Low Power RF

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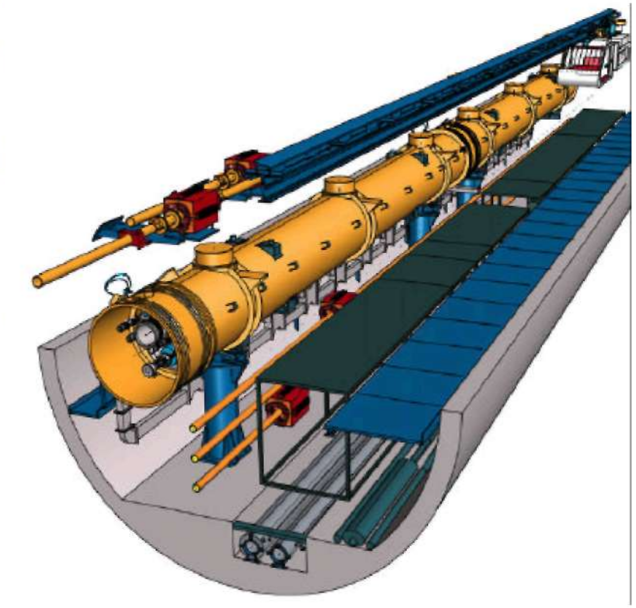
Requirements for ILC

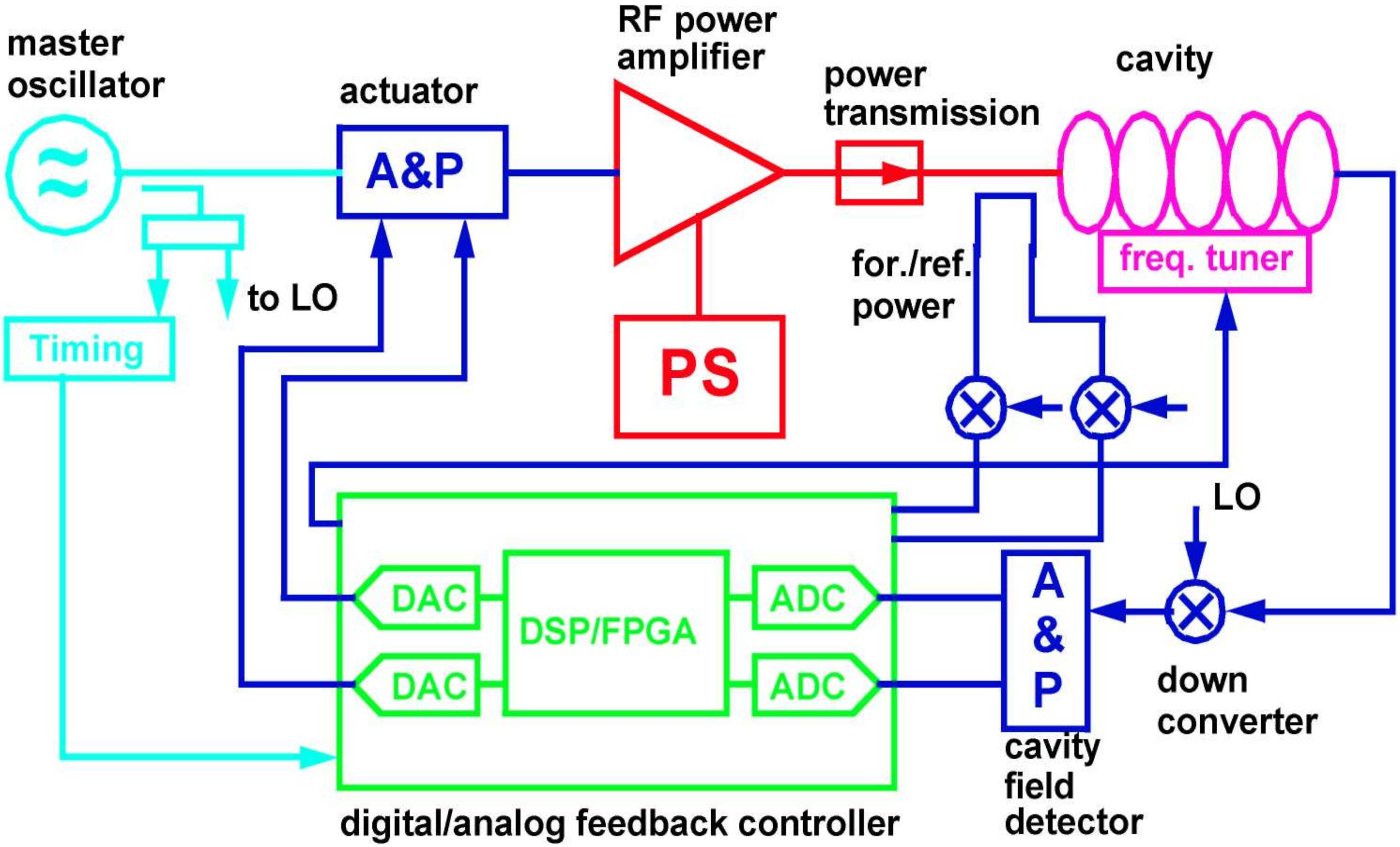
- CM energy: 500 GeV. Range 200 - 500 MeV. Upgradeability to 800 GeV
- Luminosity and reliability of the machine should allow L_{eq} = 500 fb^{-1} four years
- Energy scans between 200 GeV and 500 GeV. Energy change should take less than 10% of data taking time.
- Beam energy stability and precision should be below the tenth of percent level

RF Systems for ILC

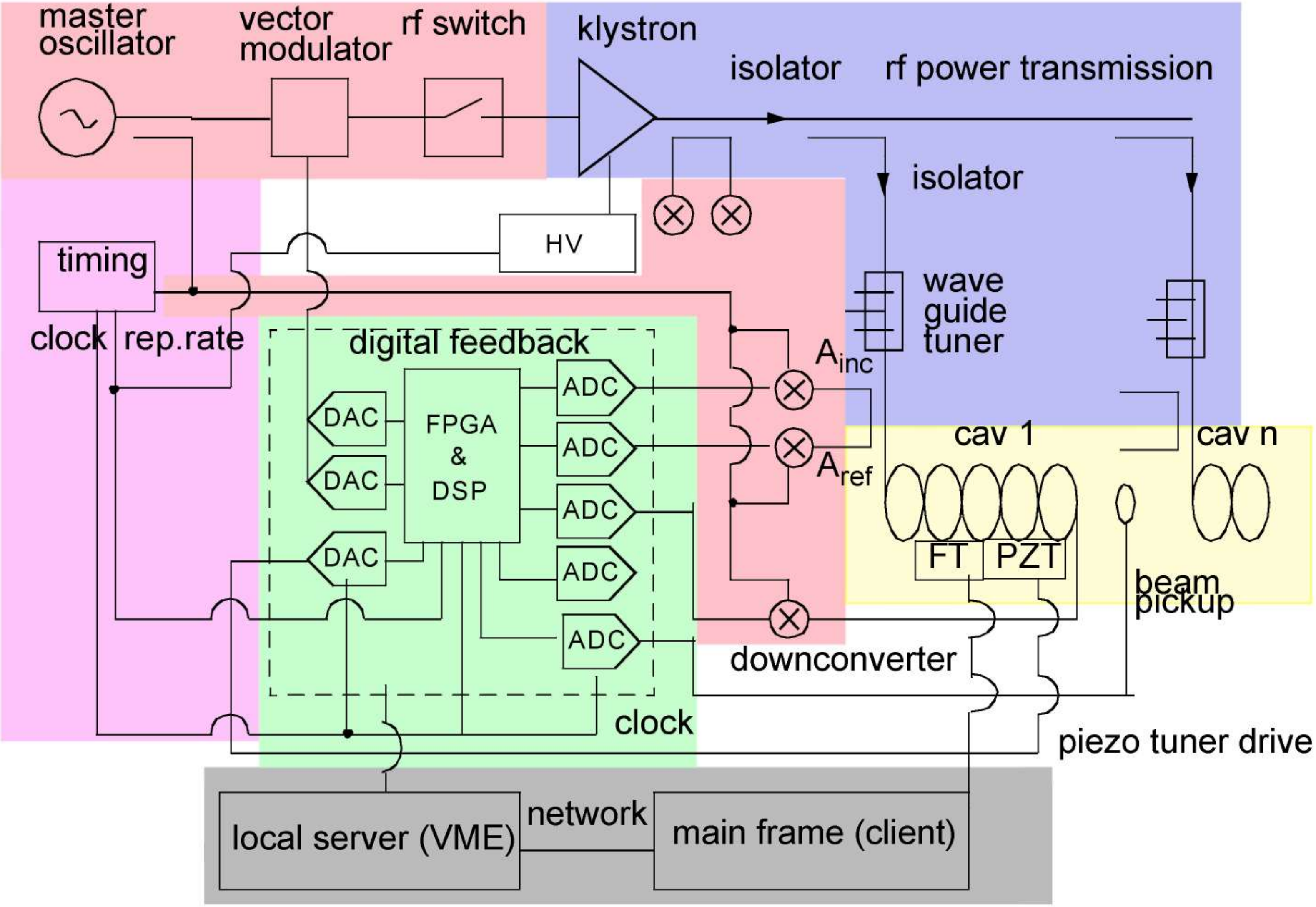
- e^- and e^+ source
- Injectors
- Damping Rings
- Main Linacs
- Crab cavities at IP



RF System Architecture



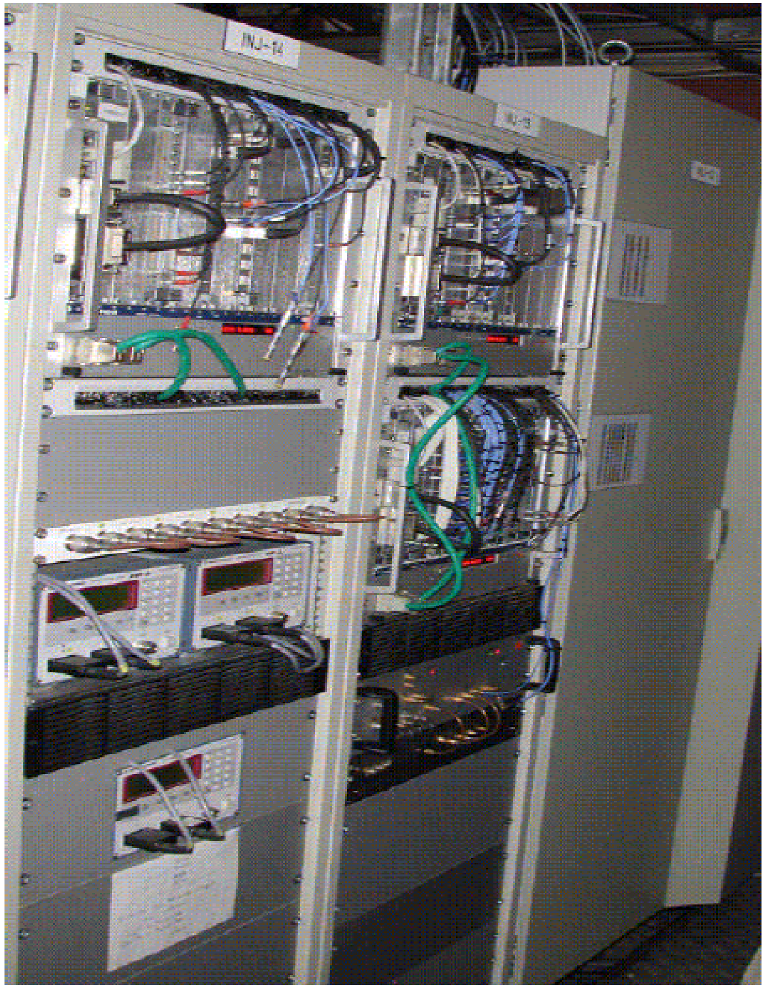
Architecture of LLRF System

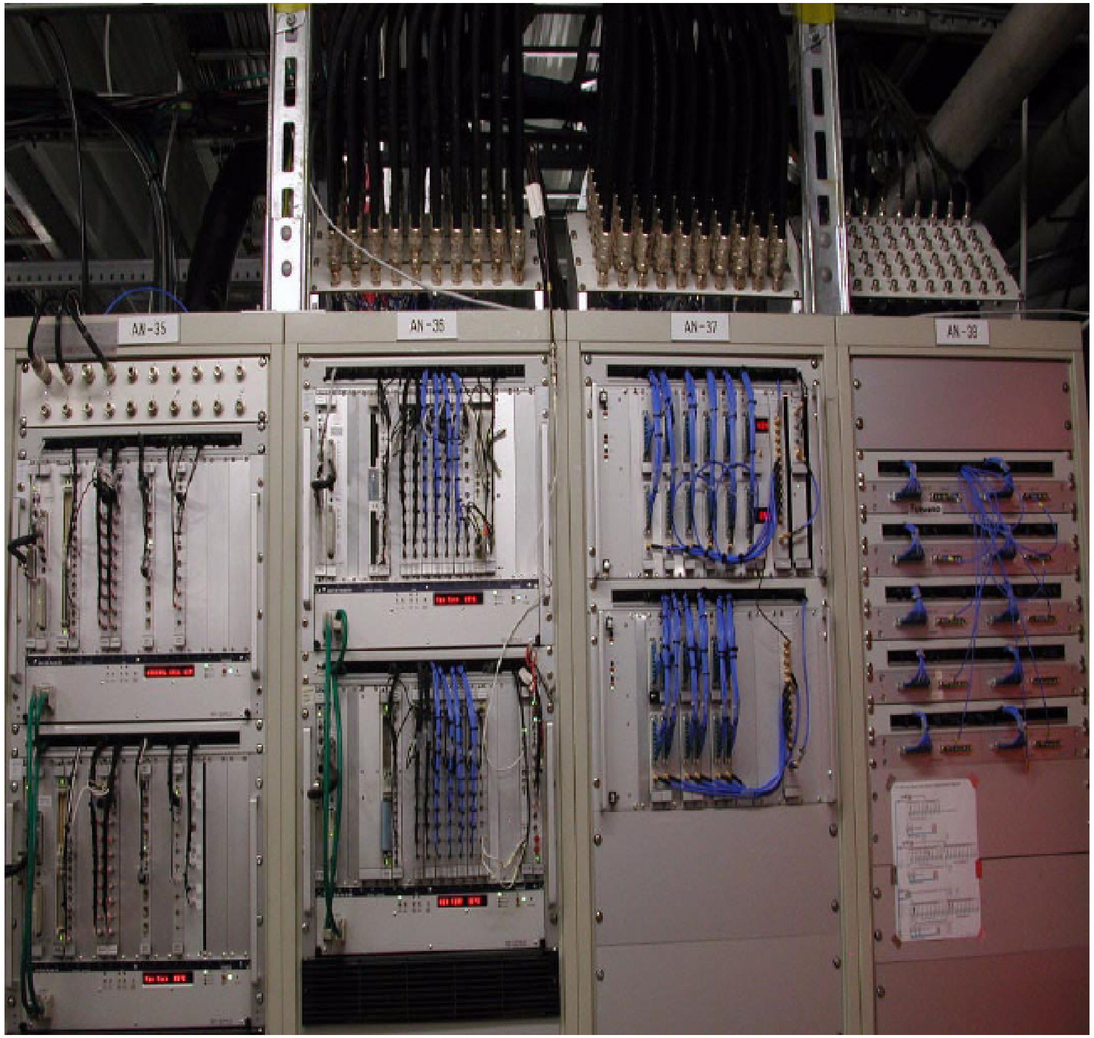


LLRF Installation at FLASH

Gun and ACC1

ACC2, ACC3, ACC4 & ACC5

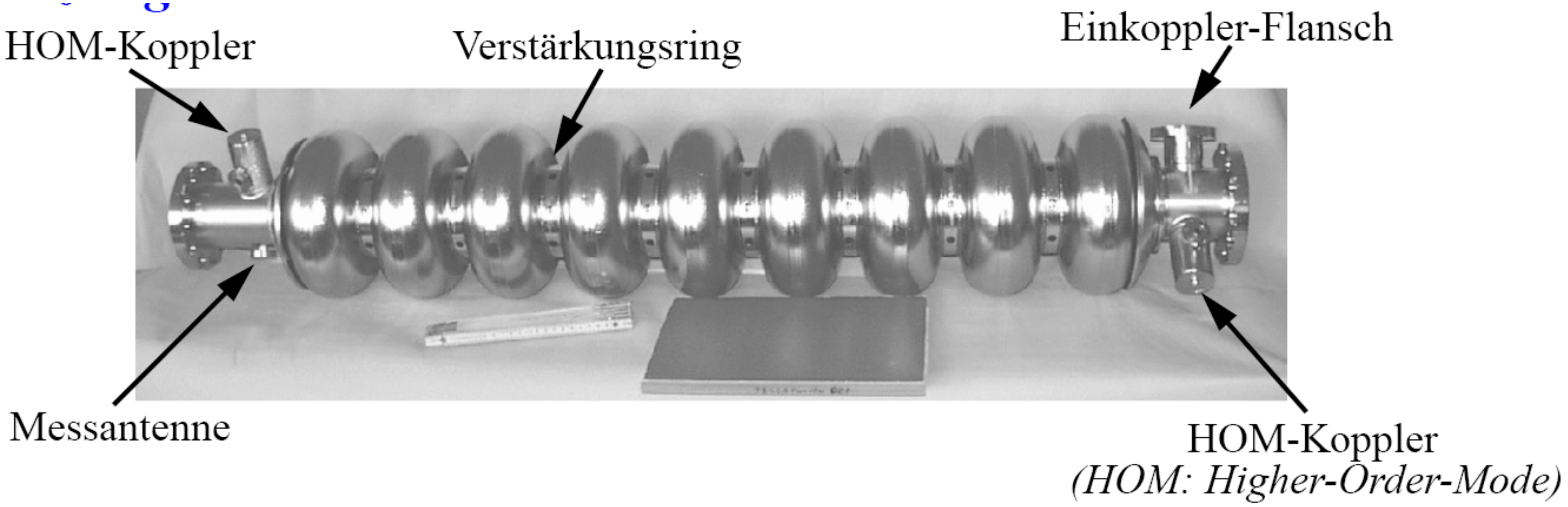




Scope of Main Linac RF

total number of klystrons / cavities per linac	~ 280/ 7,280
per rf station (klystron):	
# cavities / 10 MW klystron	~ 26
# of precision vector receivers (probe, forward, reflected power, reference line, beam)	~78
# piezo actuator drivers / motor tuners	~ 26/26
# waveguide tuner motor controllers	~ 26
# vector-modulators for klystron drive	1
Total # of meas. /control channels per linac	~22,000 / ~22,000

9-Cell Cavity



Parameter	Wert
Resonatortyp	**Stehwelle, 9 Zellen**
Beschleunigungsmode	TM_{010}
Frequenz der Beschl.-mode	**1300 MHz**
aktive Länge	**1.038 m**
$\Delta f / \Delta L$	**315 Hz / µm**
unbelastete Güte	$>10^{10}$
belastete Güte, Bandbreite	$2.5\ 10^{6}$, **260 Hz**

Why vector-sum control

Benefit :

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

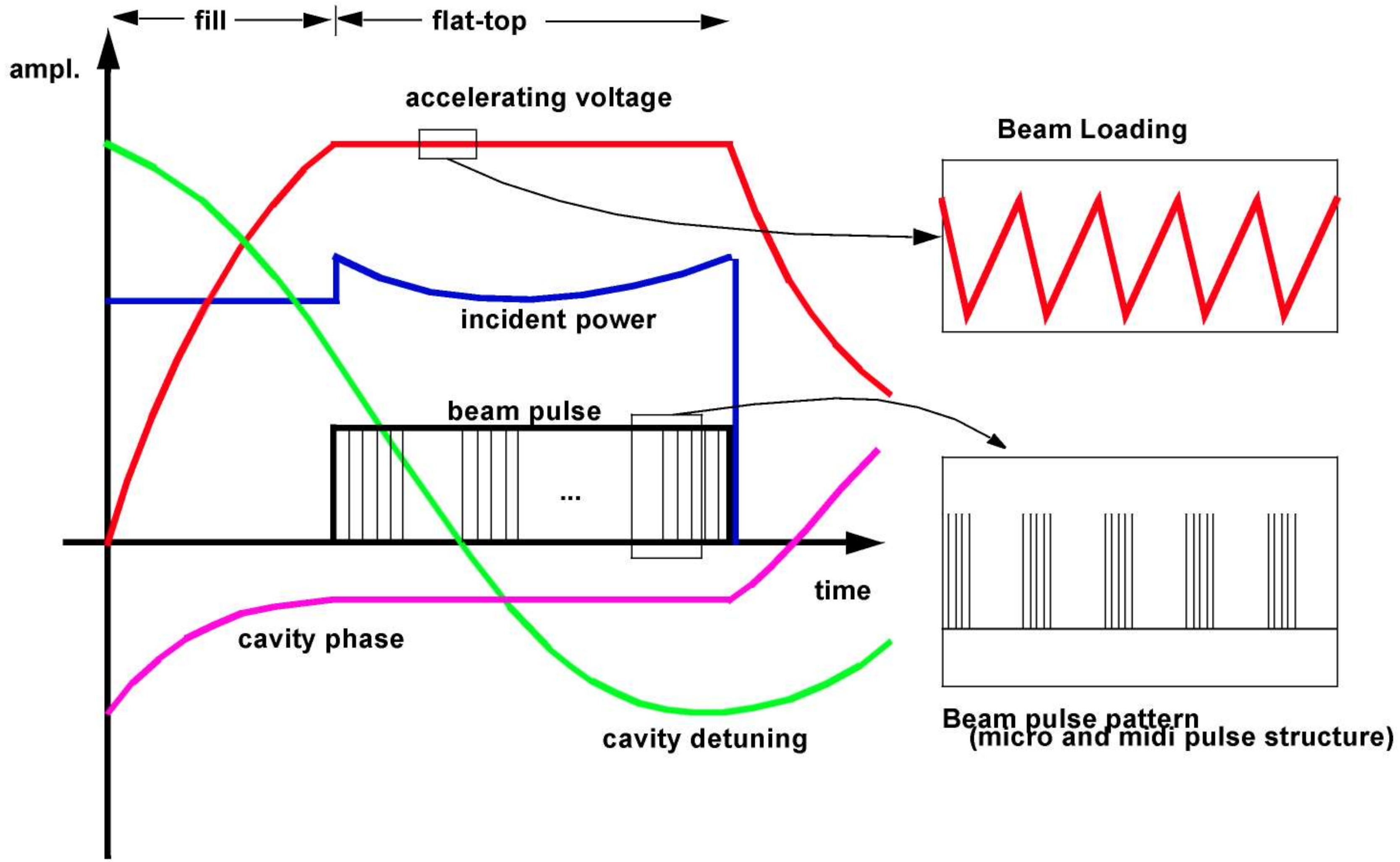
Disadvantage

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

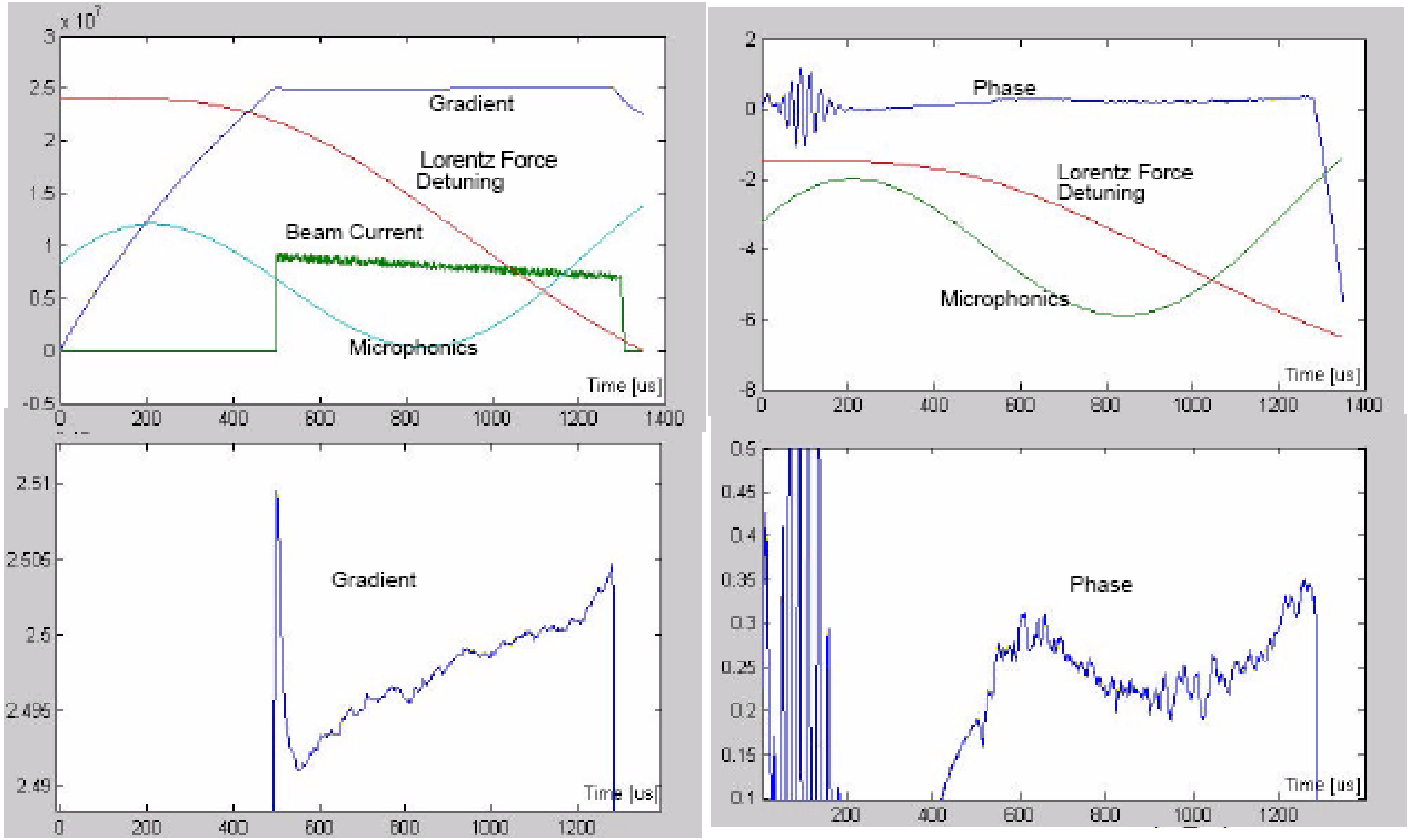
Why digital control

- 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)

Typical Parameters in Pulsed System



Cavity Field Regulation (Simulation)



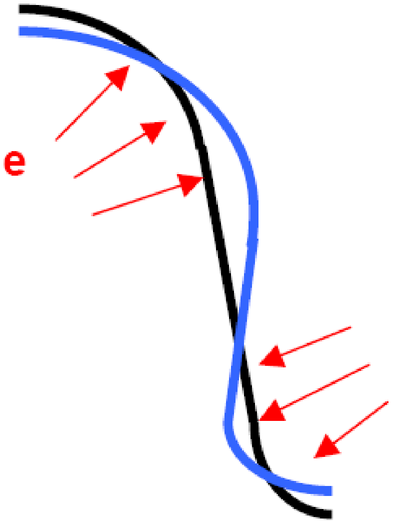
Sources of field perturbations

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 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>**Cavity drive signal**</u> - **HV- Pulse flatness** - **HV PS ripple** - **Phase noise from master oscillator** - **Timing signal jitter** - **Mismatch in power distribution**	o <u>**Other**</u> - **Response of feedback system** - **Interlock trips** - **Thermal drifts (electronics, power amplifiers, cables, power transmission system)**

Lorentz Force Detuning

- Radiation pressure : $P = (\mu_0 H^2 - \varepsilon_0 E^2)/4$

- Deformation of the cavity shape:

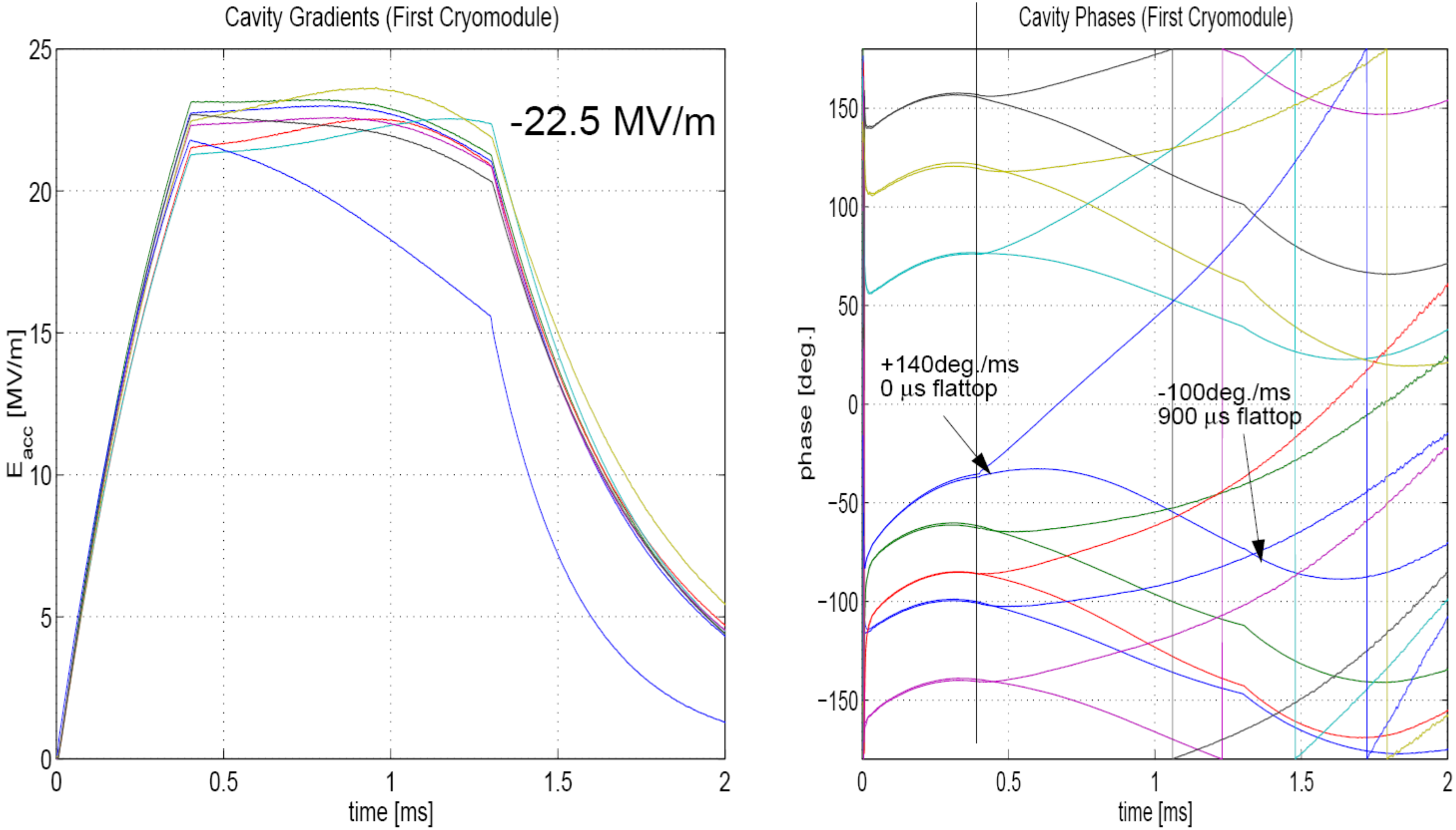


Outward pressure at the equator

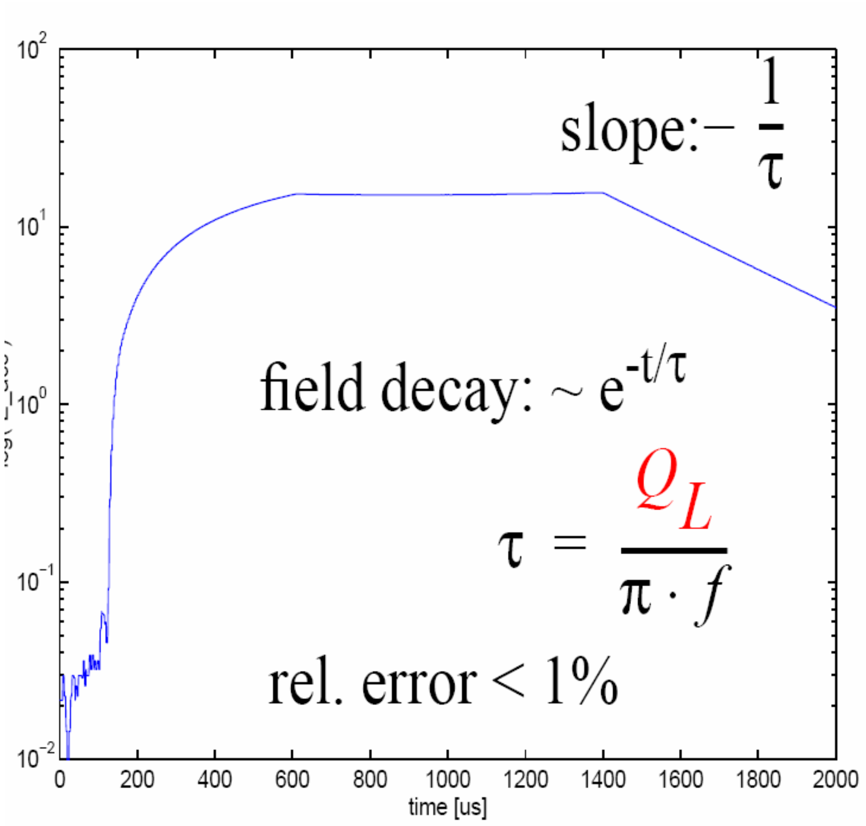
Inward pressure at the iris

- Frequency shift : $\Delta f = KL^* E^2_{acc}$

Lorentz Force Detuning



Measurement of Q_L and $\Delta\omega$



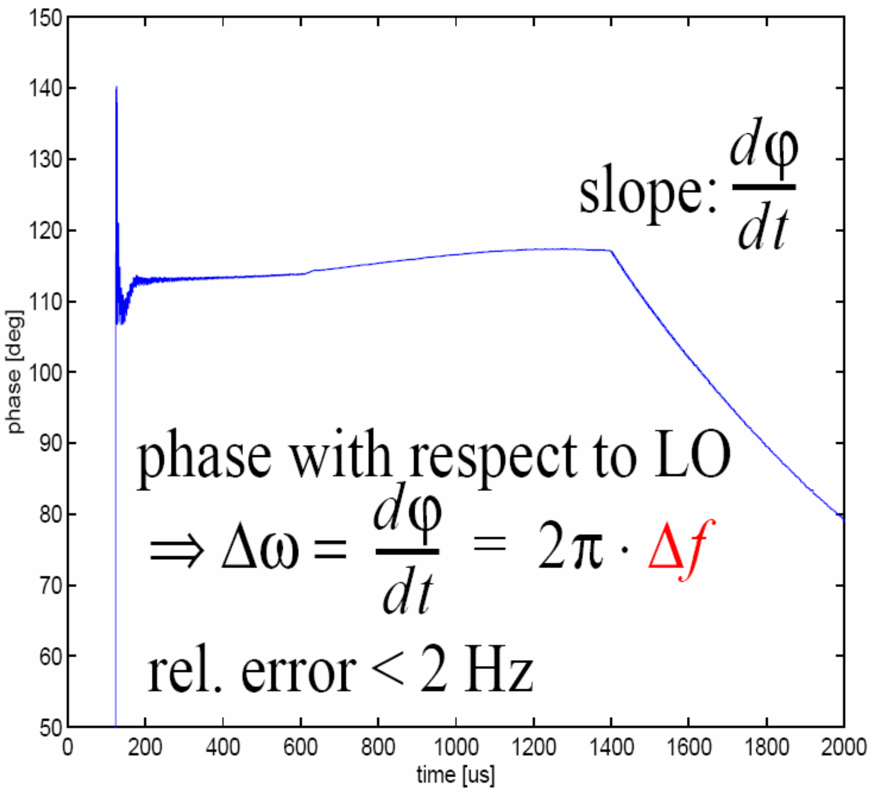
slope: $-\dfrac{1}{\tau}$

field decay: $\sim e^{-t/\tau}$

$$\tau = \frac{Q_L}{\pi \cdot f}$$

rel. error < 1%

Loaded Q



slope: $\dfrac{d\varphi}{dt}$

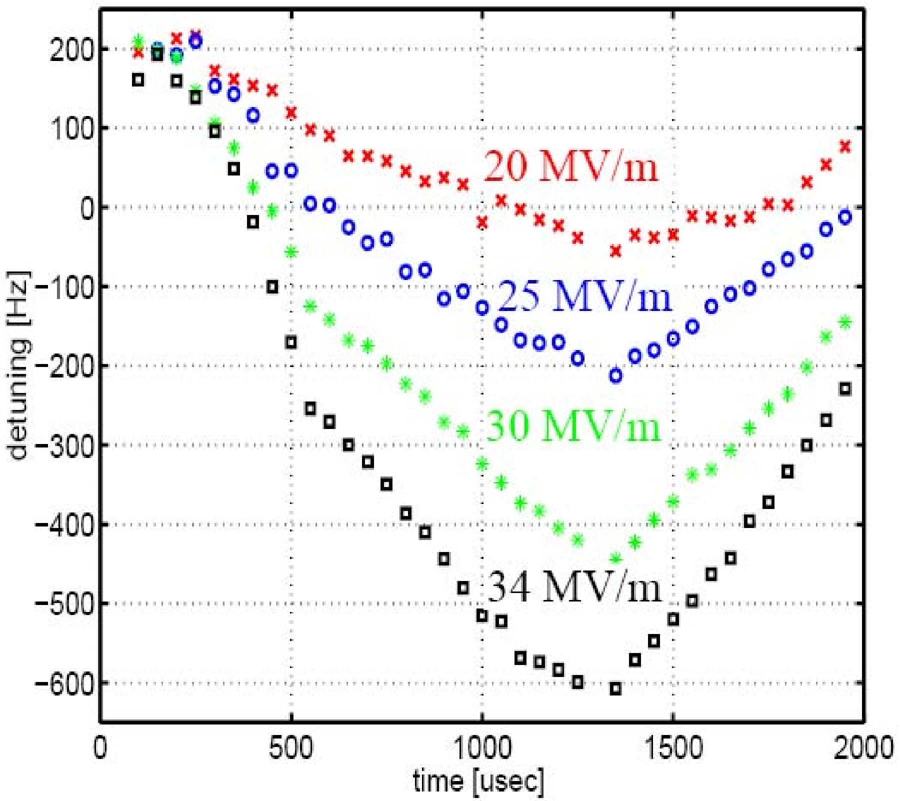
phase with respect to LO

$$\Rightarrow \Delta\omega = \frac{d\varphi}{dt} = 2\pi \cdot \Delta f$$

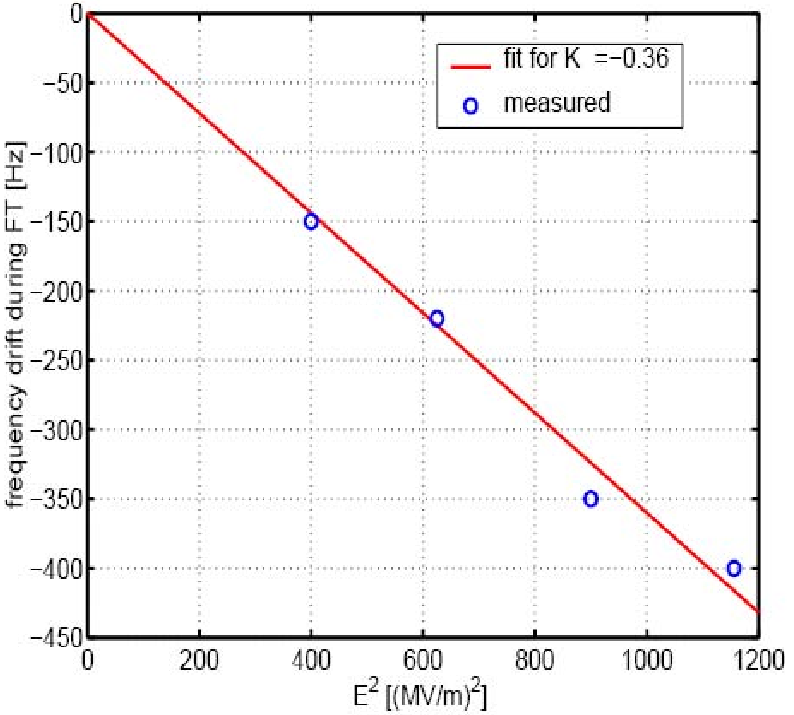
rel. error < 2 Hz

Detuning

Measurement of Lorentz Force Detuning



TESLA 9-cell cavity

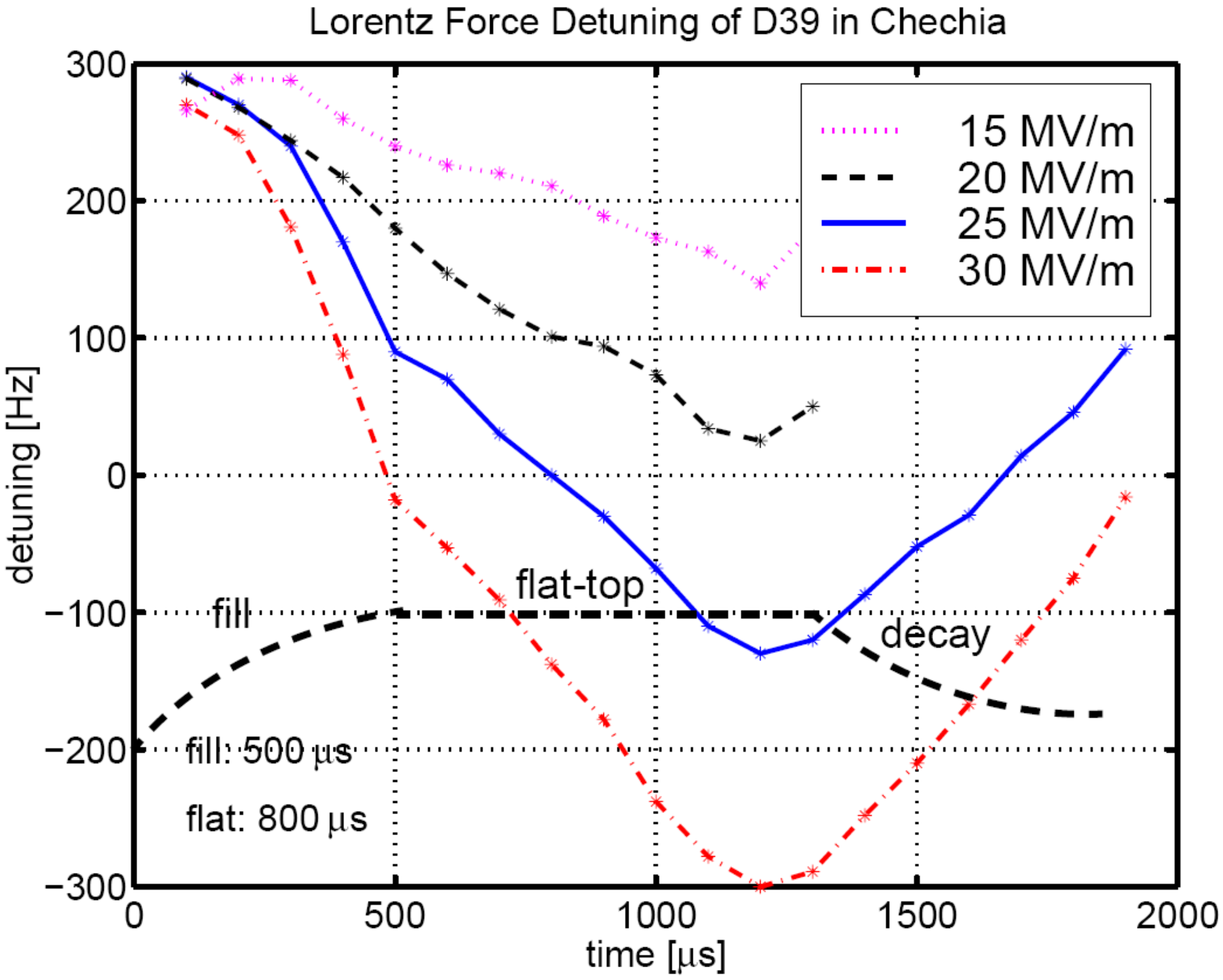


Frequency drift during 800µs flat top

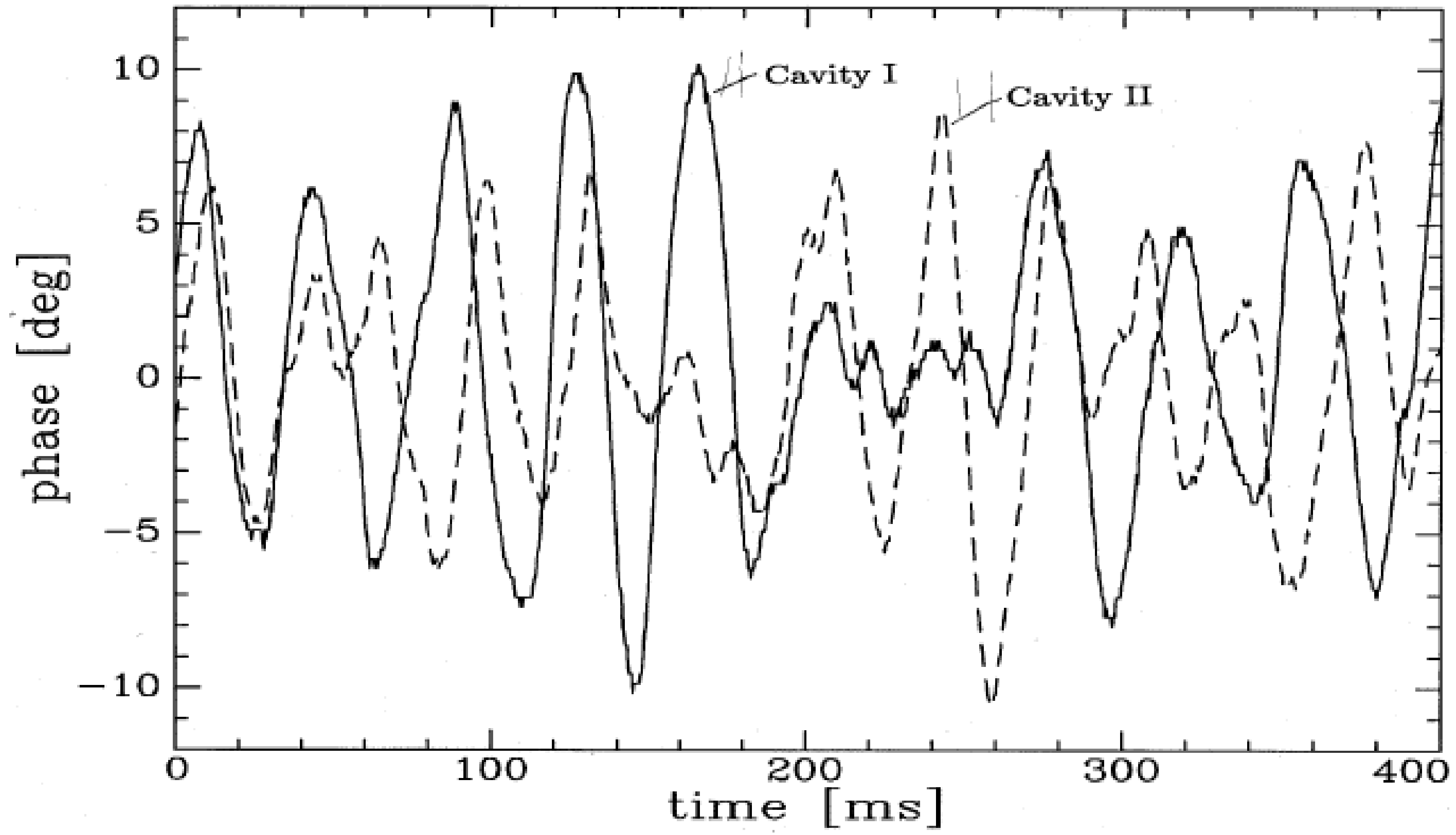
Frequency drift during 950 µs flat top (TESLA 9-cell cavity):

$$\Delta f_{FT} \approx -(0.4 \text{ to } 0.65)\frac{Hz}{MV/m^2}E_{acc}^2$$

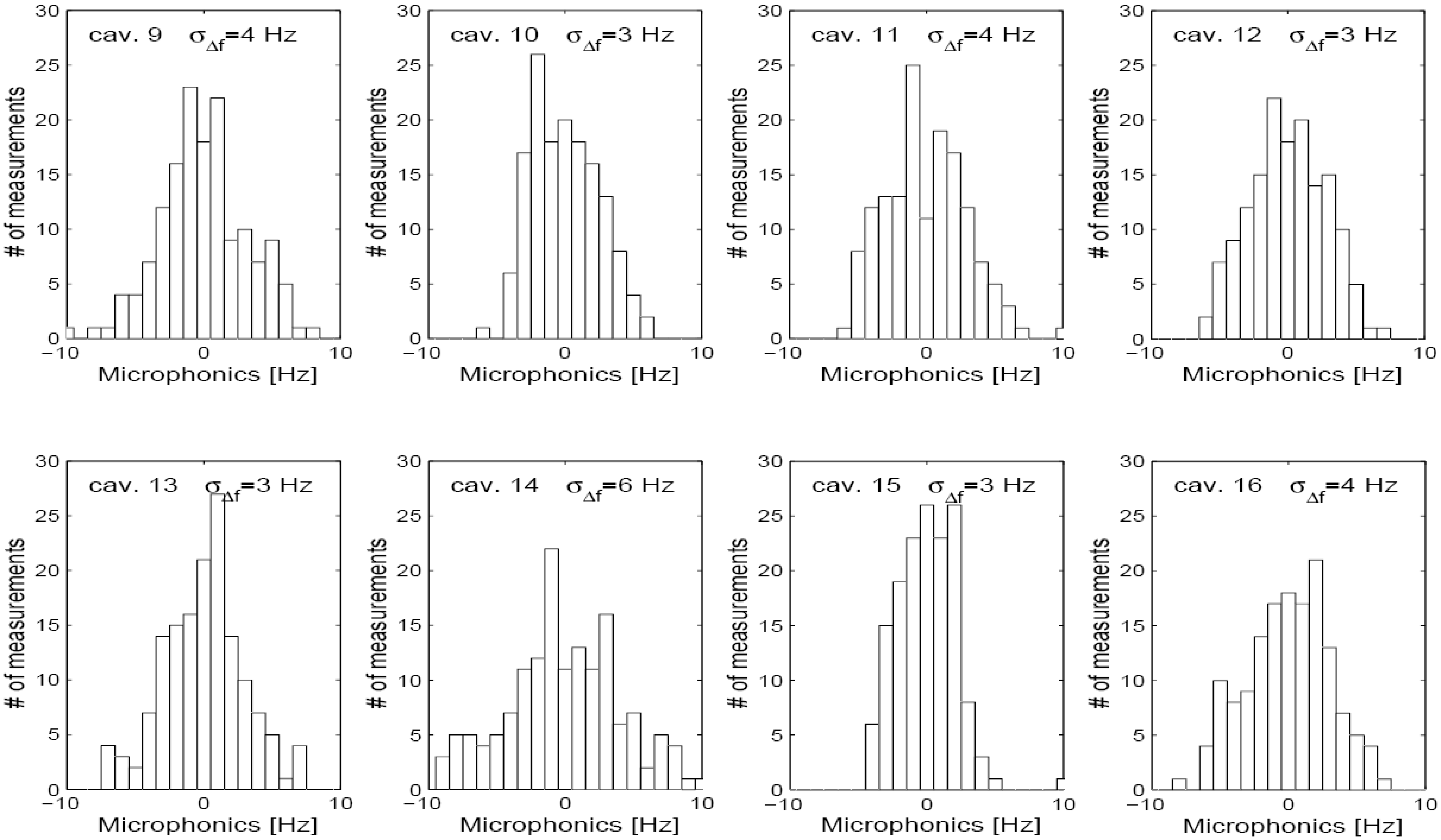
Lorentz force detuning



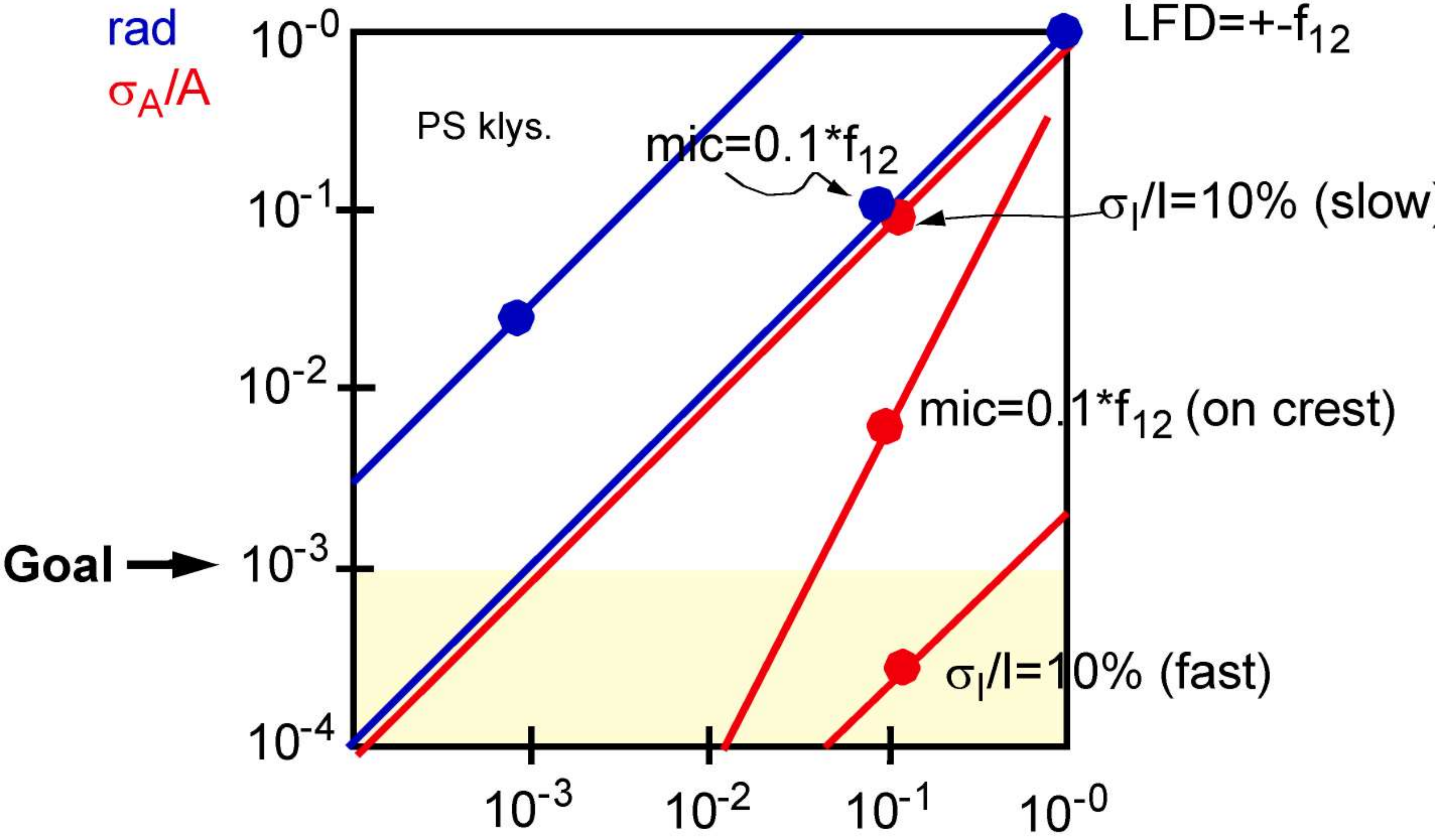
Microphonics at JLAB



Microphonics at FLASH



Error Map


rad
σ_A/A
10^{-0}
10^{-1}
10^{-2}
Goal
10^{-3}
10^{-4}
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}

LLRF System Requirements

- Maintain Phase and Amplitude of the accelerating field within given tolerances to accelerate a charged particle beam to given parameters
    - up to 0.07% for amplitude and 0.24 deg. for phase

- 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

LLRF Requirements (C'tnd)

- **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 errors

Requirements for Main Linac

- LLRF stability requirements (@ ML and BC) are < 0.07%, and 0.24deg. respectively
- In order to satisfy these requirements, feedback (FB) with proper feedforward (FF) control will be carried out.

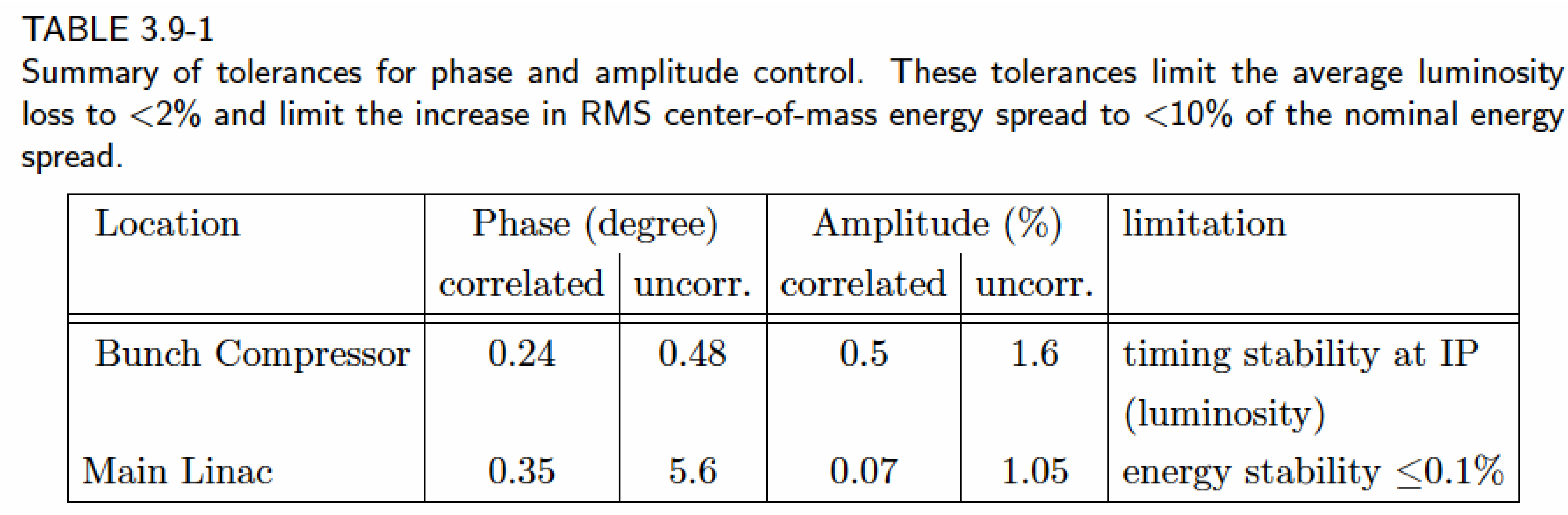


TABLE 3.9-1

Summary of tolerances for phase and amplitude control. These tolerances limit the average luminosity loss to <2% and limit the increase in RMS center-of-mass energy spread to <10% of the nominal energy spread.

Location	Phase (degree)		Amplitude (%)		limitation
	correlated	uncorr.	correlated	uncorr.	
Bunch Compressor	0.24	0.48	0.5	1.6	timing stability at IP (luminosity)
Main Linac	0.35	5.6	0.07	1.05	energy stability $\leq 0.1\%$

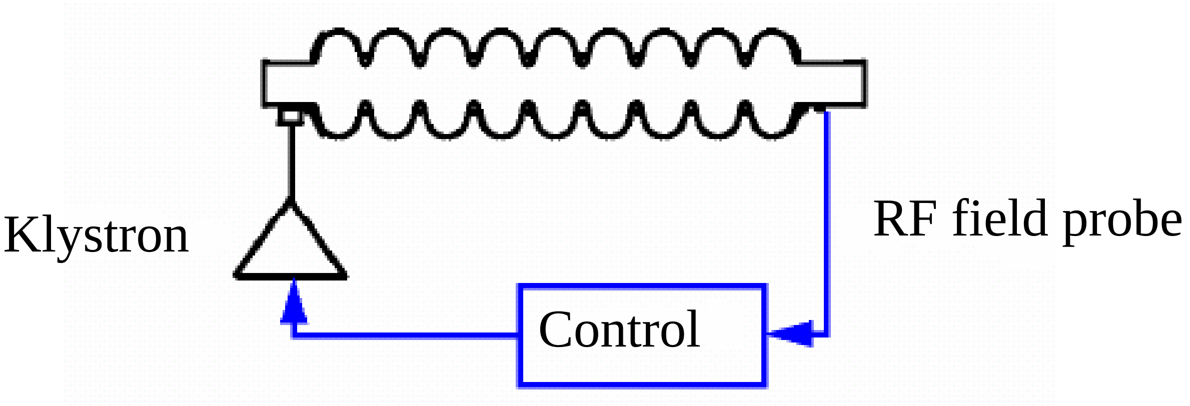
Requirements

- **Reliability**
  - not more than 1 LLRF system failure / week
  - minimize LLRF induced accelerator downtime
  - Redundancy of LLRF subsystems
  - ...
- **Operability**
  - “One Button” operation (State Machine)
  - Momentum Management system
  - Automated calibration of vector-sum
  - ...
- **Reproducible**
  - Restore beam parameters after shutdown or interlock trip
  - Recover LLRF state after maintenance work
  - ...

Requirements

- **Maintainable**
  - Remote diagnostics of subsystem failure
  - "Hot Swap" Capability
  - Accessible Hardware
  - ...
- **Well Understood**
  - Performance limitations of LLRF fully modelled
  - No unexpected "features"
  - ...
- **Meet (technical) performance goals**
  - Maintain accelerating fields - defined as vector-sum of 24 cavities - within given tolerances
  - Minimize peak power requirements
  - ...

The Simple Picture: LLRF Control

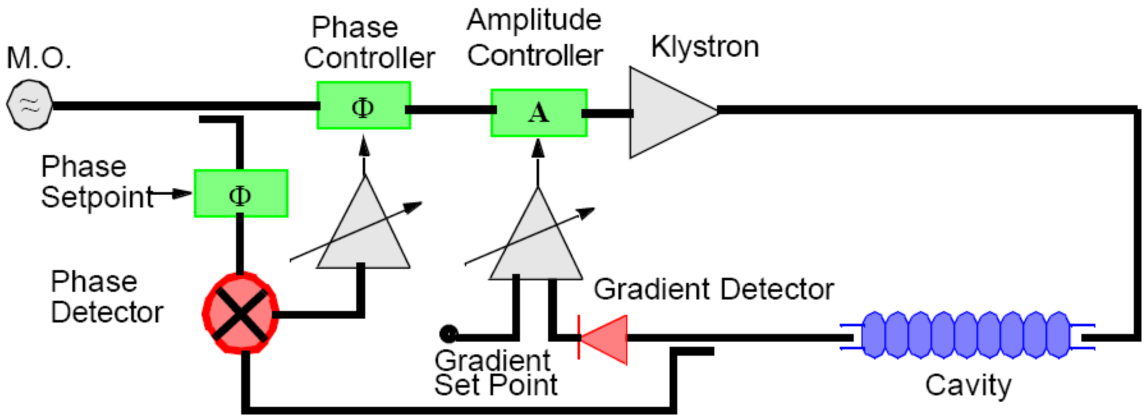


- Measure cavity RF field
- Derive new klystron drive signal to stabilize the cavity RF Field

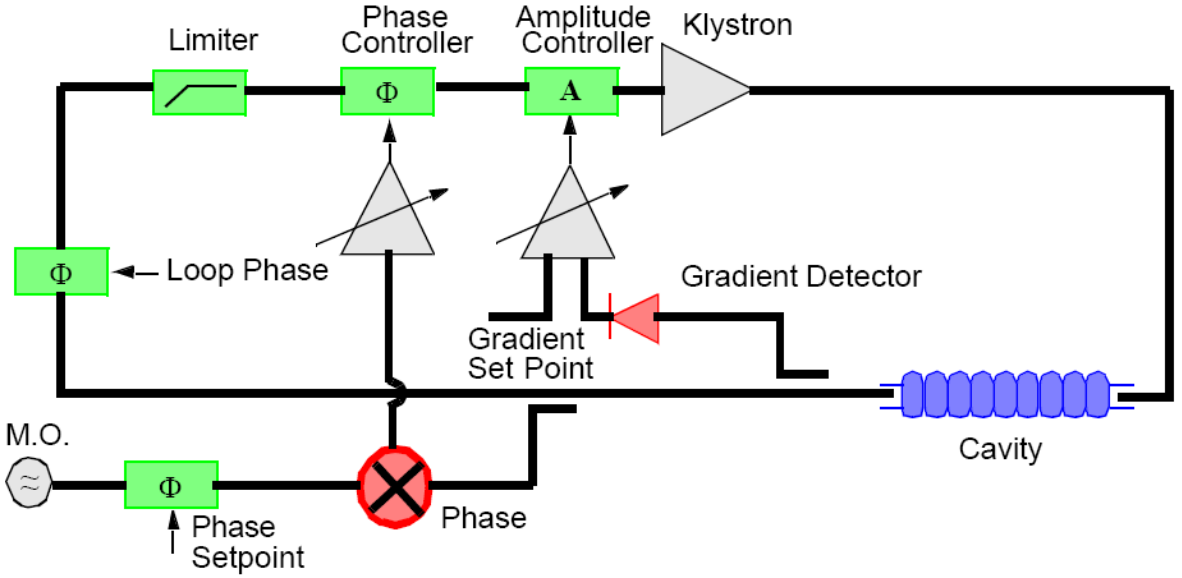
Control Choices (1)

- 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)

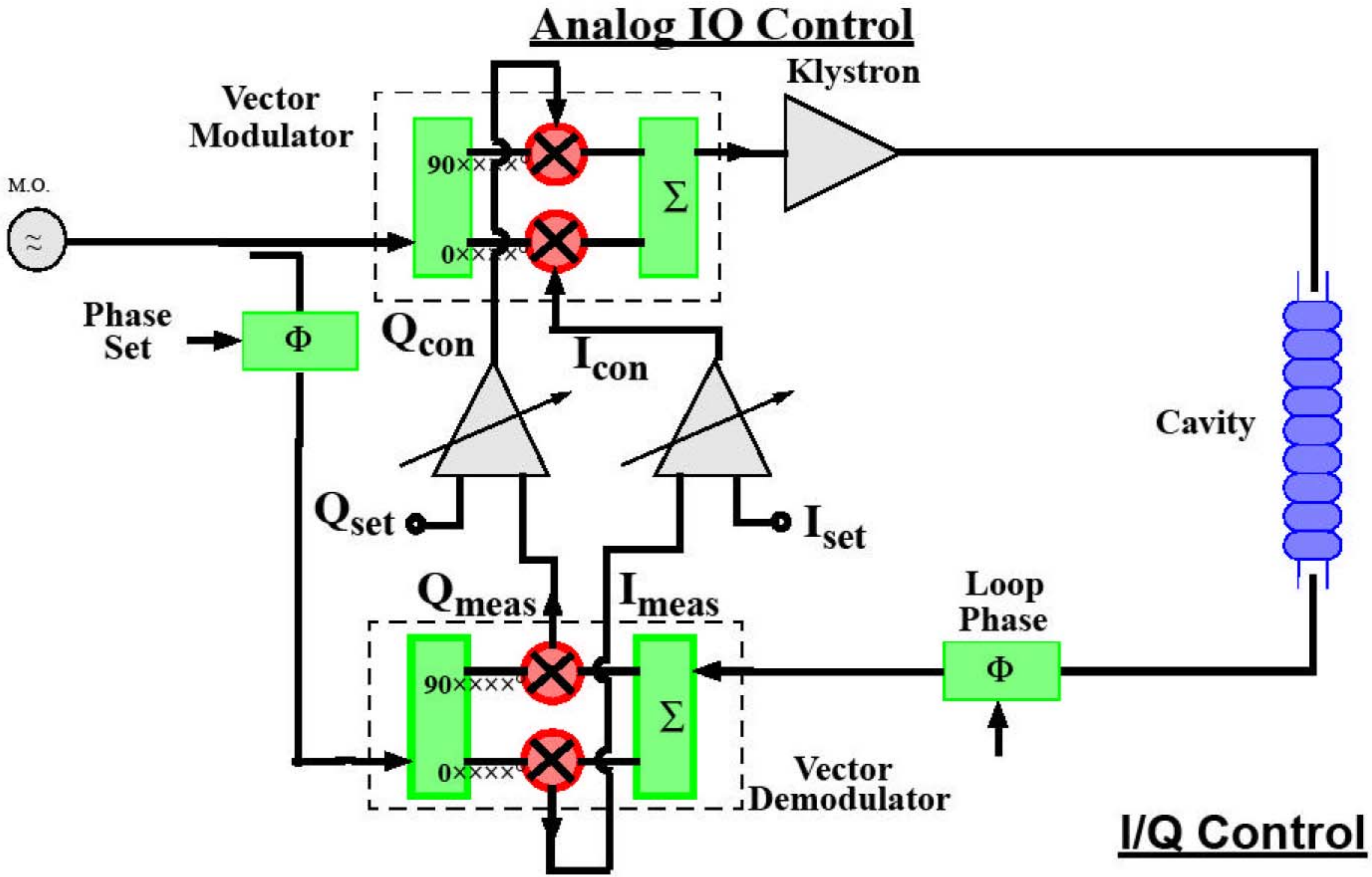


Generator Driven Resonator

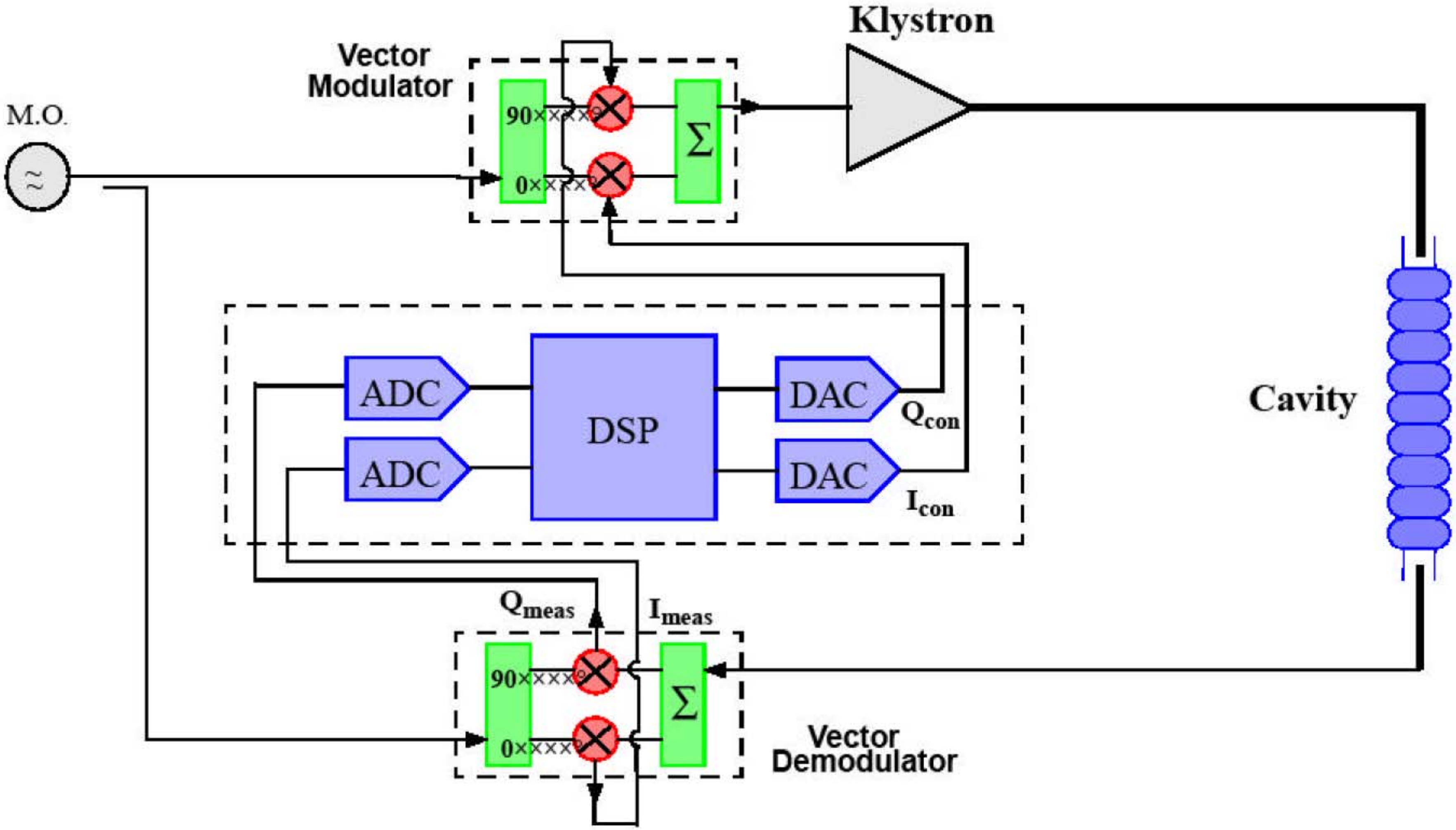


Self Excited Loop

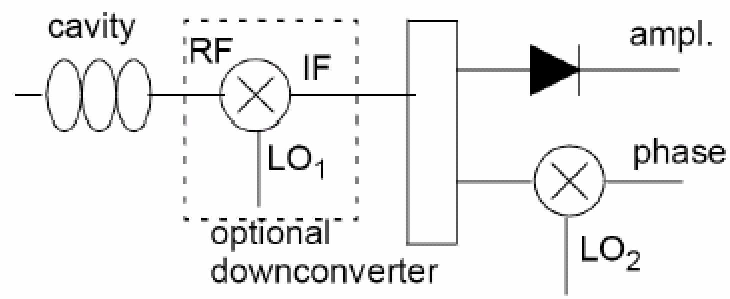
Analog IQ Control



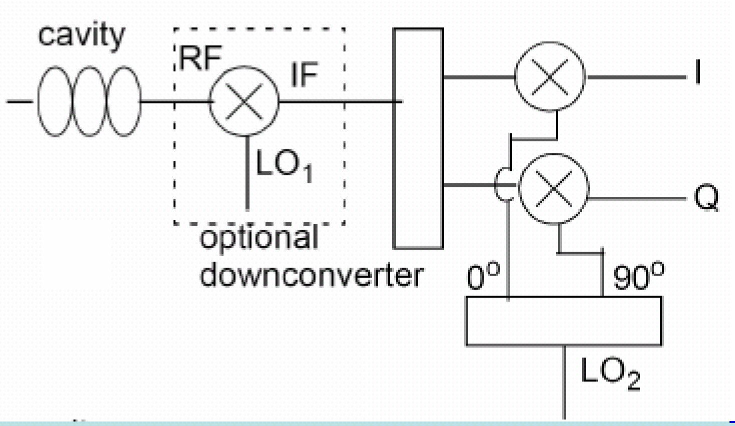
Digital IQ Control



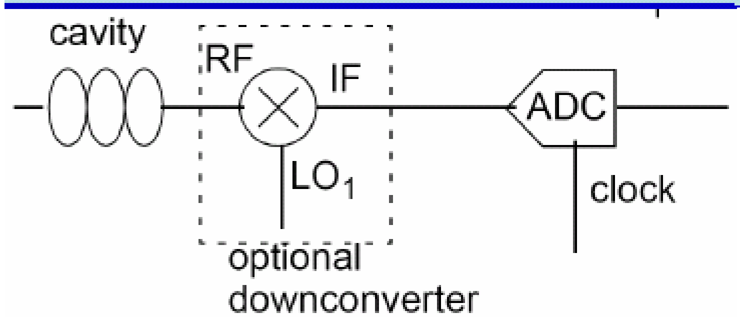
Design Choices: Field Detectors



- Traditional amplitude and phase detection
- Works well for small phase errors

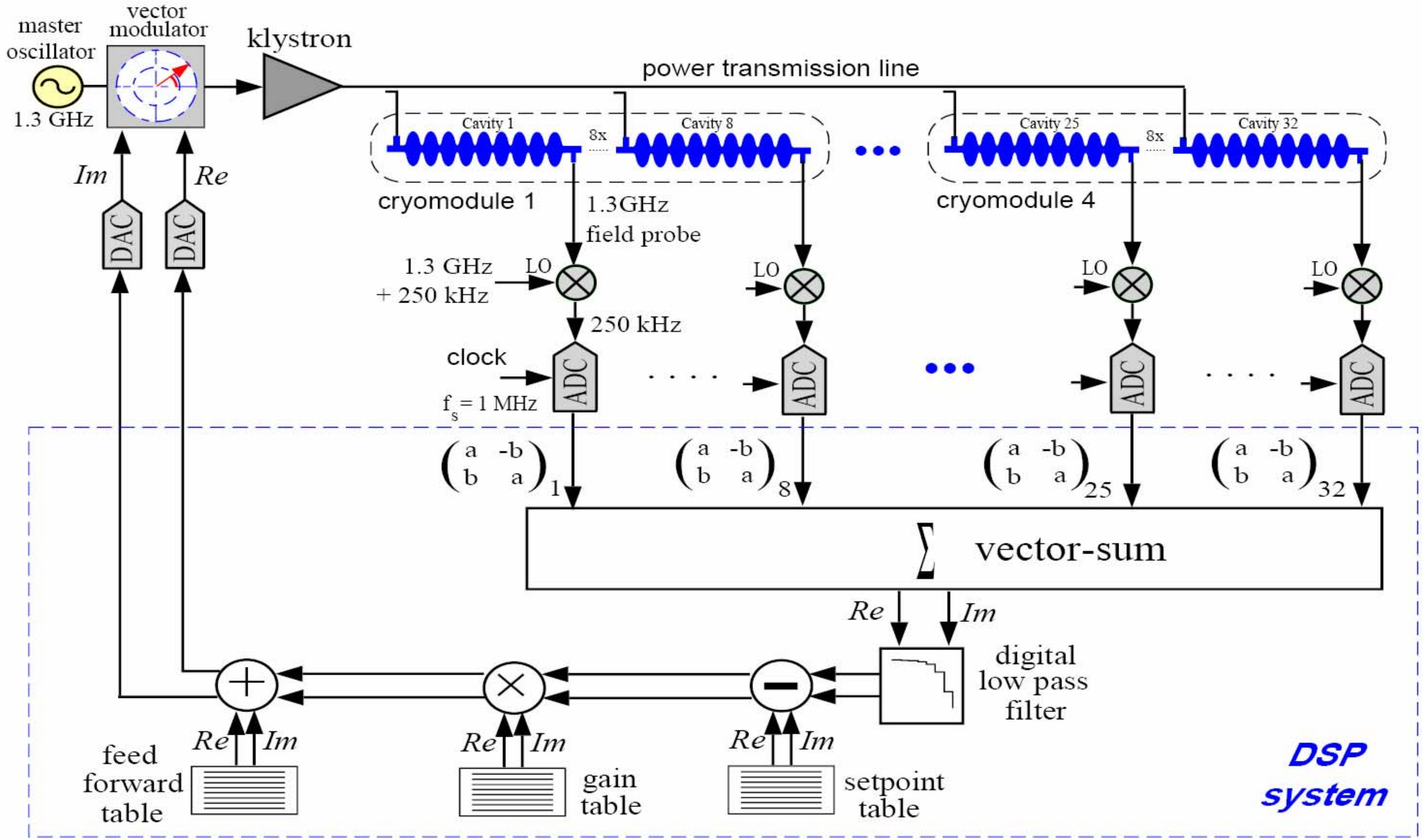


- I /Q detection: real and imaginary part of the complex field vector
- Preferable in presence of large field errors

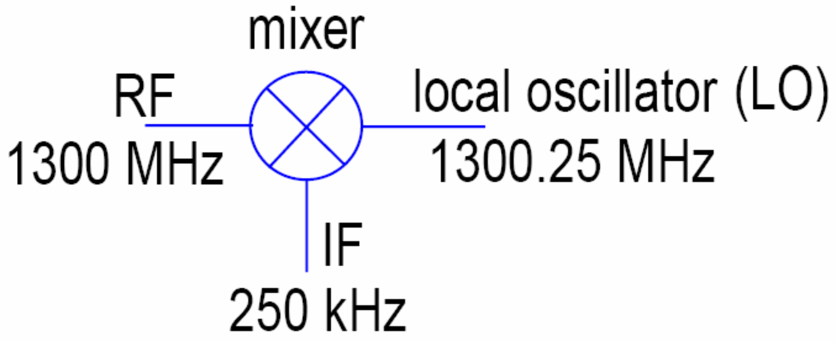


- Digital I / Q detection
- Alternating sample give I and Q component of the cavity field

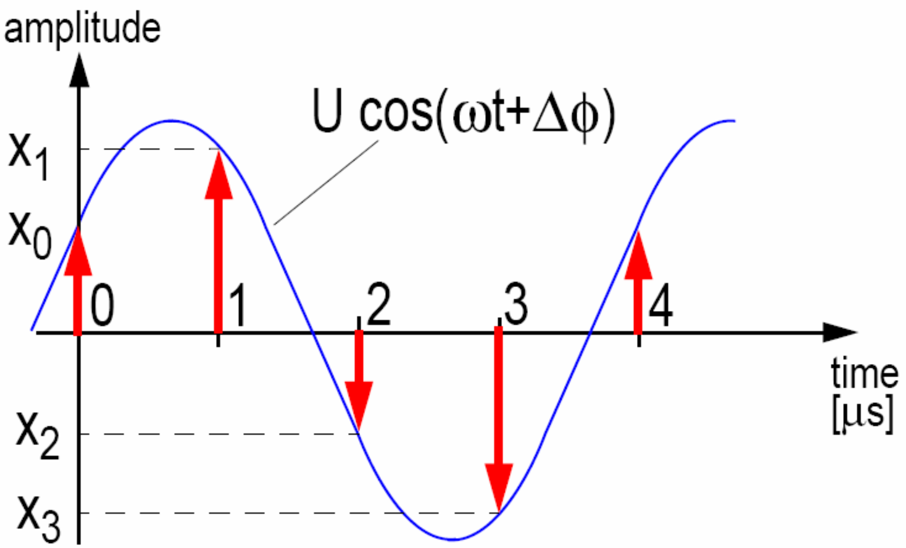
Digital RF Control at FLASH



Digital field detection



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

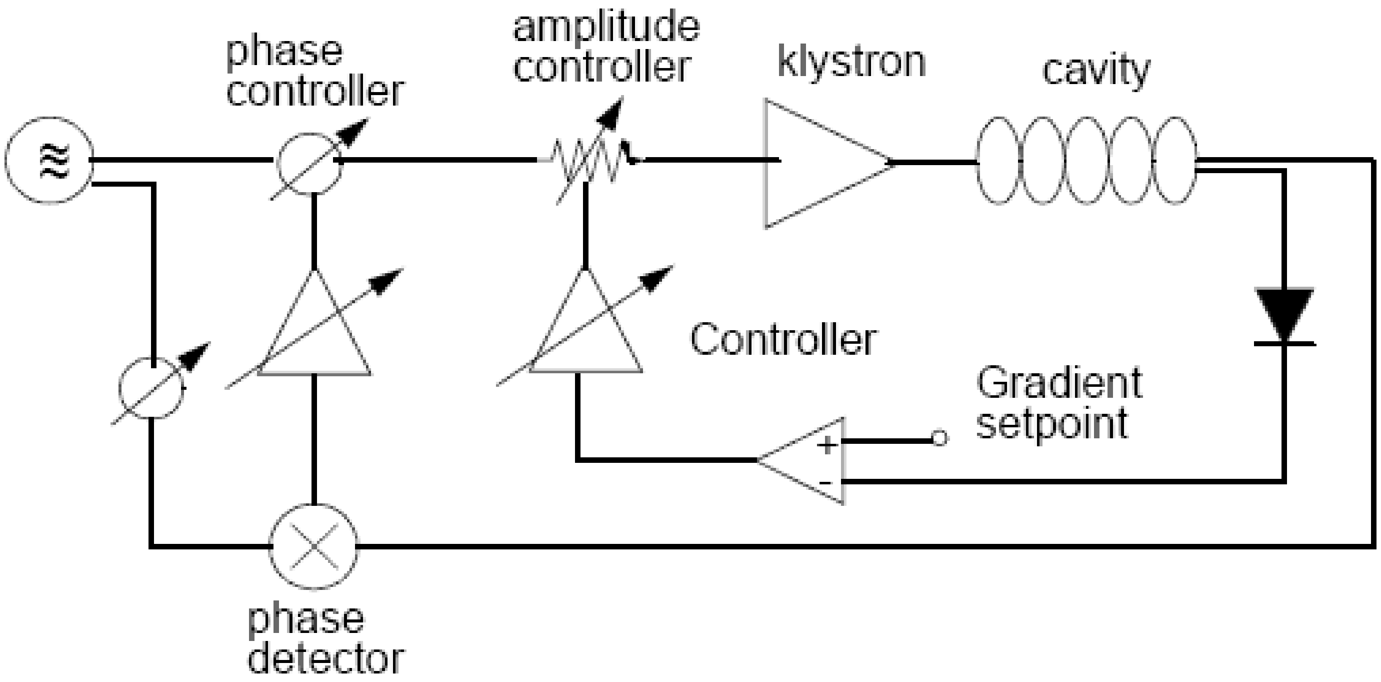


- sample IF signal at 1MHz rate
- subsequent samples describe real and imaginary component of the cavity field.

RF Control Model

Goal:
Maintain stable gradient and phase

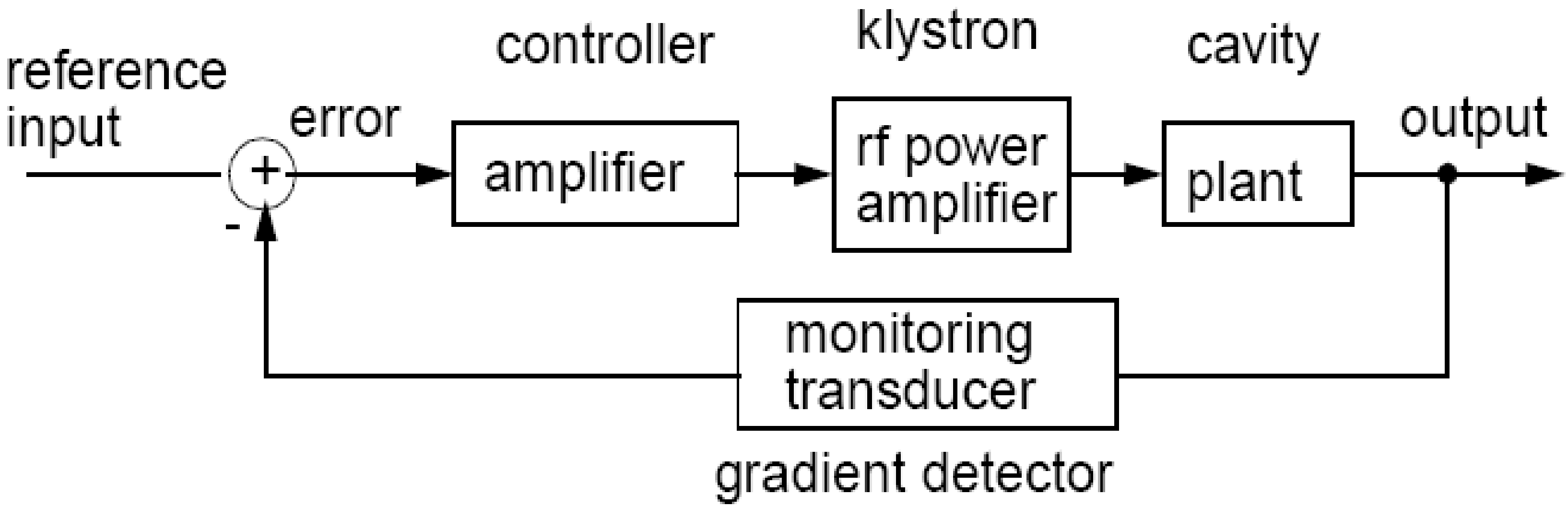
Solution:
Feedback for gradient amplitude and phase:



RF Control Model

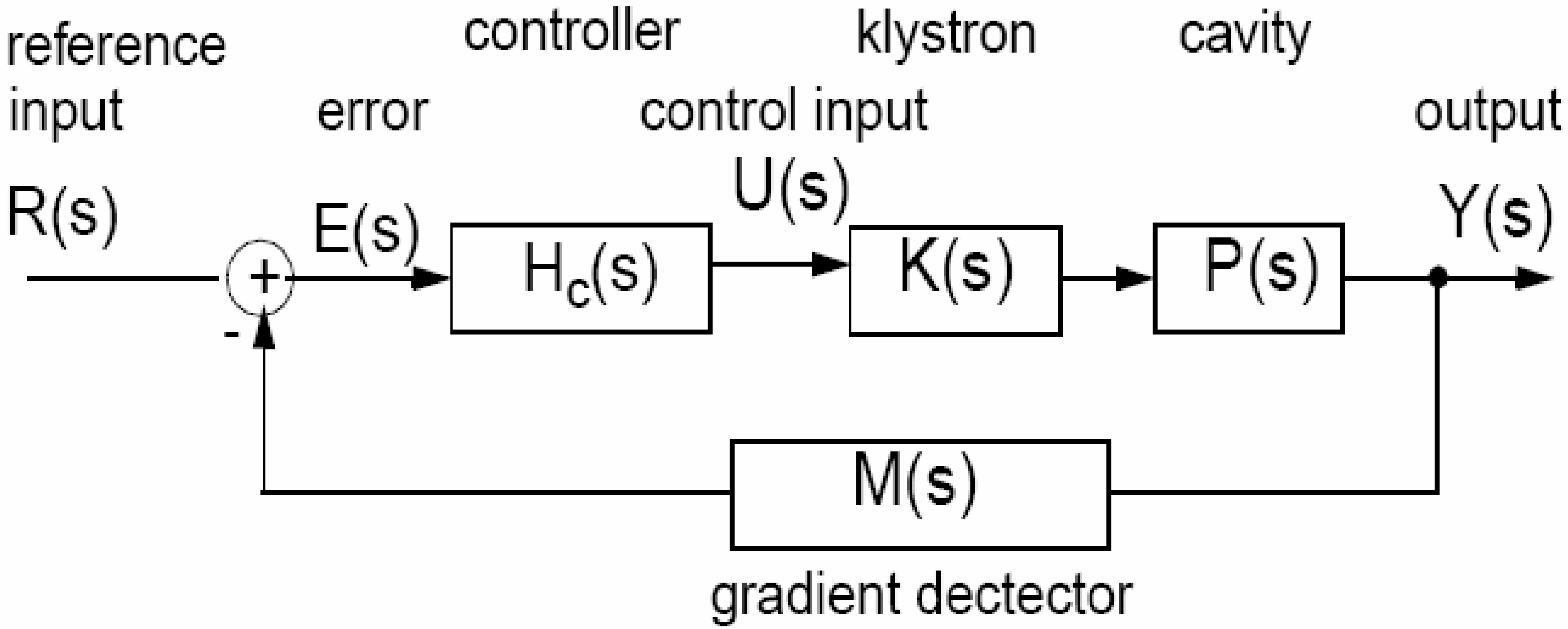
Model:
Mathematical description of input-output relation of components combined with block diagram:

Amplitude Loop (general form):

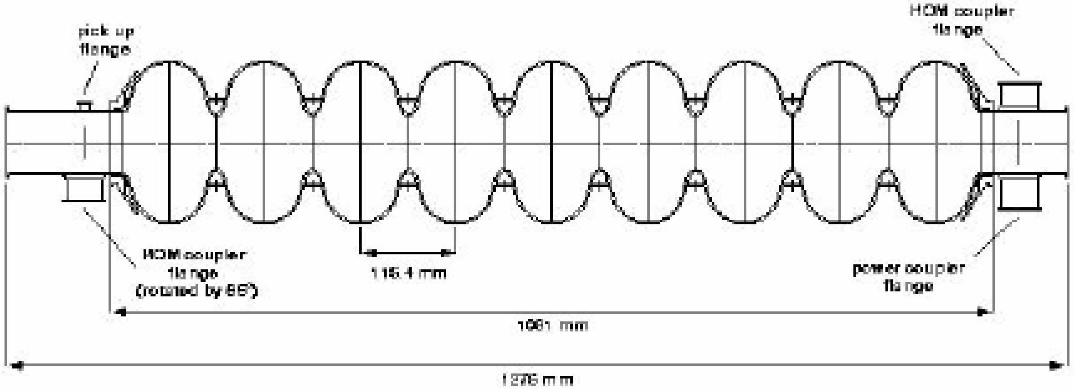


RF Control Model

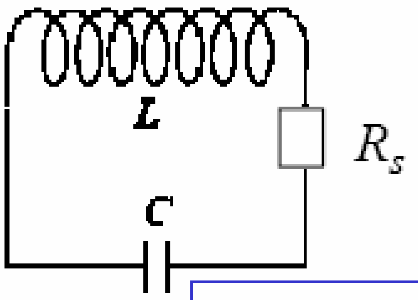
RF Control model using "transfer functions"



Cavity Model

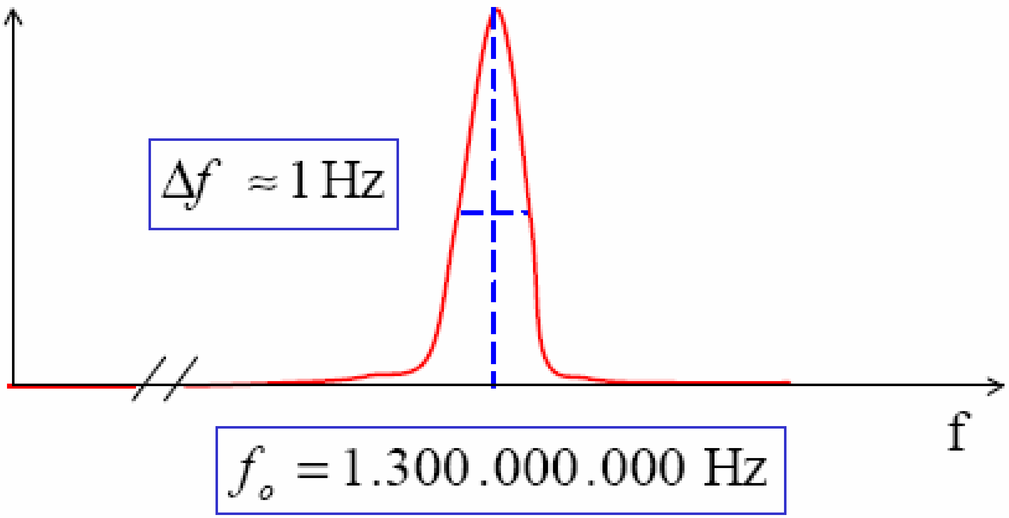


Schwingkreis:



Frequenz: $f_o = \dfrac{1}{2\pi\sqrt{LC}}$

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

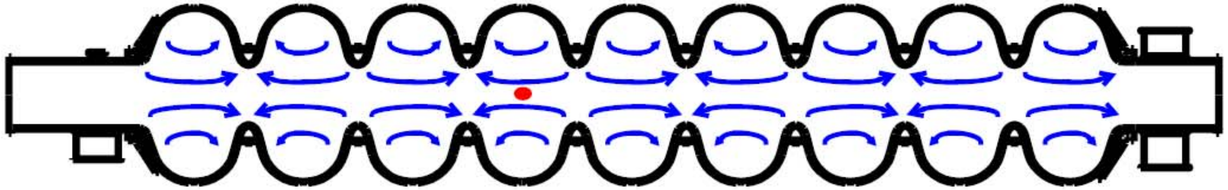


$\Delta f \approx 1\,\mathrm{Hz}$

$f_o = 1.300.000.000\ \mathrm{Hz}$

$\Rightarrow$ Q0 $\approx 10^{9}$ -10^{10}

Principle of Acceleration



Beschleunigungsspannung:

$$V_{acc} = \frac{\text{maximaler Energiegewinn}}{\text{Ladung}} = \left| \int_{-L/2}^{L/2} E_z e^{i\omega(z/c)} dz \right|$$

Shunt-Impedanz:

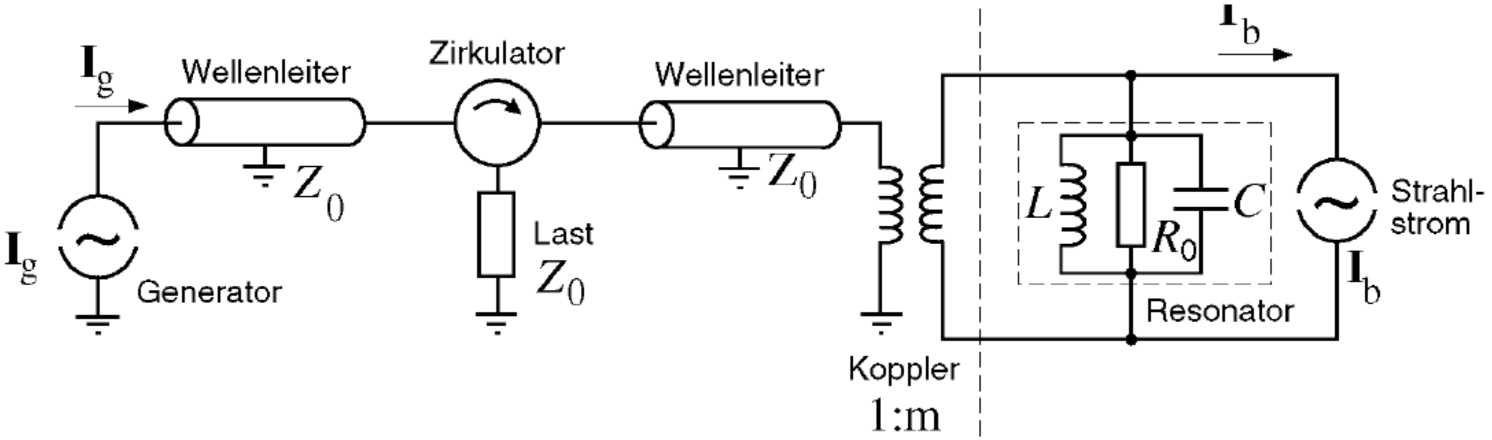
$$R_{\text{sh}} = \frac{(V_{acc})^2}{2P_{\text{Wand}}}$$

Unbelastete Güte:

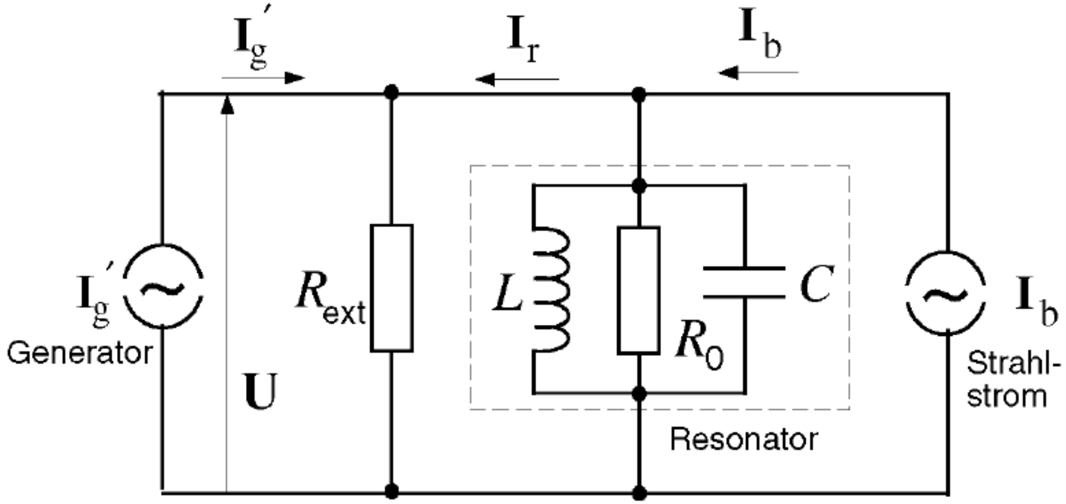
$$Q_0 = \frac{\omega W}{P_{\text{Wand}}}$$

$$\left(\frac{R_{\text{sh}}}{Q_0}\right) = \frac{(V_{acc})^2}{2\omega W} = 518\ \Omega$$

Cavity Model



Equivalent circuits



Cavity Model

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

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

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

Reduction to model for envelope

Only envelope of rf (real and imaginary part) is of interest:

$$\begin{aligned}
\mathbf{U}(t) &= (U_r(t) + iU_i(t)) \cdot \exp(i\omega_{HF}t) \\
\mathbf{I}_g(t) &= (I_{gr}(t) + iI_{gi}(t)) \cdot \exp(i\omega_{HF}t) \\
\mathbf{I}_b(t) &= (I_{b\omega r}(t) + iI_{b\omega i}(t)) \cdot \exp(i\omega_{HF}t) = 2(I_{b0r}(t) + iI_{b0i}(t)) \cdot \exp(i\omega_{HF}t)
\end{aligned}$$

Envelope equations for real and imaginary component

$$\begin{aligned}
\dot{U}_r(t) + \omega_{1/2} \cdot U_r + \Delta\omega \cdot U_i &= \omega_{HF}\left(\frac{r}{Q}\right) \cdot \left(\frac{1}{m} I_{gr} + I_{b0r}\right) \\
\dot{U}_i(t) + \omega_{1/2} \cdot U_i - \Delta\omega \cdot U_r &= \omega_{HF}\left(\frac{r}{Q}\right) \cdot \left(\frac{1}{m} I_{gi} + I_{b0i}\right)
\end{aligned}$$

Cavity Model

- 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 $\omega_{1/2} = \frac{\omega_{rf}}{2Q}$ 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

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

Cavity Model Discrete

- Discrete Model

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

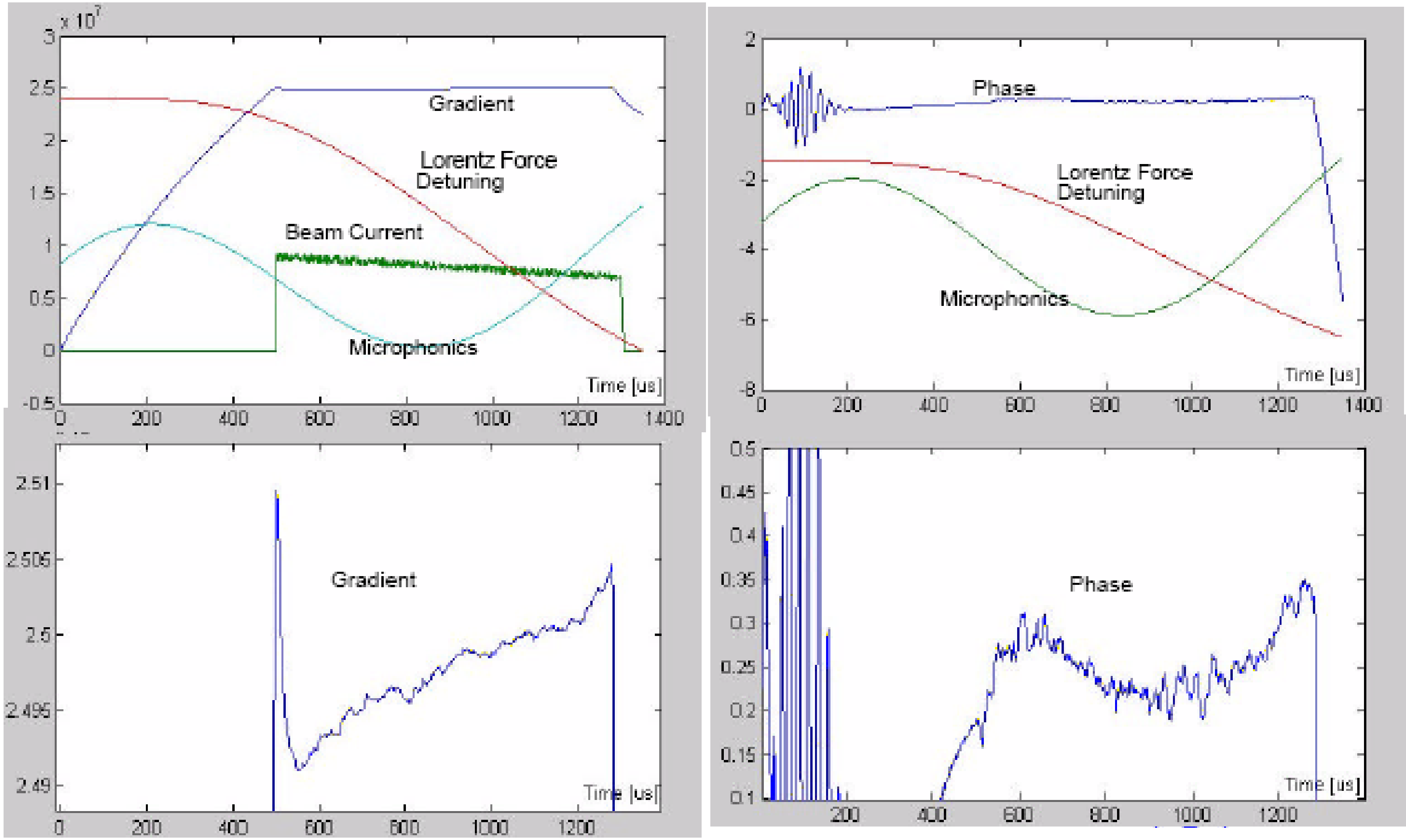
where $A_d = e^{AT_s}$ $\quad B_d = \int_0^{T_s} e^{A\tau} B d\tau$ $\quad C_d = C$ $\quad D_d = D$

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

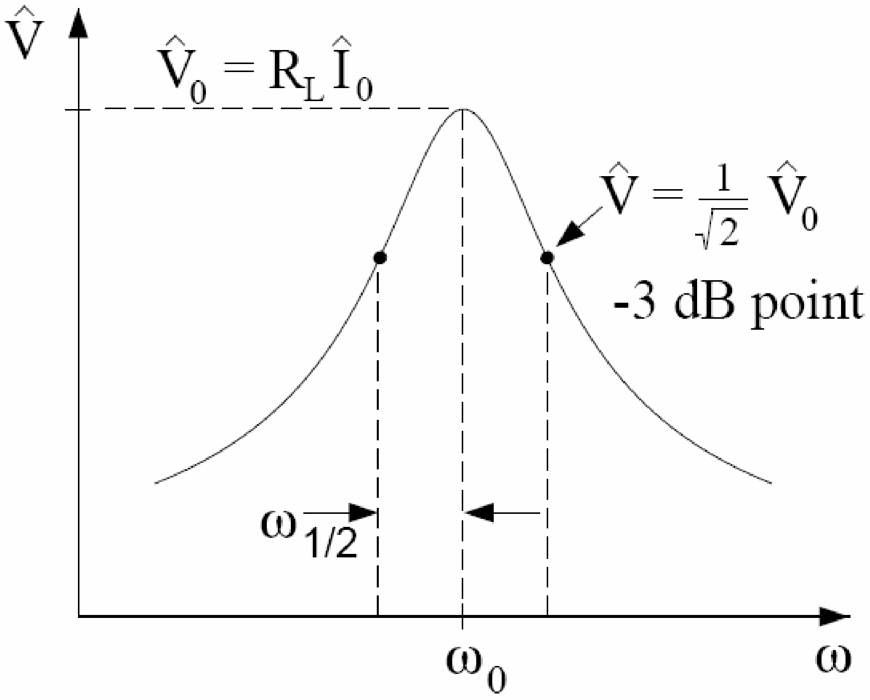
$$B_d = \quad \ldots\ldots \quad \approx \begin{bmatrix} \omega_{1/2} T_s & \Delta\omega\omega_{1/2} T_s^2/2 \\ \Delta\omega\omega_{1/2} T_s^2/2 & \omega_{1/2} T_s \end{bmatrix}$$

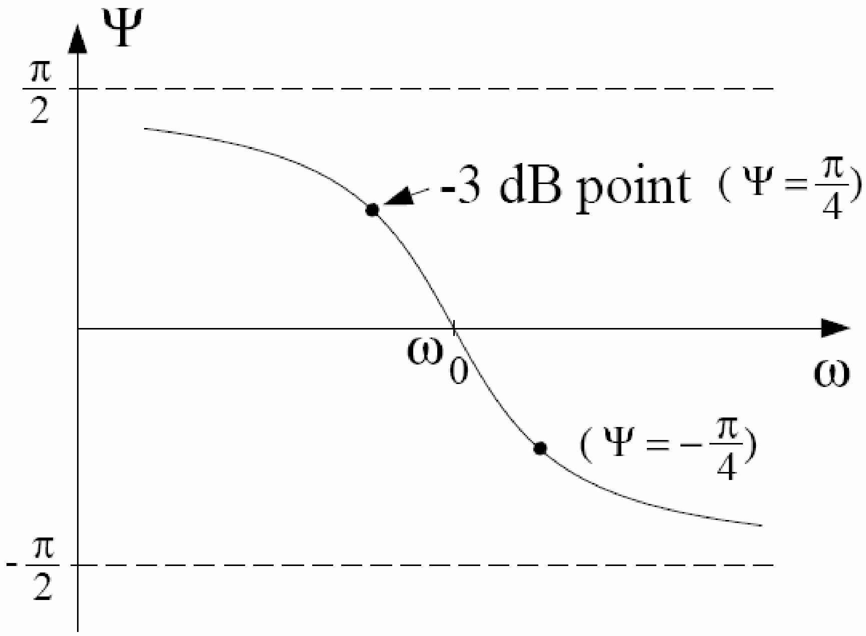
with solution
$$x(k) = A^k \cdot x(0) + \sum_{i=1}^{k} A^{i-1} \cdot B \cdot u(k-i)$$

Cavity Field Regulation (Simulation)



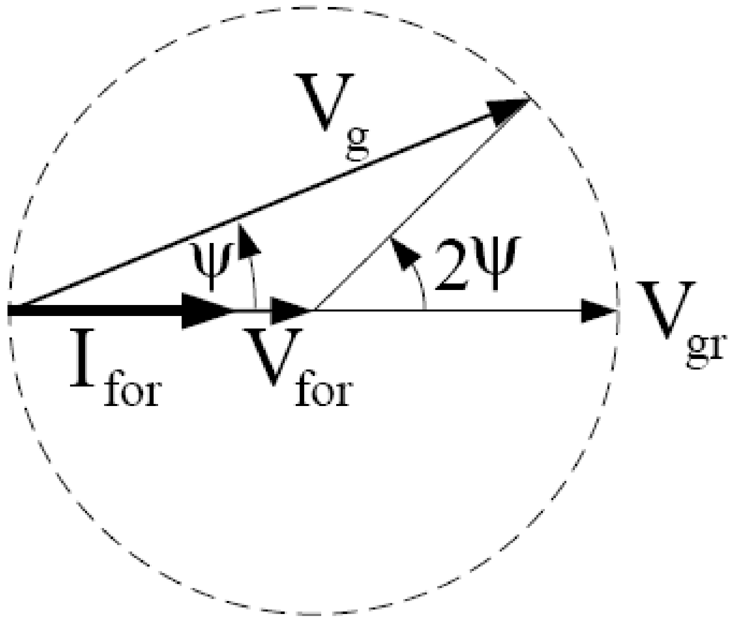
Resonance curve of cavity





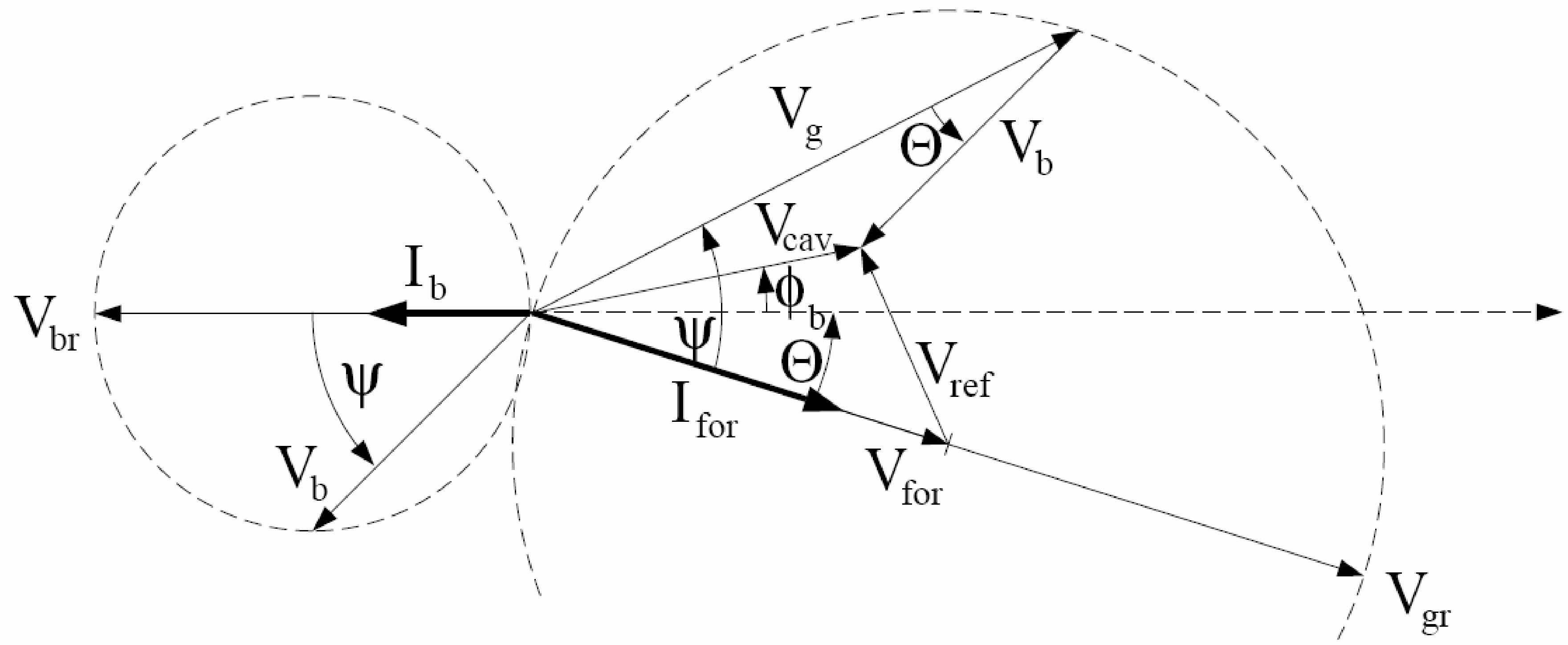
$$\hat{V}(\Delta\omega) \approx \frac{R_L \hat{I}_0}{\sqrt{1 + (2Q_L \frac{\Delta\omega}{\omega})^2}} \qquad \tan\psi \approx 2Q_L \frac{\Delta\omega}{\omega} = 2Q_L \frac{\Delta f}{f}$$

Induced voltage as funct. of detuning angle



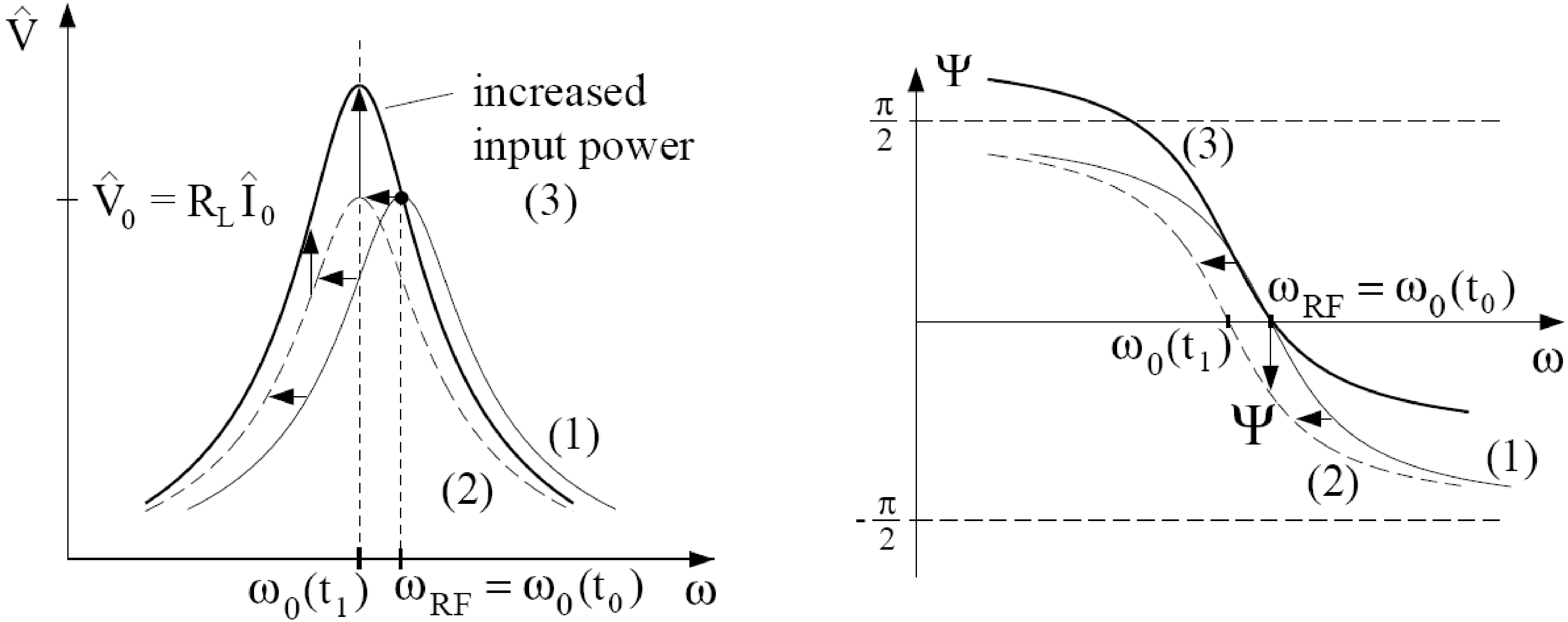
Induced cavity voltage as a function of the tuning angle ψ. The voltage induced by a generator current $\mathbf{I}_g$ on resonance is denoted by an index 'r'. This applies to both generator- and beam-induced voltages. In the case of superconducting cavities with $Q_0 \gg Q_{ext}$, the voltage $\mathbf{V}_{gr}$ is twice that of the incident wave $\mathbf{V}_{for}$.

Vector diagram of generator and beam induced voltages



Vector diagram of generator- and beam-induced voltages in a detuned cavity. The angle ϕ_b denotes the beam phase and ψ the tuning angle.

Effect of change in resonance frequency



Principle of RF control. The change of the resonance frequency (left plot, curve (1) to curve (2)) results in a decreasing amplitude at the operating frequency ω_{RF}. This is compensated by adjusting the input power (curve (3)). The resonance frequency variation yields also in a phase shift (right plot) corrected by applying a phase shift in the opposite direction.

Klystron Power in presence of detuning

$$P_g = \frac{V_{cav}^2}{\left(\frac{r}{Q}\right) Q_L} \frac{1}{4} \left(\left[1 + \frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}} \cos \phi_b \right]^2 + \left[\frac{\Delta f}{f_{1/2}} + \frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}} \sin \phi_b \right]^2 \right)$$

Optimum detuning $\tan \psi_{opt} = - \frac{2\, R_L I_{b0}}{V_{cav}} \sin \phi_b$

Power Required as function of detuning

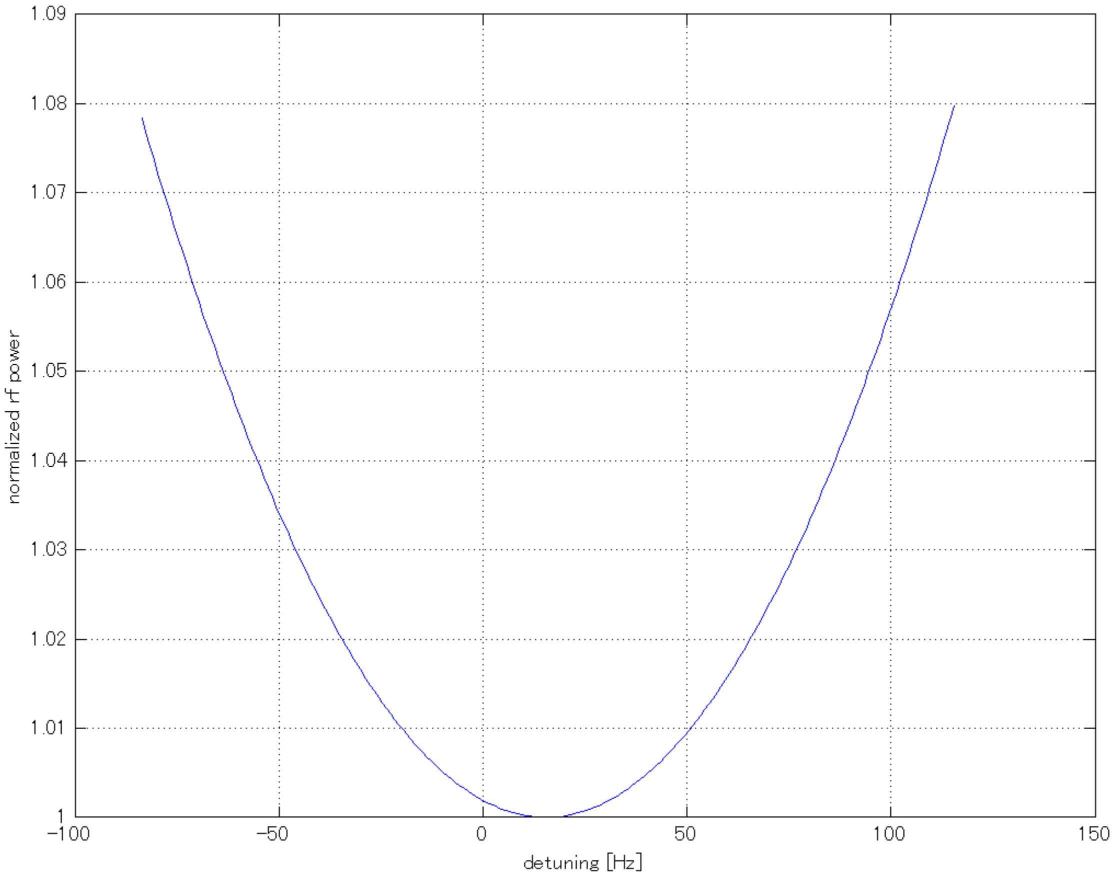
$V_{cav} = 25\ \mathrm{MV},\ Q_L = 3 \cdot 10^6;\ \text{no beam:}$

$$P_g = 50kW \cdot \left(1 + \left(\frac{\Delta f}{f_{1/2}}\right)^2\right)$$

$V_{cav} = 25\ \mathrm{MV},\ Q_L = 3 \cdot 10^6;\ I_b = 8\ \mathrm{mA};\ \phi_b = 0^\circ\ \text{(on-crest):}$

$$P_g = 50kW \cdot \left(4 + \left(\frac{\Delta f}{f_{1/2}}\right)^2\right)$$

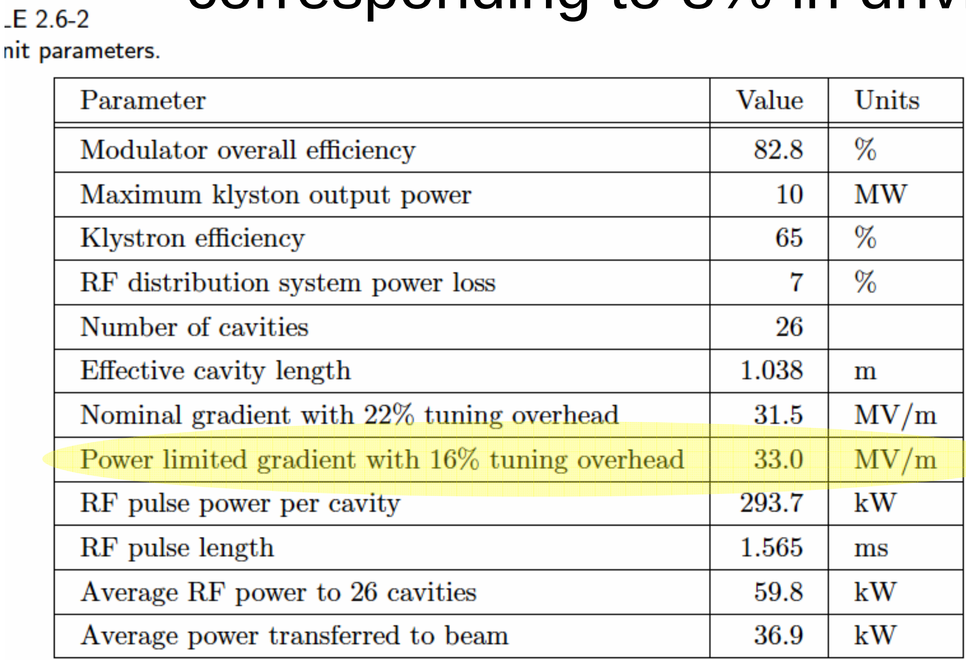
Detuning vs rf power



- 50 Hz detuning requires additional 2% rf power

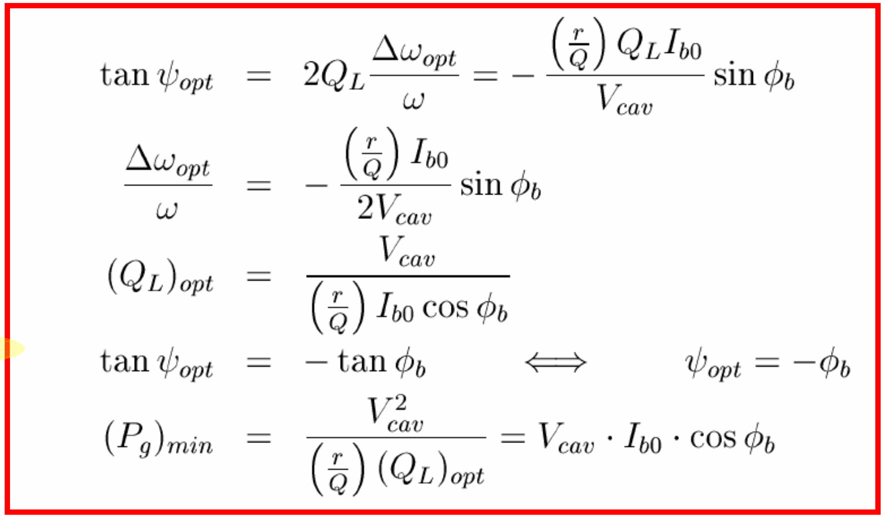
LLRF Tuning Overhead

- As in RDR, llrf tuning overhead is only 16% in power. corresponding to 8% in driving amplitude.



E 2.6-2
nit parameters.

Parameter	Value	Units
Modulator overall efficiency	82.8	%
Maximum klyston output power	10	MW
Klystron efficiency	65	%
RF distribution system power loss	7	%
Number of cavities	26	
Effective cavity length	1.038	m
Nominal gradient with 22% tuning overhead	31.5	MV/m
Power limited gradient with 16% tuning overhead	33.0	MV/m
RF pulse power per cavity	293.7	kW
RF pulse length	1.565	ms
Average RF power to 26 cavities	59.8	kW
Average power transferred to beam	36.9	kW



$$\tan\psi_{opt} = 2Q_L\frac{\Delta\omega_{opt}}{\omega} = -\frac{\left(\frac{r}{Q}\right)Q_L I_{b0}}{V_{cav}}\sin\phi_b$$

$$\frac{\Delta\omega_{opt}}{\omega} = -\frac{\left(\frac{r}{Q}\right)I_{b0}}{2V_{cav}}\sin\phi_b$$

$$(Q_L)_{opt} = \frac{V_{cav}}{\left(\frac{r}{Q}\right)I_{b0}\cos\phi_b}$$

$$\tan\psi_{opt} = -\tan\phi_b \quad\Longleftrightarrow\quad \psi_{opt} = -\phi_b$$

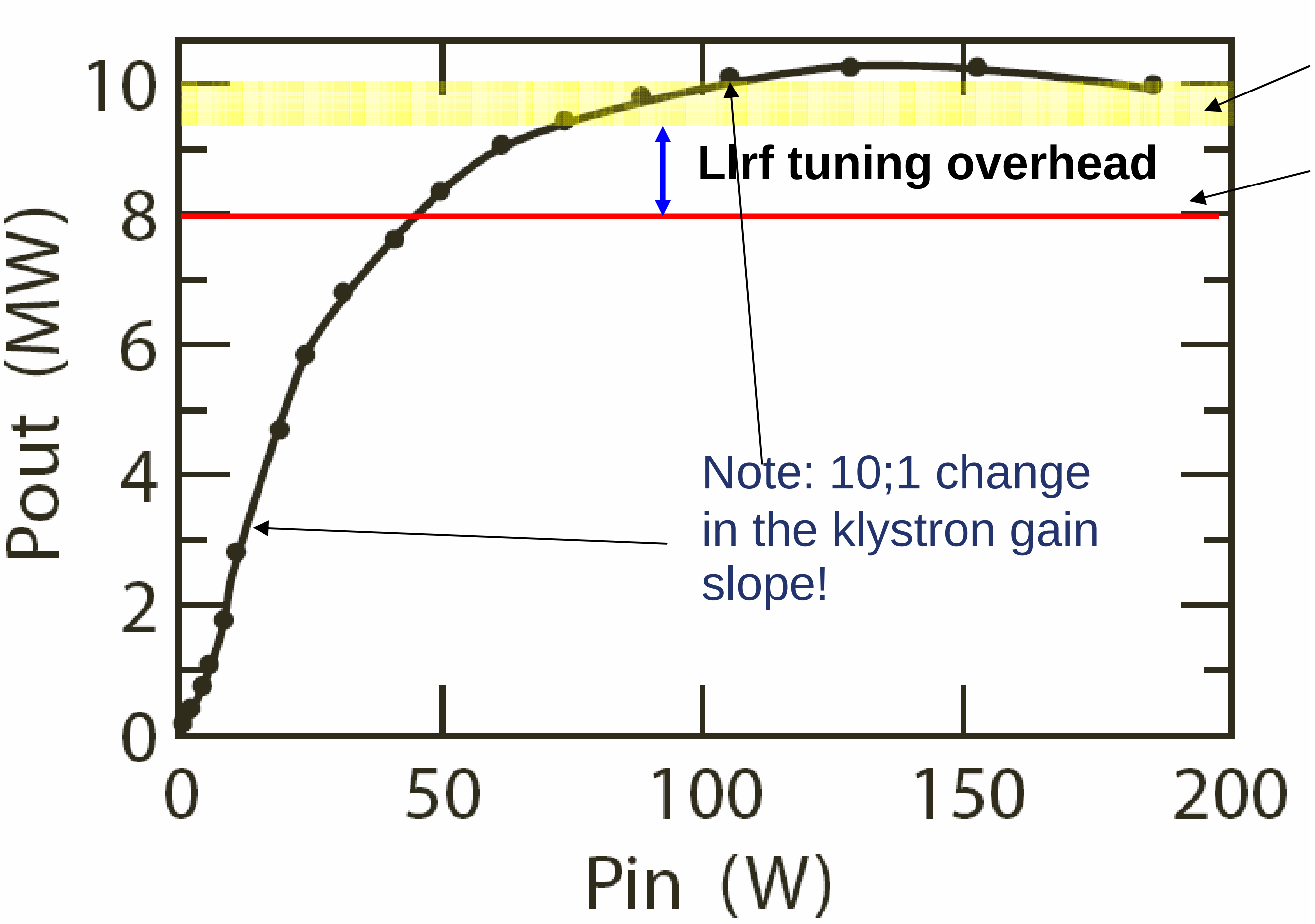
$$(P_g)_{min} = \frac{V_{cav}^2}{\left(\frac{r}{Q}\right)(Q_L)_{opt}} = V_{cav}\cdot I_{b0}\cdot\cos\phi_b$$

- Under optimal Ql and detuning, Pg becomes minimum.

Pg= 33 MV/m*1.038 m *9 mA *cos(5deg.)*26 cav.= 7.98 MW ~ 8 MW
RF loss (7%) -> available rf power= 9.3 MW
Llrf overhead = 9.3/7.98 -1 ~16%

LLRF operating point

- As in RDR, llrf tuning overhead is only 16% in power. corresponding to 8% in driving amplitude. (too narrow!)



Llrf tuning overhead

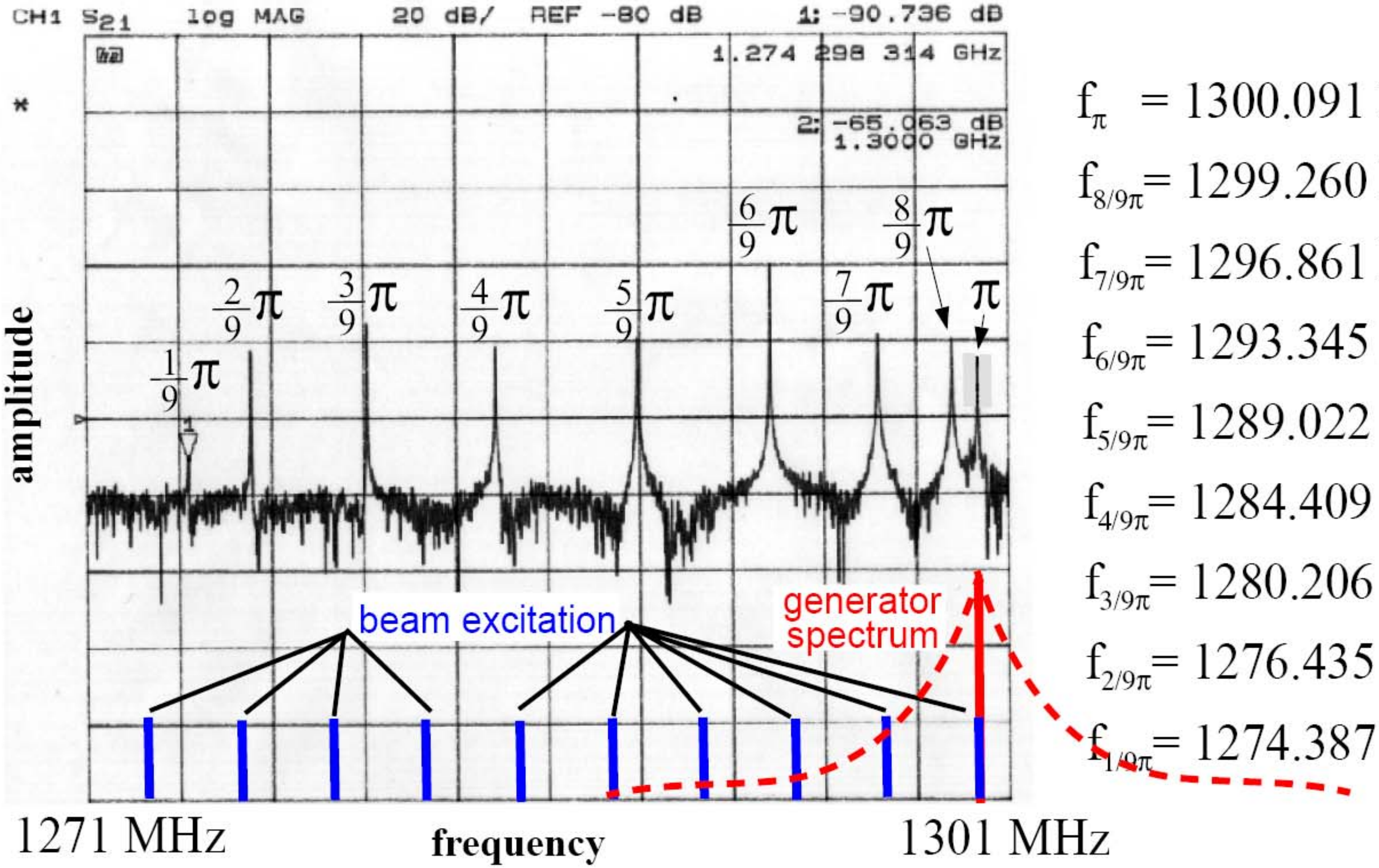
Waveguide loss (7%)

operation
(~8 MW @33 MV/m)

Note: 10;1 change in the klystron gain slope!

Other Passband Modes

Example: TESLA 9-cell cavity



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

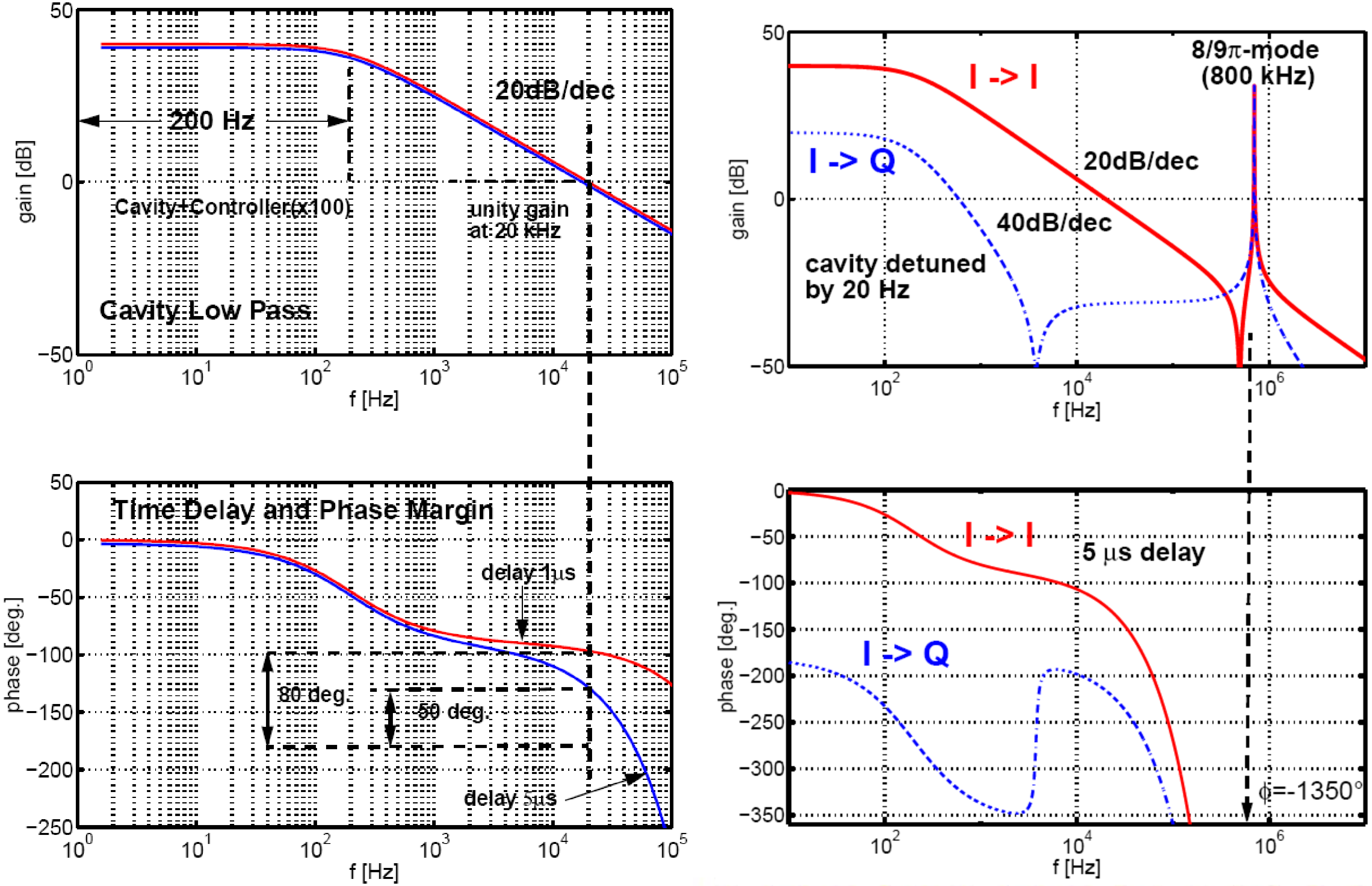
$f_{4/9\pi}$ = 1284.409 MHz

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

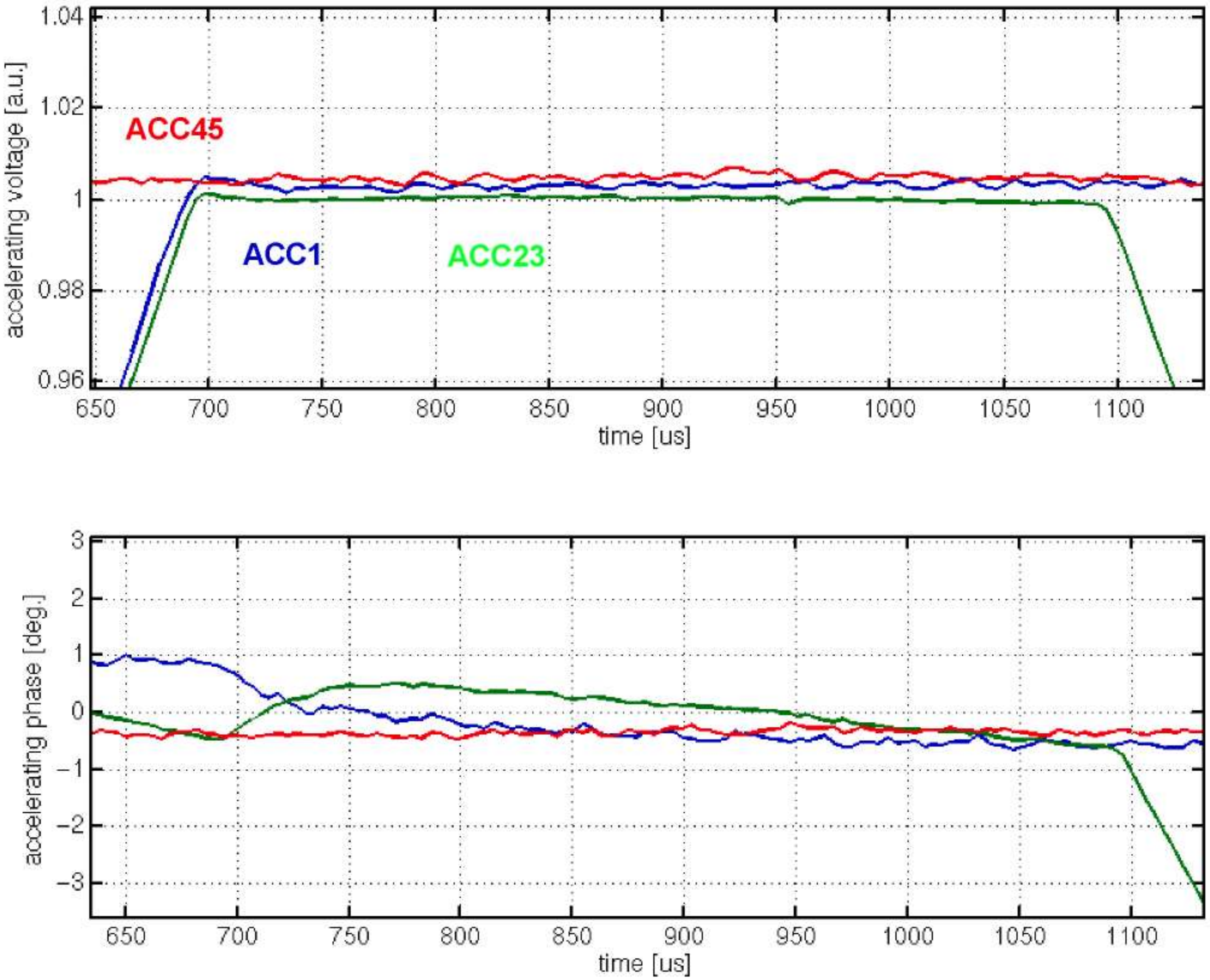
$f_{2/9\pi}$ = 1276.435 MHz

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

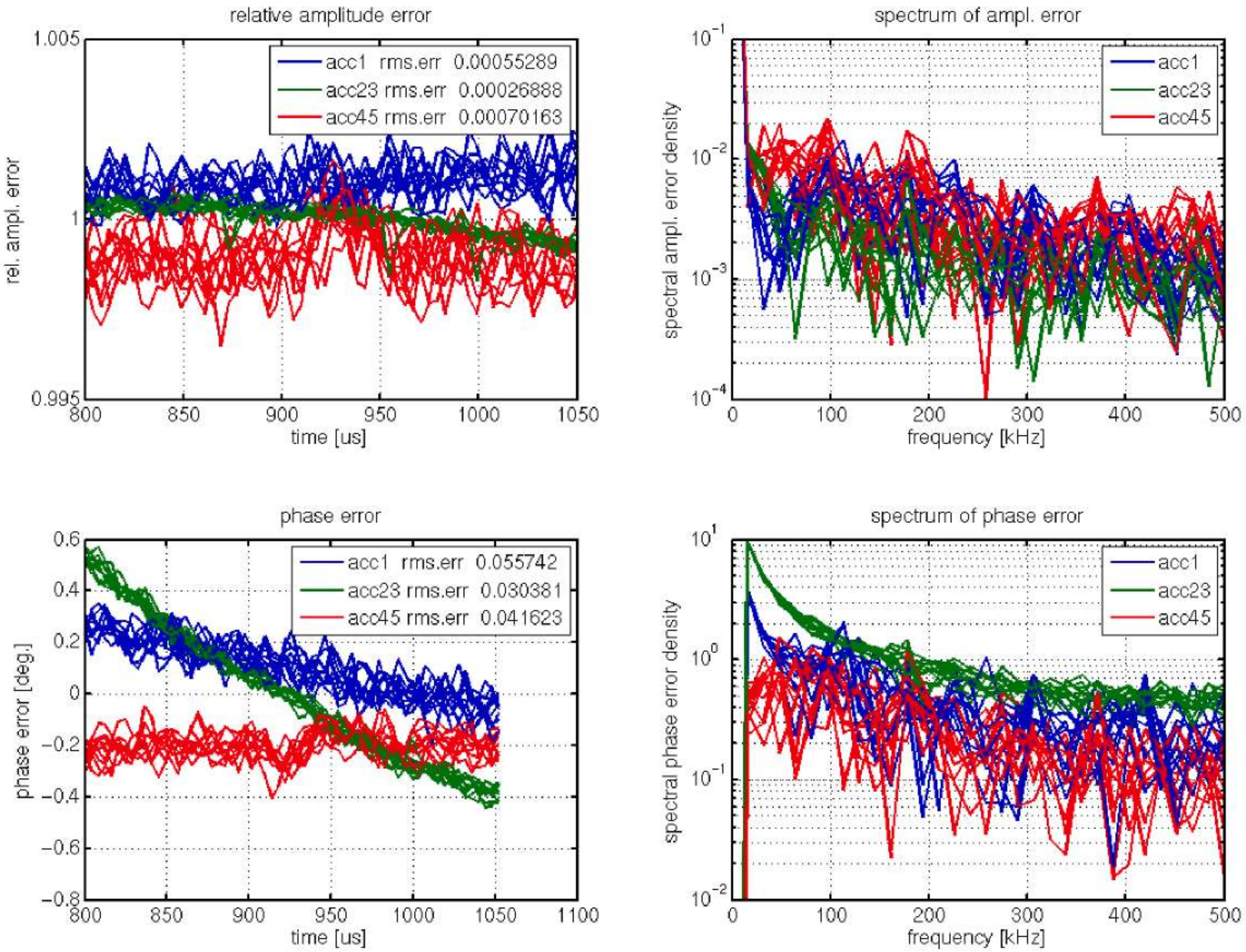
Bode Plot Cavity (wout/w 8/9-pi mode)



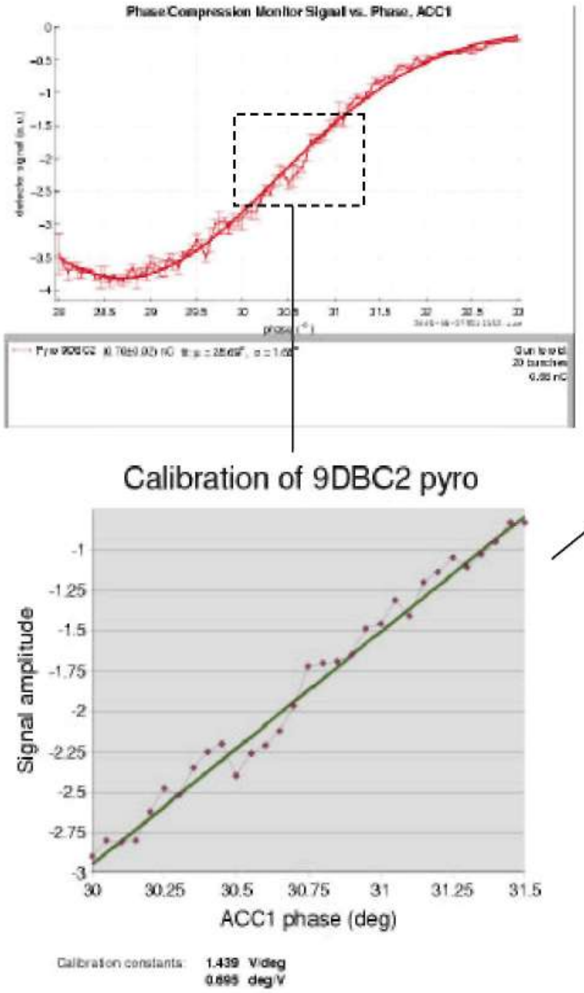
Field Regulation at FLASH

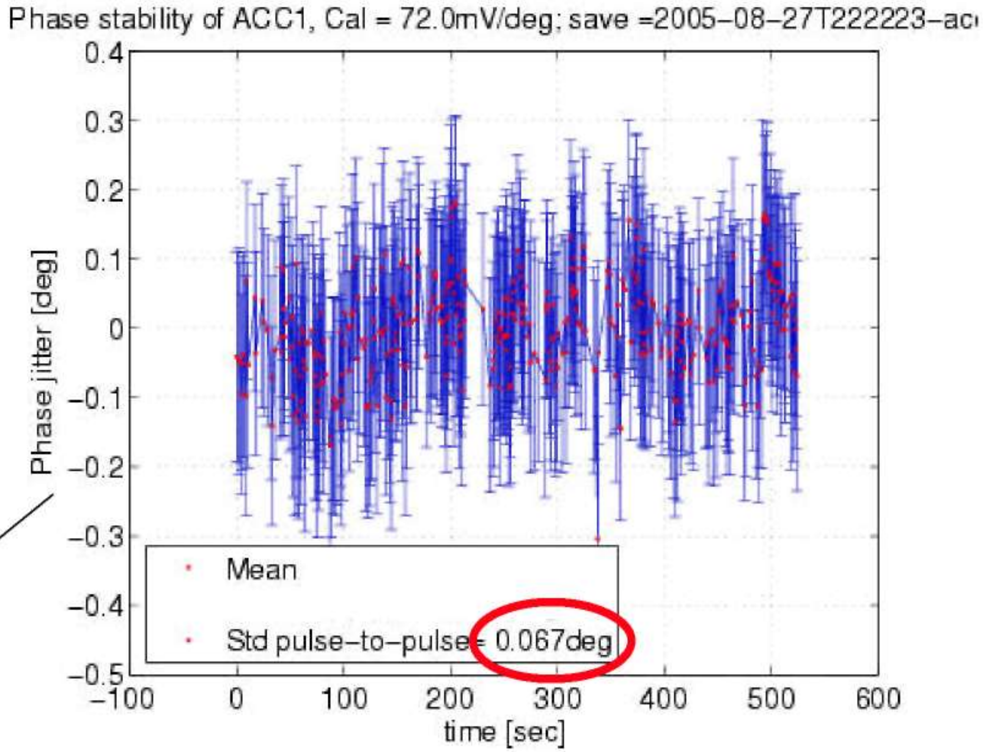


Field Regulation at FLASH



Field Regulation at FLASH

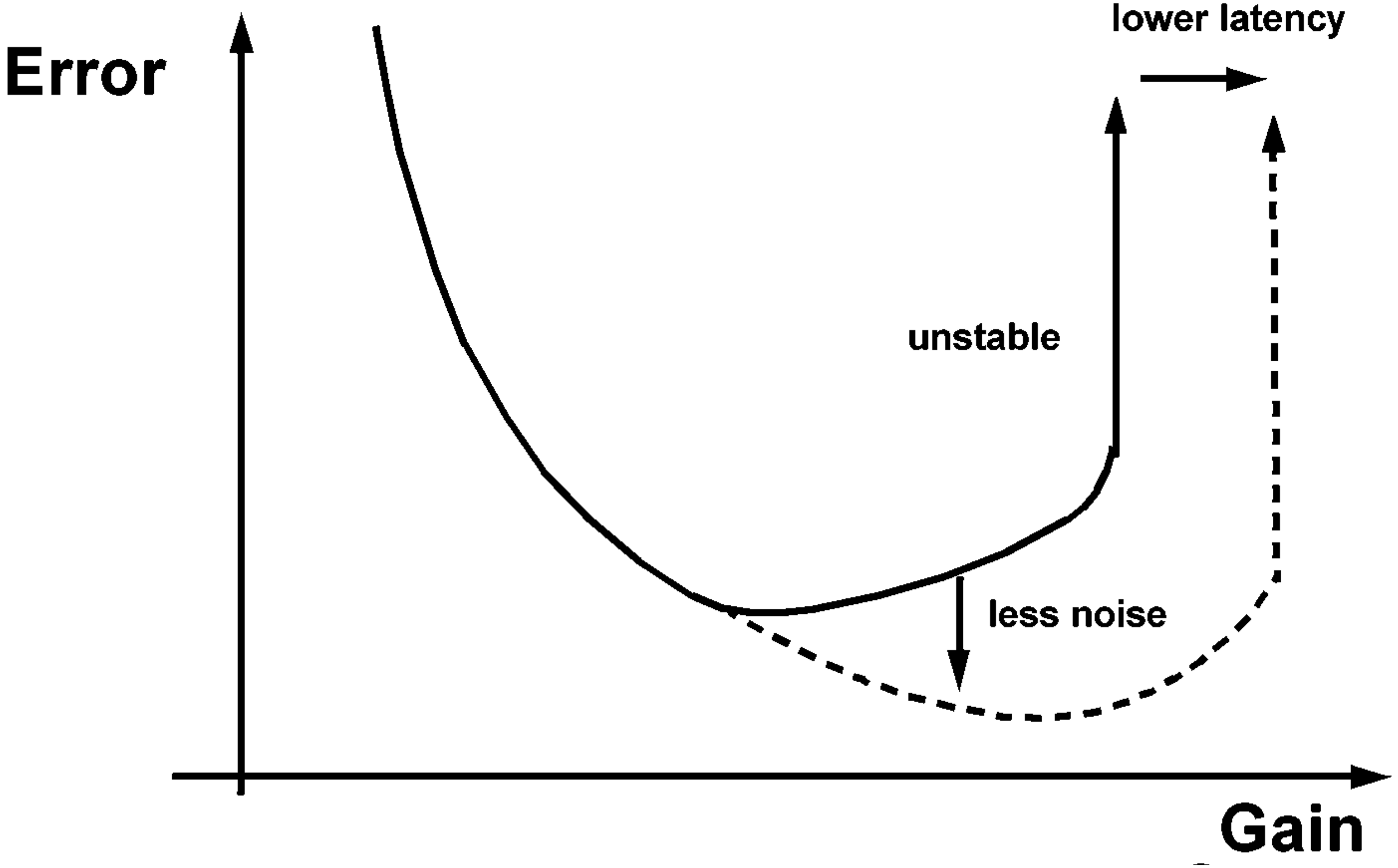




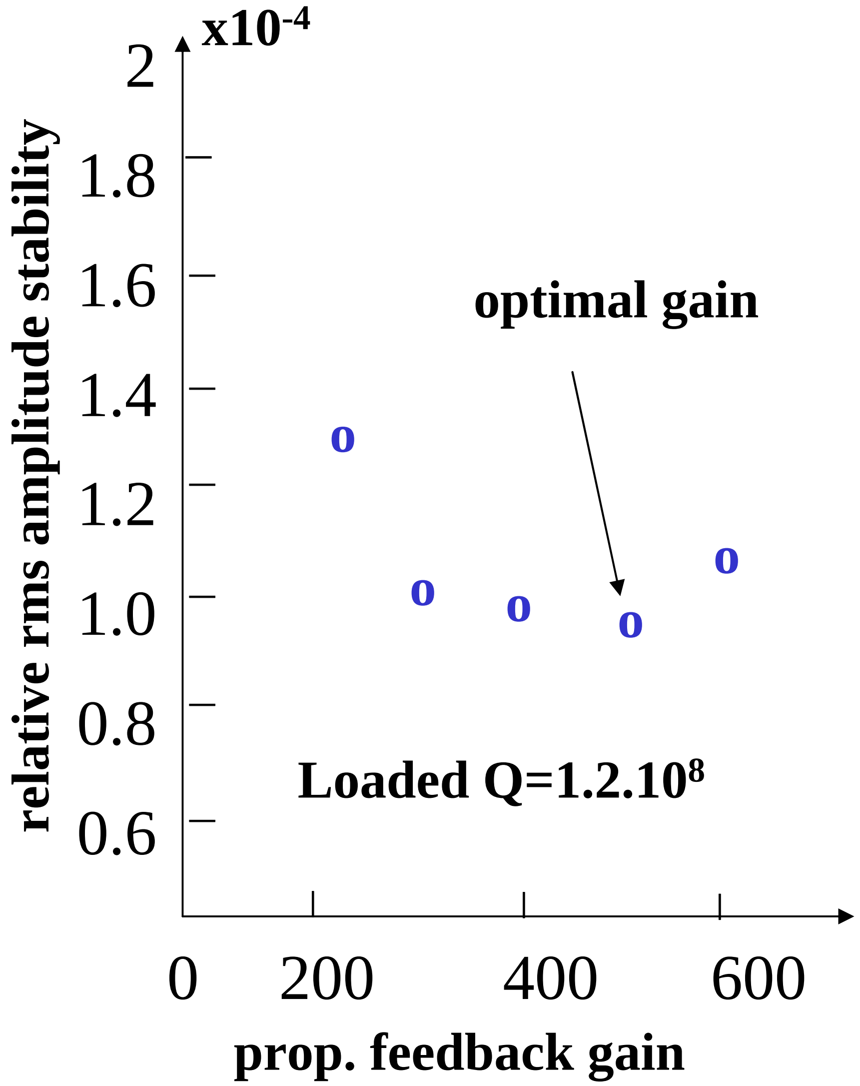
But! This is the phase stability between the beam arrival into the acceleration module relative to the RF phase!!!

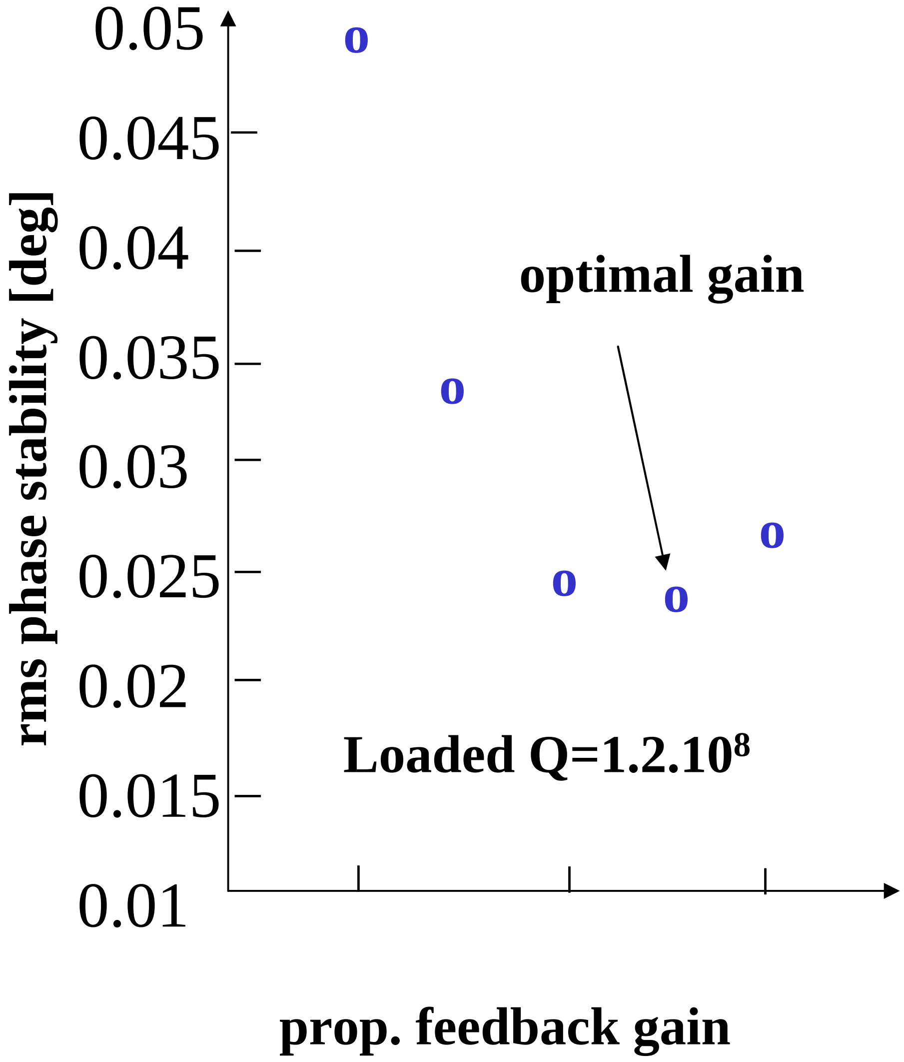
=> Major contribution is likely from laser

RMS Error as Function of Gain



Cornell RF Control Test at the TJLab FEL





Motivation for beam based feedback

Motivation to use beam based feedbacks:

⇒ to improve machine stability

⇒ to increase machine performance

⇒ to enhance operability of machine

⇒ to improve the reproducibility

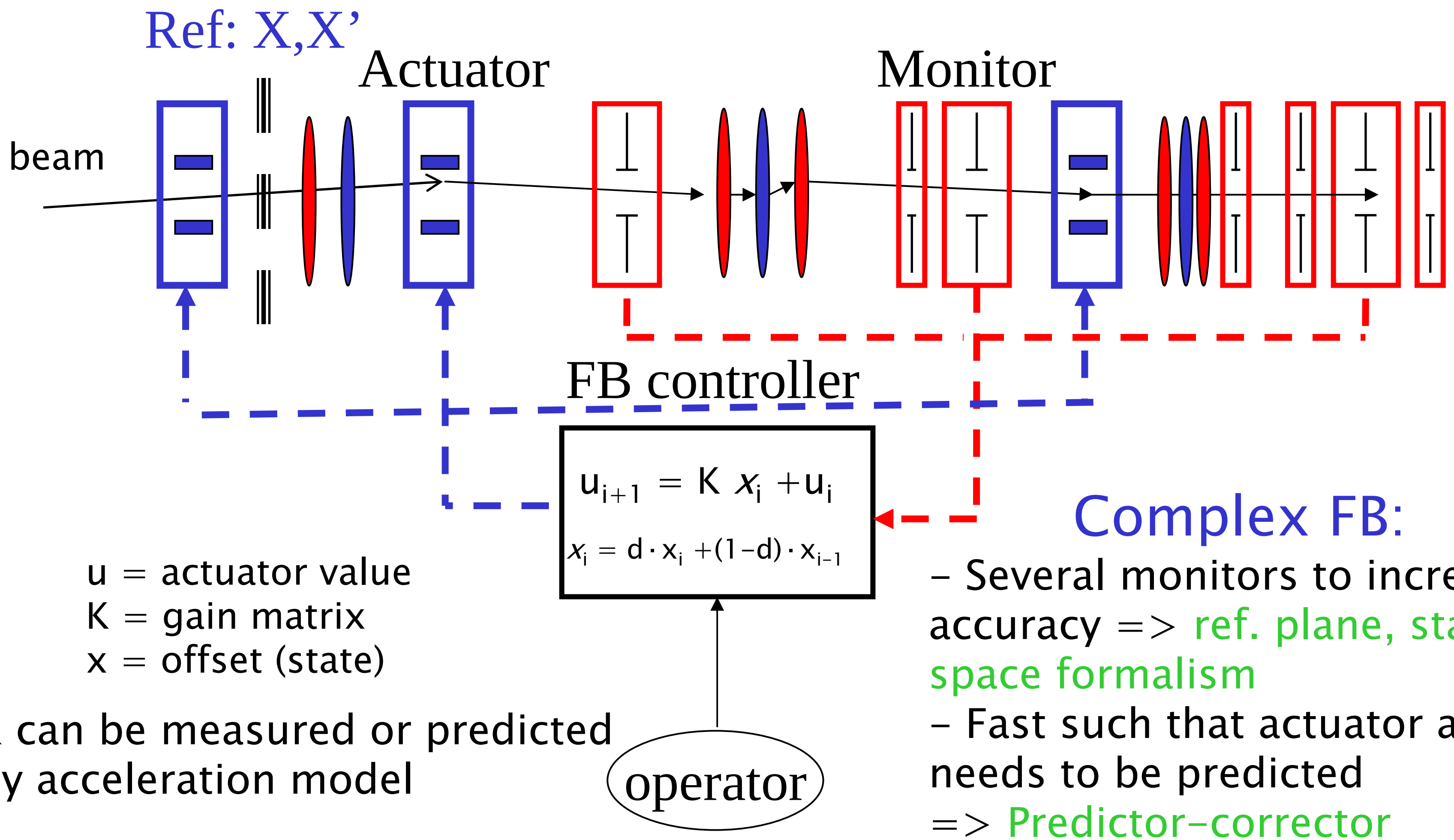
Why beam based?

-Because of technical, physical or financial reasons acceleration subsystems cannot be made drift/jitter free

-Ultimate goal: beam needs to be stable (not sub-systems)

-Beam based measurement can be more accurate

Principle of beam based feedback



Ref: X,X'

Actuator

Monitor

beam

FB controller

$u_{i+1} = K\ x_i + u_i$

$x_i = d \cdot x_i + (1-d) \cdot x_{i-1}$

operator

u = actuator value
K = gain matrix
x = offset (state)

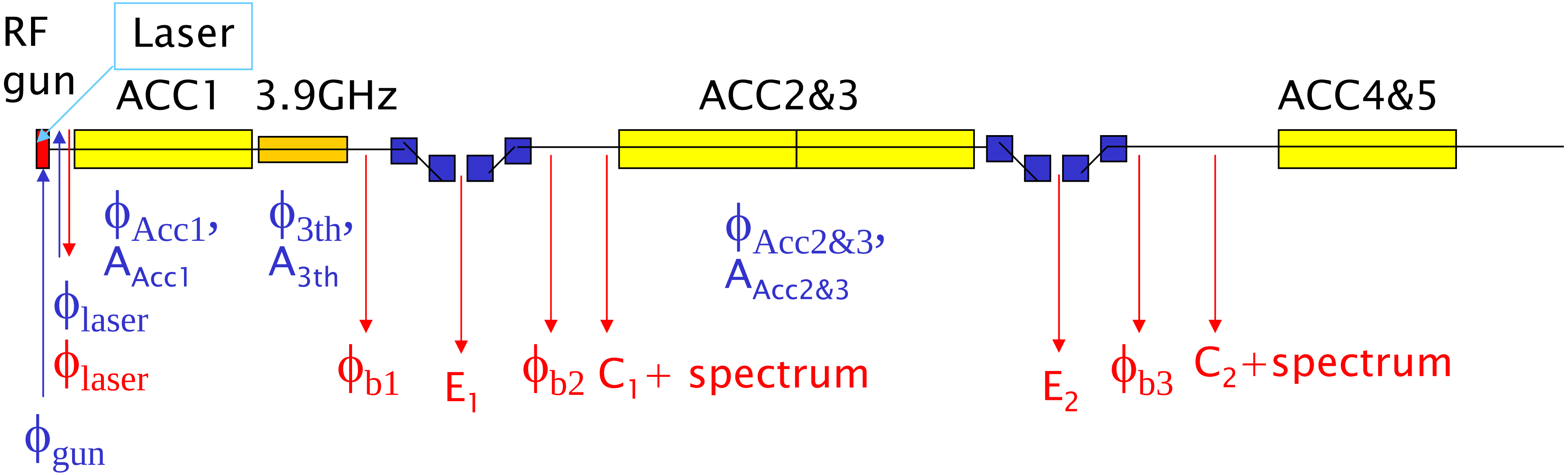
K can be measured or predicted by acceleration model

Complex FB:

- Several monitors to increase accuracy => ref. plane, state space formalism
- Fast such that actuator action needs to be predicted => Predictor-corrector formalism of dig. control theory
-Cascaded FBs …

See.: L. Hendrickson et al. (SLAC)

Longitudinal feedback with 3rd harmonic



Monitors: arrival phase laser, up stream BC1, downstream BC1&2
energy BC1, BC2, compression downstream BC1&BC2
very like longitudinal bunch shape also required

Actuators: laser phase, gun phase, phase & ampl. ACC1 & ACC23

Response Act->Mon: strongly depending on operation point

Cavity Model

Cavity Field

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

Mechanical Properties

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

or

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

Typical Parameters

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

$\omega_0 = 2\pi \cdot 1.3 \cdot 10^9$, $Q_L = 3 \cdot 10^6$, $\left(\dfrac{r}{Q}\right) = 1030\ \dfrac{\Omega}{m}$

$K_m = -1\ \mathrm{Hz/(MV/m)}^2$

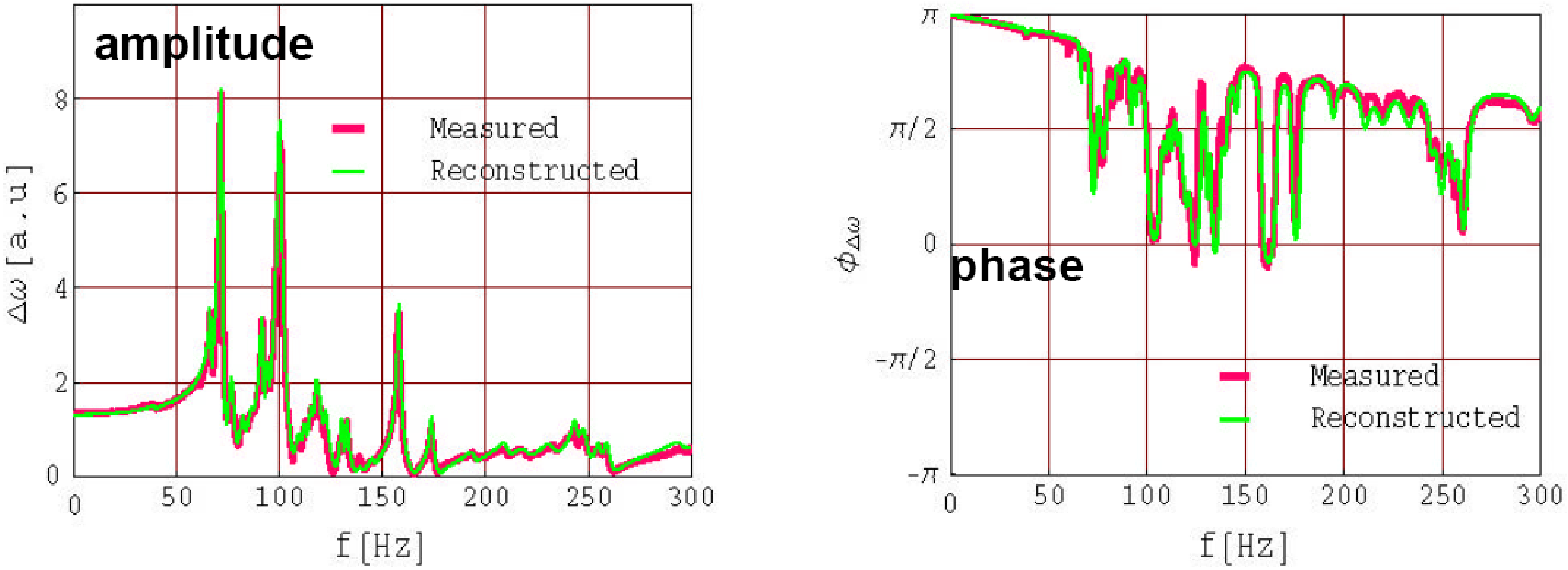
Modelling Lorentz Force Detuning

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

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.

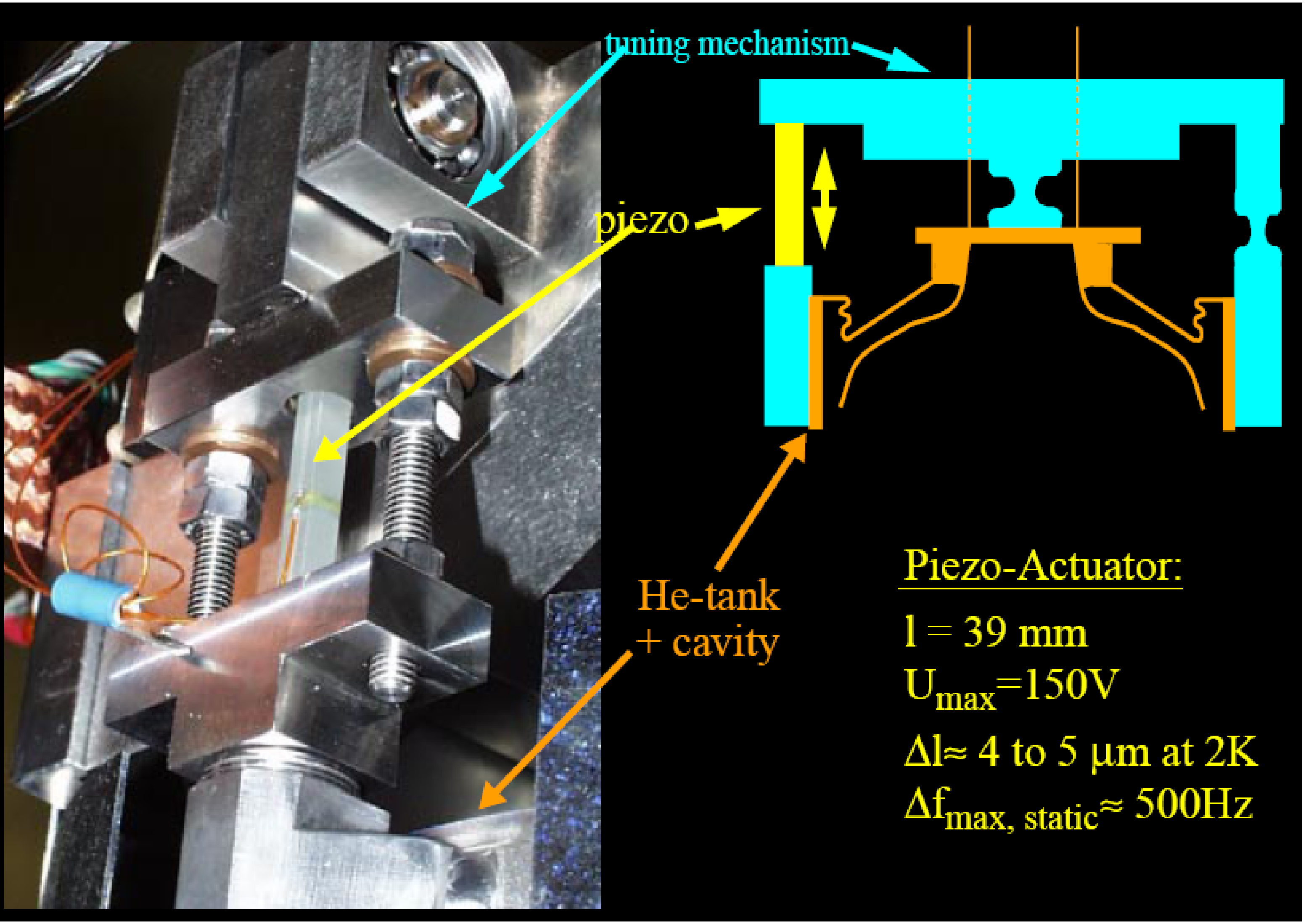
Lorentz Force Detuning

Transfer function Lorentz Force --> Detuning, SNS cavity



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

Piezotuner



Piezo-Actuator:

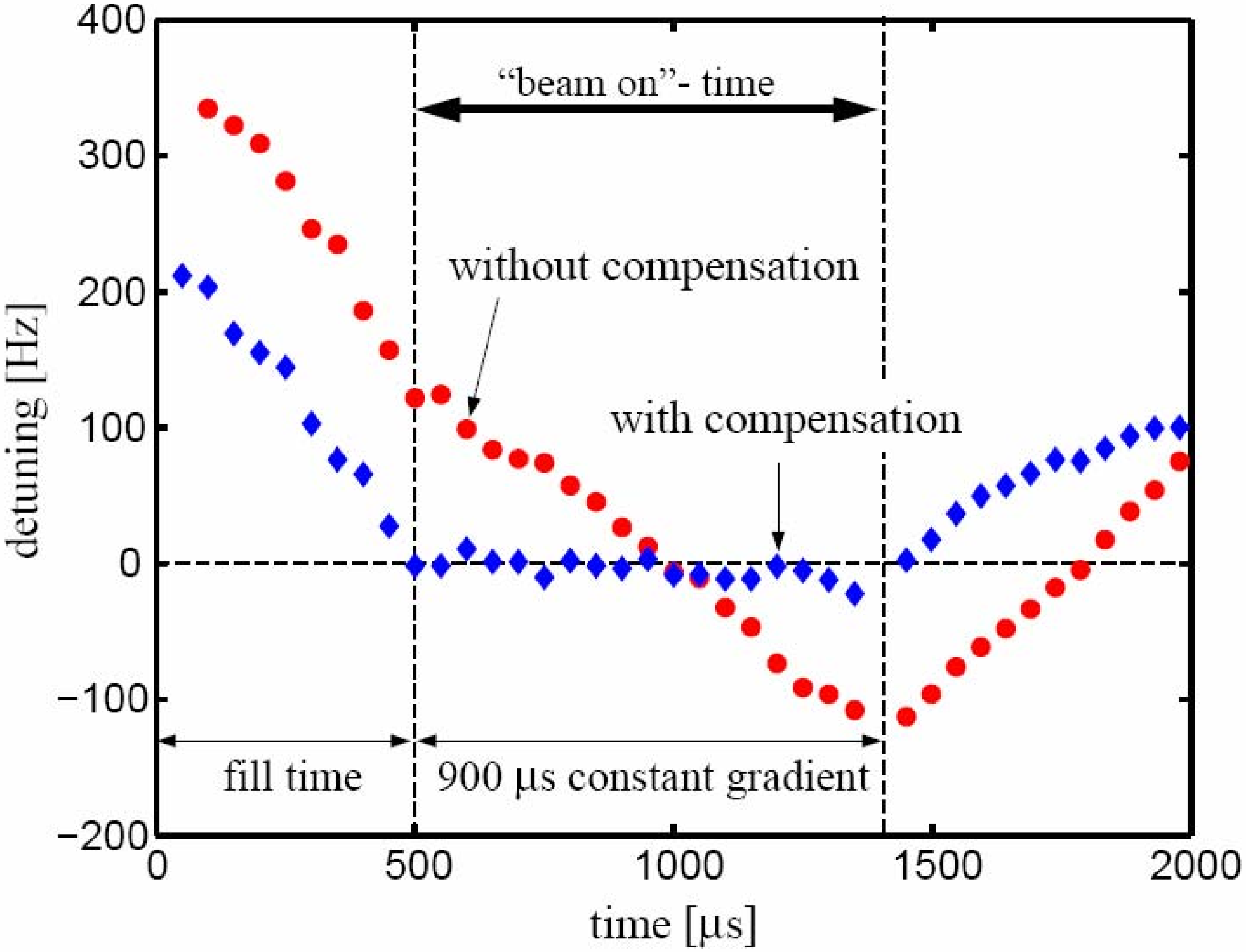
l = 39 mm

U_{max}=150V

Δl≈ 4 to 5 µm at 2K

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

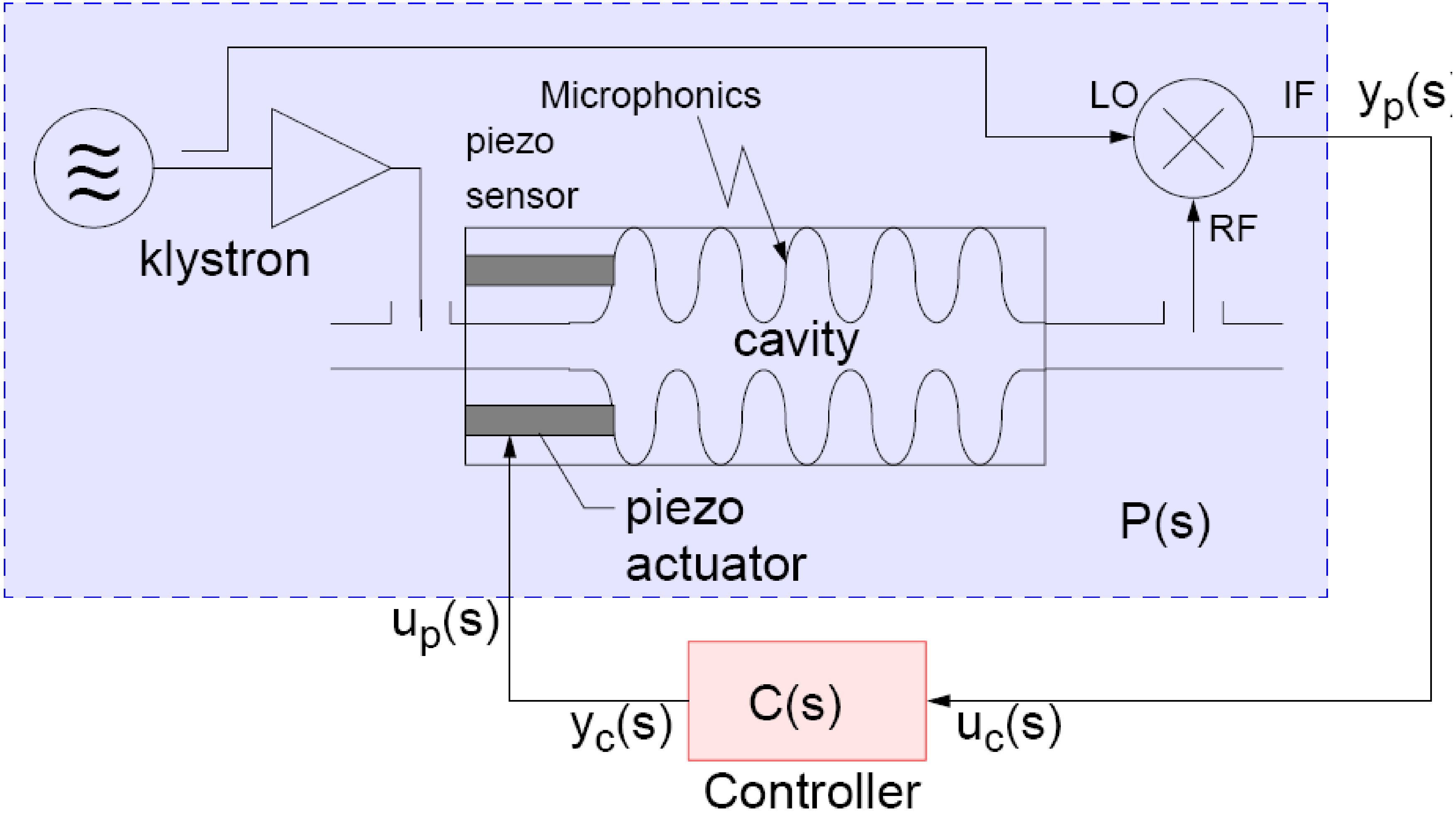
Active Compensation of Lorentz Force Detuning



9-cell cavity operated at 23.5 MV/m

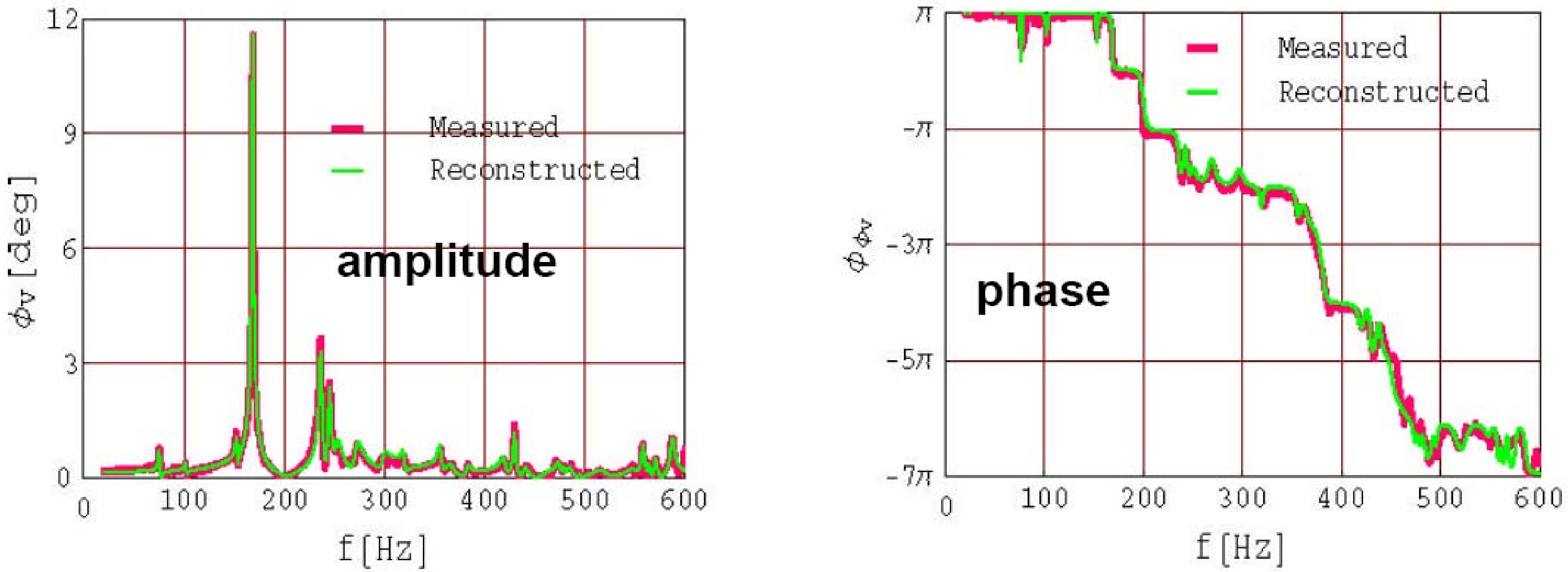
Lorentz force compensated with fast piezoelectric tuner

Concept for Controlling Microphonics



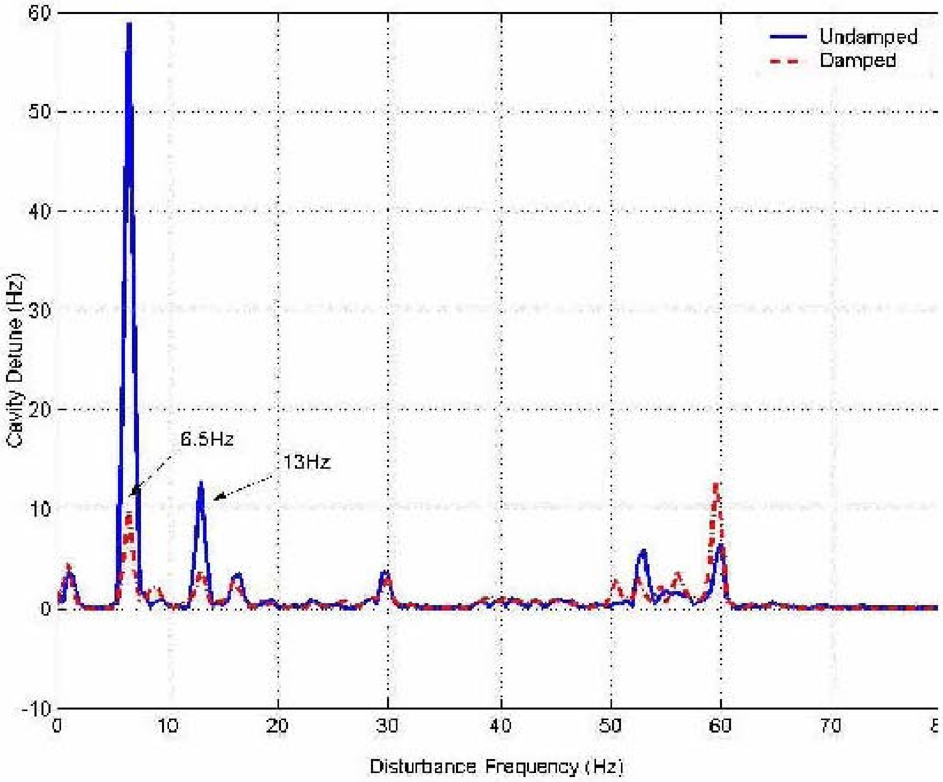
Transferfunction Piezo - Detuning

Transfer function Piezo Tuner --> Detuning, SNS cavity

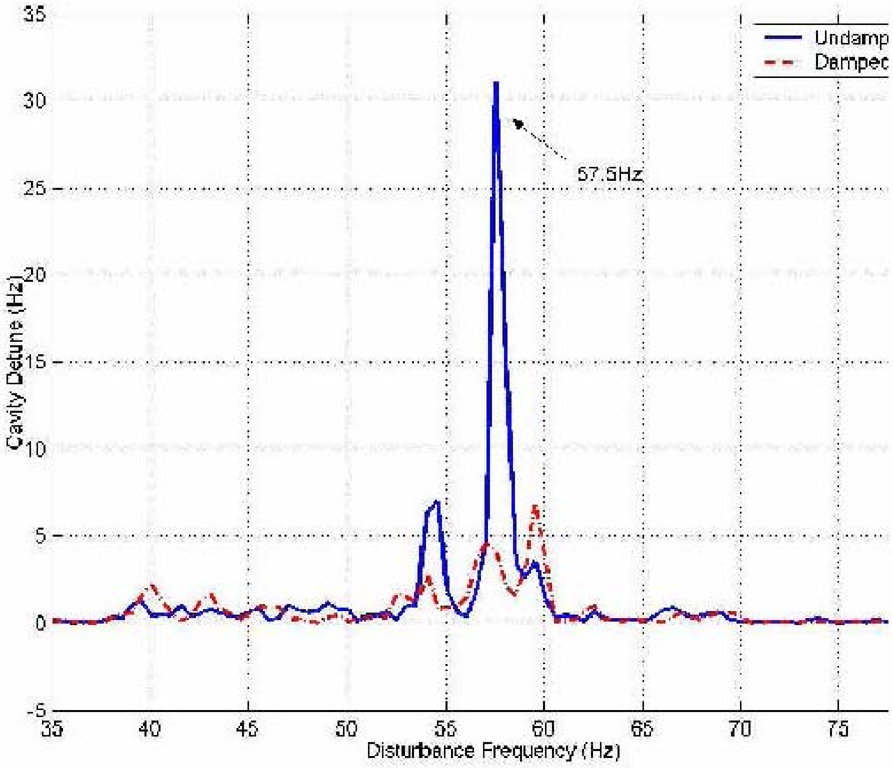


courtesy: J. Delayen, JLAB, M. Doleans, ORNL

Microphonic Suppression with Feedforward



Active damping of helium oscillations at 2K.



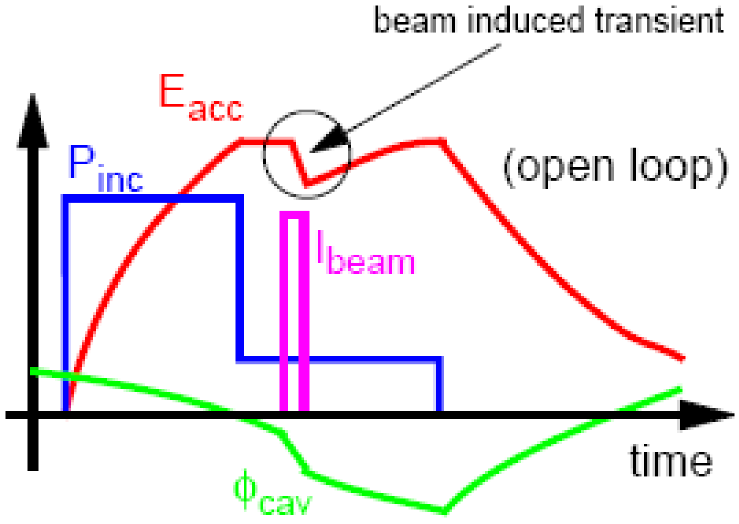
Active damping of external vibration at 2K.

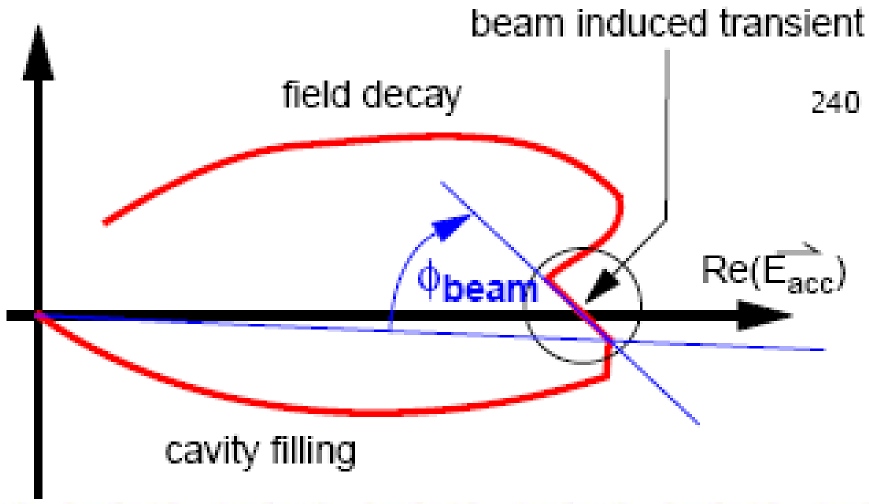
T. Grimm

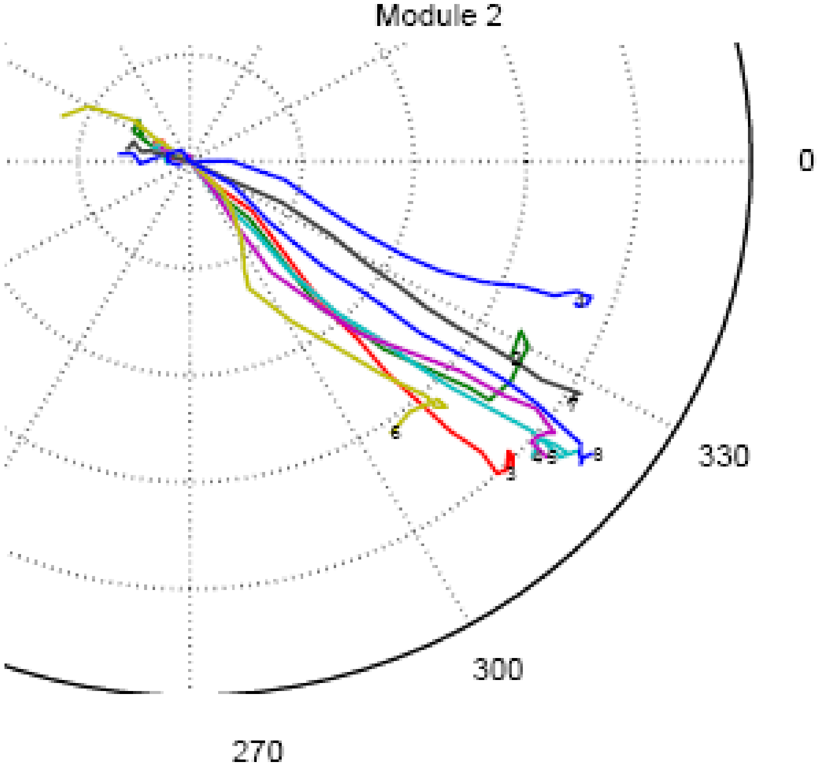
Challenges for RF Control

- Topics
  - **Vector-Sum Calibration (Ampl. & Phase)**
  - **Operation close to performance limits**
  - **Exception Handling**
  - **Automation of operation**
  - **Piezo tuner lifetime and dynamic range**
  - **Optimal field detection and controller (robust)**
  - **Operation at different gradients**
  - **Defining stándards for electronics (such as ATCA)**
  - **Interfaces to other subsystems**
  - **Reliability**

Beam Transient Based Phase/Gradient Calibration



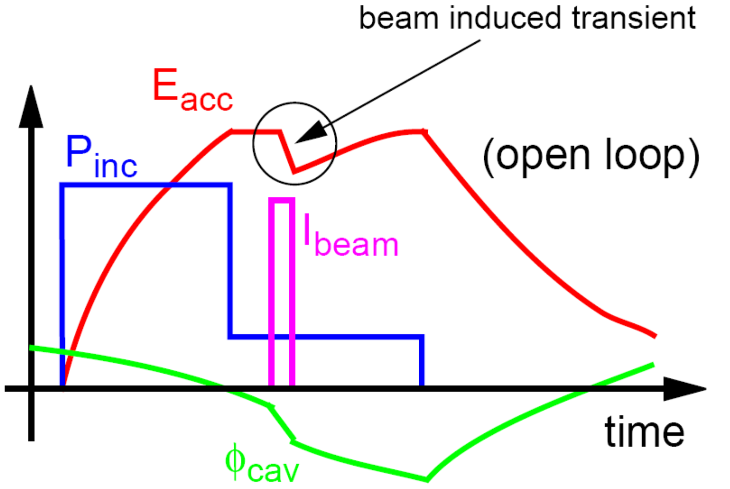


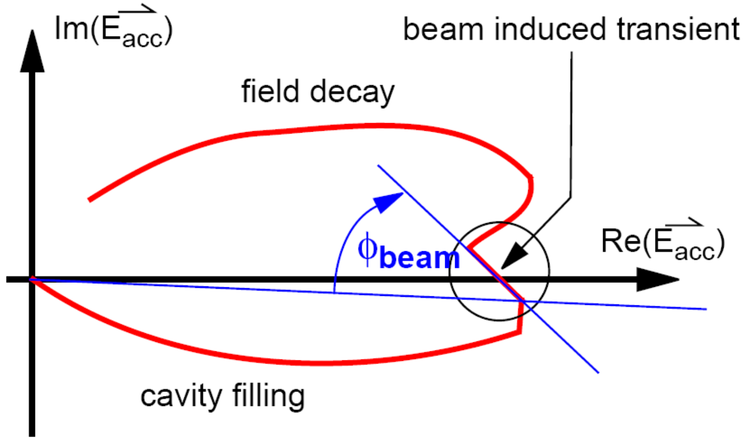


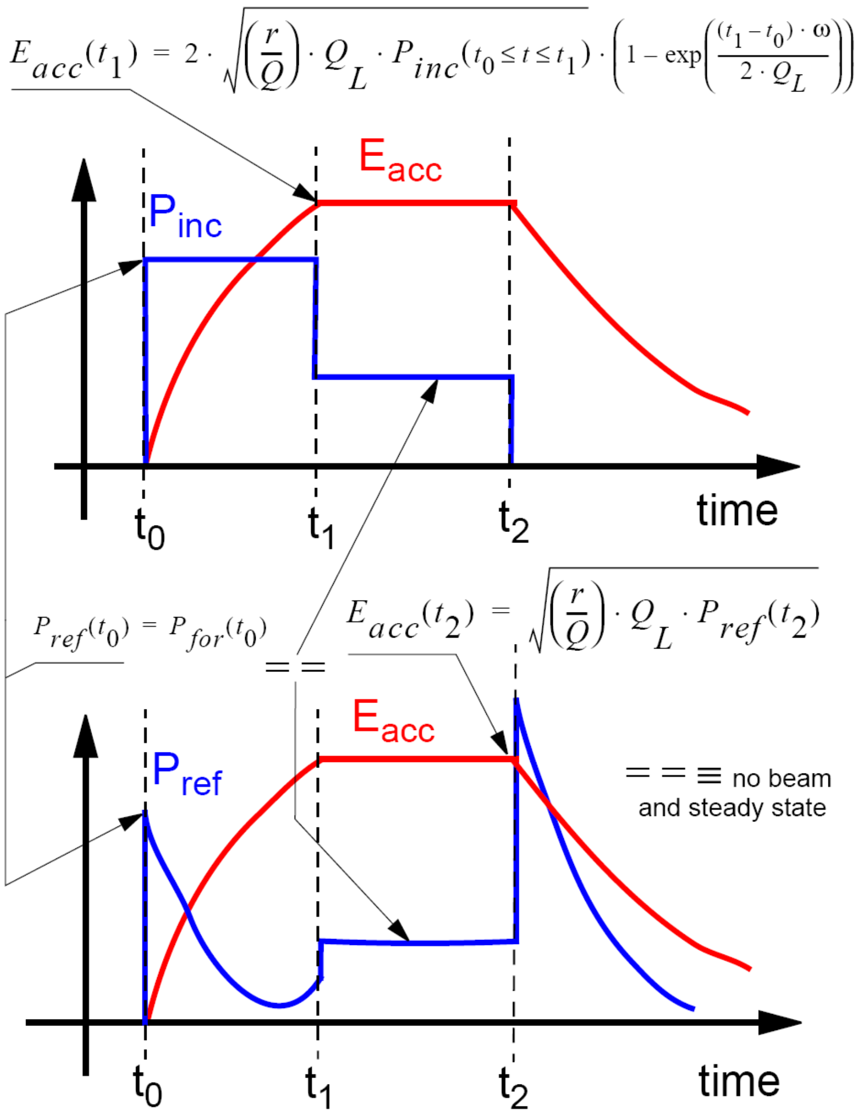
for $\Delta t << \tau_{cav}$:

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

Gradient and Power Calibration







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

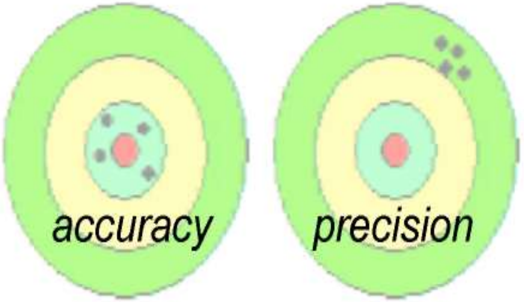
$$P_{ref}(t_0) = P_{for}(t_0)$$

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

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

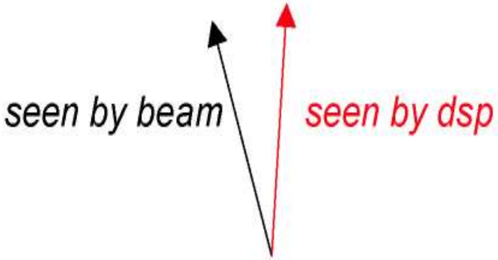
$$\Delta V_{ind} = I\cdot\Delta t\cdot\left(\frac{r}{Q}\right)\cdot\pi\cdot f$$

Vector-Sum Calibration

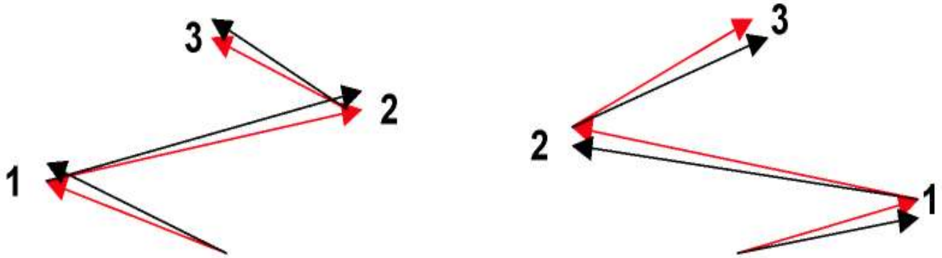


How precise can we measure the vectorsum seen by the beam (not: how good can we control the vectorsum...). We are not interested in *accuracy* but in *precision*!

Every vector carries an error that is assumed to be constant:

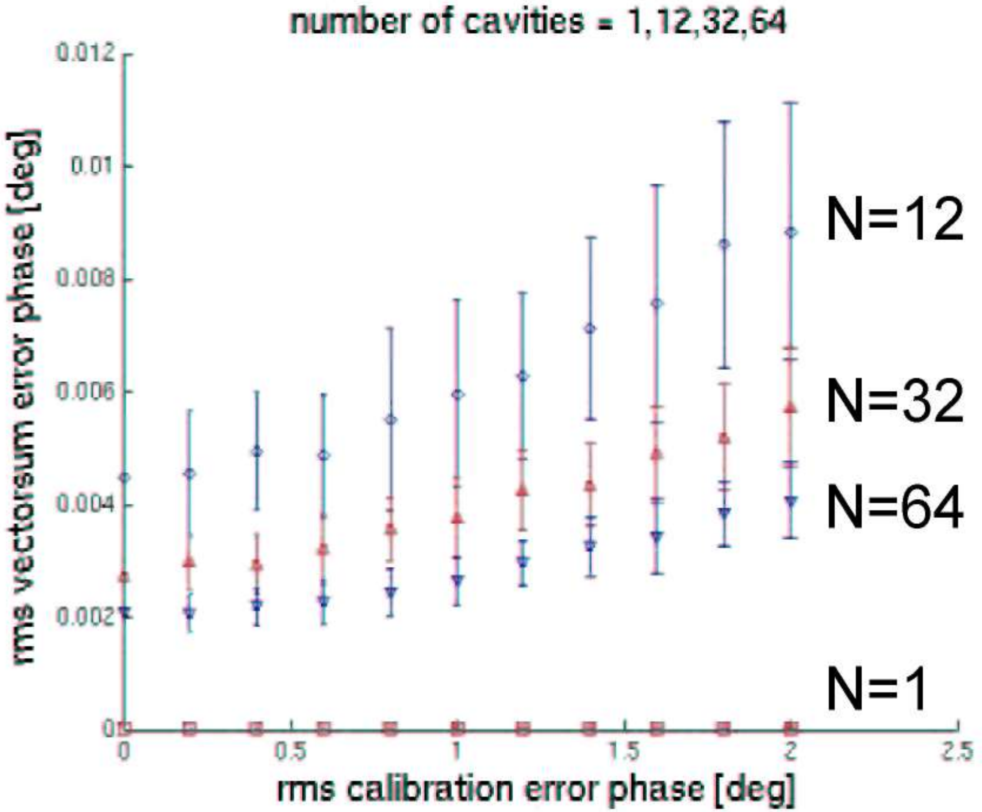


Two extreme configuration: the dsp sees identical vectorsums but the beam does not!



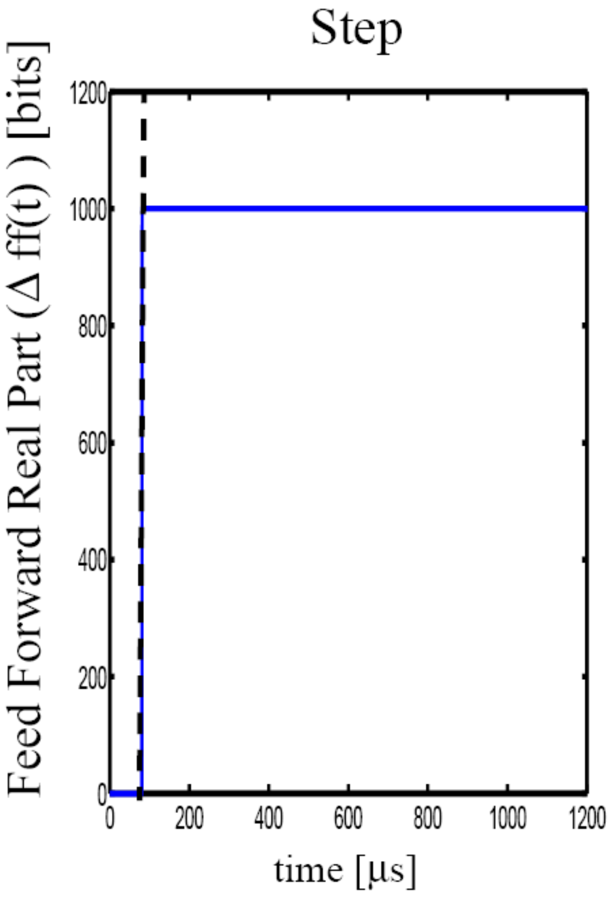
Vector-Sum calibration

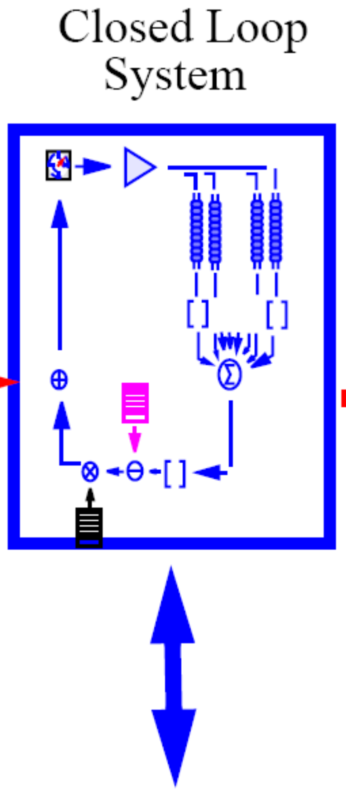
Number of cavities: 1,12,32,64, Predetuning: 50 Hz, Detuning-Spread: 11 Hz, Amplitude cal. error: 0.01

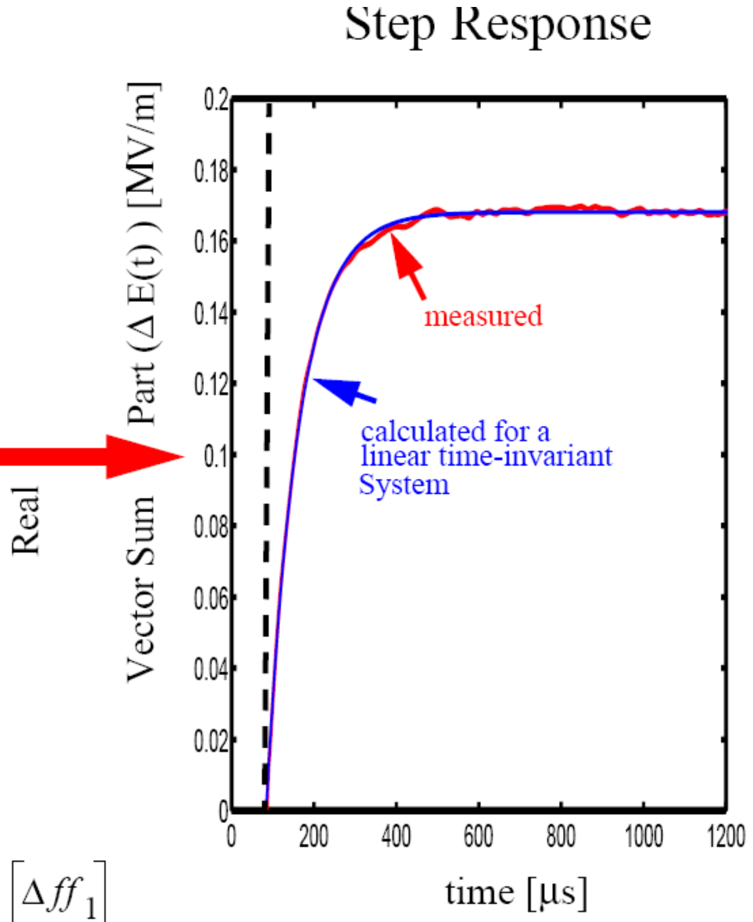


Surprising result: the more we measure, the better we get!

Adaptive Feedforward



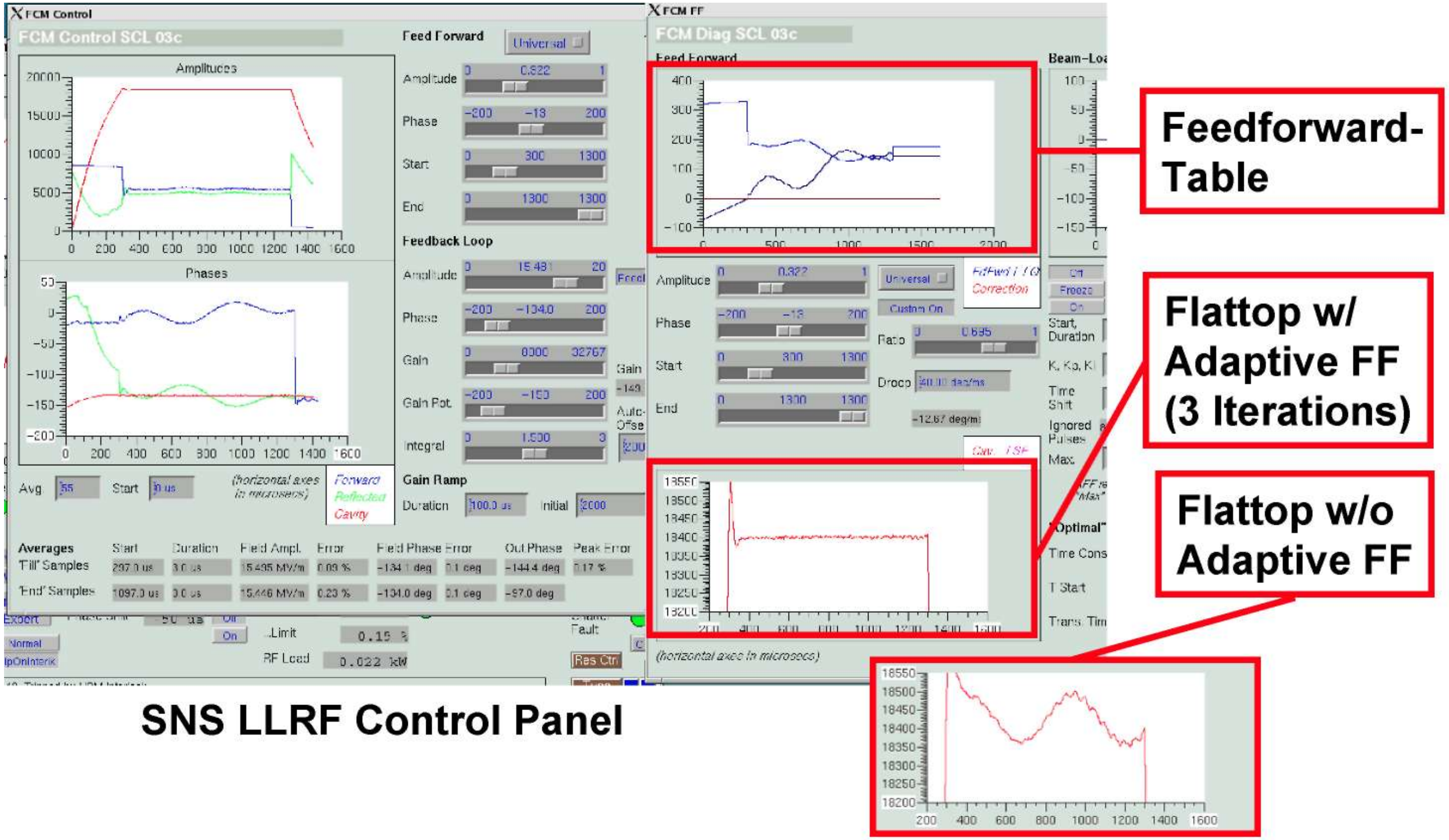




$$\begin{bmatrix} \Delta E(\tau_1) \\ \Delta E(\tau_2) \\ \dots \\ \Delta E(\tau_n) \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & \dots & T_{1n} \\ T_{21} & T_{22} & \dots & T_{2n} \\ \dots & \dots & \dots & \dots \\ T_{n1} & T_{n2} & \dots & T_{nn} \end{bmatrix} \begin{bmatrix} \Delta ff_1 \\ \Delta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

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

Automation: example adaptive Feedforward



Feed Forward: Universal
Amplitude: 0 | 0.622 | 1
Phase: −200 | −13 | 200
Start: 0 | 300 | 1300
End: 0 | 1300 | 1300

Feedback Loop
Amplitude: 0 | 15.481 | 20
Phase: −200 | −134.0 | 200
Gain: 0 | 8000 | 32767
Gain Rot: −200 | −150 | 200
Integral: 0 | 1.500 | 3

Gain Ramp
Duration: 100.0 us
Initial: 2000

Avg: 55
Start: 0 us
(horizontal axes in microsecs)

Averages	Start	Duration	Field Ampl.	Error	Field Phase Error		Out Phase	Peak Error
'Fill' Samples	297.0 us	3.0 us	15.495 MV/m	0.09 %	−134.1 deg	0.1 deg	−144.4 deg	0.17 %
'End' Samples	1097.0 us	0.0 us	15.446 MV/m	0.23 %	−134.0 deg	0.1 deg	−97.0 deg	

Limit: 0.15 %
RF Load: 0.022 kW

FCM Diag SCL 03c
Amplitude: 0 | 0.322 | 1
Phase: −200 | −13 | 200
Start: 0 | 300 | 1300
End: 0 | 1300 | 1300
Ratio: 0 | 0.695 | 1
Droop: 40.00 deg/ms
−12.67 deg/ms
(horizontal axes in microsecs)

Feedforward-Table

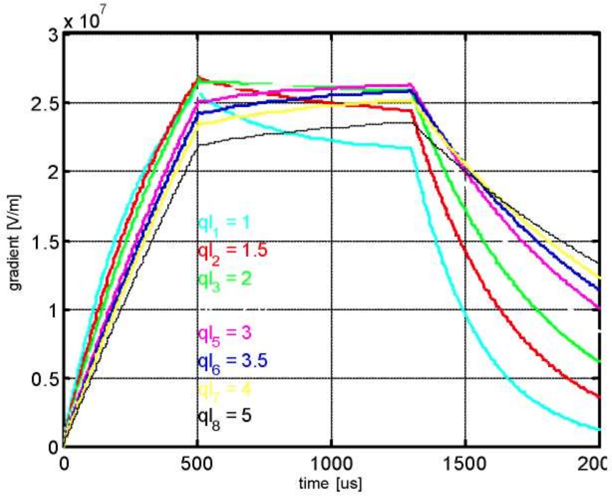
Flattop w/ Adaptive FF (3 Iterations)

Flattop w/o Adaptive FF

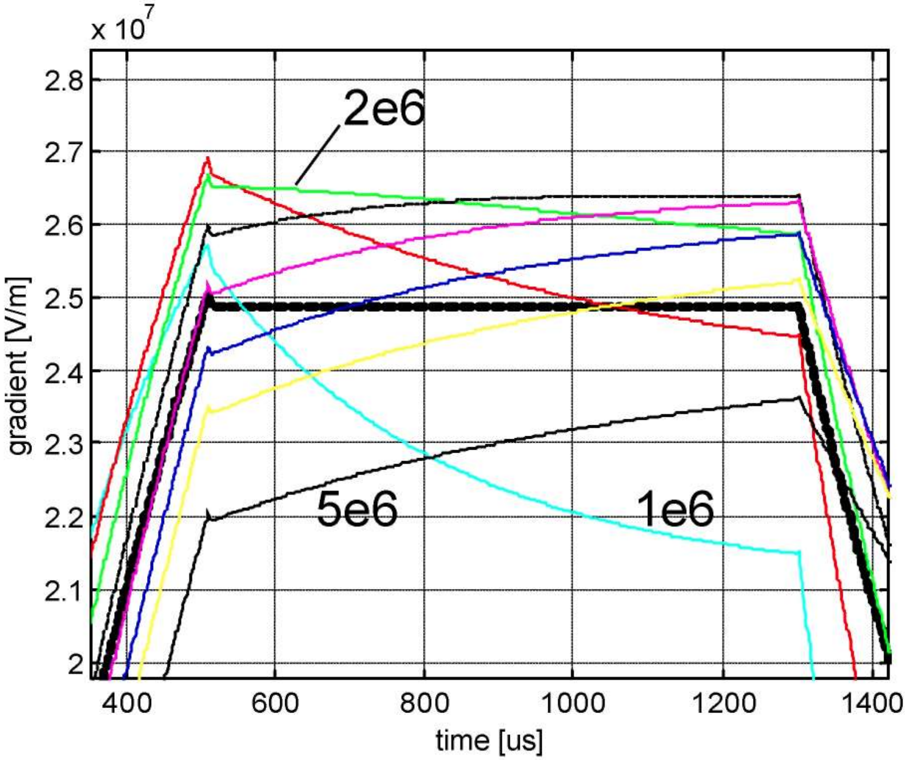
SNS LLRF Control Panel

Operation at different gradients

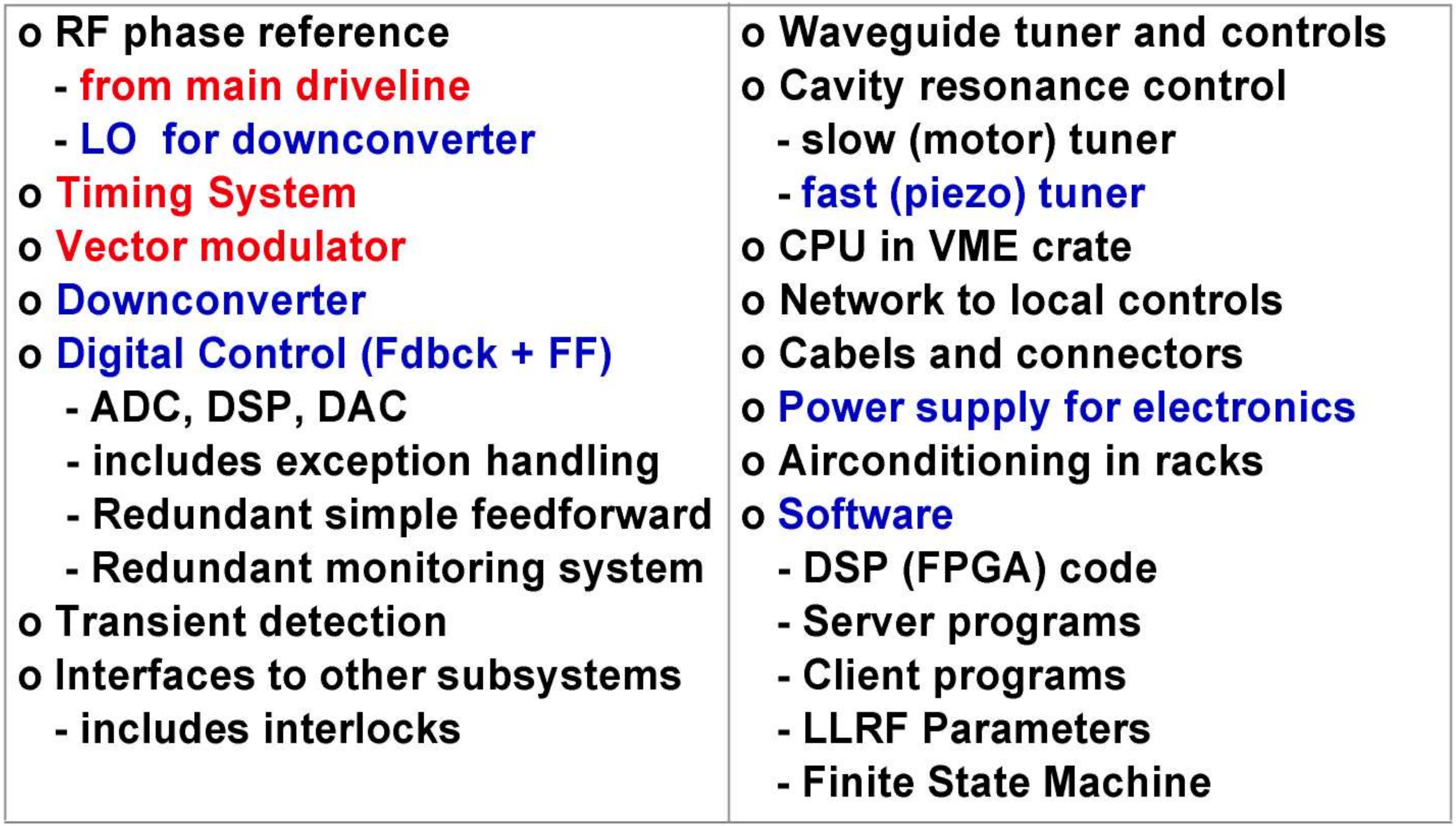
Variations in Loaded Q



8 cavities



Subsystem Susceptible to Failure



- o RF phase reference
  - from main driveline
  - LO for downconverter
- o Timing System
- o Vector modulator
- o Downconverter
- o Digital Control (Fdbck + FF)
  - ADC, DSP, DAC
  - includes exception handling
  - Redundant simple feedforward
  - Redundant monitoring system
- o Transient detection
- o Interfaces to other subsystems
  - includes interlocks

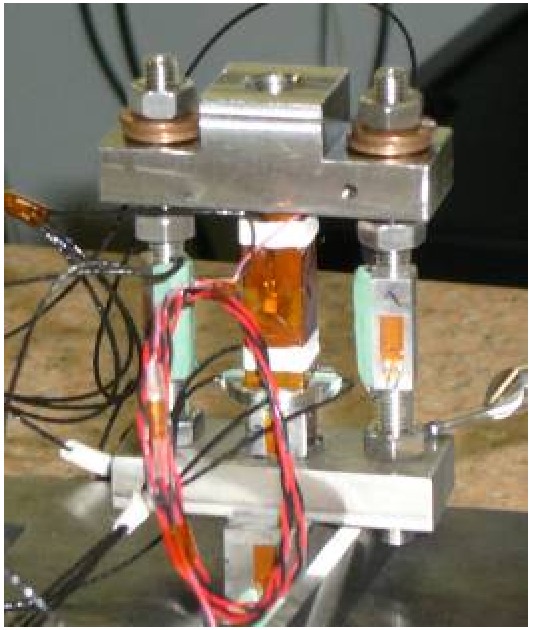
- o Waveguide tuner and controls
- o Cavity resonance control
  - slow (motor) tuner
  - fast (piezo) tuner
- o CPU in VME crate
- o Network to local controls
- o Cabels and connectors
- o Power supply for electronics
- o Airconditioning in racks
- o Software
  - DSP (FPGA) code
  - Server programs
  - Client programs
  - LLRF Parameters
  - Finite State Machine

Piezo Tuner

Calibrated "Bullet" Strain Gauge Sensor to measure preload changes during cooldown and stepping motor operation

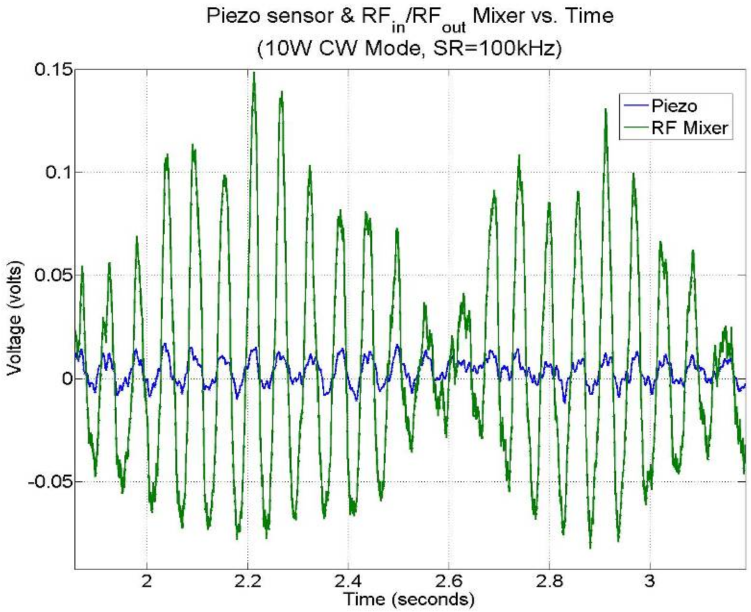
CC2 Piezo assembly instrumentation:

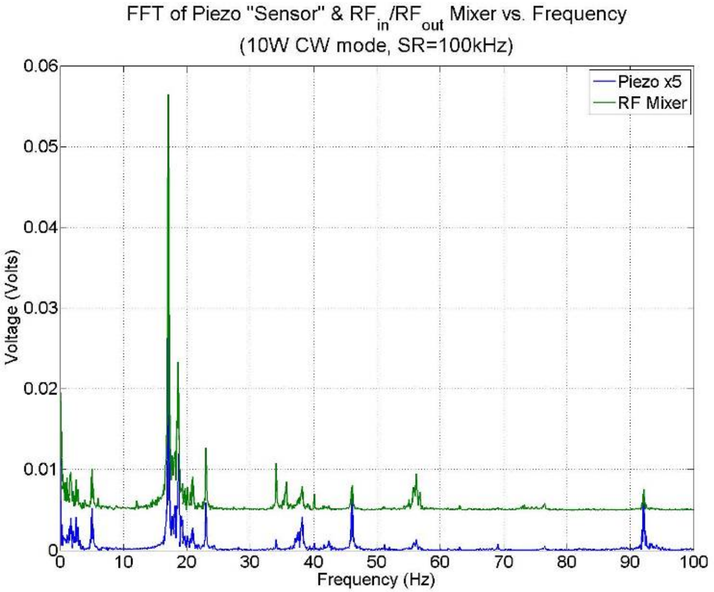
- 11 strain gauges
- 2 RTDs



Piezo as Vibration Sensor

Piezo Tuner & RF Mixer Measurement of CC2 @10W CW Mode





There is a good correlation between the Piezo Tuner and the RF Mixer in the time domain.

An FFT of the Piezo Tuner and the RF Mixer signals show close agreement in the frequency domain.

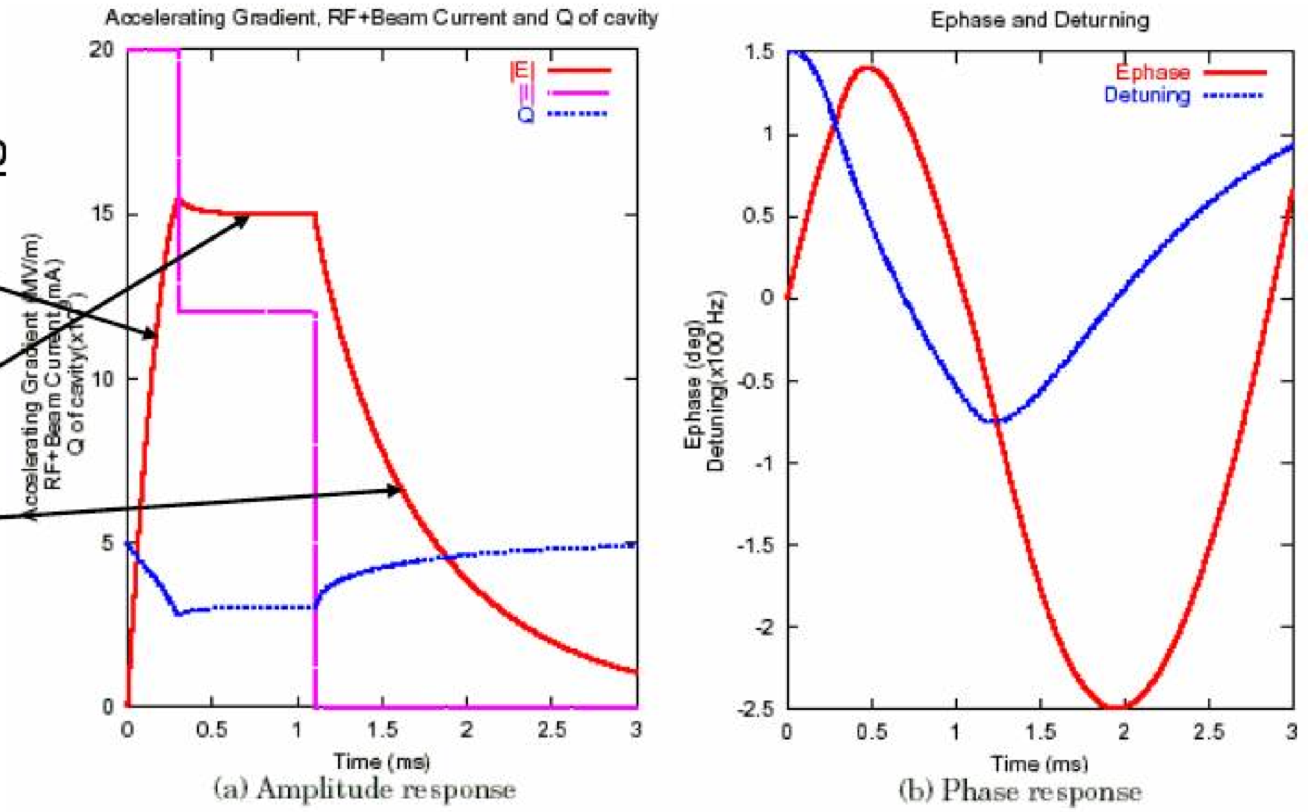
Real Time Cavity Simulator

Test run of ILC Cavity Simulator (no beam)

1)fill: 0 - 0.3 ms at 20 mA (full power)

2)flat-top: 0.3 -1.1 ms at 12 mA

3)cavity emptying, decay curve shows high Q of cavity.



(a) Amplitude response

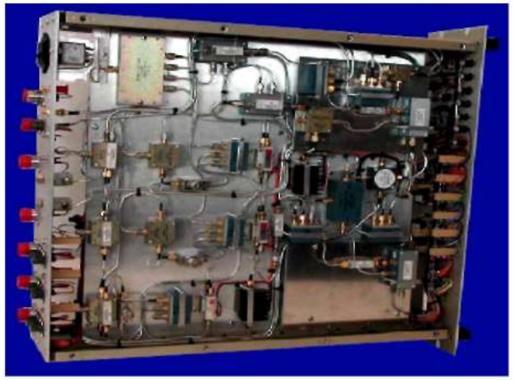
(b) Phase response

Compare with TESLA cavity measurements: **Shapes are similar, model is working.**

IF in these simulations is 50 MHz.

Evolution of Hardware at SNS

1st Generation
Control Chassis

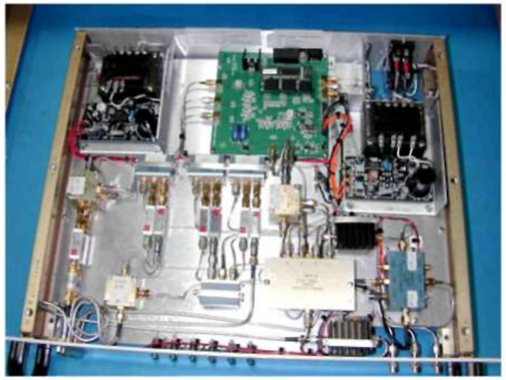


MEBT Rebunchers

4 installed, 1 spare

Retrofitted with FCM
Nov 04

2nd Generation
Control Chassis



RFQ & DTL

7 installed, 3 spares

Retrofitted with FCM
Jul 04

3rd Generation
Field Control Module

CCL, SCL & HEBT

Retrofit to MEBT, RFQ & DTL

98 systems + spares

Evolutionary Development: build on proven concepts, hardware and software

October 10, 2005

Lesson Learned at SNS

- Document the system requirements.
  - Avoid feature creep.
- Document the development plan.
- Make a resource-loaded schedule and budget.
- Use proven solutions. Don’t reinvent the wheel. Resist the “not invented here” syndrome.
- Keep it simple.
- If your schedule is at risk, ask for help.
- Your team must “take ownership” of the system.
- Software support and development is an integral and essential part of the process.
- Be willing to cross functional and subsystem boundaries.
- Avoid dictating the choice of software tools and languages if possible.

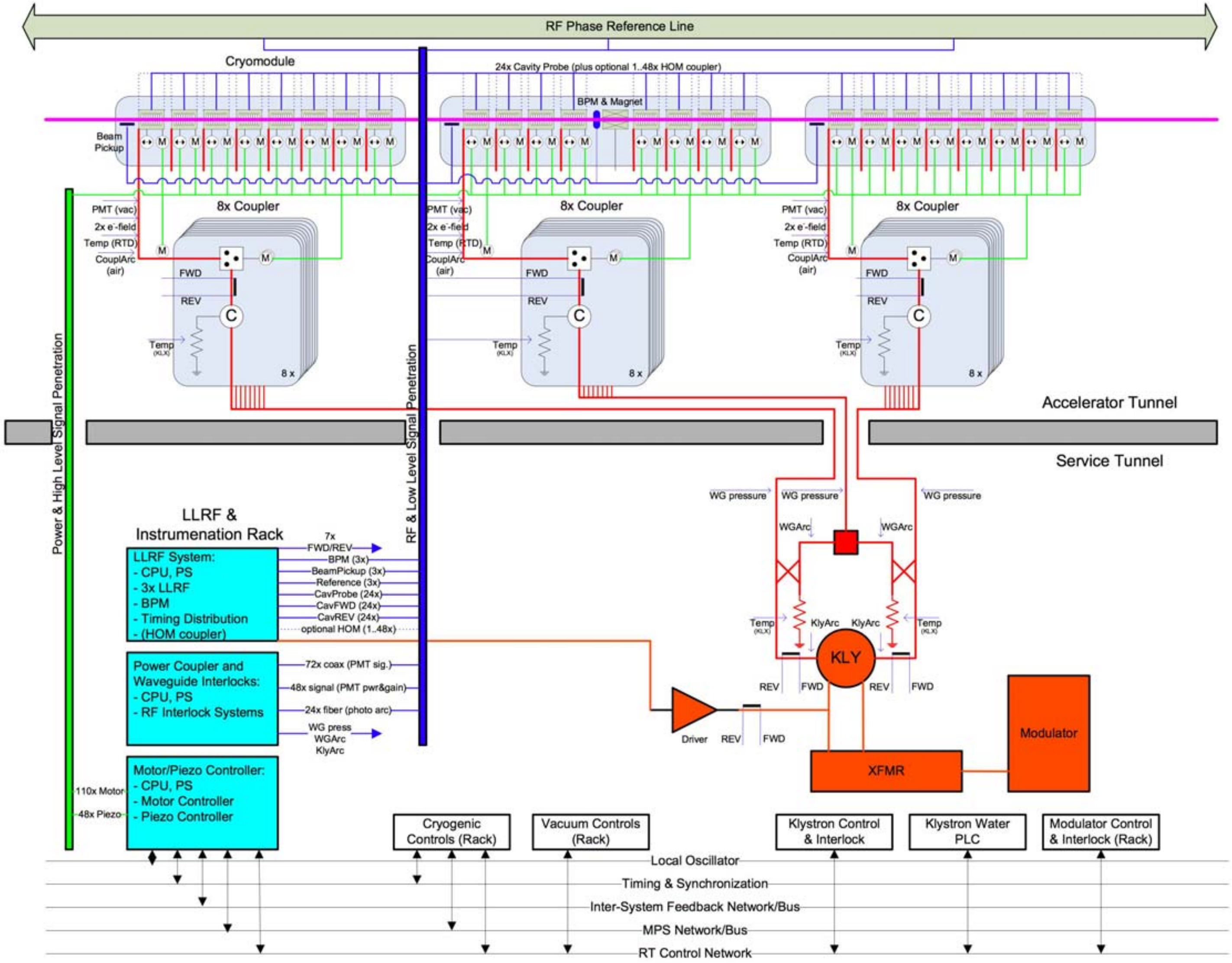
Ref. M. Champion

Advice for Hardware Development

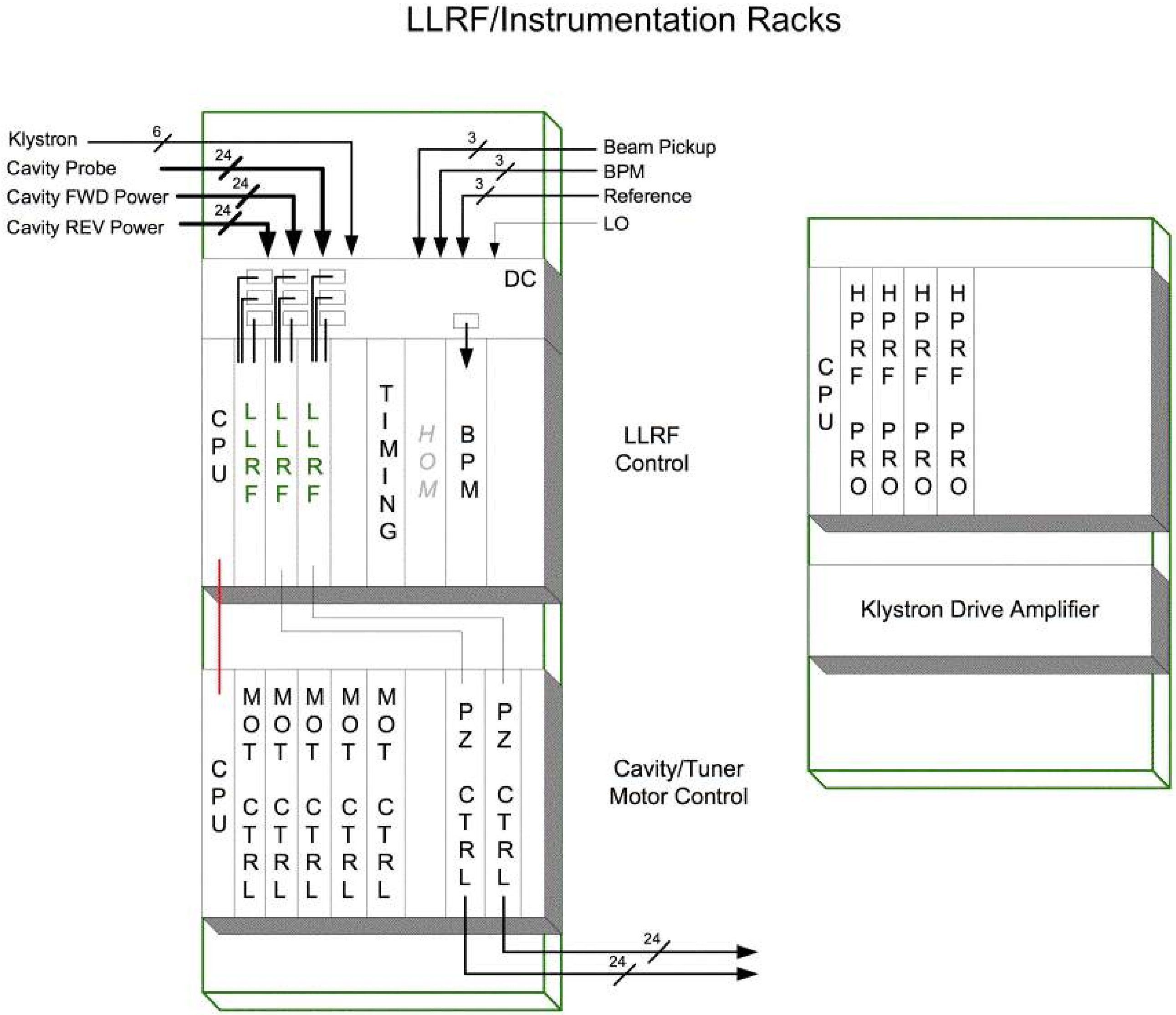
- Avoid early parts obsolescence.
- Install a RF PIN switch diode on your RF output.
- Install extra channels – you will need them later!
- Verify your parts can withstand a wet wash process following SMT assembly.
- Do not use epoxy-mount components (difficult to replace)
- Provide adequate shielding between motherboard and daughterboard.
- Provide "clean" DC power to your circuits.
  - Beware of DC-to-DC switching supplies. The switching frequency (usually 200 kHz) will find its way into your system!
- Don't waste your time building cables. Let a vendor do it.
- Use a symmetric layout for your ADC clock distribution and pay attention to impedance matching.
- Think about how you will test, troubleshoot and repair your circuit boards when you do your board design and layout (not after you receive the circuit boards)

Ref.: M. Champion

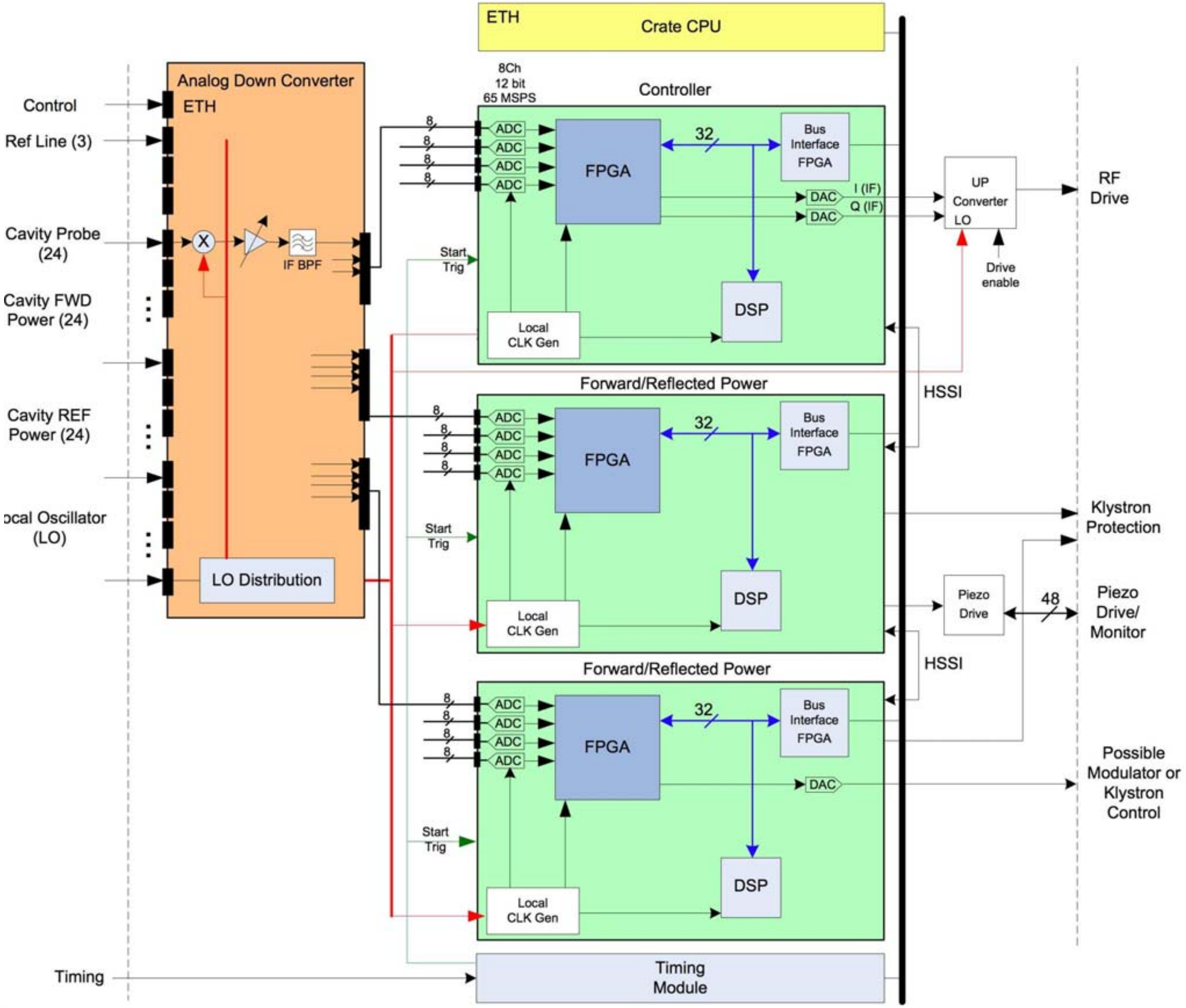
RF Station with 3 Cryomodules



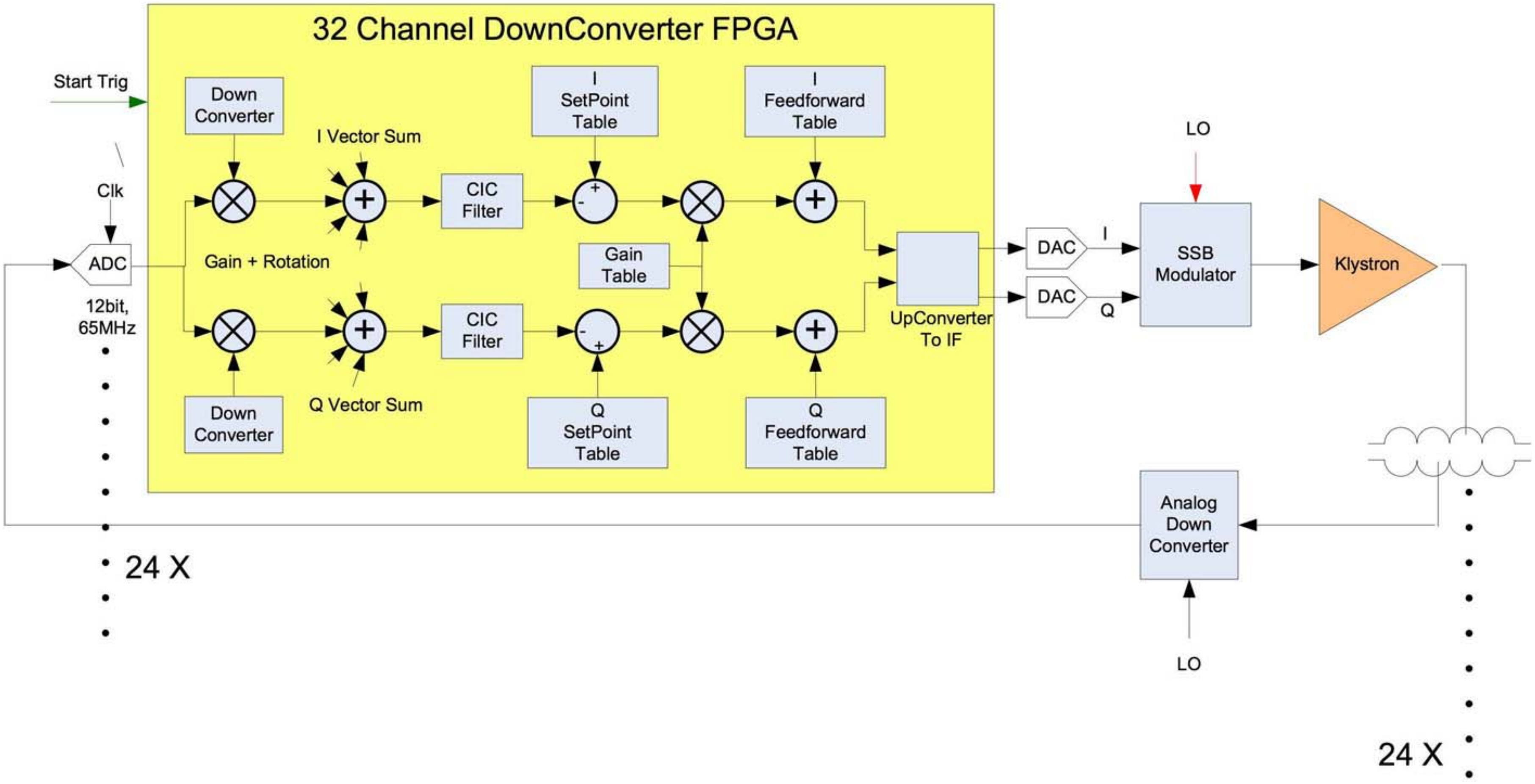
Rack Layout


LLRF/Instrumentation Racks
Klystron
6
Cavity Probe
24
Cavity FWD Power
24
Cavity REV Power
24
3
Beam Pickup
3
BPM
3
Reference
LO
DC
CPU
LLRF
LLRF
LLRF
TIMING
HOM
BPM
LLRF Control
CPU
MOT CTRL
MOT CTRL
MOT CTRL
MOT CTRL
MOT CTRL
PZ CTRL
PZ CTRL
Cavity/Tuner Motor Control
24
24
CPU
HPRF PRO
HPRF PRO
HPRF PRO
HPRF PRO
Klystron Drive Amplifier

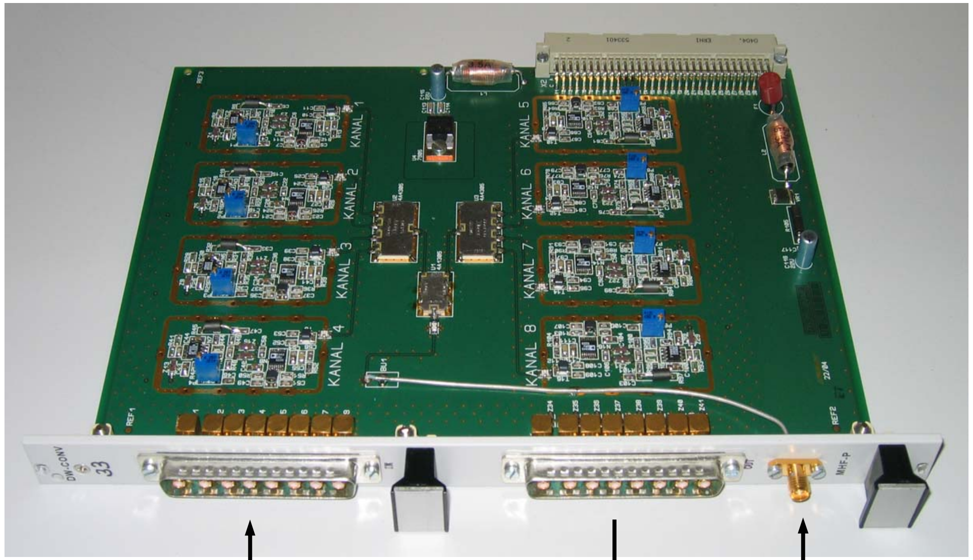
LLRF Rack Detail



LLRF Field Module Controller



Downconverter

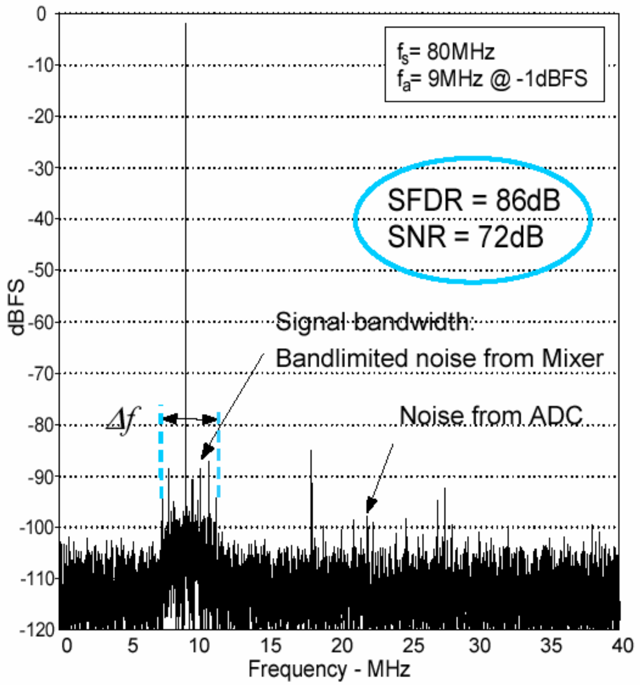


8-channels from cavity probe :

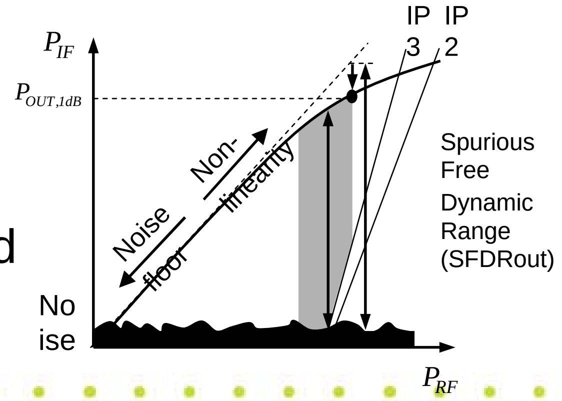
8-channels to ADC-Board :

LO-Input :

- **SNR for oversampling :**

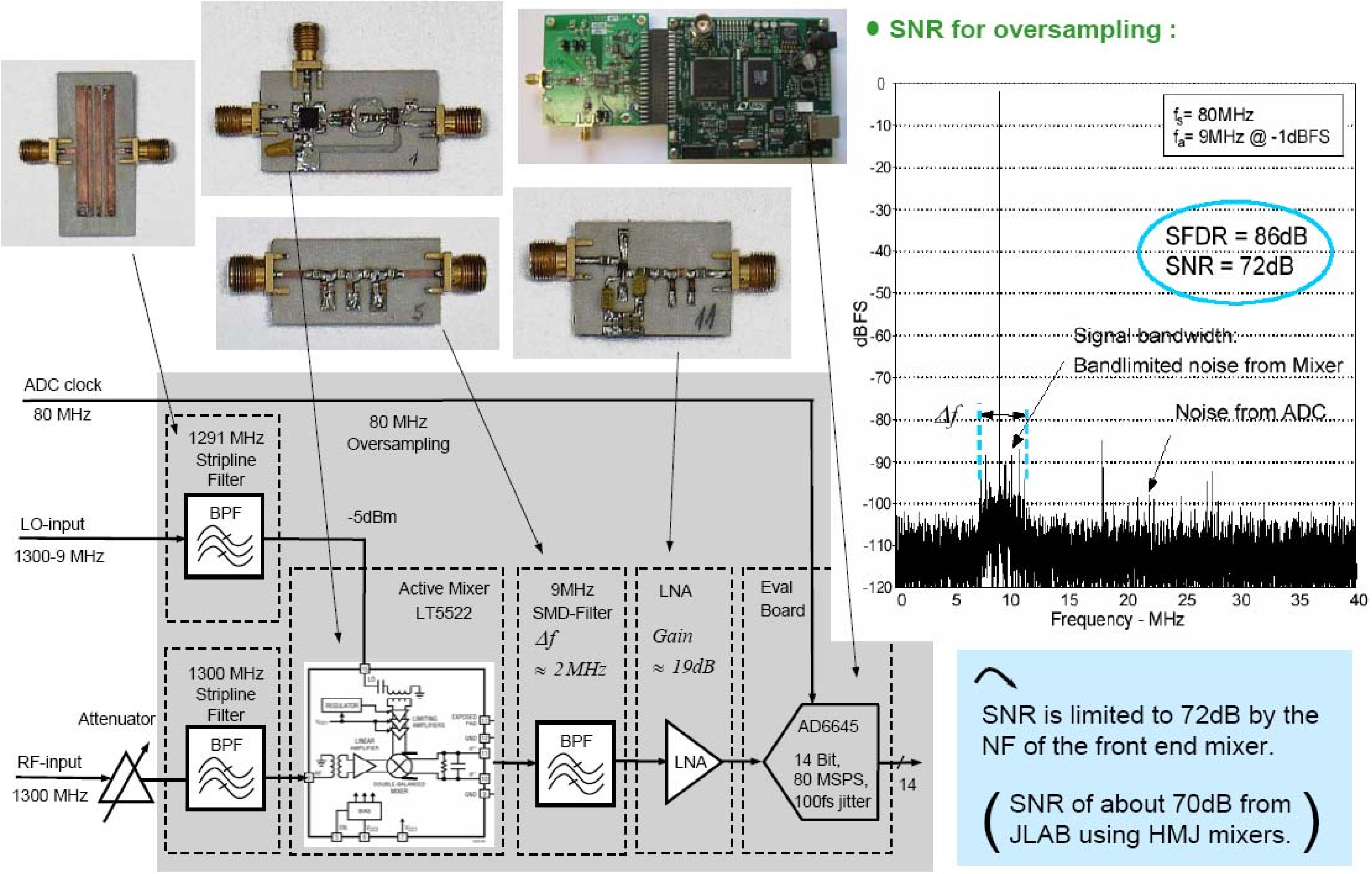


Compromise between noise and linearity



Gilbert Cell Mixer

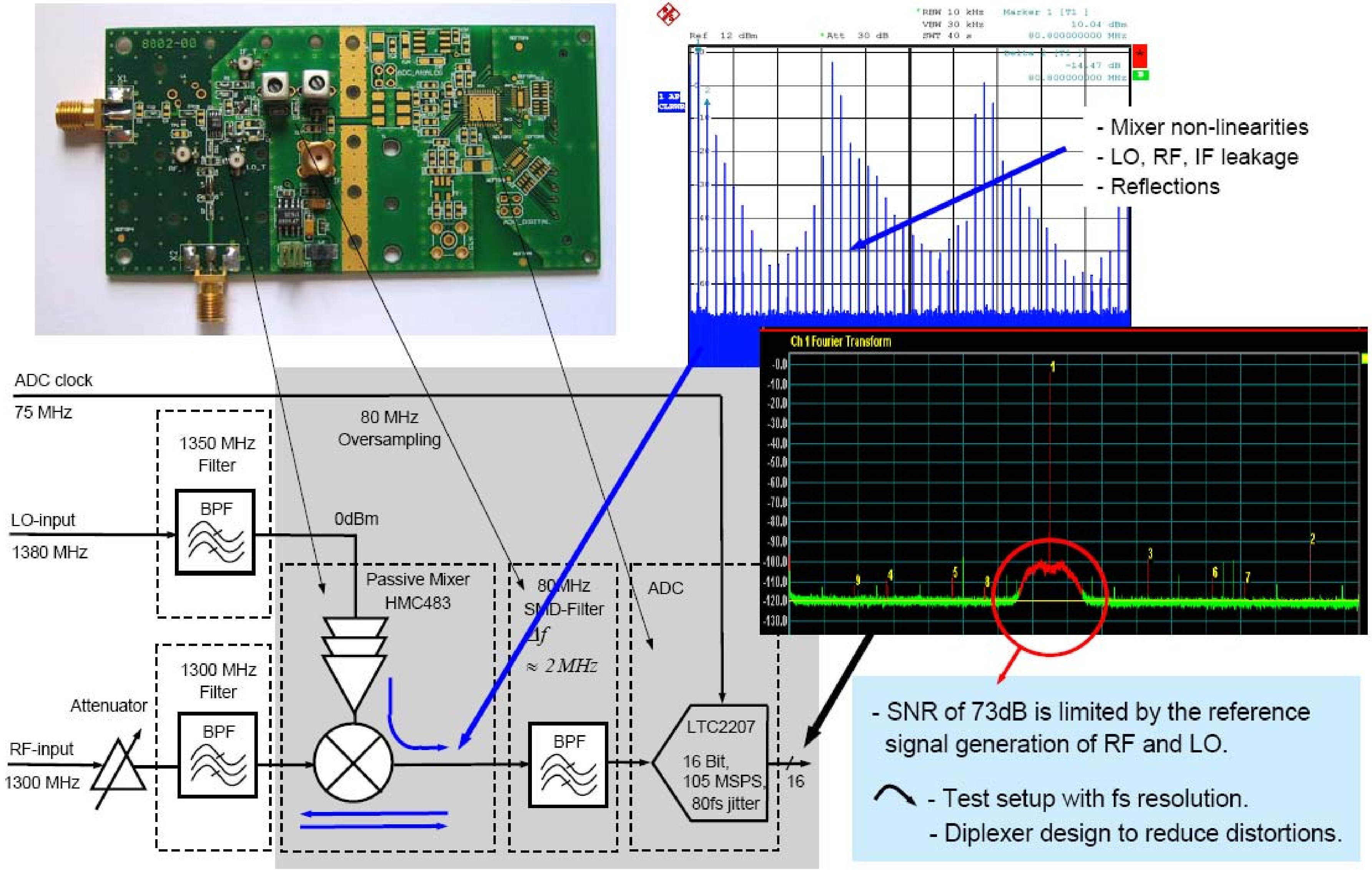
- **SNR for oversampling :**



SNR is limited to 72dB by the NF of the front end mixer.

(SNR of about 70dB from JLAB using HMJ mixers.)

Passive Mixer

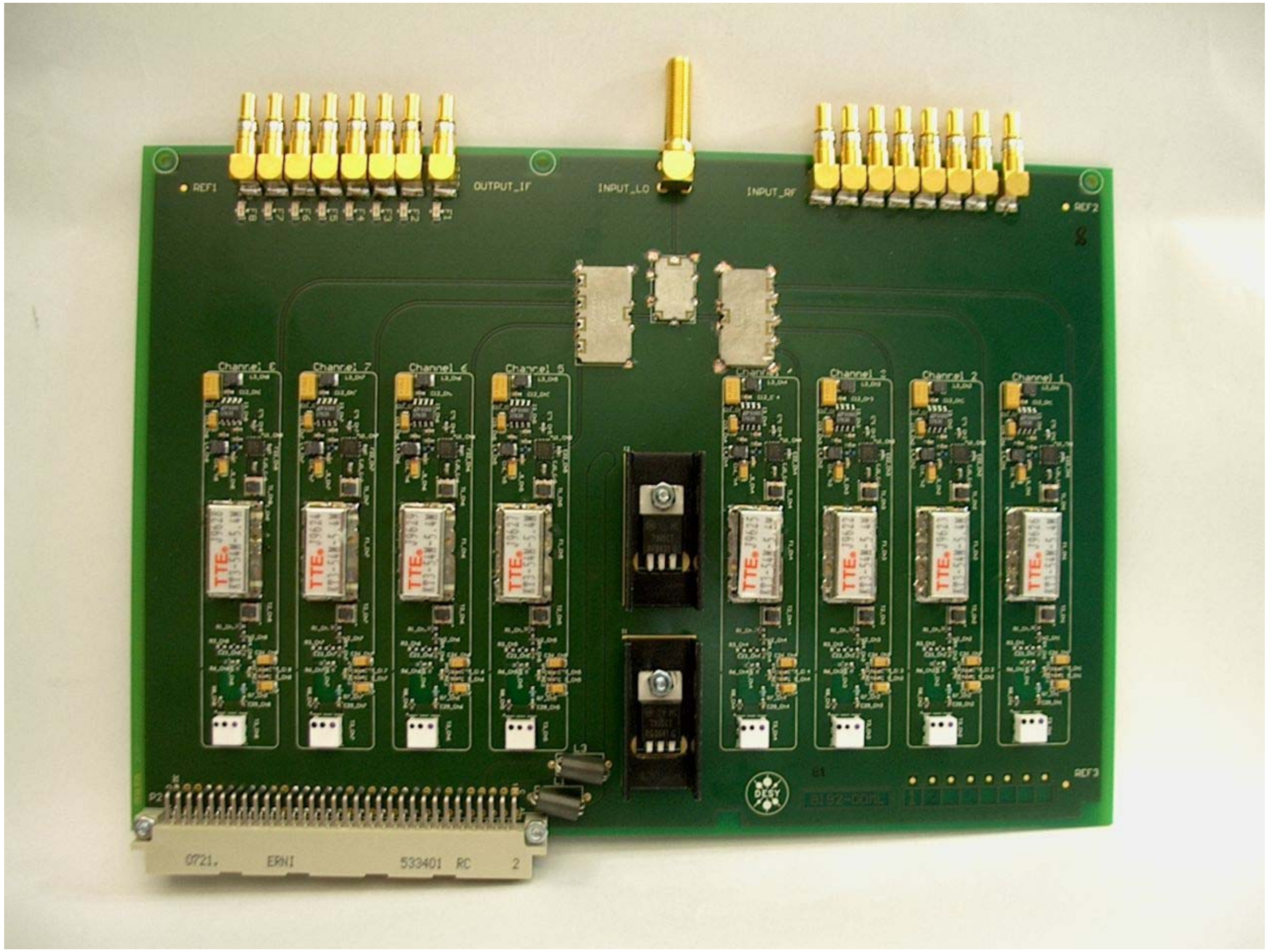


- Mixer non-linearities
- LO, RF, IF leakage
- Reflections

- SNR of 73dB is limited by the reference signal generation of RF and LO.

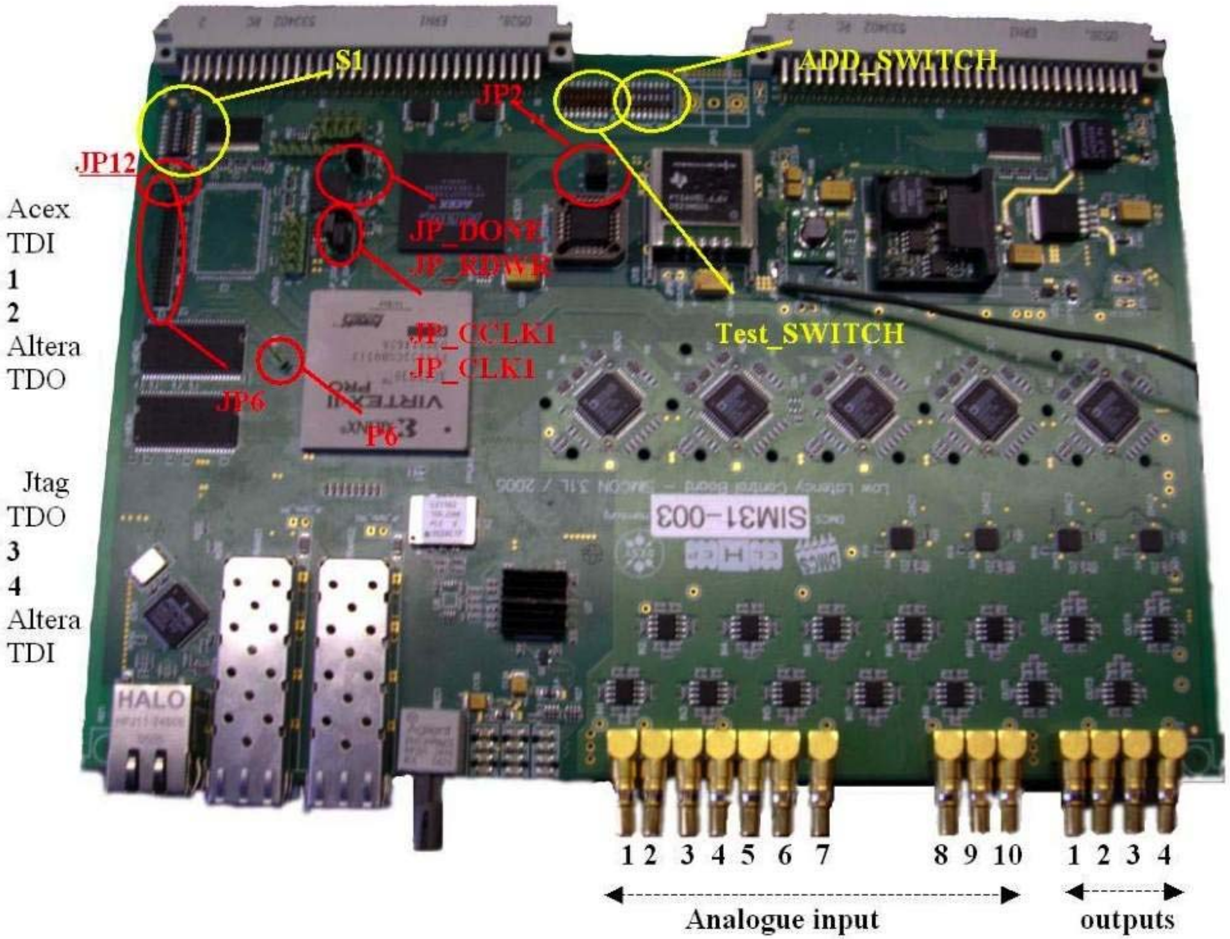
- Test setup with fs resolution.
- Diplexer design to reduce distortions.

8-channel downconverter



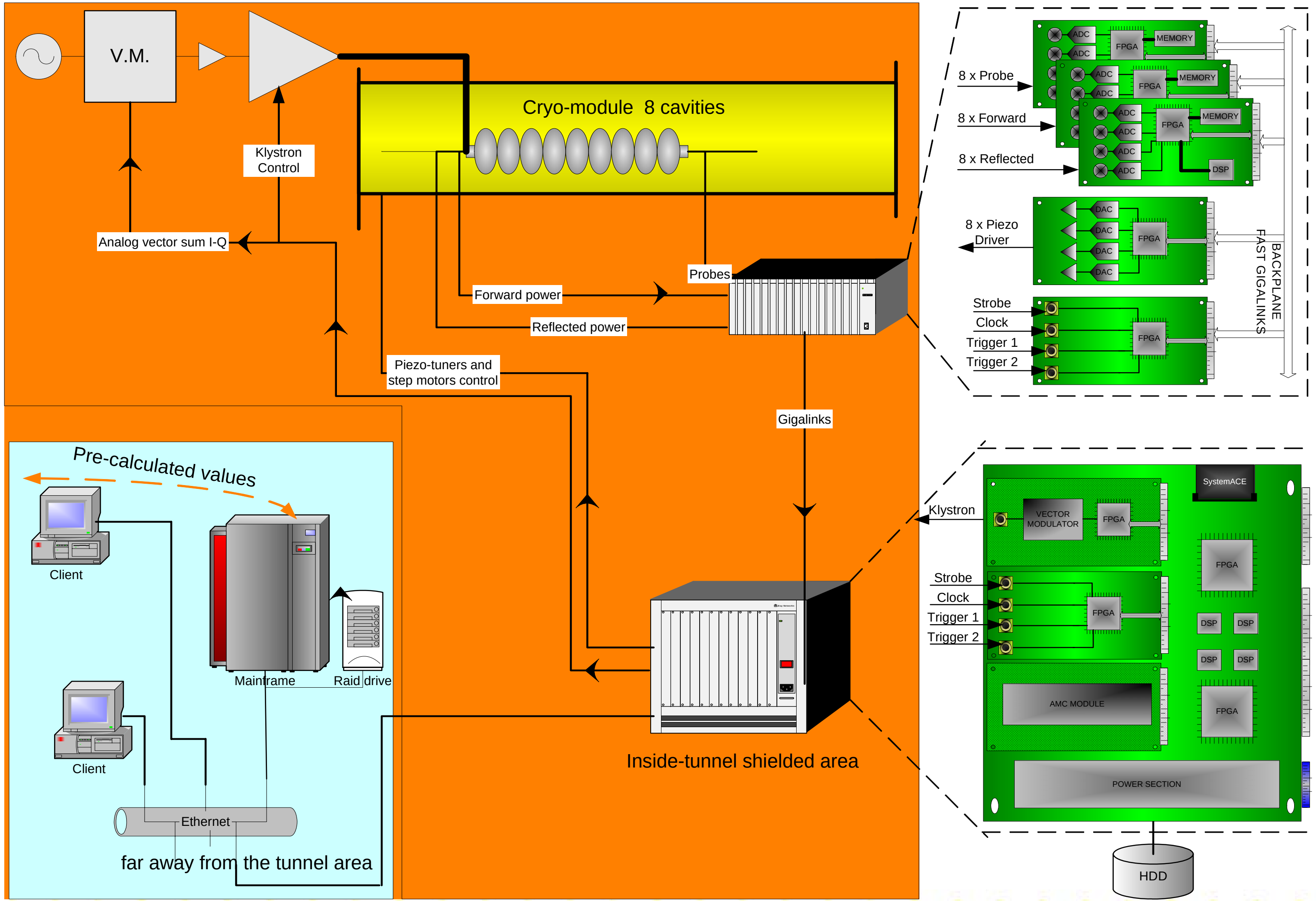
DESY SIMCON 3.1 Controller

2.SIMCON3.1 board description and schematics.

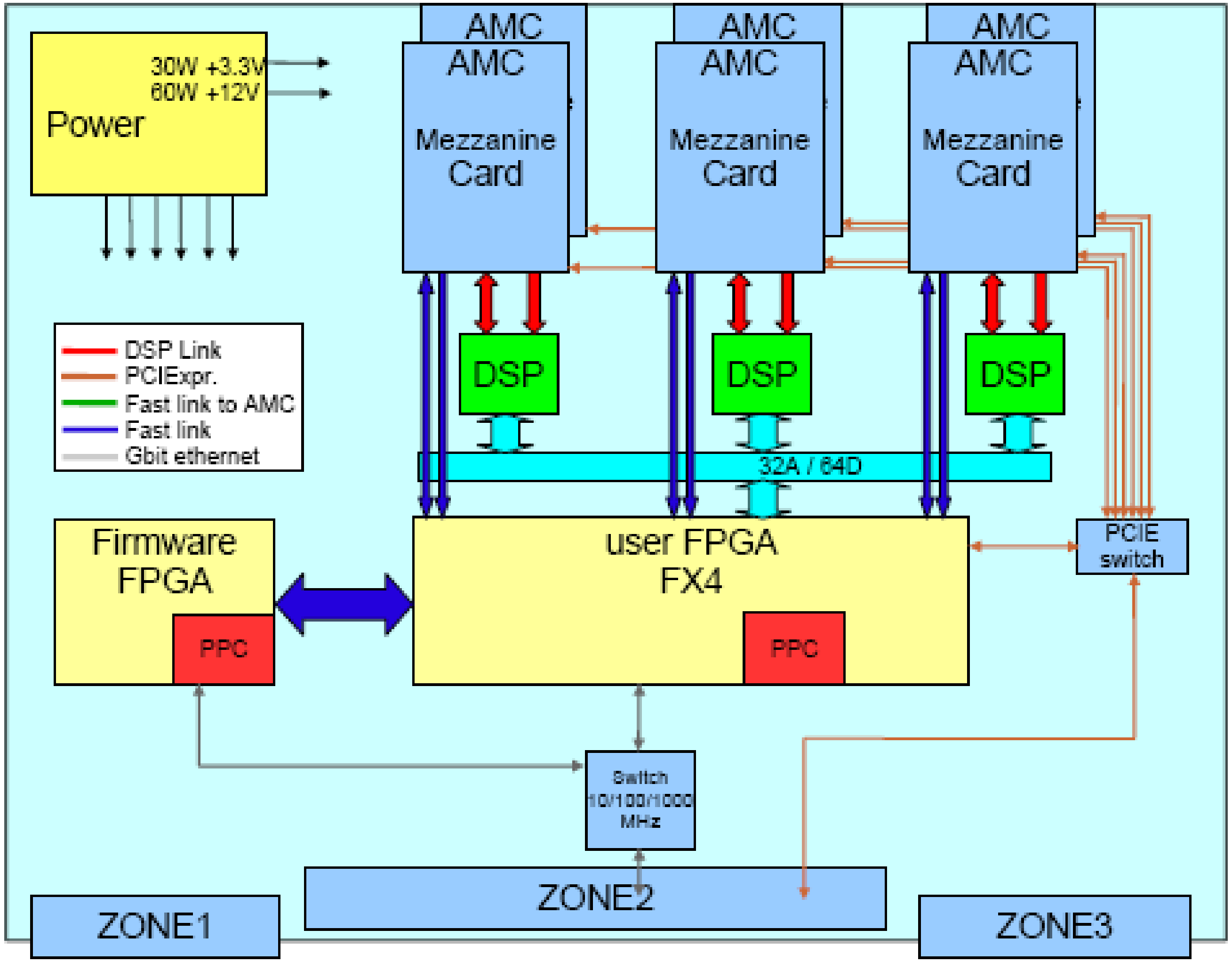


Next generation: SIMCON DSP

Next generation: ATCA

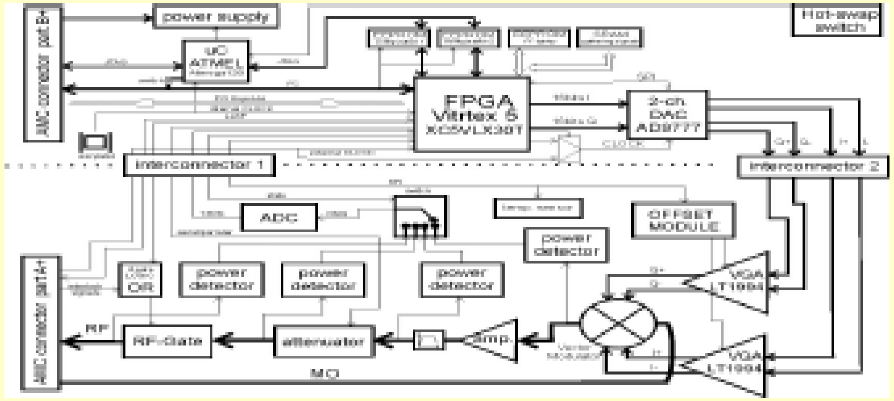


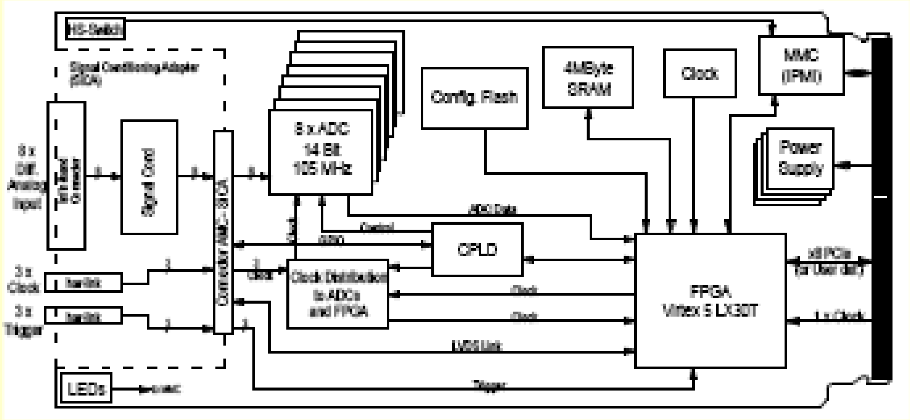
Architecture of carrier board



AMC Modules

- ***All modules:***
  - IPMI v. 1.5
  - PCIExpress
  - Fast link to the carrier (10 differential pairs)
  - Virtex 5
- ***8 channels "slow" ADC board***
  - 14 bits
  - BW 200 MHz
  - SF ext. & int. up 105 MHz
- ***2 channels. "fast" ADC board***
  - BW 1 GHz
  - 10 bits
  - SF 1-2.5 GHz
- ***Timing Module***
  - Receive coded clock signal, produces 6 different clocks
- ***Vector Modulator***
  - Digital input
  - 1.3 GHz, 0dBm

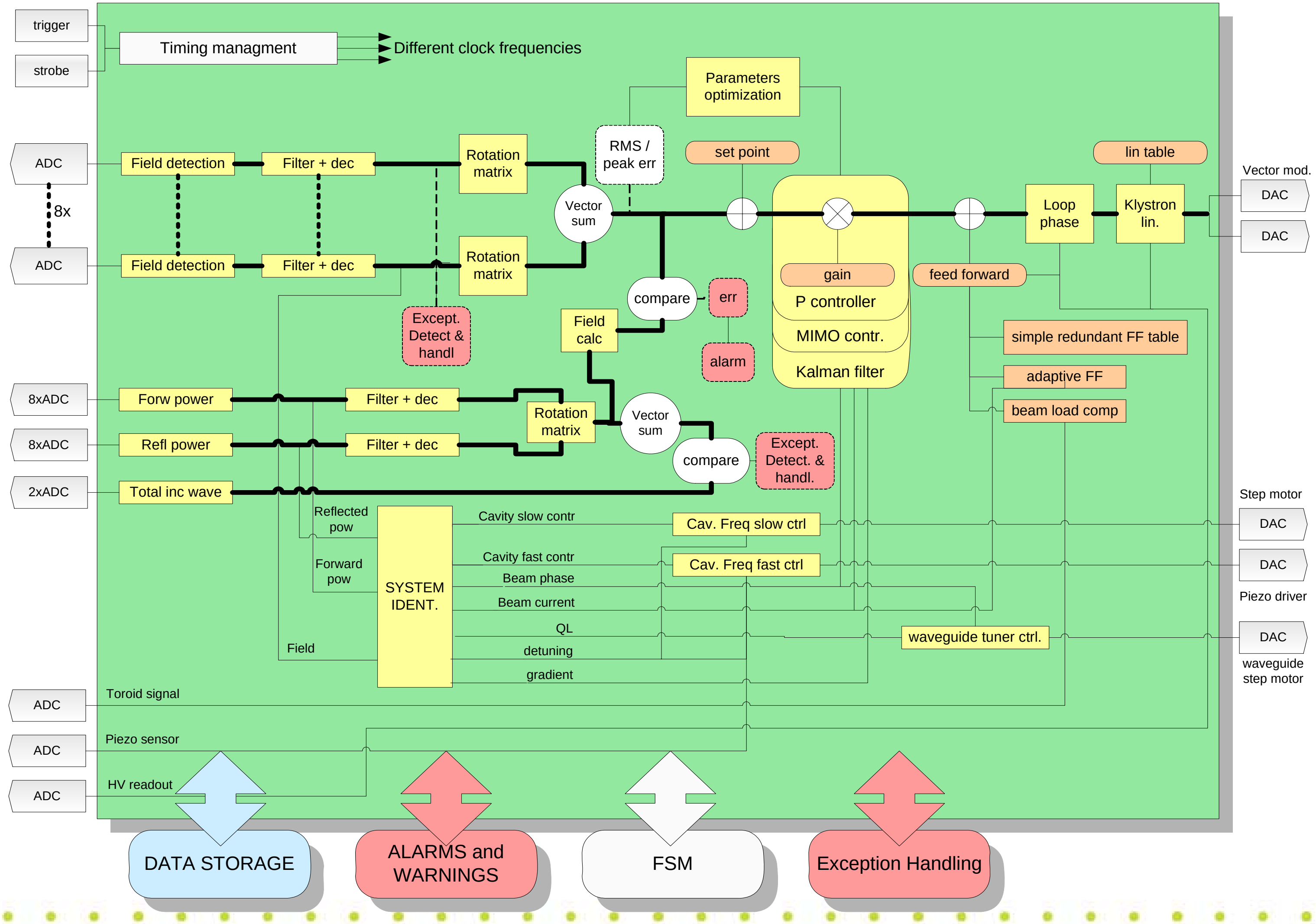




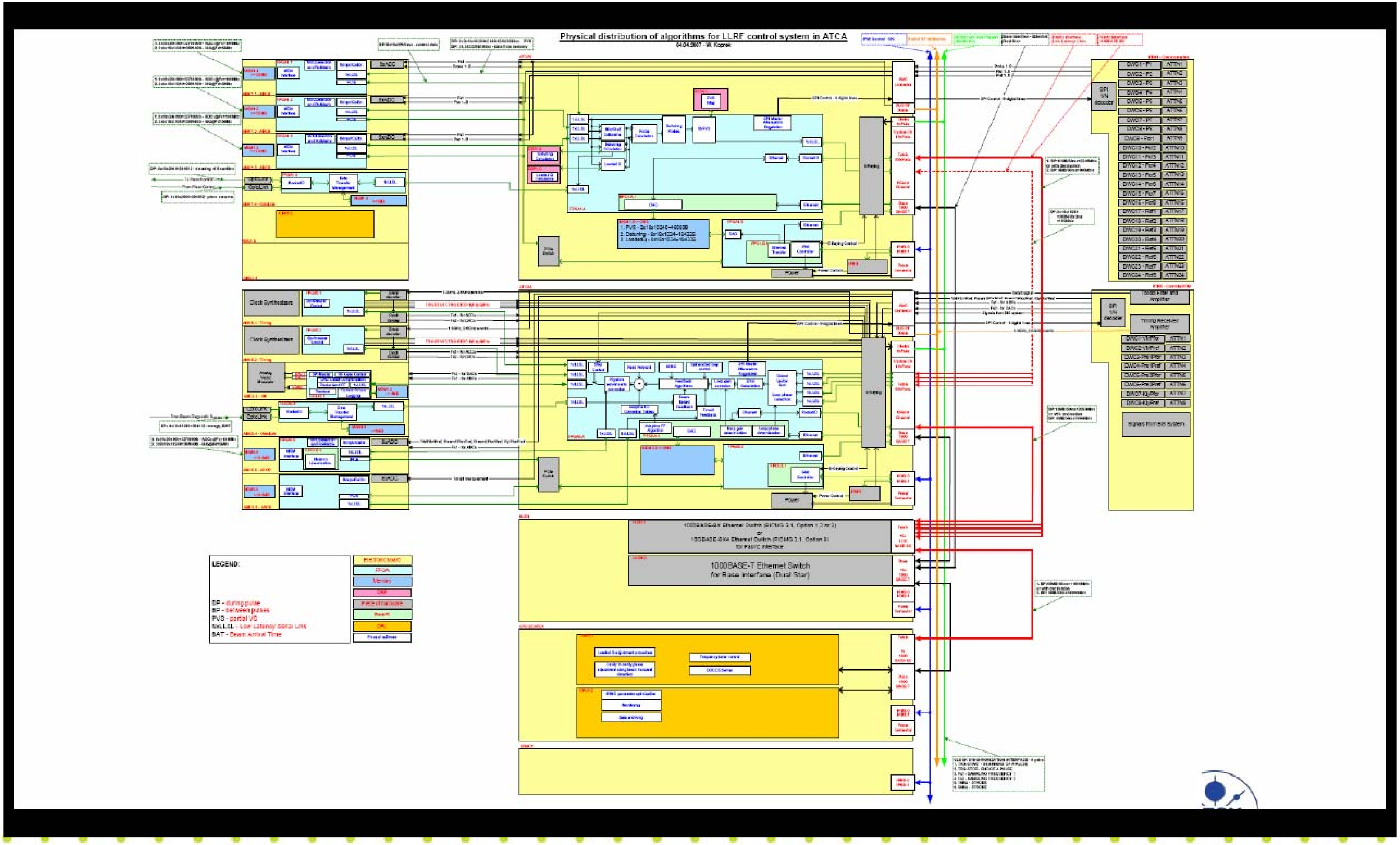
Software Modules (Examples)

- Control Algorithms (Fdbck/ Feedforward)
- Meas. QL and detuning
- Cavity Frequency Control (Fast and Slow)
- Amplitude/Phase Calibration
- Vector-Sum Calibration
- Loop phase and loop gain
- Adaptive Feedforward
- Exception Handling
- Klystron Linearization
- Lorentz Force Compensation

Software Architecture



Software Architecture with Comm. Links



Example Use Cases for Acc. Section

- **Basic Use Cases**
- Set and maintain beam end energy or energy gain and phase of accelerator section
- Stabilize end energy with use of beam based feedback
- Monitor radiation levels (neutrons and gammas) in real time

- **Advanced Use Cases**
- Limit field emission and cryo heatload
- Provide rf pulses for machine studies
- Conditioning of cavities/couplers
- Assess performance and limitations of accelerator section
- Diagnose problems and identify the source especially if beam quality is unsatisfactory.

Example Use Cases for RF Station

- **Basic Use Cases**
- Establish moderate RF power and cavity gradients
- Enable and perform measurements of all LLRF relevant signals
- Stabilize fields for beam operation

- **Advanced Use Cases**
- Set parameters to maximize availability during beam operation
- Optimize parameters for best beam stability
- Assess performance and performance limitations of rf station
- Diagnose problems and identify the source (hardware/software)
- Detect and handle exceptions

Examples for Scenarios

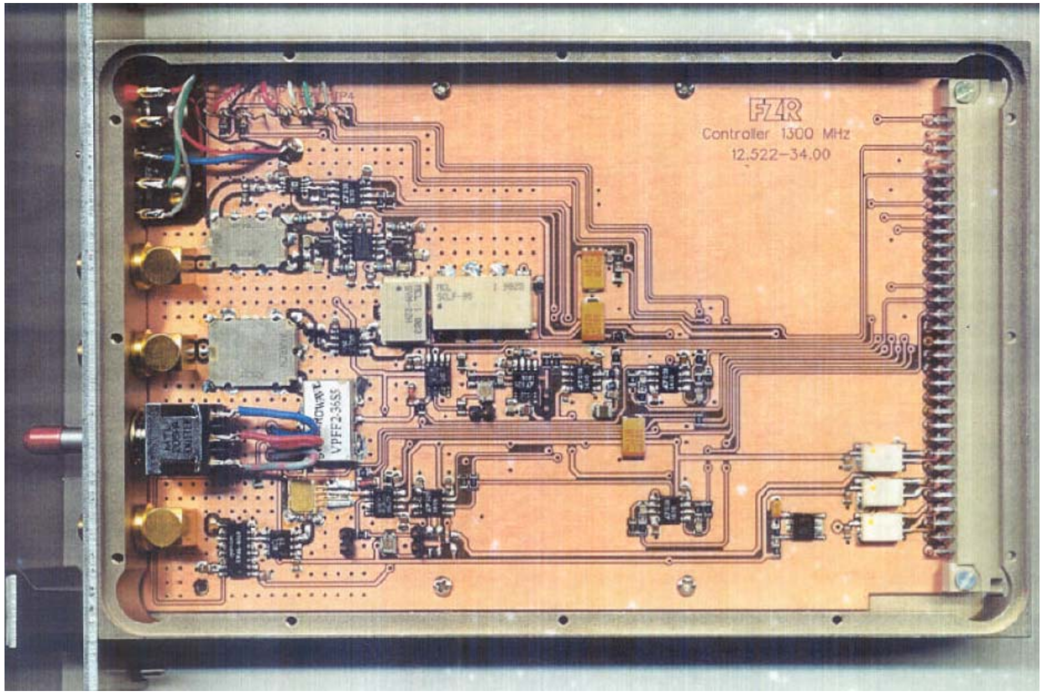
- 1. Coarse tuning of cavity resonance with motor tuner
- 2. Compensate Lorenz force detuning
- 3. By-pass (and un-bypass) cavities
- 4. Adjust klystron HV for sufficient power margin
- 5. Set correct timing
- .. rf gate, rf pulse, klystron HV, flat-top with respect to beam
- 6. Limit field emission in cavities
- 7. Apply adaptive feedforward
- 8. (Re)-start missing or faulty llrf servers
- 9. (Re)-calibrate rf station
- 10. Calibrate vector-sum with full beam loading
- 11. Correct downconverter linearity
- 12. Klystron linearization

Work breakdown for the LLRF project

- Risk Assessment
- **LLRF Project Management**
- Major System Requirements

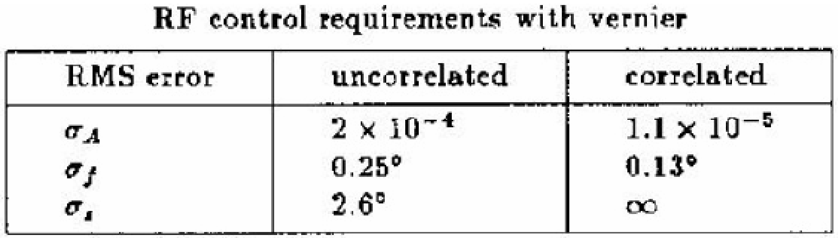
- **Hardware**
  - 1.1 MO & distr.
  - 1.2 Digital Feedback
  - 1.3 Field det. & Actuators
  - 1.4 Piezo Control
  - 1.5 Radiation monitoring
  - 1.6 Communication interfaces
  - 1.7 Slow control
- **Software**
  - 2.1 Controller
  - 2.2 Low Level Applications
  - 2.3 High Level Applications
  - 2.4 Communication protocols
  - 2.5 Control system (DOOCS)
- **Infrastructure Inst/Maint.**
  - 3.1 Cabling
  - 3.2 Racks and crate
  - 3.3 Documentation and Operation Manuals
  - 3.4 QA and QC
  - 3.5 Redundancy, Availability Analysis
  - 3.6 System integration
  - 3.7 Installation in FLASH/MTS/XFEL
- **Commissioning/ Operation**
  - 4.1 Operation and Evaluation in FLASH/MTS
  - 4.2 Procedures
  - 4.3 Automation
  - 4.4 Diagnostics
  - 4.5 Simulation
- **Special Topics**
  - 5.1 Transients detection
  - 5.2 WGT Control
  - 5.3 Interfaces to other systems
  - 5.4 Radiation Immunity
  - 5.5 Calibration parameters database

Rossendorf / ERLP (Daresbury)



- Developed for cw operation of 1.3 GHz s.c. cavities at ELBE
- Analog amplitude and phase control
- Achieved very good field stability at QL=107:
  - 0.02% in amplitude
  - 0.03 deg in phase
- Adopted by Daresbury for the ERL Prototype

CEBAF LLRF 1993

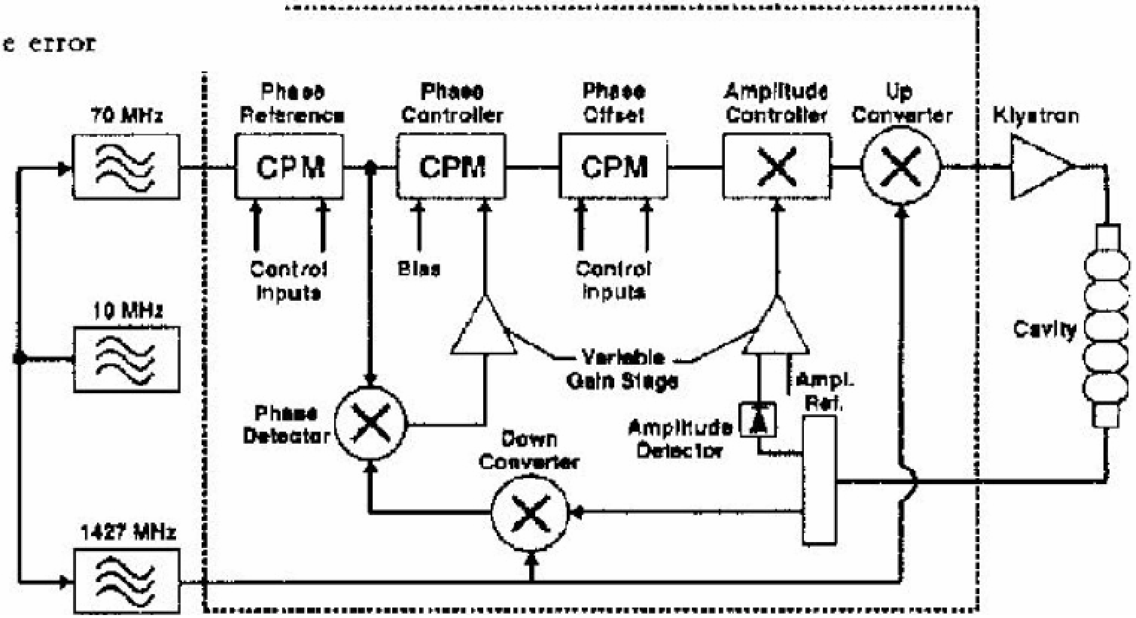


RF control requirements with vernier

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

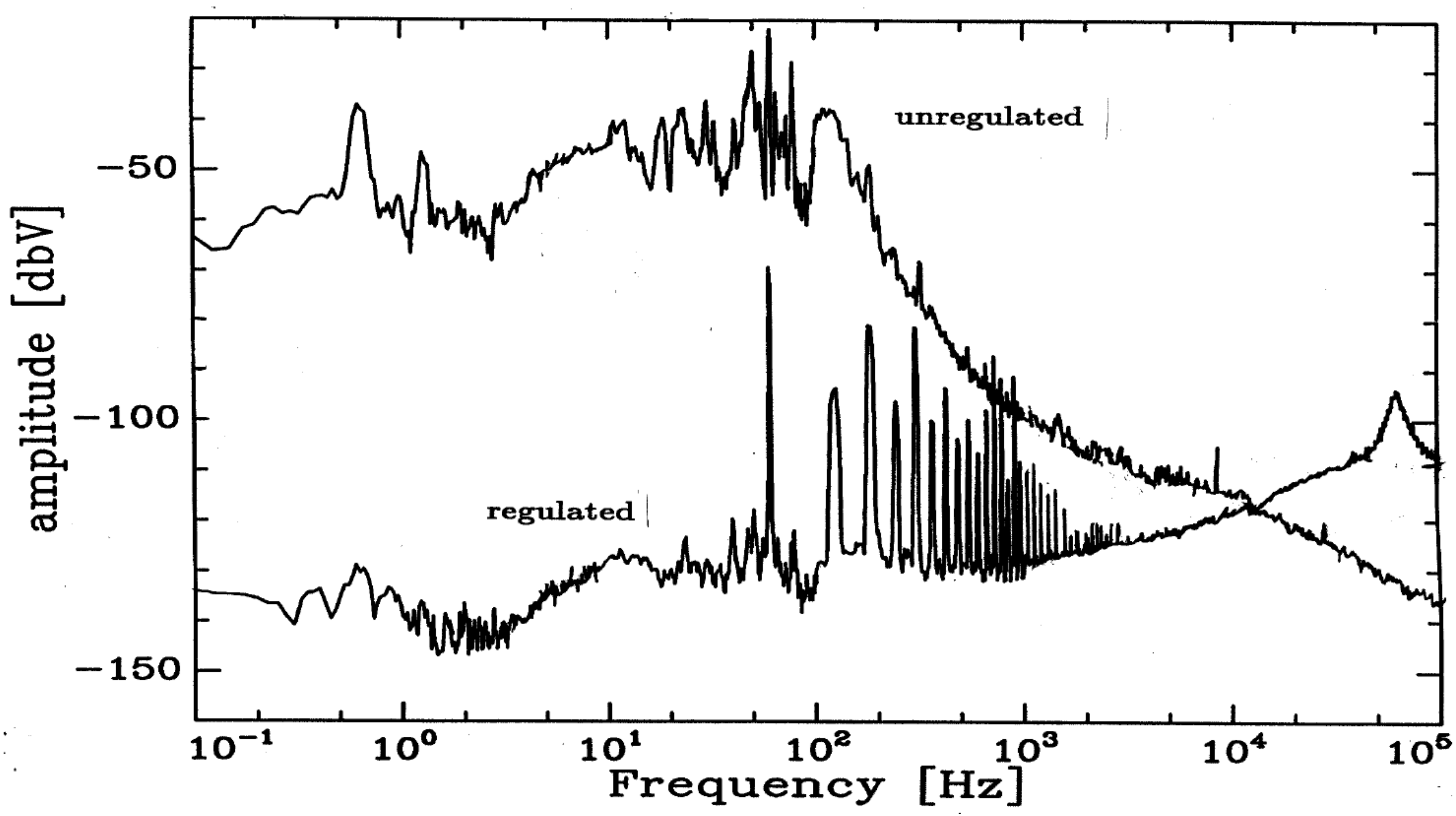
σ_A : relative RMS amplitude error
σ_f : fast RMS phase error
σ_s : slow RMS (along linac) phase error

Loaded Q $\approx 7 \cdot 10^6$
< 12 MV/m
I $\approx$ 400 μA



Achieved stability: about 0.007 %, 0.02 deg !

Spectrum of noise sources at JLAB



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