LLRF Experience at TTF and Development for XFEL and ILC

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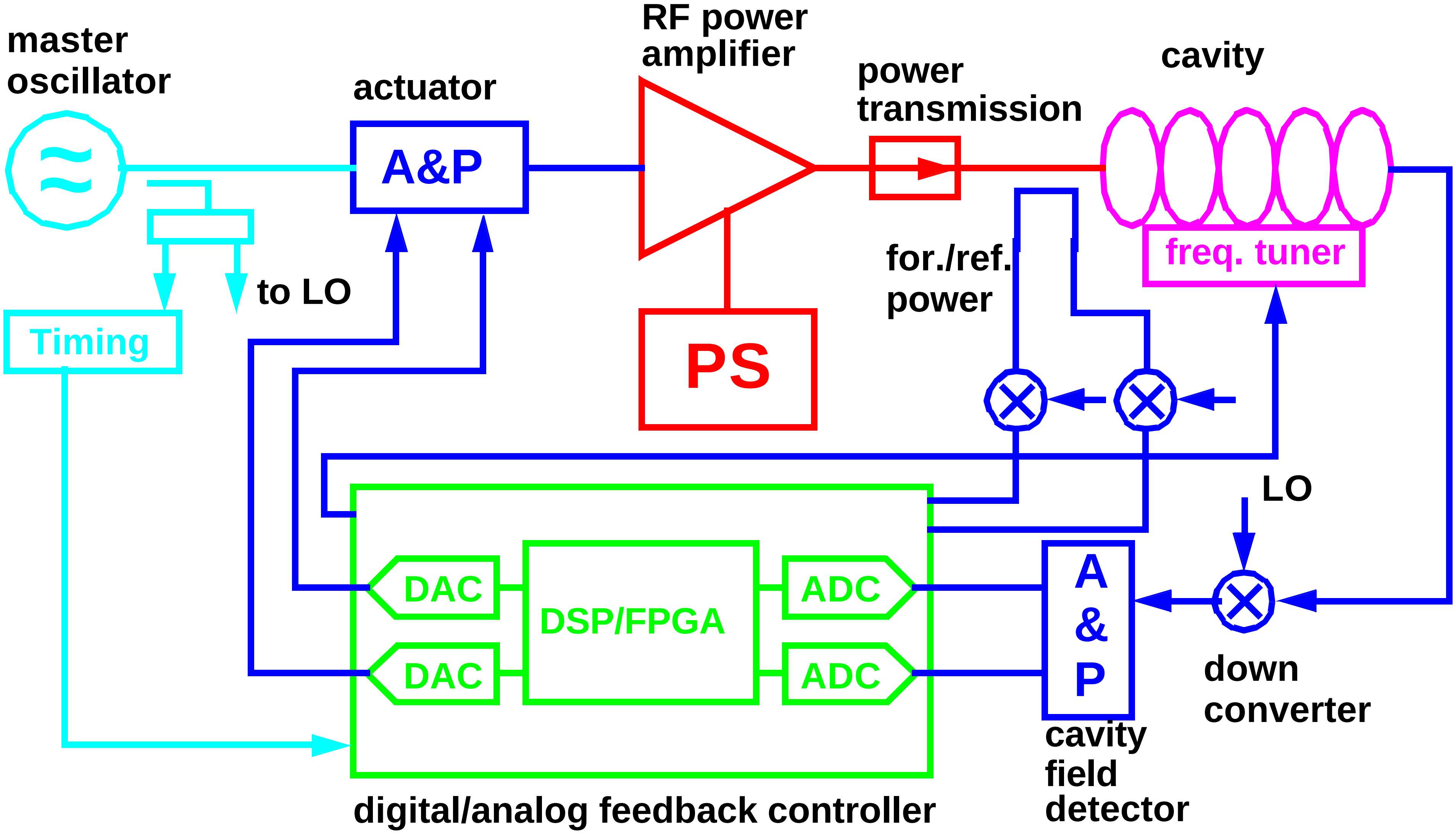
Outline

- RF System Architecture
- Requirements for RF Control
- Sources of Perturbations
- RF Control Design Considerations
- 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

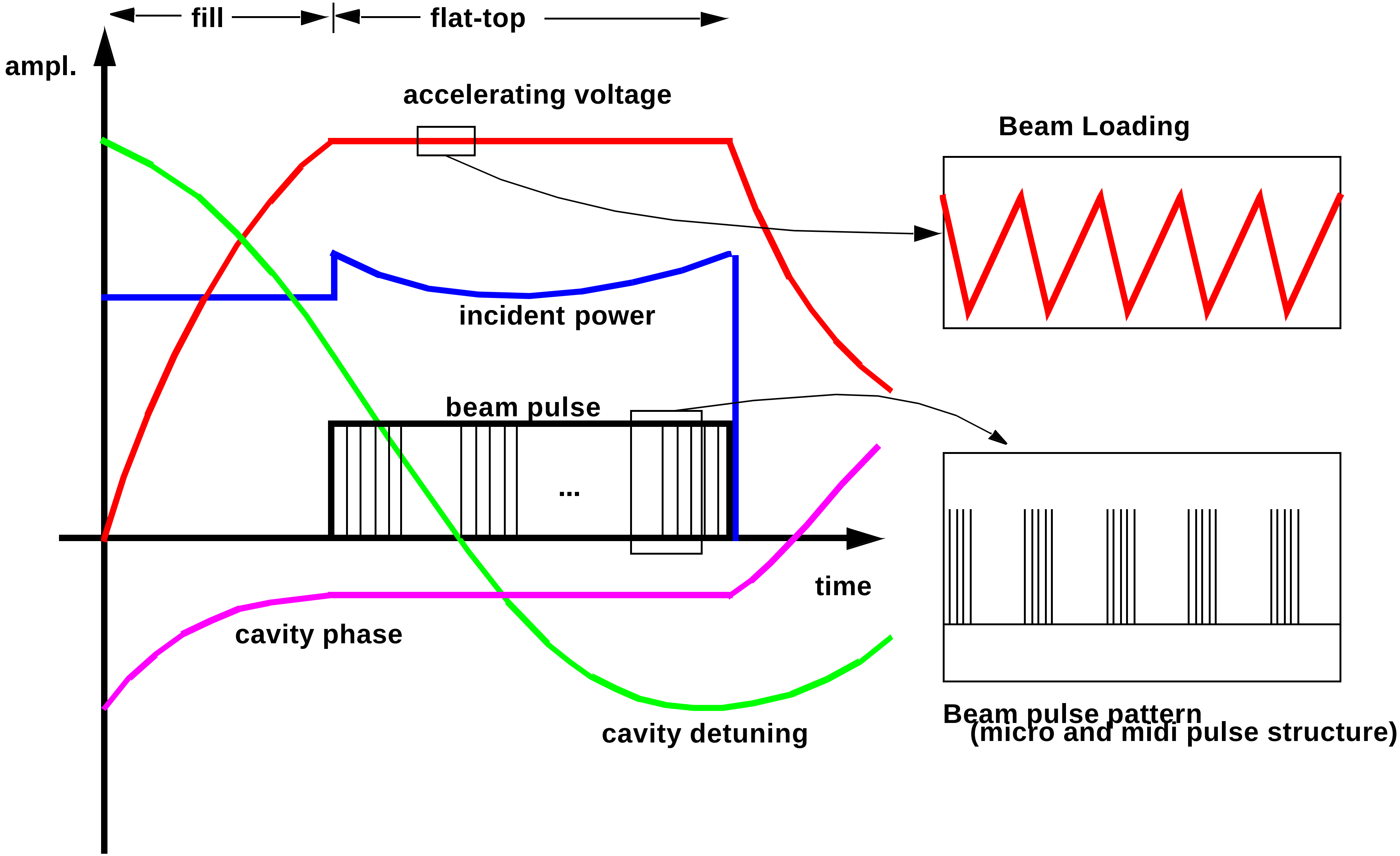
Requirements RF Control

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

- Different accelerators have different requirements on 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

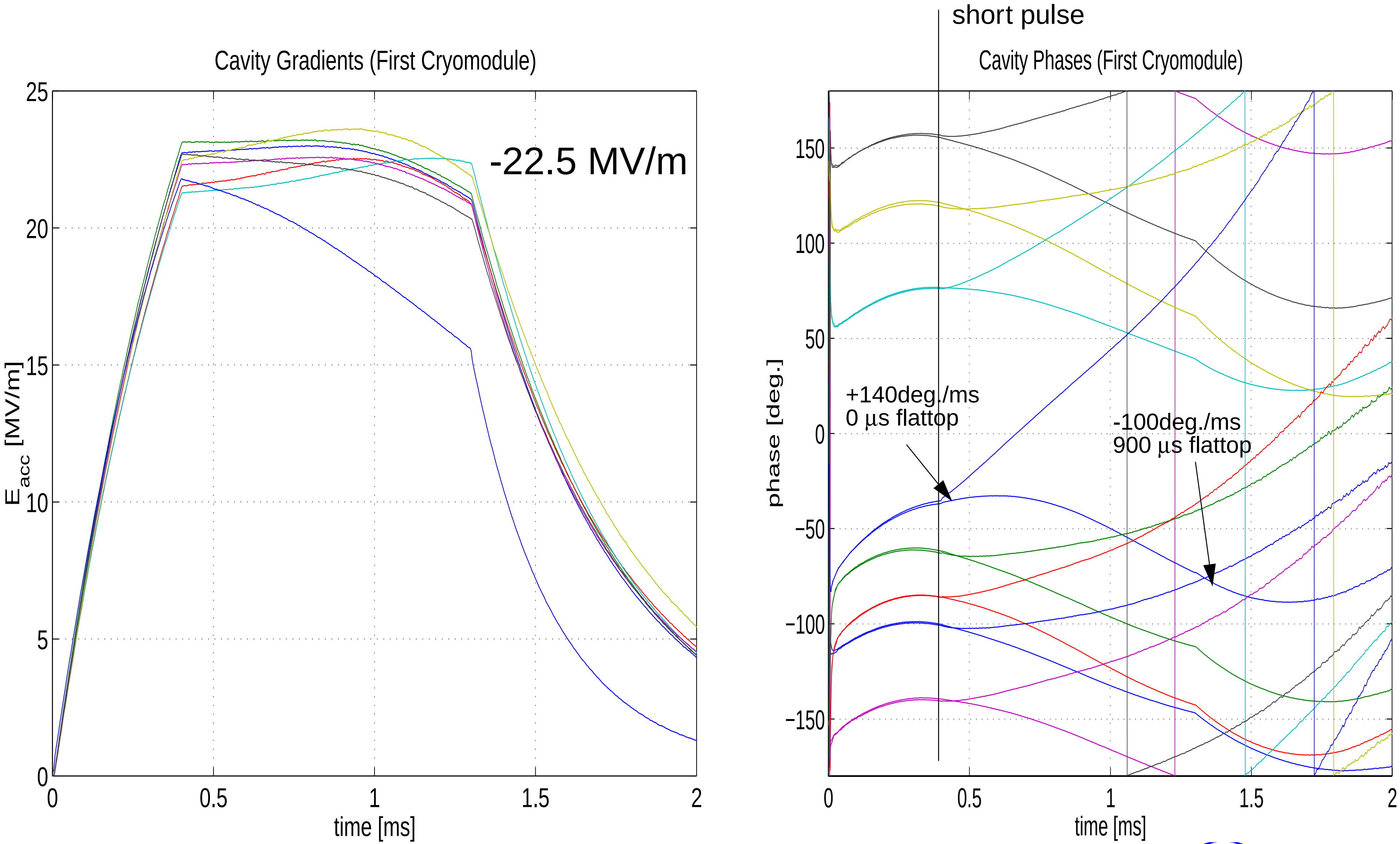
Typical Parameters in a Pulsed RF System



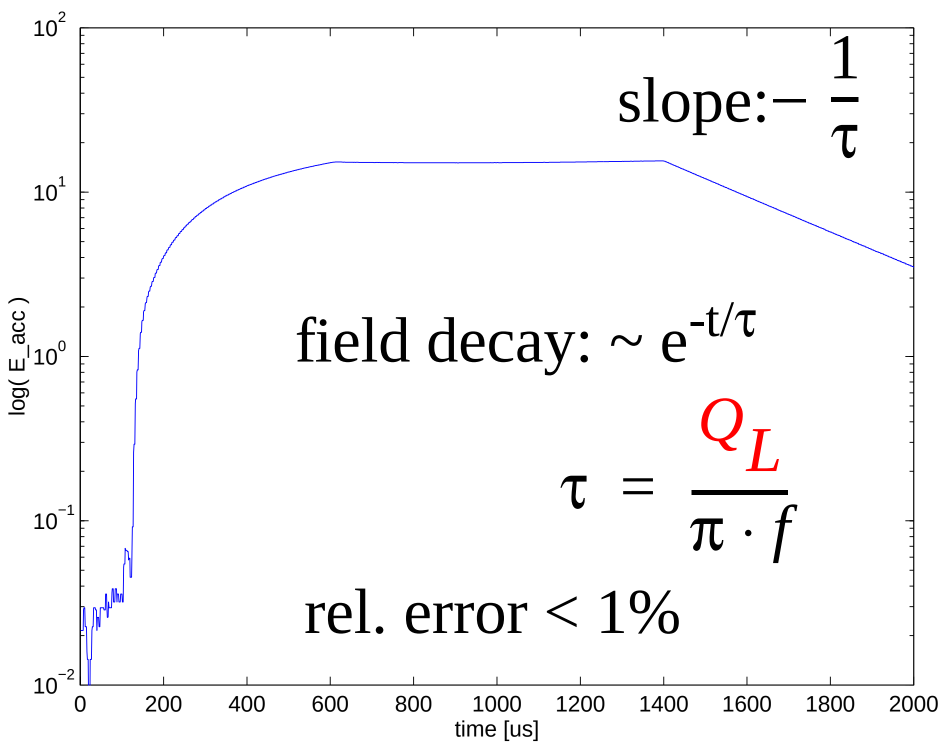
Sources of Perturbations

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

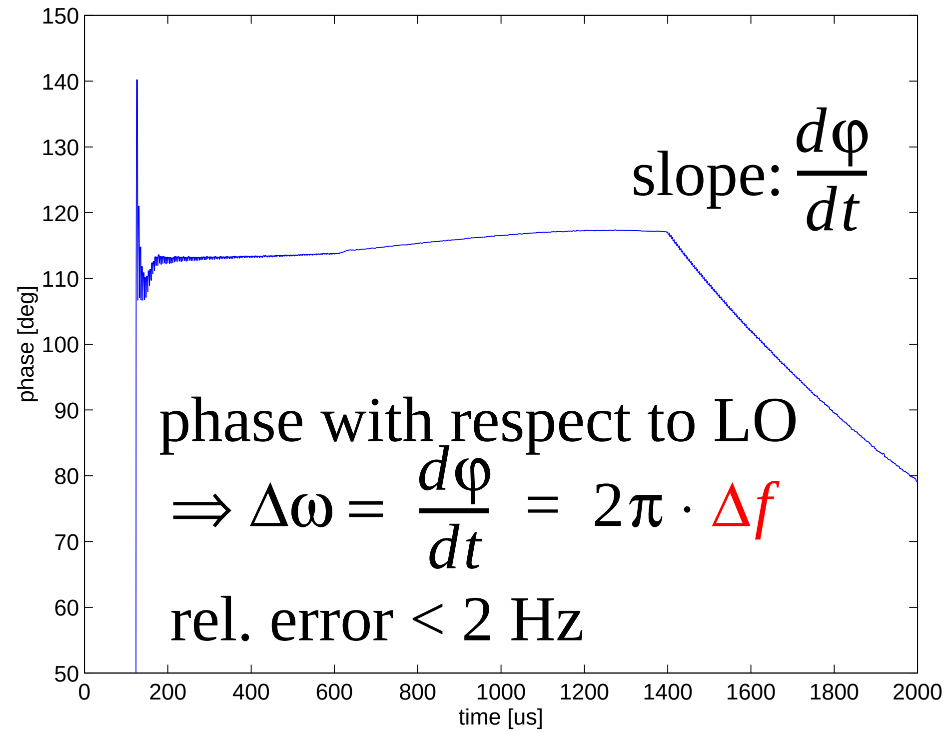
Impact of Lorentz Force Detuning



Measurement of Cavity Q_L and Detuning

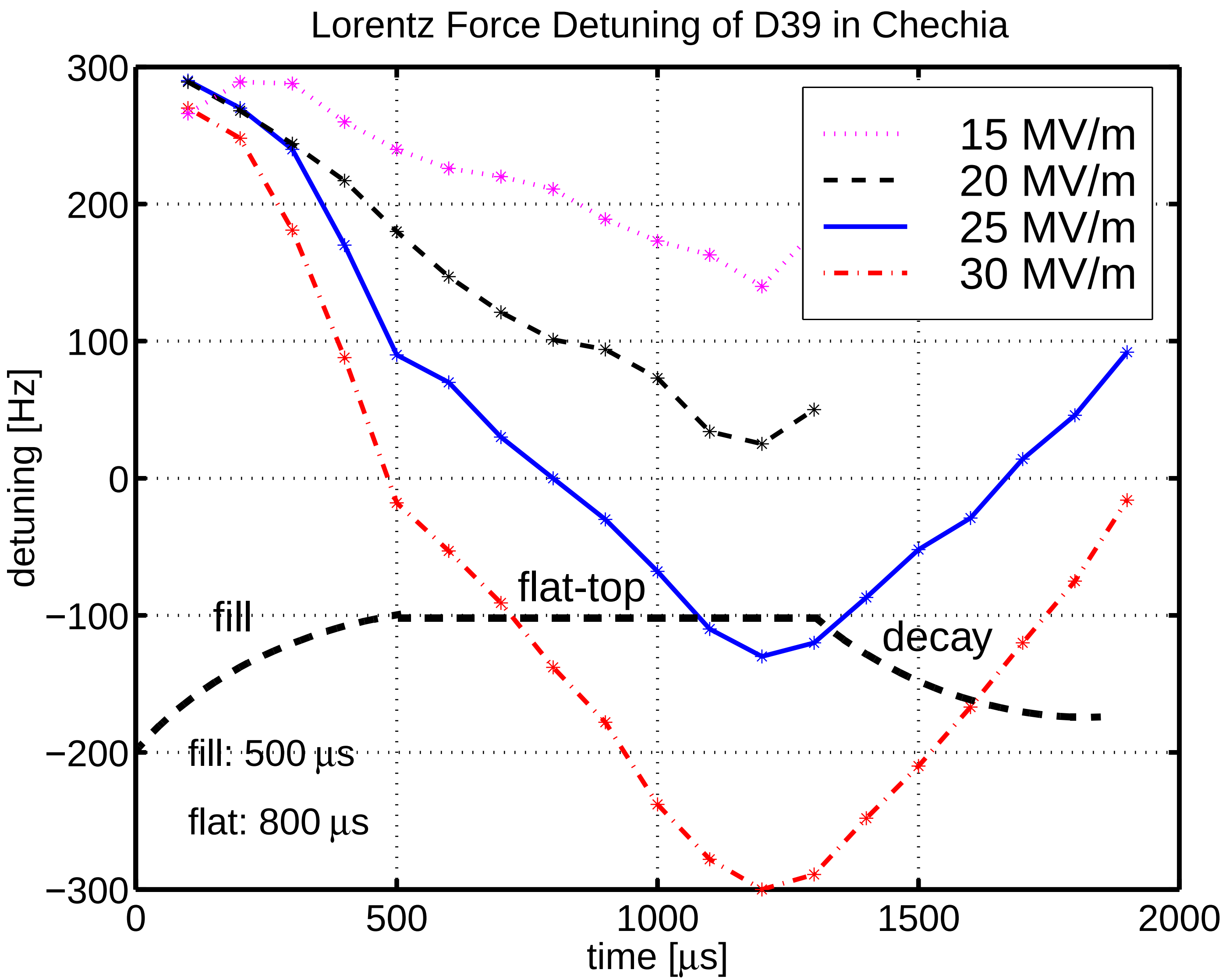


Loaded Q

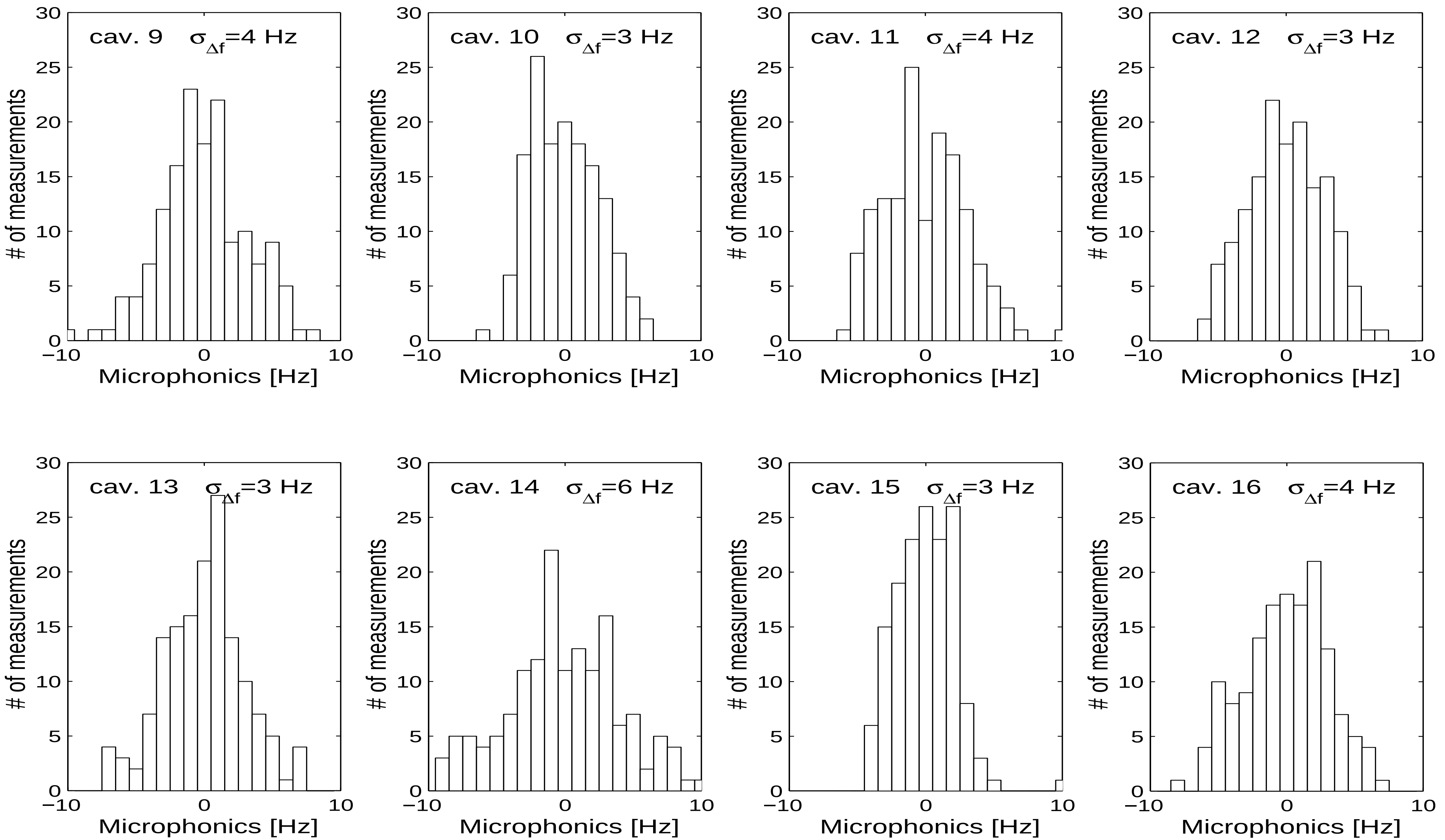


Detuning

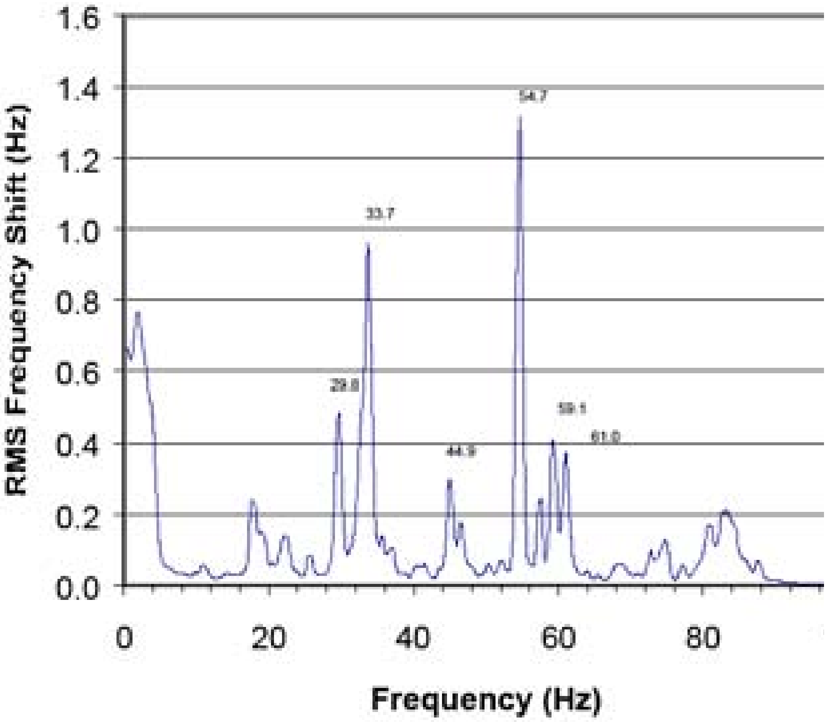
Lorentz Force Detuning



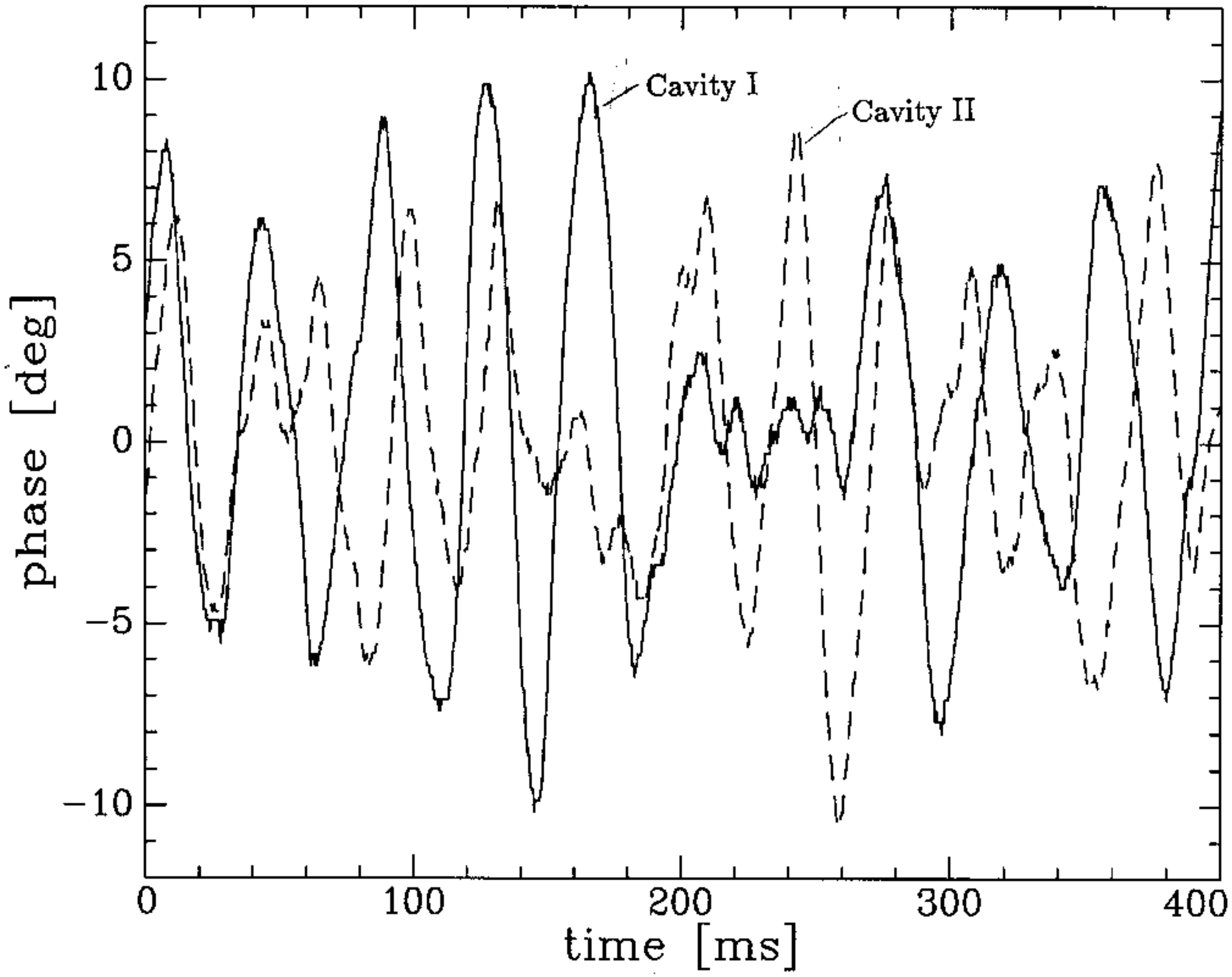
Microphonics at TTF



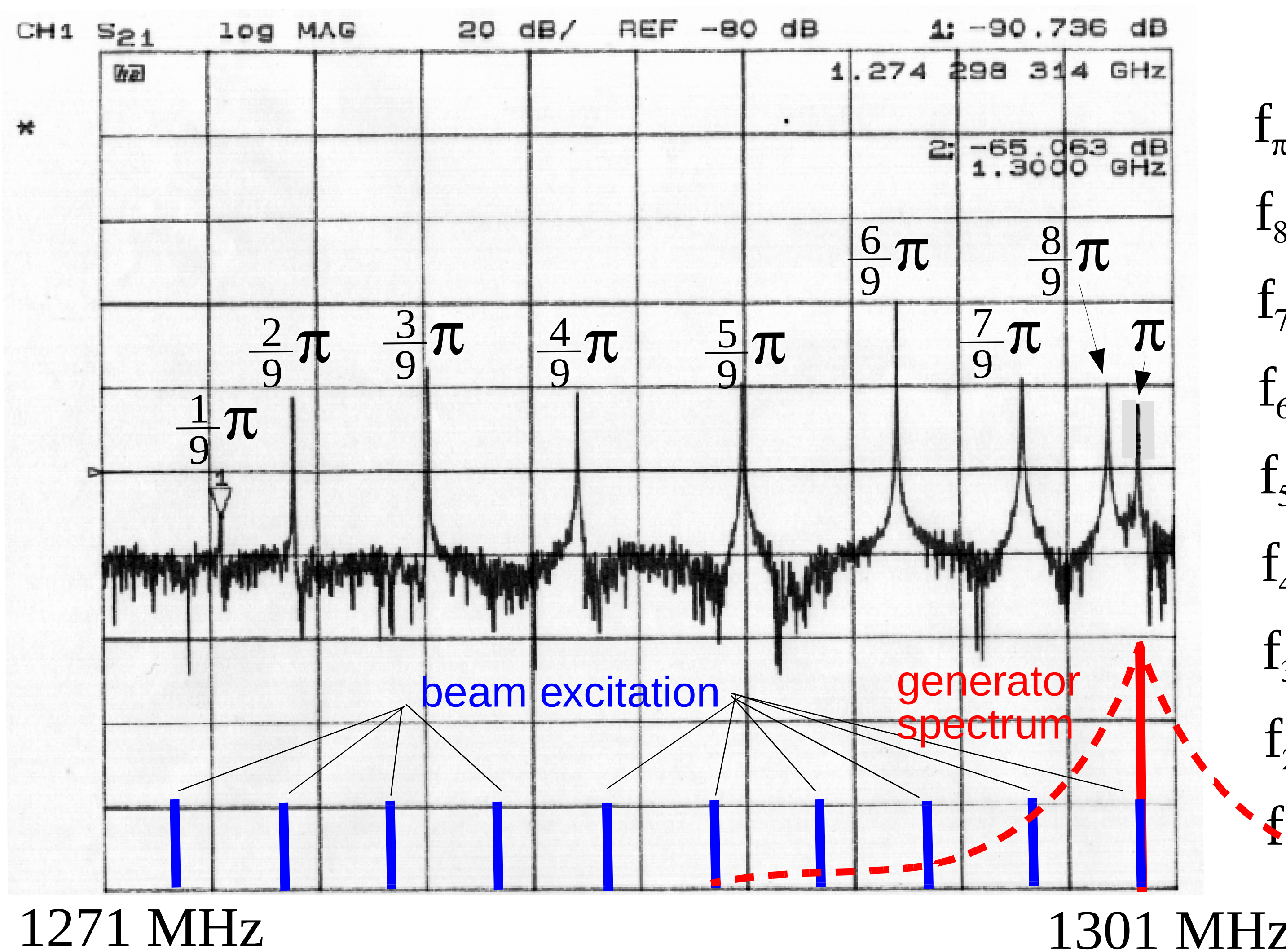
Microphonics at JLAB



Actual 7-cell cavity microphonics baseline.



Excitation of other Passband Modes



f_{π} = 1300.091 MHz

$f_{8/9\pi}$ = 1299.260 MHz

$f_{7/9\pi}$ = 1296.861 MHz

$f_{6/9\pi}$ = 1293.345 MHz

$f_{5/9\pi}$ = 1289.022 MHz

$f_{4/9\pi}$ = 1284.409 MHz

$f_{3/9\pi}$ = 1280.206 MHz

$f_{2/9\pi}$ = 1276.435 MHz

$f_{1/9\pi}$ = 1274.387 MHz

Control Choices (1)

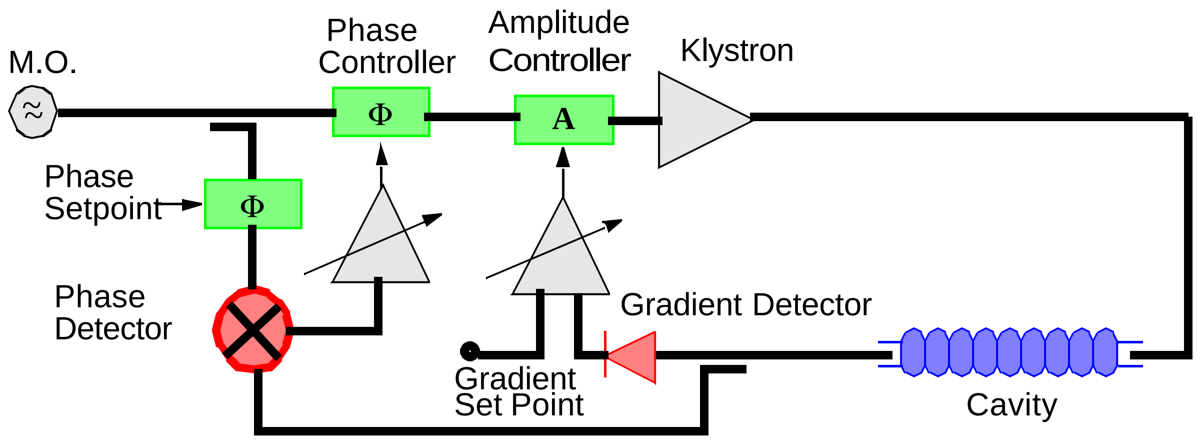
- Self-excited Loop (SEL) vs
  Generator Driven System (GDR)

- Vector-sum (VS) vs individual cavity control

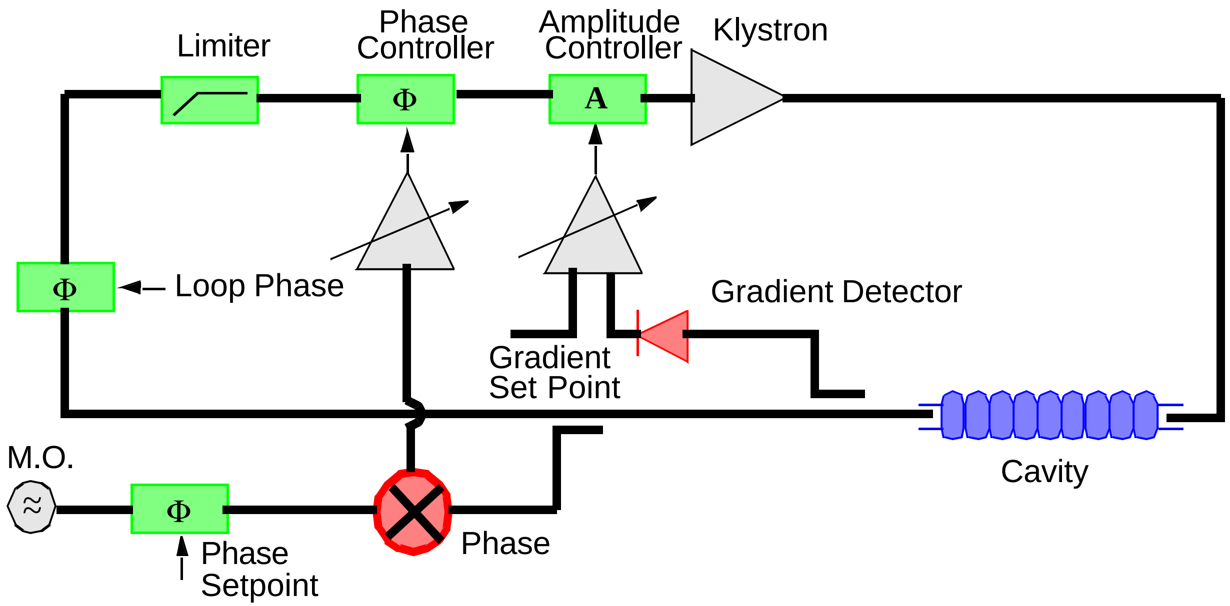
- Analog vs Digital Control Design

- Amplitude and Phase (A&P) vs
  In-phase and Quadrature (I/Q) detector and controller

Control Choices (2)

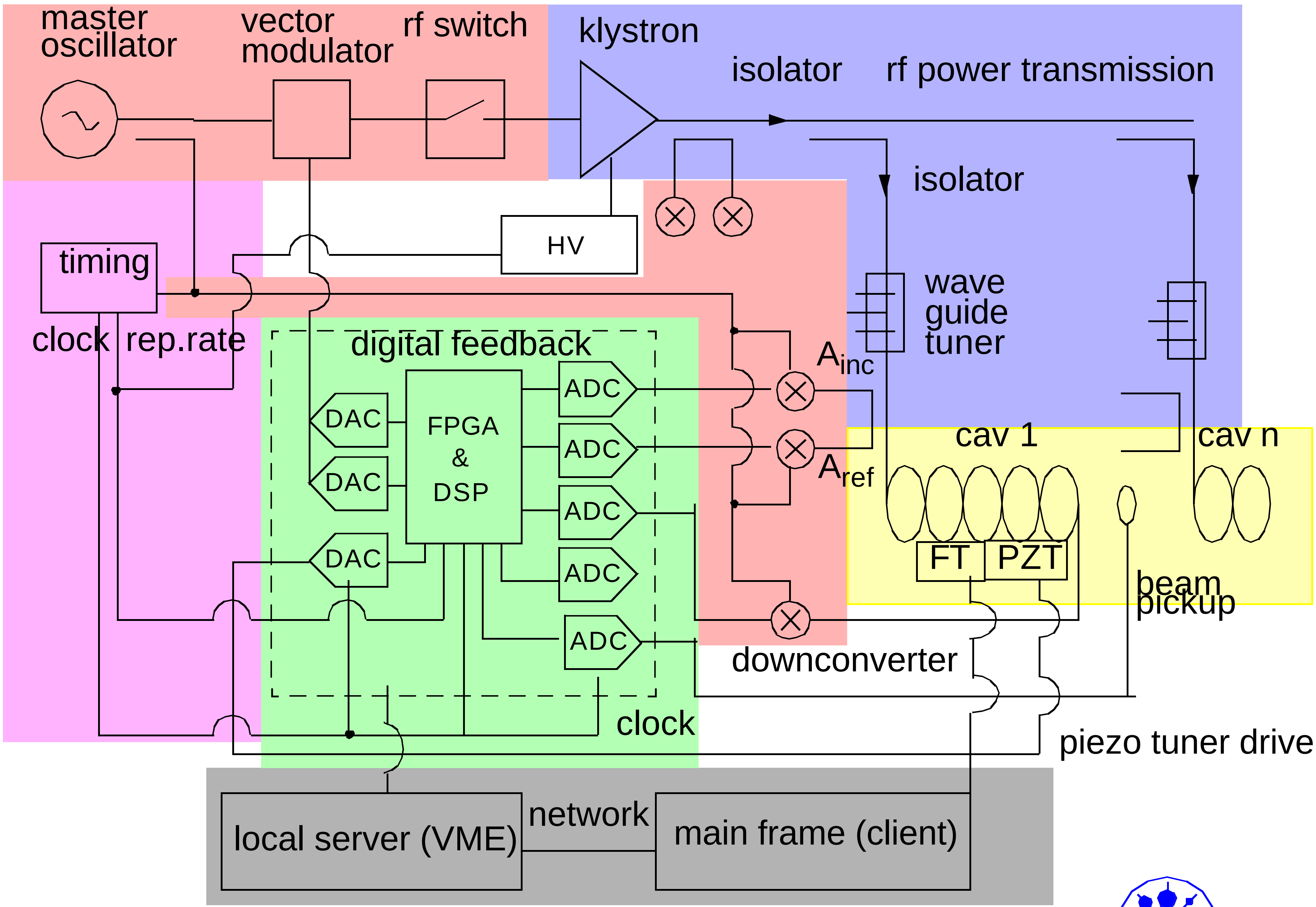


Generator Driven Resonator



Self Excited Loop

Architecture of digital RF Control



Why Vector-Sum Control

Benefit :

- Significant cost savings
- Maintenance reduced
- Less units to be controlled

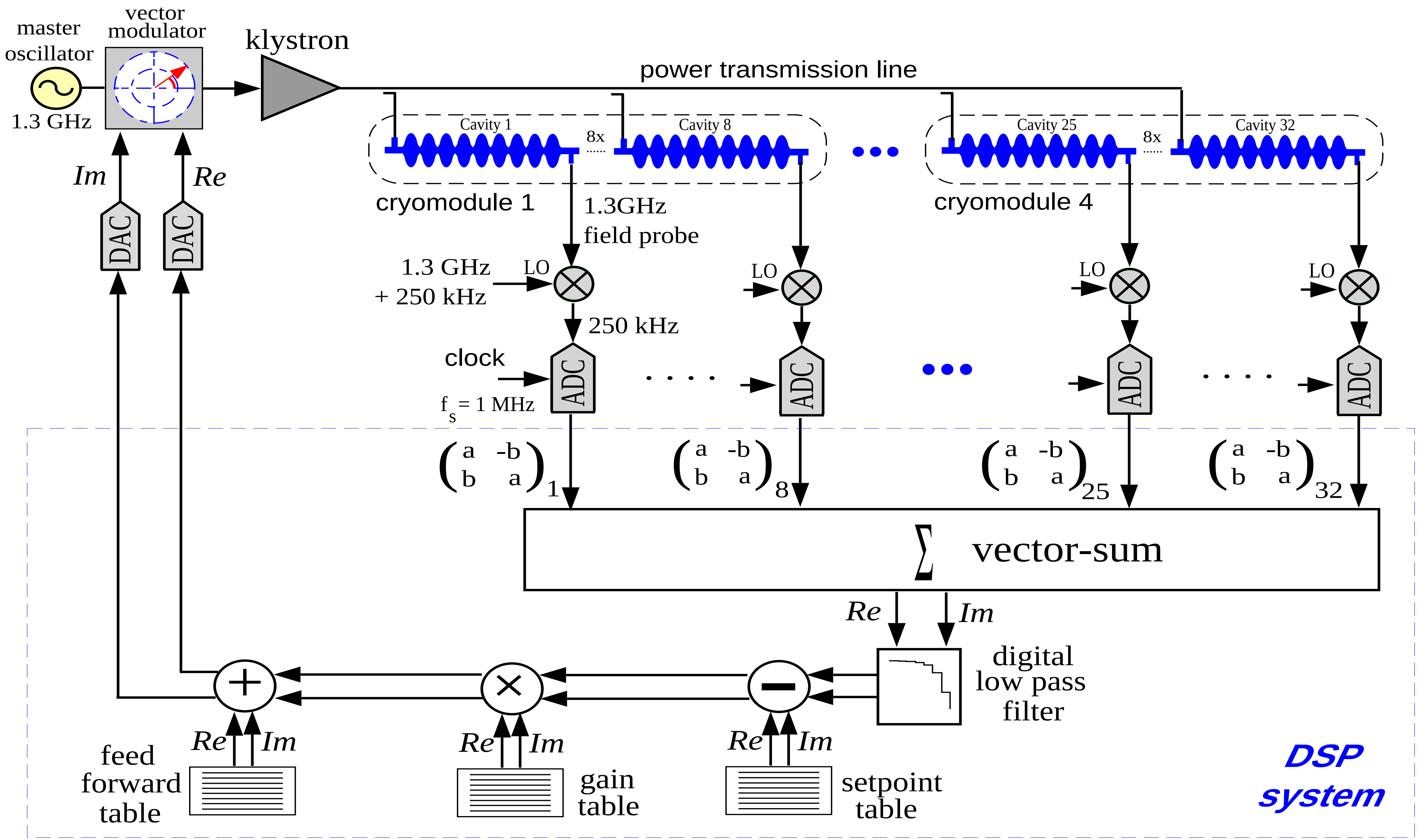
Disadvantage

- Calibration of vector-sum challenging
- Cannot operate each cavity at individual limit
- RF power distribution must be precise (power, phase)
- By-passing of individual cavities more difficult

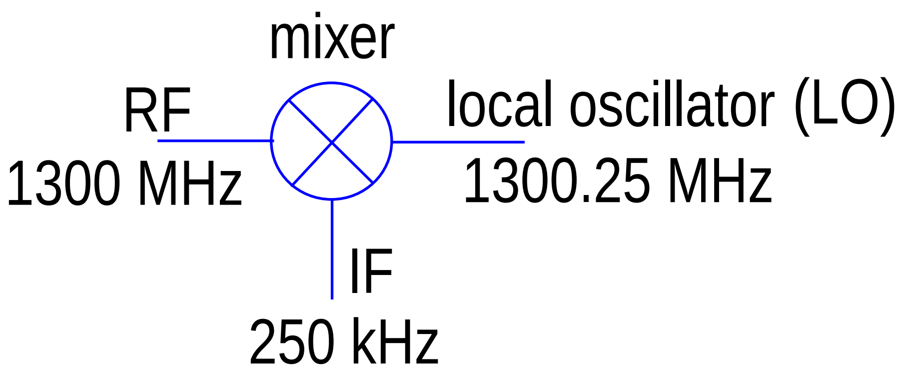
Why Digital RF Control

- Vector-sum calibration software programmable
- Time-varying setpoint during cavity filling
- Digital IQ detection for measurement of rf field vector and forward and reflected wave
- Robust & flexible feedback algorithms (optimal controller)
- (Adaptive) feedforward to compensate repetitive errors
- Need for automated operation such as fault recovery and changing beam energy
- High level applications (example: automated cavity tuning)
- Exception handling (example: recovery from cavity quench)

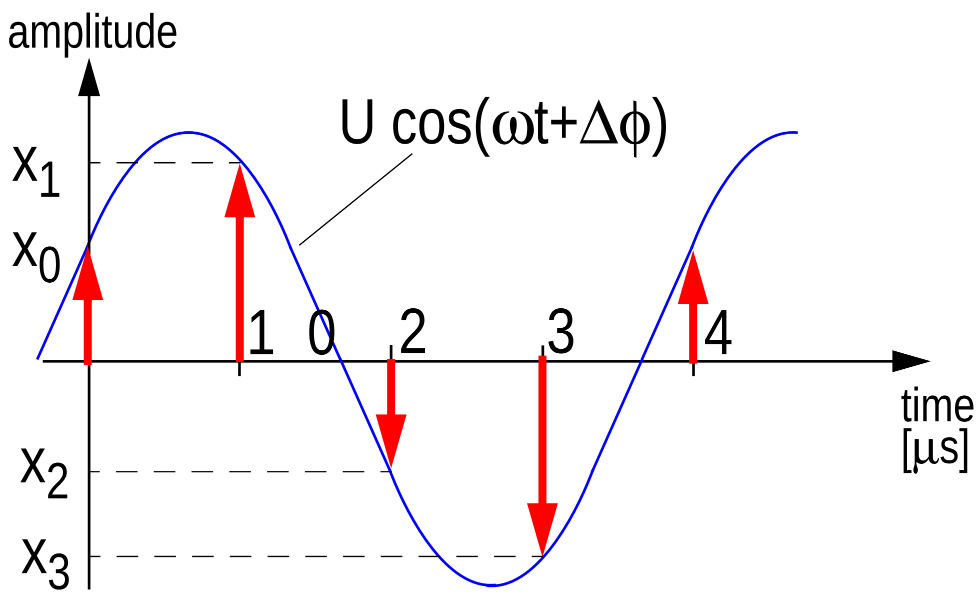
Digital Control at the TTF



Digital I/Q Detection

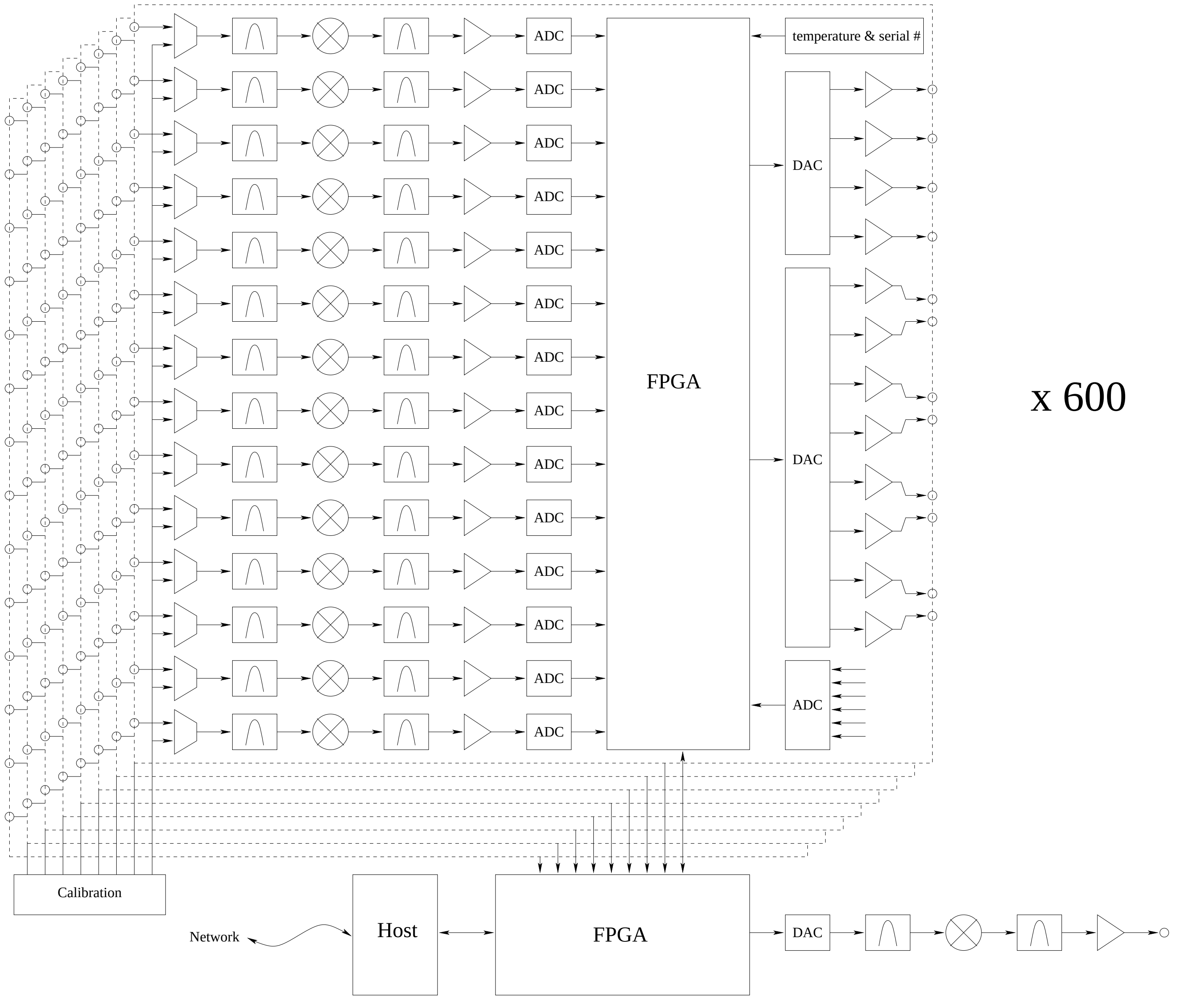


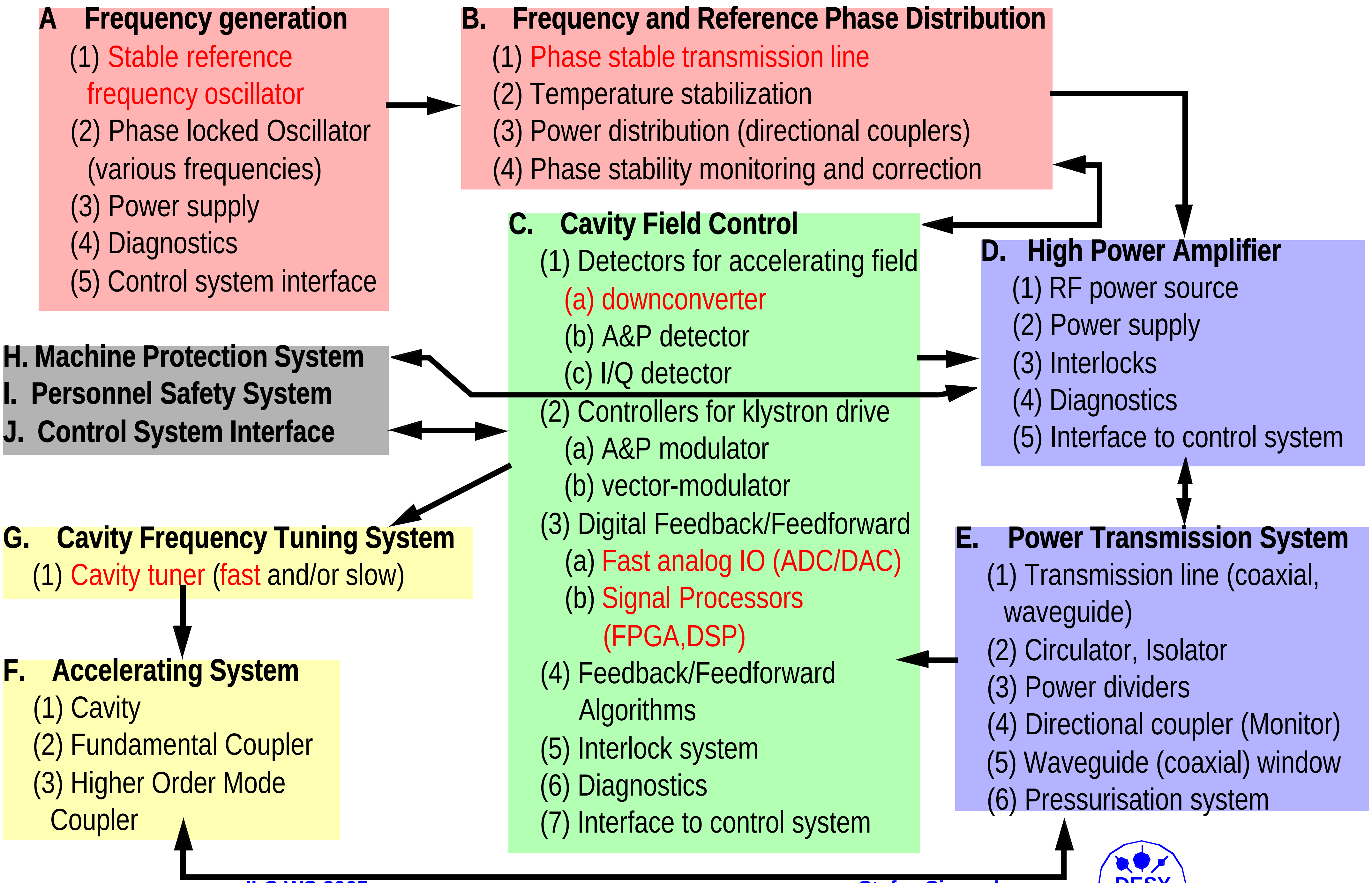
- downconversion of cavity field to IF frequency at 250 kHz
- complete phase and amplitude information of the accelerating field is preserved.



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

Familiar block diagram, scaled for ILC LLRF





Linac RF Subsystems

LLRF Control Algorithms

A. FIELD CONTROL ALGORITHMS

(1) Feedback
- (a) PID filter
- (b) Kalman filter
- (c) adaptive filters
- (d) optimal controller

(2) Feedforward
- (a) beam loading compensation

(3) Beam based feedbacks
- (a) rf phase feedback
- (b) beam energy feedback
- (c) bunch length feedback

(3) Klystron linearization

(4) Exception handling
- (a) quench detection and handling
- (b) error from beam loading

B. LLRF System Measurement Algorithms

(1) Loop phase rotation matrix

(2) Field calibration rotation matrix

(based on rf, beam based transients, and spectrometer)
- (a) gradient calibration
- (b) phase calibration

(3) Vector-sum calculation

(4) Meas. of incident phase (vector-sum !)

(5) Beam phase measurement

(6) forward/reflected power calibration
- (a) correct for directivity of couplers

(7) Cavity detuning
- (a) average during pulse
- (b) detuning curve during pulse

(8) Loaded Q

LLRF Control Algorithms

D. High level procedures

(1) Adaptive feedforward
- (a) response matrix or T.F. based
- (c) robustness
- (d) different beam modes

(1) System identification
- (a) beam phase and current
- (b) loaded Q
- (c) incident phase

(3) Waveguide tuner control

(4) Momentum management system

(5) Field control parameters optimization

(6) Operation at different gradients

(7) Operation at the performance limit
- (a) maximize availability
- (b) maximize field stability

(8) Hardware diagnostics

(9) On-line rf system modelling

(10) Automated fault recovery

(11) Finite state machine

C. Cavity Resonance Control

(1) Slow tuner
- (a) maintain average resonance frequency (pre-detuning)
- (b) maximize tuner lifetime

(2) Fast tuner (ex. piezoelectric tuner)
- (a) dynamic Lorentz force compensation
- (b) microphonics control
- (c) minimize rf power required for control

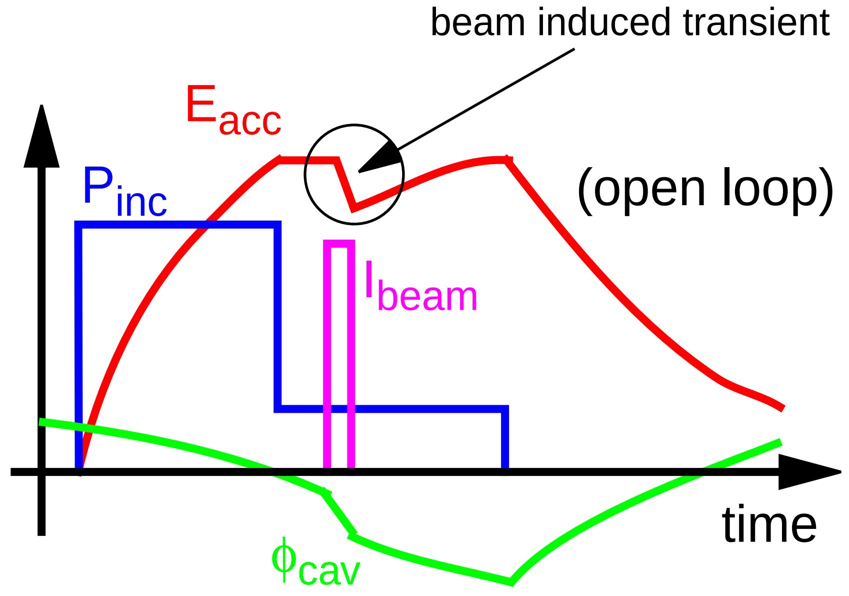
E. Other

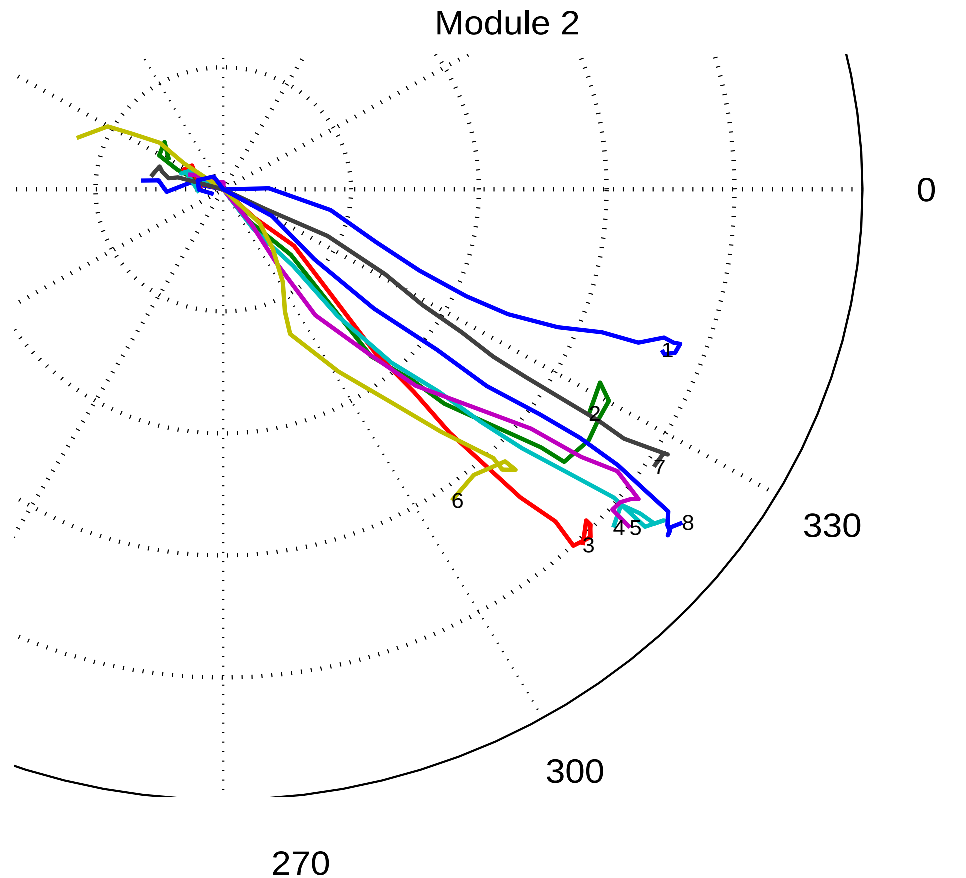
(1) RF System Database
- (a) calibration coefficients
- (b) subsystem characteristics

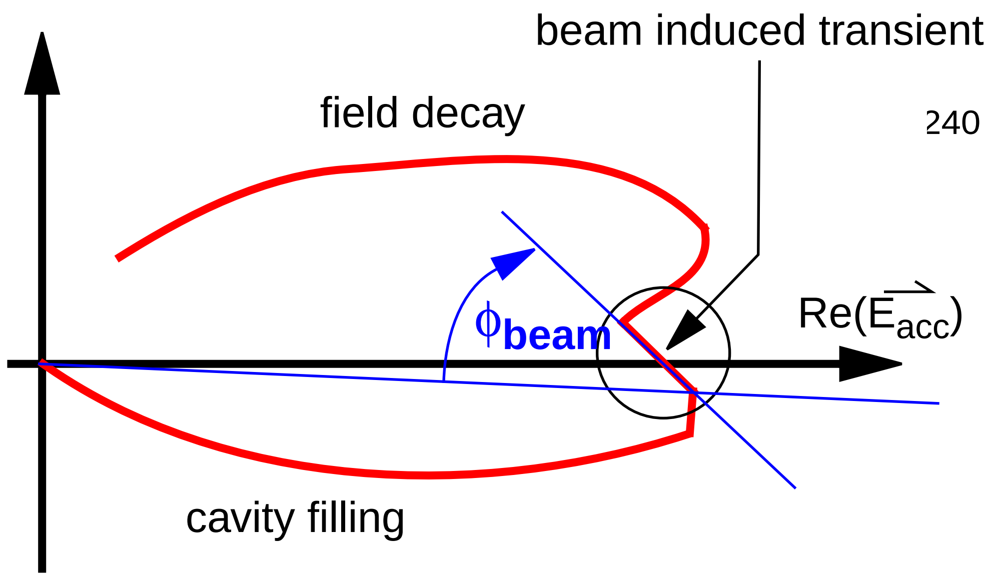
(2) Alarm and warning generation

(3) Control System functions

Beam Transient based Phase and Gradient Calibration





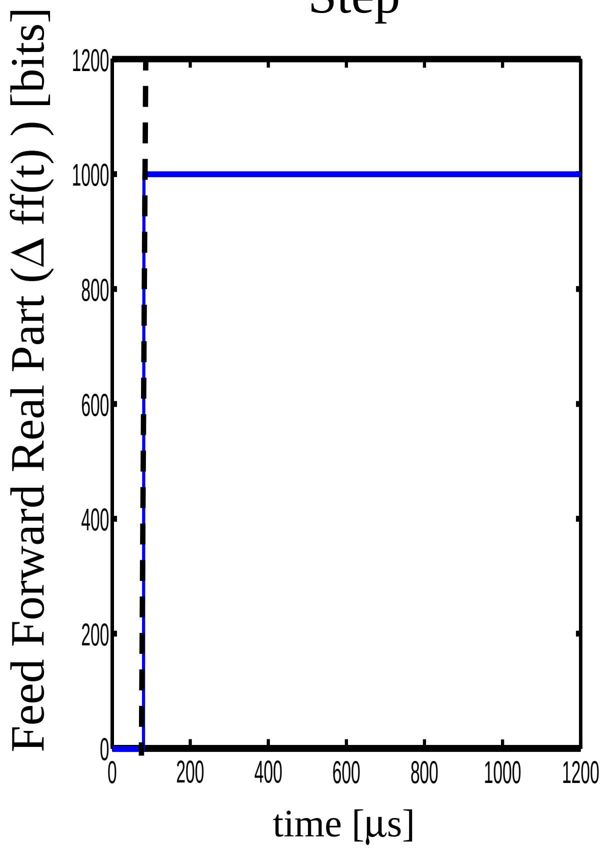


for $\Delta t << \tau_{cav}$:

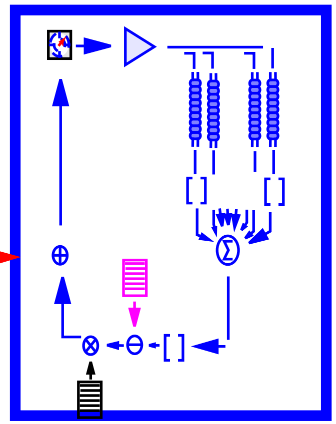
$$\Delta V_{ind} = I \cdot \Delta t \cdot \left(\frac{r}{Q}\right) \cdot \pi \cdot f$$

Adaptive Feedforward

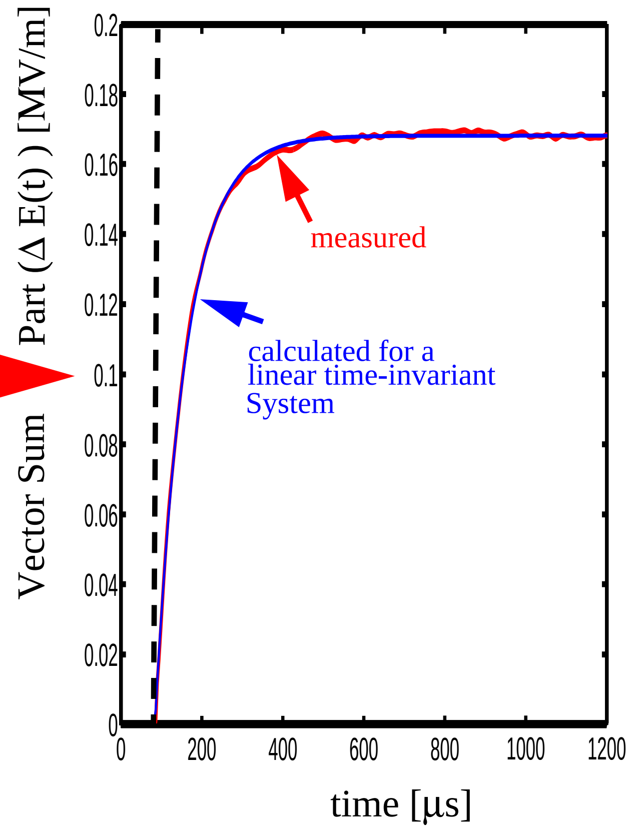
Step



Closed Loop System



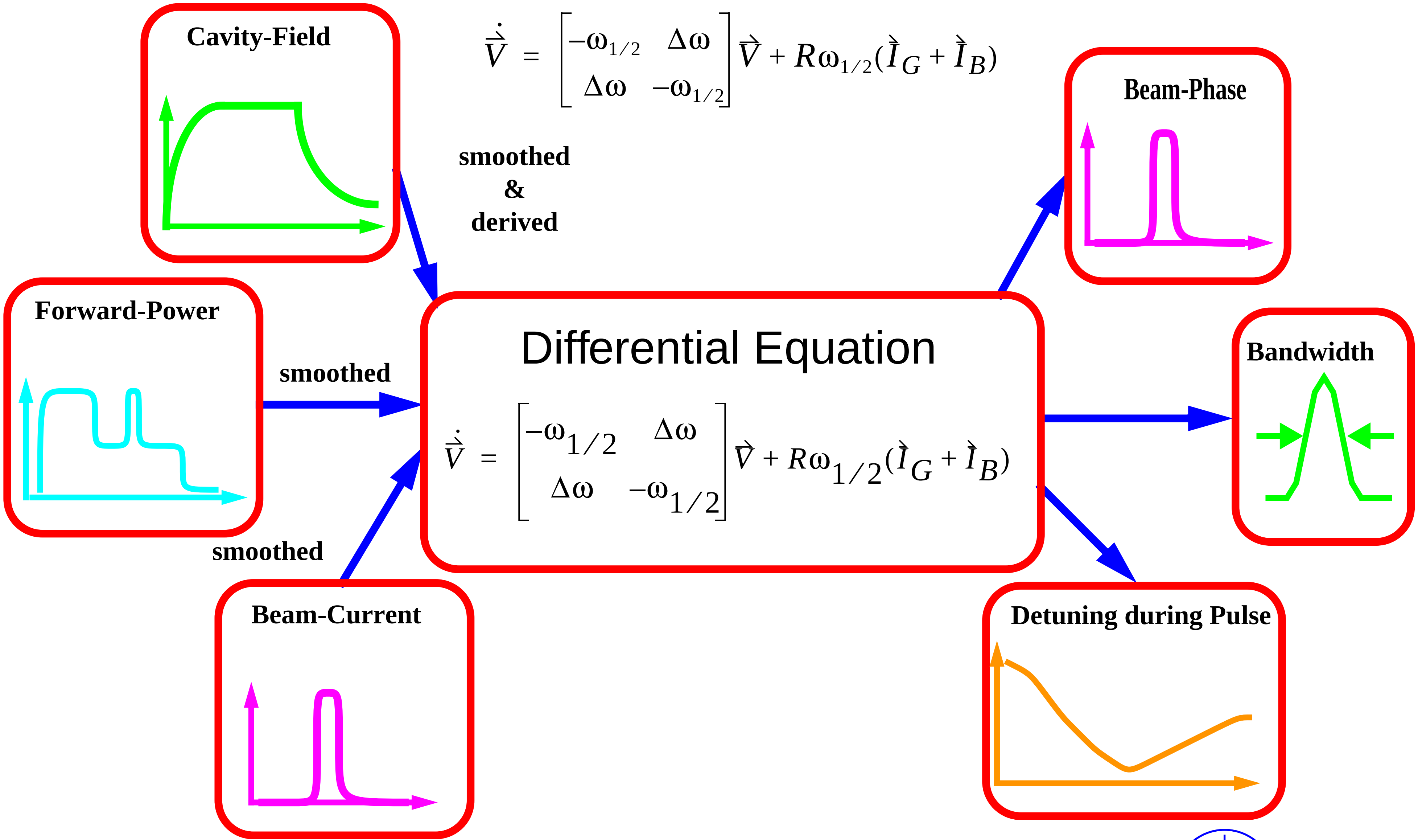
Step Response



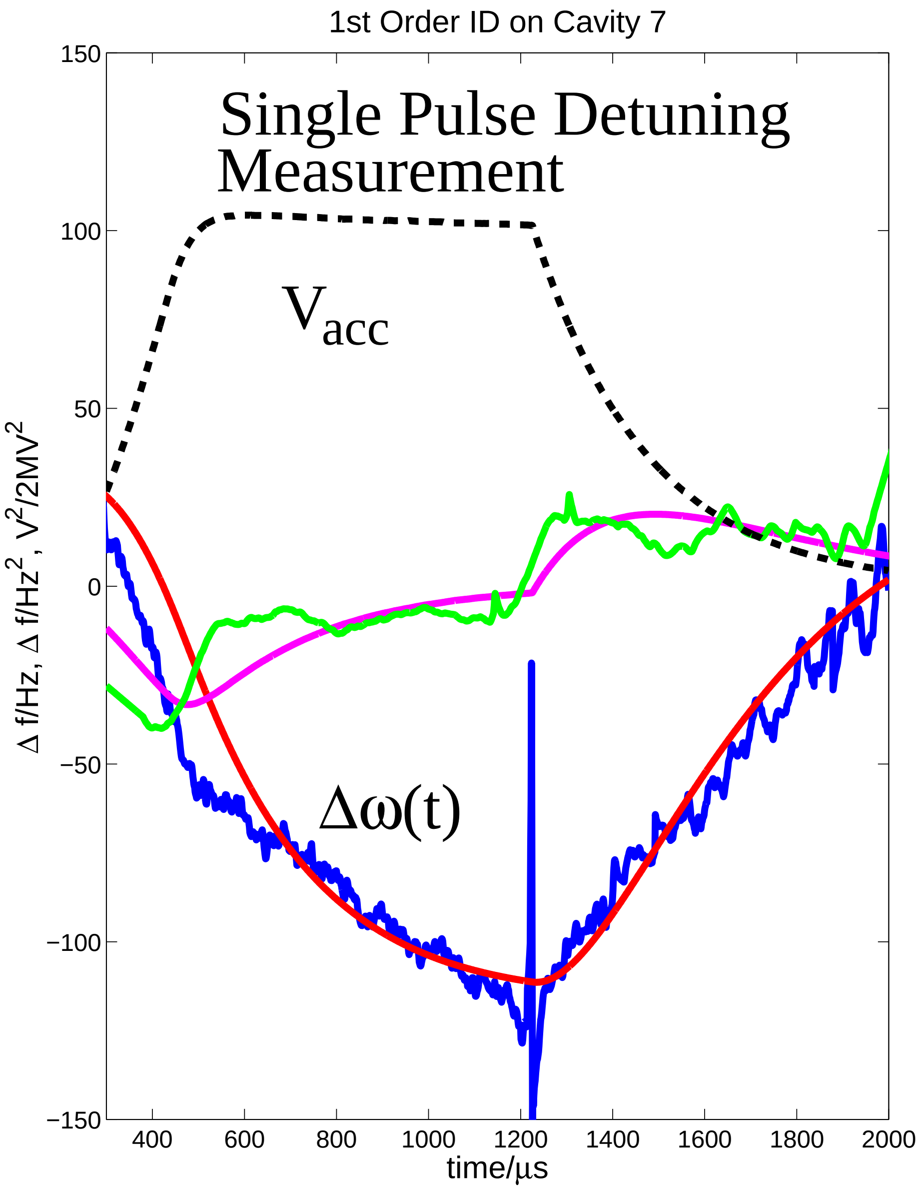
$$\begin{bmatrix} \Delta E(\tau_1) \\ \Delta E(\tau_2) \\ \dots \\ \Delta E(\tau_n) \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & \dots & T_{1n} \\ T_{21} & T_{22} & \dots & T_{2n} \\ \dots & \dots & \dots & \dots \\ T_{n1} & T_{n2} & \dots & T_{nn} \end{bmatrix} \begin{bmatrix} \Delta ff_1 \\ \Delta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

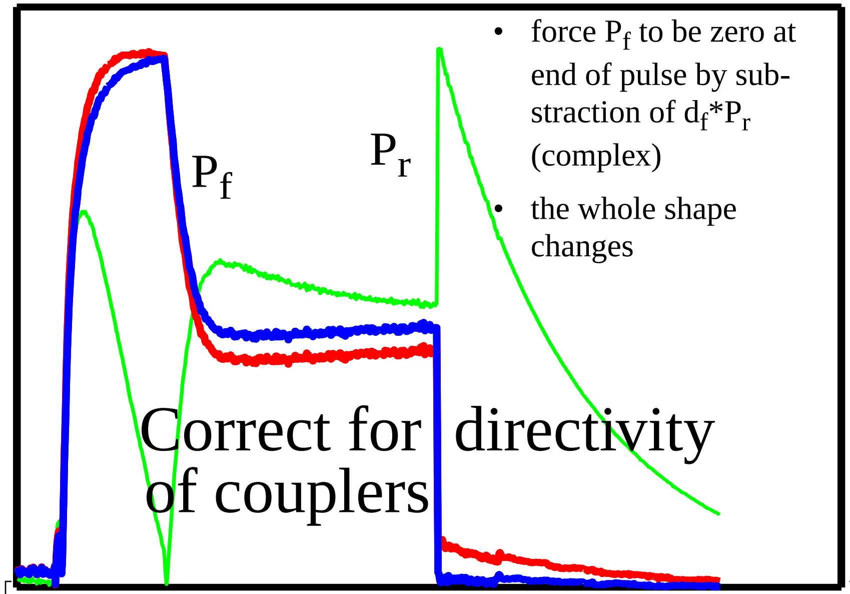
$$\Delta ff(t) = \sum_j \Delta ff_j \Theta(t - t_j).$$

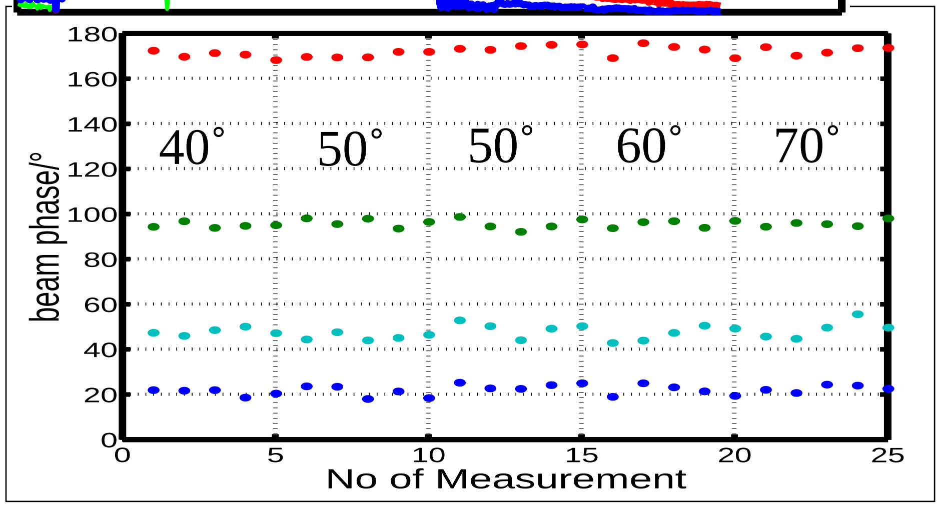
System Identification (1)



System Identification (2)



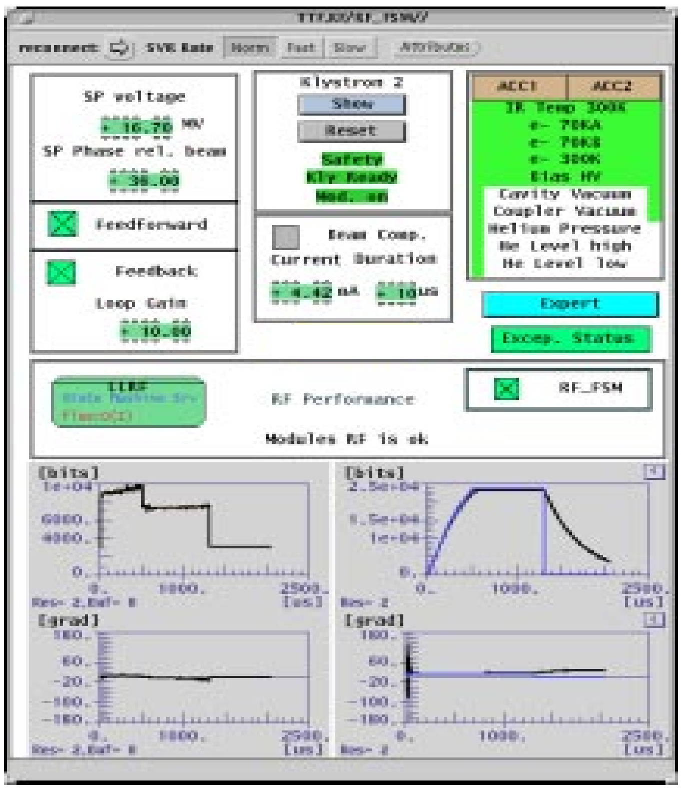


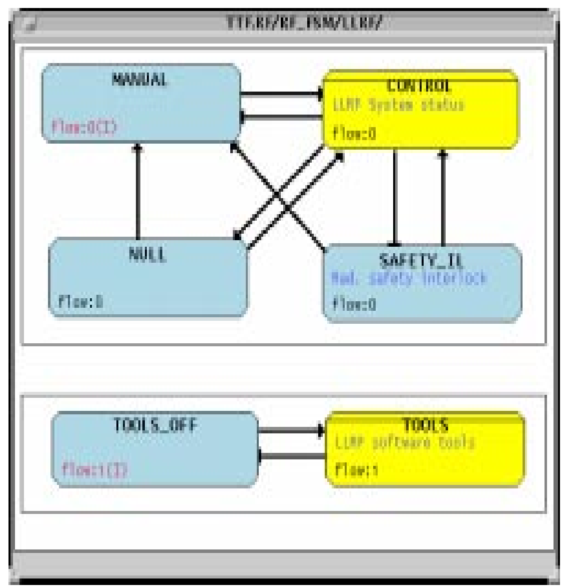


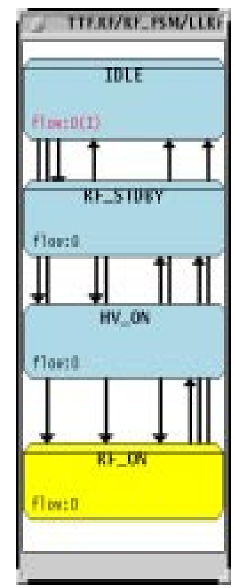
Beam phase of 4 cavities for different phase of V_{acc}

Automated Operation by Finite State Machine

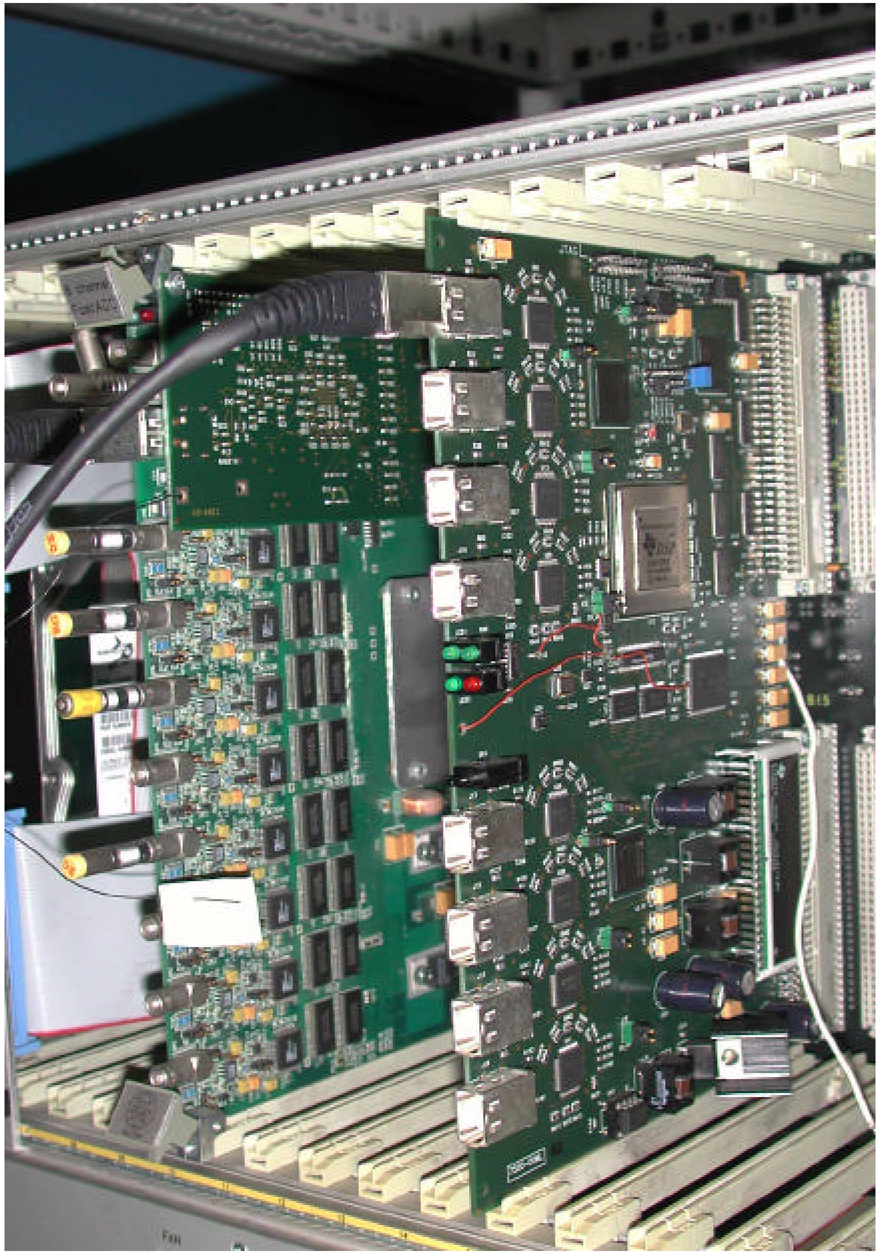
- High degree automation of accelerator operation
- Reduce workload of operators
- Maximize availability of accelerator



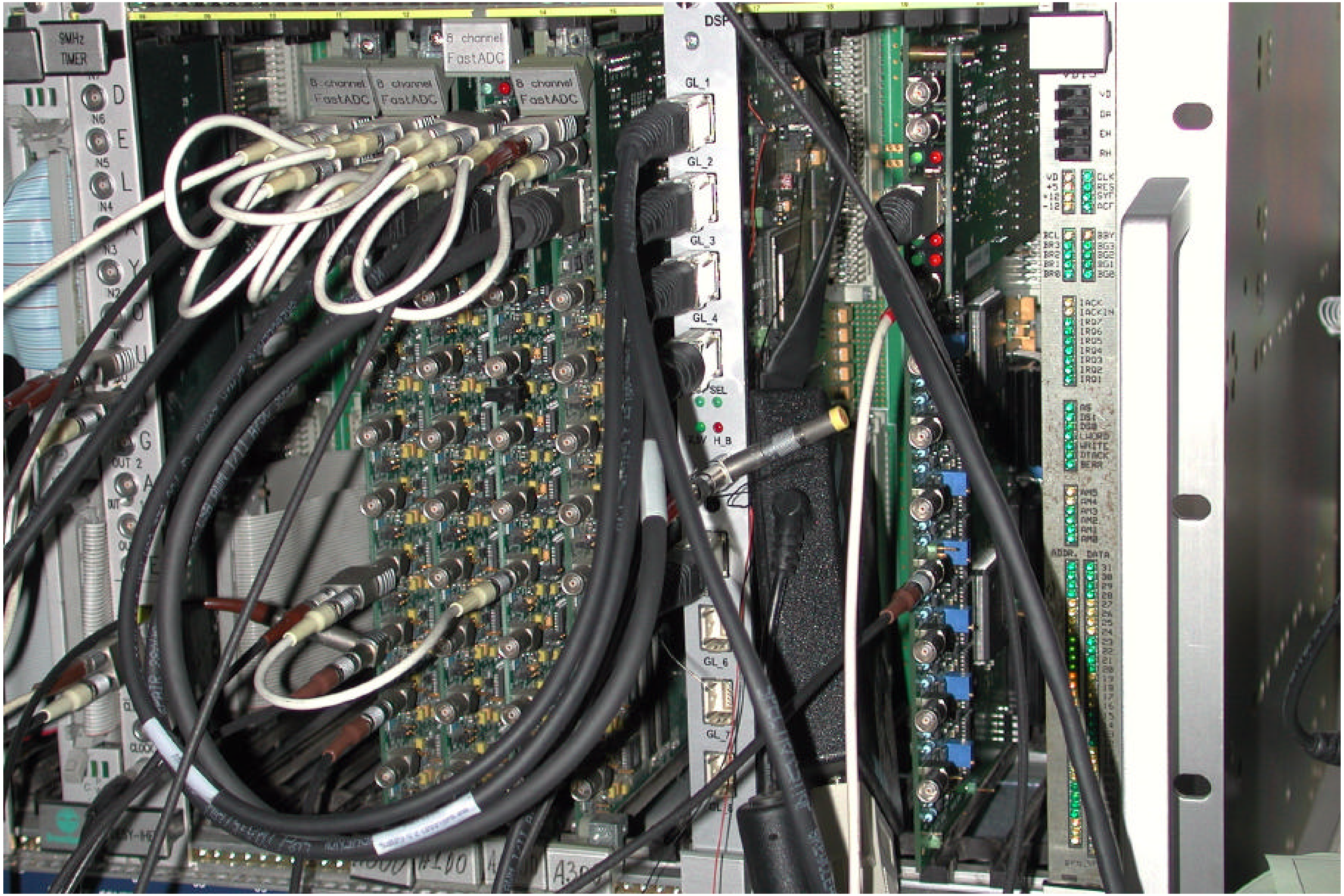




C67 DSP board

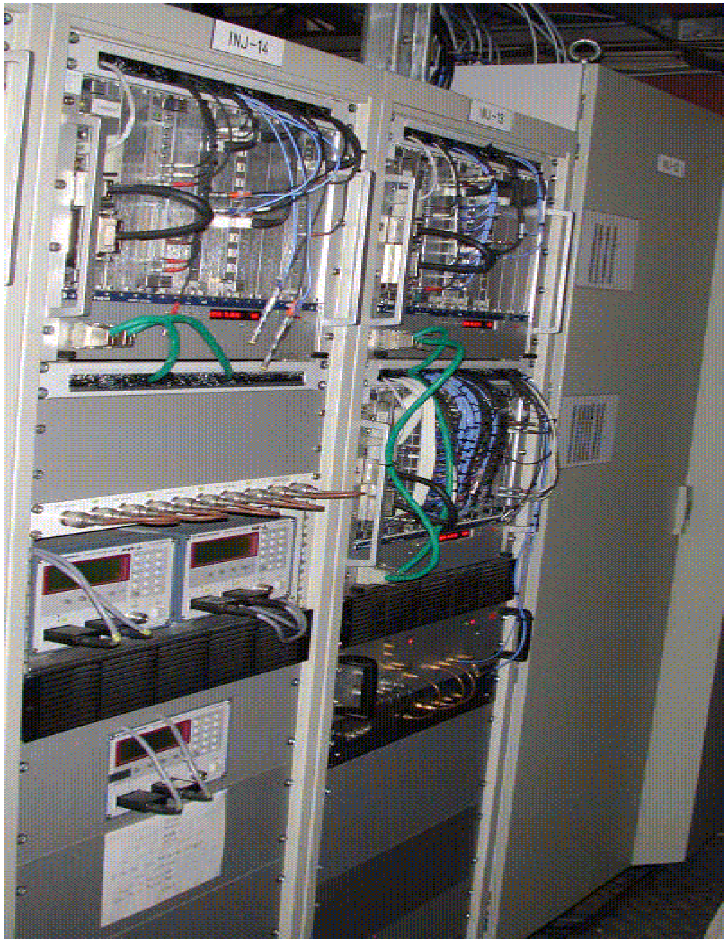


C67 DSP board

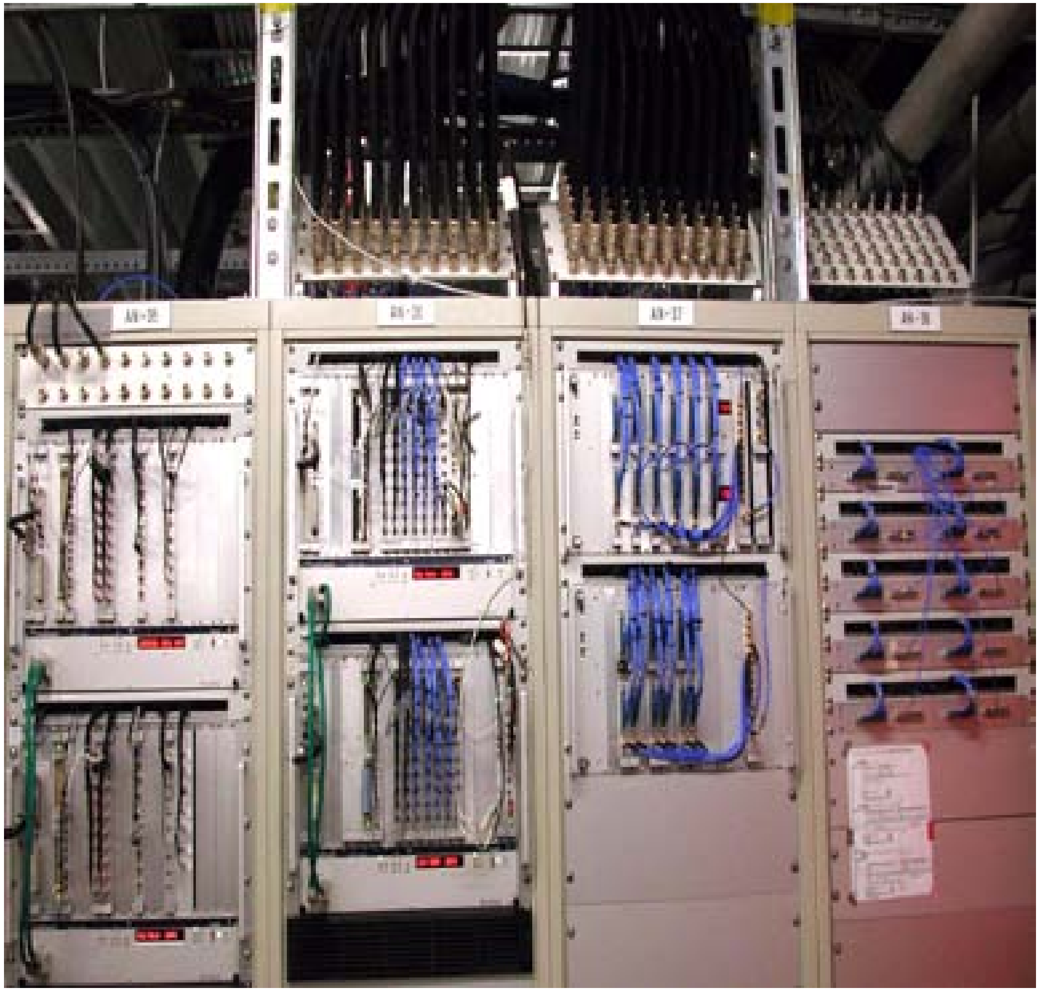


Digital Feedback Hardware

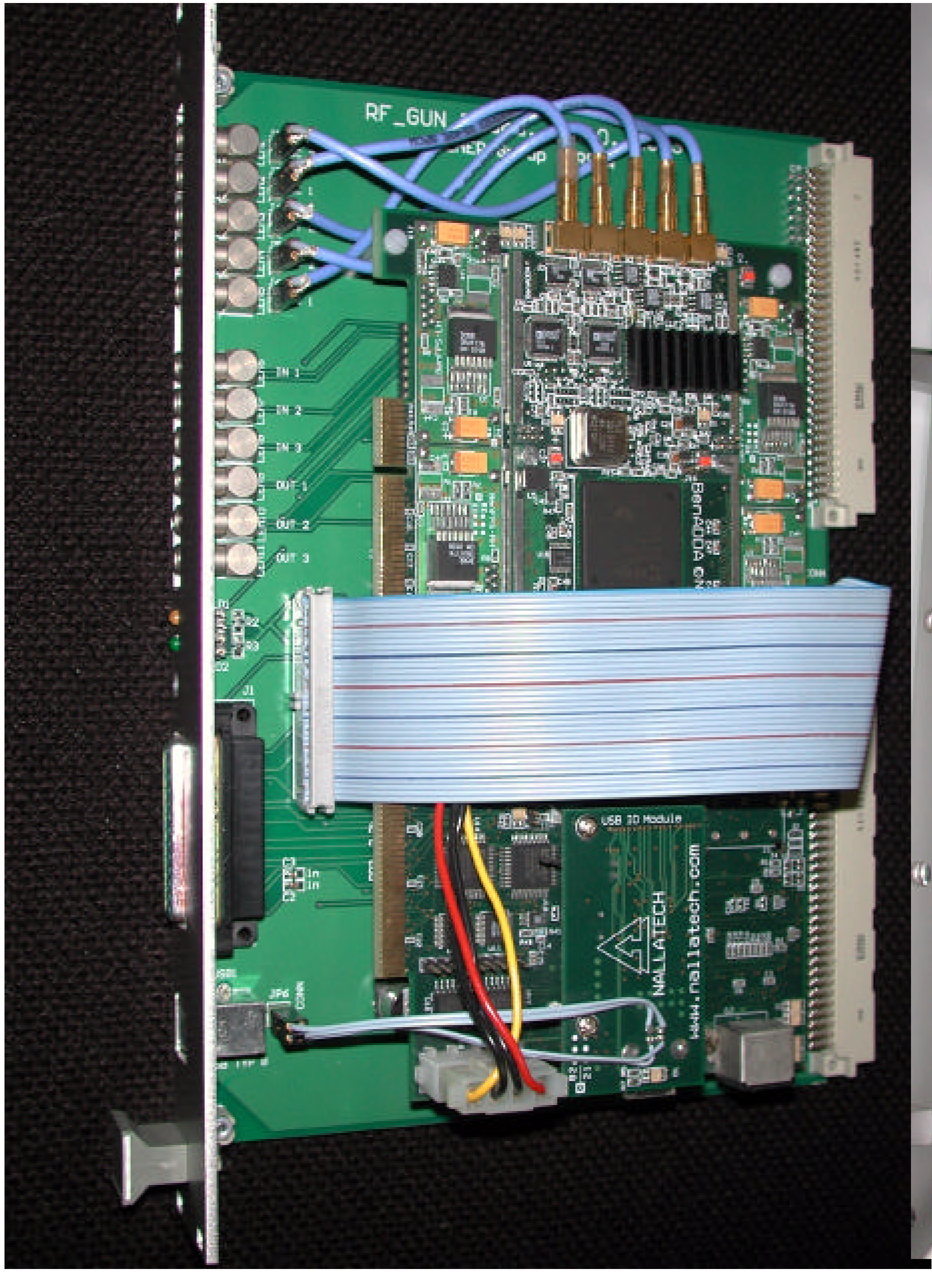
Gun and ACC1

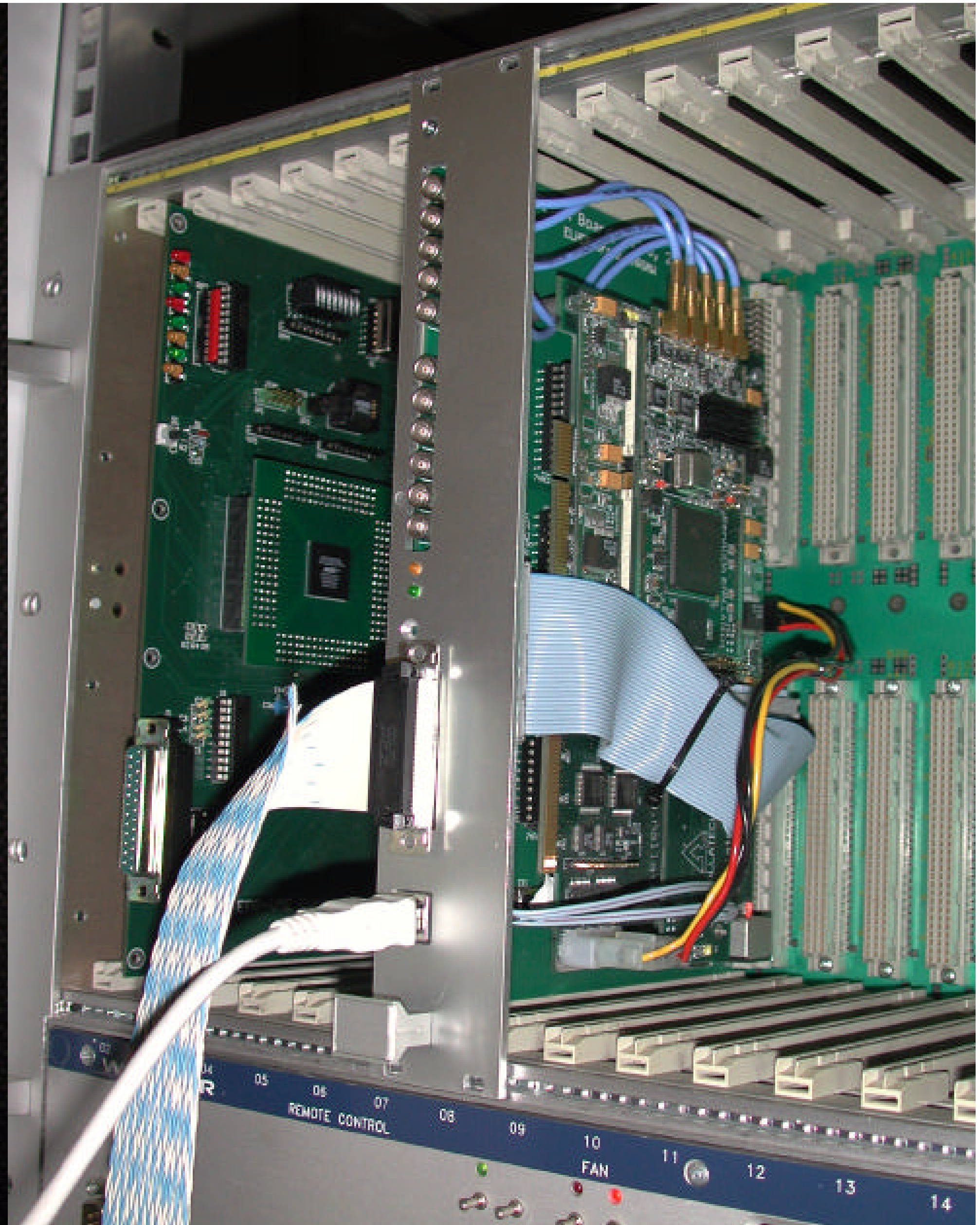


ACC2, ACC3, ACC4 & ACC5

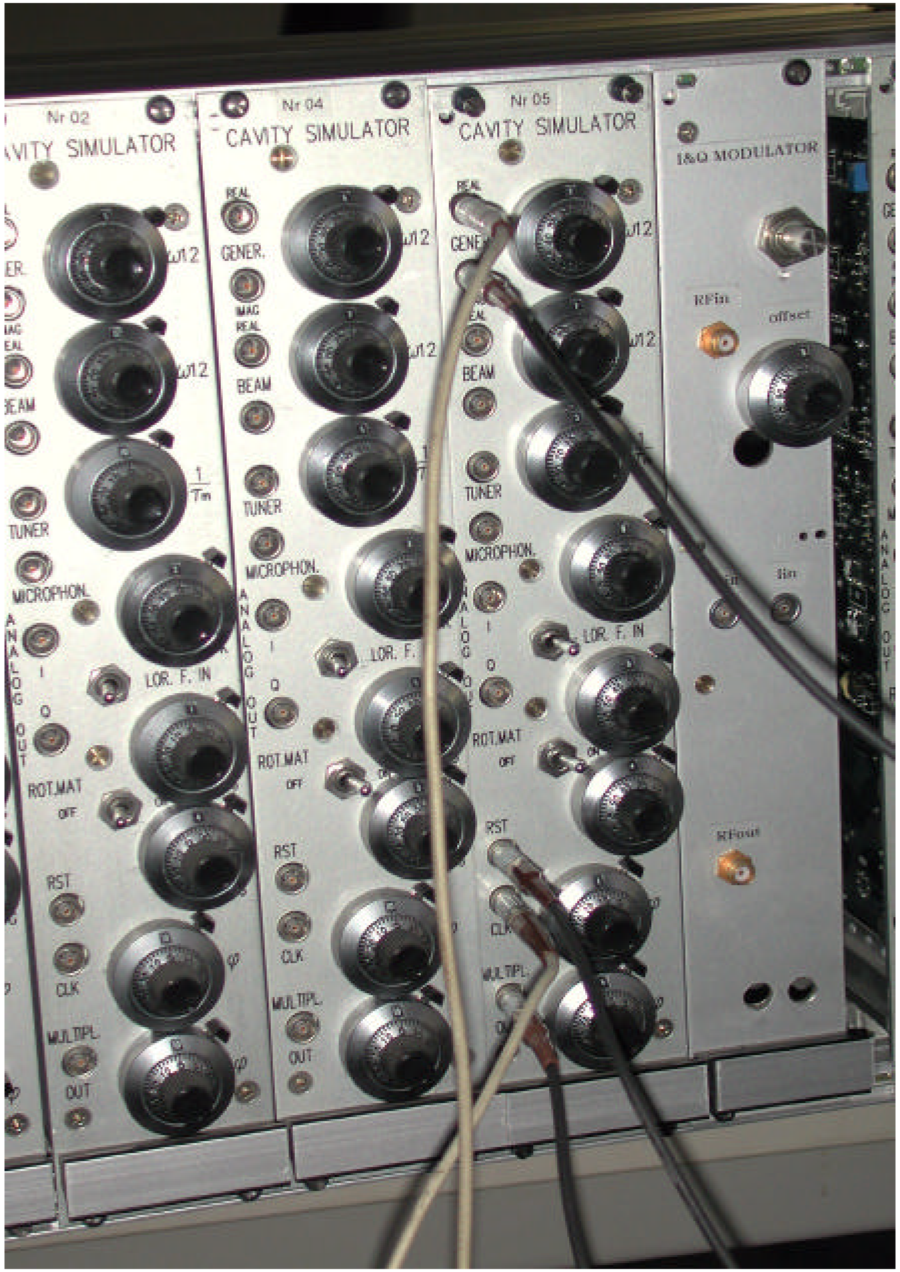


FPGA based RF Gun Controller

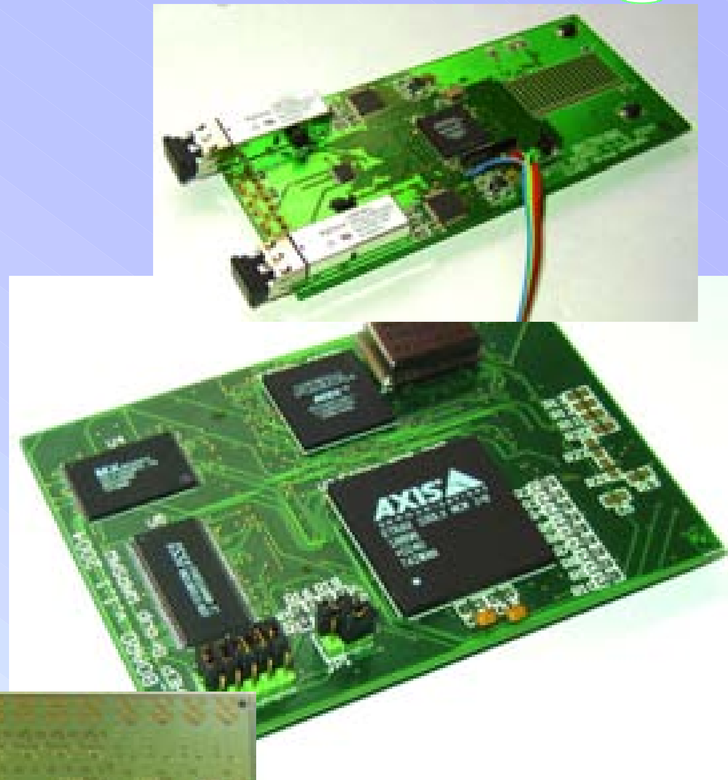




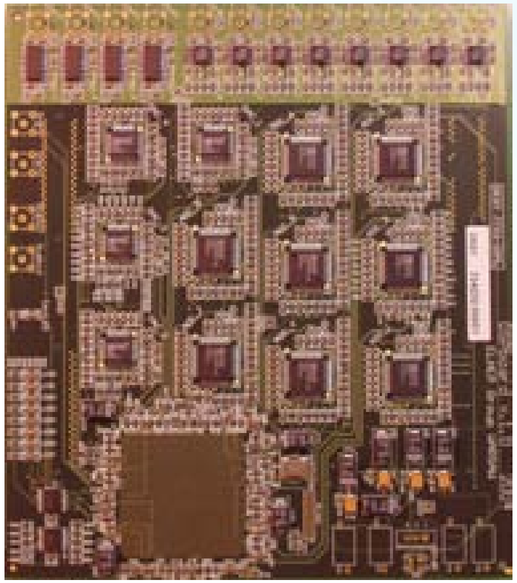
Cavity Simulator

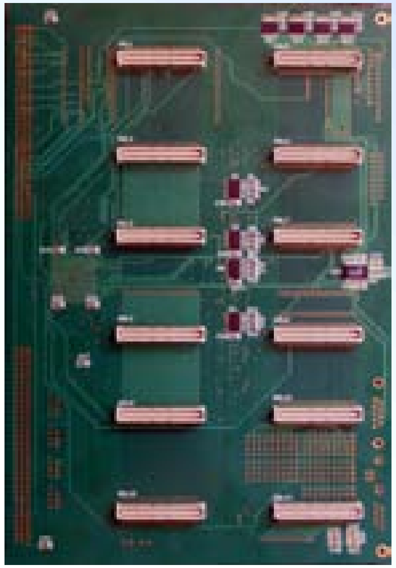


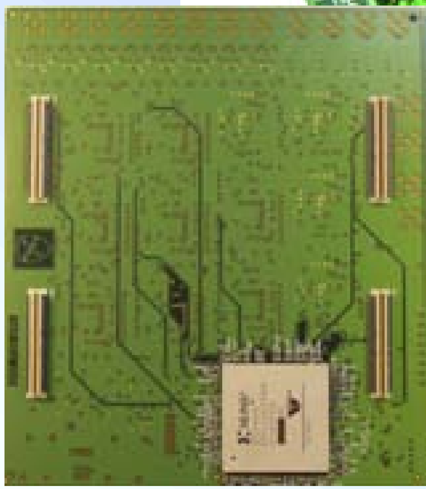
Third Generation RF Control Hardware



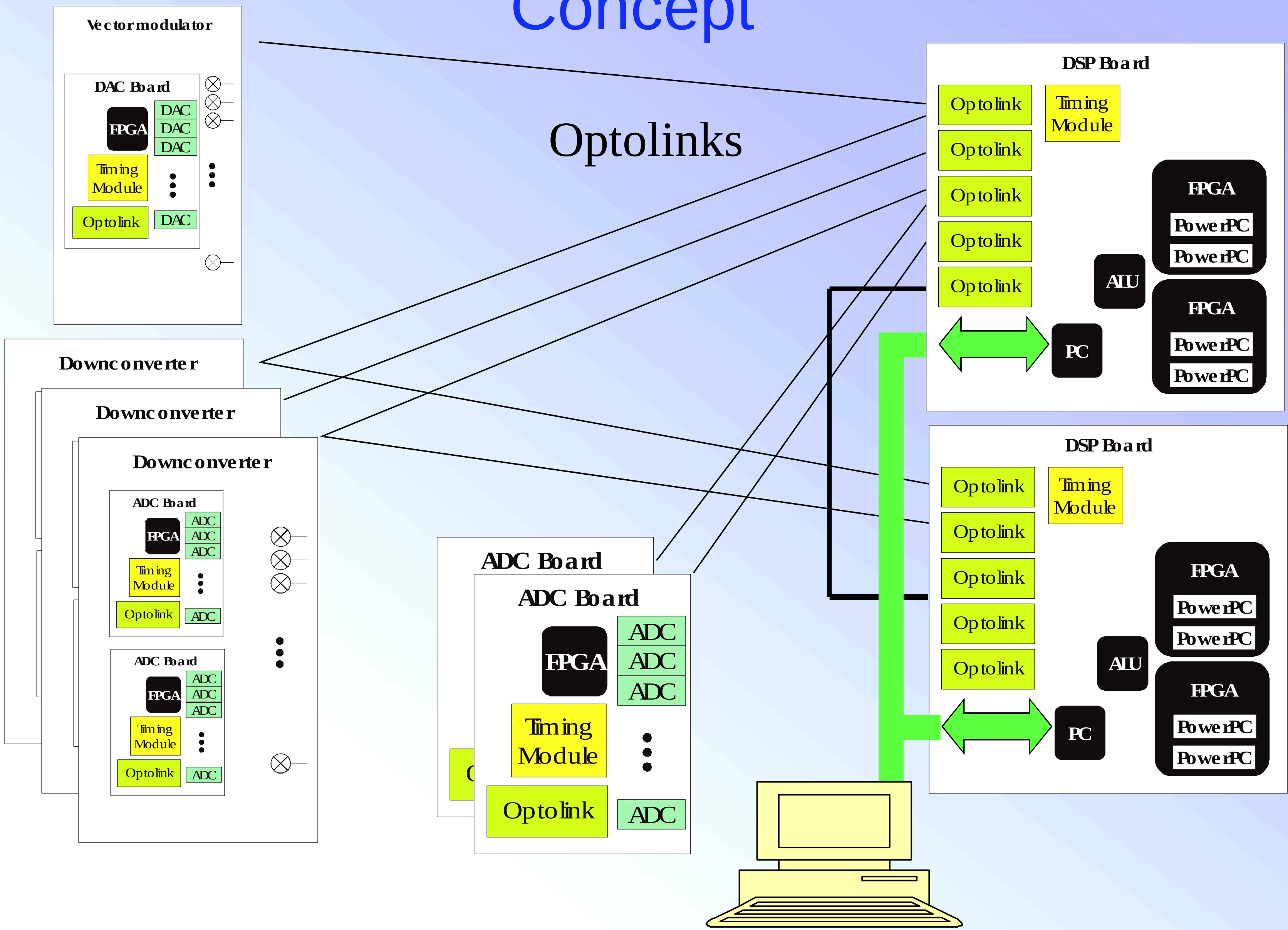
- 8 ADCs 14 bits, 80 MHz
- 4 DACs, 14 bits, 125 MHz
- DSP Board – Virtex2 XC2V4000
- Optolink – 3.125 GHz







Third Generation RF Control Concept



Multichannel Downconverter

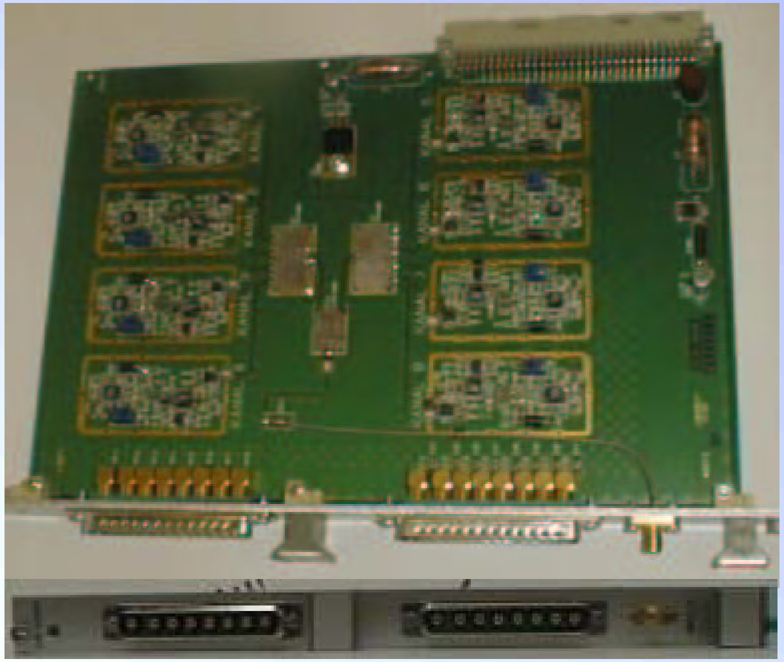
Meeting the high field stability requirements demands for new, noise-reduced, highly linear downconverters.

New downconverters are already installed in VUV-FEL and undergo intensive testing.

Picture of 3rd generation downconverter.

- 8 in/output channels, 1 LO input
- Linearity <-50dB
- Crosstalk between channels <-50dB
- LO leakage <-50dB @ 1.3GHz
- LO stability –15dB - –5dB

Design and assembly at DESY, layouting by external company



RF Gun Control

Requirements:

- Accelerating gradient: 40 MV/m
- Repetition rate: 1-10 Hz
- rf pulse length: 100-900 µs
- Amplitude stability: ± 0.25%
- Phase stability: ± 2°

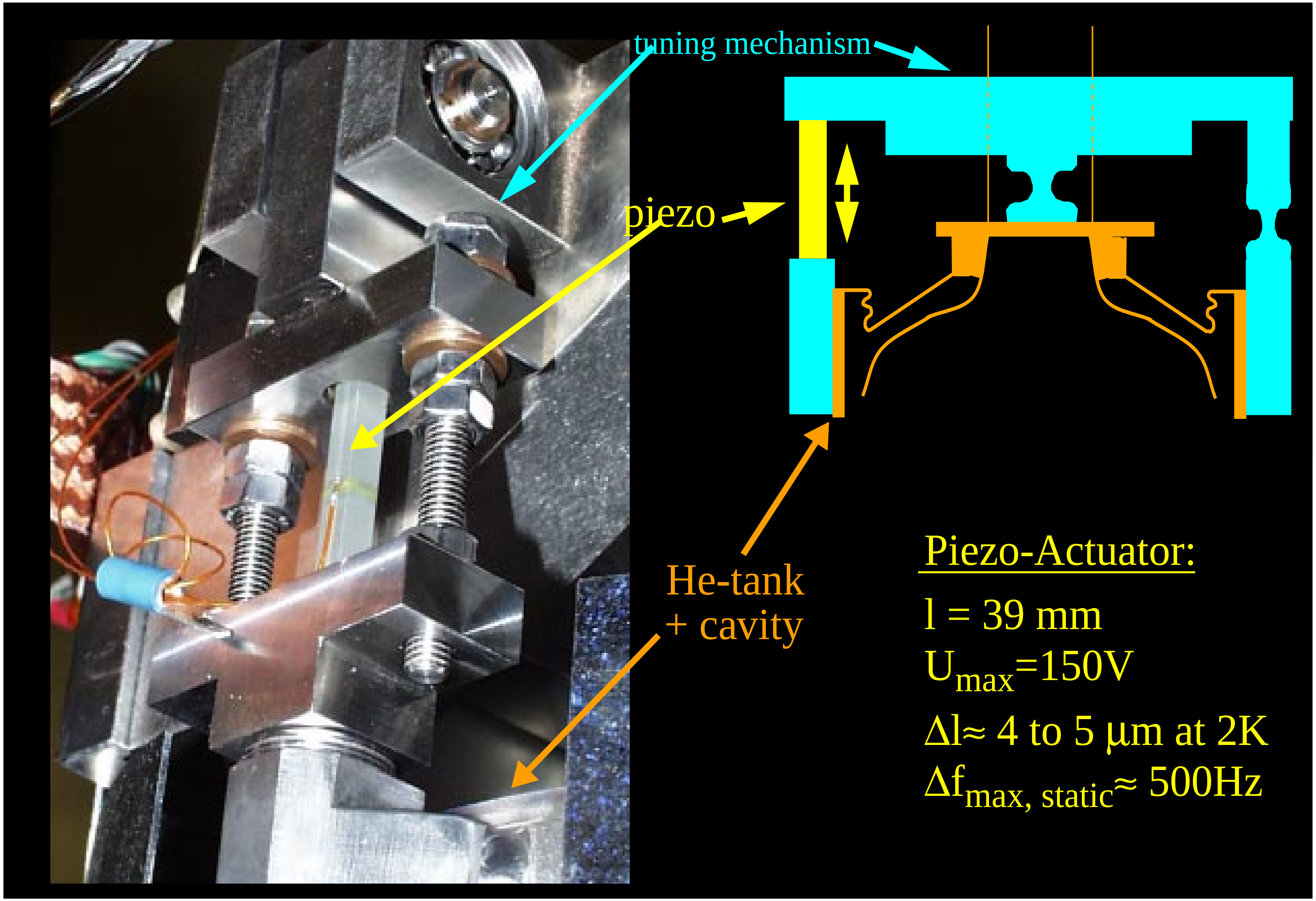
Difficulties:

- No probe in the gun
- Low time constant of the cavity
- High precision needed

Solutions:

- Use forward and reflected power
- Precise IQ detectors for field control
- Fast logarithmic detectors with big dynamic range for measurement of decaying field

Active Compensation of Lorentz Force Detuning (1)



Piezo-Actuator:

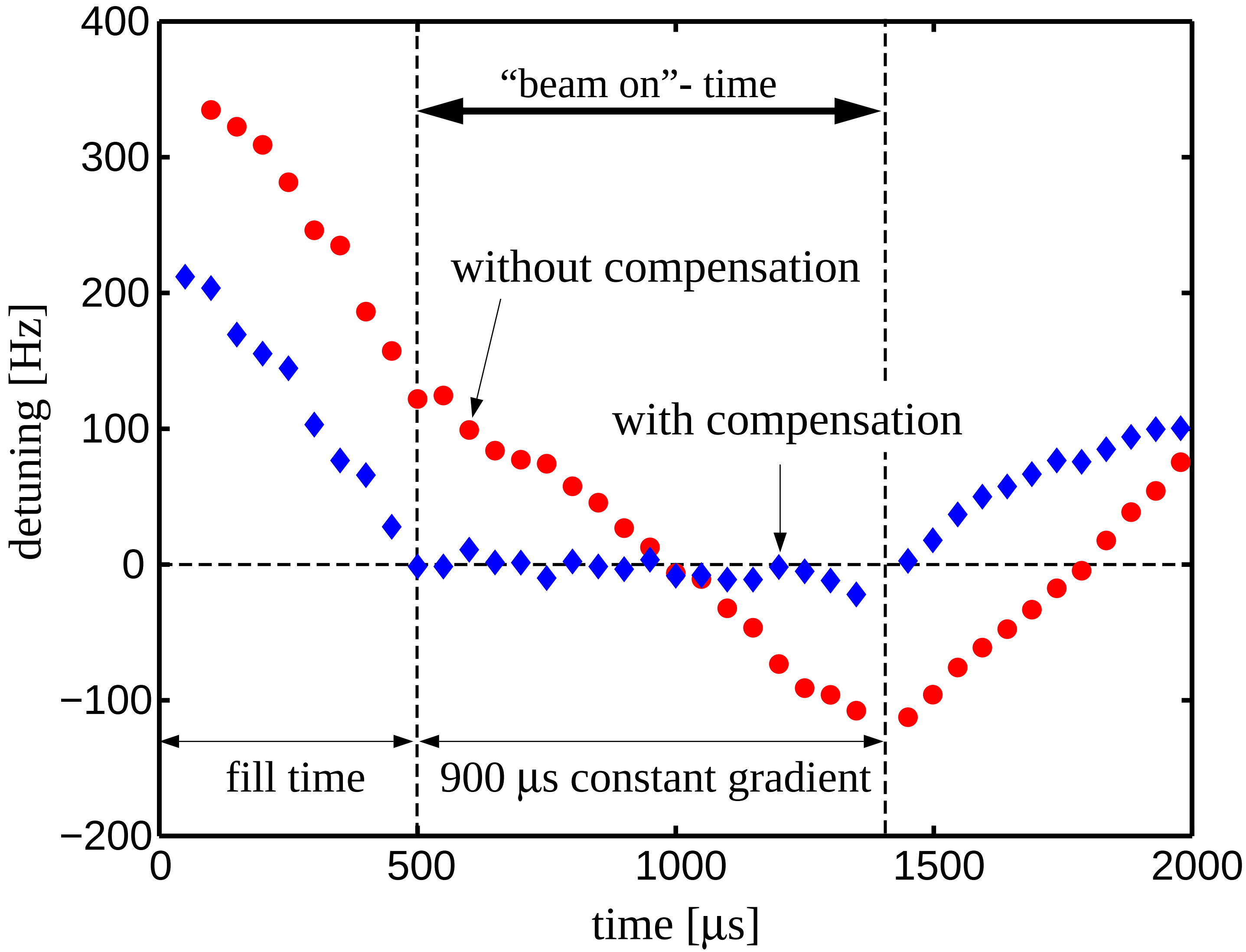
l = 39 mm

U_{max}=150V

$\Delta l \approx$ 4 to 5 µm at 2K

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

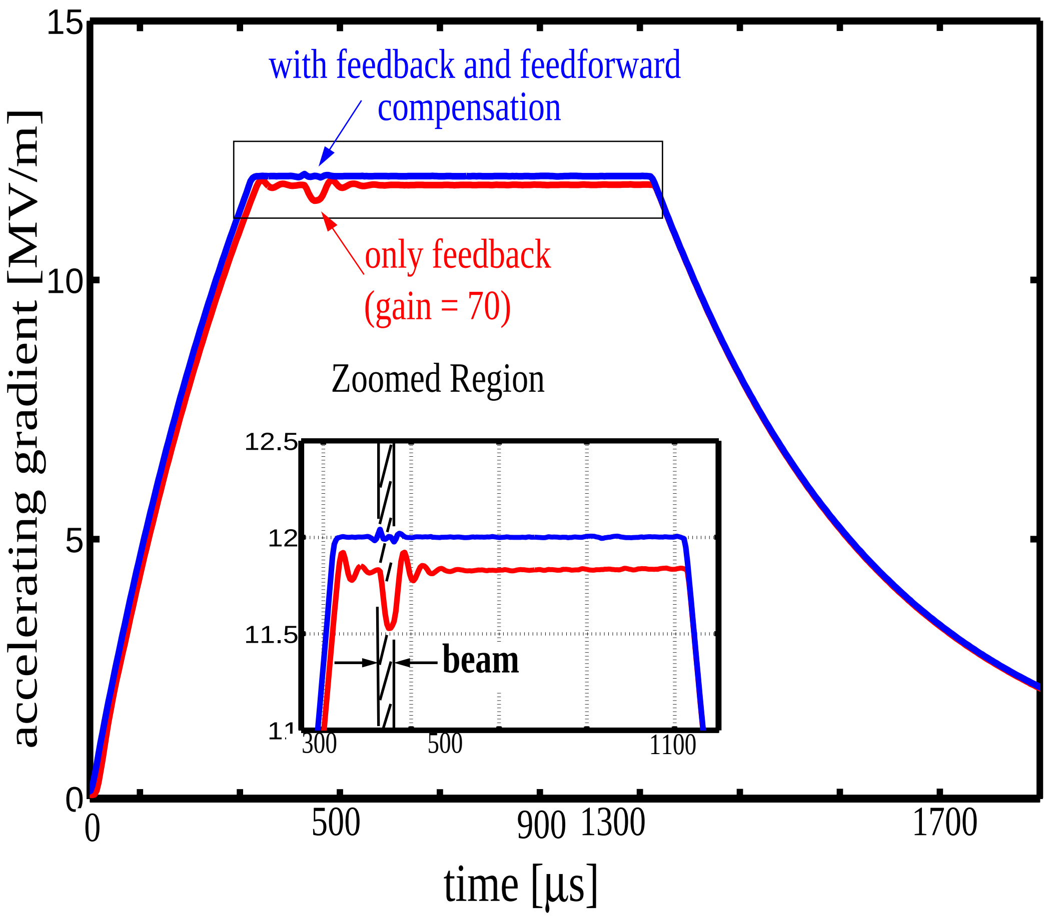
Active Compensation of Lorentz Force Detuning (2)



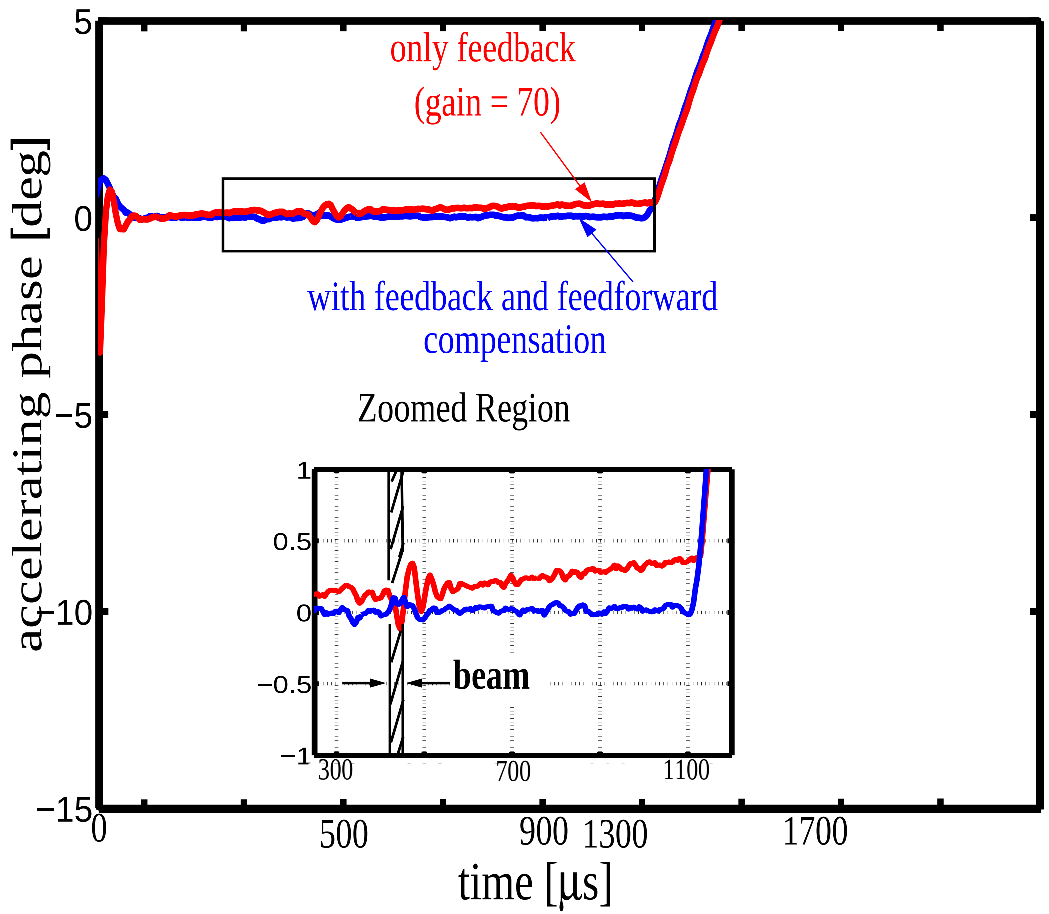
9-cell cavity operated at 23.5 MV/m

Lorentz force compensated with fast piezoelectric tuner

Performance at TTF (1)

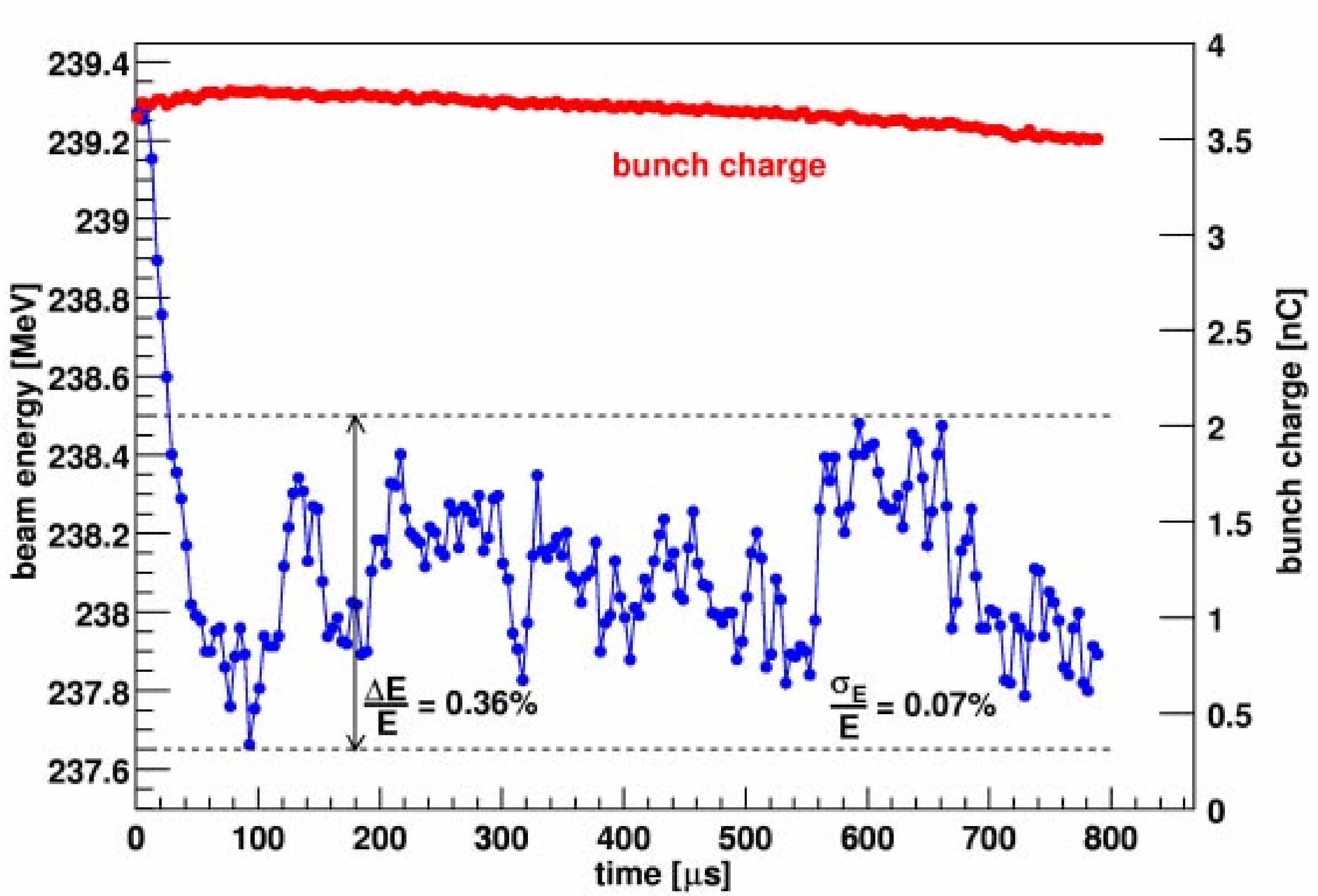


Amplitude



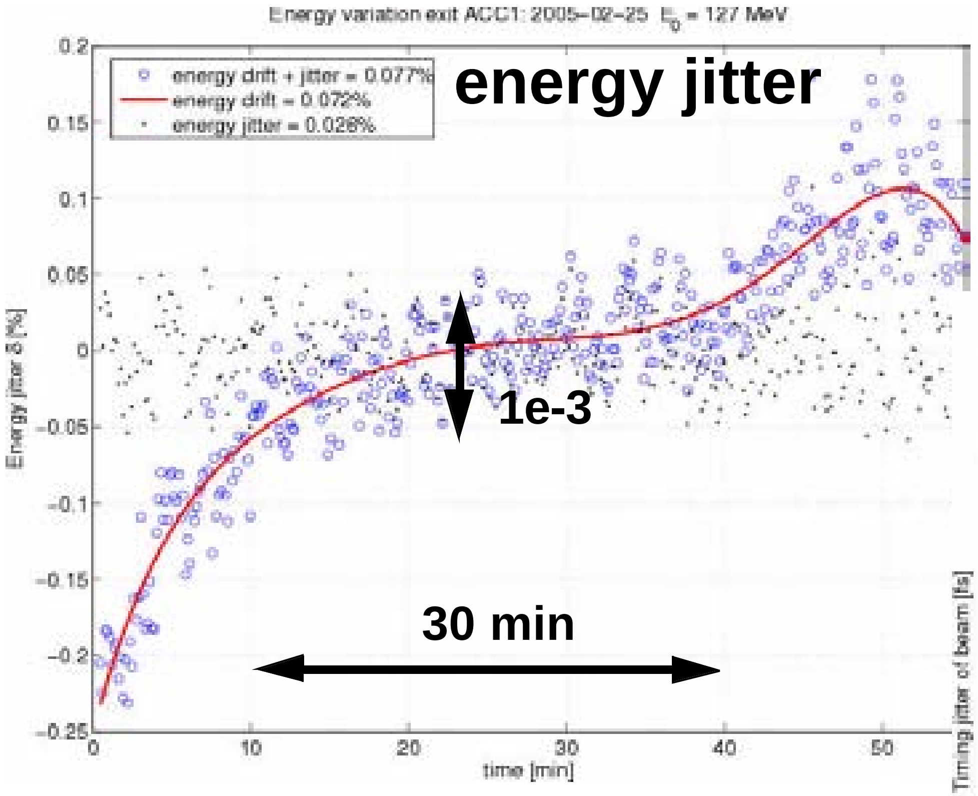
Phase

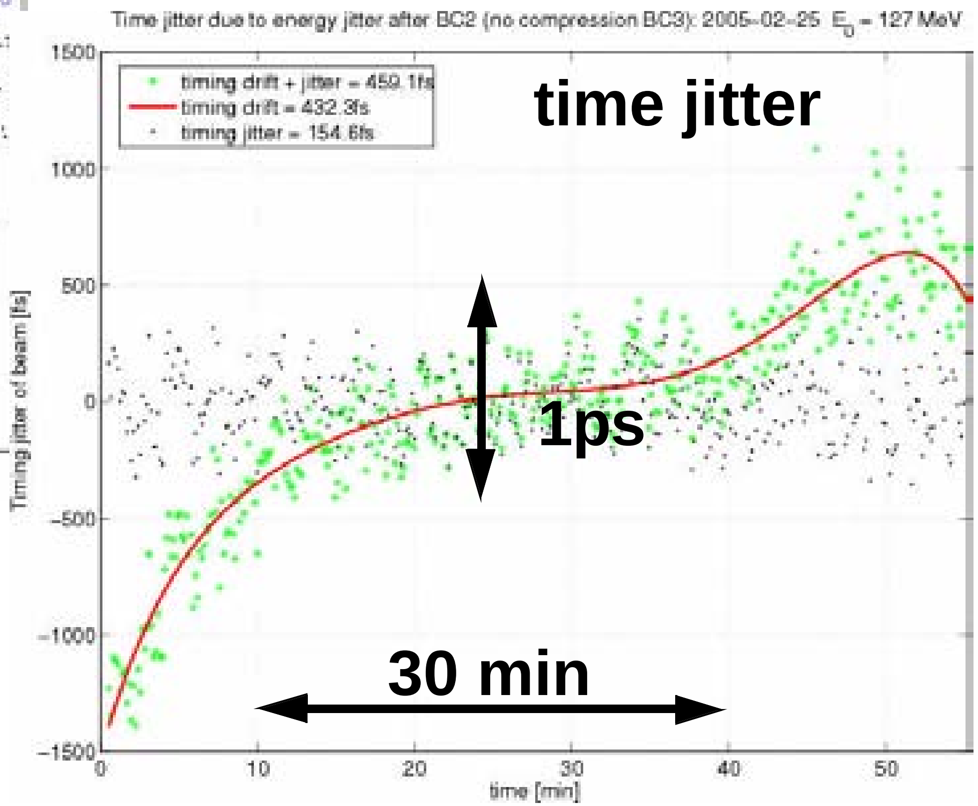
Performance at TTF (2)



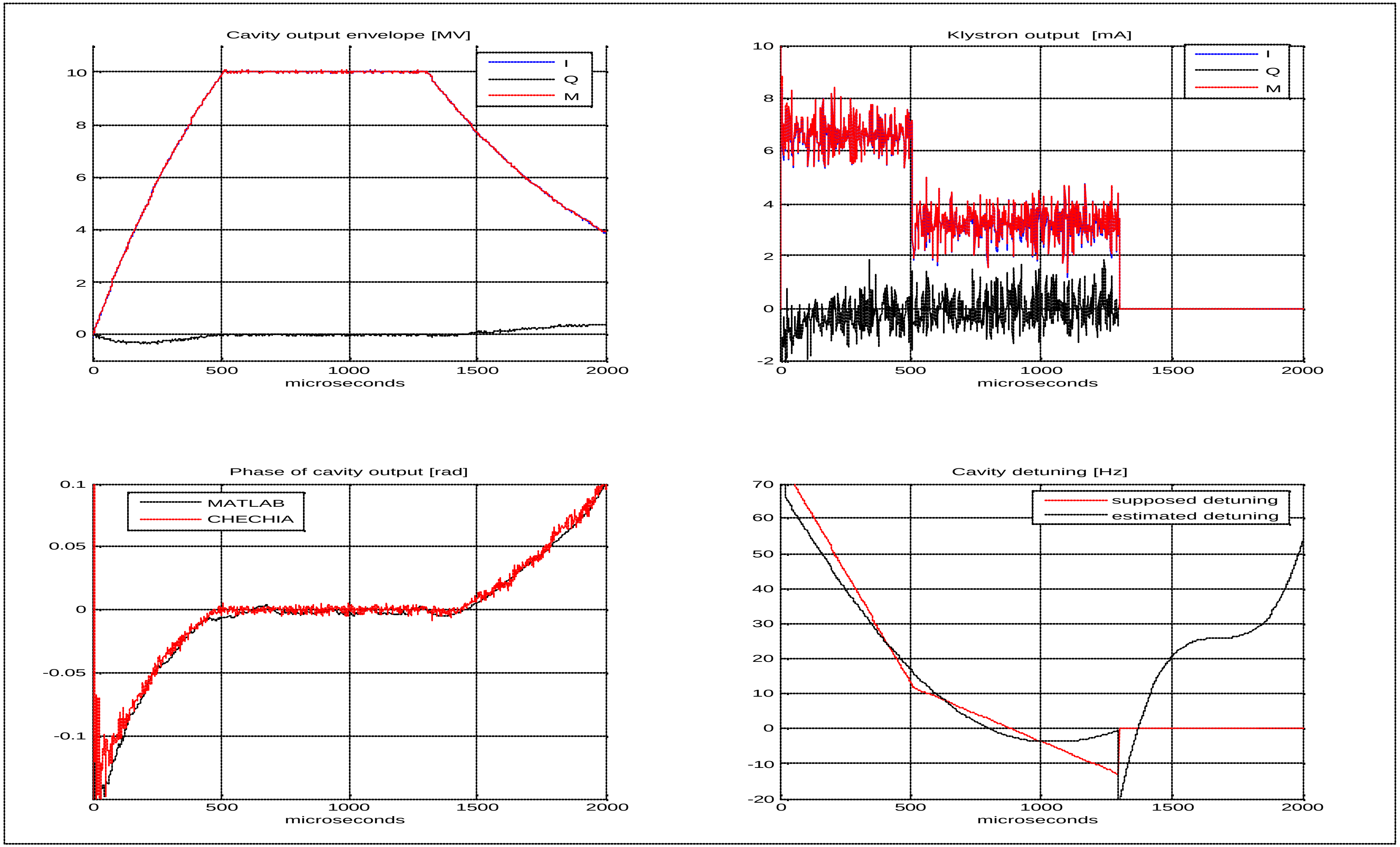
Operation with long beam pulses

Drift ACC1 (cryomodule before BC) at TTF

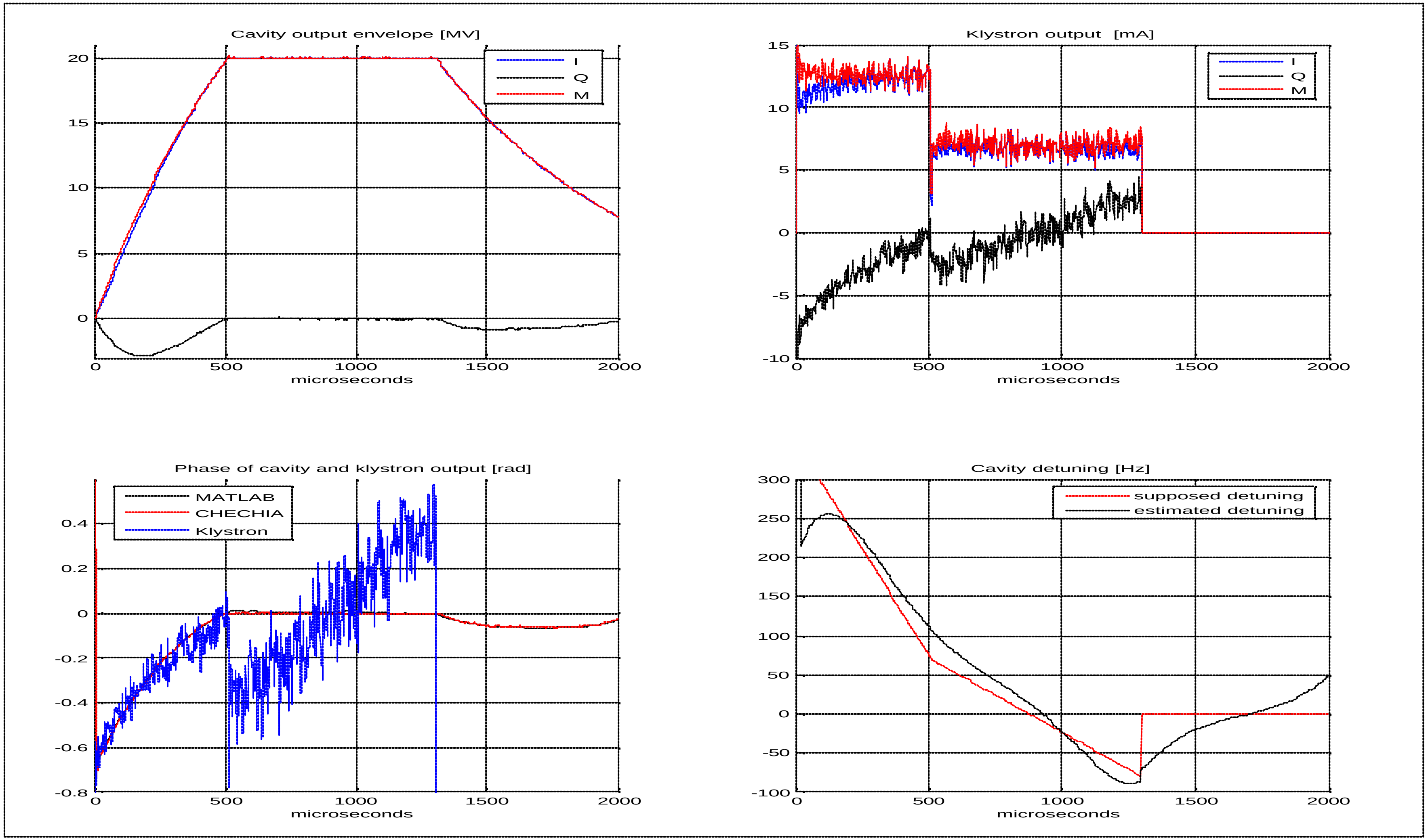




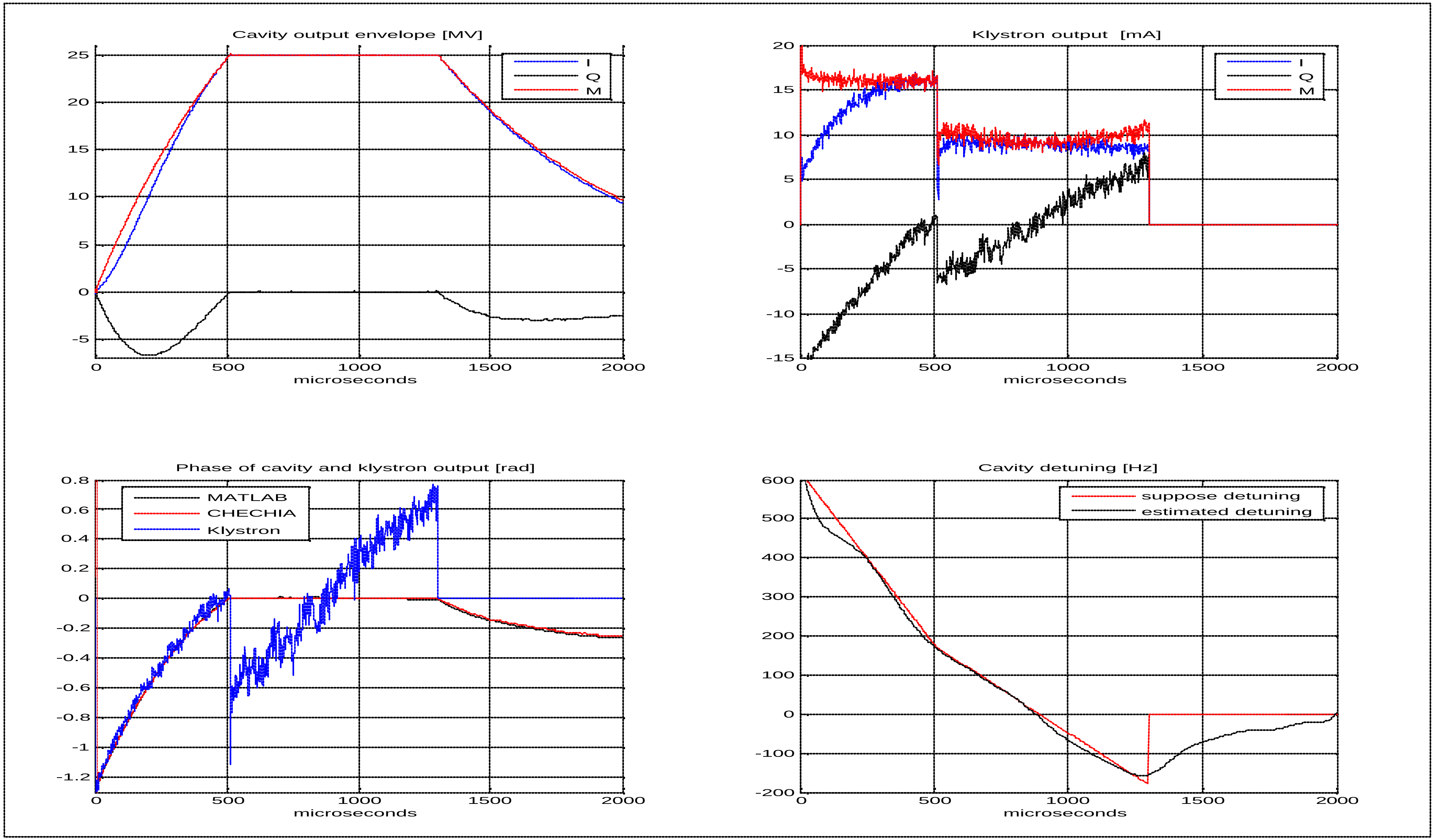
Feed-forward and feedback driving – for 10 MV



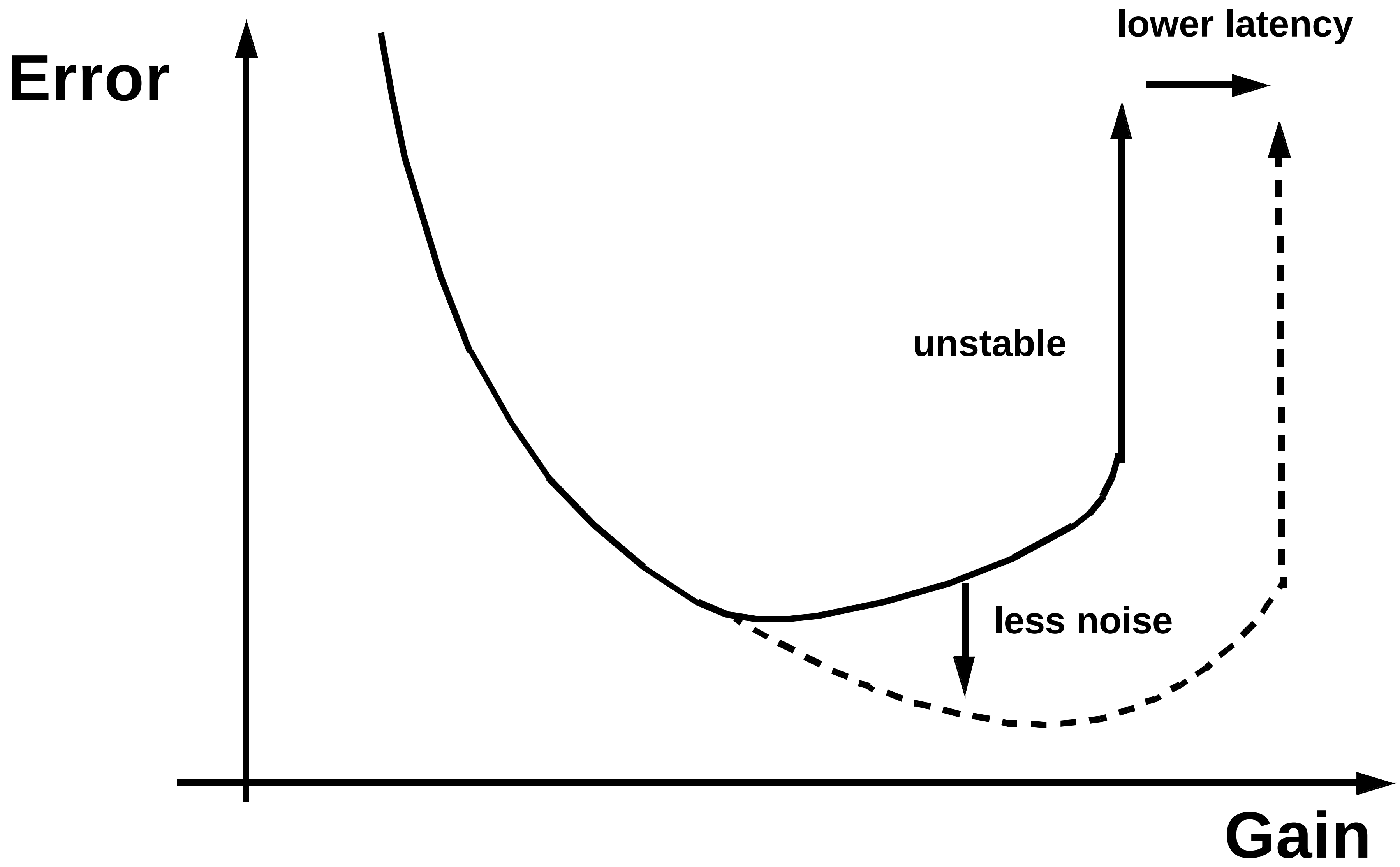
Feed-forward and feedback driving – for 20 MV

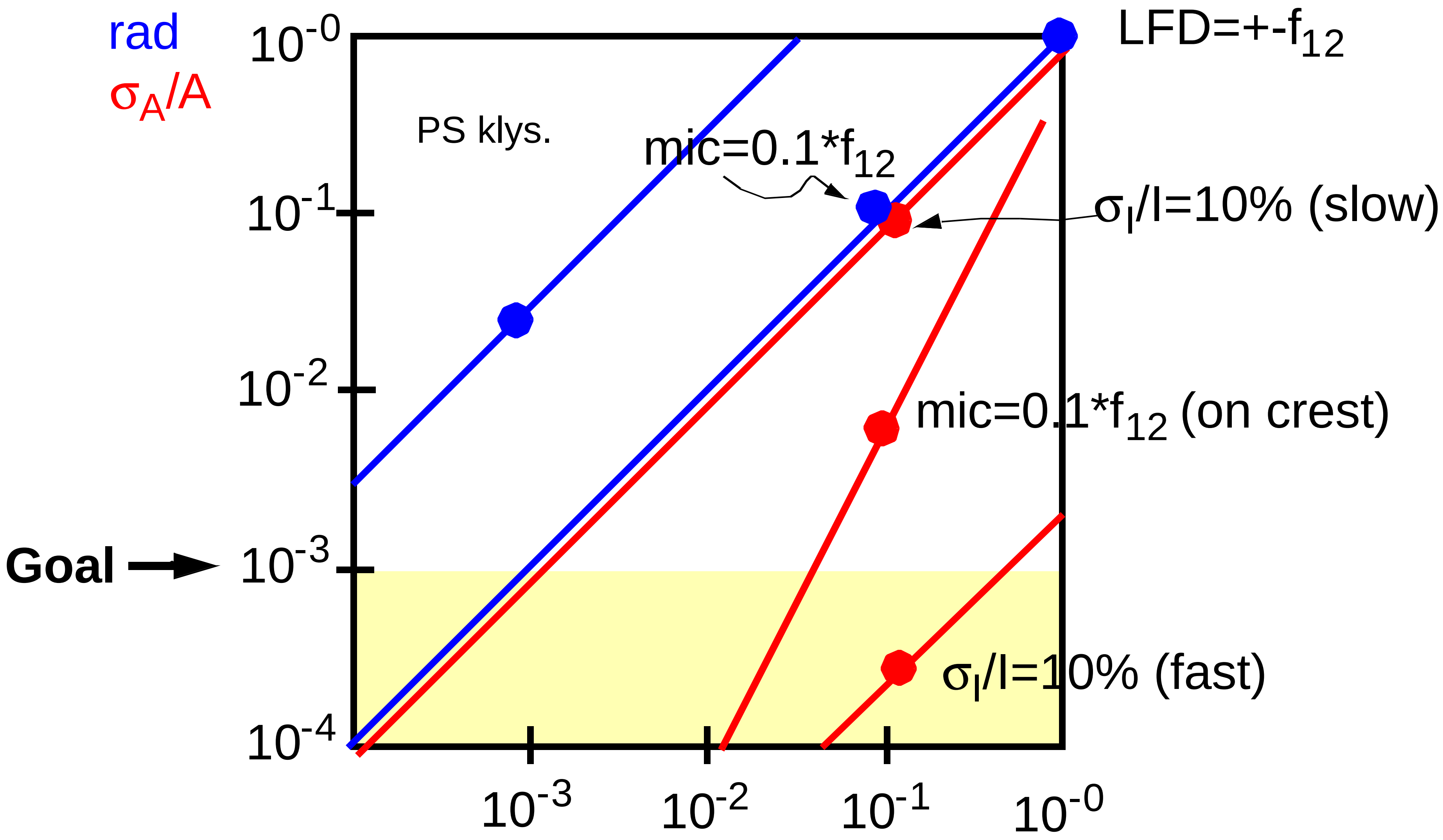


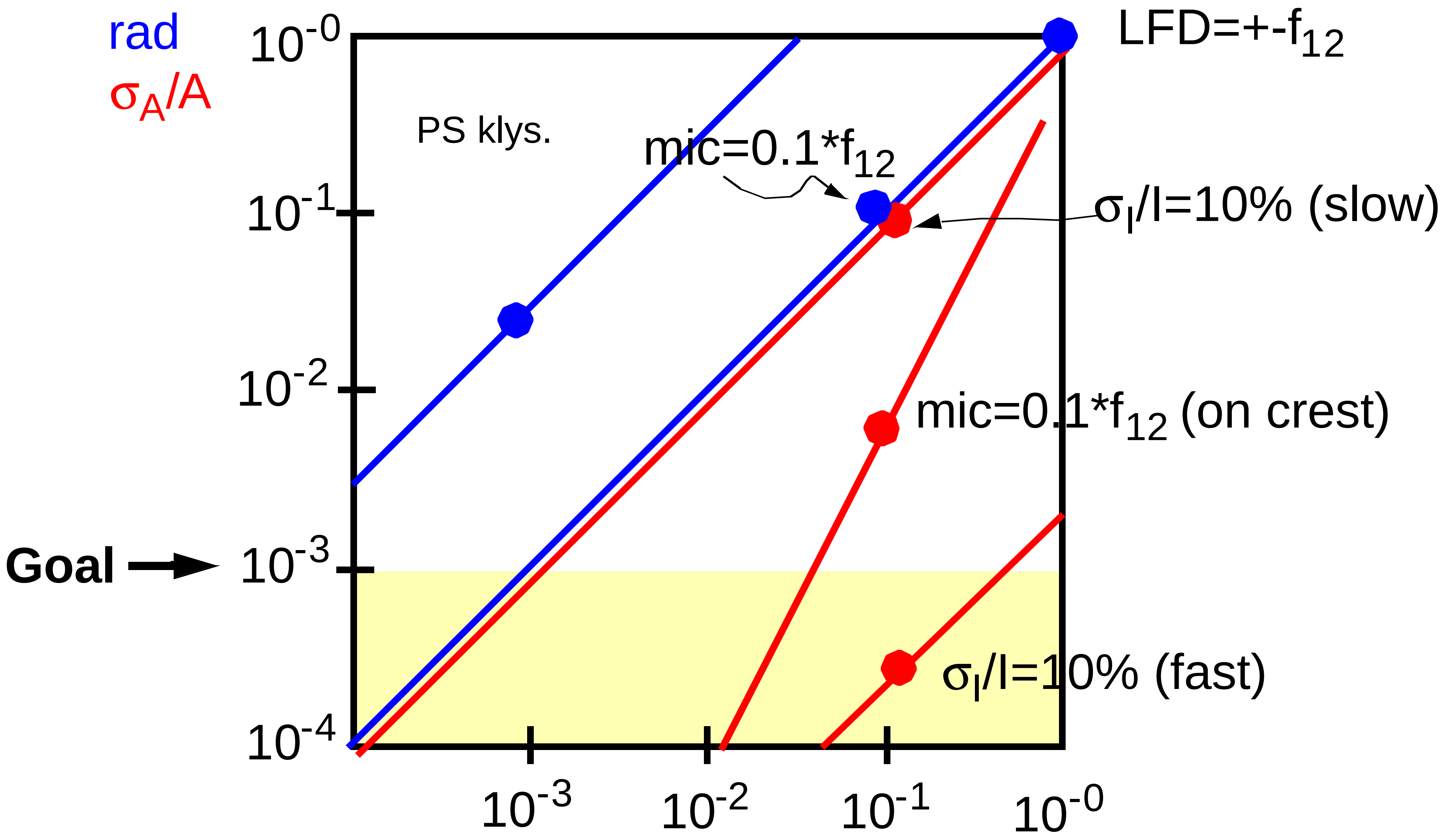
Feed-forward and feedback driving – for 25 MV



RMS Error as Function of Feedback Gain




rad
σA/A
10-0
10-1
10-2
10-3
10-4
Goal
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


rad
σ_A/A
10^{-0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Goal
PS klys.
mic=0.1*f_{12}
LFD=+-f_{12}
σ_I/I=10% (slow)
mic=0.1*f_{12} (on crest)
σ_I/I=10% (fast)
10^{-3}
10^{-2}
10^{-1}
10^{-0}

Additional Requirements for X-FEL & ILC

- Installation in Tunnel
  - Packaging (airconditioned racks)
  - Availability (Redundancy)
  - Maintenance
  - Upgradability (20 years operation)
- Radiation environment
  - Total ionizing dose
  - Single Event Upset (SEU)
- Large Scale Installation
  - Operability (Automated operation with FSM)
  - Exception handling
- X-FEL specific: Field stability and higher rep. rate
- ILC specific: High gradient (35MV/m)

Linac Commissioning Issues

- Coupler and cavity conditioning
- Cavity frequency tuning
- Closed loop operation and parameter optimization
- Initial phasing of cavities with single bunch
- Calibration of gradients
- Establishing long beam pulses (beam loss !)

Linac Operation Issues

- Operation of linac with 10,000 cavities
  - automated operation with finite state machine (FSM)
- Subsystem failure or performance degradation
  - redundany where possible (simple redundant feedforward)
  - exception handling
  - momentum management
- Energy variation and energy scans
- Maximize availability of linacs
- Operation close to the performance limit

Maintenance

- Extensive build-in diagnostics to detect system failure and degradation
- Preventative maintenance during maintenance days
- Design for partial redundancy
- Design for long MBTF and short MTTR
- Design for upgradebility to newer technology

Other Issues

- Electromagnetic interference
- Grounding and shielding
- Airconditioning of electronics
- Cabling of between subsystems
- Interfaces to other subsystems
- Radiation and shielding in single tunnel

Conclusion

- Field regulation of the order of 10^{-3} for amplitude and 0.1 deg. for phase will be required for future superconducting linear colliders
- Noise sources for superconducting cavities are understood
- Present achievements
- $3x10^{-3}$ in ampl. and 0.03 deg. have been achieved for vector-sum
- Main challenges for the LLRF system for the ILC are
  - Operability, Reliability, Reproducibility, Maintainability
- Most personpower will be invested in intelligent software
- Similar electronics is needed for other subsystems (ex. beam diagnostics). ==> Collaboration mandatory.
- Test facilities are available to evaluate new concepts