Piezo Control at DESY, from FLASH to XFEL

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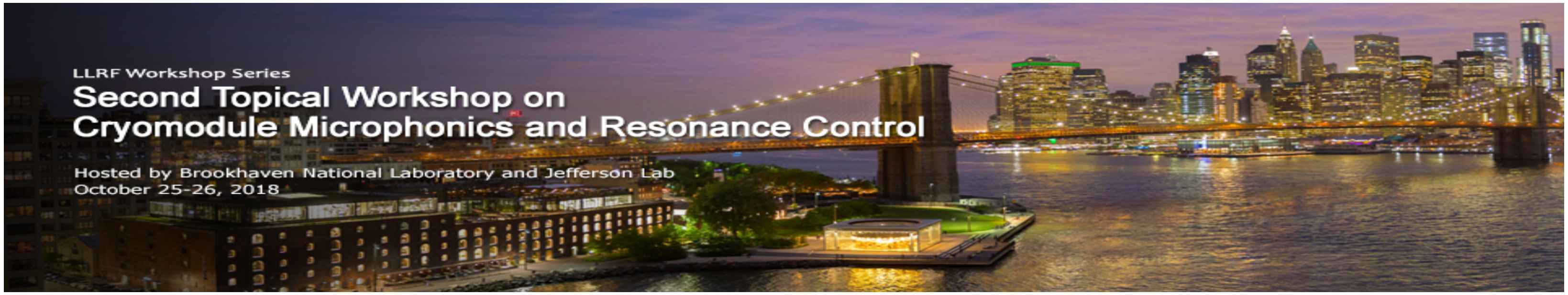

LLRF Workshop Series
Second Topical Workshop on
Cryomodule Microphonics and Resonance Control

Hosted by Brookhaven National Laboratory and Jefferson Lab
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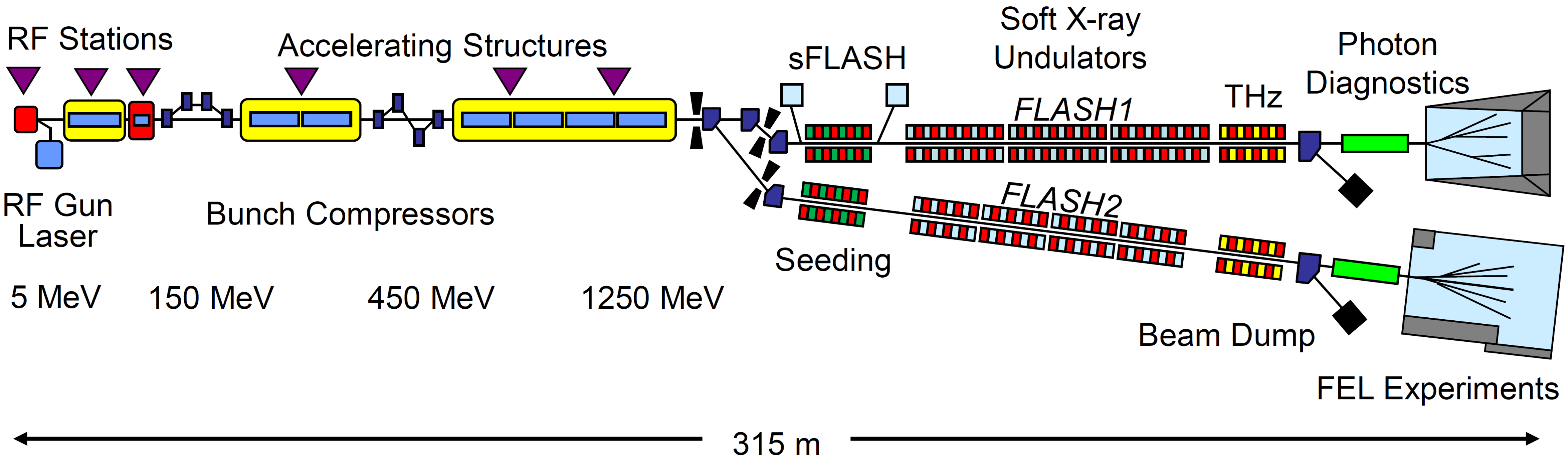
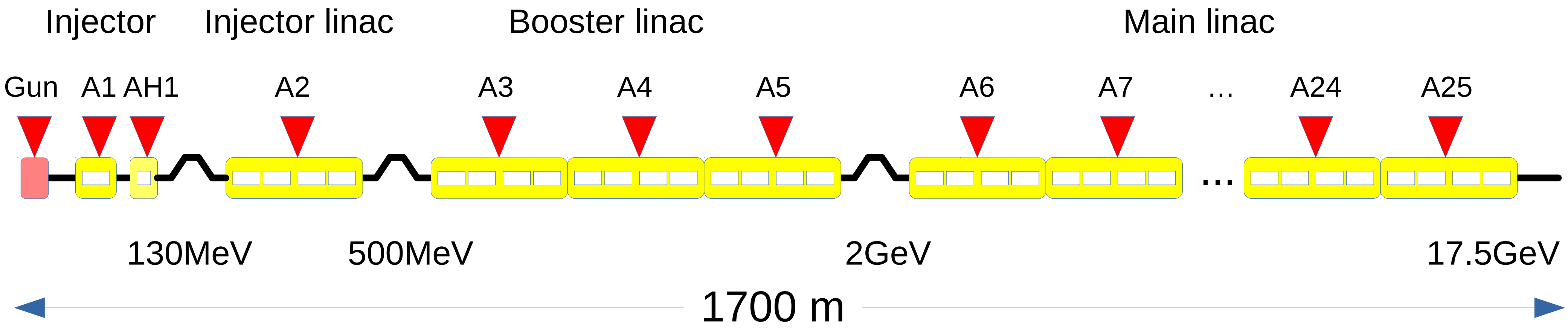
FLASH



- A1, A6, A7 – double piezos (PI)
- A3 – single piezos (Noliac/PI)
- A5 – single piezos (Noliac)
- A2, A4 – no piezos

XFEL



Injector Injector linac Booster linac Main linac

Gun A1 AH1 A2 A3 A4 A5 A6 A7 … A24 A25

…

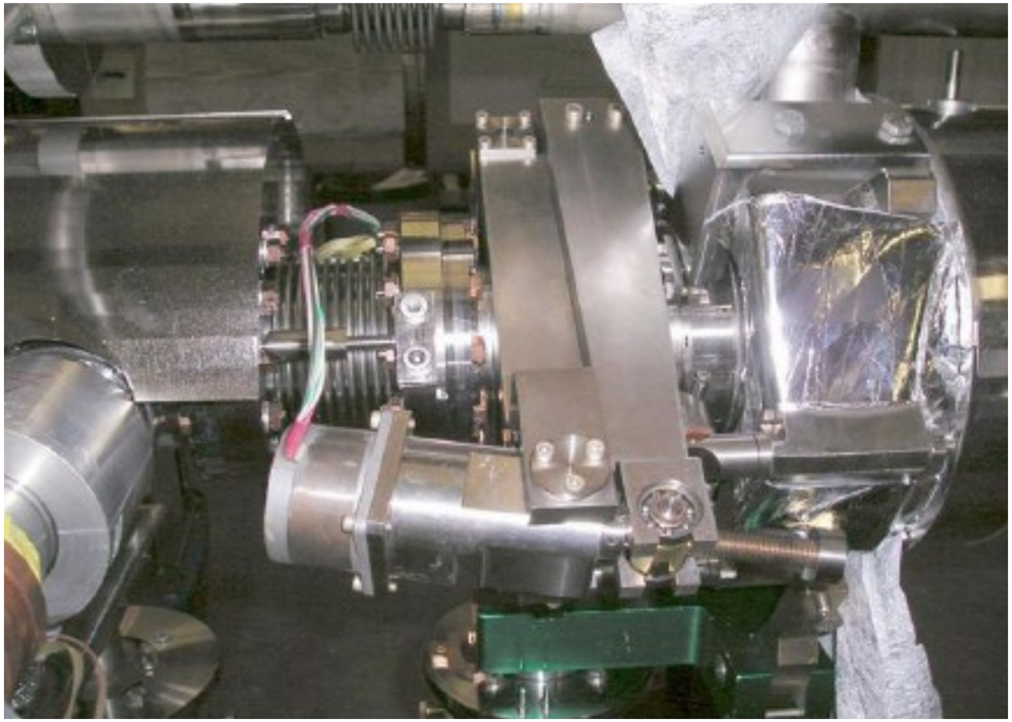
130MeV 500MeV 2GeV 17.5GeV

1700 m

- A1, A2, … A25 – double piezos, in total 776 cavities with double piezos (PI)
- AH1 – no piezos

TESLA Cavity Tuning

The slow tuner is used for pretuning. It might work at LHe temperature. It allows moving the cavity by ±5 mm, which corresponds to frequency shift of ±2.6 MHz. The theoretical resolution of stepper motor is 1.5 nm for one step.

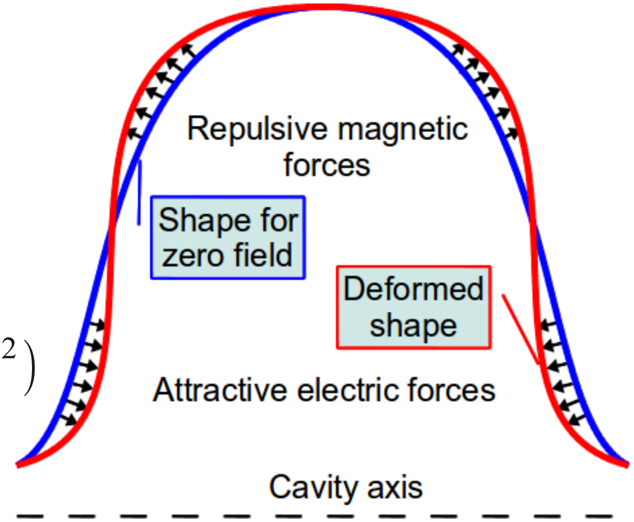


Application of piezo tuners at SRF cavities

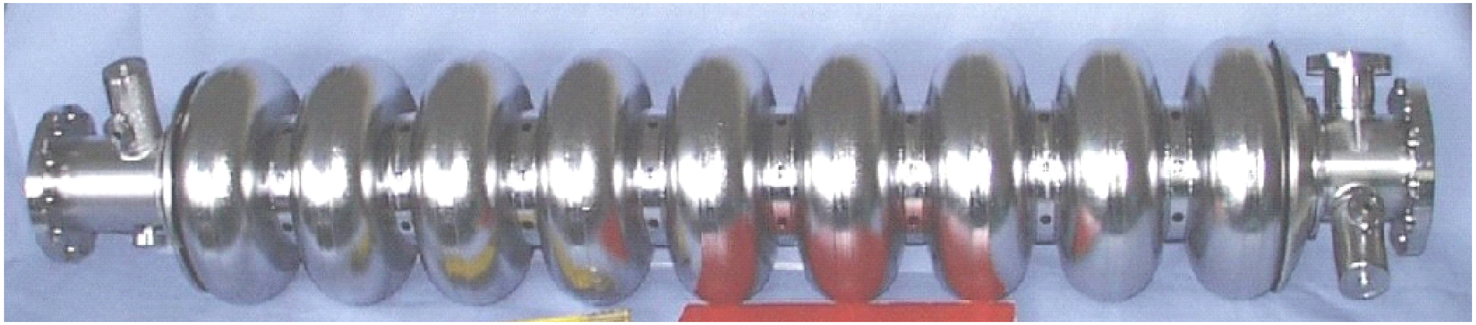
- Compensation for Lorentz Force Detuning (LFD)

$$P_s = \frac{1}{4}\left(\mu|\vec{H}|^2 - \varepsilon_0|\vec{E}|^2\right)$$

$$\hat{\Delta} f_0 = -K\,E_{acc}^2$$



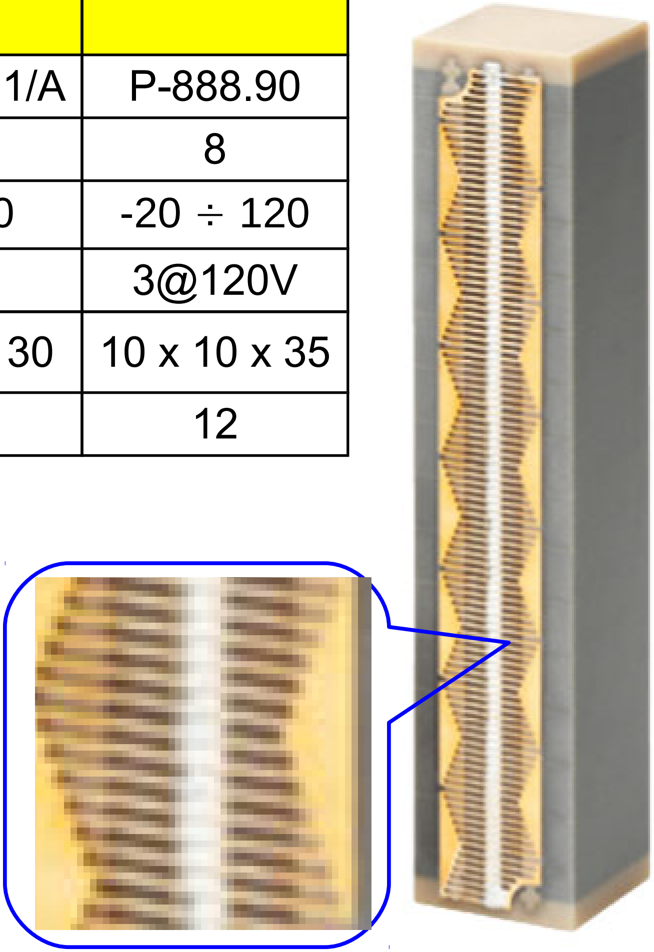
- Cavity fine tuning (±70V → ~600Hz)
- Microphonics measurements and compensation



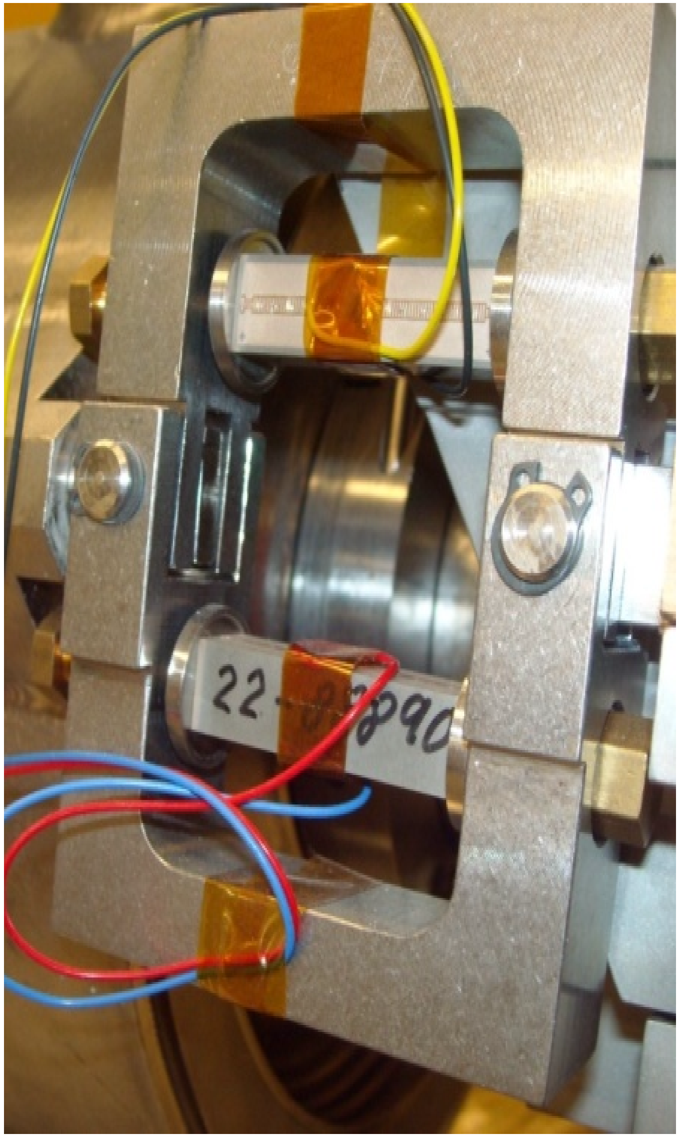
Piezo's at FLASH at XFEL

Manufacturer ratings	Noliac	PI Ceramics
Model	SCMAS/S1/A	P-888.90
Cells	8	8
Voltage range [V]	0 ÷ 200	-20 ÷ 120
Blocking Force [kN]	6	3@120V
Size [mm^3]	10 x 10 x 30	10 x 10 x 35
Capacitance [uF]	6	12

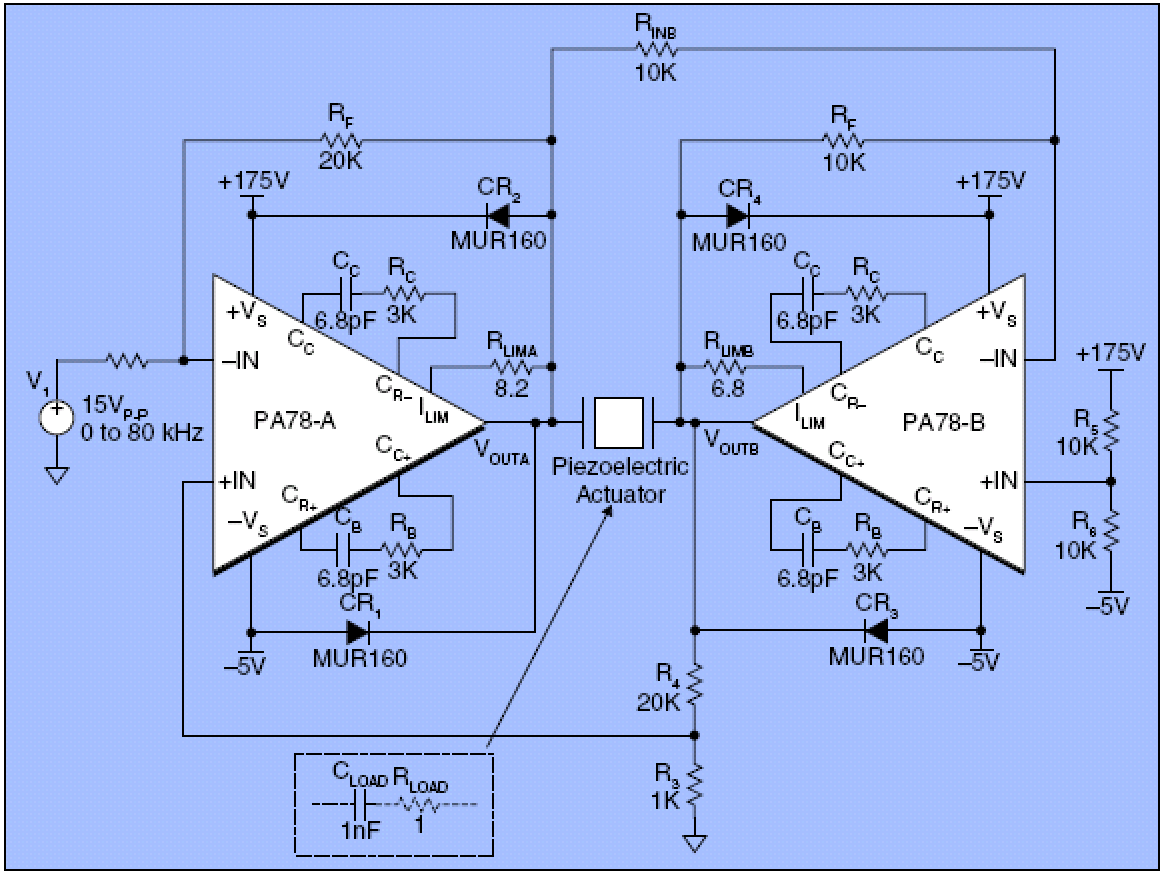
Manufacturer: **NOLIAC**
Dimensions: **10x10x30mm**



Manufacturer: **PI**
Dimensions: **10x10x36mm**

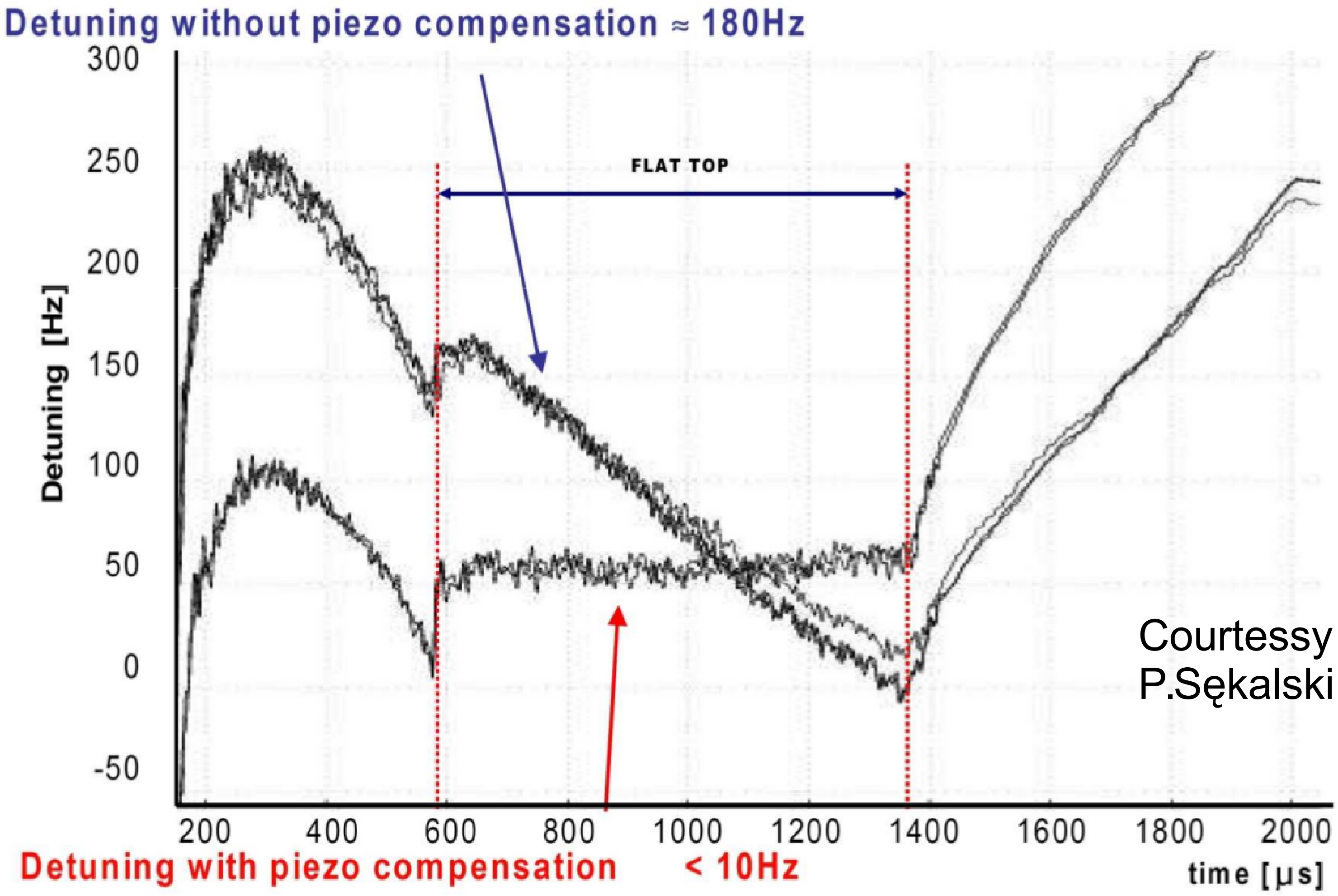


Old Piezo Driver



- designed by Nikolay Ignatian
- “Old” piezo driver used in FLASH
  - based on PA58, full bridge
  - 2 separate amplifiers on single euro PCB
  - low gain (40V/V) not allowing to use SIMCON to drive the piezo amplifier

ACC1 cav.5 LFD compensation (~2004)



Courtessy P.Sękalski

Cavity detuning with and without piezostack-based system measured in cav5, ACC1, FLASH accelerator. The accelerating field gradient is 20MV/m.

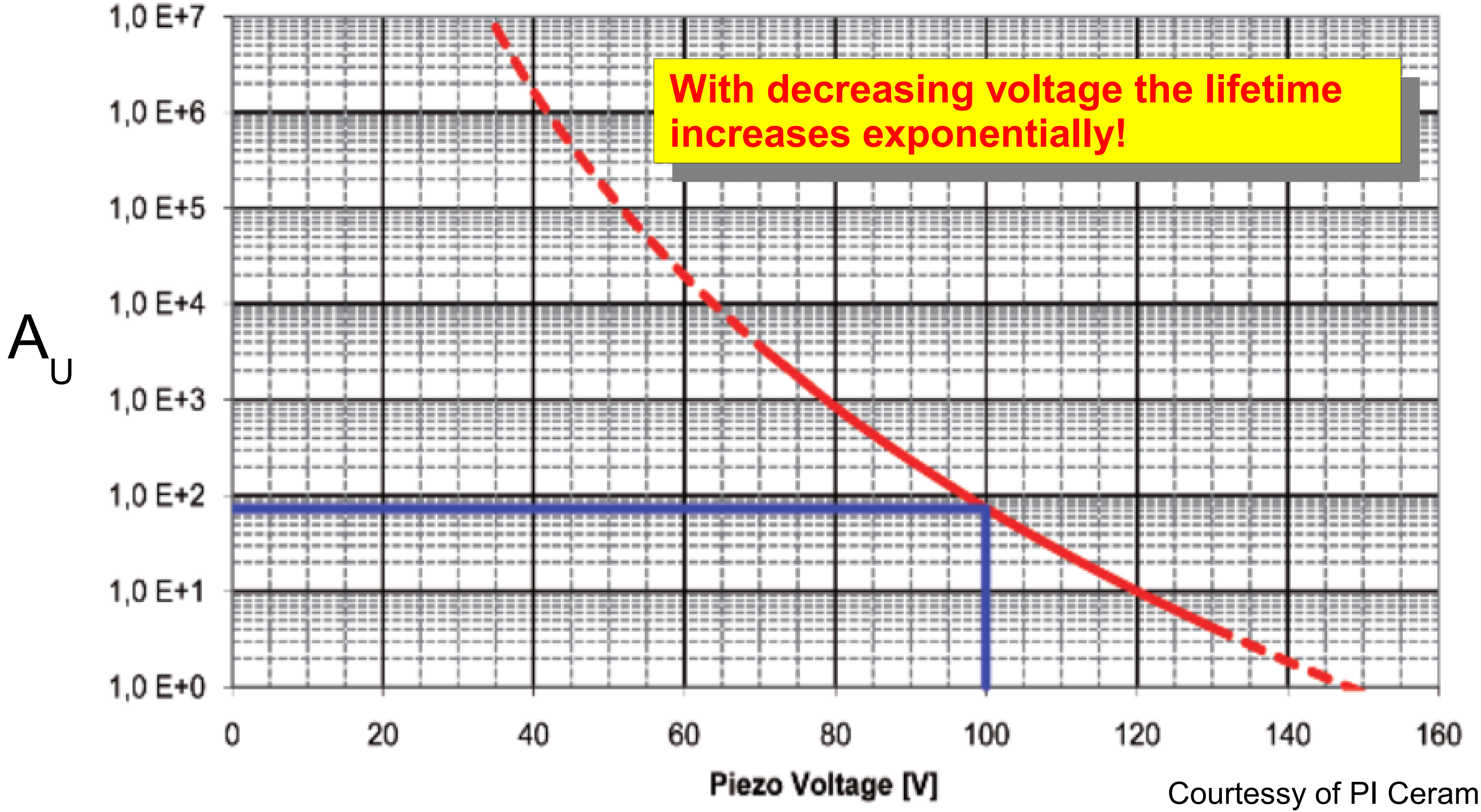
Piezo reliability

MTTF = $A_U * A_T * A_F$

A_U – voltage factor

A_T – temperature factor (constant for cryho conditions)

A_F – humidity factor (constant for cryho conditions)

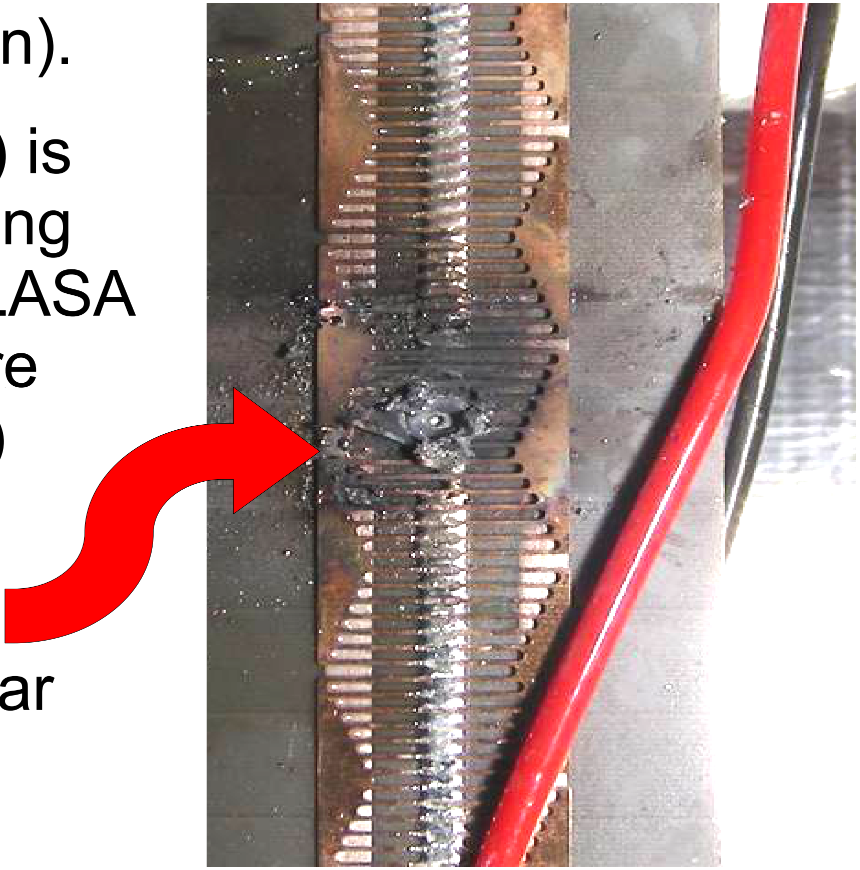


With decreasing voltage the lifetime increases exponentially!

Courtessy of PI Ceramic GmbH

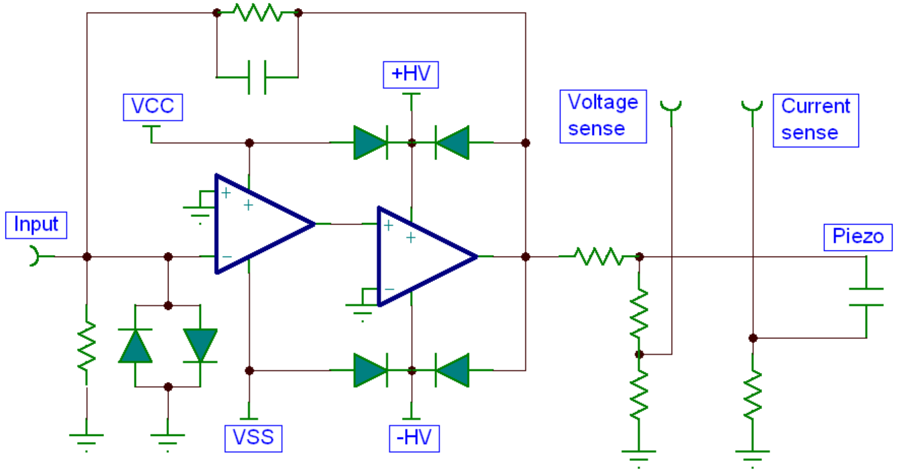
Piezo driving

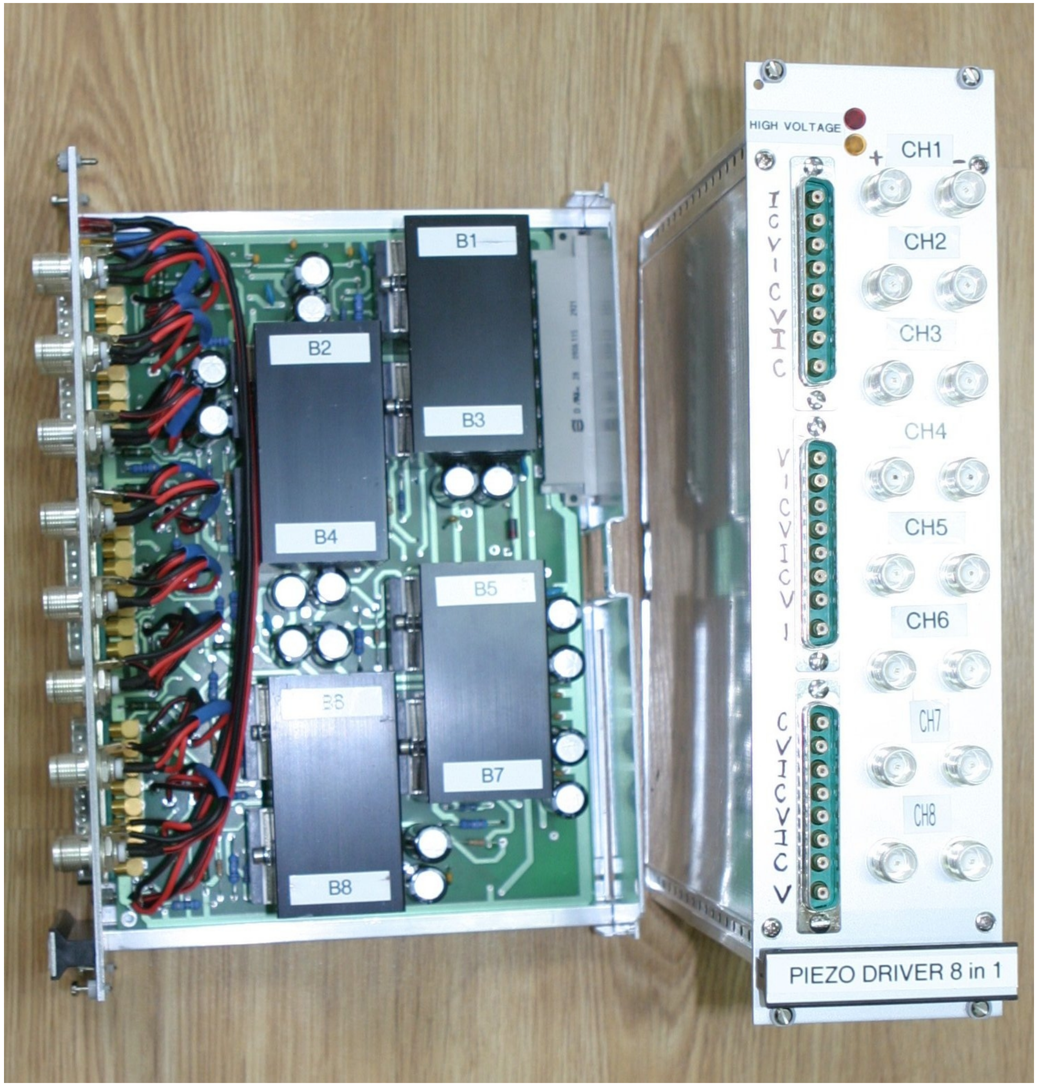
- We need the peak-to-peak voltage for LFD compensation. For unipolar operation the maximum piezo voltage is ~2x higher than for bipolar mode. That reduces reliability.
- At cryo temperature piezos can be driven with bipolar mode (PI engineer opinion).
- Bipolar driving at 77K (liquid nitrogen) is safe for piezos. That was proven in long term experiment performed at INFN LASA Milano (76 days, 3.3e9 pulses → more than 10 years of operation with 10Hz)
- Bipolar driving while piezo is worm is dangerous. Piezo can be broken with relatively low voltage. Therefore bipolar driving must be done together with temperature checkout.



Main parameters of Piezodriver

- Suitable for both types of piezostacks up to 5μF:
  - Physik Instrumente (P-888.90 PIC255); C_{2K}4,4 μF
  - NOLIAC (SCMAS/S1/A/10/10/20); C_{2K} 2,4 μF
- Maximal supply voltage up to ± 150 V (nominal operating voltage ±80V)
- Input voltage ± 1 V, amplifier gain Gu= 100V/V,
- Operational temperature Tc < 75°C (Tj <125 °C)
- Pass-band frequency up to 1 kHz (for load 5μF)
- Monitoring of output voltage and current
- Single channel PZD with Apex PB51
- 8 channels on single board

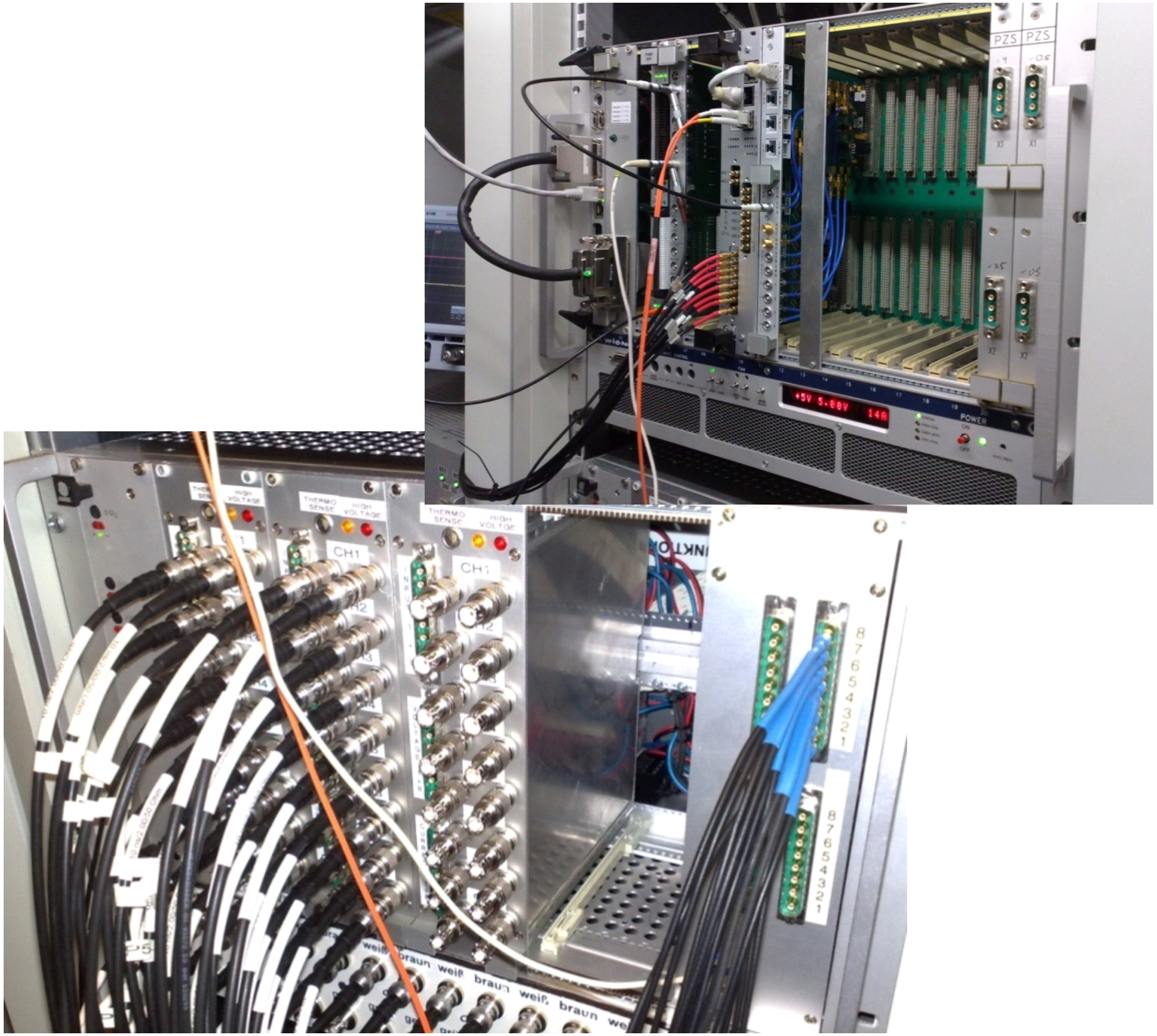


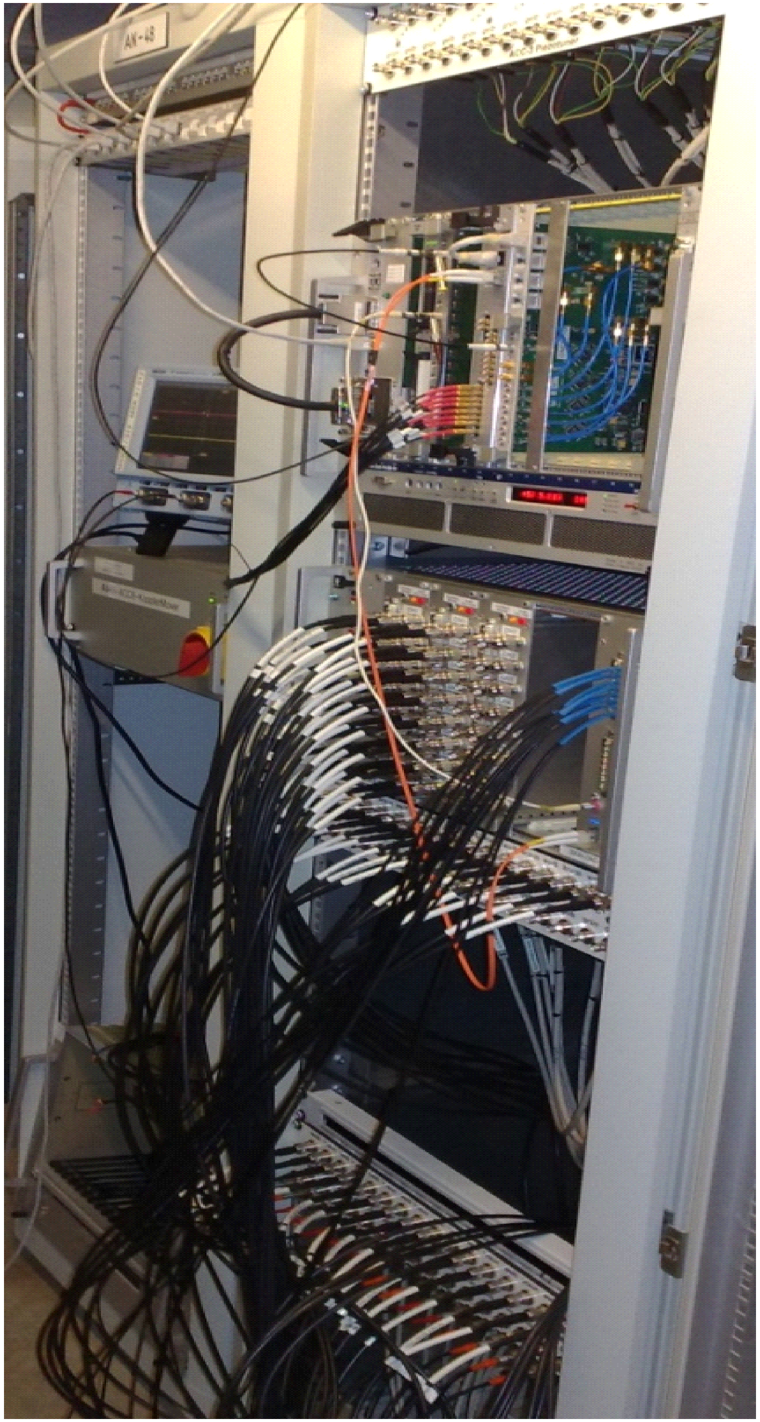


Piezo driver of class D

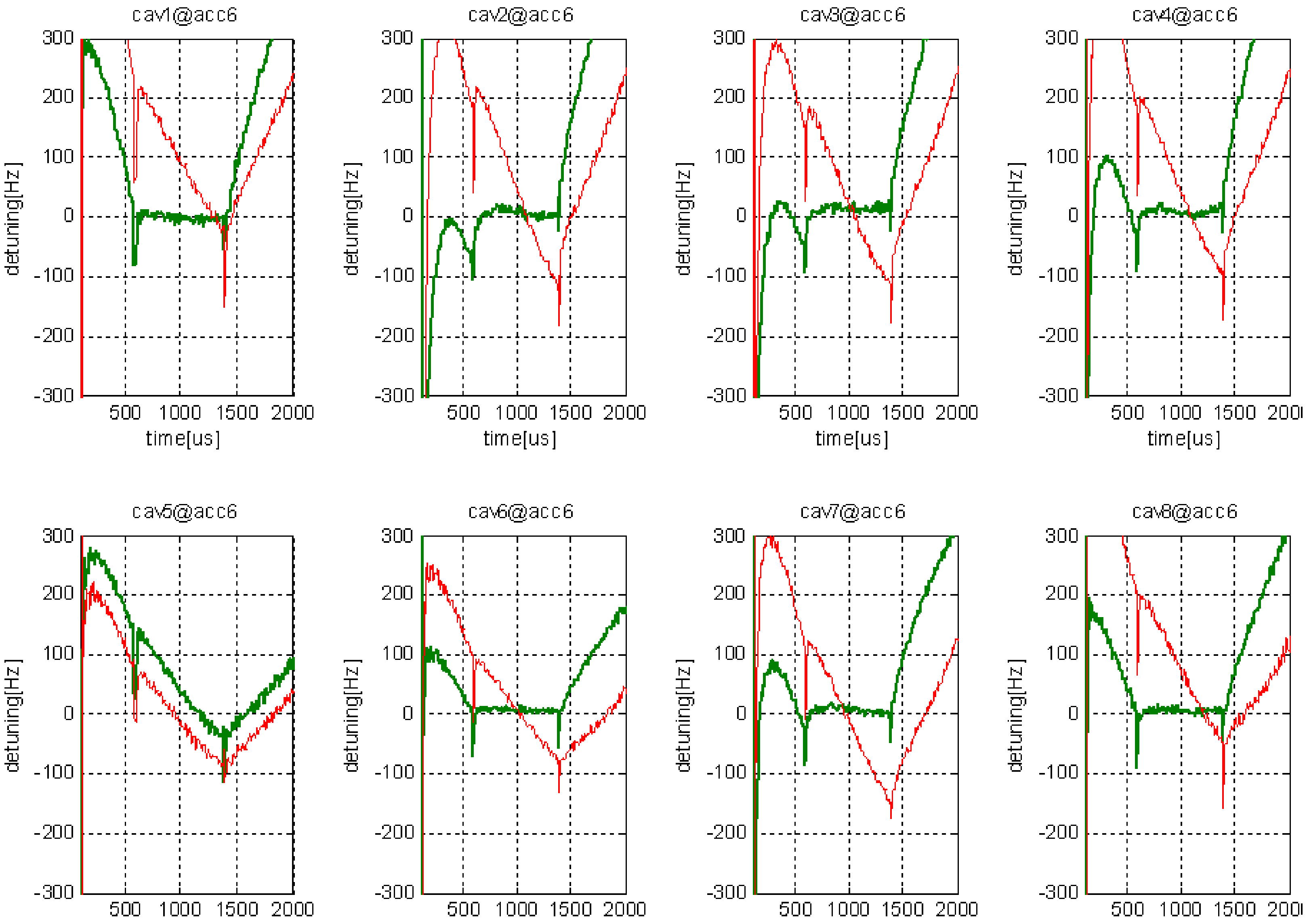
- To reduce power losses (and thus reduce heatsinks) – higher assembling density
- APEX SA50CE as a candidate
- Possible EMC interaction with other system components
- Tested in 2009
  - output filter is critical part (it is huge for good filtering)
  - power dissipation comparable to analogue driver, in reality no gain in power consumption

Piezo Control at ACC3,5,6,7



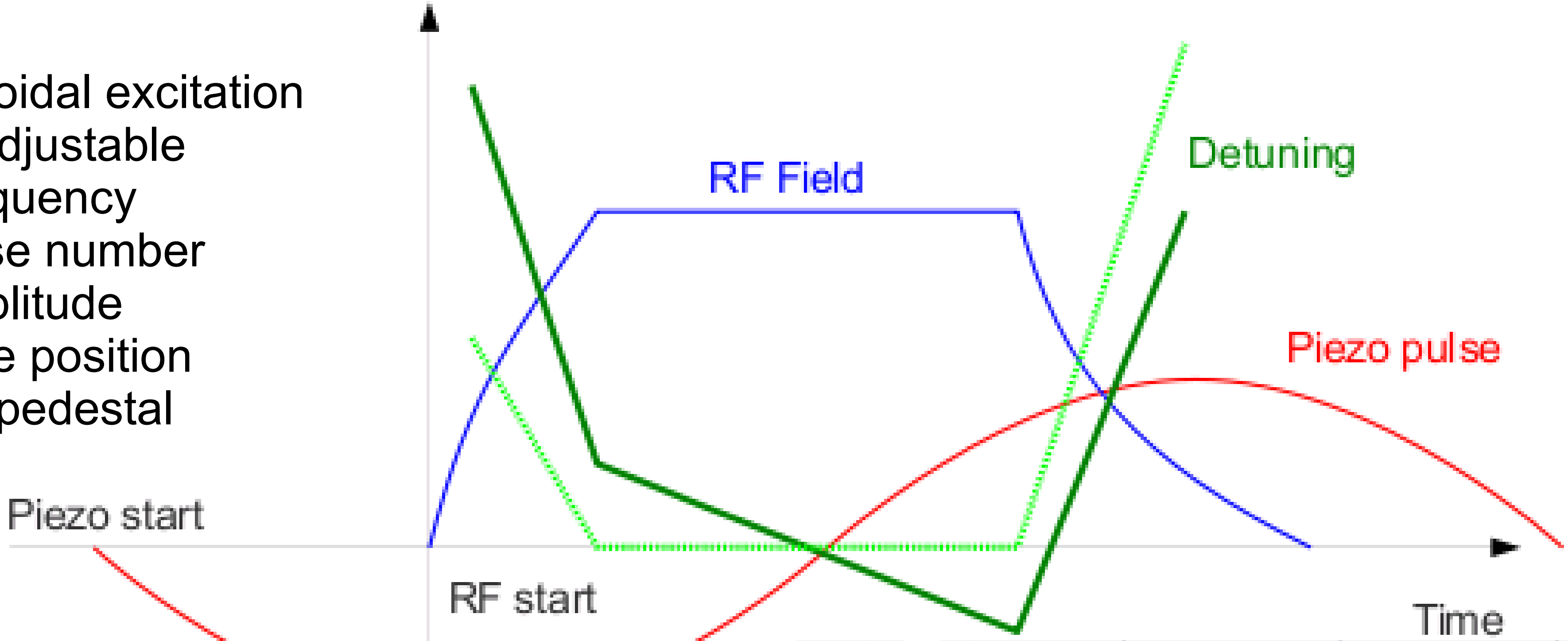


ACC6 (SP = 20 MV/m, rep = 5 Hz)



Piezo control for LFD compensation

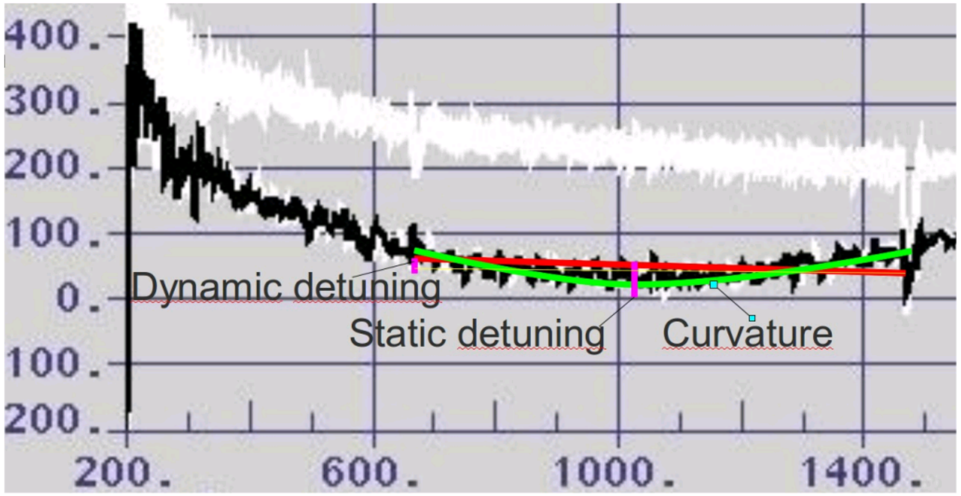
Sinusoidal excitation with adjustable
- Frequency
- Pulse number
- Amplitude
- Time position
- DC pedestal



Amplitude → dynamic detuning

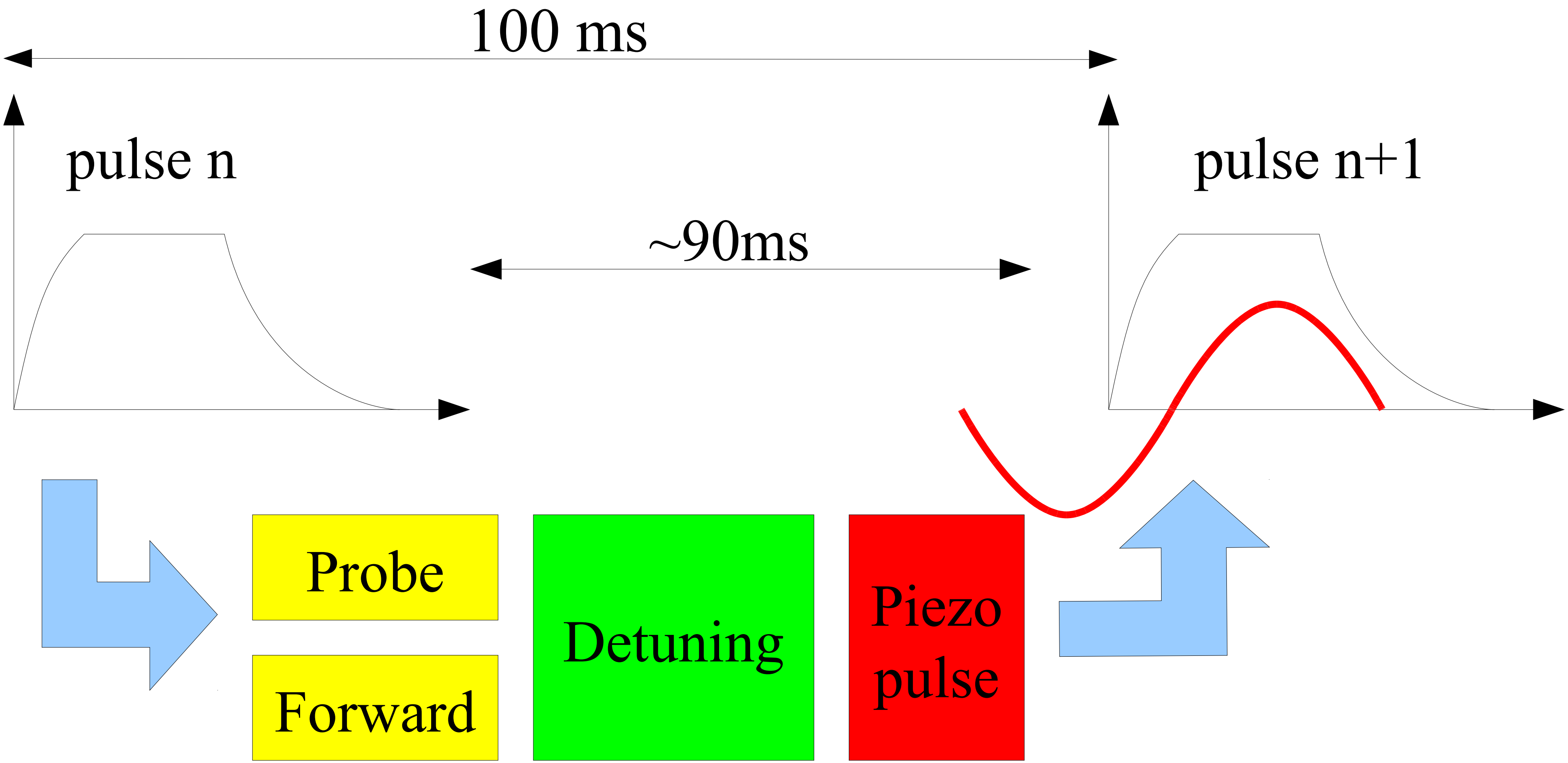
DC pedestal → static detuning

Time position → curvature



Lorentz force detuning

Piezo control algorithm (adaptive FF)



100 ms

pulse n

~90ms

pulse n+1

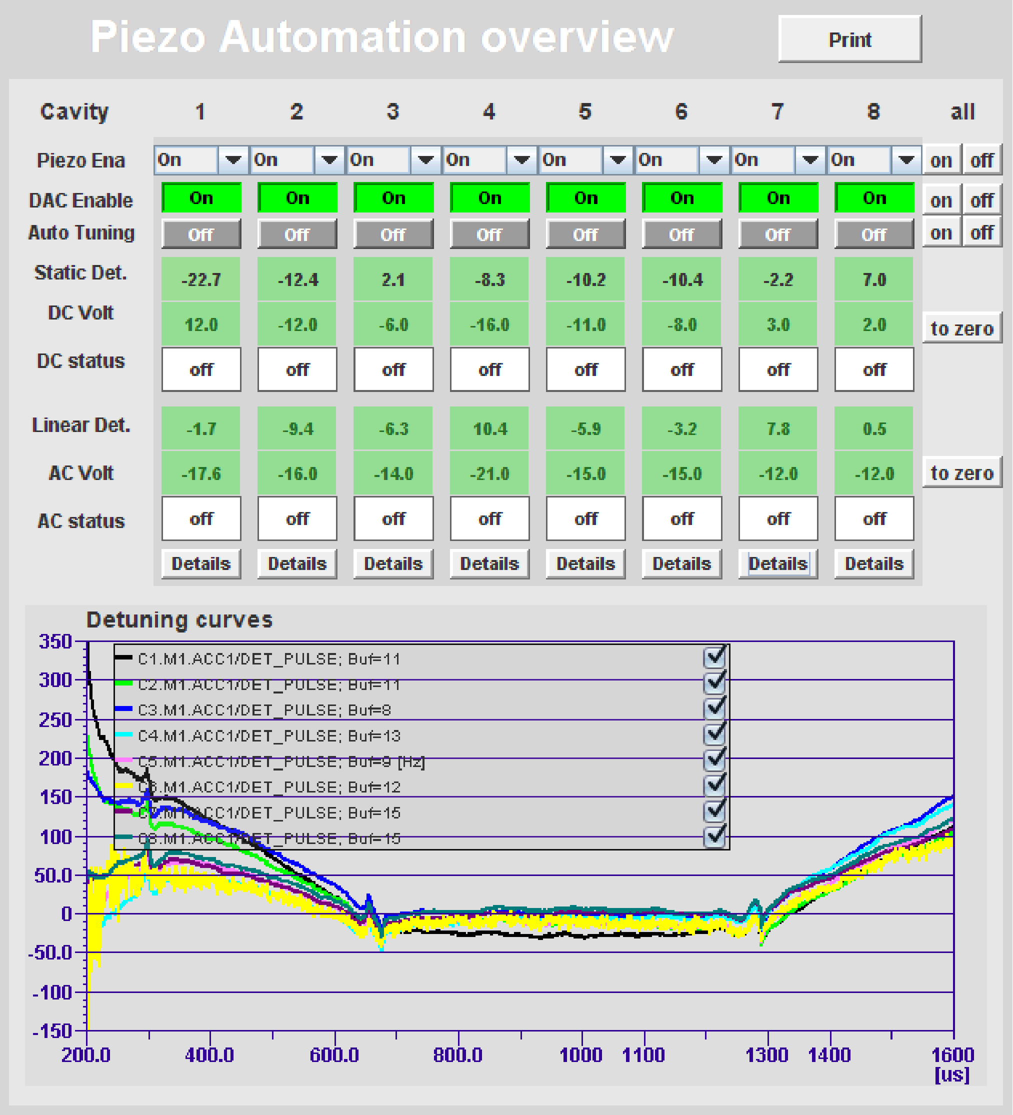
Probe

Forward

Detuning

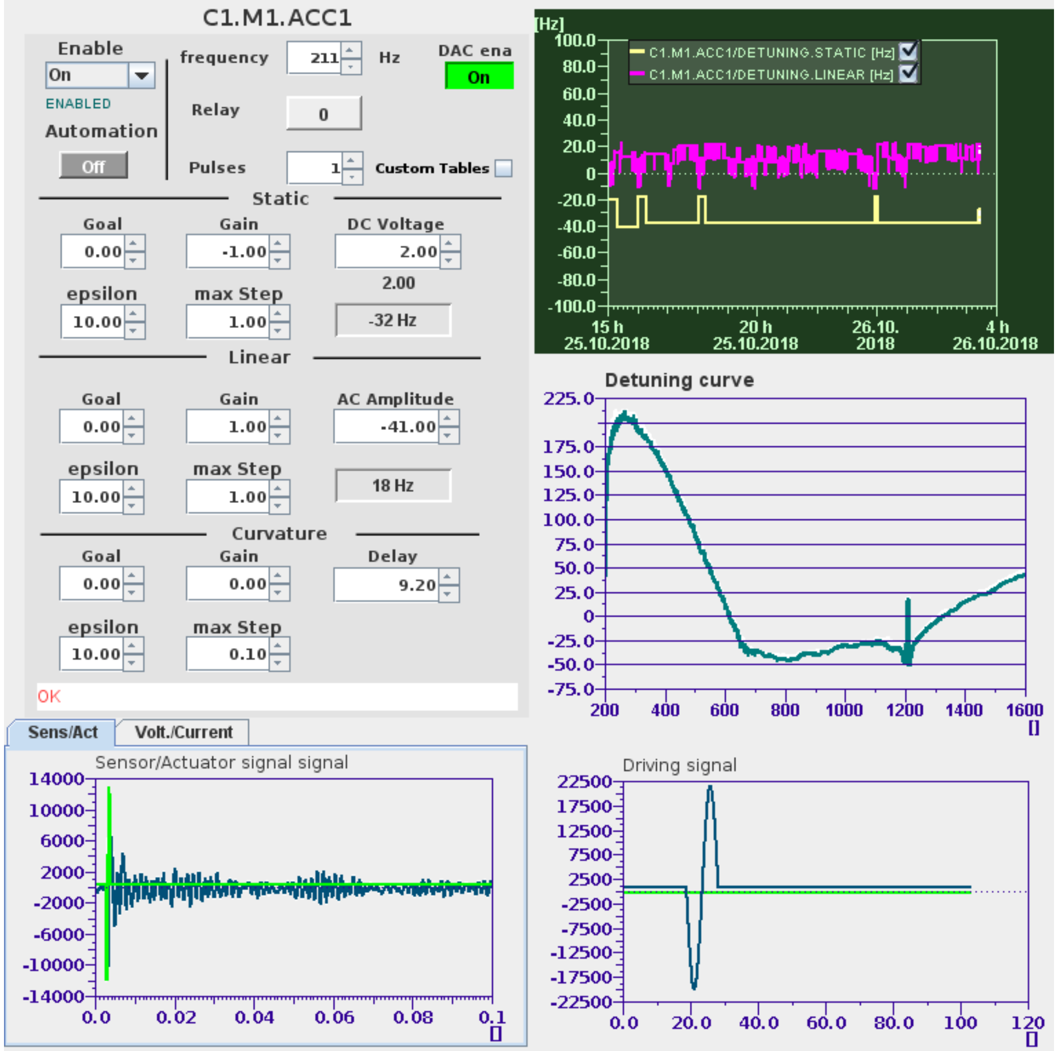
Piezo pulse

Piezo control panels (FLASH)



Cavity	1	2	3	4	5	6	7	8	all
Piezo Ena	On	On	On	On	On	On	On	On	on off
DAC Enable	On	On	On	On	On	On	On	On	on off
Auto Tuning	Off	Off	Off	Off	Off	Off	Off	Off	on off
Static Det.	-22.7	-12.4	2.1	-8.3	-10.2	-10.4	-2.2	7.0	
DC Volt	12.0	-12.0	-6.0	-16.0	-11.0	-8.0	3.0	2.0	to zero
DC status	off	off	off	off	off	off	off	off	
Linear Det.	-1.7	-9.4	-6.3	10.4	-5.9	-3.2	7.8	0.5	
AC Volt	-17.6	-16.0	-14.0	-21.0	-15.0	-15.0	-12.0	-12.0	to zero
AC status	off	off	off	off	off	off	off	off	
	Details	Details	Details	Details	Details	Details	Details	Details	

Detuning curves



C1.M1.ACC1

Enable: On
ENABLED
Automation: Off
frequency: 211 Hz
Relay: 0
Pulses: 1
Custom Tables ☐
DAC ena: On

Static
Goal: 0.00
Gain: -1.00
DC Voltage: 2.00
2.00
epsilon: 10.00
max Step: 1.00
-32 Hz

Linear
Goal: 0.00
Gain: 1.00
AC Amplitude: -41.00
epsilon: 10.00
max Step: 1.00
18 Hz

Curvature
Goal: 0.00
Gain: 0.00
Delay: 9.20
epsilon: 10.00
max Step: 0.10

OK

LLRF Control System for XFEL (ATCA based)

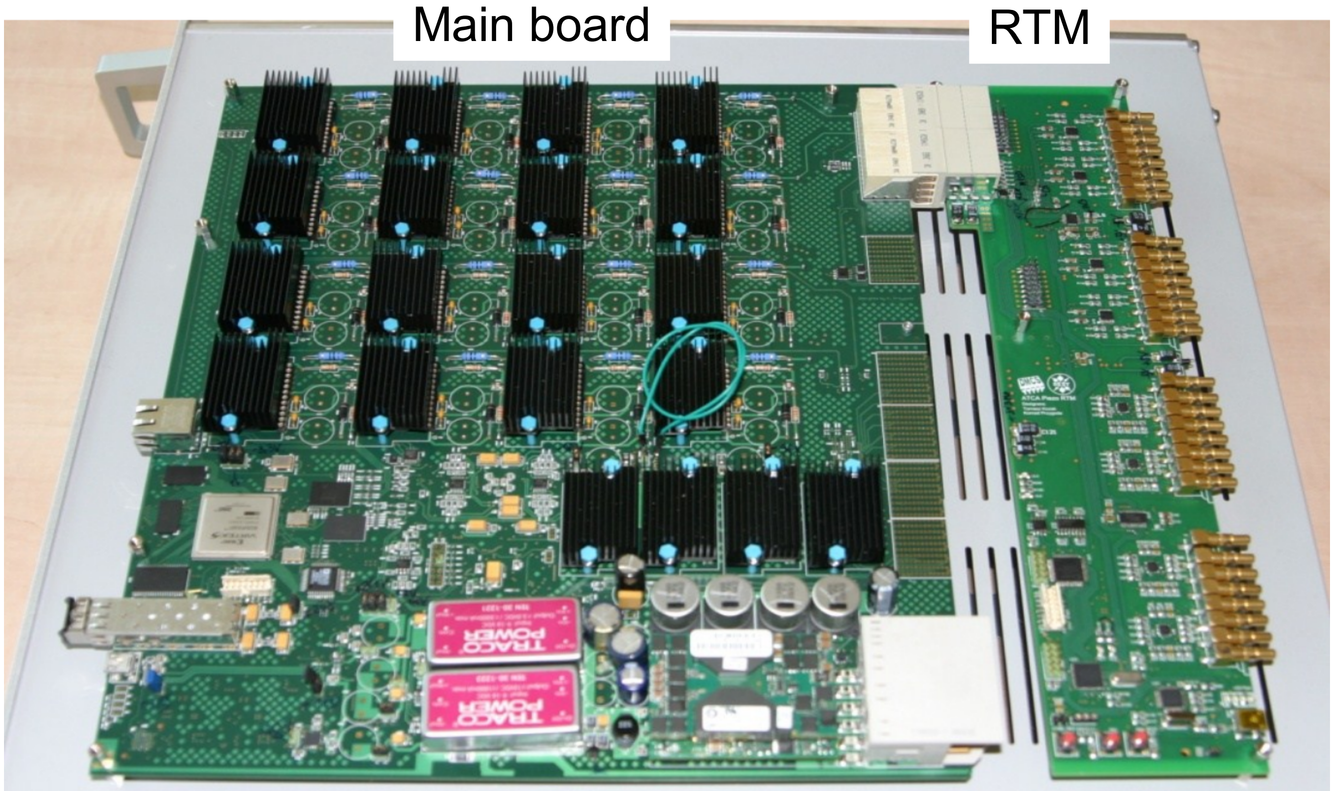
front side

rear side

Piezo Control PCB (ATCA based)

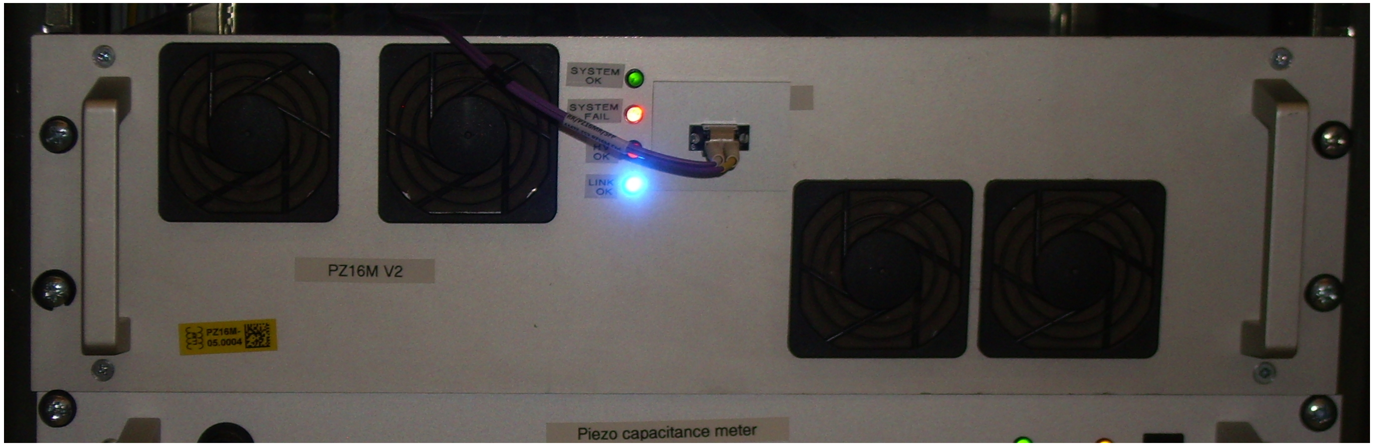
Basic piezo driver parameters:

- 16 channels (due to LLRF system architecture)
- Maximal output voltage range +-70V
- Operational temperature of the power amplifier Tc < 75°C (Tj <125 °C)
- Pass-band frequency up to 1 kHz (for load 5μF)
- DAC/ADC sampling rate at least 20kHz
- Monitoring of output voltage and current
- Up to 4 periods of sinus wave 70V, 200 Hz in 5μF load, 10 Hz repetition rate (thermal limit)



Piezo Control System for MTCA (19 inch module)

- essentially copied project for the ATCA crate
- power supply adjusted (input AC 230V instead of DC 48V)
- communication through external fiber link instead of backplane links
- first modules installed at FLASH after FLASH LLRF upgrade to MTCA (2013)



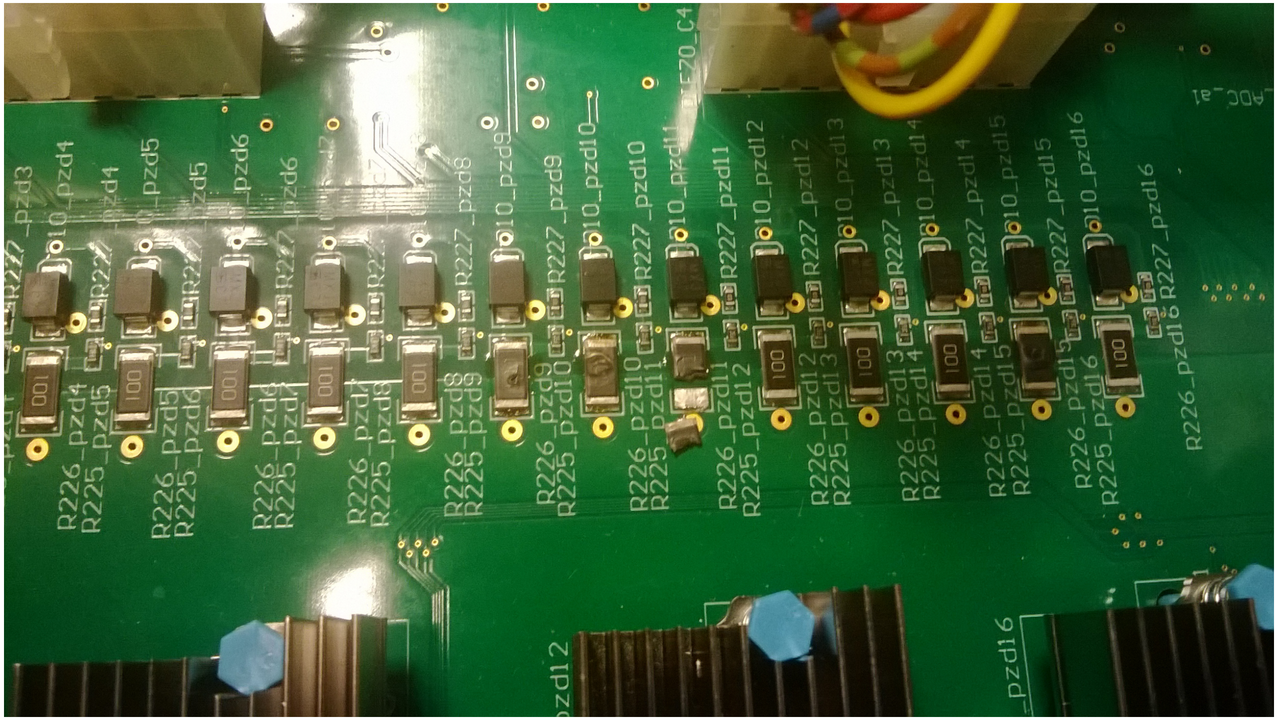
Piezo events at FLASH

- ~2005 (ACC1 cav. 5 piezo died)
  - not clear what really happened, after investigation the cabling was blamed – high self-inductance of the long cables)
- November 21 2010 (ACC7 cav.1 actuator died)
  - during scan of the static detuning versus DC offset voltage applied to the piezo. The range of the voltage applied to the piezo was changed from maximum negative (-70V) voltage up to maximum positive (+70V) voltage with single step of 5 V and then the whole process repeated with single transition from +70V to -70V
- Sometime in 2011 (ACC3 cav.1 actuator died)
  - Not clear how it happened and when. Problem noticed after event.
- October 29 2013 (ACC7 cav.2 sensor and cav.3 actuator died)
  - During the firmware update at PZ16M and uTC at ACC67 on 29.10.2013 the erroneous behavior of PZ16 was observed that destroyed two piezos and also piezo driver.

Understanding the October 29 2013 event (1)

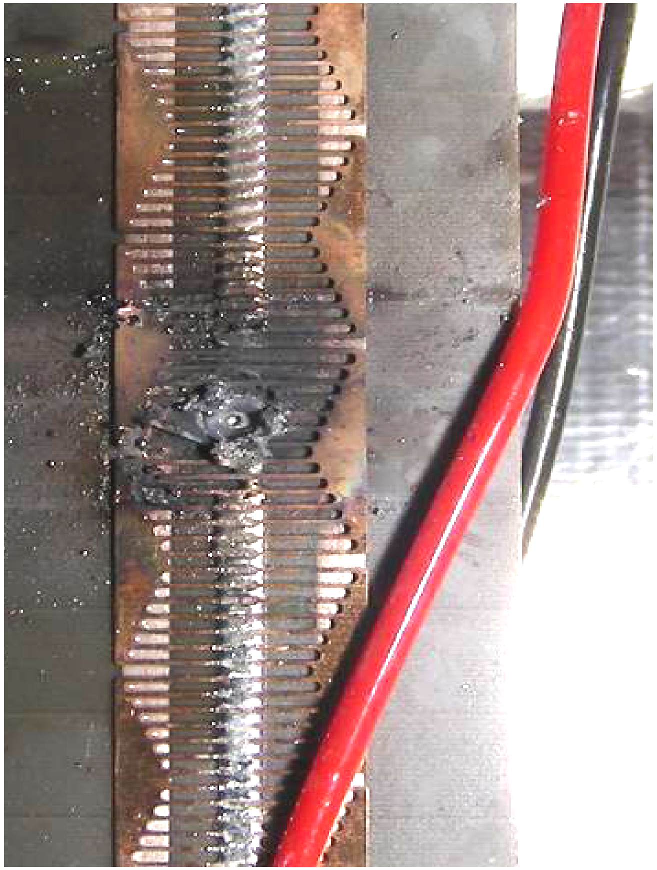
During the firmware update at PZ16M and uTC at ACC67 on 29.10.2013 the erroneous behavior of PZ16 was observed. The uTC generated random data bitstream that was driving the DAC and output switching relays. After some time (at least 30s, but it could be also few minutes – it was time needed to recognize something is wrong, removing the box upper cover, recognizing the relays clicking, etc.) the piezo control system was turned-off. Up to this time the relays clicks was heard and also a smell of burning components was felt.

During the event the DAC output was set to the random voltage levels with sampling frequency of 3.125kHz. Rough estimation of the average current for random data sent leads to ~0.92A for current limit 1.5A. The high value of the output current is confirmed by destroyed resistors at the output of the piezo driver and by the destroyed piezo driver in one channel. The dissipated power was 9.2W and 78W at the output resistors (10Ω) and power driver respectively.



Understanding the October 29 2013 event (2)

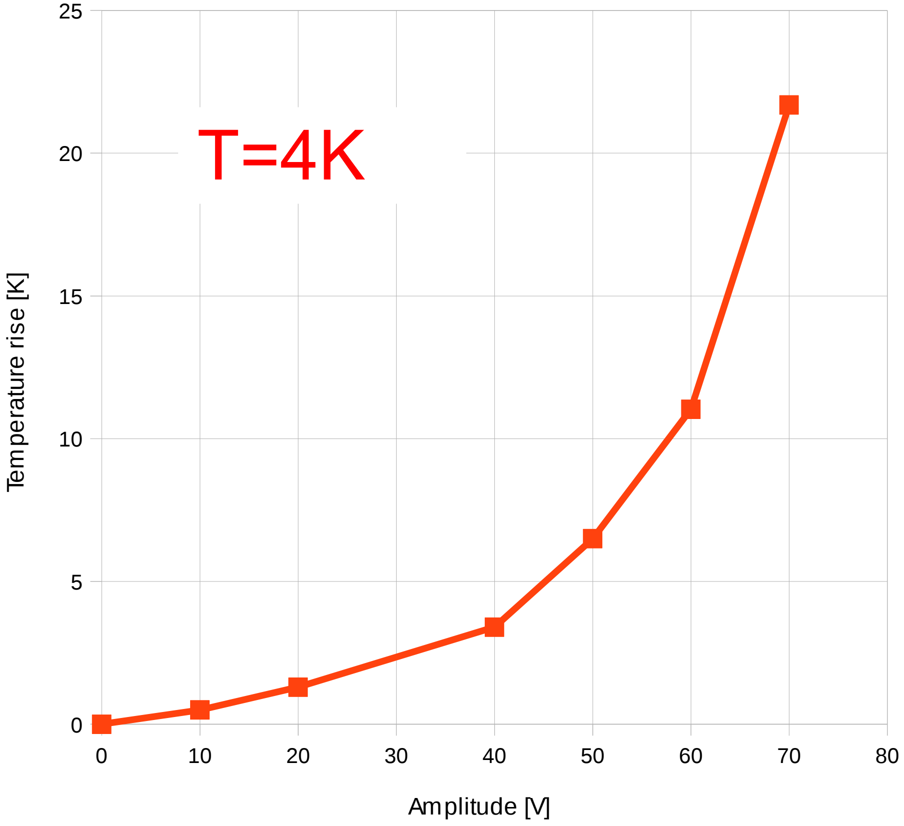
The expected heat dissipation at piezo can be estimated from Q vs. V characteristics (available for 77K only). For the full recharge cycle (+-70V) the dissipated heat is ~30mJ. Therefore one can estimate the average heat dissipation at piezo for 0.92A to ~18.4W. Since the relays were also randomly switching piezos the current and power dissipation were distributed between both piezos and therefore for single piezo the average current and heat power should be divided by 2. Anyway, ~9W dissipated at piezo for several tens of seconds with very limited heat transfer to the ambient (only through support) heats up the piezo (in particular the middle part) by several tens of degrees. As the destructive test has proven, warming up the piezo to 120K is dangerous. Applying reverse bias in such condition may lead to voltage breakout of the ceramics and to discharging of contiguous electrodes causing a significant metal sputtering and thus short-circuiting the piezo.

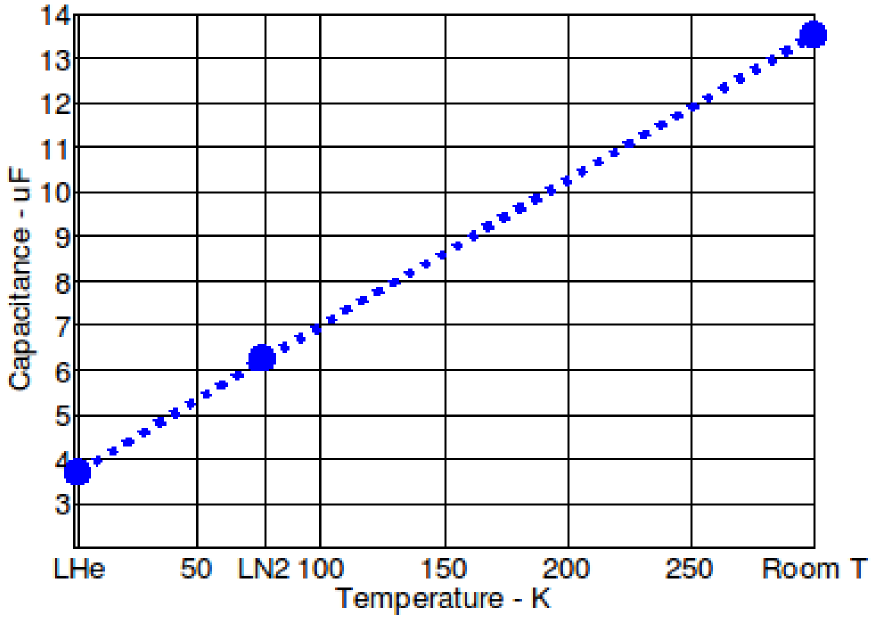


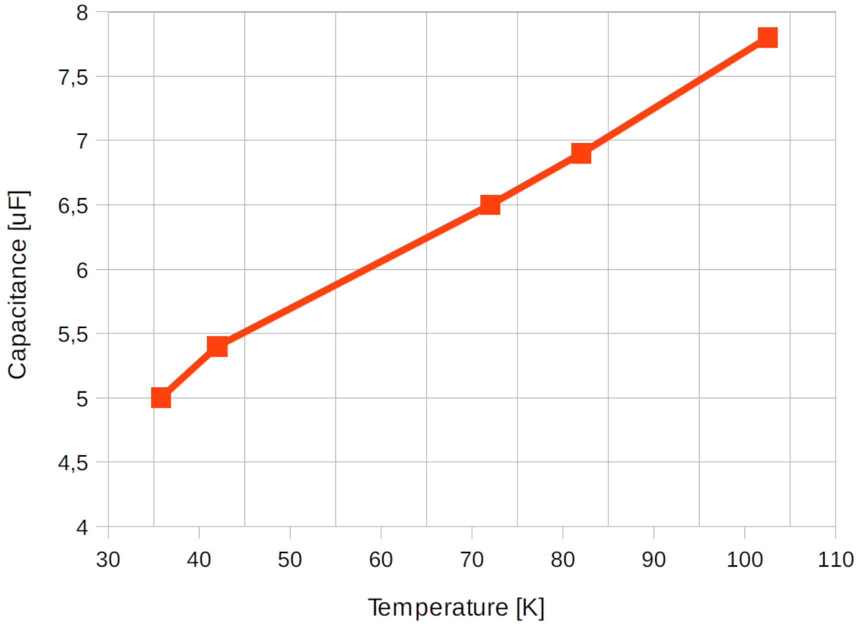
Decisions made after 2013 event

- provide a measures to prevent piezo destruction due to overheating and driving in bipolar mode at high temperature
  - determine the safe temperature range for piezo operation
  - develop the method for measurement of piezo temperature during operation
- equip the piezo driver with hardware solution (no firmware or software!) limiting the energy dissipation at the piezo
- equip the piezo driver with measures against possible hardware failures (piezo operation must be fail-safe)

Piezo thermal properties

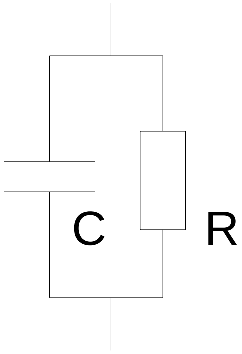






Temperature rise in function of pulse amplitude, single pulse, 10Hz repetition rate

How to measure piezo capacitance?



$$I = I_C + I_R = C\frac{dV}{dt} + \frac{1}{R}V = C\dot{V} + GV \qquad \dot{V} = \frac{dV}{dt}$$

$$I_i - GV_i - C\dot{V}_i = 0$$

$$C = \frac{\left(N\bar{I}\bar{V} - \sum IV\right)\left(N\bar{V}\bar{\dot{V}} - \sum V\dot{V}\right) - \left(N\bar{I}\bar{\dot{V}} - \sum I\dot{V}\right)\left(N\bar{V}\bar{V} - \sum V^2\right)}{\left(N\bar{V}\bar{\dot{V}} - \sum V\dot{V}\right)^2 - \left(N\bar{V}\bar{\dot{V}} - \sum \dot{V}^2\right)\left(N\bar{V}^2 - \sum V^2\right)} t_{sampl}$$

$$G = \frac{1}{R} = \frac{\left(N\bar{V}\bar{\dot{V}} - \sum V\dot{V}\right)\left(N\bar{I}\bar{\dot{V}} - \sum I\dot{V}\right) - \left(N\bar{V}\bar{\dot{V}} - \sum \dot{V}^2\right)\left(N\bar{I}\bar{V} - \sum IV\right)}{\left(N\bar{V}\bar{\dot{V}} - \sum V\dot{V}\right)^2 - \left(N\bar{V}\bar{\dot{V}} - \sum \dot{V}^2\right)\left(N\bar{V}^2 - \sum V^2\right)}$$

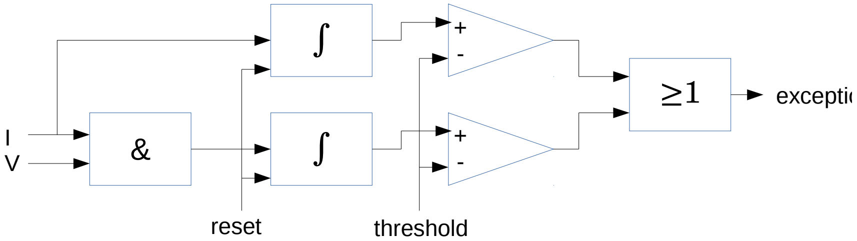
$$\bar{V} = \frac{1}{N}\sum V \qquad \bar{I} = \frac{1}{N}\sum I \qquad \bar{\dot{V}} = \frac{1}{N}\sum \dot{V}$$

and N – number of samples

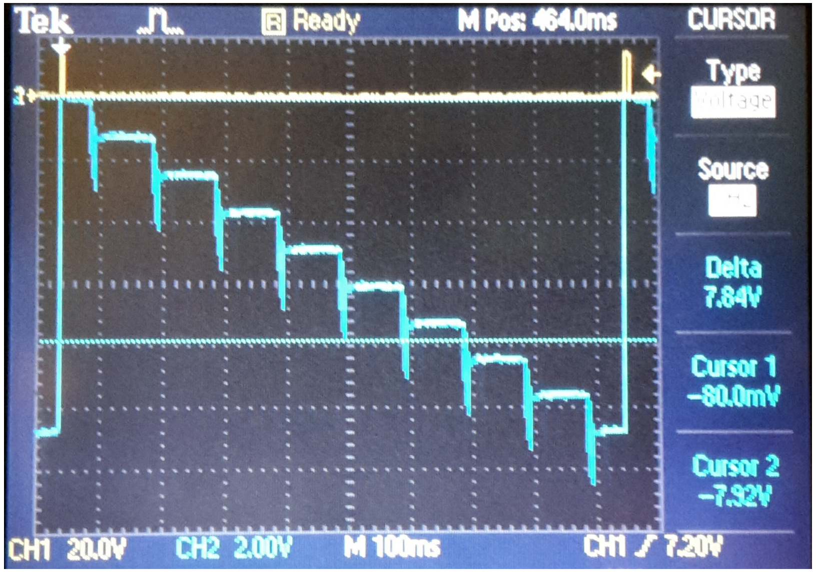
If ADC's offsets are negligible:

$$C = \frac{\sum V_i^2 \sum \dot{V}_i I_i - \sum V_i \dot{V}_i \sum V_i I_i}{\sum V_i^2 \sum \dot{V}_i^2 - \left(\sum V_i \dot{V}_i\right)^2} \qquad G = \frac{1}{R} = \frac{\sum V_i I_i \sum \dot{V}_i^2 - \sum \dot{V}_i I_i \sum V_i \dot{V}_i}{\sum V_i^2 \sum \dot{V}_i^2 - \left(\sum V_i \dot{V}_i\right)^2}$$

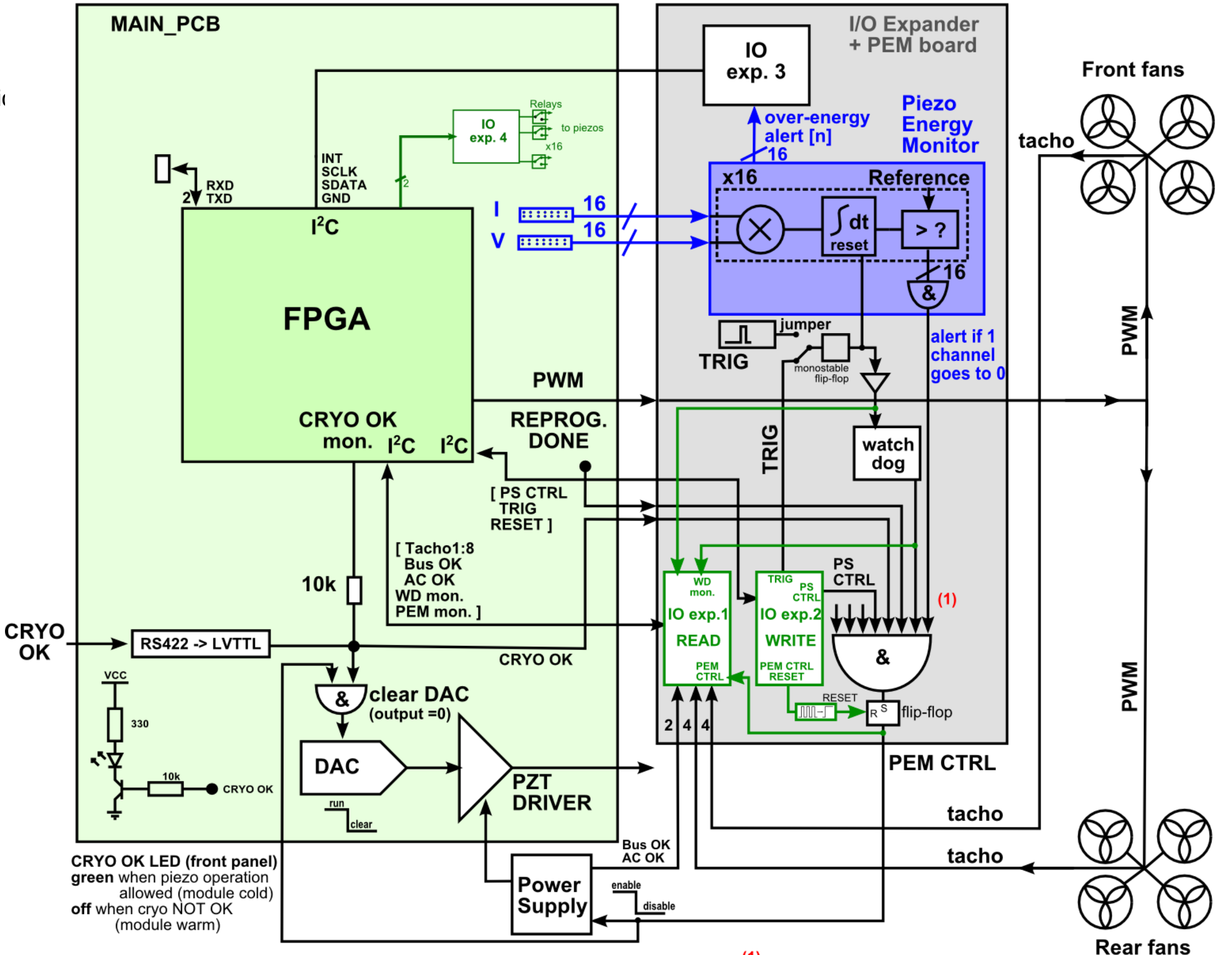
PEM (Power and Energy Monitor)



PEM block diagram



PEM – energy integration

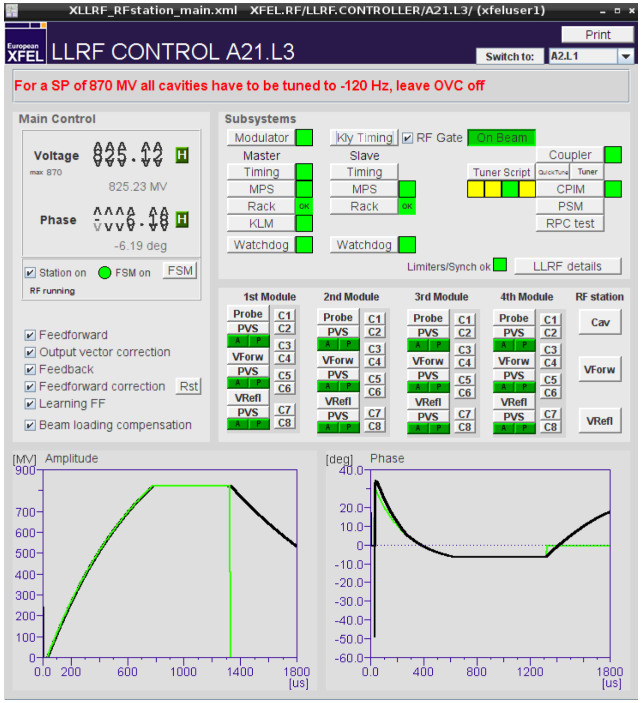


CRYO OK LED (front panel)
green when piezo operation allowed (module cold)
off when cryo NOT OK (module warm)

(1) all inputs should be equipped with by-pass pull-up pull-down resistors

PEM operation logic (simplified)

PZ16M installed at XFEL


XLLRF_RFstation_main.xml XFEL.RF/LLRF.CONTROLLER/A21.L3/ (xfeluser1)

LLRF CONTROL A21.L3

Switch to: A2.L1

For a SP of 870 MV all cavities have to be tuned to -120 Hz, leave OVC off

Main Control

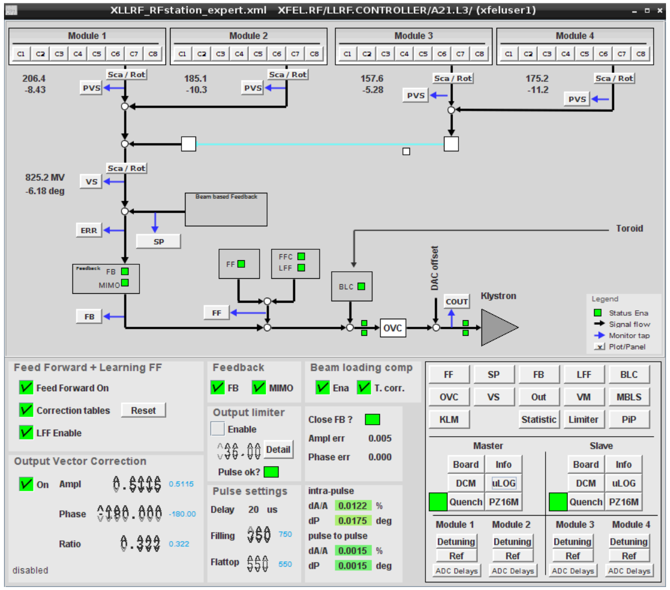
Voltage 825.23 MV, max 870

Phase -6.19 deg

☑ Station on ● FSM on

RF running

☑ Feedforward
☑ Output vector correction
☑ Feedback
☑ Feedforward correction
☑ Learning FF
☑ Beam loading compensation


XLLRF_RFstation_expert.xml XFEL.RF/LLRF.CONTROLLER/A21.L3/ (xfeluser1)

Feed Forward + Learning FF: ☑ Feed Forward On, ☑ Correction tables, ☑ LFF Enable

Output Vector Correction: ☑ On, Ampl 0.5115, Phase -180.00, Ratio 0.322

disabled

Feedback: ☑ FB ☑ MIMO

Output limiter: ☐ Enable

Pulse ok?

Pulse settings: Delay 20 us, Filling 750, Flattop 550

Beam loading comp: ☑ Ena ☑ T. corr.

Close FB ?

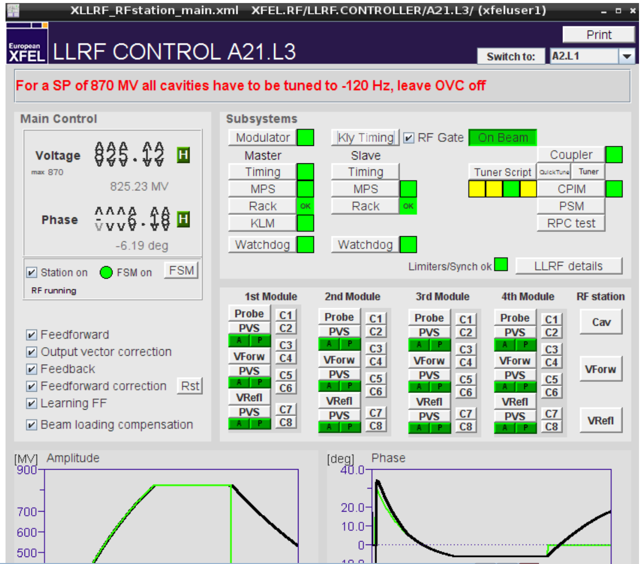
Ampl err 0.005

Phase err 0.000

intra-pulse: dA/A 0.0122 %, dP 0.0175 deg

pulse to pulse: dA/A 0.0015 %, dP 0.0015 deg

PZ16M installed at XFEL



XLLRF_RFstation_main.xml XFEL.RF/LLRF.CONTROLLER/A21.L3/ (xfeluser1)

LLRF CONTROL A21.L3

For a SP of 870 MV all cavities have to be tuned to -120 Hz, leave OVC off

Main Control

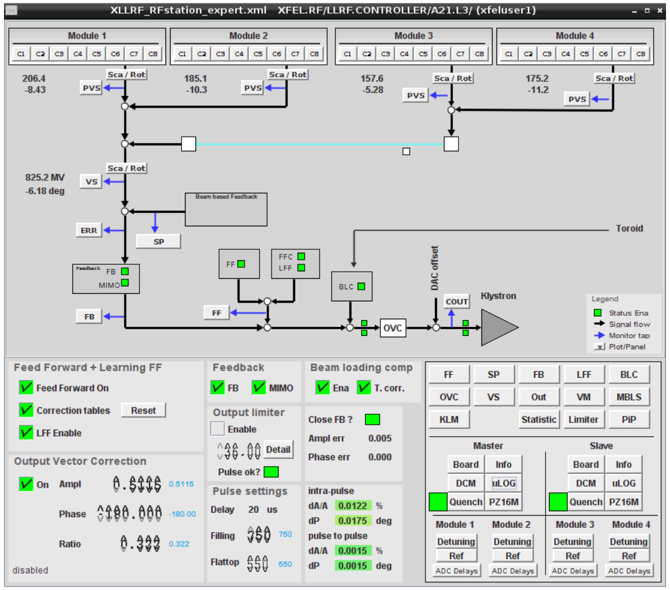
Voltage 825.23 MV

Phase -6.19 deg

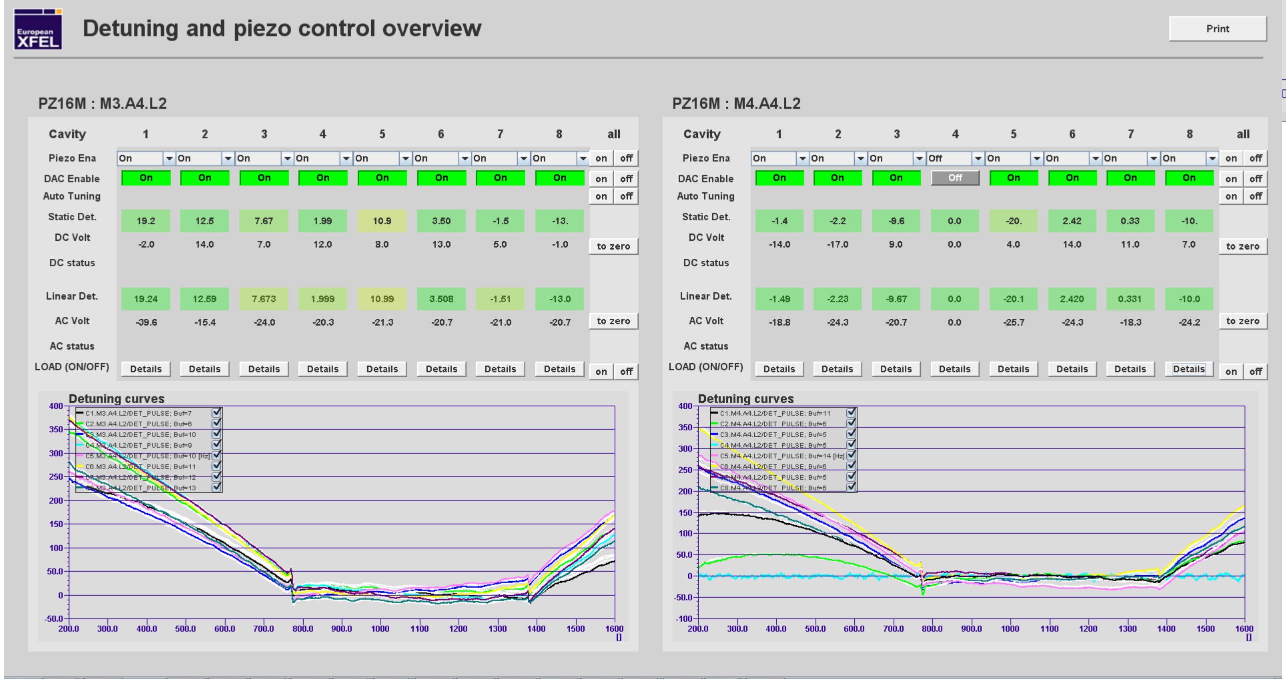
☑ Station on ● FSM on

RF running

☑ Feedforward
☑ Output vector correction
☑ Feedback
☑ Feedforward correction
☑ Learning FF
☑ Beam loading compensation



XLLRF_RFstation_expert.xml XFEL.RF/LLRF.CONTROLLER/A21.L3/ (xfeluser1)



XLLRF_piezo_station_view.xml XFEL.RF/LLRF.PIEZO/M34.A4.L2/

Detuning and piezo control overview

PZ16M : M3.A4.L2

Cavity	1	2	3	4	5	6	7	8	all
Piezo Ena	On	On	On	On	On	On	On	On	on off
DAC Enable	On	On	On	On	On	On	On	On	on off
Auto Tuning									on off
Static Det.	19.2	12.5	7.67	1.99	10.9	3.50	-1.5	-13.	
DC Volt	-2.0	14.0	7.0	12.0	8.0	13.0	5.0	-1.0	to zero
DC status									
Linear Det.	19.24	12.59	7.673	1.999	10.99	3.508	-1.51	-13.0	
AC Volt	-39.6	-15.4	-24.0	-20.3	-21.3	-20.7	-21.0	-20.7	to zero
AC status									
LOAD (ON/OFF)	Details	Details	Details	Details	Details	Details	Details	Details	on off

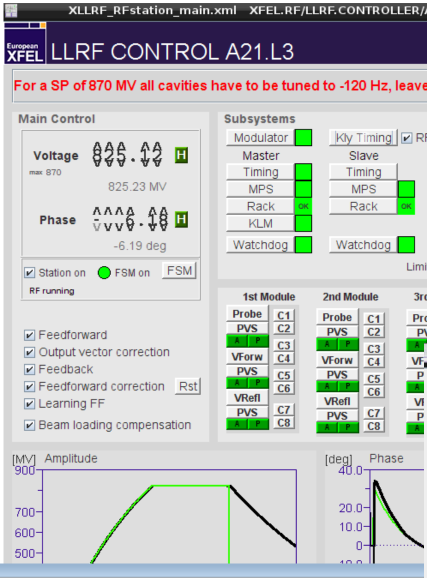
Detuning curves

PZ16M : M4.A4.L2

Cavity	1	2	3	4	5	6	7	8	all
Piezo Ena	On	On	On	Off	On	On	On	On	on off
DAC Enable	On	On	On	Off	On	On	On	On	on off
Auto Tuning									on off
Static Det.	-1.4	-2.2	-9.6	0.0	-20.	2.42	0.33	-10.	
DC Volt	-14.0	-17.0	9.0	0.0	4.0	14.0	11.0	7.0	to zero
DC status									
Linear Det.	-1.49	-2.23	-9.67	0.0	-20.1	2.420	0.331	-10.0	
AC Volt	-18.8	-24.3	-20.7	0.0	-25.7	-24.3	-18.3	-24.2	to zero
AC status									
LOAD (ON/OFF)	Details	Details	Details	Details	Details	Details	Details	Details	on off

Detuning curves

PZ16M installed at XFEL


XLLRF_RFstation_main.xml XFEL.RF/LLRF.CONTROLLER/A21.L3/ (xfeluser1)

LLRF CONTROL A21.L3

For a SP of 870 MV all cavities have to be tuned to -120 Hz, leave OVC off

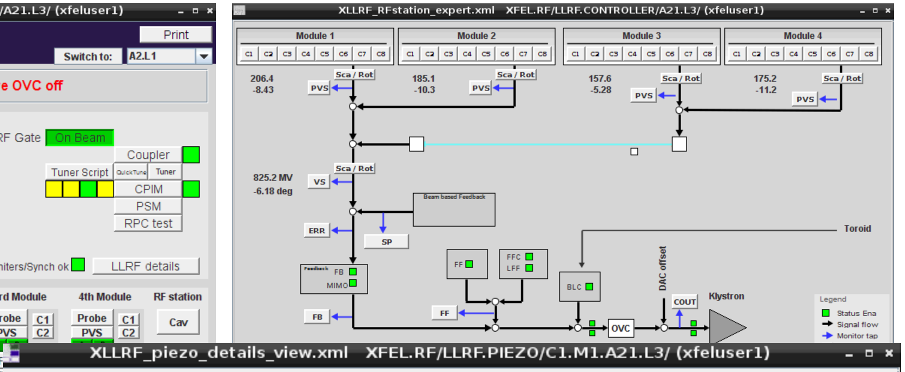
Main Control

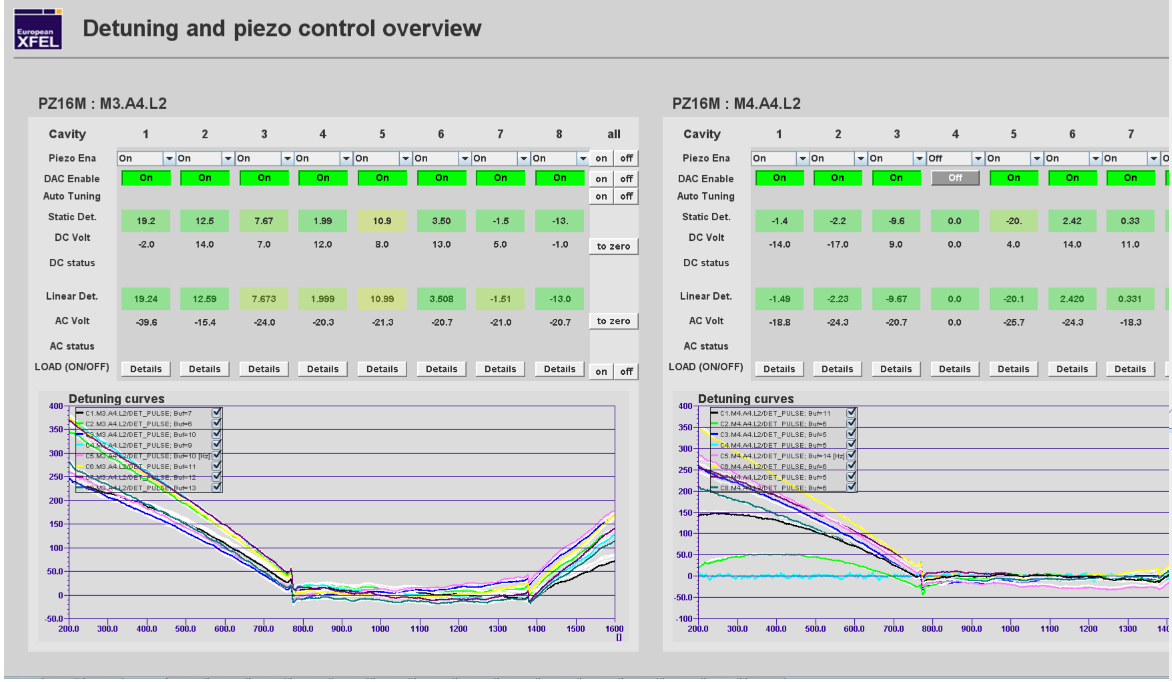
Voltage 825.23 MV (max 870)

Phase -6.19 deg

☑ Station on ● FSM on — RF running

☑ Feedforward
☑ Output vector correction
☑ Feedback
☑ Feedforward correction
☑ Learning FF
☑ Beam loading compensation


XLLRF_RFstation_expert.xml XFEL.RF/LLRF.CONTROLLER/A21.L3/ (xfeluser1)


XLLRF_piezo_station_view.xml XFEL.RF/LLRF.PIEZO/M34.A4.L2/

Detuning and piezo control overview

PZ16M : M3.A4.L2

Cavity	1	2	3	4	5	6	7	8	all
Piezo Ena	On	On	On	On	On	On	On	On	on off
DAC Enable	On	On	On	On	On	On	On	On	on off
Auto Tuning									on off
Static Det.	19.2	12.5	7.67	1.99	10.9	3.50	-1.5	-13.	
DC Volt	-2.0	14.0	7.0	12.0	8.0	13.0	5.0	-1.0	to zero
DC status									
Linear Det.	19.24	12.59	7.673	1.999	10.99	3.508	-1.51	-13.0	
AC Volt	-39.6	-15.4	-24.0	-20.3	-21.3	-20.7	-21.0	-20.7	to zero
AC status									
LOAD (ON/OFF)	Details	Details	Details	Details	Details	Details	Details	Details	on off

Detuning curves

PZ16M : M4.A4.L2

Cavity	1	2	3	4	5	6	7
Piezo Ena	On	On	On	Off	On	On	On
DAC Enable	On	On	On	Off	On	On	On
Auto Tuning							
Static Det.	-1.4	-2.2	-9.6	0.0	-20.	2.42	0.33
DC Volt	-14.0	-17.0	9.0	0.0	4.0	14.0	11.0
DC status							
Linear Det.	-1.49	-2.23	-9.67	0.0	-20.1	2.420	0.331
AC Volt	-18.8	-24.3	-20.7	0.0	-25.7	-24.3	-18.3
AC status							
LOAD (ON/OFF)	Details	Details	Details	Details	Details	Details	Details

Detuning curves


XLLRF_piezo_details_view.xml XFEL.RF/LLRF.PIEZO/C1.M1.A21.L3/ (xfeluser1)

C1.M1.A21.L3

Enable: On — ENABLED

frequency: 270 Hz

DAC ena: On

Relay: 1 — LOAD

Pulses: 1 — Custom Tables ☐

Static

DC Voltage: 10.00 — 10.00

Detun.: -2 Hz

Linear

AC Amplitude: -14.40

Detun.: -2 Hz

Curvature

Delay: 15.00

OK

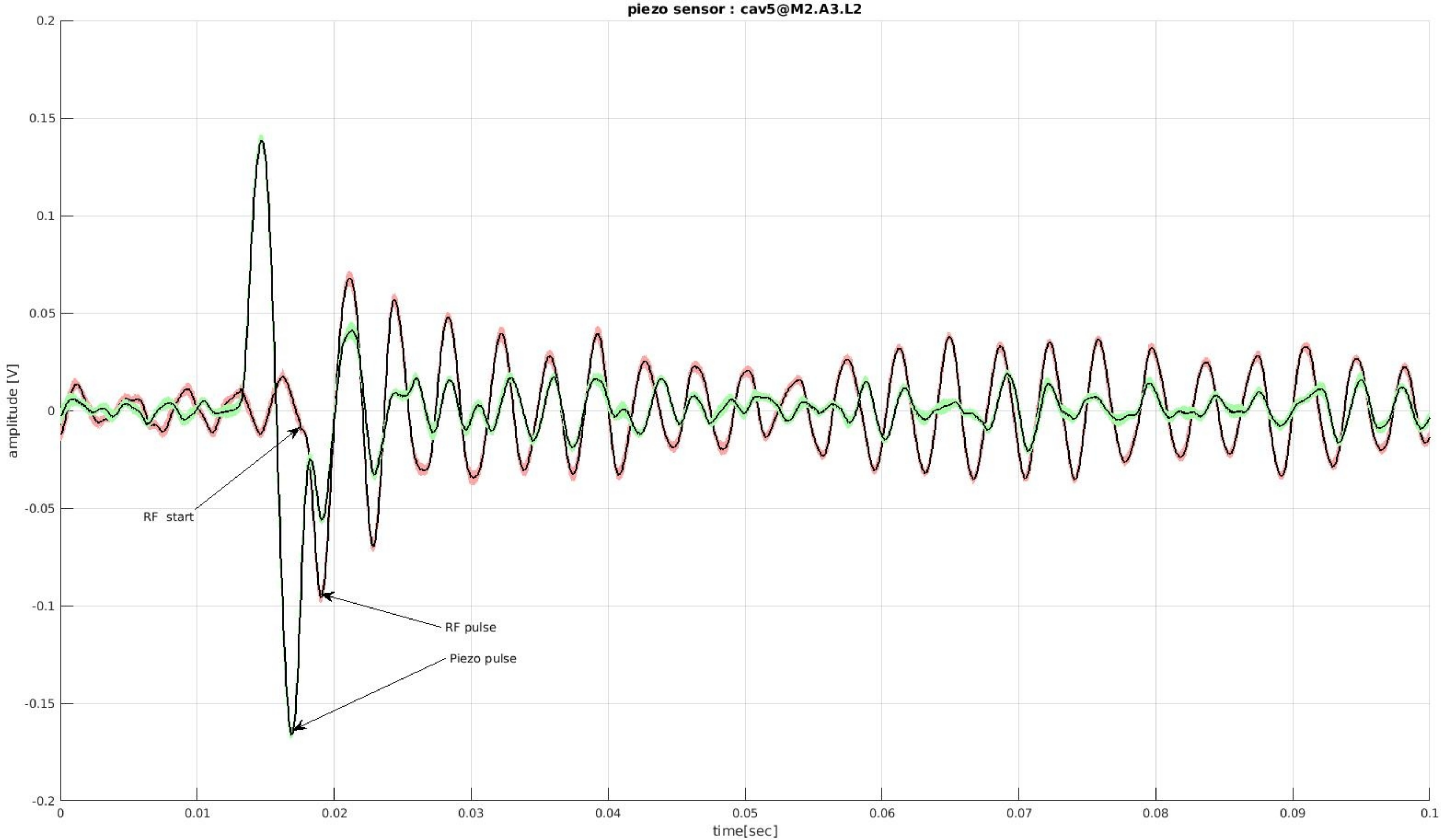
Conclusion

- Piezo control system has been designed, installed, commissioned and operated at FLASH. At XFEL it is installed in a few stations and it is being currently commissioned. In parallel a mass production and testing is being performed. The installation is to be completed during winter shutdown.
- Hard lessons learned breaking piezos at FLASH.
- The experience gained during FLASH operation triggered a big system upgrade to assure safe piezo operation (and also delayed the production for XFEL).
- The main purpose of the presented system is to compensate LFD in pulsed operation mode, however system is so flexible that it can be used (with adapted firmware) also in CW (already demonstrated at CMTB).

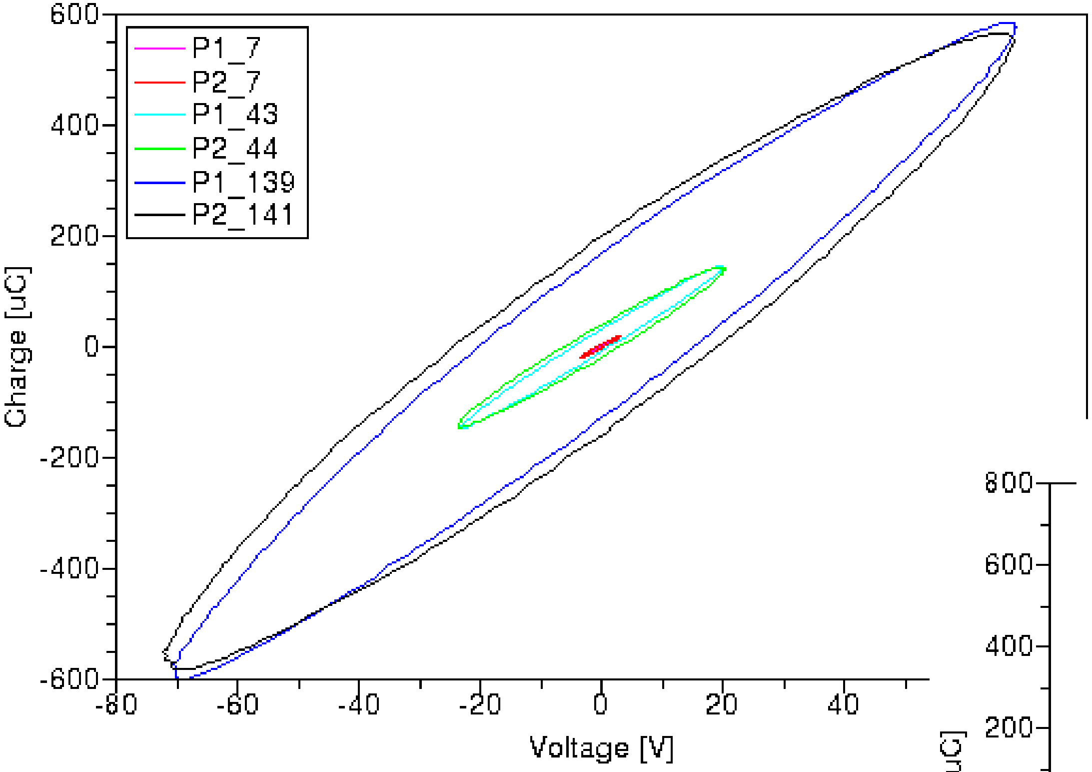
Thank you for your attention

Backup slides

Piezo sensor signal

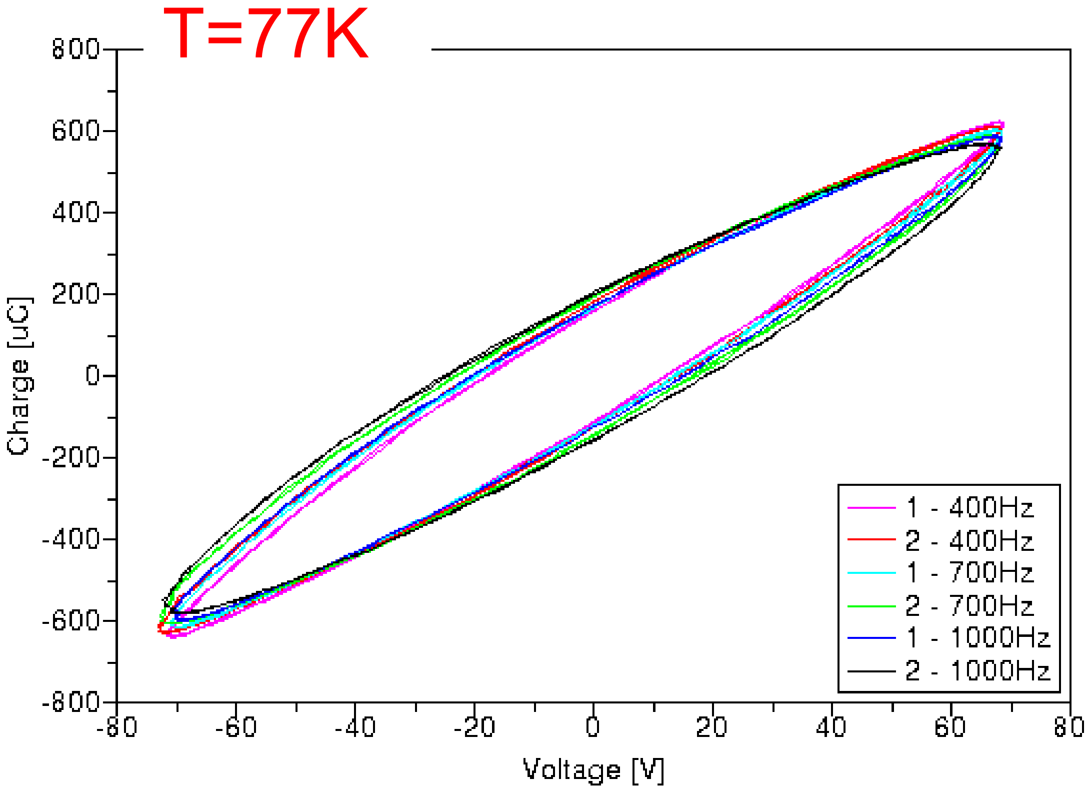


Piezo capacitance

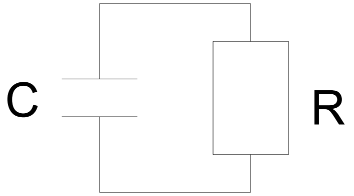


$E \sim V^2$
E=~30mJ/cycle at ±70V
(that gives ~0.3W at 10Hz
single pulse)

T=77K

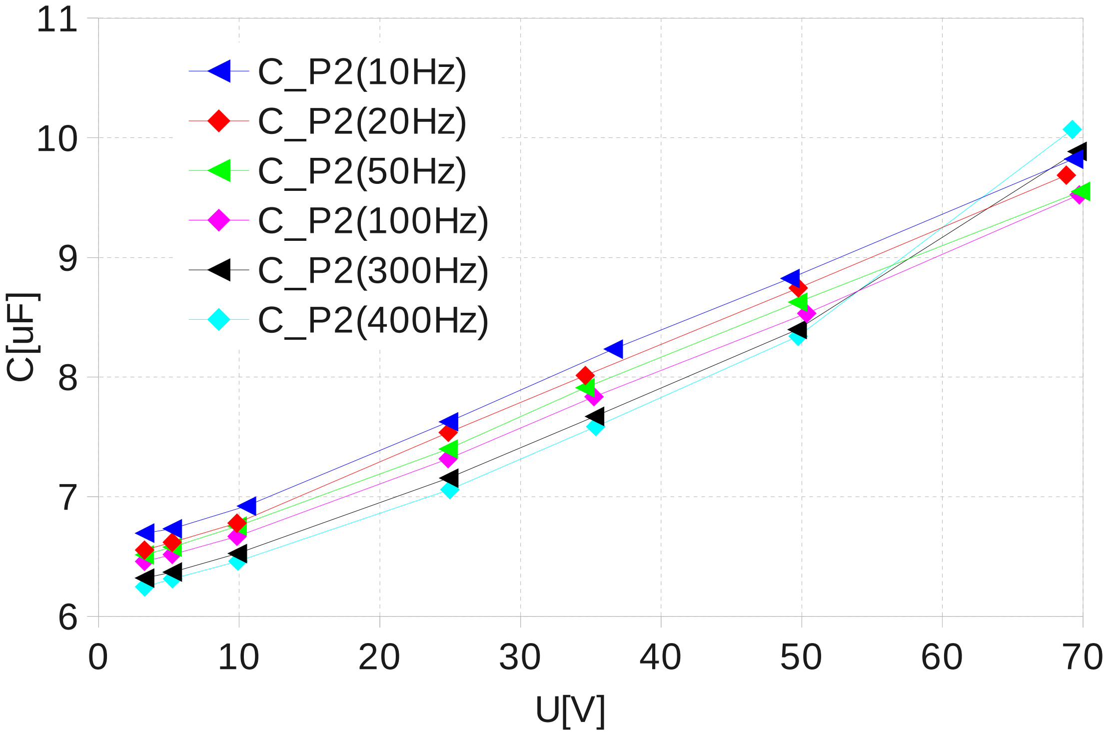


$$C = \frac{dQ}{dV}$$



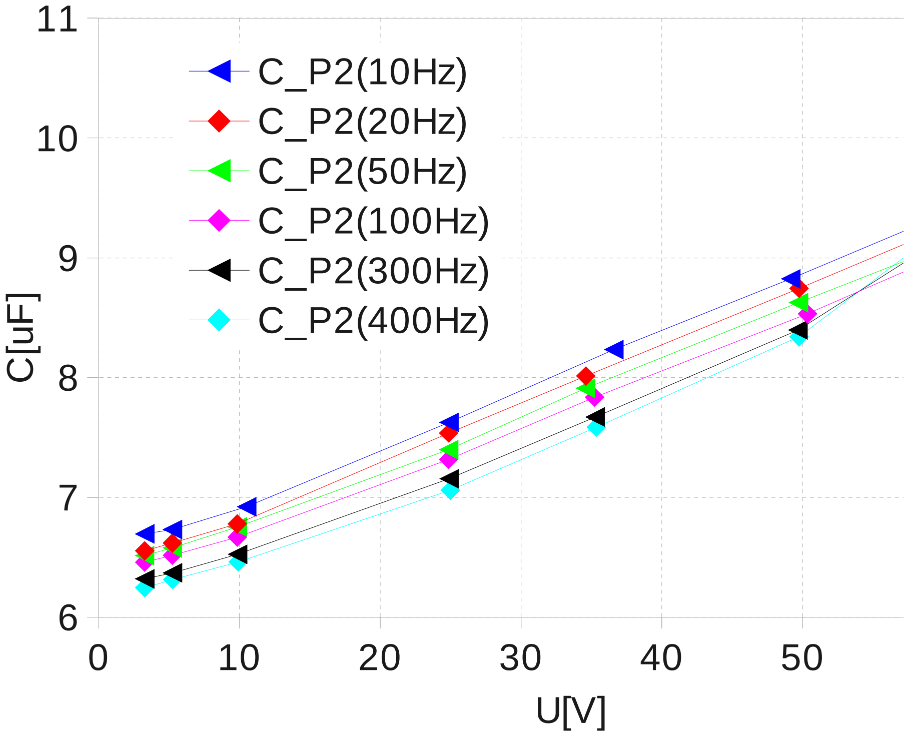
$$Y_p = \frac{1}{R_1} f + j\,2\pi f\,C \qquad Z_p = \frac{Z_1}{f}$$

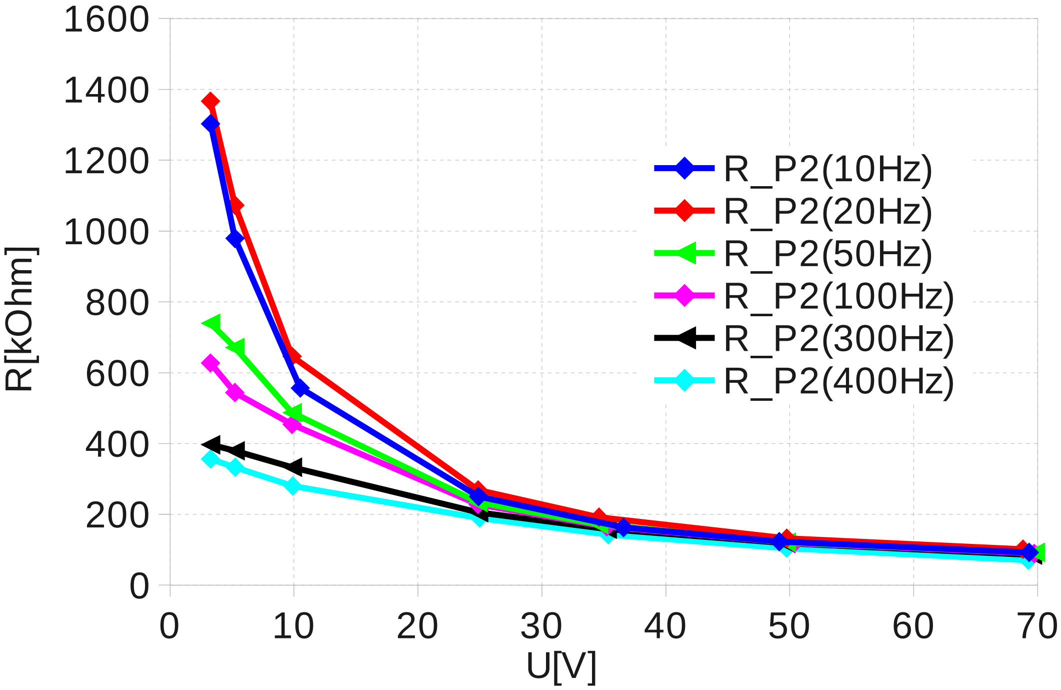
Piezo electrical parameters



T=77K

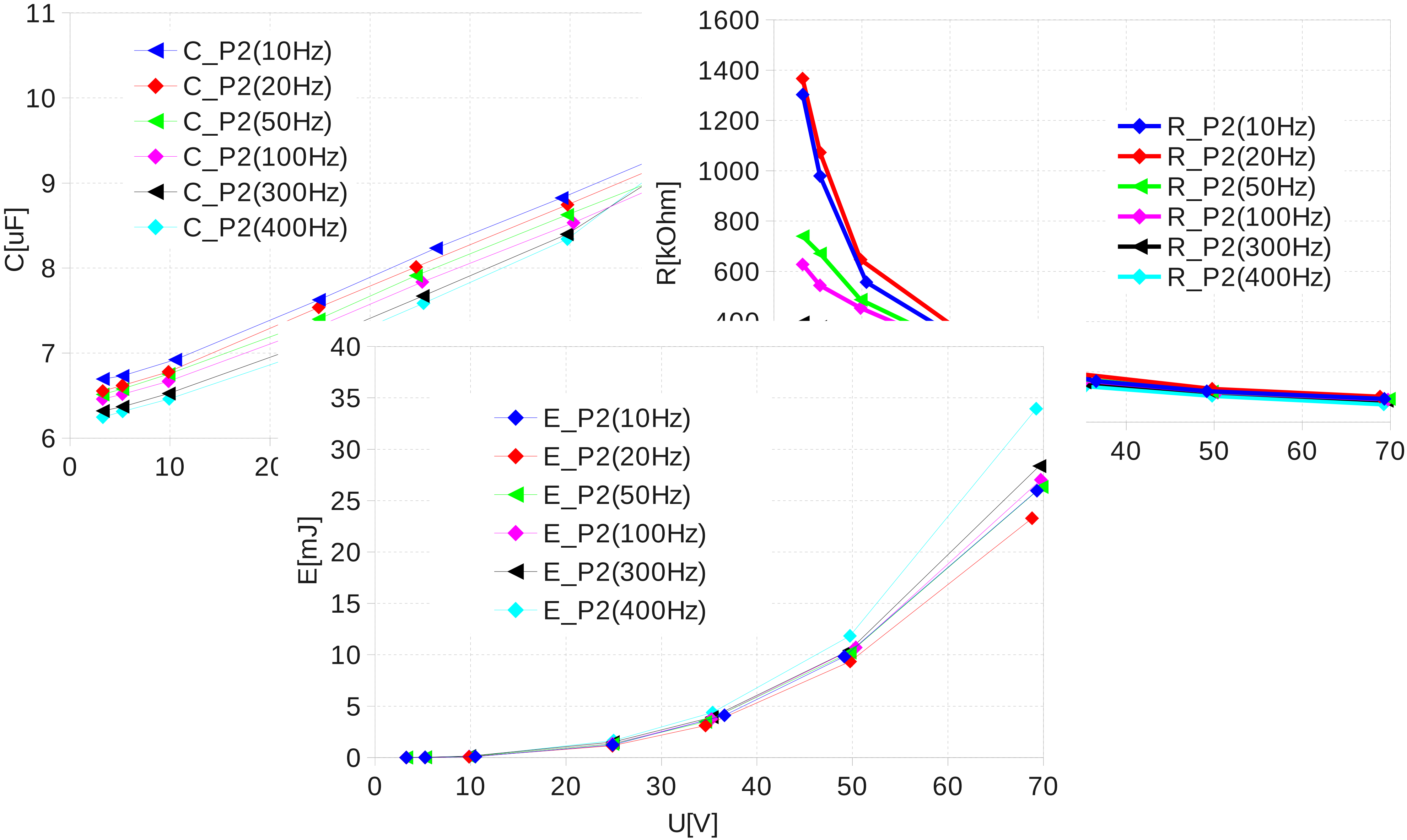
Piezo electrical parameters





T=77K

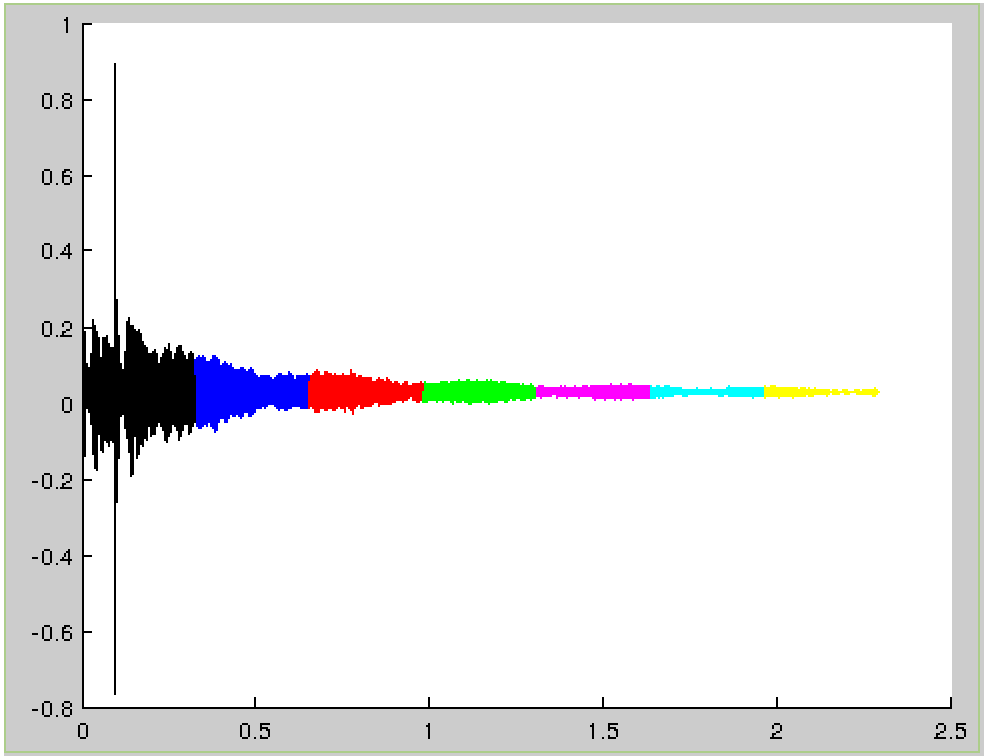
Piezo electrical parameters



T=77K

Dynamic properties

- Piezo resonant frequency ~40kHz
- When mounted the dynamics is dominated by cavity (resonant frequency ~200Hz)



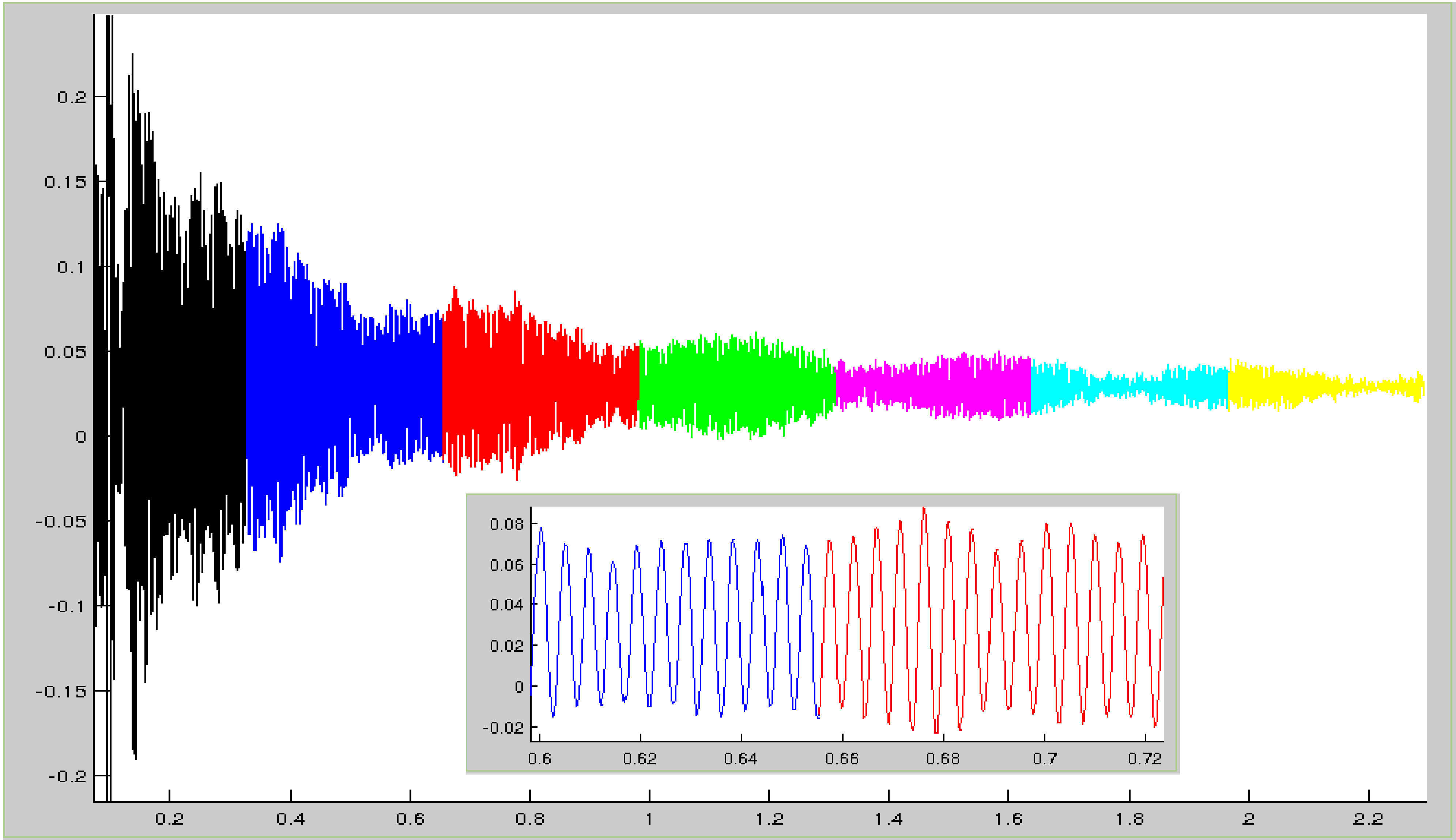
- Tests conditions:

  No RF in the module

  Piezo excited by sequence of sinusiodal pulses (A=70V, f=200Hz, frep=10Hz)

  After input pulses have been stopped the piezo response recordered (fs=5.6KHz, trec=40ms)

Dynamic response of piezo & cavity



Dynamic response of the piezo mounted in cavity