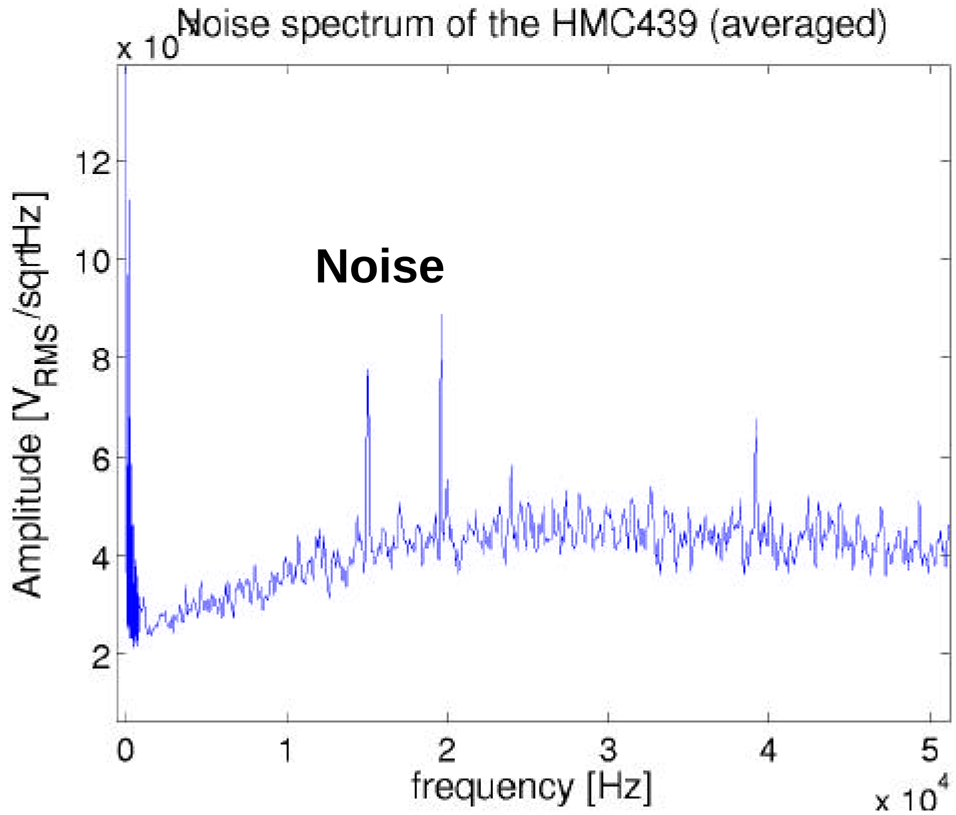
General Description

The HMC439QS16G is a digital phase-frequency detector intended for use in low noise phase-locked loop applications for inputs from 10 to 1300 MHz. Its combination of high frequency of operation along with its ultra low phase noise floor make possible synthesizers with wide loop bandwidth and low N resulting in fast switching and very low phase noise. When used in conjunction with a differential loop amplifier, the HMC439QS16G generates an output voltage that can be used to phase lock a VCO to a reference oscillator. The device is packaged in a low cost, surface mount 16 lead QSOP package with an exposed base for improved RF and thermal performance.

HMC439



Characteristic of the HMC439 detector at Δ f = 294 Hz
output [V]
time [s]
x 10^-3
Linearity



Noise spectrum of the HMC439 (averaged)
Amplitude [V_RMS/sqrtHz]
frequency [Hz]
x 10^4
Noise

Hittite MICROWAVE CORPORATION v00.0504

HMC497LP4

SiGe WIDEBAND DIRECT MODULATOR RFIC, 100 - 4000 MHz

Typical Applications

The HMC497LP4 is suitable for various modulation systems:

- UMTS, GSM or CDMA Basestations
- Fixed Wireless or WLL
- ISM Transceivers, 900 & 2400 MHz
- GMSK, QPSK, QAM, SSB Modulators

Features

Very Low Noise Floor, -161 dBm/Hz

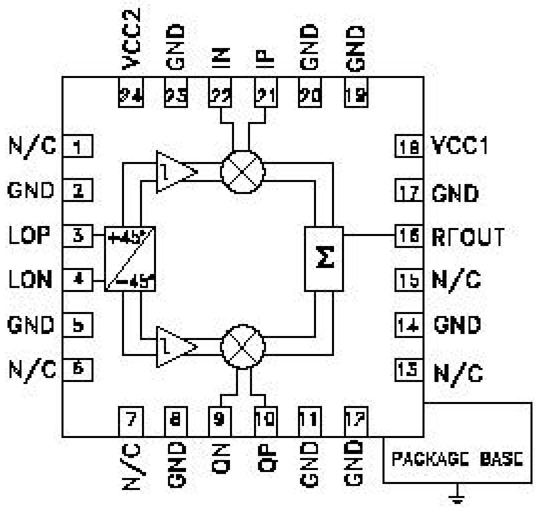
Very High Linearity, +22 dBm OIP3

High Output Power, +9 dBm Output P1dB

High Modulation Accuracy

DC – 700 MHz Baseband Input

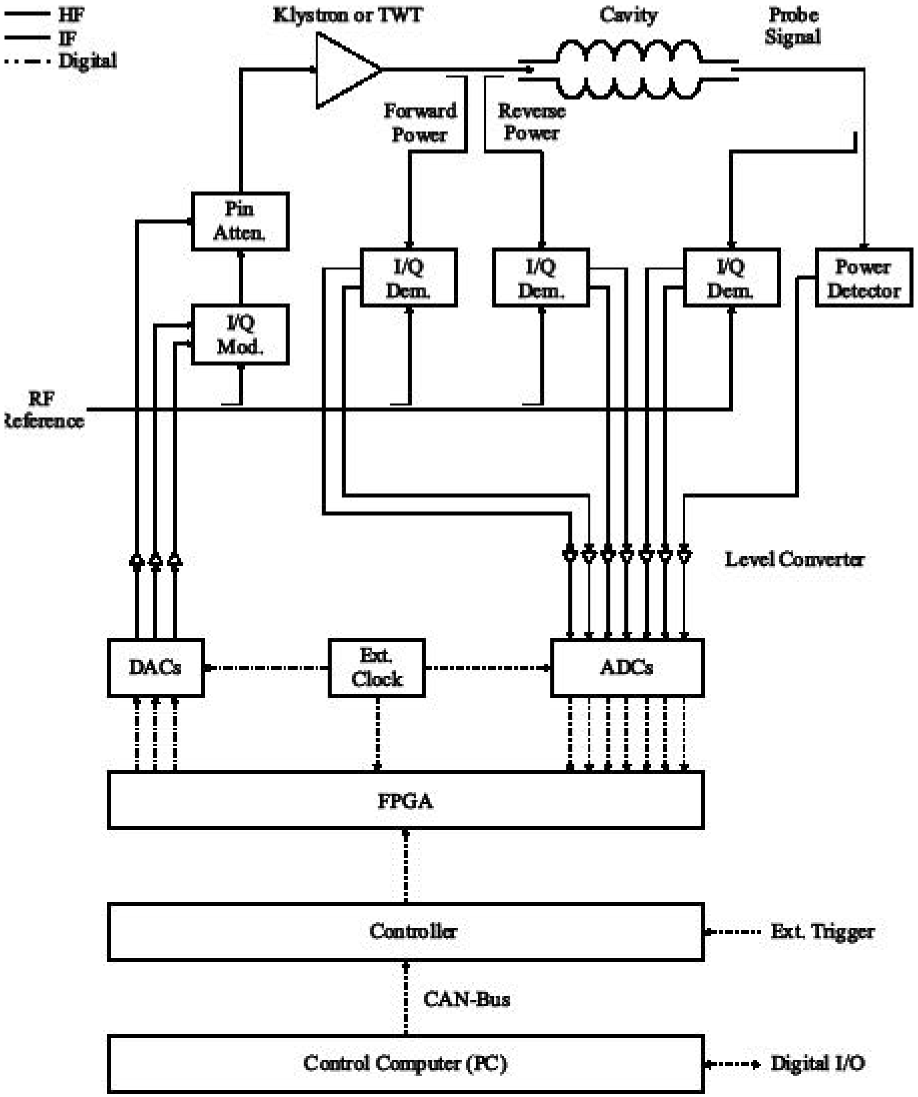
Functional Diagram

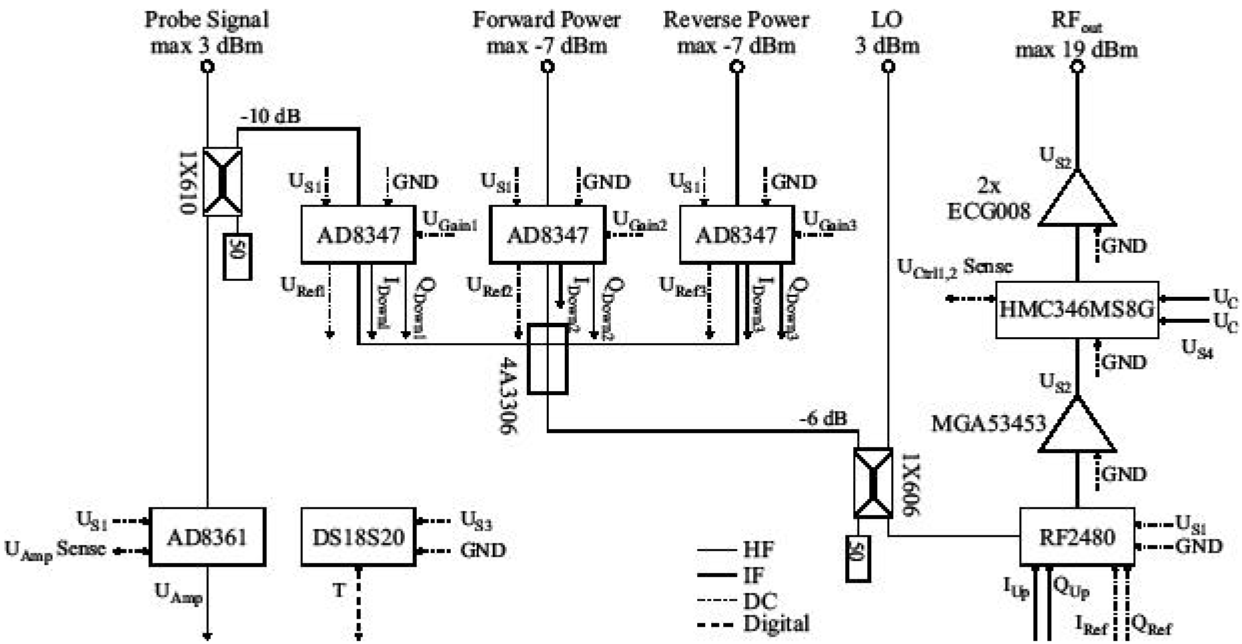


General Description

The HMC497LP4 is a low noise high linearity Direct Quadrature Modulator RFIC which is ideal for digital modulation applications from 100 - 4000 MHz including; Cellular/3G, Broadband Wireless Access & ISM circuits. Housed in a compact 4x4 mm (LP4) SMT QFN package, the RFIC requires minimal external components & provides a low cost alternative to more complicated double up-conversion architectures. The RF output port is single-ended and matched to 50 Ohms with no external components. The LO requires -6 to +6 dBm and can be driven in either differential or single-ended mode while the baseband inputs will support modulation inputs from DC - 700 MHz typical. This device is optimized for a supply voltage of +4.5V to +5.5V and consumes 170 mA @ +5.0V supply.

Field Detector and Act. for Ctrl (Darmstadt)





Requirement for CEBAF (JLAB)

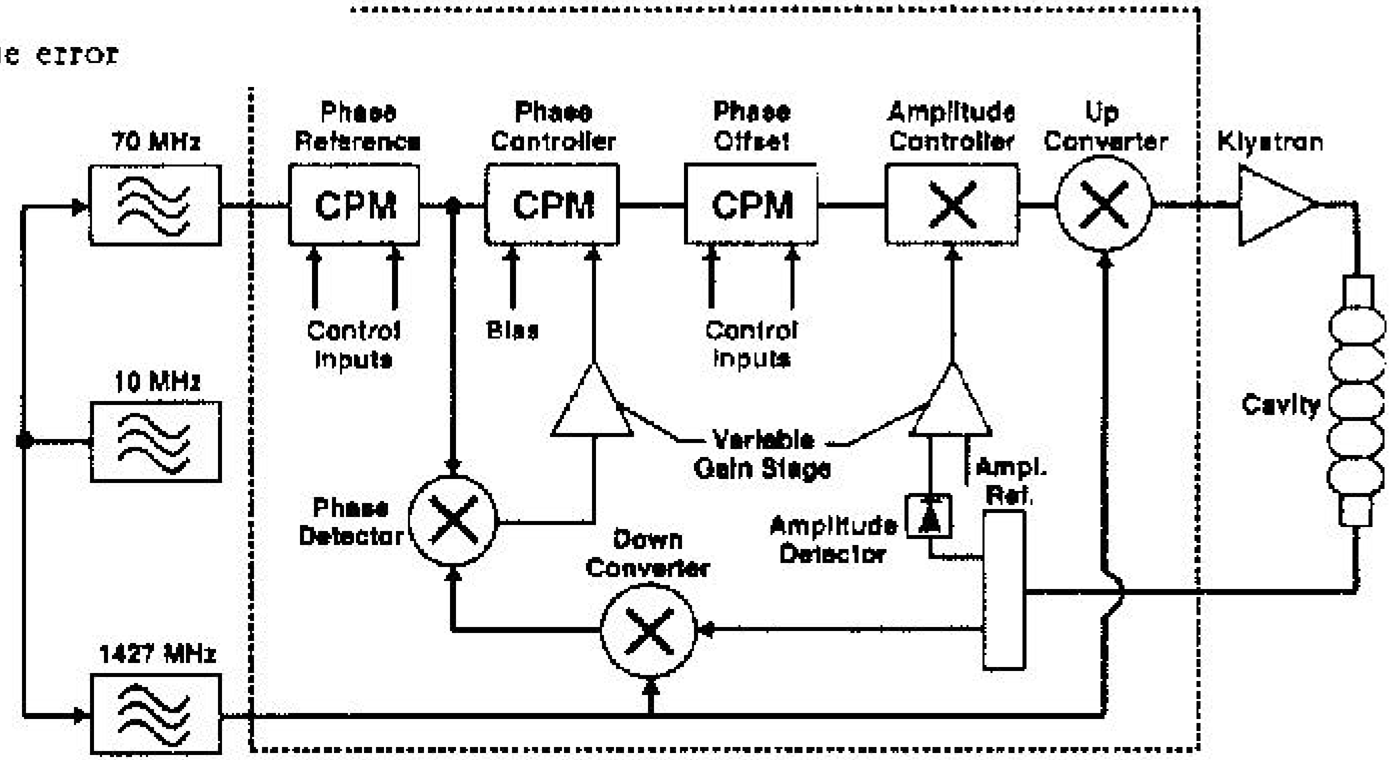
RF control requirements with vernier

RMS error	uncorrelated	correlated
σ_A	2×10^{-4}	1.1×10^{-5}
σ_f	$0.25°$	$0.13°$
σ_s	$2.6°$	∞

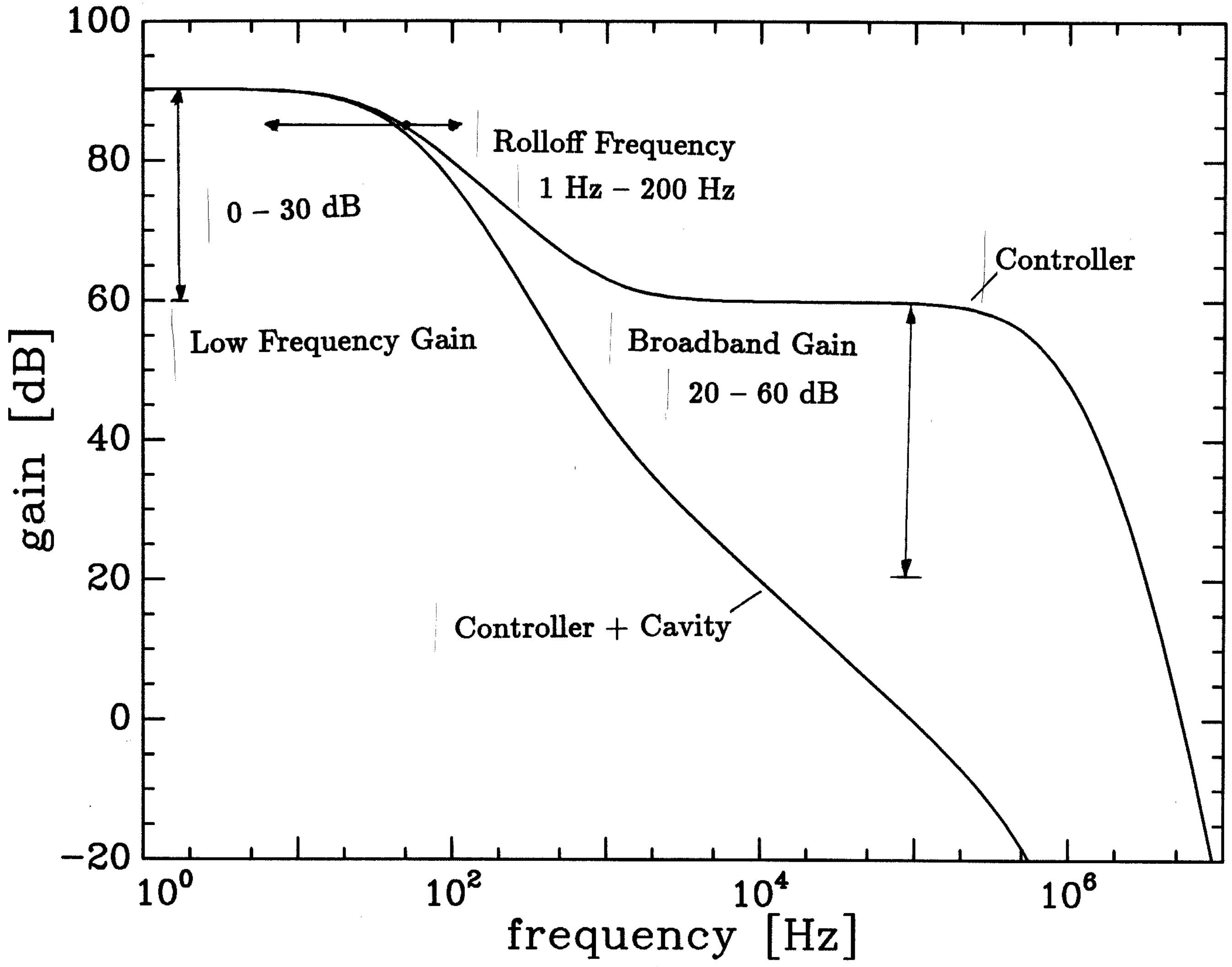
σ_A : relative RMS amplitude error

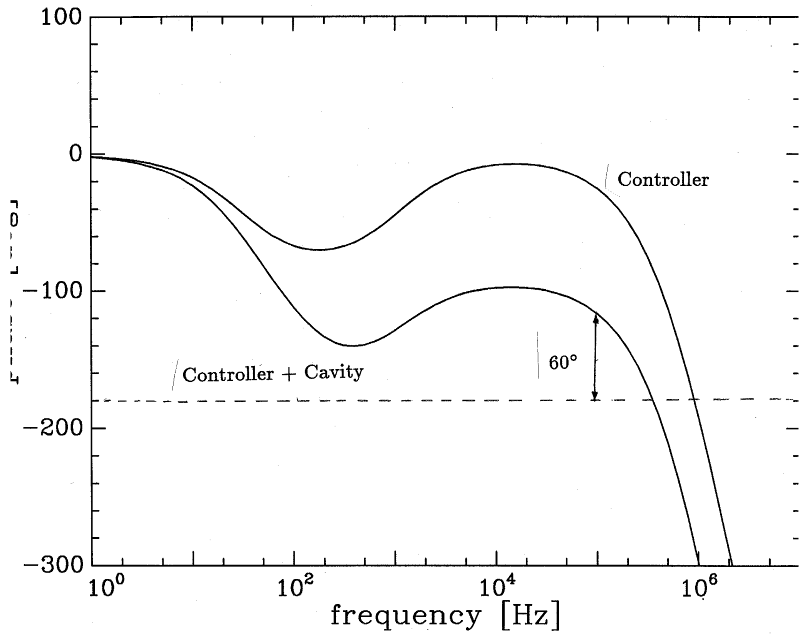
σ_f : fast RMS phase error

σ_s : slow RMS (along linac) phase error

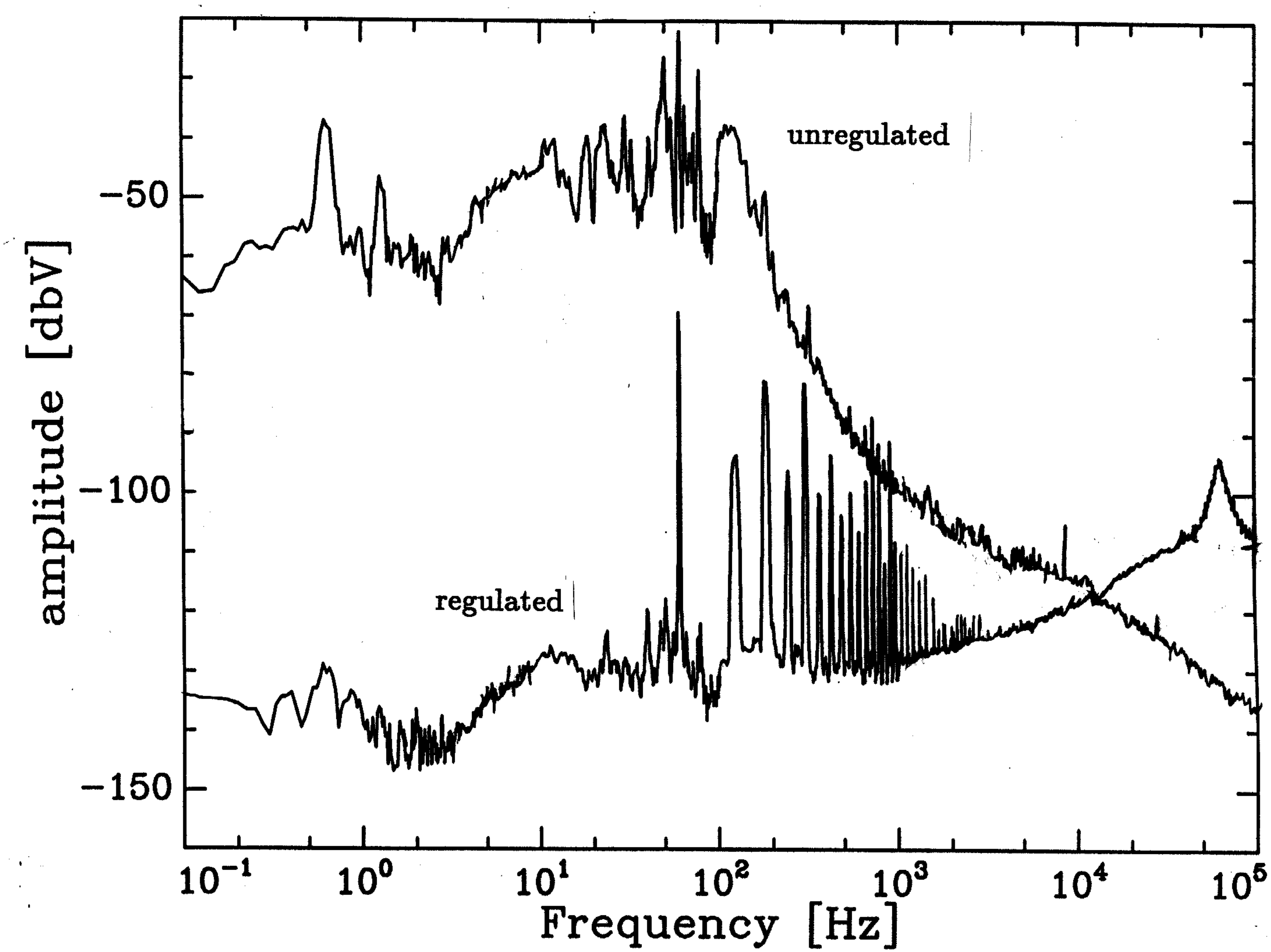


Bode Plot of Controller at JLAB





Performance Measured at JLAB



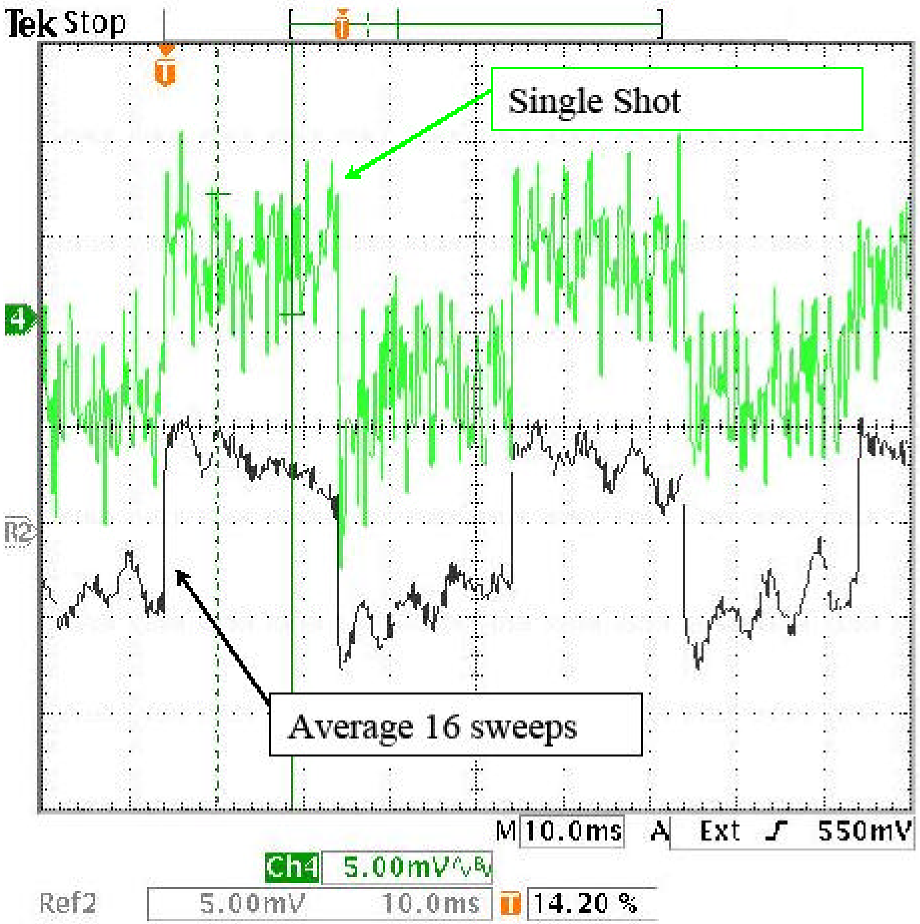
Performance Measure at JLAB

Measured RMS errors

Frequency Range [Hz]	Relative Amplitude Error	Phase Error [°]
$0 - 10^0$	5.5×10^{-6}	1.1×10^{-3}
$0 - 10^1$	1.1×10^{-5}	1.2×10^{-3}
$0 - 10^2$	3.5×10^{-5}	3.0×10^{-3}
$0 - 10^3$	4.1×10^{-5}	4.6×10^{-3}
$0 - 10^4$	5.5×10^{-5}	7.0×10^{-3}
$0 - 10^5$	7.0×10^{-5}	1.6×10^{-2}
$0 - 10^6$	7.5×10^{-5}	

Performance at Rossendorf

CW SRF at Rossendorf – 8 June 2004



Courtesy of F. Gabriel

- Q_{ext} = 1E7
- 7.64 MV/m
- 50% Duty Cycle
- 0.464 mA Peak

0.03° rms Phase Stability!

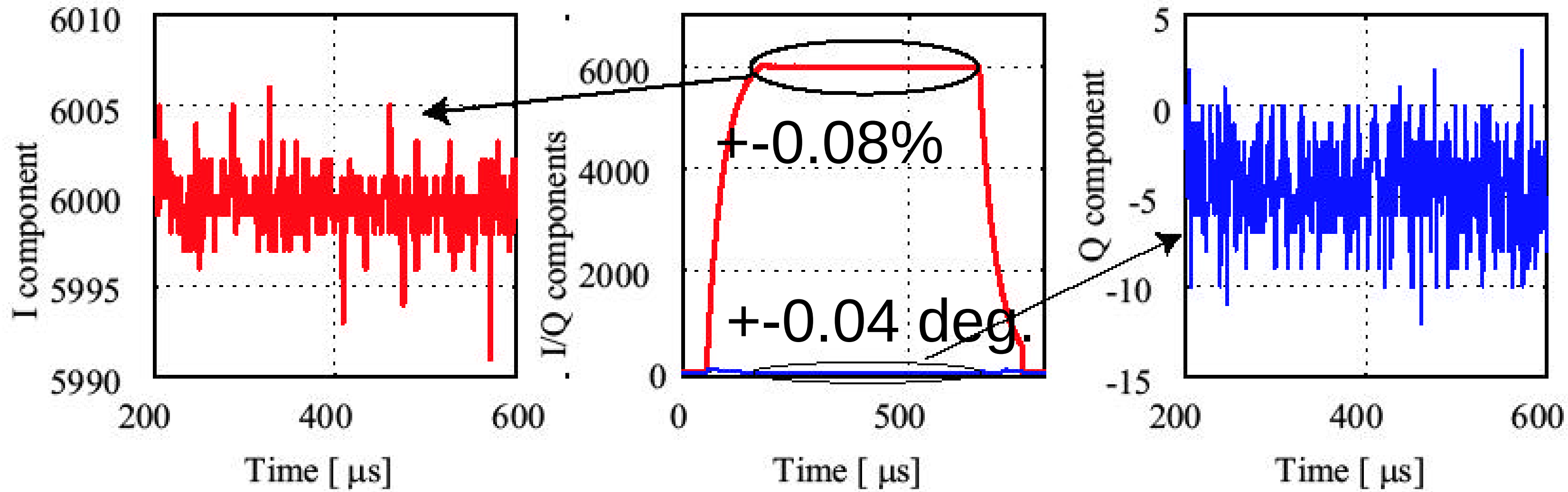
Underlying 300 Hz structure at 0.015°

AC Line pickup or Real Phase drift?

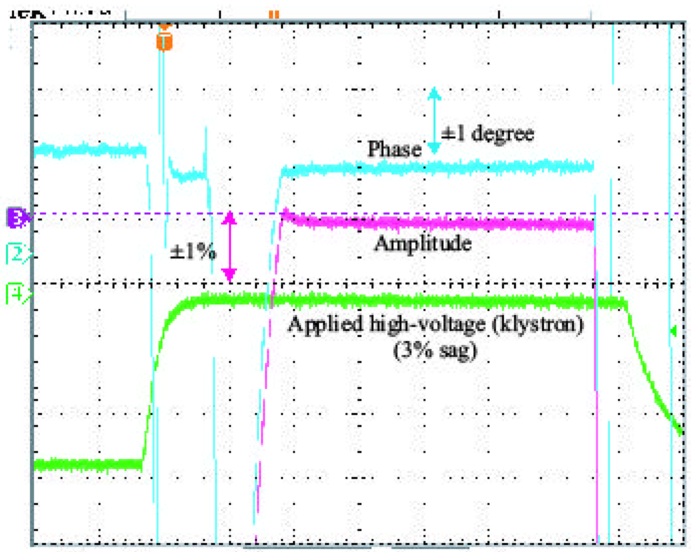
Feed Forward Required?

8 Jun 2004
17:01:56

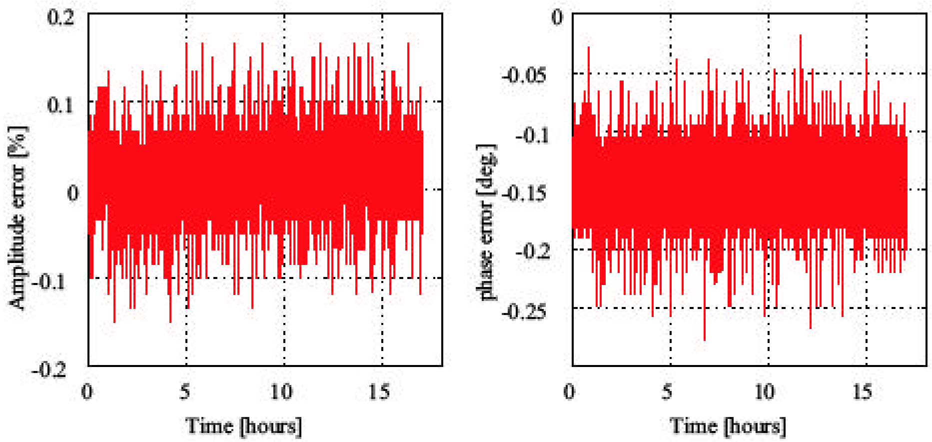
Stability Measured for J-PARC



Measured I/Q components during rf operation. Fullscale I/Q:center, expansion I: left, expansion Q: right. No feedforward was used. The proportional and integral gains for the feedback are 10 and 15/1000 at a 48-MHz clock, respectively.



Waveforms of the amplitude and phase obtained by external monitors.

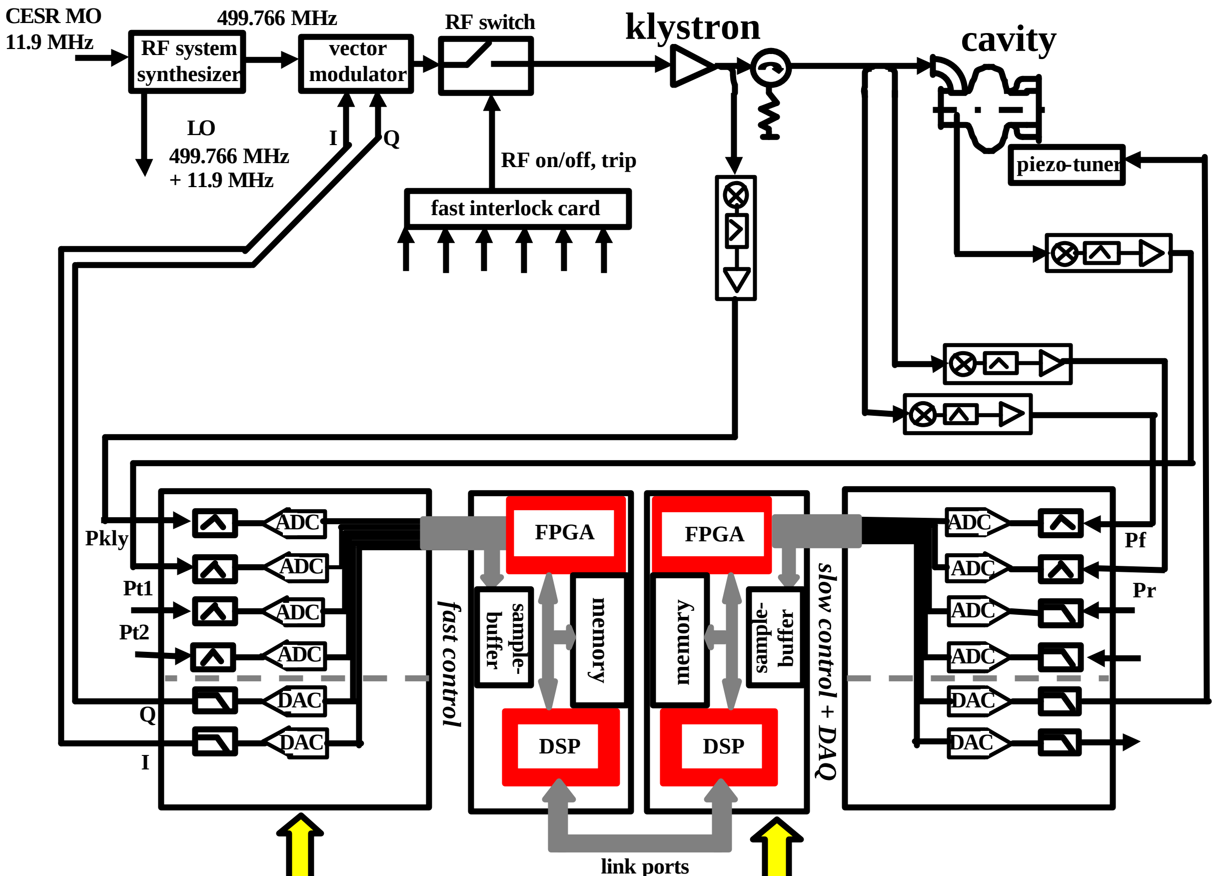


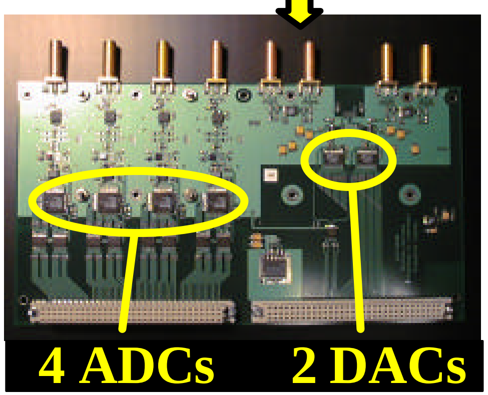
Trend-graphs of the amplitude and phase stabilities.

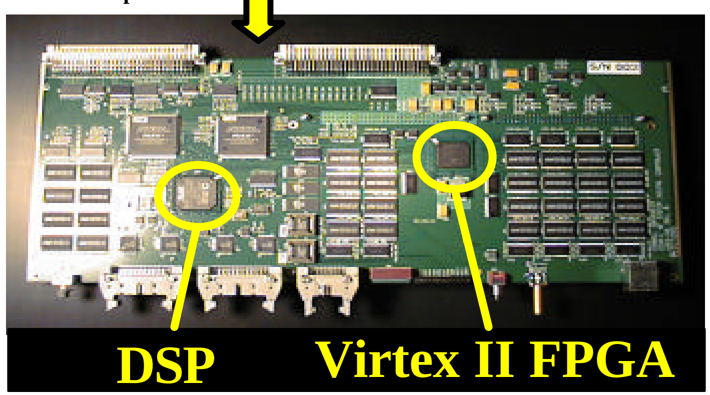
S. Michizono

Matthias Liepe
CORNELL UNIVERSITY

Ultra-Fast Digital RF Field Control System for CESR and ERLs







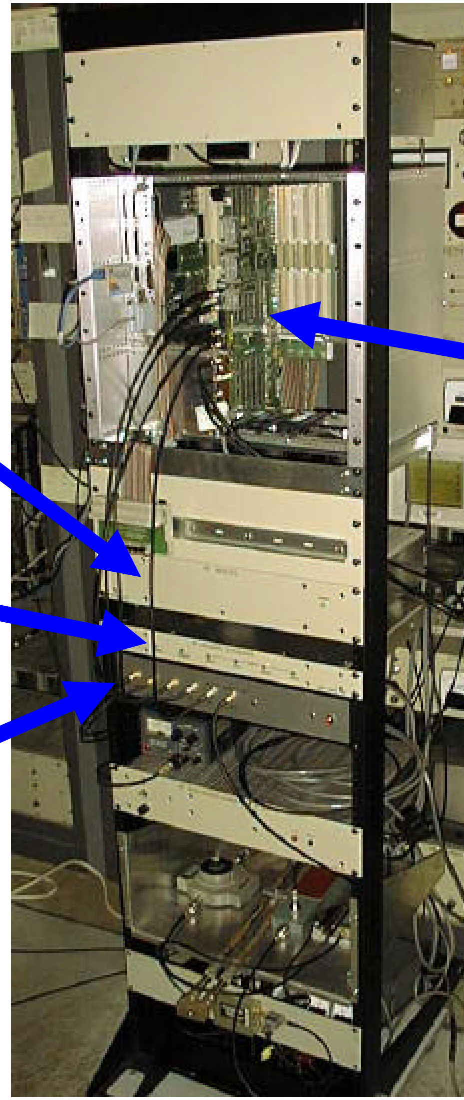
- *very low delay in the control loop (» 1 ms)*
- *Field Programmable Gate Array (FPGA) design combines the speed of an analog system and the flexibility of a digital system*
- *high computation power allows advanced control algorithms*
- *all boards have been designed in house*
- *generic design: digital boards can be used for a variety of control and data processing applications*

Cornell's Digital RF Control System:

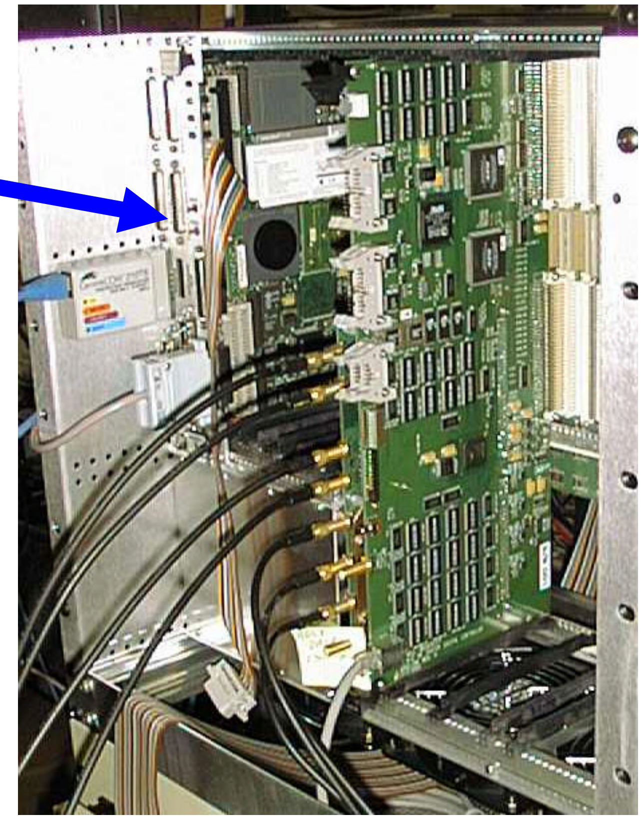
RF Down-Converters

500 MHz frequency synthesizer

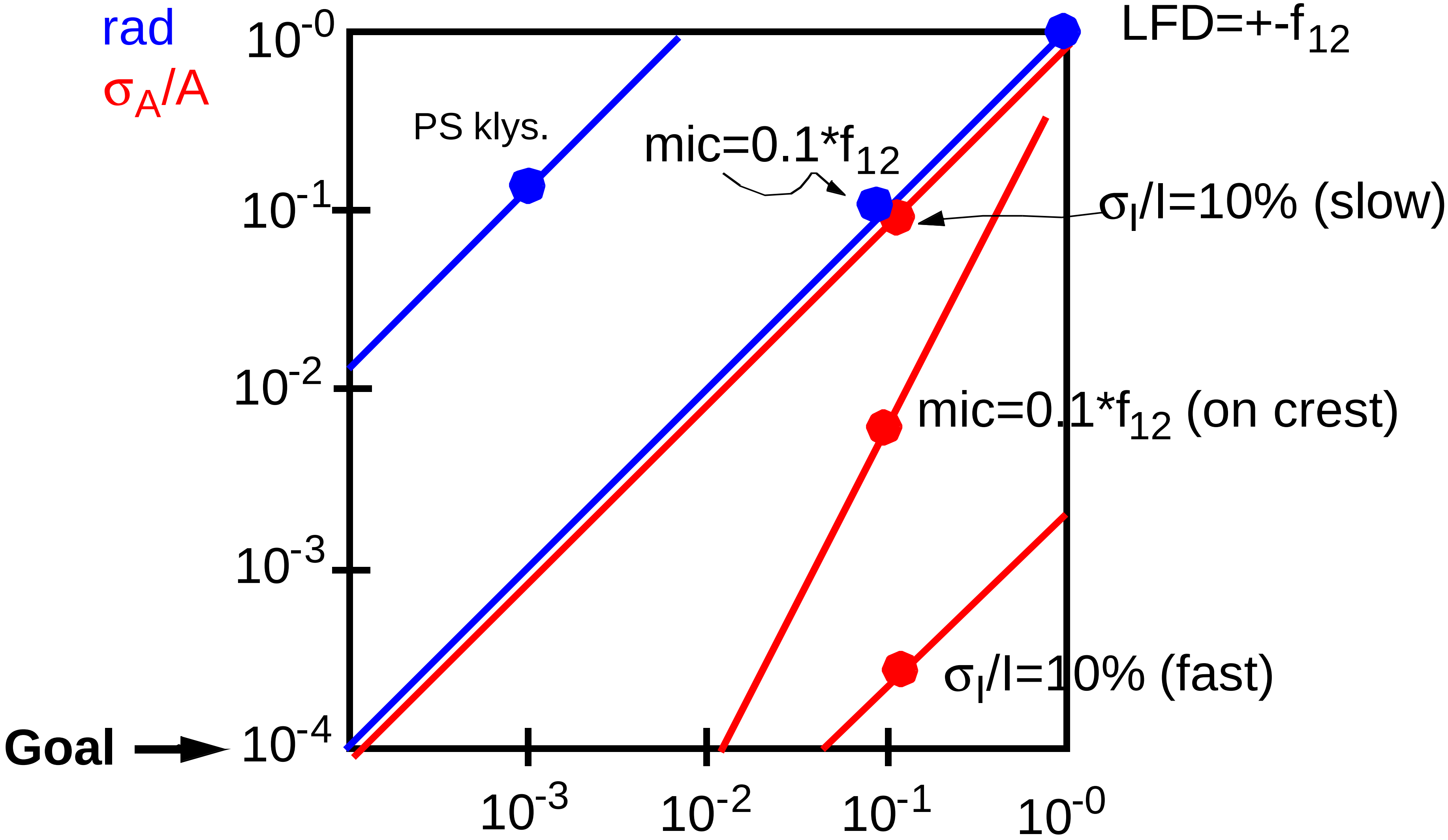
vector modulator



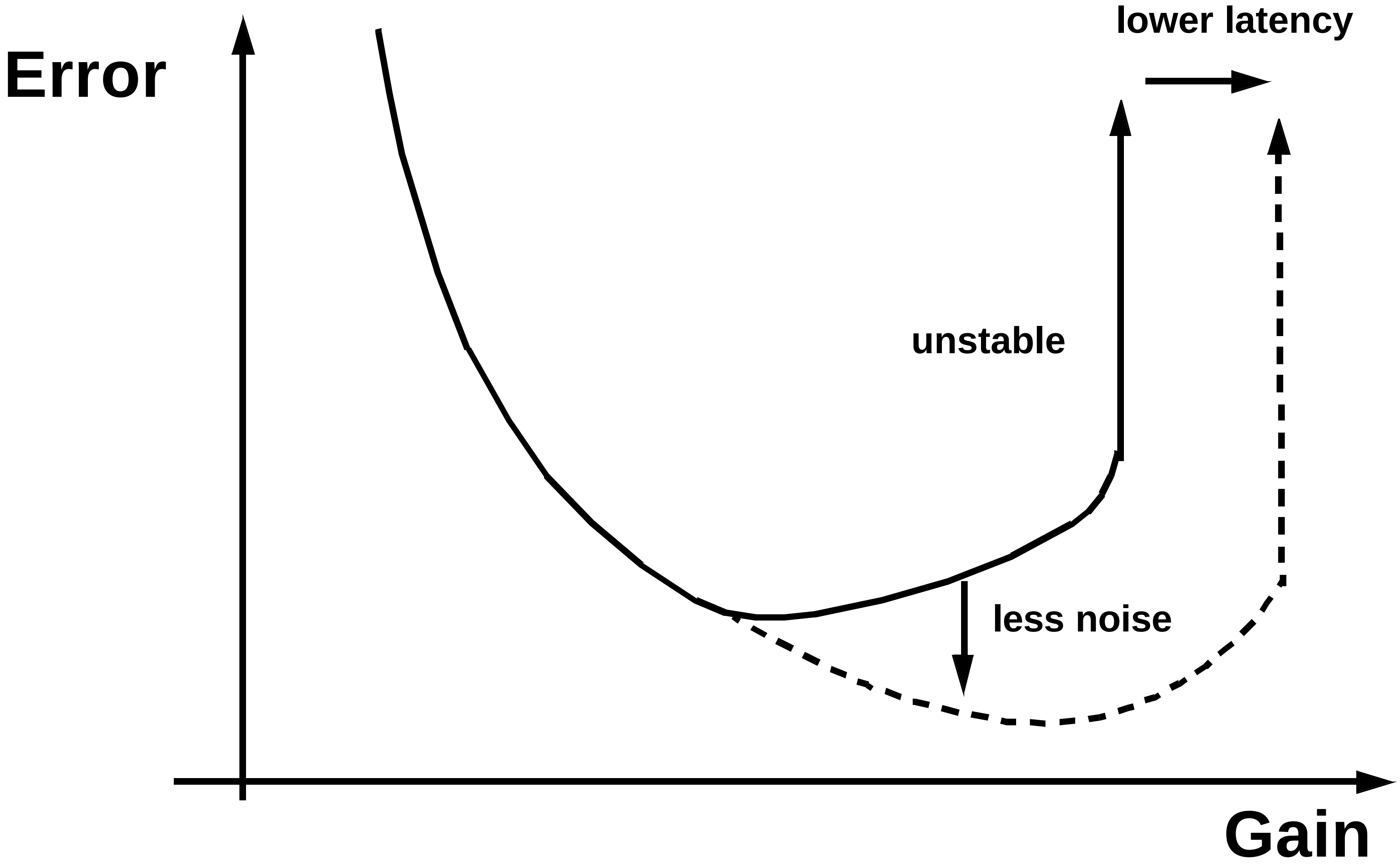
Digital Boards:



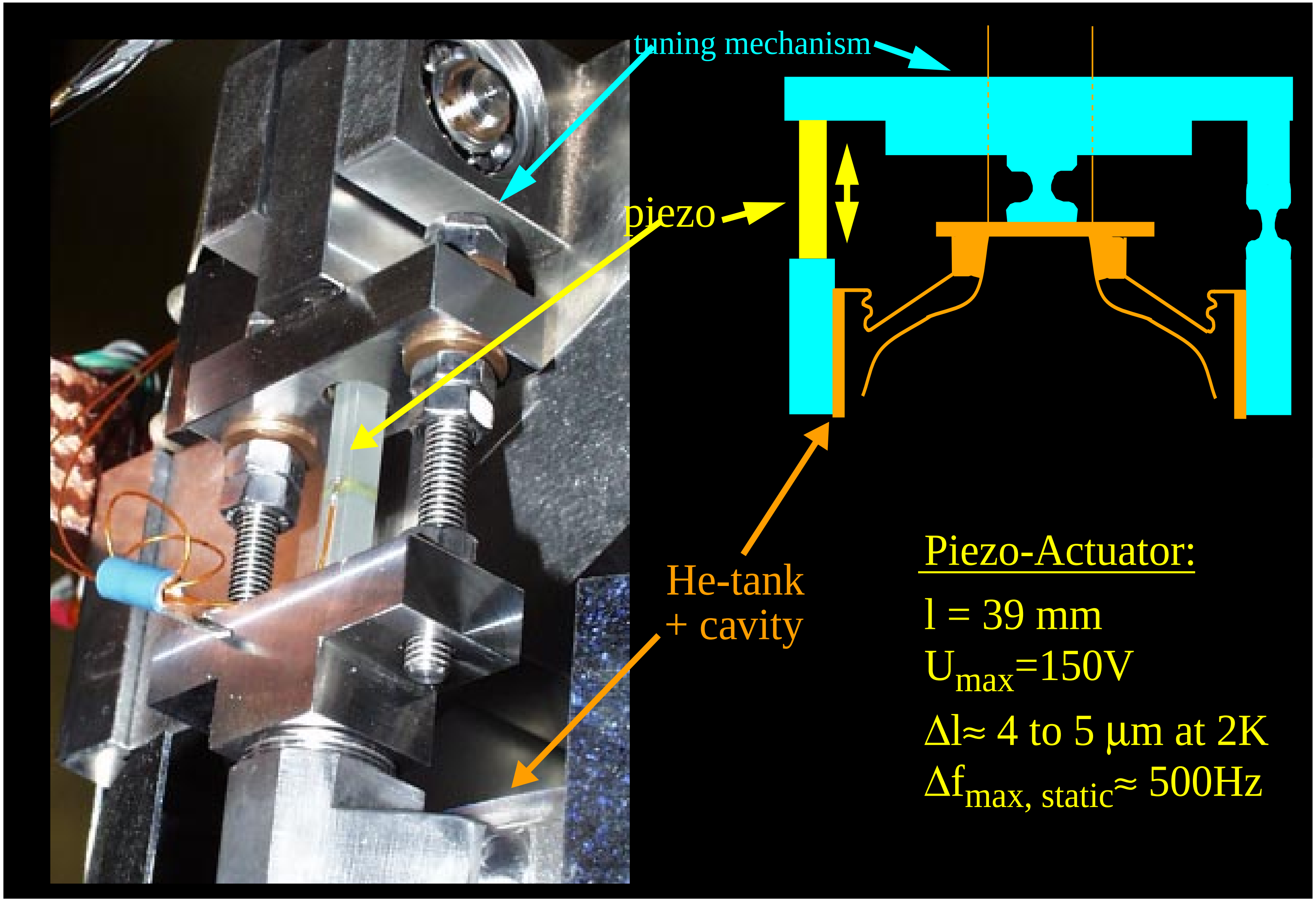
Open Loop Errors



RMS Error as Function of Feedback Gain



Active Compensation of Lorentz Force Detuning (1)



Piezo-Actuator:

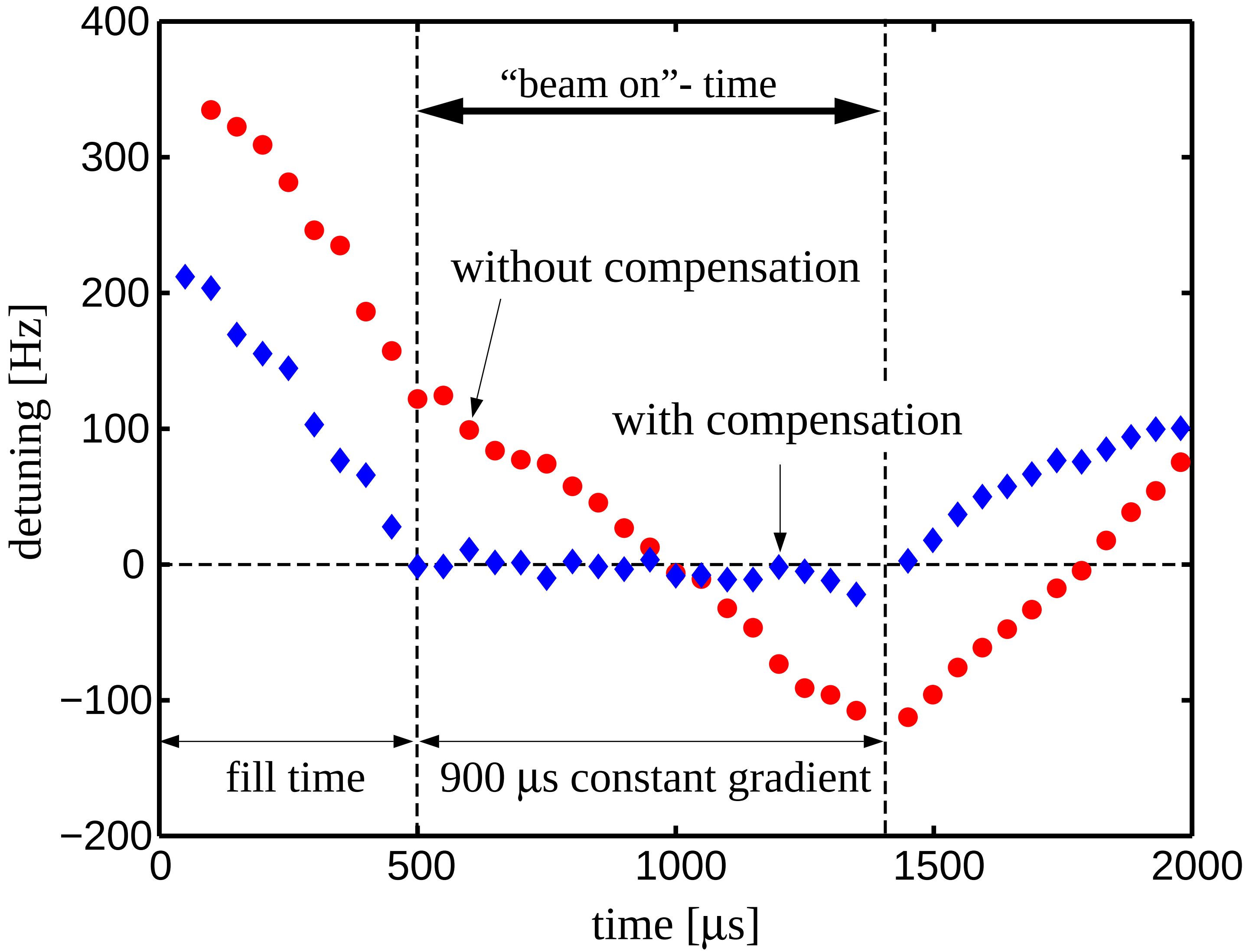
l = 39 mm

U_{max}=150V

$\Delta l \approx$ 4 to 5 μm at 2K

$\Delta f_{max,\ static} \approx$ 500Hz

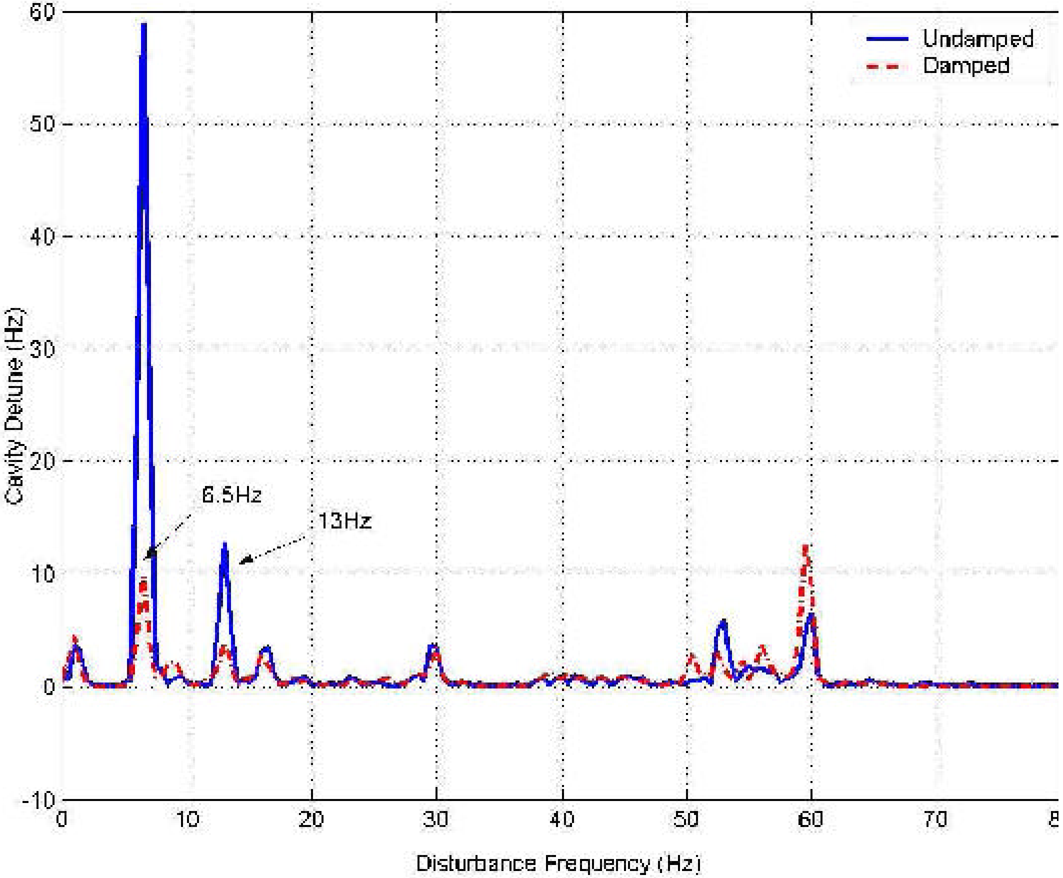
Active Compensation of Lorentz Force Detuning (2)



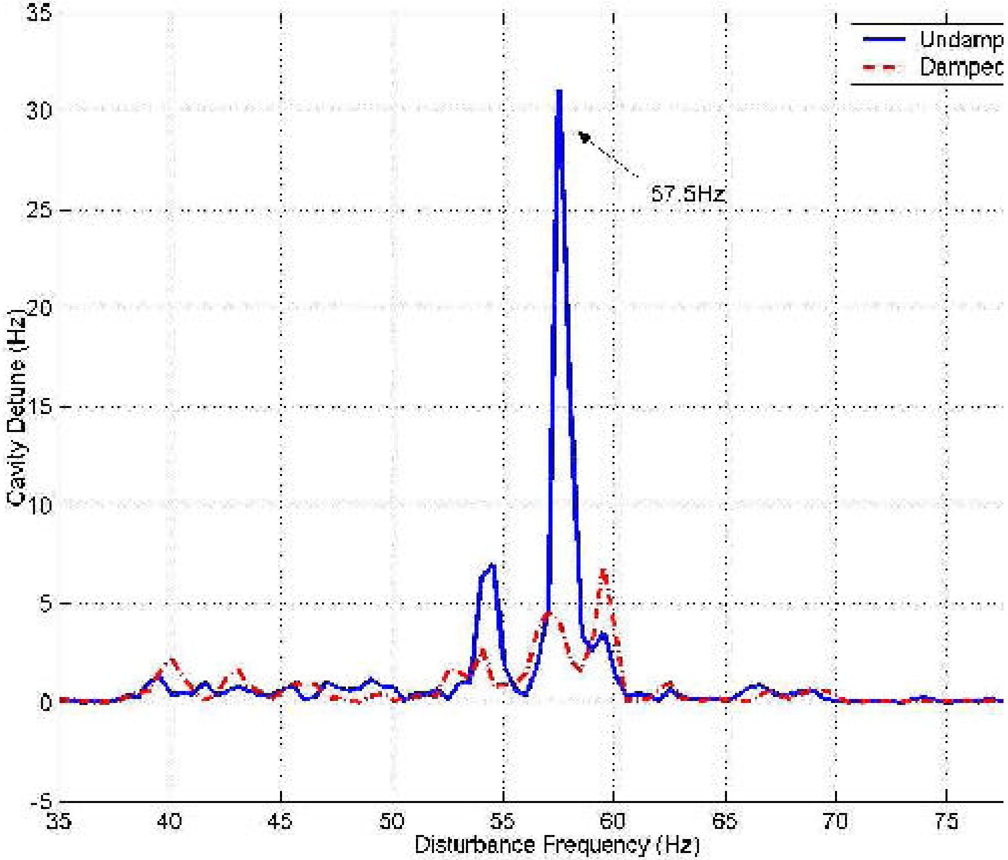
9-cell cavity operated at 23.5 MV/m

Lorentz force compensated with fast piezoelectric tuner

Microphonics Suppression with Feedforward



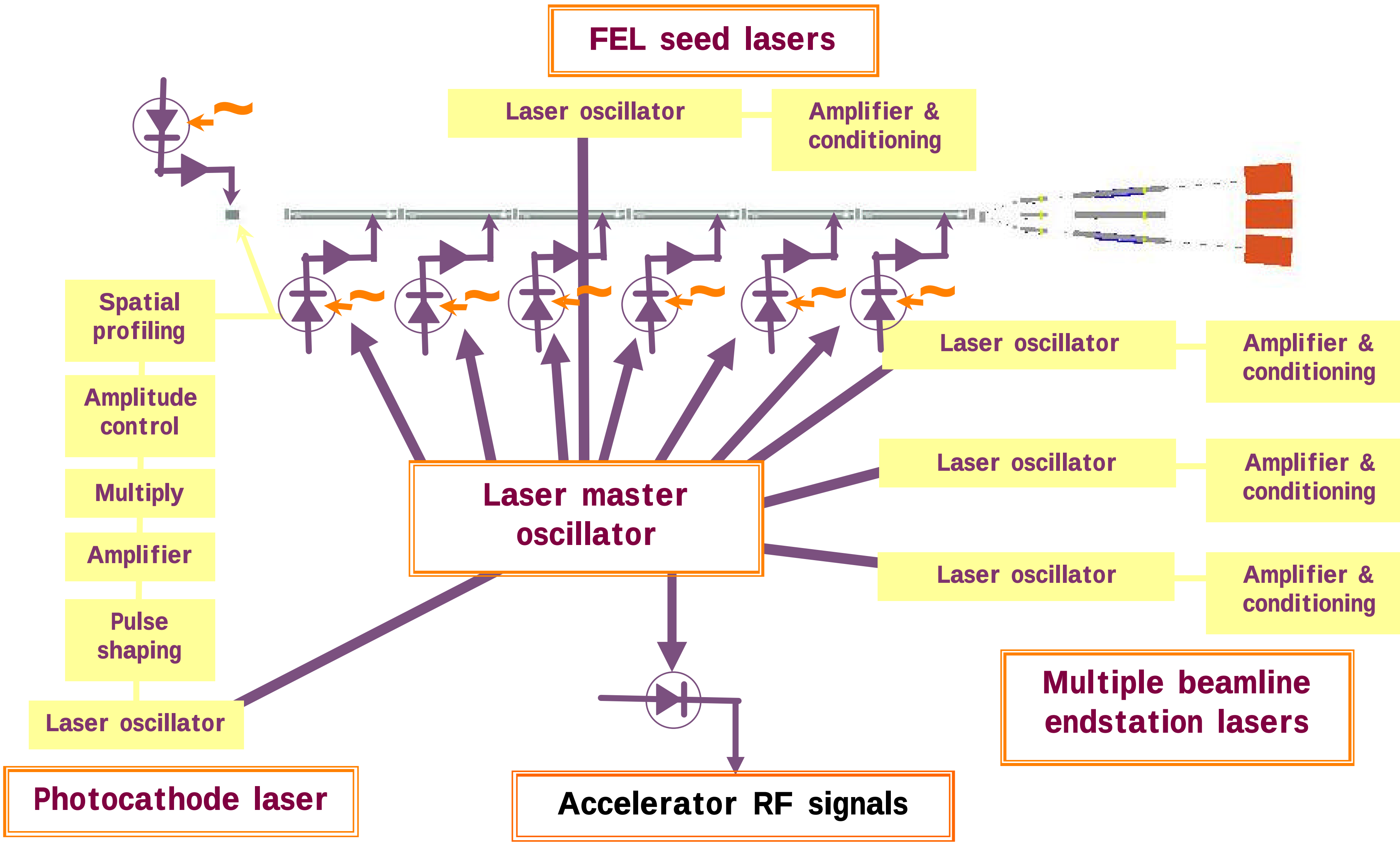
Active damping of helium oscillations at 2K.



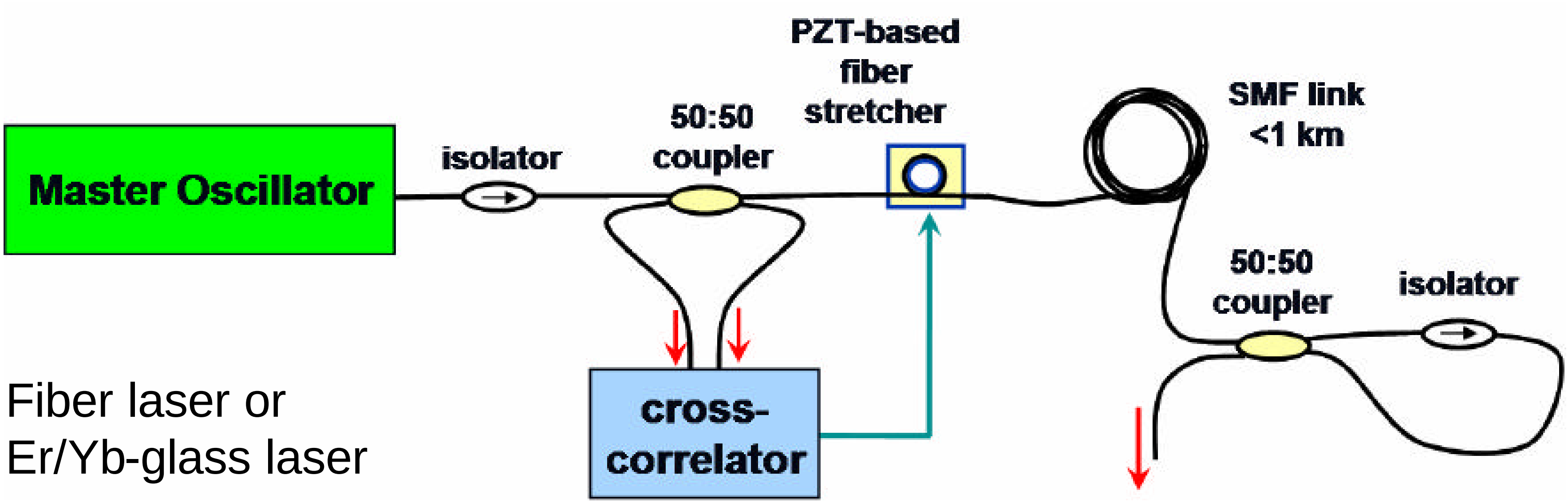
Active damping of external vibration at 2K.

T. Grimm

rf signals for the accelerator may also be derived from the laser master oscillator



Timing Stabilized Fiber Links (~1 km)



Fiber laser or
Er/Yb-glass laser

Assuming no fiber length fluctuations faster than 2L/c (~100 kHz)

Thermal fluctuations: ~ 20 μm (~ 100 fs) over 1 km for 0.1°C

Conclusion

- Field regulation ranging from 1% to 10^{-4} amplitude and 1 deg. to 0.01 deg. for phase (in critical sections) will be required for future superconducting and normalconducting accelerators
- Noise sources for superconducting cavities are understood
  - Microphonics (typ. 10 Hz)
  - Lorenz force detuning (1-3 Hz/(MV/m)^2)
  - Beam loading (few %)
- Rapid development in digital technology (DSP, FPGA, ADC, DAC) favors digital design for feedback/feedforward control.
- Fast Control with incident wave
  - feedforward for repetitive errors (beam,LFD, klystr.)
  - feedback (stochastic errors)

- Limitation of feedback: Latency in Loop (limits loop gain) and Noise
- Limitation of feedforward: Measurement and Estimation of Perturbations
- Resonance control with fast tuner promising
  - Lorentz force compensation successfully demonstrated
  - For microphonics control first result promising results
- Present achievements
  - 10^{-4} in amplitude and 0.03 deg. have been achieved at QL=1e7
- Outlook: Phase stability of 0.01 deg. appears feasible

LLRF Contributions at the LINAC 2004

MOP69	A. Hofler et al.	RF Control Modelling Issues for Future Superconducting Accelerators
TUP75	D. Dong et al.	The High Accuracy RF Phase Detector Research for the 200 MeV LINAC
TUP76	T. Kandil et al.	Adaptive Feedforward Cancellation (AFC) of SInusoidal Disturbances in Superconducting RF (SCRF) Cavities
TUP77	K. Fong et al.	Status of RF Control System for ISAC II Superconducting Cavities
TUP78	T. Jezynski at al.	On-Line Diagnostics for the Low Level RF Control for the European XFEL
TUP79	C. Hovater et al.	A New RF System for the CEBAF Normal Conducting Cavities
TUP89	S.P.M. Sekalski et al.	Static Absolute Force Measurement for Preload Piezoelements Used for Active Force Force Detuning
TUP98	W. Cichalewski et al.	The Finite State Machine for Klystron Operation for TESLA and the European XFEL Linear Accelerator
THP52	T. Kobayashi et al..	RF Reference Distribution System for J-PARC Linac
THP56	S. Michizono et al.	Control of Low Level RF System for J-Parc Linac
THP57	S. Michizono et al.	Digital Feedback System for J-Parc Linac RF Source
THP59	J. Mourier et al.	Low Level RF Including a Sophisticated Phase Control System for CTF3
THP66	T.L. Grimm et al.	Measurement and Control of Microphonics in High Loaded-Q Superconducting RF Cavities