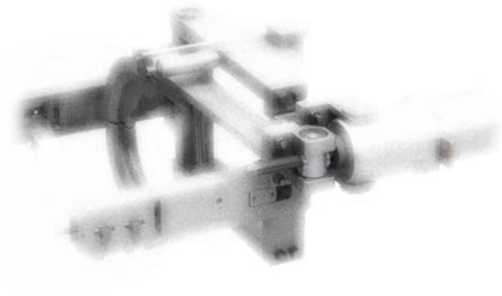
WG3 Roundtable:
Tuners, Passive and Active Resonance Control

Yuriy Pischalnikov

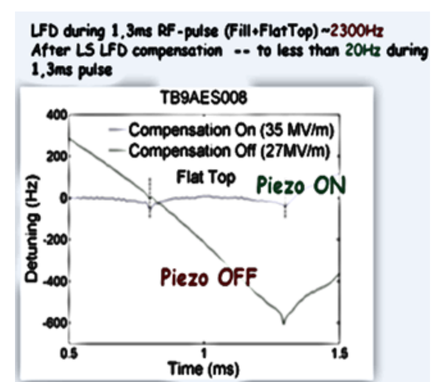
SRF Roadmap Workshop

10 February, 2017

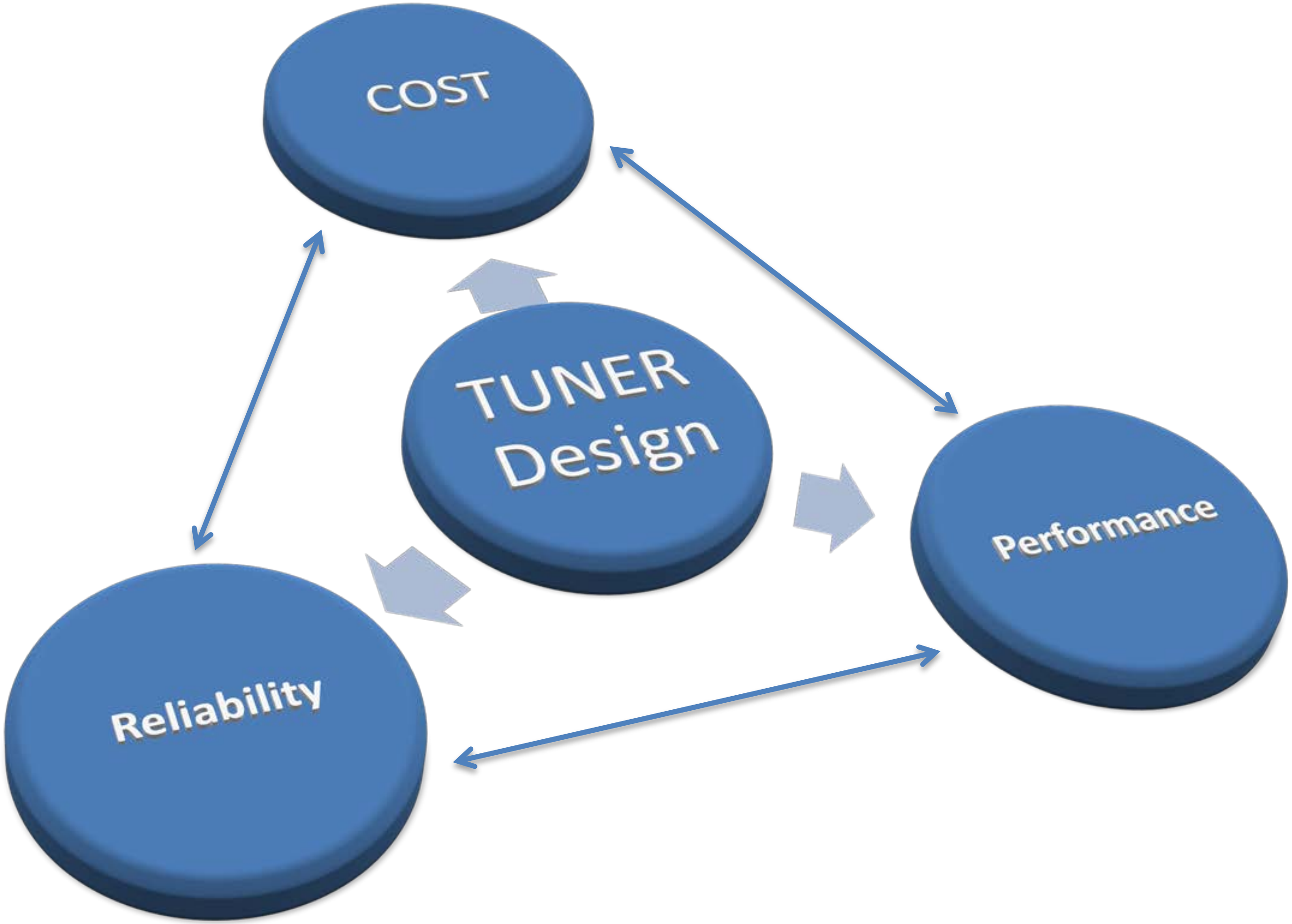


SRF Cavity Tuners

- Protect cavity during CMs assembly and cool-down & warm-up
- Tune cavity to operating frequency after cool-down of 2K (4K)
- Keep cavity (dynamically) on the resonance
- Active Resonance Control
    - Active piezo compensation
        - LFD
        - df/dp
        - microphonics



SRF Cavity Tuner Optimization for Future Accelerators



Tuner Cost Optimization

Cold vs warm ?

Compact (coaxial (blade) or compact lever tuner) → length of linac/ cost of tunnel

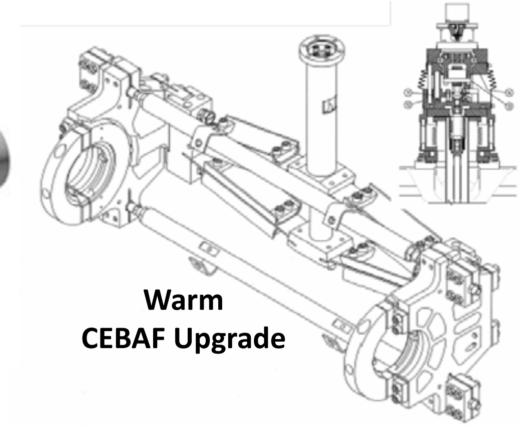
Simple ("classic") vs newest (?) design (bearing VS flex)

Non-traditional material (316LN SS & Ti vs <u>Al alloys</u>, etc.) to machine frame

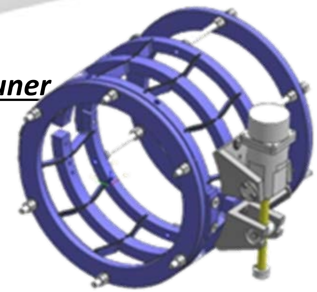
"Ceramic" vs traditional steel bearing (cost, magnetic properties and lifetime)

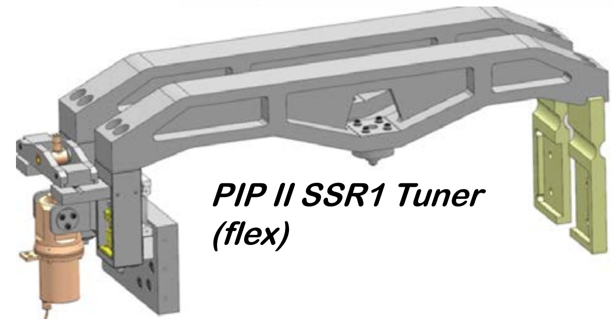
Electromechanical Actuator (stepper/gear/spindle /traveling nut) – $4k (LCLS II) → work with industry

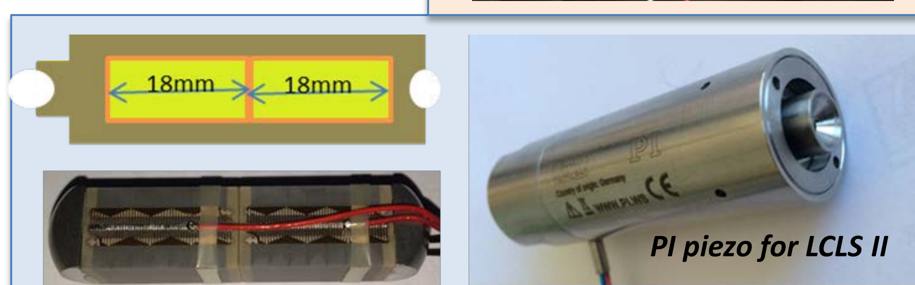
Capsulated/ preloaded Piezo-actuators (cost- optimization)



Blade Tuner







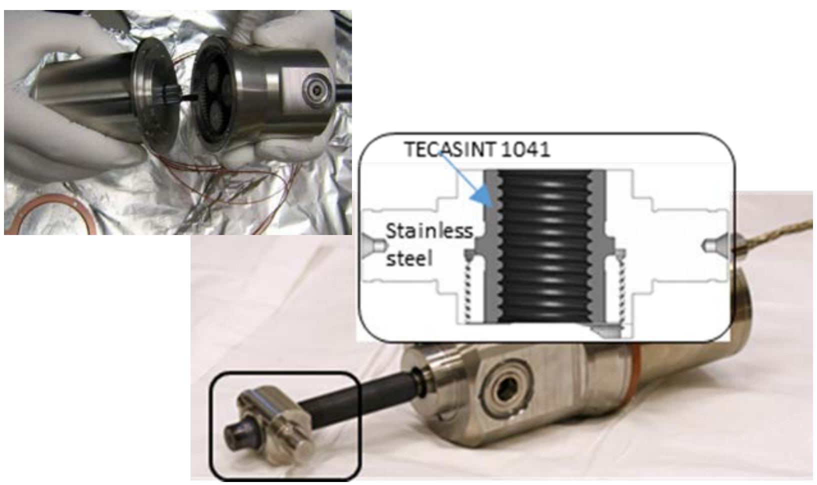
Tuner Reliability

- **Lifetime & rad. hardness of active components: electromechanical & piezo actuators are major concerns.**
- **Cold insulated vacuum environment (challenges for active components):**
  - **Elect. mechanical actuator: challenge-cryo/vacuum lubrication**
  - **Piezo actuator: <u>over-heating piezo ceramic with large stroke & pulse operation</u>**

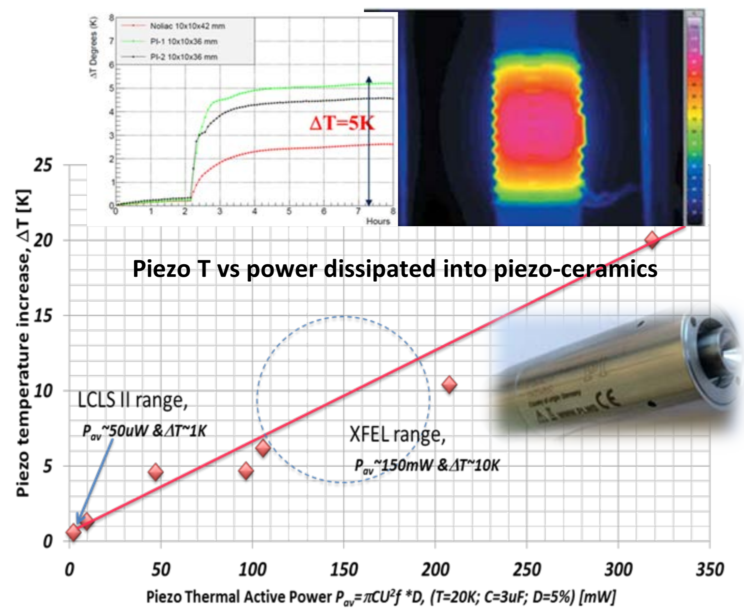
  (there is plan/ideas for joint R&D efforts with PI how significantly increase piezo-actuator reliability for high rate operation)

<u>Joint project of FNAL and Phytron& Physik Instrumente for LCLS II Project</u>

Electromechanical actuator



Tested at cold/ins. vacuum for 30 lifetimes
Rad. hardness test up to 5*10^{8}Rad.



Rad. hardness test up to 5*10^{8}Rad (stroke decreased on 10%).
Overheating piezo-ceramics operated into insulated vacuum can be a problem for ILC/PIP II operation.

Tuner Performance

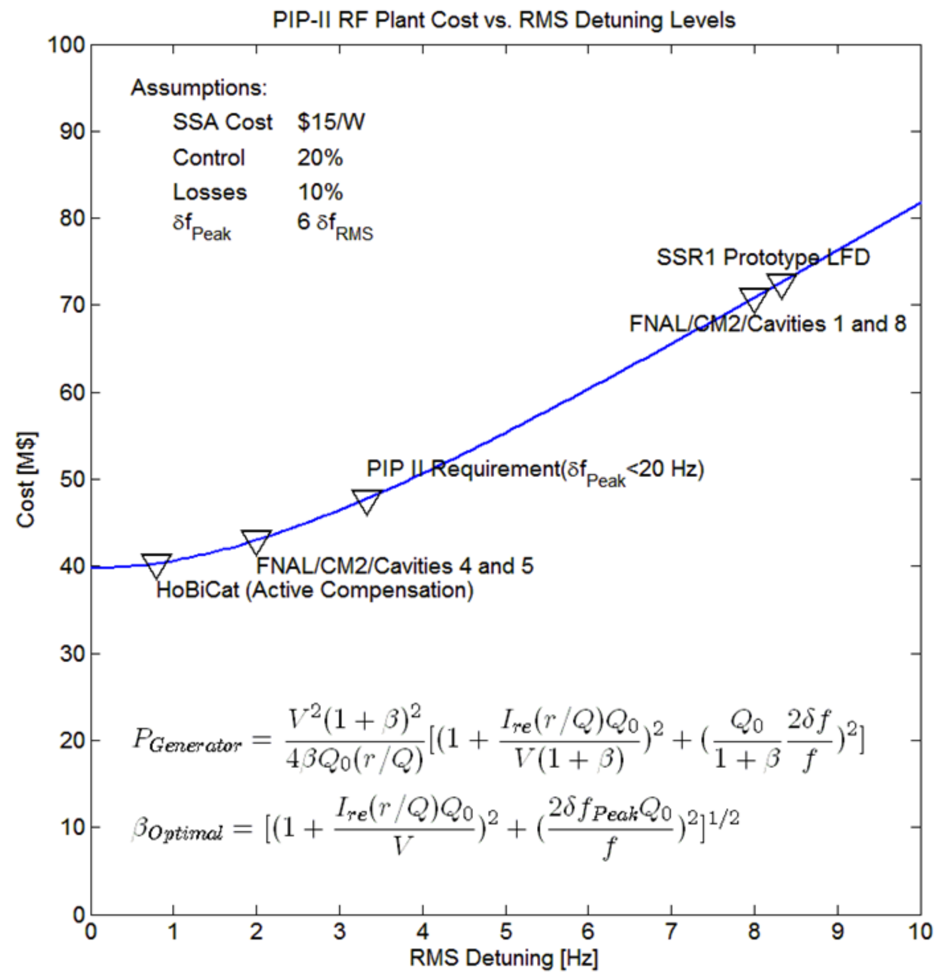
- **Tech. specs will dictate design choice:**
  - **Optimization of tuner/cavity system (stiffness) to minimize df/dp and LFD.**
  - **Slow/coarse tuner range…**
  - **Cavity df per one step … no micro-stepping into insulated vacuum.**
  - **Small group delay in response of fast/piezo tuner or/and piezo-tuner resolution**
  - **Piezo stroke VS blocking forces (length and cross section of piezo-actuator)**
  - **…..**

Examples:

- ***ILC –like: Pulse machine with E_{acc}=40MV/m → LFD ~2kHz piezo tuner with large stroke… and small group delay***
- ***PIP II : (1) narrow BW cavity; 25 short pulse per second → LFD & microphonics; (2) 650MHz – 20kN/mm cavity… piezo blocking forces & stroke compromise***

Cost of Cavity Detuning

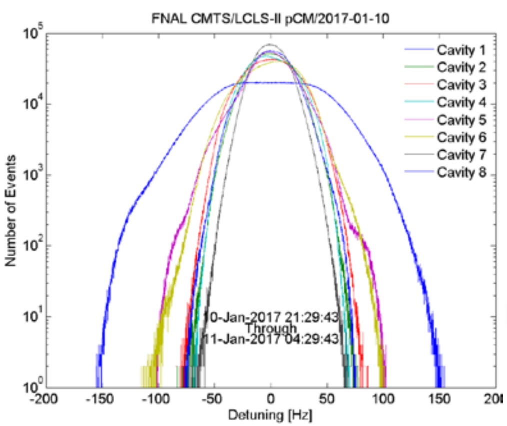
- **Detuned cavities require more RF power to maintain constant gradient**
- **Providing sufficient reserve increases both the capital cost of the RF plant and the operating cost of the machine**
- **PEAK detuning drives the RF costs**
  - **Beam will be lost if RF reserve is insufficient to overcome PEAK detuning**

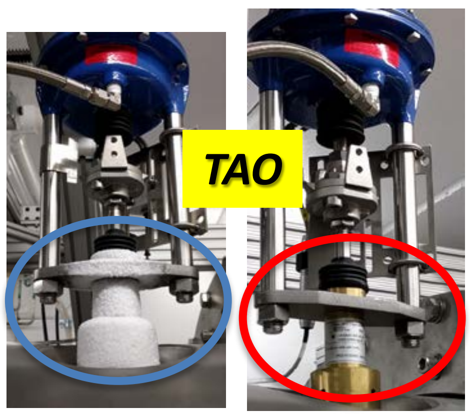


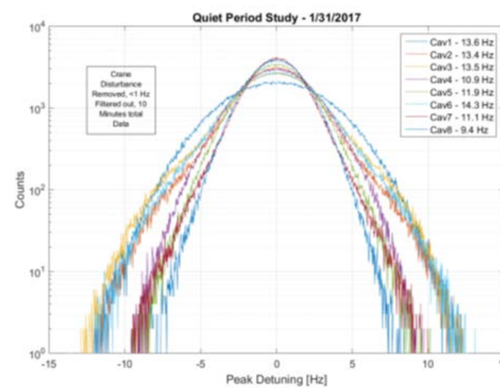
Passive Resonance Control

PASSIVE: Design of cryo-module must start from passive resonance control/analysis by multi-disciplinary team of expert (cryo/mech/RF/control)

- **Recent experience with LCLS II pCM**
  - ***TAO in cryo-valve → Large microphonics (peak detuning ~ Δf ~200-300Hz in the vibration range f~10-100Hz). Modification of the cryo-valves suppressed microphonics to 10-20Hz (peak). Mechanical resonances of the tuner/cavity system above are above180Hz.***





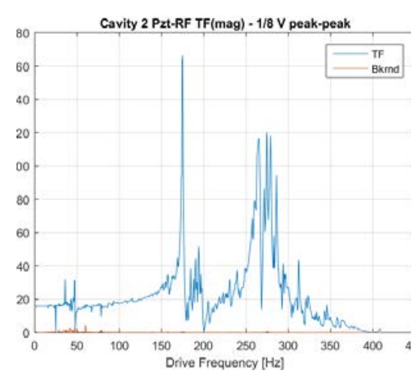


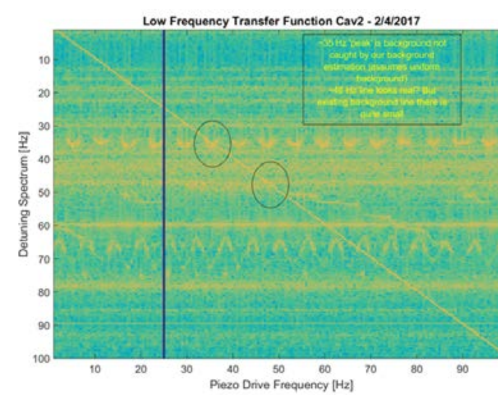
	Before	After
	Peak, Hz	Peak, Hz
1	166	18
2	85	14
3	87	14
4	73	11
5	113	12
6	113	15
7	82	11
8	80	10

Practically any facility/team will provide “passive resonance control lessons-learned” horror stories:

- **SRF cavity Tuner at JLAB**
- **Pump near CM at DESY**
- **Cryo-induced vibration at JLAB**
- **Cryo-burst at ERL Injector**
- **FNAL/HTS experience**

Summary of First Microphonics Workshop at FNAL (2015)





Active Resonance Control

Development/implementation of the piezo control algorithms in large systems

Pulsed SRF accelarators, existing and projects	Cavity Half-bandwidth, Hz	LFD, Hz	LFD/HBW
ESS	500	400	0.8
XFEL	141	550	4
PIP II	30	330	11
ILC (50-60MV/m)	55	2500-3600	40-60

Lorentz Force Detune is an issue!

$(df_{LFD}/df_{HWR} \sim gradient^3)$

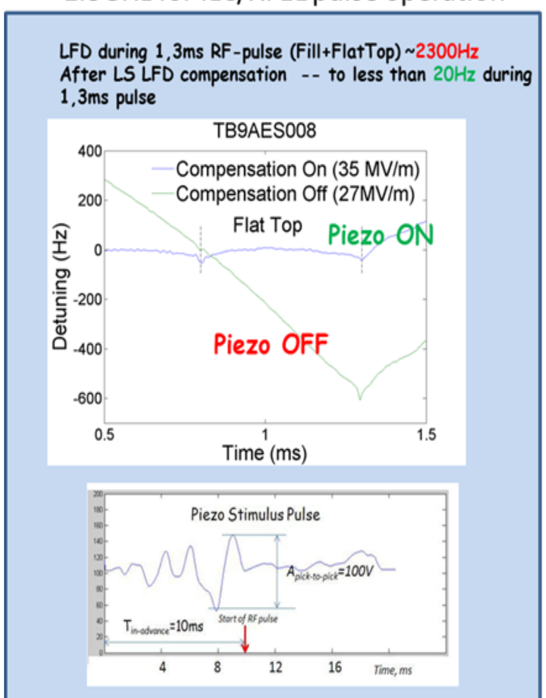
When machine operate at high rep rate (10-25Hz) residual vibration from previous pulse will contribute into detuning…

FNAL Adaptive Least Square Algorithm for LDF compensation

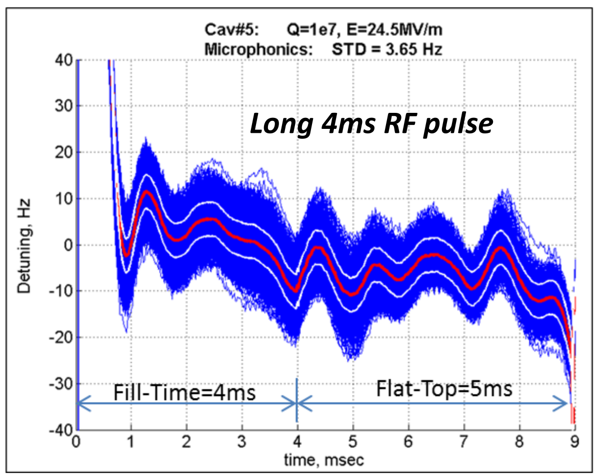
Initially developed during ILC program to compensate LDF detuning for 9-cell 1,3GHz elliptical cavities operating (1ms-fill+1ms-flat). Algorithm deployed at KEK during S1G program (for different type of cavity/tuner systems). This algorithm is universal enough … also successfully applied for

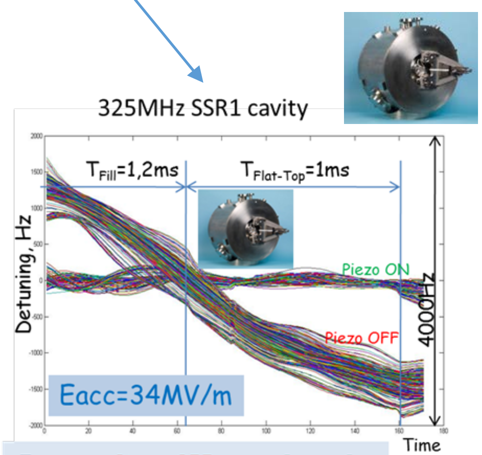
- *ILC cavities operating at 1ms RF pulse* ***LFD suppression from 2000Hz → 30Hz***
- *SSR1 cavities operating at (1ms-flat+1ms-flat)* **(HINS)** ***LFD suppression from 3,5KHz → to 75Hz***

1.3GHz for ILC/XFEL pulse operation



Residual Detuning over 30 minutes (1800pulses) during operation at $Q_L=10^7$ and E_{acc} =24.5 MV/m.





Eacc	Piezo OFF	Piezo On
34MV/m	3500Hz	75Hz

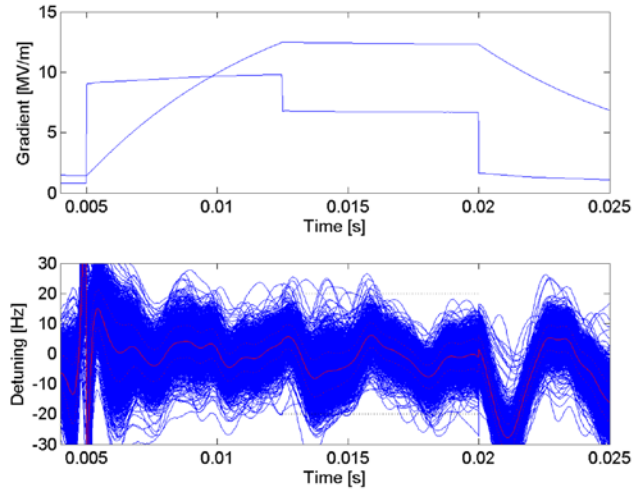
$\Delta F=-kE_{acc}^2$ K~1,2Hz/(MV/m)²

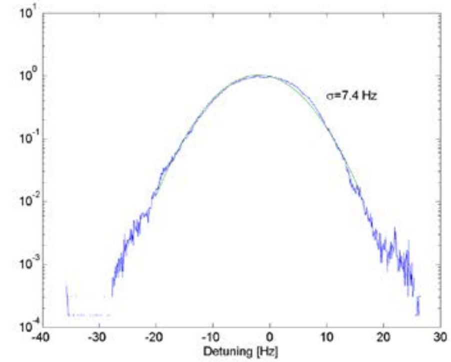
Y. Pischalnikov and W.Schappert, "Adaptive Lorentz Force Detuning Compensation" Fermilab Preprint-TM2476-TD

W.Schappert et. al.," Resonance Control in SRF Cavities at FNAL", PAC2011, New York, USA

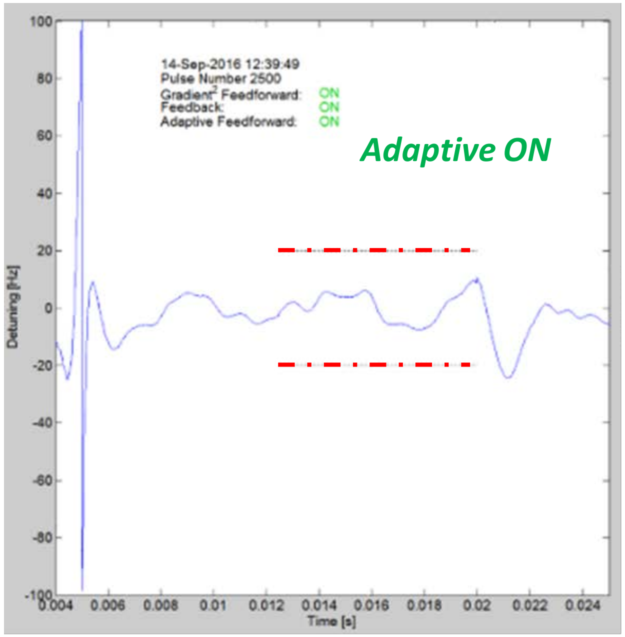
PIP II (SSR1 at STC) Active Resonance Control

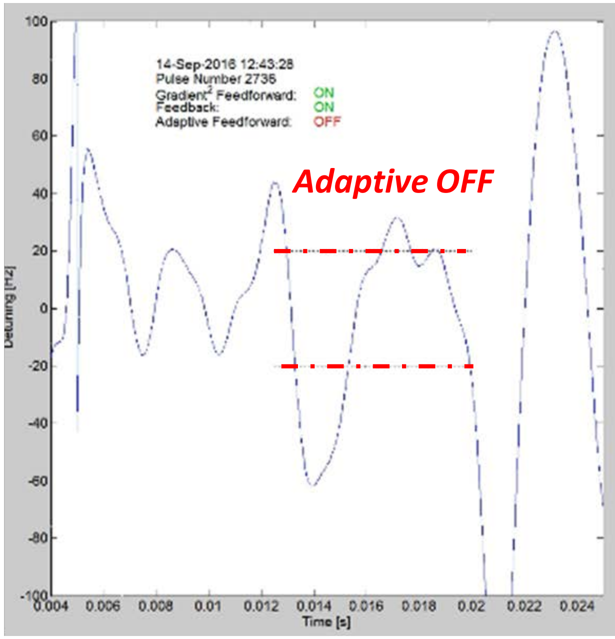
- Cavity run with
  - Gradient Feedforward,
  - Feedback manually tuned up in CW and
  - Adaptive Feedforward
- Adaptive Feedforward turned ON and OFF





~7.4 Hz RMS detuning on the flattop. Specification is a peak detuning of 20 Hz, so a further improvement in RMS of ~2 is needed.

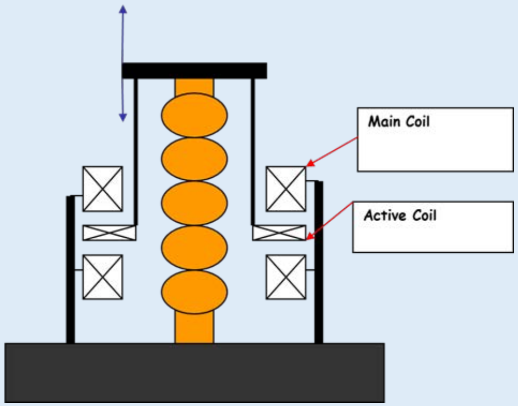


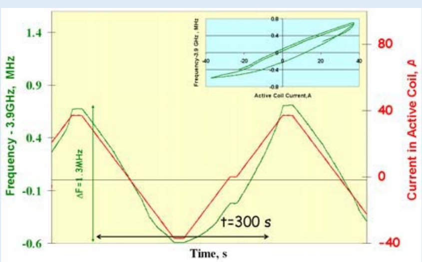


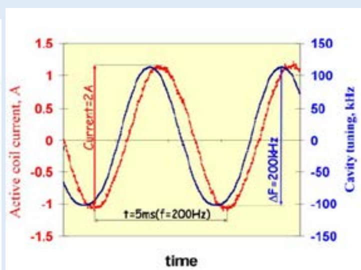
Novel Ideas for SRF cavity Tuners

Electromagnetic SCRF Cavity Tuner

FNAL team work. Published at PAC09.







Piezo based coarse & fine (fast) tuner

FERROELECTRIC BASED HIGH POWER TUNER FOR L-BAND ACCELERATOR APPLICATIONS

S.Kazakov, V.Yakovlev,…

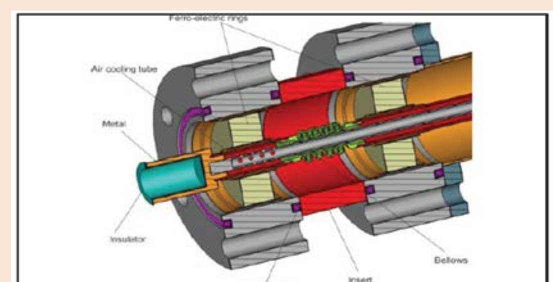


Figure 4: 3D CAD model of the phase shifter.

Milestones for Tuners/Resonance Control Tasks

- **Short-term R&D (2-3 years) milestones for LCLS II/PIP II/ILC**
  - **Production/testing/commissioning Tuner system for LCLS II CMs.**
  - **Development of the tuners for PIP II.**
  - **PIP II Tuner Design Verification work.**
  - **Development and deployment of Active Piezo Res. Control for LCLS II at CMTF**
- **Mid-term R&D (4-5 years) milestones**
  - **Production/testing/commissioning Tuner system for PIP II CMs.**
  - **Collaboration with industry to develop cost-reduced and highly reliable active components (piezo and el.-mechanical actuators)**
  - **Development of algorithms for pulsed operation for narrow bandwidth cavities (PIP II and ILC)**
- **Long-term R&D (10 years) milestones**
  - **Commissioning Tuner system for PIP II machine.**
  - **Deployment Active Piezo Resonance control for operation PIP II**
  - **Development of Tuner system based on new ideas/technology**
  - **Development of reliable universal active resonance control systems**

Additional Slides

Electromechanical Actuator

Accelerated Lifetime Test

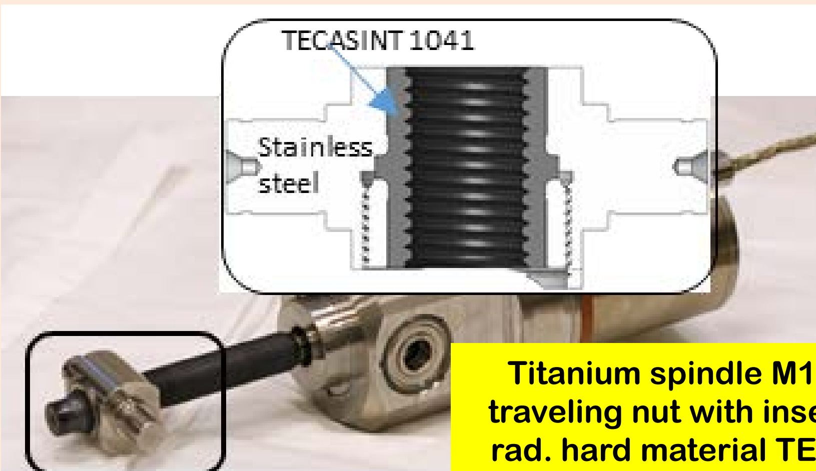
Picture	Name	Motor	Gear Box	Spindle/Nut	Forces	Longevity tested
	LCLS II	Phytron 1.2A	planetary gear (ration 1:50)	Titanium & SS M12*1	3 +/-1300N	tested in ins. vacuum at HTS for 5000 turns (5 XFEL lifetimes). In the force range +/-1500N. Motor run with current 0.7A

Estimations

~1,000 spindle rotation with piezo tuner

~20,000 spindle rotation without piezo tuner

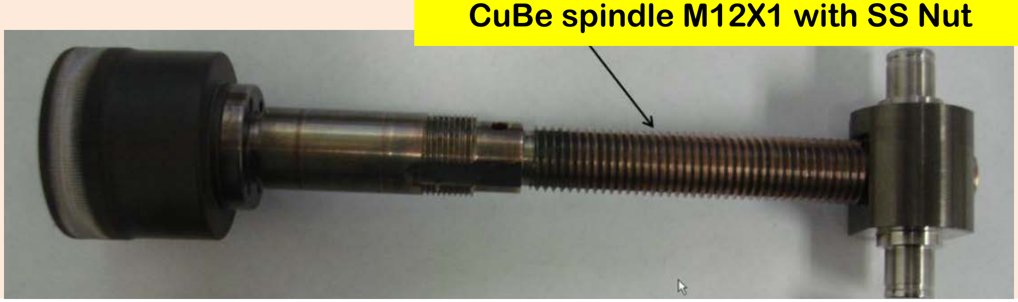
2



Titanium spindle M12X1 with SS traveling nut with insert made from rad. hard material TECASINT 1041 (polyimide; fillers 30% Molybdenum disulfide (MoS_2)

VS

CuBe spindle M12X1 with SS Nut



1

Planetary gear vs Harmonics drive

Requirements to the piezo for operation in XFEL and LCLS II

Impact on the longevity of the piezo

	XFEL	LCLS II	FNAL-test-stand *(2month)*	
Operation	10 pulses/sec	CW	CW	
stimulus pulse, Hz	200 *(2 sinewave per pulse)*	40	5000	
Vpp, V	120	2	2	
piezo stroke,[um]	5	0.2	0.2	
number pulses for 20 years	1E+10	2E+10	2E+10	
total stroke of piezo for 20years, [km]	60	5	5	
Piezo-stack motion speed (rms) (mm/s)	4.5	0.02	2.2	
Piezo-stack motion acceleration (rms)(g)	0.6	0.0004	7	*$P_{av}=\pi CU^2 f$ *D, where D is dissipation Factor (~5-20%)*
Heat dissipation, [mW]	90	0.05	6	estimated
Piezo ΔT raised	20K	0.1K	2K	measured

High reliability of tuner components (piezo-actuator)

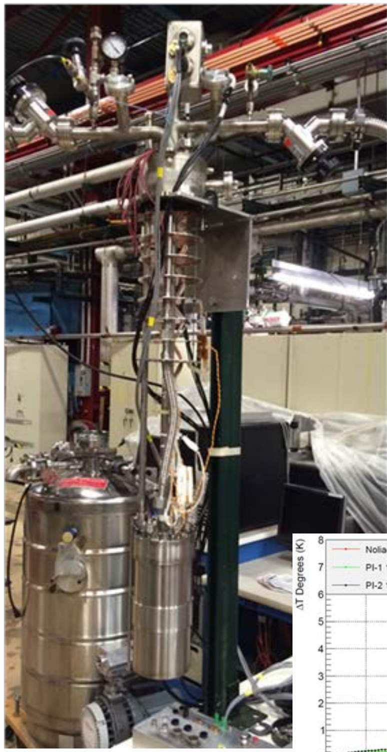
Accelerated Piezo Lifetime test at FNAL

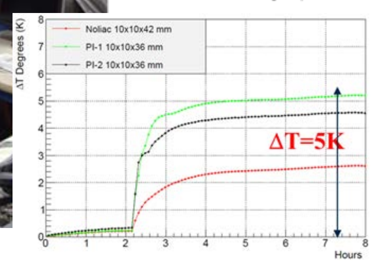
Designated facility at FNAL to test piezo at the CM environment (insulated vacuum and LHe)

Insert into LHe dewar with cryo/vacuum and electrical connections

Capsules (up to 5) with Piezo-stacks Mounted on the copper block

- RTD (Cernox) –to mount on Piezos
- Geophones (to monitor piezo stroke)





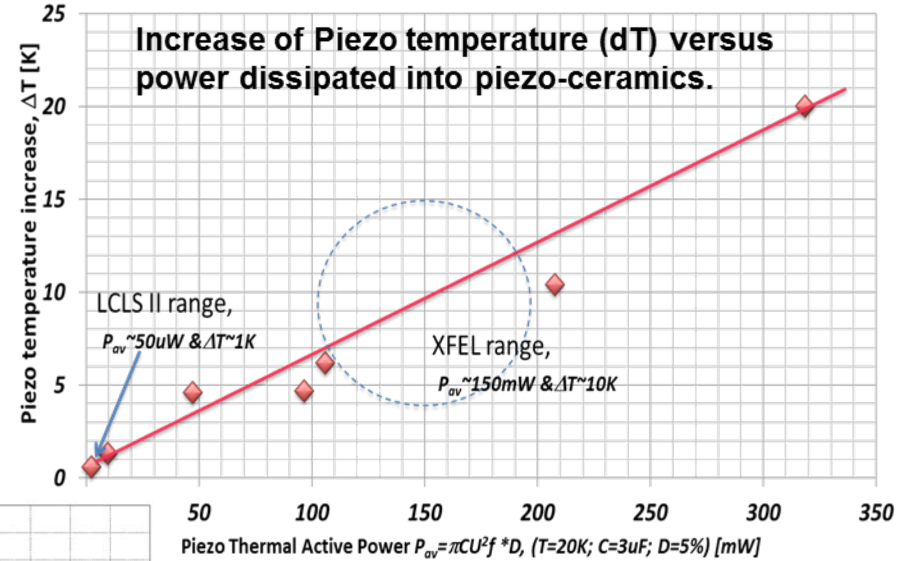
Accelerated piezo-stack lifetime test

$2*10^{10}$ pulses (V_{pp} = 2V & F = 40Hz)

20years → 2 month (40Hz→5kHz)

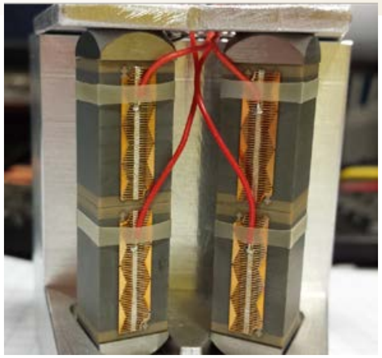
LCLS II --- P_{av}~ 50μW (40Hz, 2V)

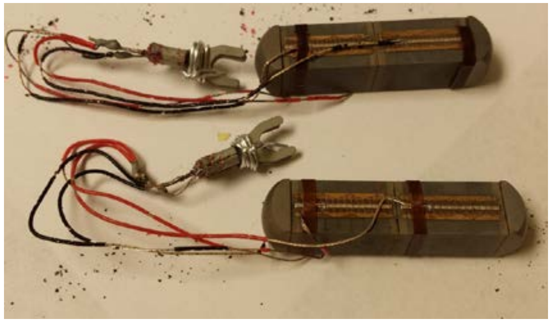
During ALT at 5kHz P_{av}~ 6mW (ΔT~2K)



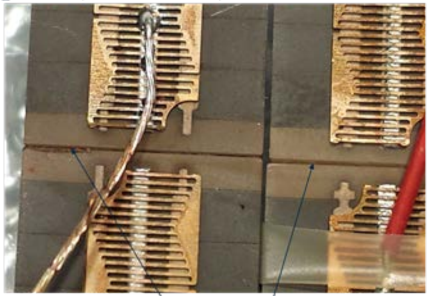
LCLS II Tuner piezo-stacks run for $2.5*10^{10}$ pulses (or 125% of LCLS II expected lifetime) without any degradation or overheating

Irradiation of the Piezo-stacks up to 10^9Rad (gamma)

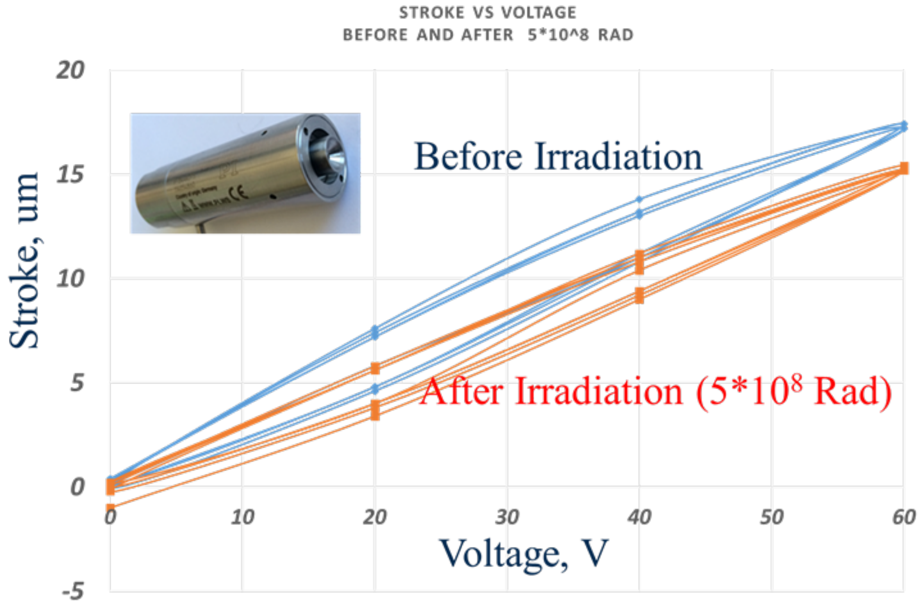




Sample A($5*10^8$ Rad) Sample C (0 Rad)



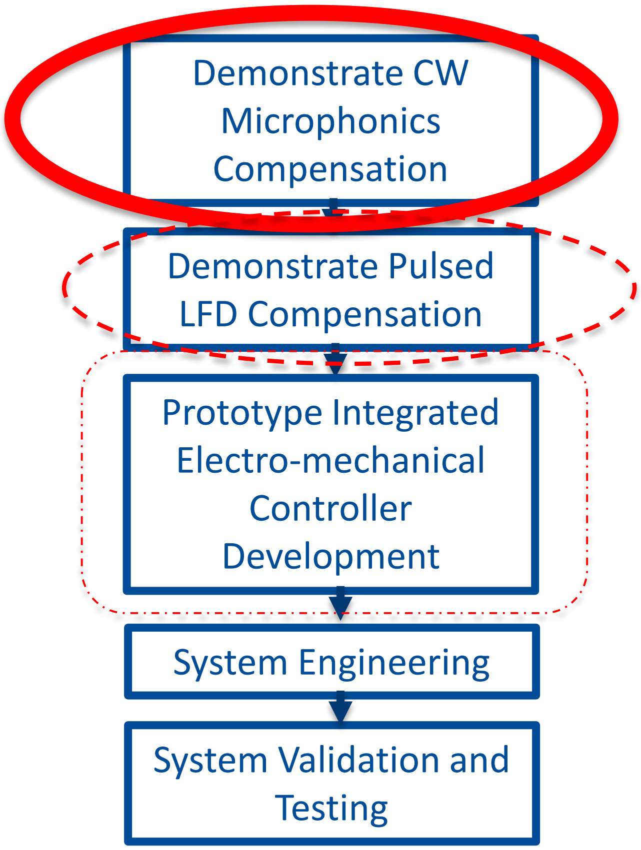
Discoloration of the thing layer of Epoxy



Stroke of the piezo-stack decreased only on 10% after irradiation up to 10^9 Rad

Current Resonance Control Program for PIP-II

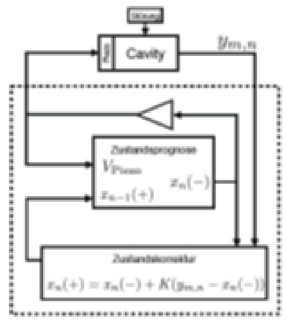
- Focus is still on unambiguous demonstration of CW microphonics compensation
  - Adaptive LFD control of pulsed cavities well understood
    - Preliminary demonstration of feedforward LFD control in pulsed cavities
  - Largest source of residual detuning are pulse-to-pulse variations
  - Compensation requires feedback
    - Feedback at the levels required for PIP-II has been demonstrated at low gradients using ad-hoc techniques
- Optimal control provides a coherent mathematical framework for this type of problem



Optimal Control

- Optimal control techniques pioneered by Kalman in the early 1960s
  - –Recursive, weighted, least-squares fit at every point in time
- Will be first tested in SRF gun cavity at BESSY

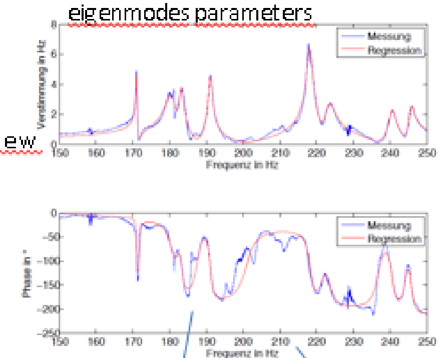
Plots here are from thesis (2014)



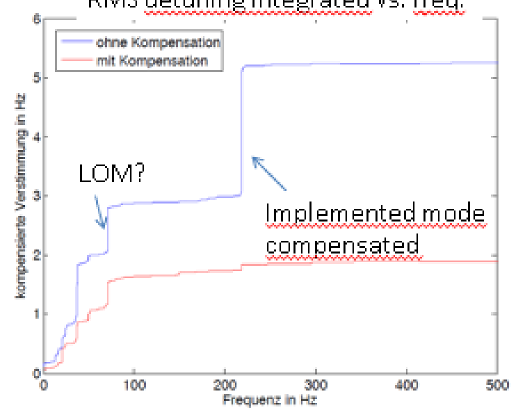
Scheme with simple Proportional state Feedback, Implemented on Labview FPGA

Limited to one eigenmode

Fitted transfer function to obtain eigenmodes parameters



RMS detuning integrated vs. freq.



Prediction

$$x_n(-) = A_{n-1} \cdot x_{n-1}(+) + B_{n-1} \cdot u_{n-1}$$

$$P_n(-) = A_{n-1} P_{n-1}(+) A^{\mathrm{T}}_{n-1} + Q_{n-1}$$

Kalman gain update

$$K_n = P_n(-) H^{\mathrm{T}} \cdot \left(H P_n(-) H^{\mathrm{T}} + R_n \right)^{-1}$$

$$P_n(+) = (1 - K_n H)\, P_n(-)$$

$$x_n(+) = x_n(-) + K_n \left(y_{m,n} - H \cdot x_n(-) \right)$$

State correction

➡ Implemented in Xilinx Artix-7, pipelined more than 9 eigenmodes at least possible to calculate (2016)

Courtesy Axel Neumann