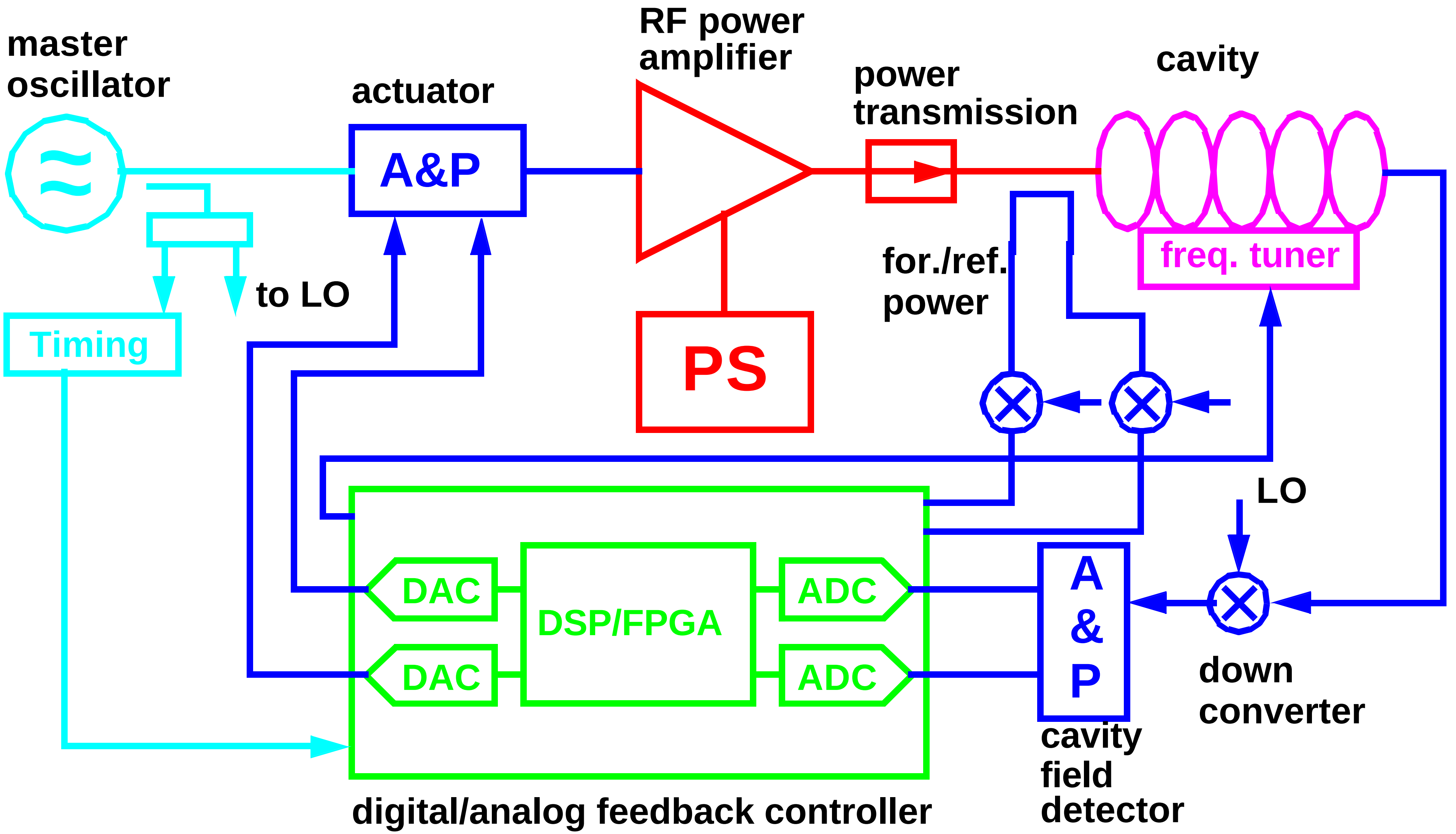
LLRF Development for TTF II and Applicability to X-FEL & ILC

S. Simrock, DESY

Outline

- RF System Architecture
- Requirements for RF Control
- Sources of Perturbations
- RF Control Design Considerations
- Measured and Predicted Performance
- Conclusion

RF System Architecture



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

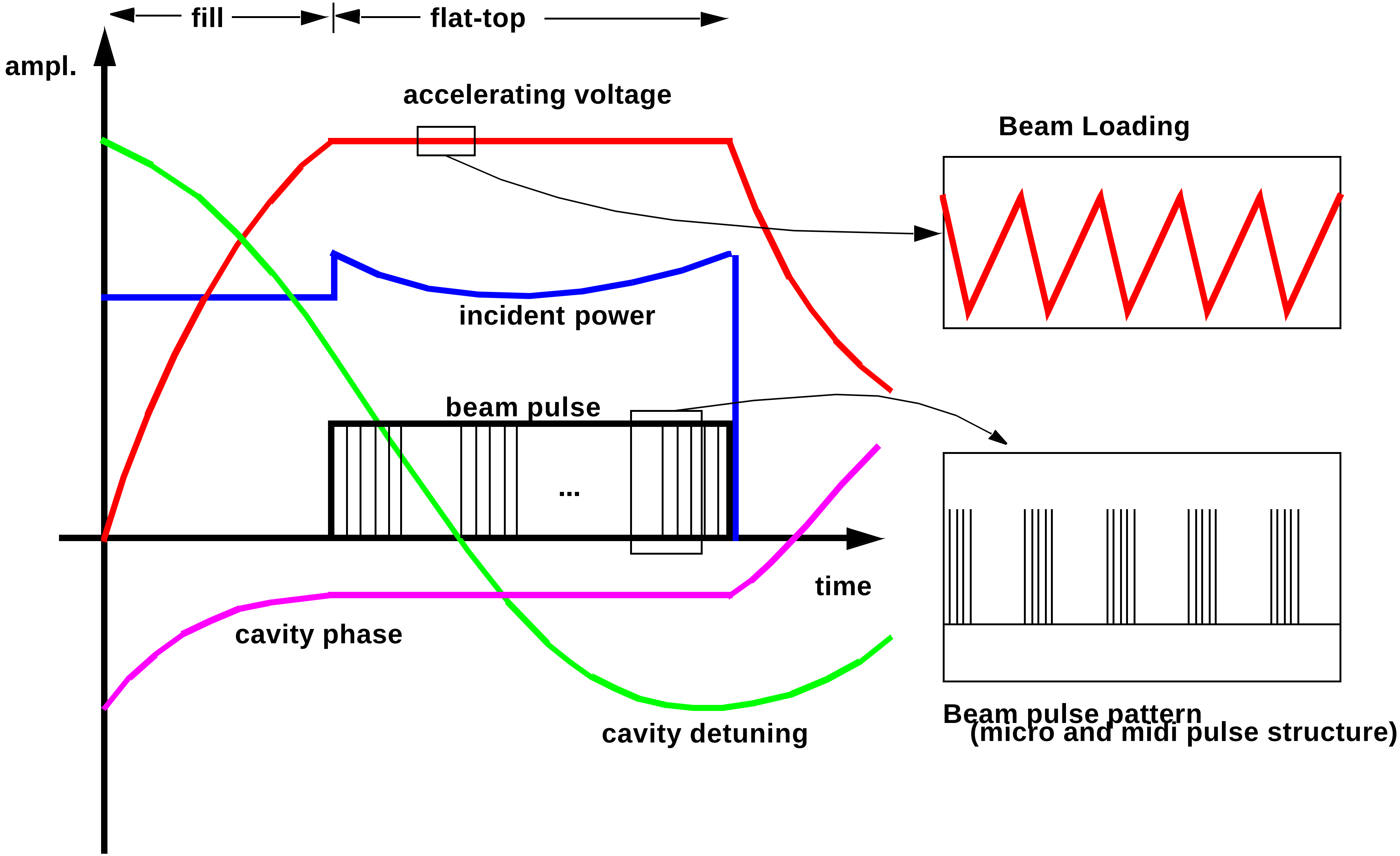
Requirements RF Control

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

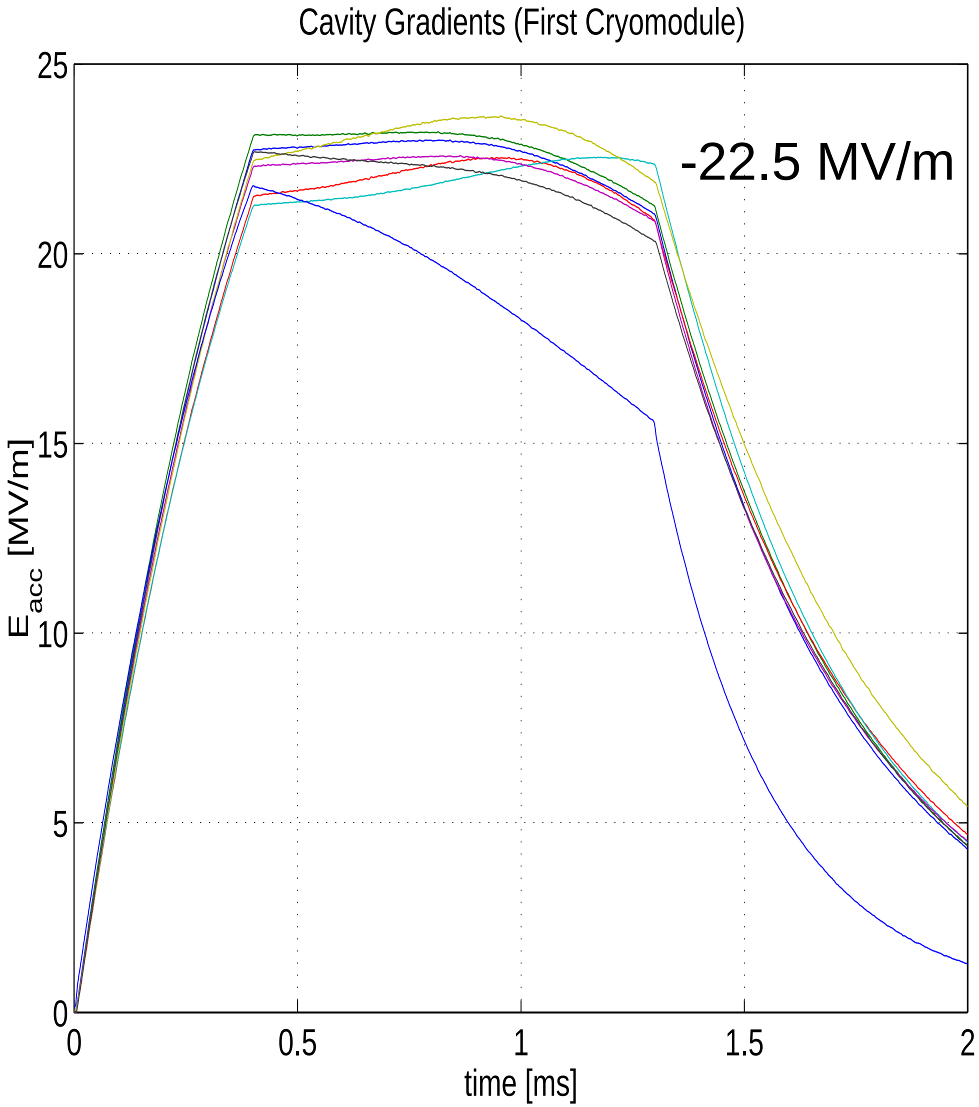
- Different accelerators have different requirements on field stability (approximate RMS requirements
  - 1% for amplitude and 1 deg. for phase (example: SNS)
  - 0.1% for amplitude and 0.1deg.for phase (linear collider)
  - up to 0.01% for amplitude and 0.01 deg. for phase (XFEL)

Note: Distinguish between correlated and uncorrelated error

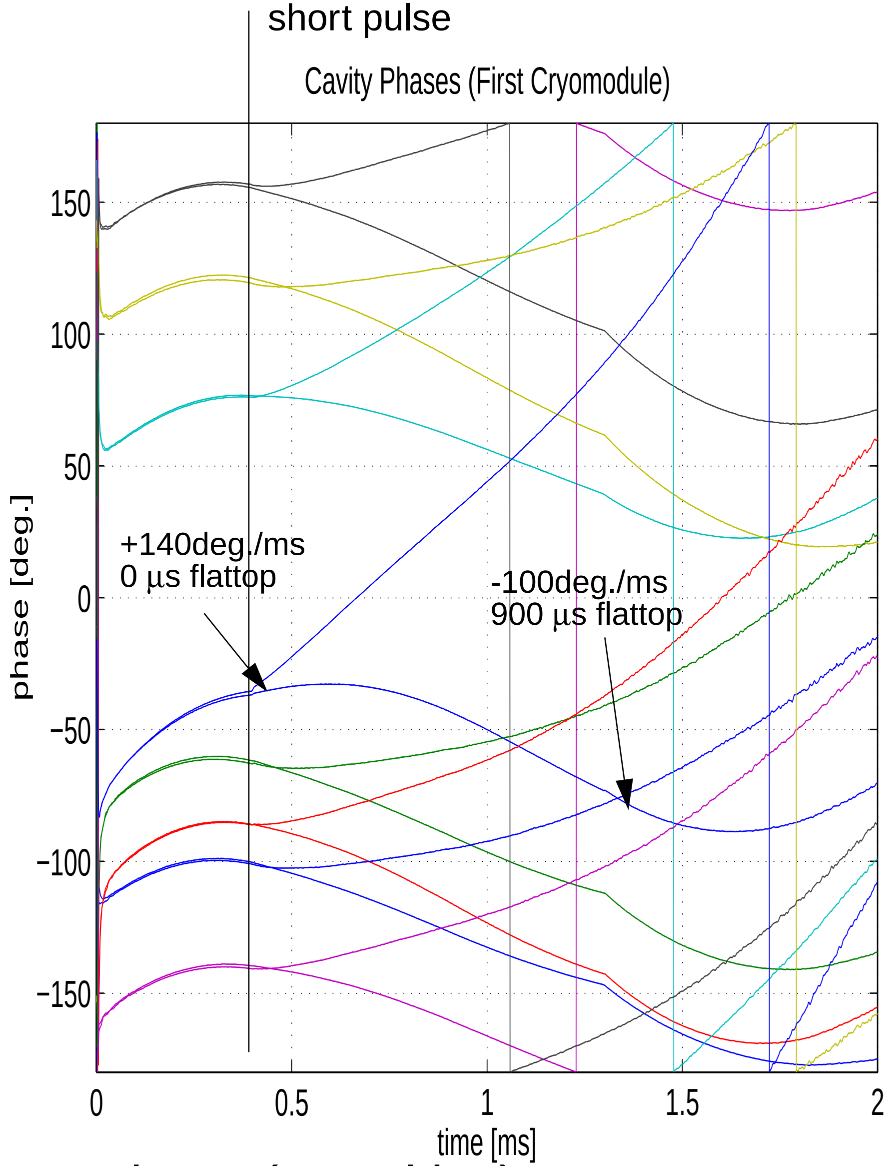
Typical Parameters in a Pulsed RF System



Pulsed Operation at High Gradients



Gradient (8 cavities)

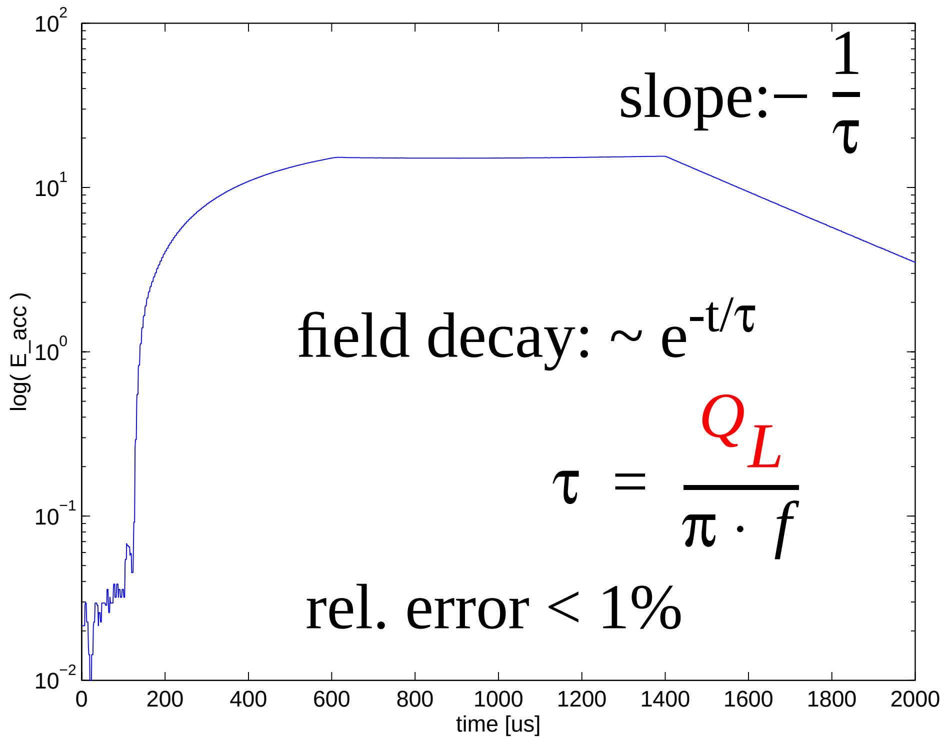


Phase (8 cavities)

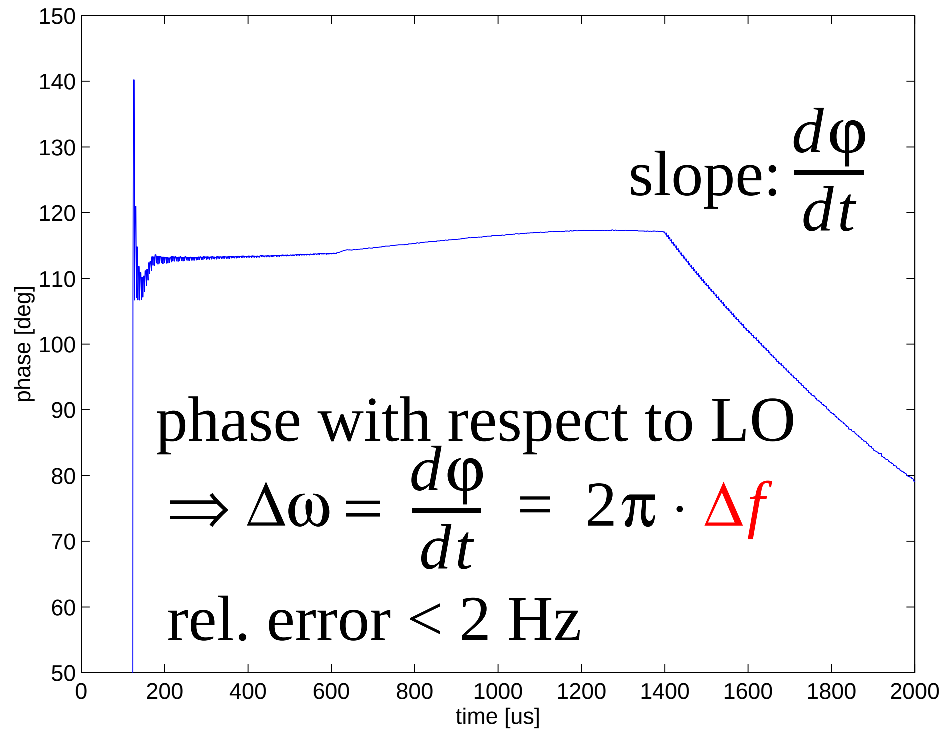
Sources of Perturbations

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)

Measurement of Cavity Q_L and Detuning

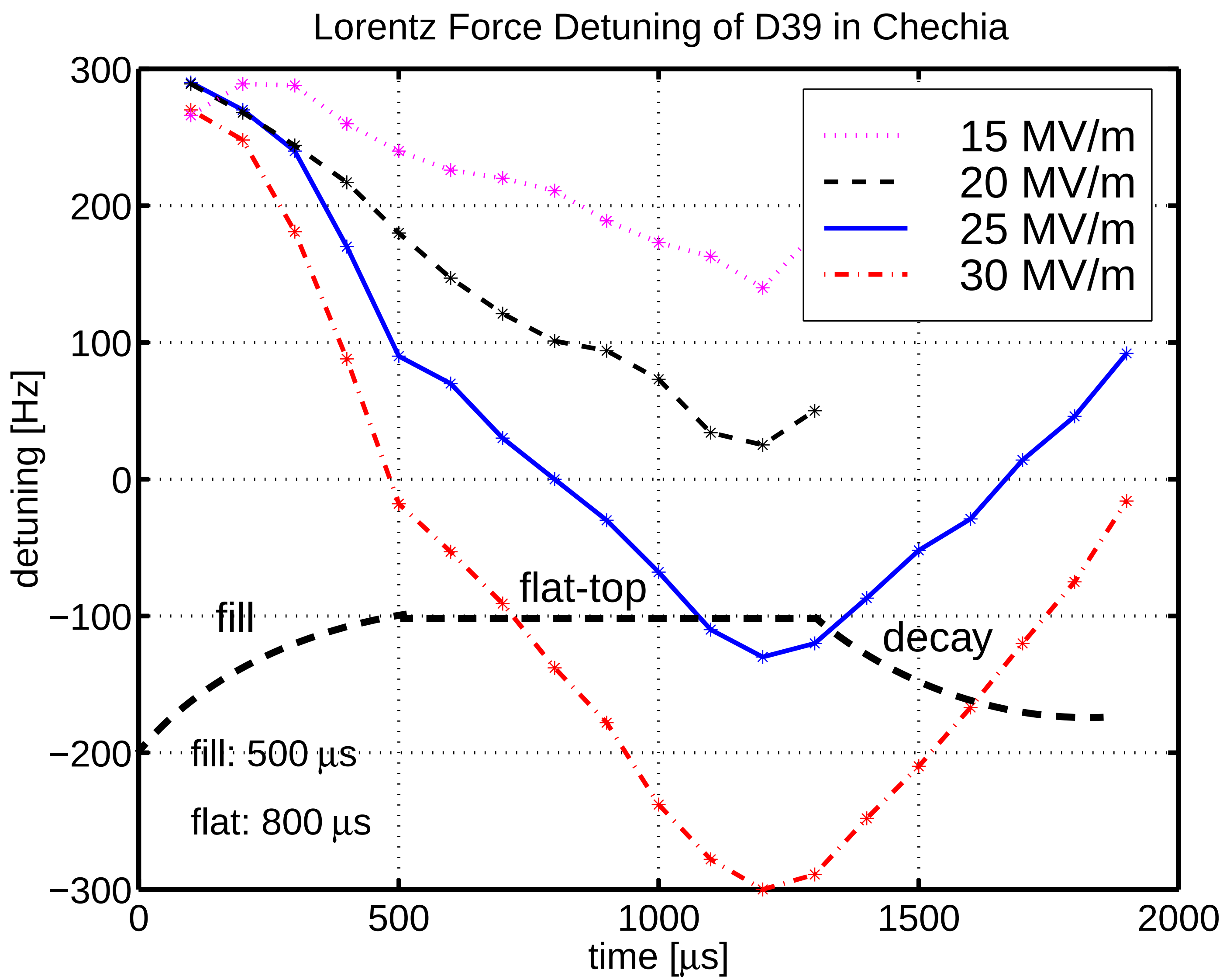


Loaded Q

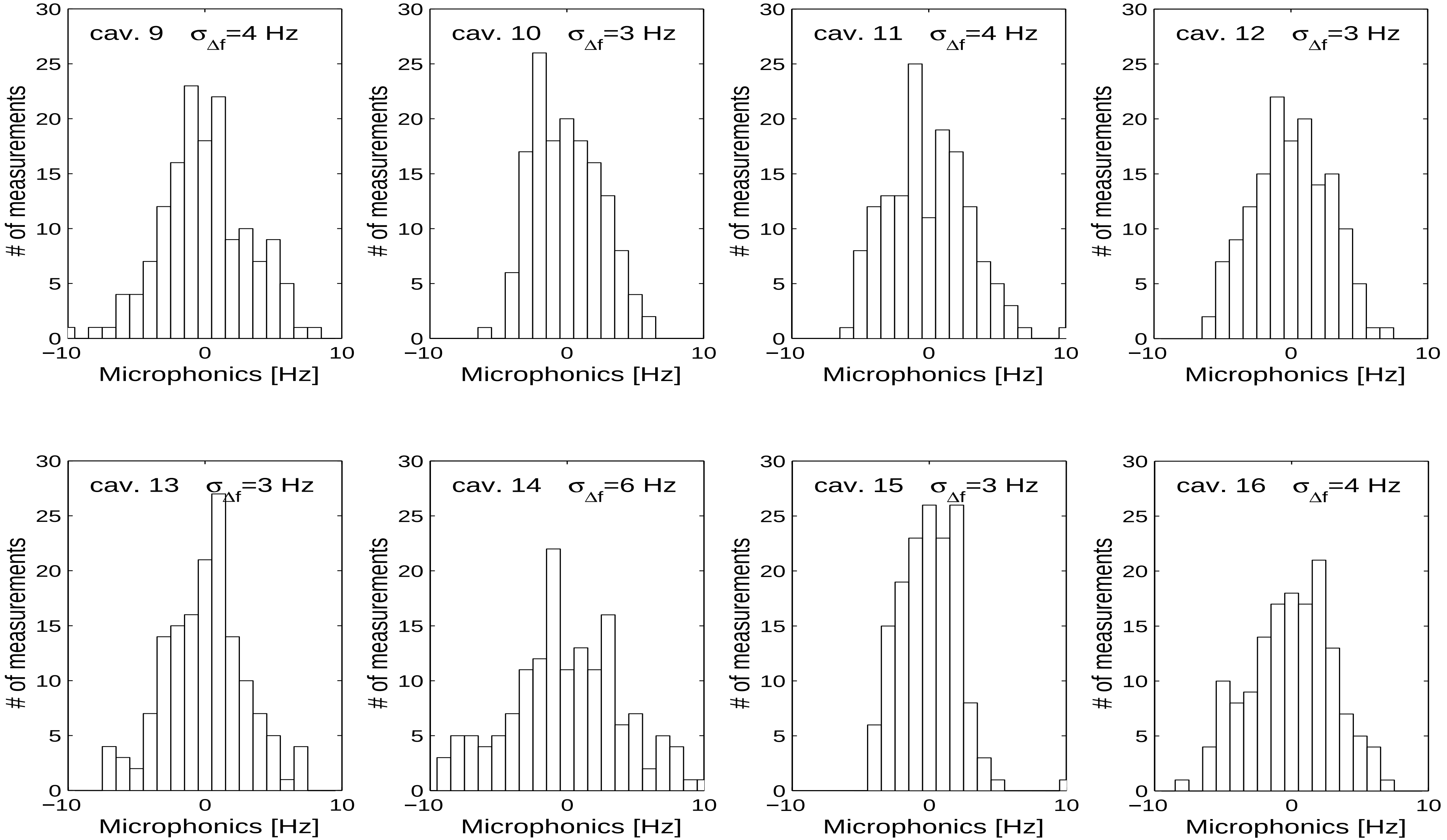


Detuning

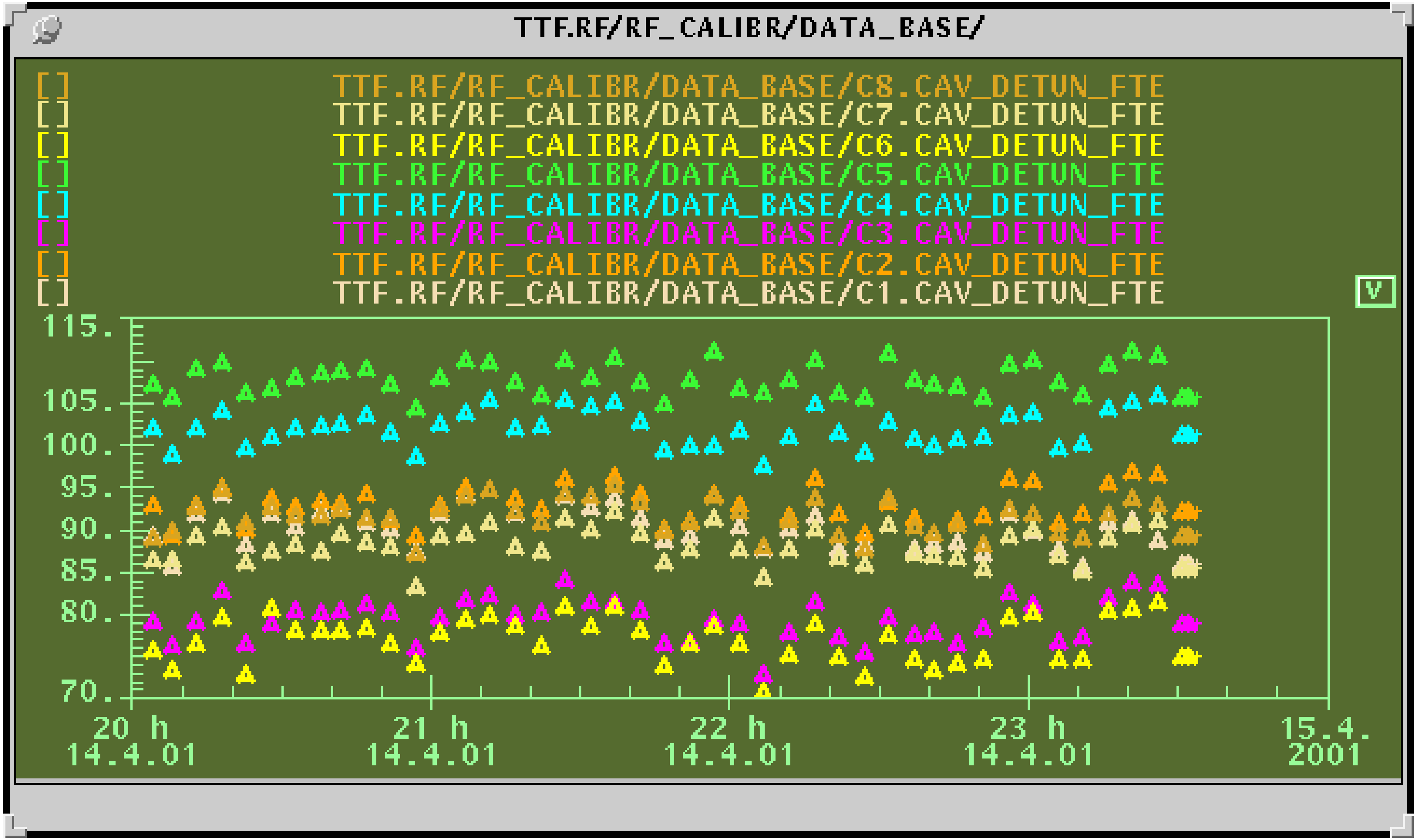
Lorentz Force Detuning



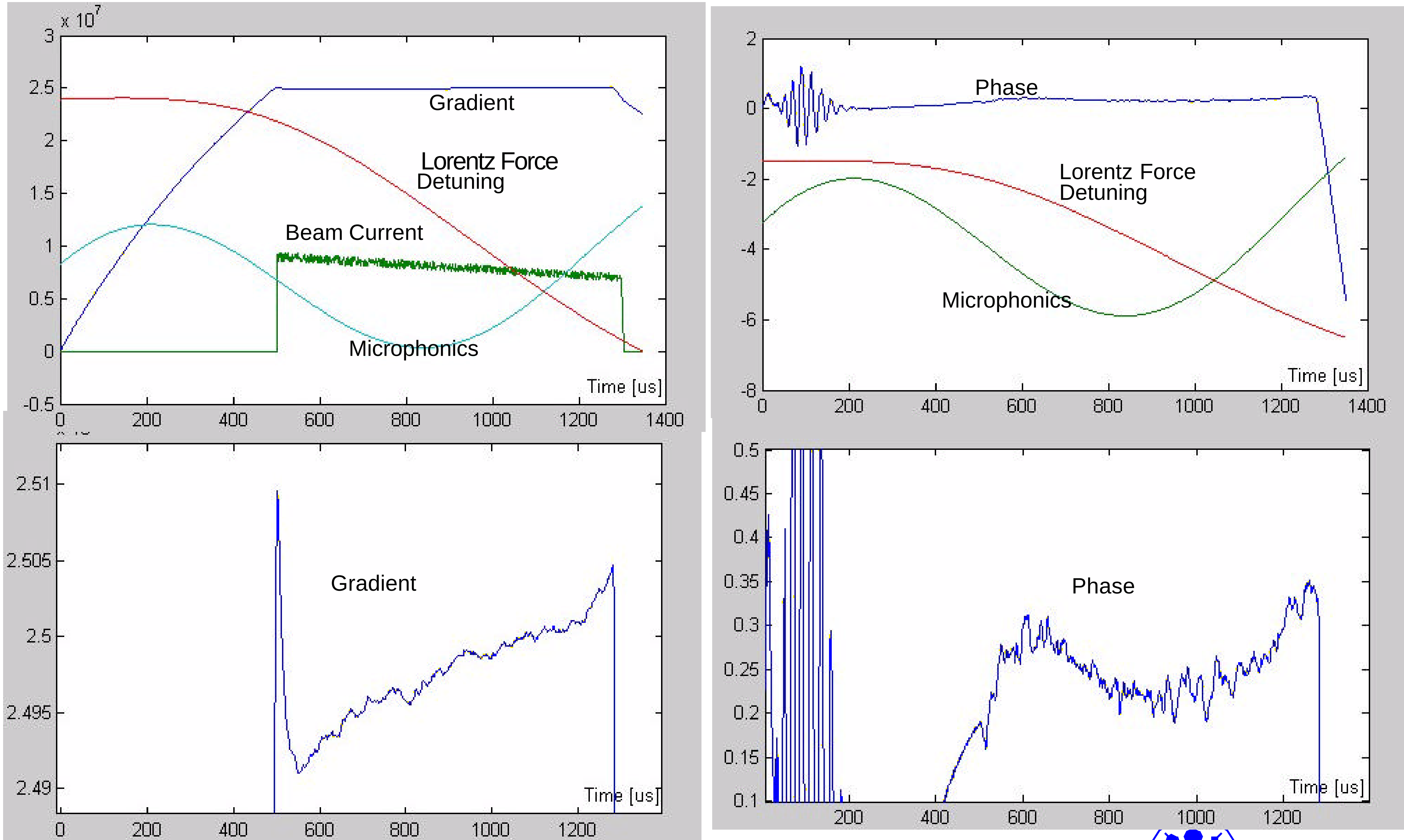
Microphonics at TTF



Long Term Drift of Resonance Frequency



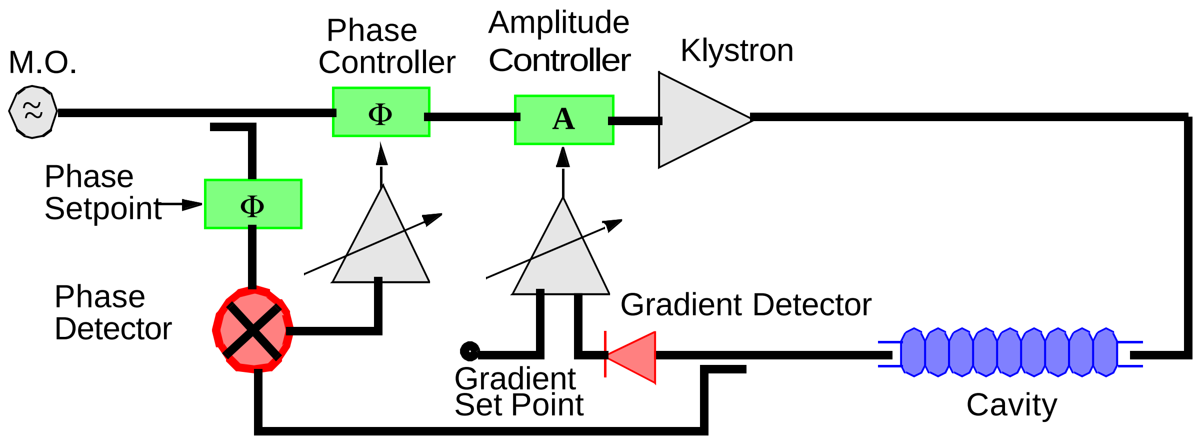
RF Regulation TESLA Cavity (Simulation)



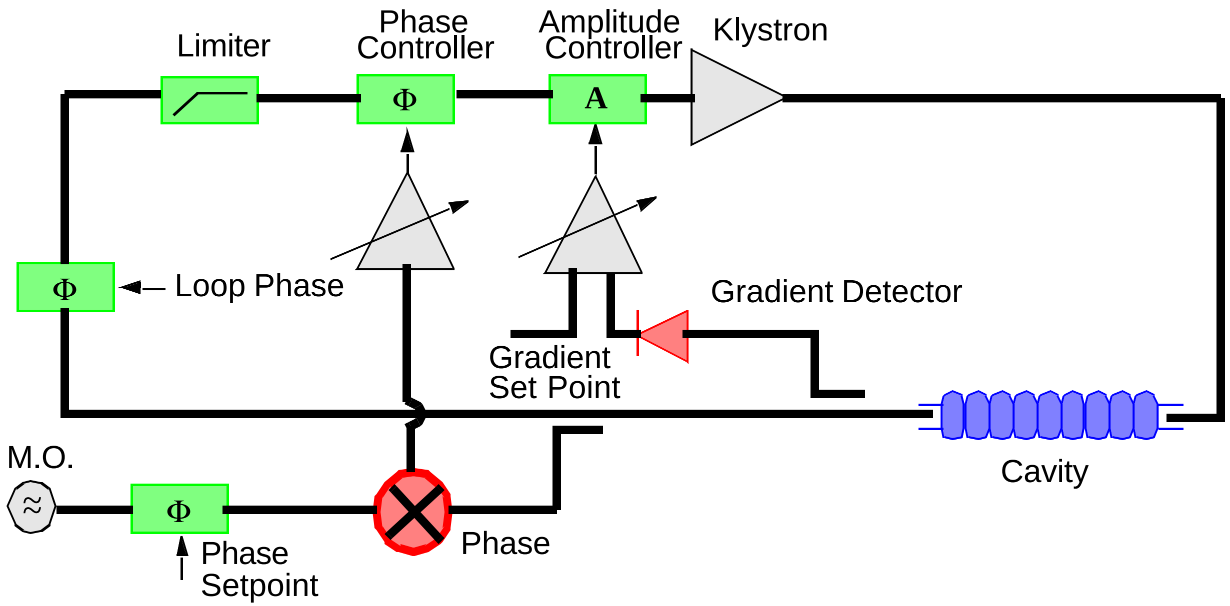
Control Choices (1)

- 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)

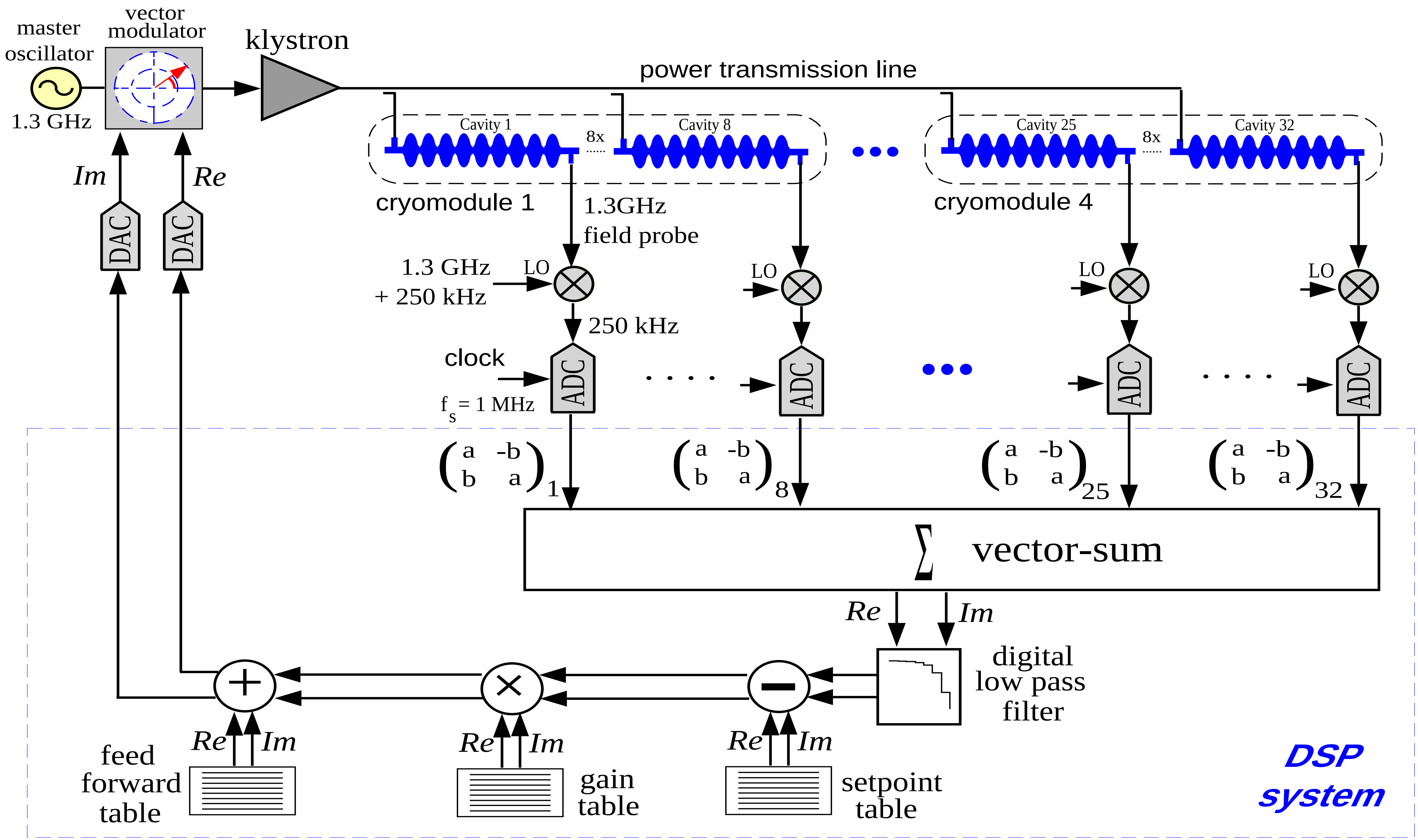


Generator Driven Resonator

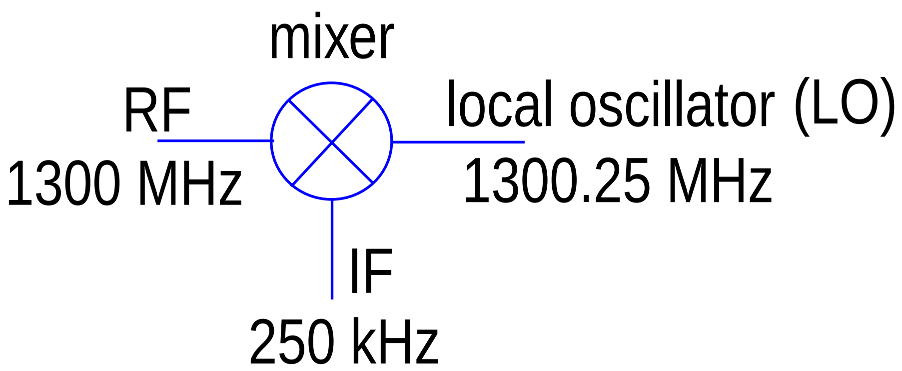


Self Excited Loop

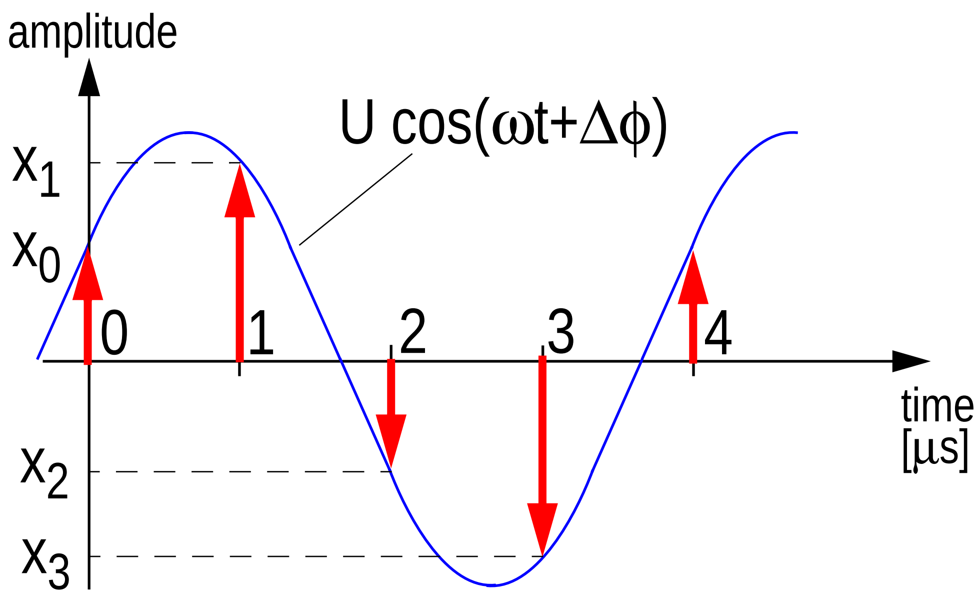
Digital Control at the TTF



Digital I/Q Detection

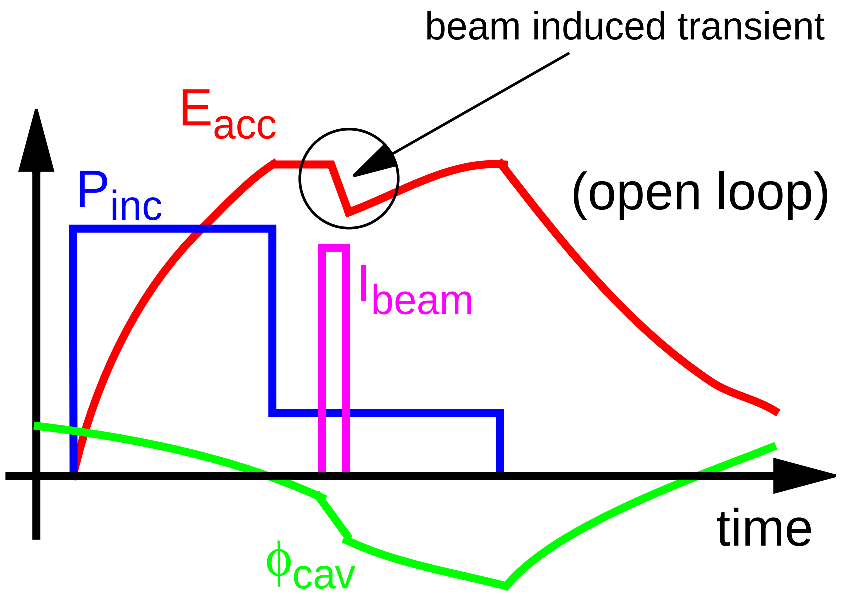


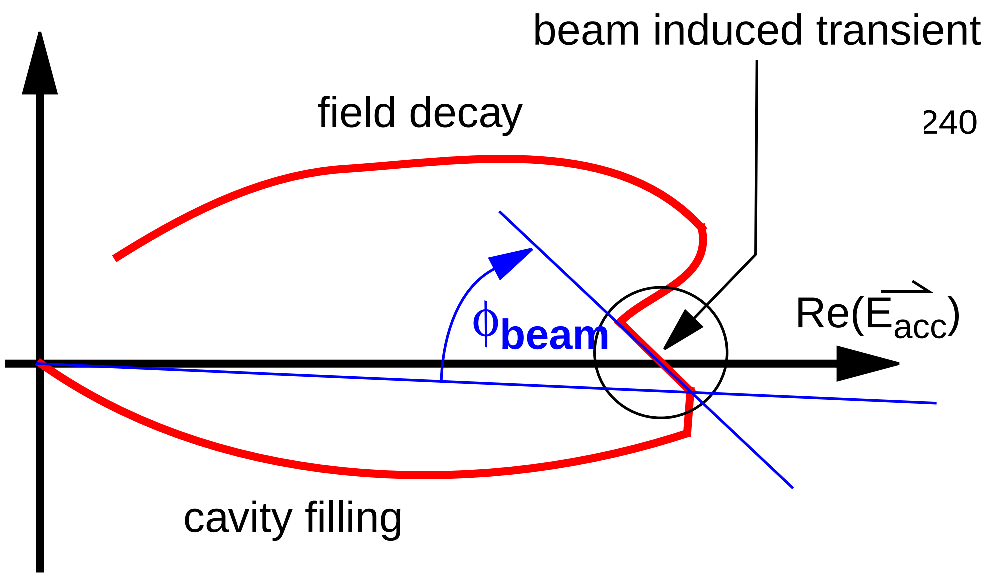
- downconversion of cavity field to IF frequency at 250 kHz
- complete phase and amplitude information of the accelerating field is preserved.

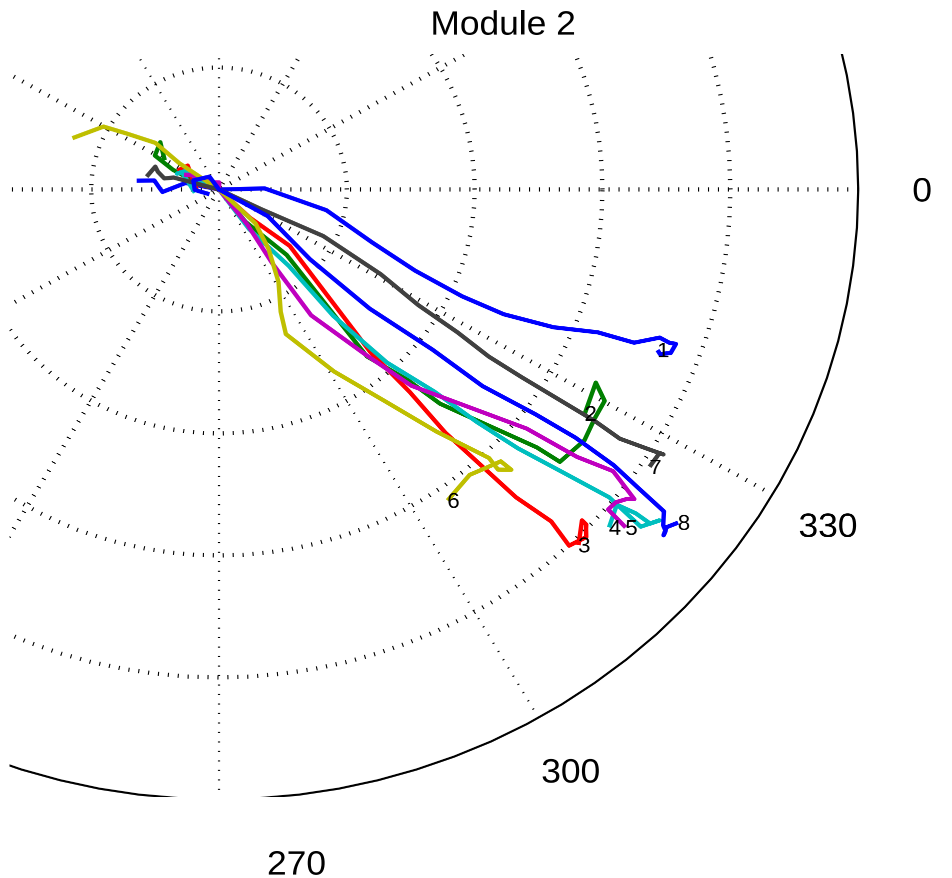


- sample IF signal at 1MHz rate
- subsequent samples describe real and imaginary component of the cavity field.

Beam Transient based Phase and Gradient Calibration



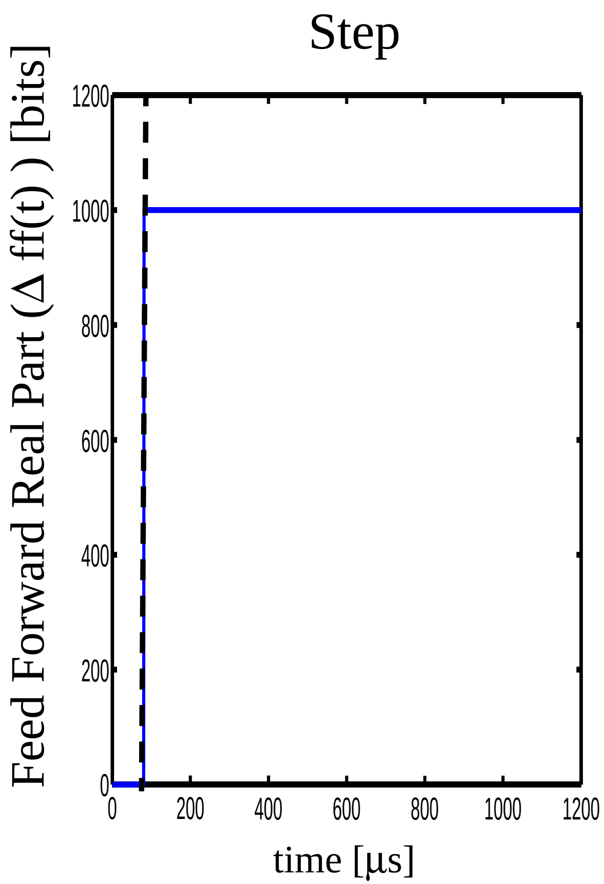


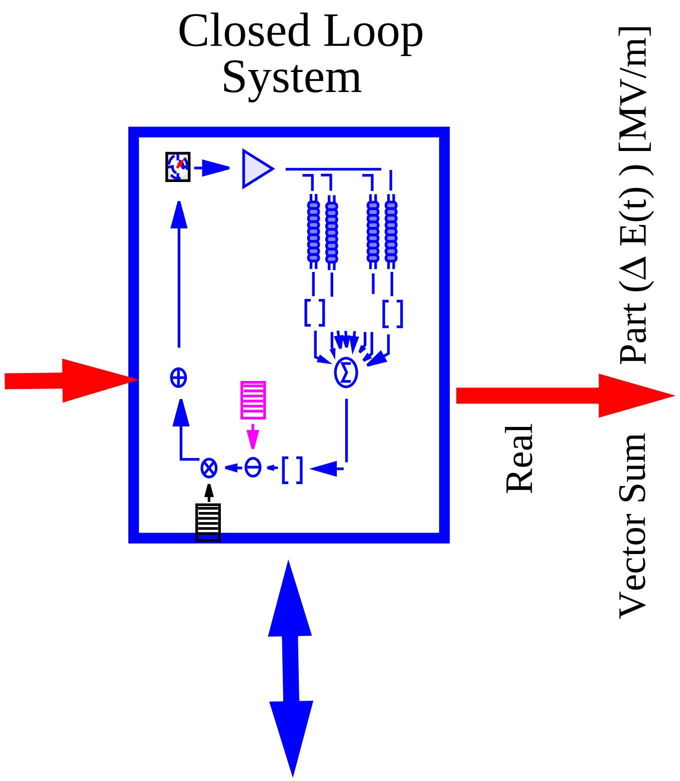


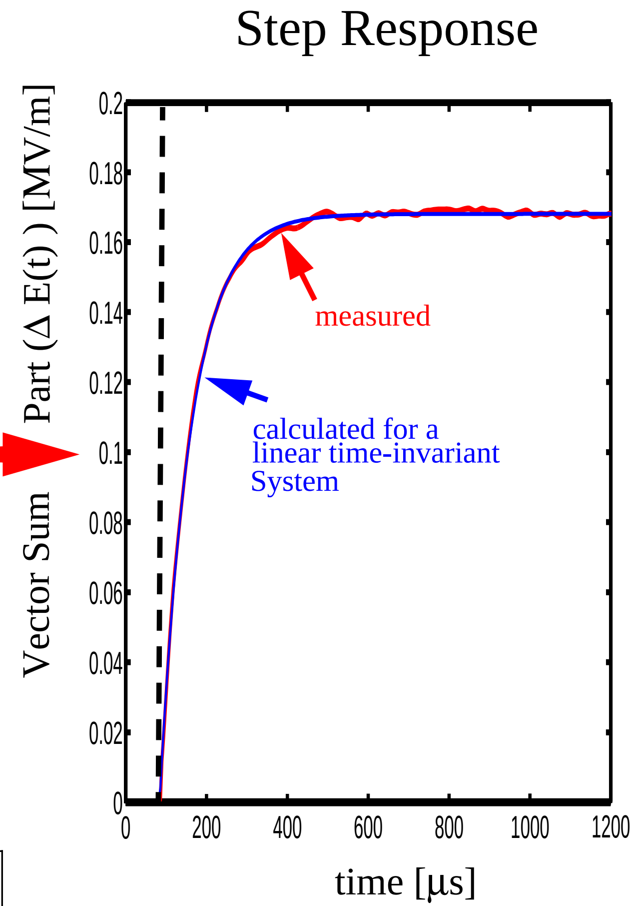
for $\Delta t \ll \tau_{cav}$:

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

Adaptive Feedforward



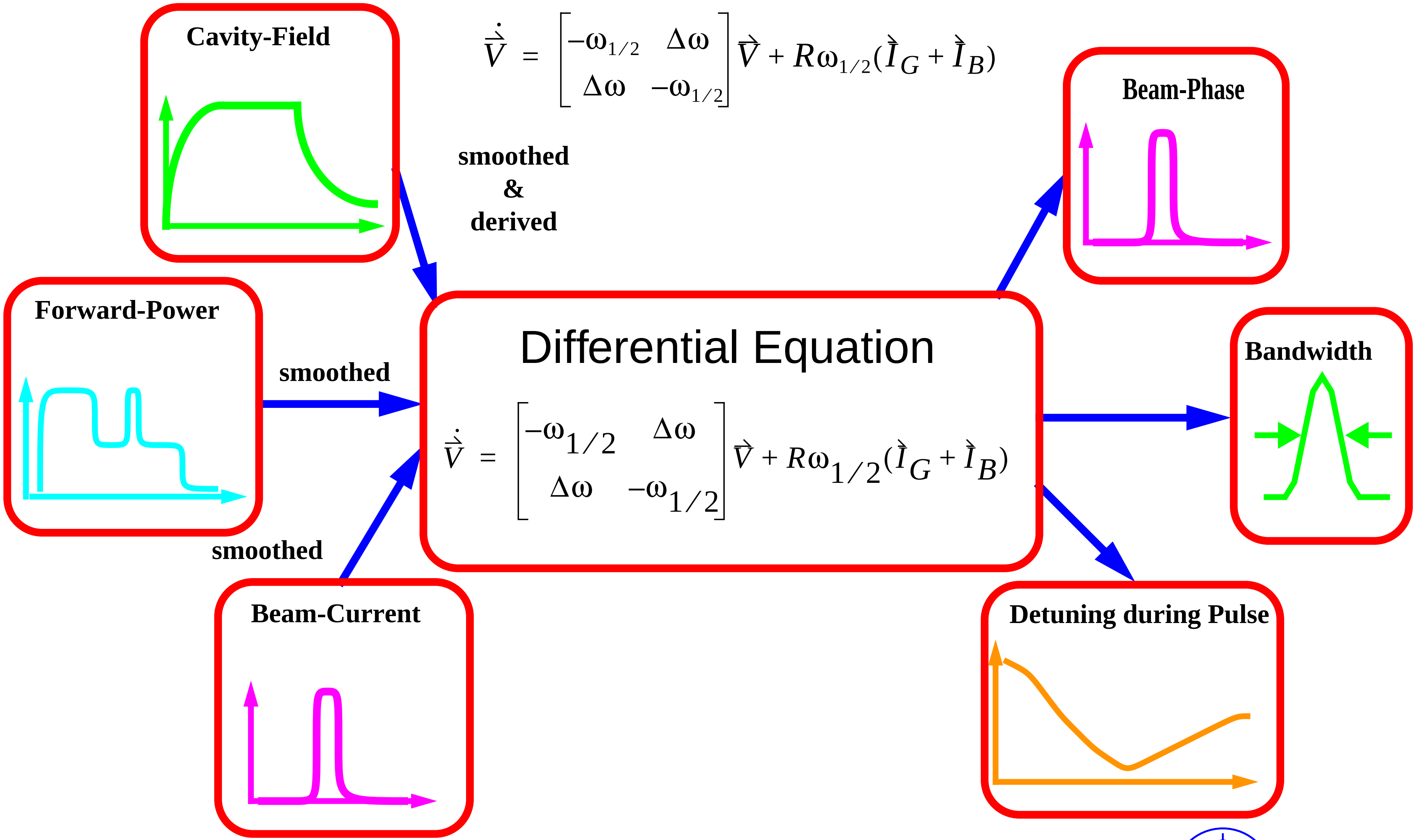




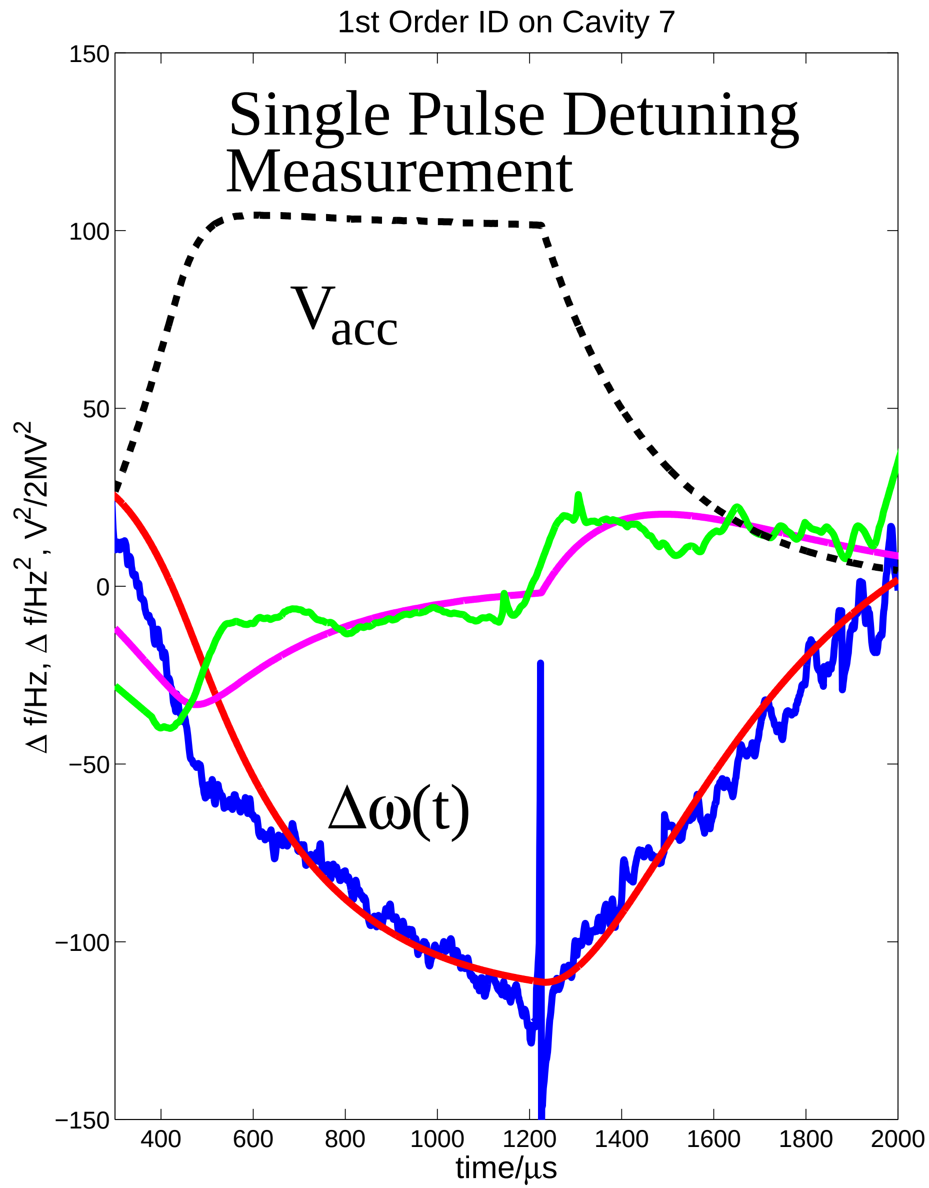
$$\begin{bmatrix} \Delta E(\tau_1) \\ \Delta E(\tau_2) \\ \dots \\ \Delta E(\tau_n) \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & \dots & T_{1n} \\ T_{21} & T_{22} & \dots & T_{2n} \\ \dots & \dots & \dots & \dots \\ T_{n1} & T_{n2} & \dots & T_{nn} \end{bmatrix} \begin{bmatrix} \Delta ff_1 \\ \Delta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

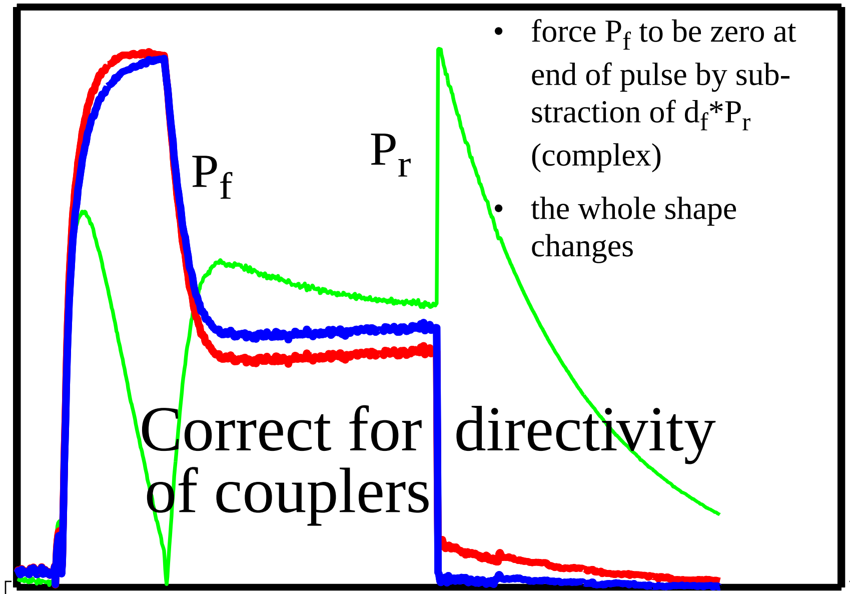
$$\Delta ff(t) = \sum_j \Delta ff_j \Theta(t - t_j).$$

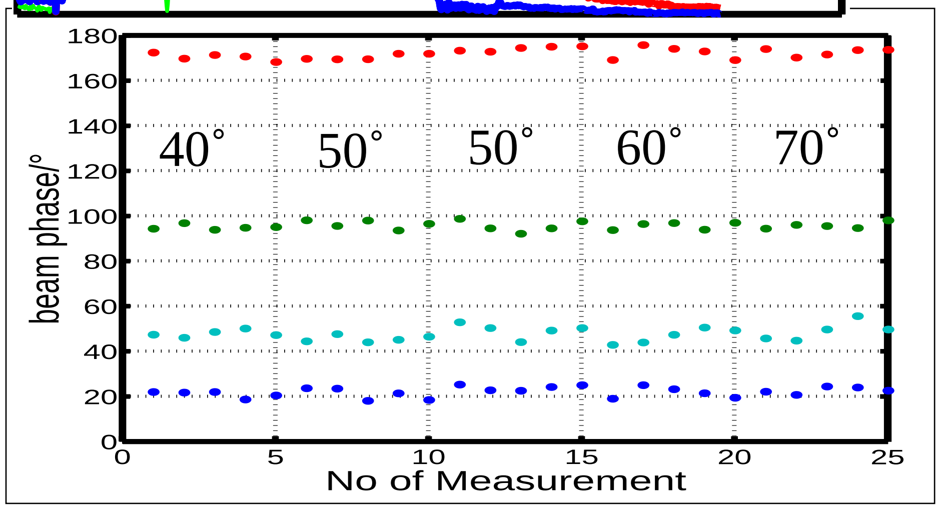
System Identification (1)



System Identification (2)

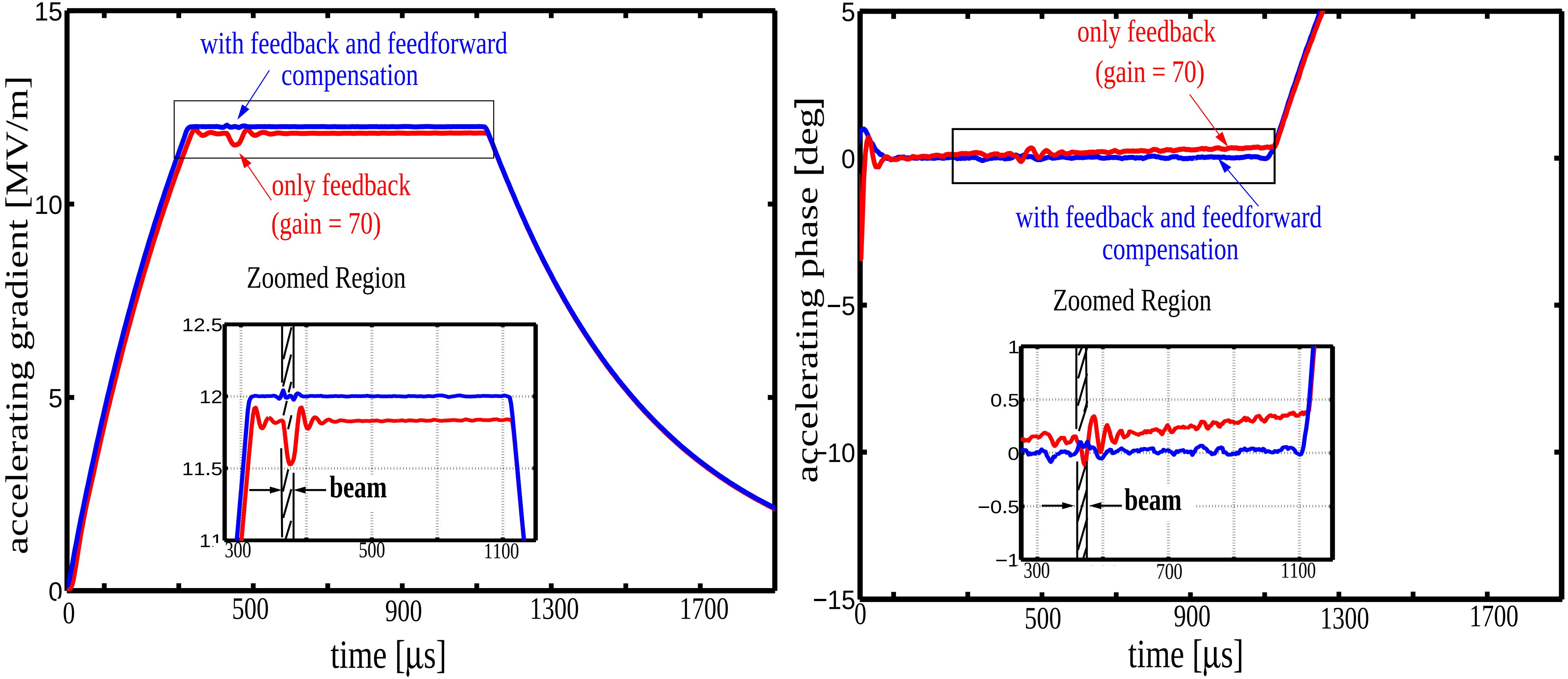






Beam phase of 4 cavities for different phase of V_{acc}

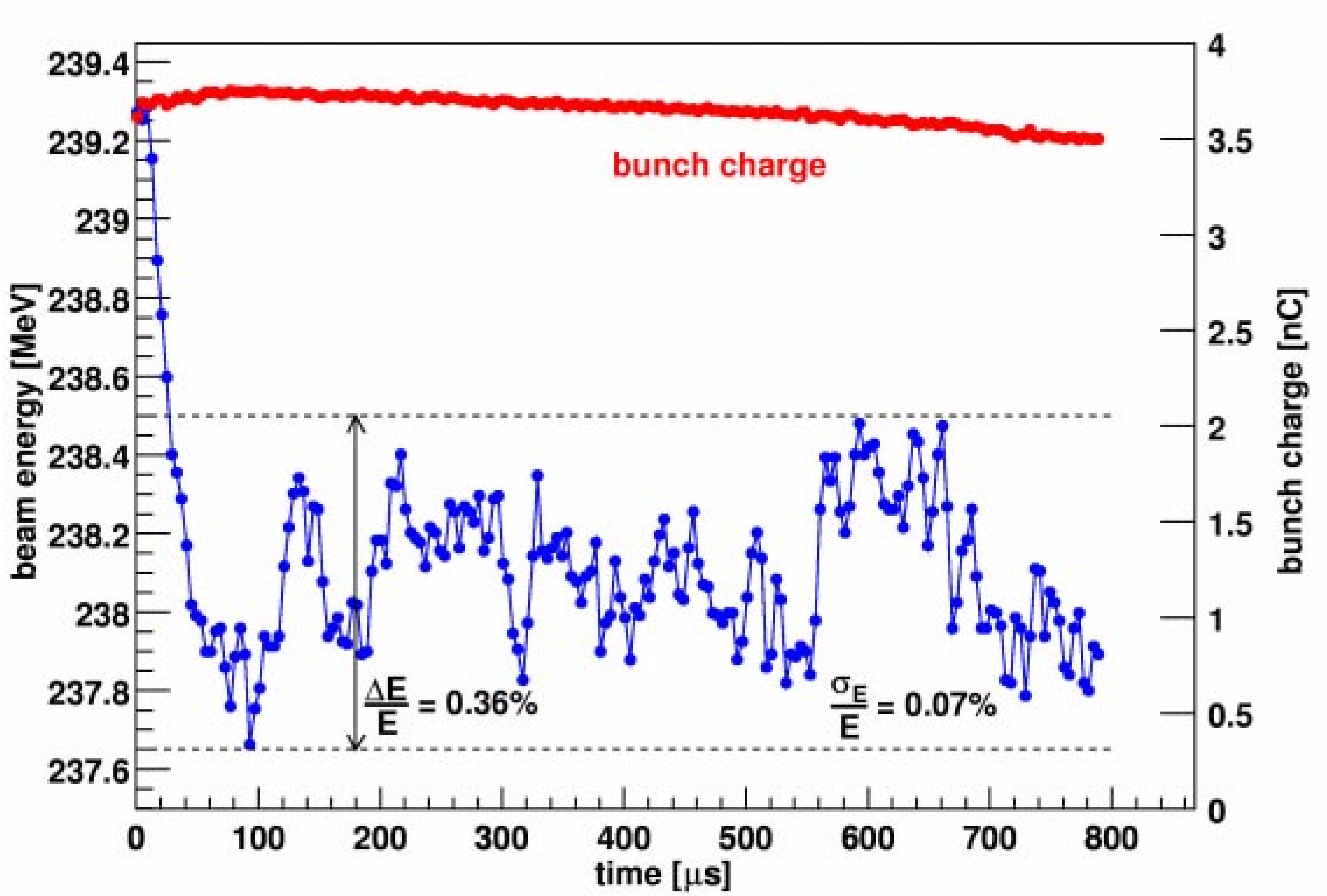
Performance at TTF (1)



Amplitude

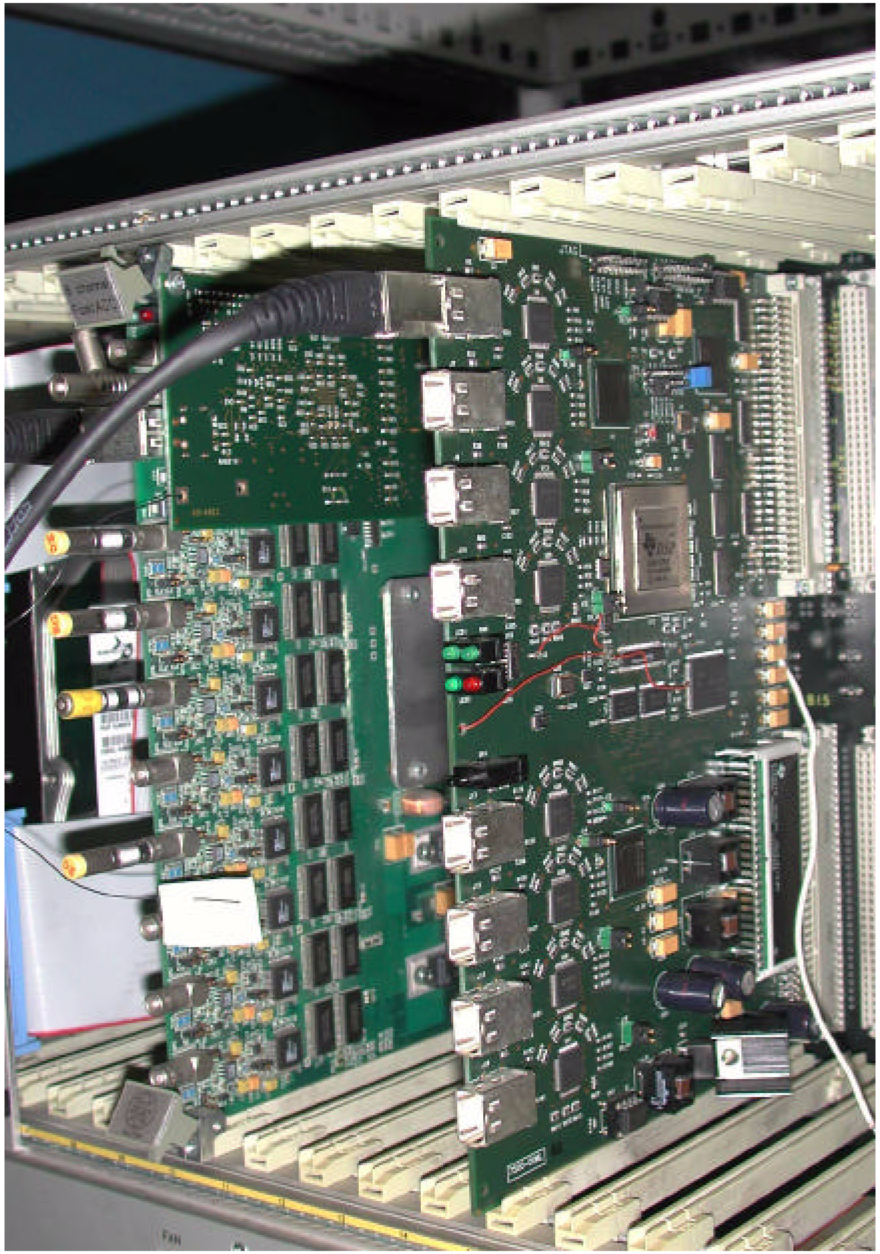
Phase

Performance at TTF (2)

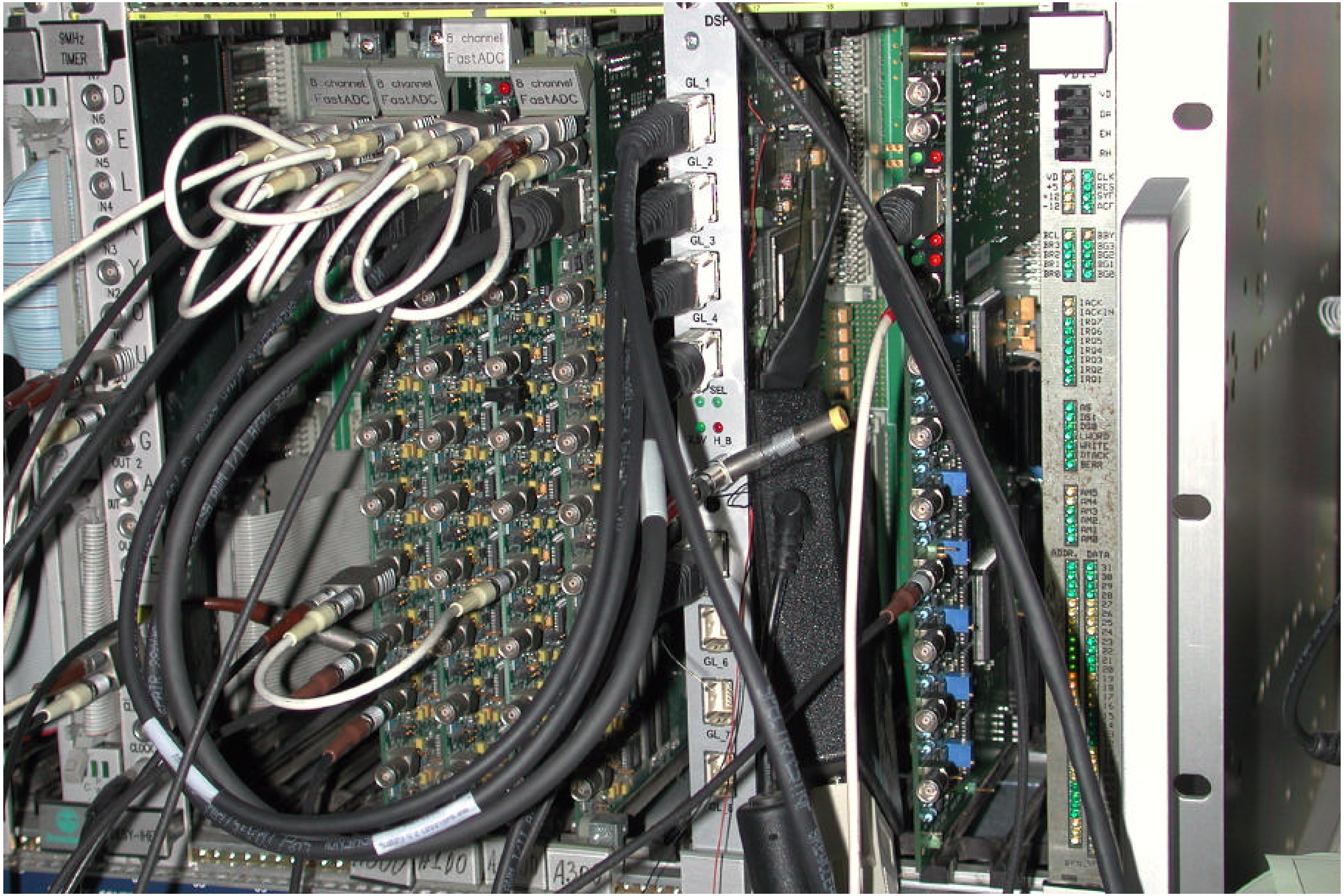


Operation with long beam pulses

C67 DSP board

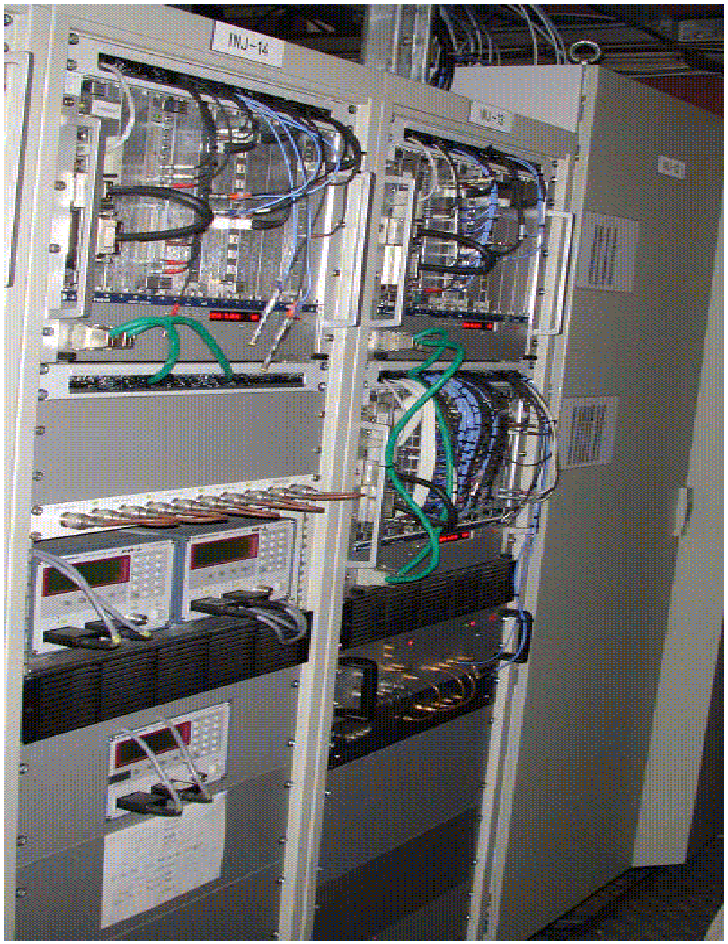


C67 DSP board

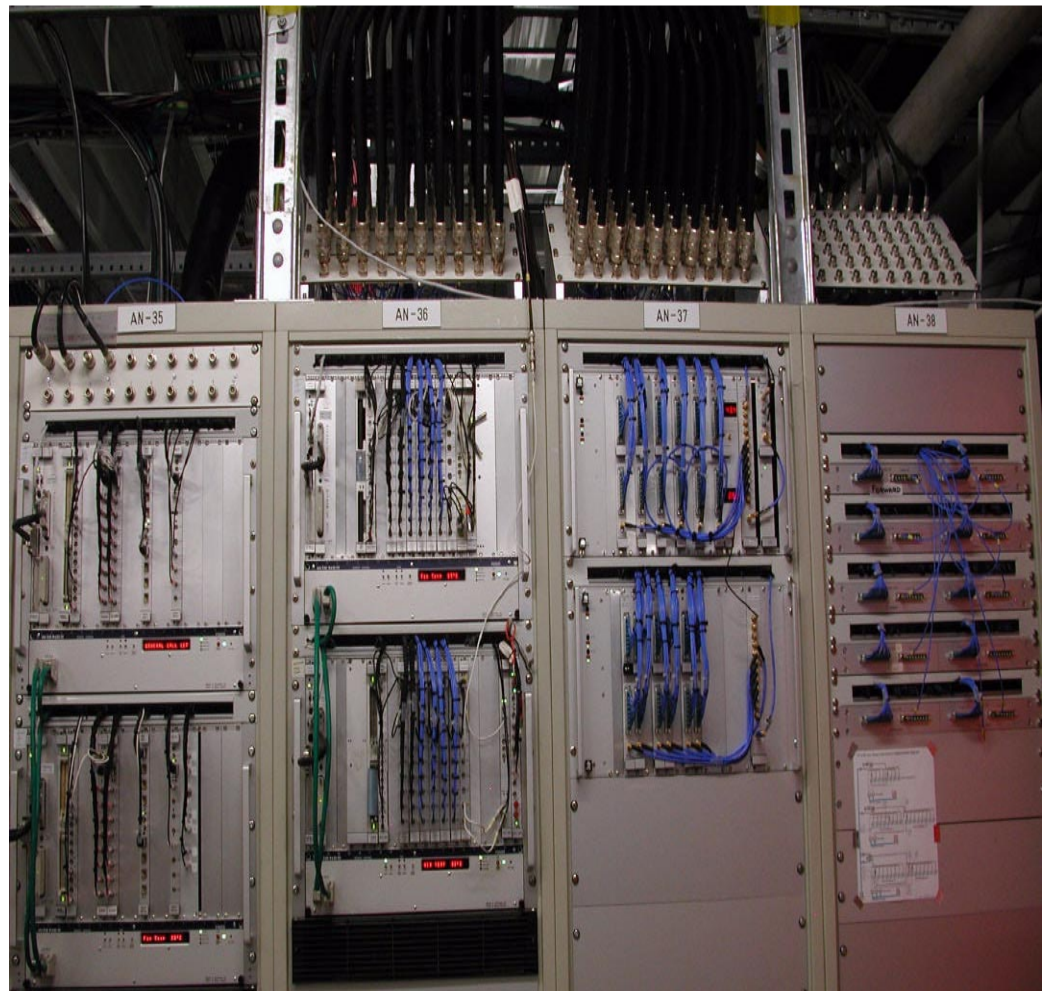


Digital Feedback Hardware

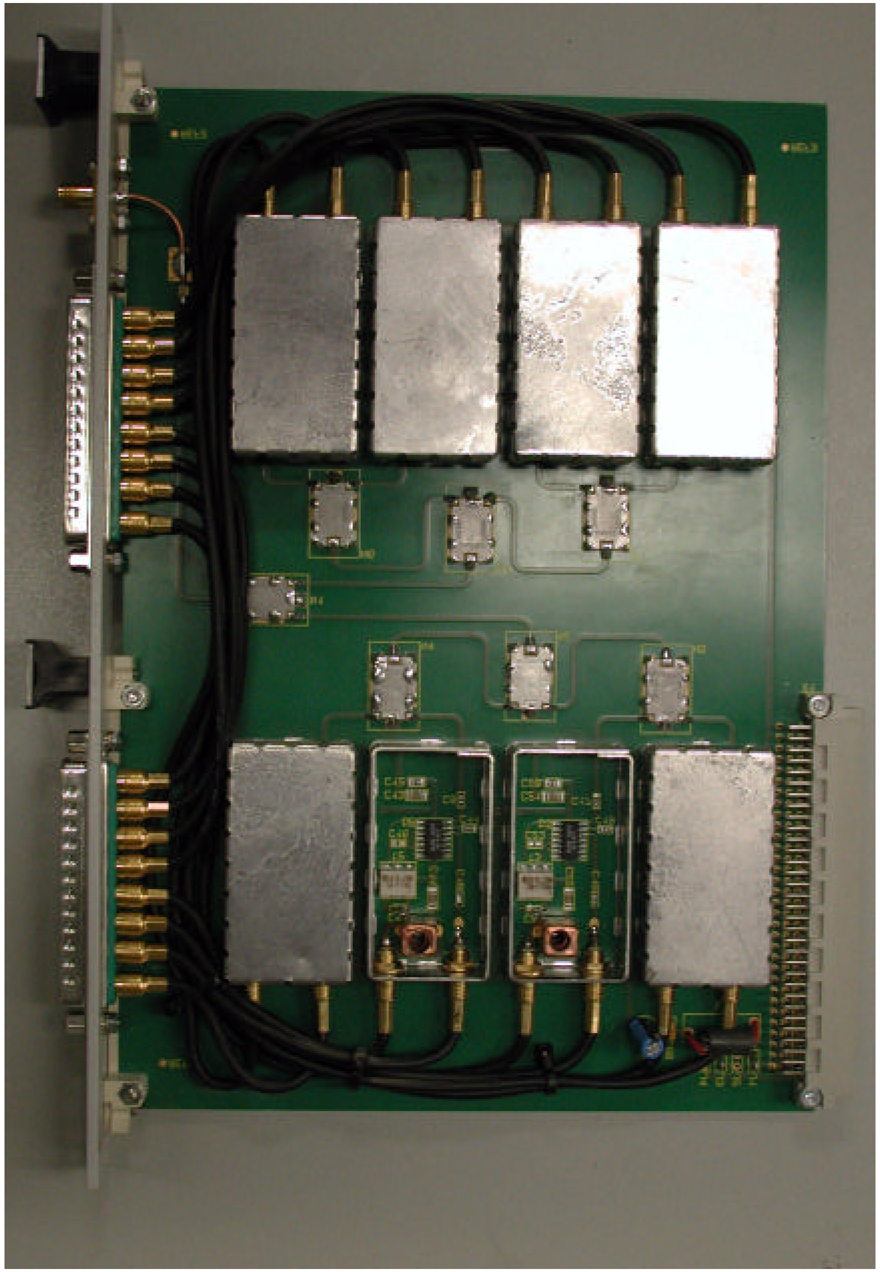
Gun and ACC1

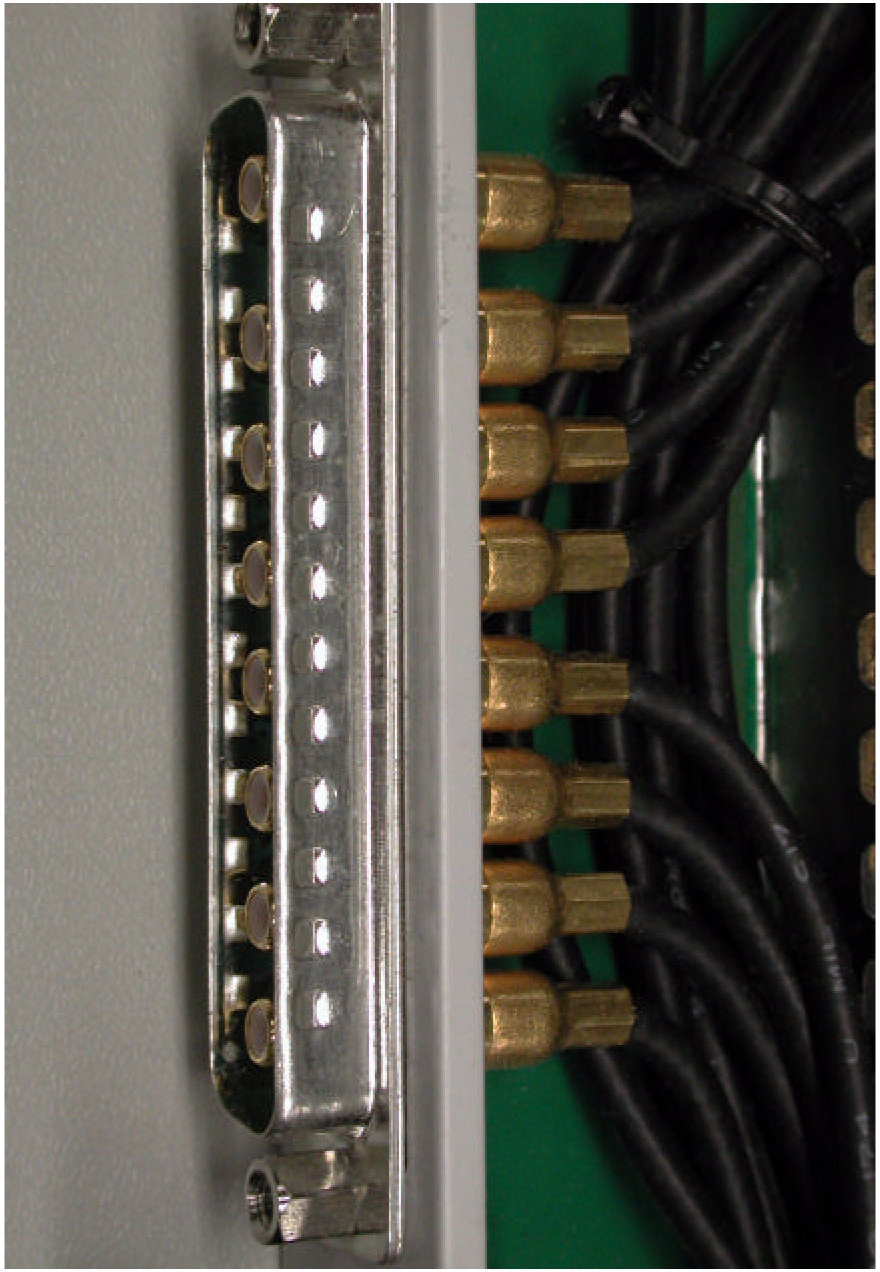


ACC2, ACC3, ACC4 & ACC5

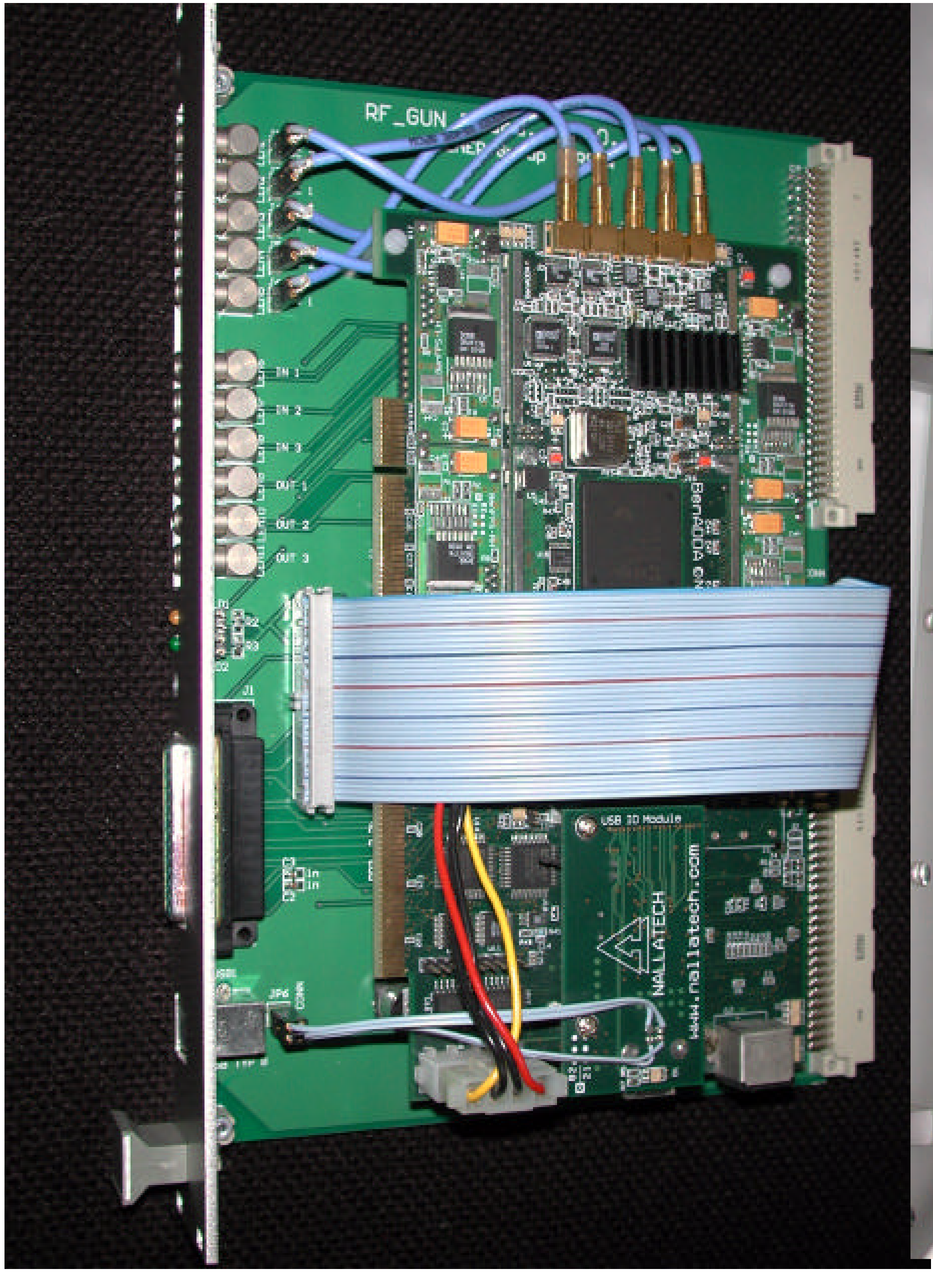


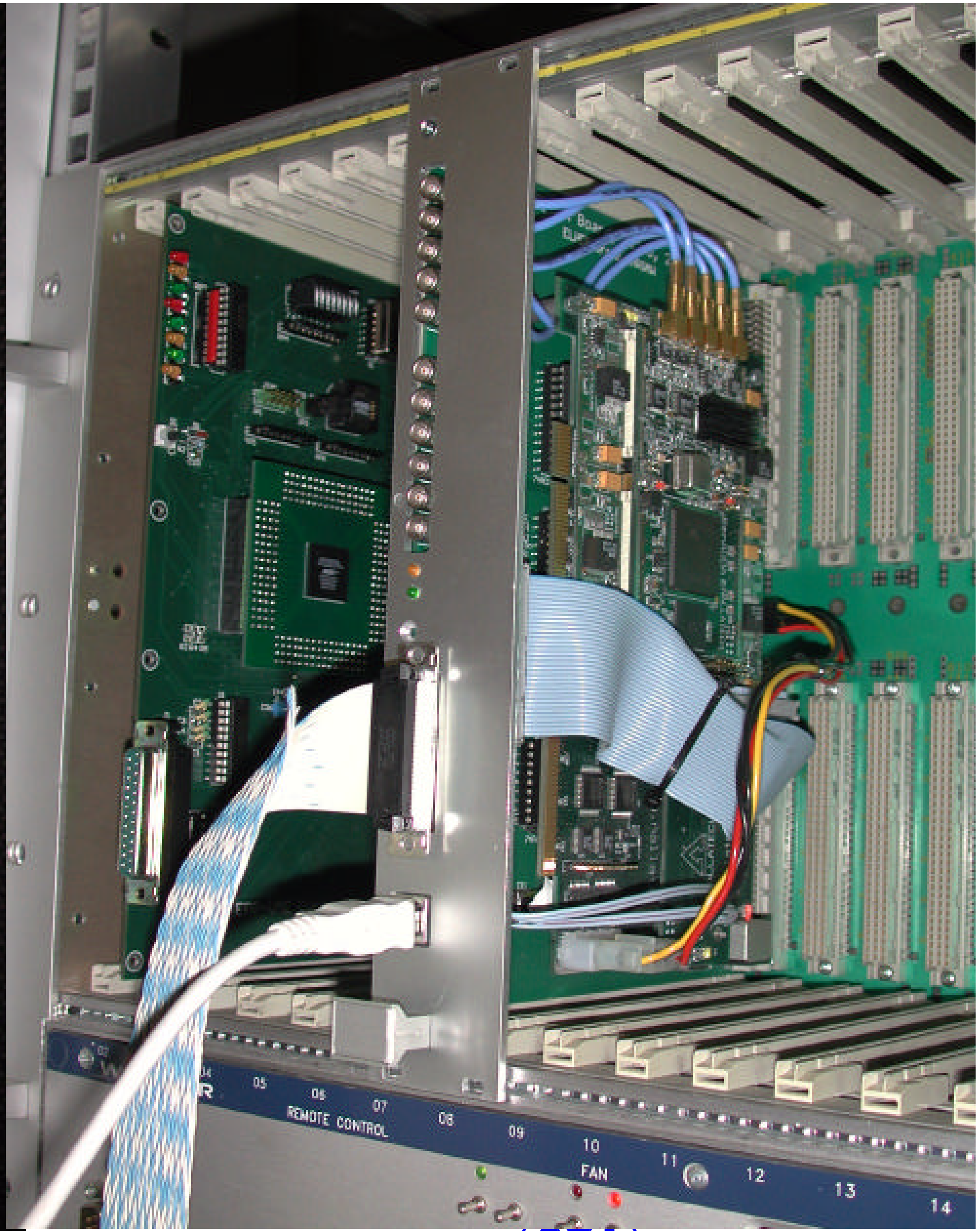
Downconverter



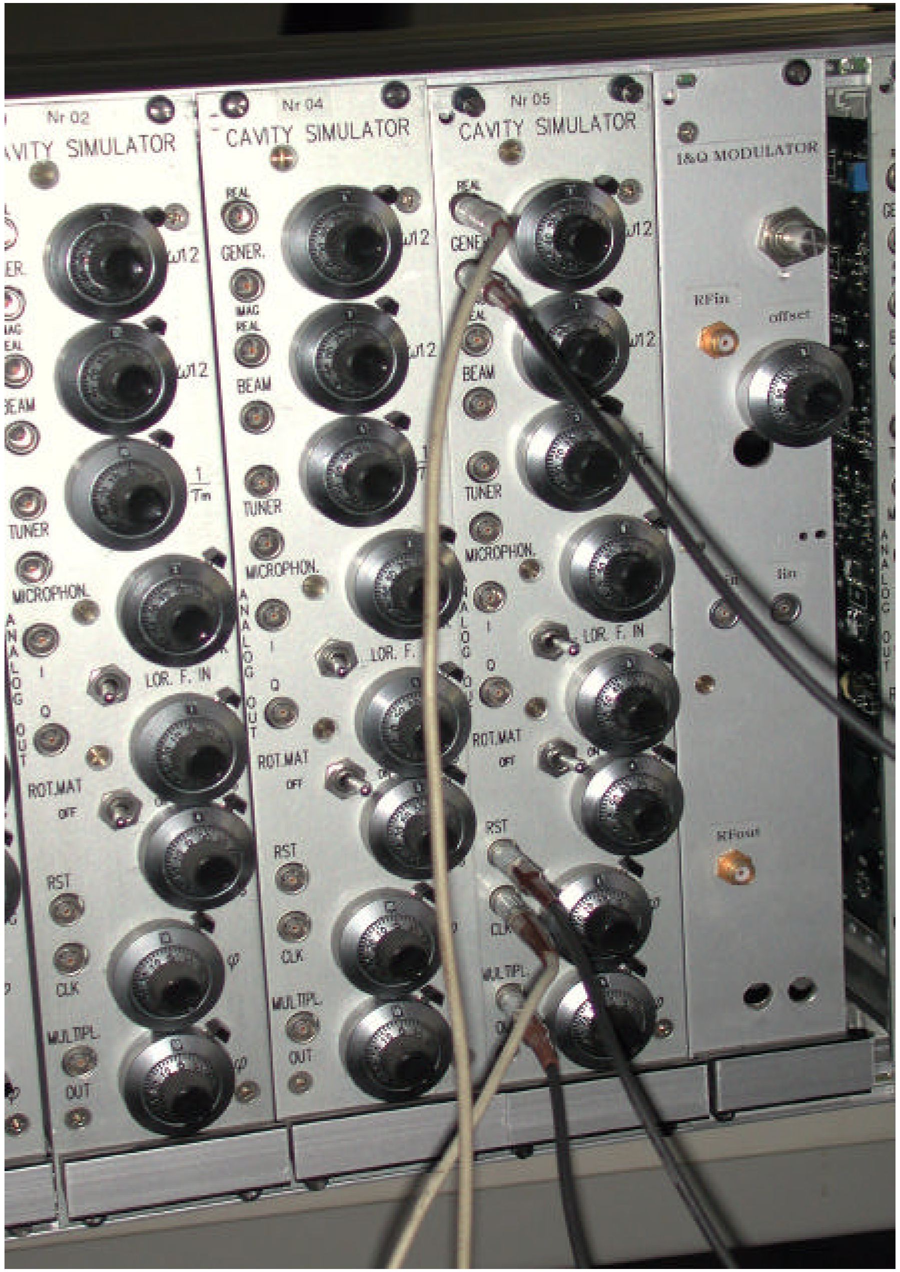


FPGA based RF Gun Controller

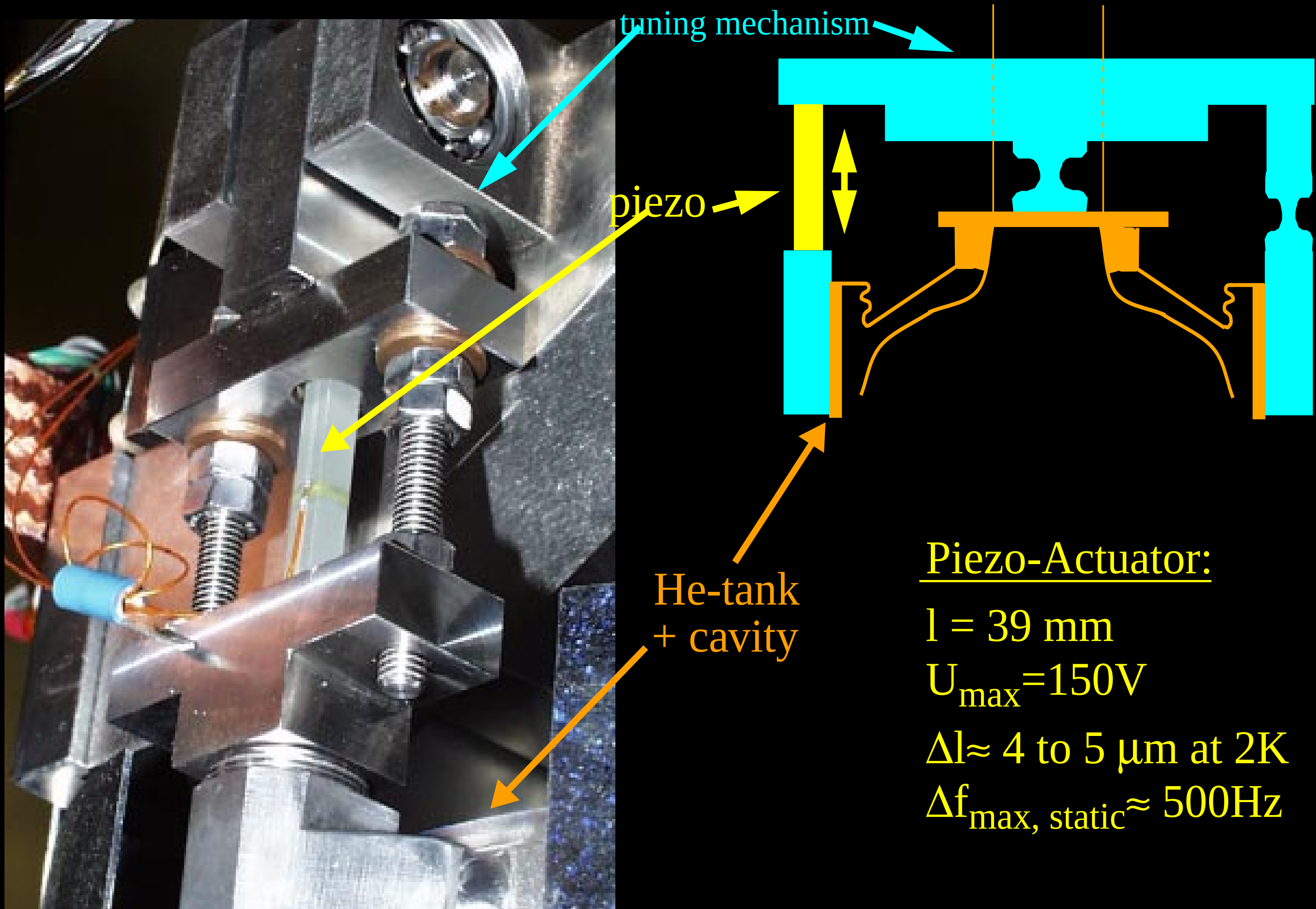




Cavity Simulator



Active Compensation of Lorentz Force Detuning (1)



Piezo-Actuator:

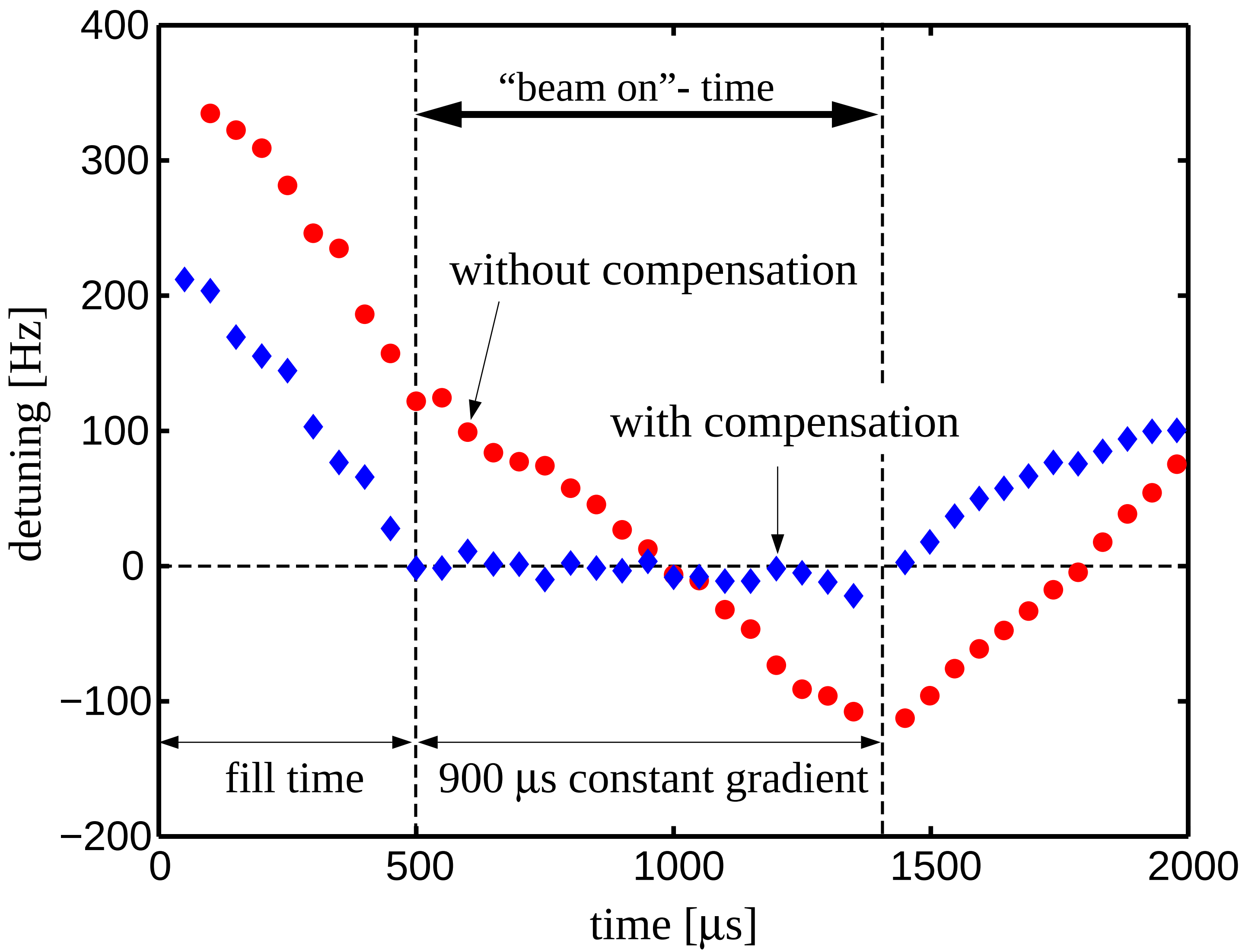
l = 39 mm

U_{max}=150V

Δl≈ 4 to 5 μm at 2K

$\Delta f_{max,\ static}$≈ 500Hz

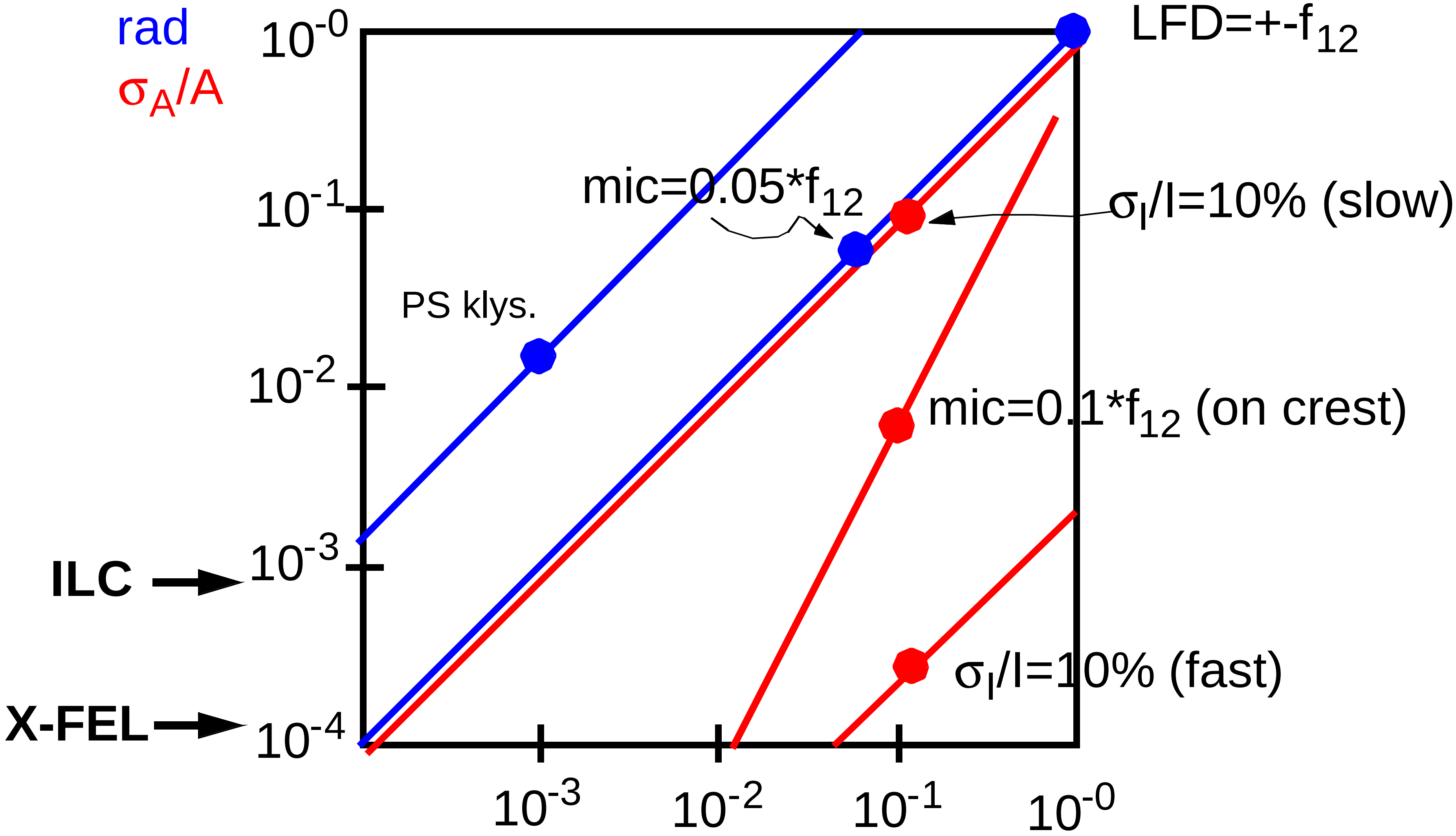
Active Compensation of Lorentz Force Detuning (2)



9-cell cavity operated at 23.5 MV/m

Lorentz force compensated with fast piezoelectric tuner

Open Loop Errors



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 mechanical 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

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)

RFC-1925 - The Fundamental Truths

April 1, 1996

(1) It Has To Work.

(2) No matter how hard you push and no matter what the priority, you can't increase the speed of light.

   a. (corollary). No matter how hard you try, you can't make a baby in much less than 9 months. Trying to speed this up *might* make it slower, but it won't make it happen any quicker.

(3) With sufficient thrust, pigs fly just fine. However, this is not necessarily a good idea. It is hard to be sure where they are going to land, and it could be dangerous sitting under them as they fly overhead.

(4) Some things in life can never be fully appreciated nor understood unless experienced firsthand. Some things in ~~networking~~ ACCELERATORS can never be fully understood by someone who neither builds commercial ~~networking~~ ACCELERATOR equipment nor runs an operational ~~network~~ ACCELERATOR.

(5) It is always possible to agglutinate multiple separate problems into a single complex interdependent solution. In most cases this is a bad idea.

RFC-1925 - The Fundamental Truths – cont.

(6) It is easier to move a problem around (for example, by moving the problem to a different part of the overall ~~networking~~ ACCELERATOR CONTROLS architecture) than it is to solve it.
   a. (corollary). It is always possible to add another level of indirection.

(7) It is always something
   a. (corollary). Good, Fast, Cheap: Pick any two (you can't have all three).

(8) It is more complicated than you think.

(9) For all resources, whatever it is, you need more.
   a. (corollary) Every ~~networking~~ ACCELERATOR problem always takes longer to solve than it seems like it should.

(10) One size never fits all.

(11) Every old idea will be proposed again with a different name and a different presentation, regardless of whether it works.
   a. (corollary). See rule 6a.

(12) In ~~protocol~~ LLRF design, perfection has been reached not when there is nothing left to add, but when there is nothing left to take away.