Active Control of Lorentz-Detuning and Microphonics

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I Why?

Lorentz-force detuning, microphonics
and power requirements

II How?

The piezoelectric tuner: principle, layout, control, ...

III Can it work?

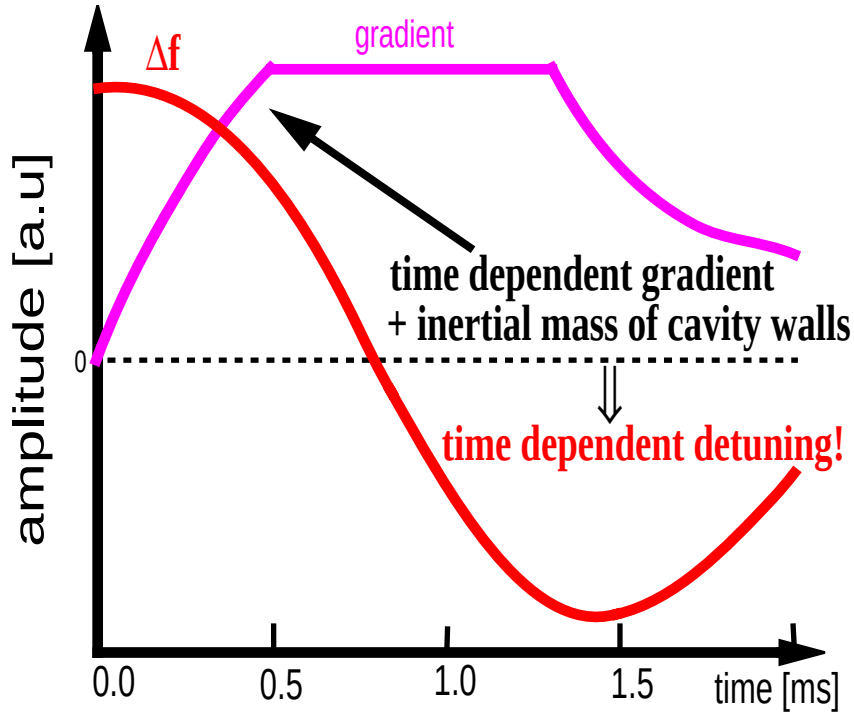
Reliability: high dynamic operation, low temperature, radiation,
Controllability: coupling to mechanical modes

IV First Results

The piezo as a sensor: microphonics, mechanical oscillations,
The piezo as an active element: lorentz-detuning compensation

I Why?

- ***Pulsed Operation of s.c. Cavities:***



TESLA: **950 µs flat top**
5 to 10 Hz repetition rate

SNS: **1 ms flat top**
60 Hz (!) repetition rate

electromagnetic field exerts Lorentz-forces

⇓

deformation of cavity

⇓

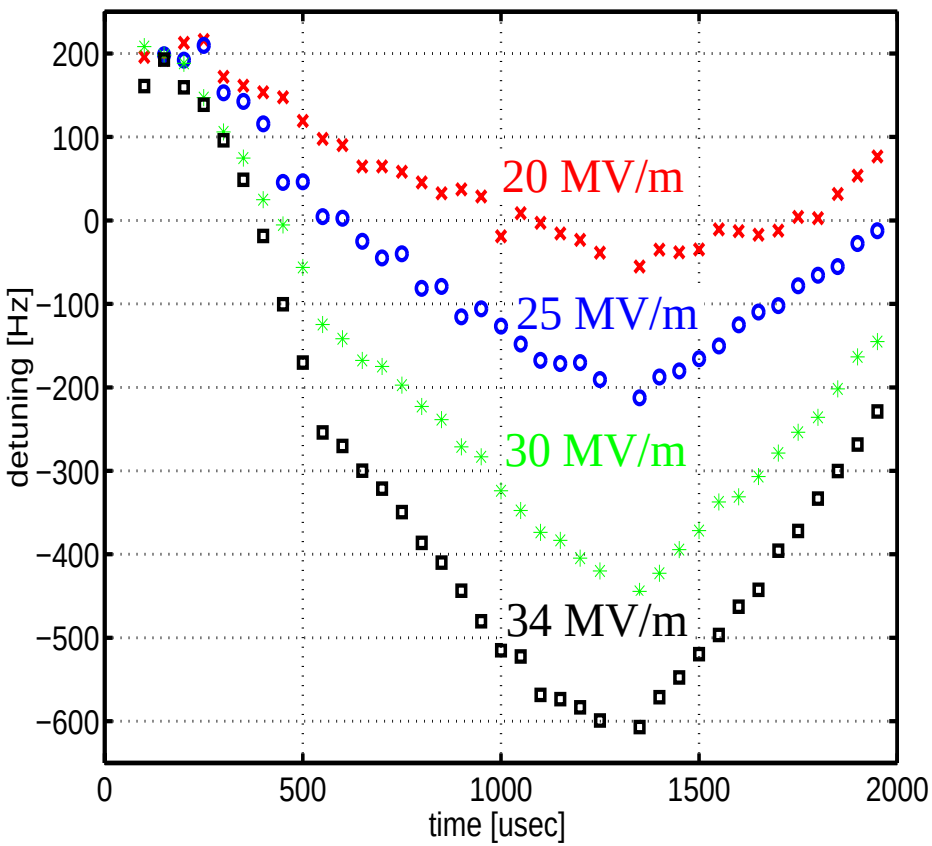
resonance frequency shift Δf (detuning) $\Delta f = f_{\mathrm{cav}} - f_{\mathrm{gen}}$

Lorentz-vibration model: differential equation for mode #*k*:

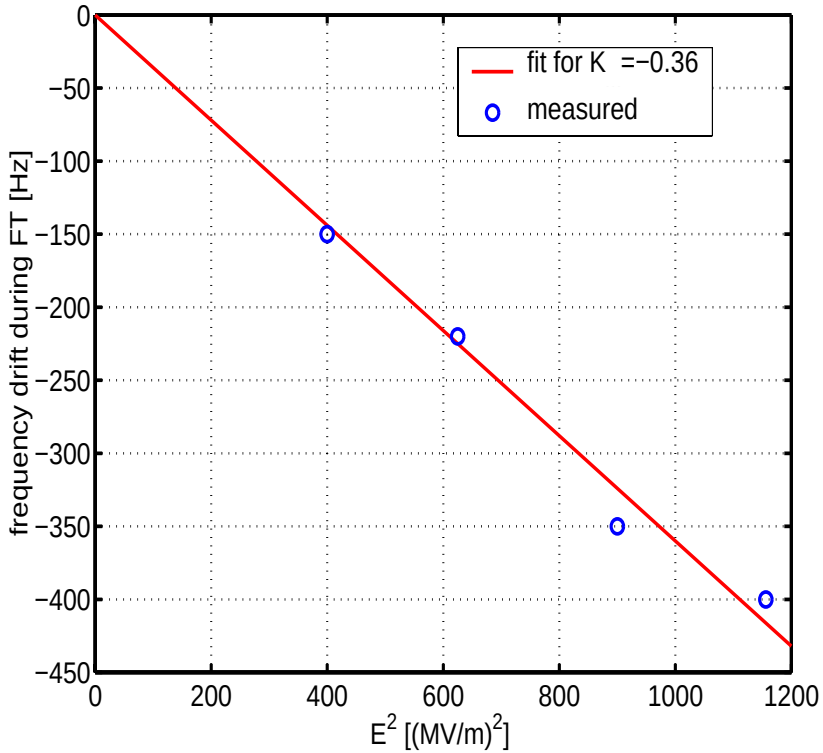
$$\frac{d^2 \Delta f_k}{dt^2} + \frac{\omega_k}{Q_k}\frac{d\Delta f_k}{dt} + \omega_k^2 \Delta f_k = K_k E_{acc}^2 \qquad \Delta f = \sum_k \Delta f_k$$

• *Lorentz-Force Detuning:*

TESLA 9-cell cavity



Frequency drift during 800µs flat top



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

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

- ***The Problem:***

detuning of cavity during 950 µs FT:

$$\Delta f_{FT} = f_{\mathrm{cav}} - f_{\mathrm{gen}} = -KE^2$$

TESLA 9-cell cavity:

K=0.4 ... 0.65 Hz/(MV/m)^2

required power to keep the gradient and phase constant:

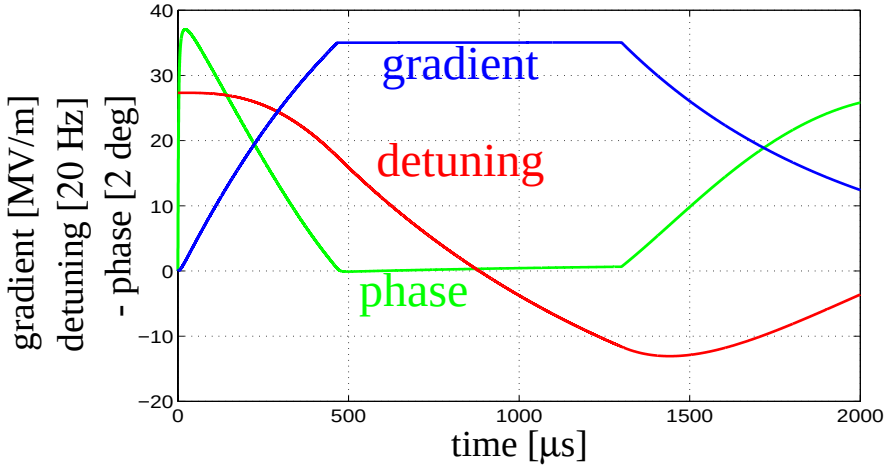
$$\frac{P_{\mathrm{comp}}}{P_{(\Delta f\,=\,0)}} = \frac{1}{4}\left[\frac{\Delta f}{f_{1/2}}\right]^2 \propto E^4$$

⇒ **At high gradients significant additional power would be required to keep the gradient and phase constant!**

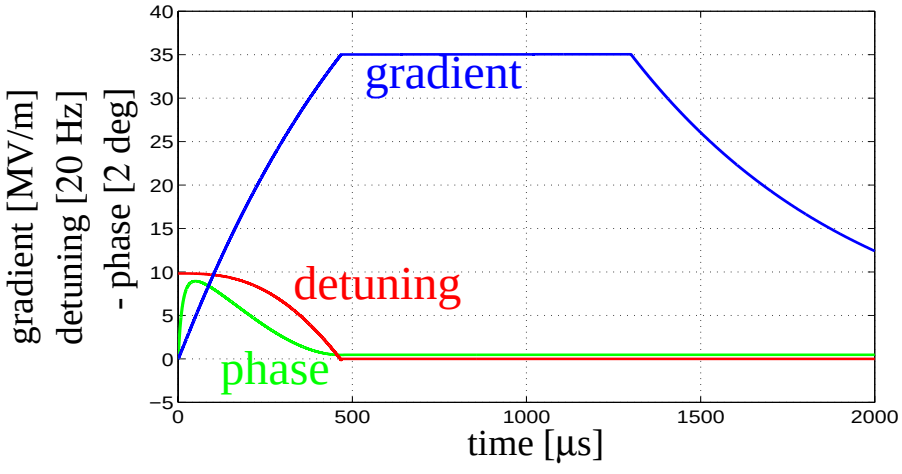
⇒ **Increase stiffness of the cavity or use a fast piezo-tuner for *active* Lorentz-force compensation.**

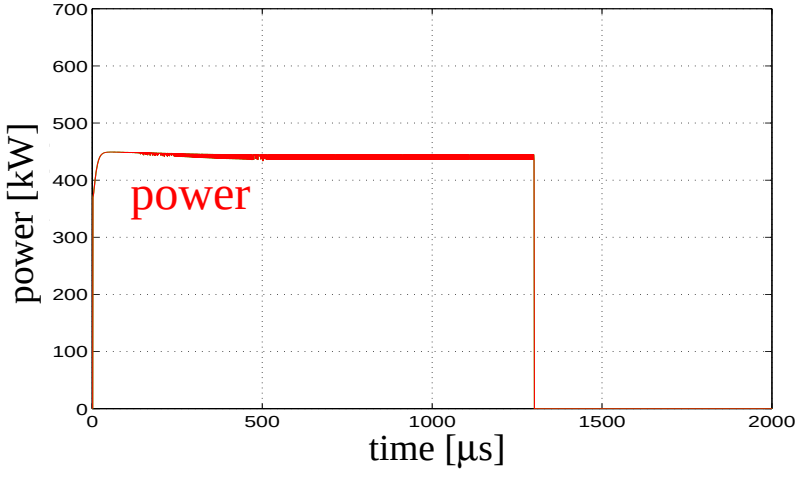
• *Simulation for 35 MV/m (TESLA800):*

TESLA 9-cell cavity with detuning:

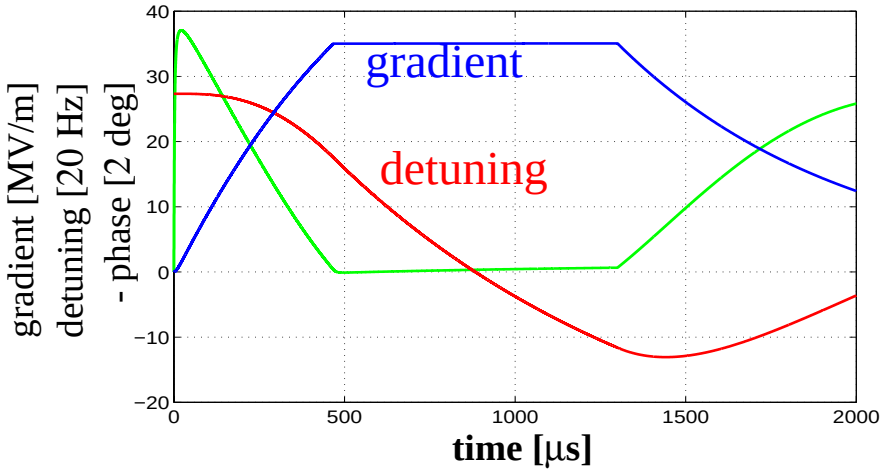


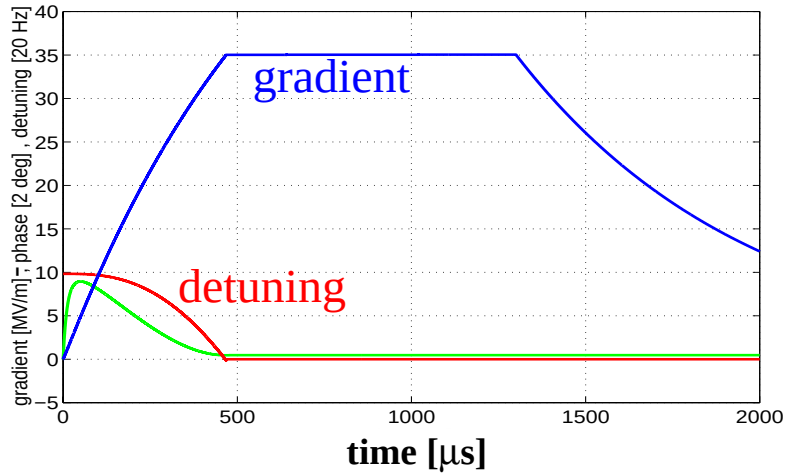
TESLA 9-cell cavity with compensated detuning during flat top:

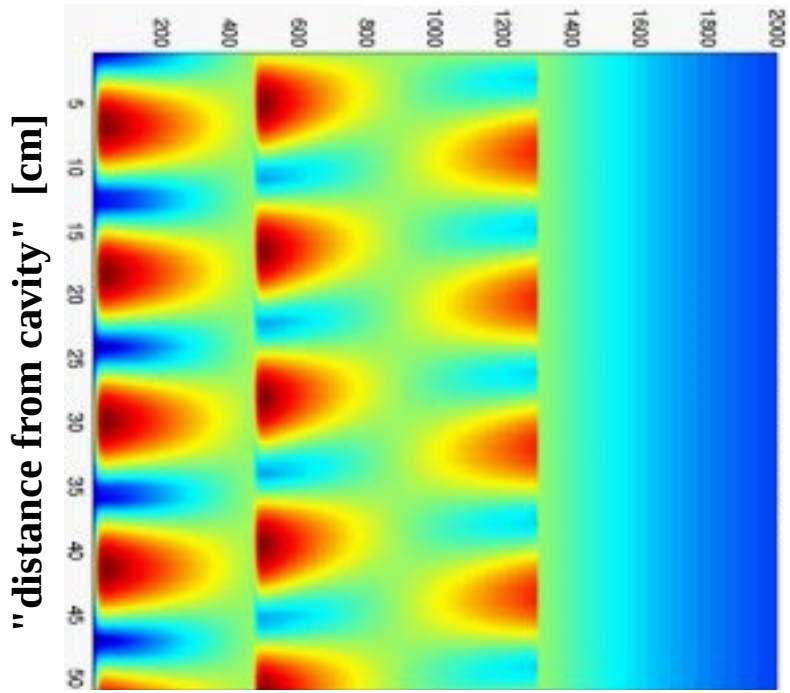


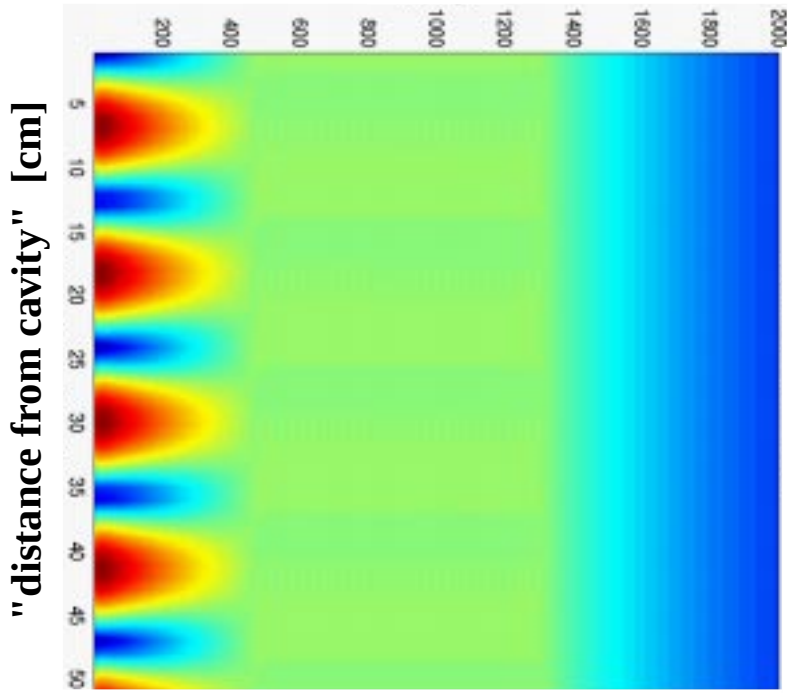


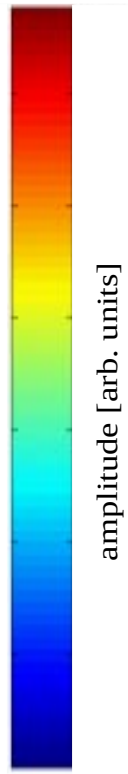
• *Standing Waves in the Input Coupler / Waveguide:*











• *CW Operation of s.c. Cavities:*

- ***Microphonics:*** **modulation of resonance frequency by external mechanical disturbances**
- **thin wall-thickness and small bandwidth of superconducting cavities**

$\Rightarrow$ **sensitive to microphonics**

detuning of cavity due to microphonics

$\Rightarrow$ **additional power required to keep the gradient and phase constant**:

$$\frac{P_{\text{comp}}}{P_{(\Delta f\,=\,0)}} = \frac{1}{4}\left[\frac{\Delta f}{f_{1/2}}\right]^2$$

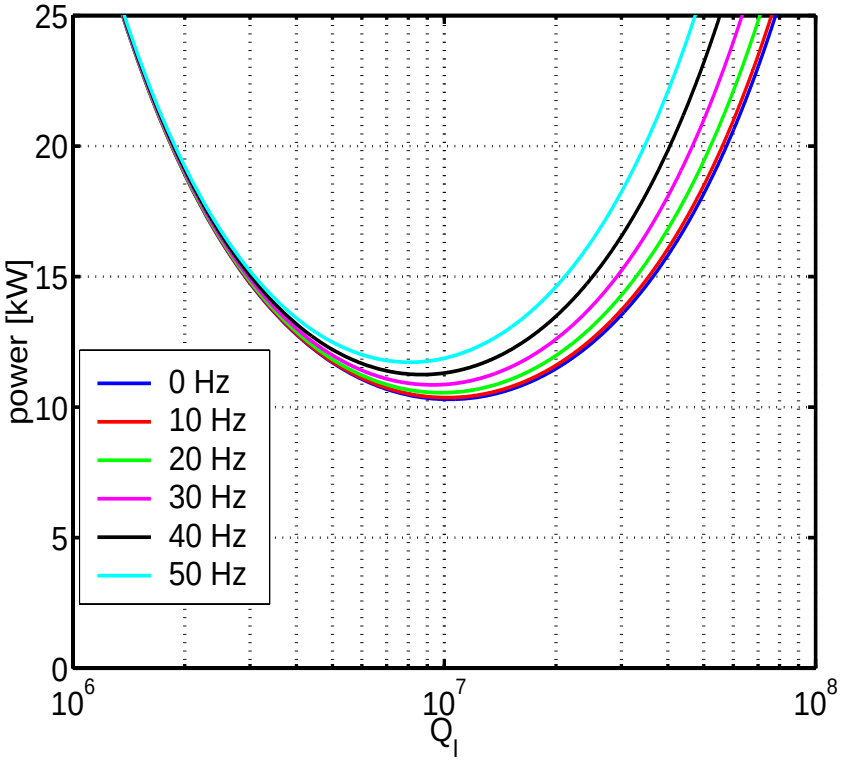
for matched Q_L:

$$Q_L = \frac{V_{acc}}{(R/Q)I_{beam}}$$

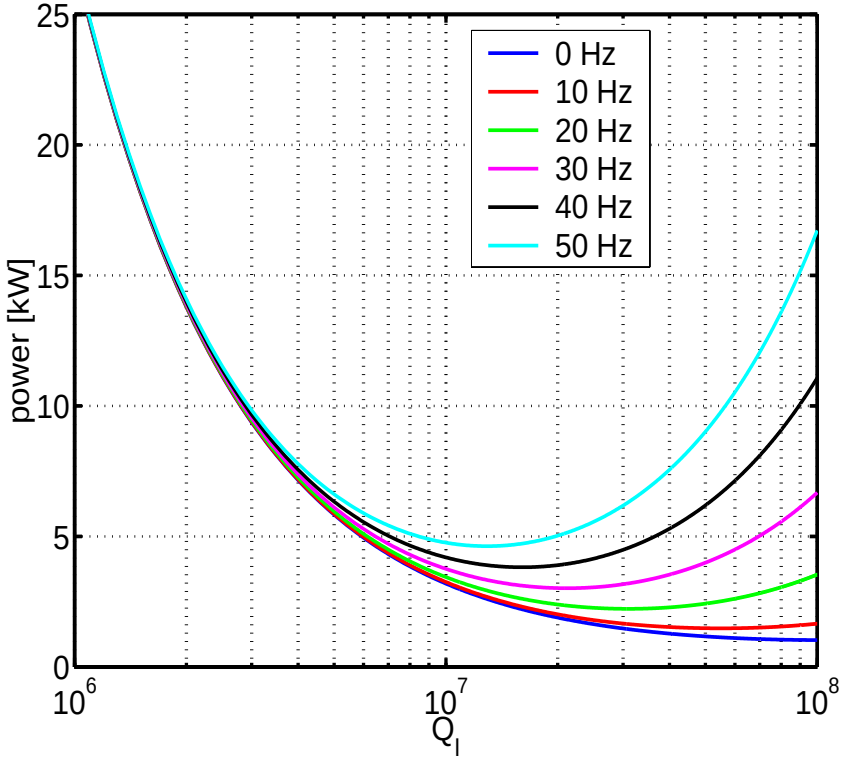
$\Rightarrow$ At high Q_L (i.e. low beam current) significant additional power would be required to keep the gradient and phase constant!

- ***Example: TESLA 9-cell Cavity at 10 MV/m***

beam current: 1mA



beam current: 0.1mA



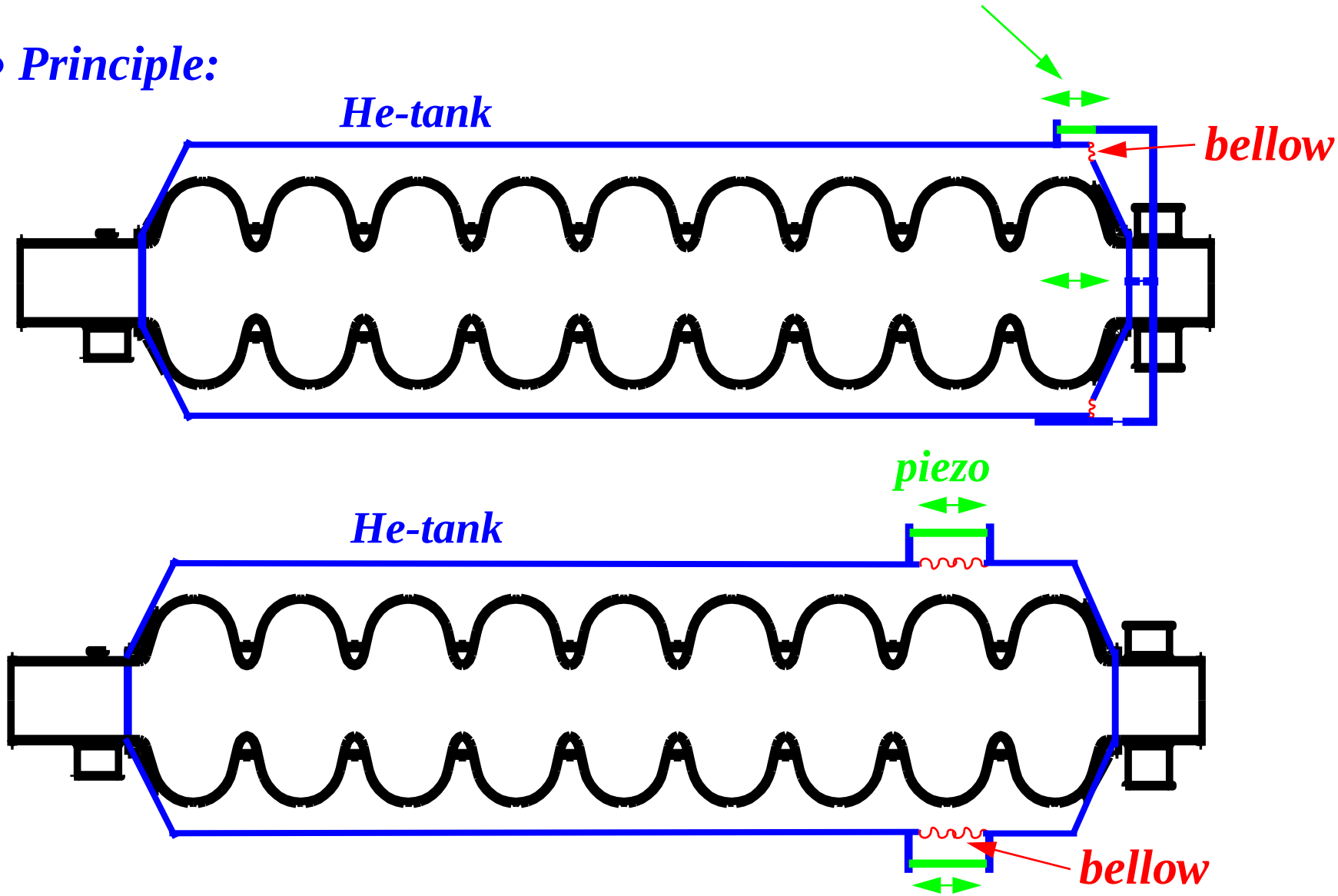
⇒ At low beam currents microphonics should be low!

Use a fast tuner to compensate external mechanical disturbances.

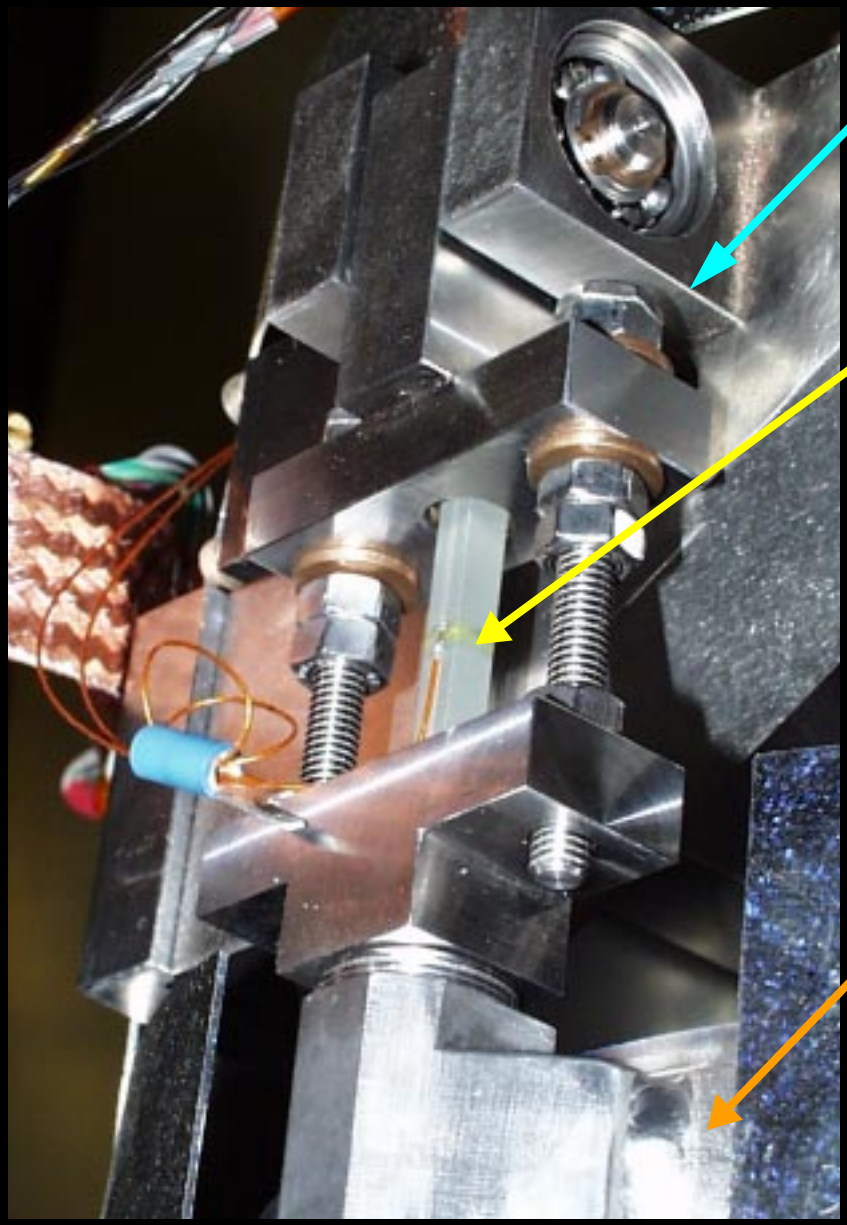
II How?

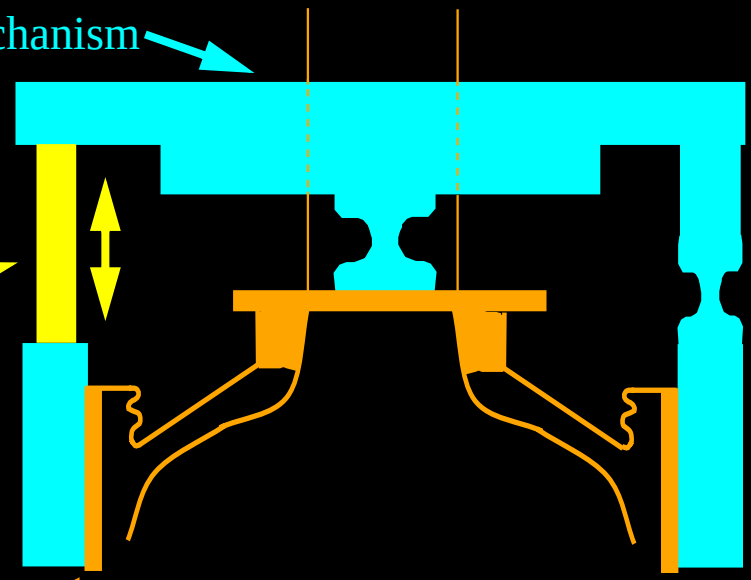
$\Rightarrow$ **fast frequency tuner based on piezotranslators!**

- ***Principle:***



• *Proof of Principle Setup of a fast Piezo-Tuner:*





Piezo-Actuator:

$l = 39$ mm

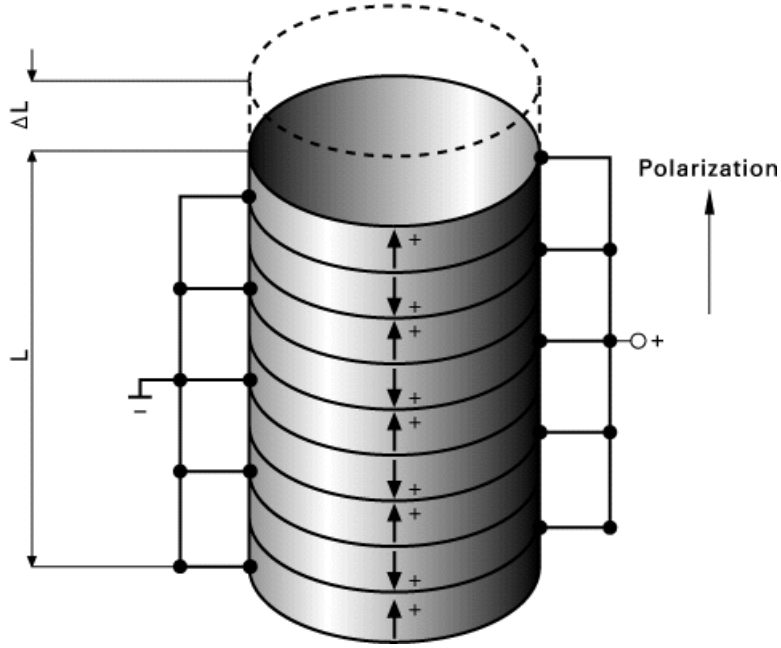
U_{max}=150V

$\Delta l \approx 4$ to 5 µm at 2K

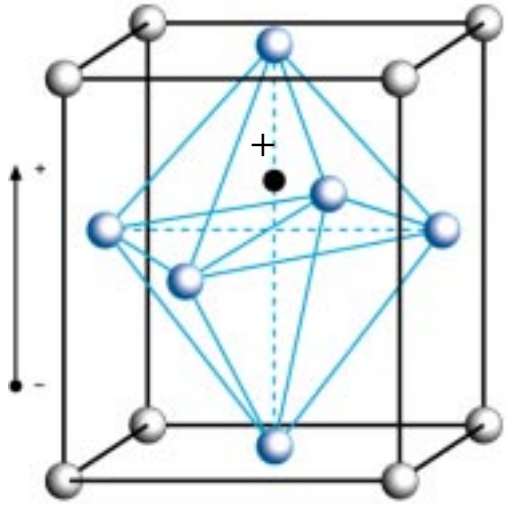
$\Delta f_{max,\ static} \approx 500$Hz

• *Fundamentals of Piezo-Actuators:*

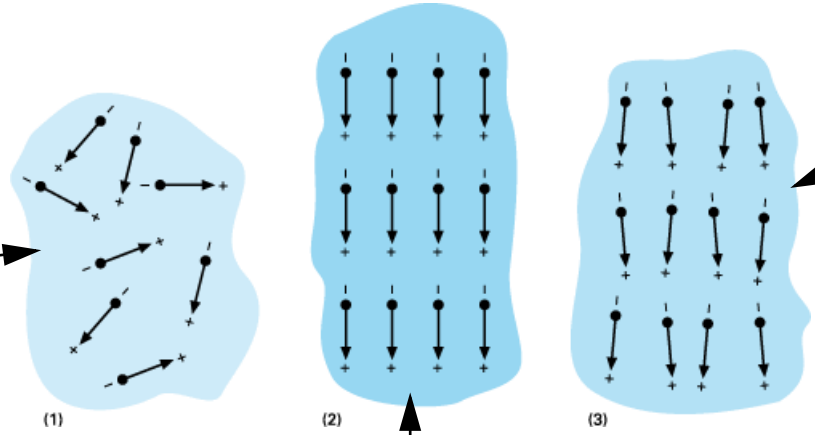
multilayer design



electric dipoles:
anisotropic crystal structure
after poling



before poling:
randomly orientated
Weiss domains
(group of parallel
orientated dipoles)

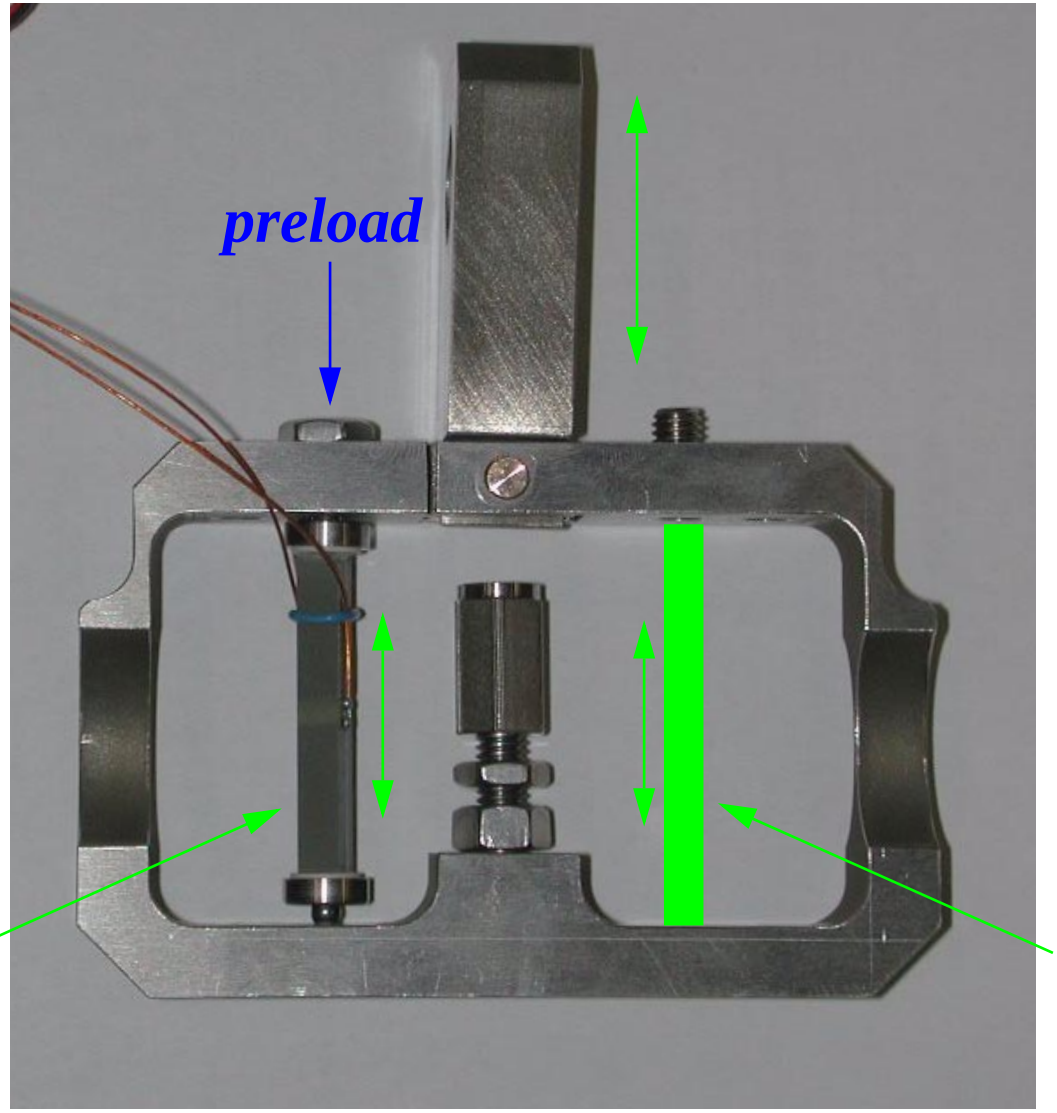


after poling:
remanent polarization

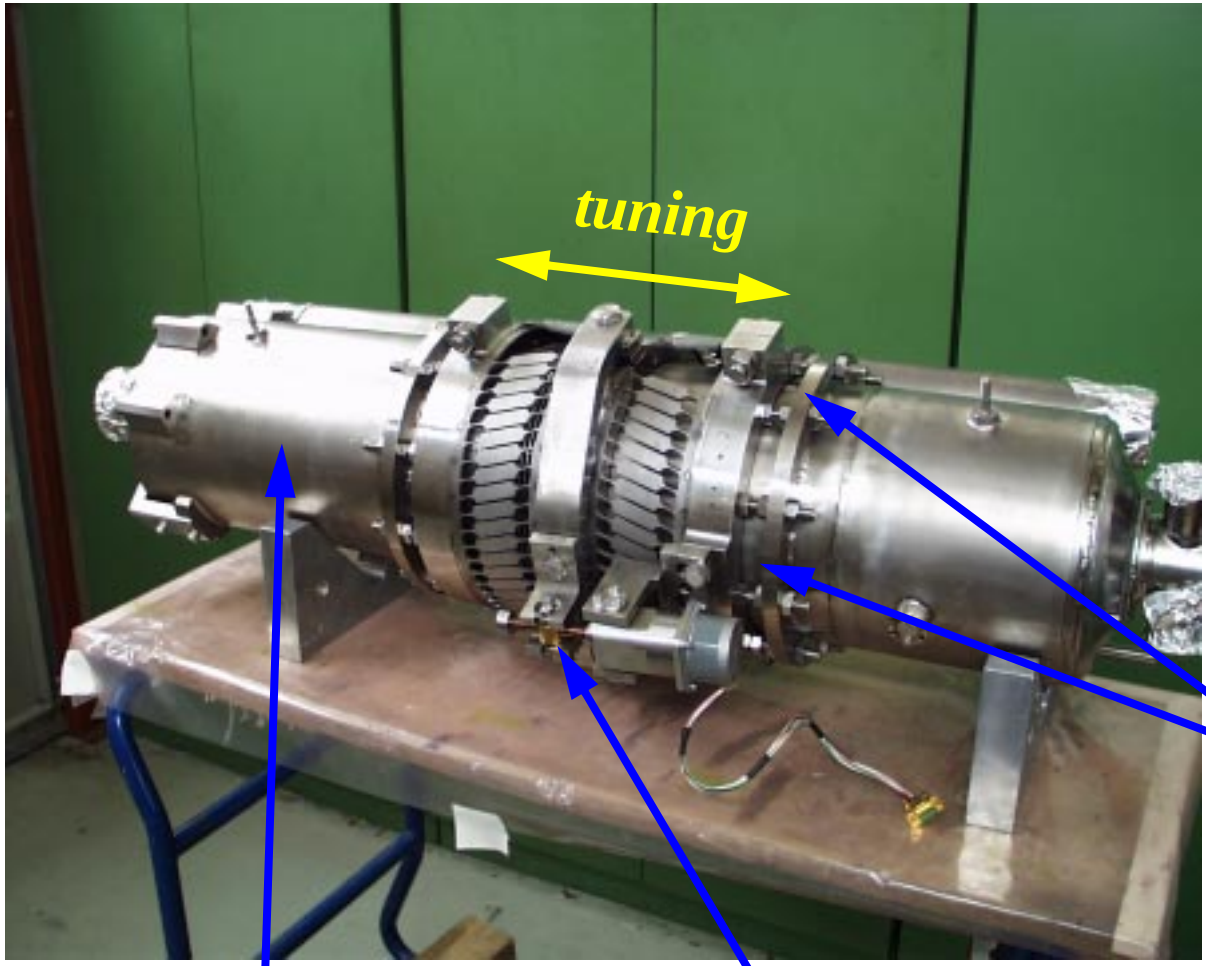
When an electric voltage
is applied, the Weiss
domains increases
their alignment and
the material expands.

poling (electric field applied to the piezo):
electric dipoles align, material expands along the field axis

- ***New Piezo-Holder for two Stacks with Lever Motion Amplifier:***



- ***Prototype Tuner for TESLA***



possible position for piezos? ⇒ under study

cavity with He-tank

mechanical tuner (dog bone design)

• *Piezostacks:*

- **maximum stroke at room temperature:** **≈ 0.1% of stack length without external forces**

- **maximum stroke at 2K:** **≈ 10 to 15% of stroke at room temp.**

- **stiffness:** **depends on Young's Modulus of the ceramic (≈ 25% that of steel), the cross section and the length of the ceramic (plus a number of nonlinear parameters)**

- **maximum force generation:** **high pushing forces < stiffness * max. stroke, but reduction in displacement!**

- **preload:** **zero point is offset, but piezostack will not lose any travel**

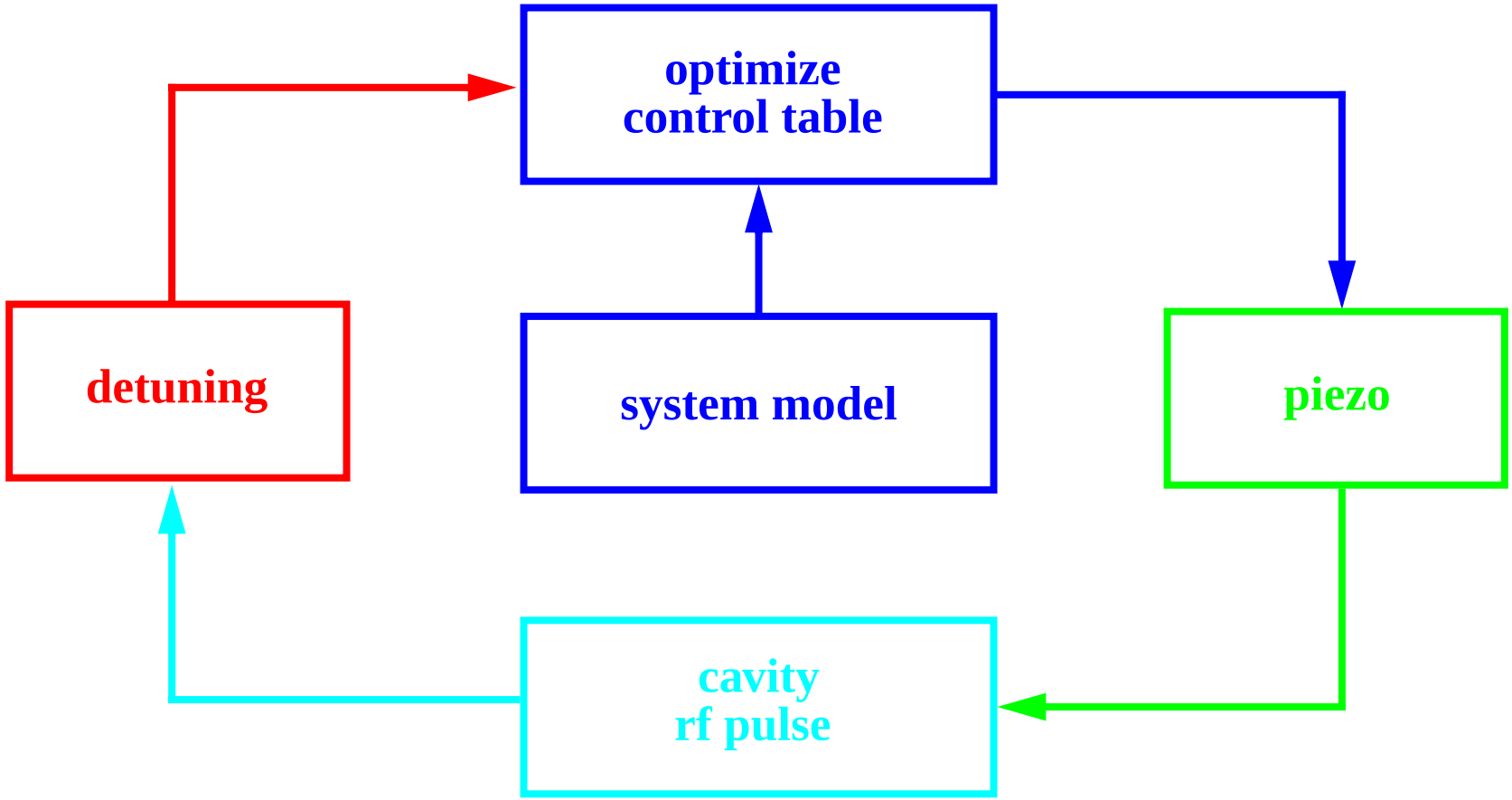
- **mechanical damage:** **piezo ceramics cannot withstand high pulling forces or shear forces**

- **electrical behavior:** **capacitor (first order estimation)**

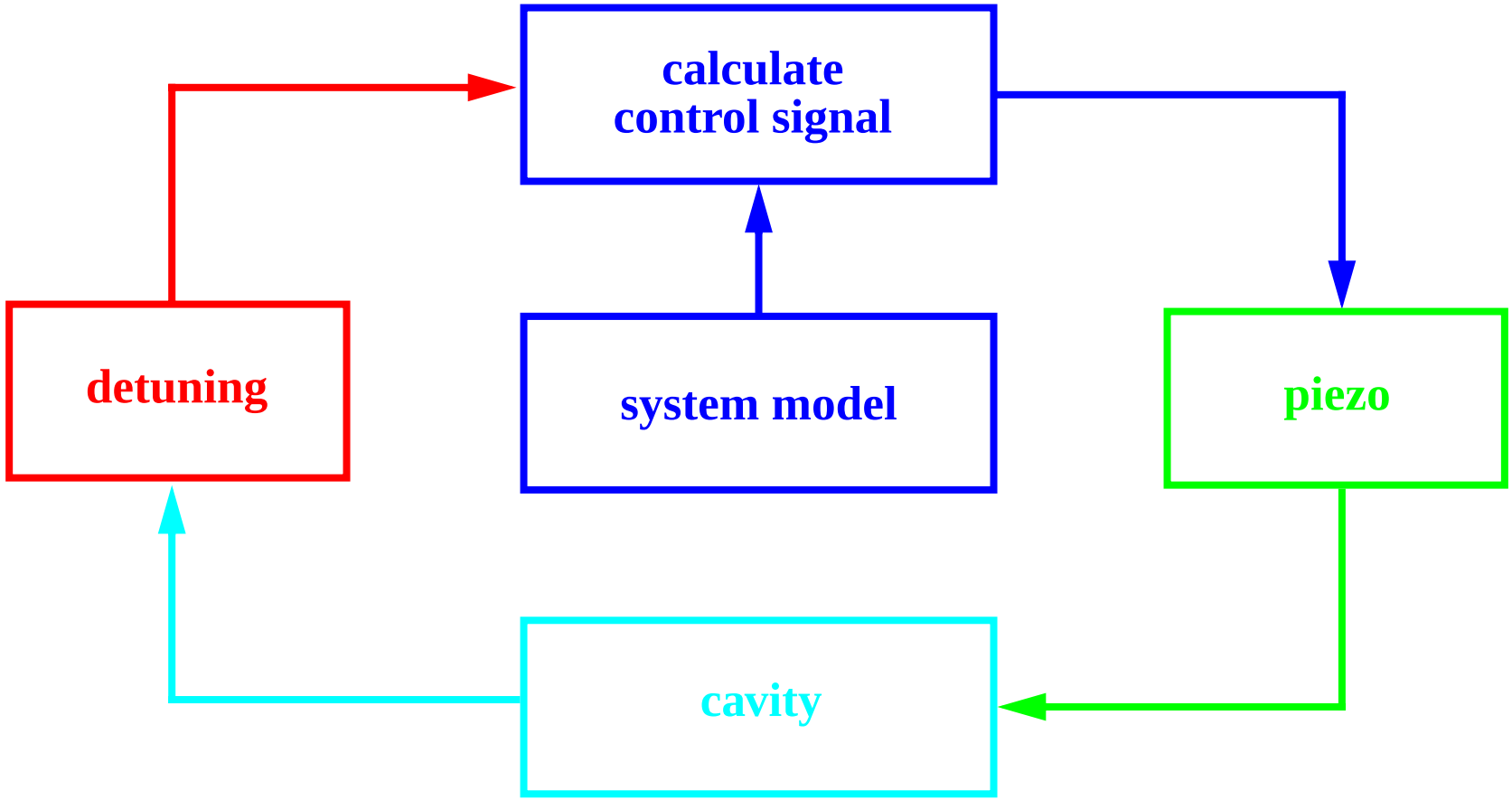
- **heat generation:** **loss factor in the order of 1 to 2% (at room temp.)**

- ***Control Principle: Lorentz-Force Compensation***

⇒ Adaptive feedforward control:



- ***Control Principle: Compensation of Microphonics***



$\Rightarrow$ A simple proportional feedback control can not be used!
(mechanical resonances)

III Can it work?

The piezo-actuator has to work reliable at

- **high dynamic operation:**

  TESLA: $3 \cdot 10^9$ rf-pulses in 10 years of operation (10 Hz)

  SNS: $2 \cdot 10^{10}$ rf-pulses in 10 years of operation (60 Hz)

- **at 2K:**

  only a few μm travel ⇒ low mechanical stress

- **in radiational environment:**

  up to some MGray / 10 years

• *High Dynamic Operation of a Piezo:*

Statement by PIEZOMECHANIK:

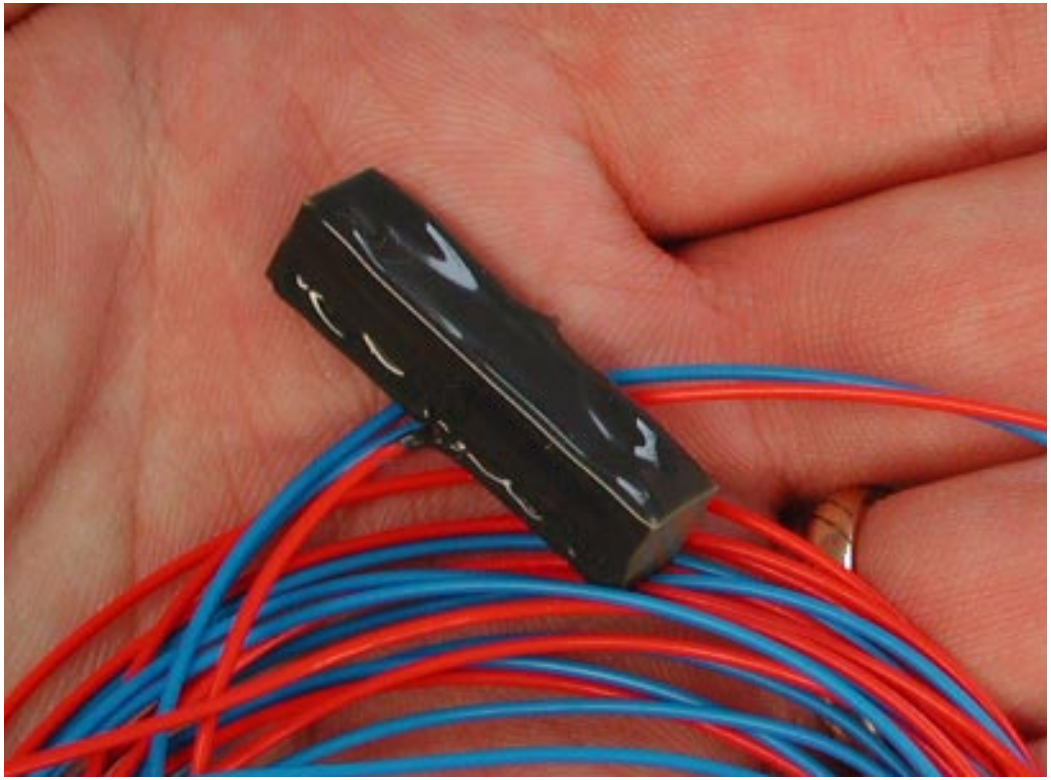
"This operation mode is characterized by the high acceleration forces acting in the piezostack or ring. One popular application in the near future will be the piezo triggered Diesel fuel injection, where the control valve is piezoactuated in the µs-range with maximum stroke.

In the early days of this application, a typical failure mechanism was the generation of cracks inside the ceramic, which was the starting point for electrical break down and short-circuiting of the stacks. ...

An essential contribution to the stack's reliability under dynamic cycling is the sufficiently high preloading of stacks in the range of 50% to 100% of the specified maximum loads.

PIEZOMECHANIK's actuator are well-known for their excellent stability under high dynamic operation showing a performance of more than 10^{10} cycles. ..."

- ***Piezo used for Diesel Fuel Injection:***



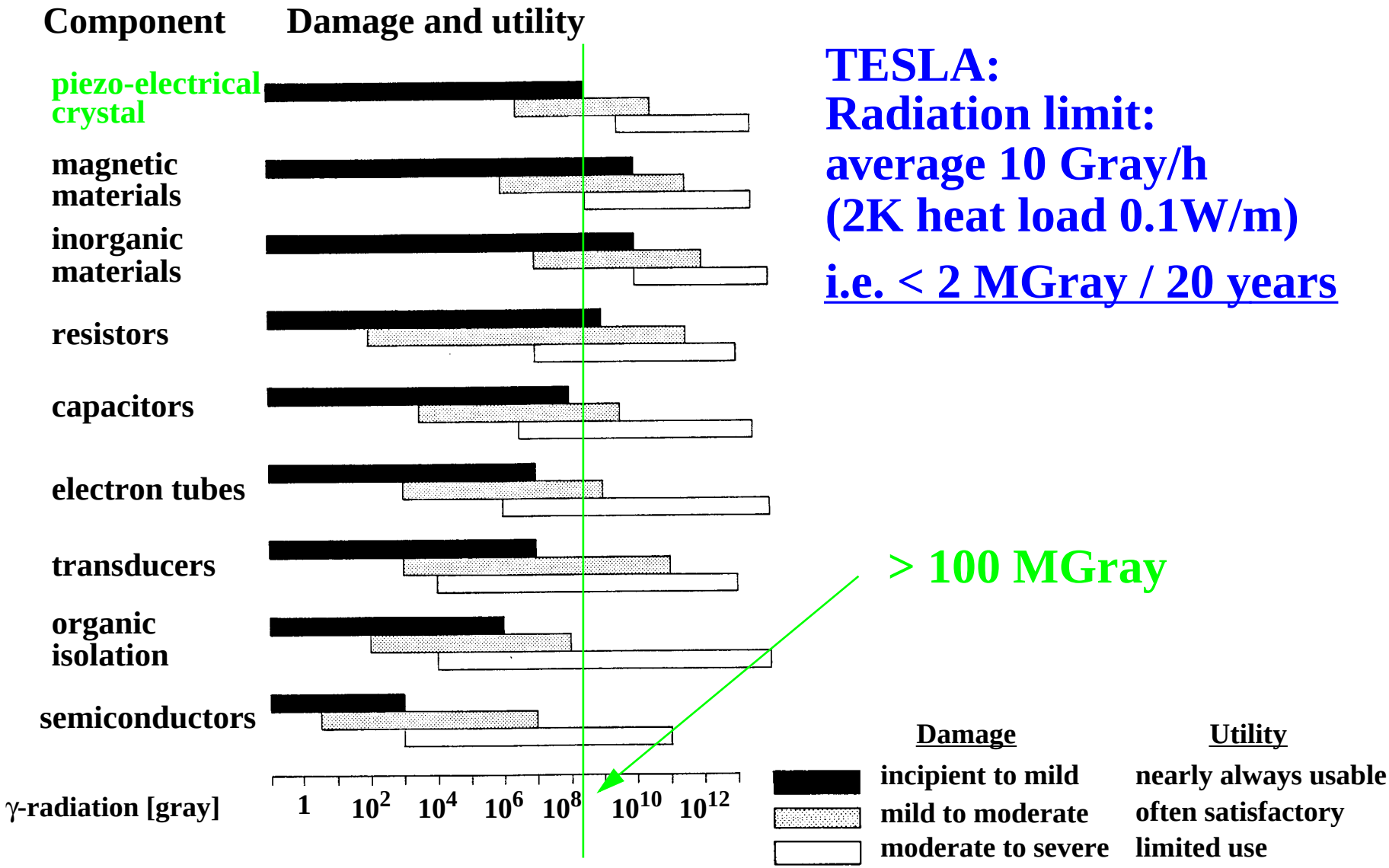
size: 30 x 7 x 7 mm

U = -60 to 160 V

$\Delta l \approx 40\ \mu m$ at room temp.

• *Sensitivity of a Piezostack to Radiation:*

From Cern Report: 75-18



TESLA:
Radiation limit:
average 10 Gray/h
(2K heat load 0.1W/m)

i.e. < 2 MGray / 20 years

• *Controllability:*

for a linear system:

i*deal system*: same coupling to all modes:

$$\begin{bmatrix} \Delta f(\omega_1) \\ \dots \\ \Delta f(\omega_N) \end{bmatrix} = K \begin{bmatrix} V_{piezo}(\omega_1) \\ \dots \\ V_{piezo}(\omega_N) \end{bmatrix}$$

real system:

$$\begin{bmatrix} \Delta f(\omega_1) \\ \dots \\ \Delta f(\omega_N) \end{bmatrix} = \begin{bmatrix} K_{11} & \dots & K_{1N} \\ \dots & \dots & \dots \\ K_{N1} & \dots & K_{NN} \end{bmatrix} \begin{bmatrix} V_{piezo}(\omega_1) \\ \dots \\ V_{piezo}(\omega_N) \end{bmatrix}$$

$\Rightarrow$ $\boldsymbol{K}$ is invertible, if all rows are $\neq 0$,

i.e. if the piezo is coupling to all modes

(and if all rows and columns are different).

If not, place second piezo at a *appropriate place*.

IV First Results

- **used piezo as a sensor:**

  $\Rightarrow$ *measure piezo-voltage*

  $\Rightarrow$ **oscillations (rf-pulses, microphonics)**

- **tested piezo as an active element:**

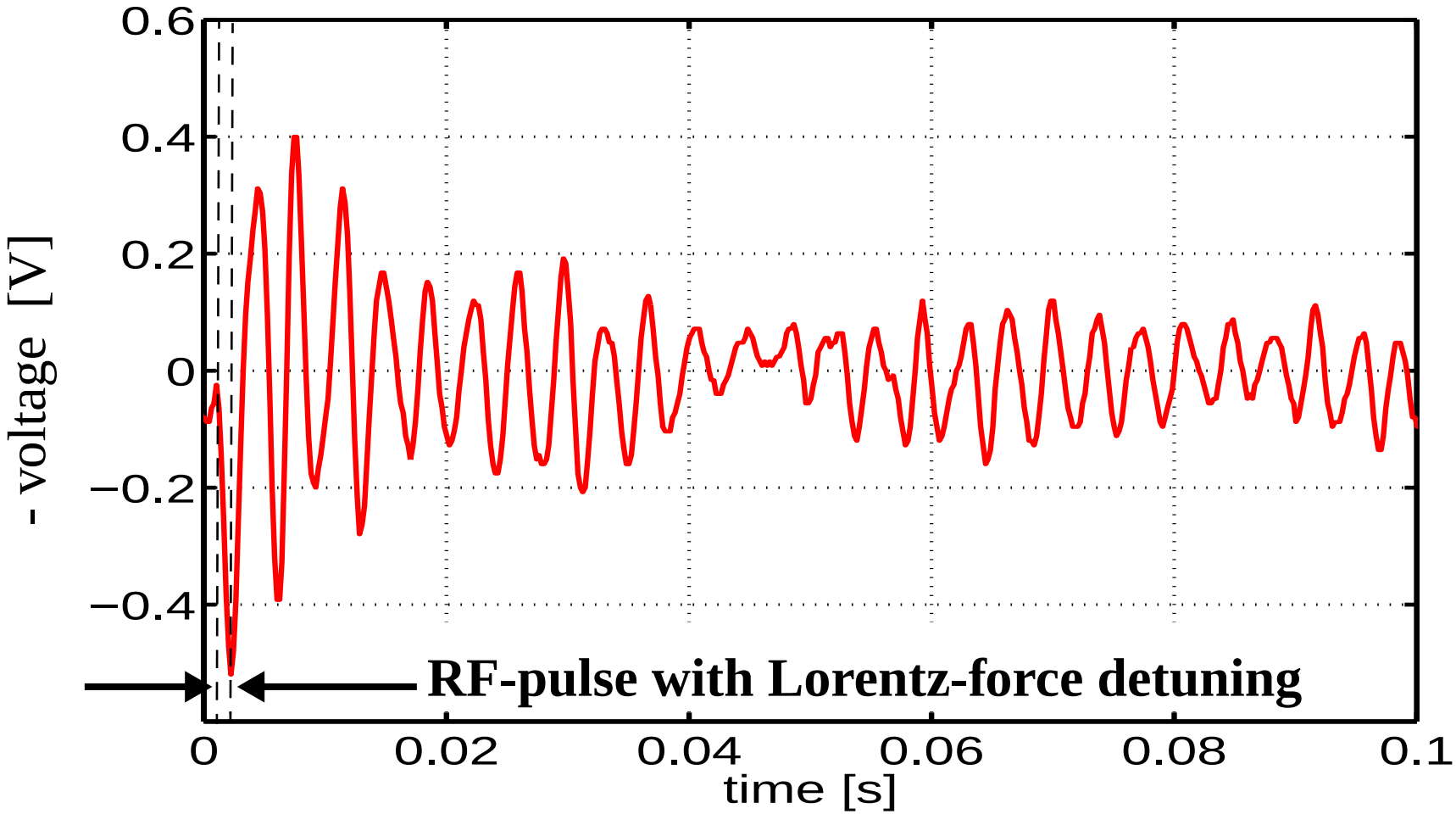
  $\Rightarrow$ *apply voltage to piezo*

  $\Rightarrow$ **damping / excitation of oscillations**

  $\Rightarrow$ **Lorentz-force compensation**

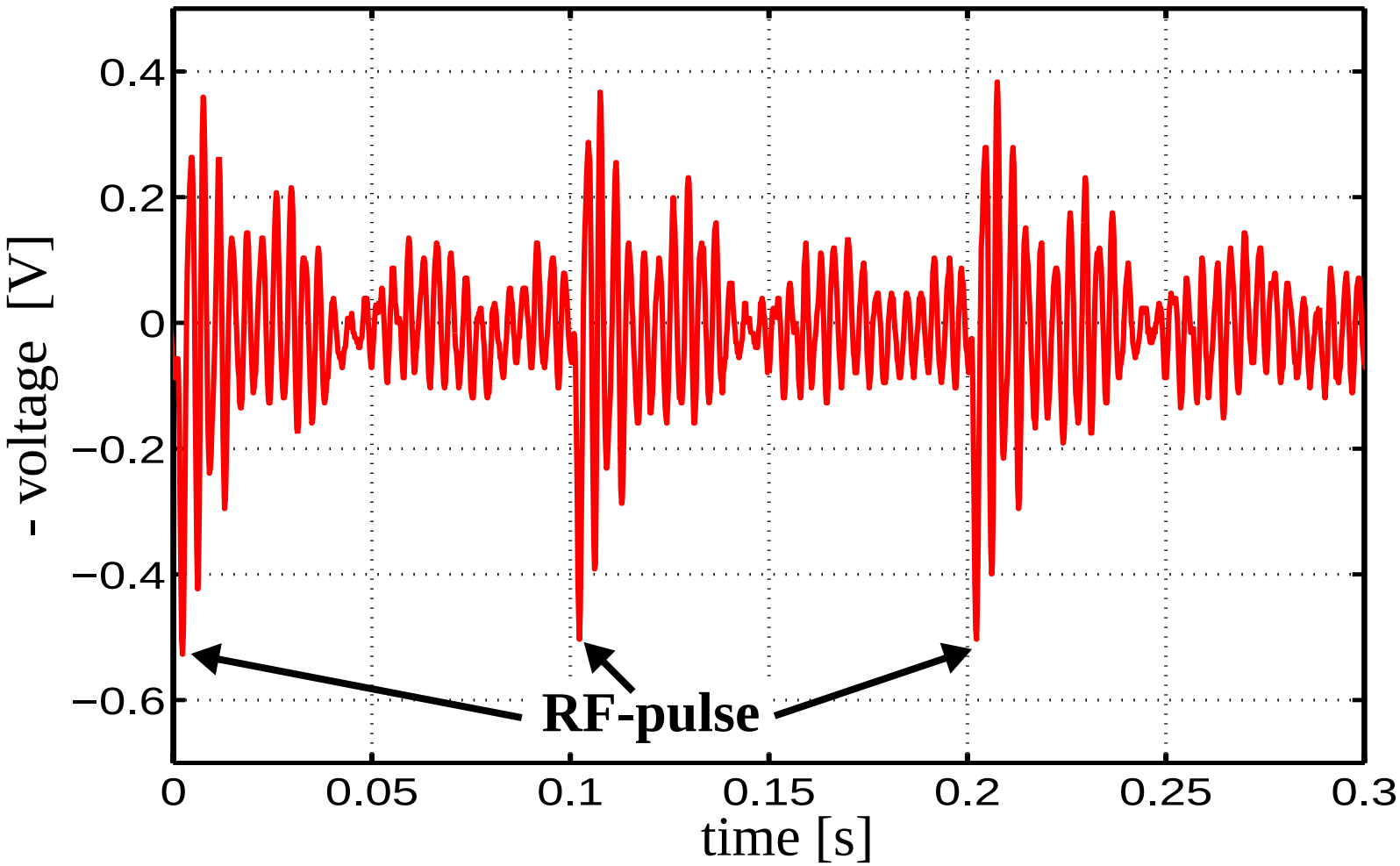
- ***The Piezo as Sensor:***
  mechanical oscillations due to Lorentz-force detuning:

TESLA 9-cell Cavity at 30 MV/m with 10 Hz repetition rate:



The cavity oscillates between the RF-pulses.

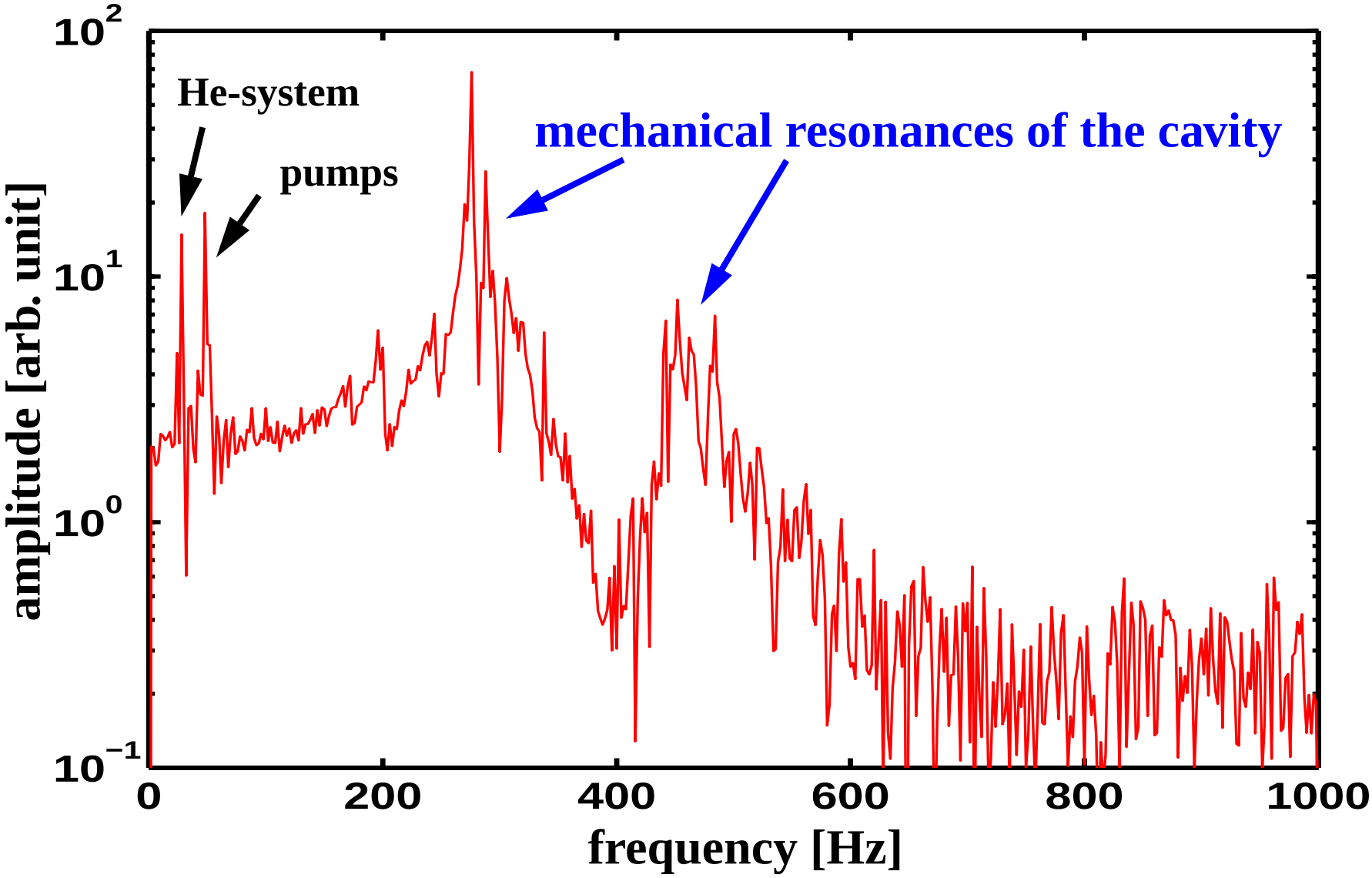
TESLA 9-cell Cavity at 30 MV/m with 10 Hz repetition rate:



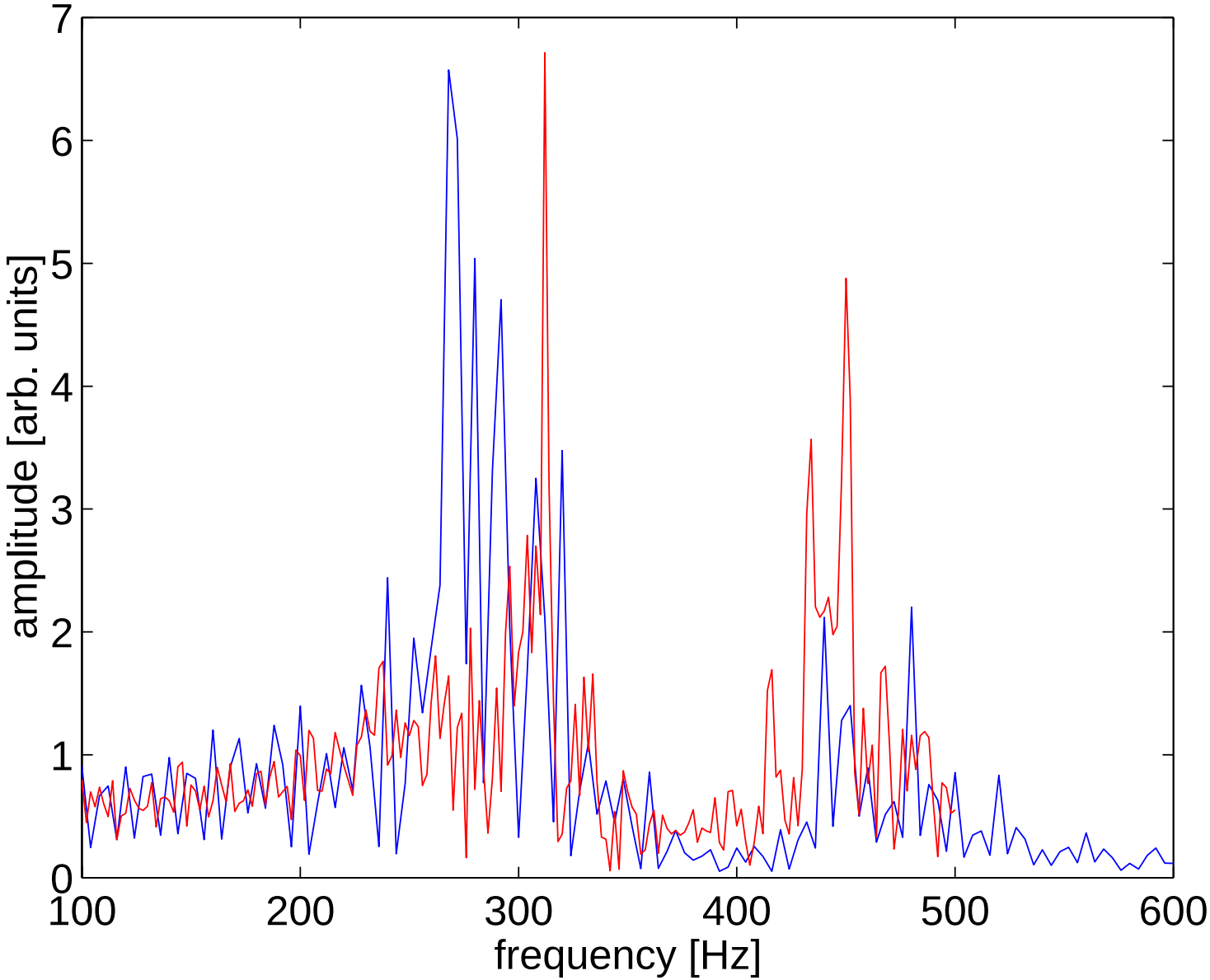
The oscillation is highly repetitive from pulse to pulse.

$\Rightarrow$ ***Same initial detuning at the beginning of the RF pulses!***

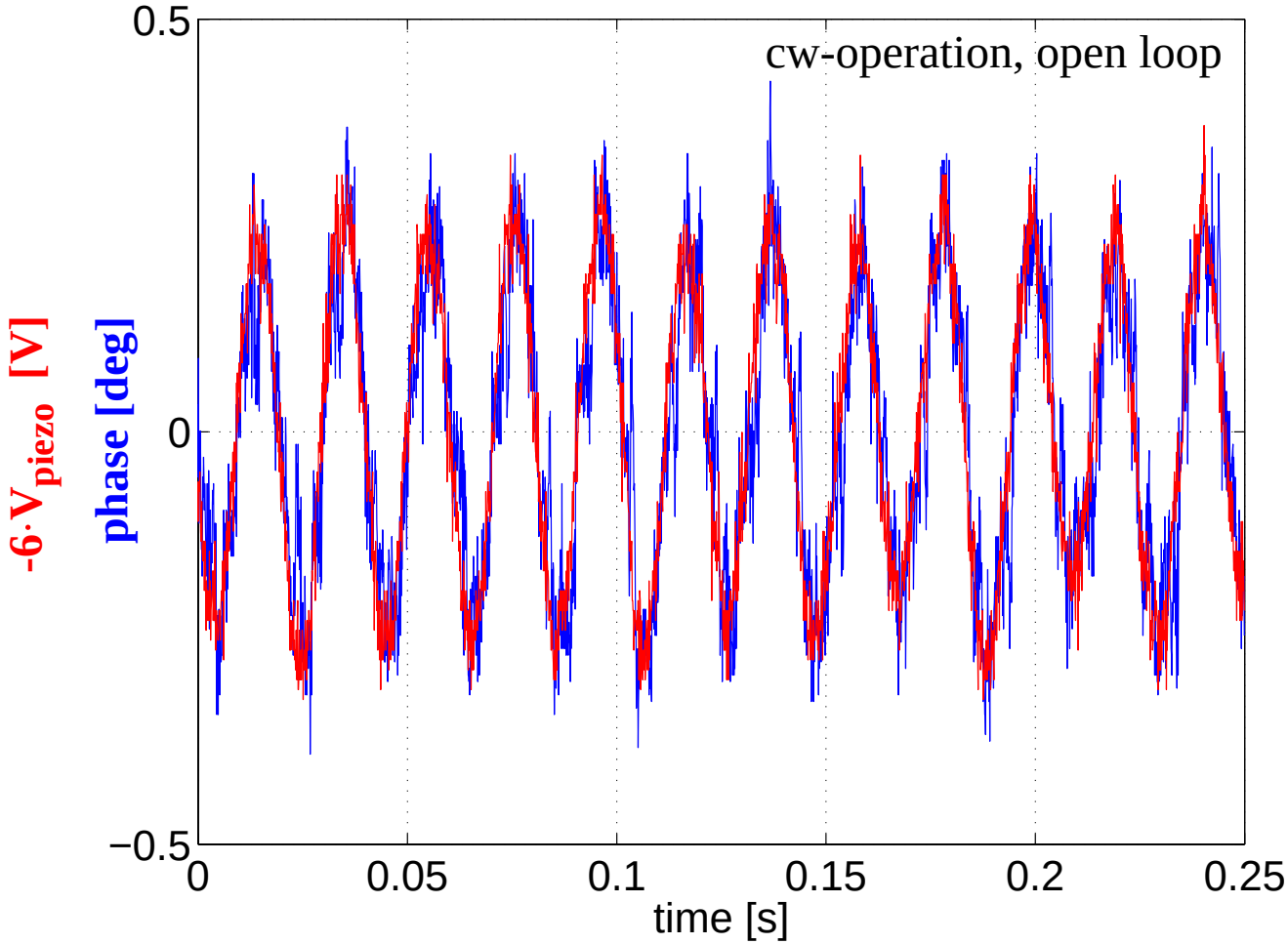
- ***Spectrum of the mechanical Oscillations due to the RF Pulses (Example):***



• *Frequency Spectrum of Oscillation for 2 Cavities (30MV/m 2Hz)*



- ***Comparison between the Piezo Signal and the Phase-Variation due to Microphonics (Example):***

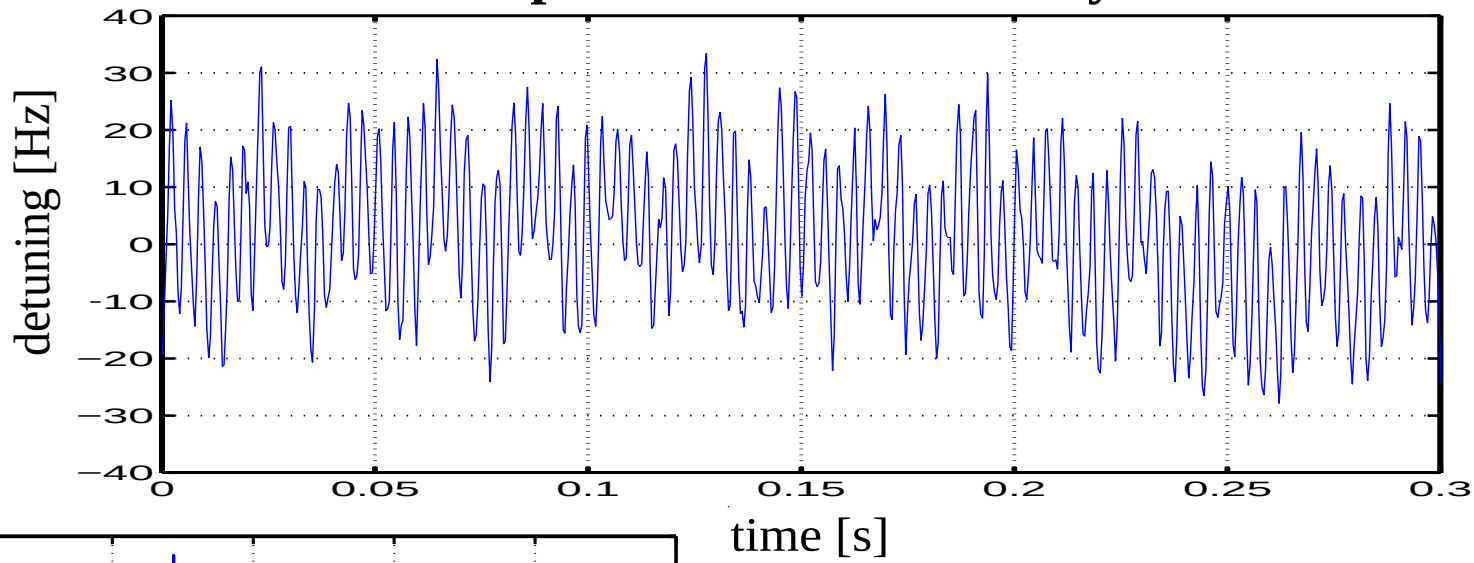


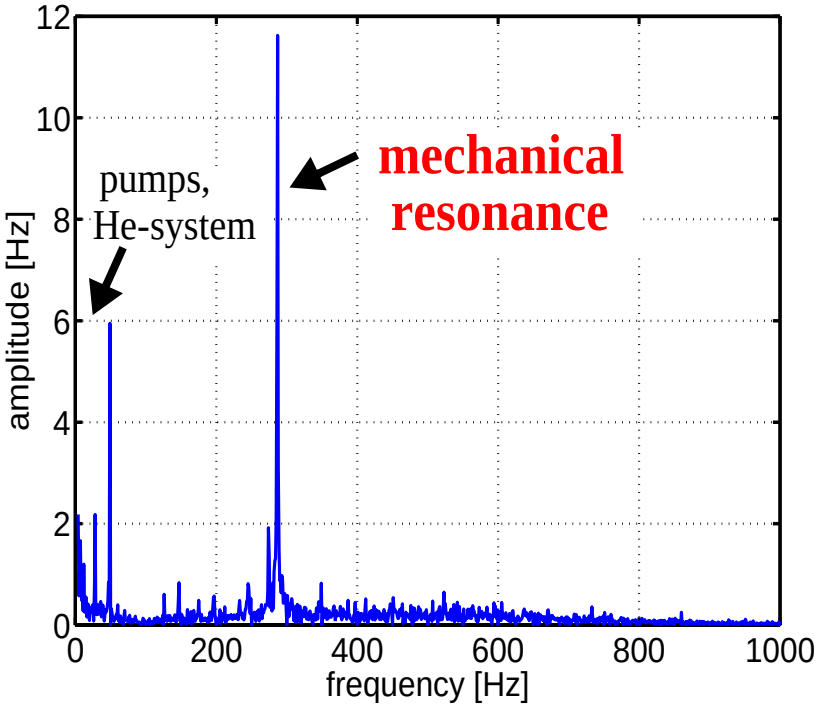
⇒ Clear correlation!

⇒ Oscillation can be damped by a piezo-tuner.

• *Microphonics Spectrum:*

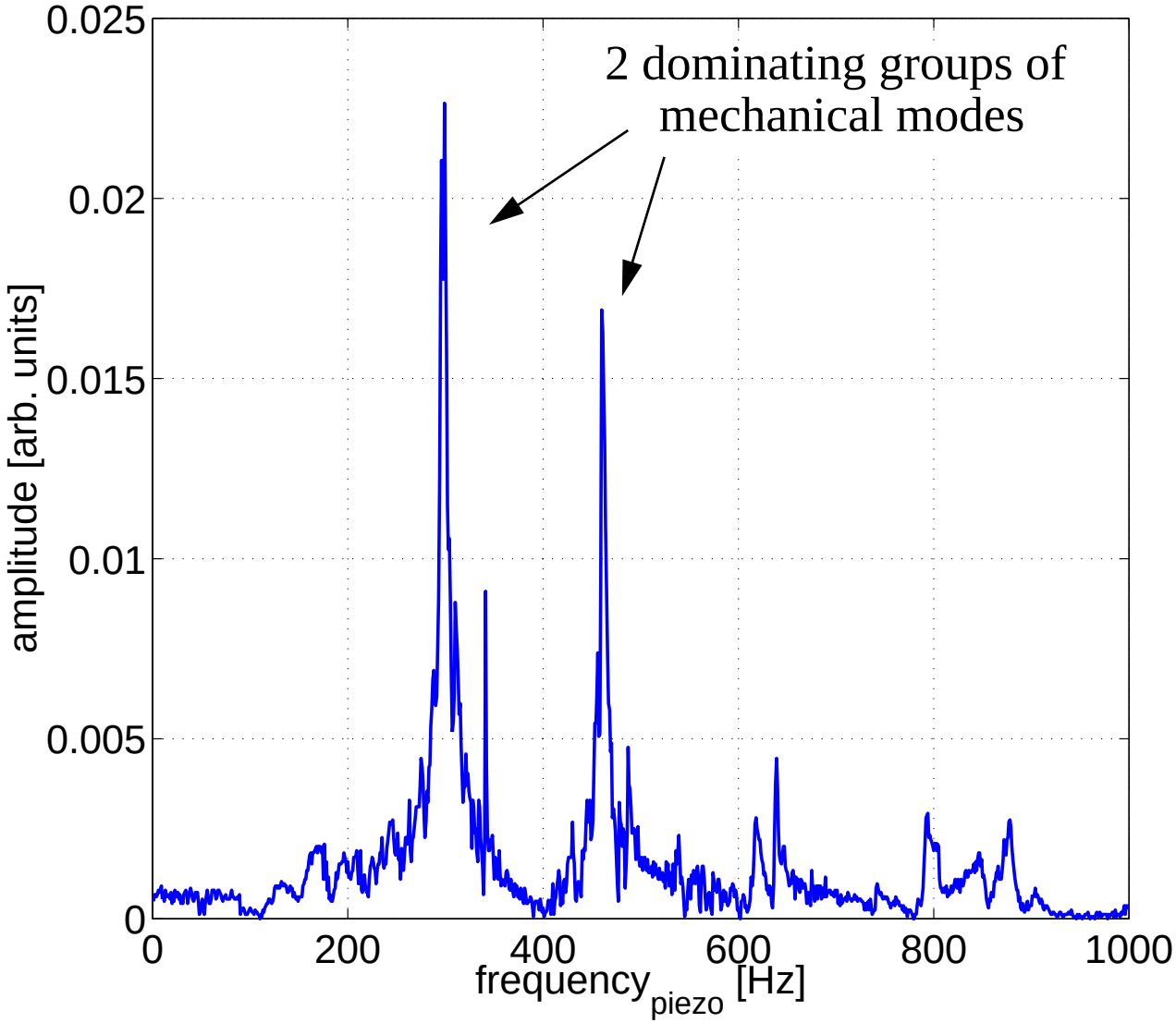
cw-operation of 9-cell cavity





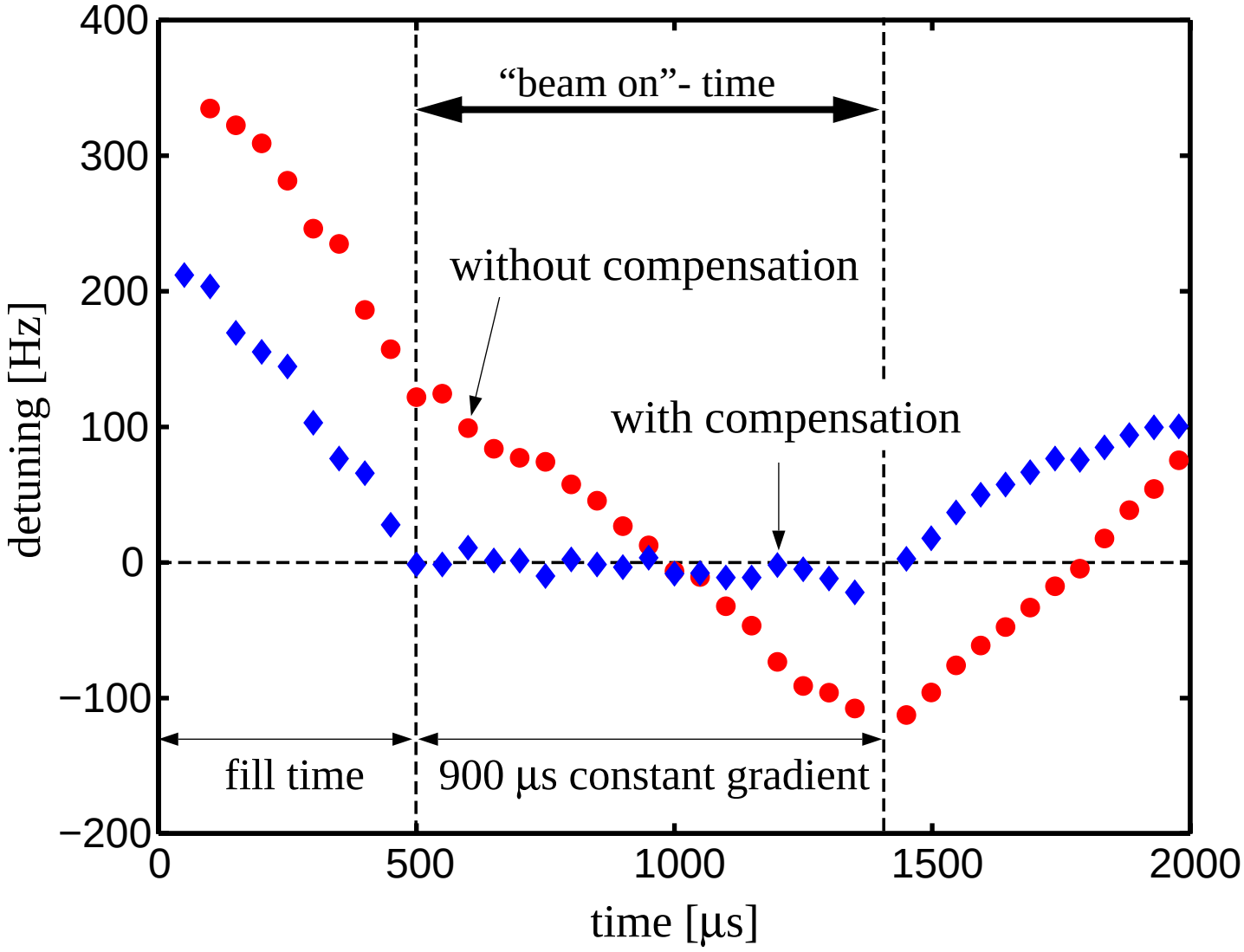
⇒ ***Only a few frequencies!***

- ***Piezo as an active Element: Excitation of mechanical Modes***



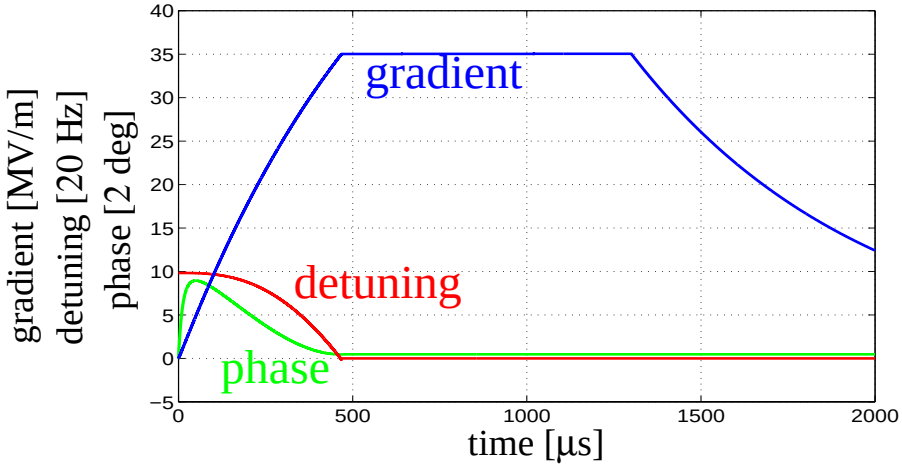
• *Piezo as an active Element: Lorentz-Detuning Compensation*

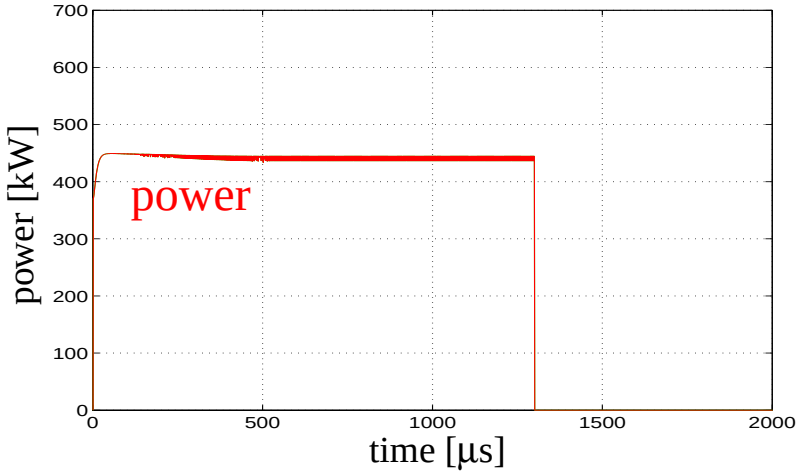
TTF 9-cell cavity operated in pulsed mode at 23.5 MV/m (TESLA500)



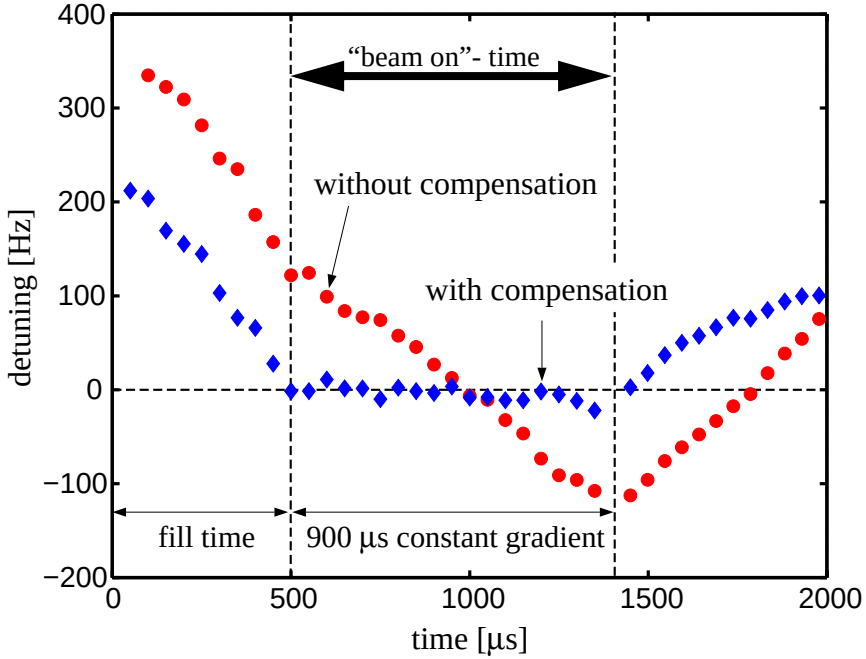
• *Lorentz-Detuning Compensation:*

Simulation:





Measurement:



- **Future Plans:**

Proof of Principle: Active Lorentz-Detuning Compensation ✓

Investigate mechanical oscillations of cavities in detail:

measurements, FE-models.

Test reliability:

Long term operation at 2K and radiation hardness of different types of piezoactuators.

Design, built and test a prototype piezo-tuner.

Develop feedforward control.

work started

→ **Reliable, well understood piezoelectric tuner.**