Low Power RF (LLRF) Part I

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DESY, Hamburg, Germany

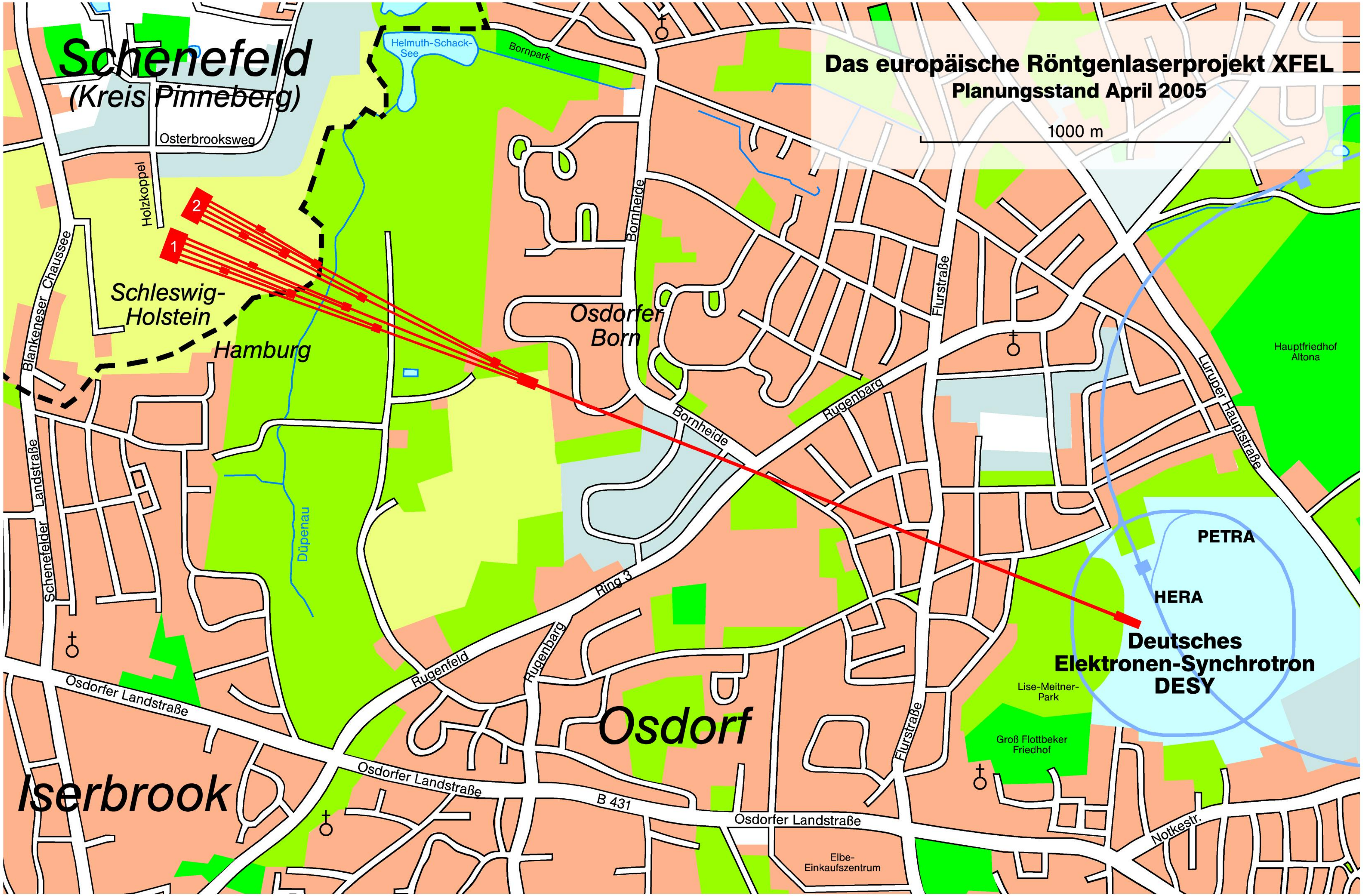
Lecture Schedule (March 2008)

- LLRF Part I (Requirements and Design)
  - March 6, 13:30
- LLRF Part 2 (Maschine Studies at FLASH)
  - March 7: 10:00
- LLRF Part 3 (LLRF for the XFEL)
  - March 11 at 13:30
- Timing and Sync. Part I (Concepts)
  - March 14 at 10:00
- Timing and Sync. Part II (Design)
  - March 17 at 10:00
- European XFEL (Project Overview)
  - March 26 at 13:30

Outline LLRF Part I

- FLASH European XFEL
- RF System
- LLRF
  - Requirements
  - Sources of perturbation
  - Control Concept
  - Performance at FLASH
- Conclusion


HERA
PETRA



Das europäische Röntgenlaserprojekt XFEL
Planungsstand April 2005
1000 m
Schenefeld
(Kreis Pinneberg)
Osterbrooksweg
Helmuth-Schack-See
Bornpark
Holzkoppel
2
1
Schleswig-Holstein
Hamburg
Blankeneser Chaussee
Osdorfer Born
Bornheide
Flurstraße
Rugenbarg
Hauptfriedhof Altona
Luruper Hauptstraße
Landstraße
Schenefelder
Düpenau
Ring 3
PETRA
HERA
Deutsches
Elektronen-Synchrotron
DESY
Lise-Meitner-Park
Groß Flottbeker Friedhof
Rugenfeld
Osdorfer Landstraße
Osdorf
Iserbrook
B 431
Notkestr.
Elbe-Einkaufszentrum

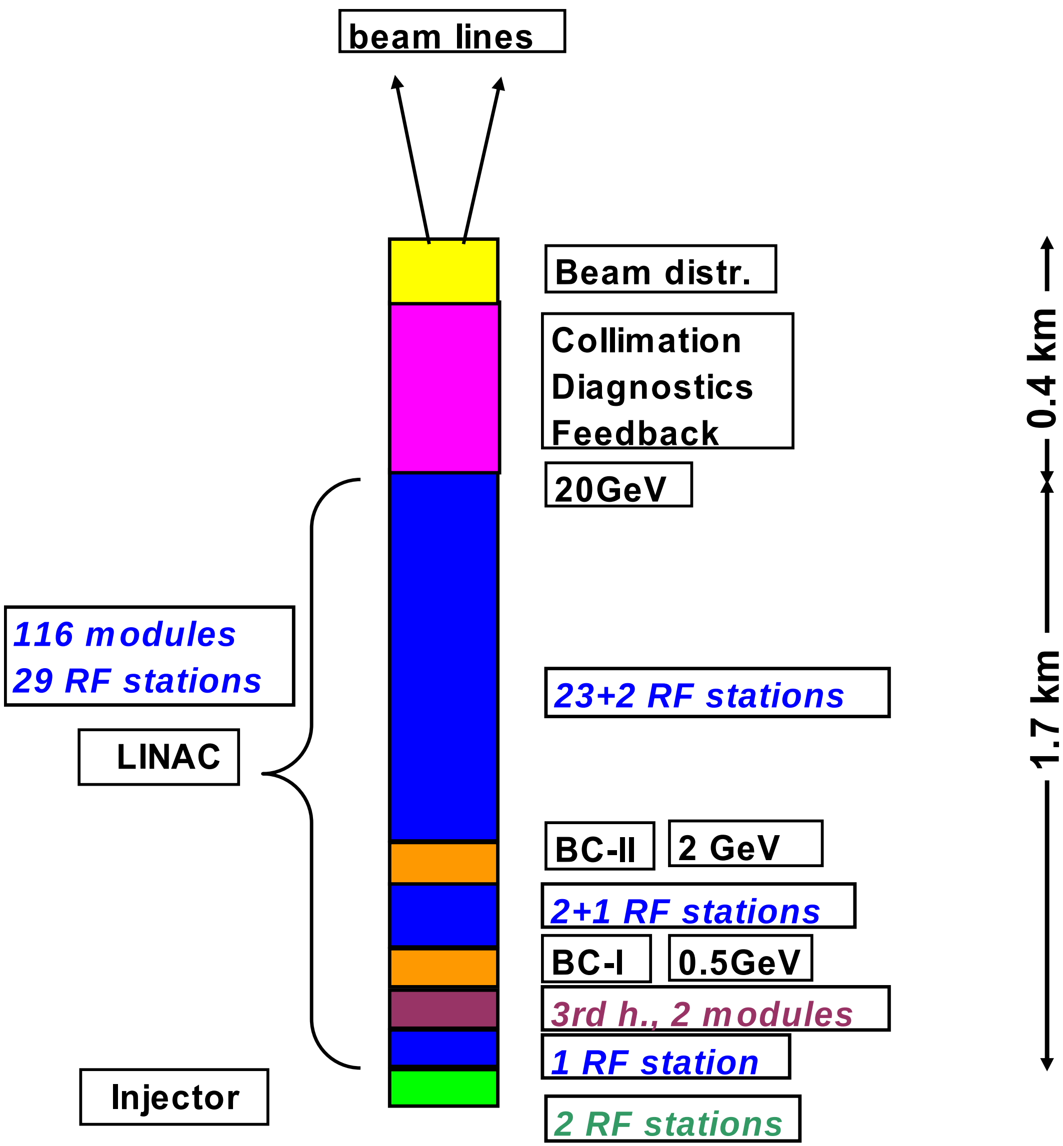
layout supports high availability since … the XFEL Linac …

XFEL Linac:

100 – 500 MeV
- 4 acc.mod.
- 32 cavities at 12.5 MV/m
- RF station outside tunnel

500 – 2000 MeV
- 12 acc.modules
- 96 cavities at 15.1 MV/m or
- 64 cavities at 22.6 MV/m
- (2 + 1) RF stations inside tunnel

2 – 20 GeV
- (23 + 2) x 4 = 100 acc.modules
- 800 cavities at 21.7 MV/m or
- 736 cavities at 23.6 MV/m
- (23 + 2) RF stations inside tunnel



FLASH and XFEL
Time to explore the femtosecond dynamics of nature

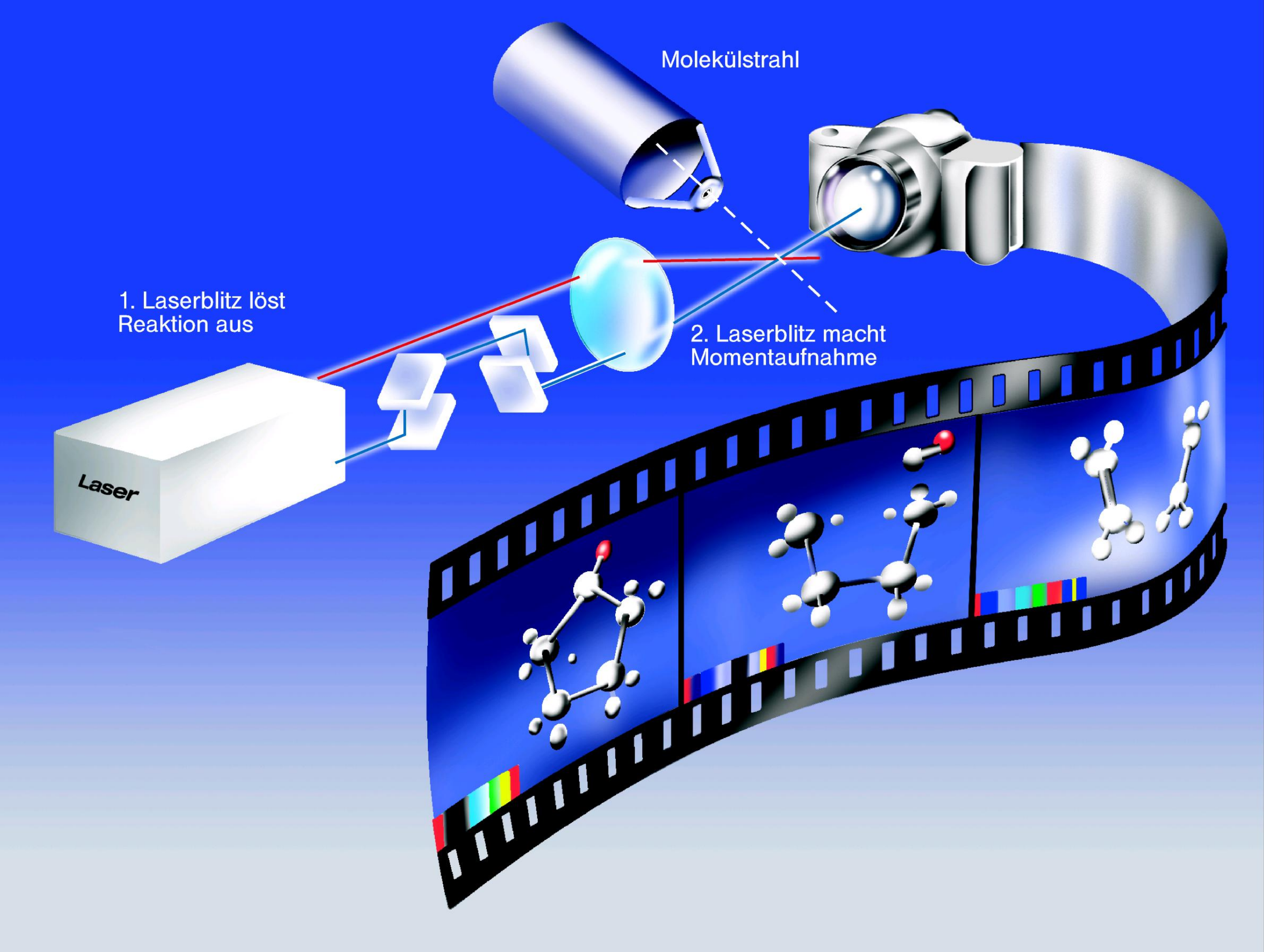
- ***Ever seen the machinery of a living cell at work at atomic resolution?***

- ***Observed how molecules change shape in femtoseconds during chemical or biochemical reactions?***

- ***Watched a drug molecule enter a protein receptor in real time?***

Soon X-ray free-electron lasers will enable us to probe ultra fast physical, chemical and biochemical processes at atomic resolution, opening new frontiers for science and technology.
At long last we may see, and not just model, how molecular machines really work.

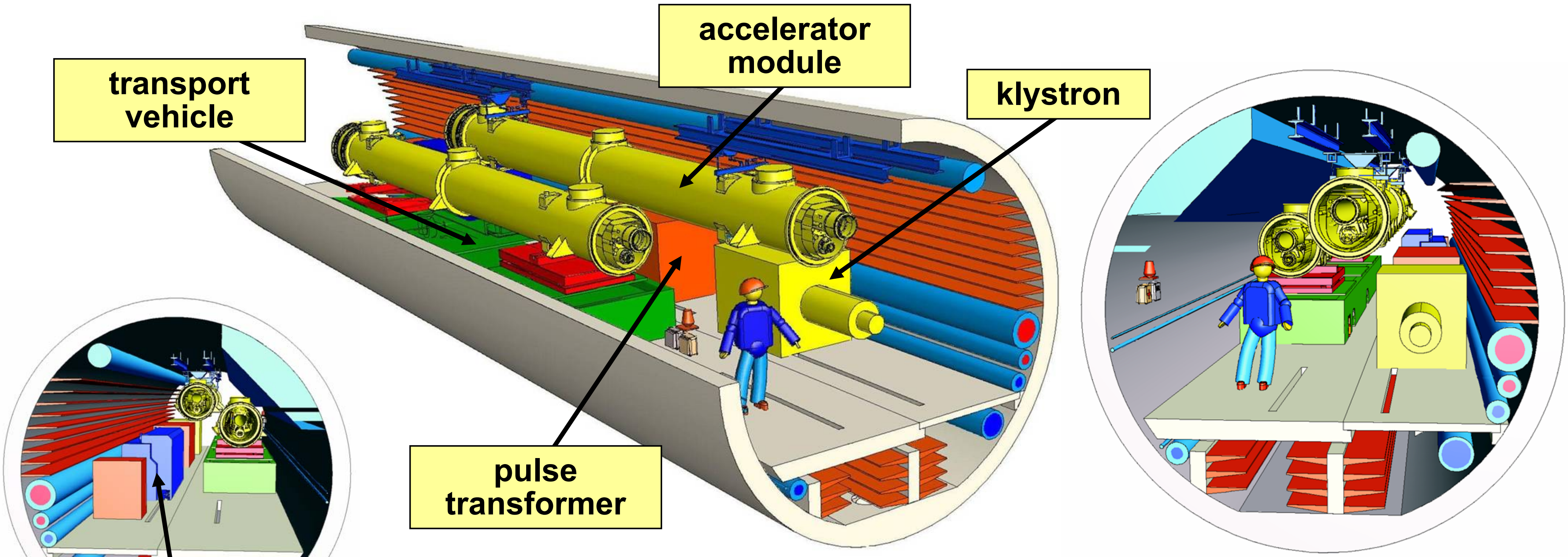
See more: FLASH booklet, published in June 2007



Molekülstrahl
1. Laserblitz löst Reaktion aus
2. Laserblitz macht Momentaufnahme
Laser

XFEL
X-Ray Free-Electron Laser

XFEL Linac - 3D Tunnel Model



Replacement of accelerator modules is extremely unlikely but klystrons / electronics / other consumables need maintenance.

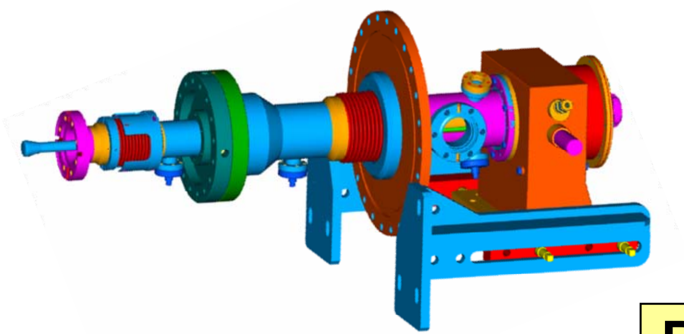
attach accelerator modules to the tunnel ceiling

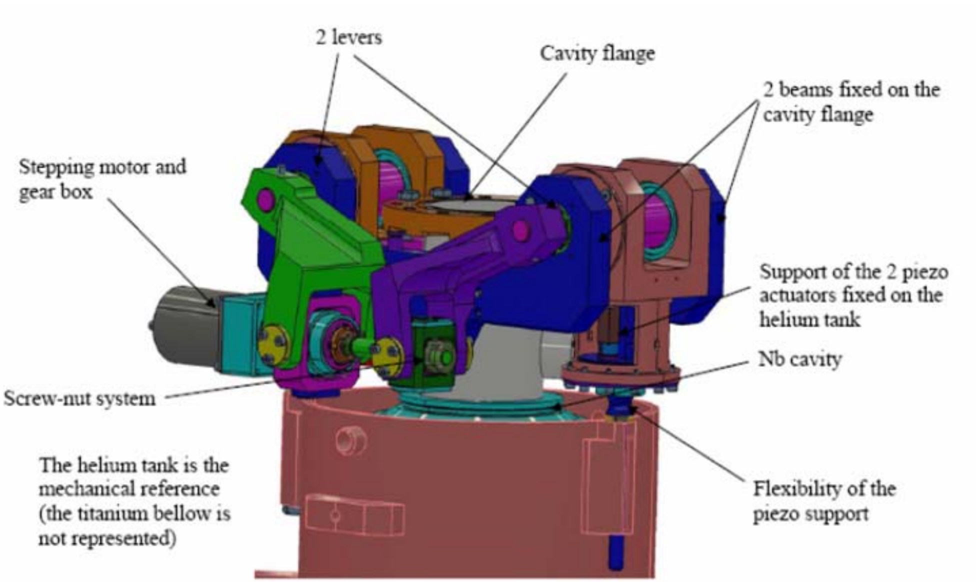
put pulse cables & 10 kV cables below the floor

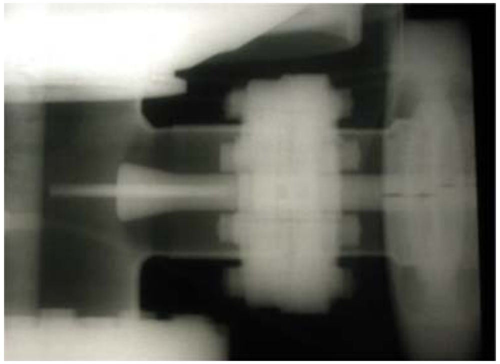
install klystrons / vacuum pumps / electronics right next to the transportation area

XFEL Accelerator Module

all components tested at TTF/VUV-FEL







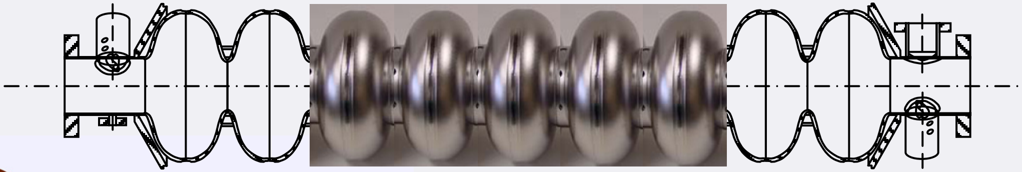
Before string assembly:

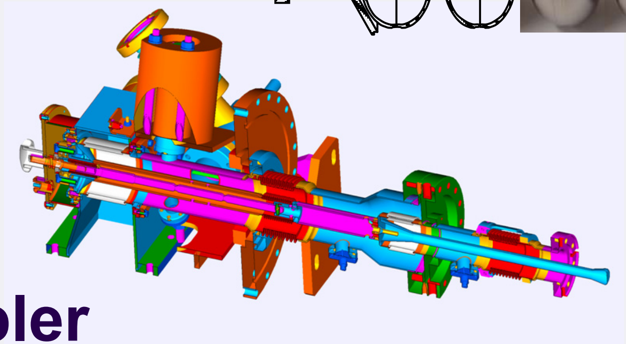
- accelerating cavities are individually tested
- RF power couplers are conditioned
- cold tuners are tested at cold temperature

After string / module assembly all accel. modules are tested (full performance check, i.e. cold and RF).

FLASH Accelerator Components

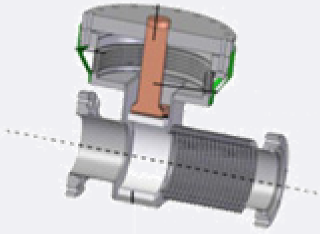
cavities





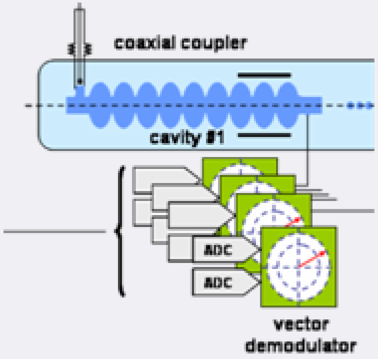
coupler

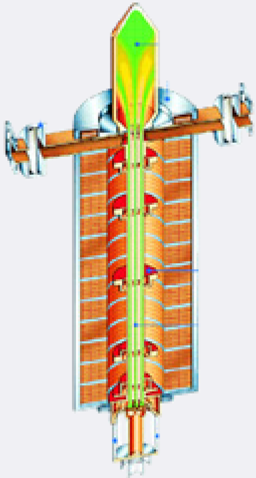
TESLA Technology



HOMs

LLRF

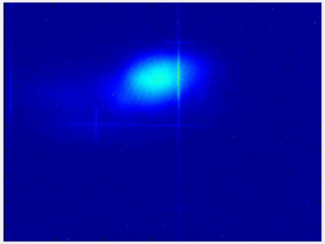




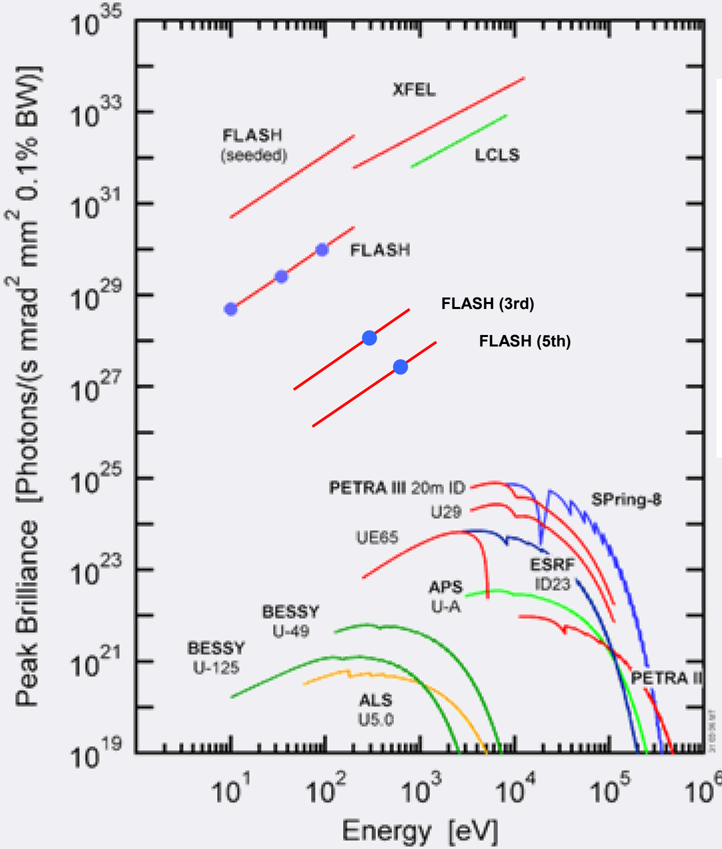
RF

This is, where we are…

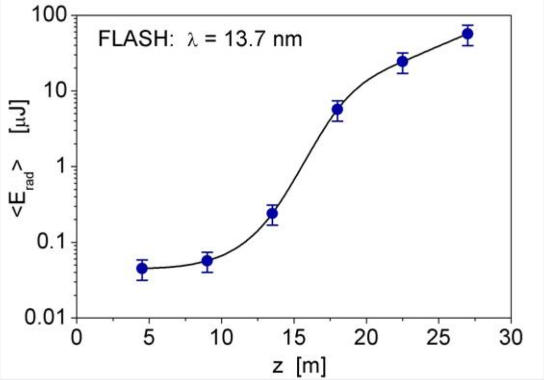
April 26, 2006

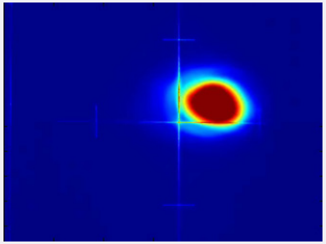


<E> = 5 µJ



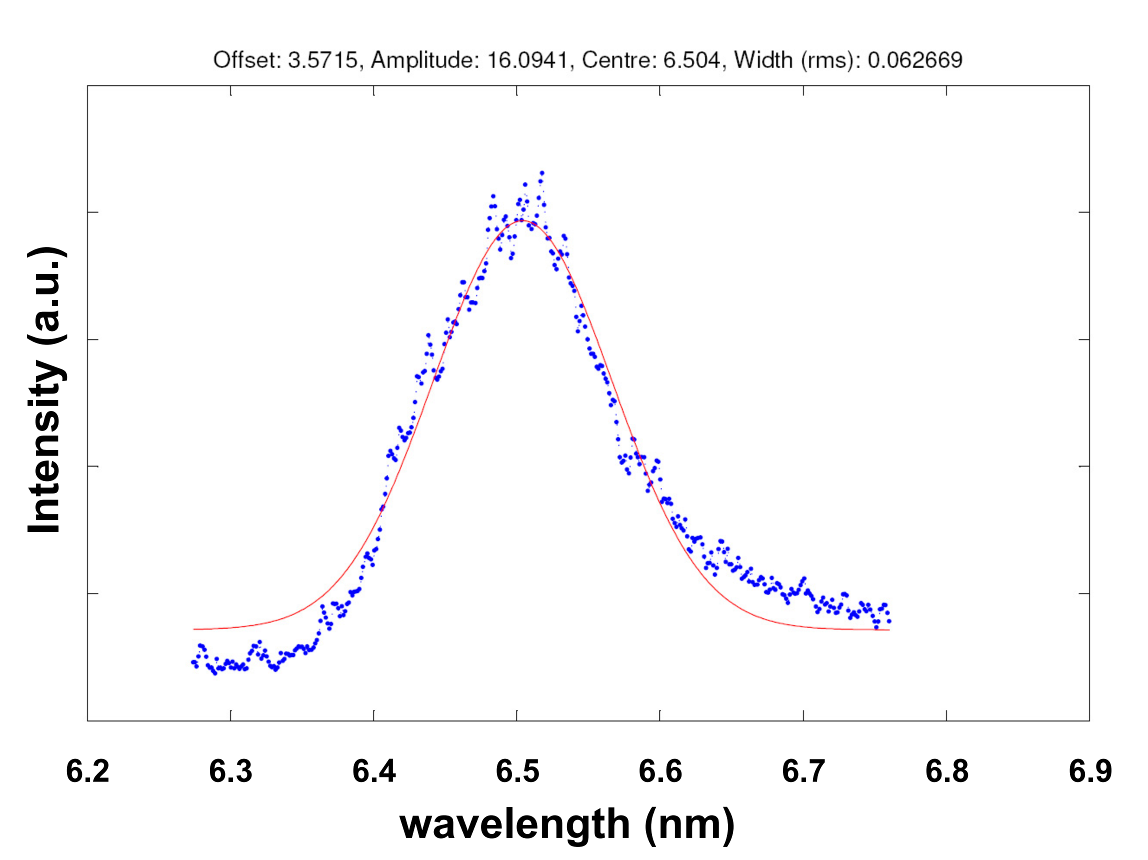
Recent User run 2006 / 2007





<E> = 70 µJ

… and lasing at 6.5 nm …



… and the best:

- first lasing at 80 nm (TTF1) took months
- first lasing at 6.9 nm instead of the previously reached 13 nm took hours

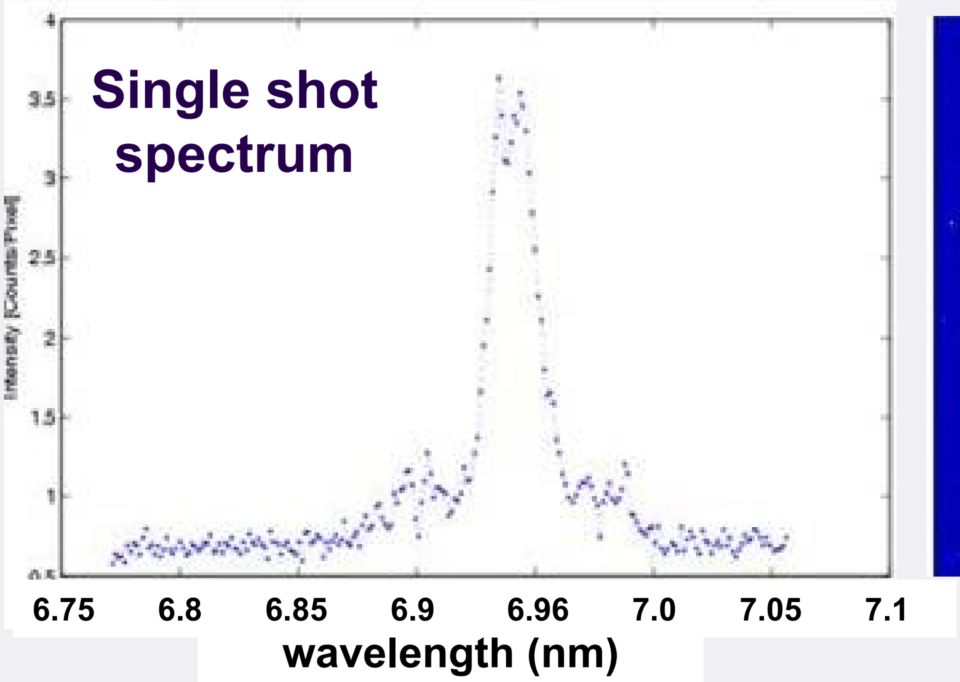
This demonstrates the scalability of the concept towards the XFEL.

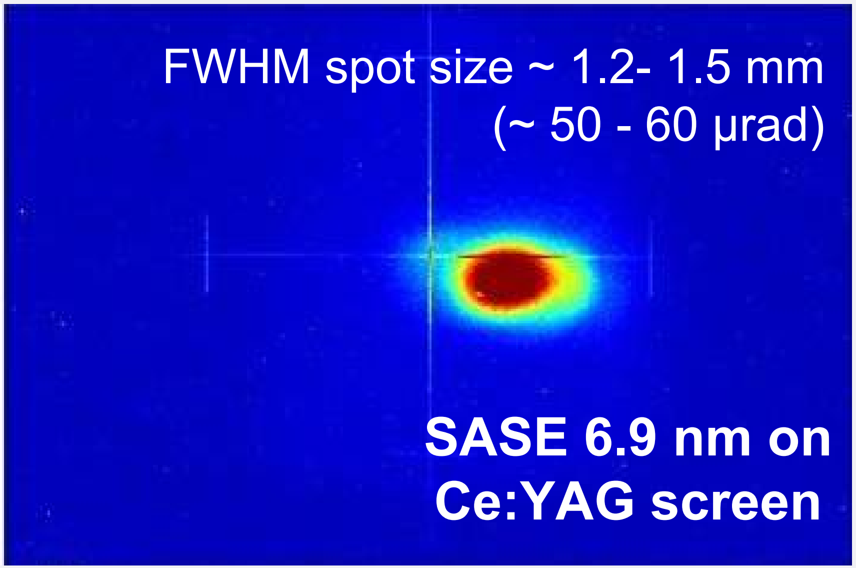
… preliminary FLASH radiation properties …

Lasing could be demonstrated at 6.5 nm and 6.9 nm;
(already now, 7 nm requested by users)

Estimate: 2 μJ level (±50%)

the single shot spectra show a small number of modes → preliminary estim. pulse length: in the 5 fs range (rough extrapolation from the 13 nm)

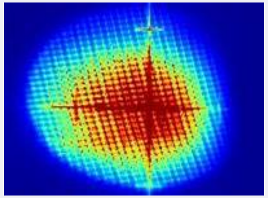




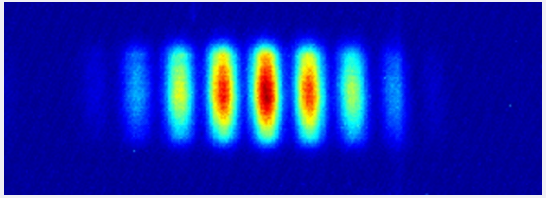
The FLASH Photon Beam

e.g. 25.5 nm wavelength

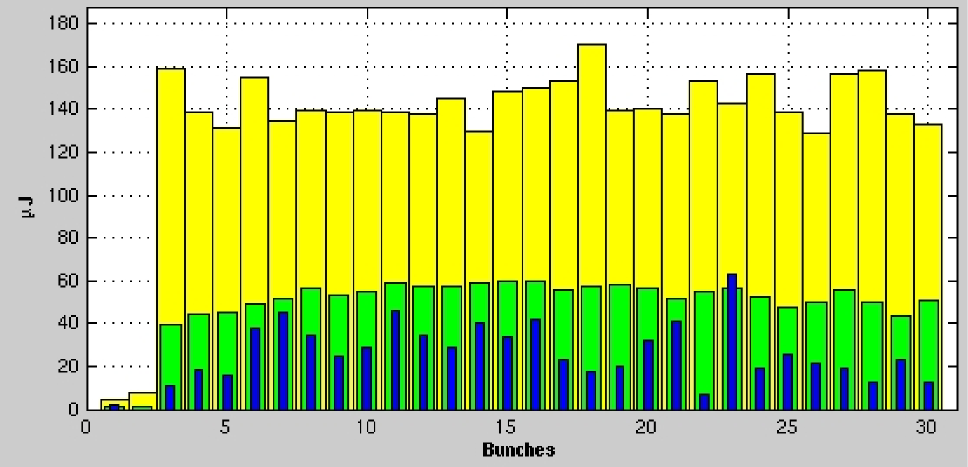
spot size



double slit diffraction pattern



3 mm spot size (FWHM) @ 18.5 m distance
angular divergence 160 µrad
→ high degree of coherence



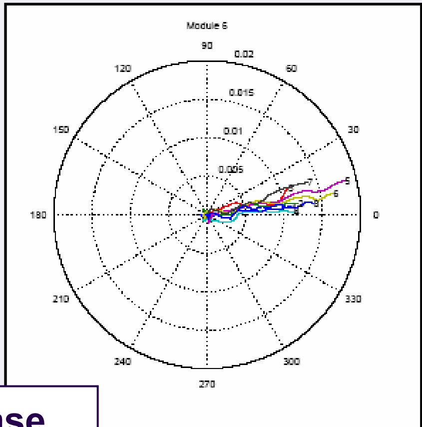
Wavelength (fundamental)	**47 – 6.5**	**nm**	**(tunable!!!)**
FEL range (harmonics)	**→ 2.7**	**nm**	
Average energy per pulse	up to 100	µJ	
Maximum energy per pulse	200	µJ	
Radiation pulse duration	10 – 50	fs	
Peak power (calc. from average)	~ 3 – 4	GW	
Spectral width (FWHM)	**0.5 – 1**	**%**	
Angular divergence (FWHM)	160	µrad	
Peak brilliance (calc. from max)	**5-10×10^{29}**	ph/s/$mrad^2$/mm^2/(0.1% bw)	

Multibunch SASE signal (µJ) recorded with MCP Detector

max
average
single

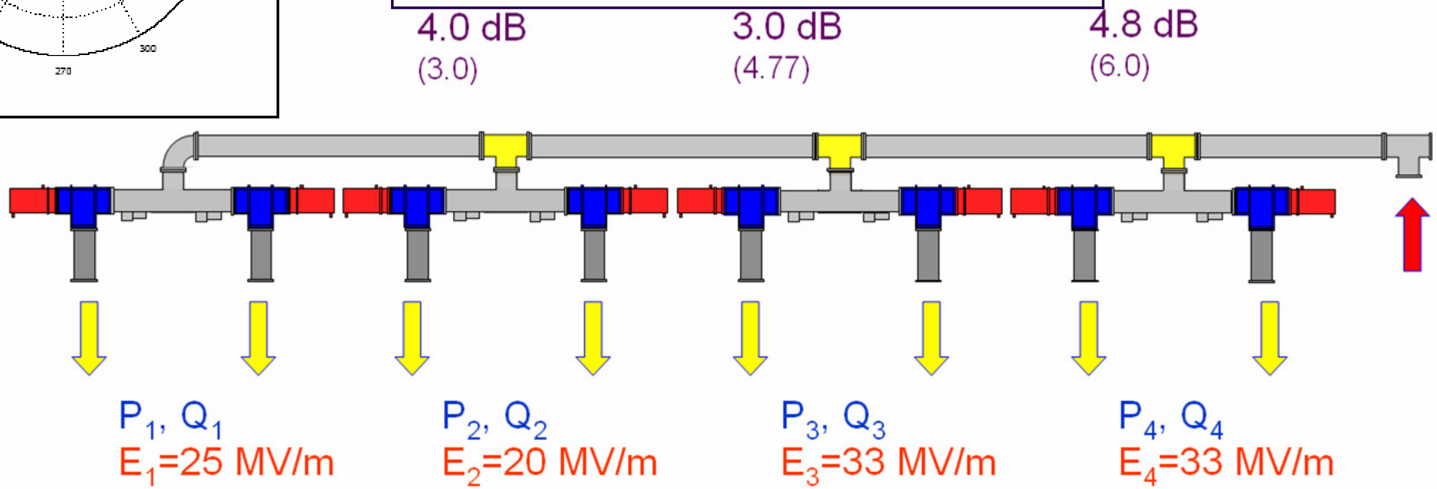
New pre-adjusted waveguide distribution system for ACC6

Power distribution and phase distribution for the individual cavities almost perfect



Initial phase distribution

Waveguide distribution ACC6

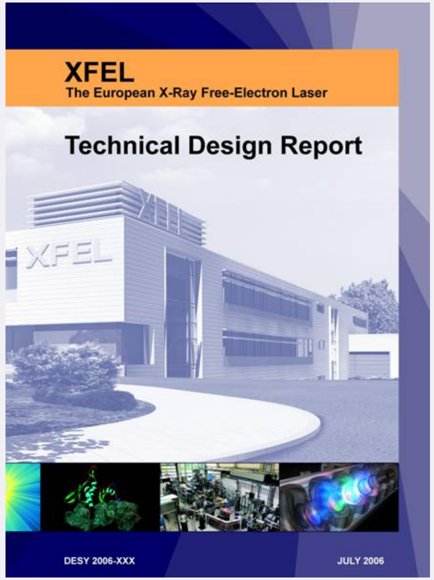


Tunnel Mock-Up Completed and Installations Ongoing

The XFEL is based on the feasibility of a single tunnel design including the support of the cryomodules from the ceiling. Installation procedures to be trained at the mock-up.

The XFEL Technical Design Report (DESY 2006-097)

M. Tigner, A Possible Apparatus for Electron Clashing-Beam Experiments Il Nuovo Cimento Vol. XXXVII, No.3 (1965)



03/2001	**XFEL as part of the TESLA LC**
10/2002	**Separation of the XFEL**
2005	**Detailed XFEL accelerator layout**
2006	**Final TDR incl. detailed technical layout and experiments**
2007	**project start on June 5th, 2007**

International Project Organization

XFEL Steering Committee ISC (Chair: H. Schunck, Germany)

- Representatives of all countries intending to contribute to the XFEL facility
- *13 countries have signed MoU (project preparation phase)*

CH	CN	DE	DK	ES	FR	GB	GR	HU	IT	PL	RU	SE

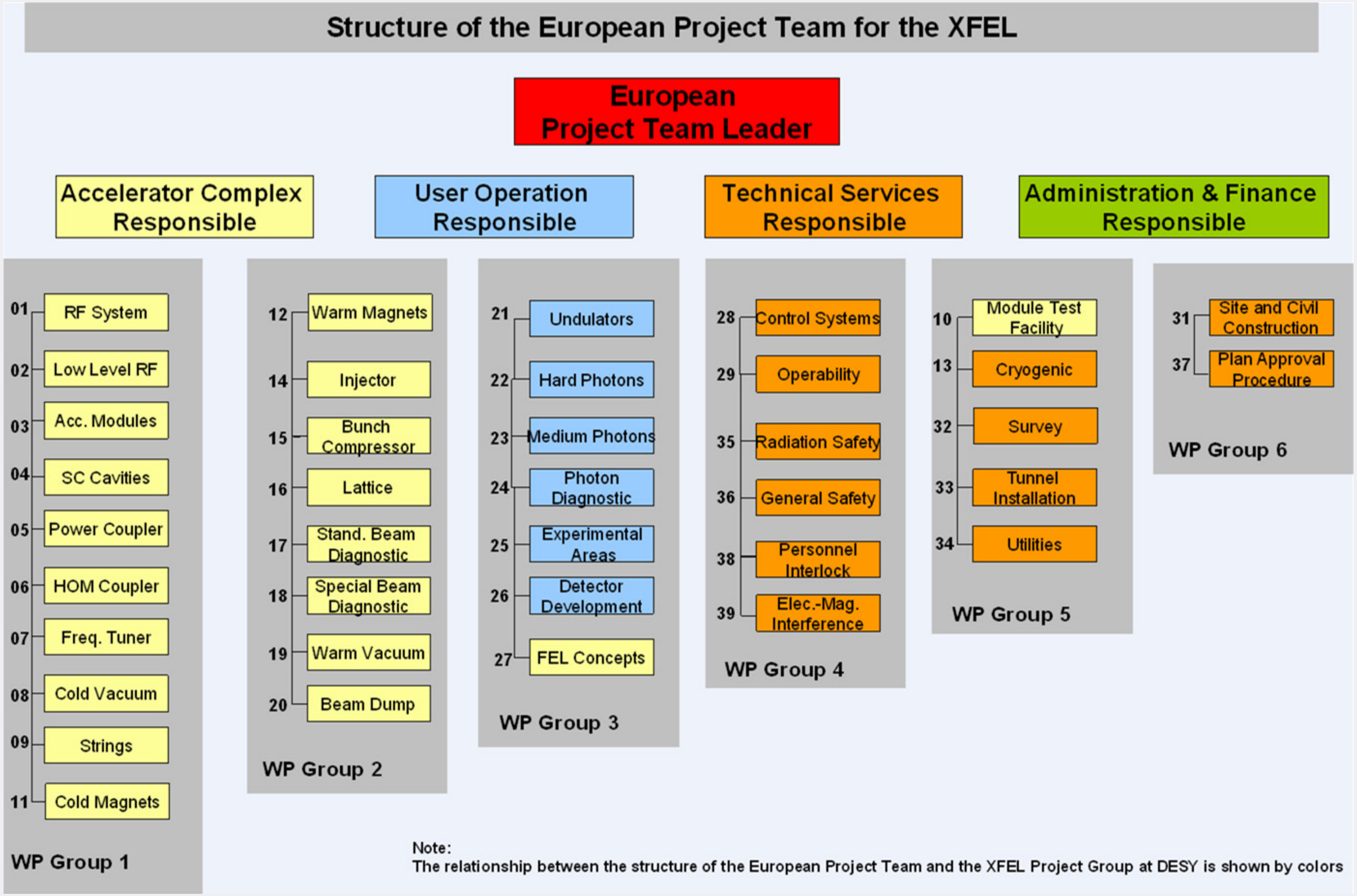
- *European Project Team (Leader: Massimo Altarelli)*

WG on Scientific and Technical issues	WG on Administrative and Funding issues

Bi-lateral negotiations between Germany and signature countries on funding contributions are ongoing.

The MoU for the project phase is still to be signed.

XFEL Project Organization



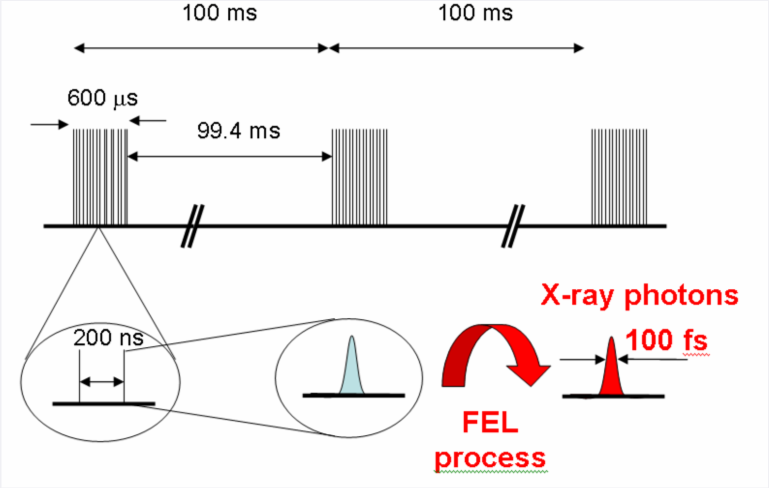
Properties of XFEL radiation

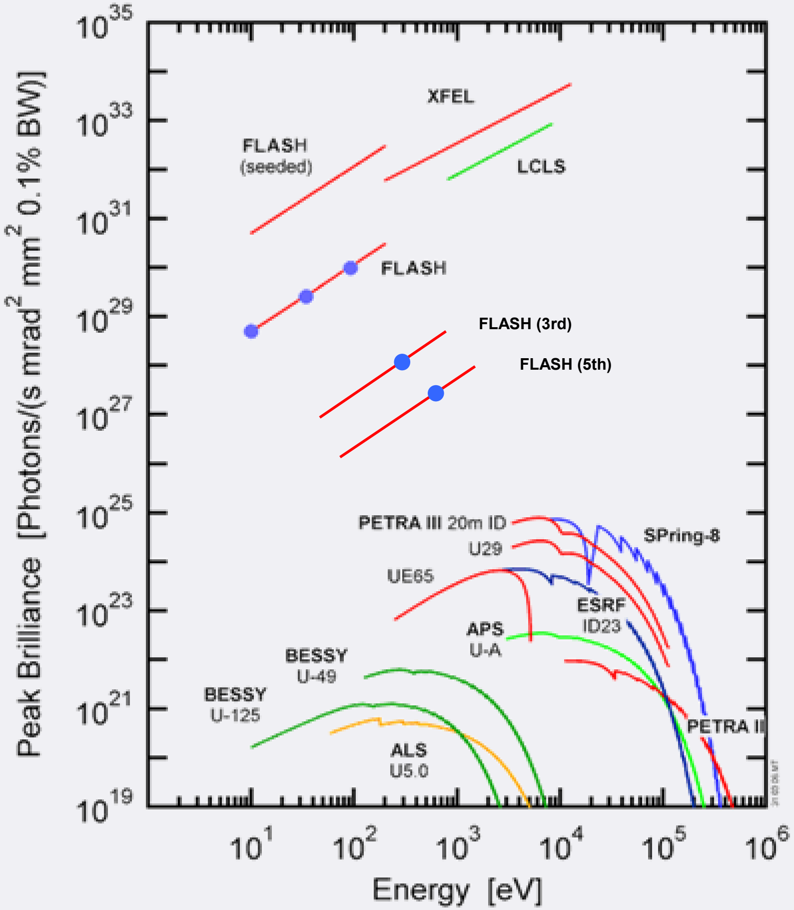
X-ray FEL radiation (0.2 - 14.4 keV)

- ultrashort pulse duration   <100 fs (rms)
- extreme pulse intensities 10^{12}-10^{14} ph
- coherent radiation   x10^9
- average brilliance   x10^4

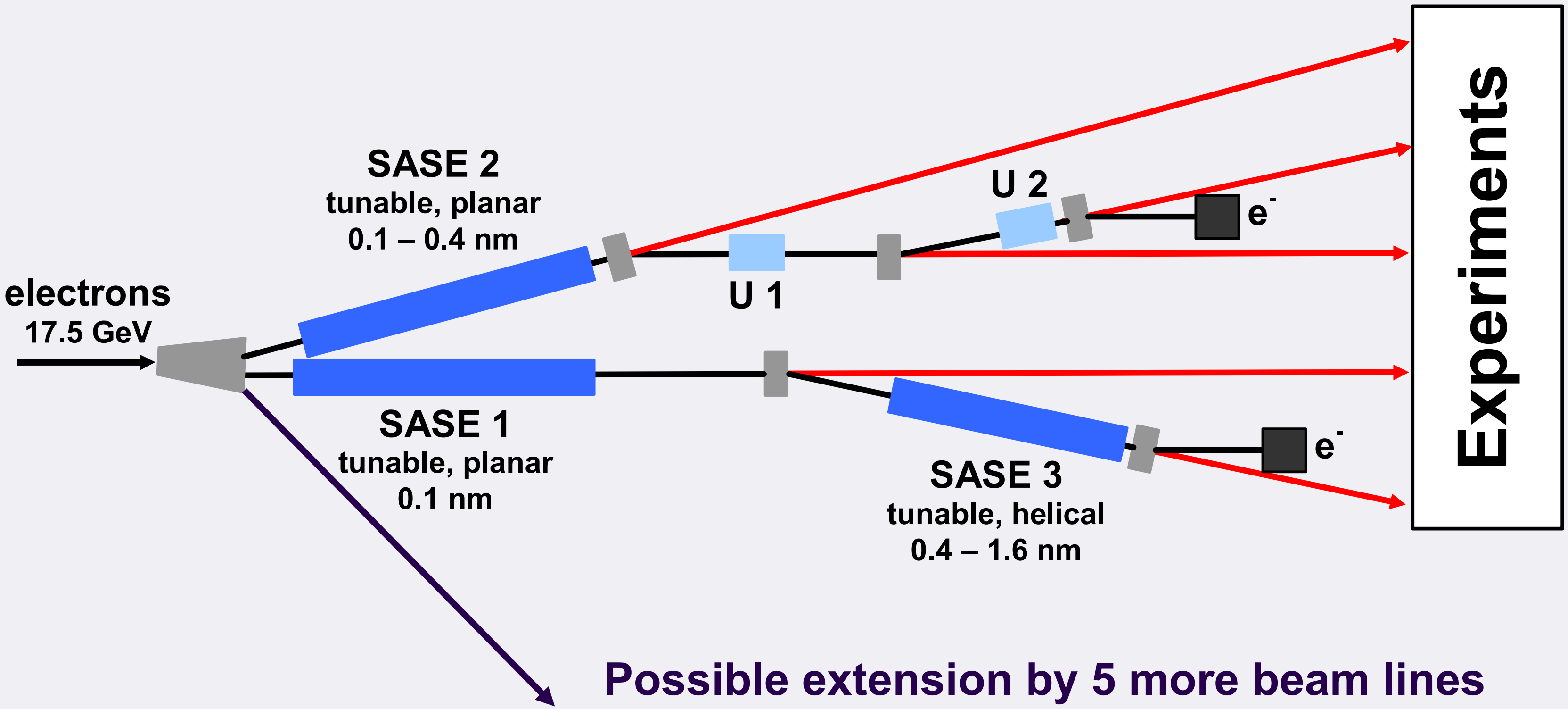
Spontaneous radiation (20-100 keV)

- ultrashort pulse duration   <100 fs (rms)
- high brilliance





Photon Beam Lines (TDR Layout)

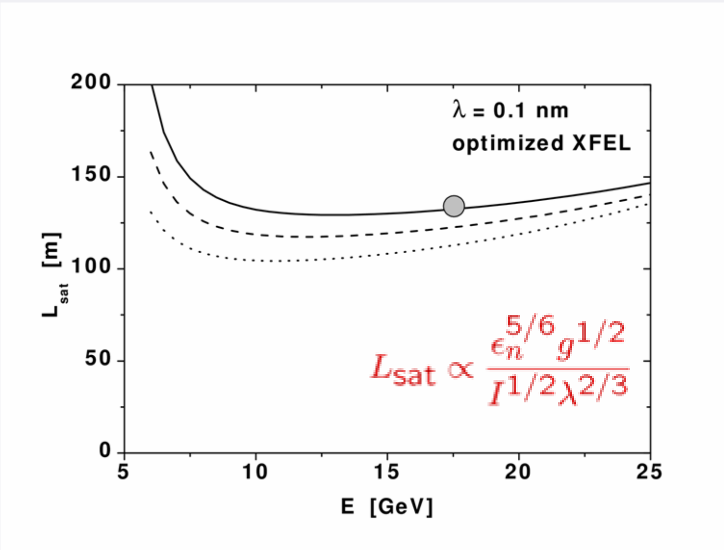


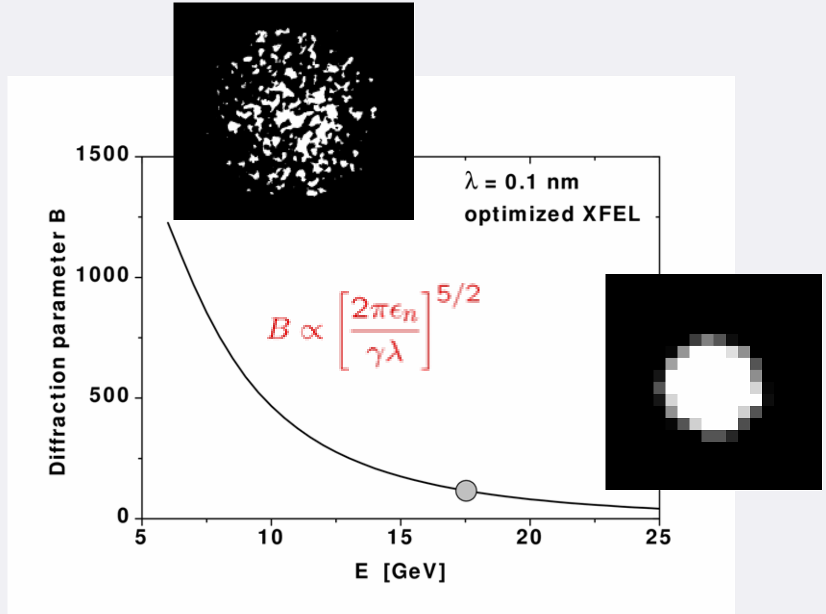
Possible extension by 5 more beam lines and 10 experimental stations

Start-up scenario has only 3 undulator beam lines.

Choice of Beam Energy: 17.5 GeV for 0.1nm Wavelength

gap = 6 mm, 8mm, and 10 mm





→ Good photon beam coherence

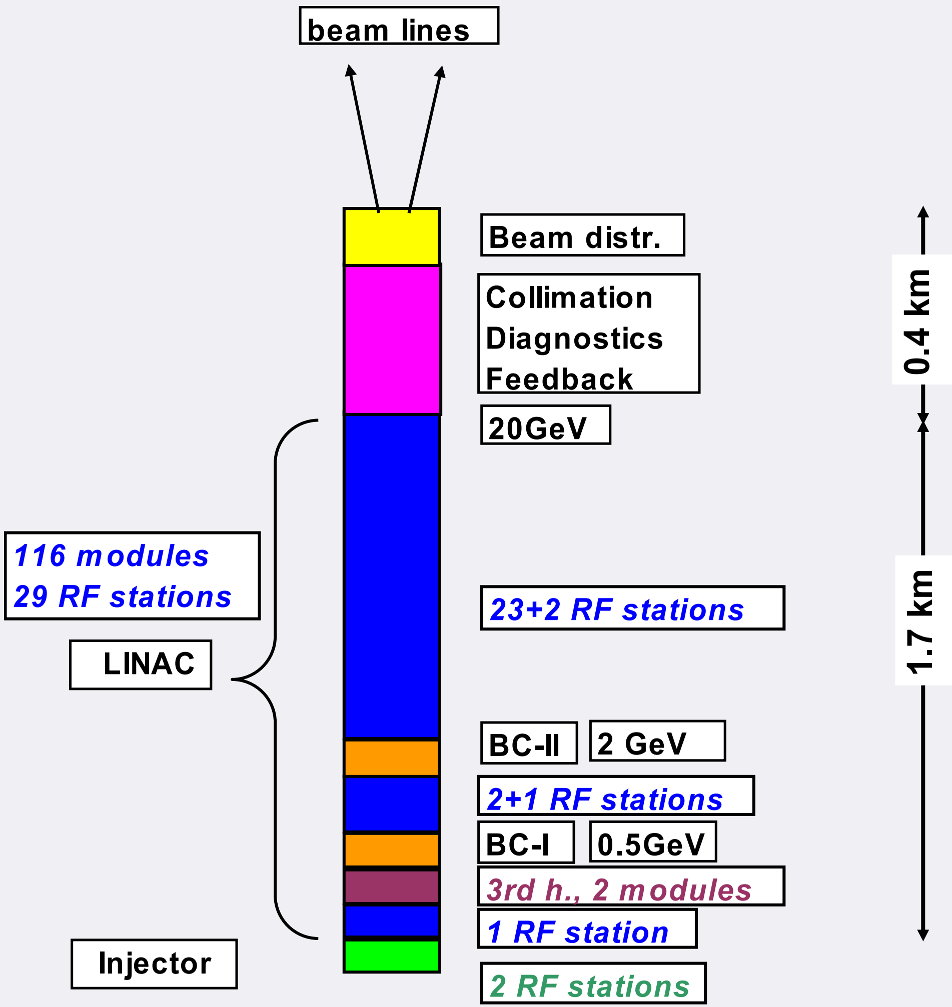
(65 – 85% at 0.1 – 0.15nm, ε_n = 1.4mm*mrad)

XFEL Accelerator Layout

XFEL TDR included reserve units to provide high operational availability.

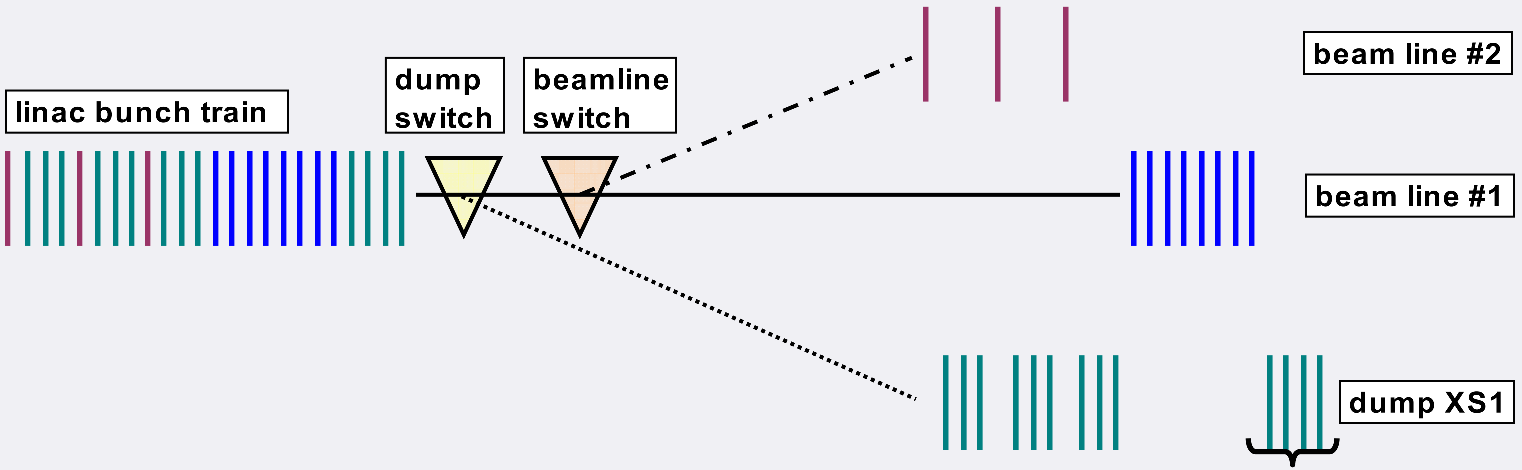
The design accelerating gradient of 23.6 MV/m aimed for 20 GeV – potential for energy upgrade.

The actual funding scenario leads to a reduction in the number of accelerator modules (101 in total). But a safe operation at 17.5 GeV can be assumed.



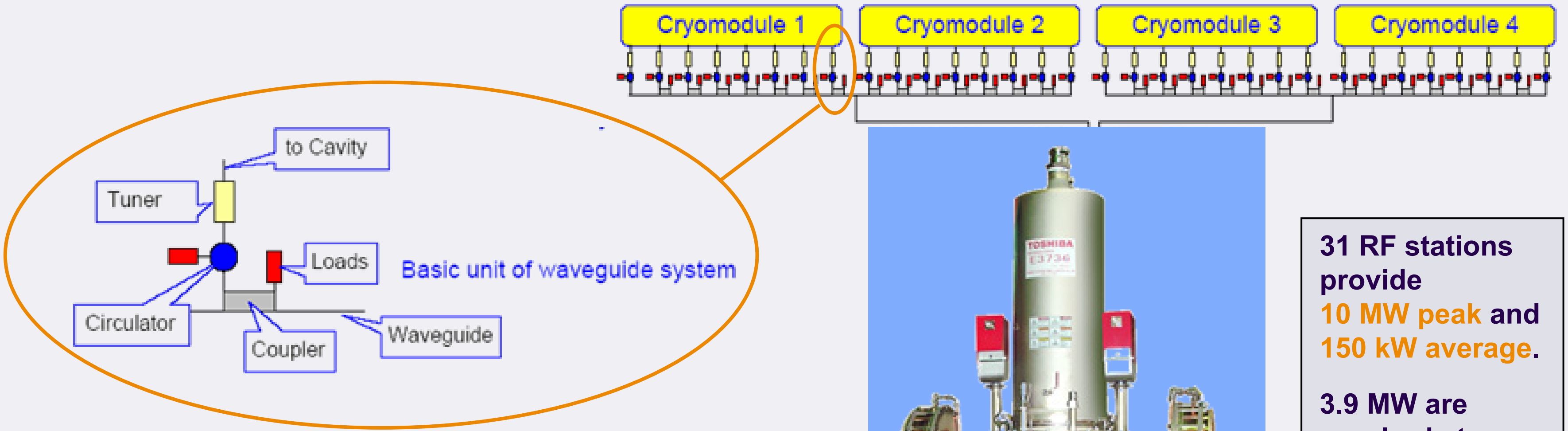
Operational Flexibility

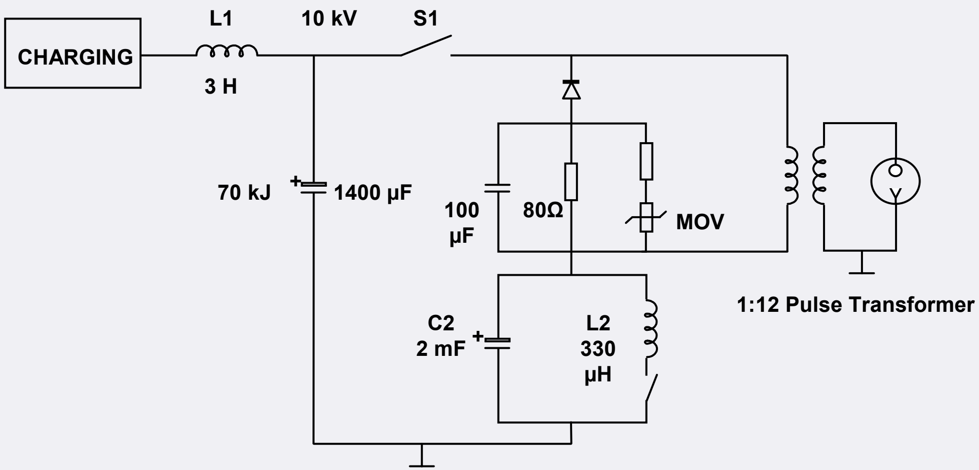
Different beam time structure to different experiments – concept using kicker devices permits large flexibility without having to change the (preferably homogenous) bunch train structure in the linac



Fast intra-bunch train feedback system → **"Steering bunches"**

High Power RF System





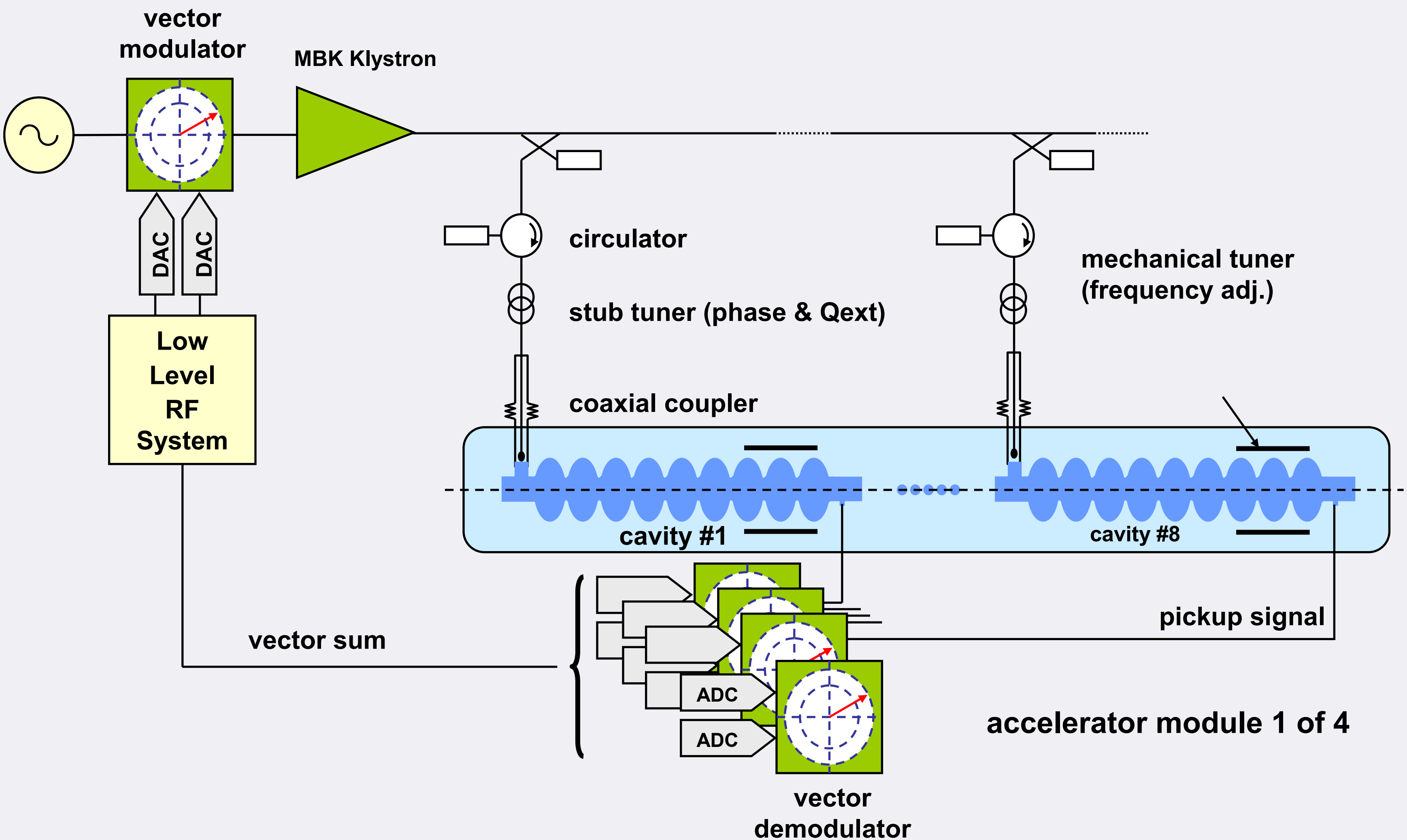

Toshiba E3736

31 RF stations provide **10 MW peak** and **150 kW average**.

3.9 MW are required at nominal beam parameters and 20 GeV.

Incl. waveguide losses (6%) and regulation reserve (15%) **5.2 MW**.

Low Level RF Control



XFEL Schedule

2004

2006

2012/13 → 2014/15

preparation

project start

construction

2009: LCLS start operation (SLAC)

beam operation

SASE1

SASE2+3, spont. rad

industrialization of all Linac sub-systems

production

commissioning

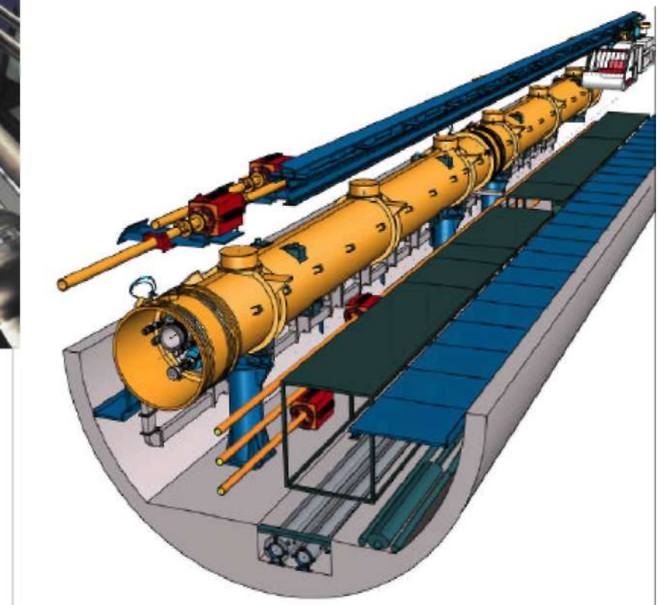
acceptance test and installation

input for ILC

FLASH FLASH FLASH operation experience XFEL XFEL XFEL

RF Systems for XFEL

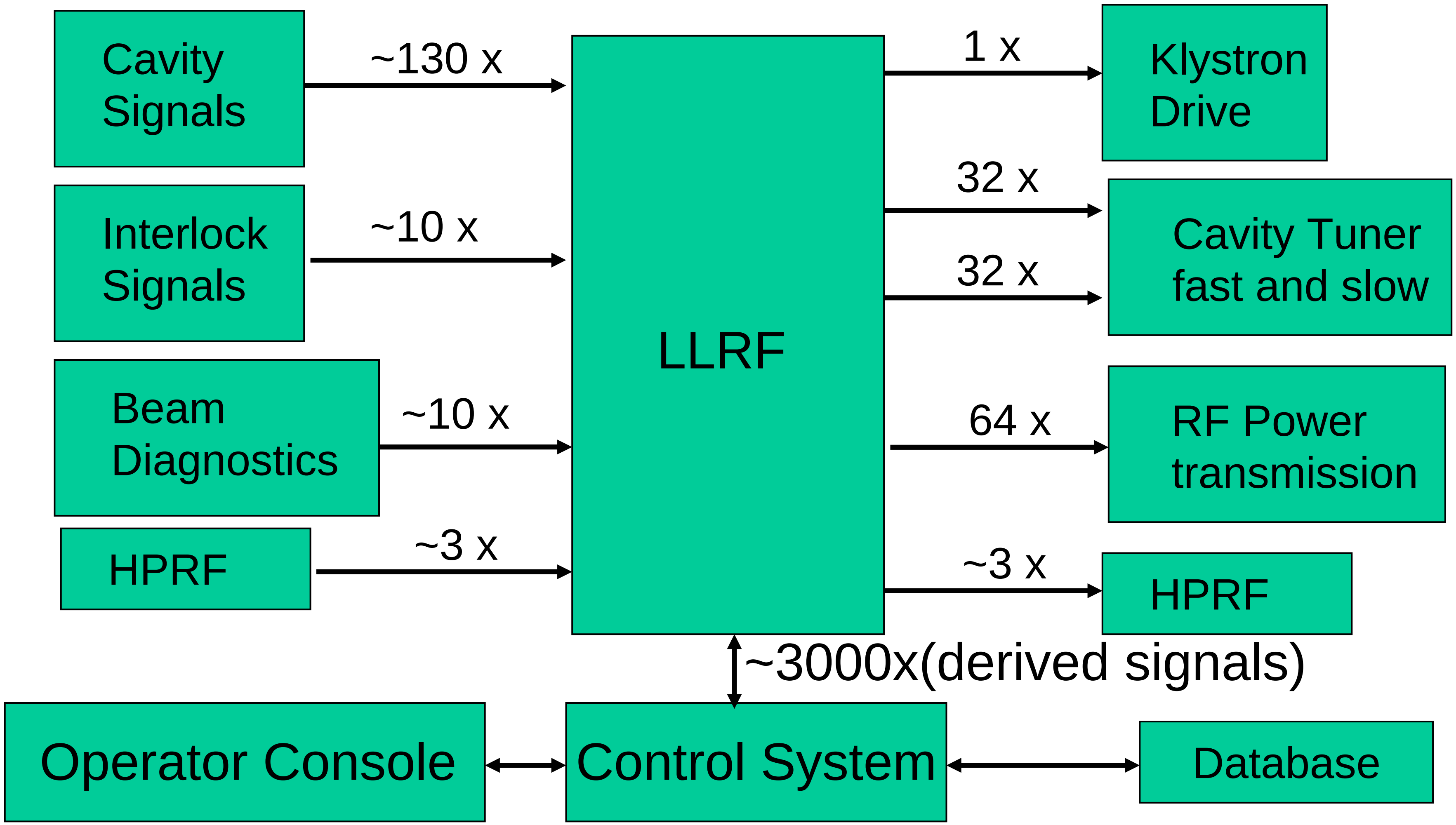
- RF Gun
- Injector
- Booster
- Main Linac
- LOLA (Diagnostics)



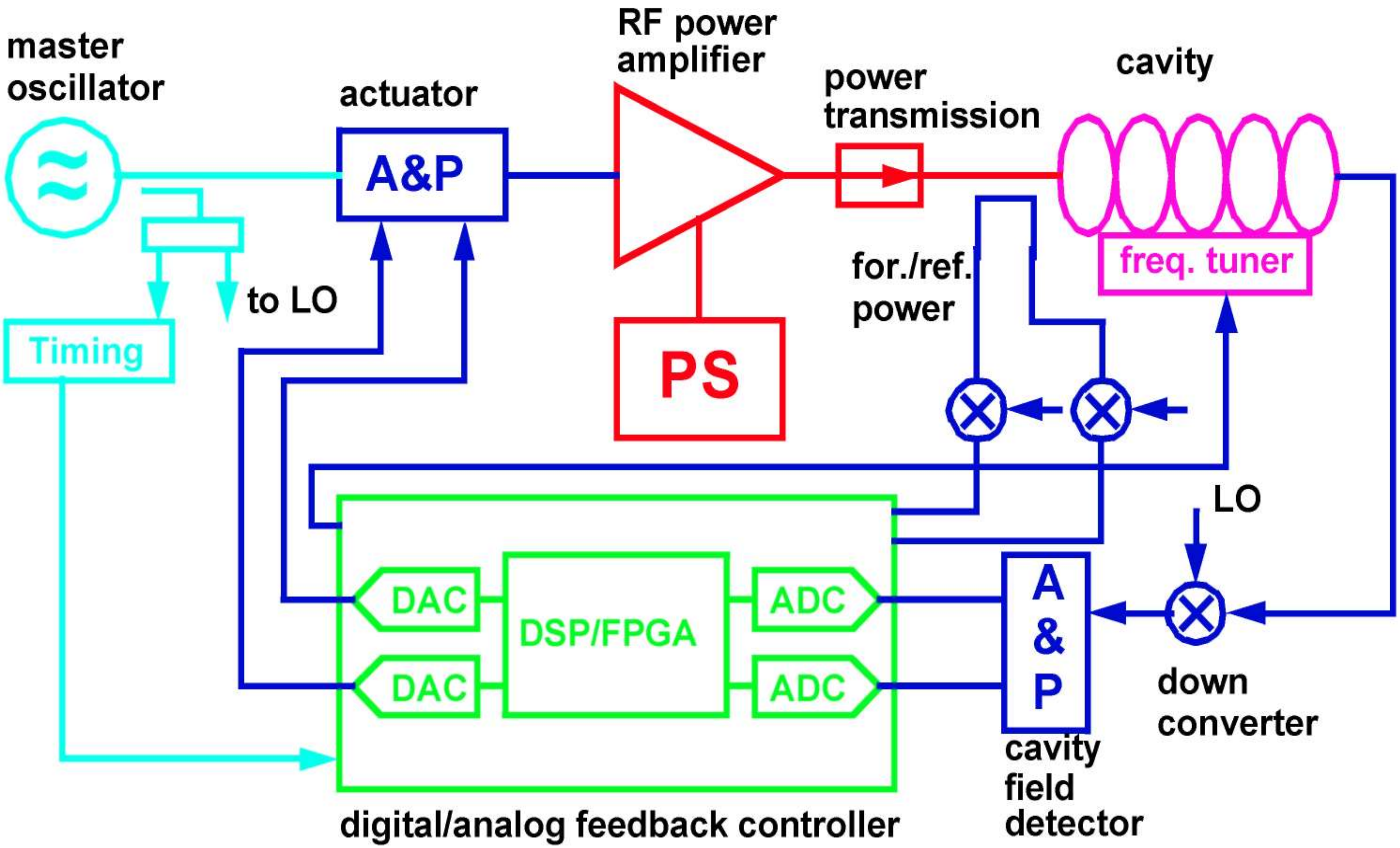
Scope of Main Linac RF

total number of klystrons / cavities per linac	~ 25/ 800
per rf station (klystron):	
# cavities / 10 MW klystron	~ 32
# of precision vector receivers (probe, forward, reflected power, reference line, beam)	~100
# piezo actuator drivers / motor tuners	~ 32/32
# waveguide tuner motor controllers	~ 32
# vector-modulators for klystron drive	1
Total # of meas. /control channels	~3200 / ~2,400

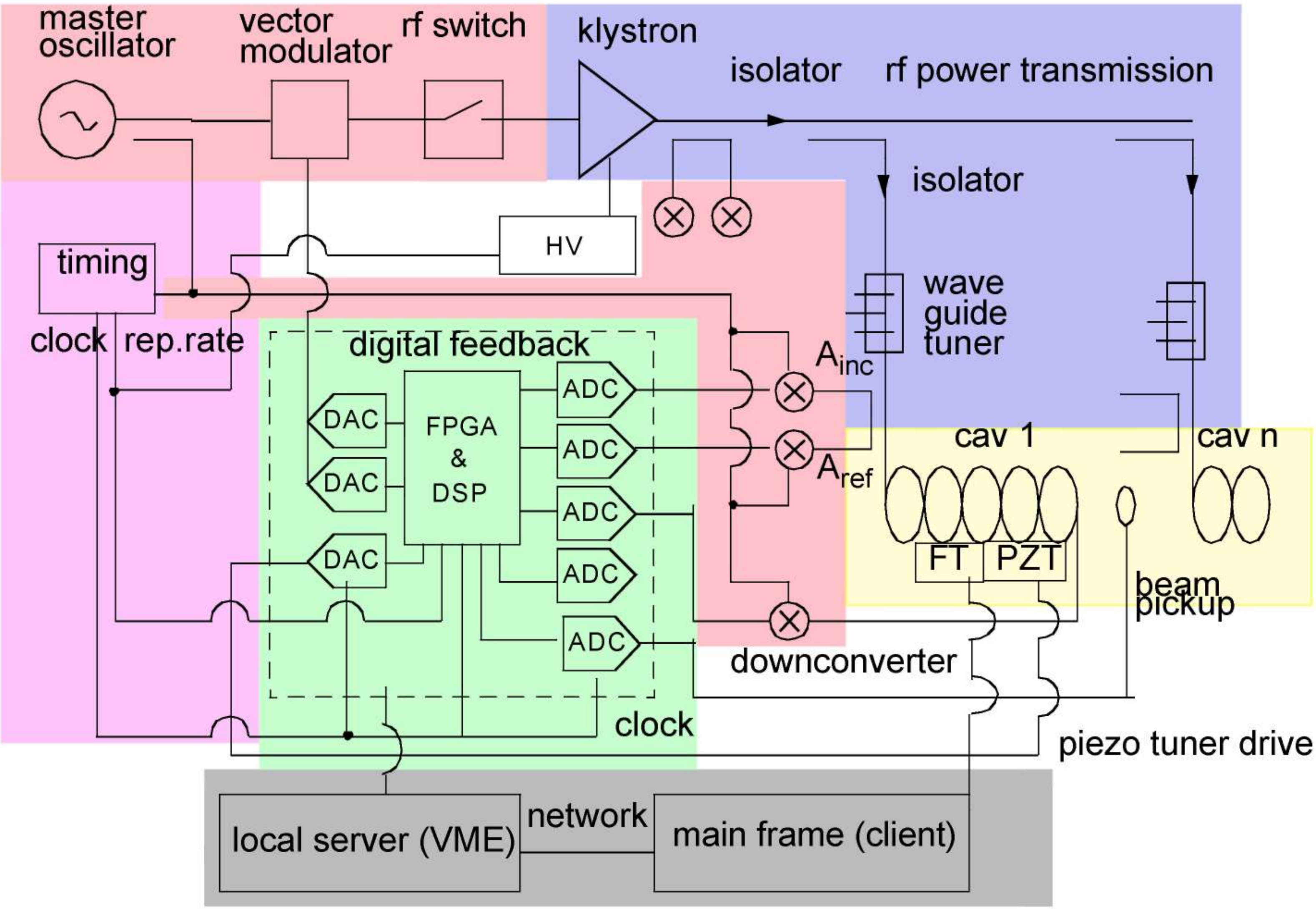
Signal diagram for RF Control (1 RF Station)



RF System Architecture

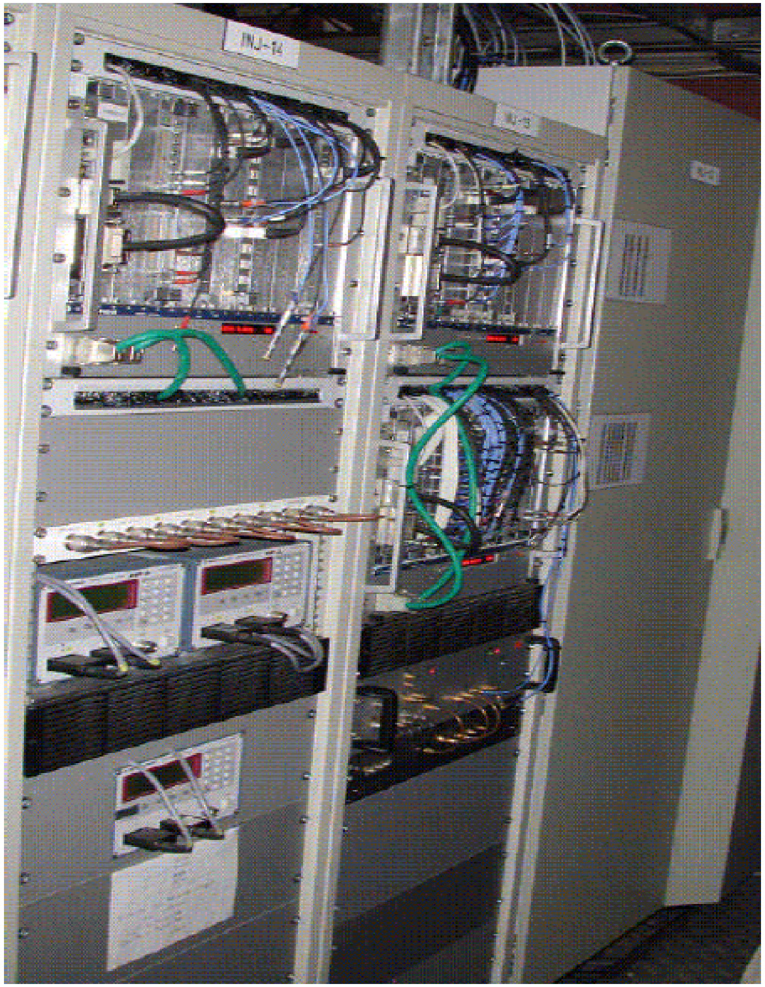


Architecture of LLRF System

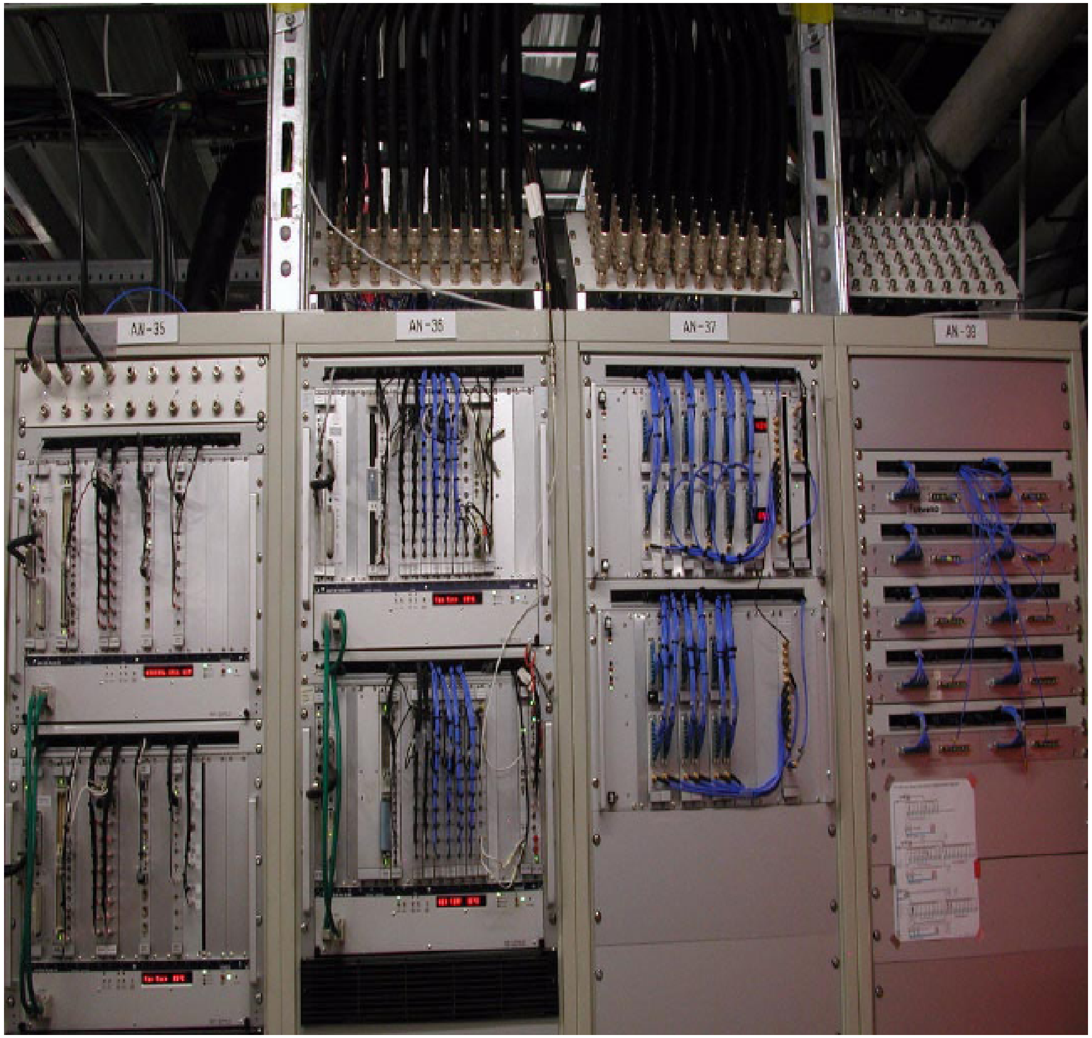


LLRF Installation at FLASH

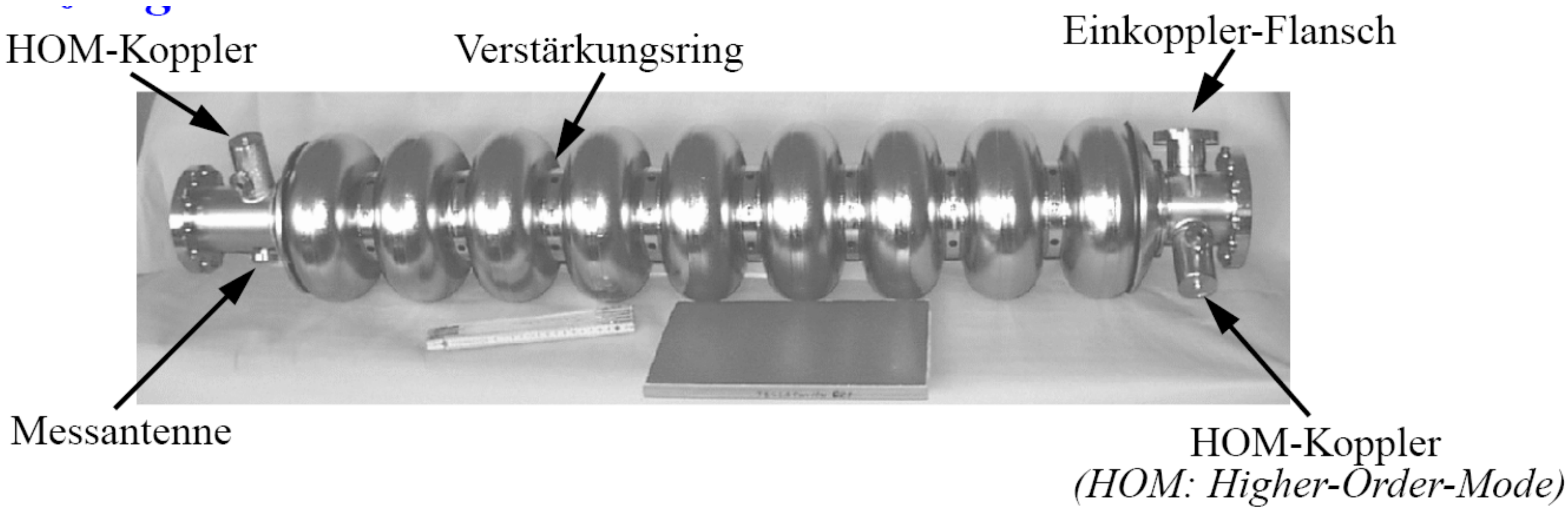
Gun and ACC1



ACC2, ACC3, ACC4 & ACC5



9-Cell Cavity



Parameter	Wert
Resonatortyp	Stehwelle, 9 Zellen
Beschleunigungsmode	TM_{010}
Frequenz der Beschl.-mode	1300 MHz
aktive Länge	1.038 m
Δf / ΔL	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

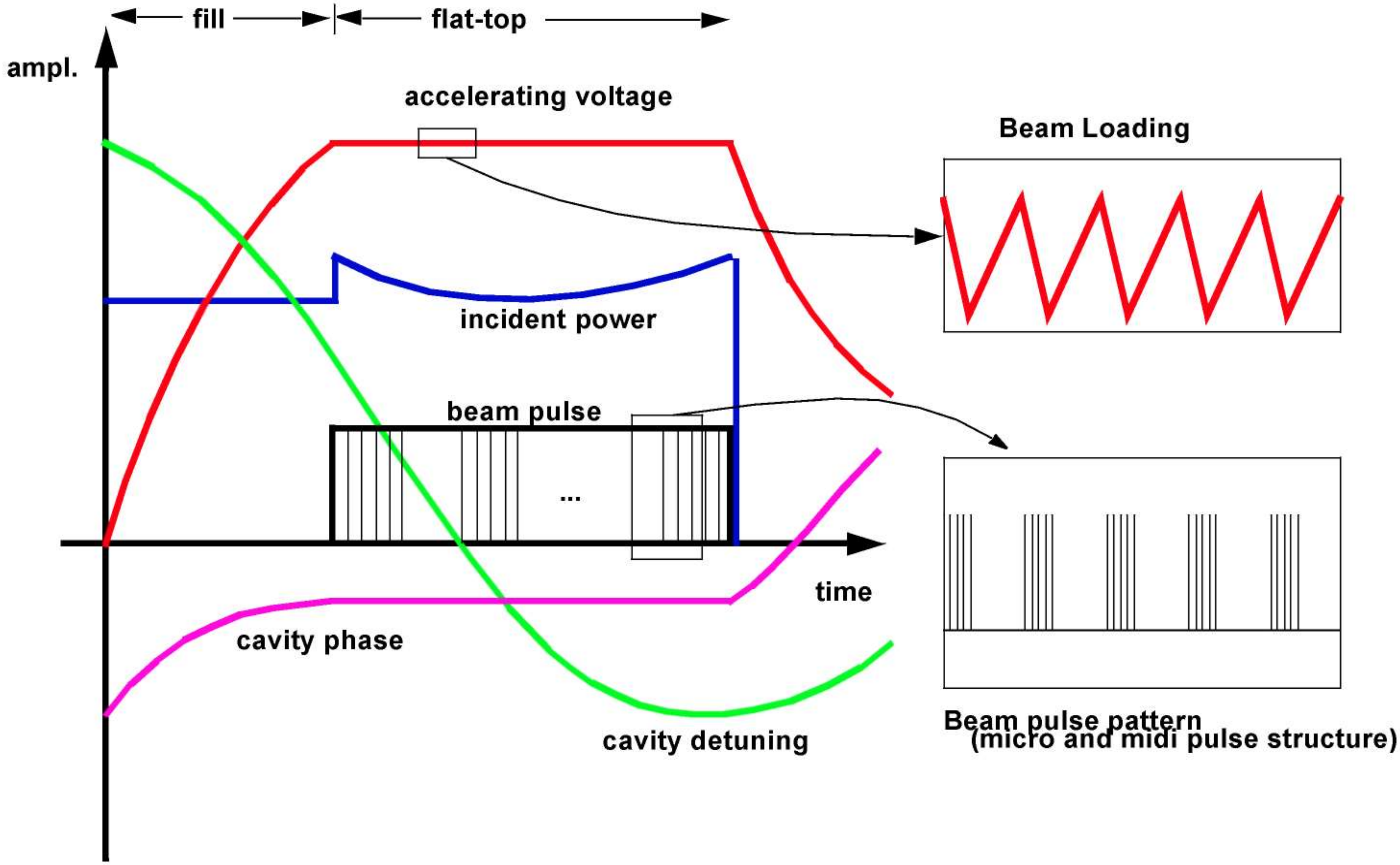
Disadvantage

- 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

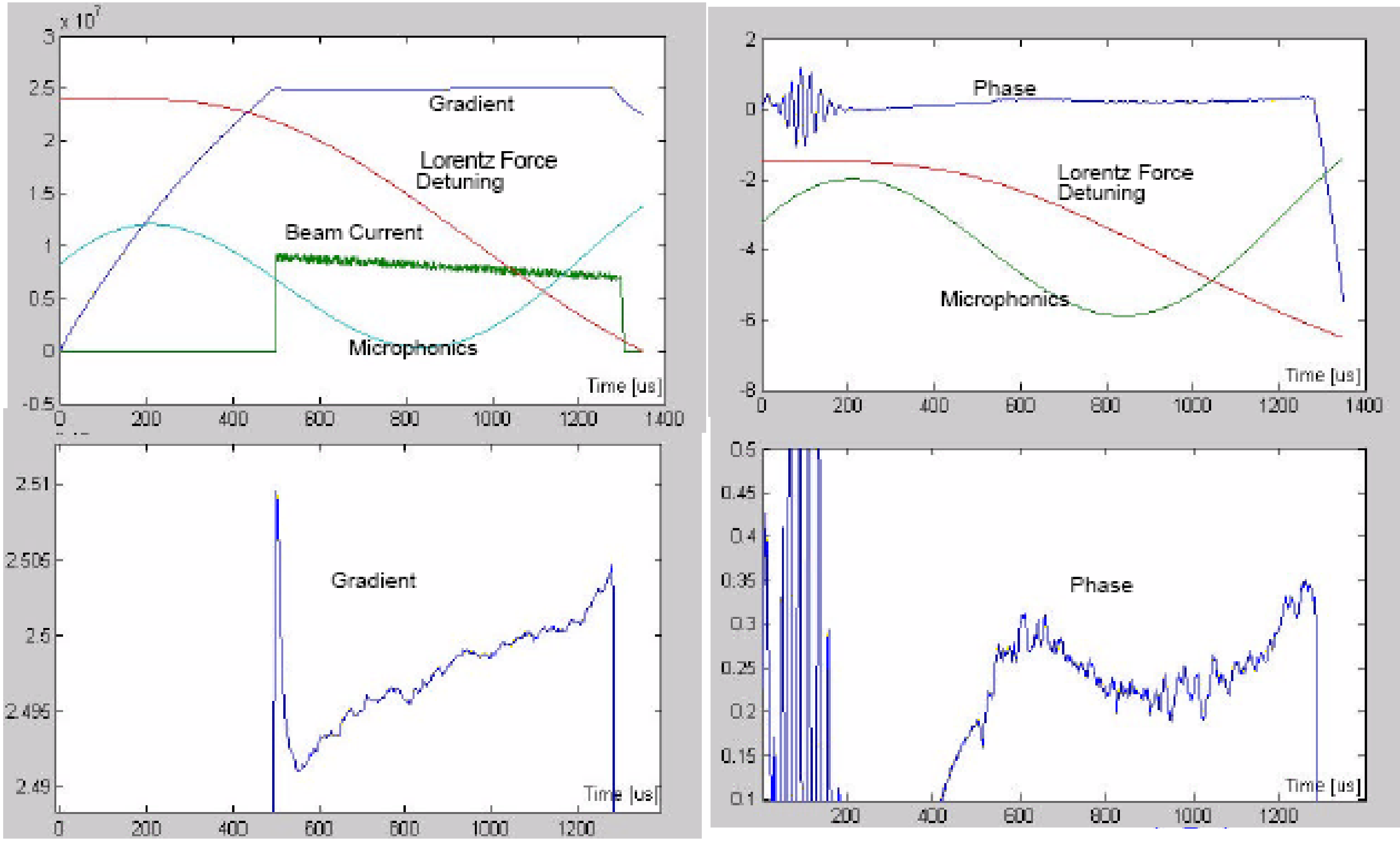
Why digital control

- 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)



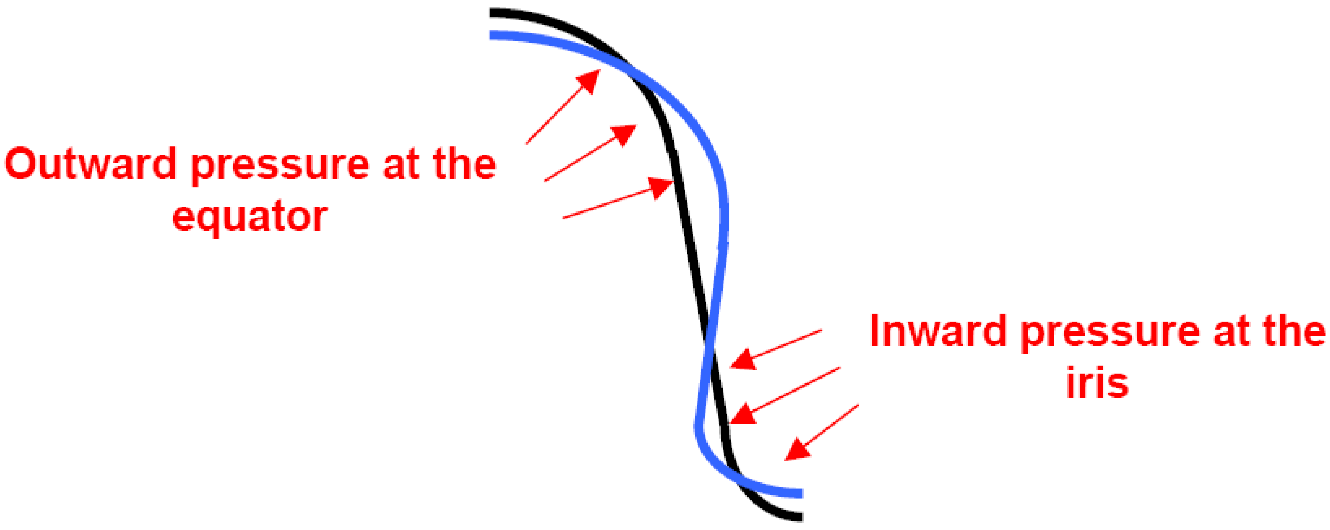
Sources of field perturbations

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

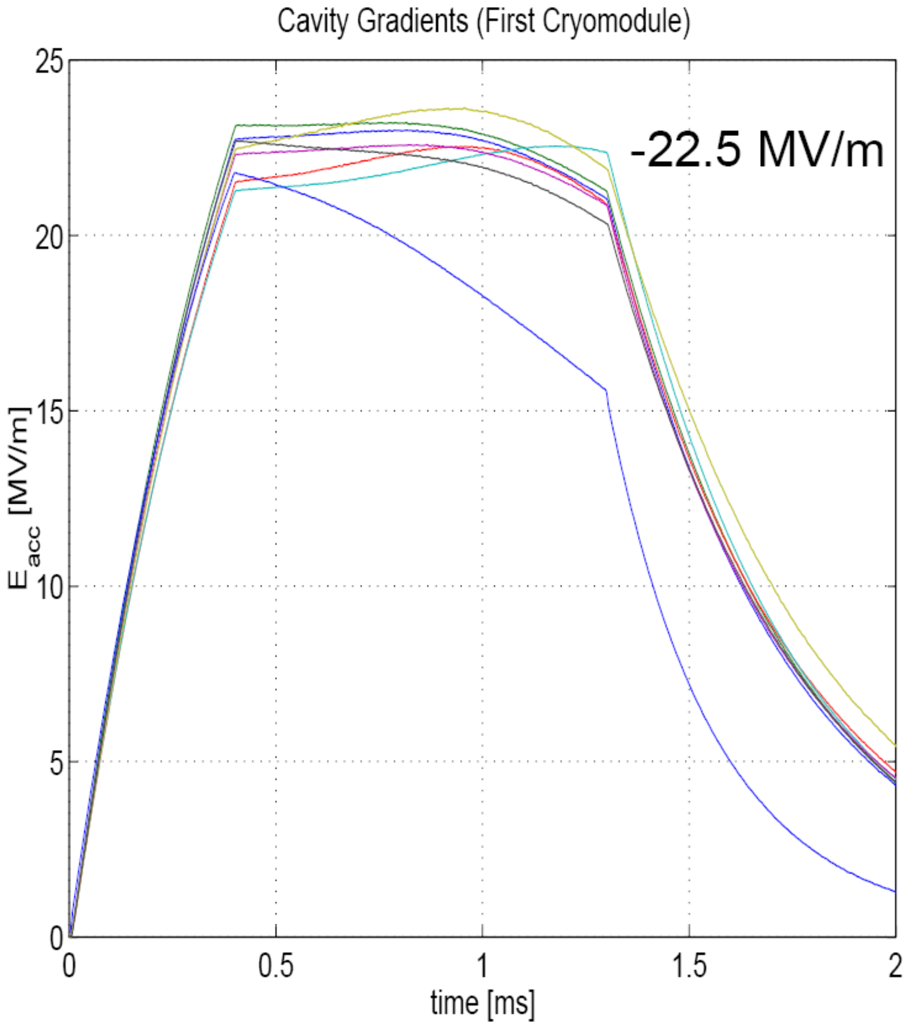
- Radiation pressure : $P = (\mu_0 H^2 - \varepsilon_0 E^2)/4$

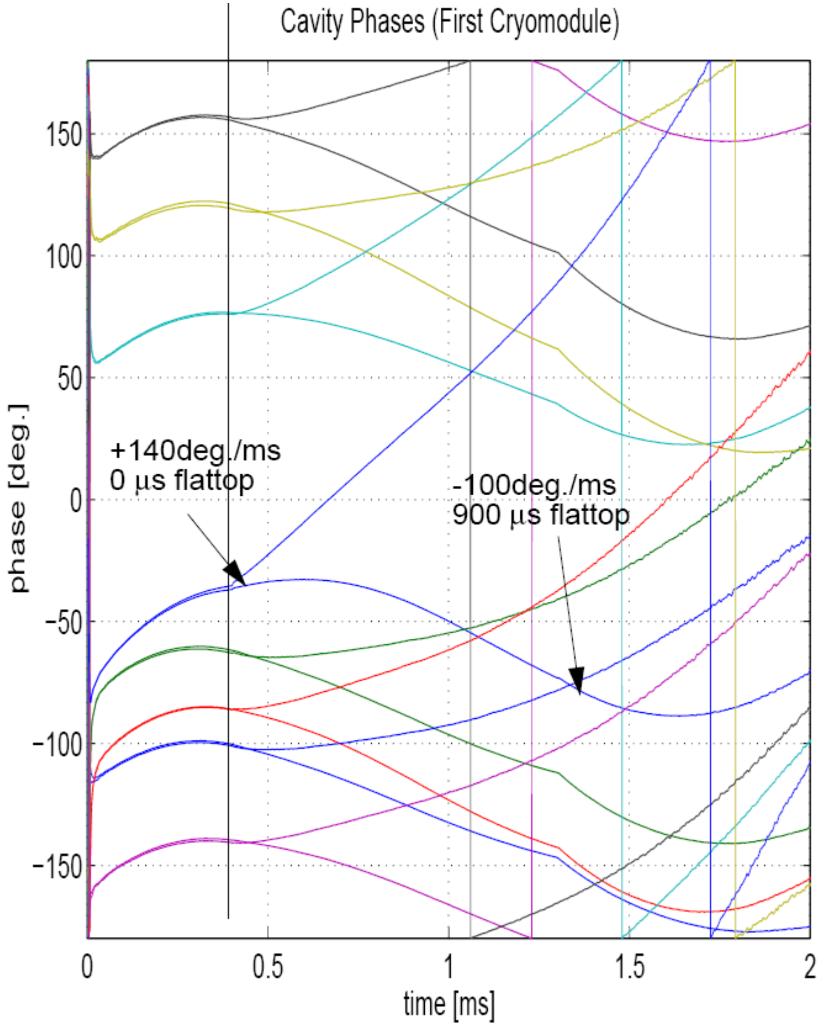
- Deformation of the cavity shape:



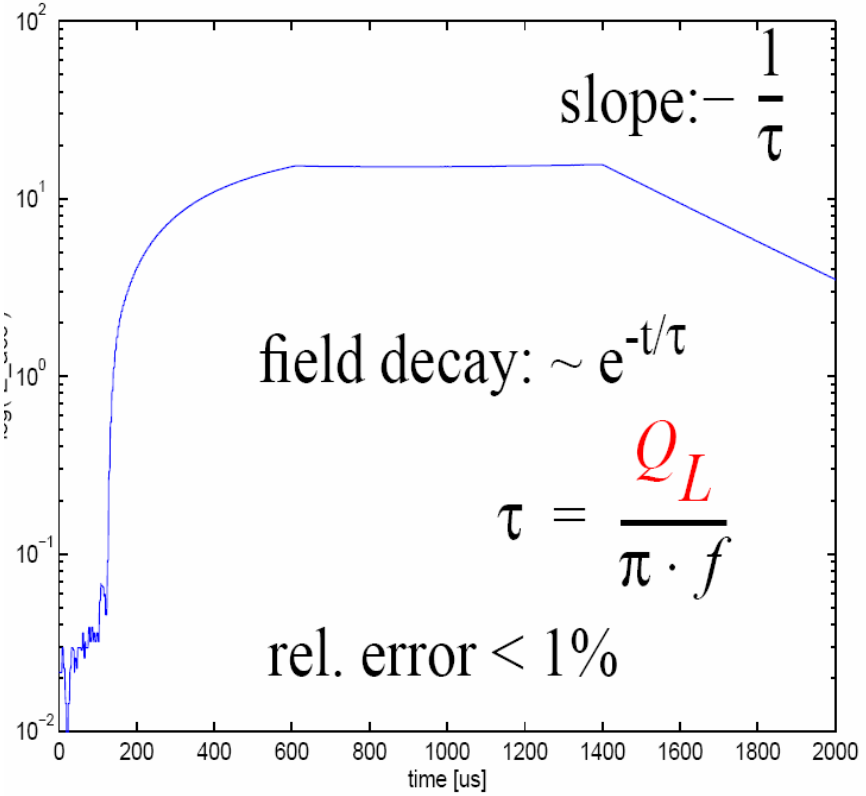
- Frequency shift : $\Delta f = KL^* E^2_{acc}$

Lorentz Force Detuning

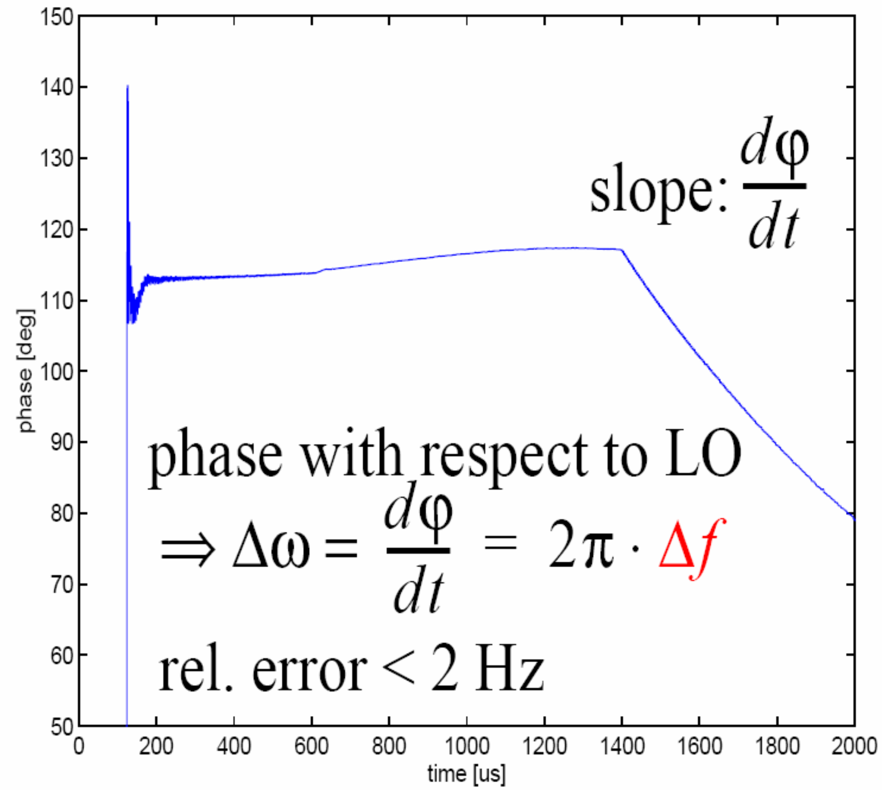




Measurement of Q_L and $\Delta\omega$

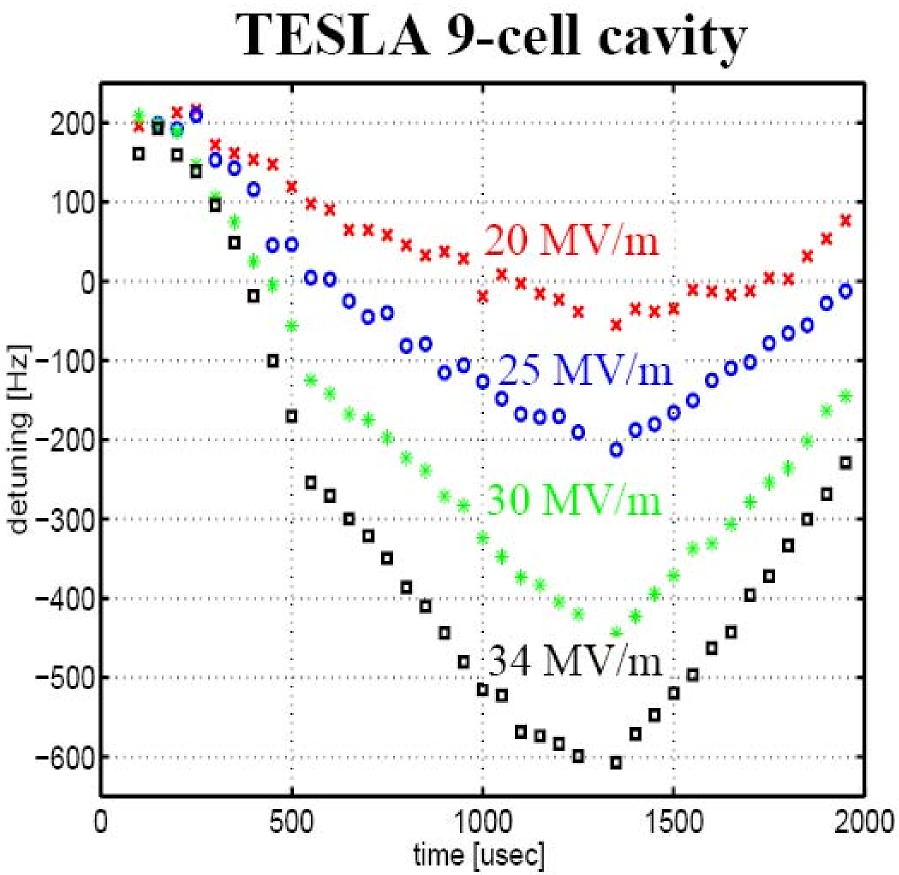


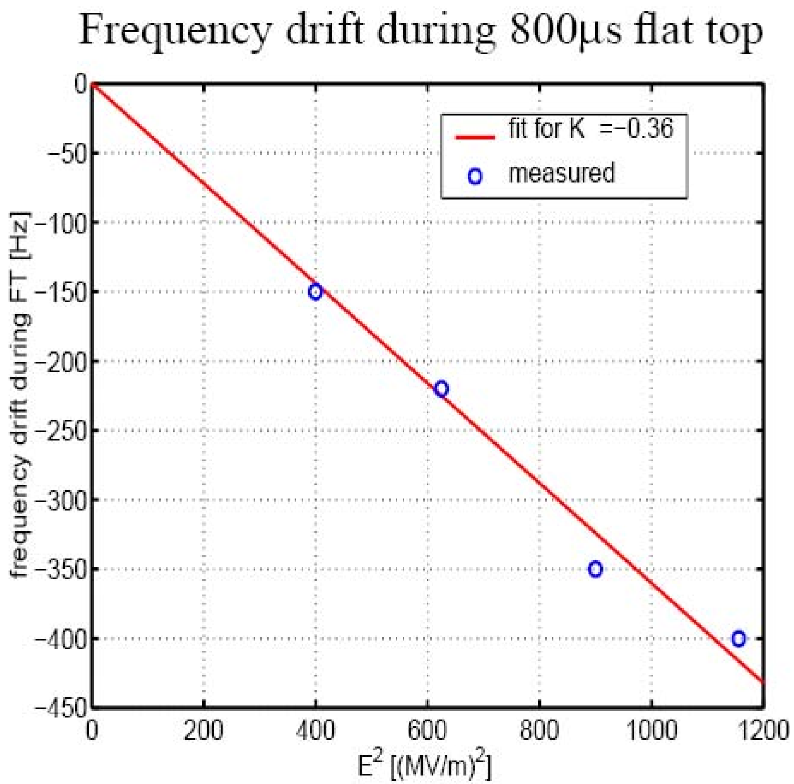
Loaded Q



Detuning

Measurement of Lorentz Force Detuning

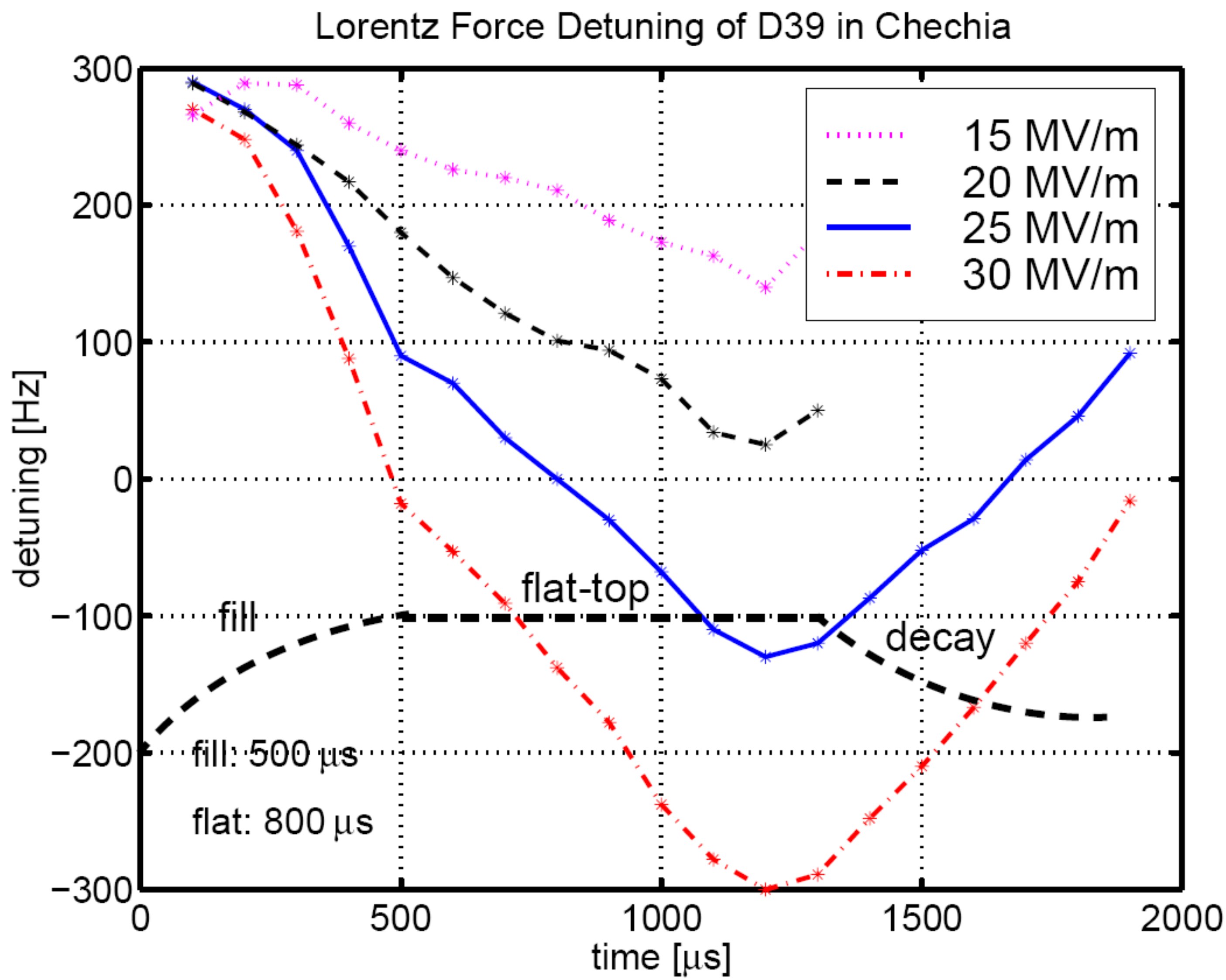




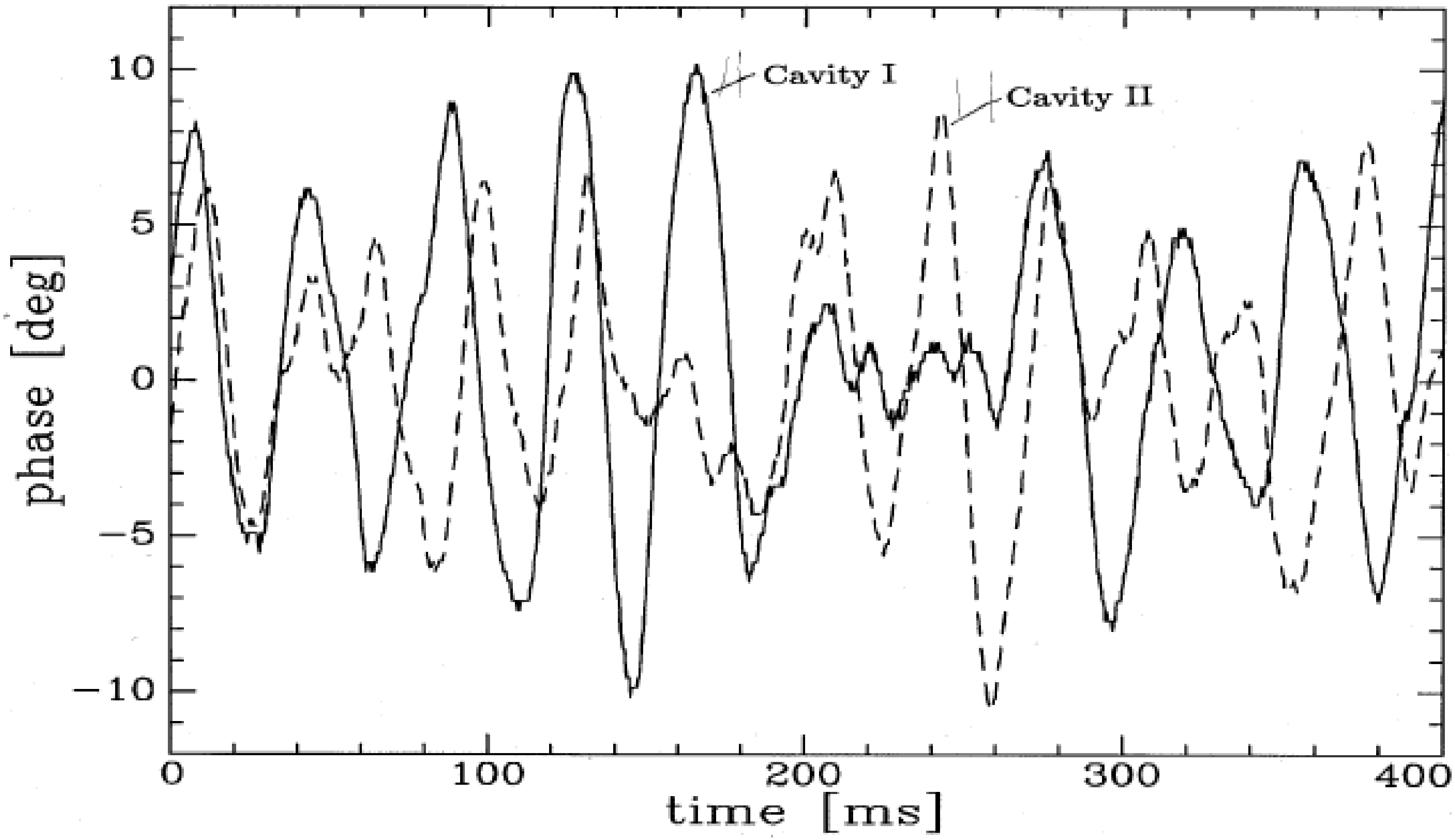
Frequency drift during 950 µs flat top (TESLA 9-cell cavity):

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

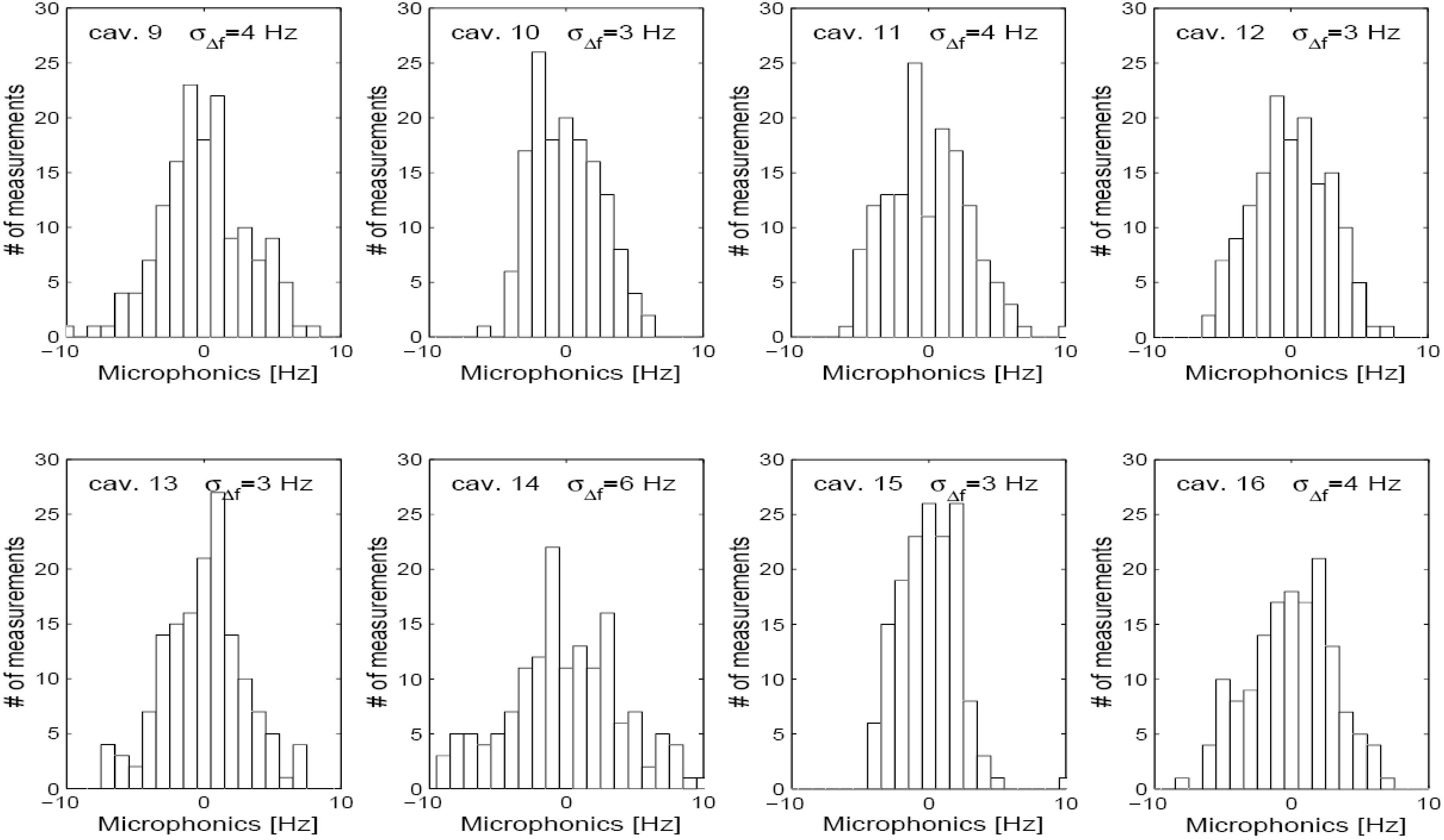
Lorentz force detuning



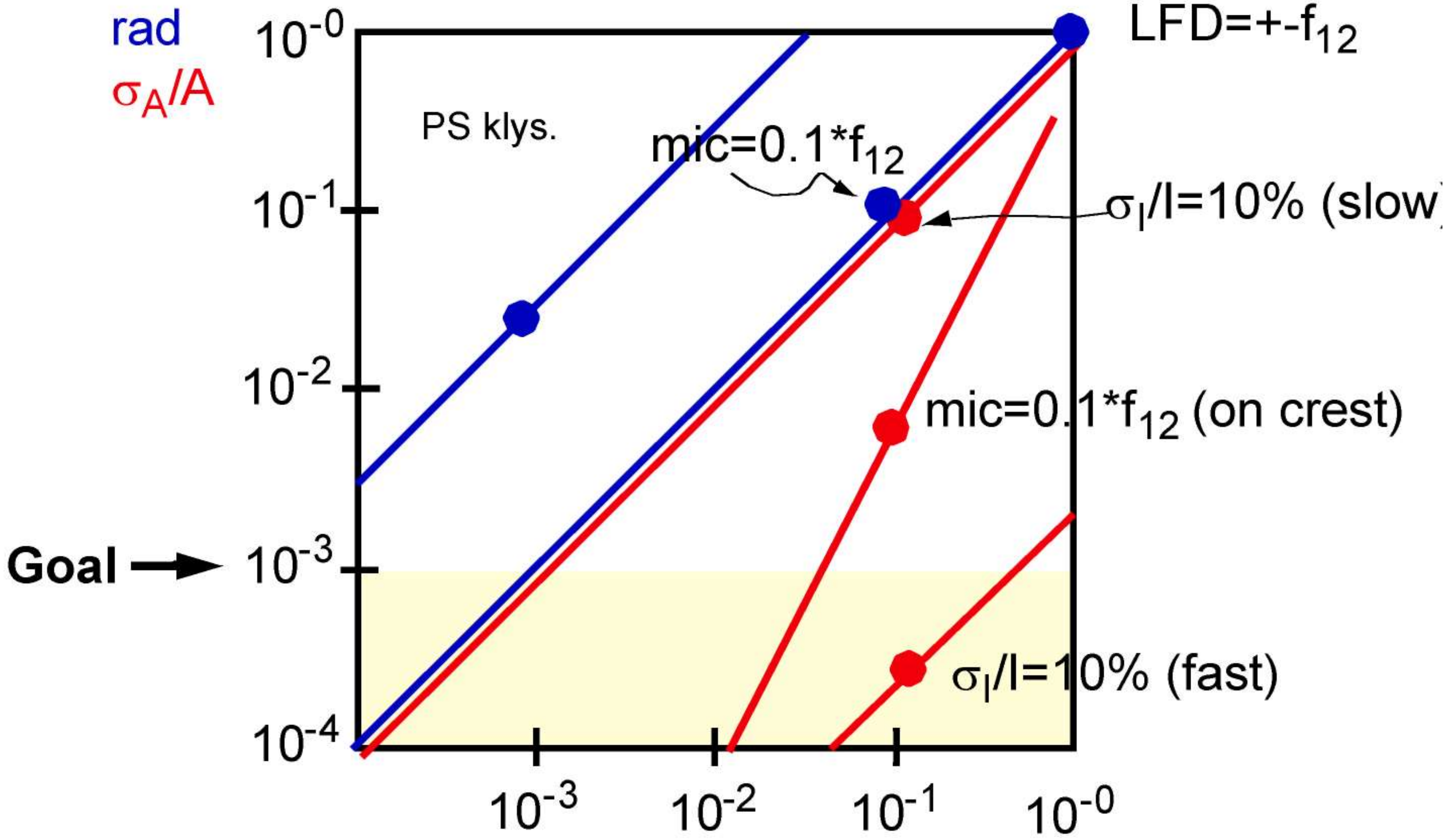
Microphonics at JLAB



Microphonics at FLASH



Error Map



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

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

- **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

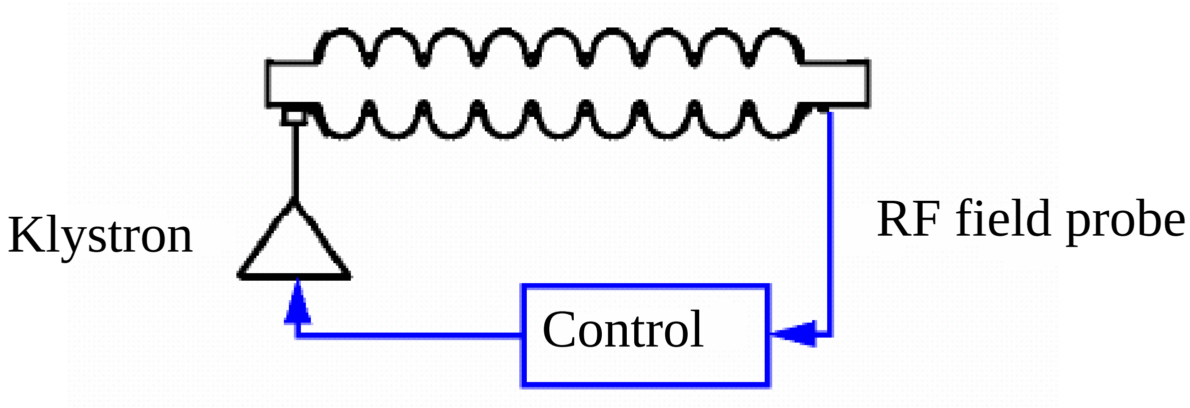
Requirements

- **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



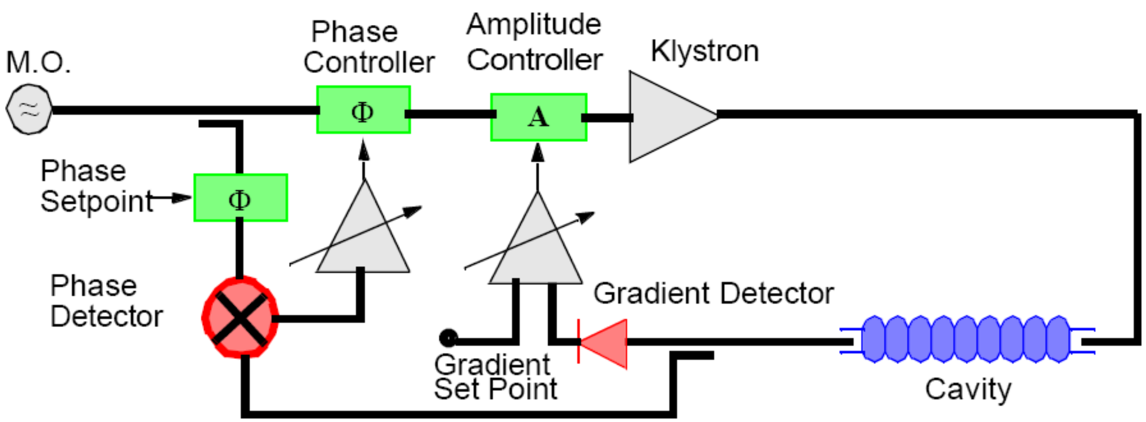
- Measure cavity RF field

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

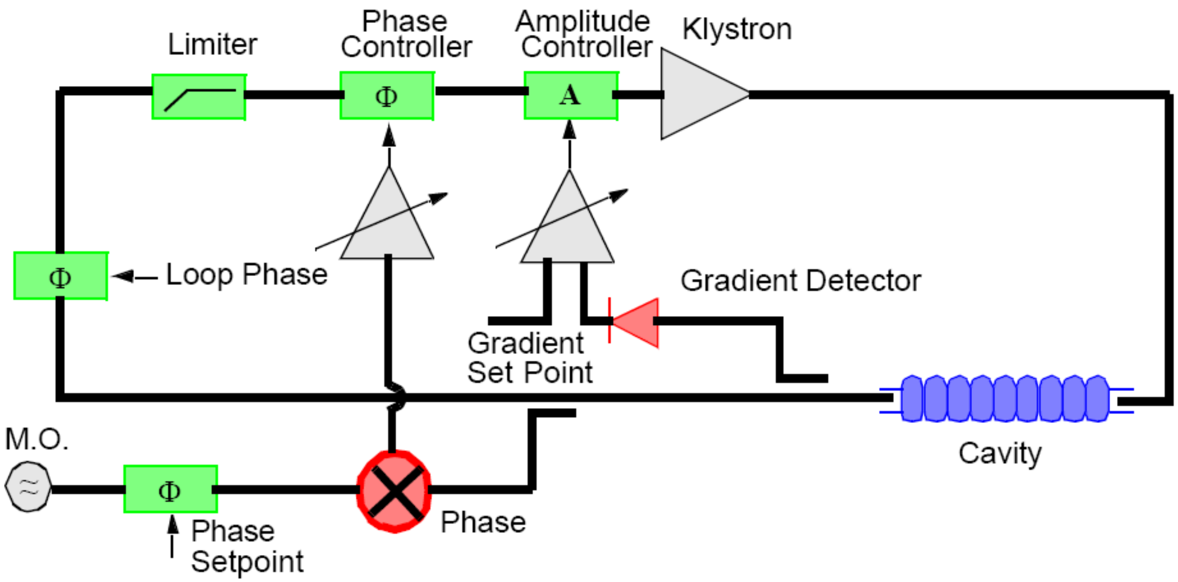
Control Choices (1)

- 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)

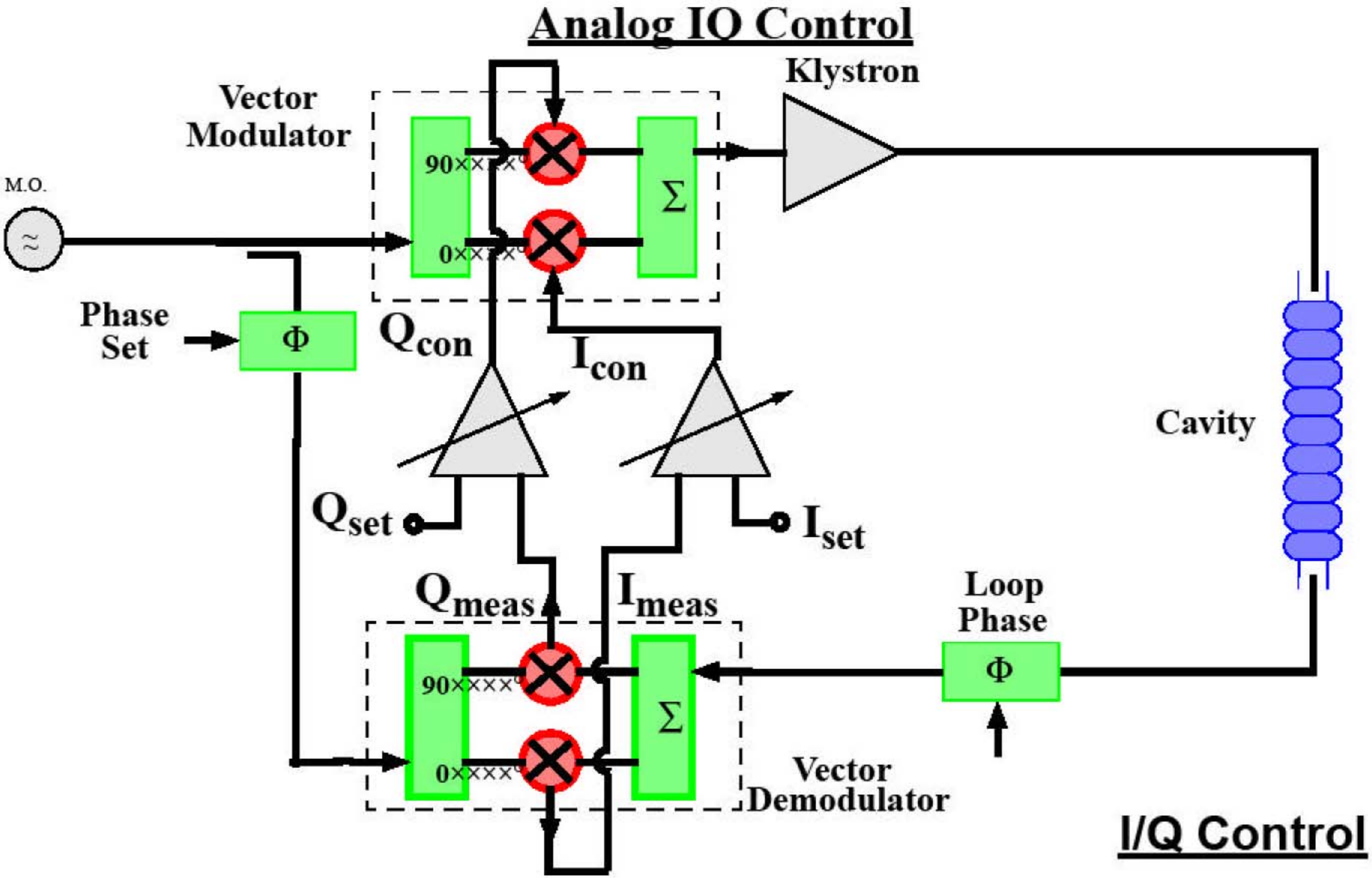


Generator Driven Resonator

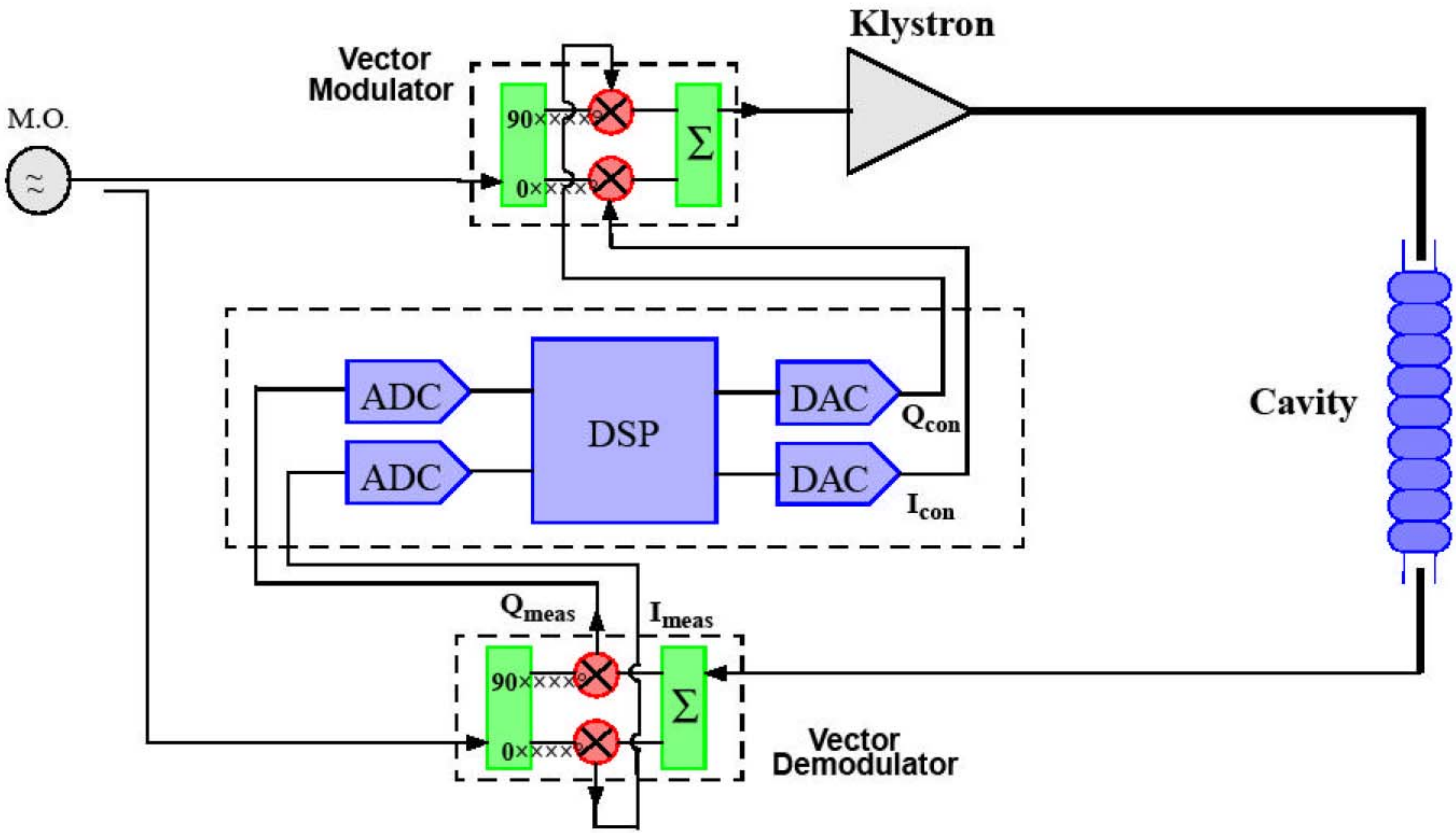


Self Excited Loop

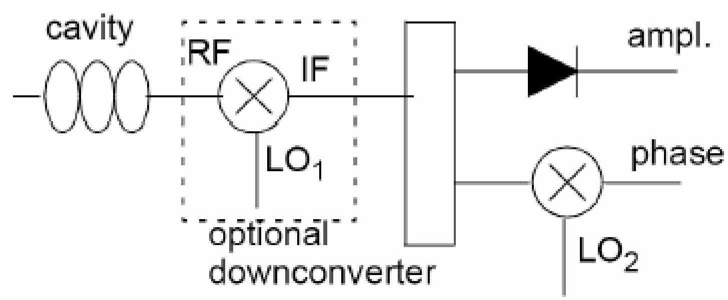
Analog IQ Control



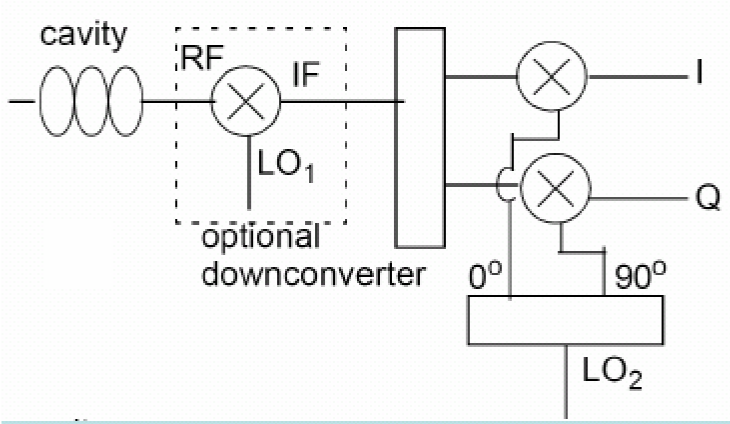
Digital IQ Control



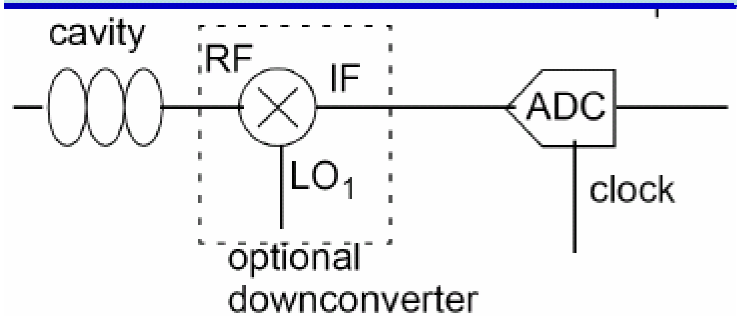
Design Choices: Field Detectors



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

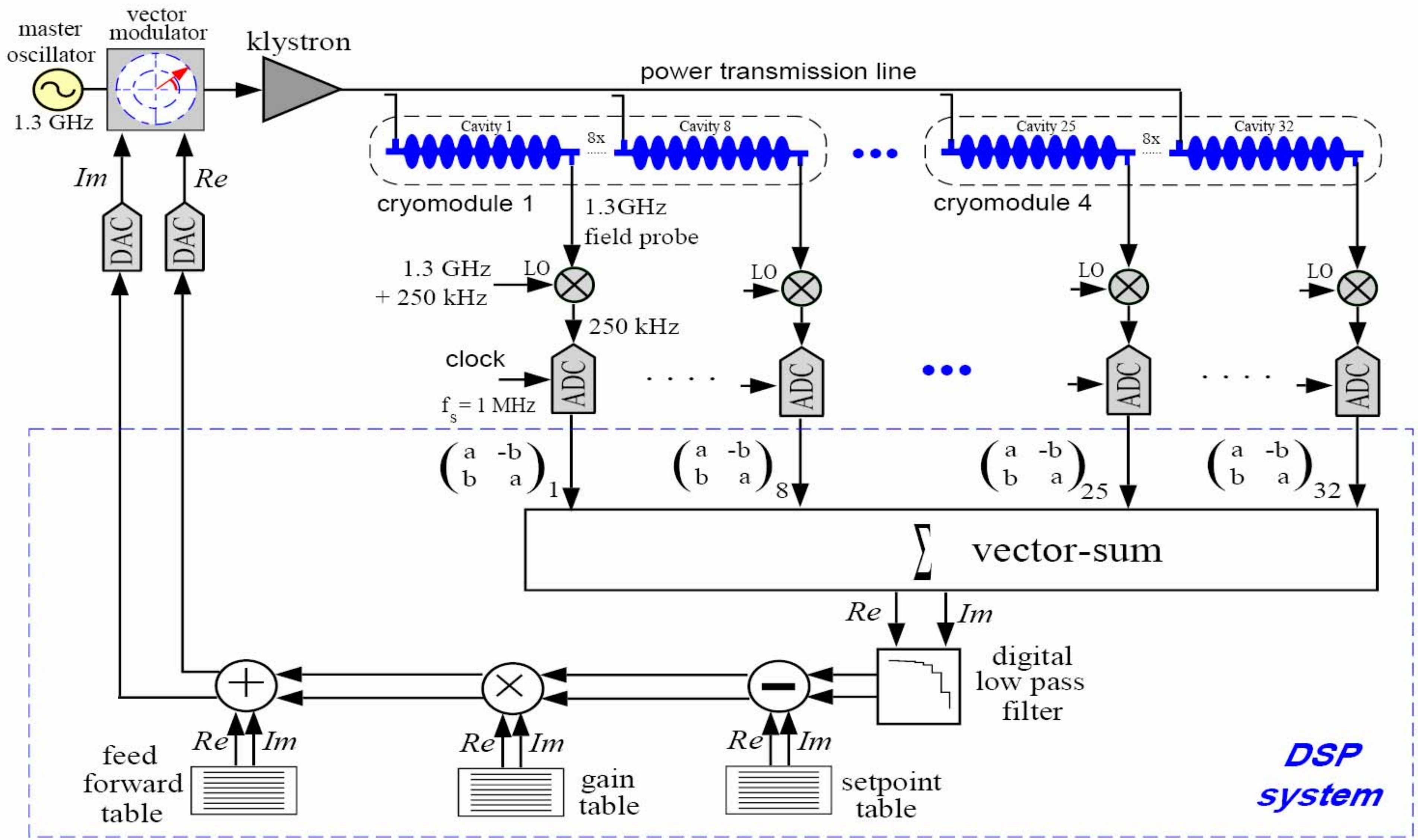


- I /Q detection: real and imaginary part of the complex field vector
- Preferable in presence of large field errors

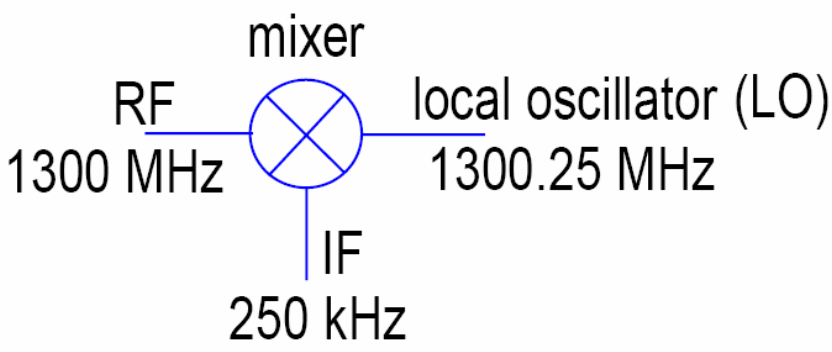


- Digital I / Q detection
- Alternating sample give I and Q component of the cavity field

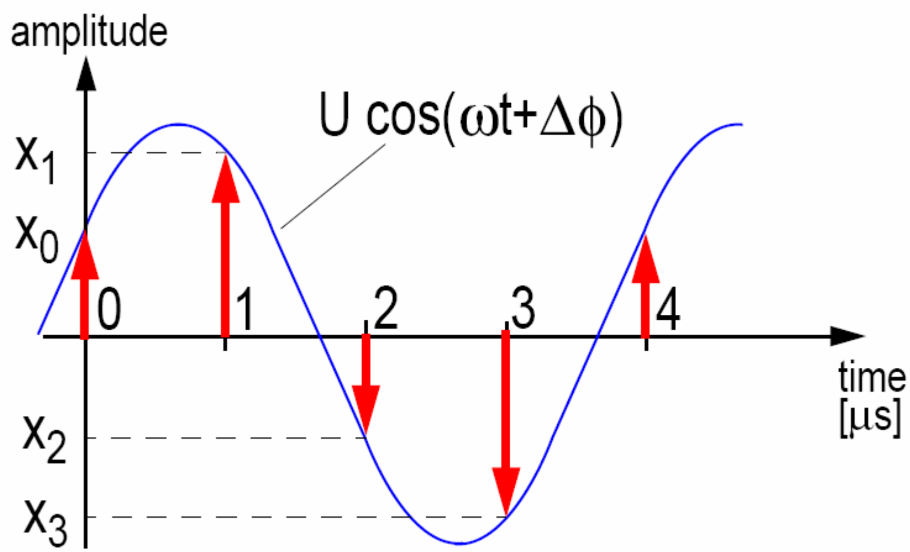
Digital RF Control at FLASH



Digital field detection



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

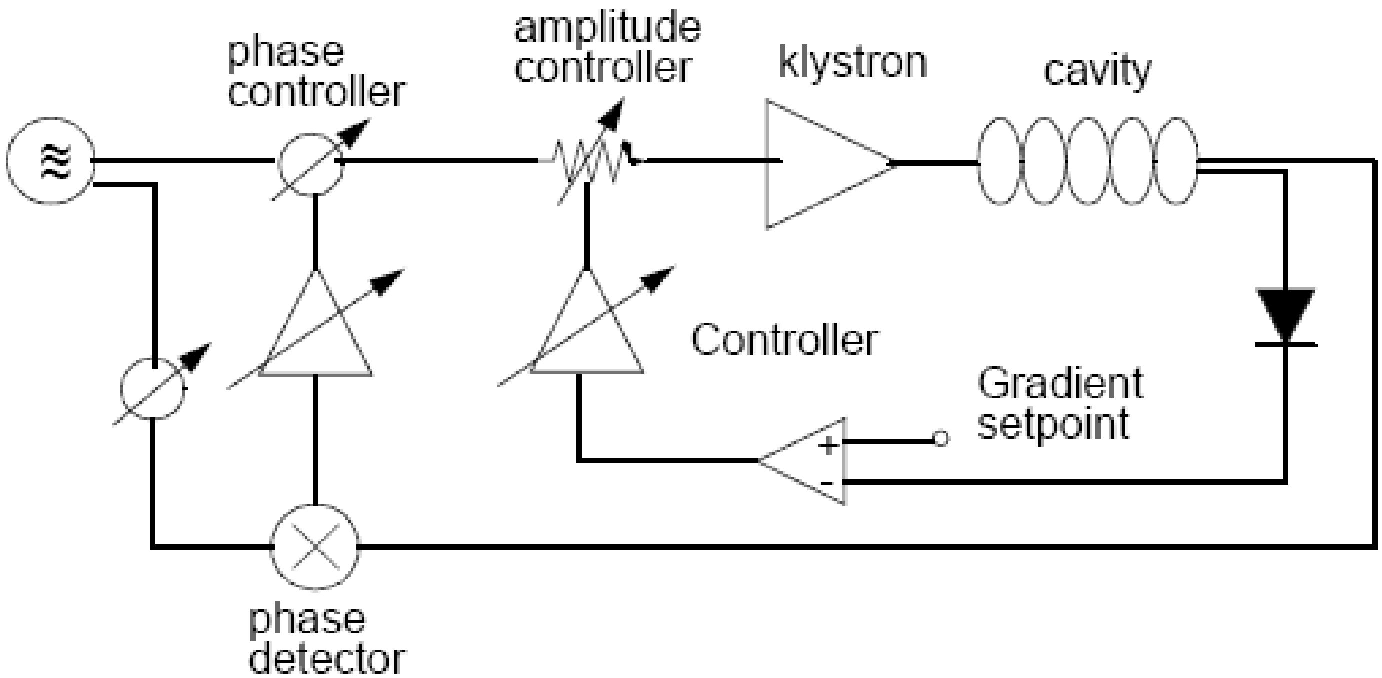


- sample IF signal at 1MHz rate
- subsequent samples describe real and imaginary component of the cavity field.

RF Control Model

Goal:
Maintain stable gradient and phase

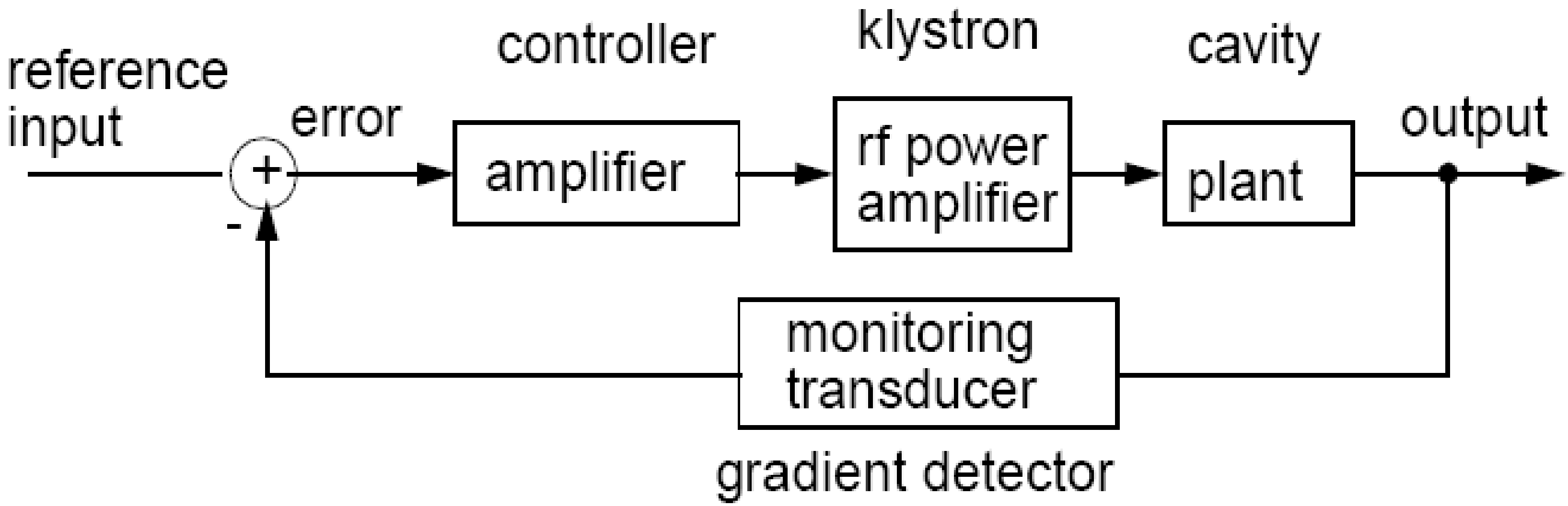
Solution:
Feedback for gradient amplitude and phase:



RF Control Model

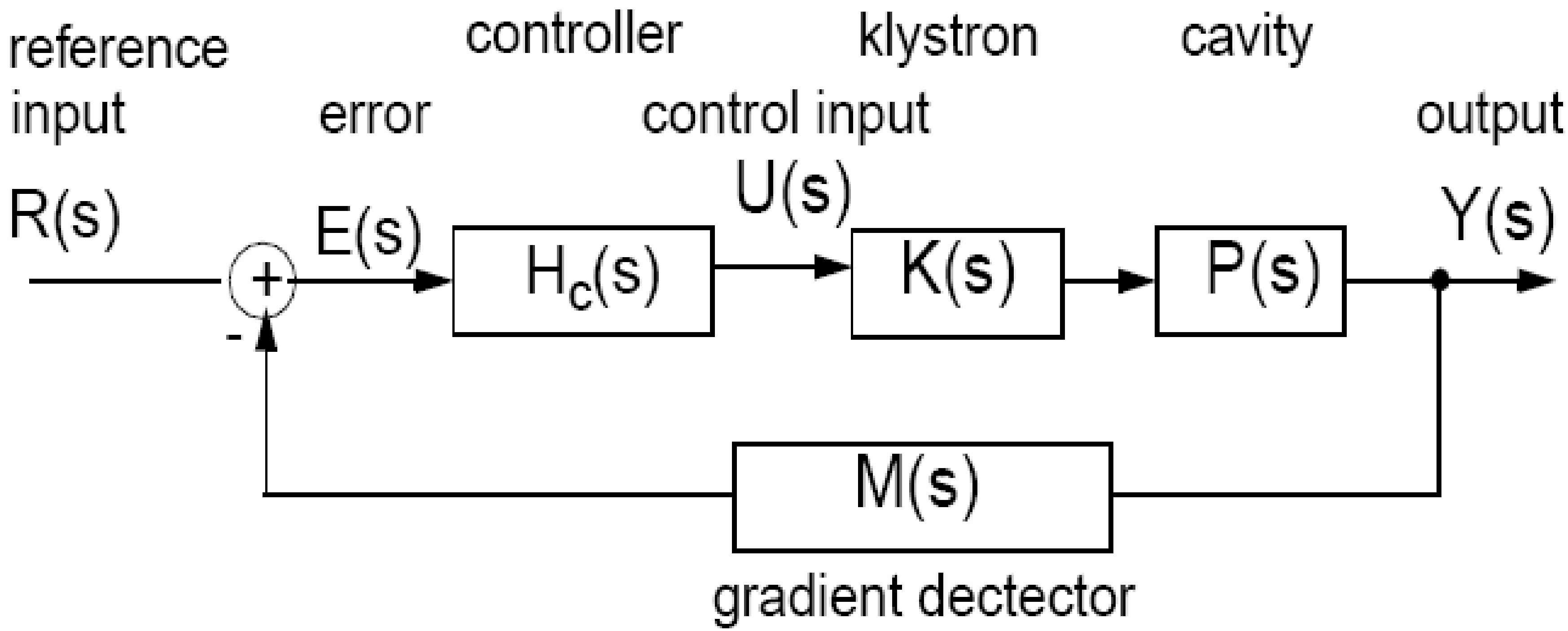
Model:
Mathematical description of input-output relation of components combined with block diagram:

Amplitude Loop (general form):

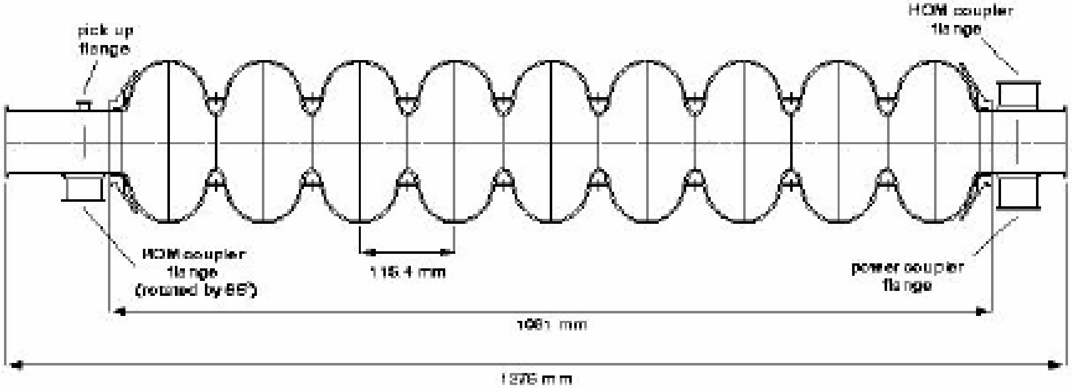


RF Control Model

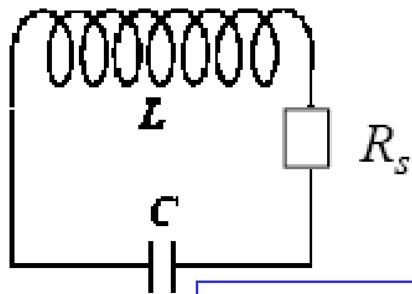
RF Control model using "transfer functions"



Cavity Model

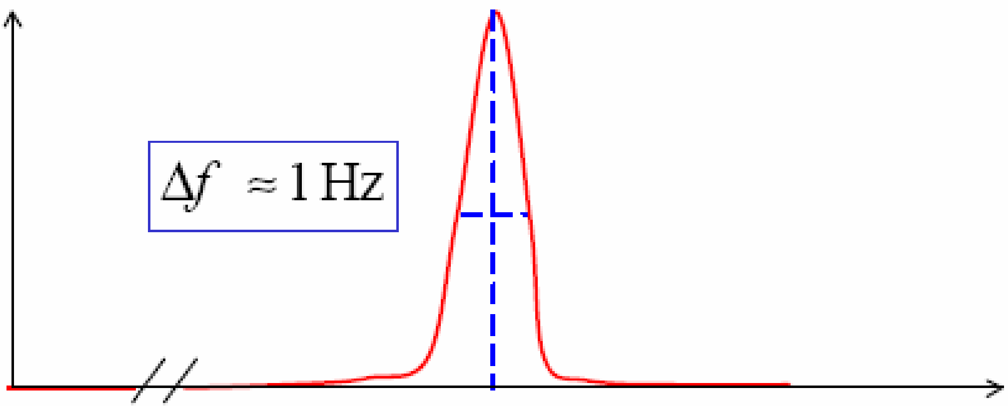


Schwingkreis:



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

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



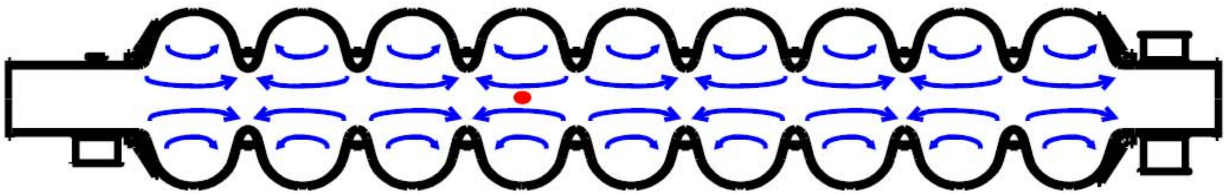
$\Delta f \approx 1\,\text{Hz}$

f

$f_o = 1.300.000.000\ \text{Hz}$

$\Rightarrow$ 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:

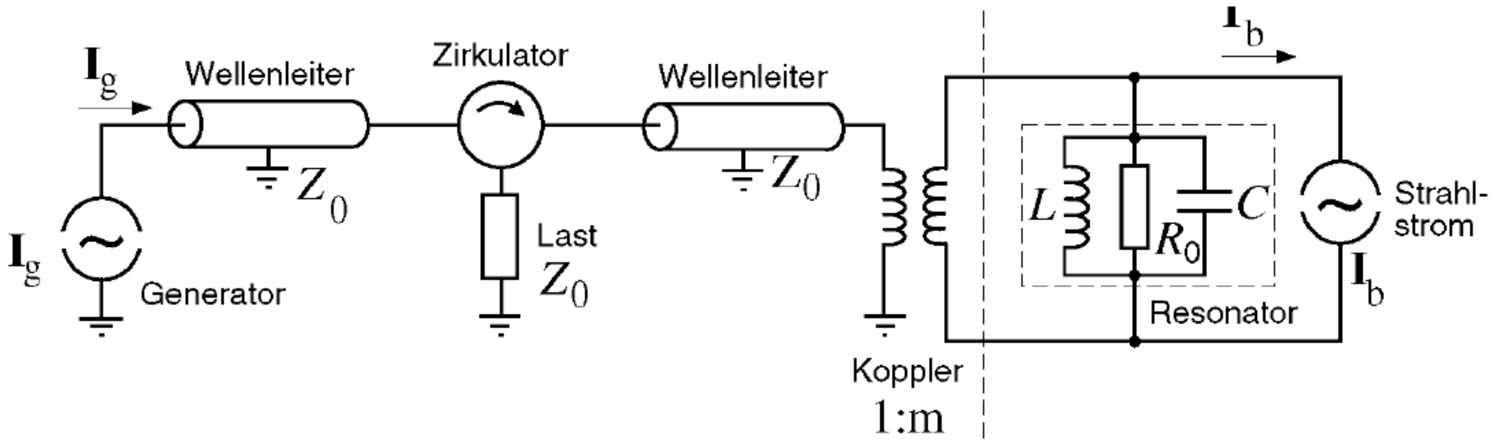
$$R_{\text{sh}} = \frac{(V_{acc})^2}{2P_{\text{Wand}}}$$

Unbelastete Güte:

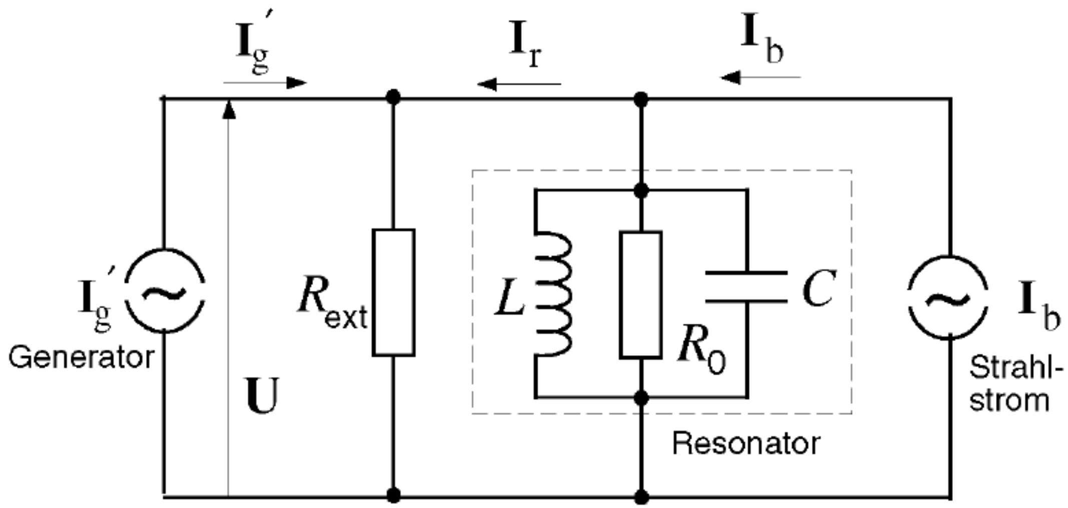
$$Q_0 = \frac{\omega W}{P_{\text{Wand}}}$$

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

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

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

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

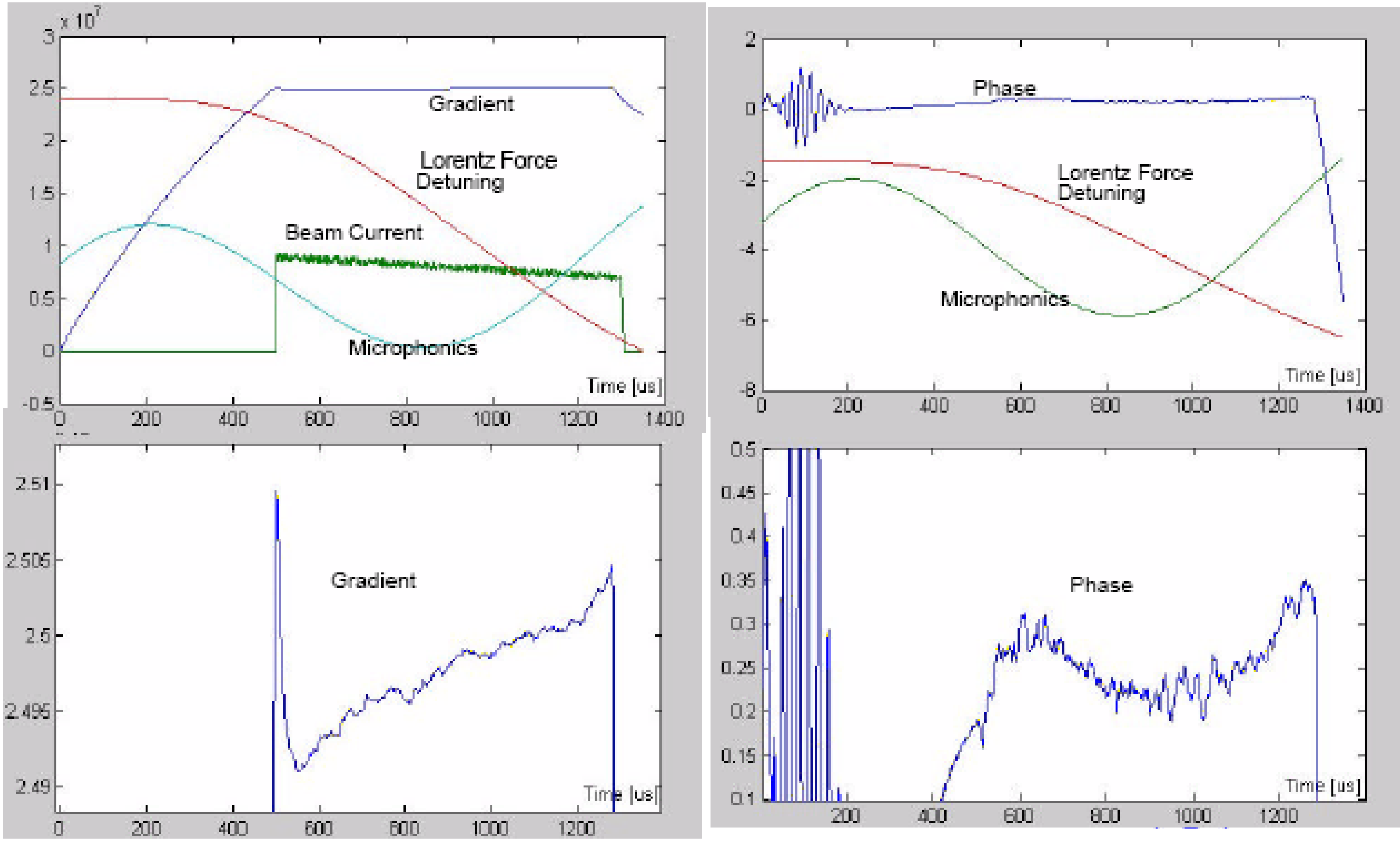
where $A_d = e^{AT_s}$ $\quad B_d = \int_0^{T_s} e^{A\tau} B d\tau$ $\quad C_d = C$ $\quad D_d = D$

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

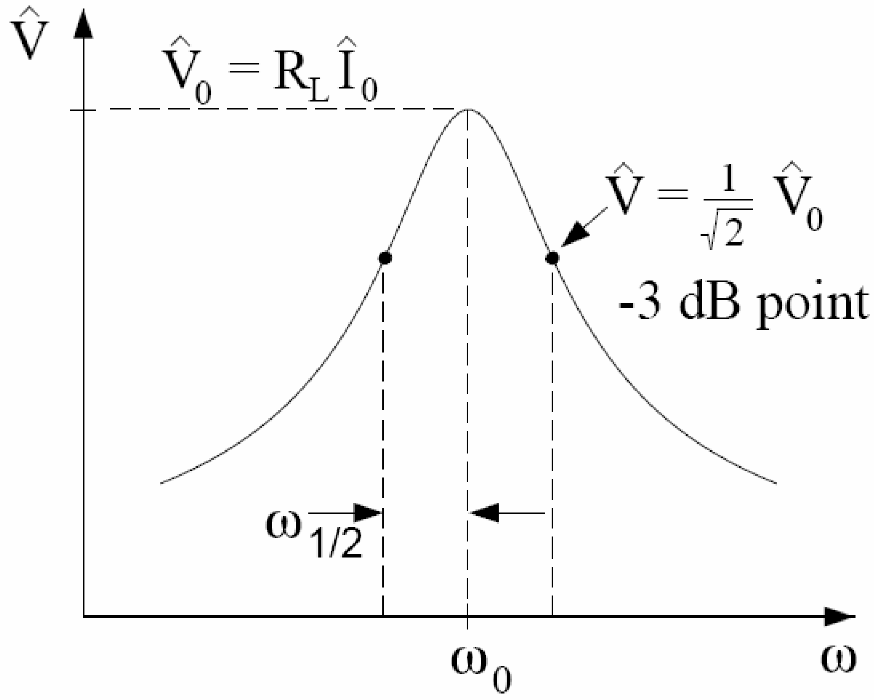
$$B_d = \quad ..... \quad \approx \begin{bmatrix} \omega_{1/2} T_s & \Delta\omega\omega_{1/2} T_s^2/2 \\ \Delta\omega\omega_{1/2} T_s^2/2 & \omega_{1/2} T_s \end{bmatrix}$$

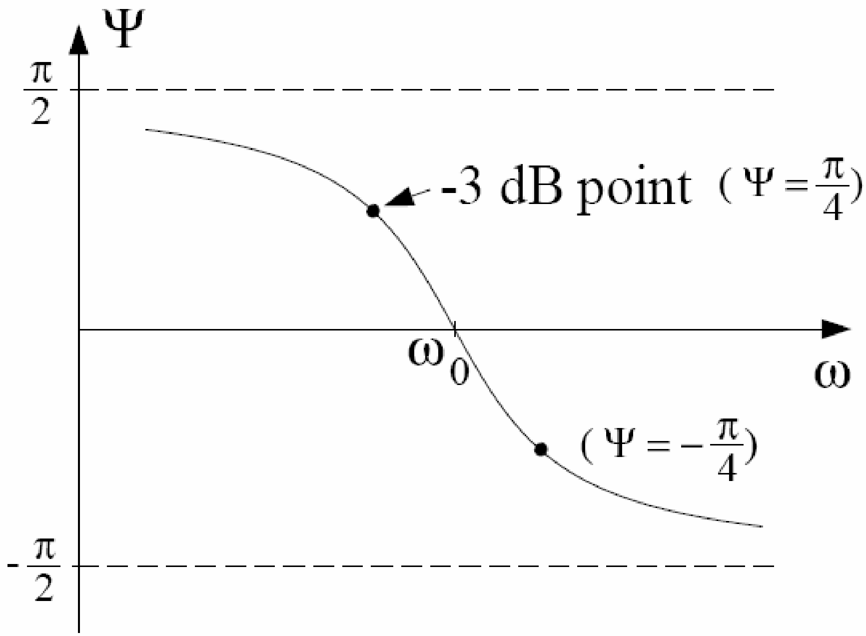
with solution
$$x(k) = A^k \cdot x(0) + \sum_{i=1}^{k} A^{i-1} \cdot B \cdot u(k-i)$$

Cavity Field Regulation (Simulation)



Resonance curve of cavity

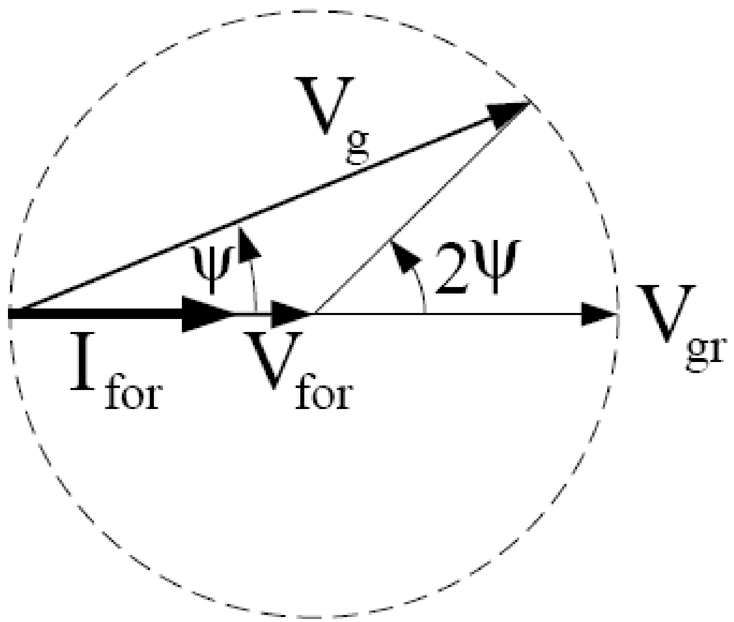




$$\hat{V}(\Delta\omega) \approx \frac{R_L \hat{I}_0}{\sqrt{1 + (2Q_L \frac{\Delta\omega}{\omega})^2}}$$

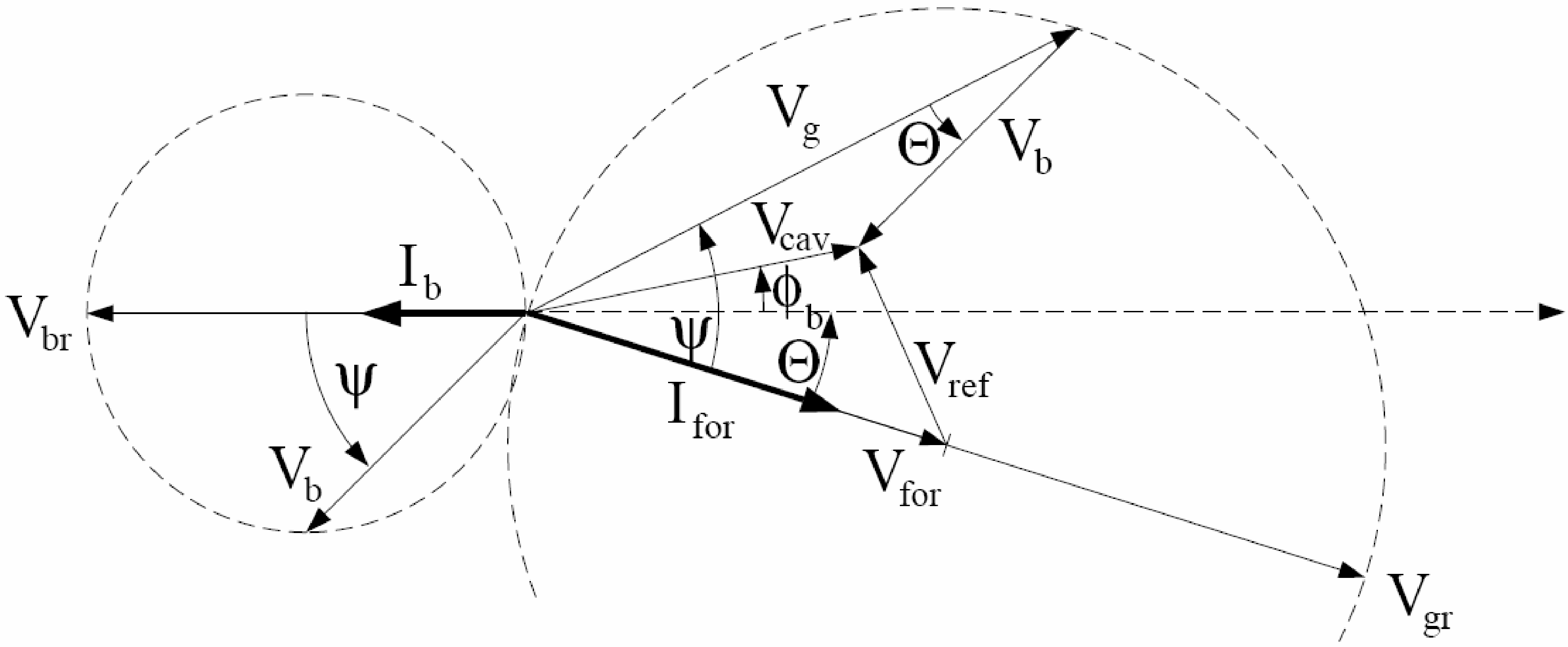
$$\tan\psi \approx 2Q_L \frac{\Delta\omega}{\omega} = 2Q_L \frac{\Delta f}{f}$$

Induced voltage as funct. of detuning angle



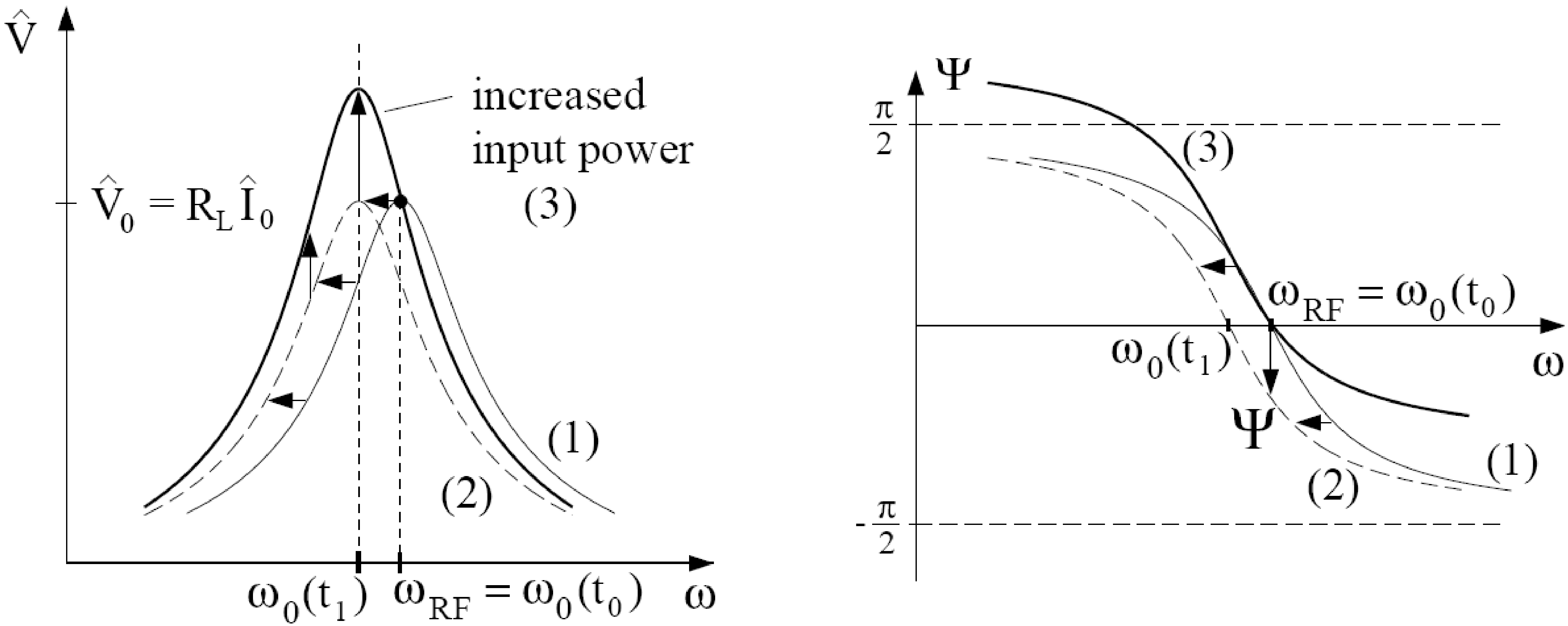
Induced cavity voltage as a function of the tuning angle ψ. The voltage induced by a generator current $\mathbf{I}_g$ on resonance is denoted by an index 'r'. This applies to both generator- and beam-induced voltages. In the case of superconducting cavities with $Q_0 \gg Q_{ext}$, the voltage $\mathbf{V}_{gr}$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

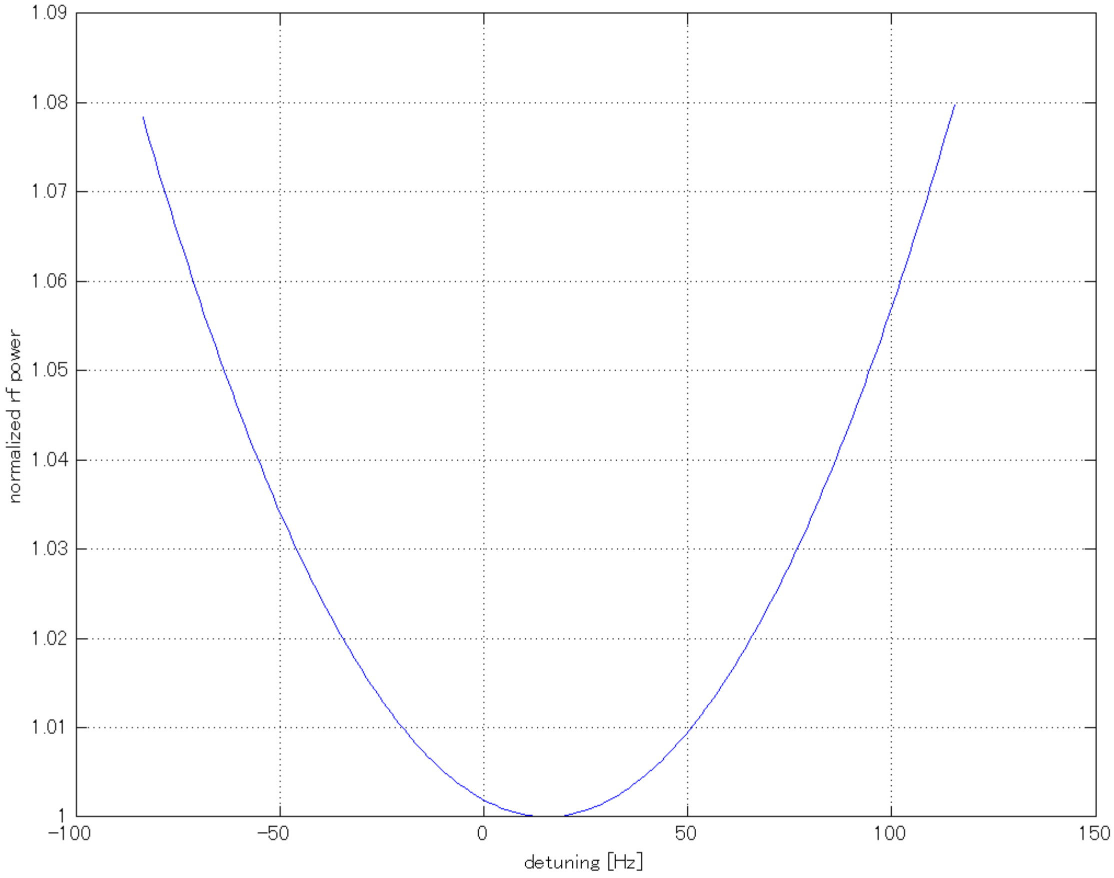
$V_{cav} = 25\ \mathrm{MV},\ Q_L = 3 \cdot 10^6$; no beam:

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

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

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

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

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

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

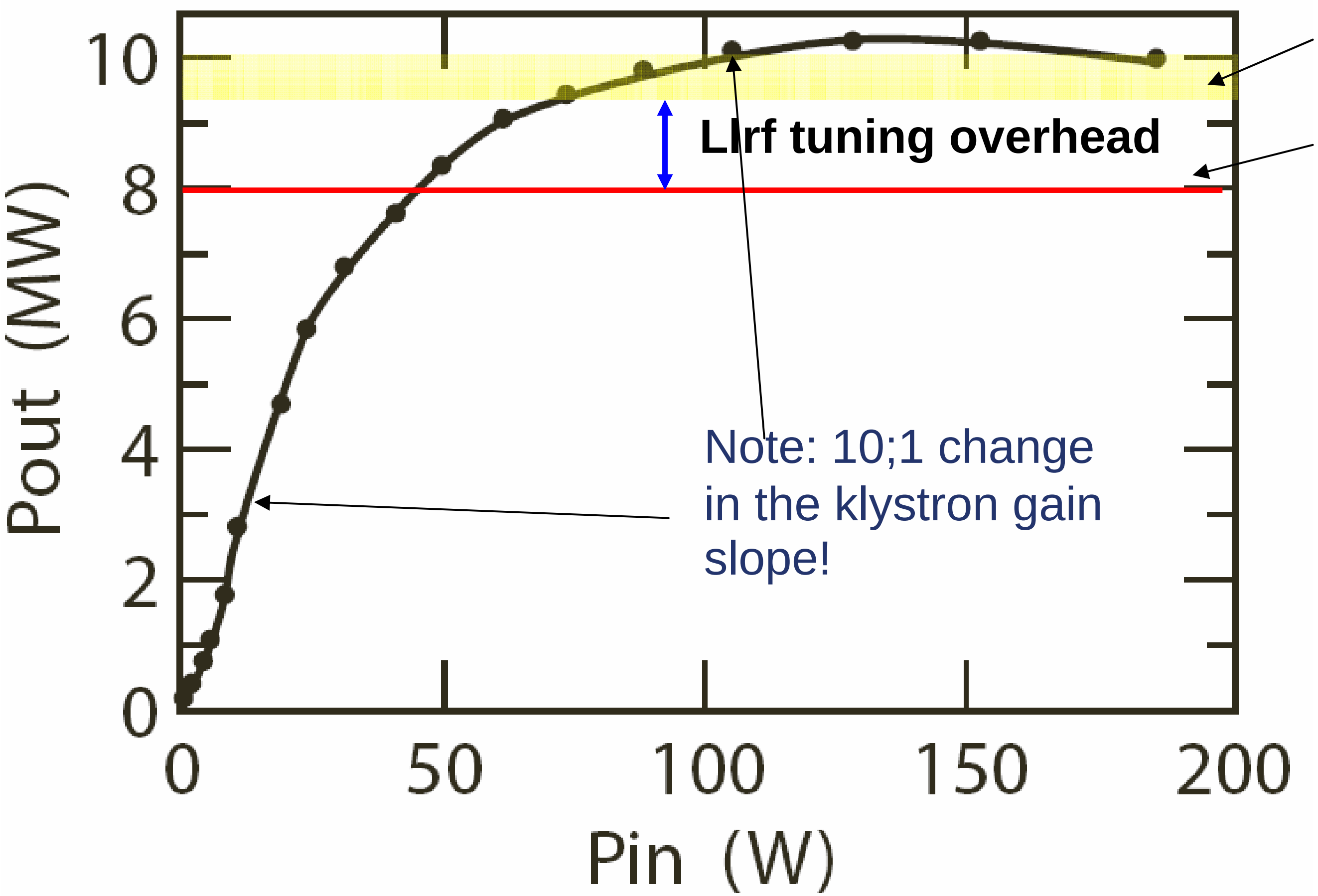
$$(P_g)_{min} = \frac{V_{cav}^2}{\left(\frac{r}{Q}\right)(Q_L)_{opt}} = V_{cav}\cdot I_{b0}\cdot\cos\phi_b$$

- 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!)

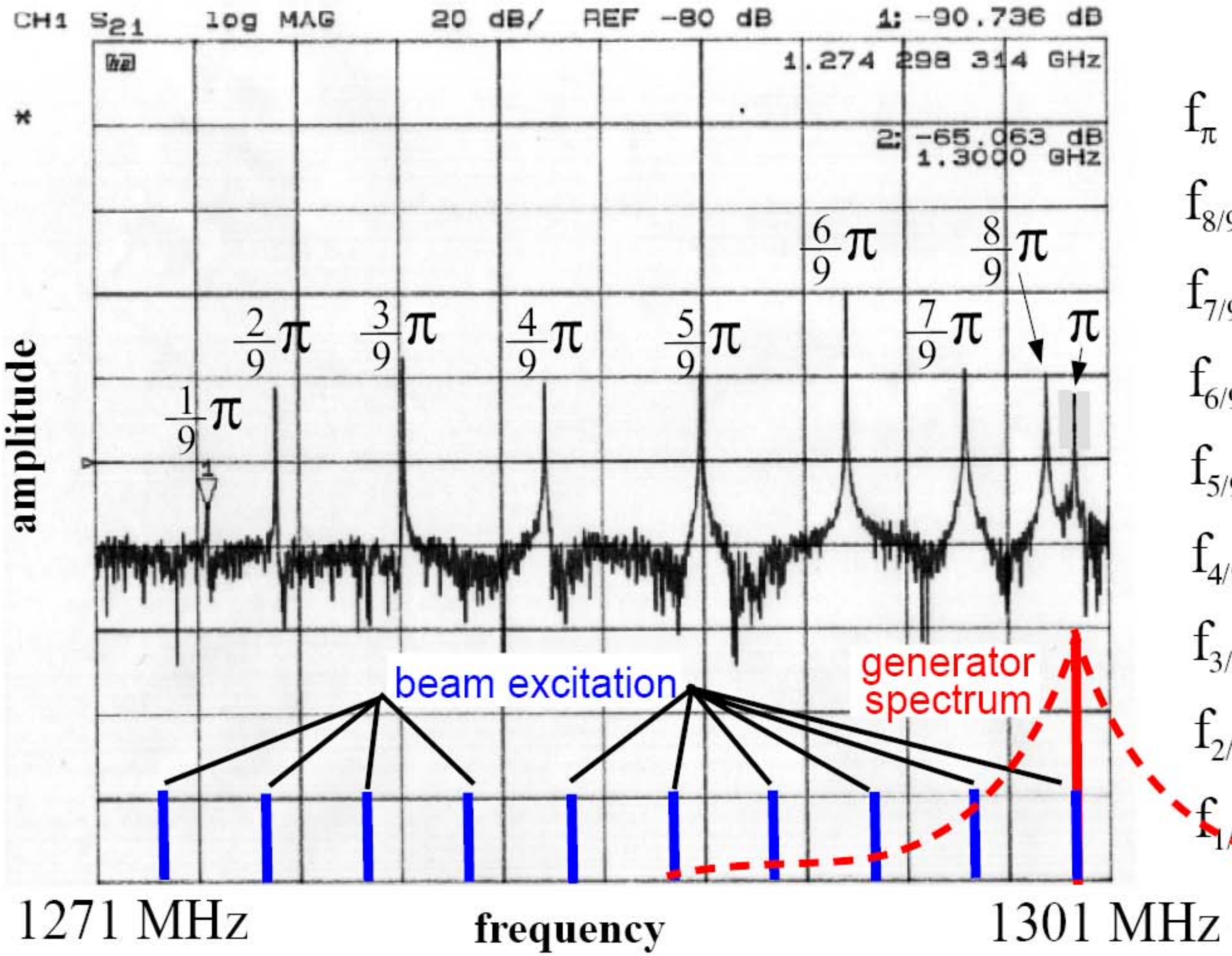


Waveguide loss (7%)

operation (~8 MW @33 MV/m)

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

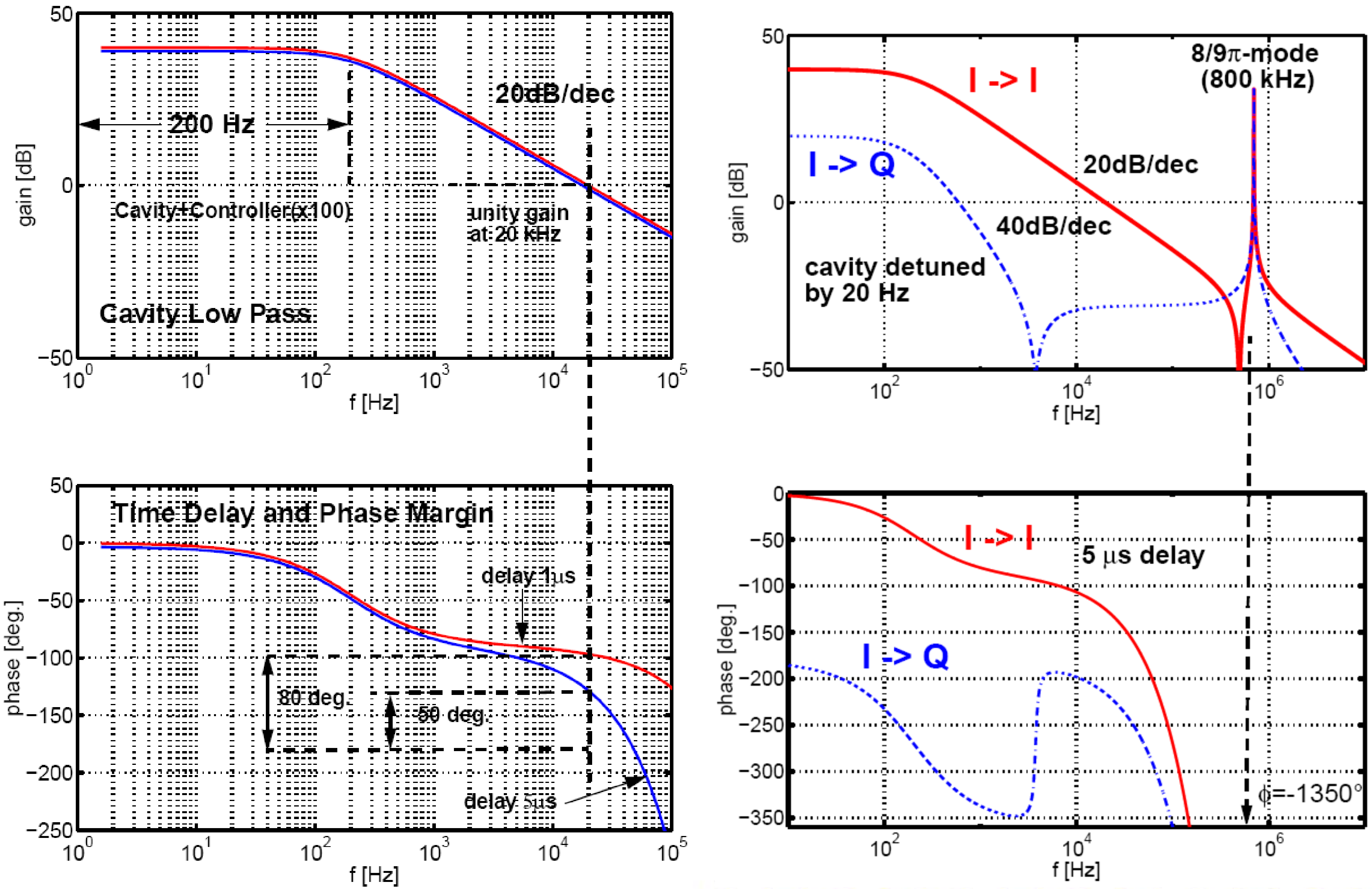
$f_{4/9\pi} = 1284.409$ MHz

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

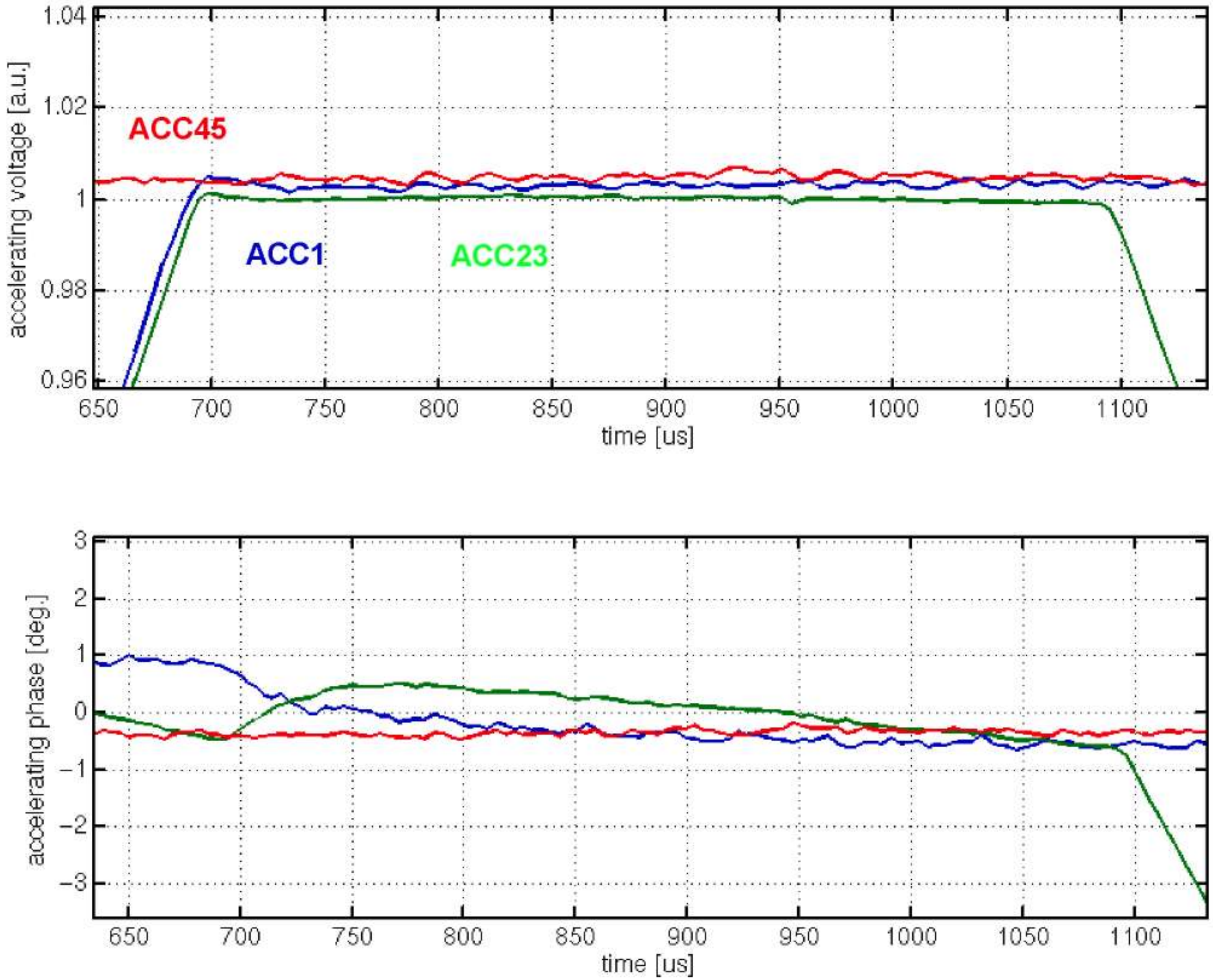
$f_{2/9\pi} = 1276.435$ MHz

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

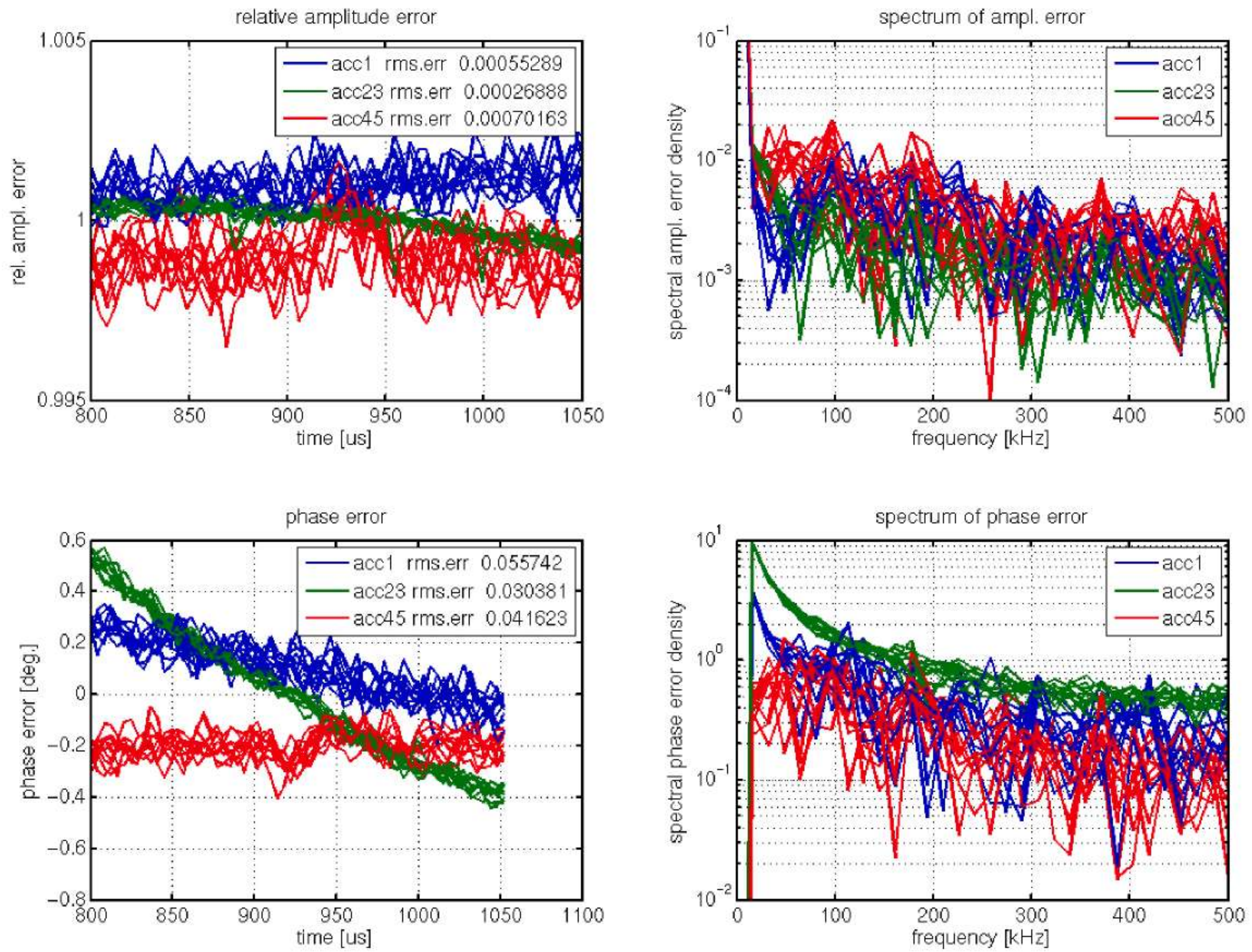
Bode Plot Cavity (wout/w 8/9-pi mode)



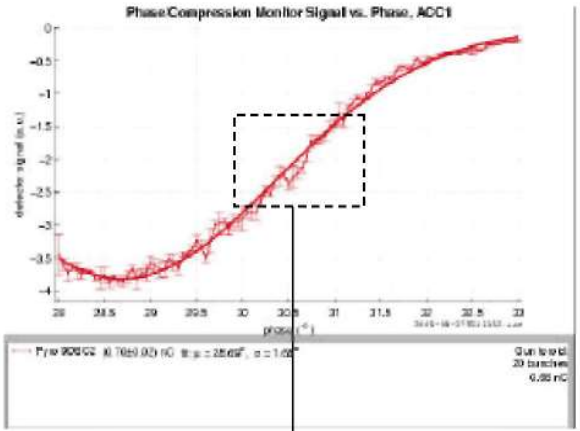
Field Regulation at FLASH

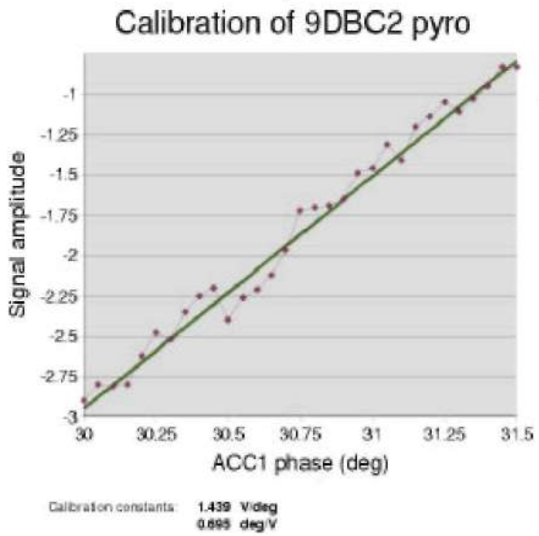


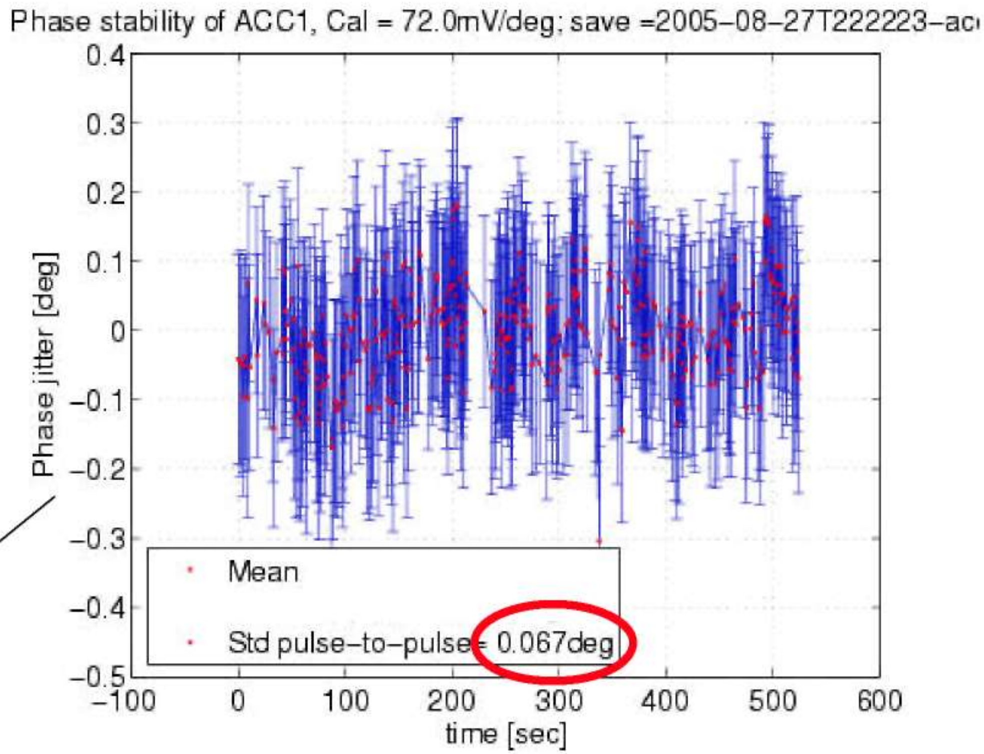
Field Regulation at FLASH



Field Regulation at FLASH



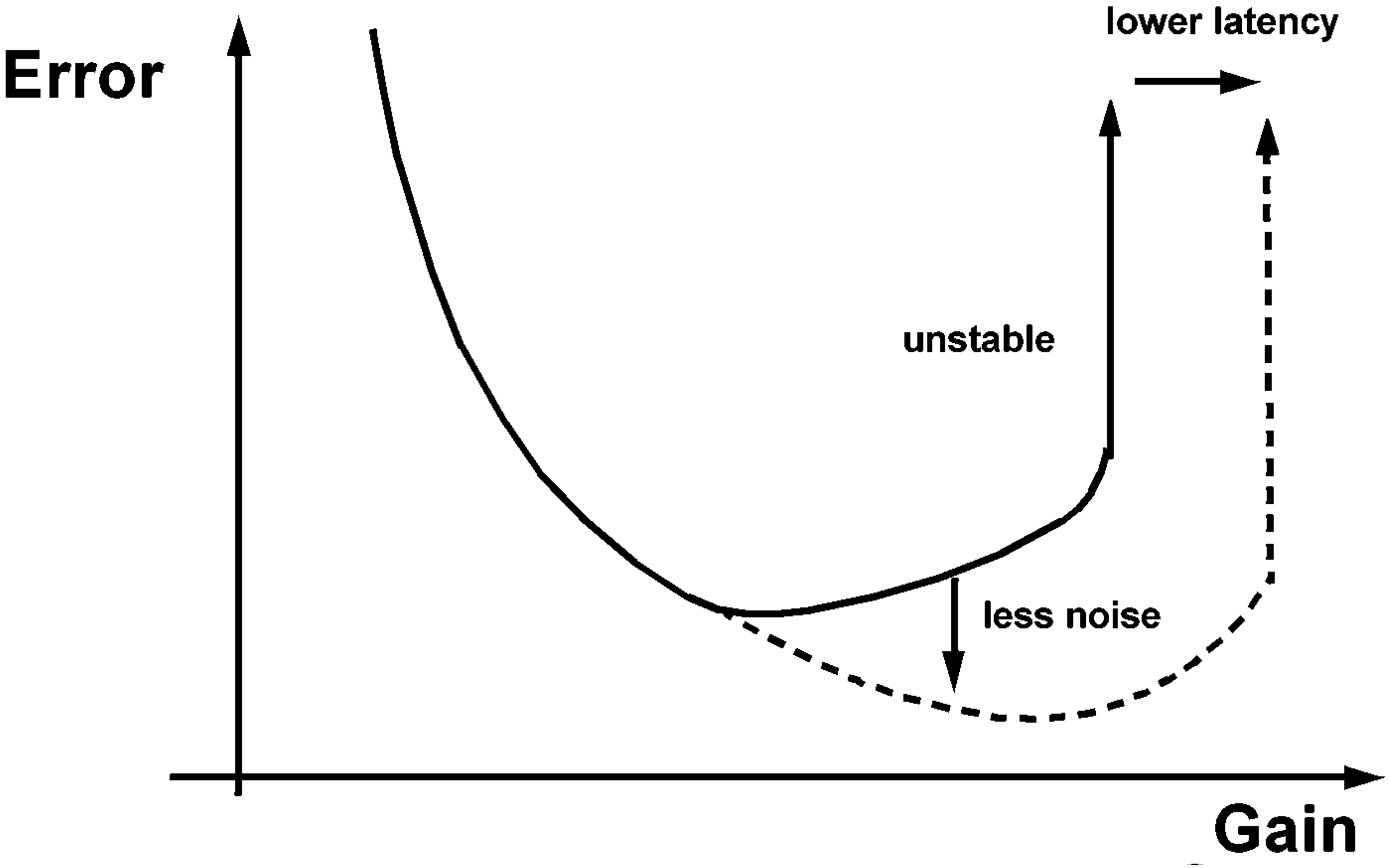




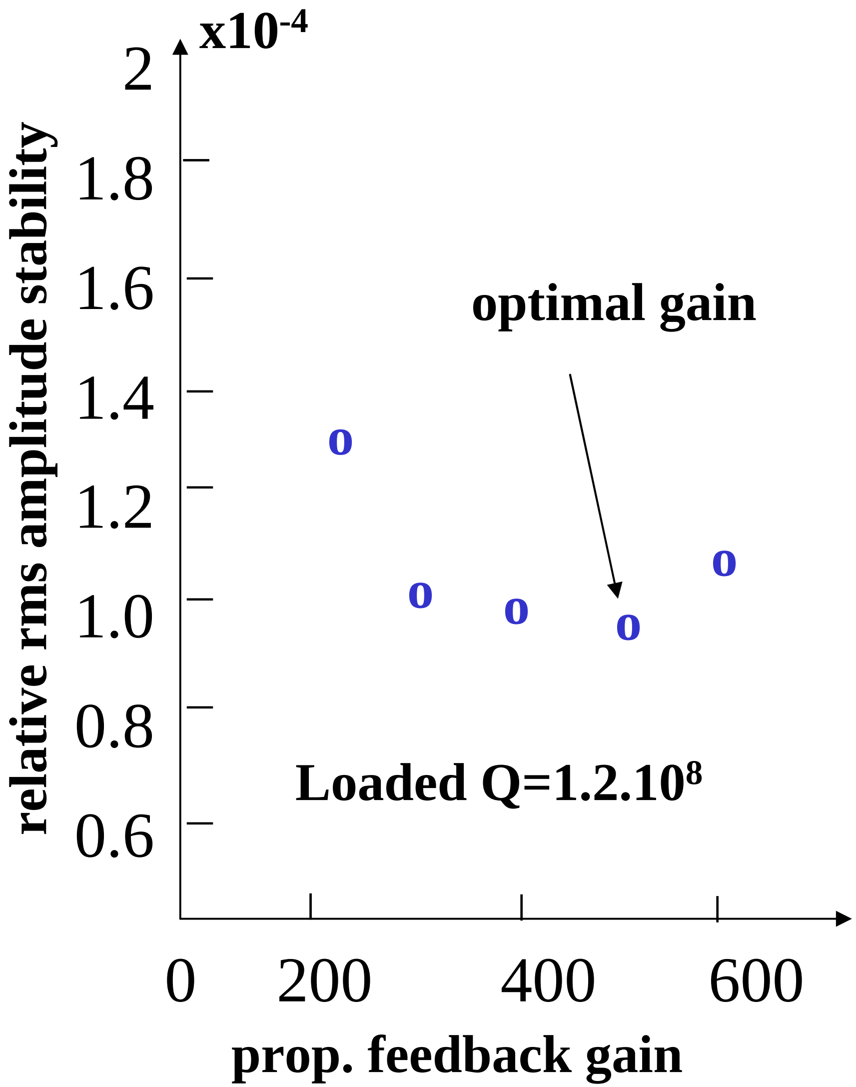
But! This is the phase stability between the beam arrival into the acceleration module relative to the RF phase!!!

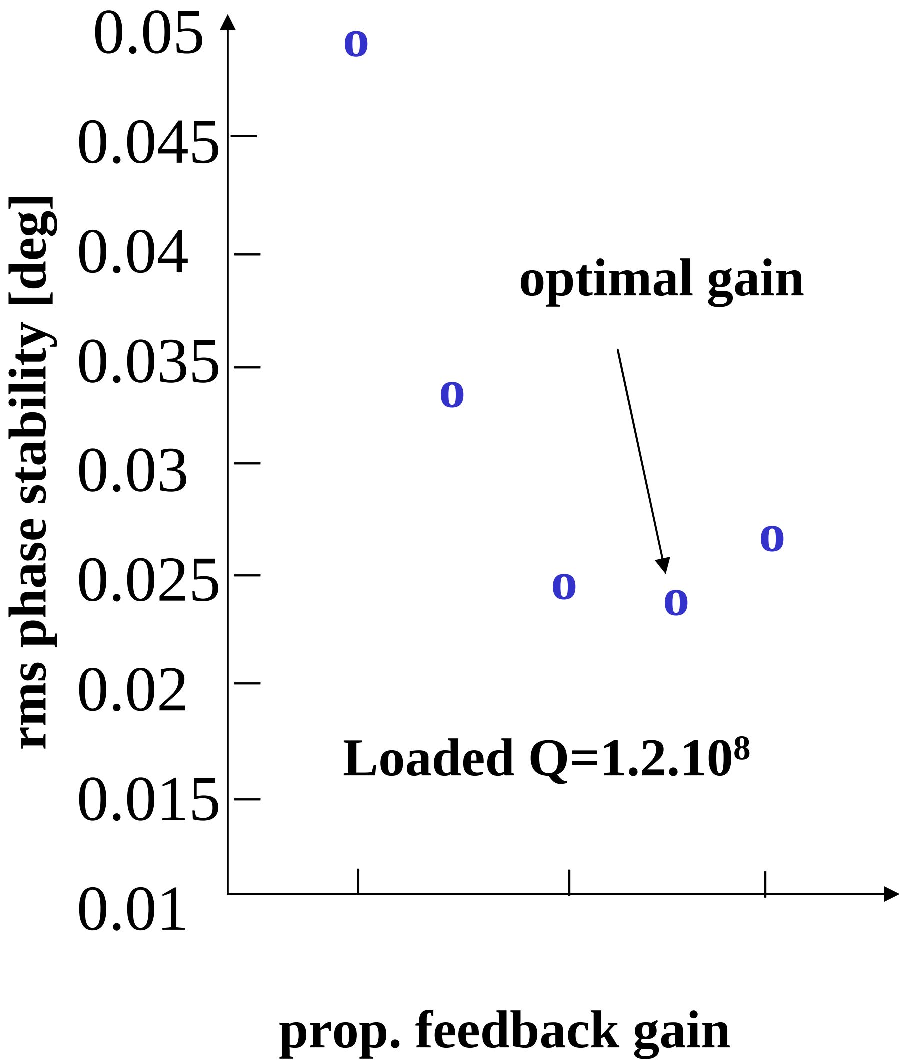
=> Major contribution is likely from laser

RMS Error as Function of Gain

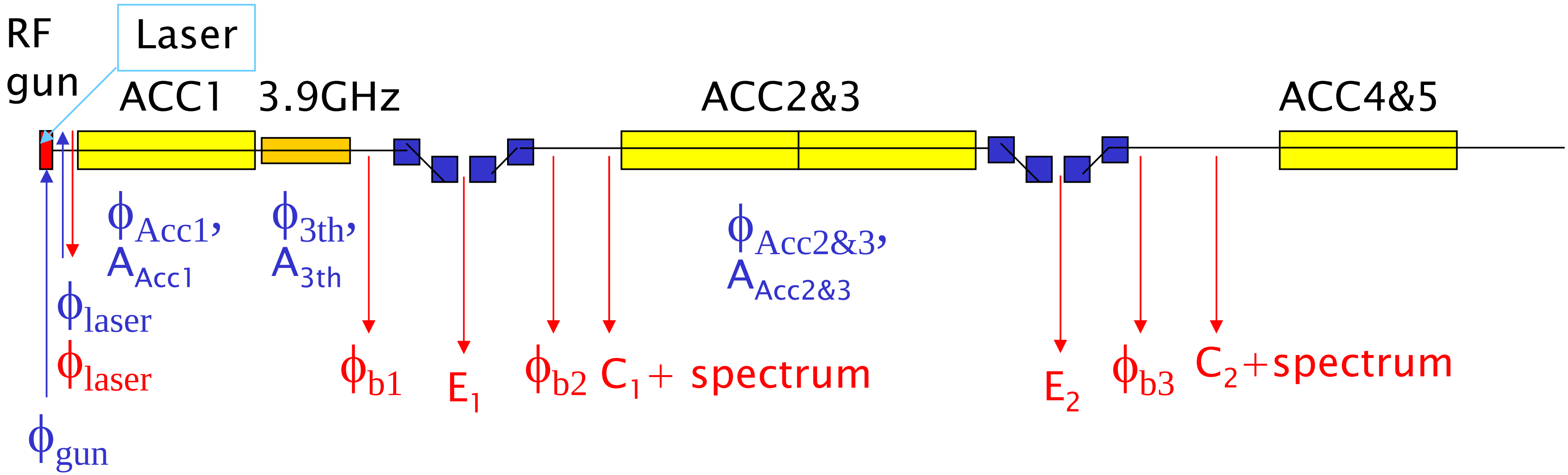


Cornell RF Control Test at the TJLab FEL





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

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

Mechanical Properties

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

or

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

Typical Parameters

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

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

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

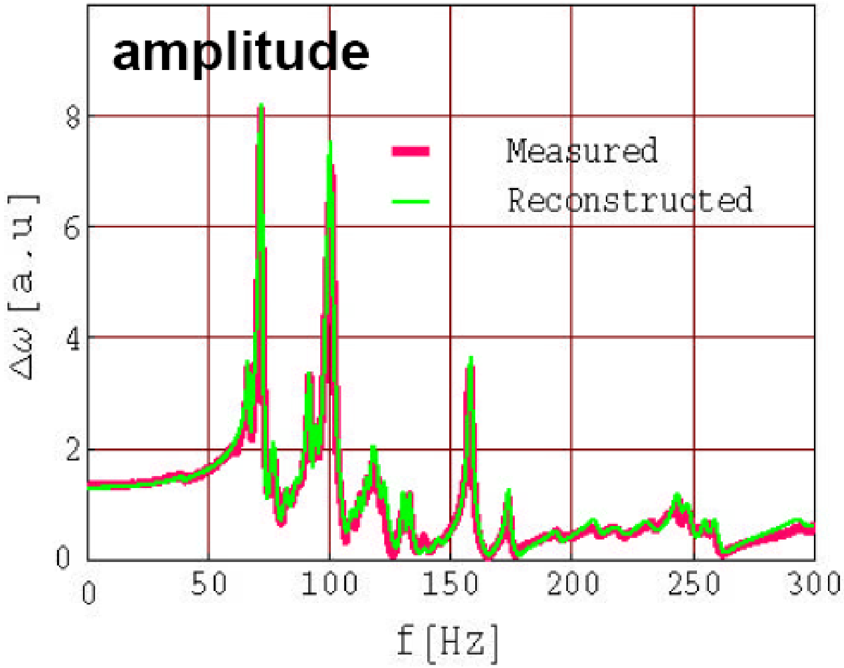
Modelling Lorentz Force Detuning

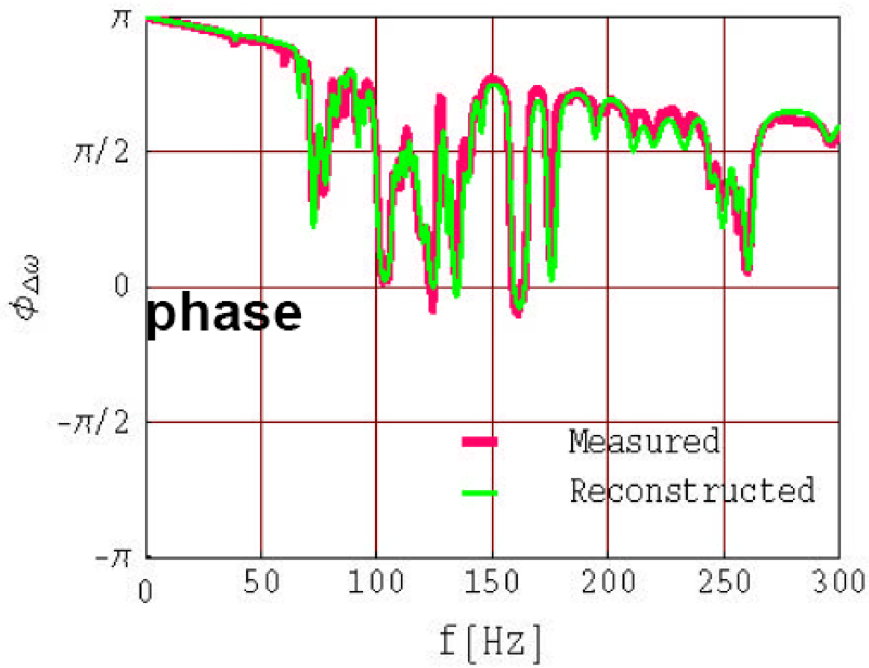
$$
\begin{bmatrix} \Delta\dot{\omega}_1 \\ \Delta\ddot{\omega}_1 \\ \vdots \\ \Delta\dot{\omega}_N \\ \Delta\ddot{\omega}_N \end{bmatrix} = \begin{bmatrix} 0 & 1 & \dots & 0 & 0 \\ -\omega_1^2 & -\frac{1}{\tau_1} & \dots & 0 & 0 \\ & & \vdots\vdots & & \\ 0 & 0 & \dots & 0 & 1 \\ 0 & 0 & \dots & -\omega_N^2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

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

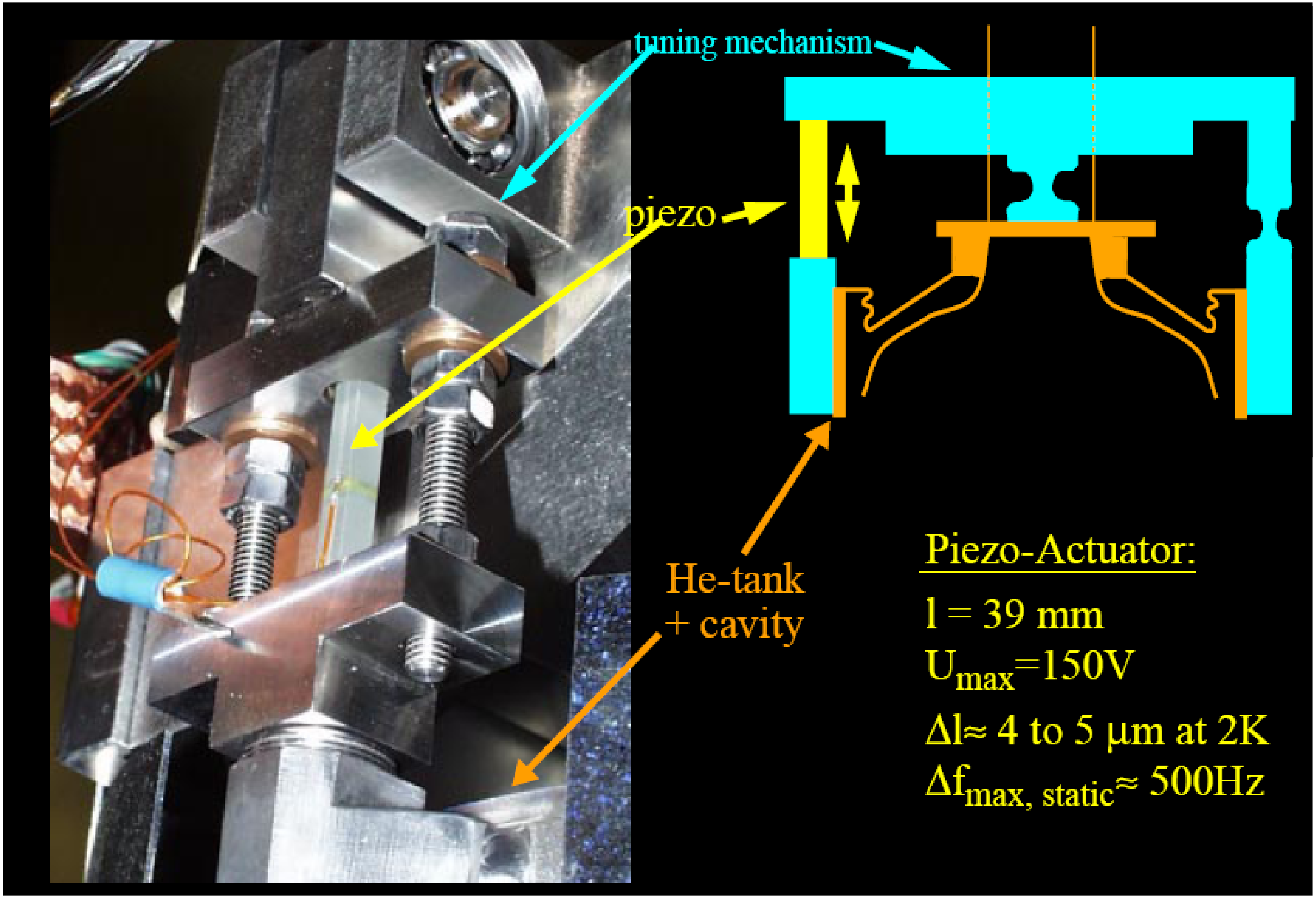
Transfer function Lorentz Force --> Detuning, SNS cavity



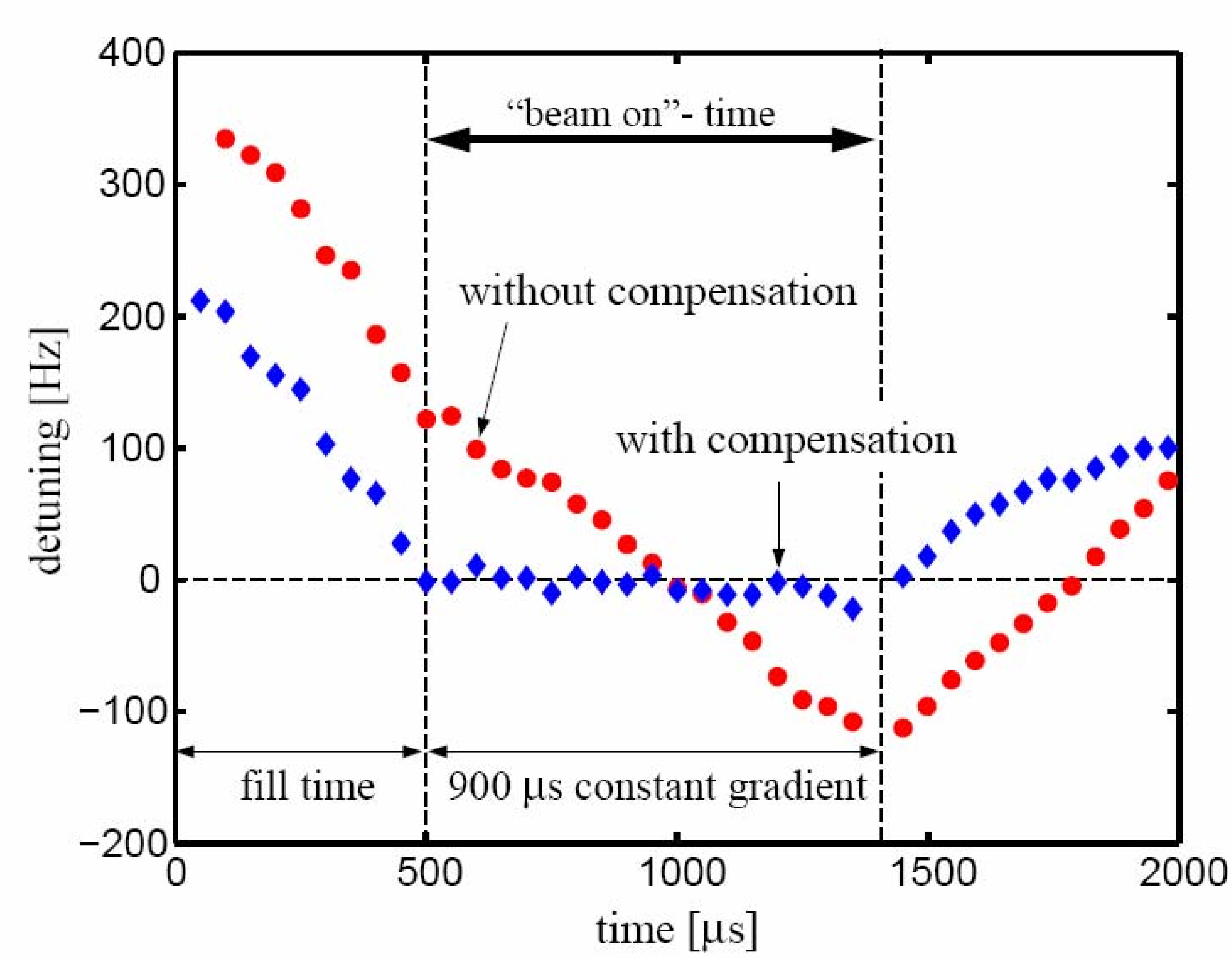


courtesy: J. Delayen, JLAB, M. Doleans, ORNL

Piezotuner


tuning mechanism
piezo
He-tank
+ cavity
Piezo-Actuator:
l = 39 mm
Umax=150V
Δl≈ 4 to 5 µm at 2K
Δfmax, static≈ 500Hz

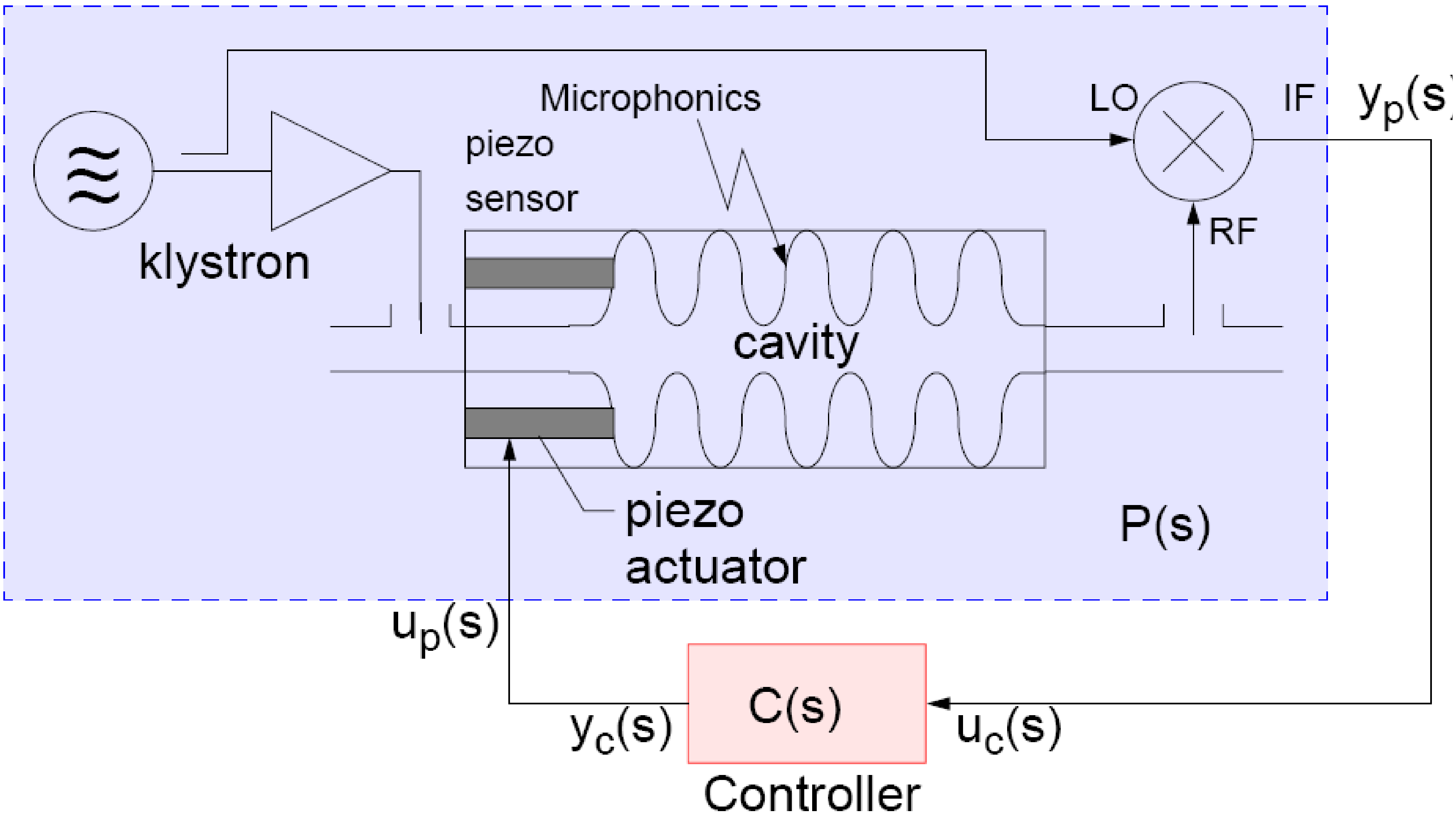
Active Compensation of Lorentz Force Detuning



9-cell cavity operated at 23.5 MV/m

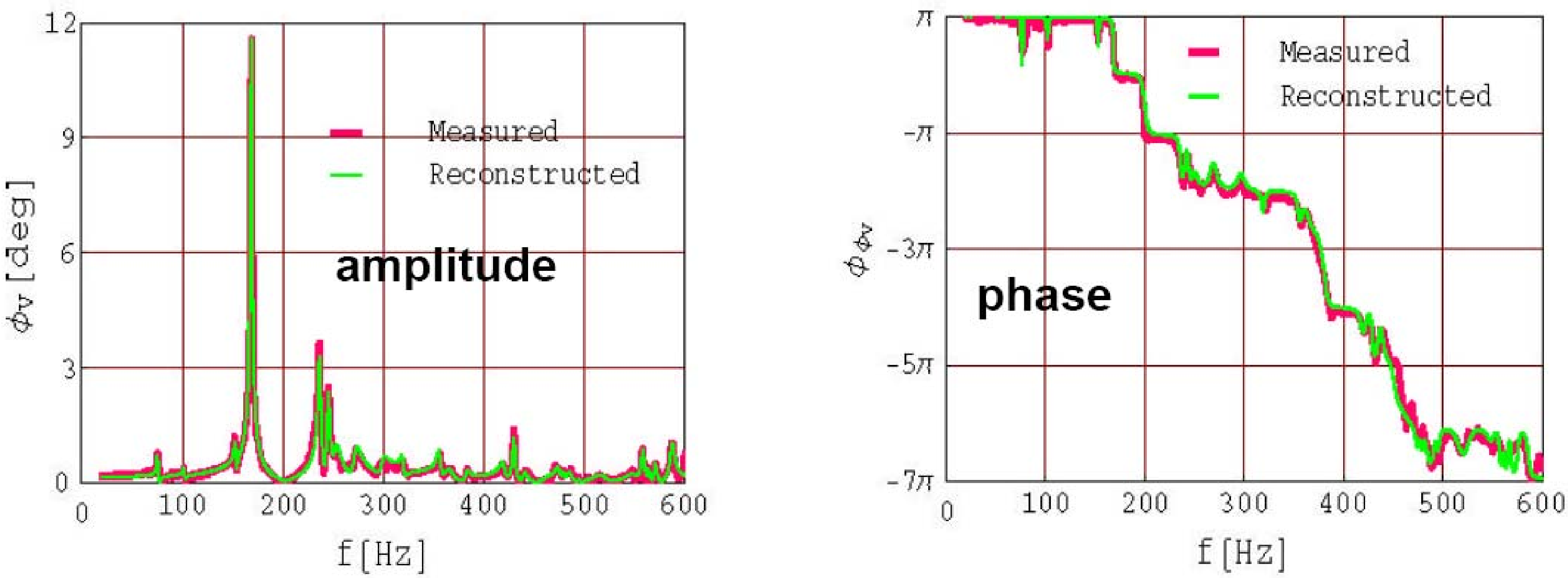
Lorentz force compensated with fast piezoelectric tuner

Concept for Controlling Microphonics



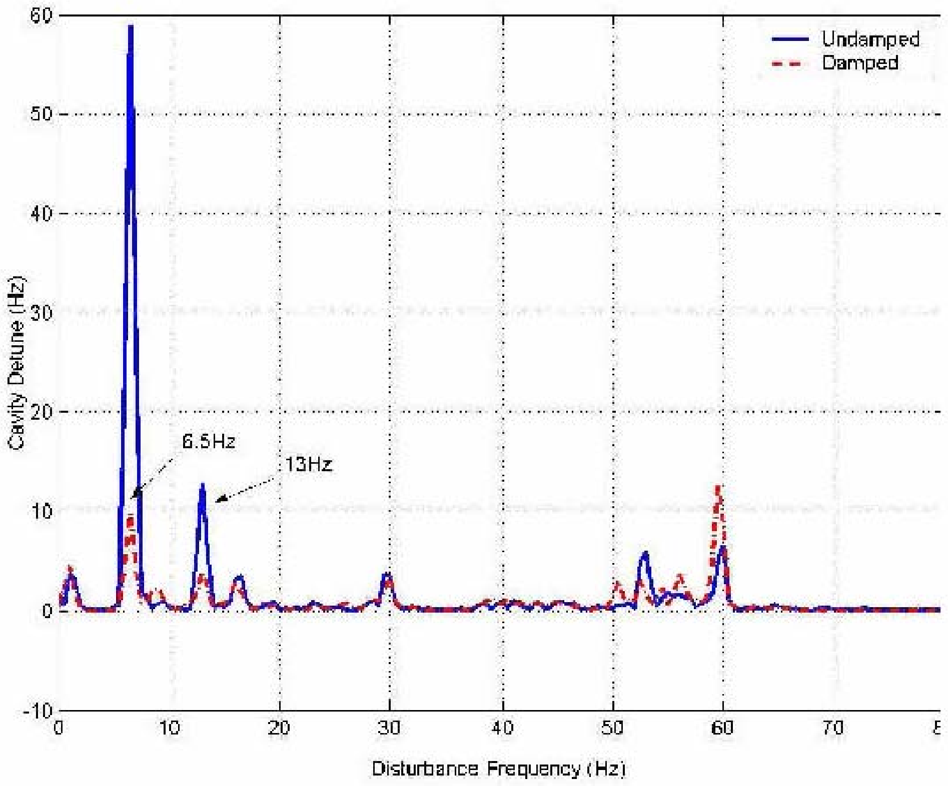
Transferfunction Piezo - Detuning

Transfer function Piezo Tuner --> Detuning, SNS cavity

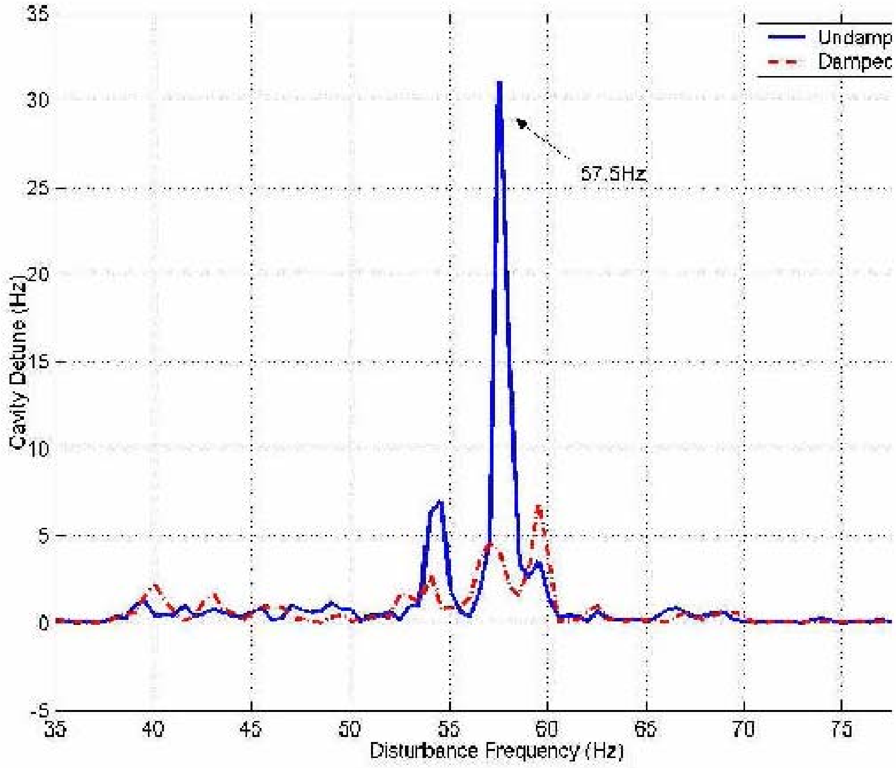


courtesy: J. Delayen, JLAB, M. Doleans, ORNL

Microphonic Suppression with Feedforward



Active damping of helium oscillations at 2K.



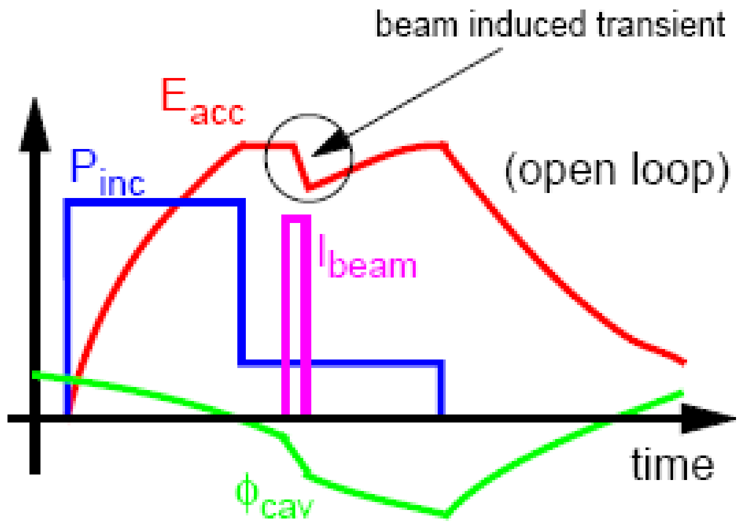
Active damping of external vibration at 2K.

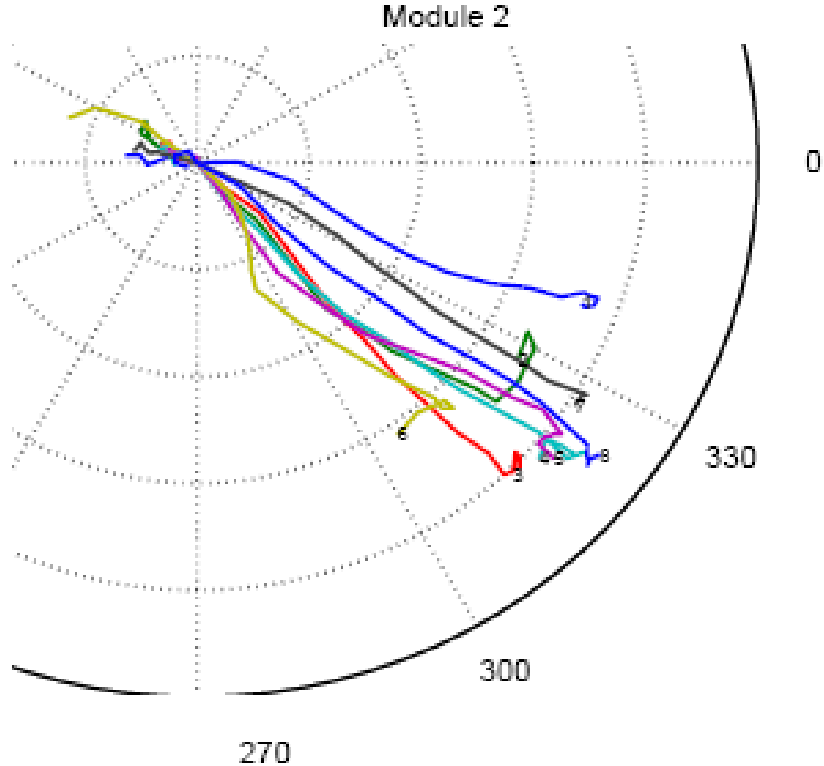
T. Grimm

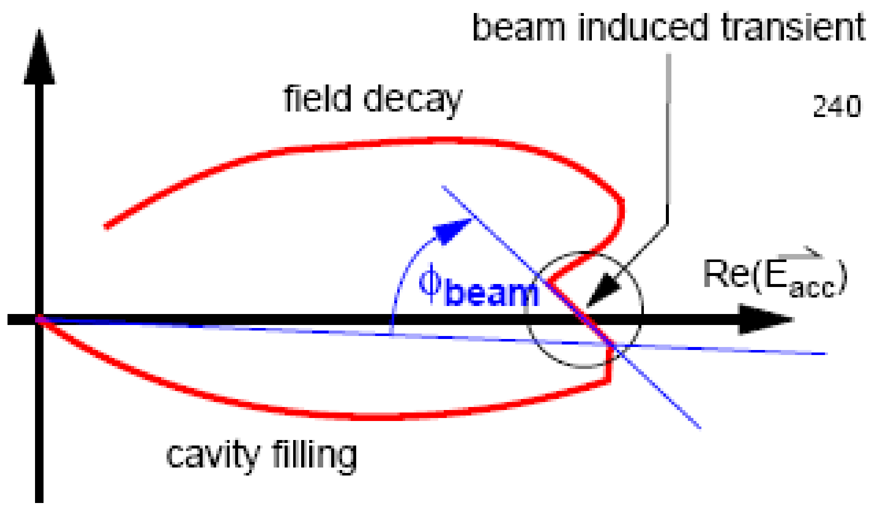
Challenges for RF Control

- 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



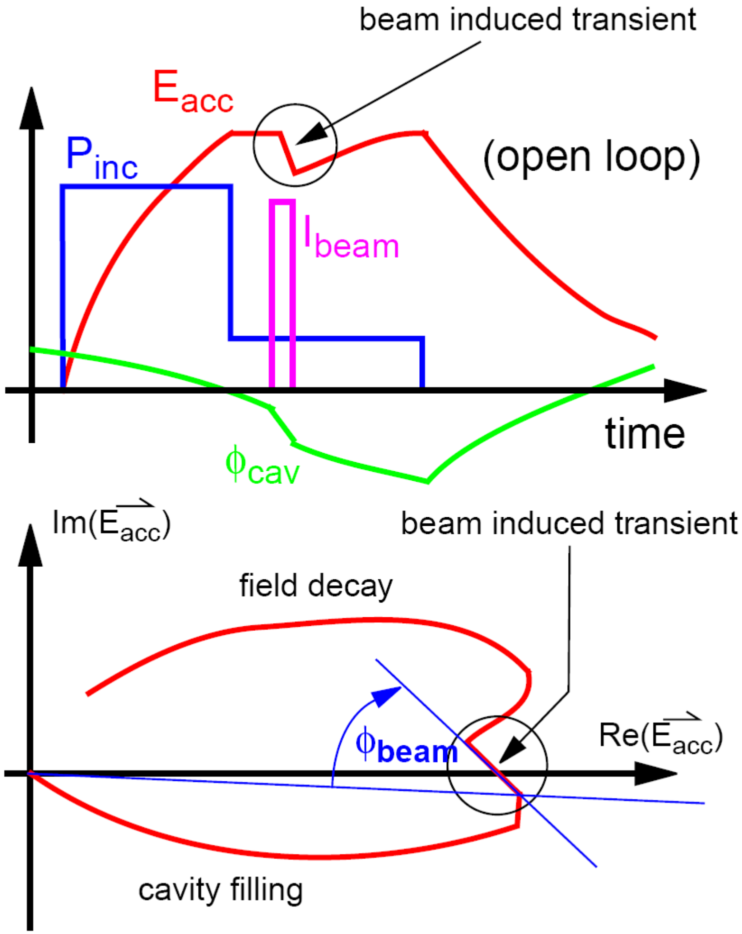




for $\Delta t \ll \tau_{cav}$:

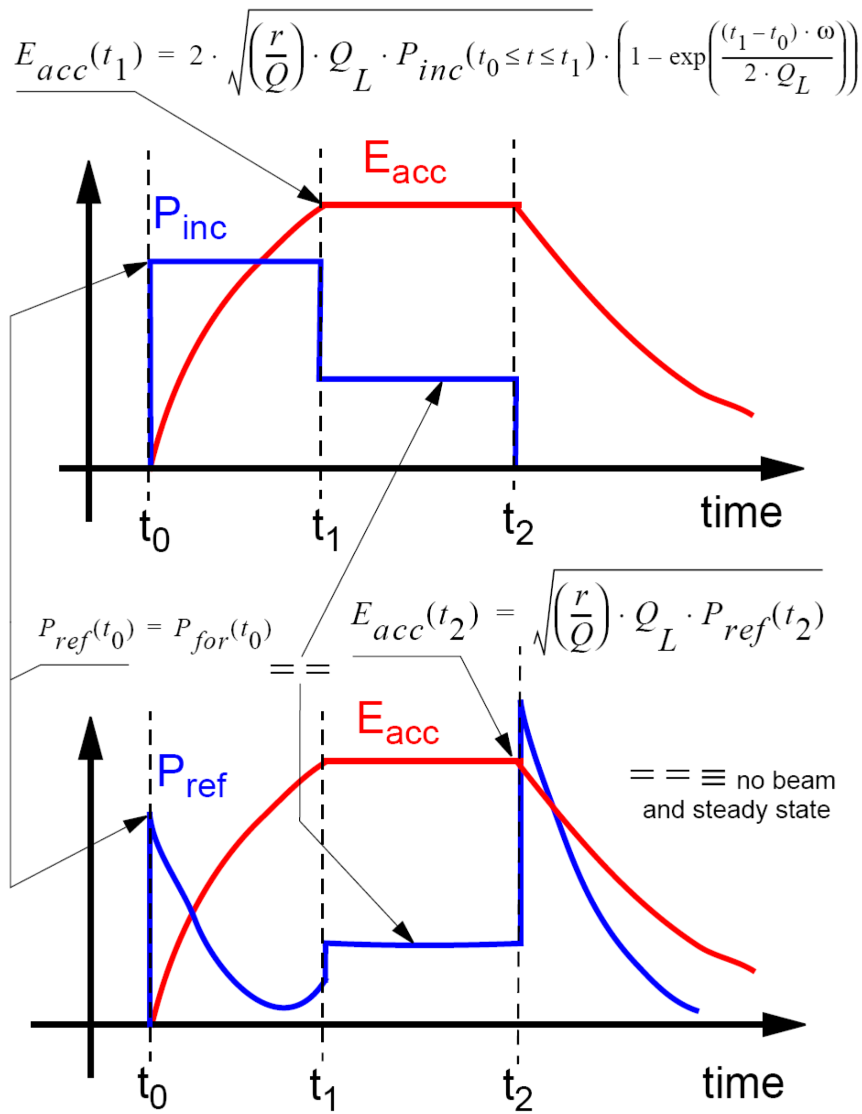
$$\Delta V_{ind} = I \cdot \Delta t \cdot \left(\frac{r}{Q}\right) \cdot \pi \cdot f$$

Gradient and Power Calibration

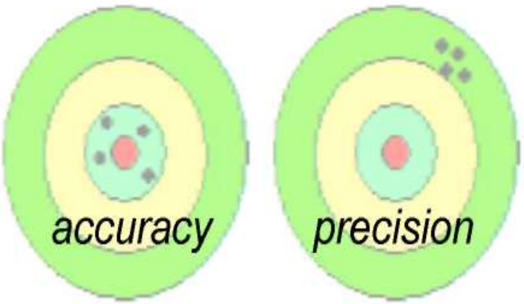


for $\Delta t << \tau_{cav}$:

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

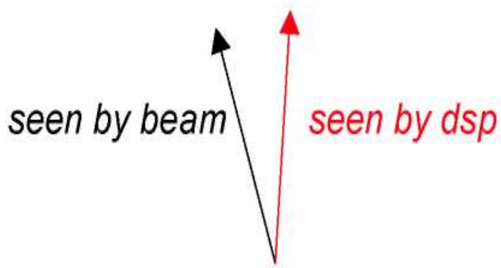


Vector-Sum Calibration

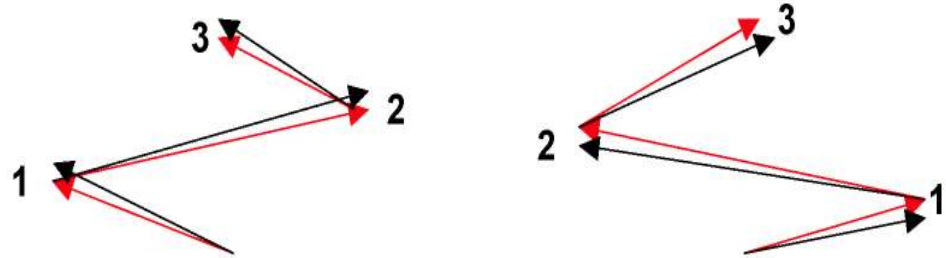


How precise can we measure the vectorsum seen by the beam (not: how good can we control the vectorsum...). We are not interested in *accuracy* but in *precision*!

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

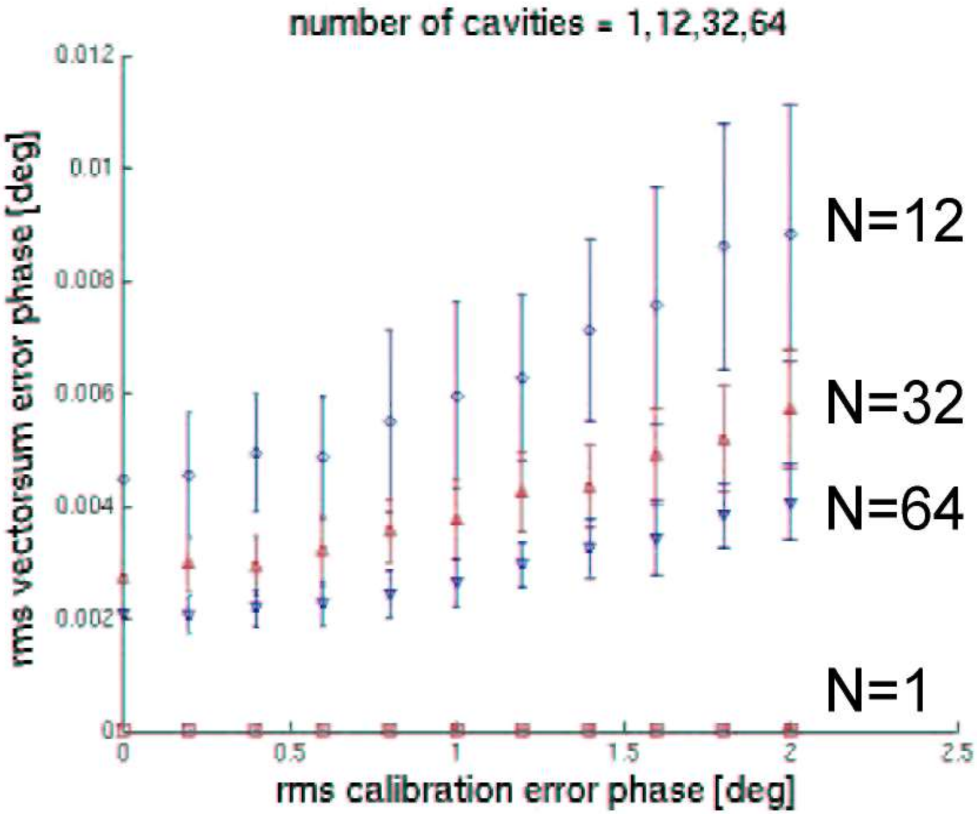


Two extreme configuration: the dsp sees identical vectorsums but the beam does not!



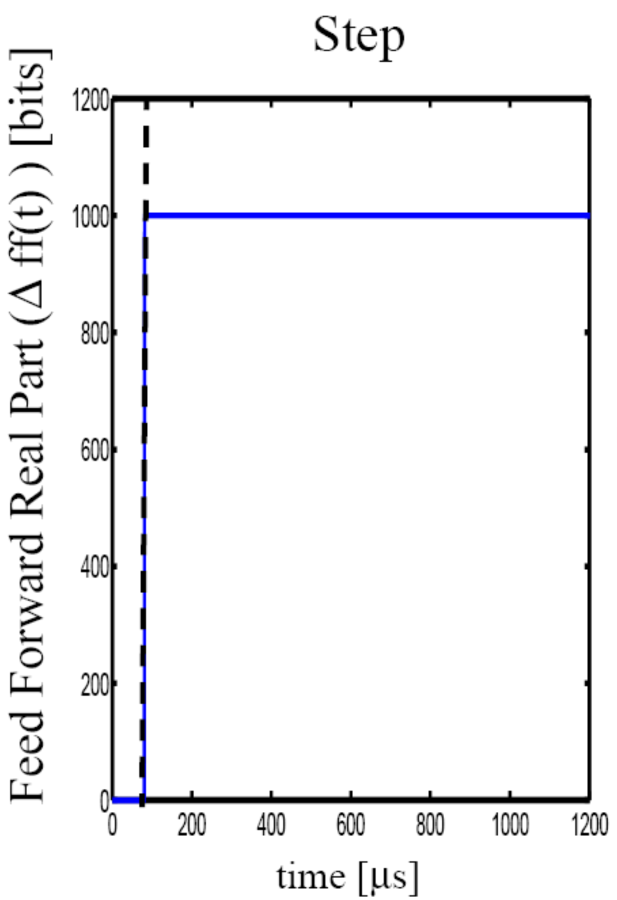
Vector-Sum calibration

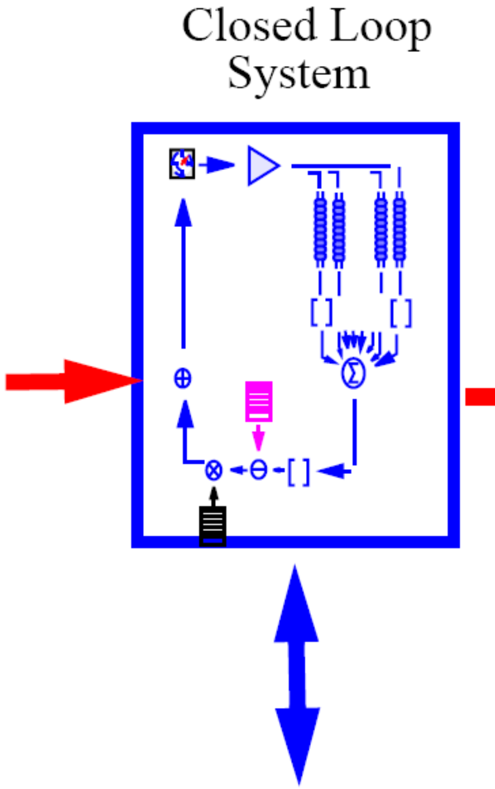
Number of cavities: 1,12,32,64, Predetuning: 50 Hz, Detuning-Spread: 11 Hz, Amplitude cal. error: 0.01

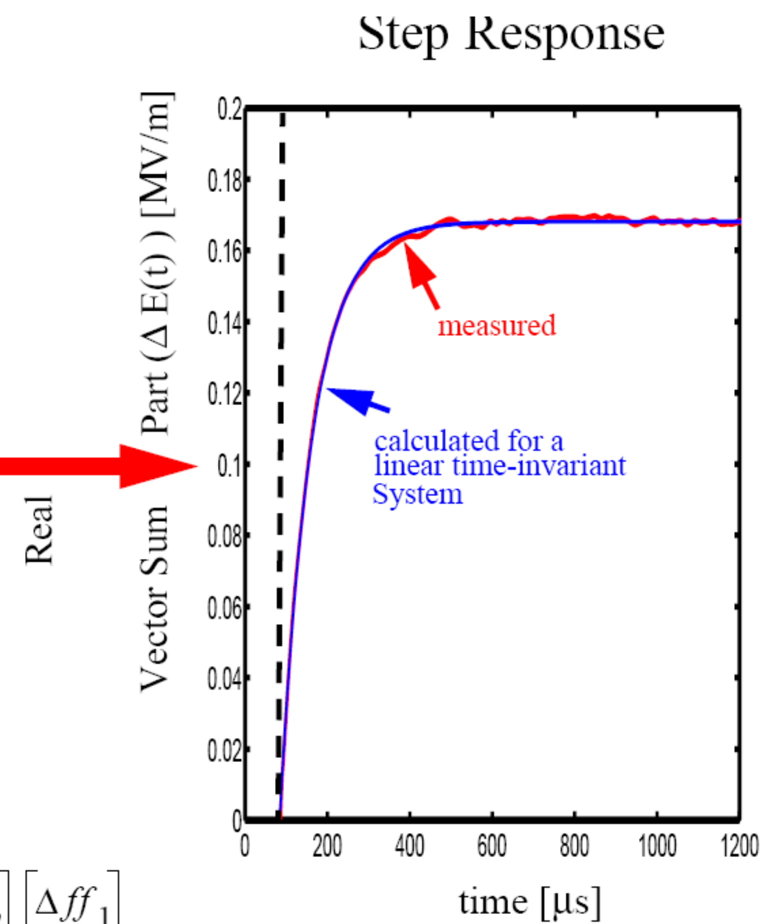


Surprising result: the more we measure, the better we get!

Adaptive Feedforward



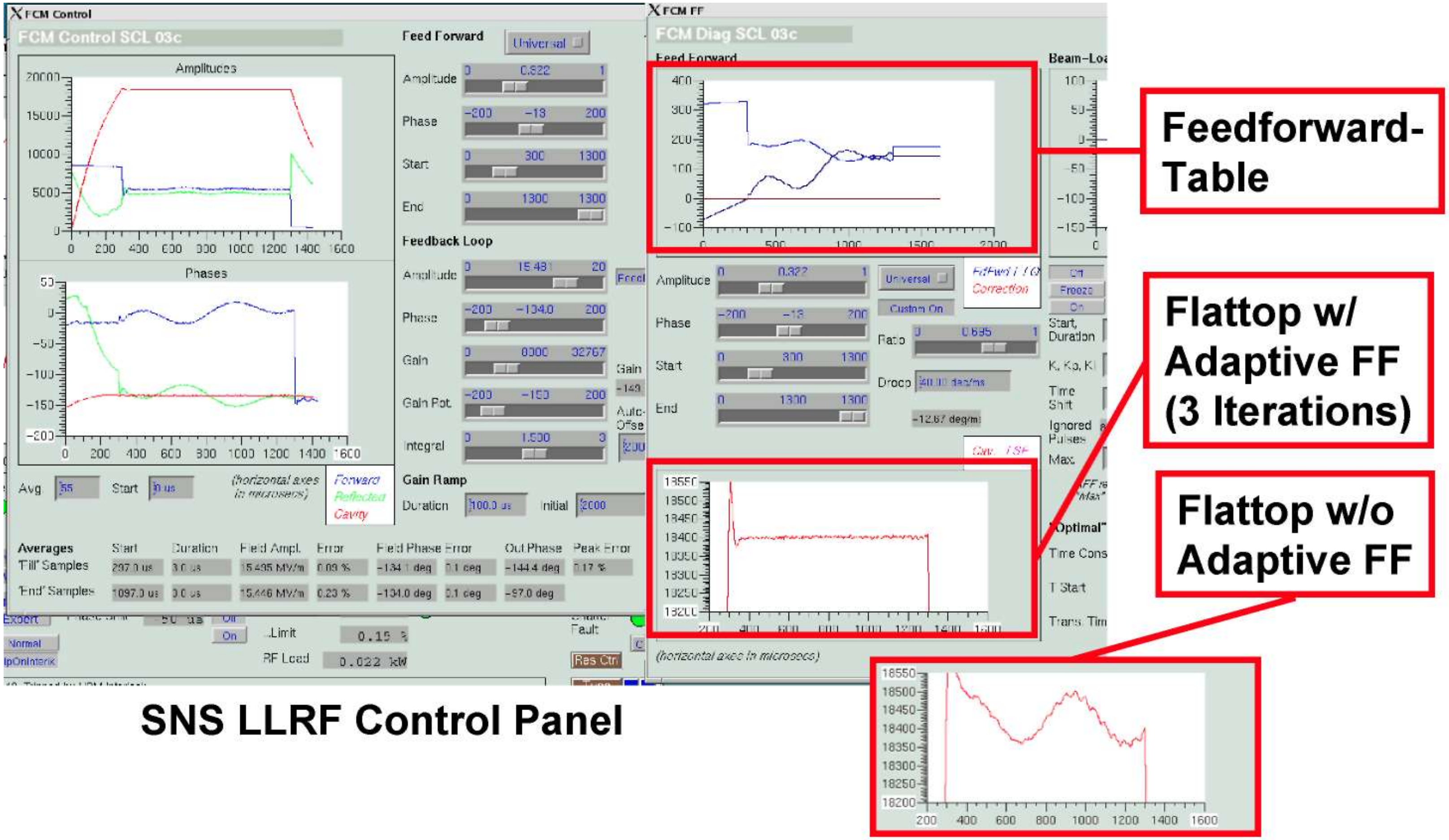




$$\begin{bmatrix} \Delta E(\tau_1) \\ \Delta E(\tau_2) \\ \dots \\ \Delta E(\tau_n) \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & \dots & T_{1n} \\ T_{21} & T_{22} & \dots & T_{2n} \\ \dots & \dots & \dots & \dots \\ T_{n1} & T_{n2} & \dots & T_{nn} \end{bmatrix} \begin{bmatrix} \Delta ff_1 \\ \Delta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

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

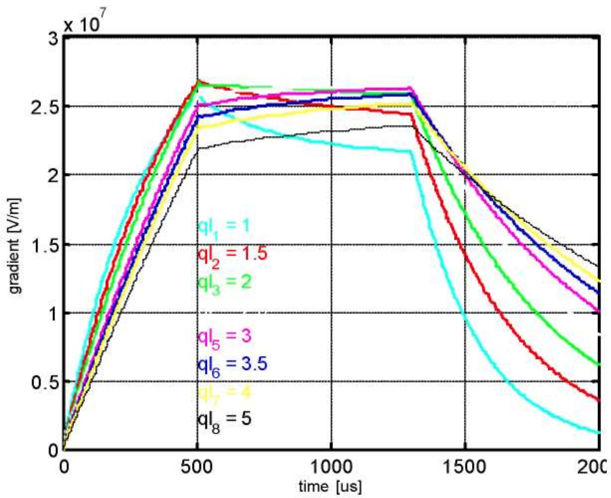
Automation: example adaptive Feedforward



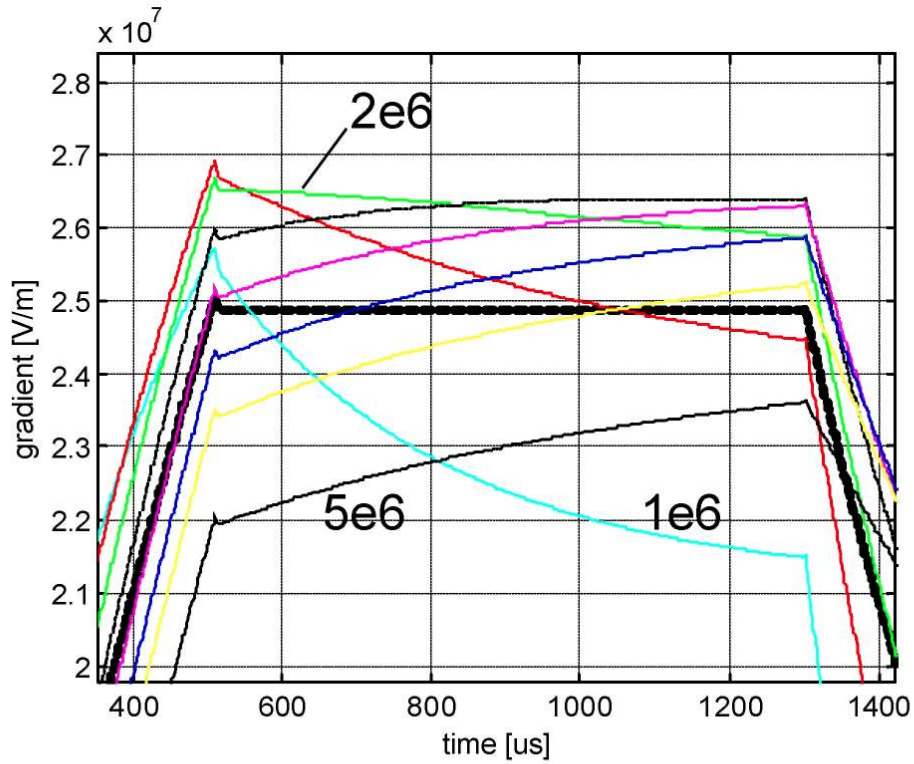
SNS LLRF Control Panel

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