A control and systems theory approach to the high gradient cavity detuning compensation

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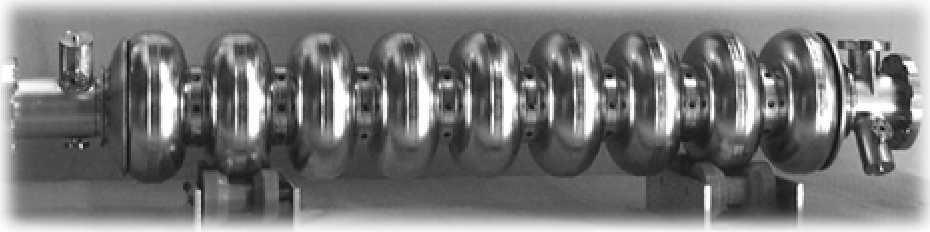
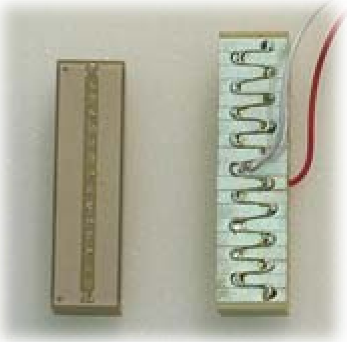
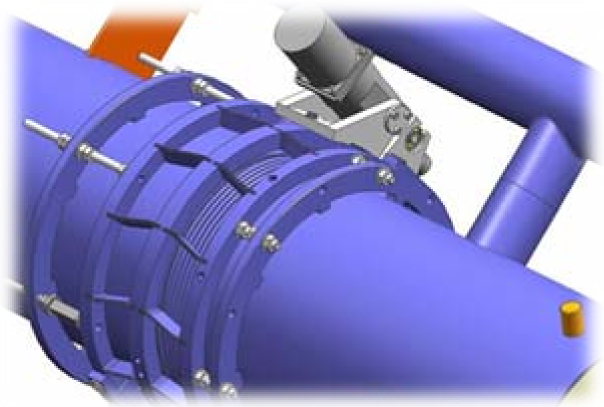


- Introduction
- Cavity detuning
  - Dynamic detuning characterization
  - Fast frequency tuners and piezoelectric actuators
- Open-loop compensation of the Lorentz Force Detuning (LFD)
  - Piezo timing analyses for a single pulse
  - LFD compensation strategies and results
  - A proposal analytical modeling
- Toward a complete detuning controller
- Conclusion

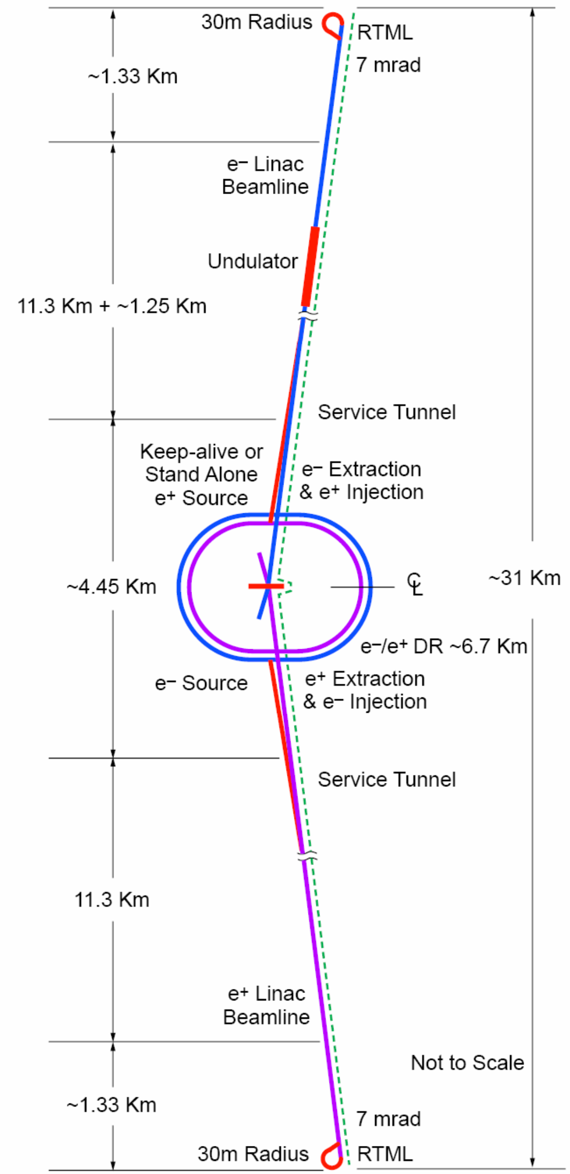




The International Linear Collider

" The ILC design has been developed to achieve the following physics performance goals:

- ***a continuous center-of-mass energy range between 200 GeV and 500 GeV***
- *a peak luminosity of $2{\cdot}10^{34}$ $cm^{-2}s^{-1}$*
- ***an energy stability and precision of 0.1% …** "*



2008-2011 **ILC-HiGrade** project
in the European FP7:

INFN-Milan is in charge for the realization of the 24 Blade Tuners chosen for the preparatory phase.

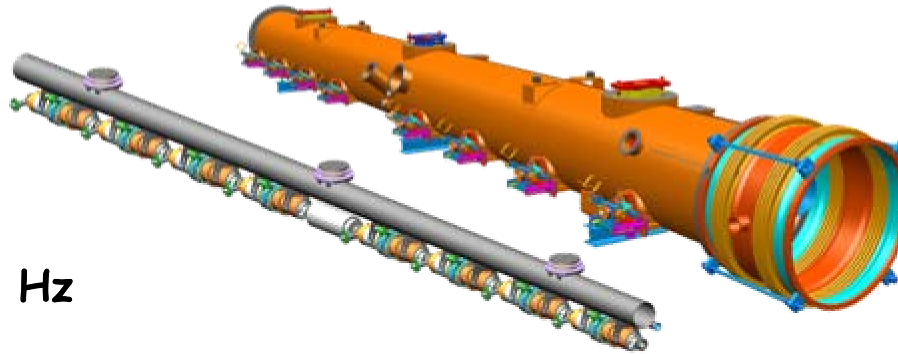
ILCTA module2:

8 Blade Tuners installed for the 2nd module of the FNAL test bench

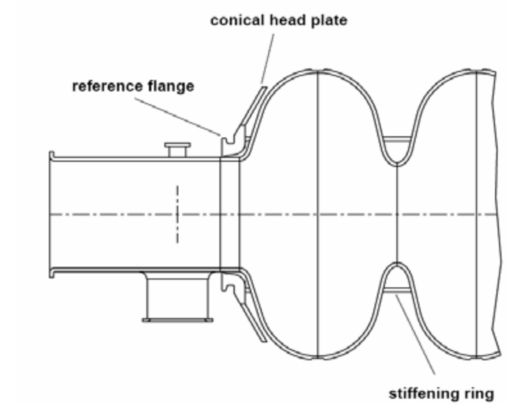
European XFEL:

INFN-Milan sharing the responsibility for the "Tuners" WP

The TESLA resonator



- **Nb 9-cell, 1.3 GHz** TM_{010} mode frequency
- E_{acc} **of 31.5 MV/m** for ILC, 35 MV/m for qualification tests
- Average Q_{EXT} of $3.5\ 10^6$ and Δf_{FWHM} **of 370 Hz**
- About **3 N/µm** longitudinal stiffness
- **315 Hz/µm** longitudinal tuning sensitivity

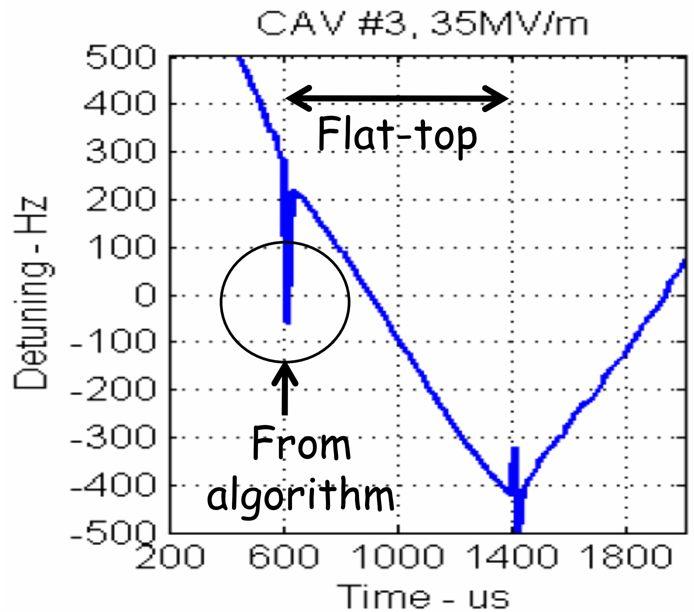


Since 2004 **FLASH, Free electron LASer in Hamburg**, formerly VUV-FEL and TTF. As of today, a 260 m long 1 GeV linac with 6 SCRF cryomodules.

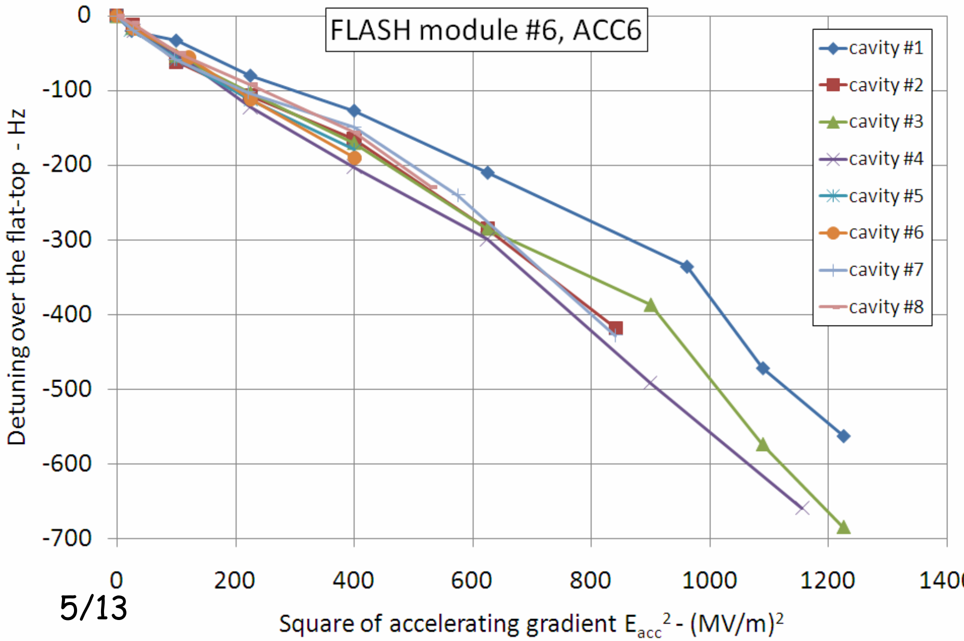
FLASH linac represents the basis also for the incoming **European XFEL** project for a TESLA technology based, 3.4 km long X-rays source facility soon under construction.

The Lorentz Force Detuning, LFD

- A pressure distribution is generated by the Lorentz Force on cavity walls
- **μm-level** complex deformation of the cavity shape
- When pulsed, LF excites several mechanical modes leading to a dynamic detuning during the RF pulse.
- The induced repetitive **frequency drift** pattern makes power consumption and stability performances of the LLRF control critical.



FLASH Module #	Avg. K_L' [Hz/(MV/m)^2] (800 μs flat-top)
6	-0.45 ± 0.1
7	-0.47 ± 0.04
ILC RDR	-0.414

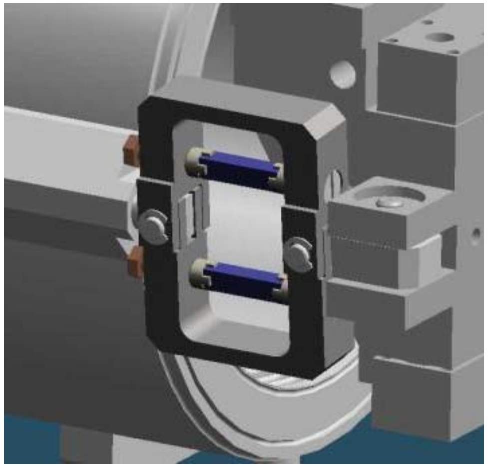


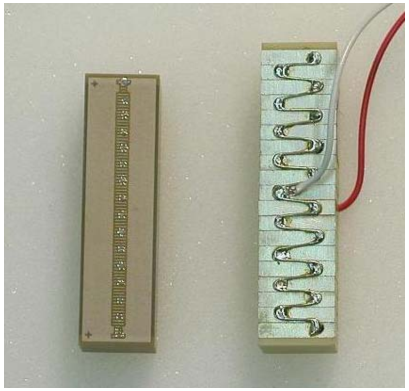
Saclay-I

From original TTF tuner, installed at cavity end

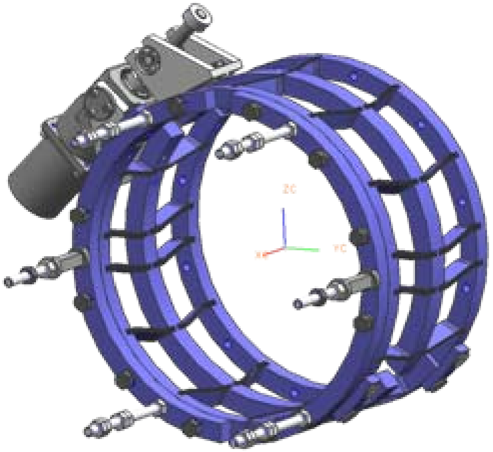
INFN Blade Tuner

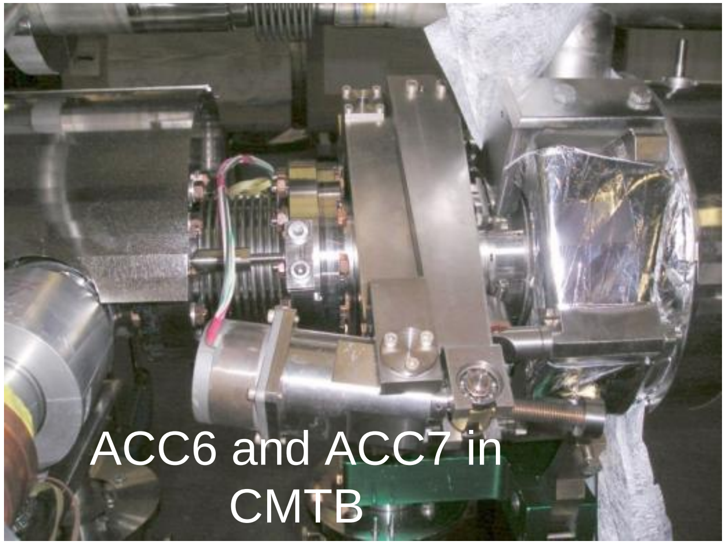
Coaxial to the cavity, designed for ILC





Piezoelectric actuators



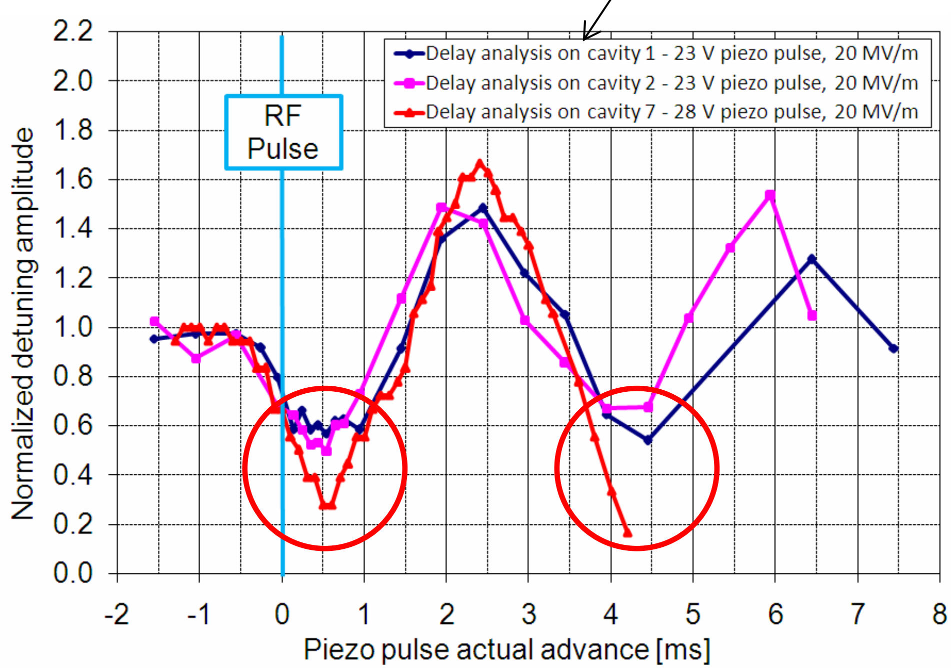


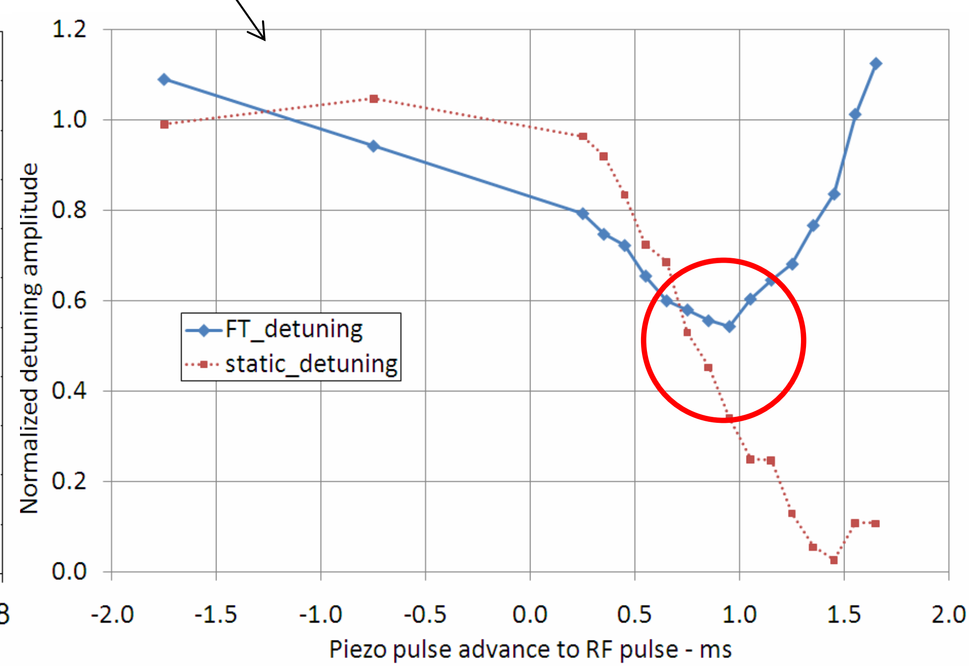
Piezo pulse timing analysis

The chosen strategy makes use of **single semi-sinusoidal piezo pulse** :

- a pulse width of 2.5 ms leads to a rise time of about 1.3 ms that roughly replicate the kind of excitation provided by the RF pulse itself
- it avoids sharp transitions that would lead to undesirable current peaks
- shorter pulses / steeper rises would not be far more effective
- its amplitude determines the rate of frequency change
- effect of pulse delay / lead from the start of the RF pulse has been investigated for both Saclay-I assembly and Blade Tuner assembly

	Saclay-I ms	**Blade Tuner** ms
1st	0.65	0.95
2nd	4.5	

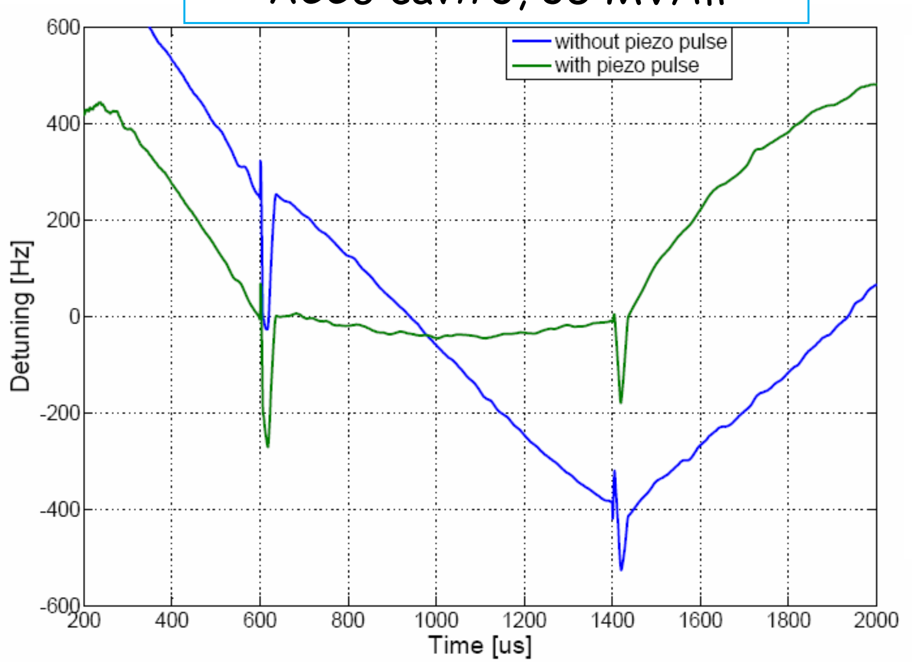




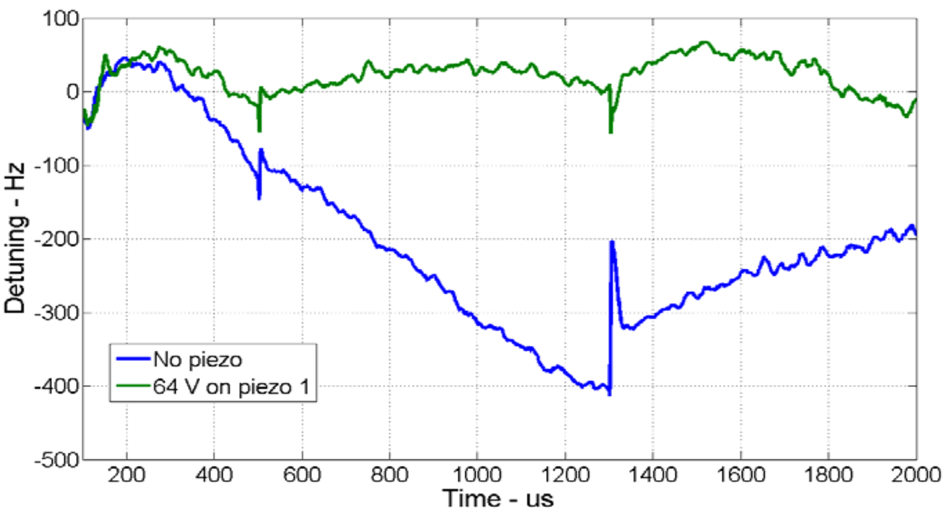
The 1st cavity oscillation is used for LFD compensation:

- LFD fully compensated independently for each cavity of ACC6 in CMTB
- 630 Hz compensated at 35 MV/m for cav#3 (80 V piezo pulse, max 120 V)
- All the 300 Hz LFD achieved at maximum gradient compensated also for the Z86 cavity equipped with Blade Tuner (60 V piezo pulse, max 200 V)

ACC6 cav#3, 35 MV/m



Z86 cavity, 23 MV/m



Simultaneous LFD compensation with LLRF feedback on

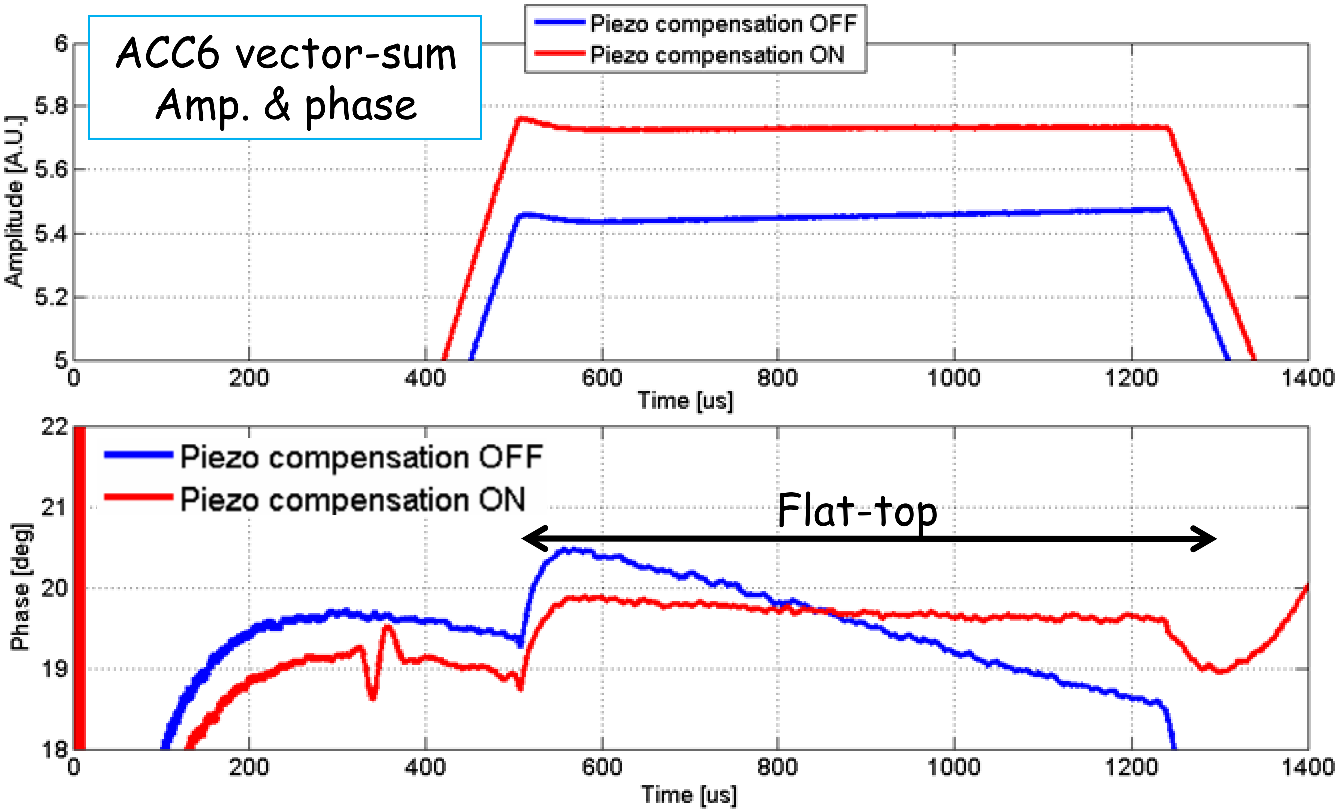
For the ACC6 in the CMTB the LFD has been compensated simultaneously in a closed LLRF feedback loop:

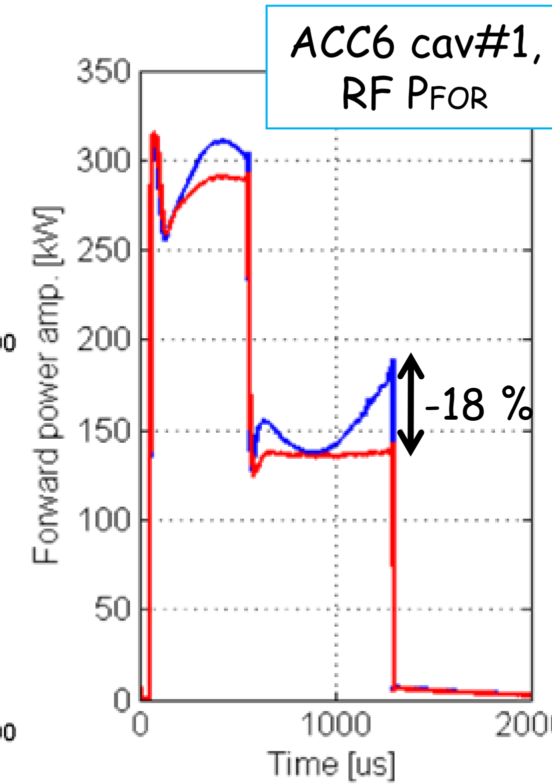
▪A compromise has been found making use of only 2 different piezo pulses

Multichannel piezo controller is needed for optimal performances …

… although simplification is feasible:

▪same pulse shape and timing, few sets of different amplitudes.



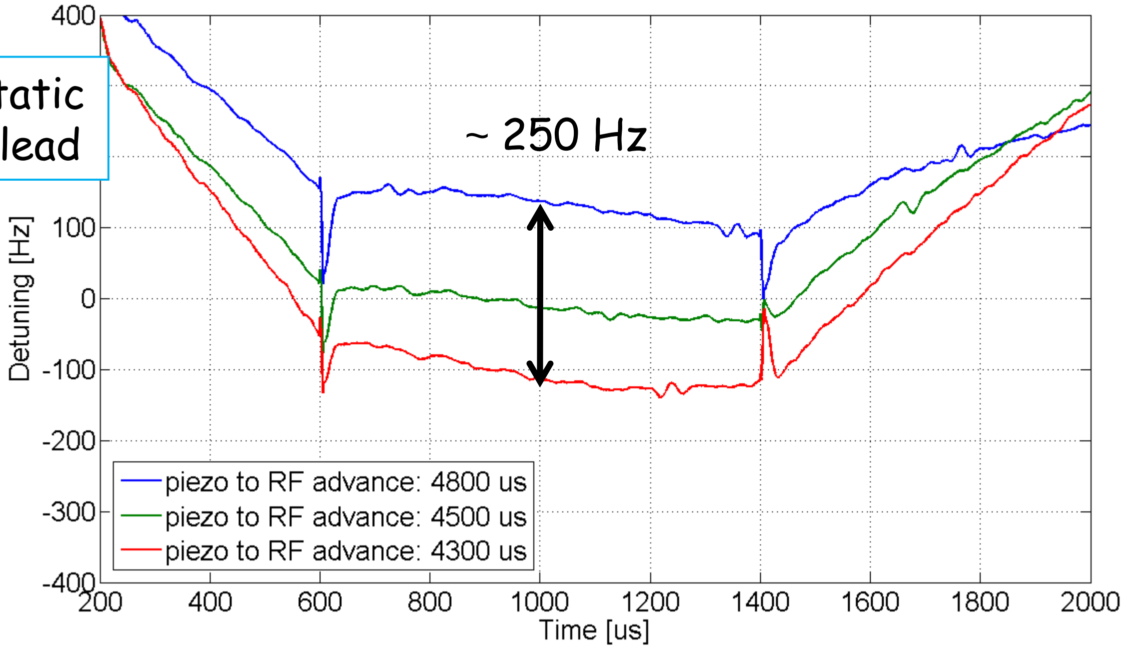


LFD compensation with 2nd cavity oscillation

The second induced cavity oscillation is here used for LFD compensation:

- Comparable LFD compensation performances (Hz/V)
- no additional static detuning is added by piezo pulse.
- static and dynamic detuning controls are decoupled to two different parameters: the piezo pulse timing and amplitude respectively.
- small static detuning variation can be compensated without moving the stepper motor.

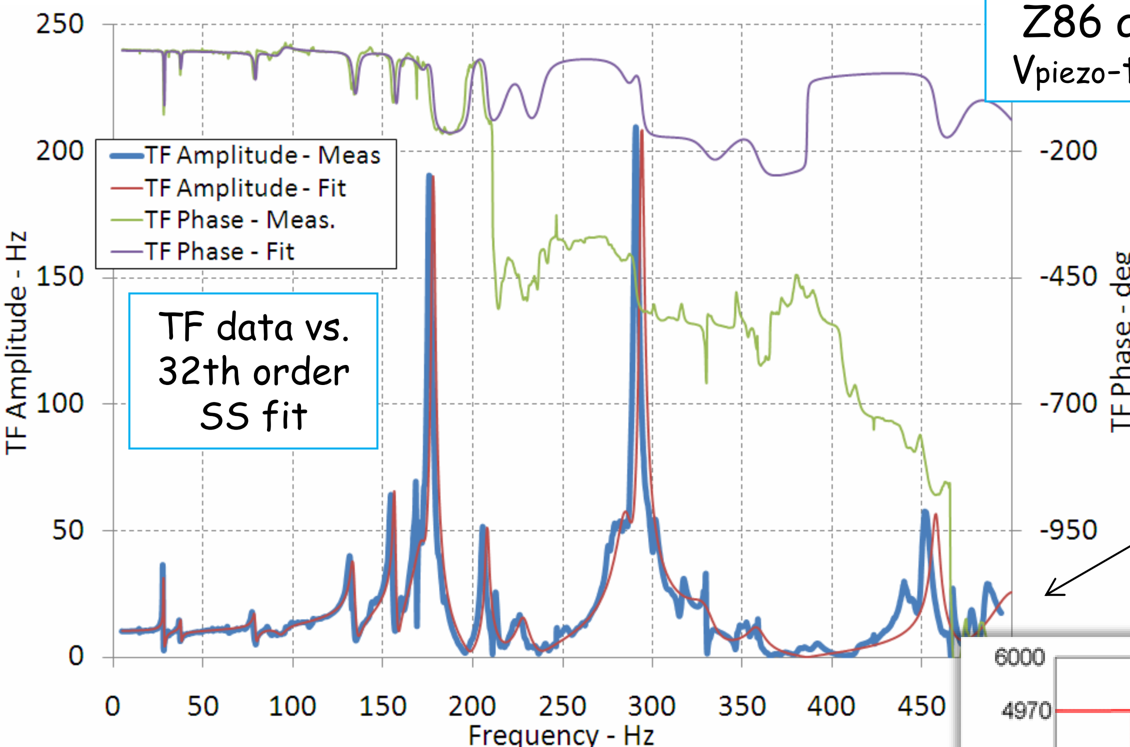
ACC6 cav#4: control of static detuning with piezo pulse lead



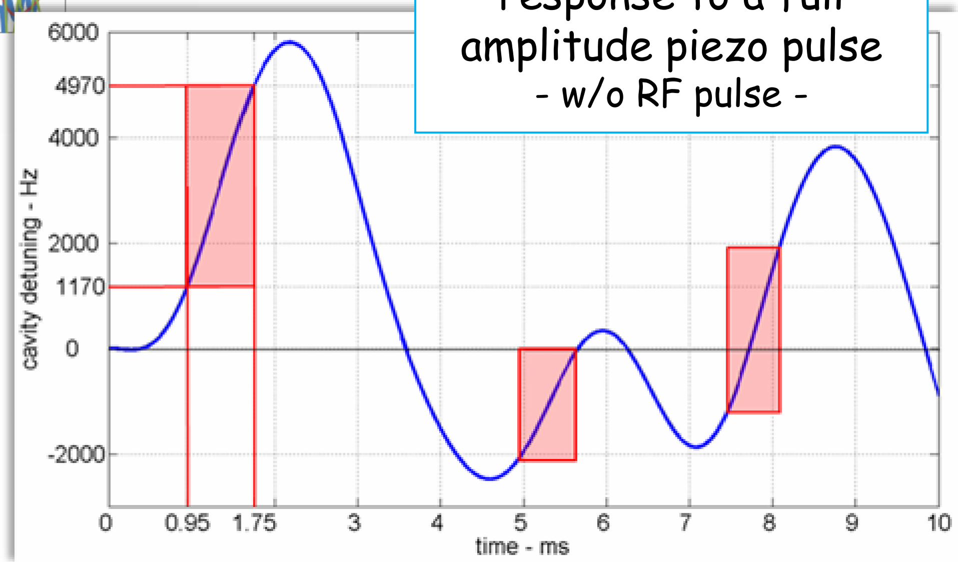
Correctly interpreted through the analytical modeling of the piezo/tuner/cavity system

Analytical modeling

Z86 and Blade Tuner assembly
Vpiezo-to-detuning transfer function



An analytical model of the system under control is achieved through detailed measurements of both the **dynamic** and **static** actuator tuning range.



Simulated detuning response to a full amplitude piezo pulse
- w/o RF pulse -

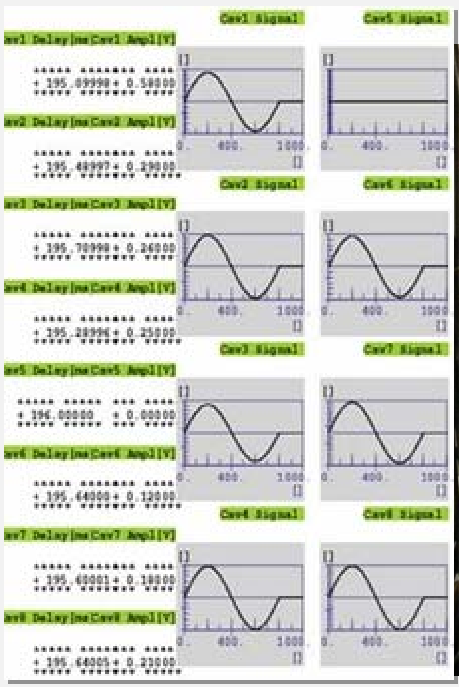
Accurate data fit, State-Space model:

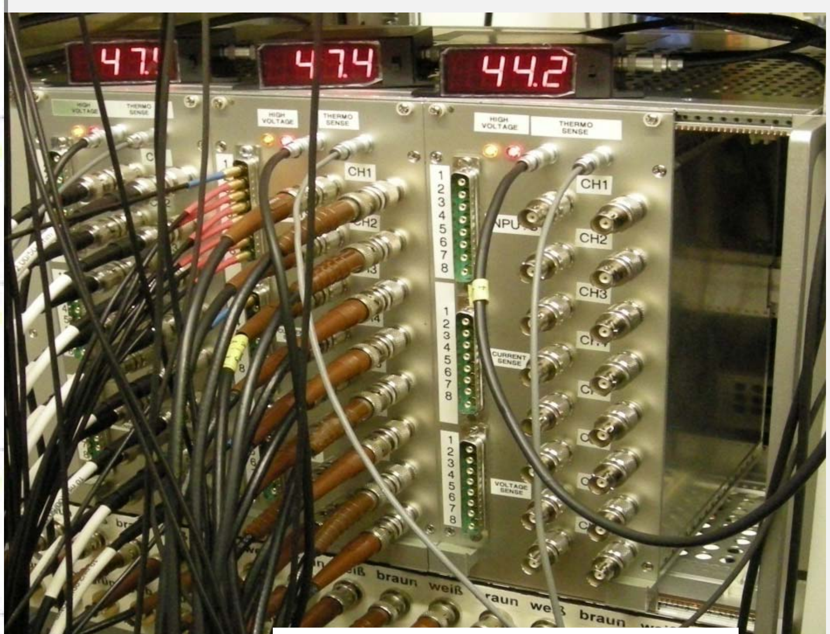
- coupling to main mechanical modes (bending, compressive)
- group delay of the assembly
- DC tuning range and non-linearity

Toward a complete detuning controller

Guidelines:

- Replicate the presented open-loop control of LFD on more cavities simultaneously
- Integrate in the controller the fast FPGA computation of detuning
- Realize an adaptive control able to iteratively tune pulse parameters
- Exploiting the experience matured in the CW scenario, investigate even microphonics identification and active compensation.





Courtesy of K. Przygoda

- Implemented and tested on SIMCON_DSP Hardware
- GUI for multichannel pulses setting
- 8 cavity on-line detuning computation
- Adaptive update of pulses amplitude table
- Based on the presented 2nd oscillation setting
- 32 channel integrated board under finalizing

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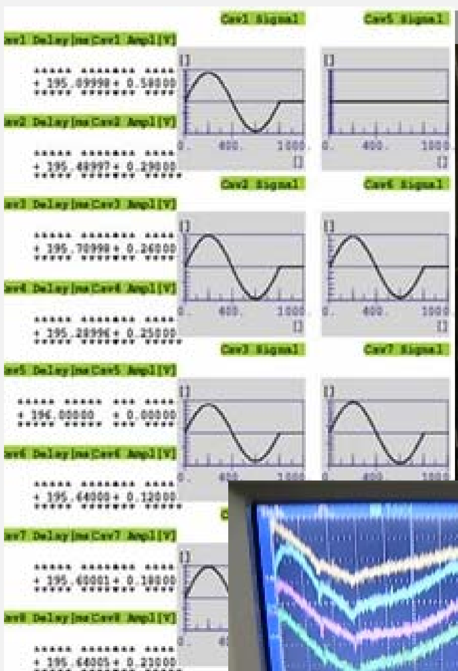

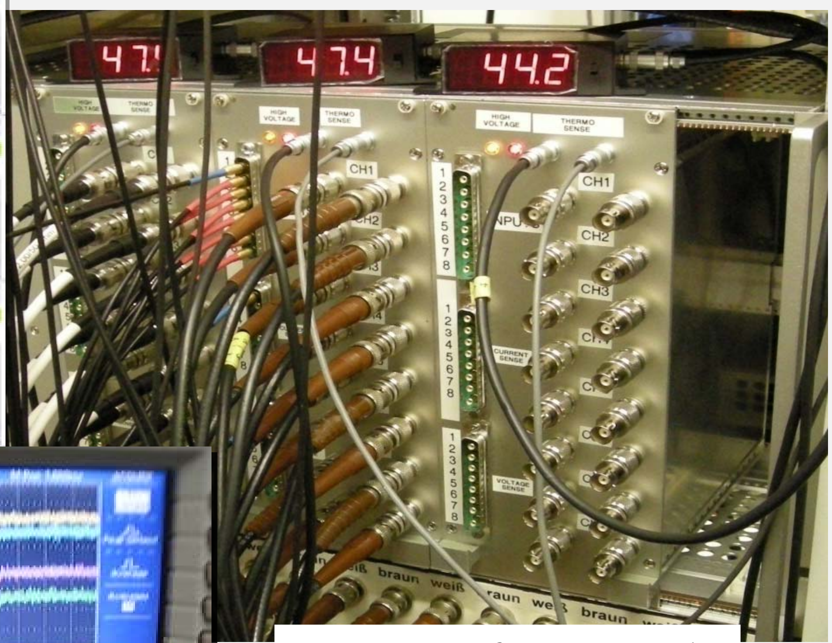

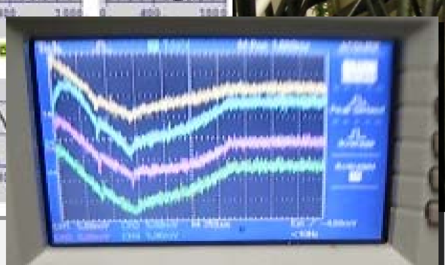

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Conclusion

Great results have been achieved in these past two years addressing the issue of active compensation of dynamic detuning for TESLA superconducting cavity.

As of today, a complete, adaptive and multi-cavity controller is on the way to realization, exploiting the presented successful compensation and analysis experiences.

Experiences jointly achieved within a precious collaboration with many persons in different laboratories that should be strongly acknowledged:

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