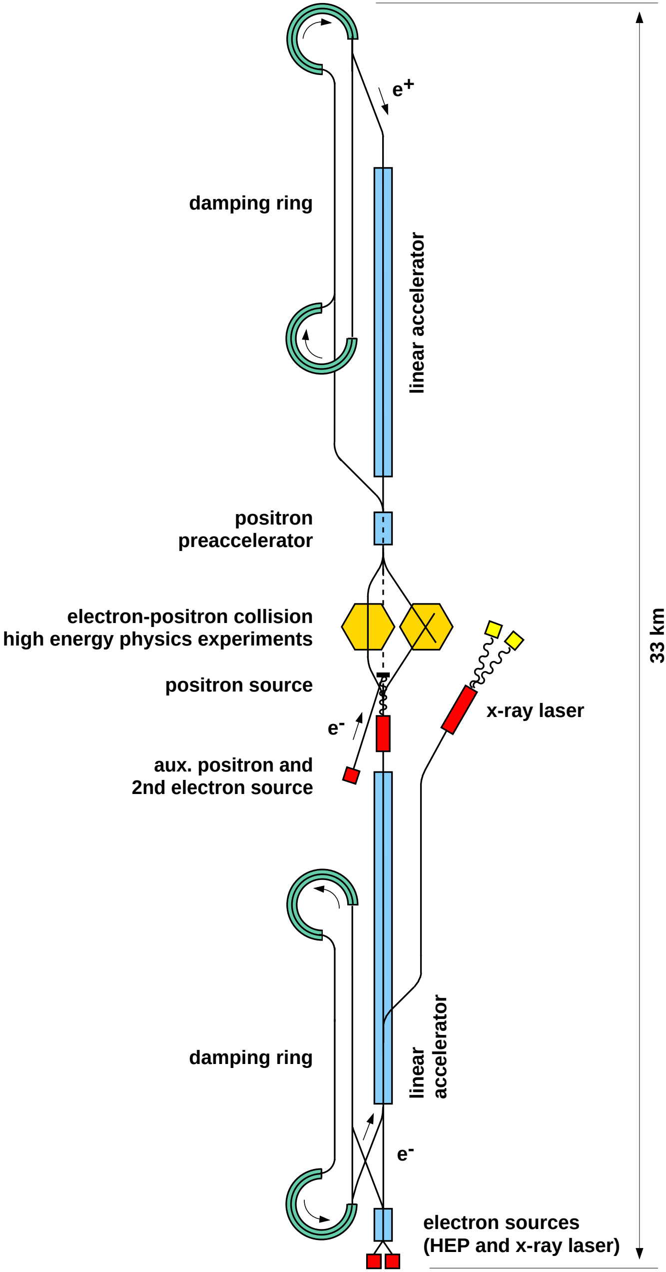
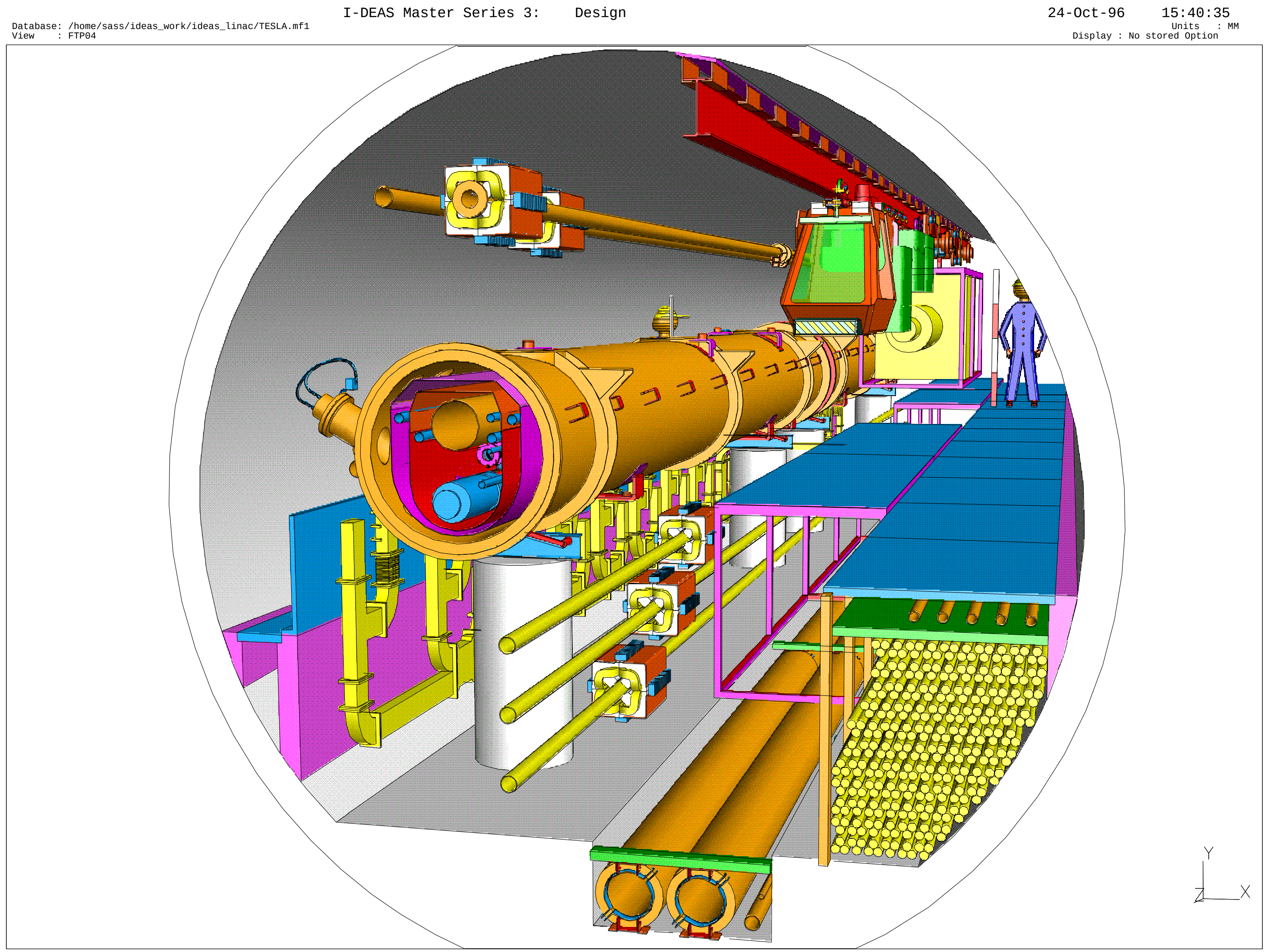
TESLA RF Control

(S. Simrock, DESY)

- RF Control Issues for TESLA
  - Requirements (Field Stability)
  - Sources of Perturbations
  - Lorentz Force Detuning
- RF System Design
  - Digital Control Concept
  - Feedback and Feedforward
  - Build-in Diagnostics
- Operational Experience
  - Amplitude and Phase Stability
  - Operational Limitations
- Conclusion



e+
damping ring
linear accelerator
positron
preaccelerator
electron-positron collision
high energy physics experiments
positron source
x-ray laser
33 km
e-
aux. positron and
2nd electron source
damping ring
linear
accelerator
e-
electron sources
(HEP and x-ray laser)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X

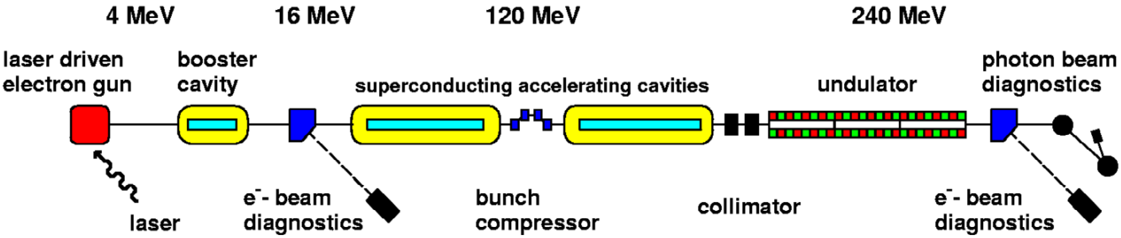


Figure 2.2.1: *Schematic layout of the TESLA Test Facility Linac (TTFL). The total length is* $\sim 120\,m$.

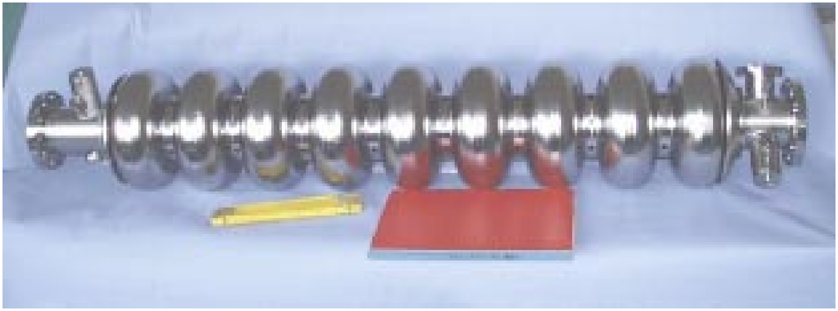


Figure 3.2.1: *The 9-cell niobium cavity for TESLA.*

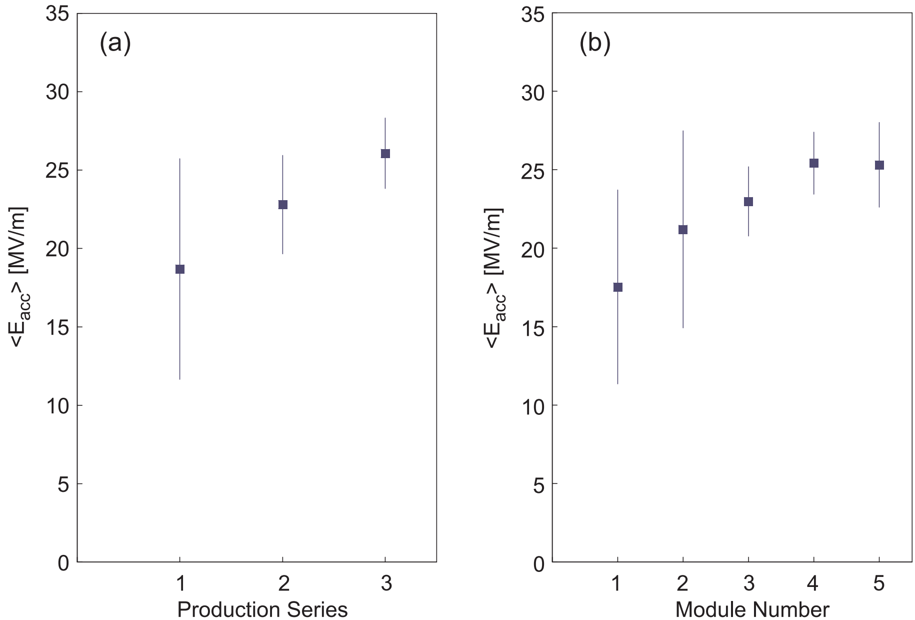


Figure 3.2.2: *Average accelerating gradients at a quality factor* $Q_0 > 10^{10}$ *measured in the vertical test cryostat:*
(a) of the cavities in the three production series; (b) of the cavities installed in the first five cryogenic modules for TTF. The error bars give the standard deviation.

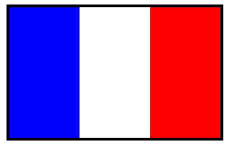
TTF RF System Parameters

Energy	1 GeV
Bunch-to-Bunch Energy Spread σ_E/E	$< 2 \cdot 10^{-3}$
RF Frequency	1.3 GHz
Accelerating Gradient	15(25)MV/m
RF Pulse Length	1300 µs
Repetition Rate of RF Pulses	10 Hz
Particles per Bunch	$5.4\ 10^{10}$
Bunch Separation	1 µs
Number of Bunches per Pulse	800
Beam Current	8 mA
Cavity Fill Time	510 µs
Cavity Q_L	$3 \cdot 10^6$
Cavity Q_0	$3 \cdot 10^9$
Cells per Cavity	9
Active cavity length	1.038 m
Number of Cavities	64
Number of Cavities / Klystron	32
RF Power / Cavity (@25 MV/m)	200 kW

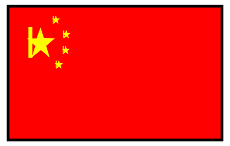
TESLA Test Facility at DESY

(TeV Energy Superconducting Linear Accelerator)

Yerevan Physics Institute

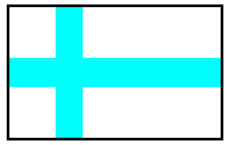


IN2P3 / IPN Orsay
IN2P3 / LAL Orsay
CEA / DSM (DAPNIA, CE Saclay)

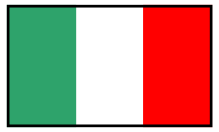


IHEP, Academia Sinica, Beijing
Tsinghua University, Beijing

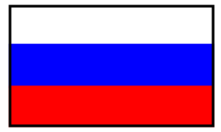
RWTH Aachen
Max-Born-Inst. Berlin
TU Berlin
TU Darmstadt
TU Dresden
Univ. Frankfurt
GKSS Geesthacht
DESY Hamburg + Zeuthen
Univ. Hamburg
FZ Karlsruhe
Univ. Rostock
Univ. Wuppertal



Institut of Physics, Helsinki

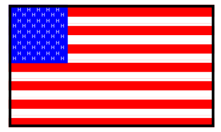


INFN Frascati
INFN Legnaro
INFN Milano
INFN and Univ. Roma II



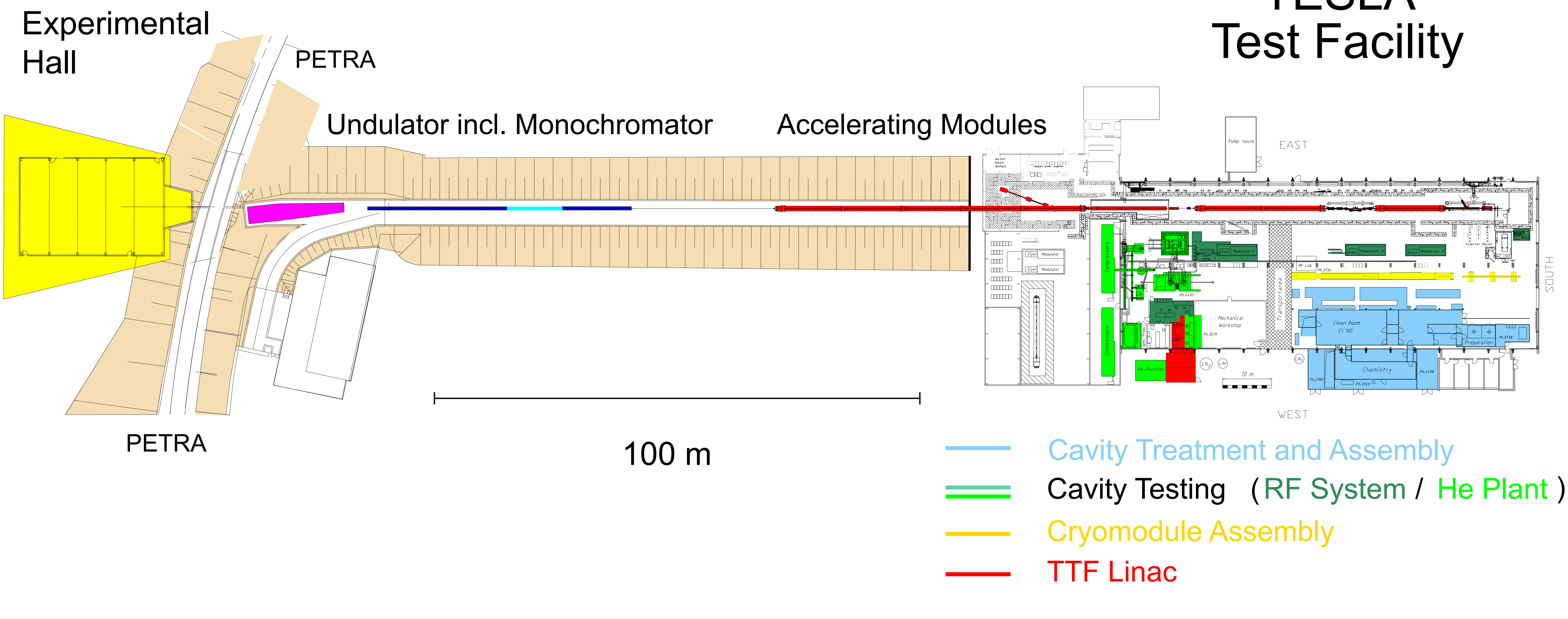
JINR Dubna
IHEP Protvino
INP Novosibirsk
INR Troitsk

Polish Academy of Science
Univ. of Warsaw
Inst. of Nuclear Physics, Cracow
Polish Atomic Energy Agency, Warsaw
Soltan Inst. for Nuclear Studies, Otwock-Swierk



ANL, Argonne IL
Cornell Univ., Ithaca NY
FNAL, Batavia IL
UCLA, Los Angeles CA

TESLA Test Facility



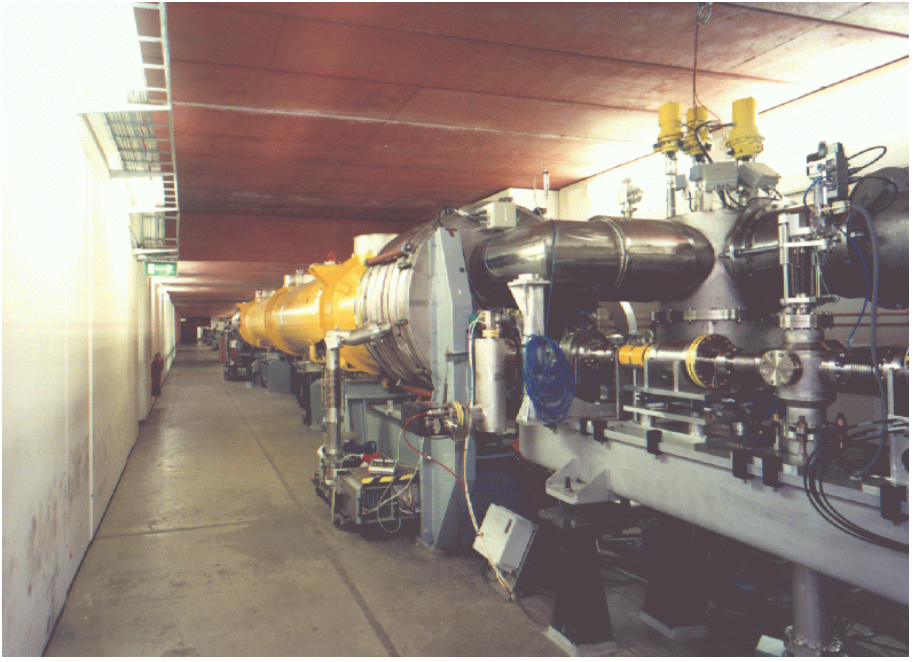
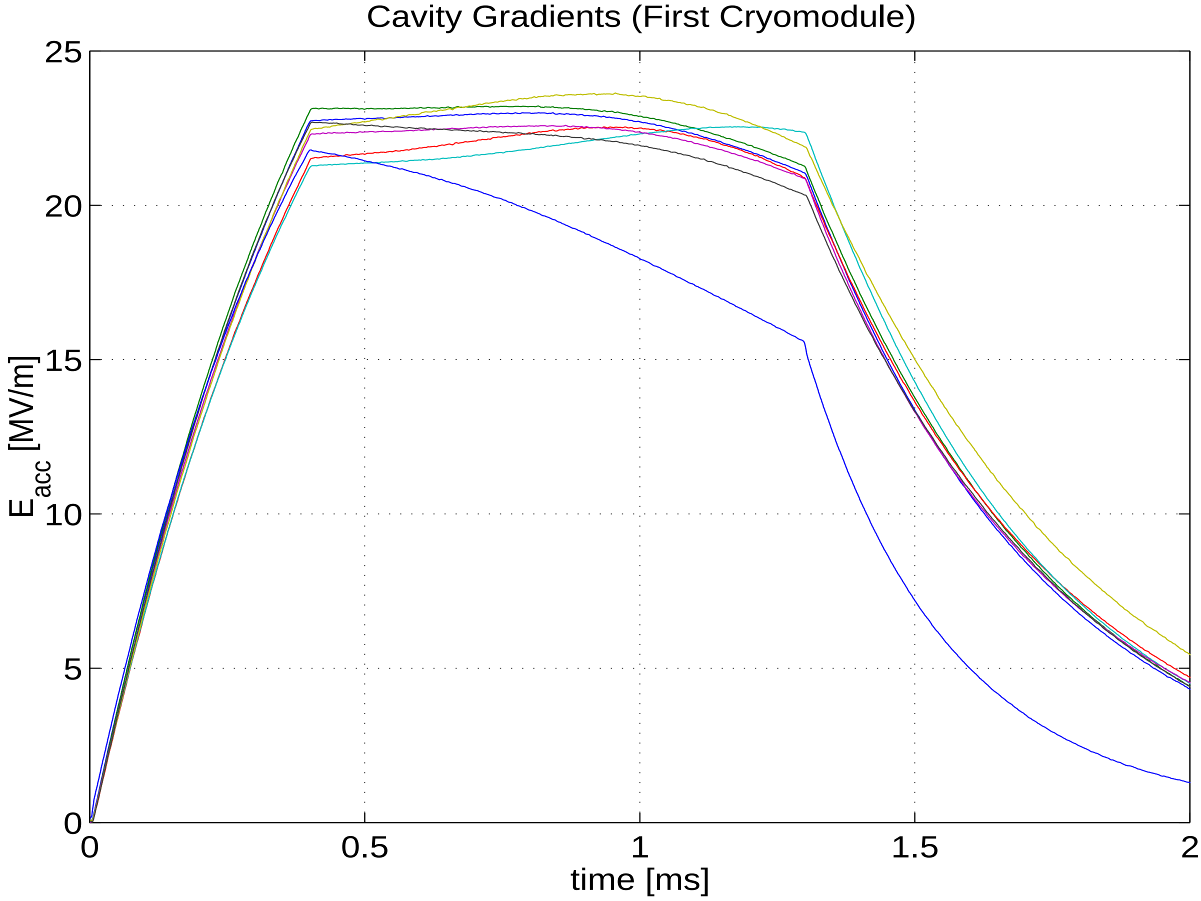
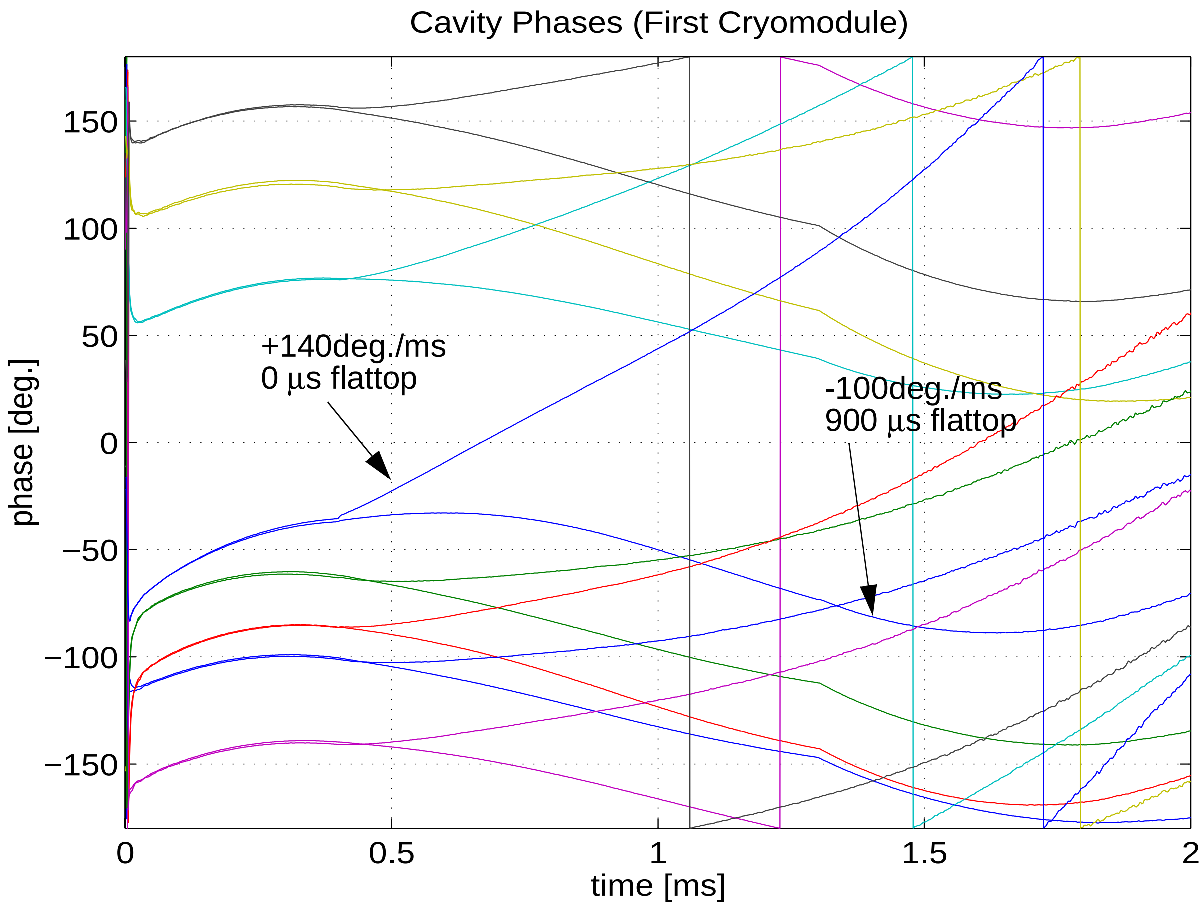


Figure 2.2.2: *View into the TTF Linac tunnel. The electron beam (already accelerated by the capture cavity) comes from the right and is injected into the first accelerator module, which can be seen in the background (yellow vessel).*



Cavity Gradients (First Cryomodule)
E$_{acc}$ [MV/m]
time [ms]
0
5
10
15
20
25
0.5
1
1.5
2



Cavity Phases (First Cryomodule)
phase [deg.]
time [ms]
+140deg./ms
0 µs flattop
-100deg./ms
900 µs flattop
150
100
50
0
−50
−100
−150
0.5
1
1.5
2

S.Simrock

RF Control Design Considerations (1)

Prerequisites

- Determine requirements for energy spread and long term energy stability
- Determine requirements for correlated and uncorrelated amplitude and phase stability and timing jitter
- Determine quantitatively the various contributions to rf field perturbations
- Determine by what factor each of these perturbations must be reduced

RF Control Design Considerations (2)

Design

- Eliminate/Reduce sources of perturbations
  - -- 60 Hz (and harmonics) ripple on HV-power supplies
  - -- HV-pulse flatness (optimize pulse forming networks)
  - -- select components with small temperature coefficient

- Passive reduction of perturbations
  - -- Lower Q of higher order mode (HOM damping)
  - -- Detune higher order modes to reduce wakefields
  - -- Temperature stabilization of cavities, electronics, power amplifier, etc.

RF Control Design Considerations (3)

Design (Cont'd)

- Feedforward
  - -- Adaptive control of high power pulse flatness
  - -- Pulse to pulse noise cancellation
  - -- Beam loading compensation

- Feedback
  - -- RF based fast amplitude and phase control
  - -- Slow and/or fast control of cavity resonance frequency
  - -- Beam based feedback
    - -- for slow (thermal) drift corrections (energy and phase)
    - -- for fast corrections of energy and energy spread

DESY

Requirements for Amplitude and Phase Stability

Allowable contribution to energy gain fluctuations for vector-sum of 32 cavities	σ_A/A correlated	σ_A/A uncorrelated 302 klystr. (22 klystr.)	σ_ϕ correlated	σ_ϕ uncorrelated 302 klystr. (22 klystr.)
σE/E (ampl, phase) = 1e-3, ϕ=-4 deg.	0.7e-3	1.2e-2 (3.3e-3)	0.6 deg.	6 deg. (2 deg.)
σE/E (amp, phasel) = 1e-3, ϕ=-10 deg.	0.7e-3	1.2e-2 (3.3e-3)	0.25 deg.	3.5 deg. (1.1 deg.)
σE/E (ampl, phase) = 3e-4, ϕ=-4 deg.	2.1e-4	3.5e-3 (1.0e-3)	0.2 deg.	2.3 deg. 0.8 deg.
σE/E (amp, phasel) = 3e-4, ϕ=-10 deg.	2.1e-4	3.5e-3 (1.0e-3)	0.07 deg.	1.1 deg. (0.3 deg.)

S.Simrock

RF Field Perturbations

o Beam loading - Beam current fluctuation - Pulsed beam transients - Multipacting and field emission - Excitation of HOMs - Wake fields o Cavity drive signal - HV- Pulse flatness - HV PS ripple - Phase noise from master oscillator - Timing signal jitter - Mismatch in power distribution system (reflections)	o Cavity dynamics - cavity filling - settling time of field o Cavity resonance frequency change - thermal effects (power dependent) - microphonics (vibrations; only sc-cavities) - radiation pressure (only sc-cavities) o Other - Instabilities in feedback system - Interlock trips - thermal drifts (electronics, power amplifiers, cables, power transmission system)

Perturbations to be Controlled

Lorenz Force

- Lorentz for detuning constant of -1 Hz/(MV/m)^2 results in a steady state detuning of -625 Hz at 25 MV/m. Due to the mechanical dynamics of the cavity the actual frequency change will be only 400 Hz (corresponding to ±45° in tuning angle in steady state). The Lorentz force detuning is a correlated perturbation.

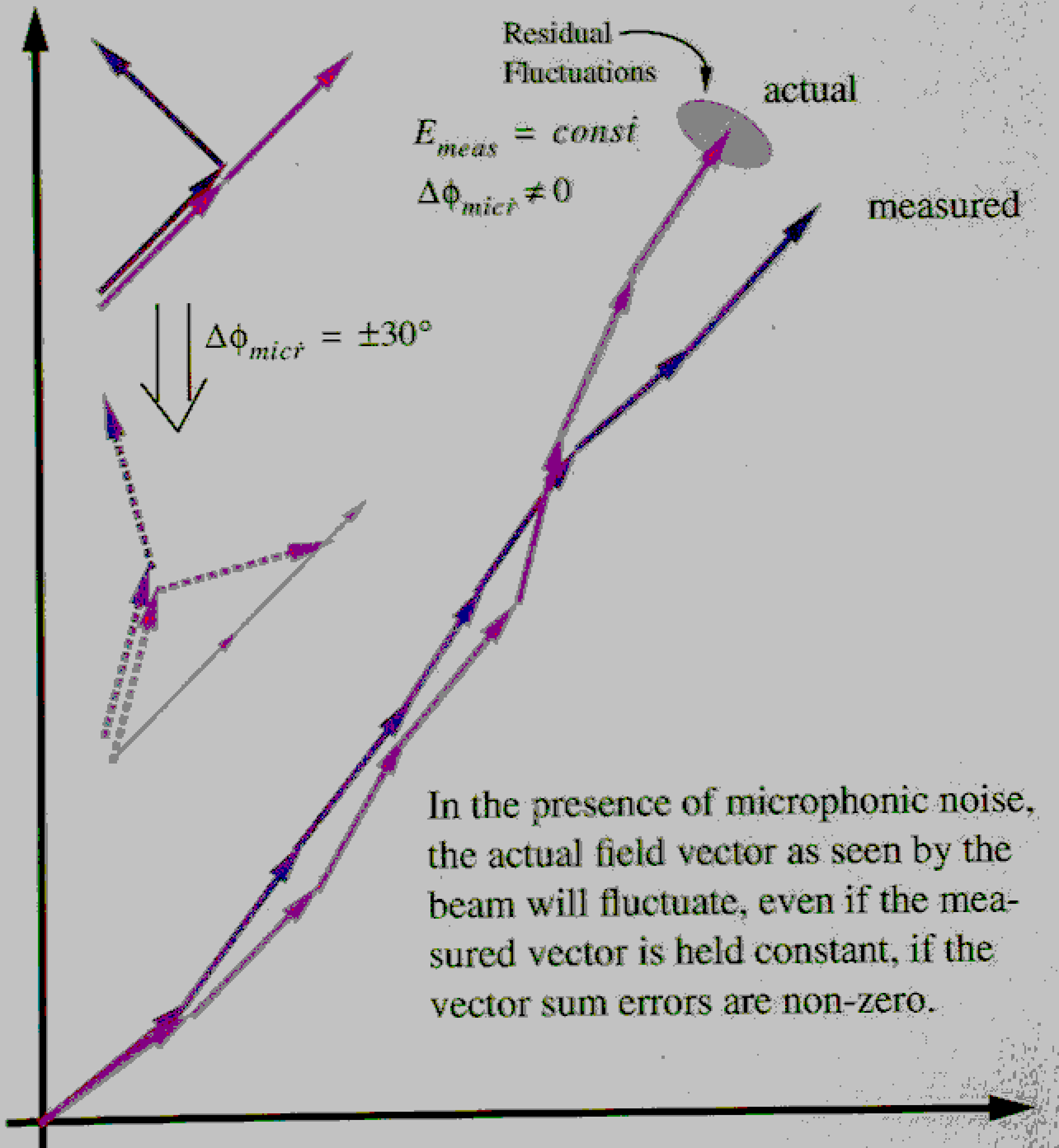
Microphonics

- The microphonic noise level measured in the TTF are about ±10 Hz (±2°). This has to be compared to the cavity bandwidth (HFHM) of 215 Hz. The microphonics are uncorrelated along the linac.

Beam Loading

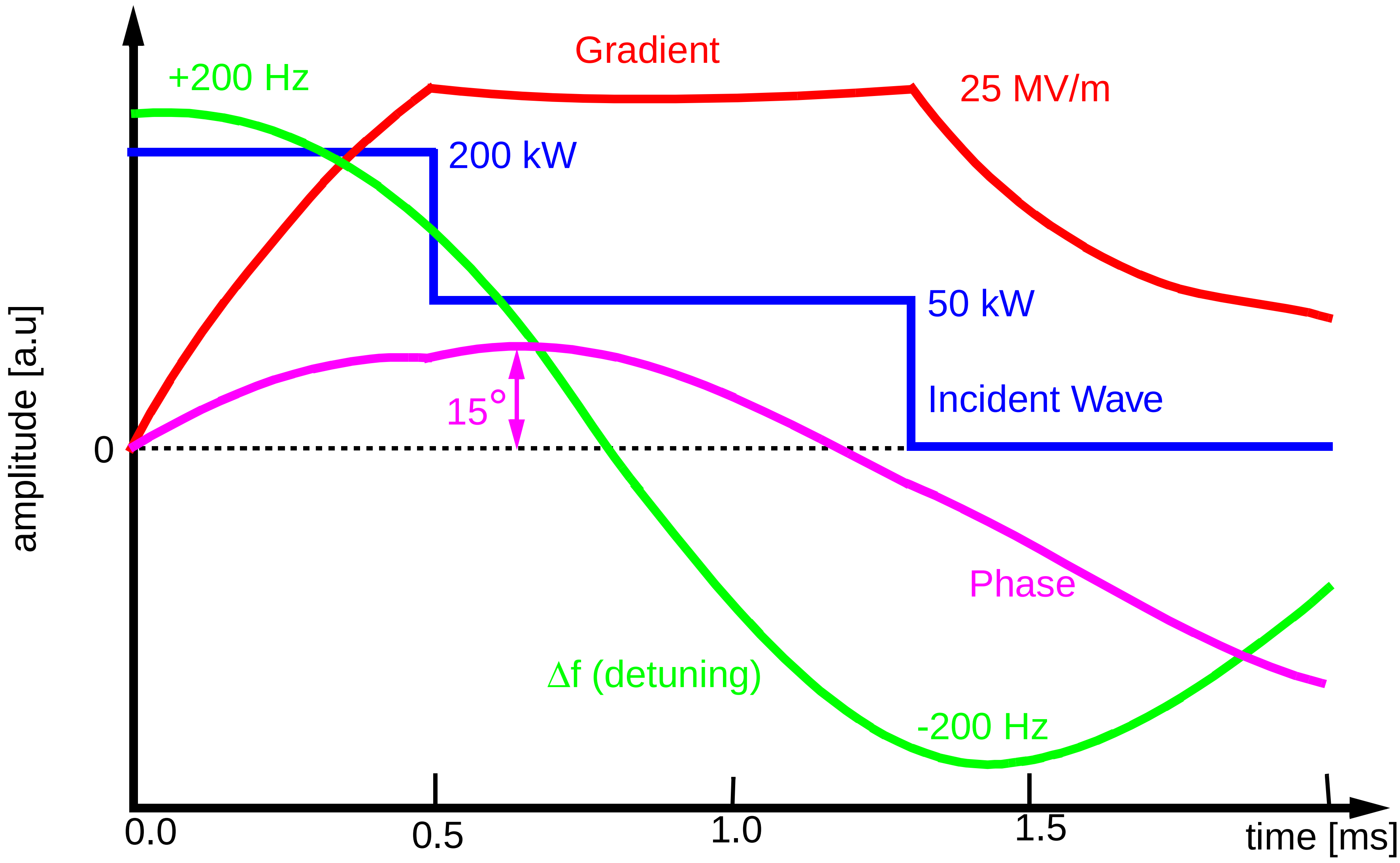
- A single bunch (5×10^{-10} e^-) induces a transient of 1.4×10^{-3} . 10% rms bunch-to-bunch charge fluctuation will result in an energy spread contribution of 1.4×10^{-4} (correlated !).

- Error in Vector Sum
  - The calibration of the vector sum can only be done to a certain accuracy. Required are ±10% for gradient calibration and ±1° or phase calibration.



In the presence of microphonic noise, the actual field vector as seen by the beam will fluctuate, even if the measured vector is held constant, if the vector sum errors are non-zero.

Open Loop Response



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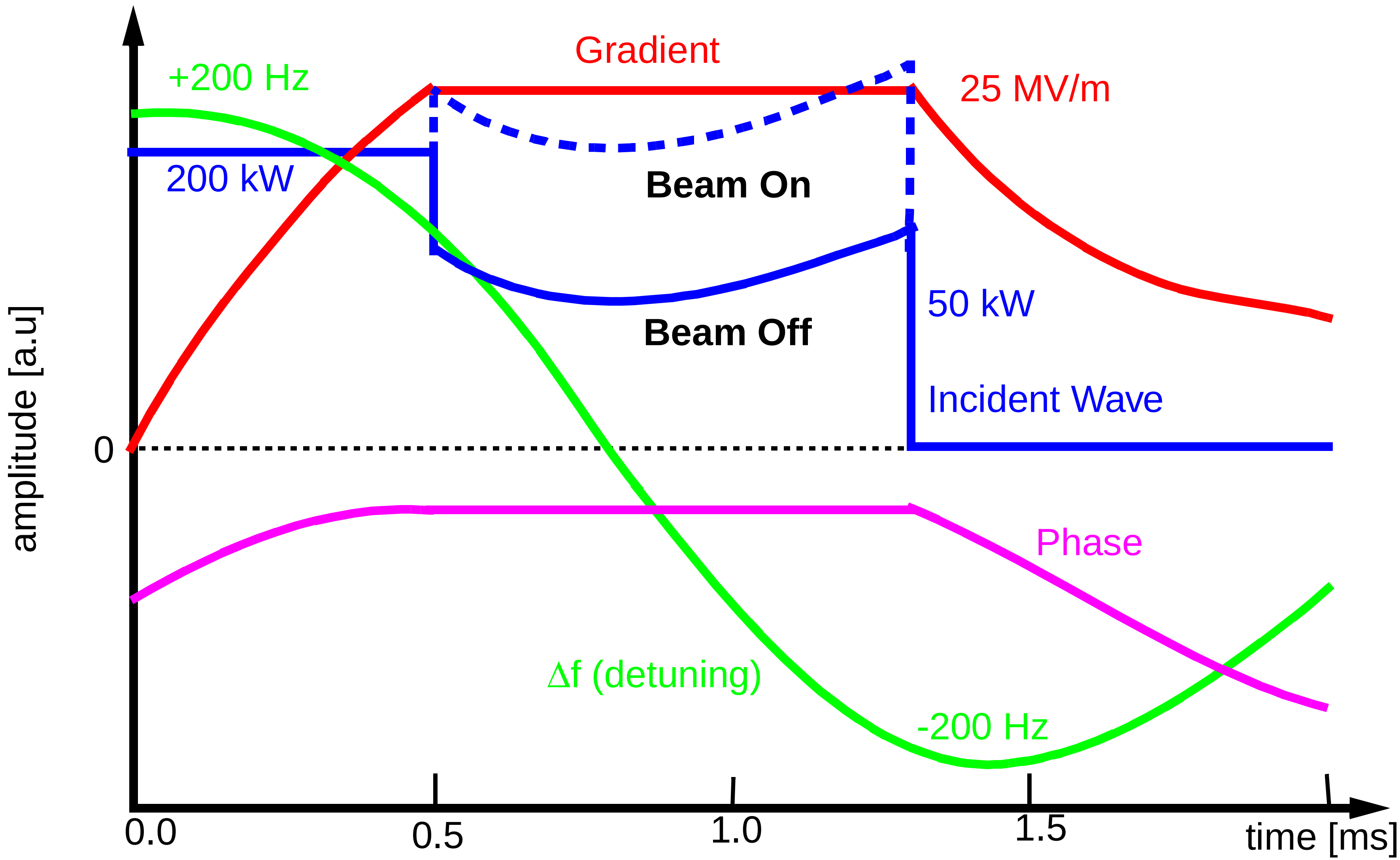
Closed Loop Response



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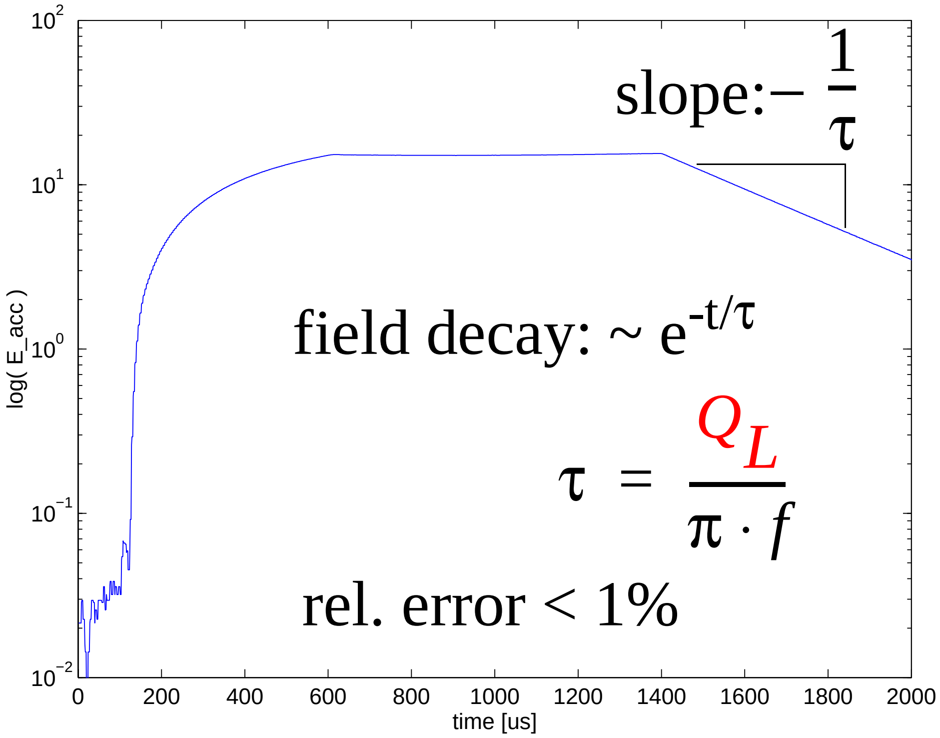
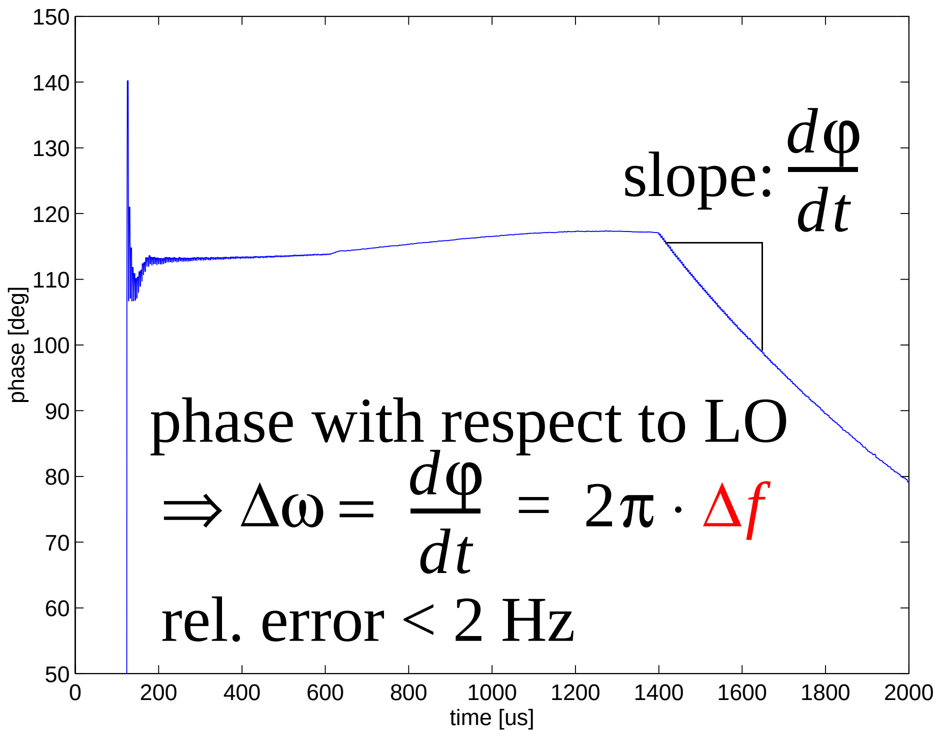
Determination of Q_L and detuning Δf

- Q_L :

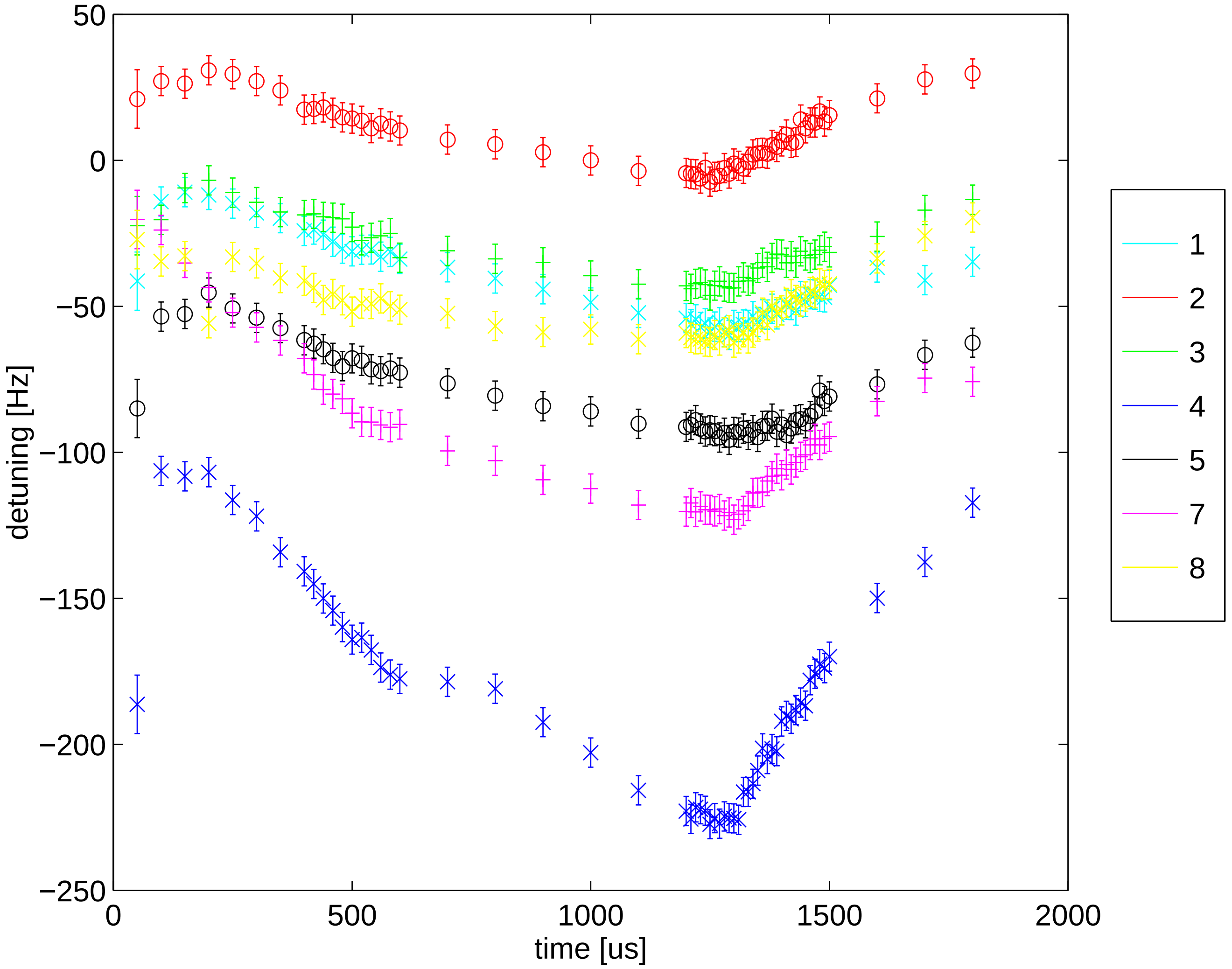


- detuning Δf :



Lorentz-Force Detuning

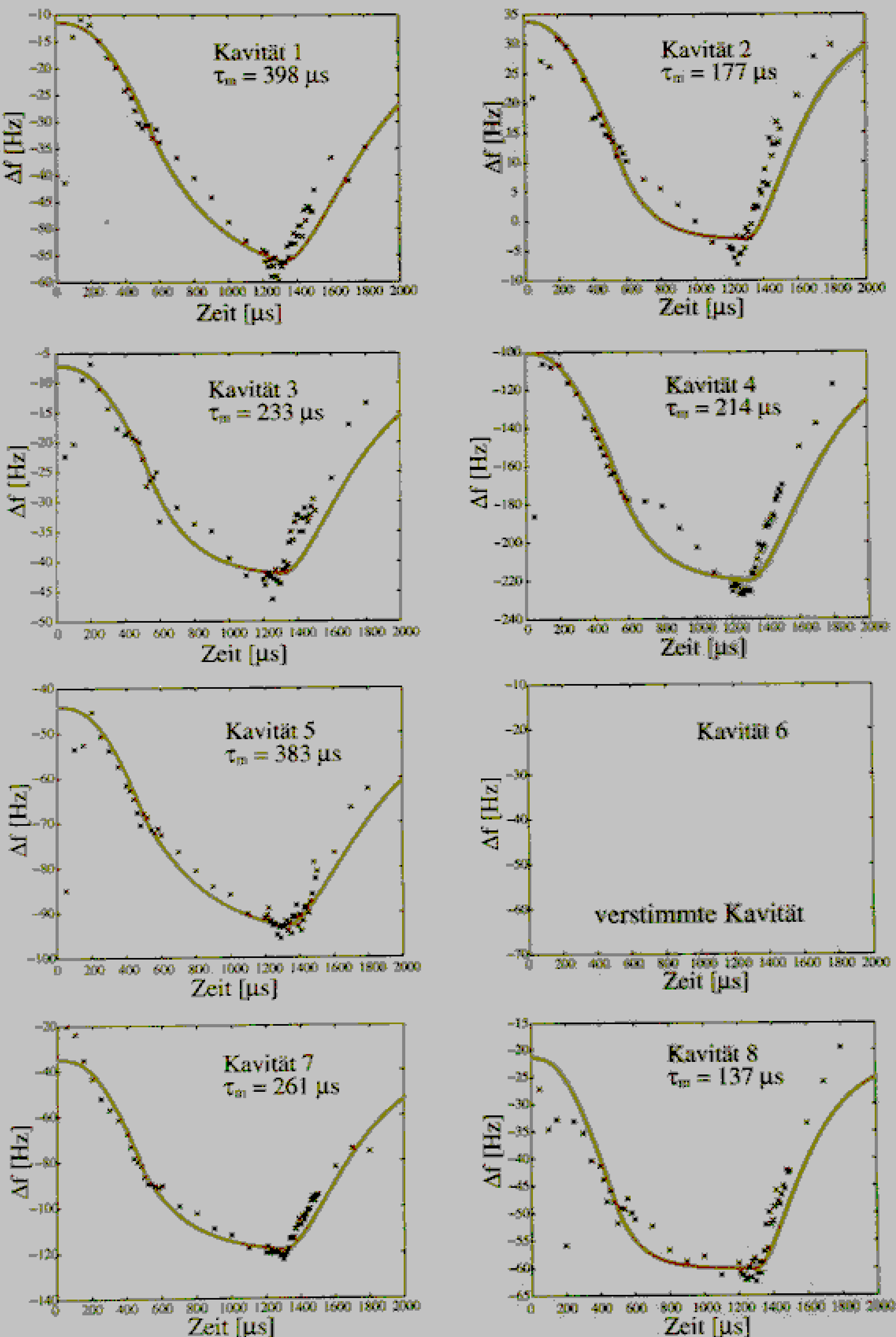
- regulate on individual cavities (only feed-back)
- vary rf pulse length in order to determine detuning at different time steps



⇒ first order equation for Lorentz-Force

Th. Schilcher

Messung der Lorentzkraft-Verstimmung während des HF-Pulses



Cavity Model

Cavity Field

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

Mechanical Properties

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

or

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

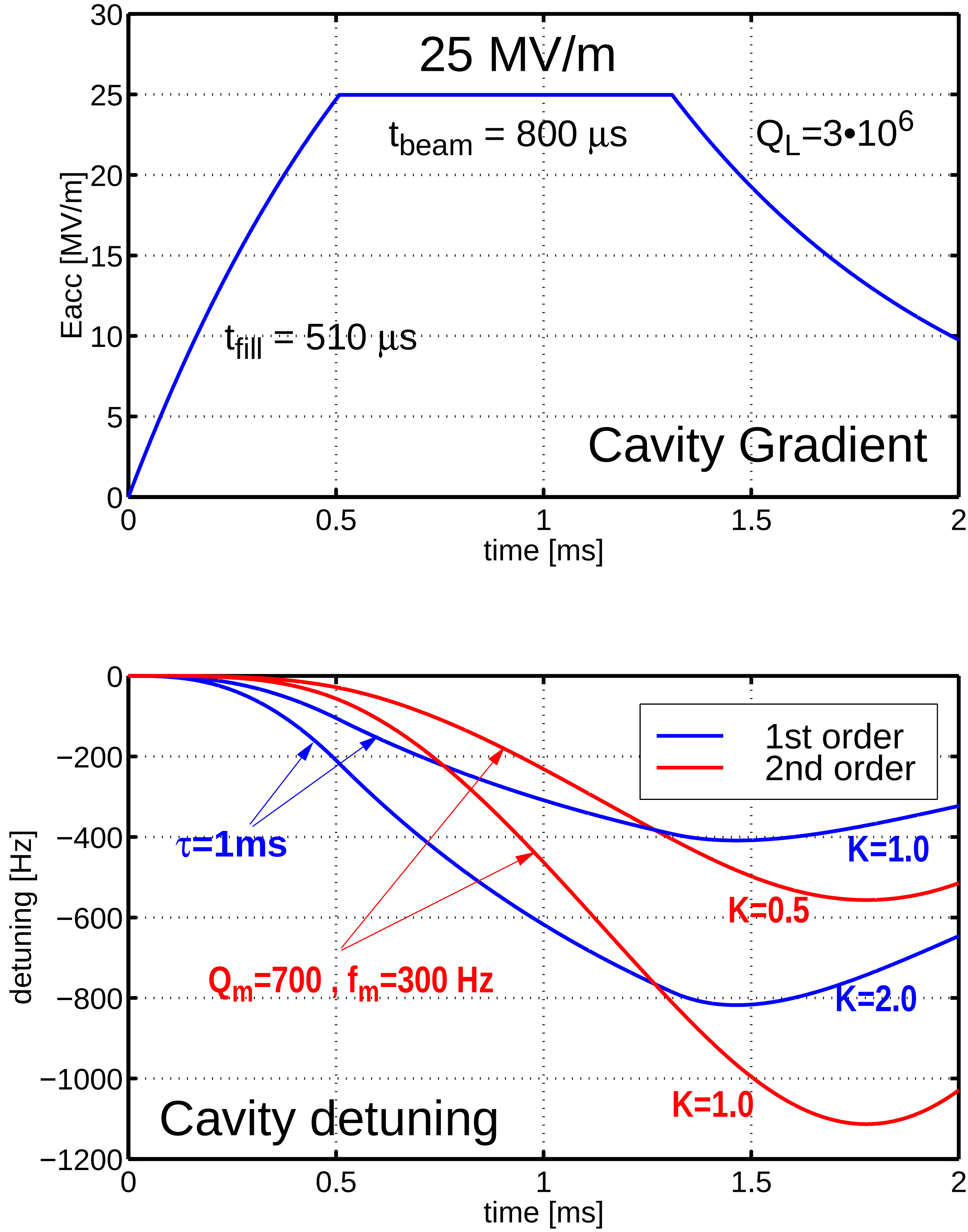
Typical Parameters

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

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

DESY

Lorentz Force Model



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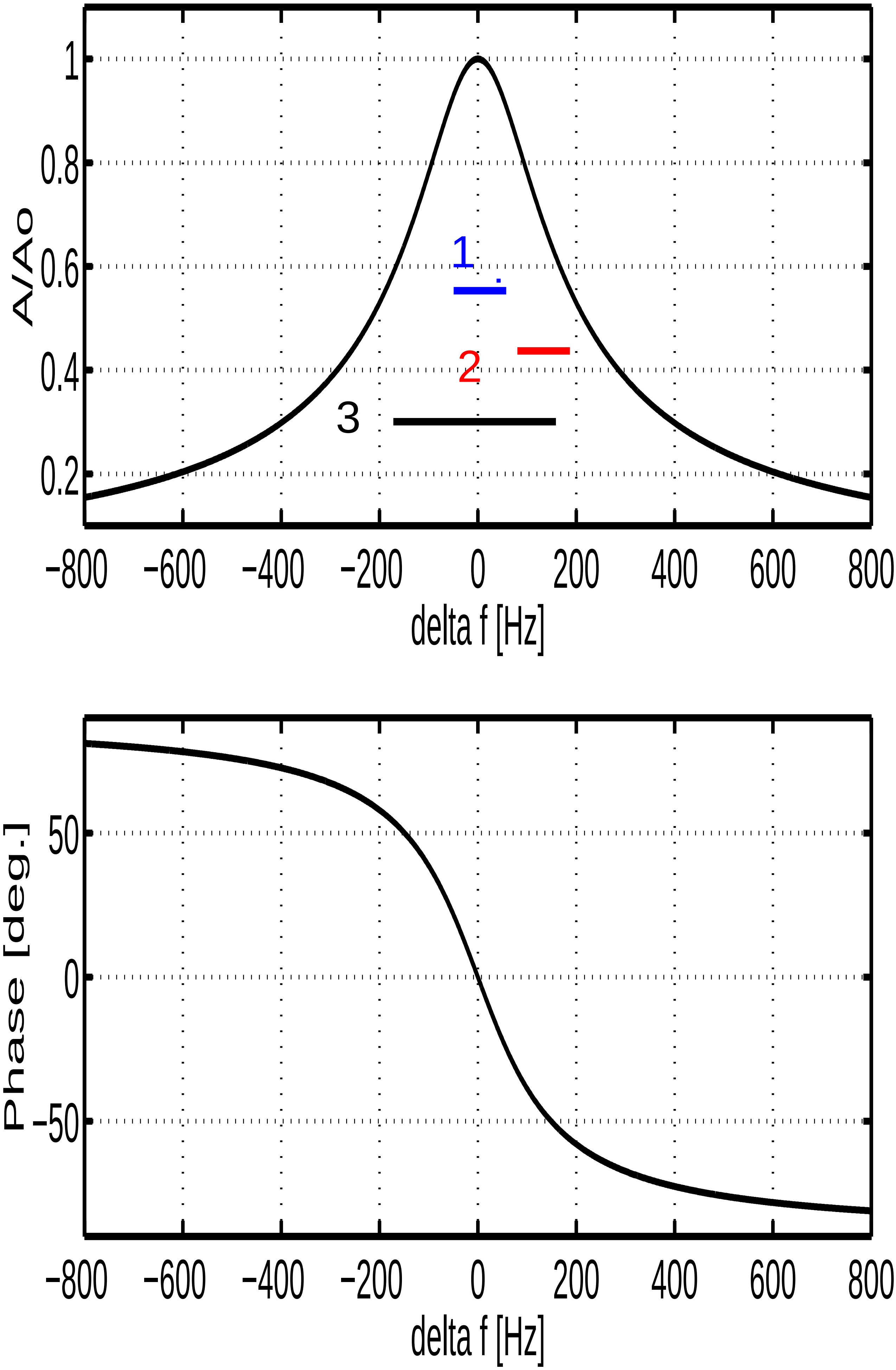
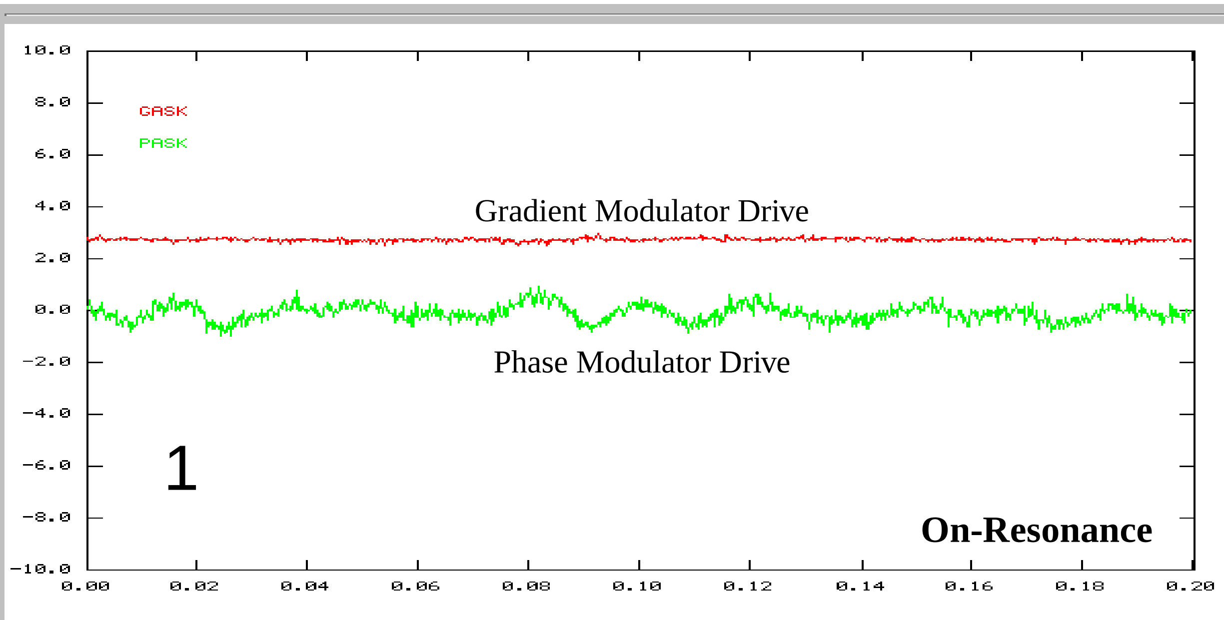
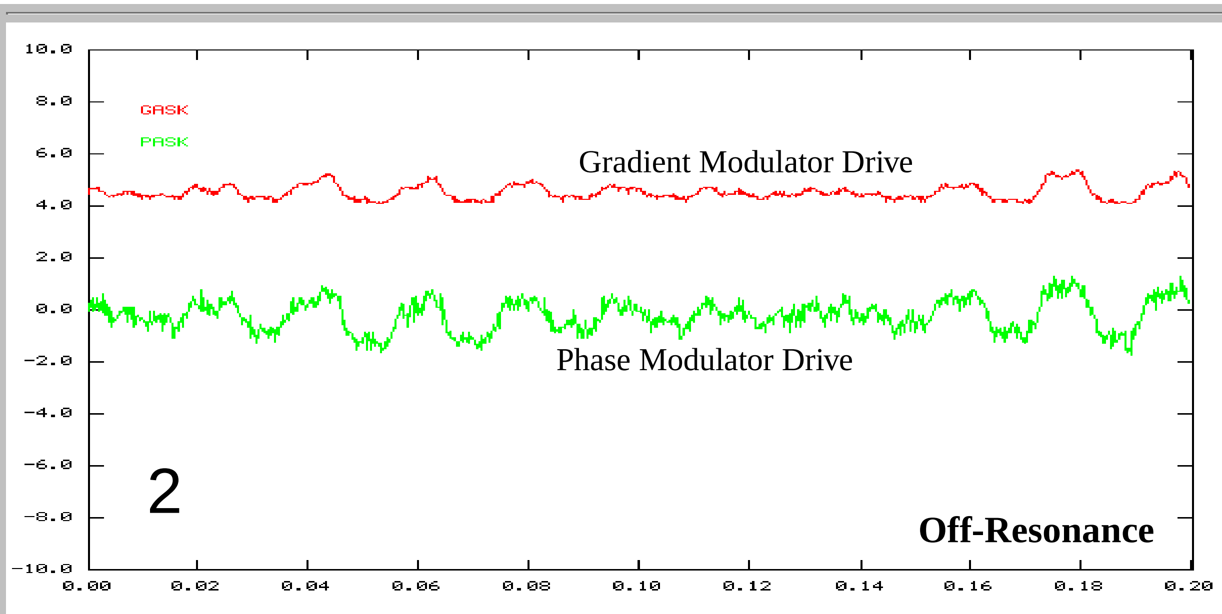
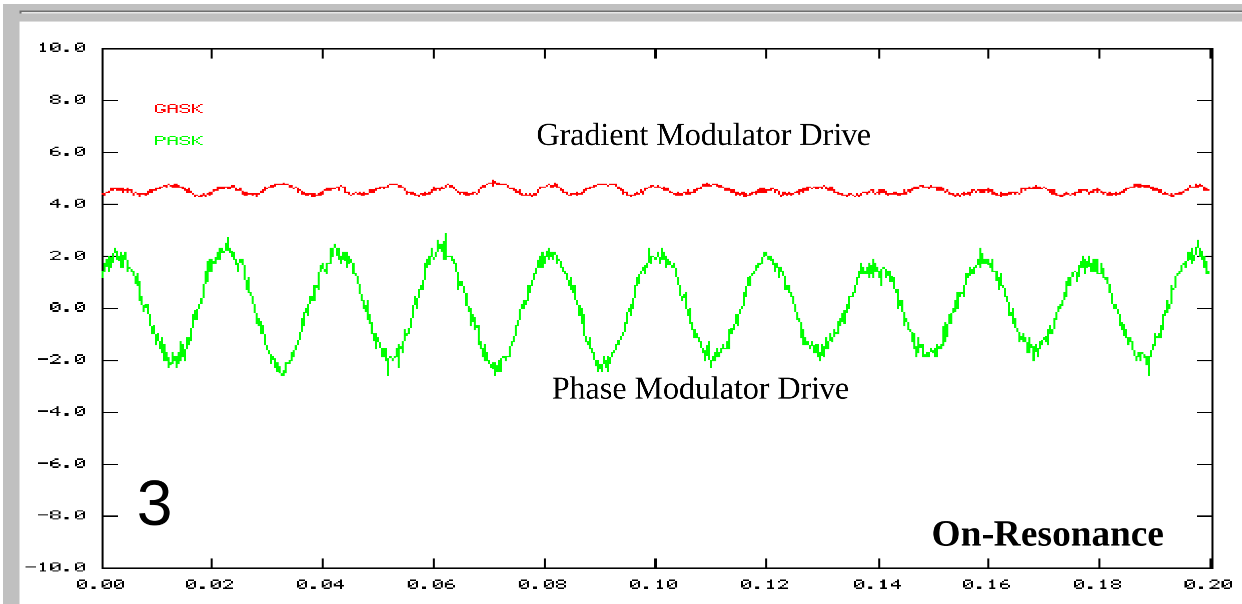

A/Ao
1
0.8
0.6
0.4
0.2
1
2
3
-800
-600
-400
-200
0
200
400
600
800
delta f [Hz]
Phase [deg.]
50
0
-50
-800
-600
-400
-200
0
200
400
600
800
delta f [Hz]



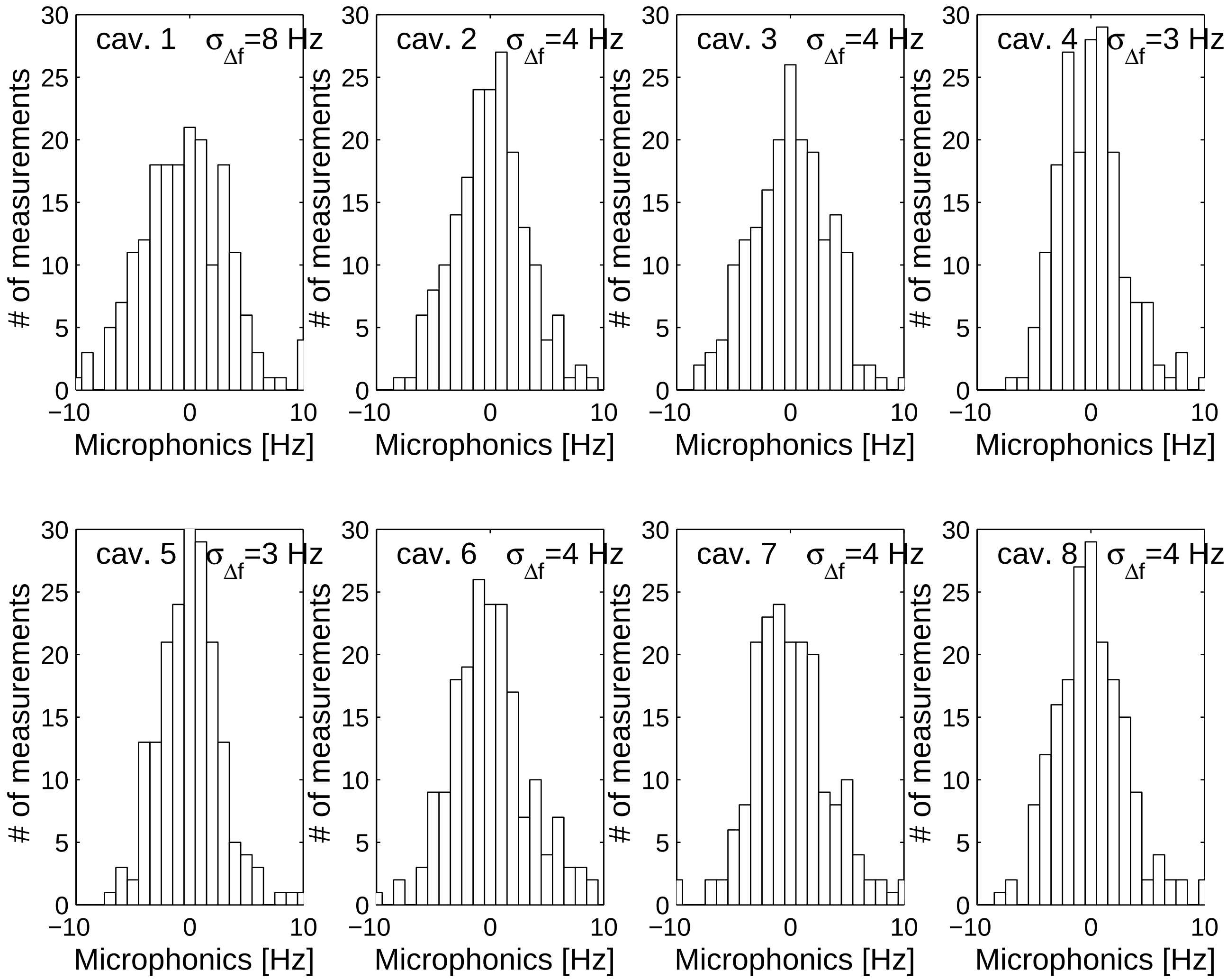
GASK and PASK for 2L13–1. Horizontal axis is time (seconds).



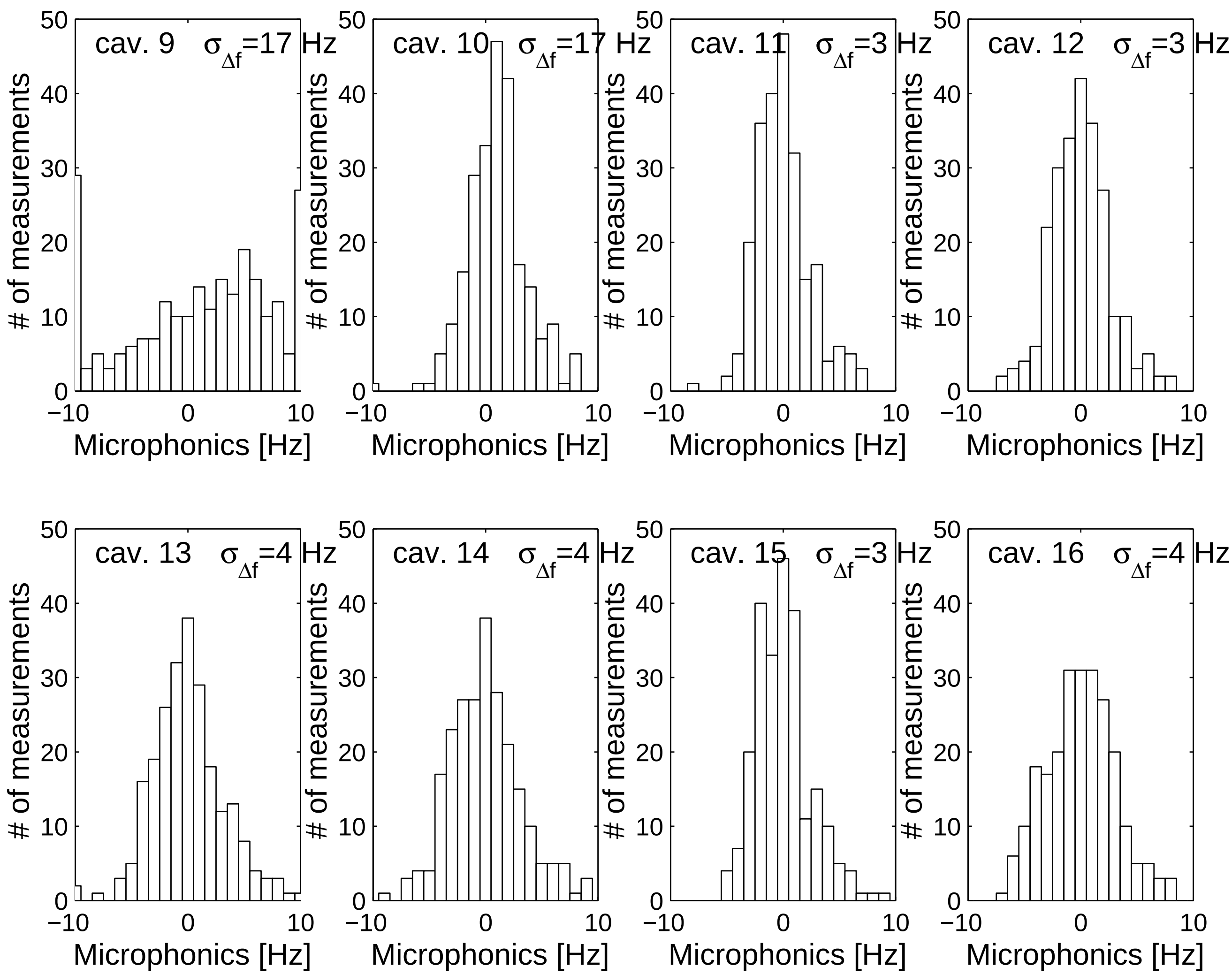
GASK and PASK for 2L07–4. Horizontal axis is time (seconds).



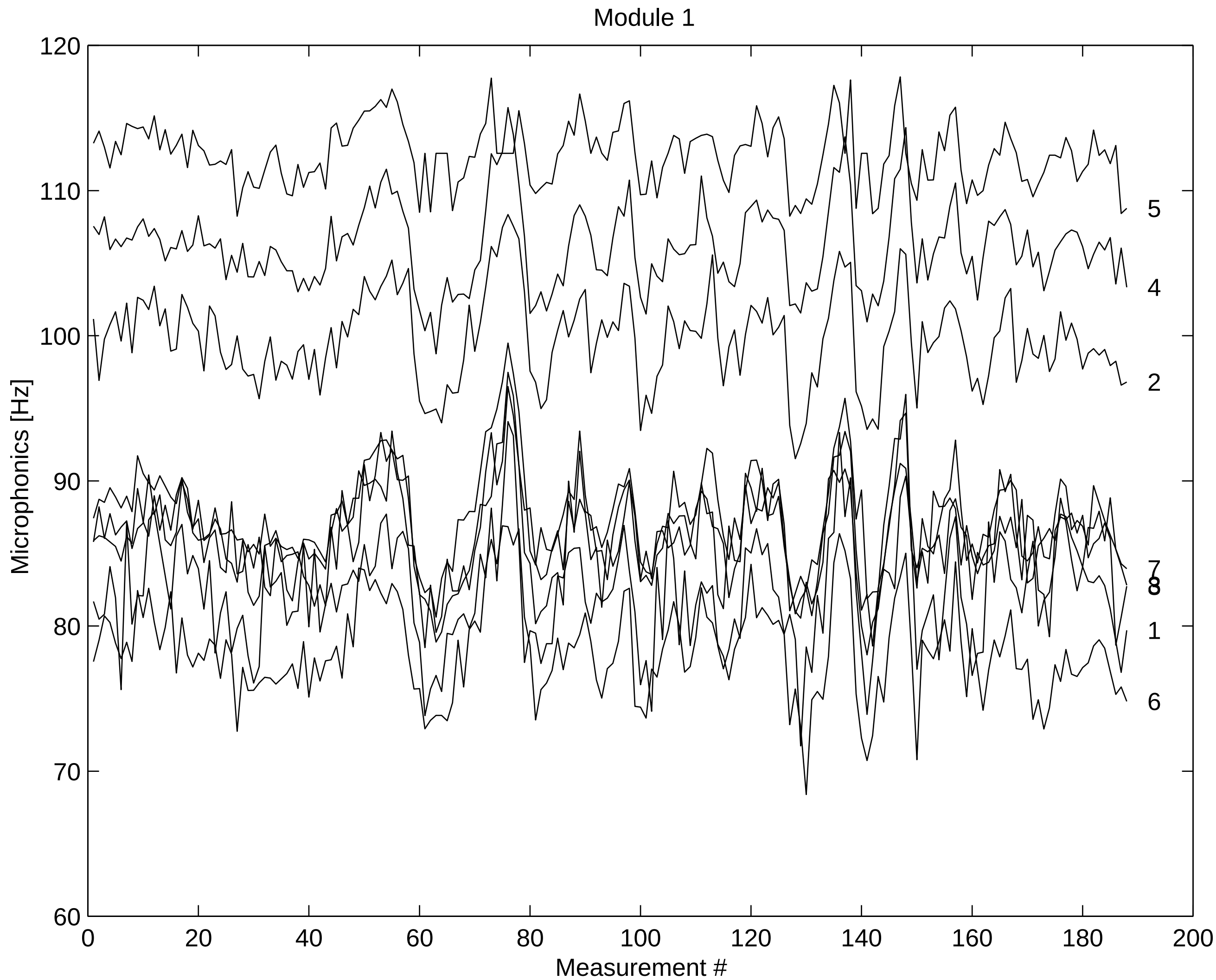
GASK and PASK for 2L17–4. Horizontal axis is time (seconds).



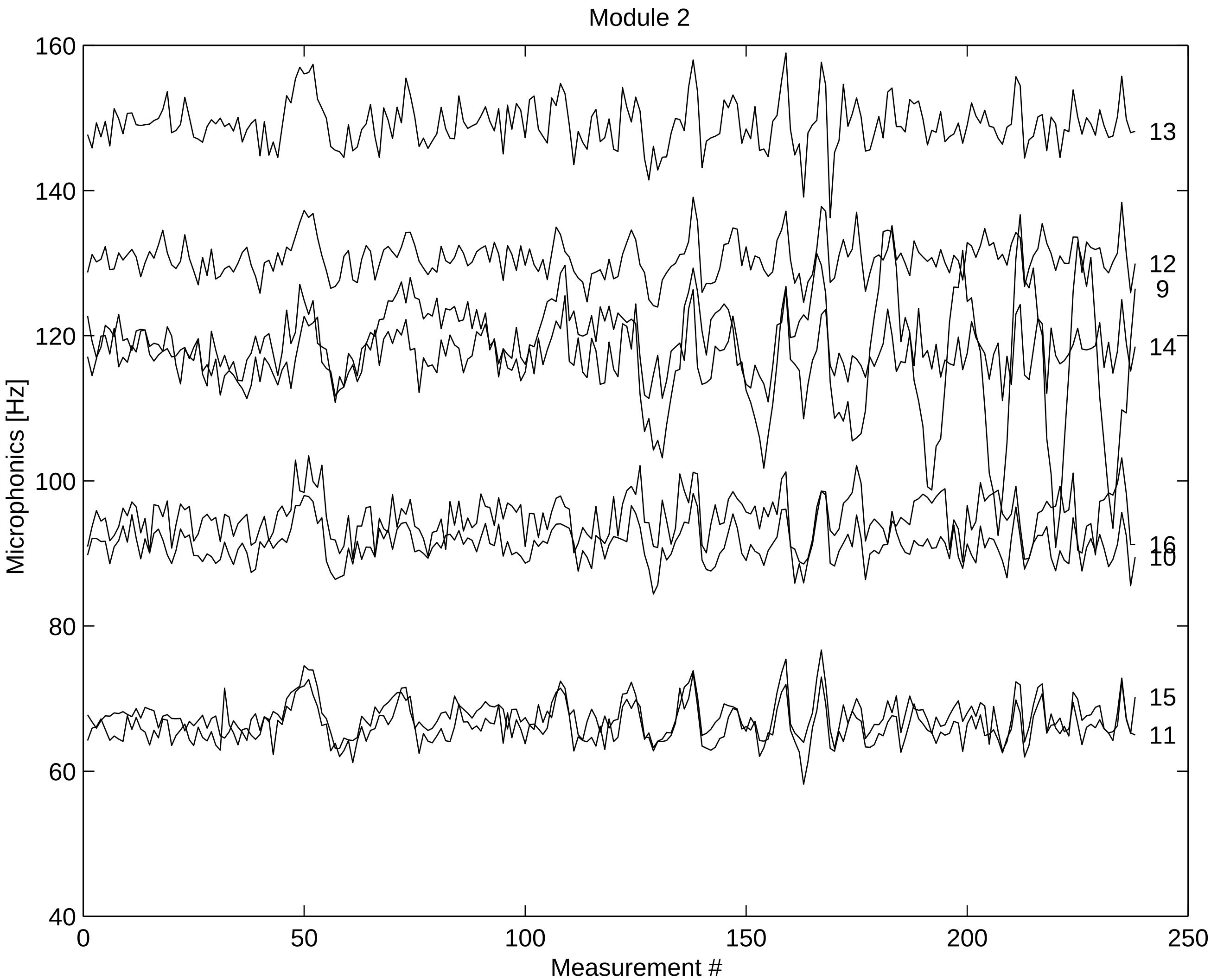
cav. 1 σΔf=8 Hz
cav. 2 σΔf=4 Hz
cav. 3 σΔf=4 Hz
cav. 4 σΔf=3 Hz
cav. 5 σΔf=3 Hz
cav. 6 σΔf=4 Hz
cav. 7 σΔf=4 Hz
cav. 8 σΔf=4 Hz
# of measurements
Microphonics [Hz]



cav. 9 σΔf=17 Hz
cav. 10 σΔf=17 Hz
cav. 11 σΔf=3 Hz
cav. 12 σΔf=3 Hz
cav. 13 σΔf=4 Hz
cav. 14 σΔf=4 Hz
cav. 15 σΔf=3 Hz
cav. 16 σΔf=4 Hz
# of measurements
Microphonics [Hz]

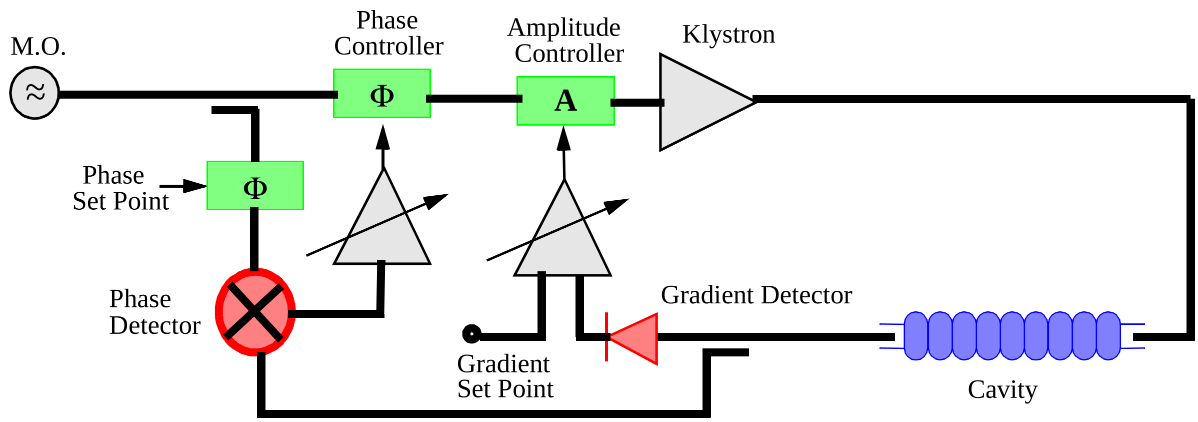


Module 1
Microphonics [Hz]
Measurement #
120
110
100
90
80
70
60
0
20
40
60
80
100
120
140
160
180
200
5
4
2
7
8
1
6

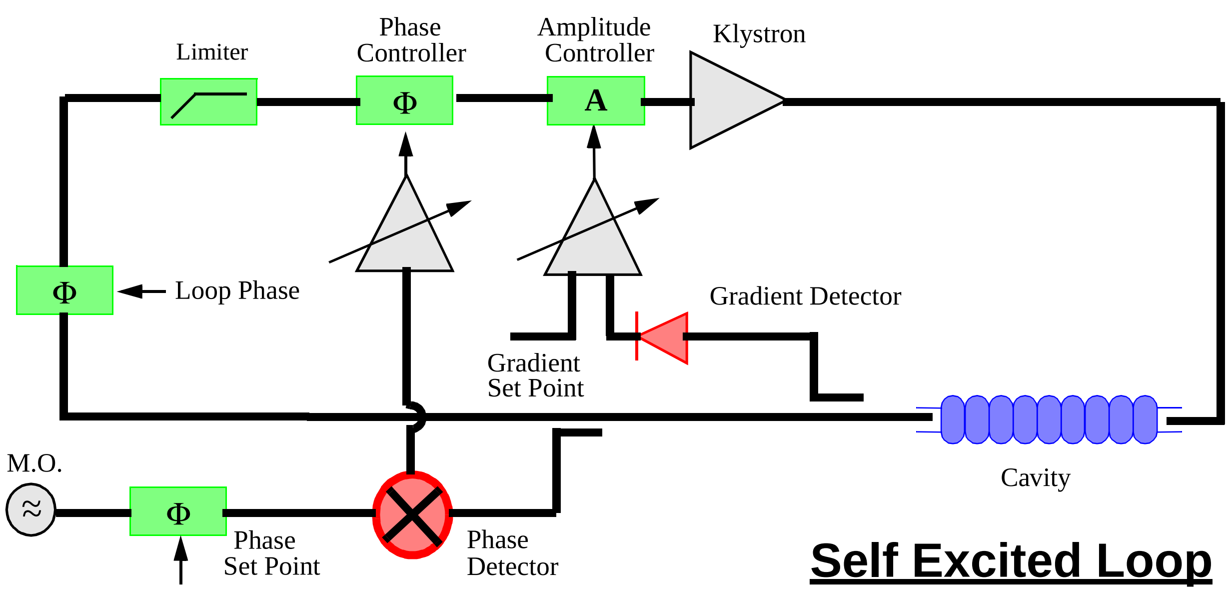


Module 2
160
140
120
100
80
60
40
0
50
100
150
200
250
Microphonics [Hz]
Measurement #
13
12
9
14
16
10
15
11

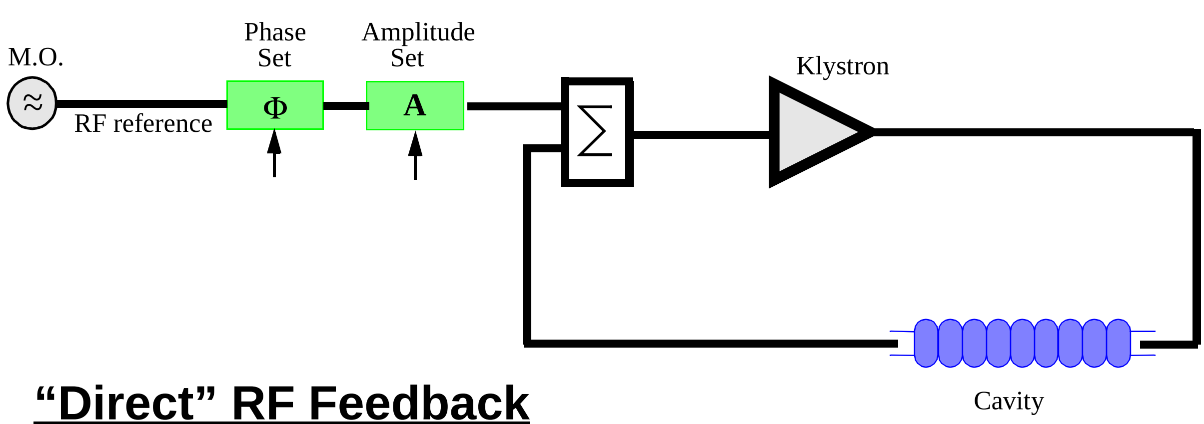
TTF



“Driven” Feedback

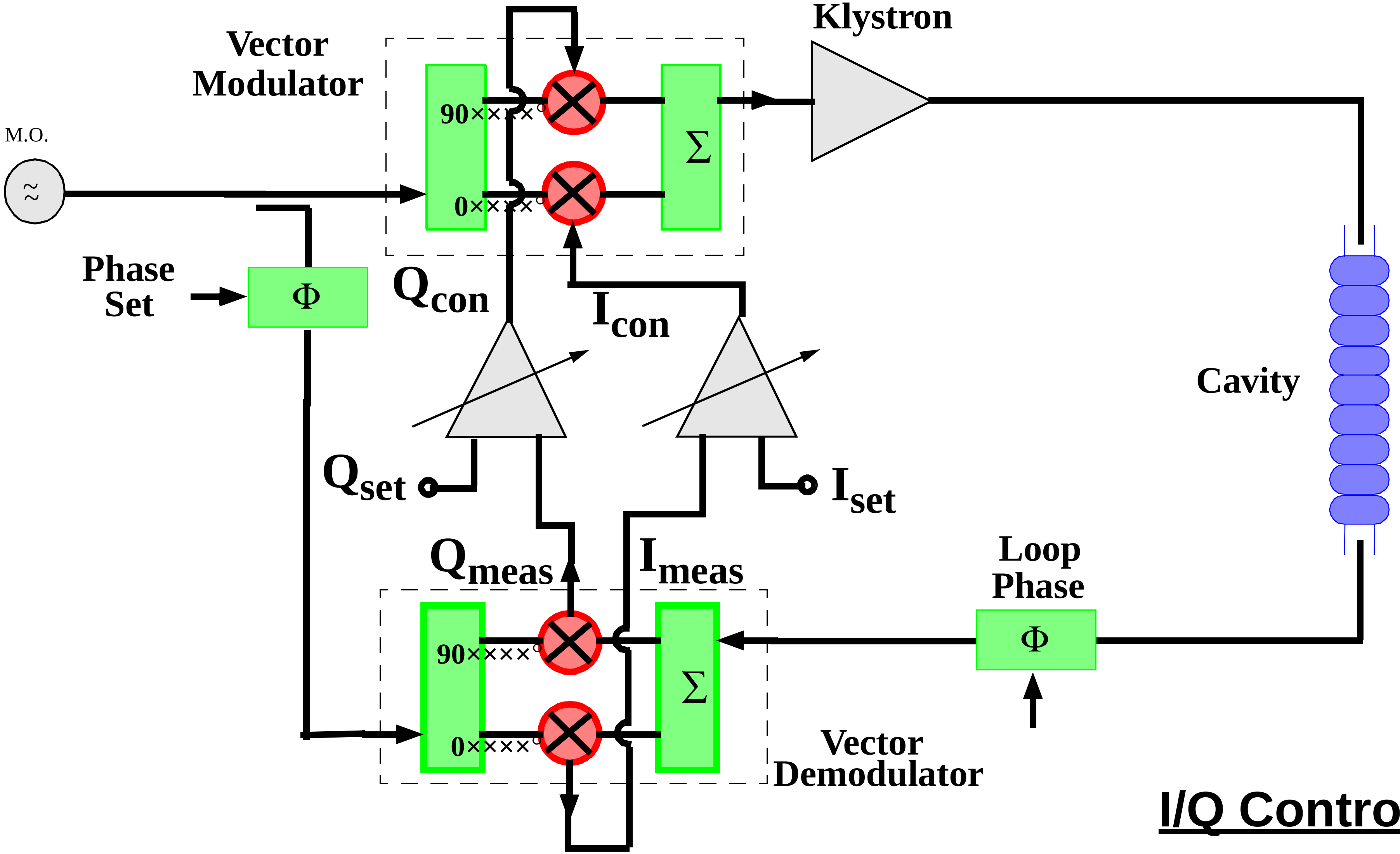


Self Excited Loop



“Direct” RF Feedback

Analog IQ Control



I/Q Control

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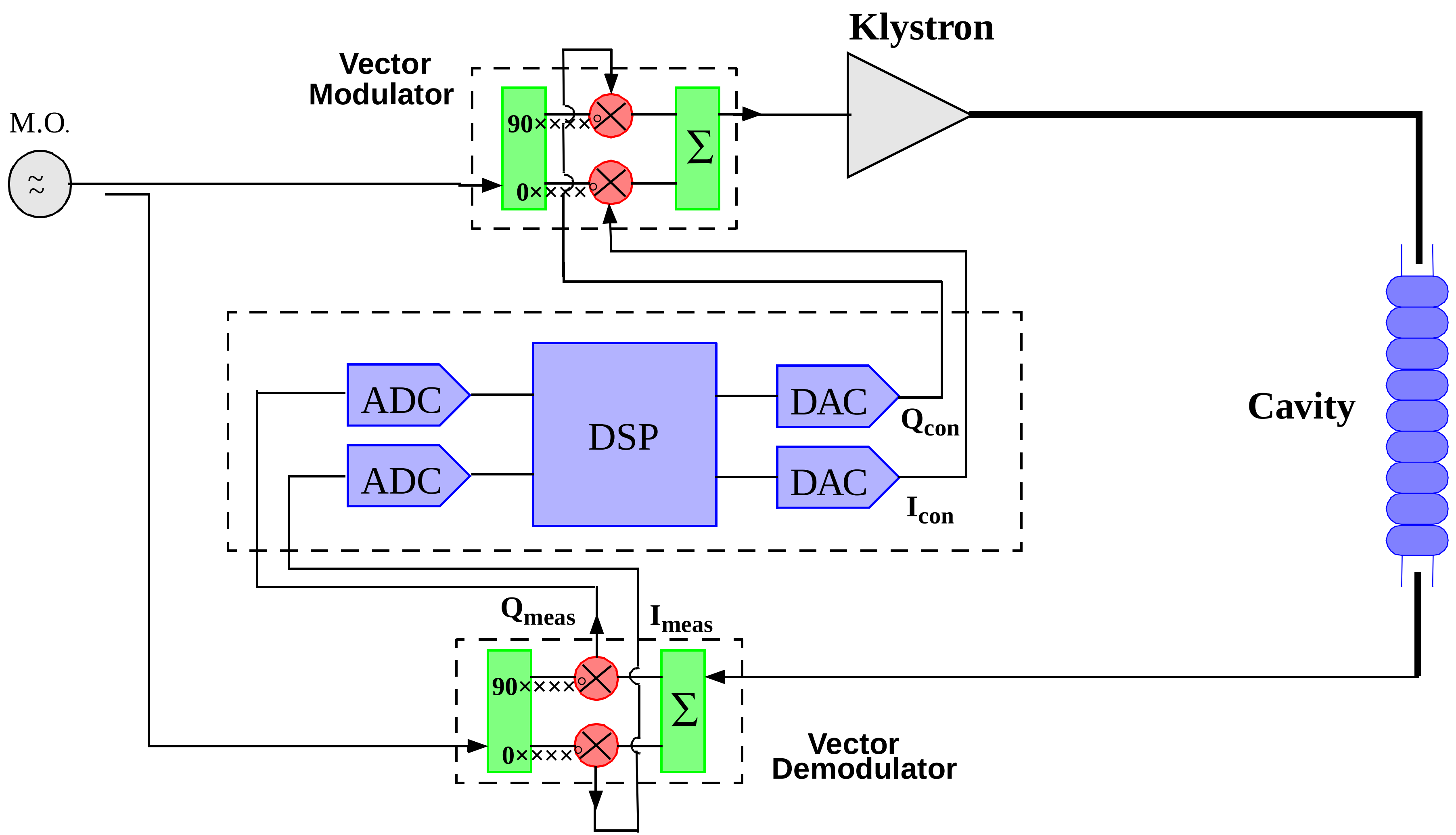
Digital IQ Control



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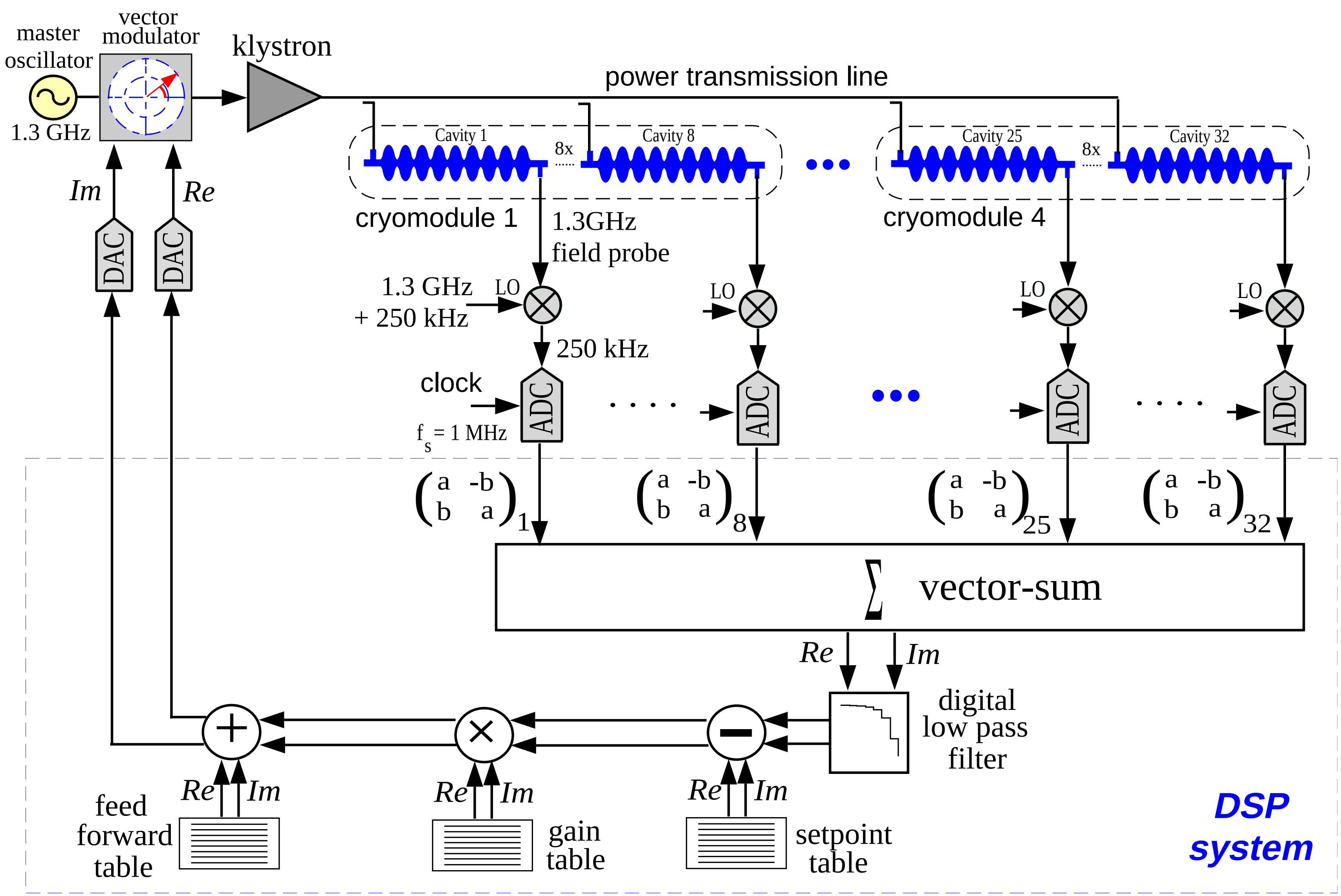
Digital RF Control Concept



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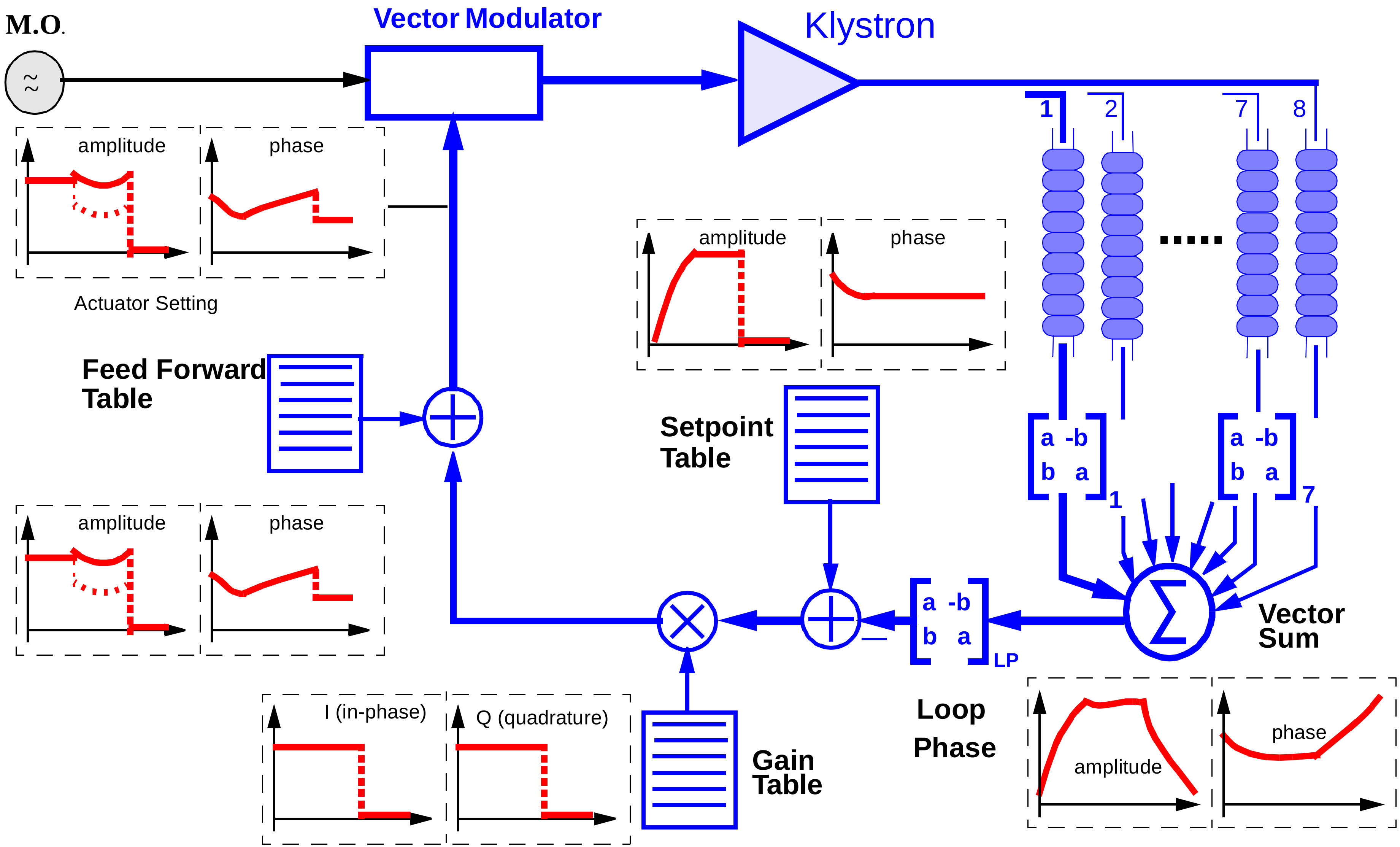
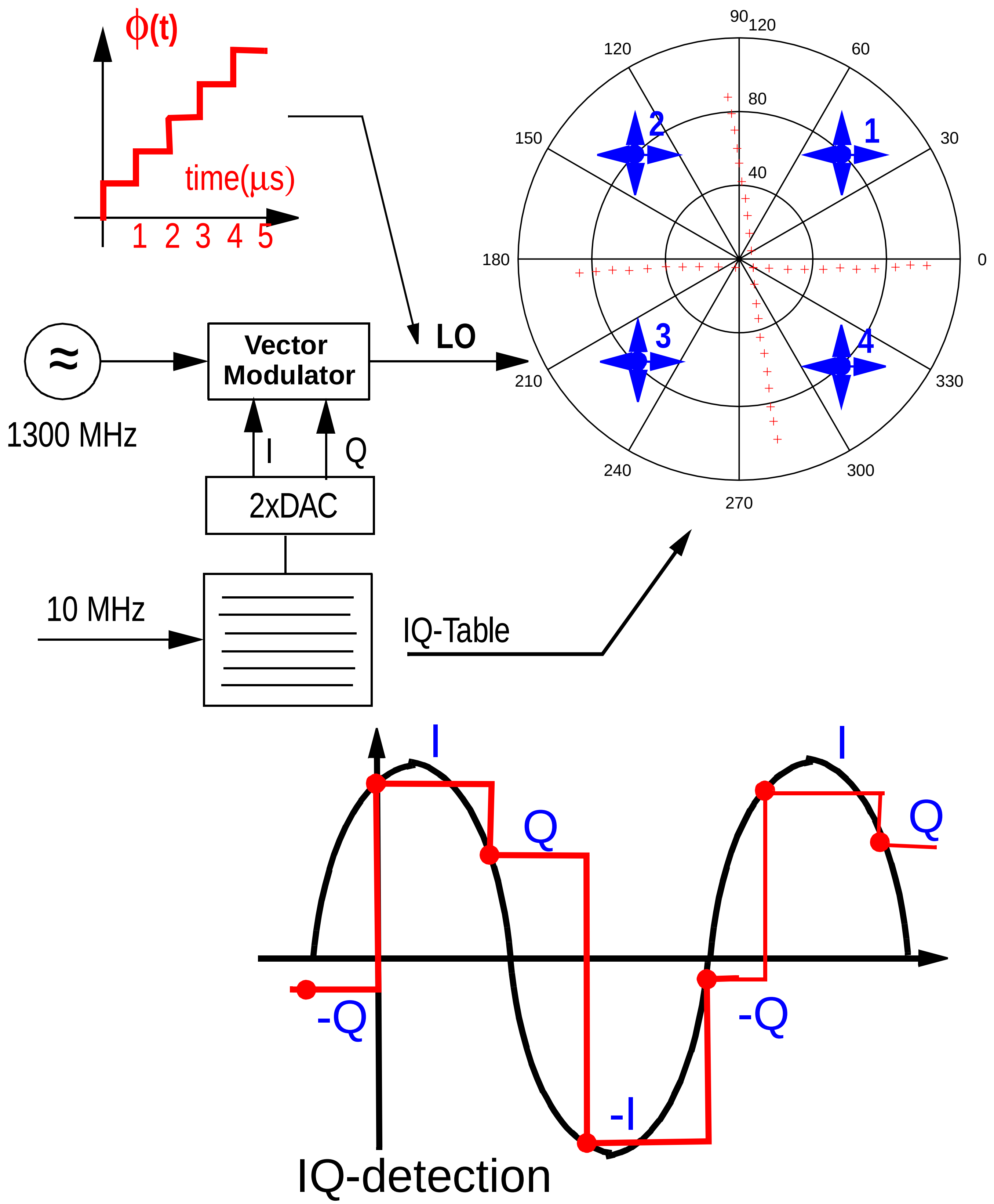
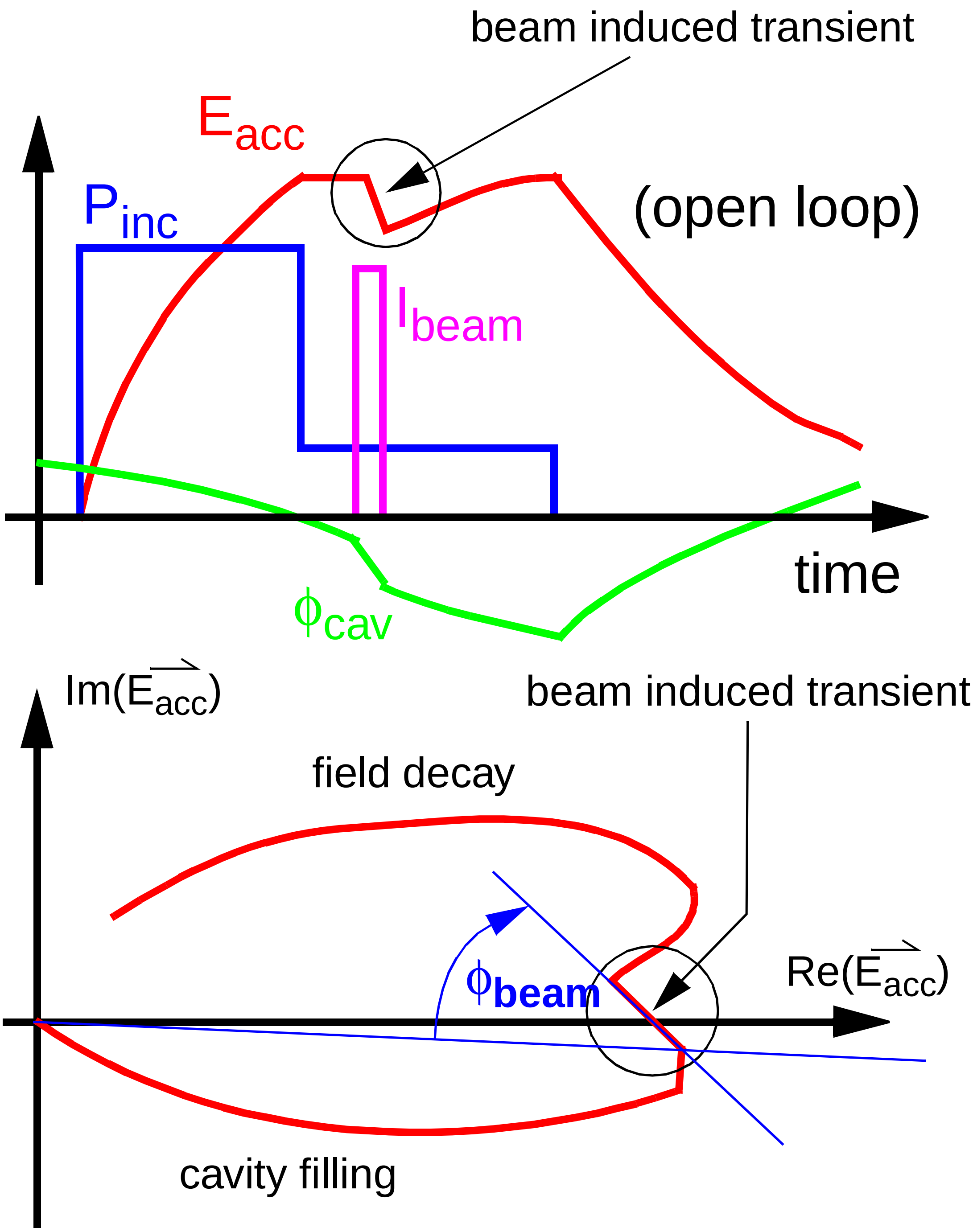
Principle of RF Control



Generation of Reference Signal



Beam Based Gradient Calibration



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

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

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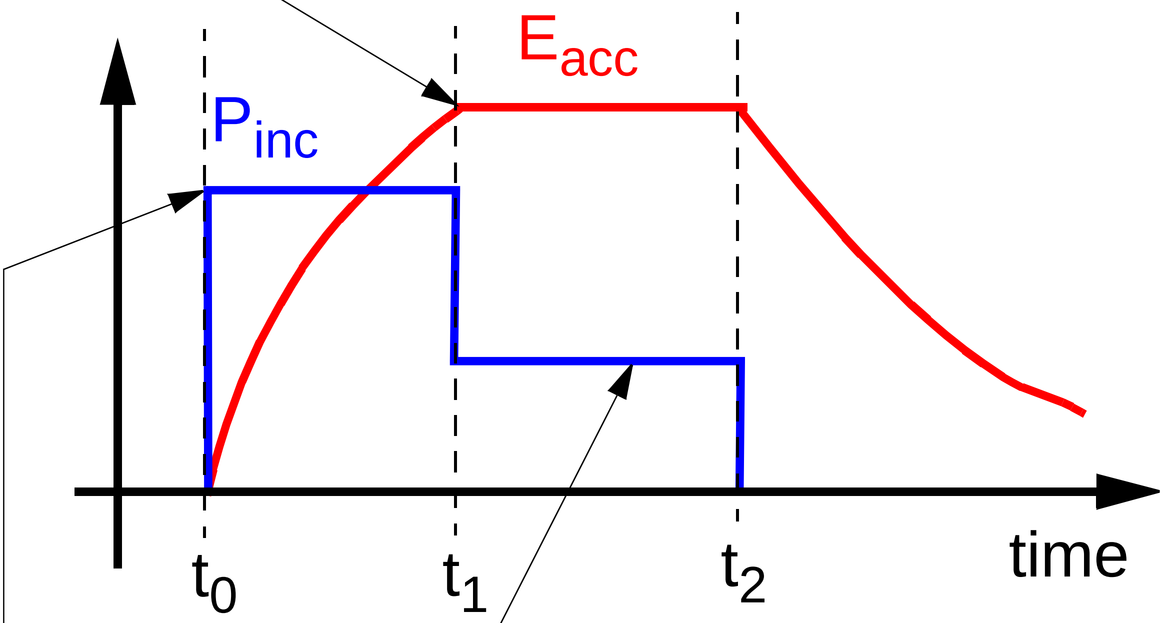
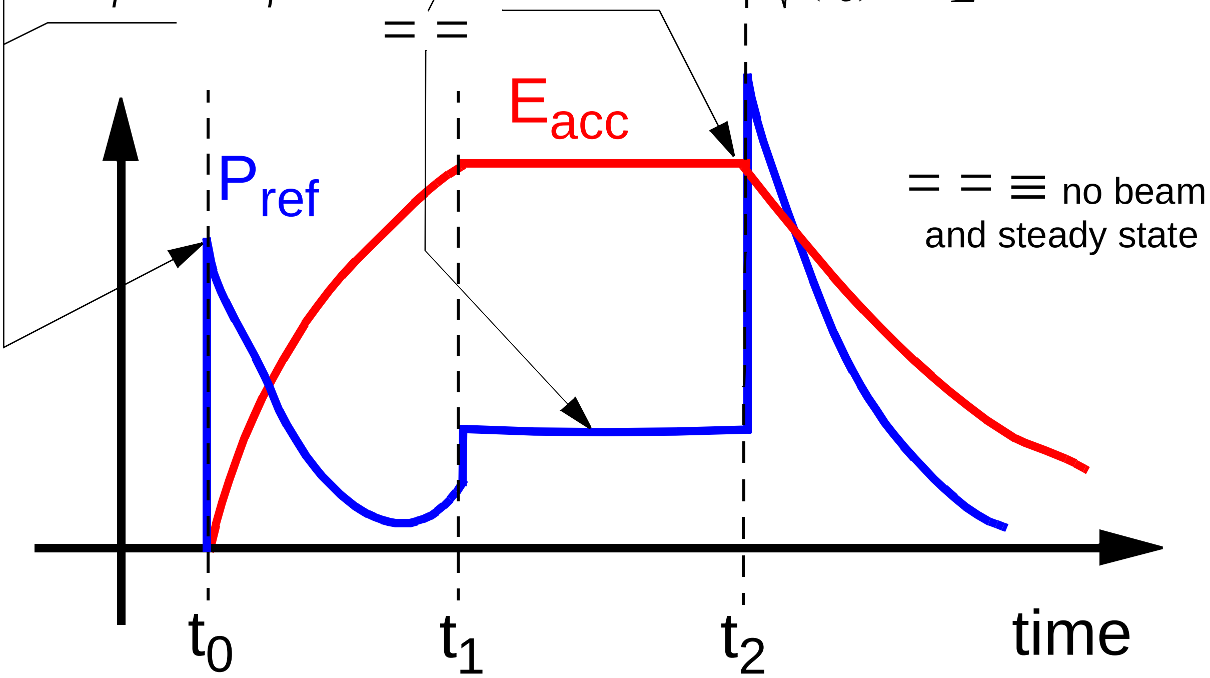
Power Calibration

$$E_{acc}(t_1) = 2 \cdot \sqrt{\left(\frac{r}{Q}\right) \cdot Q_L \cdot P_{inc}(t_0 \le t \le t_1)} \cdot \left(1 - \exp\left(\frac{(t_1 - t_0) \cdot \omega}{2 \cdot Q_L}\right)\right)$$

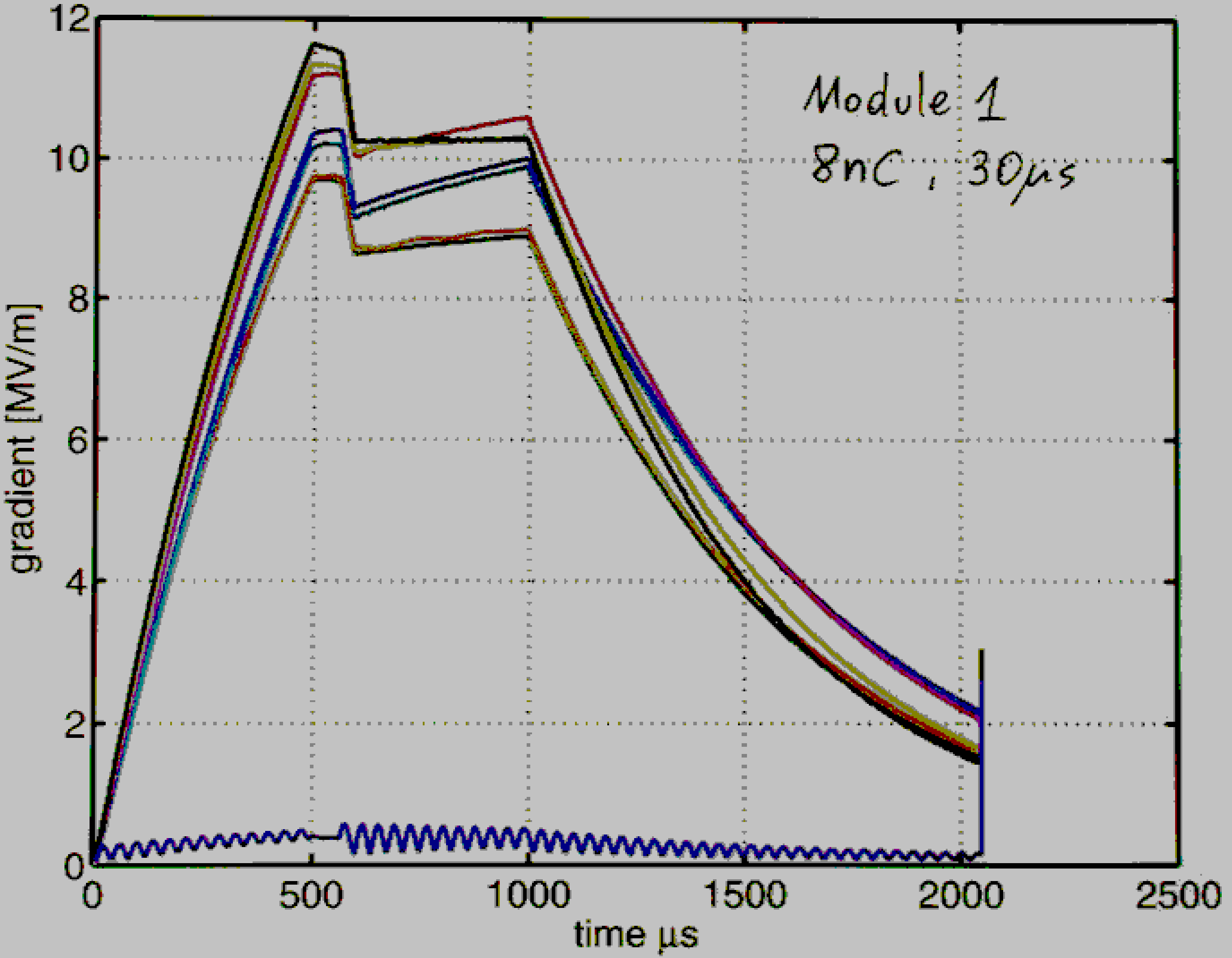


$$P_{ref}(t_0) = P_{for}(t_0)$$

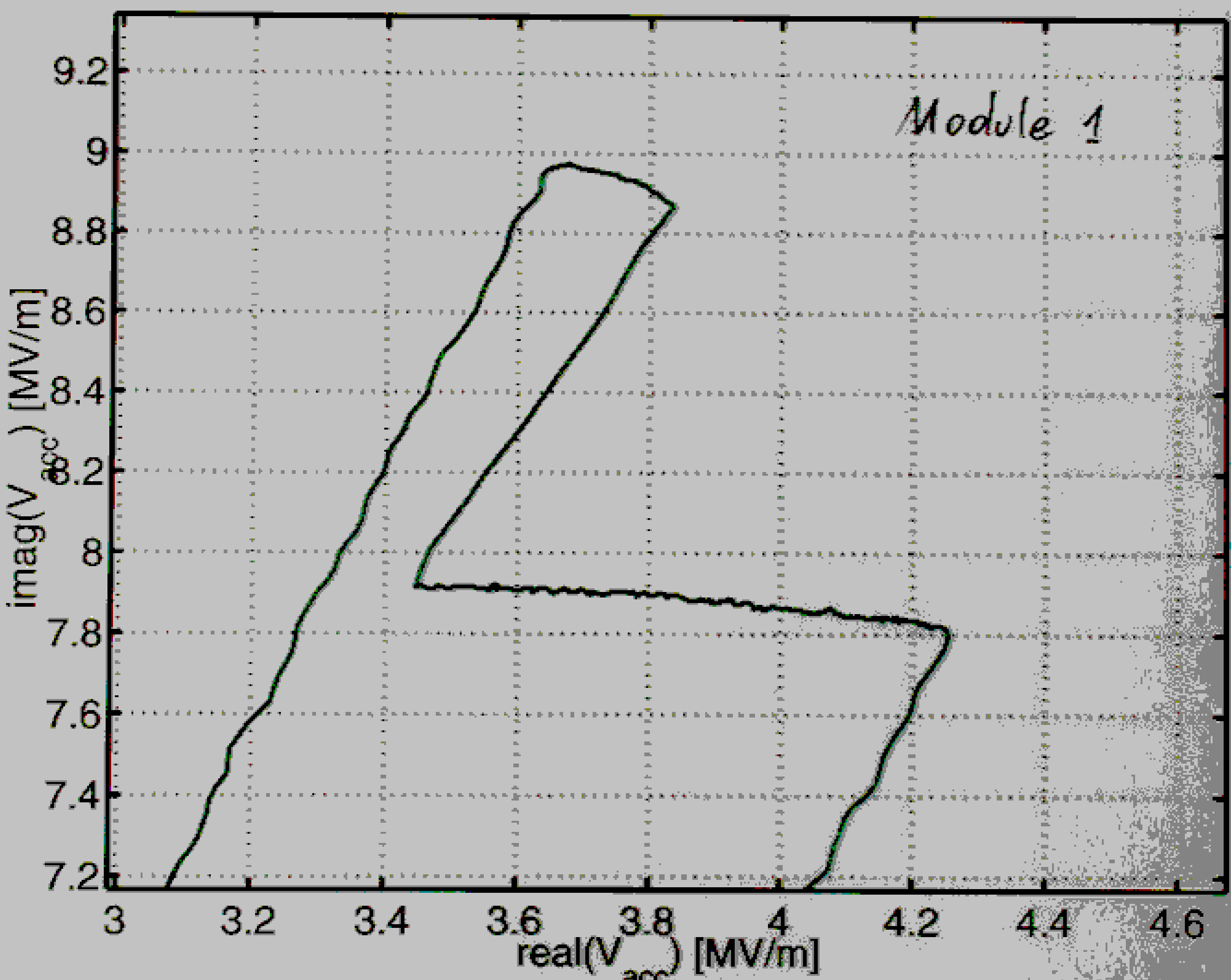
$$E_{acc}(t_2) = \sqrt{\left(\frac{r}{Q}\right) \cdot Q_L \cdot P_{ref}(t_2)}$$



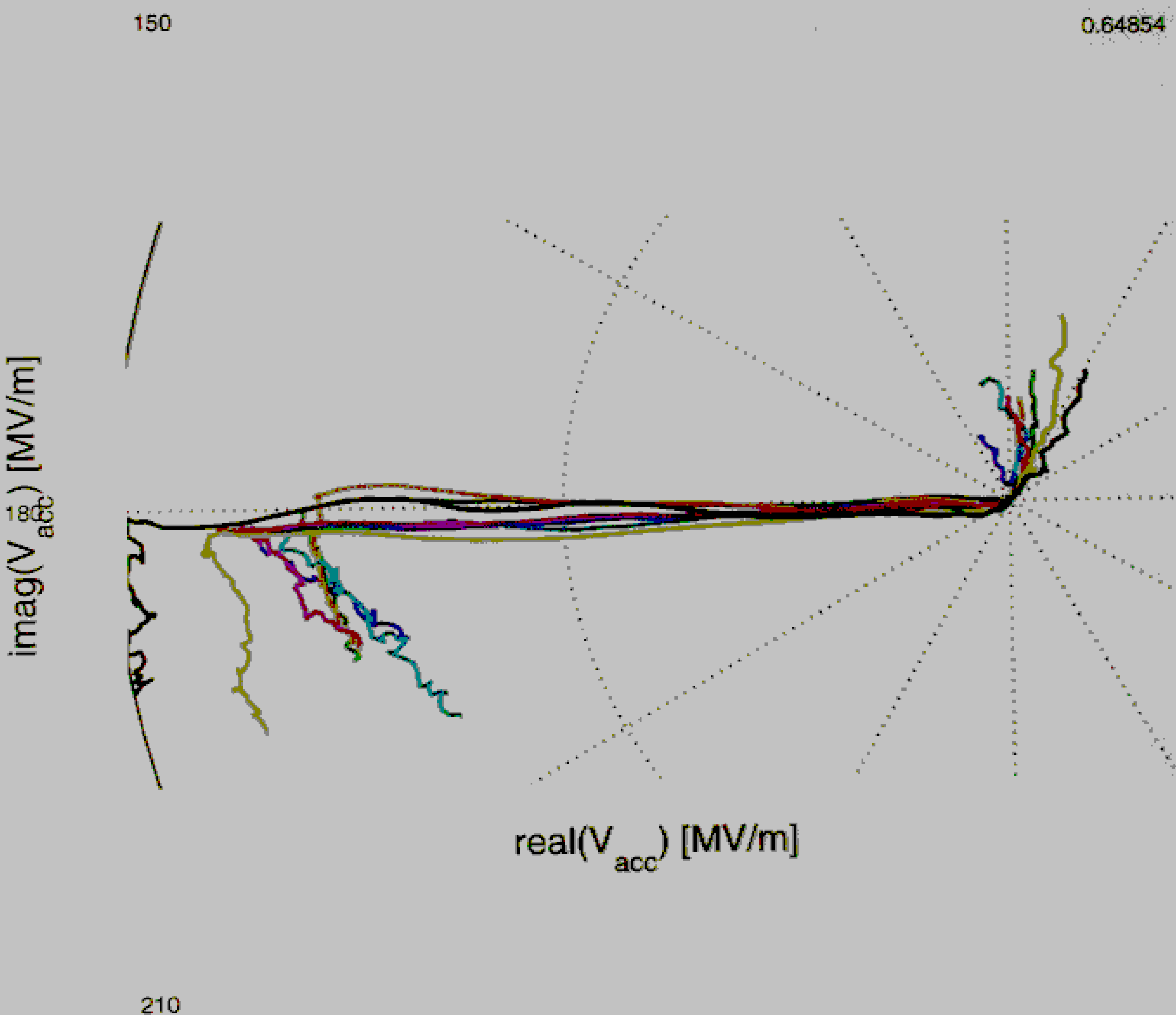
S.Simrock



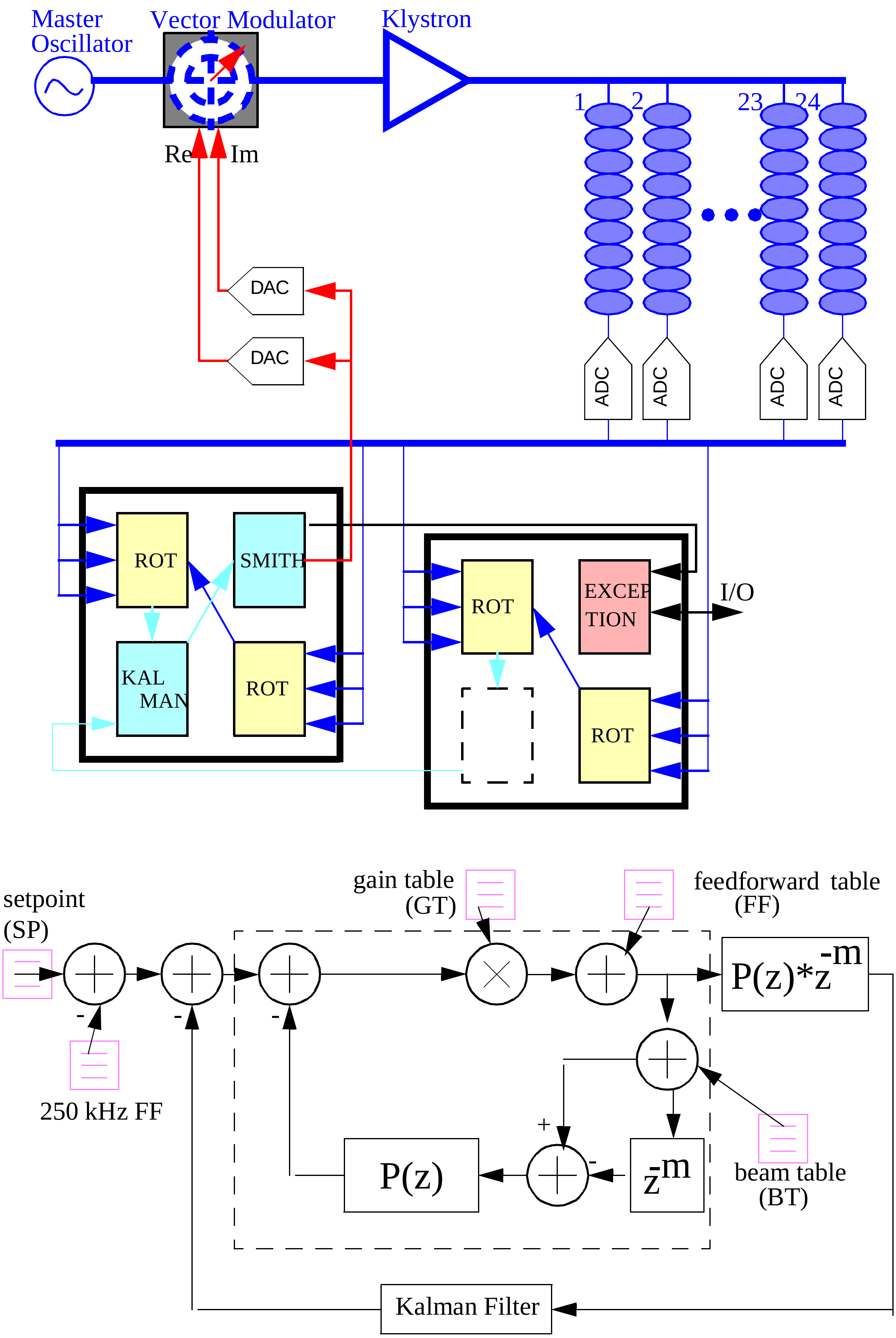
Module 1
8nC , 30μs
gradient [MV/m]
time μs
0
2
4
6
8
10
12
500
1000
1500
2000
2500



Module 1
9.2
9
8.8
8.6
8.4
8.2
8
7.8
7.6
7.4
7.2
imag(V_acc) [MV/m]
3
3.2
3.4
3.6
3.8
4
4.2
4.4
4.6
real(V_acc) [MV/m]

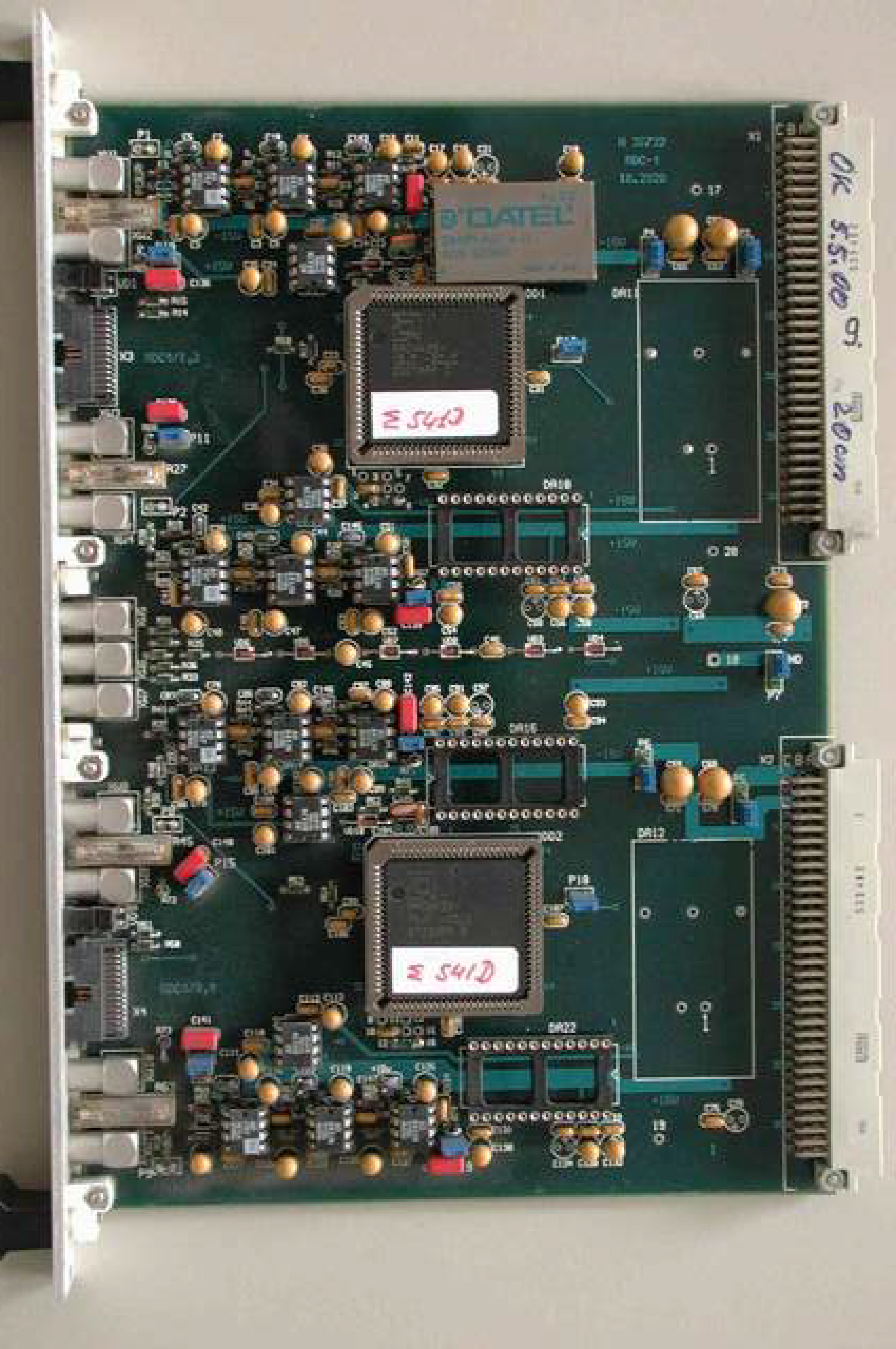

150
0.64854
180
imag(V_acc) [MV/m]
real(V_acc) [MV/m]
210

Design of 24 Cavity Control



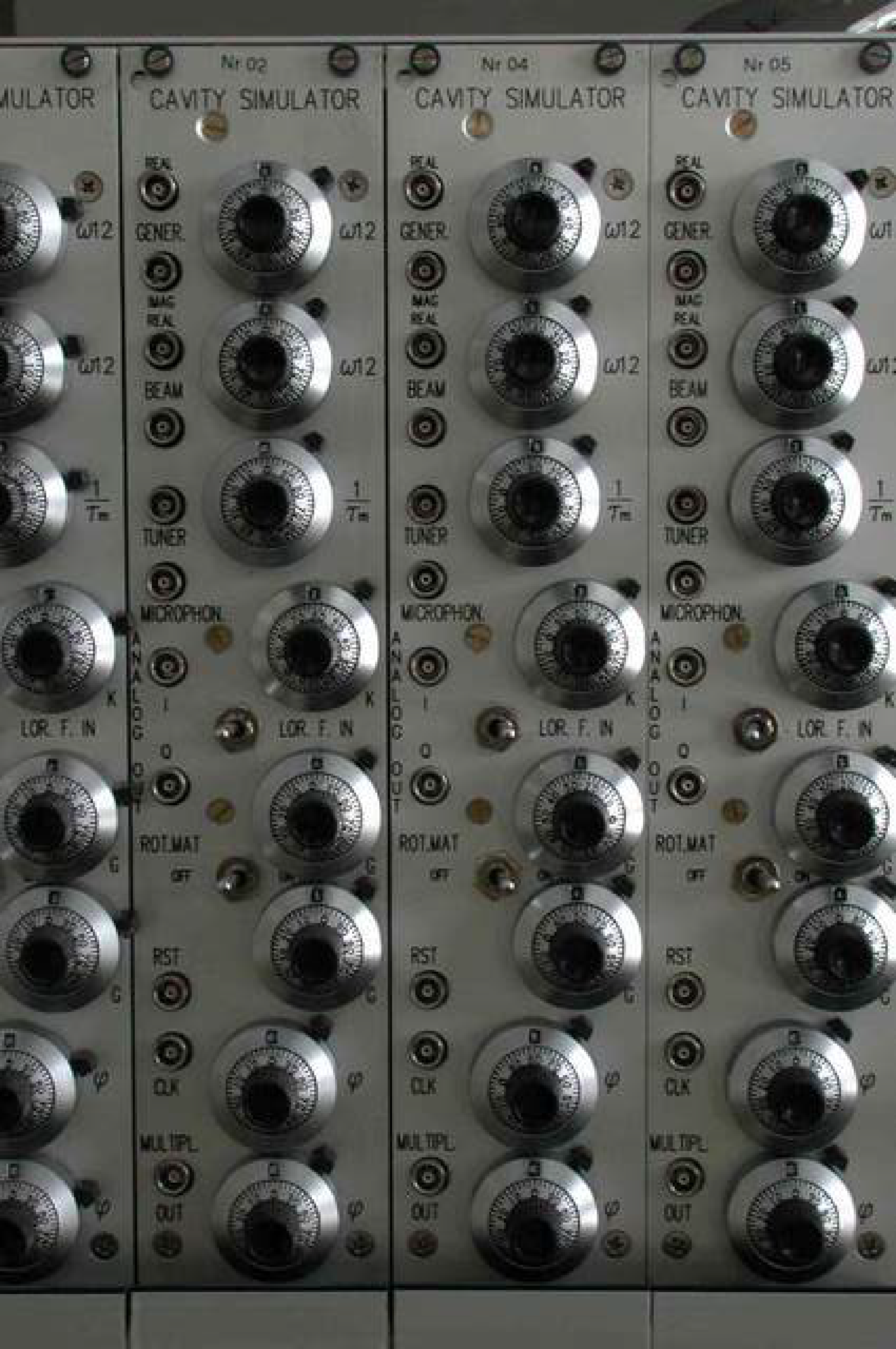
S.Simrock

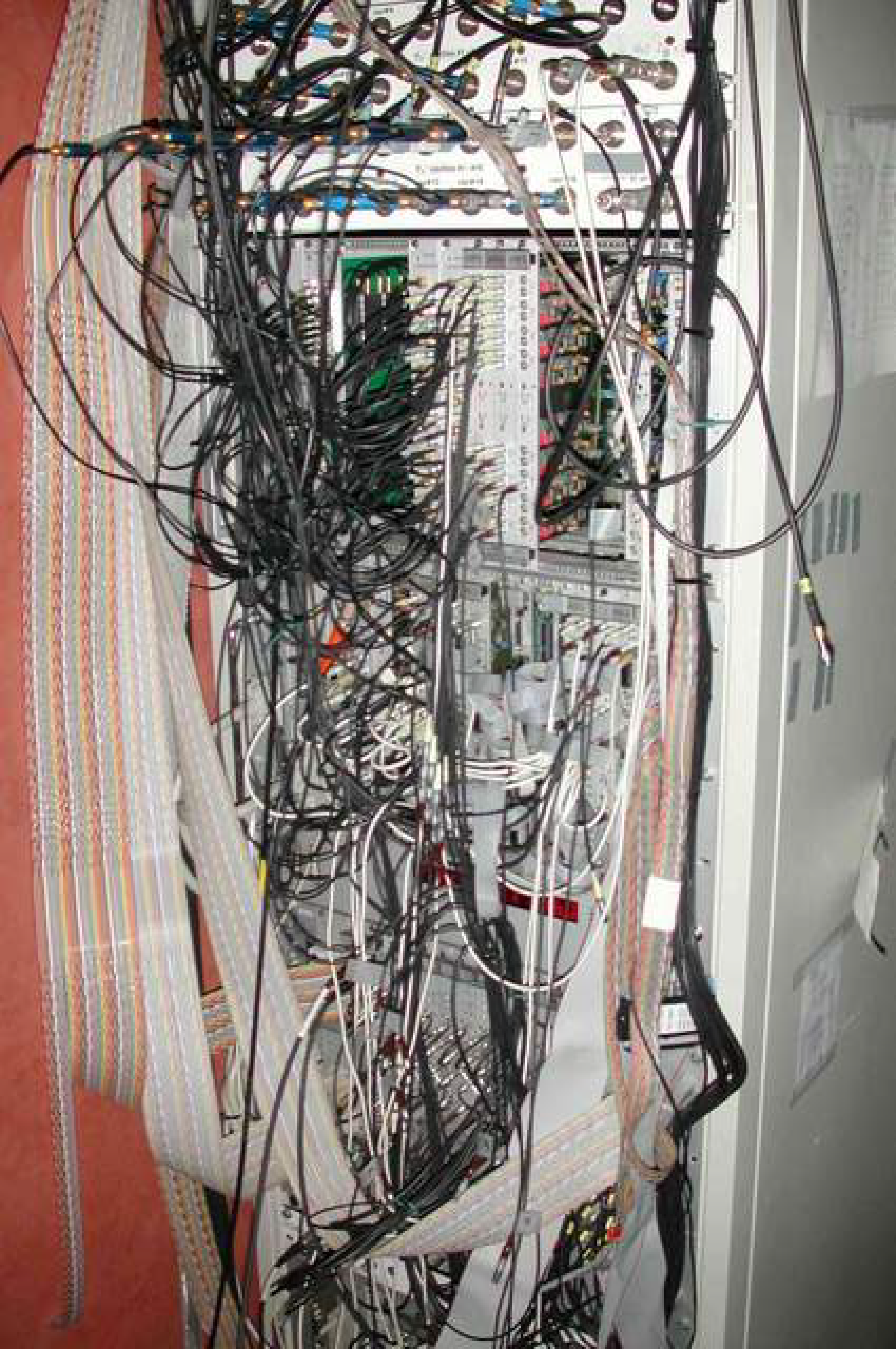

ADC4
DBV44
DELAY 8
DAC2
BUS-
SELECT
OUT1
OUT2
OUT3
OUT4
OUT5
DESY-IHEP
IHEP
PROTVINO
NETW.

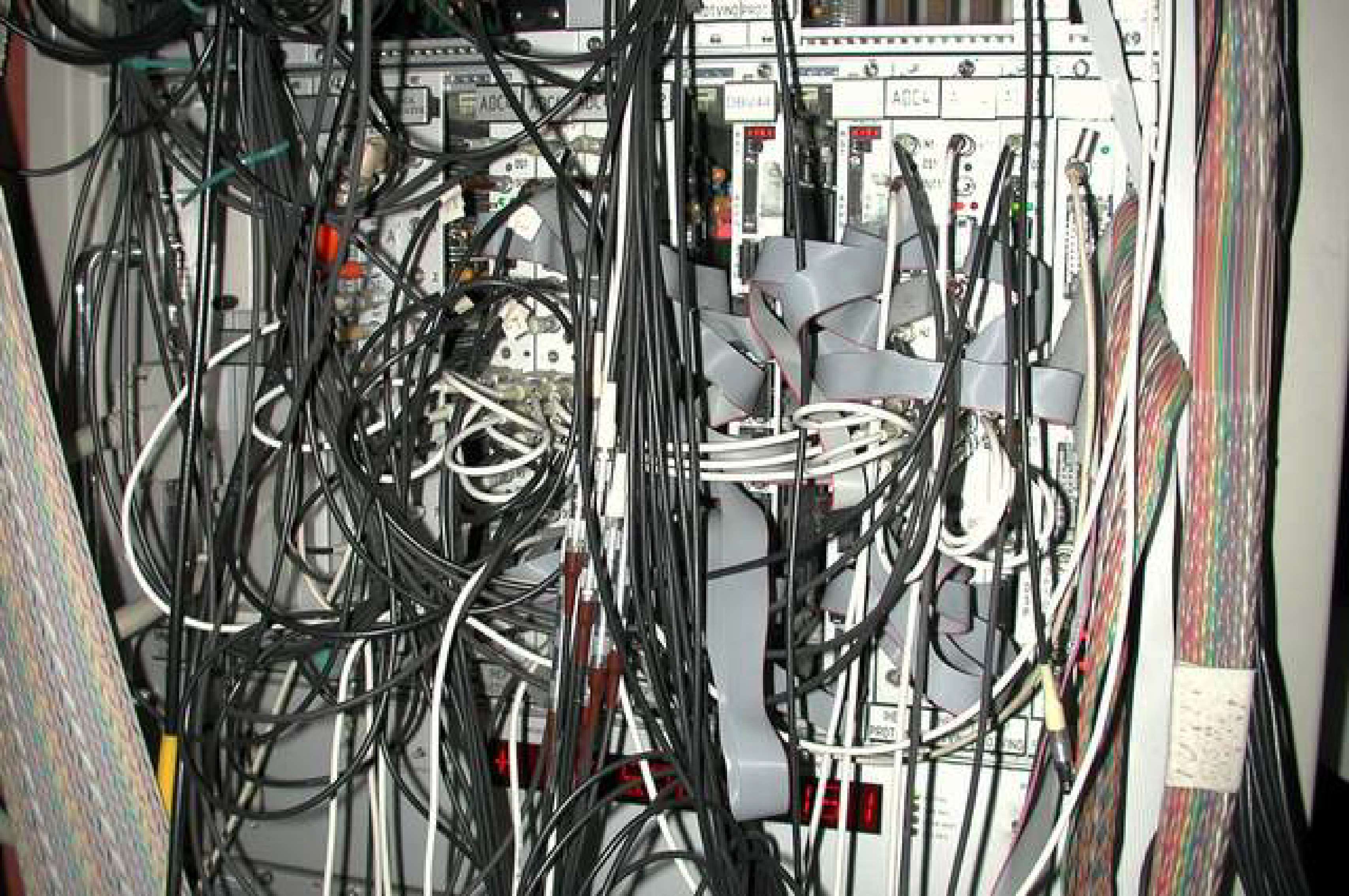

DATEL
DR18
DR16
DR12
DR22
P18

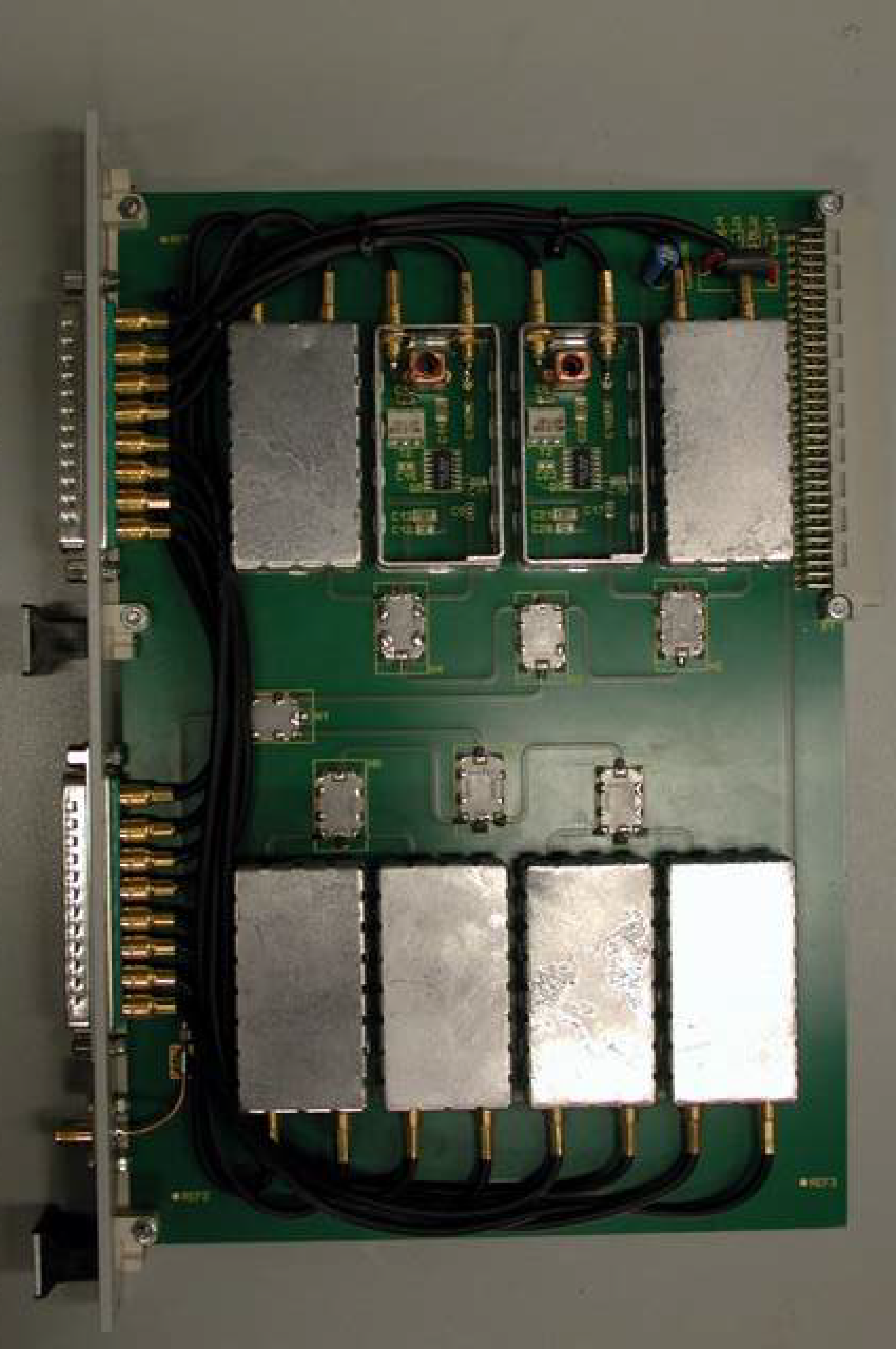
C16
C19
R12
R14
R13
R17
C17
R22
R25
C18
DA5
DA10
DA11
DA7
X2
X4
X5

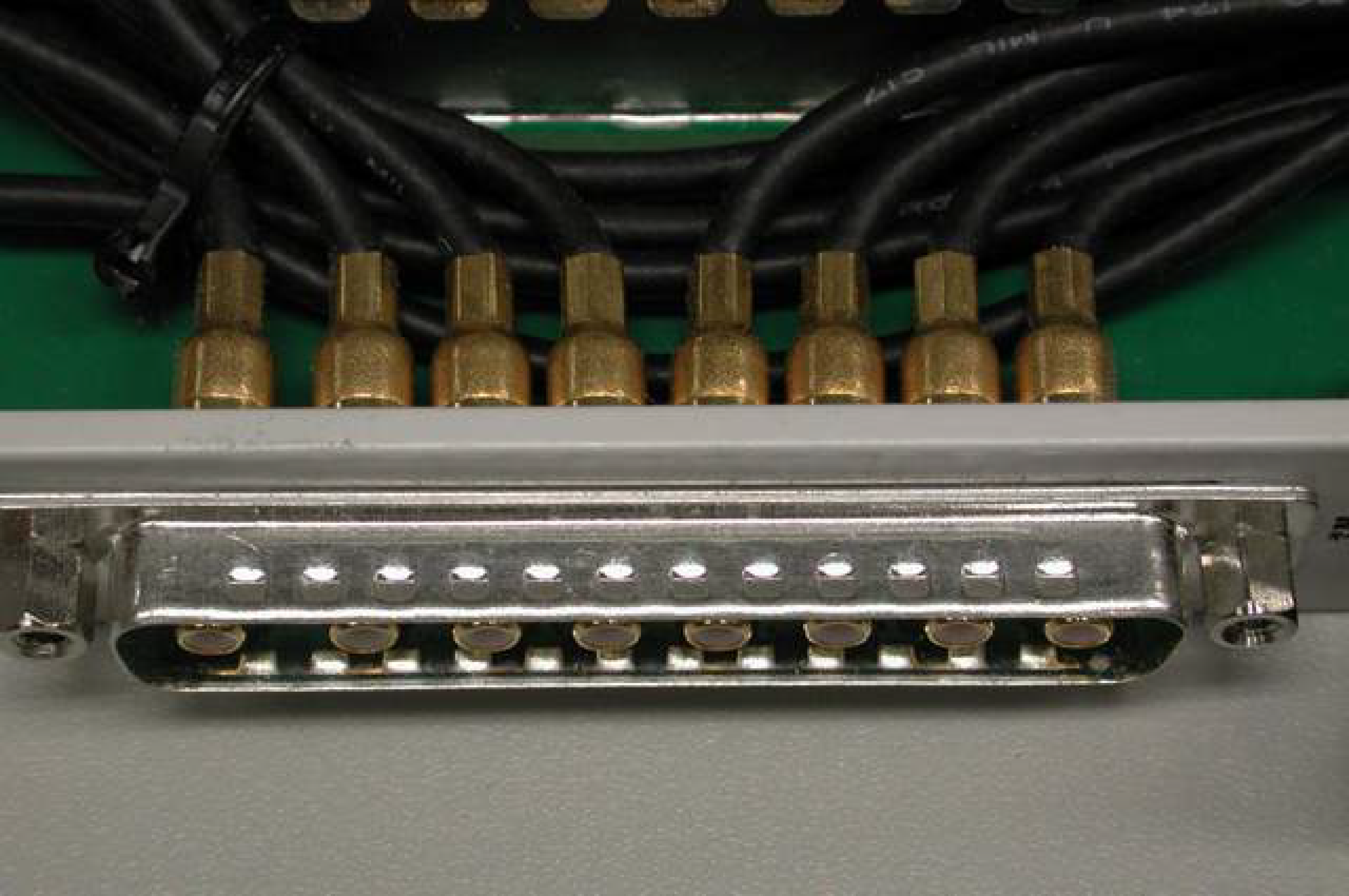

cc. D1
07FD
ac. D2
2681
D3
1C43


Nr 02
Nr 04
Nr 05
CAVITY SIMULATOR
REAL
GENER.
MAG
REAL
BEAM
TUNER
MICROPHON.
ANALOG OUT
I
Q
LOR. F. IN
ROT.MAT
OFF
RST
CLK
MULTIPL.
OUT
ω12
1/τm
K
G
φ

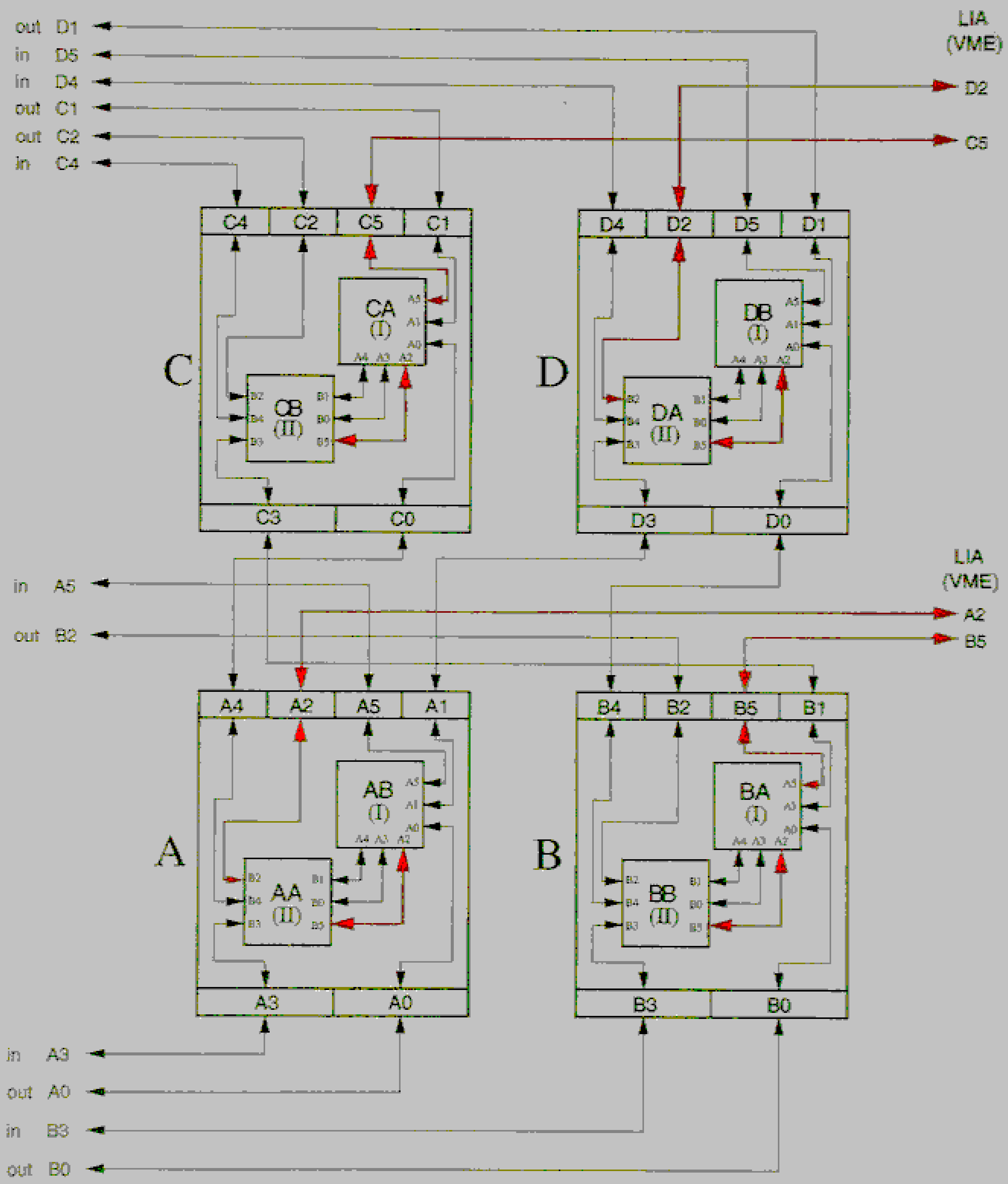



ADC4





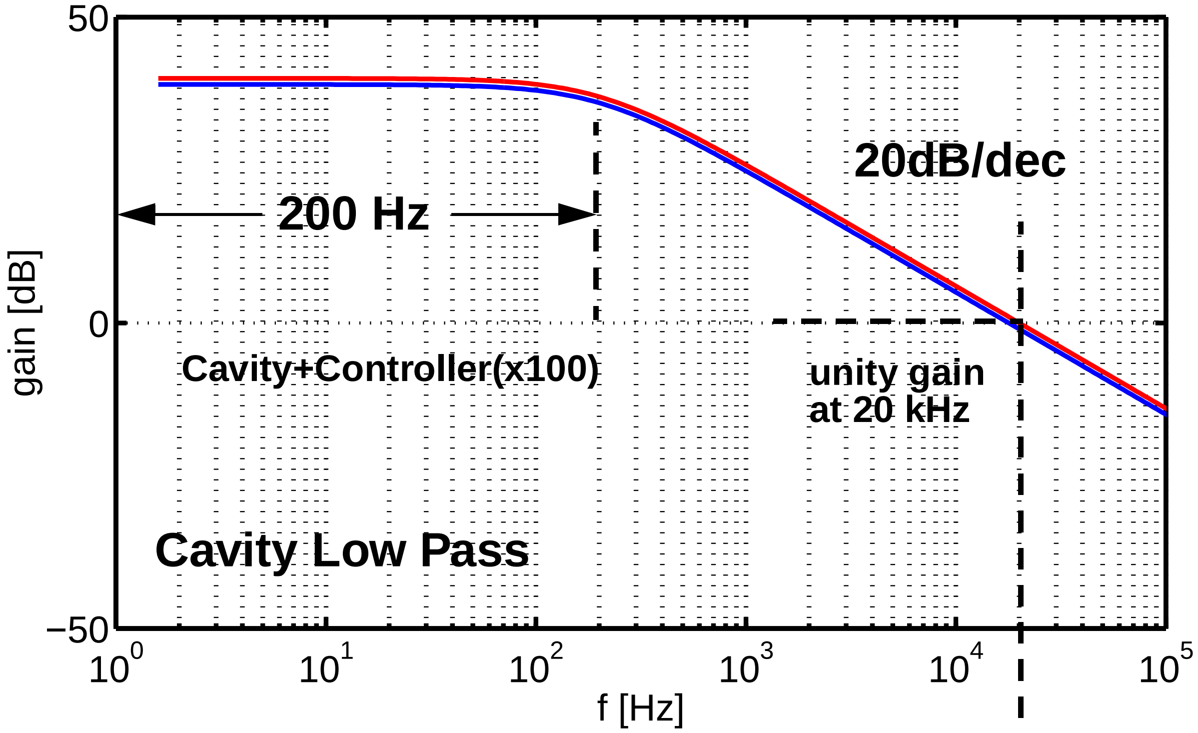
DBV44 board (V3/V4) + Twin Module MDC40T

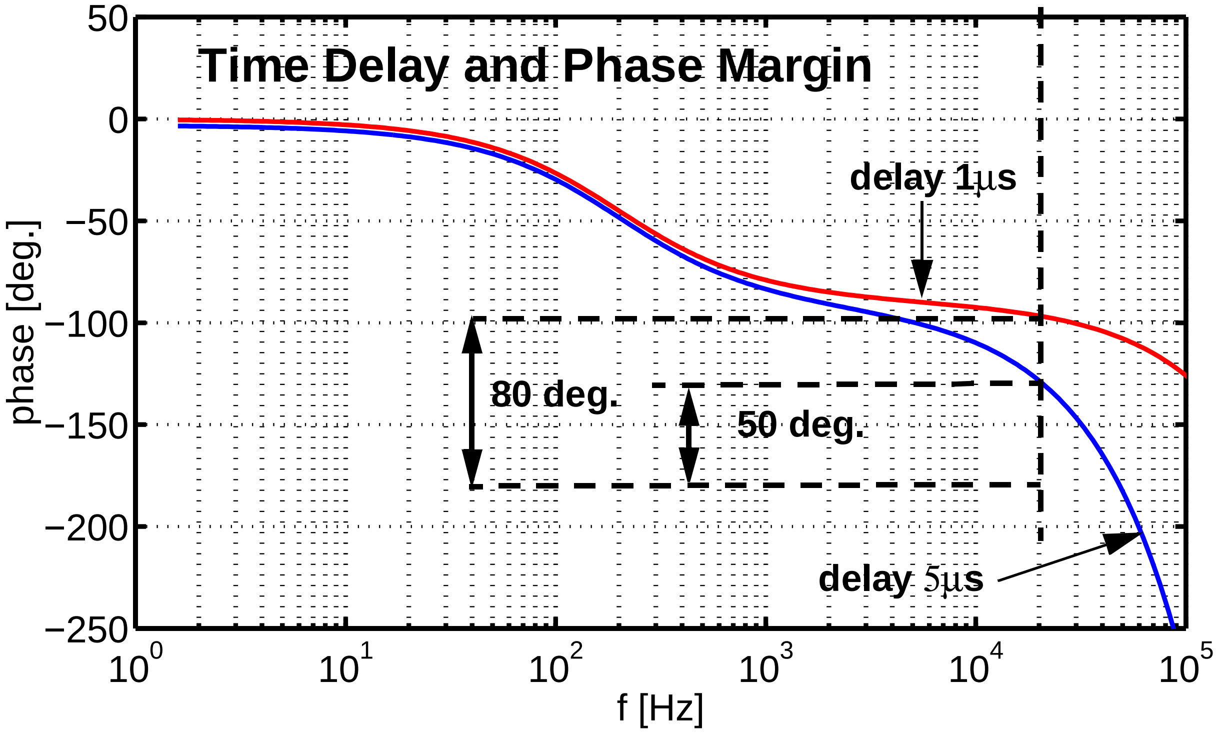


*) xA : primary processor (connected to Link Interface Adaptor)
xB : secondary processor (connected to Link Interface Adaptor via primary processor)

I : processor I (processor 1)
II : processor II (processor 2)

Cavity Transfer Function





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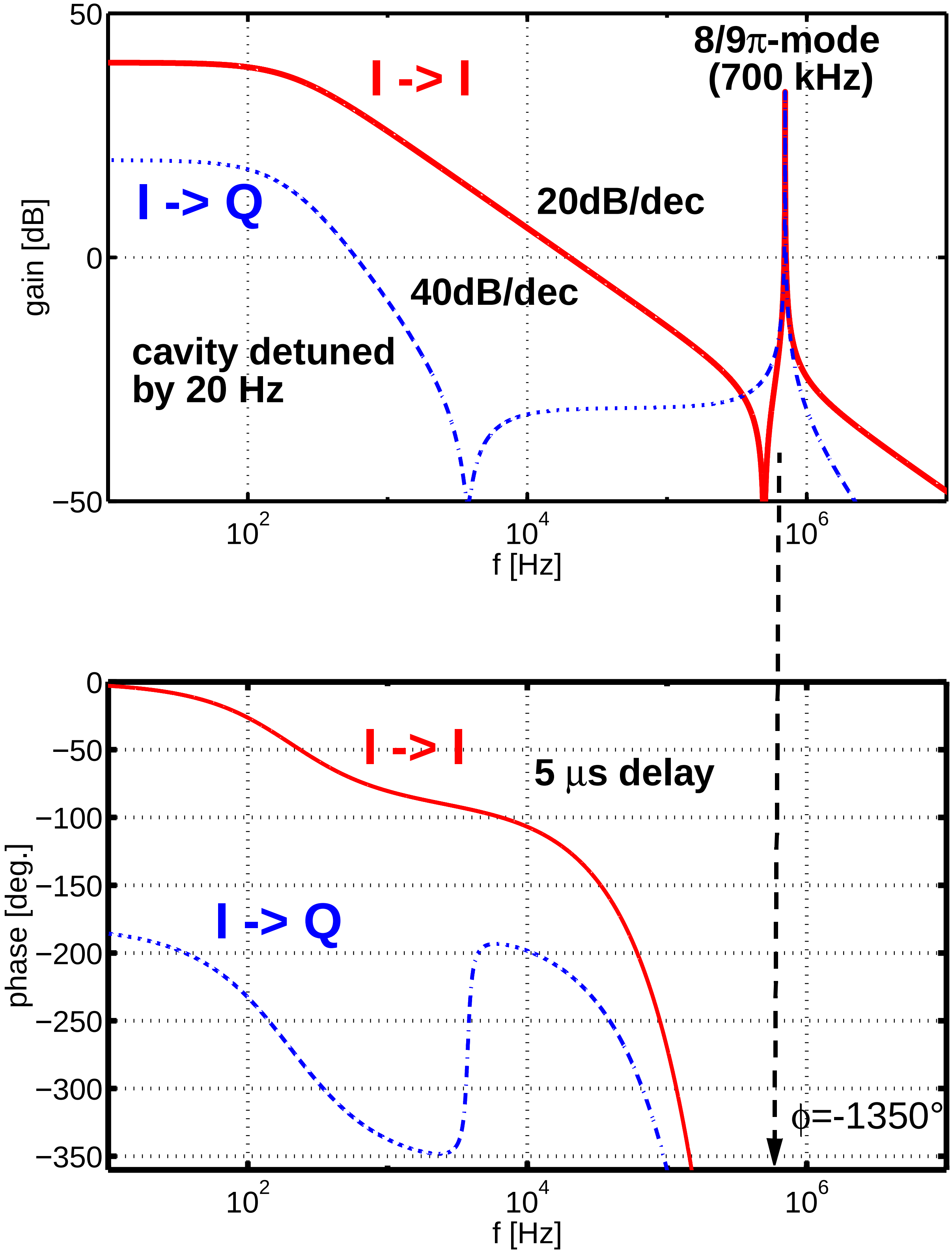
Cavity Transfer Function



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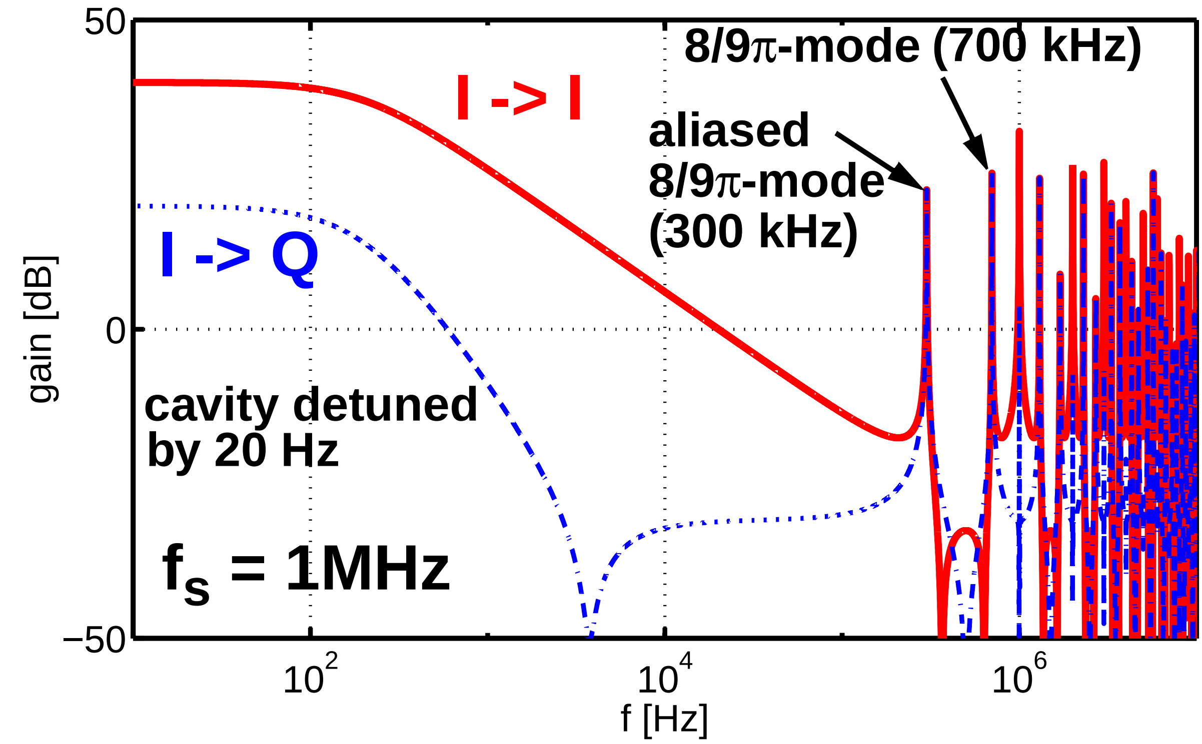
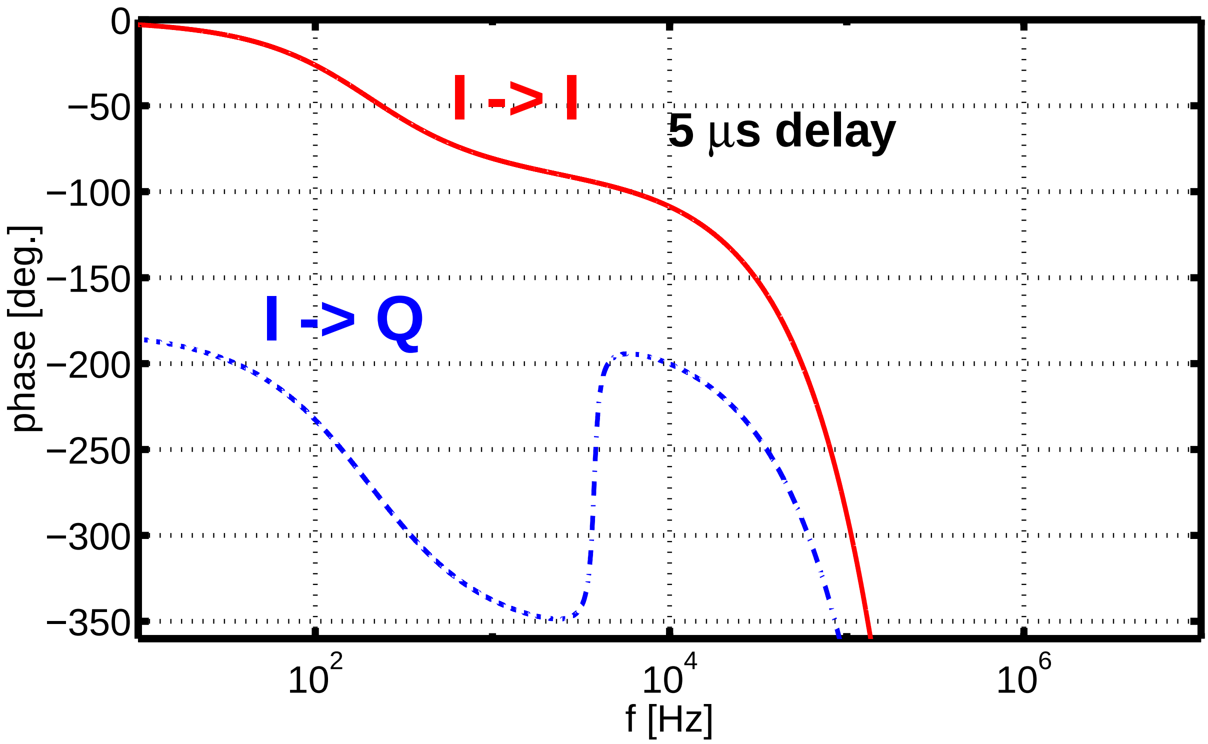
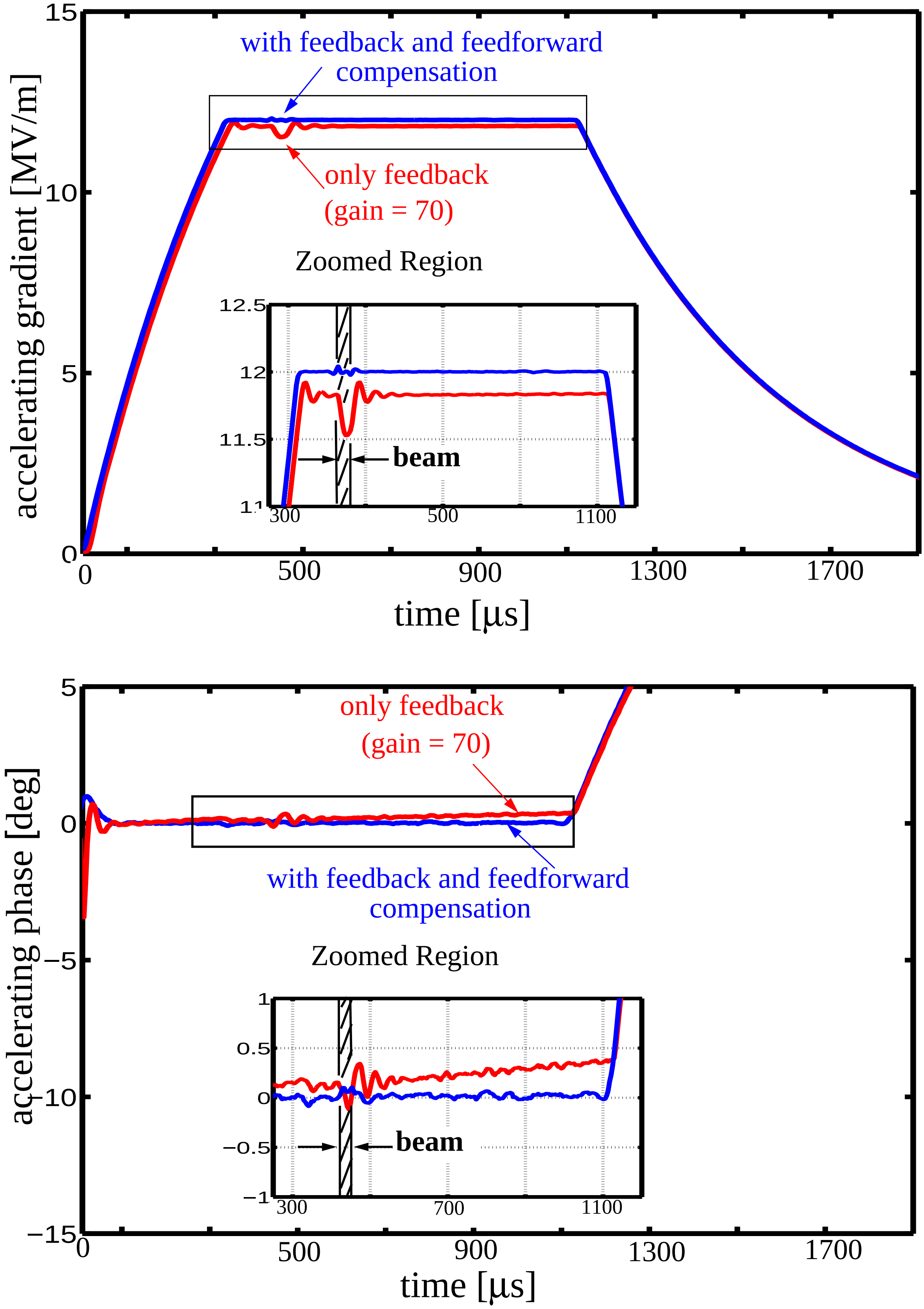
Discrete Cavity TF







with feedback and feedforward compensation
only feedback (gain = 70)
Zoomed Region
beam
accelerating gradient [MV/m]
time [μs]
with feedback and feedforward compensation
only feedback (gain = 70)
Zoomed Region
beam
accelerating phase [deg]
time [μs]

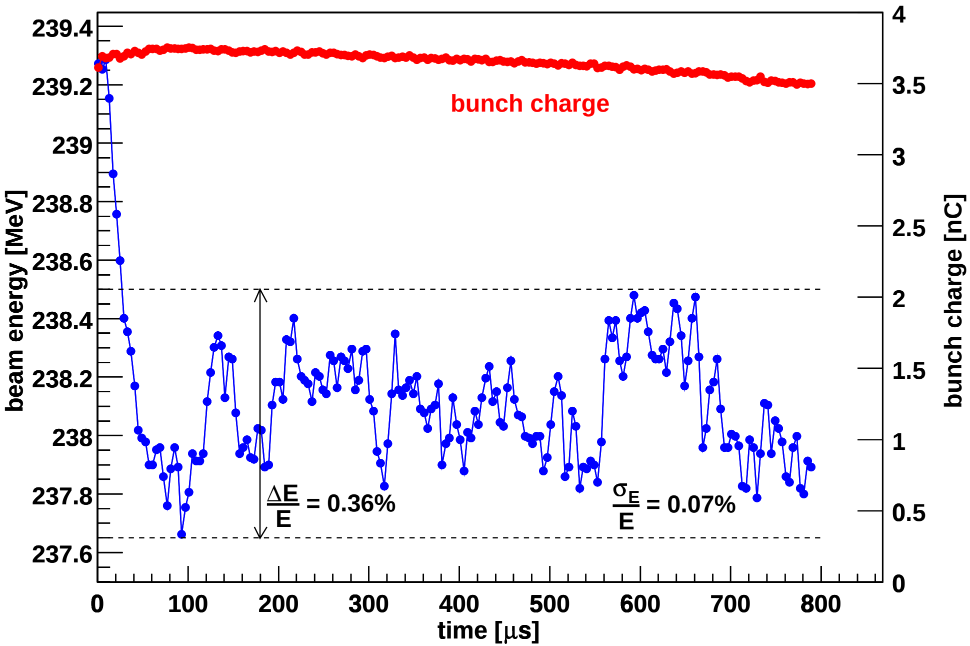
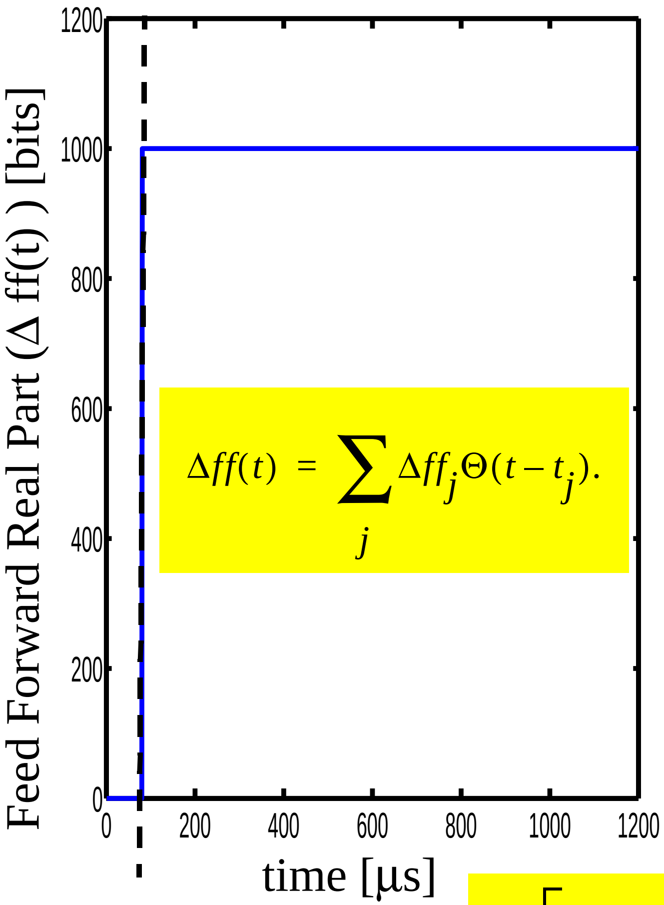


Figure 2.2.3: *Acceleration of long macro pulses. The beam energy and the bunch charge within one single macro pulse are shown. The RF control system was operated with beam loading compensation. The bunch spacing was 444 ns.*

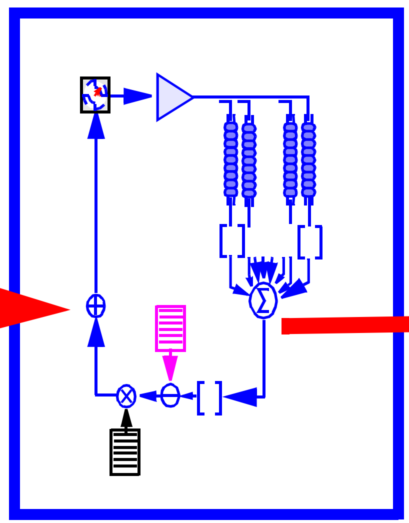
Step Response of the Closed Loop Sysem

Step

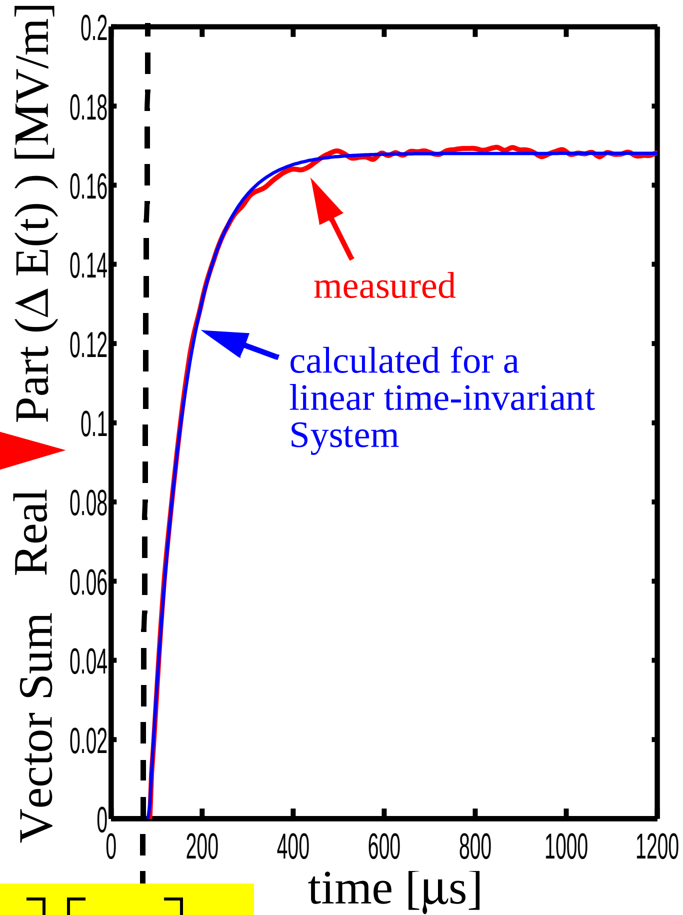


$$\Delta ff(t) = \sum_j \Delta ff_j \Theta(t - t_j).$$

Closed Loop System

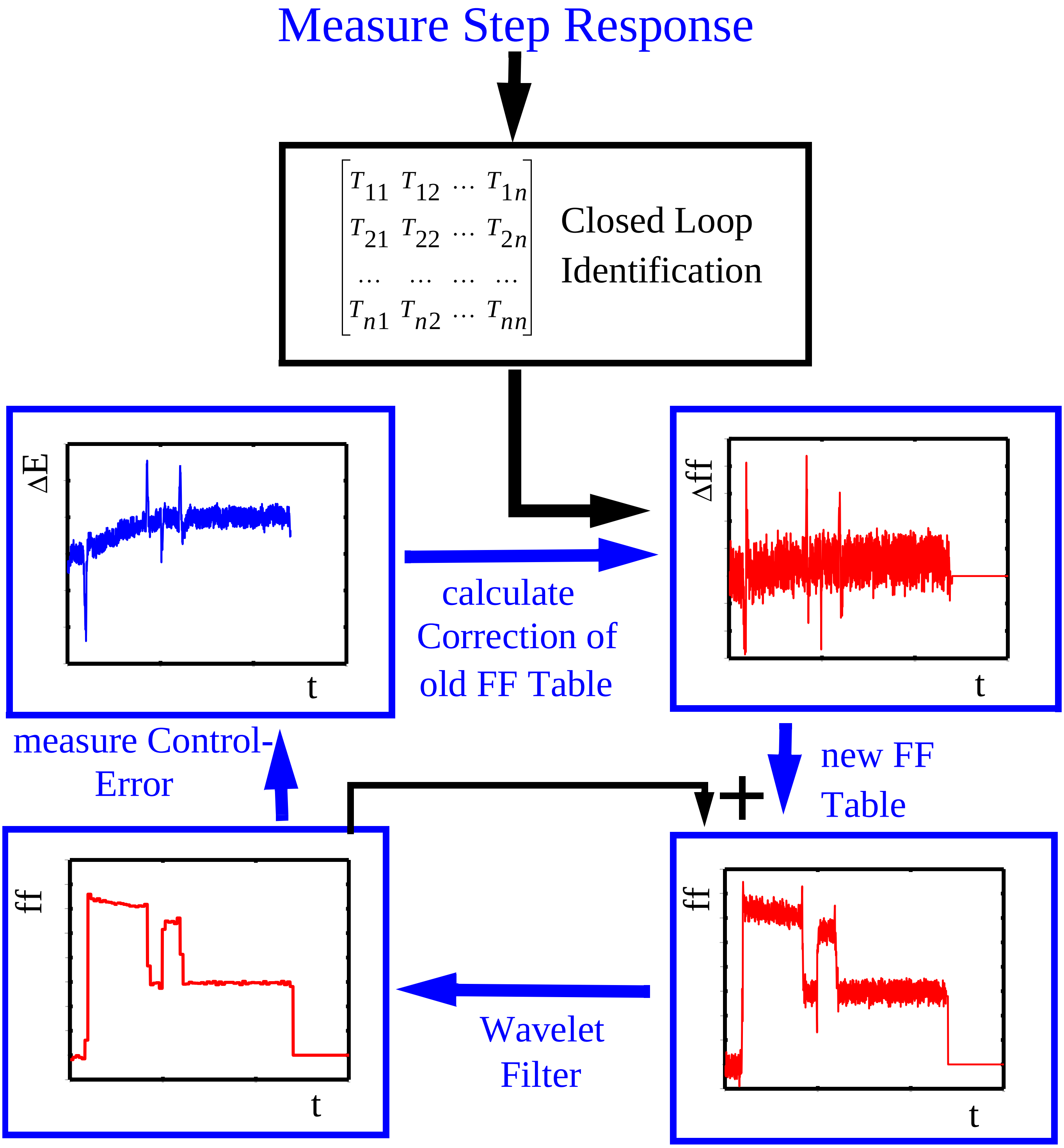


Step Response



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

Adaptive Feed Forward



Adaptive Feed Forward can handle nonlinear systems through linarisation around the operating point.

The calculation of a new feed forward table needs only a few seconds.

M. Liepe
11/97

System Identification:

Electrical Dynamics of Cavity 4

differential equations for amplitude and phase of the field

$$\dot{V} = -\omega_{1/2}V + R\omega_{1/2}I_{in}\cos(\psi_{in} - \varphi + \delta) + R\omega_{1/2}I_b\cos(\psi_b + \varphi)$$

$$\dot{\varphi} = \Delta\omega + R\omega_{1/2}\frac{I_{in}}{V}\sin(\psi_{in} - \varphi + \delta) + R\omega_{1/2}\frac{I_b}{V}\sin(\psi_b + \varphi)$$

$V, \dot{V}, \varphi, \dot{\varphi}, I_{in}, \psi_{in}, I_b$ are measured or derived from measurements

least square fit

$\omega_{1/2}$	bandwidth	Are found by fitting them to the first differential equation with the assumption that they are constant.
$R\omega_{1/2}$	shunt Impedance	
δ	phase between probe and directional coupler	
ψ_b	equivalent beamphase	

calculate $\Delta\omega(t)$

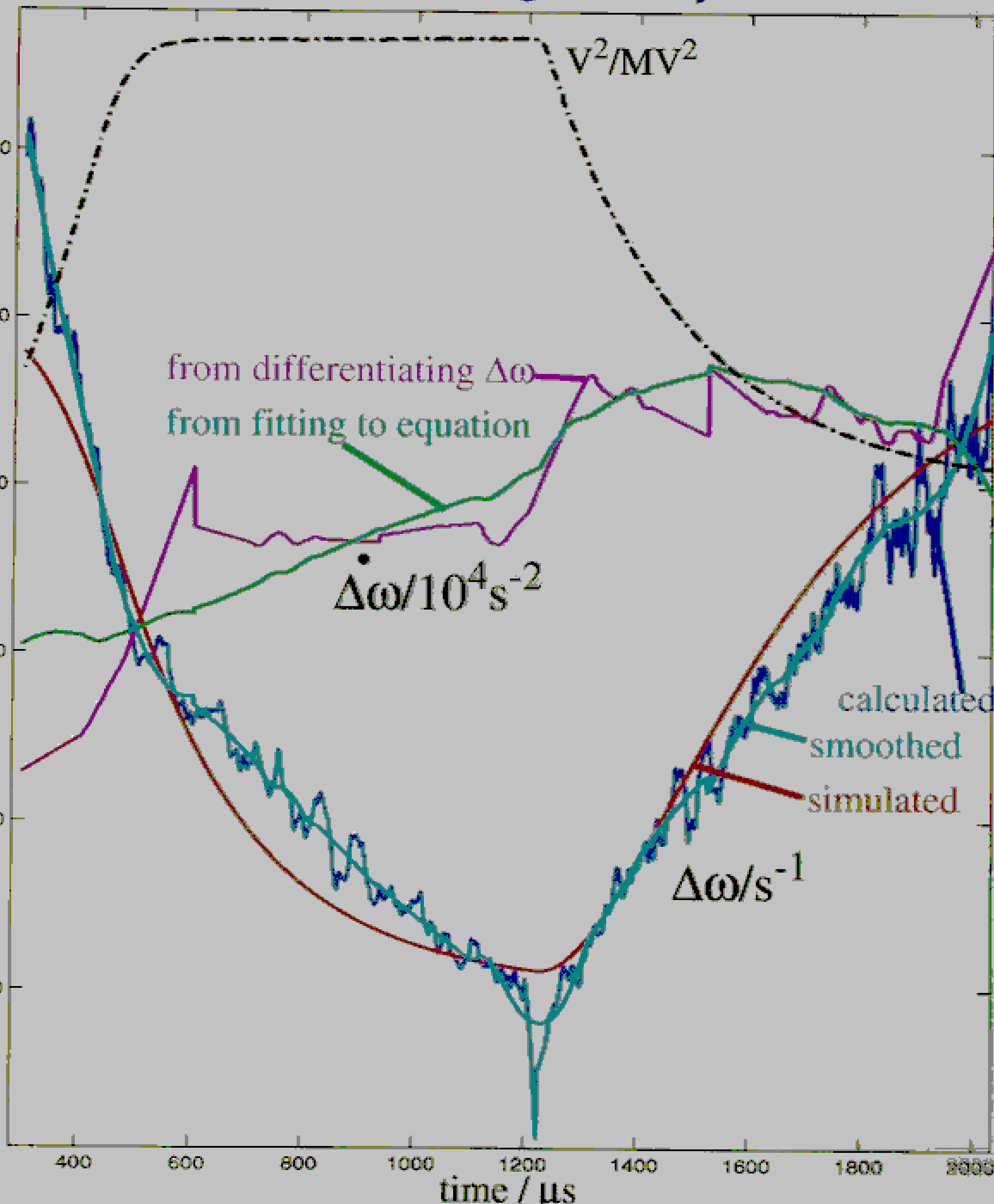
For calculation of $\Delta\omega(t)$ one only has to transform the second differential equation:

$$\Delta\omega(t) = \dot{\varphi} - R\omega_{1/2}\frac{I_{in}}{V}\sin(\psi_{in} - \varphi + \delta) - R\omega_{1/2}\frac{I_b}{V}\sin(\psi_b + \varphi)$$

...

System Identification:

Lorentz-Force-Detuning of Cavity 4 at 18MV



$$\dot{\Delta\omega} = -\frac{1}{\tau_m}(\Delta\omega - \Delta\omega_T) - \frac{2\pi K}{\tau_m}V^2$$

Markus Hüning, 19/11/97

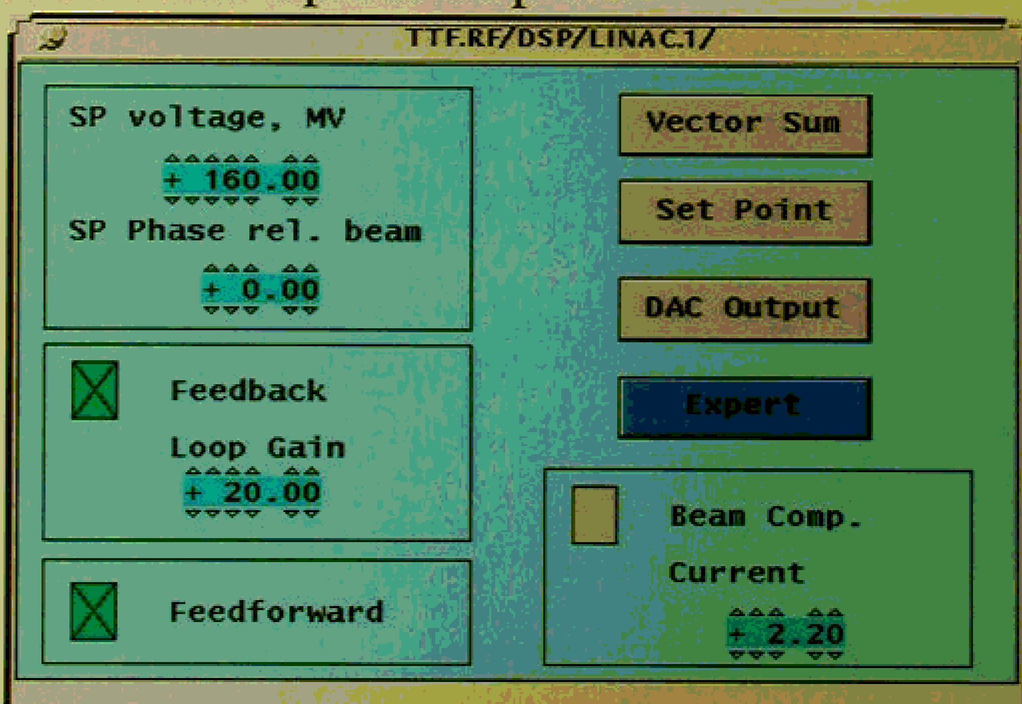
TTF

DOOCS Operator interface

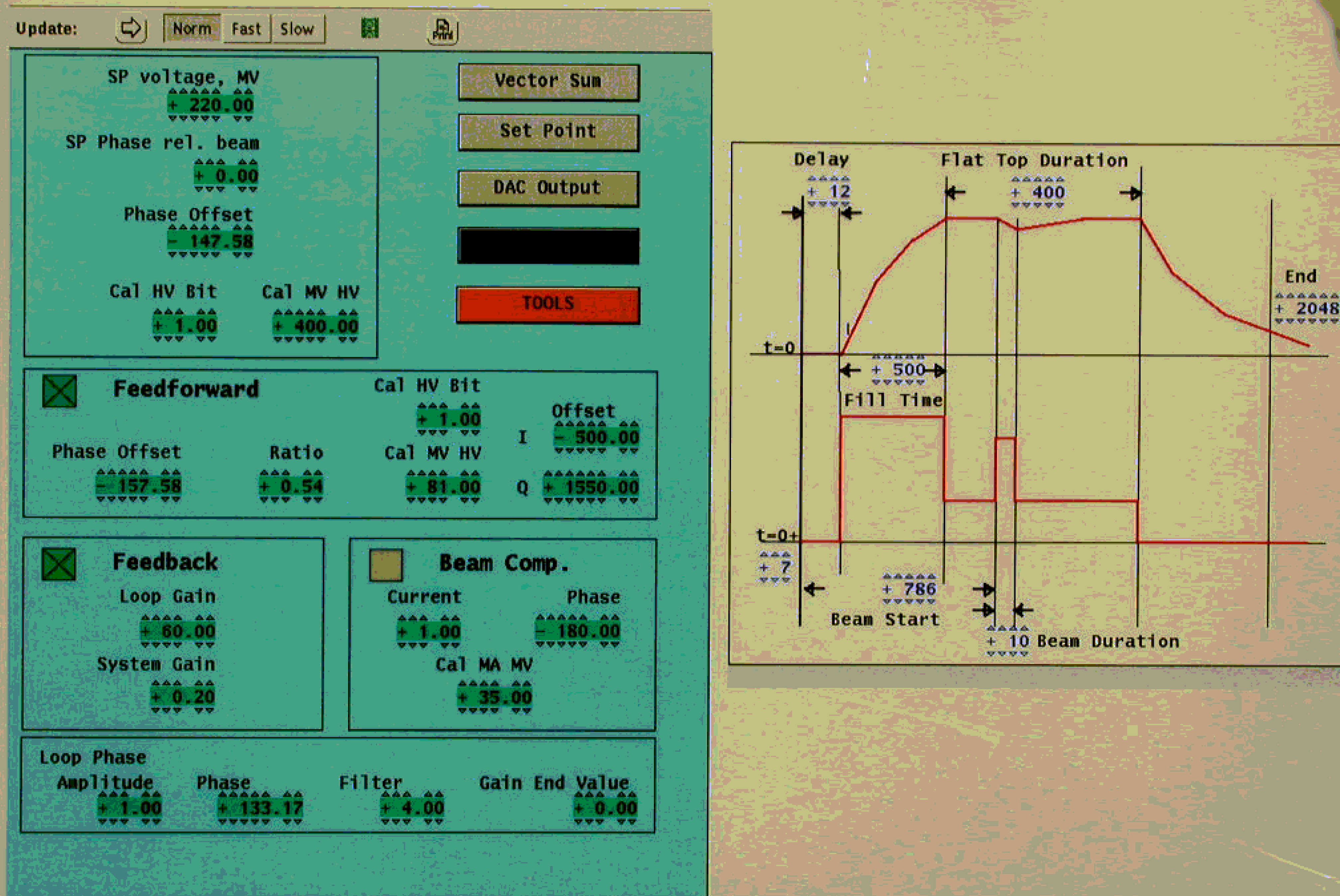
System selection:

Startup:

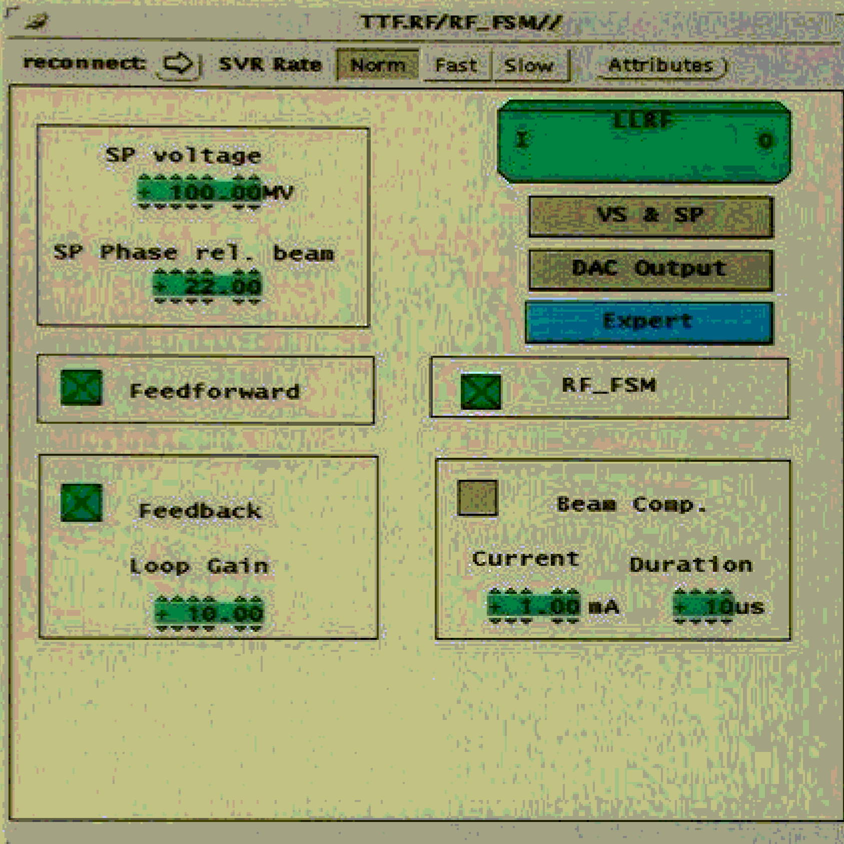
Linac LLRF operation panel:



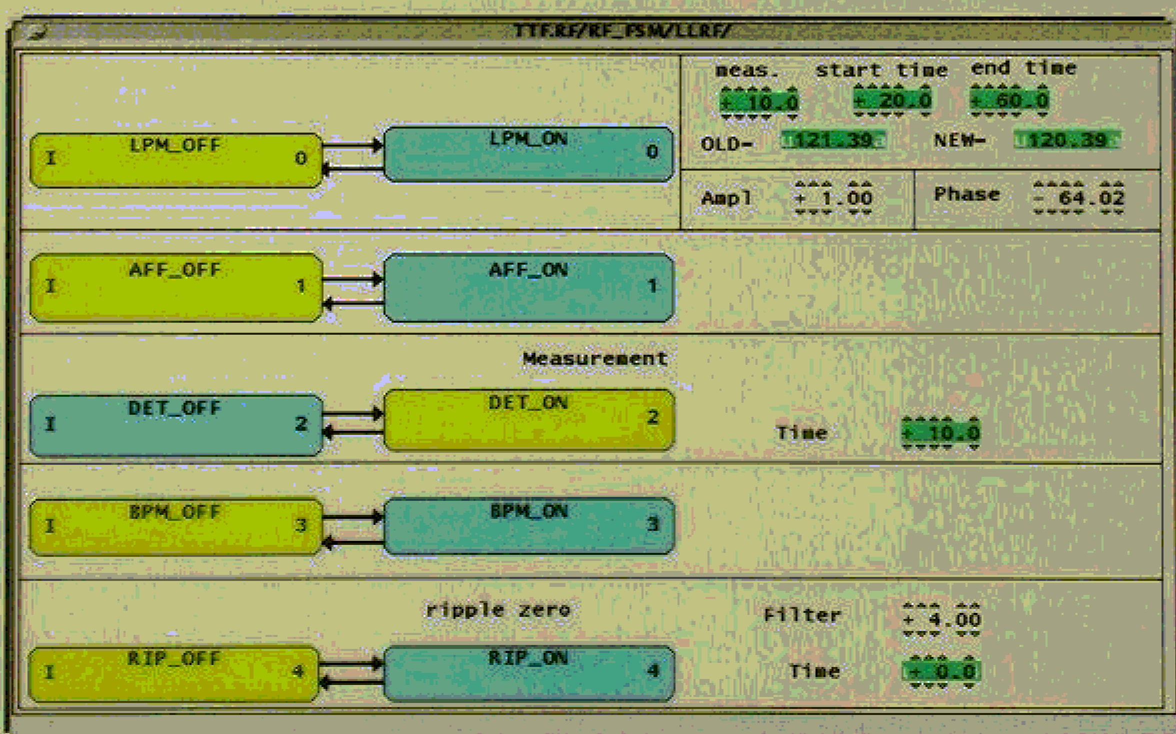
G. von Walter



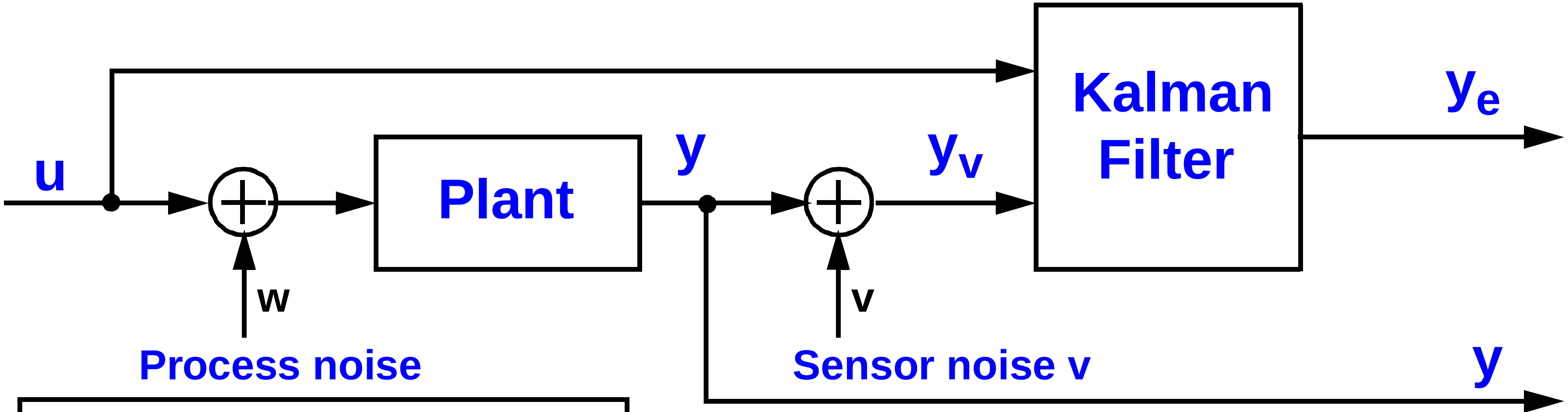
Update:
Norm
Fast
Slow
SP voltage, MV
+ 220.00
SP Phase rel. beam
+ 0.00
Phase Offset
- 147.58
Cal HV Bit
+ 1.00
Cal MV HV
+ 400.00
Vector Sum
Set Point
DAC Output
TOOLS
Feedforward
Cal HV Bit
+ 1.00
Offset
I
- 500.00
Phase Offset
- 157.58
Ratio
+ 0.54
Cal MV HV
+ 81.00
Q
+ 1550.00
Feedback
Loop Gain
+ 60.00
System Gain
+ 0.20
Beam Comp.
Current
+ 1.00
Phase
- 180.00
Cal MA MV
+ 35.00
Loop Phase
Amplitude
+ 1.00
Phase
+ 133.17
Filter
+ 4.00
Gain End Value
+ 0.00
Delay
+ 12
Flat Top Duration
+ 400
End
+ 2048
t=0
+ 500
Fill Time
t=0+
+ 7
+ 786
Beam Start
+ 10 Beam Duration


TTF.RF/RF_FSM//
reconnect:
SVR Rate
Norm
Fast
Slow
Attributes
SP voltage
+ 100.00MV
SP Phase rel. beam
+ 22.00
LLRF
I
0
VS & SP
DAC Output
Expert
Feedforward
RF_FSM
Feedback
Loop Gain
+ 10.00
Beam Comp.
Current
Duration
+ 1.00 mA
+ 10us


TTF.RF/RF_FSM/LL
NULL
IDLE
RF_STDBY
HV_ON
RF_ON
BEAM_ON
TOOLS


TTF.RF/RF_FSM/LLRF/
meas.
start time
end time
+ 10.0
+ 20.0
+ 60.0
OLD=
121.39
NEW=
120.39
Ampl
+ 1.00
Phase
- 64.02
LPM_OFF
LPM_ON
AFF_OFF
AFF_ON
Measurement
DET_OFF
DET_ON
Time
+ 10.0
BPM_OFF
BPM_ON
ripple zero
Filter
+ 4.00
RIP_OFF
RIP_ON
Time
+ 0.0

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

Kalman Filter (Cnt'd)

where M is the solution of the Riccati Equation:

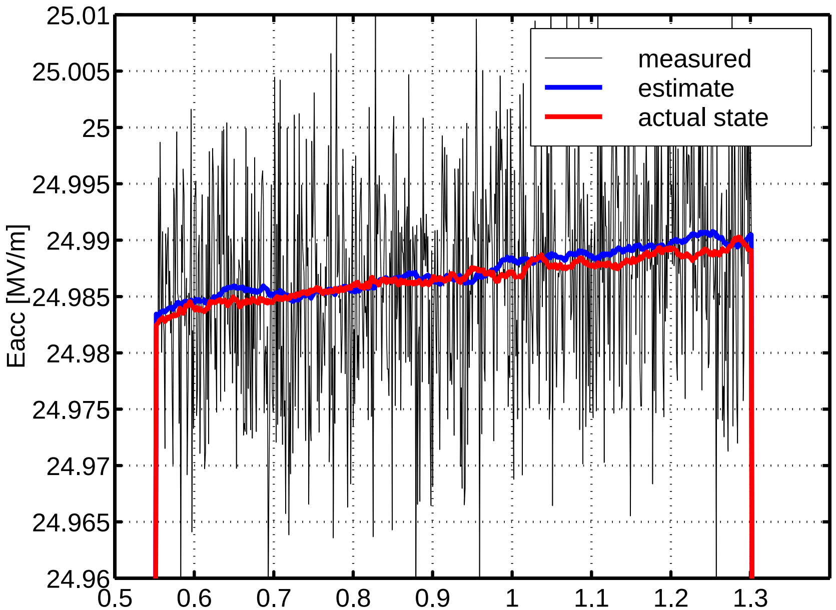
$M=Q+AMA^T-AMC^T(R+CMC^T)^{-1}CMA^T$

Combining time and measurement update into state space model (the kalman filter):

$$\hat{x}[n+1|n]] = A(I-MC)\cdot\hat{x}[n|n-1] + \begin{bmatrix} B & AM \end{bmatrix}\begin{bmatrix} u[n] \\ y_v[n]] \end{bmatrix}$$

$$\hat{y}[n|n] = C(I-MC)\cdot\hat{x}[n|n-1] + CMy_v[n]$$

This filter generates and optimal estimate $\hat{y}[n|n]$ of y[n]. Note that filter state is $\hat{x}[n|n-1]$



Example: TTF Cavity $Q_L = 3*10^6$

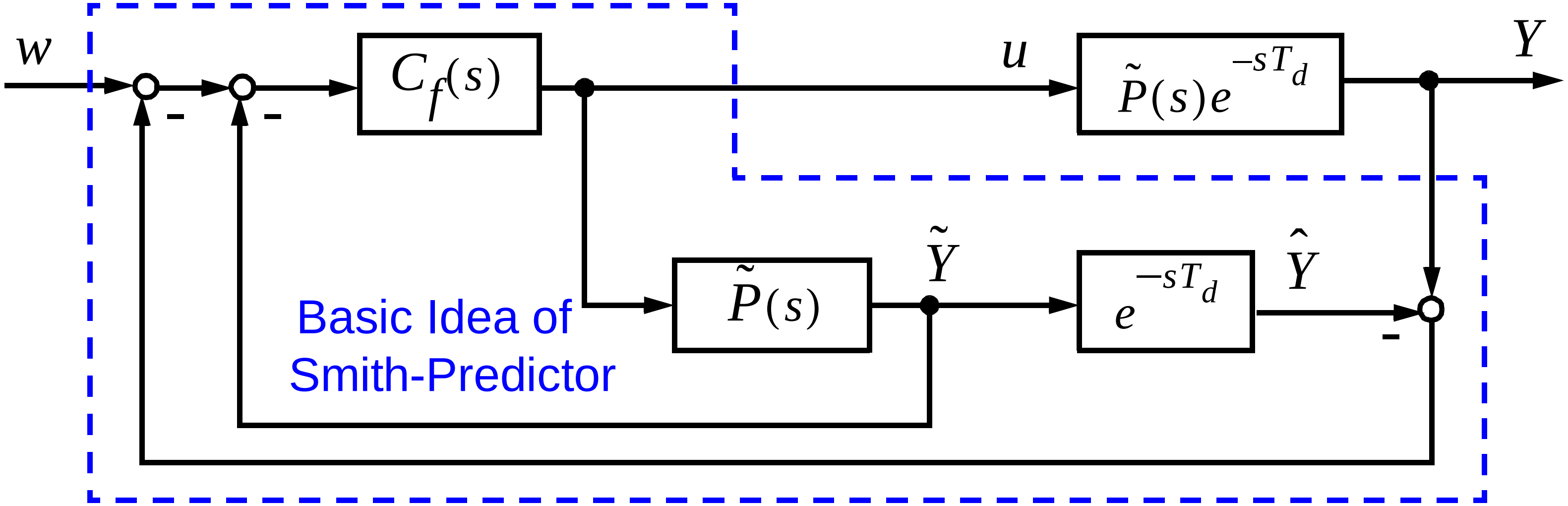
$\omega_0 = 1.3*10^9$ Hz

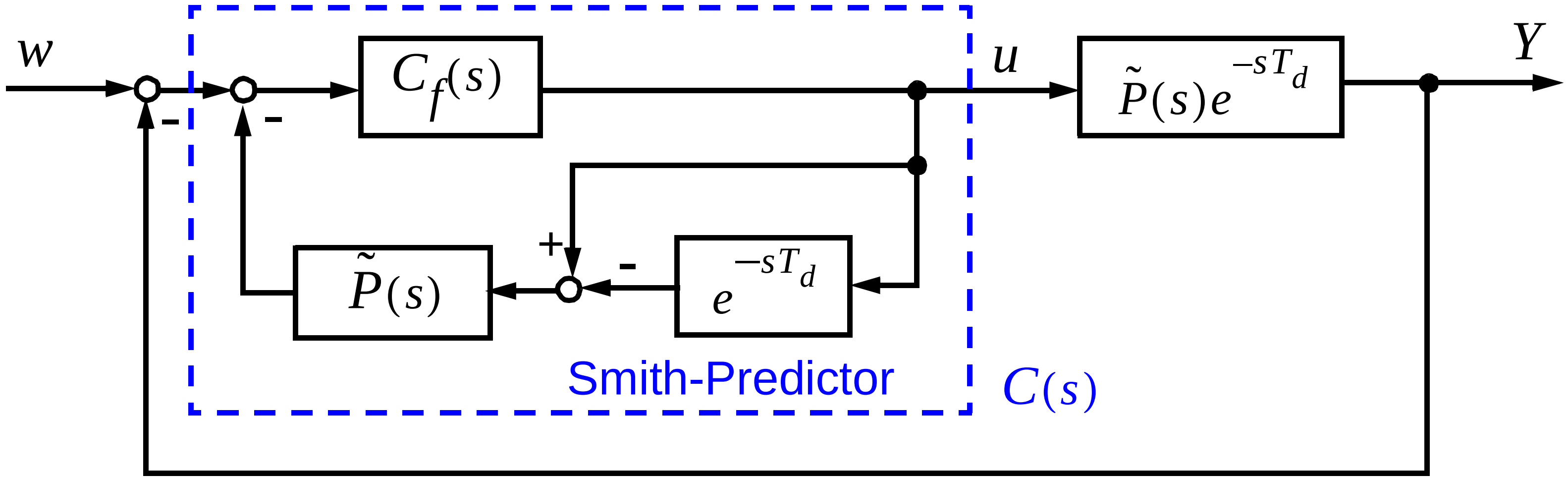
Beam noise : $\sigma(I_b)/I_b = 0.1$

Sensor noise : $\sigma(V_d)/V_d = 0.01$

$\Longrightarrow$ $\sigma_y / y = 0.0009$

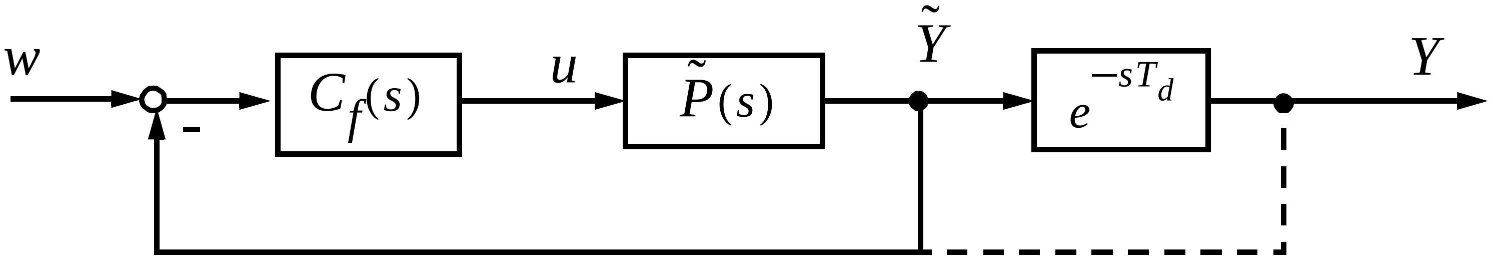
Principle of Smith Predictor





S.Simrock

Smith Predictor (Cnt'd)



Desired Feedback produced by Smith predictor

Command Step Response of Smith Predictor:

$$G_w(s) = \frac{P(s)C(s)}{1 + P(s)C(s)} = \frac{\tilde{P}(s)e^{-sT_d}C(s)}{1 + \tilde{P}(s)e^{-sT_d}C(s)}$$

hCommand Step Response of desired feedback:

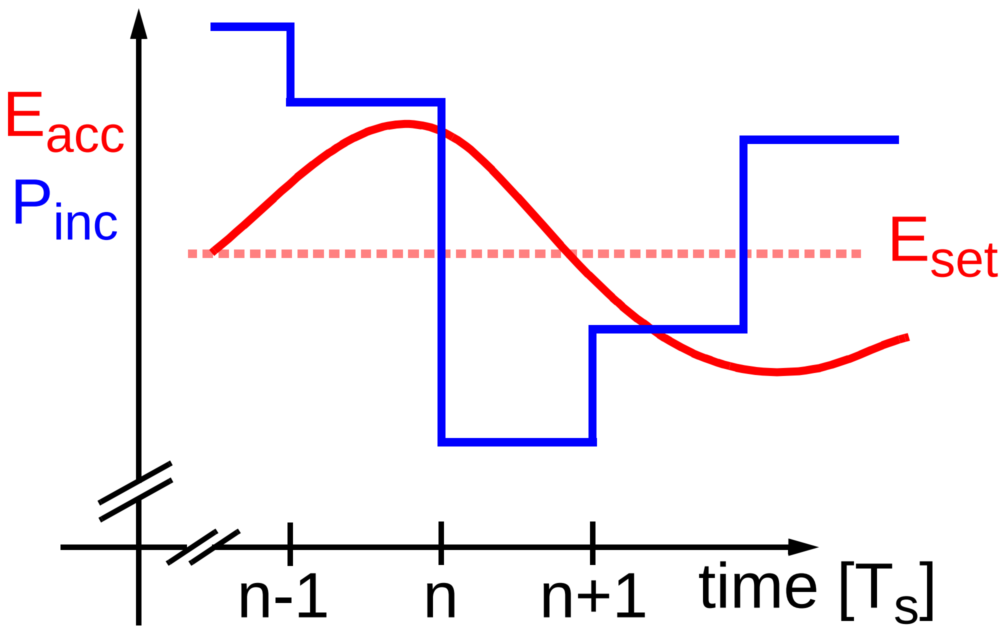
$$G_w(s) = \frac{\tilde{G}(s)C_f(s)}{1 + \tilde{G}(s)C_f(s)}e^{-sT_d}$$

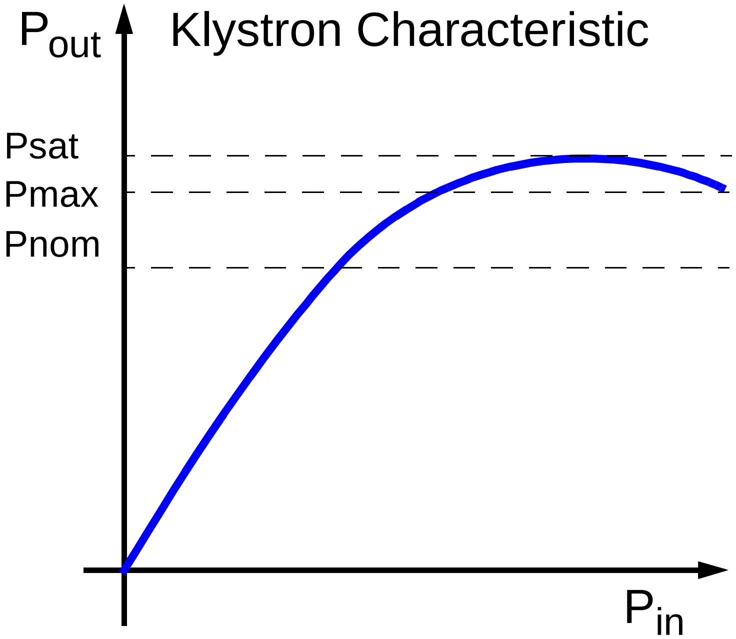
$\Longrightarrow$

Smith Predictor :

$$C(s) = \frac{C_f(s)}{1 + C_f(s)\tilde{P}(s)(1 - e^{-sT_d})}$$

Time Optimal Control





P_{nom} : nominal power (beam power)

P_{max} : maximum power useable for field control (incremental gain =0.5)

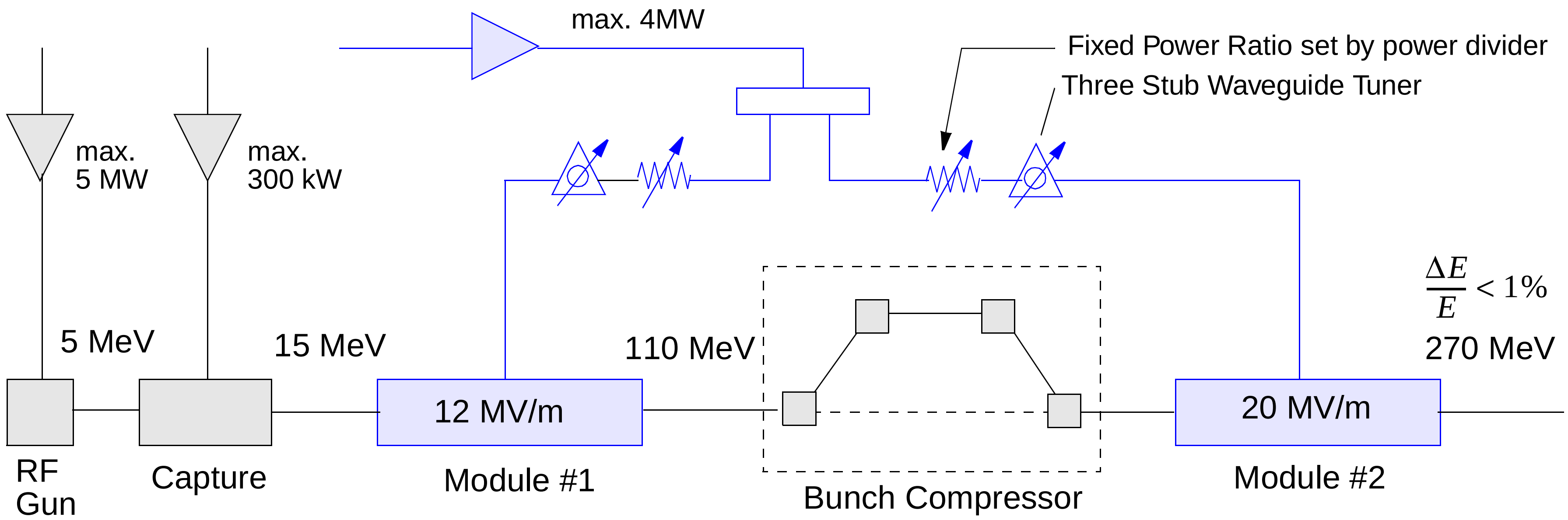
P_{sat} : klystron power in saturation

<u>Principle:</u> Power correction at time n^*T_s is such that gradient is correct at time $(n+1)^*T_s$ assuming no perturbations on plant.

$\Longrightarrow$ Optimal gain = 700 (τ_{cav}/T_s)

Note: with power reserve of 20% the maximum error that can be corrected in 1 μs is $1/7000 = 1.4^*10^{-4}$. Problems: Measurements noise and klystron saturation

RF System Diagram with Bunch Compressor



Module #1

$$V_{acc} = 95\text{MV}$$

$$\phi_{acc} = -8.7°$$

$$\frac{\Delta V_{acc}}{V_{acc}} < 1\%$$

$$\Delta\phi_{acc} < 1°$$

Bunch Compressor

$$R_{56} = 17.8\text{cm}$$

$$\text{i.e. } \approx 2.8°/\%$$

$$\Delta l \approx 8.5\text{cm} \approx 130°$$

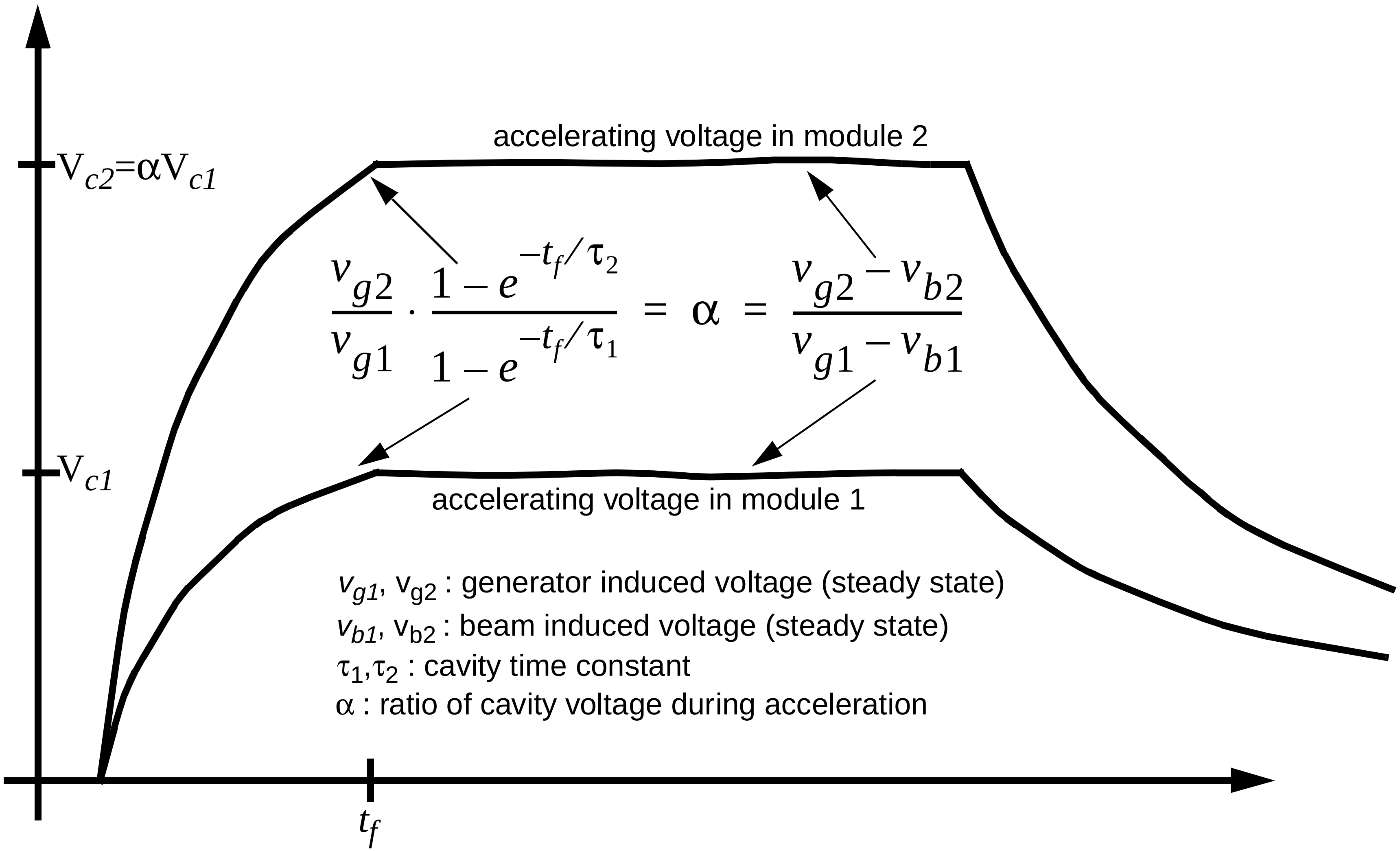
Module #2

$$V_{acc} = 160\text{MV}$$

$$\phi_{acc} = 0°$$

S.Simrock

Operation at Different Gradients (1)



$$\frac{v_{g2}}{v_{g1}} \cdot \frac{1-e^{-t_f/\tau_2}}{1-e^{-t_f/\tau_1}} = \alpha = \frac{v_{g2}-v_{b2}}{v_{g1}-v_{b1}}$$

v_{g1}, v_{g2} : generator induced voltage (steady state)

v_{b1}, v_{b2} : beam induced voltage (steady state)

τ_1,τ_2 : cavity time constant

α : ratio of cavity voltage during acceleration

S.Simrock

Operation at Different Gradients (2)

• Solution

1. Select Parameters t_f, v_1, and α

2. Solve α for $\frac{v_{g2}}{v_{g1}}$ as function of $\frac{\tau_2}{\tau_1}$, τ_1 and $\frac{v_{b1}}{v_{g1}}$

$$\frac{\frac{v_{g2}}{v_{g1}} - \frac{v_{b1}}{v_{g1}} \cdot \frac{\tau_2}{\tau_1}}{1 - \frac{v_{b1}}{v_{g1}}} = \frac{\alpha \cdot \frac{1 - e^{-t_f/\tau_2}}{1 - e^{-t_f/\tau_1}} - \frac{v_{b1}}{v_{g1}} \cdot \frac{\tau_2}{\tau_1}}{1 - \frac{v_{b1}}{v_{g1}}}$$

3. Plot solutions in contour plot and superimpose contour plot of corresponding gradients $\nu_c = \nu_g - \nu_b$ with $v_g = \sqrt{2 \cdot (r/Q) \cdot \omega\tau \cdot P}$ and $v_b = (r/Q) \cdot (\omega\tau)/2 \cdot I_b$

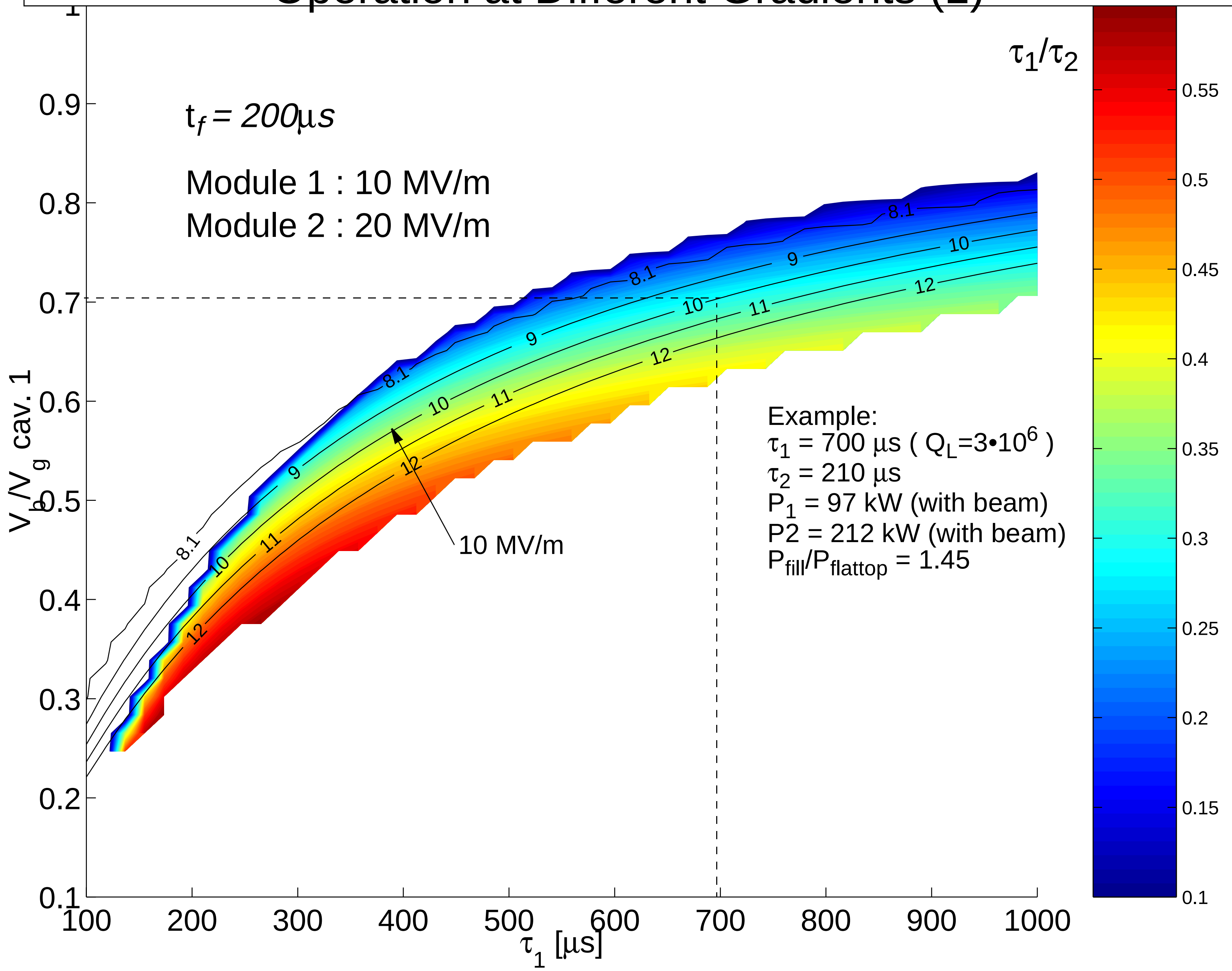
4. From the solutions with the desired gradient v_1 select one with acceptable incident power during filling and flattop and within adjustment range for τ_1 and τ_2

5. Repeat steps 1.-4. with different fill times t_f to determine the optimum solution.

6. Verify that solution is acceptable in presence of Lorentz force detuning

S.Simrock

Operation at Different Gradients (1)



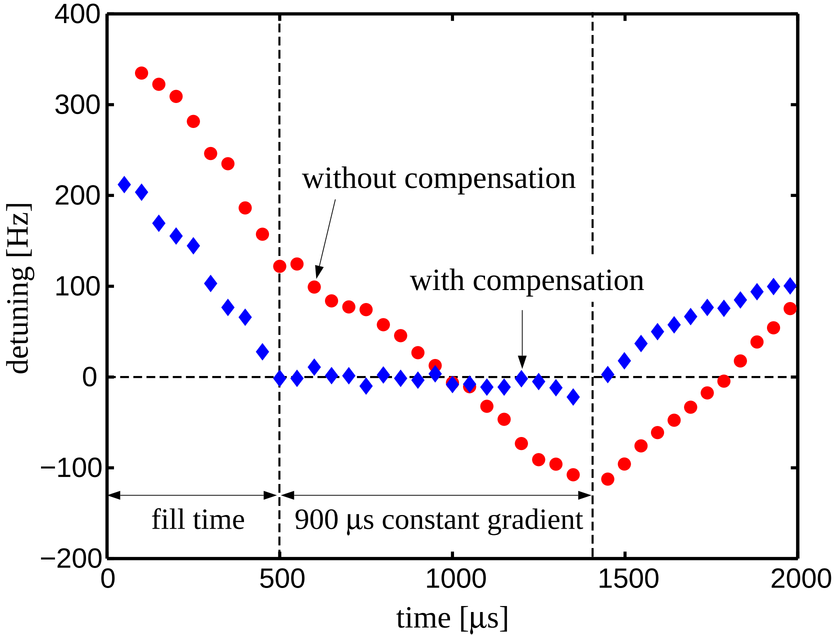


Figure 2.1.16: *Piezoelectric compensation of the Lorentz-force induced frequency shift in pulsed-mode cavity operation. The accelerating field is 23.5 MV/m.*

• Conclusion

- Superconducting cavity technology has demonstrated a to be a viable alternative to normalconducting technologie
- Gradients of 20-25 MV/m are currently state of the art. Goal is 35 MV/m for TESLA.
- The perturbations of the accelerating field caused by microphonics and Lorentz force detuning can be successfully controlled. This is even true if the vector-sum of 16 or more cavities is controlled. Performance has been demonstrated with beam.
- Digital technology allows for extensive diagnostics and exception handling.

• Outlook

- Lorentz force compensation (and microphonics !) with piezoelectric tuner.
- Operation of klystron close to saturation with dynamics linearisation scheme
- State machine for fully automated operation.