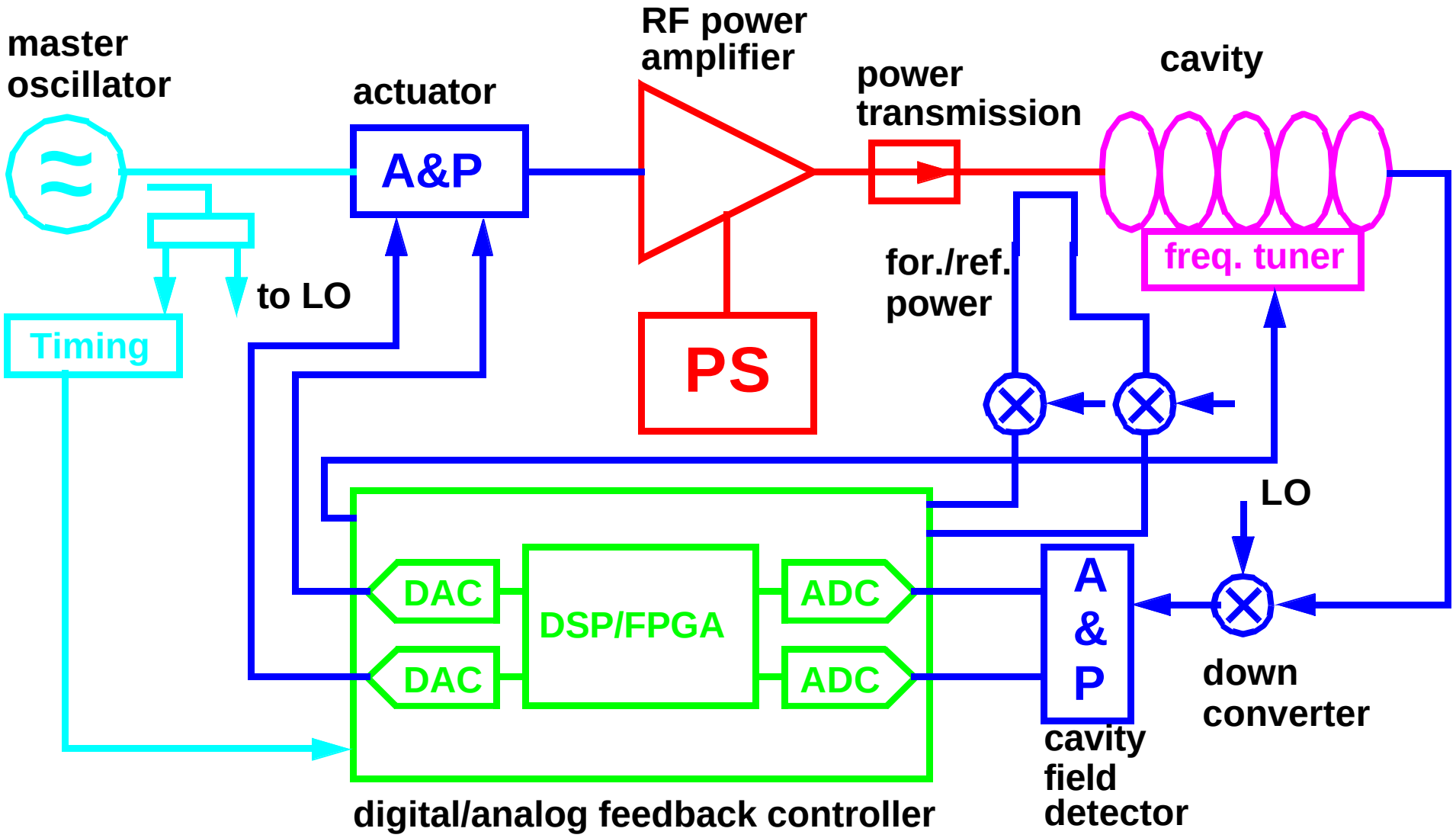
Options for RF Control & State of Art Simulation and Performance

S. Simrock, DESY

Outline

- Principle of RF Control
- State of the Art
- Simulation
- Measured Performance
- Conclusion

RF System Architecture



Requirements for LLRF Controls

- 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

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

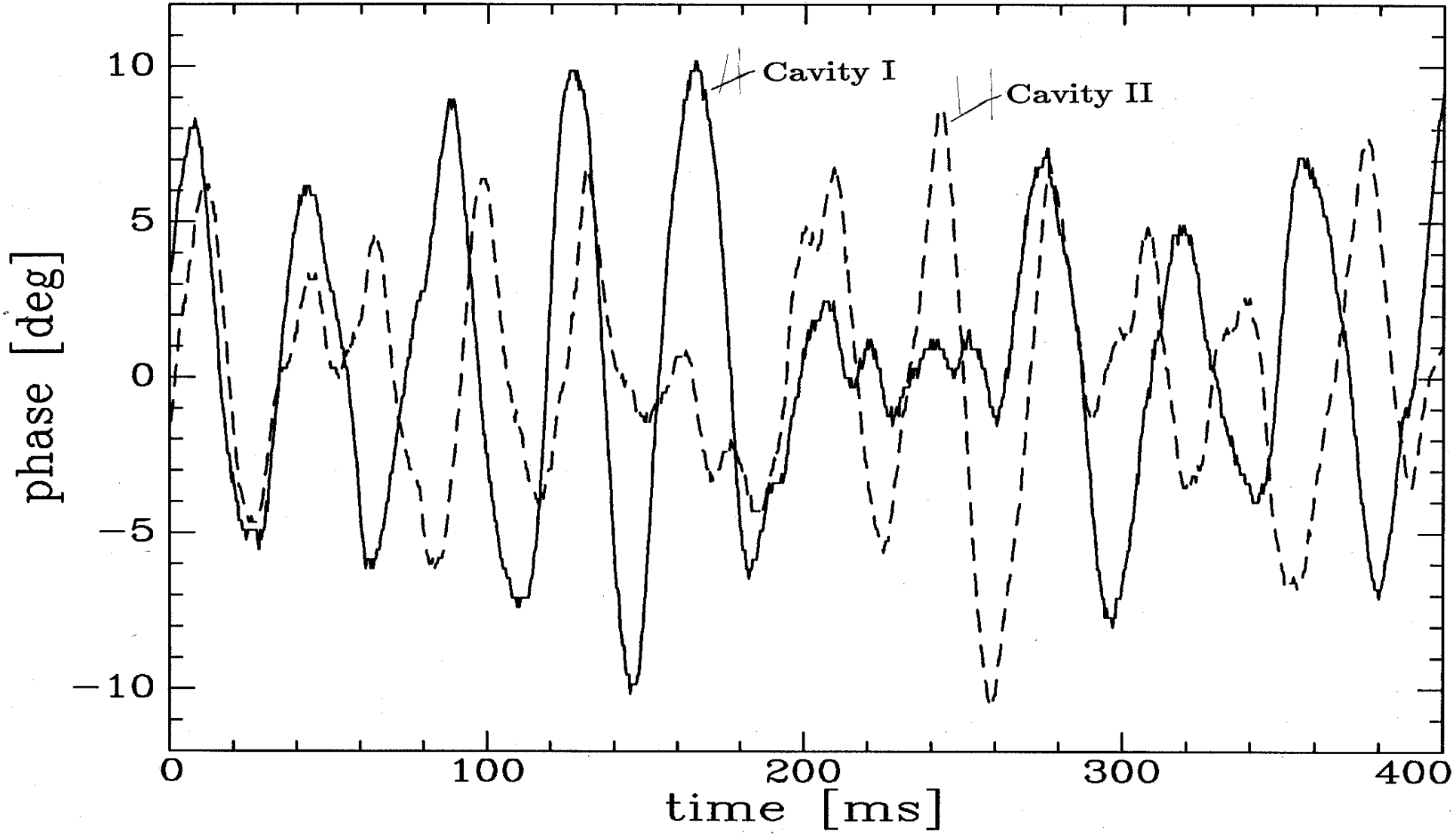
o Cavity drive signal
- HV- Pulse flatness
- HV PS ripple
- Phase noise from master oscillator
- Timing signal jitter
- Mismatch in power distribution

o Cavity dynamics
- cavity filling
- settling time of field

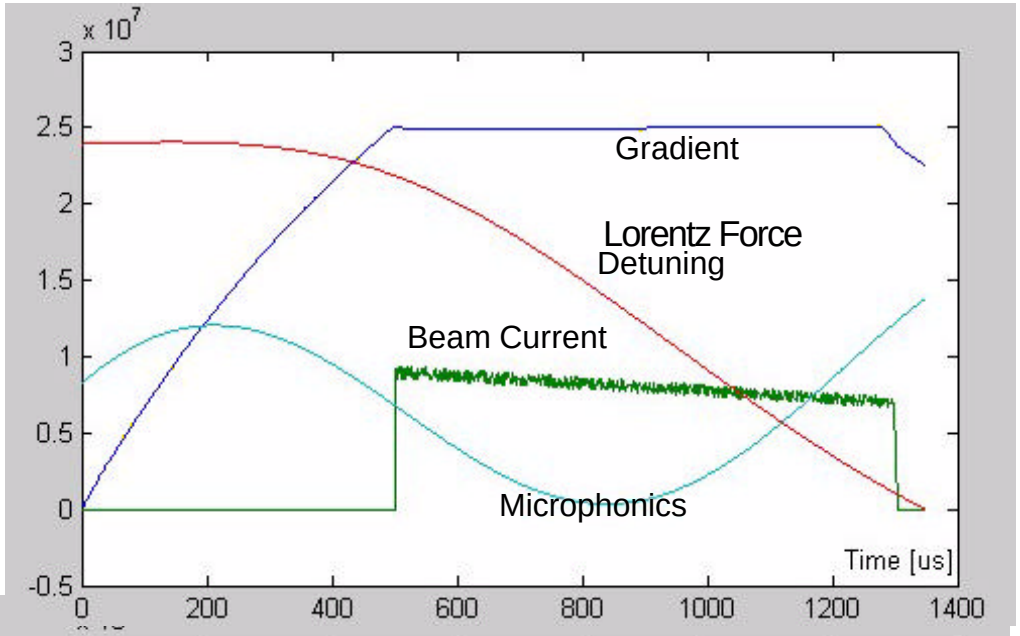
o Cavity resonance frequency change
- thermal effects (power dependent)
- Microphonics
- Lorentz force detuning

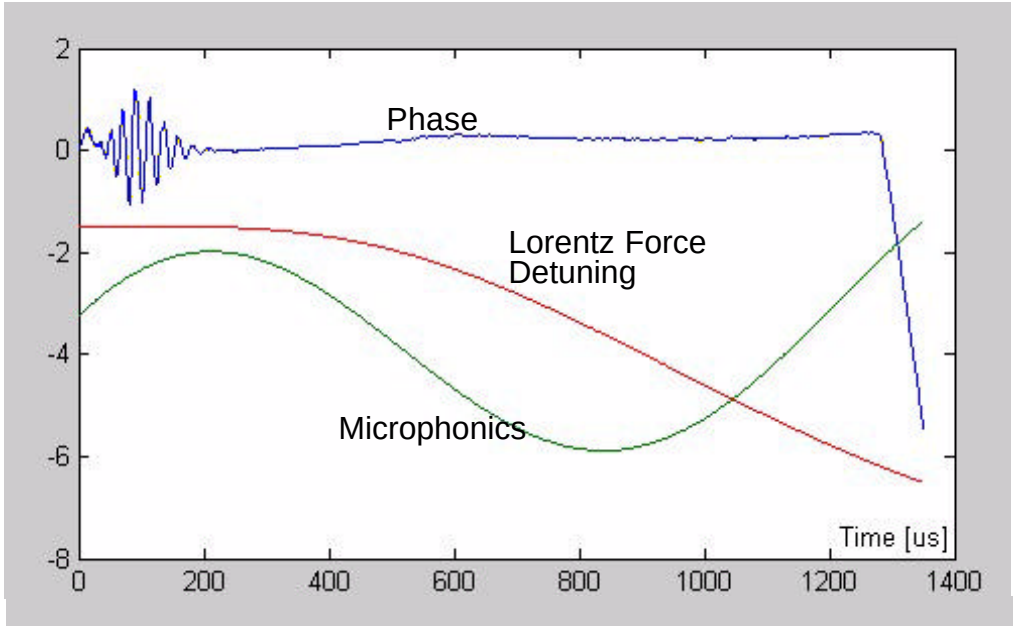
o Other
- Response of feedback system
- Interlock trips
- Thermal drifts (electronics, power amplifiers, cables, power transmission system)

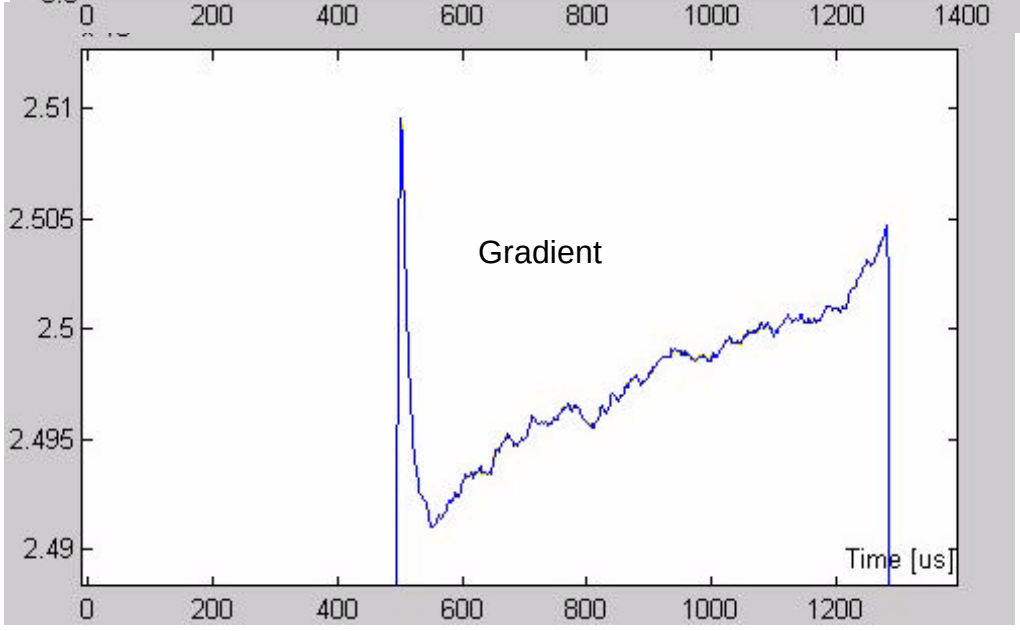
Microphonics at JLAB

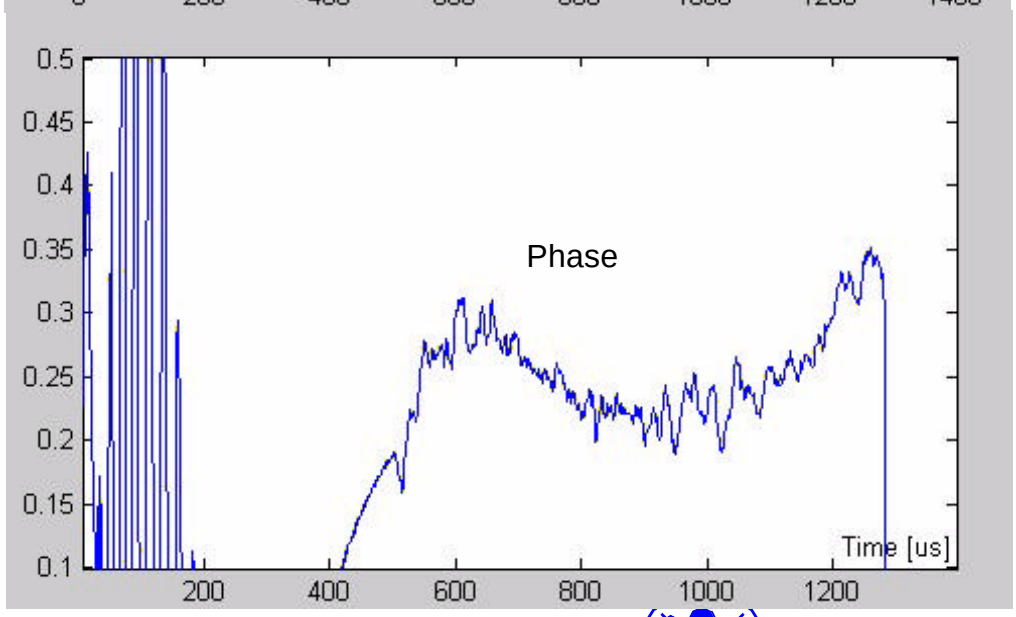


RF Regulation TESLA Cavity (Simulation)





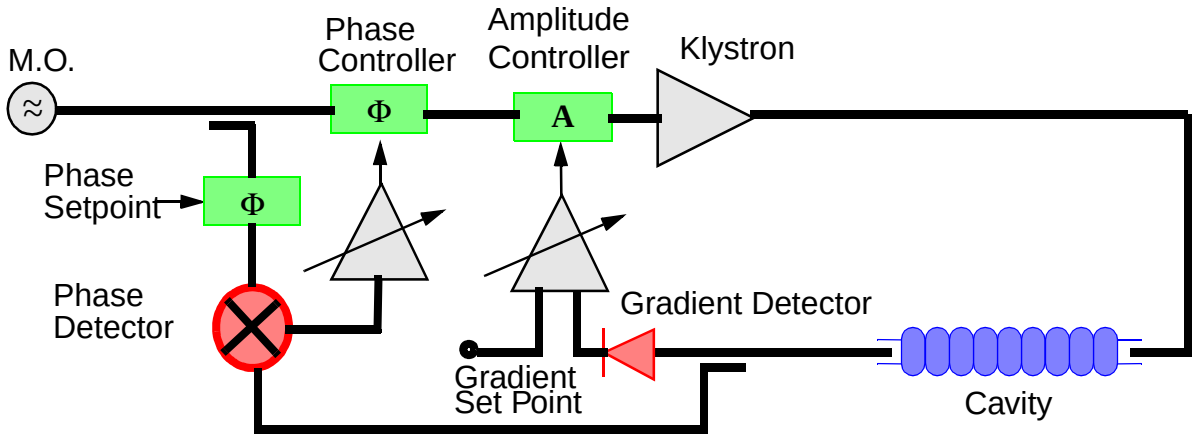




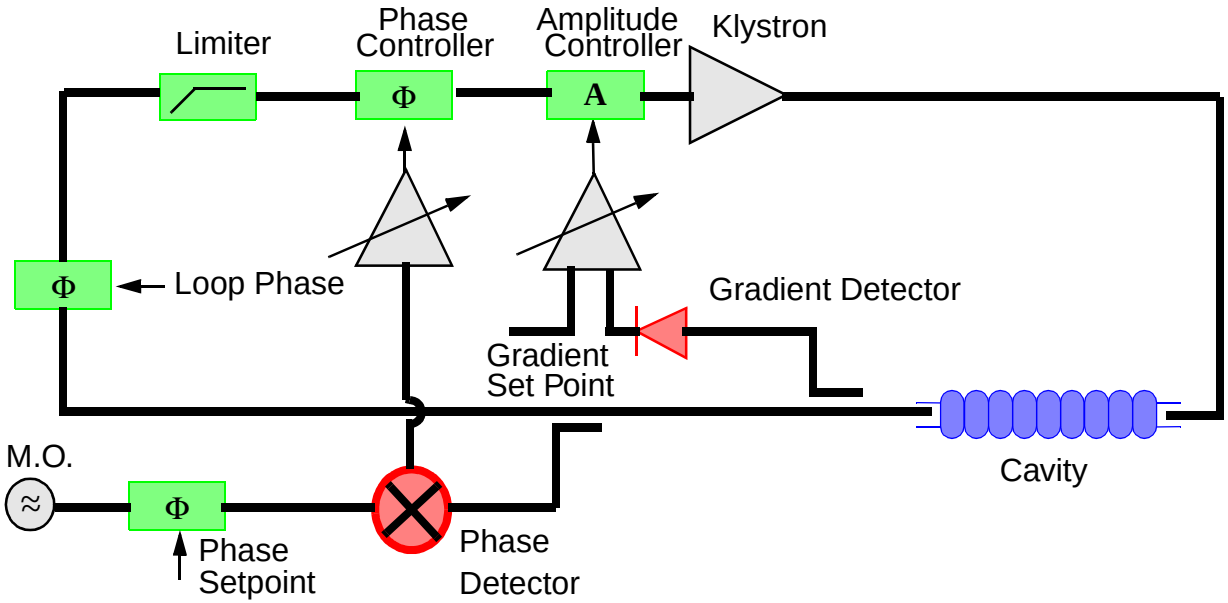
Control Choices (1)

- 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

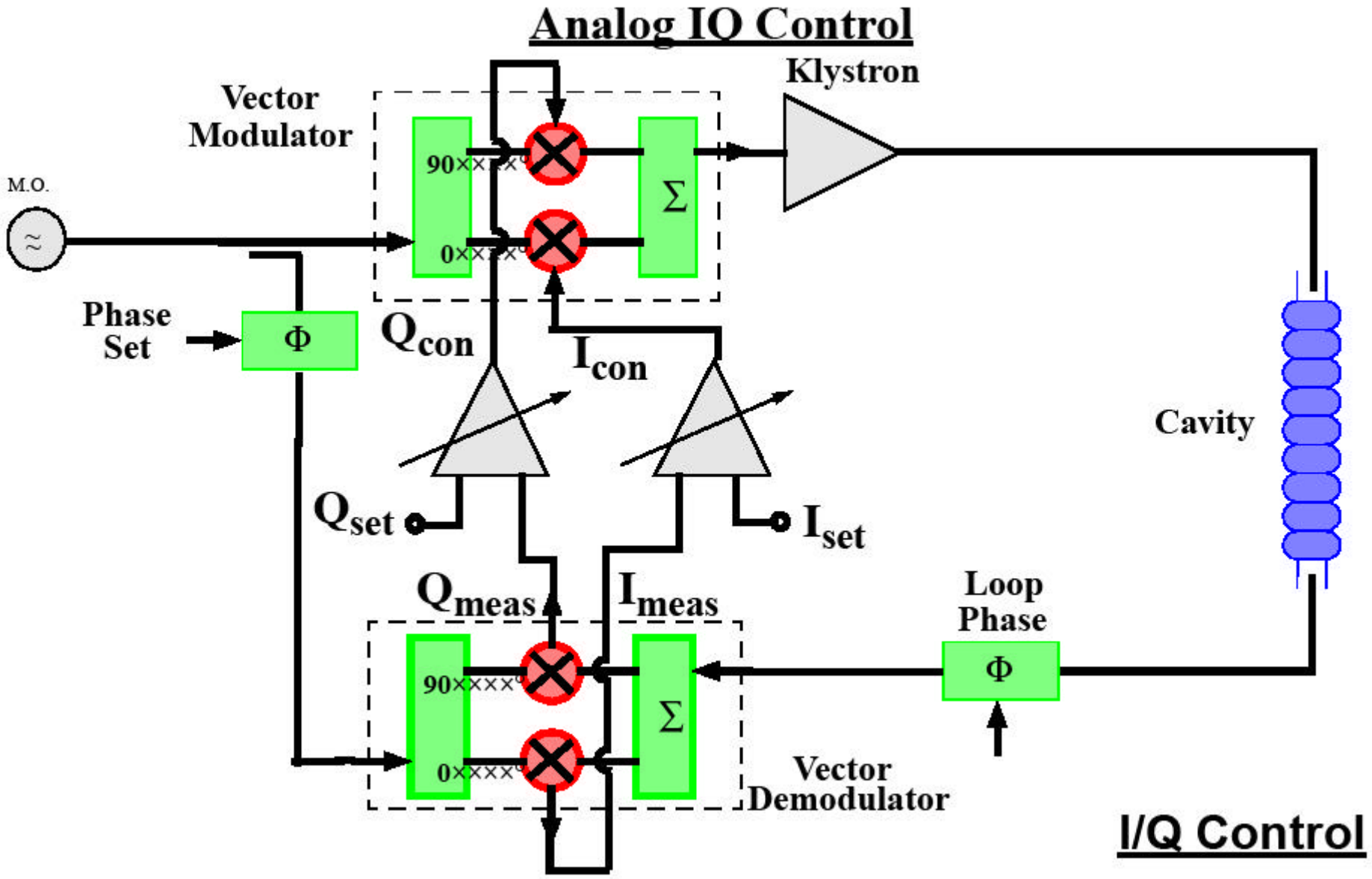
Control Choices (2)



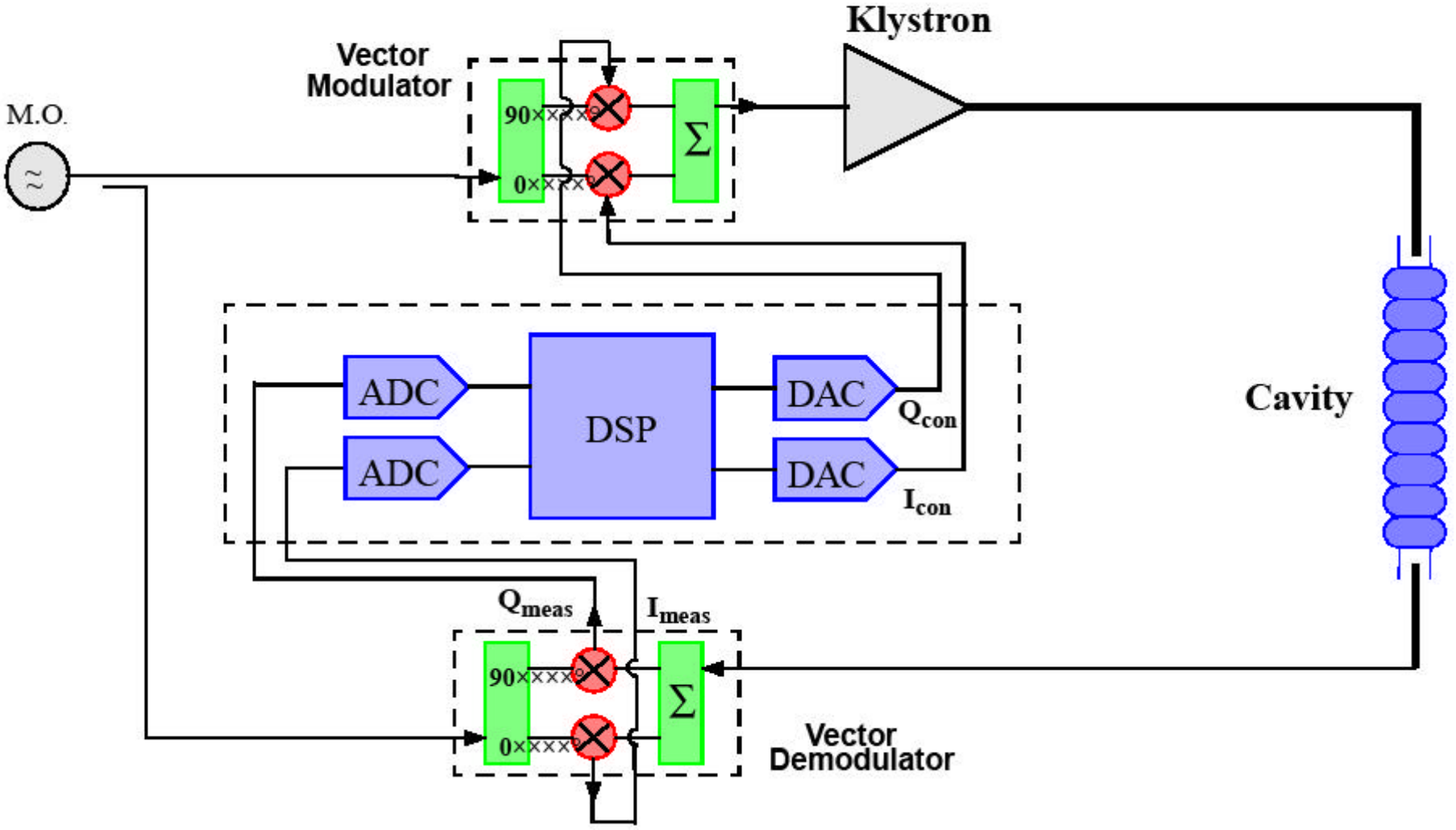
Generator Driven Resonator



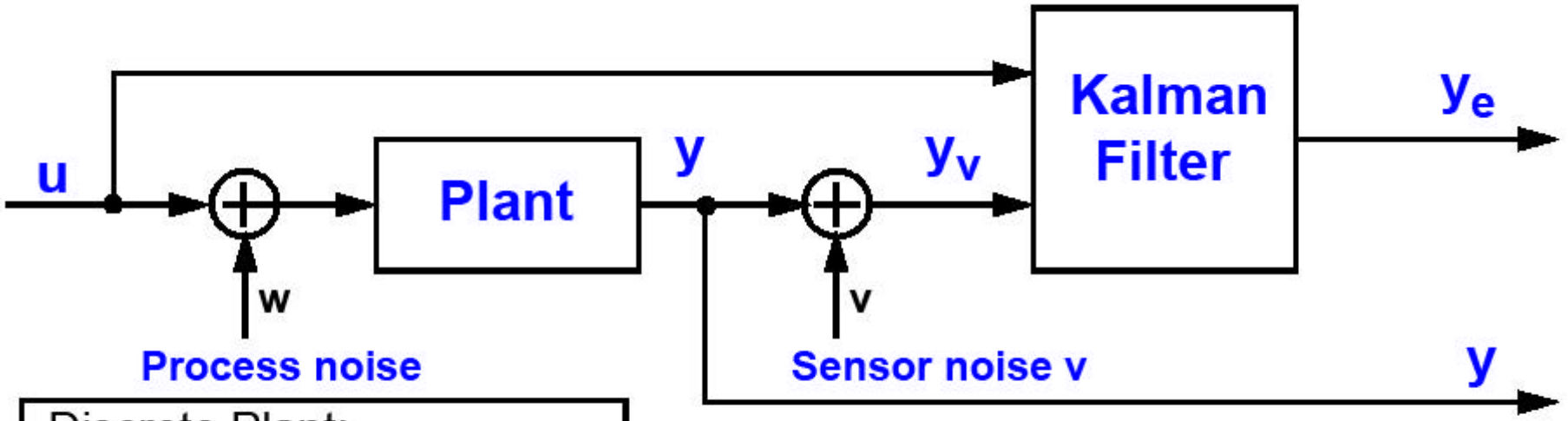
Self Excited Loop


Analog IQ Control
Klystron
Vector
Modulator
M.O.
90××××°
0××××°
Σ
Phase
Set
Φ
Qcon
Icon
Cavity
Qset
Iset
Qmeas
Imeas
Loop
Phase
Φ
90××××°
0××××°
Σ
Vector
Demodulator
I/Q 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:

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

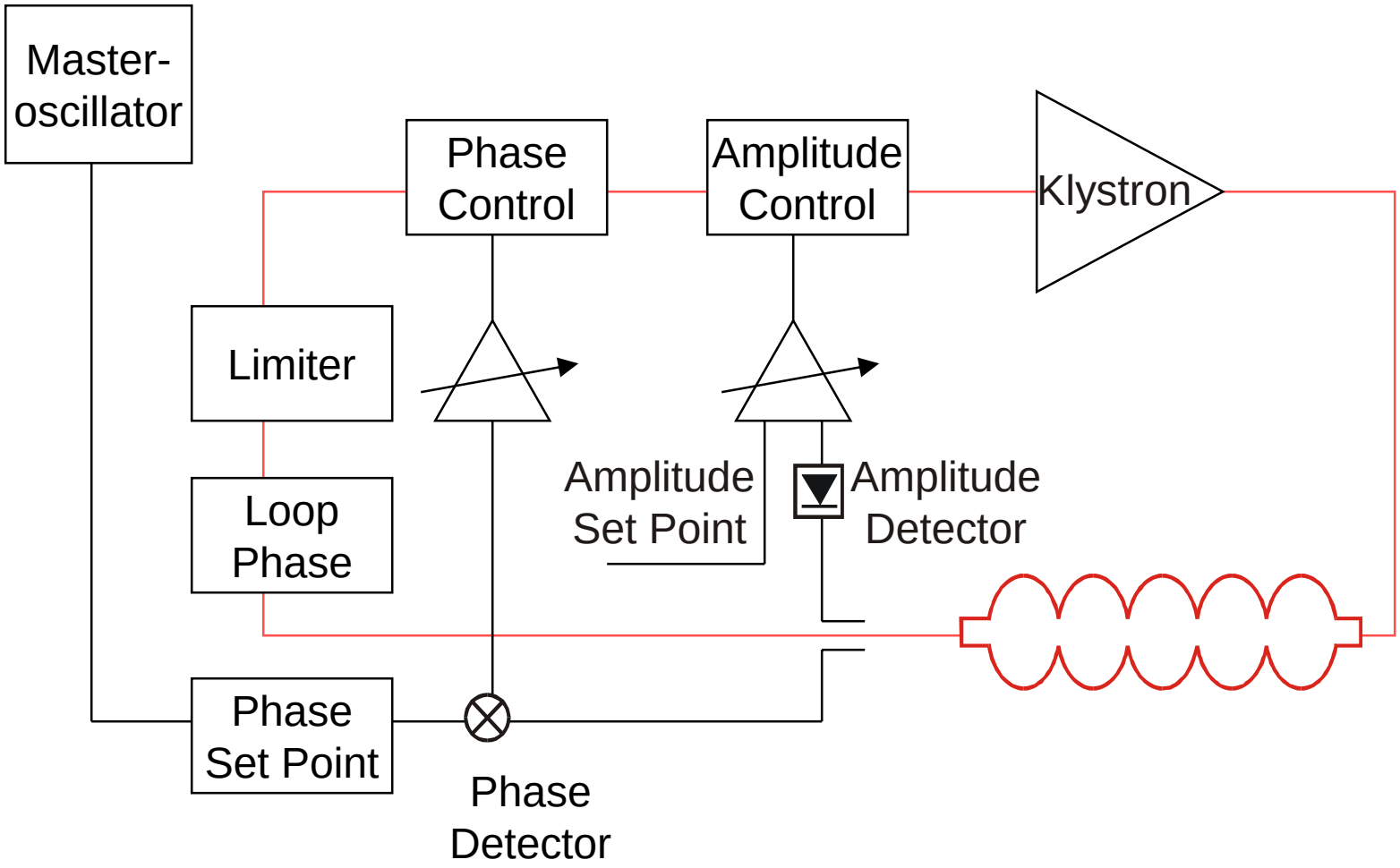
Time update: $\hat{x}[n+1|n]=A\hat{x}[n|n]+Bu[n]$

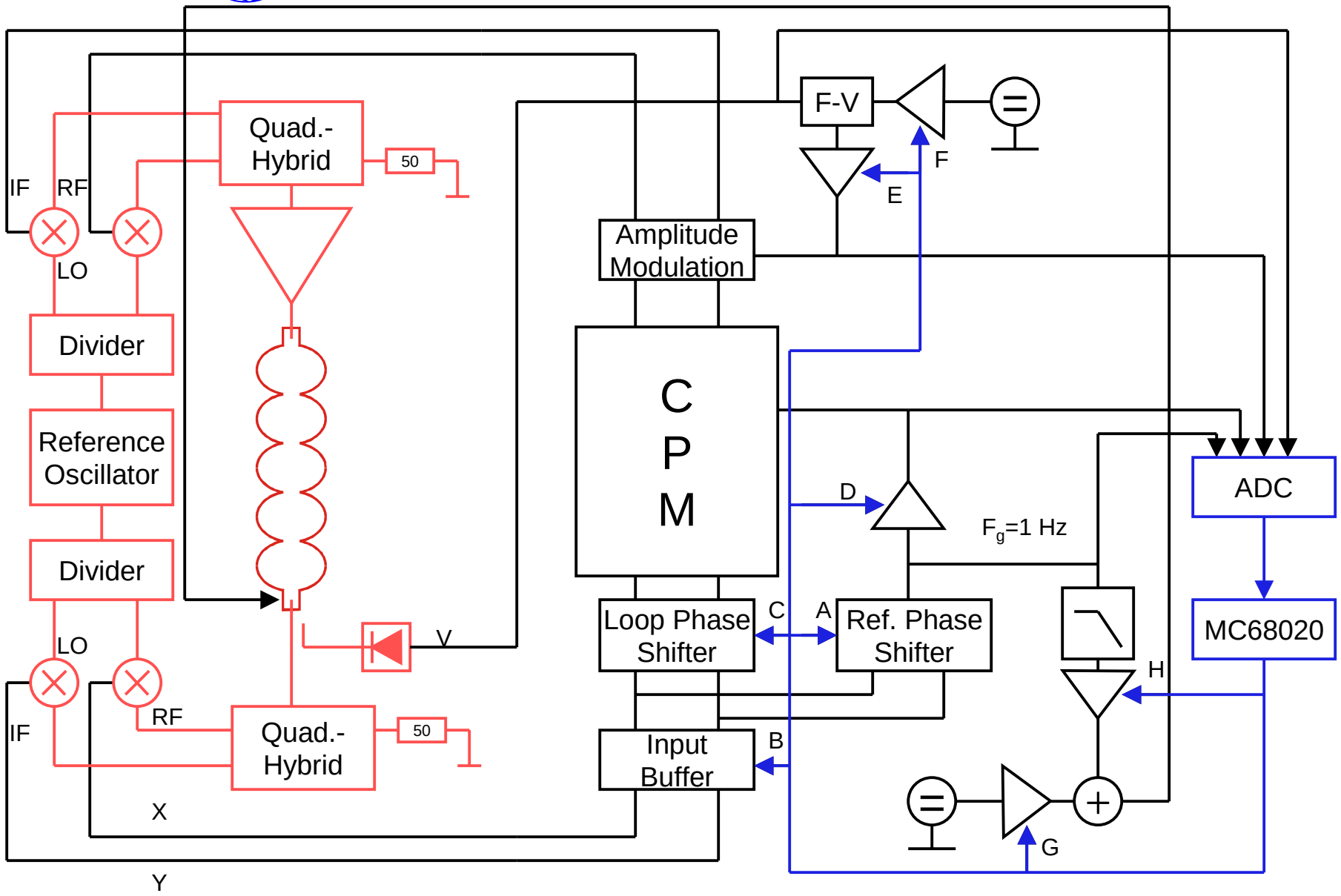
The correction term is a function of the innovation, i.e. the discrepancy

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

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 $E(v[n]v[n]^T)=R$

Self Excited Loop

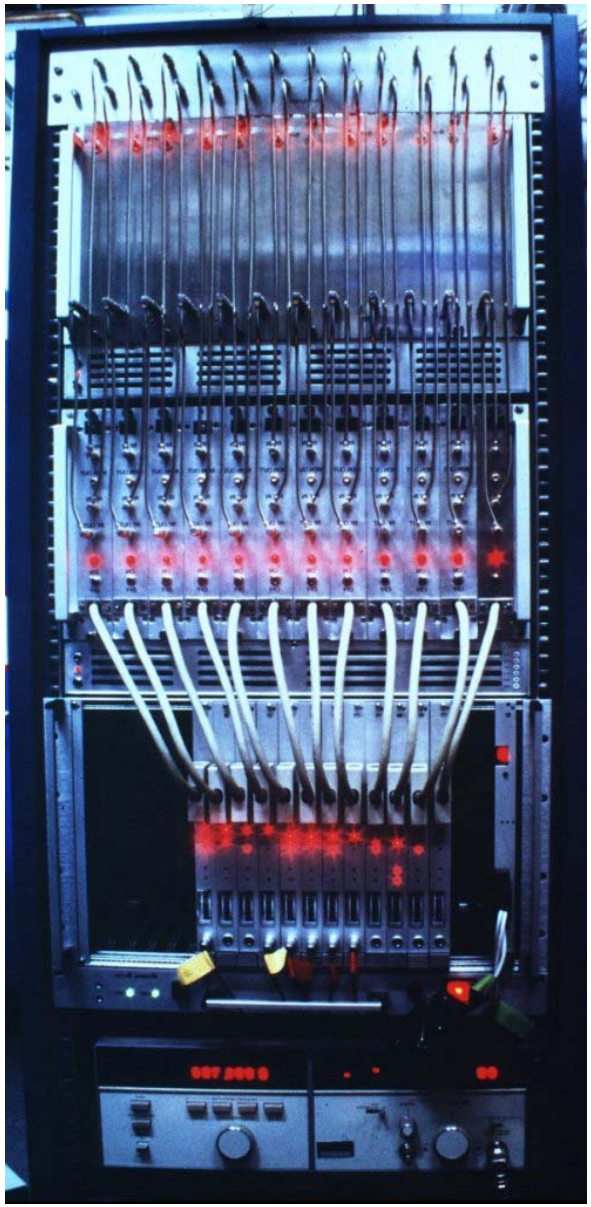



Quad.-
Hybrid
50
IF
RF
LO
Divider
Reference
Oscillator
Divider
LO
IF
RF
Quad.-
Hybrid
50
V
X
Y
F-V
F
E
Amplitude
Modulation
C
P
M
D
F_g=1 Hz
ADC
MC68020
Loop Phase
Shifter
C
A
Ref. Phase
Shifter
H
Input
Buffer
B
G

Presently achieved

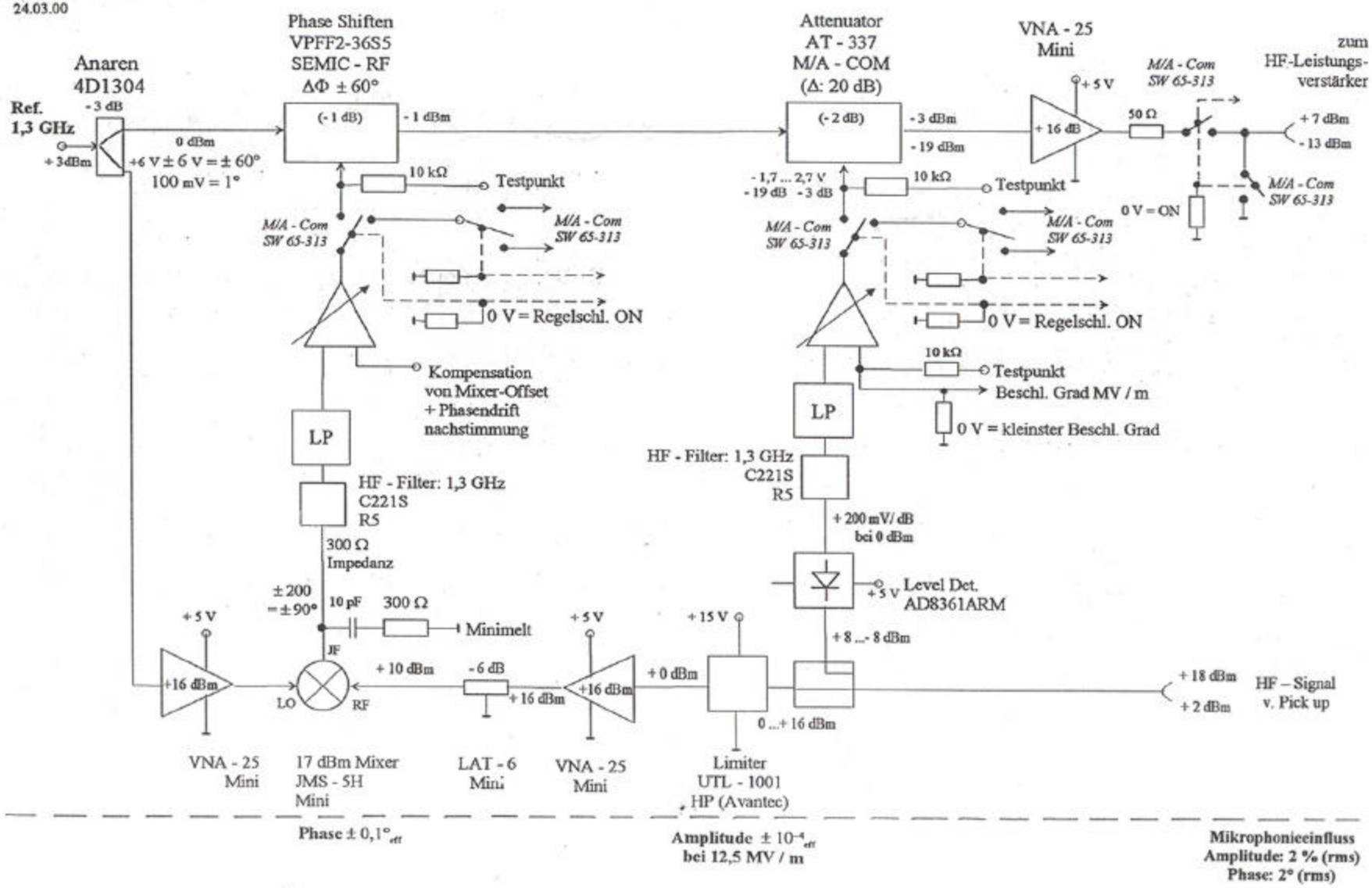
- Amplitude stability: $\Delta E/E = 1 \cdot 10^{-3}$
- Phase jitter: $\Delta\theta/\theta = \pm 0.3°$

The phase control matches the specification, the amplitude control does not!

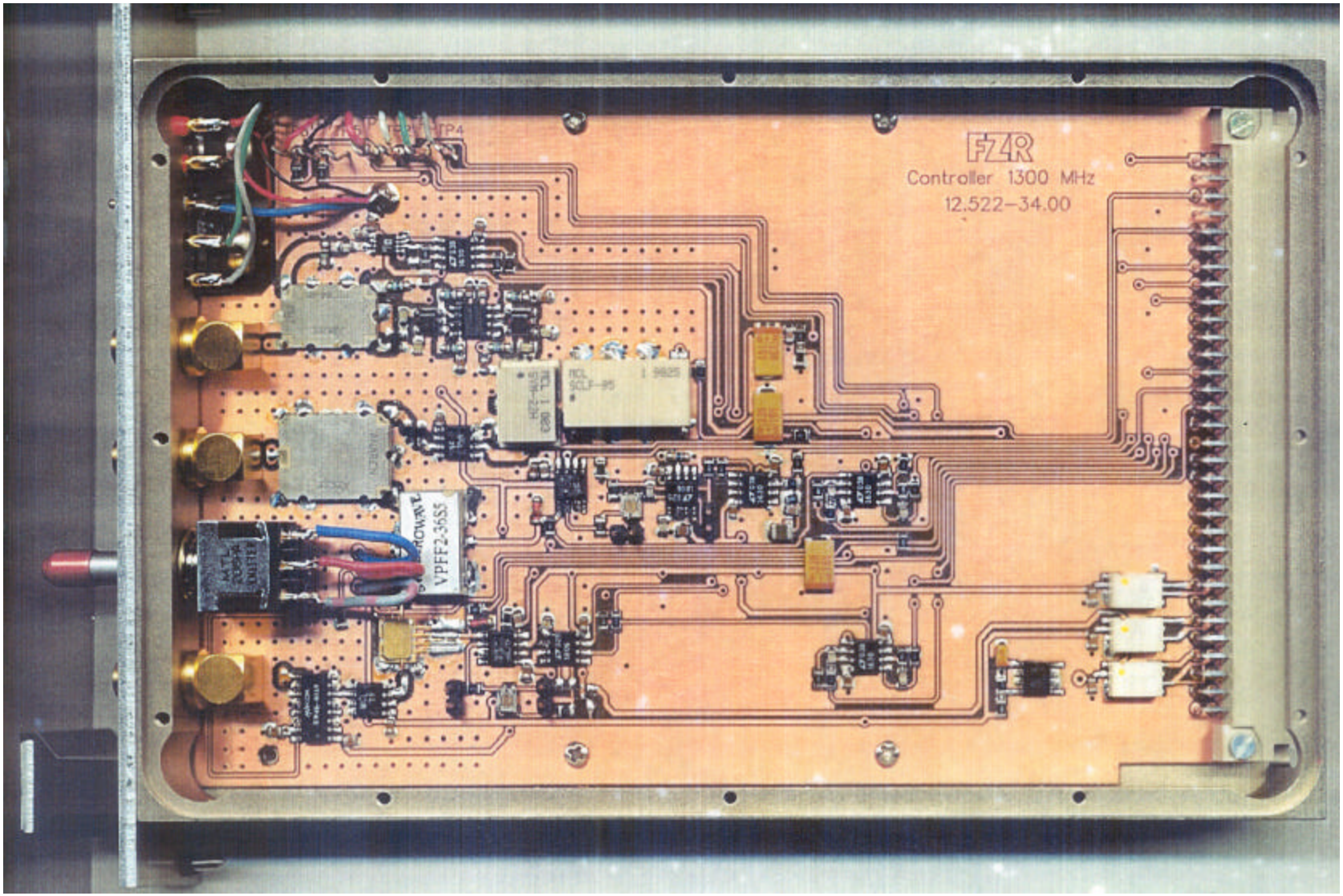


HF-Stabilisierung für Cavities
Controller

24.03.00



FZ Rossendorf

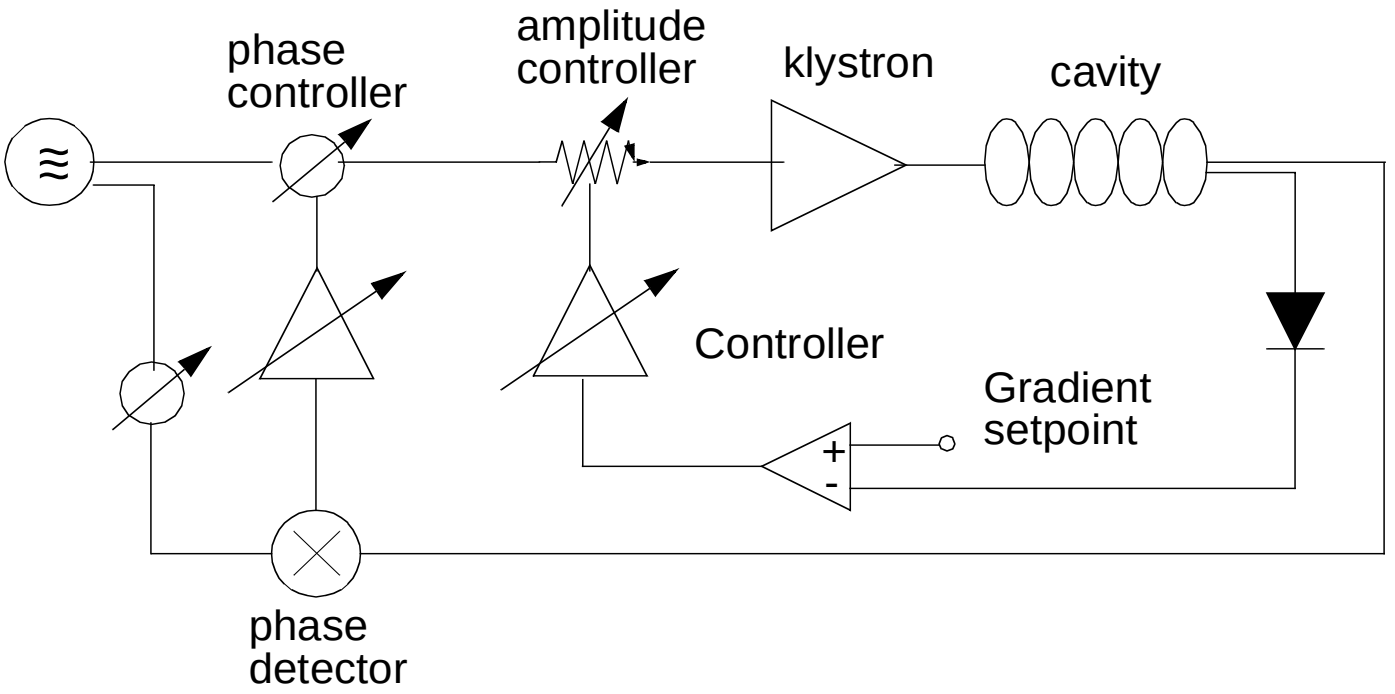


Andree Buechner
FZ Rossendorf

RF Control Model

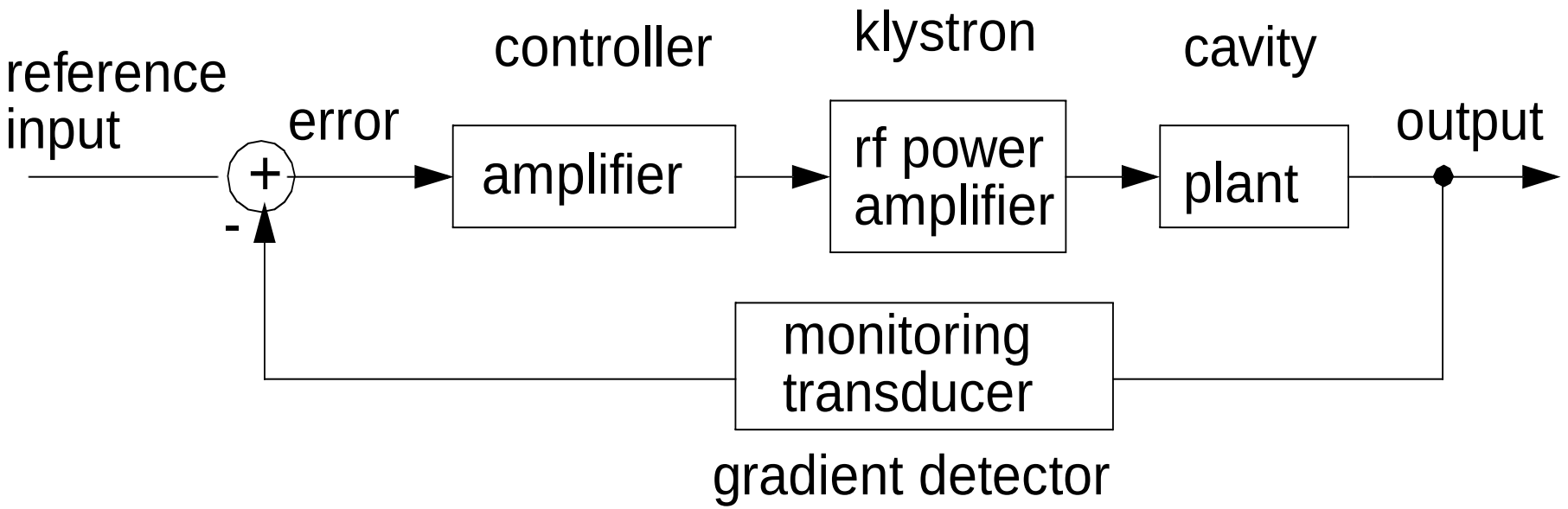
Goal:
Maintain stable gradient and phase

Solution:
Feedback for gradient amplitude and phase:

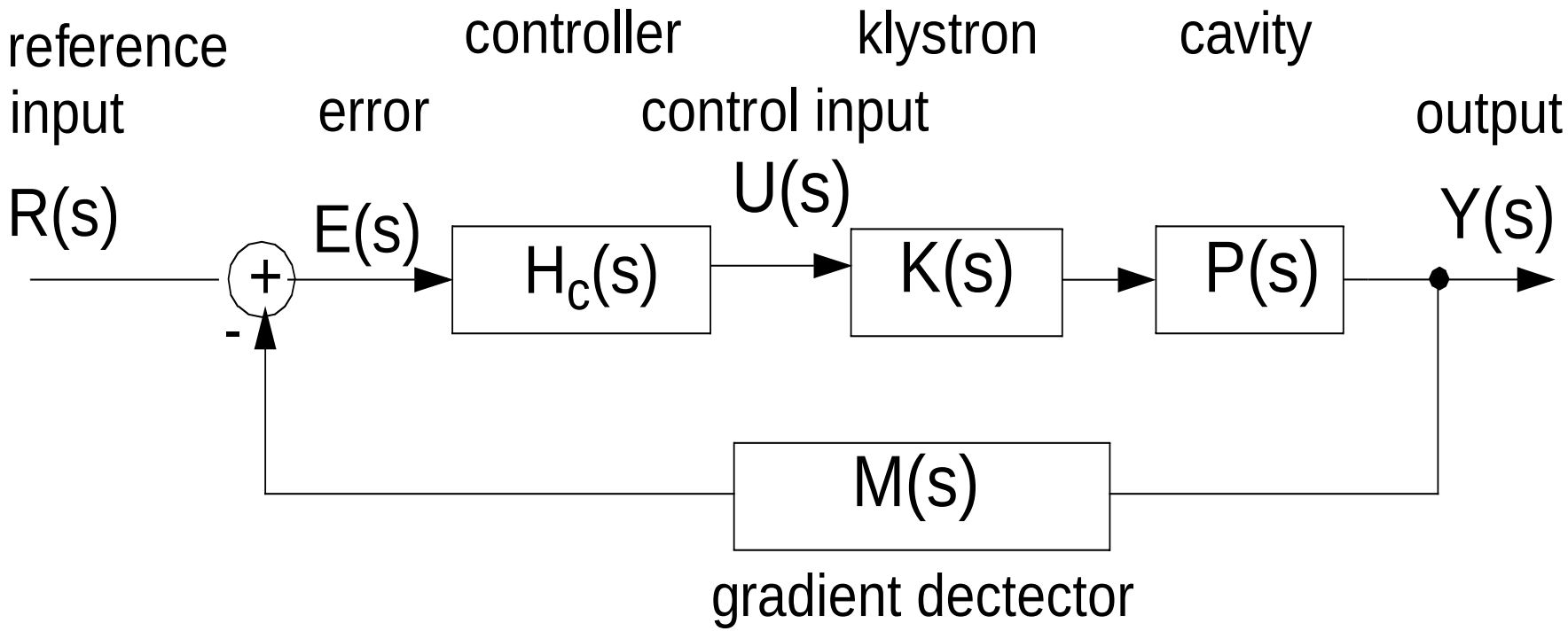


Model:
Mathematical description of input-output relation of components combined with block diagram:

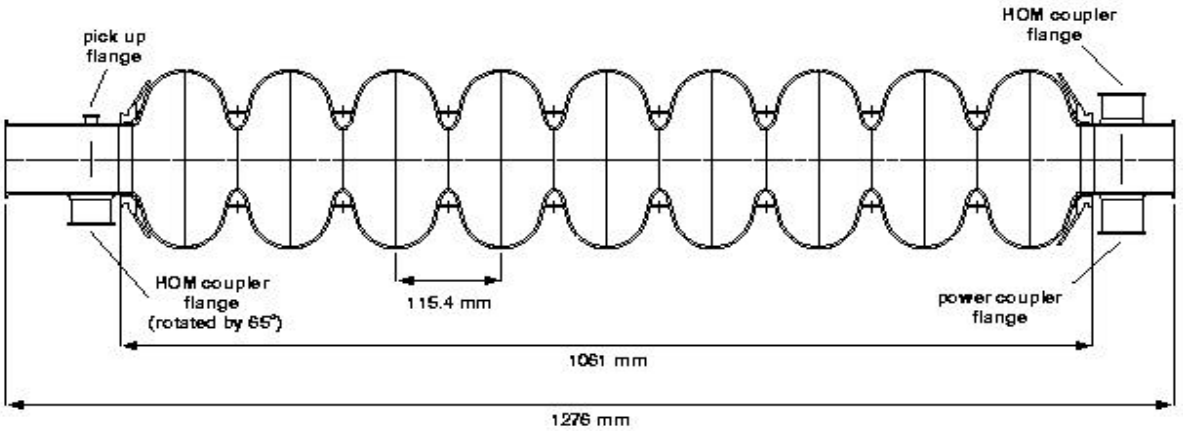
Amplitude Loop (general form):



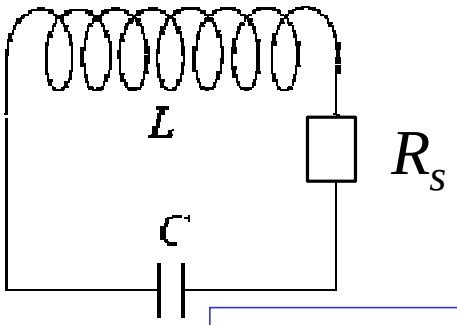
RF Control model using “transfer functions”



Kavitäten für TESLA

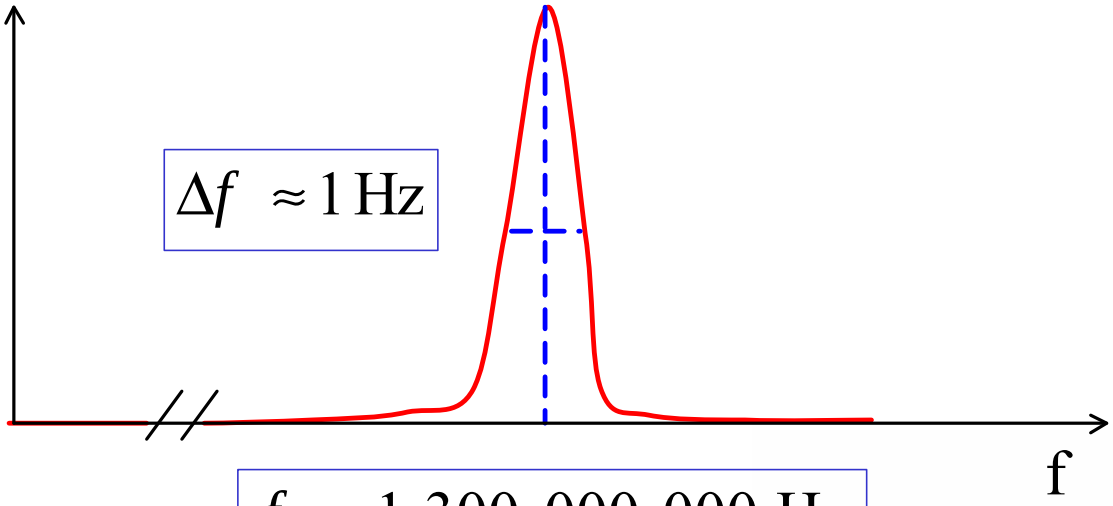


Schwingkreis:



Frequenz: $f_o = \frac{1}{2p\sqrt{LC}}$

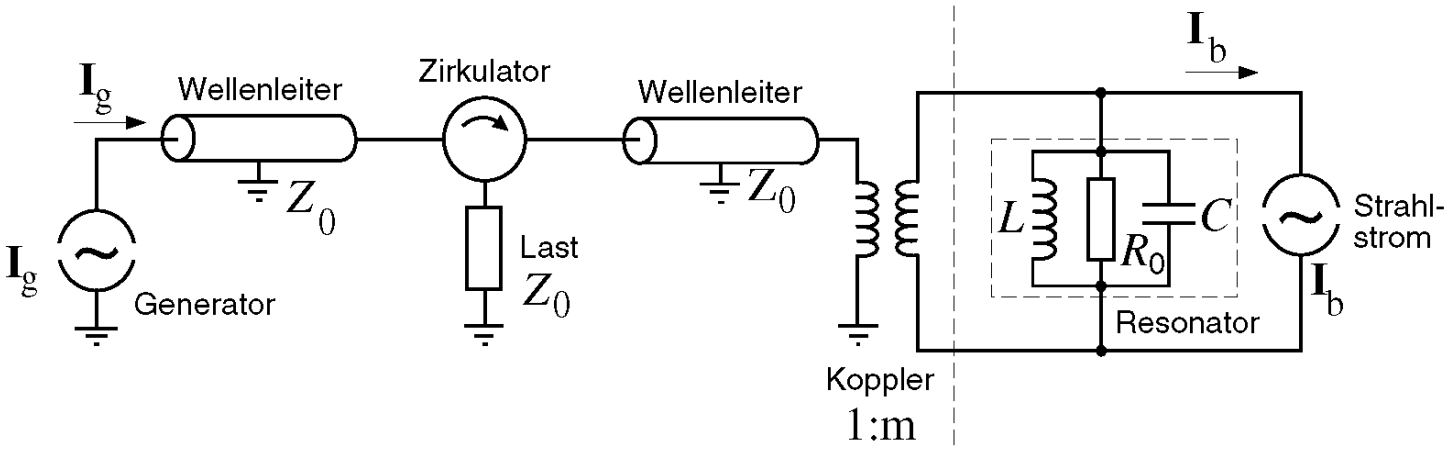
Gütefaktor: $Q_o = \frac{f}{\Delta f} = \frac{G}{R_s}$



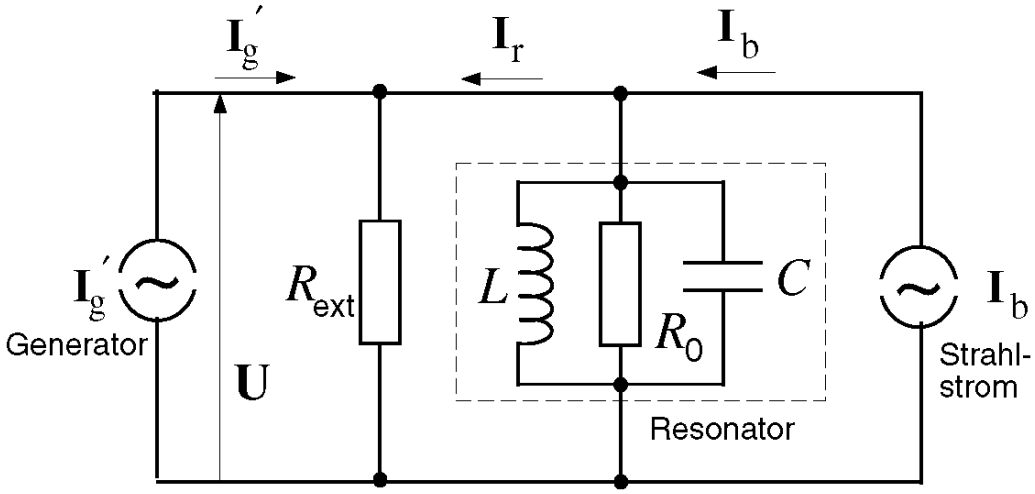
$f_o = 1.300.000.000\ \mathrm{Hz}$

Þ **Q0 » 10 ^{9} -10 ^{10}**

Cavity Model



Equivalent circuits



$$C \cdot \ddot{U} + \frac{1}{R_L} \cdot \dot{U} + \frac{1}{L} \cdot U = \dot{I}'_g + \dot{I}_b$$ L.O.D.E.

with $$\omega_{1/2} := \frac{1}{2R_L C} = \frac{\omega_0}{2Q_L}$$

$$\ddot{U} + 2\omega_{1/2} \cdot \dot{U} + \omega_0^2 \cdot U = 2R_L\omega_{1/2} \cdot (\frac{2}{m}\dot{I}_g + \dot{I}_b)$$

- Continuous Model

$$\begin{bmatrix} \dot{v}_r \\ \dot{v}_i \end{bmatrix} = \begin{bmatrix} -\omega_{1/2} & -\Delta\omega(t) \\ \Delta\omega(t) & -\omega_{1/2} \end{bmatrix} \cdot \begin{bmatrix} v_r \\ v_i \end{bmatrix} + \begin{bmatrix} R \cdot \omega_{1/2} & 0 \\ 0 & R \cdot \omega_{1/2} \end{bmatrix} \cdot \begin{bmatrix} I_r \\ I_i \end{bmatrix}$$

where $\omega_{1/2} = \dfrac{\omega_{rf}}{2Q}$ and $\Delta\omega(t) = \omega_0(t) - \omega_{rf}$

State Space Form

$$\dot{x} = A \cdot x + B \cdot u$$
$$y = C \cdot x + D \cdot u$$

with solution

$$x(t) = e^{A \cdot t} \cdot x(0) + \int_0^t e^{A \cdot \tau} \cdot B \cdot u(t - \tau) \cdot d\tau$$

• Discrete Model

State Space Form $x_{k+1} = A_d \cdot x_k + B_d u_k$

$y_k = C_d \cdot x_k + D_d u_k$

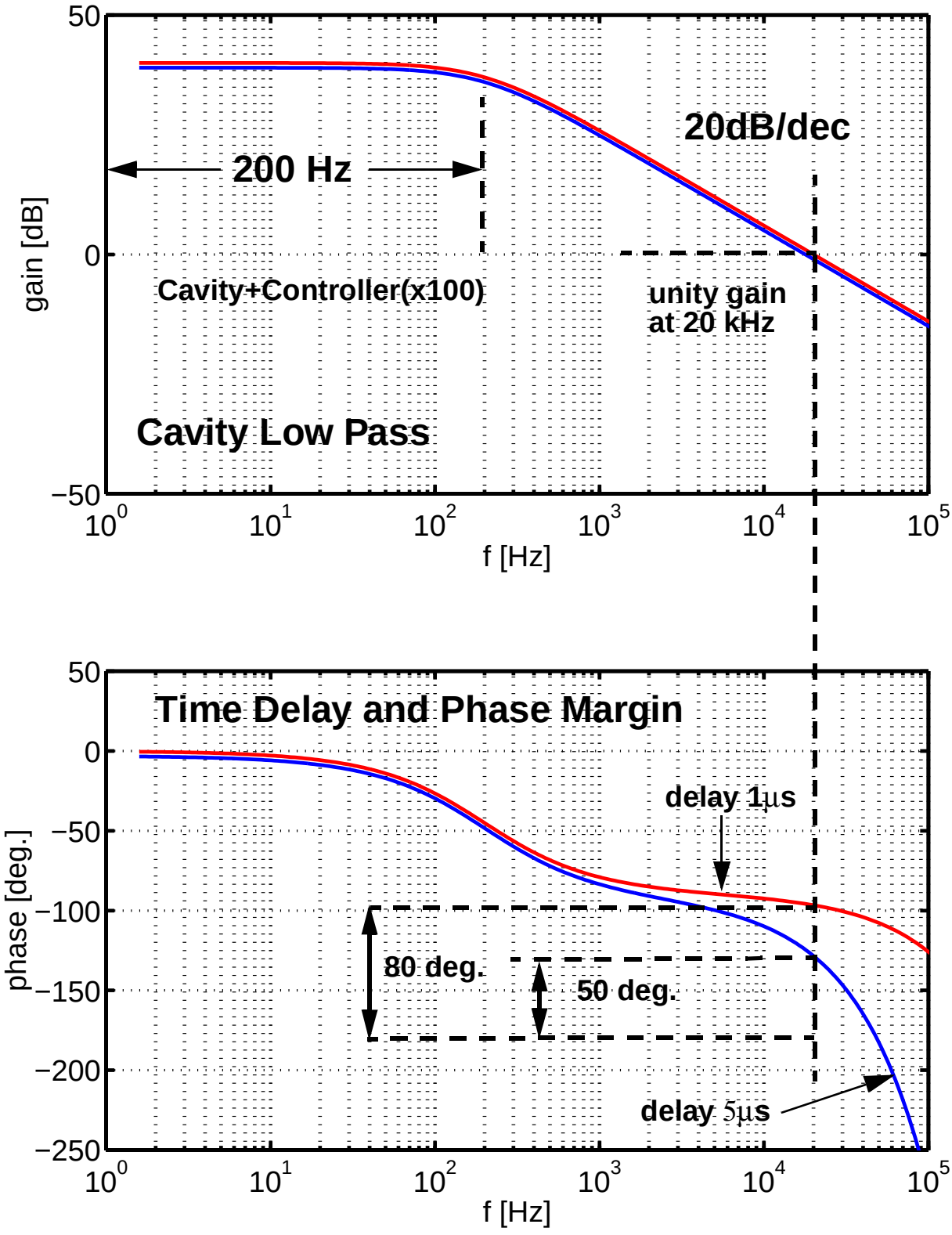
where $A_d = e^{AT_s}$ $B_d = \int_0^{T_s} e^{A\tau} B d\tau$ $C_d = C$ $D_d = D$

$$A_d = e^{-\omega_{1/2} \cdot T_s} \cdot \begin{bmatrix} \cos(\Delta\omega T_s) & -\sin(\Delta\omega T_s) \\ \sin(\Delta\omega T_s) & \cos(\Delta\omega T_s) \end{bmatrix} \approx \begin{bmatrix} 1-\omega_{1/2}T_s & -\Delta\omega T_s \\ \Delta\omega T_s & 1-\omega_{1/2}T_s \end{bmatrix}$$

$B_d =$ ..... $\approx \begin{bmatrix} \omega_{1/2}T_s & \Delta\omega\omega_{1/2}T_s^2/2 \\ \Delta\omega\omega_{1/2}T_s^2/2 & \omega_{1/2}T_s \end{bmatrix}$

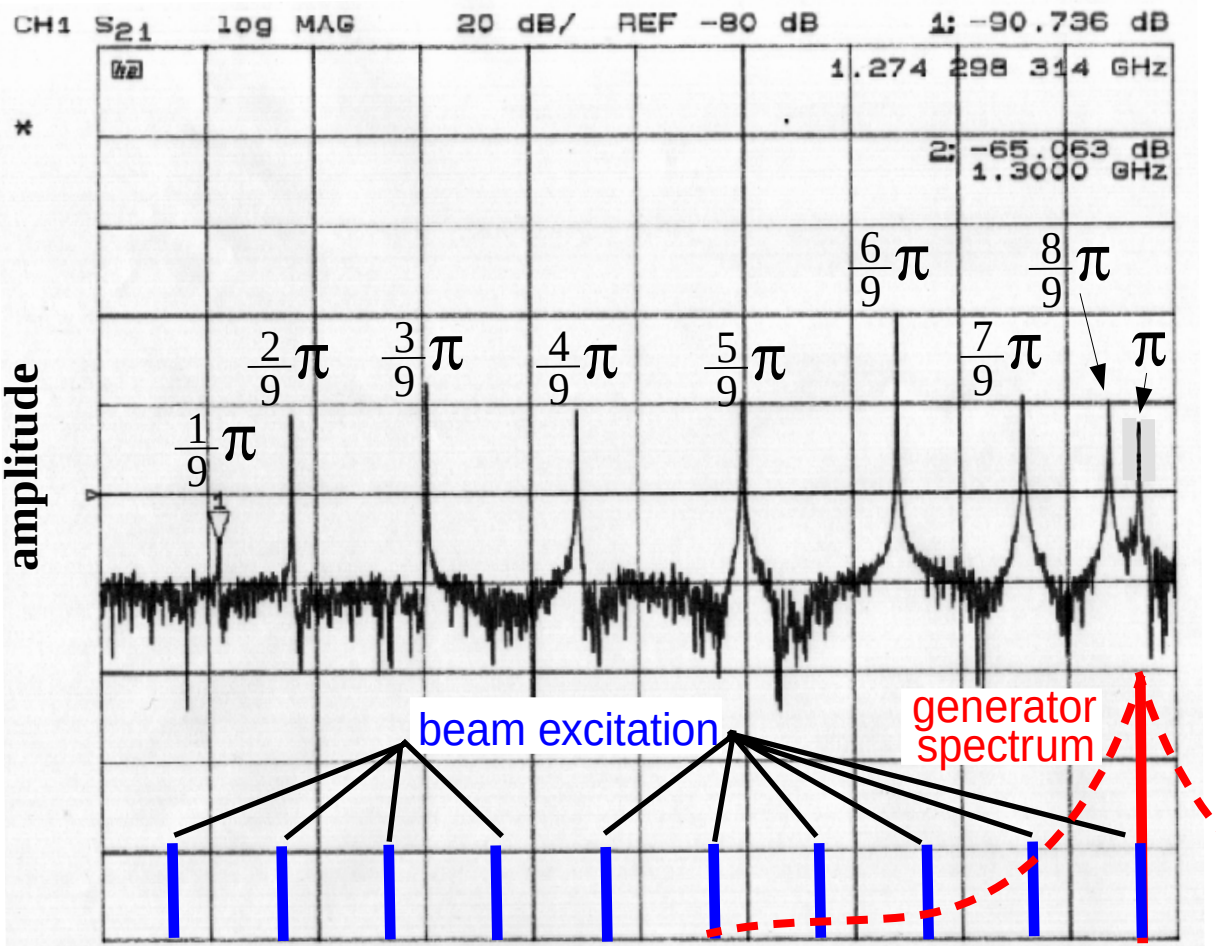
with solution $x(k) = A^k \cdot x(0) + \sum_{i=1}^{k} A^{i-1} \cdot B \cdot u(k-i)$

Cavity Transfer Function



Excitation of other Passband Modes

Example: TESLA 9-cell cavity



$f_{\pi} = 1300.091$ 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

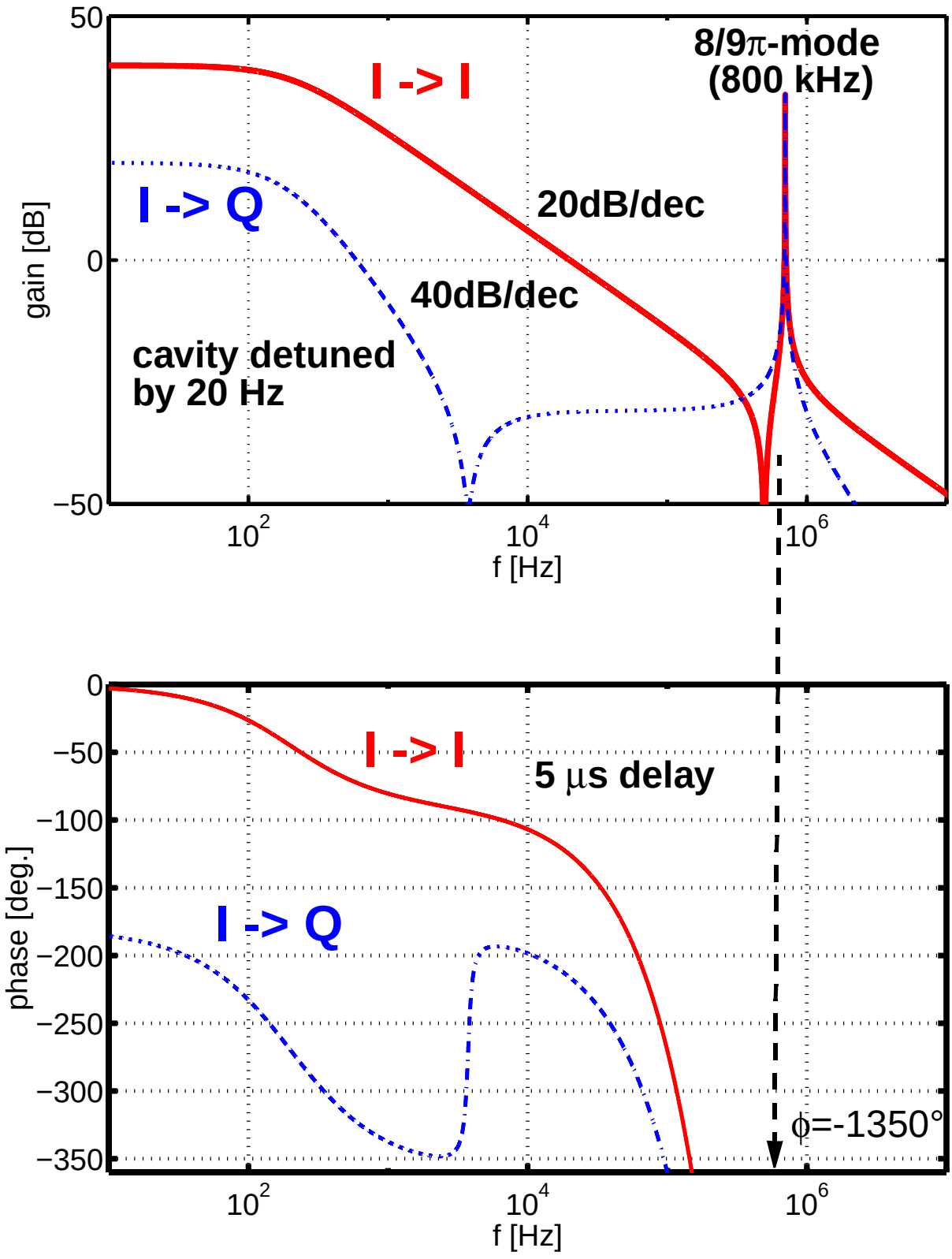
$f_{4/9\pi} = 1284.409$ MHz

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

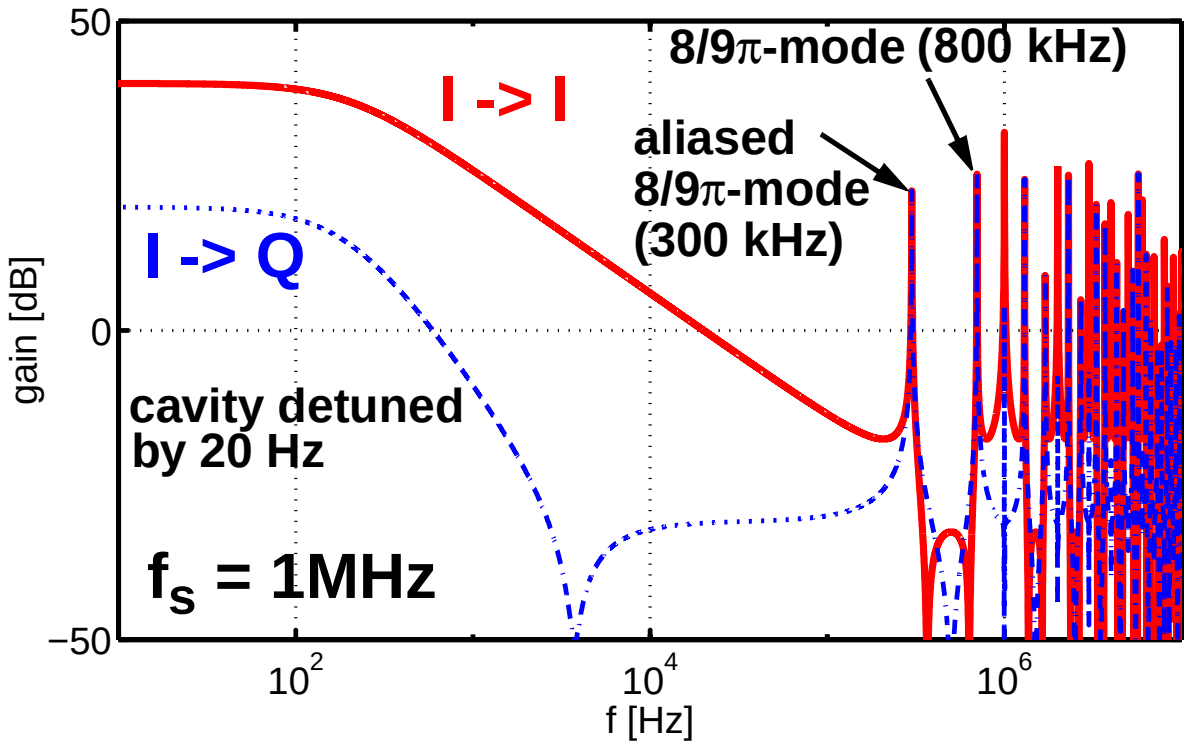
$f_{2/9\pi} = 1276.435$ MHz

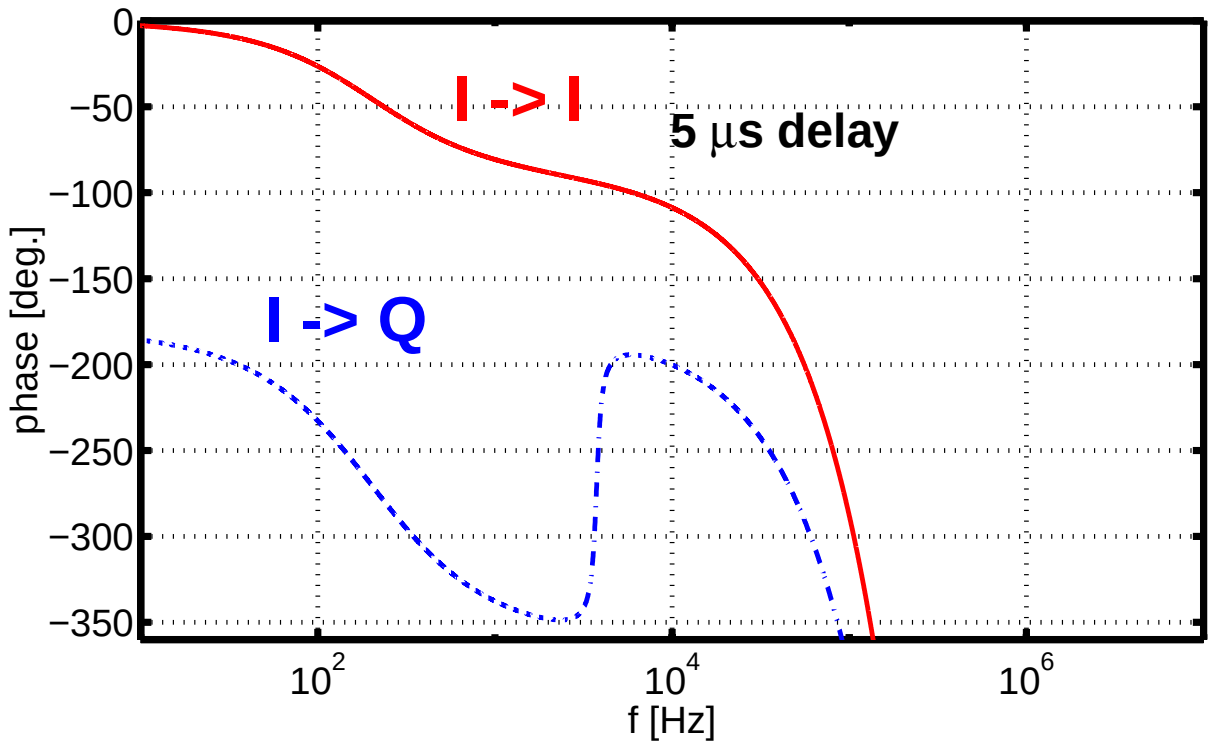
$f_{1/9\pi} = 1274.387$ MHz

Cavity Transfer Function



Discrete Cavity TF





Cavity Model

Cavity Field

$$\begin{bmatrix} \dot{v}_r \\ \dot{v}_i \end{bmatrix} = \begin{bmatrix} -\omega_{12} & -\Delta\omega \\ \Delta\omega & -\omega_{12} \end{bmatrix} \cdot \begin{bmatrix} v_r \\ v_i \end{bmatrix} + R \cdot \omega_{12} \cdot \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_r \\ I_i \end{bmatrix}$$

Mechanical Properties

$$\left[\dot{\Delta\omega}\right] = \left[-1/\tau_m\right] \cdot \left[\Delta\omega\right] + \left[-2\pi/\tau_m K_m\right] \cdot \left[(v_r^2 + v_i^2)\right]$$

or

$$\begin{bmatrix} \dot{\Delta\omega} \\ \dot{\Delta\omega} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\omega_m^2 & -1/\tau_m \end{bmatrix} \cdot \begin{bmatrix} \Delta\omega \\ \dot{\Delta\omega} \end{bmatrix} + 2\pi\omega_m^2 K_m \cdot \begin{bmatrix} 0 & 0 \\ 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ (v_r^2 + v_i^2) \end{bmatrix}$$

Typical Parameters

$\Delta\omega = \omega_0 - \omega_{rf}$, $\omega_{12} = \frac{\omega_0}{2 \cdot Q_L}$, $R = \left(\frac{r}{Q}\right) \cdot Q_L$,

$\omega_0 = 2\pi \cdot 1.3 \cdot 10^9$, $Q_L = 3 \cdot 10^6$, $\left(\frac{r}{Q}\right) = 1030\ \frac{\Omega}{m}$, $K_m = -1\ \text{Hz/(MV/m)}^2$

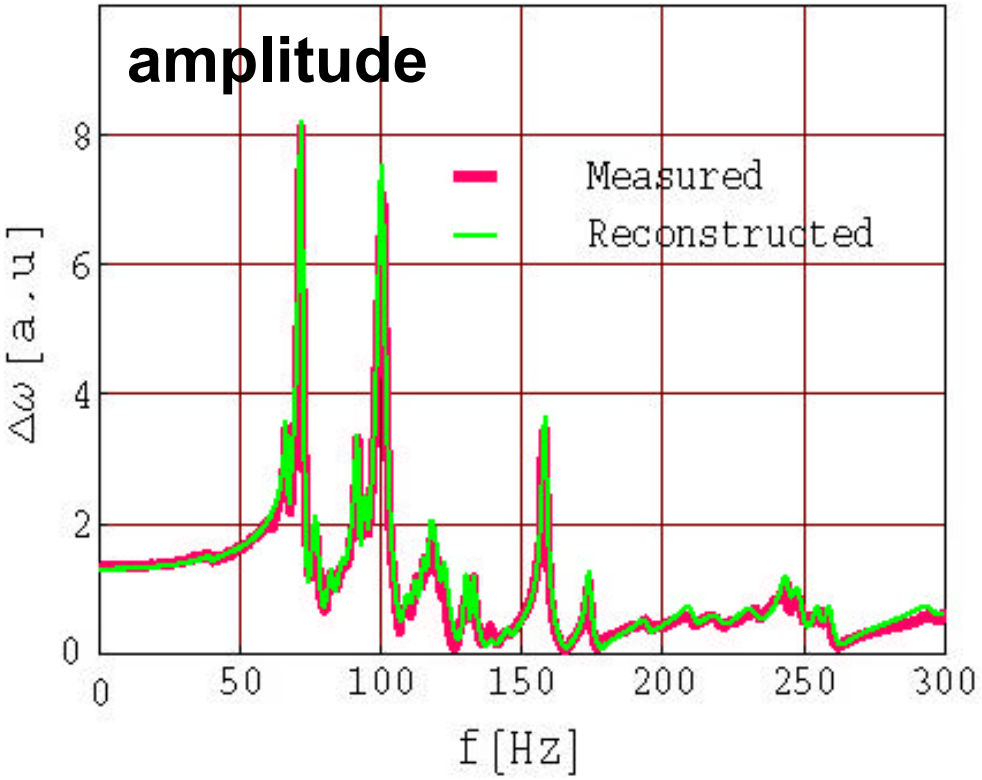
Modelling Lorentz Force Detuning

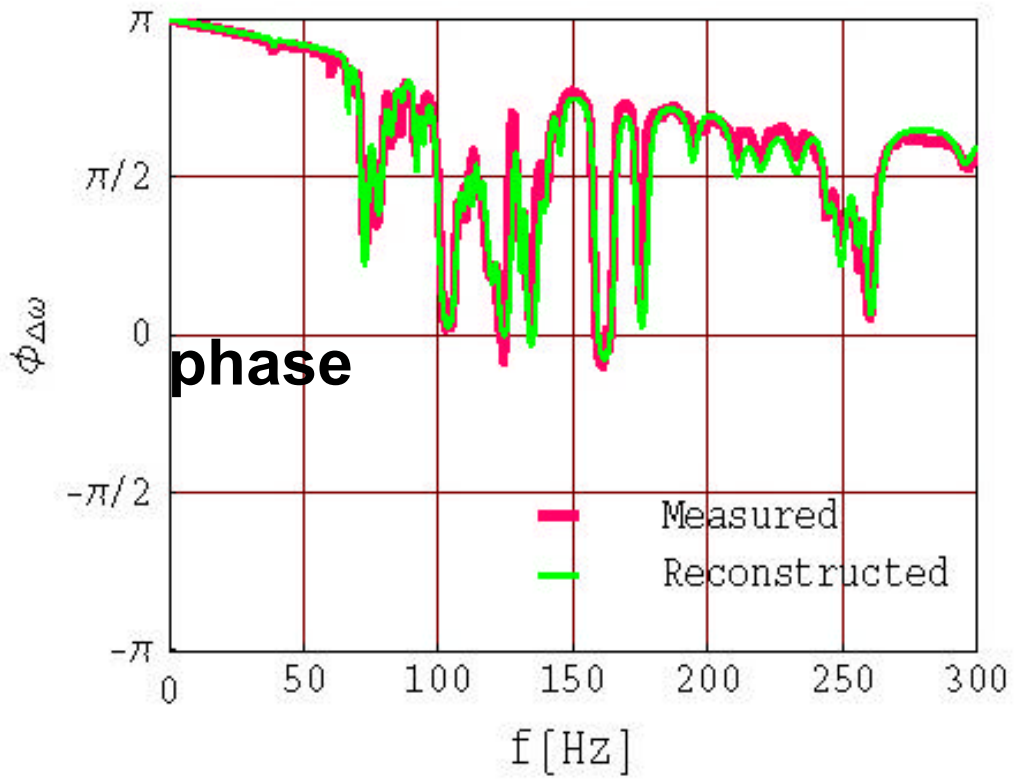
$$\begin{bmatrix} \dot{\Delta\omega}_1 \\ \ddot{\Delta\omega}_1 \\ \vdots \\ \dot{\Delta\omega}_N \\ \ddot{\Delta\omega}_N \end{bmatrix} = \begin{bmatrix} 0 & 1 & \dots & 0 & 0 \\ -\omega_1^2 & -\frac{1}{\tau_1} & \dots & 0 & 0 \\ & & :: & & \\ 0 & 0 & \dots & 0 & 1 \\ 0 & 0 & \dots & -\omega_N^2 & -\frac{1}{\tau_N} \end{bmatrix} \cdot \begin{bmatrix} \Delta\omega_1 \\ \dot{\Delta\omega}_1 \\ \vdots \\ \Delta\omega_N \\ \dot{\Delta\omega}_N \end{bmatrix} + 2\pi \begin{bmatrix} 0 \\ -K_1\omega_1^2 \\ \vdots \\ 0 \\ -K_N\omega_N^2 \end{bmatrix} \cdot \left[V_{acc}^2 \right]$$

where $\Delta\omega_m$: detuning of mode m, V_{acc} : accelerating voltage, τ_m : mechanical time constant of mode m and K_m : Lorentz force detuning constant of mode m.

Transfer Function

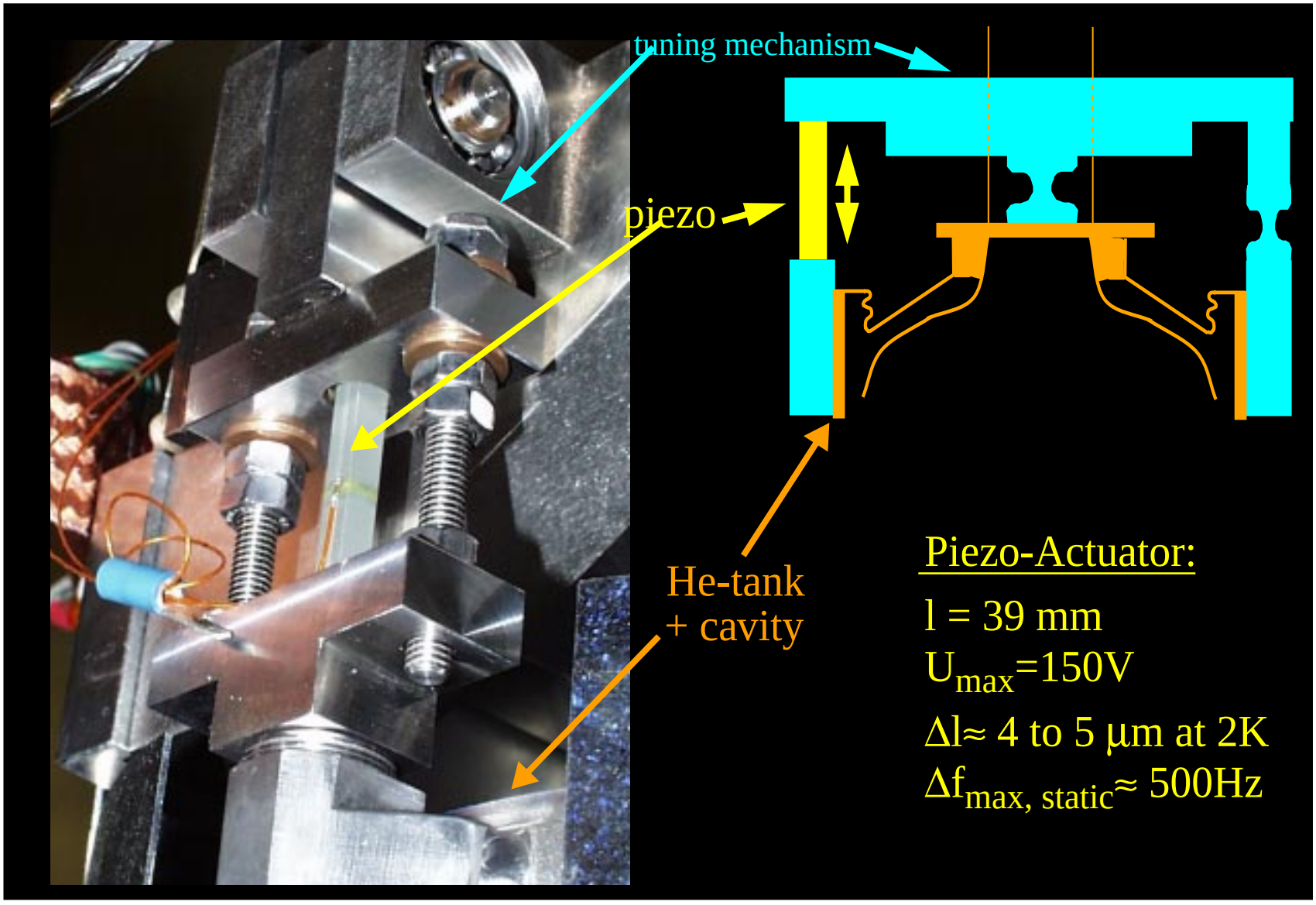
Transfer function Lorentz Force --> Detuning, SNS cavity



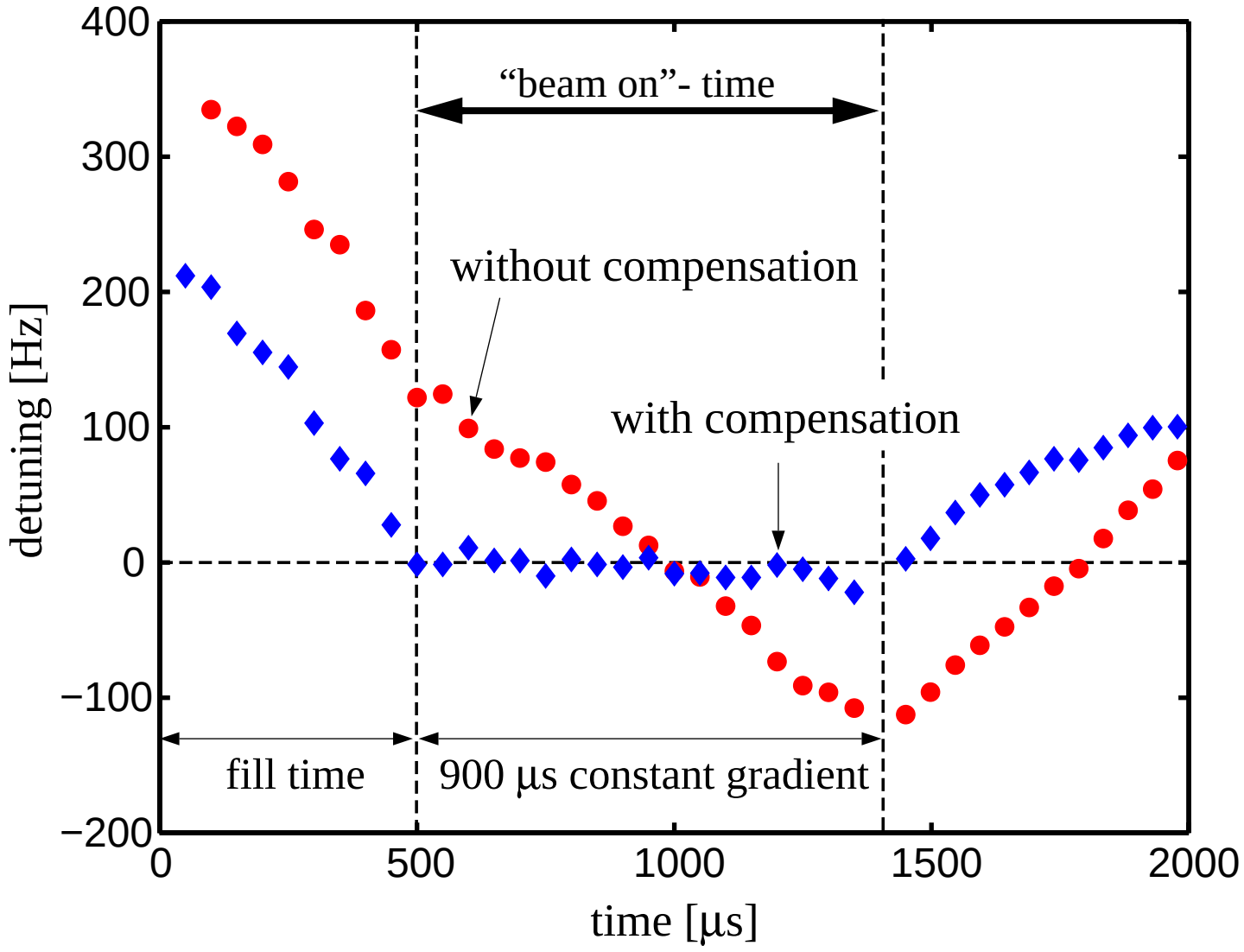


courtesy: J. Delayen, JLAB, M. Doleans, ORNL

Active Compensation of Lorentz Force Detuning (1)



Active Compensation of Lorentz Force Detuning (2)

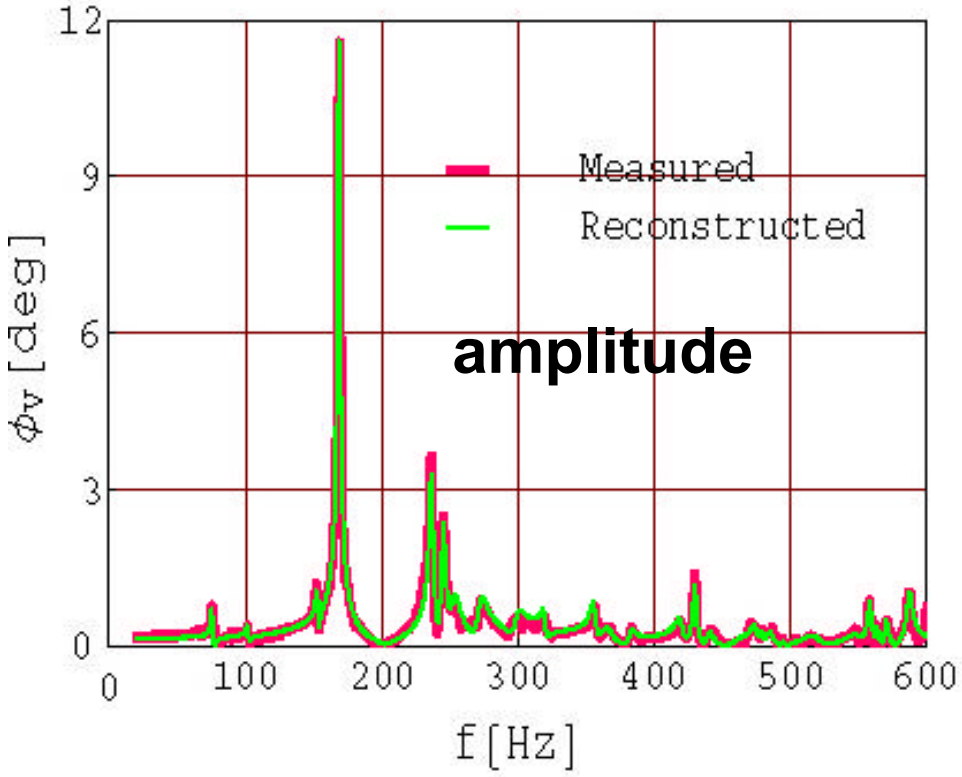


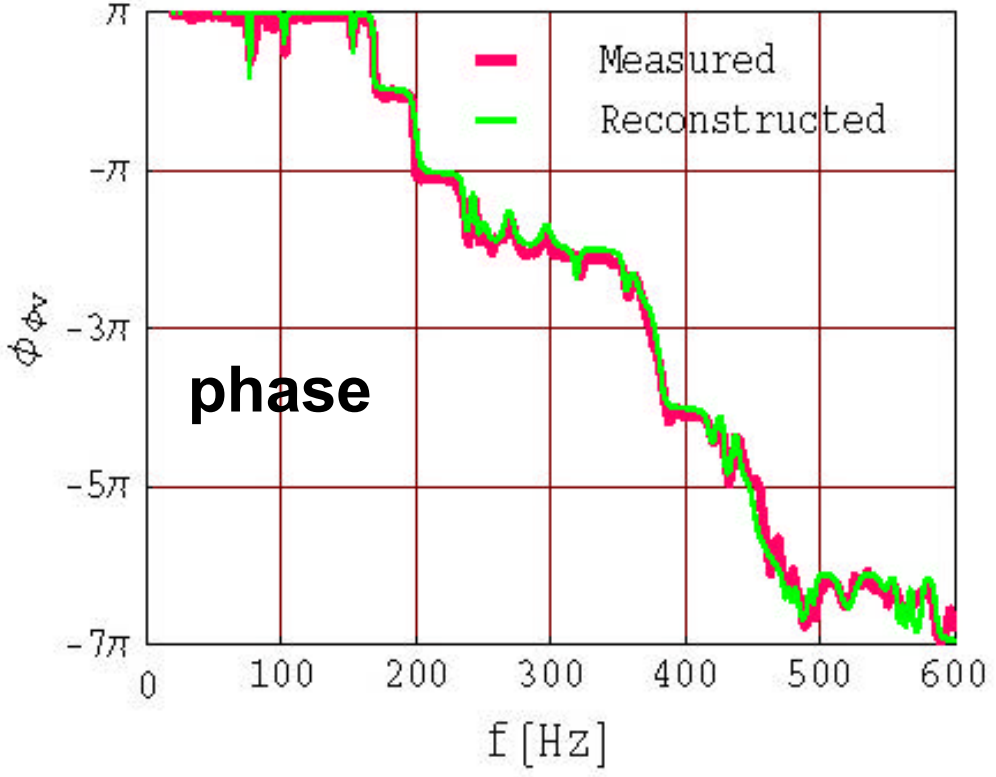
9-cell cavity operated at 23.5 MV/m

Lorentz force compensated with fast piezoelectric tuner

Transfer Function

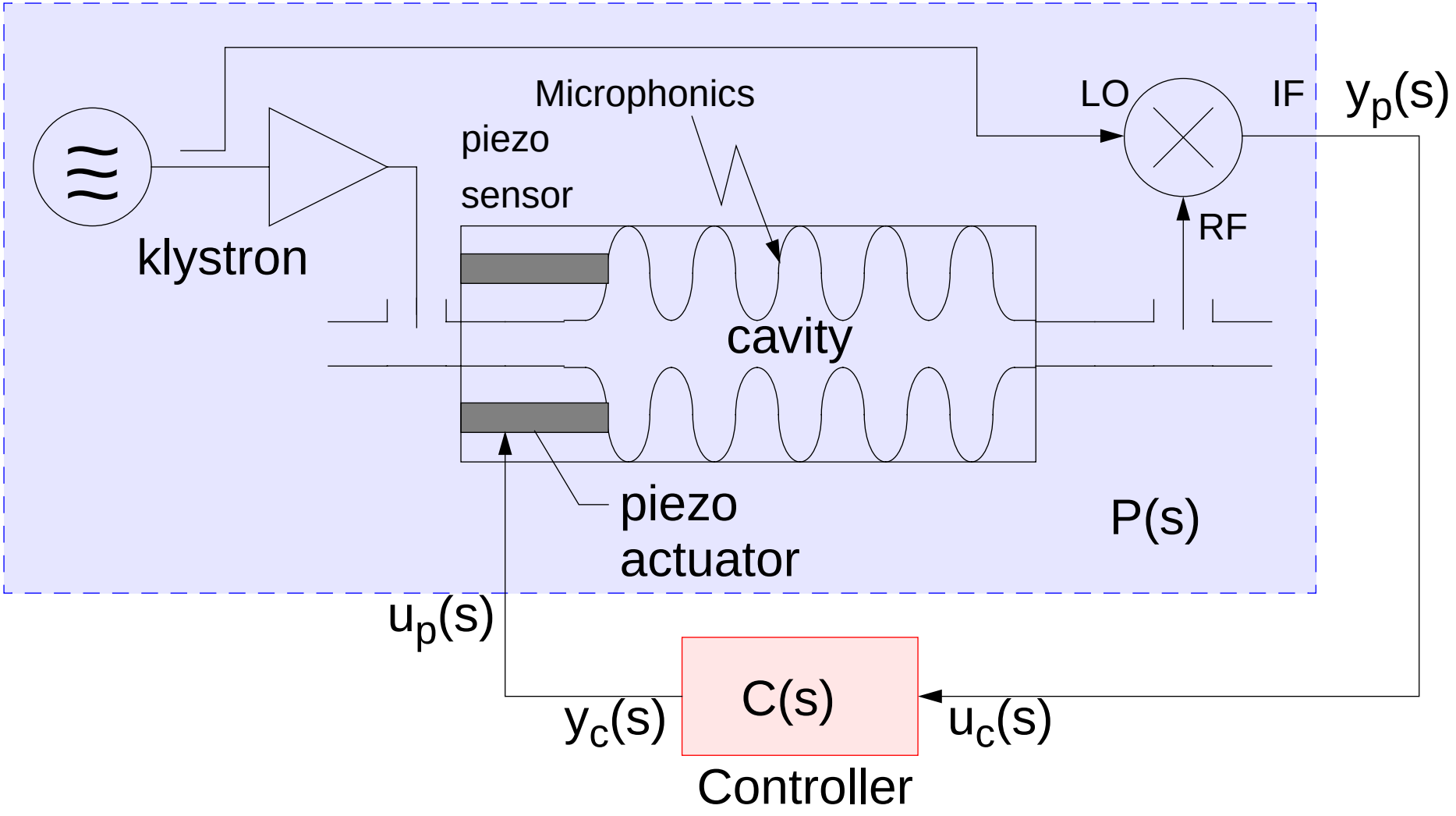
Transfer function Piezo Tuner --> Detuning, SNS cavity



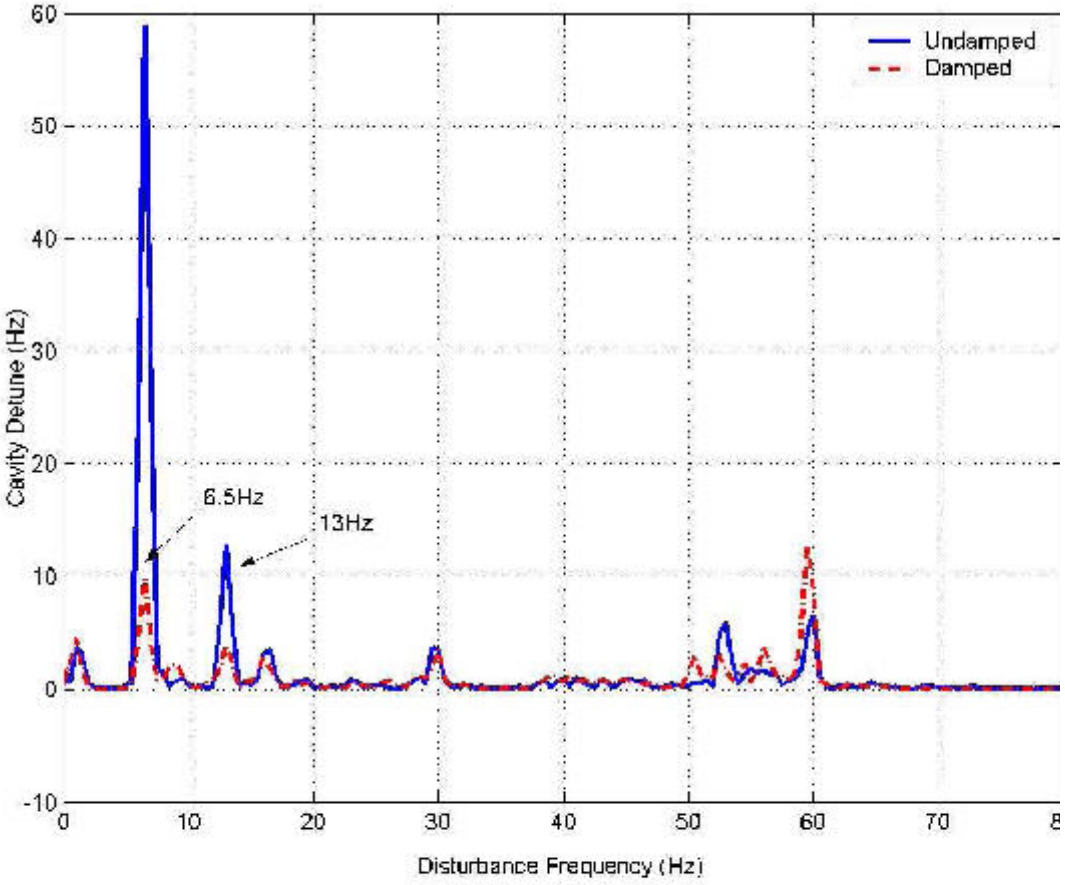


courtesy: J. Delayen, JLAB, M. Doleans, ORNL

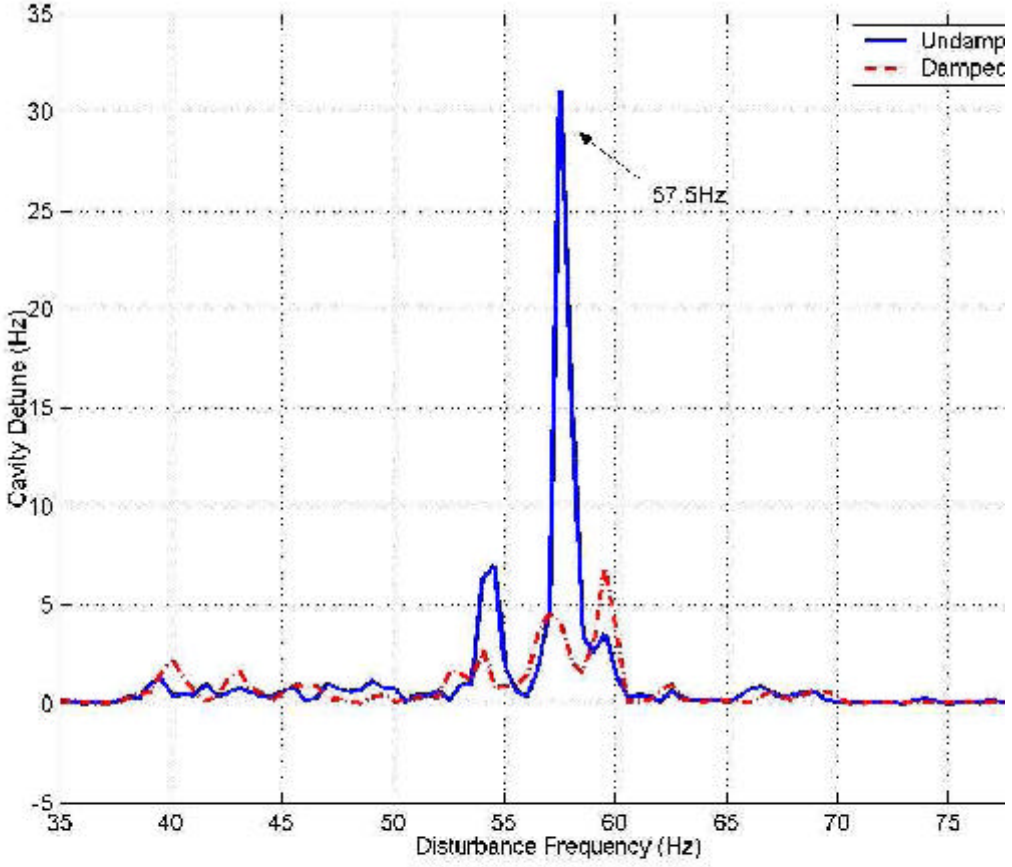
Microphonics Control



Microphonics Suppression with Feedforward



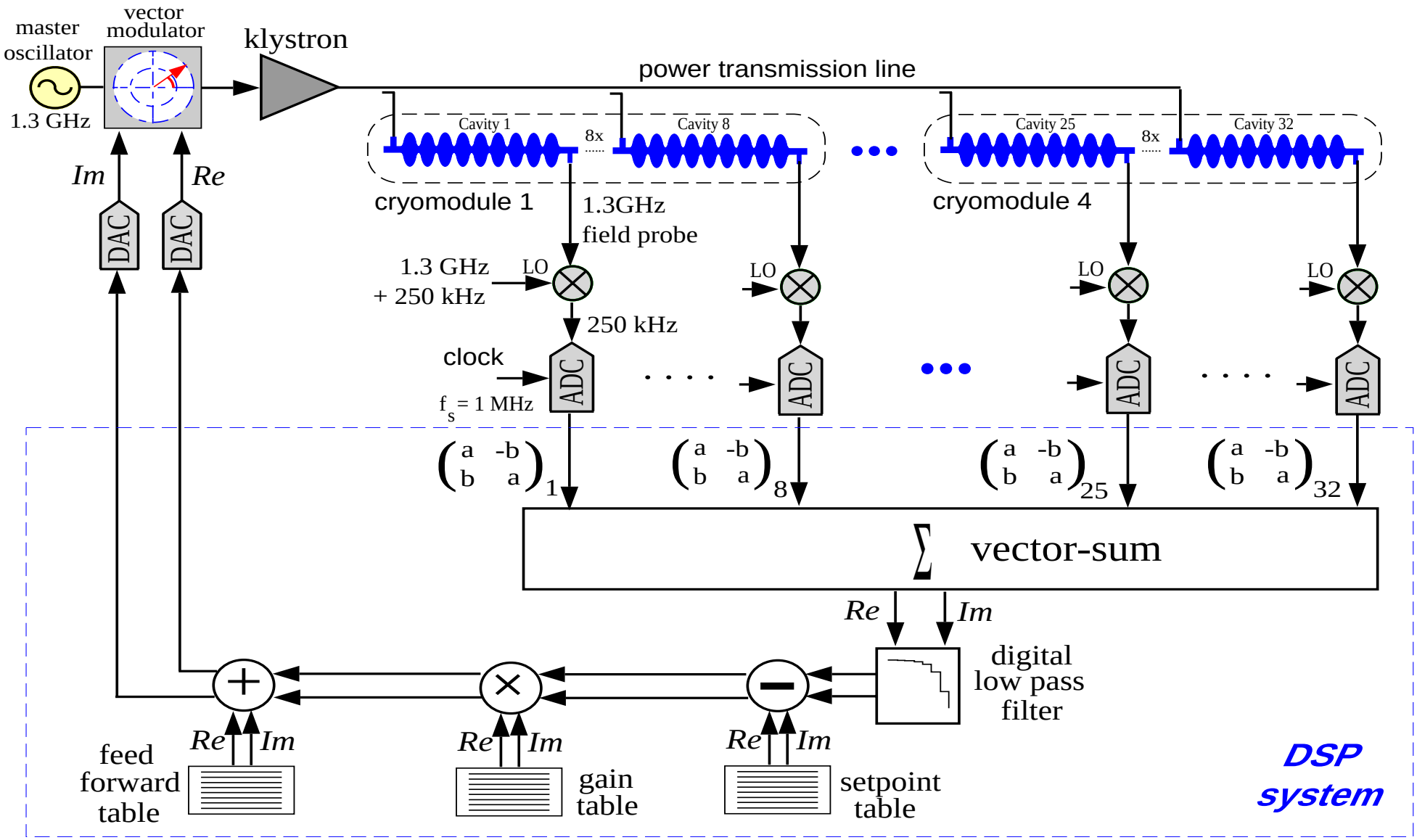
Active damping of helium oscillations at 2K.



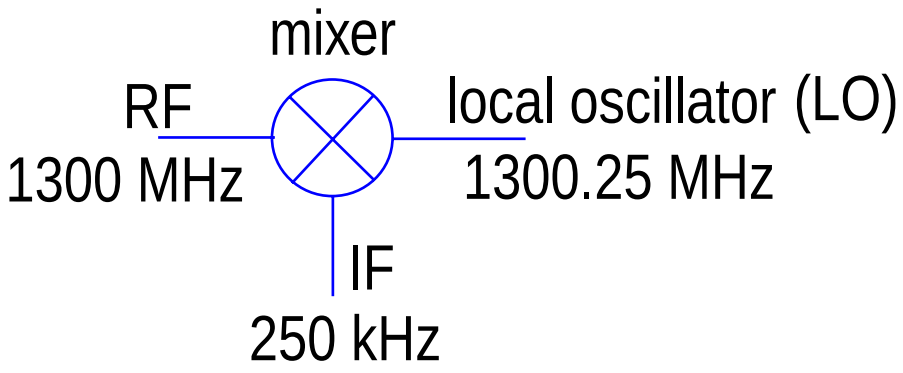
Active damping of external vibration at 2K.

T. Grimm

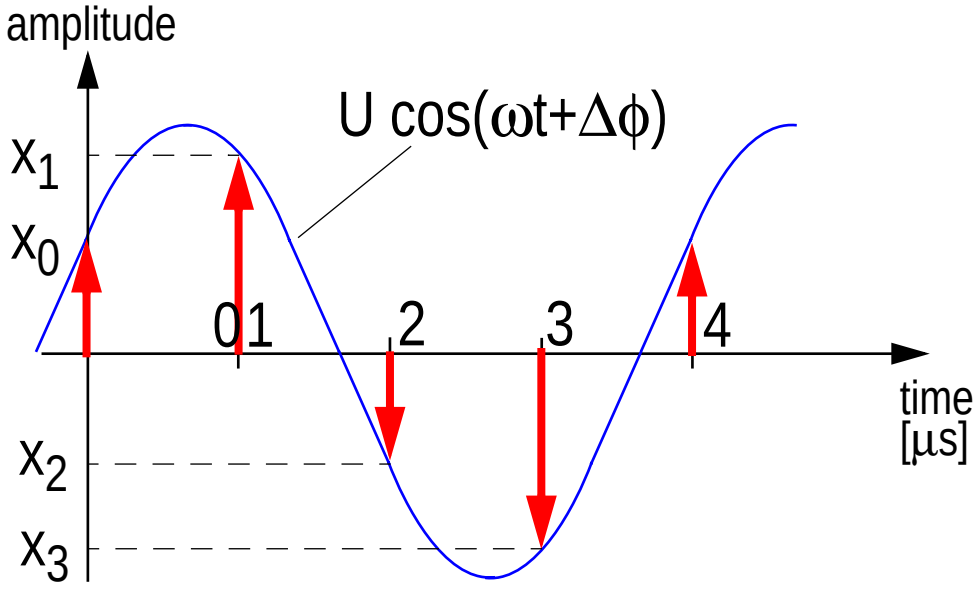
Digital Control at the TTF



Digital I/Q Detection

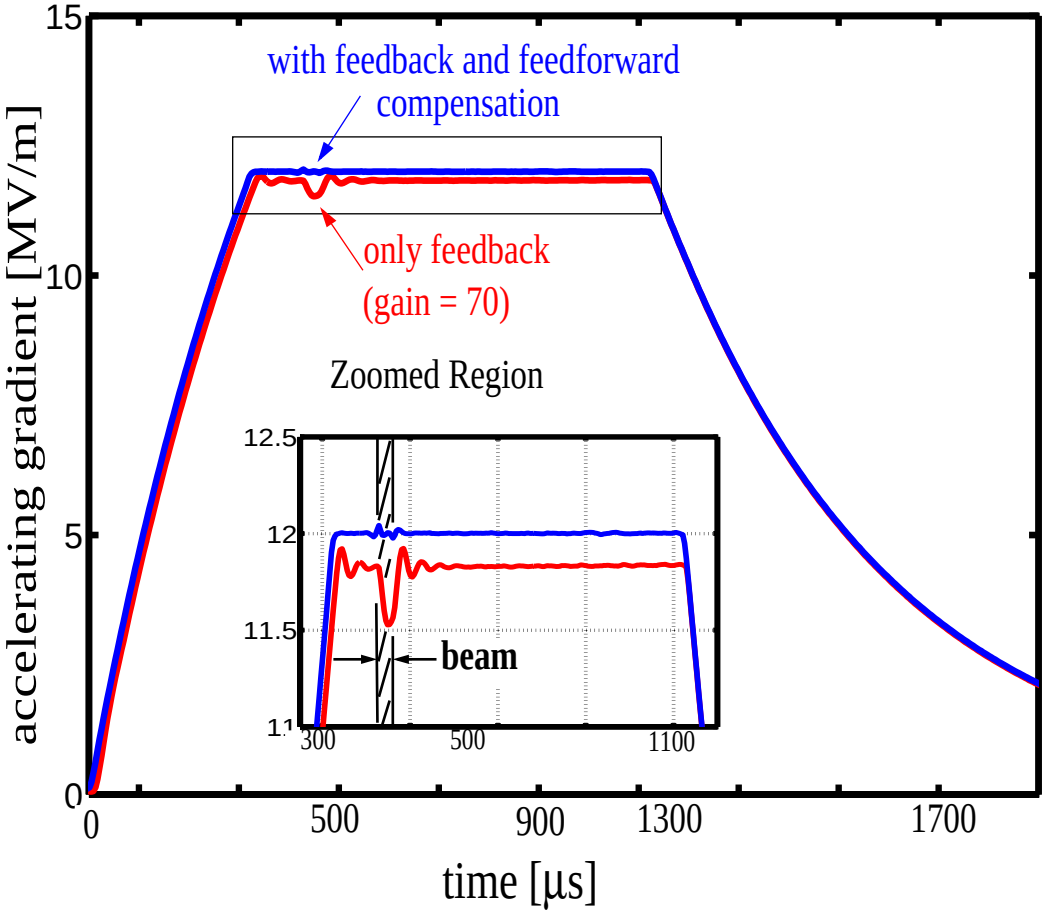


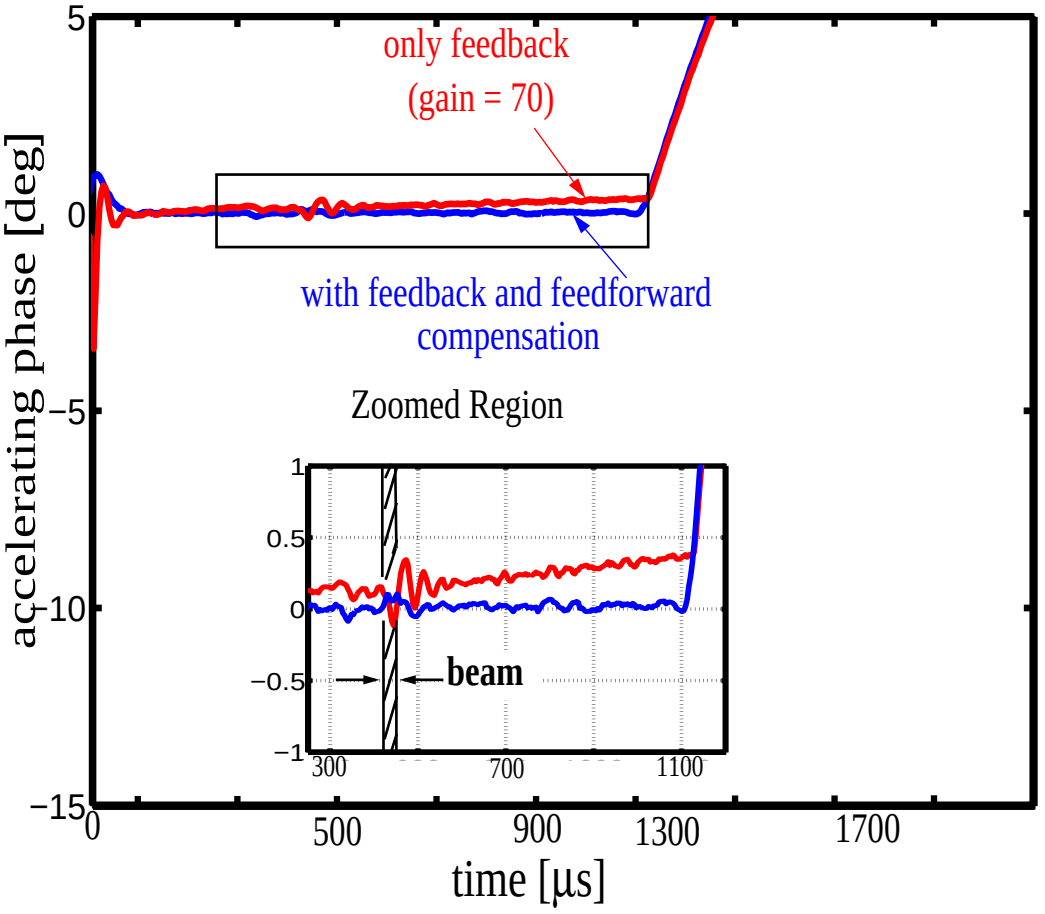
- downconversion of cavity field to IF frequency at 250 kHz
- complete phase and amplitude information of the accelerating field is preserved.



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

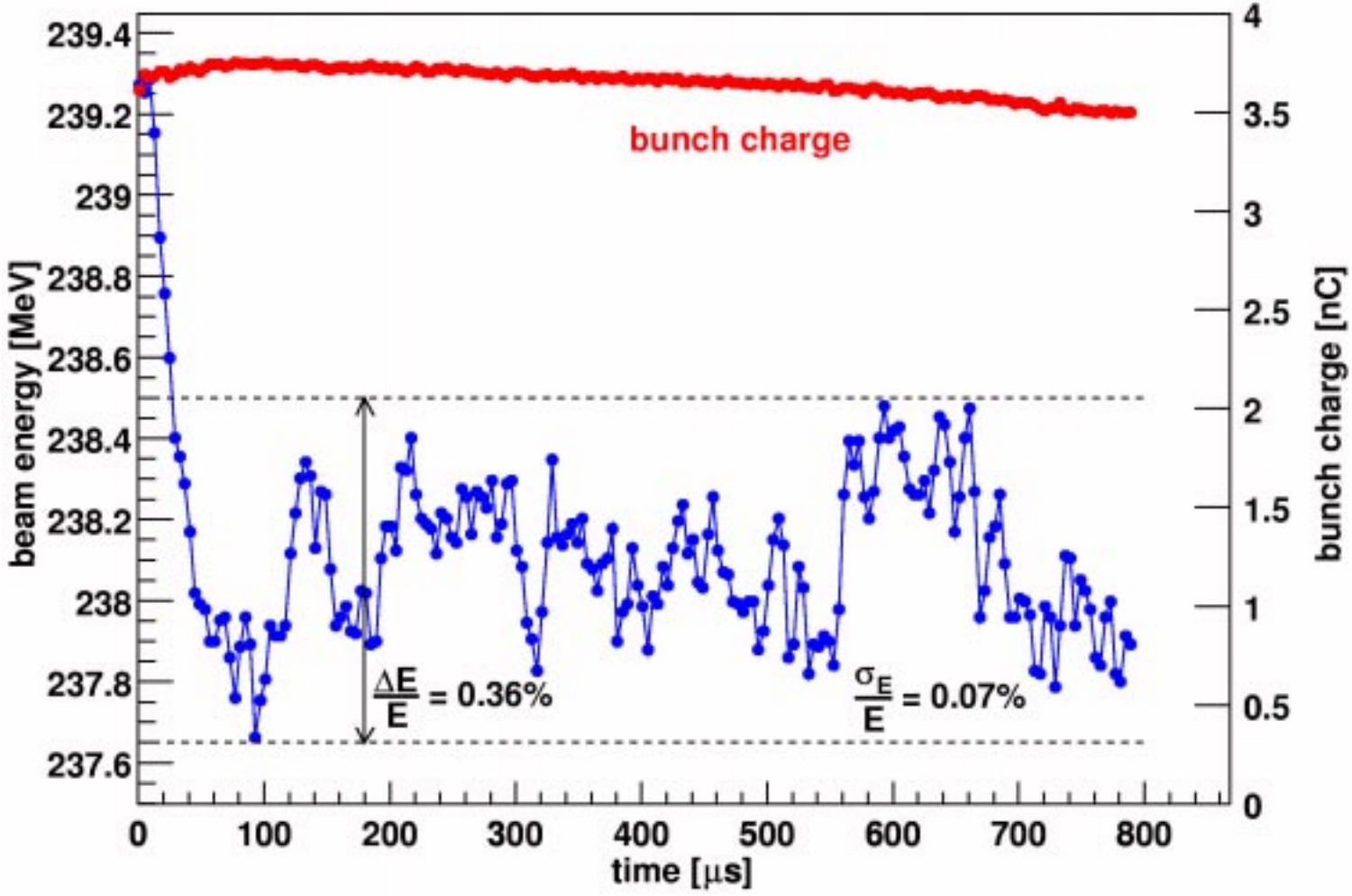
Performance at TTF (1)





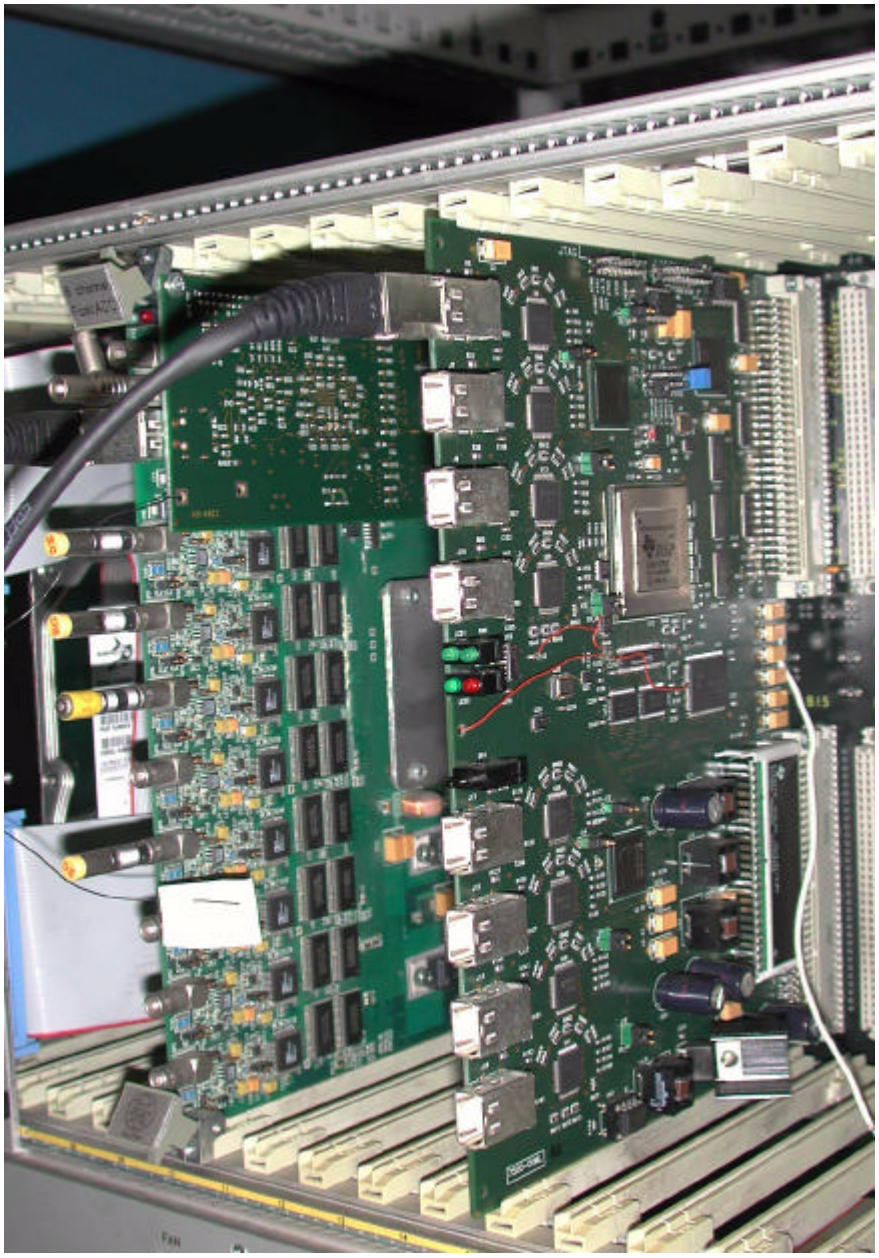
Amplitude **Phase**

Performance at TTF (2)

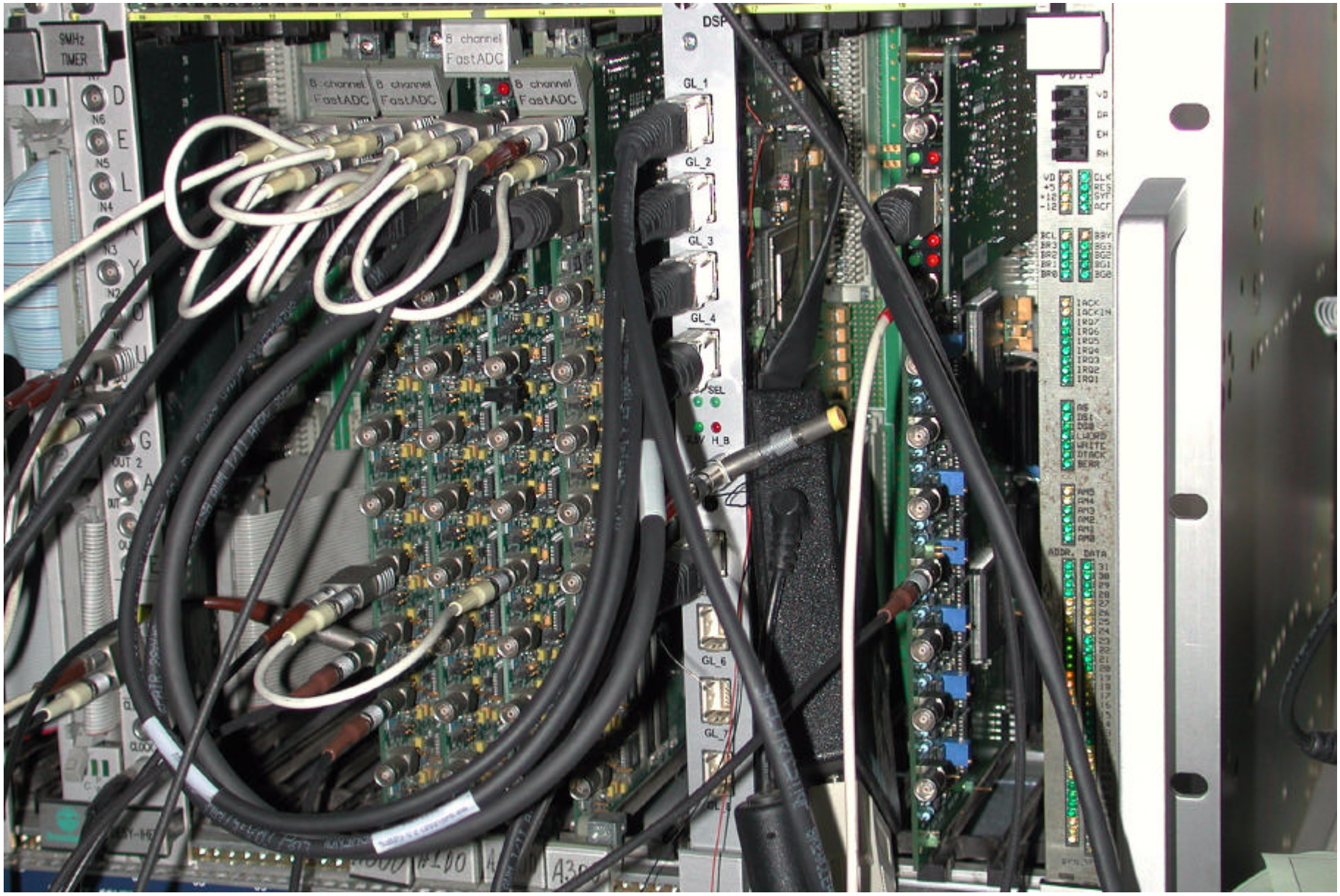


Operation with long beam pulses

C67 DSP board

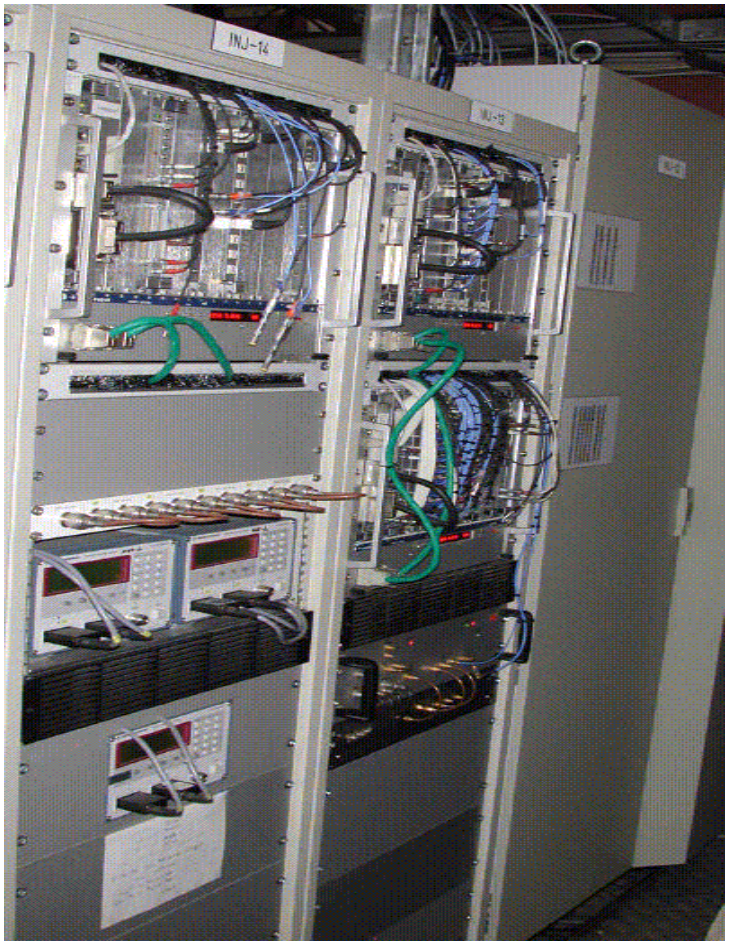


C67 DSP board

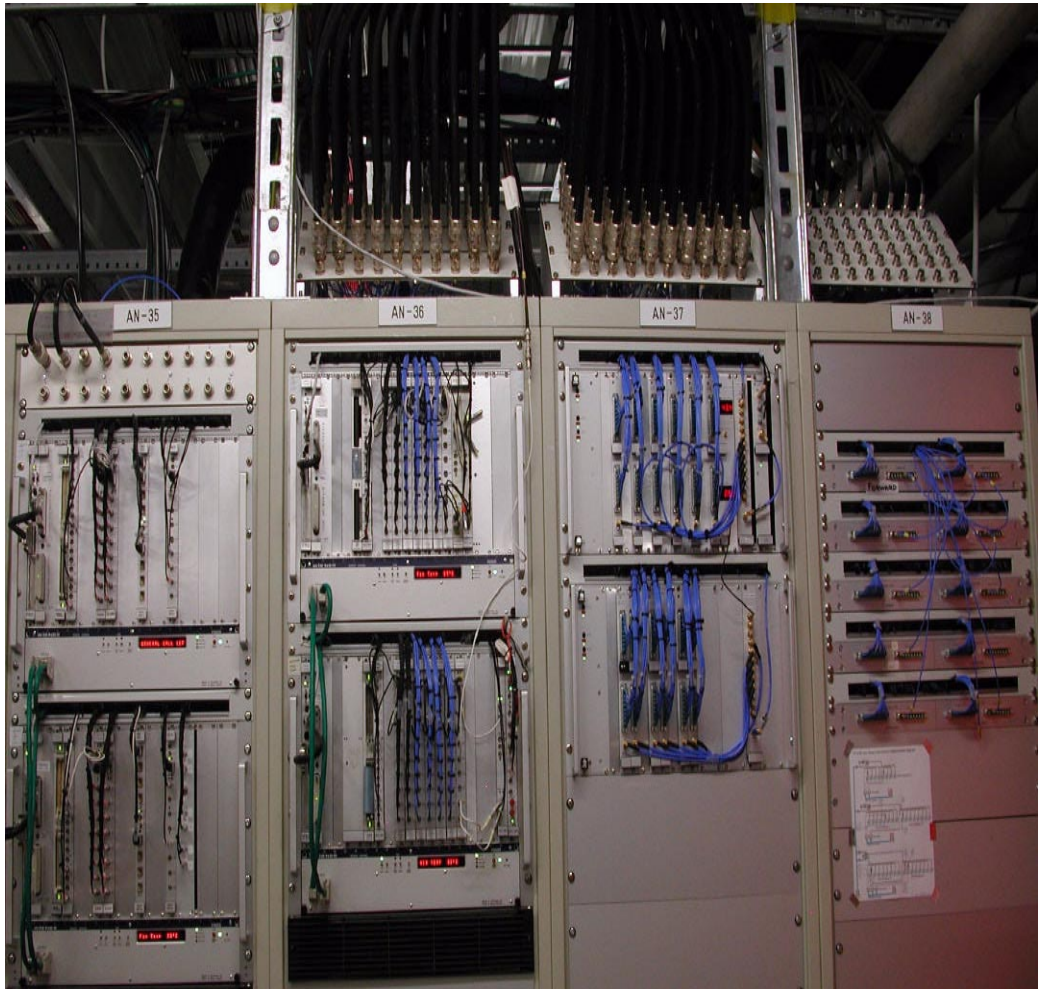


Digital Feedback Hardware (3)

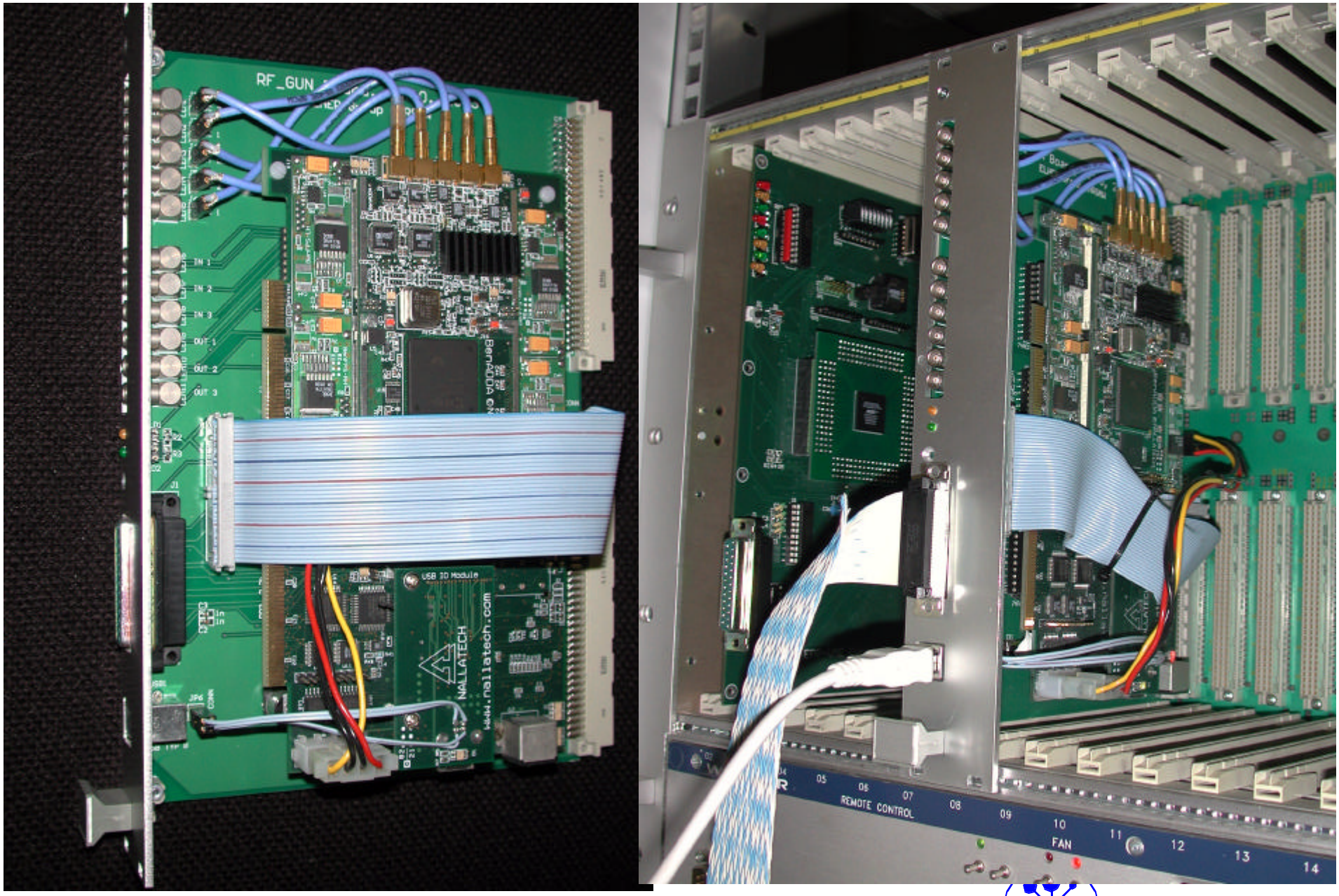
Gun and ACC1



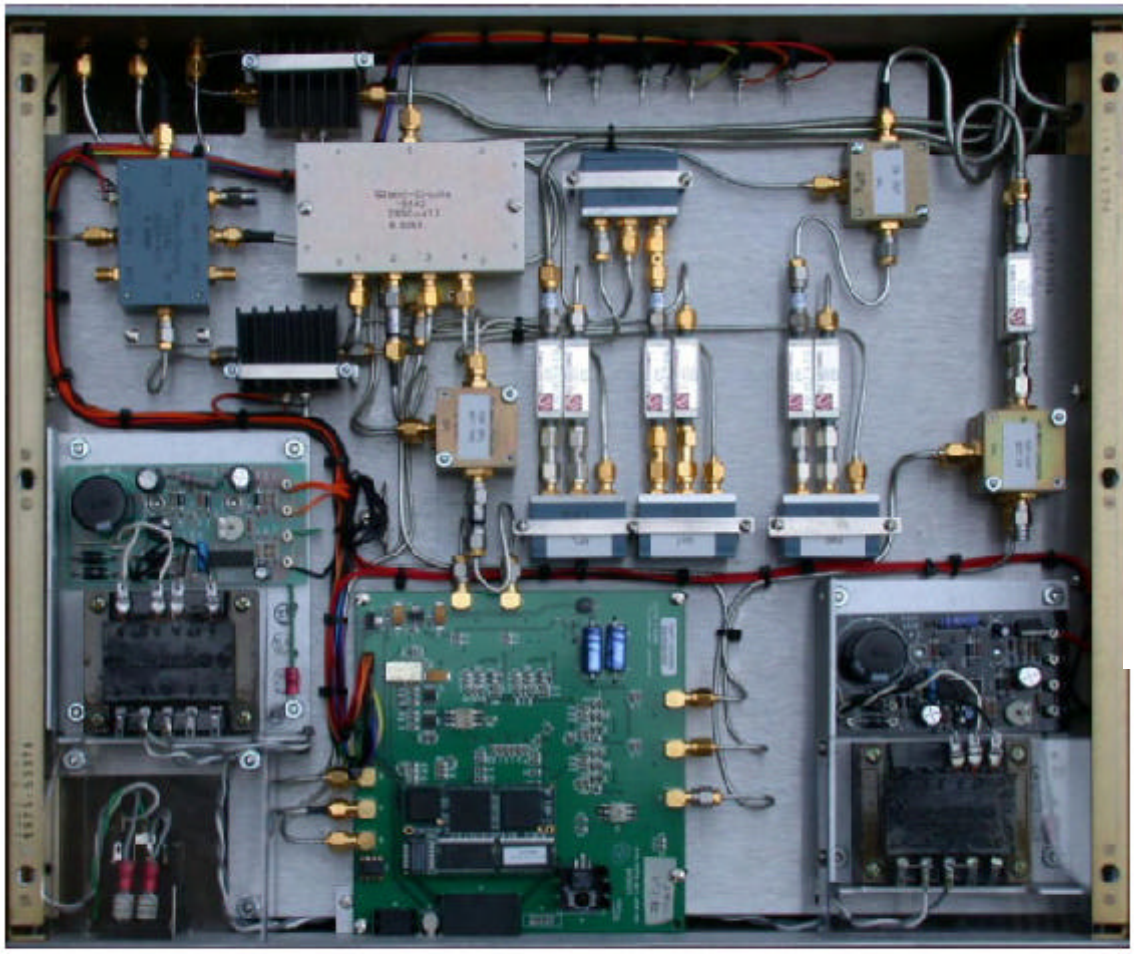
ACC2, ACC3, ACC4 & ACC5



FPGA based RF Gun Controller

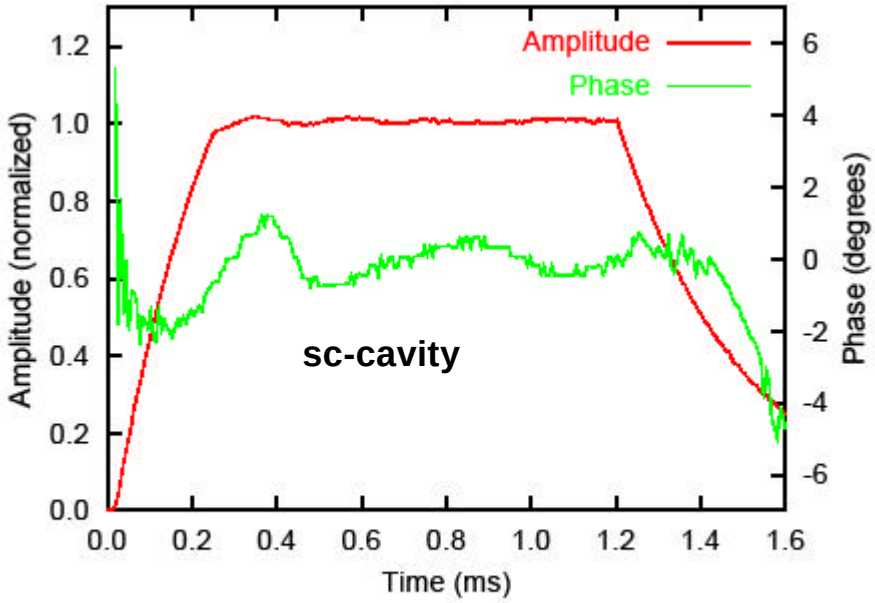


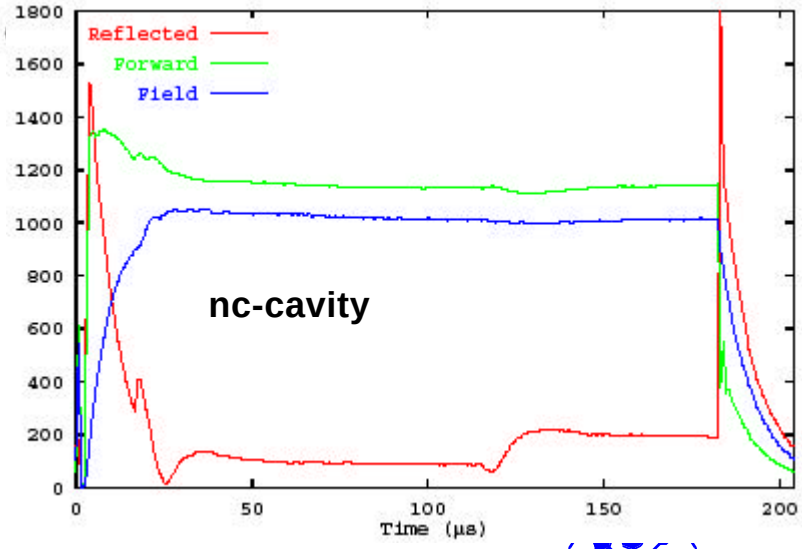
SNS Controller and Initial Performance Test



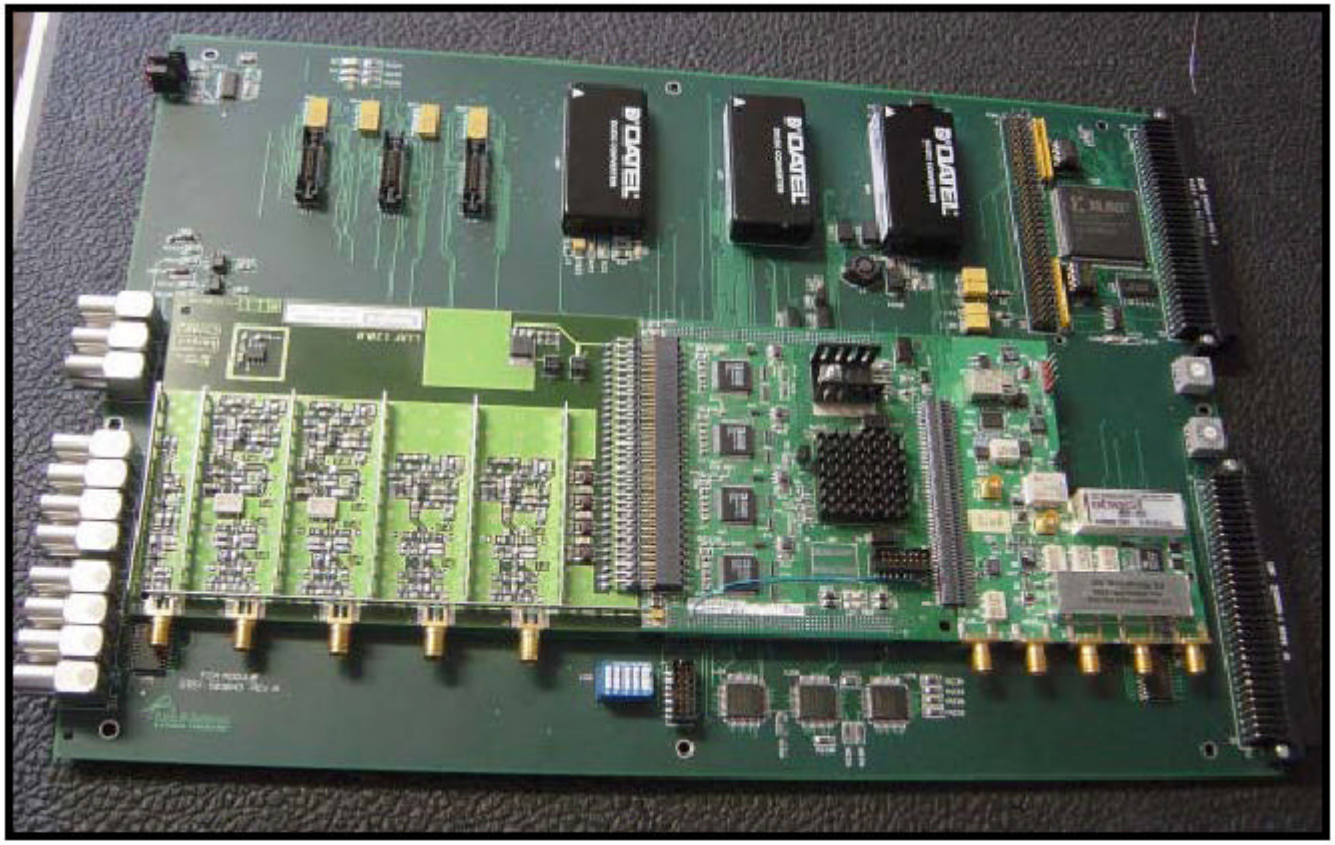
Chassis photograph.

L. Doolittle





New Field Control Module for SNS

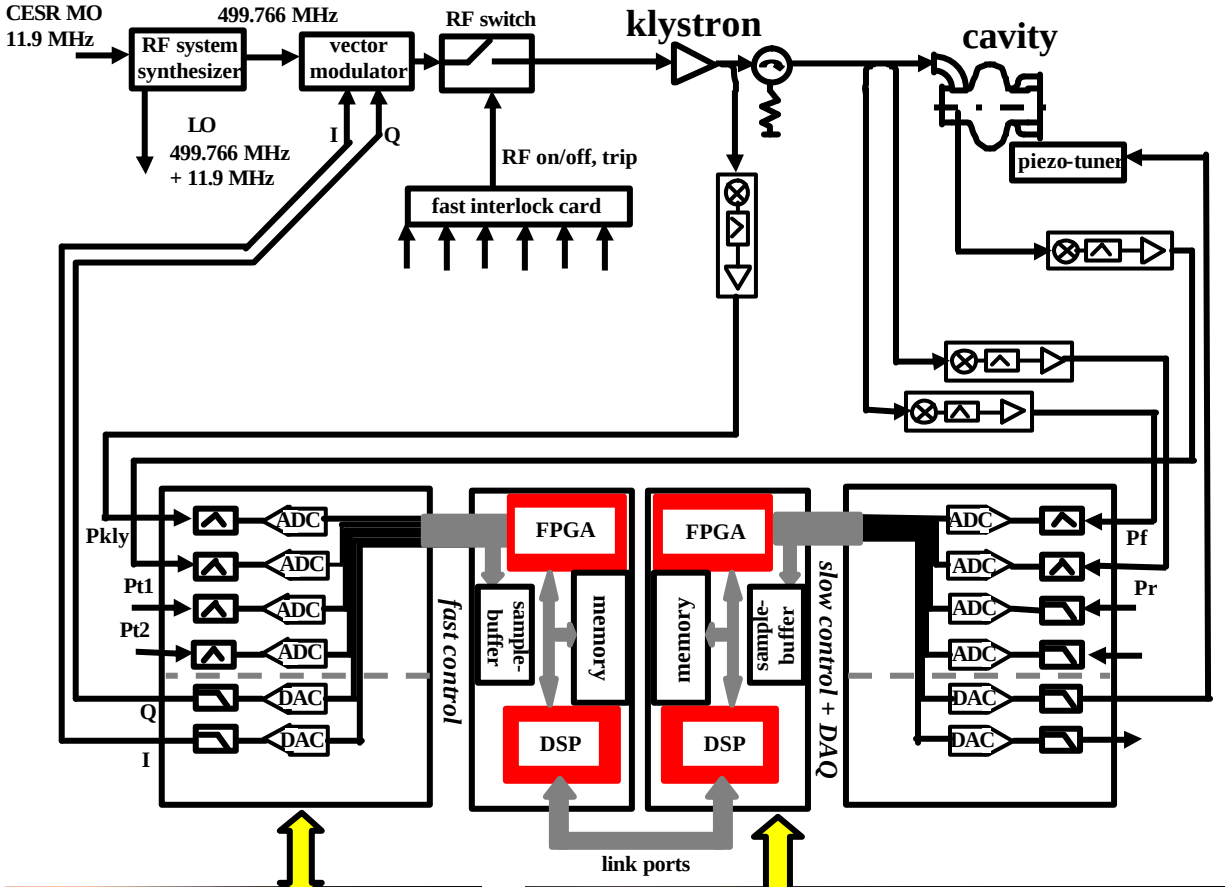


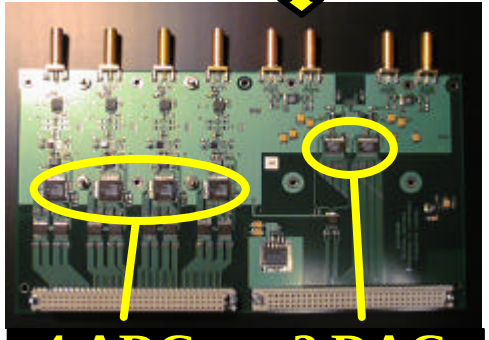
The prototype Field Control Module. The Analog Front End, Digital Front End, and RF Output daughtercards (left to right) are mounted on the VXI motherboard .

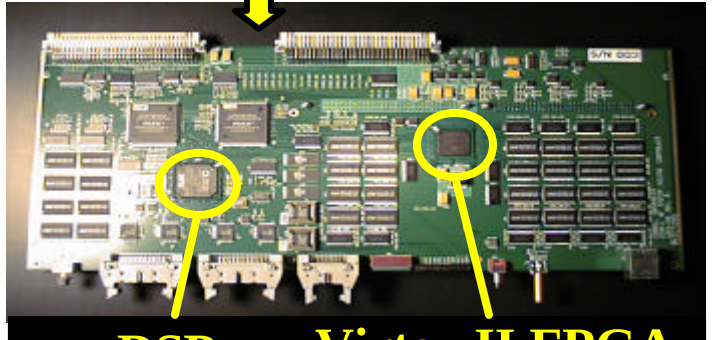
L. Doolittle

Matthias Liepe
CORNELL
UNIVERSITY

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







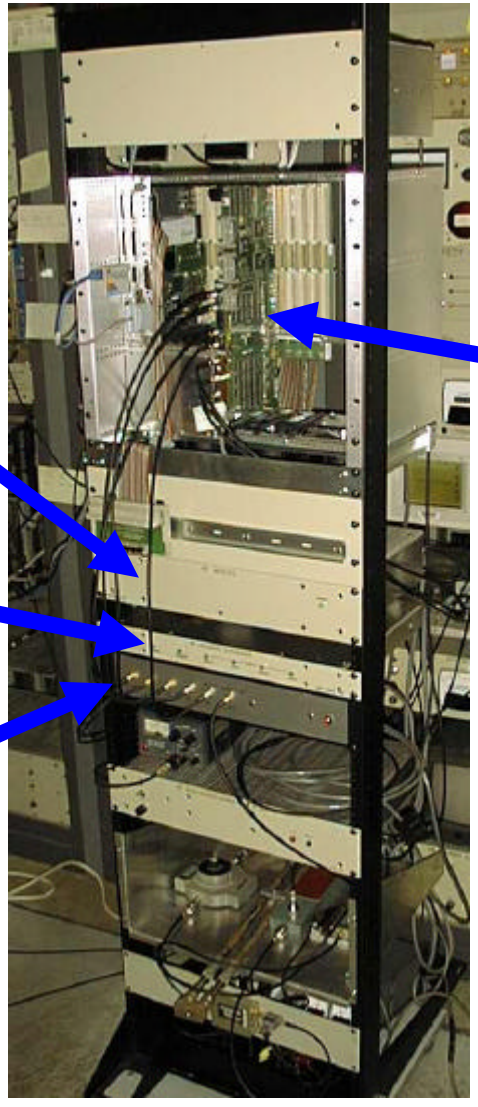
- *very low delay in the control loop (» 1 ms)*
- *Field Programmable Gate Array (FPGA) design combines the speed of an analog system and the flexibility of a digital system*
- *high computation power allows advanced control algorithms*
- *all boards have been designed in house*
- *generic design: digital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

Cornell's Digital RF Control System:

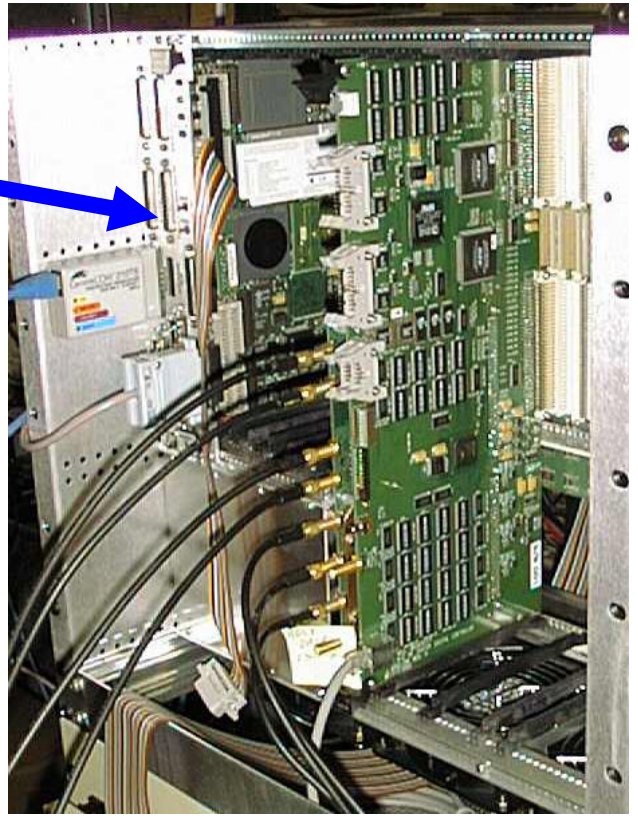
RF Down-Converters

500 MHz frequency synthesizer

vector modulator

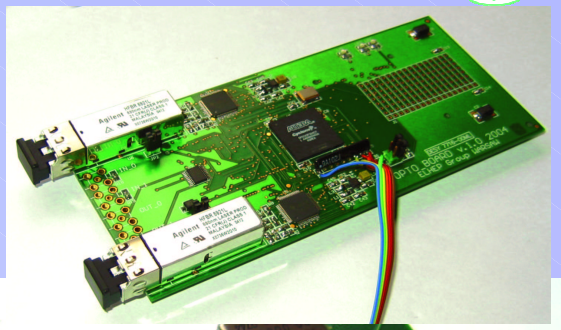


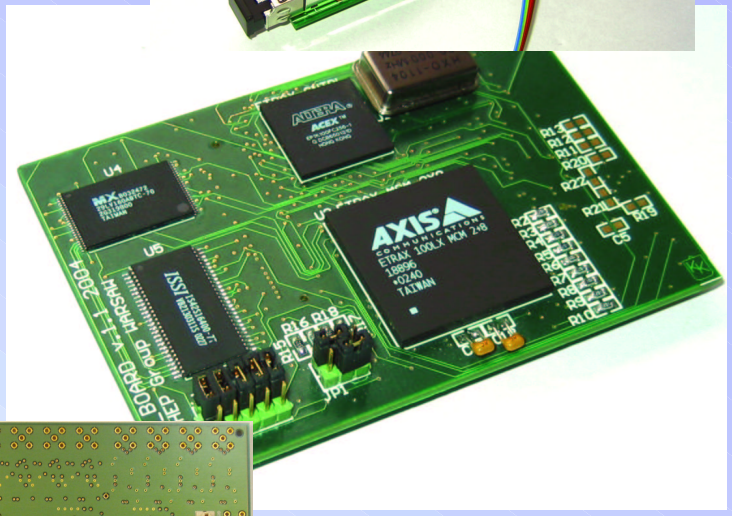
Digital Boards:

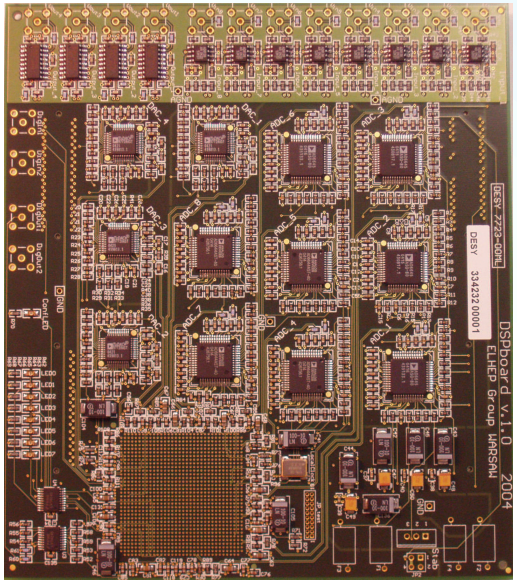


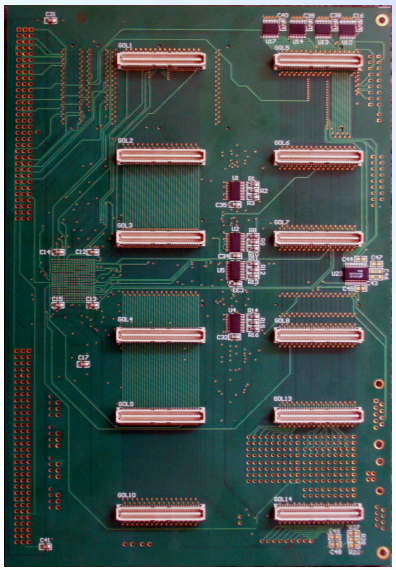
Third Generation RF Control Hardware

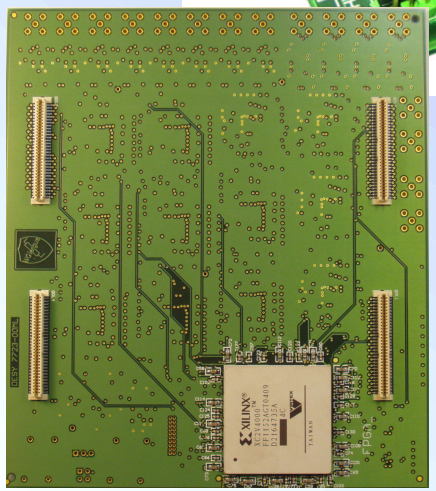
- 8 ADCs 14 bits, 80 MHz
- 4 DACs, 14 bits, 125 MHz
- DSP Board – Virtex2 XC2V4000
- Optolink – 3.125 GHz



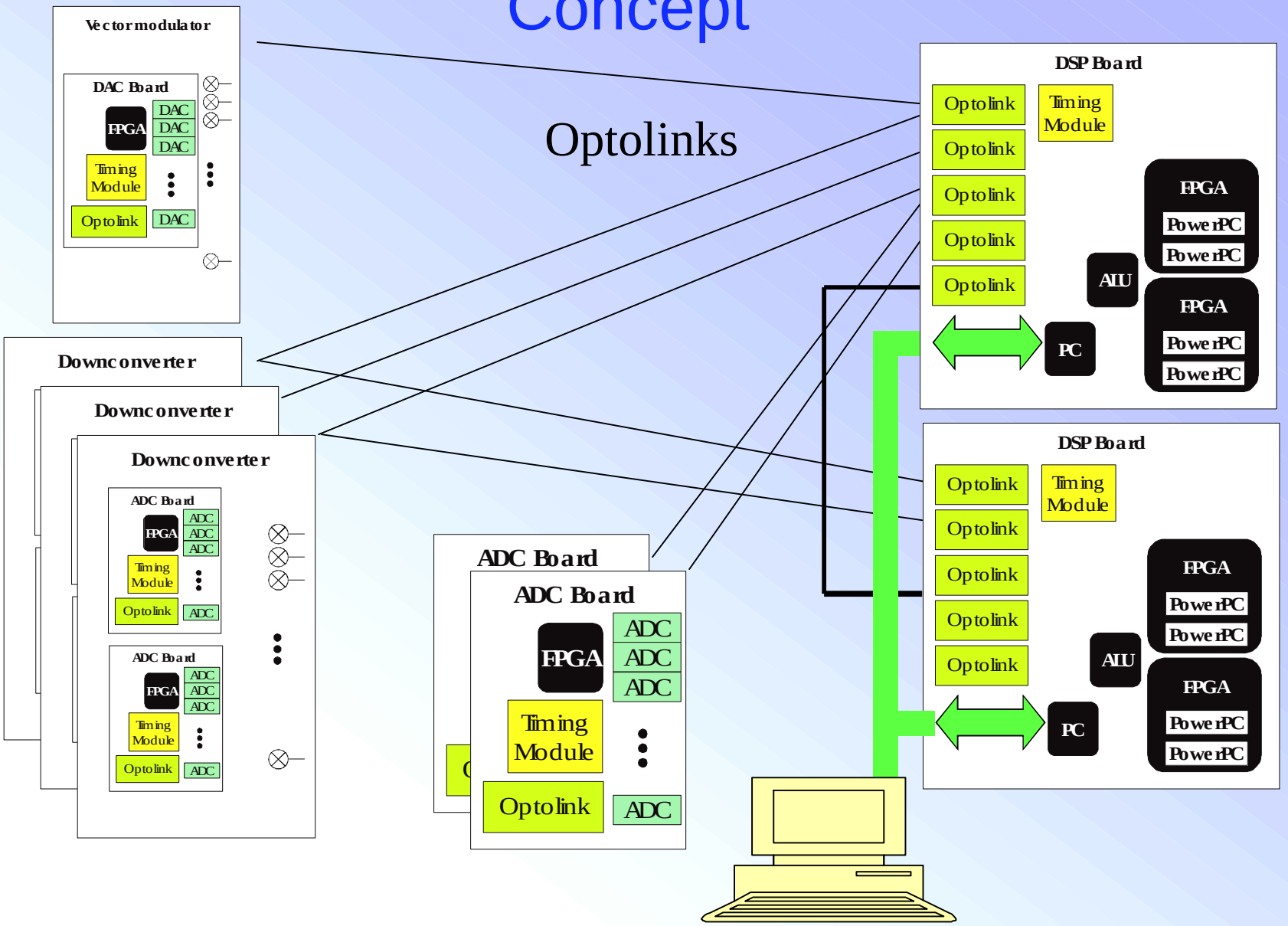








Third Generation RF Control Concept



Multichannel Downconverter

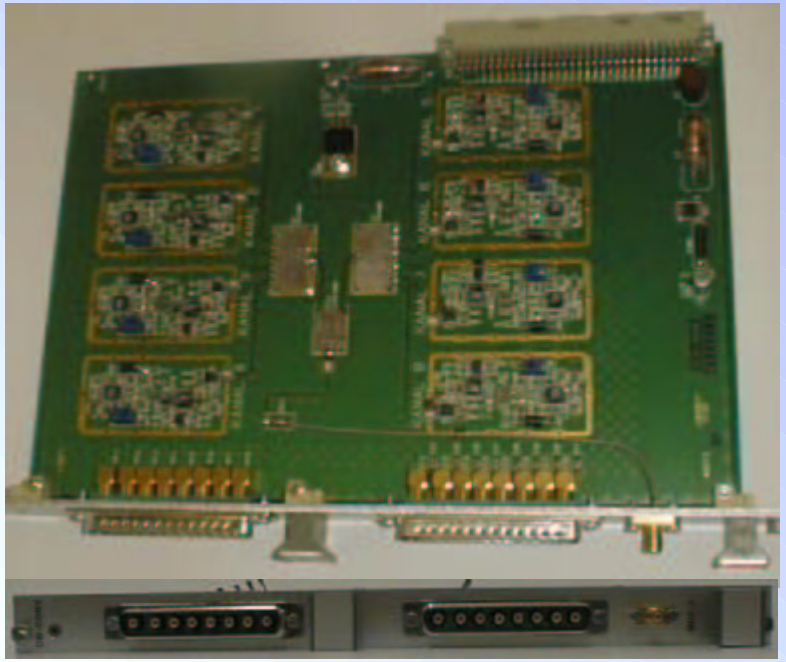
Meeting the high field stability requirements demands for new, noise-reduced, highly linear downconverters.

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:

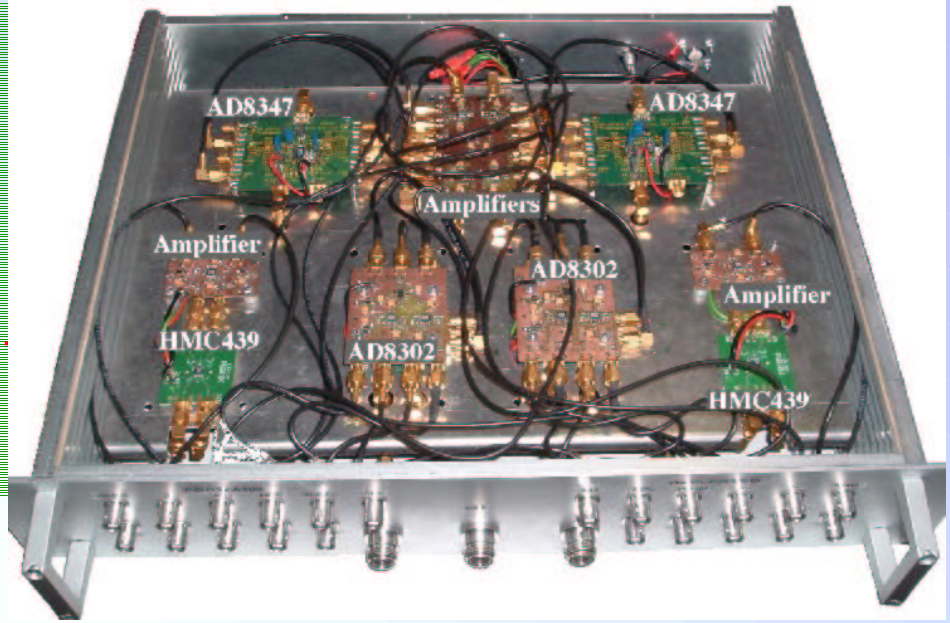
- Accelerating gradient: 40 MV/m
- Repetition rate: 1-10 Hz
- rf pulse length: 100-900 µs
- Amplitude stability: ± 0.25%
- Phase stability: ± 2°

Solutions:

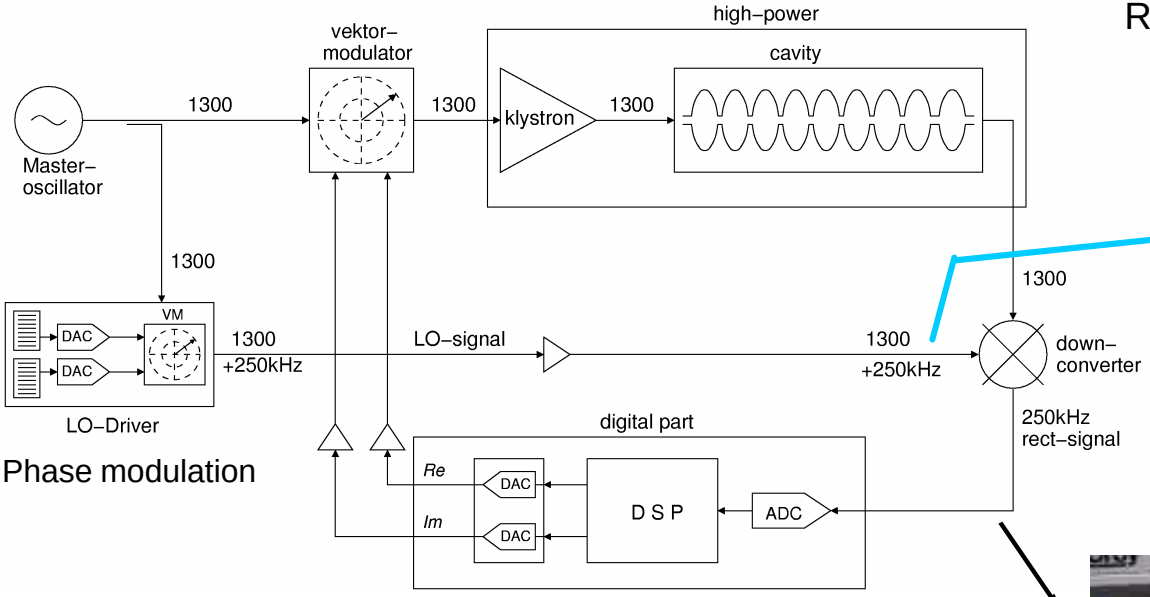
- Use forward and reflected power
- Precise IQ detectors for field control
- Fast logarithmic detectors with big dynamic range for measurement of decaying field

Difficulties:

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



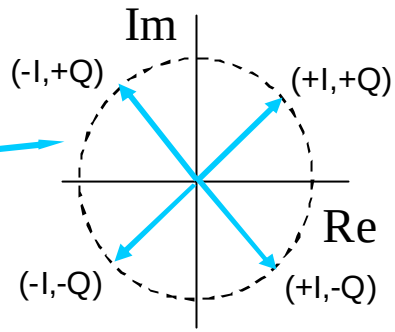
- **RF digital feedback system (TTF2) :**



Phase modulation

- **+I,-I,+Q,-Q detection scheme :**

Rotation of the LO-signal in four 90° steps



Bandwidth for transforming 250kHz squared pulses :

$$Df \approx 10\,MHz$$

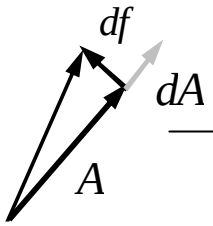
Required regulation bandwidth only :

$$Df \approx 1\,MHz$$

- **Stability requirements on phase and amplitude of the cavity field vector :**

Amplitude stability : and linearity $\frac{dA}{A} < 10^{-4}$

Phase stability : $df < 0.01°$



$dU_{XFEL} < 100\,\mu V$
(normalized to A=1V)

- **Noise measurement at input of an ADC :**

$dU_{TTF2} \approx 1.0mV = 10 \times dU_{XFEL}$

rms-voltage noise :

$$dU = \sqrt{\int_{Df} S_U(f)df} \approx \sqrt{S_U}\sqrt{Df}$$

\+ *Reduce the measuring bandwidth*

\+ *Low-noise design*

\+ *Averaging, switched low-pass!*

\- *Correlation methods*

Superposition of all noise contributions :

$$\sqrt{dU_{DWC}^2 + dU_{IQ}^2 + dU_{MO}^2 + dU_{extern}^2 + \ldots} < 100\mu V$$

Requirement for CEBAF (JLAB)

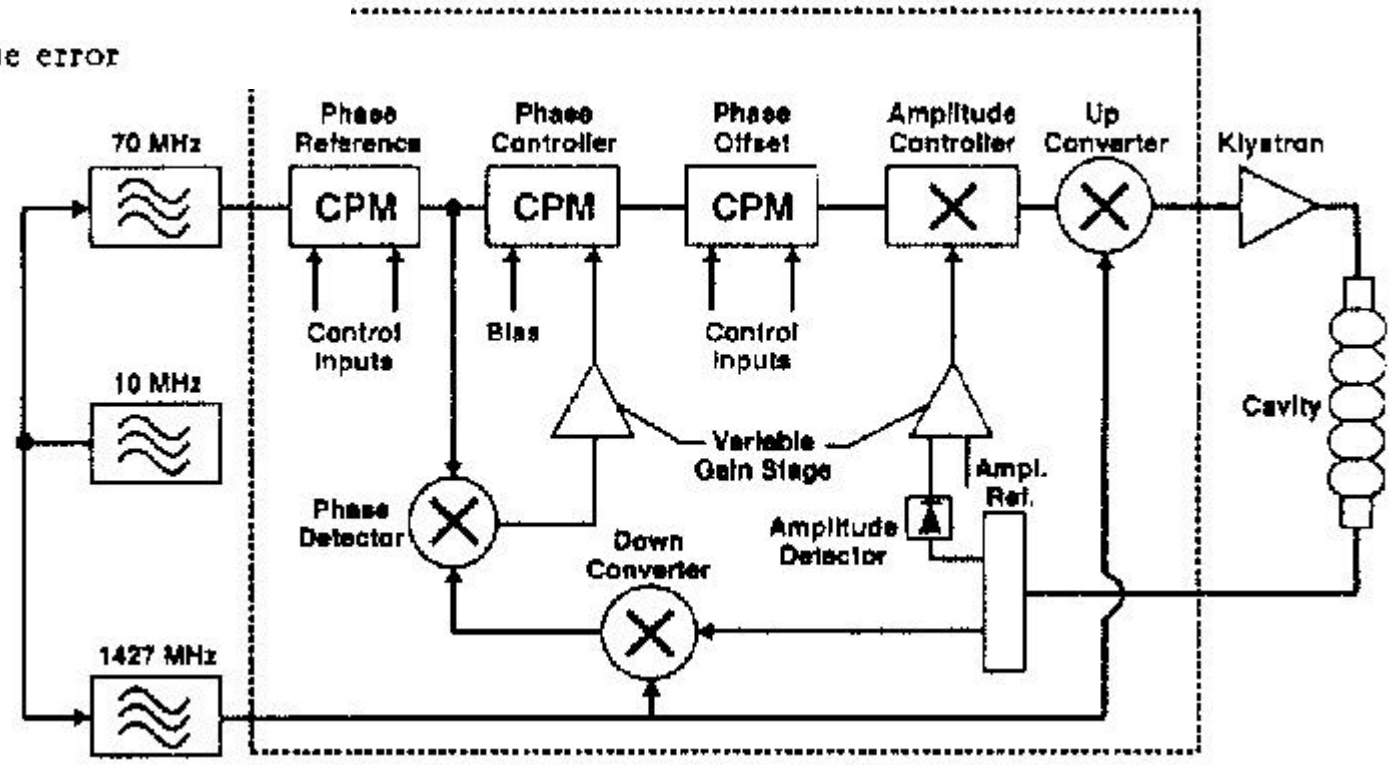
RF control requirements with vernier

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

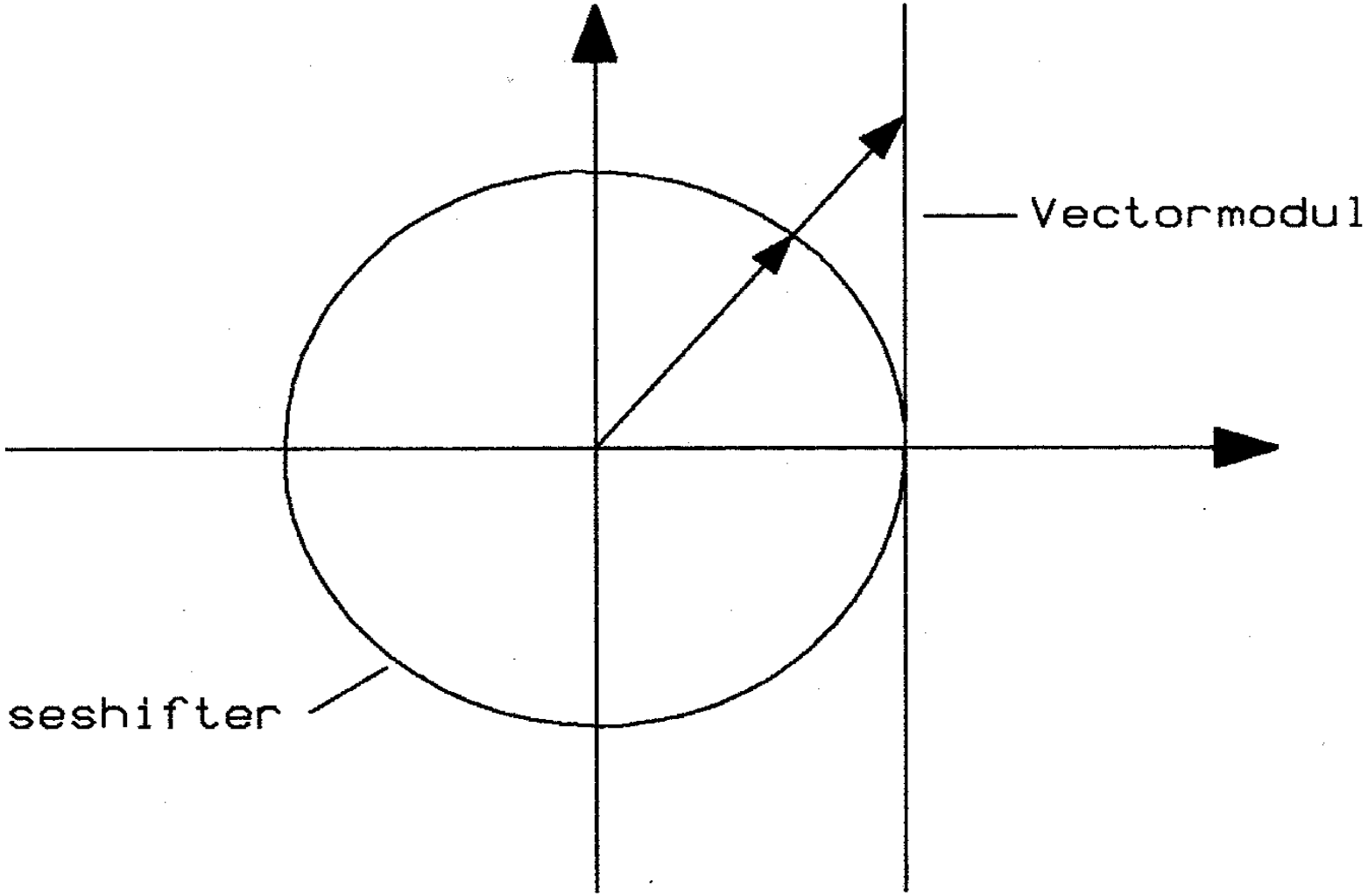
σ_A : relative RMS amplitude error

σ_f : fast RMS phase error

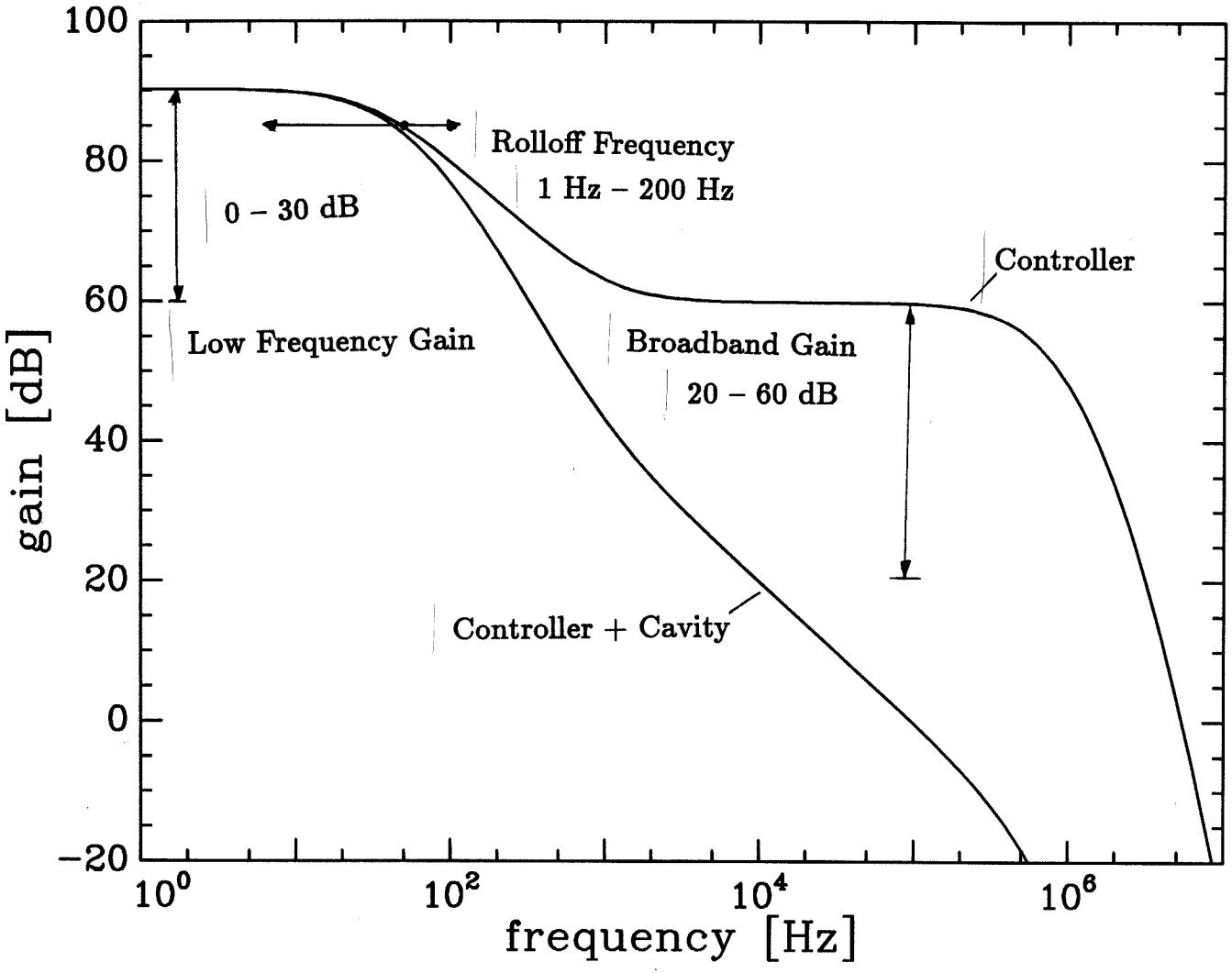
σ_s : slow RMS (along linac) phase error

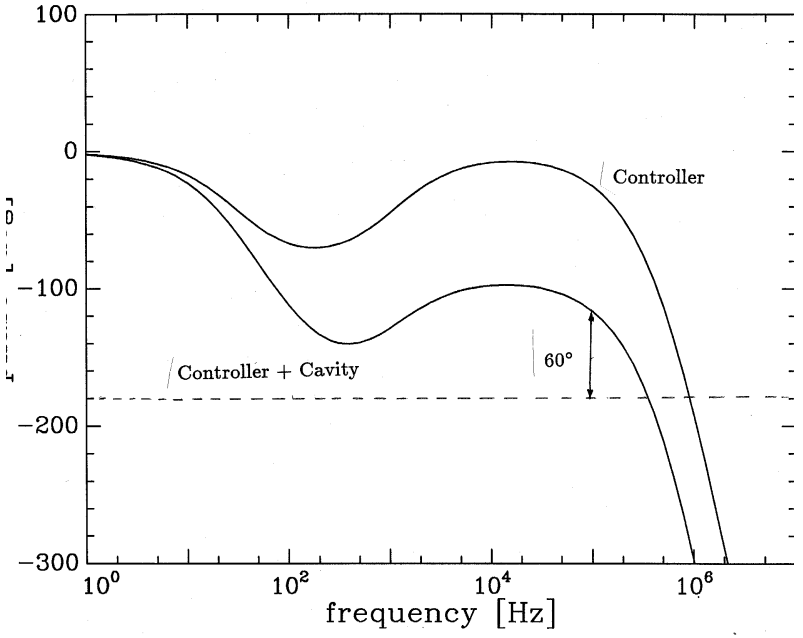


Vectormodulator vs Phaseshifter

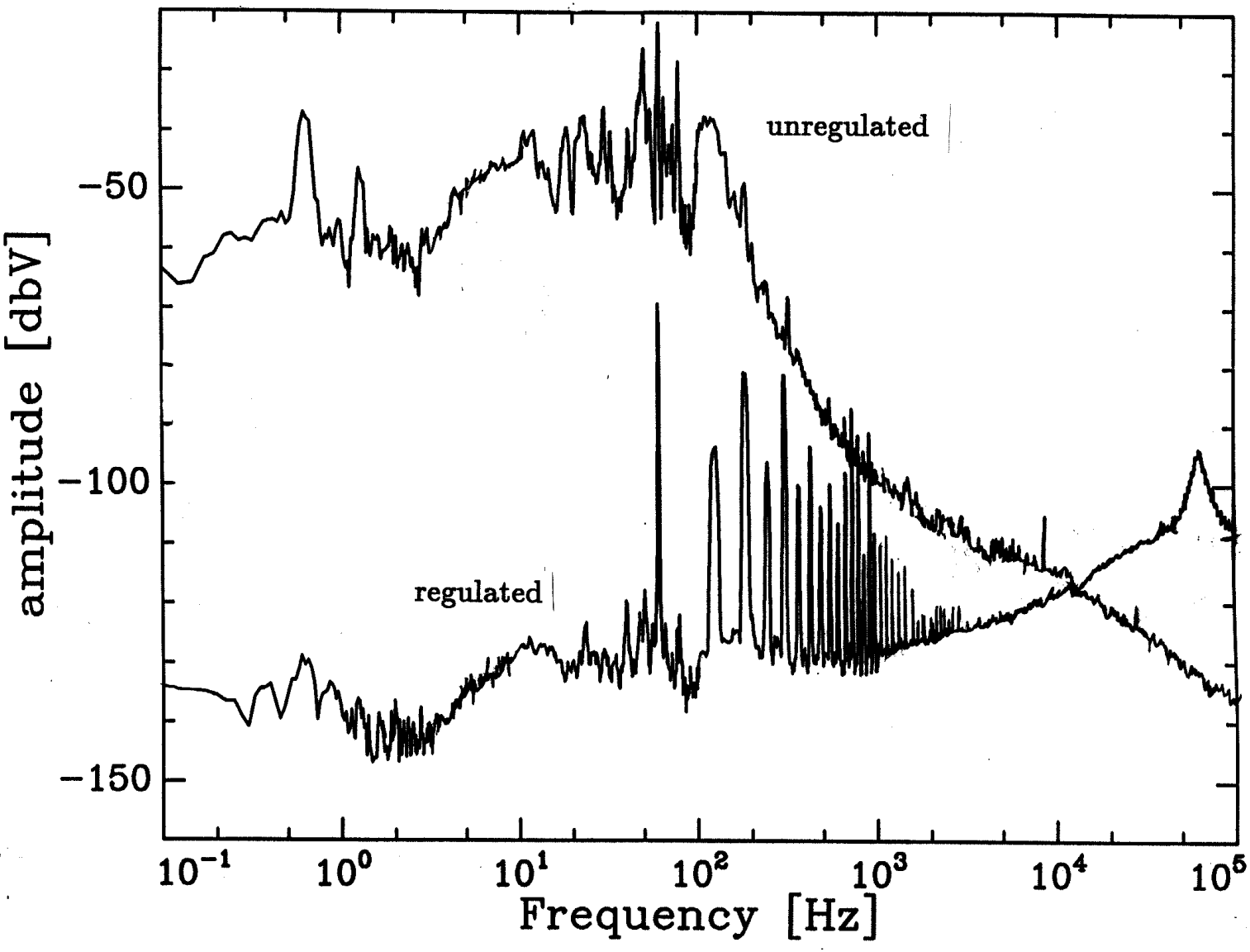


Bode Plot of Controller at JLAB





Performance Measured at JLAB



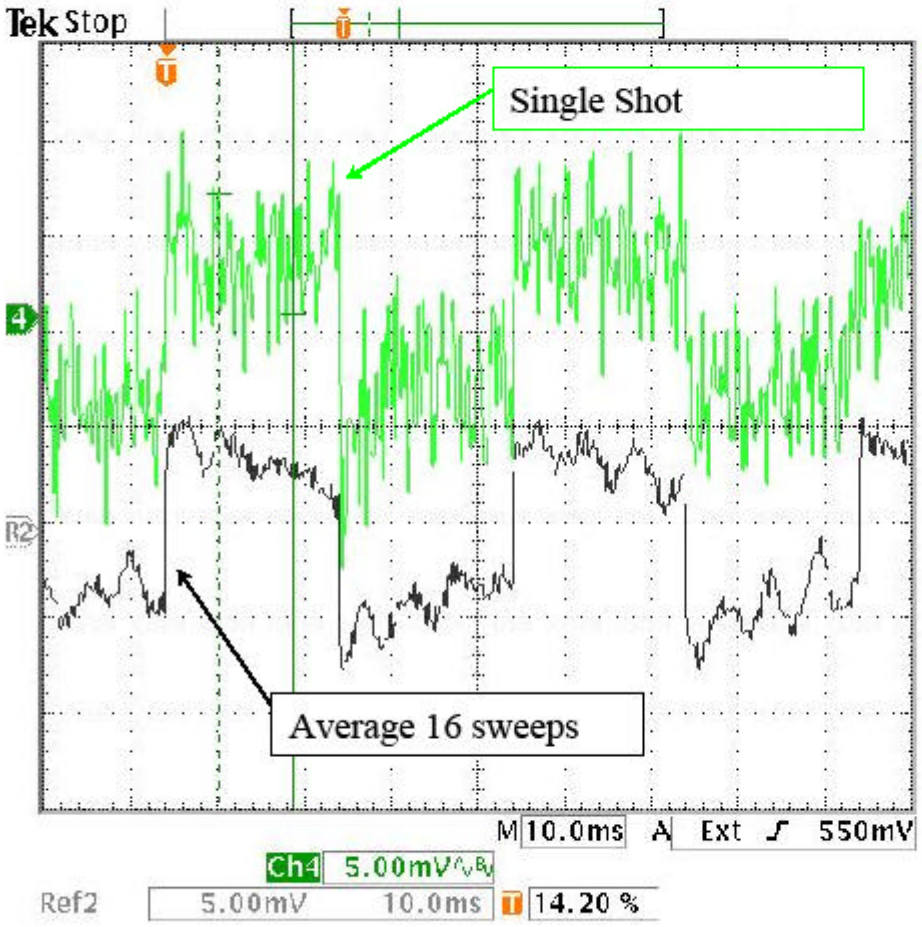
Performance Measure at JLAB

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

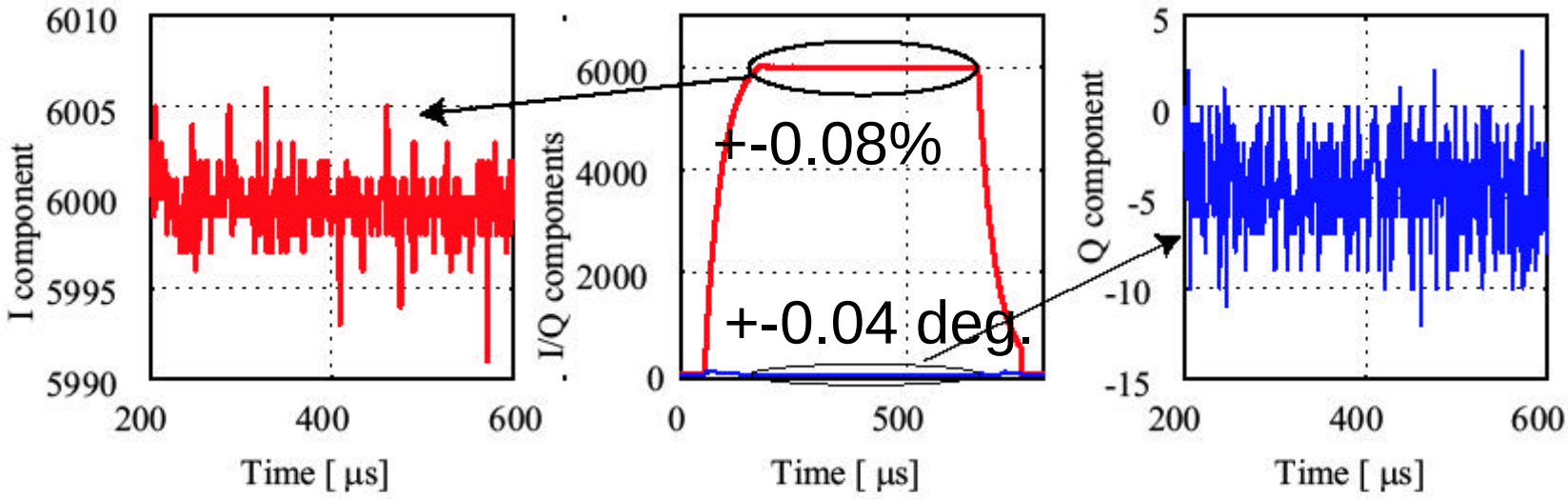
0.03° rms Phase Stability!

Underlying 300 Hz structure at 0.015°

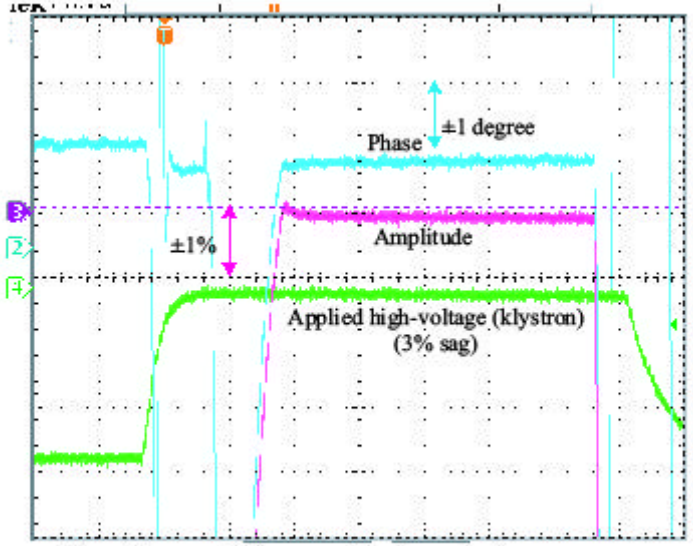
AC Line pickup or Real Phase drift?

Feed Forward Required?

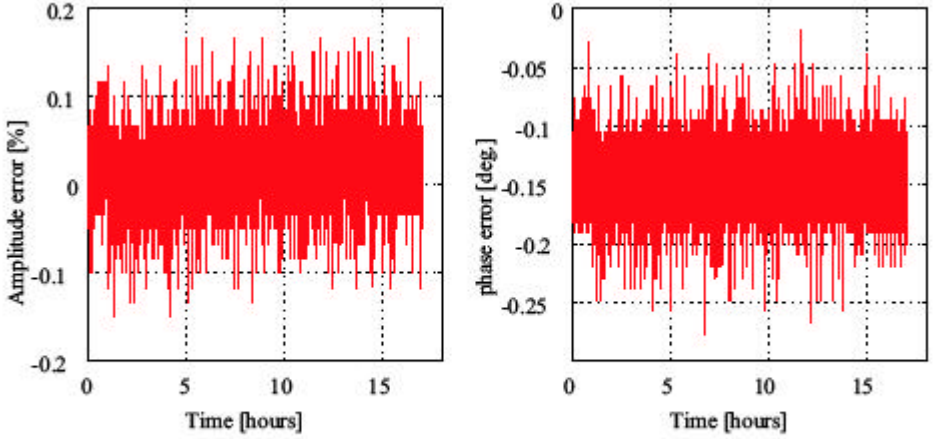
Stability Measured for J-PARC



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.

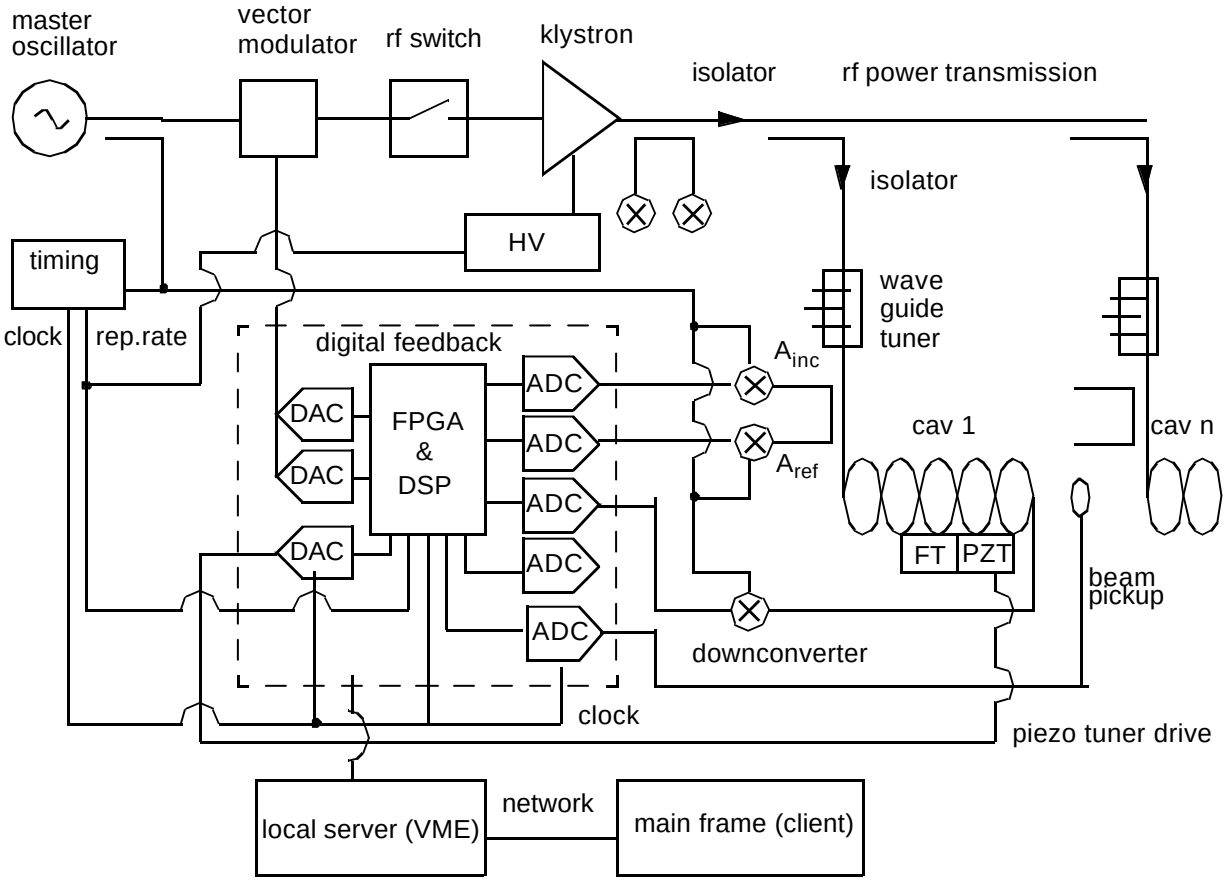


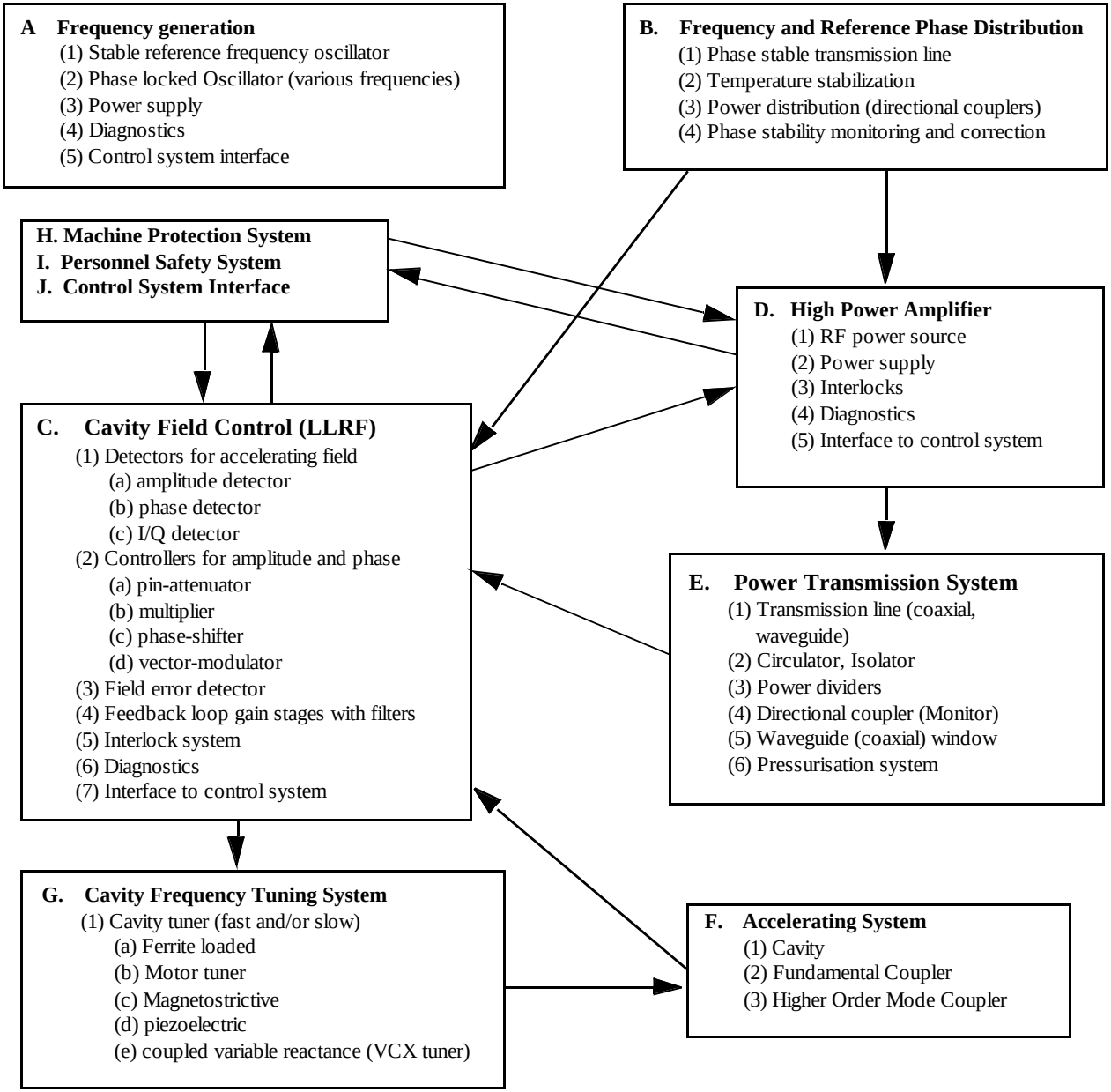
Waveforms of the amplitude and phase obtained by external monitors.



Trend-graphs of the amplitude and phase stabilities.

S. Michizono


master oscillator
vector modulator
rf switch
klystron
isolator
rf power transmission
isolator
HV
timing
clock
rep.rate
digital feedback
wave guide tuner
A_{inc}
A_{ref}
DAC
DAC
DAC
FPGA & DSP
ADC
ADC
ADC
ADC
ADC
cav 1
cav n
FT
PZT
beam pickup
downconverter
clock
piezo tuner drive
local server (VME)
network
main frame (client)


A Frequency generation
(1) Stable reference frequency oscillator
(2) Phase locked Oscillator (various frequencies)
(3) Power supply
(4) Diagnostics
(5) Control system interface
B. Frequency and Reference Phase Distribution
(1) Phase stable transmission line
(2) Temperature stabilization
(3) Power distribution (directional couplers)
(4) Phase stability monitoring and correction
H. Machine Protection System
I. Personnel Safety System
J. Control System Interface
D. High Power Amplifier
(1) RF power source
(2) Power supply
(3) Interlocks
(4) Diagnostics
(5) Interface to control system
C. Cavity Field Control (LLRF)
(1) Detectors for accelerating field
(a) amplitude detector
(b) phase detector
(c) I/Q detector
(2) Controllers for amplitude and phase
(a) pin-attenuator
(b) multiplier
(c) phase-shifter
(d) vector-modulator
(3) Field error detector
(4) Feedback loop gain stages with filters
(5) Interlock system
(6) Diagnostics
(7) Interface to control system
E. Power Transmission System
(1) Transmission line (coaxial, waveguide)
(2) Circulator, Isolator
(3) Power dividers
(4) Directional coupler (Monitor)
(5) Waveguide (coaxial) window
(6) Pressurisation system
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)
F. Accelerating System
(1) Cavity
(2) Fundamental Coupler
(3) Higher Order Mode Coupler

A. FIELD CONTROL ALGORITHMS

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

(2) Feedforward
- (a) beam loading compensation
- (b) beam energy feedback
- (c) bunch length feedback

(3) Klystron linearization

(4) Exception handling
- (a) quench detection and handling

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) Measurement of incident phase (vector-sum !)

(5) Beam phase measurement

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

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

(8) Loaded Q

C. Cavity Resonance Control

(1) Slow tuner
- (a) maintain average resonance frequency
- (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

D. High level procedures

(1) Adaptive feedforward
- (a) response matrix based
- (b) transferfunction based
- (c) robust
- (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

E. Miscellaneous

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

(2) Alarm and warning generation

(3) Automated fault recovery

(4) Finite state machine

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