Resonance Control of LB650MHz and HB650MHz SRF Cavities

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in behalf of the Tuner Team

December 7, 2017

Technical Meeting
with Peter Mcintosh and Alan Wheelhouse

Outline

- **Status of Tuner Design for LB/HB650MHz and HB650MHz SRF Cavities**
  Modification of Tuner design
  - **(goal → Lower LFD → high tuner/dressed cavity stiffness)**

- **FNAL's Resonance Control experience**
  - **(LFD & microphonics compensation)**

- **Reliability of the Piezo Tuner**

“ Some” specs for LB/HB650 MHz Tuner *(challenges)*

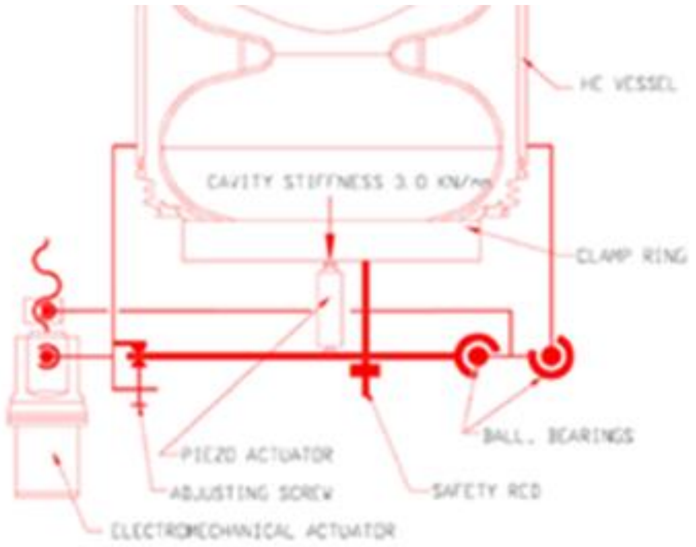
1. **To design tuner that will work with 3 types of 650MHz cavities**
   a) $K_{cav.stiffness}$ ~ 20 kN/mm (several (4?) cavities built for Project X) → **F_{max}~11 kN**
   b) $K_{cav.stiffness}$ ~ 4 kN/mm → F_{max}~4-5 kN (for newest LB/HB650)

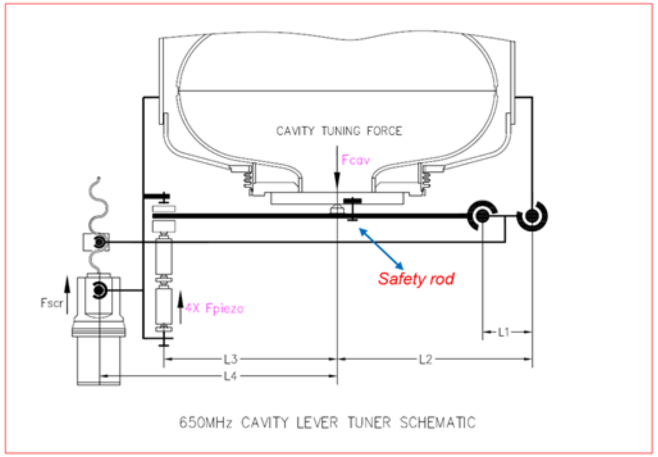
   (Overloading piezo-capsules beyond specs !!!)

   Decision to move piezo-capsules on the side of Tuner (decreased F_{max} on 50%) …to keep the required piezo stroke in the specs double amount of the piezo-capsules (in serious)

2. **To design tuner with $K_{tuner.stiffness}$ ~ 70 kN /mm**
   - To minimize K_{LFD}

Tuner specs for 650MHz cavities (0.9; 0.92; 0.61)

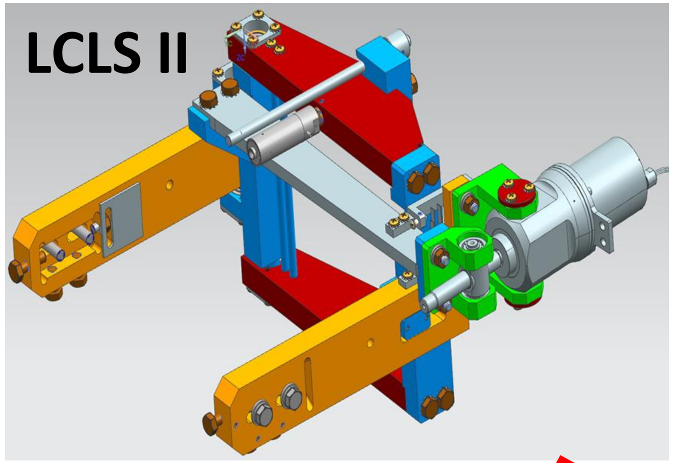


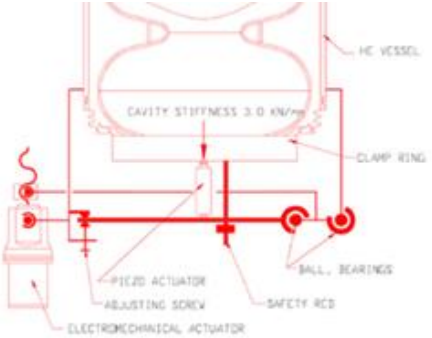


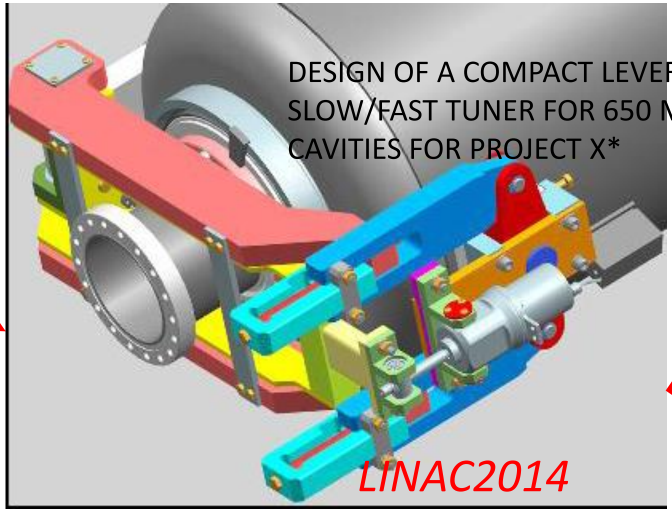
	beta			
	0.9	0.92	0.61	
stiffness, (N/um)	20	3-4	3-4	
cavity tuning sensitivity, [Hz/um]	180	160	240	
bandwidth ($F_{1/2}$), [Hz]	29	29	29	
Lorentz Force Detuning coefficient, $[Hz/MV/m]^2$	<1	<1	<1	
Cavity sensitivy to pressure, dF/dp [Hz/mbar]	20	20	20	
Tuner sfiffness [N/um]	>40	>40	>40	
required coarse tuning range, [kHz]	100(60)	200	200	
coarse tuner resolution, [Hz/step]	1-2	1-2	1-2	
fine tuner range, [Hz]	1200	1200	1200	
fine tuner range, [um] at T=20K (20% from RT)	*6.7*	*7.5*	*5*	
fine tuner range, [um] at T=300K	*33.5*	*37.5*	*25*	!
cavity resonance control reqs (peak), [Hz]	20	20	20	
fine(piezo) tuner resolution, [Hz]	1	1	1	
max. forces on the tuner system, kN	*11(7)*	*5*	*3.3*	
max. forces on the each piezo-capsule, kN	*6(3.5)*	*2.5*	*1.7*	

Requirements to built tuner "all size fit all" led to decision to move piezo-capsules to the side and install 4 piezo-capsules
Gain in 2 in forces and gain ½ in stoke

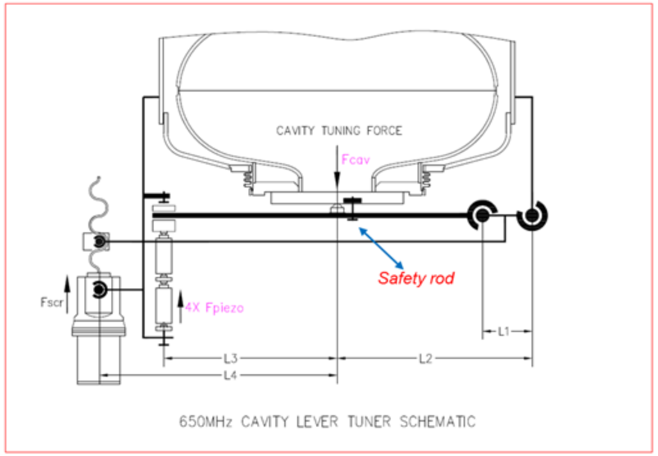
History of 650MHz Tuner design

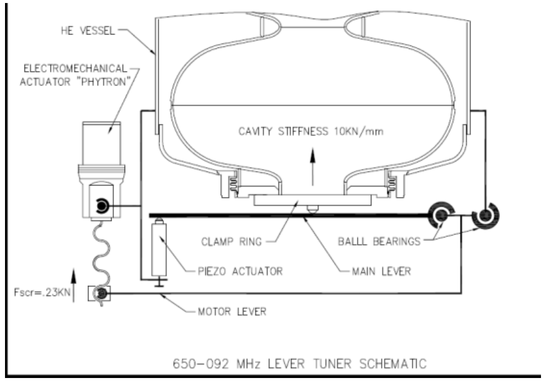


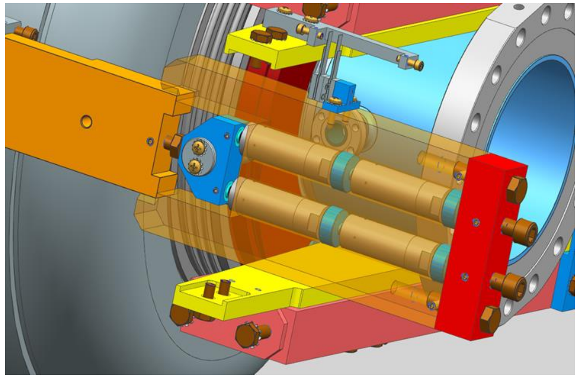


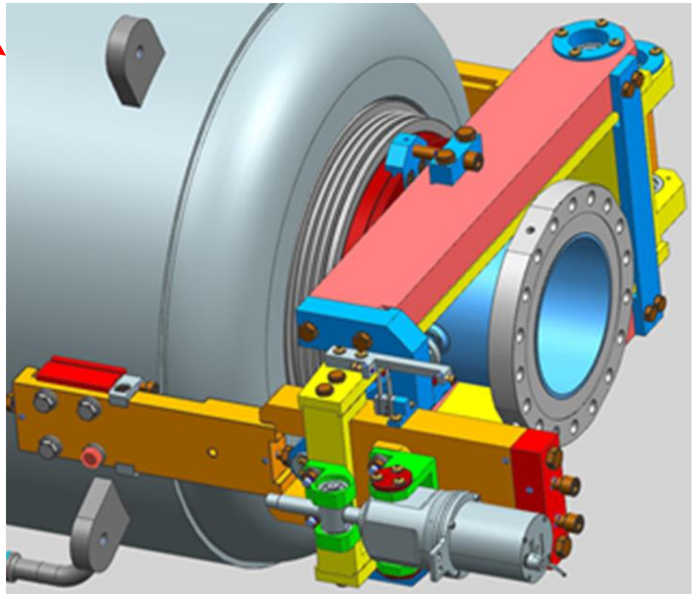


Tuner stiffness
(Ivan's simulations) ~34kN/mm

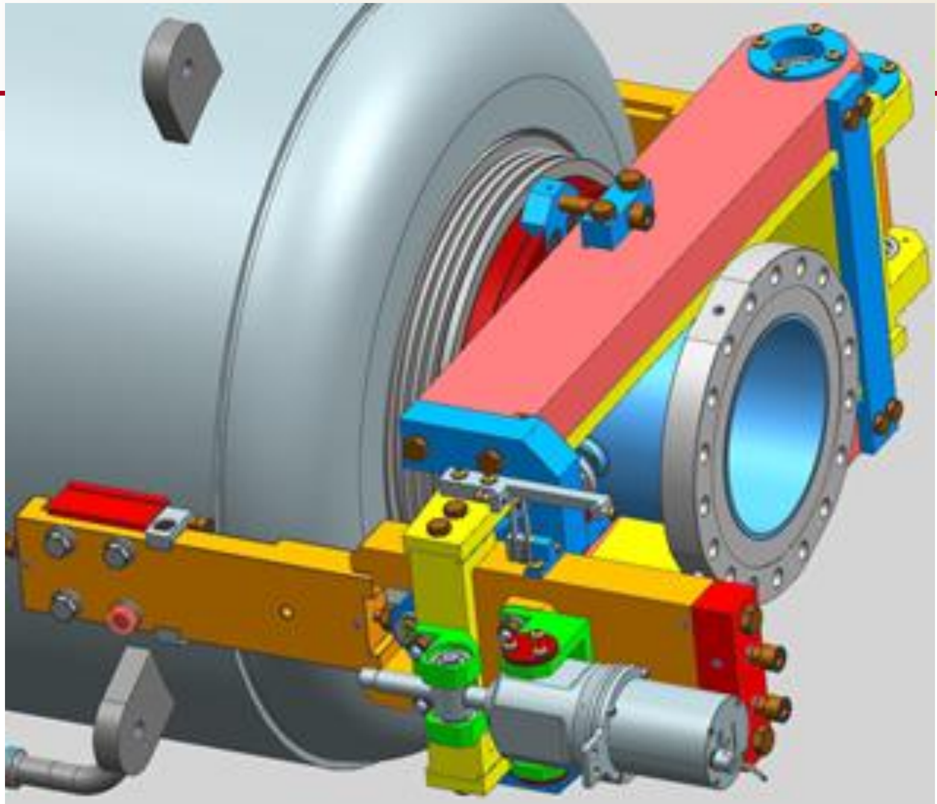




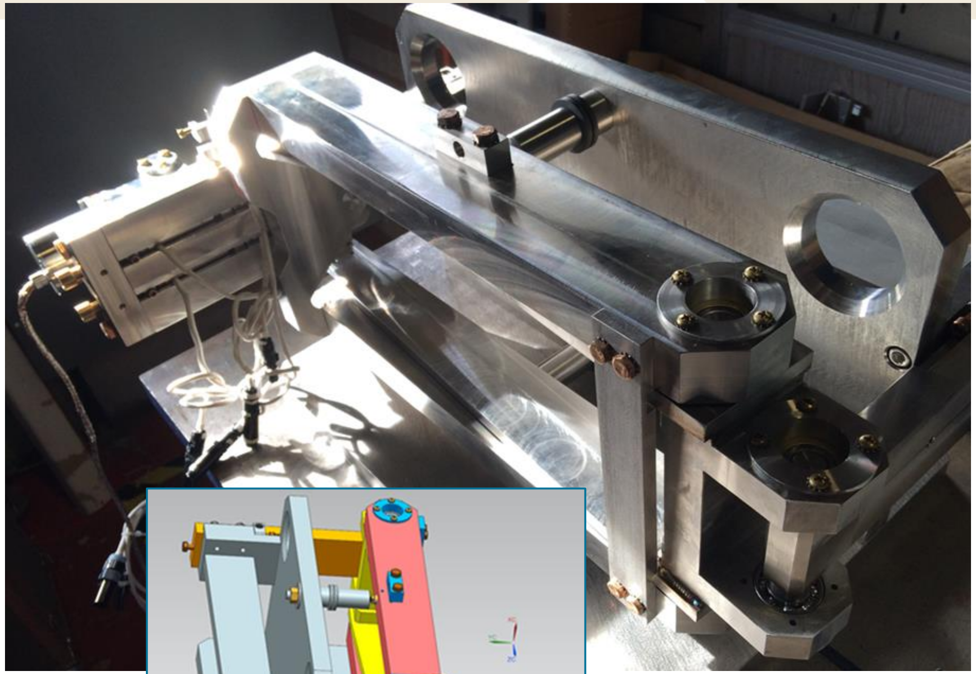


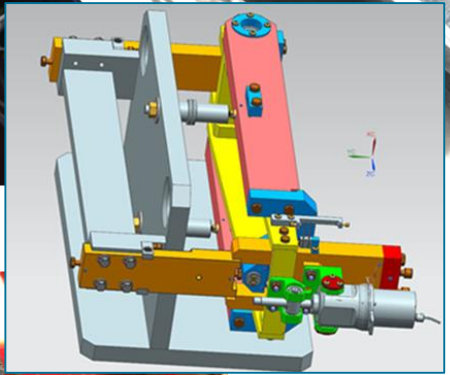


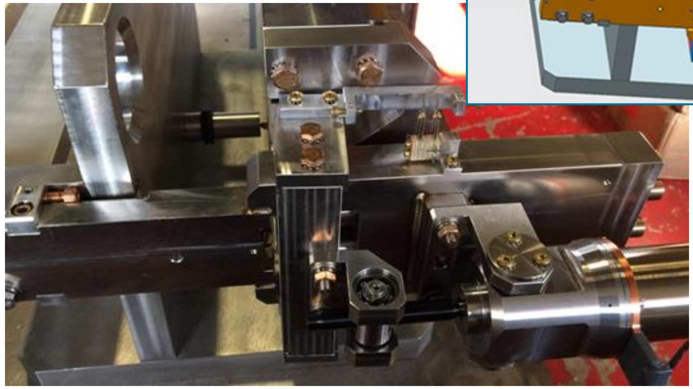
3D-model of the 650MHz tuner



First prototype tuner assembled
on the of the cavity/He vessel mock-up.
Ready for tests.





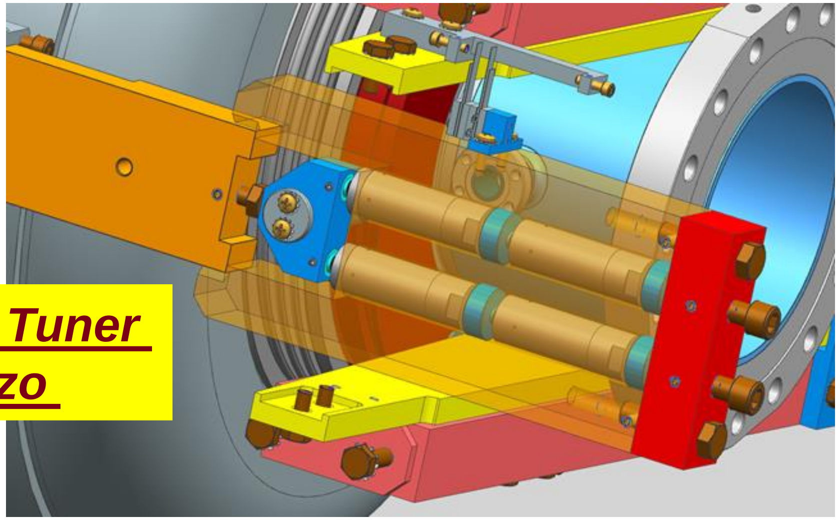


Initial ANSYS simulations (before prototype built) stated that
K_{tuner}~65-70 kN/mm .
Later we found that model/simulation was not correct… but only AFTER we built & tested first prototype.

Measurements with Prototype TUNER, mounted on the "cavity's mock-up" provided us with results that initiate TUNER MODIFICATION efforts.

1. Measured tuner stiffness is **~30kN/mm** (but not 70kN/mm as expected)
   - *Additional ANSYS expert became involved into development correct tuner model & detail simulations… NOW we have good correlation of simulations & tests results.*
2. Measured fast tuner response (stroke) was **TWO times smaller** than expected (we got at T=300K ΔX~17um instead of ~ ΔX~36um). It will translate to ΔF~700-800Hz (at T=20K)

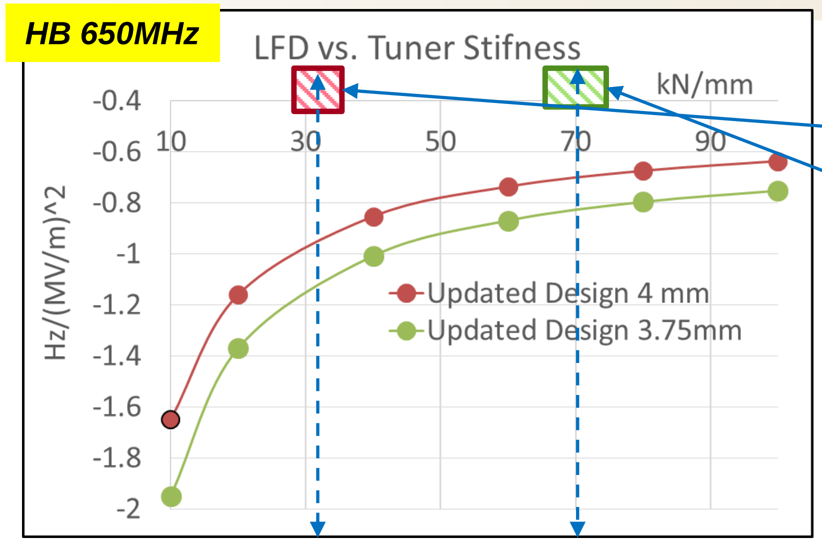
Both deficiencies (stiffness & piezo stroke) contributed to "complex" fast tuner design.

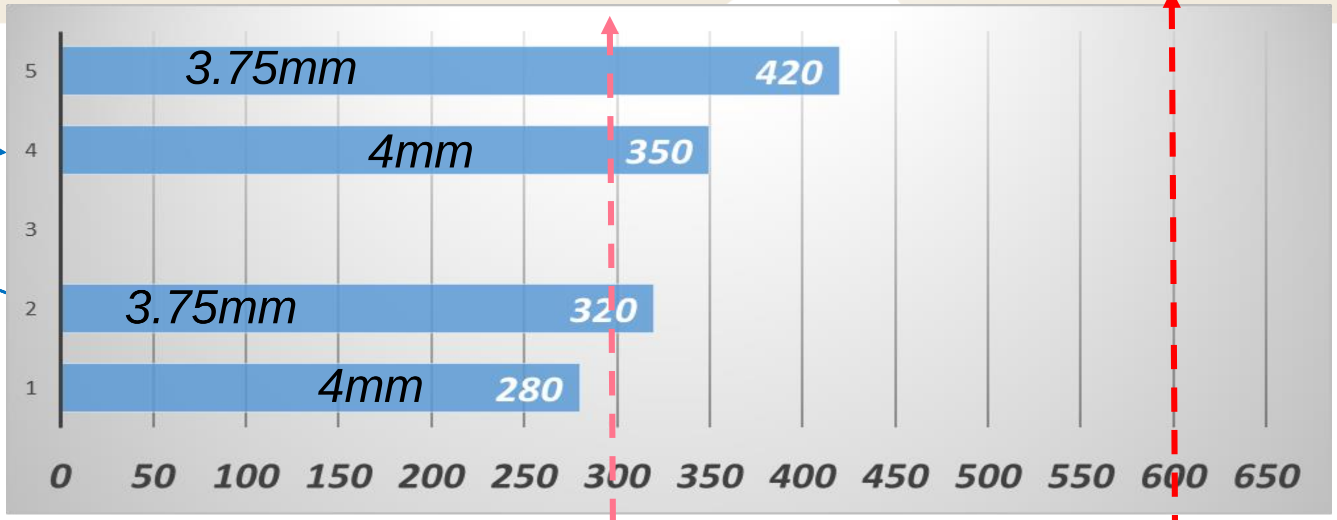


The Fast/Fine Tuner with 4 piezo

LFD static .vs. Tuner Stiffness

Estimated cavity detuning by LF (static)

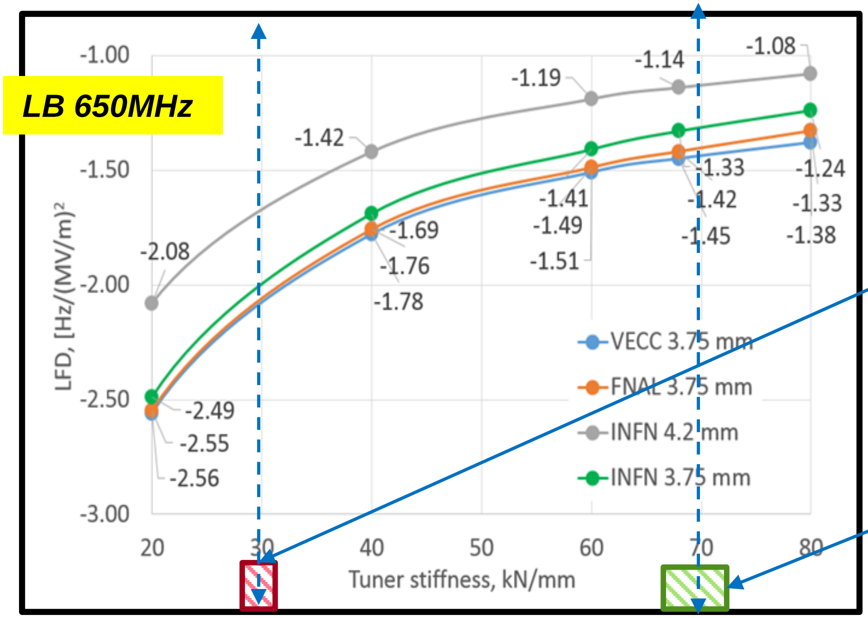




30kN/mm

70kN/mm

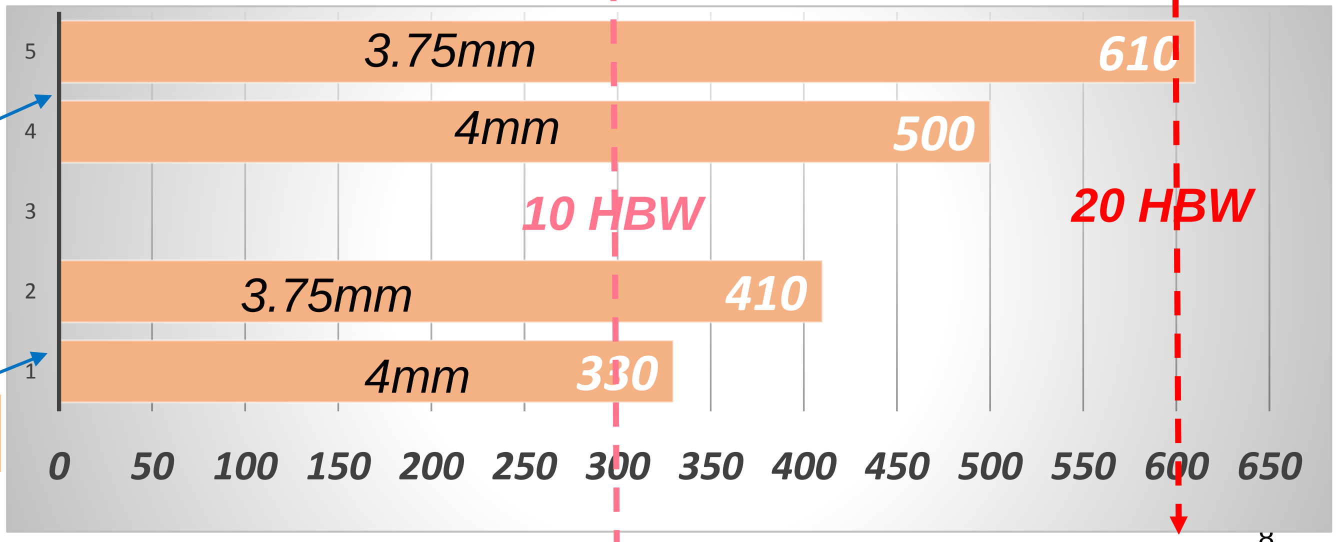
18.8 MV/m



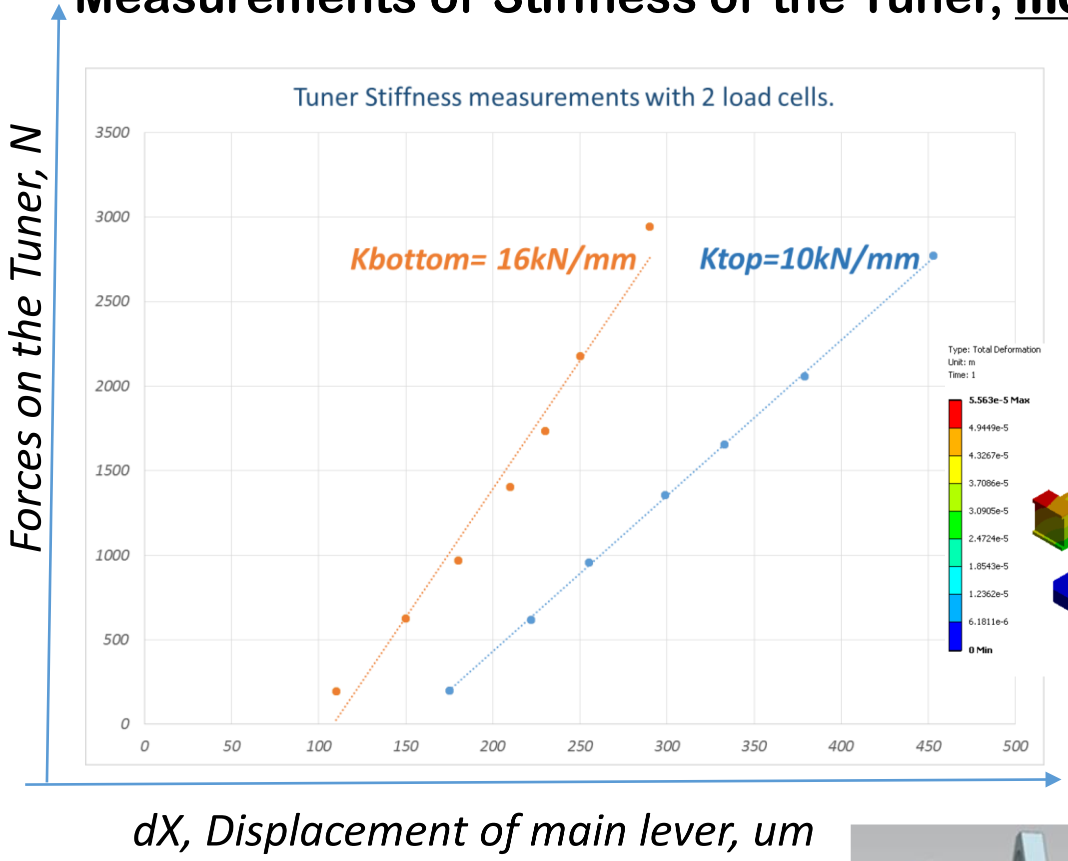
30kN/mm

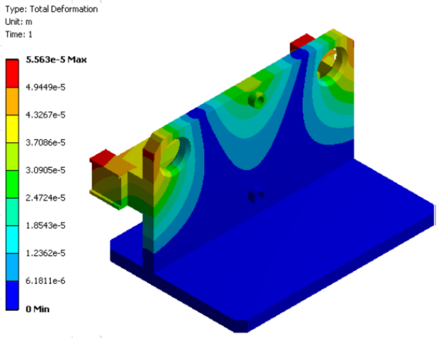
16.9 MV/m

70kN/mm



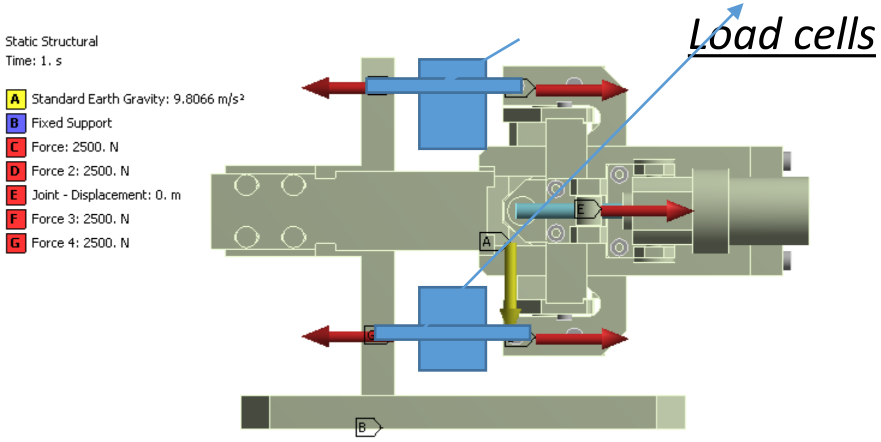
Measurements of Stiffness of the Tuner, **mounted on the test stand**

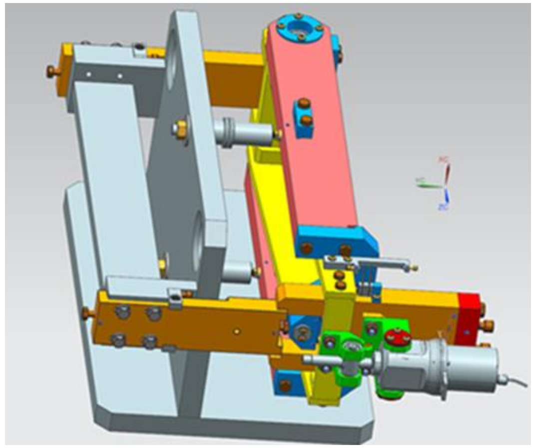




	Meas	Simul
K *top*	10	12
K *bottom*	16	20
K *tuner*	***26***	***32***

Good agreement between simulations and measurements **26kN/mm .VS. 32kN/mm**.
We contributed the slightly higher simulation K_{tuner} to the fact that simulations do not take in account bearing and fasteners..





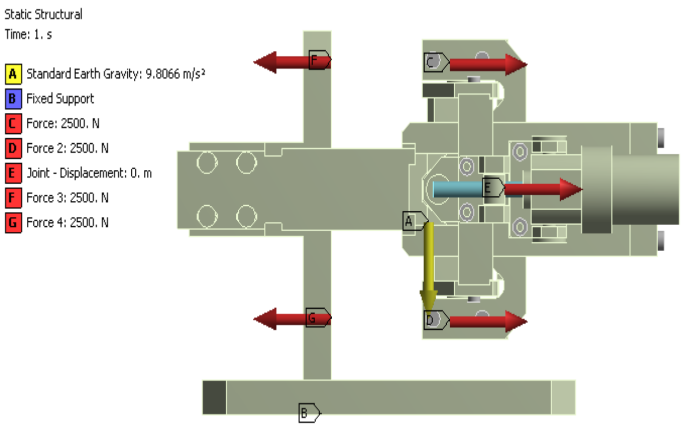
Prototype Tuner Stiffness

~30kN/mm

Tuner Model… ANSYS Simulation provided results that are close to measurements results..
Simulation tools used to optimize (increase) tuner/dressed cavity system stiffness.

Sergey Cheban is leading ANSYS Simulations efforts

GRAVITY+FORCE



TEST STAND

$$\frac{2500}{\left(\frac{2.0791e-004 + 1.9982e-004}{2}\right)} = 1.226 \times 10^{7}$$

12kN/mm

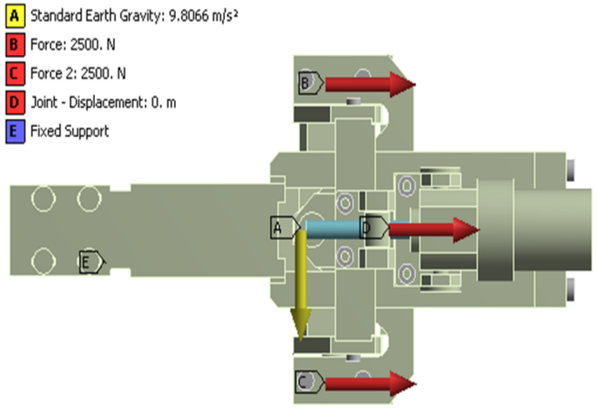
$$\frac{2500}{\left(\frac{2.0791e-004 + 1.9982e-004}{2}\right)} + \frac{2500}{\left(\frac{1.2506e-004 + 1.2115e-004}{2}\right)} = 3.257 \times 10^{7}$$

32kN/mm

$$\frac{2500}{\left(\frac{1.2506e-004 + 1.2115e-004}{2}\right)} = 2.031 \times 10^{7}$$

20kN/mm

GRAVITY+FORCE



NO TEST STAND

TUNER MOUNTED ON ABSOLUTE STIFF BLOCK

$$\frac{2500}{\left(\frac{1.2909e-004 + 1.2413e-004}{2}\right)} = 1.975 \times 10^{7}$$

20kN/mm

$$\frac{2500}{\left(\frac{1.2909e-004 + 1.2413e-004}{2}\right)} + \frac{2500}{\left(\frac{1.0926e-004 + 1.0586e-004}{2}\right)} = 4.299 \times 10^{7}$$

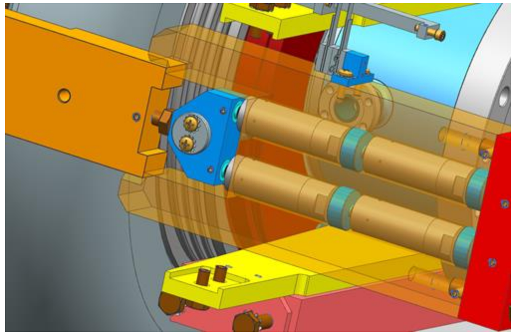
43kN/mm

$$\frac{2500}{\left(\frac{1.0926e-004 + 1.0586e-004}{2}\right)} = 2.324 \times 10^{7}$$

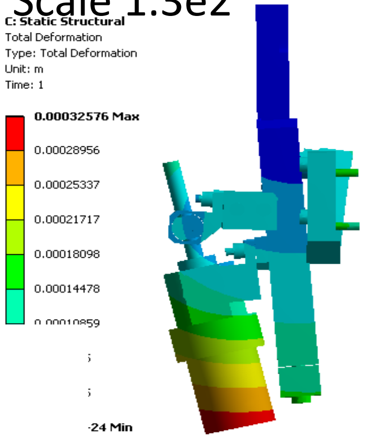
23kN/mm

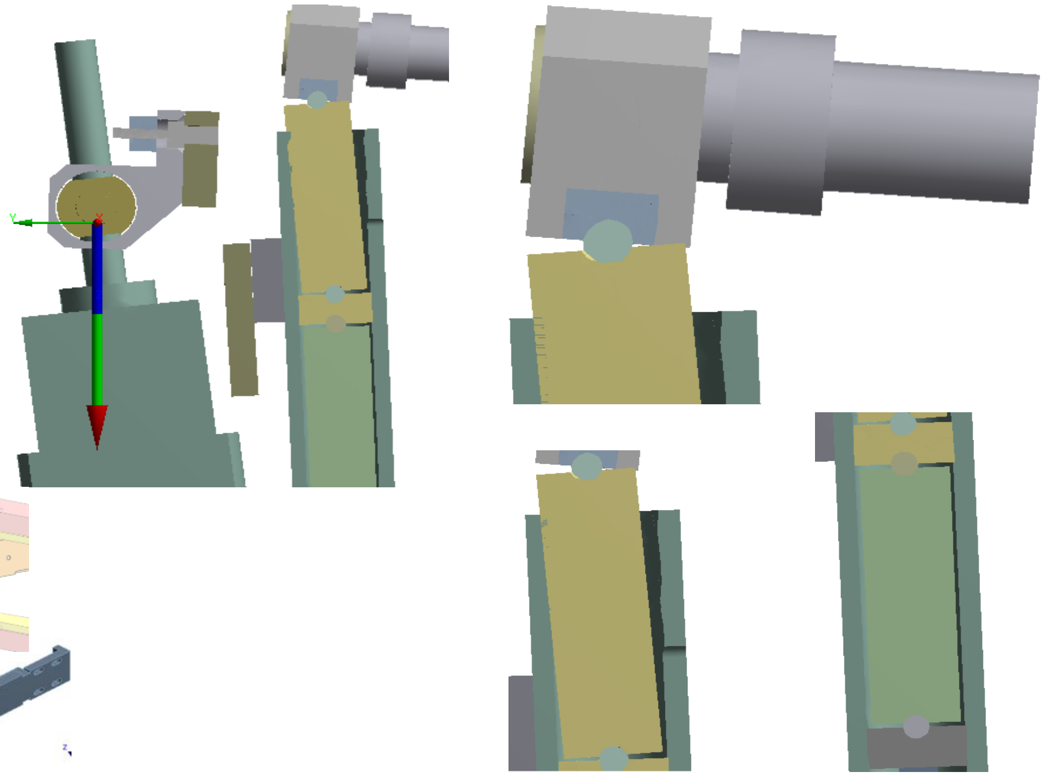
What part of the **prototype** Tuner contributed more into system stiffness ?

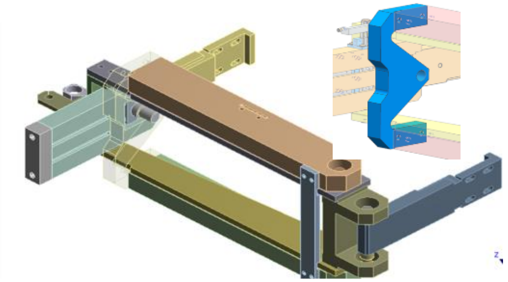
Fast/Piezo Tuner interface

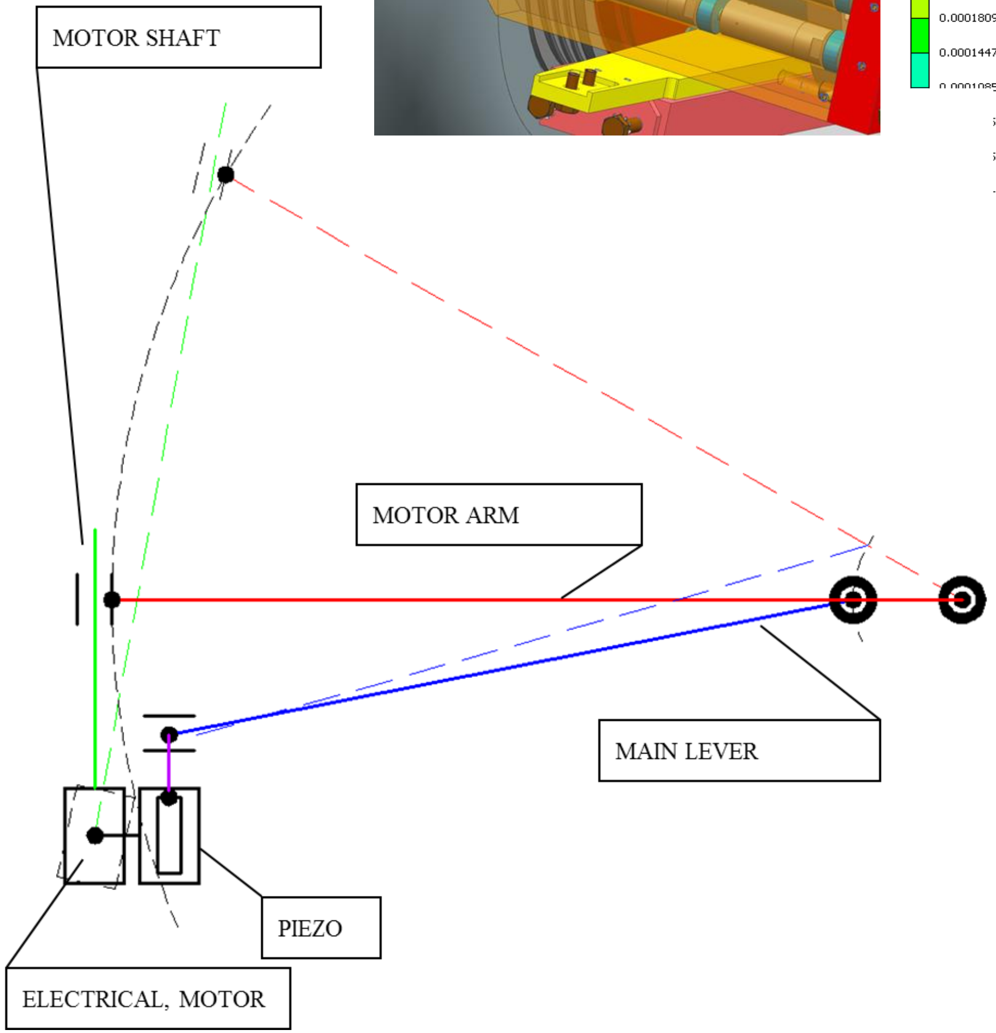


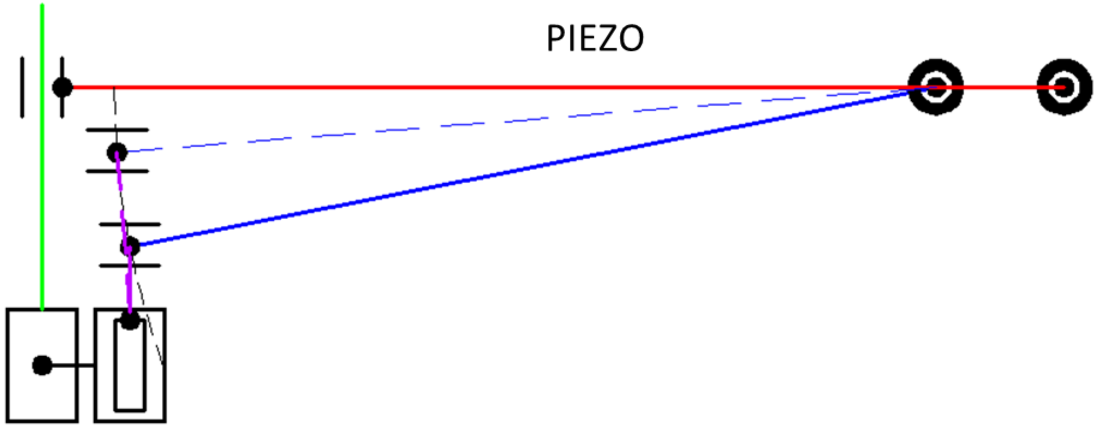
Scale 1.3e2











New (modified) Tuner Design

Decision to follow as close as possible to LCLS II Tuner Design…

- two piezo-capsule located close to cavity's He Vessel/bellow interface ring

- piezos still need to be replaceable through designated port

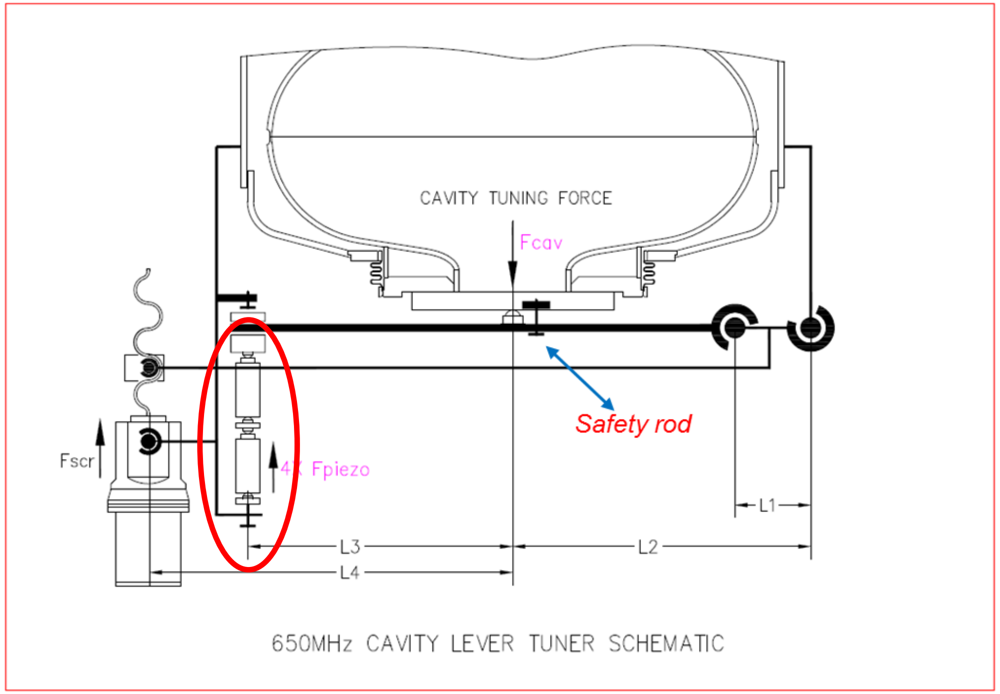
- optimization (maximization) of the $K_{\text{Tuner Stiffness}}$

- Updated ANSYS tuner model "trustful" tool to design new tuner… (from the point of view stiffness optimization)

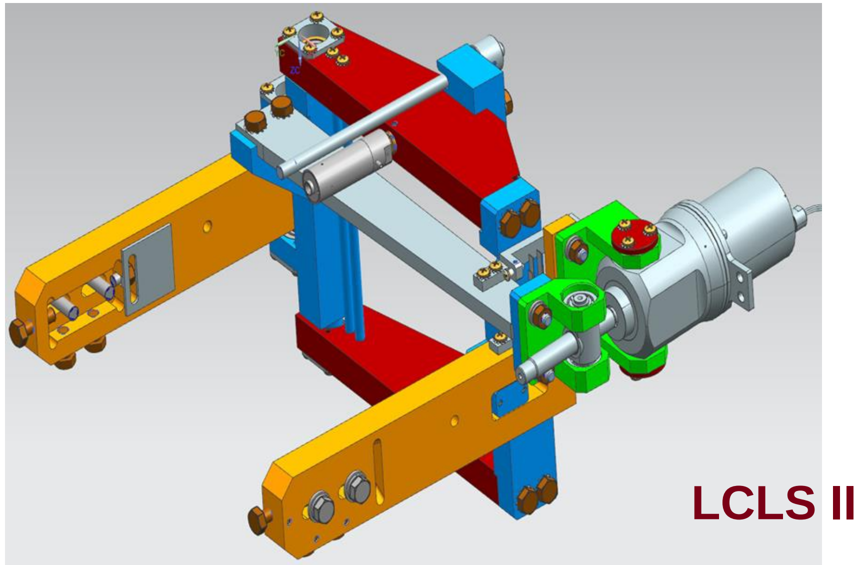
** New tuner can be used for cavity with K~20kN/mm with some limitations (shorter slow tuner range ΔF~50kHz)- to avoid piezo's overloading*

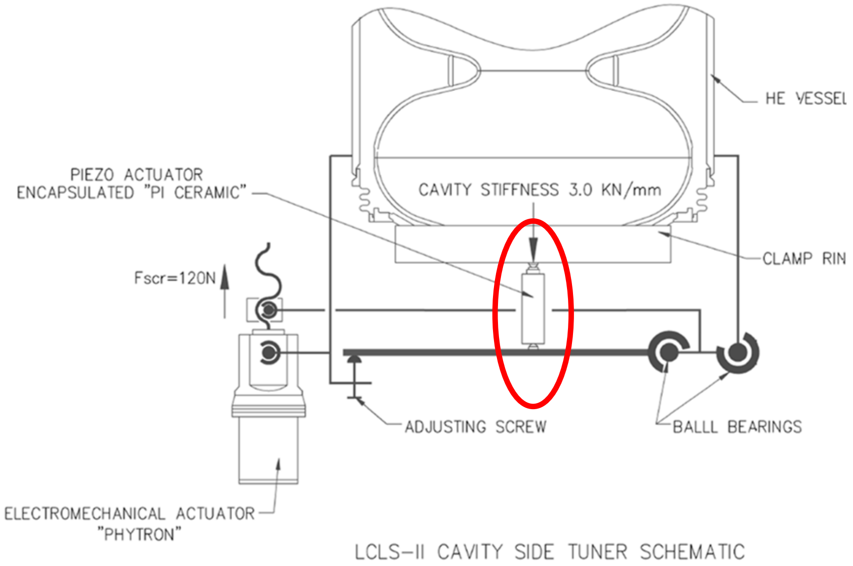
Kinematics of the LCLS II & 650MHz prototype Tuner

650MHz prototype Tuner



Piezo Location



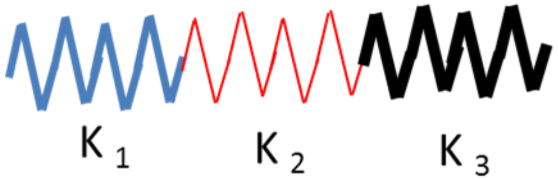


Tuner Stiffness… How stiff system we can build?

1. Important to understand that we need to talk about stiffness of the system:

"tuner-dressed cavity" that include not only "TUNER AS MECHANICAL FRAME" but also He Vessel & Tuner-to-cavity transition ring, etc…

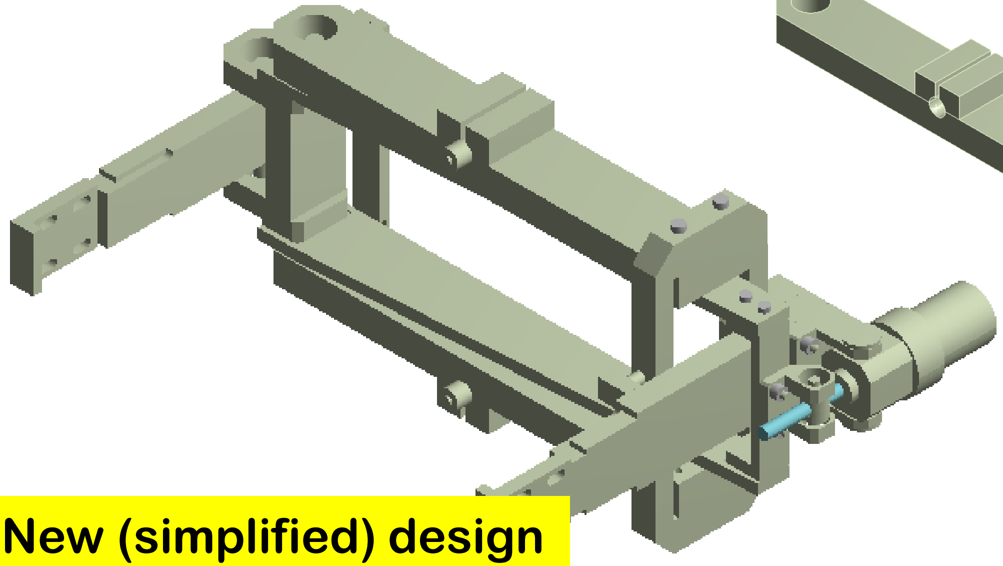
$$\frac{1}{X1} + \frac{1}{X2} + \frac{1}{X3} = \frac{1}{X}$$

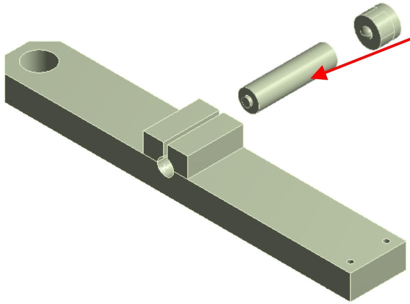


X1=100kN/mm; X2=200kN/mm; X3=300kN/mm → **X=55kN/mm**

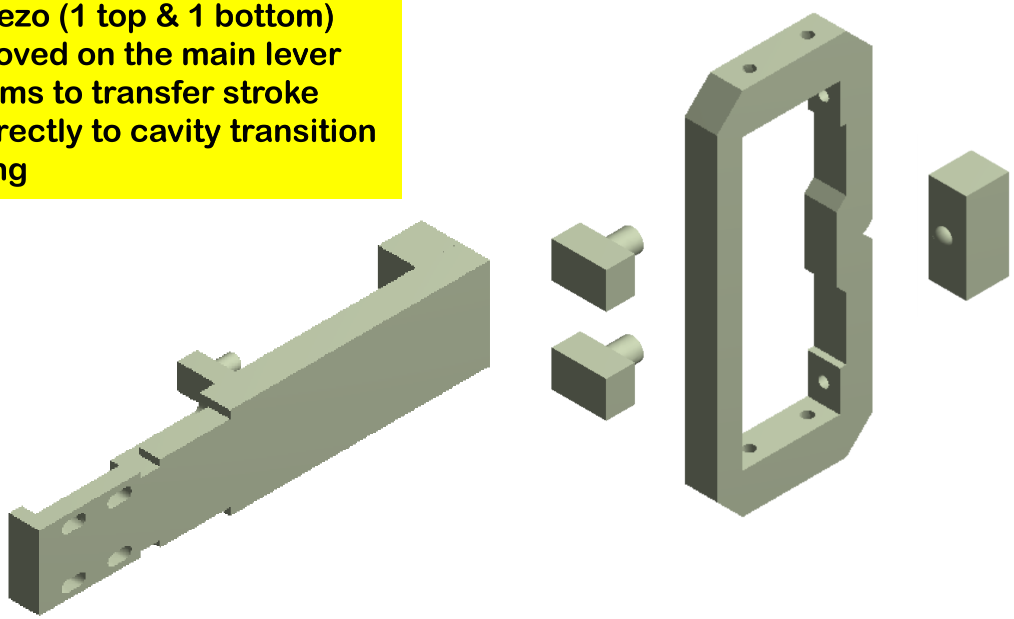
X1=150kN/mm; X2=200kN/mm; X3=300kN/mm → **X=66kN/mm**

Sergey Cheban design



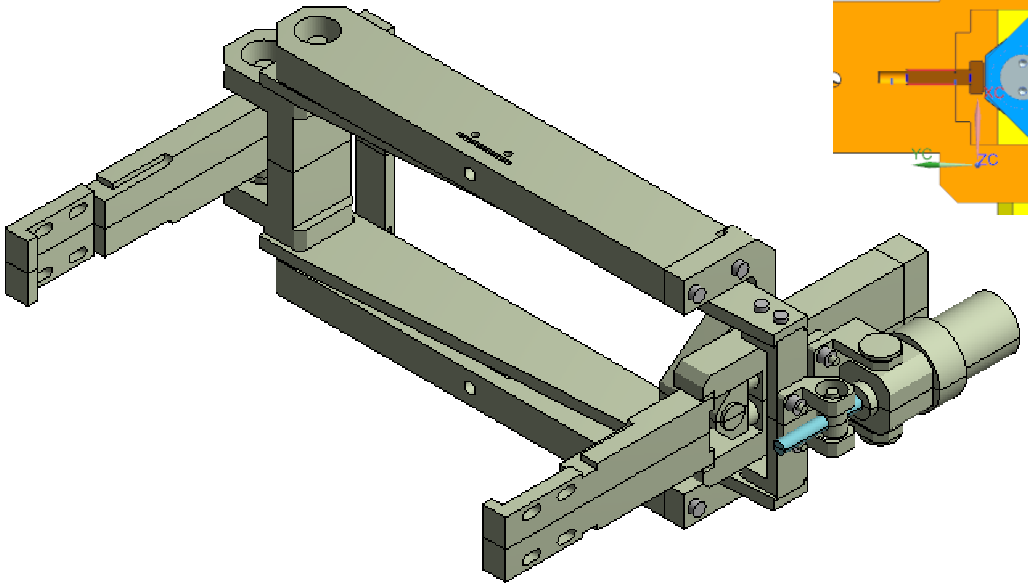


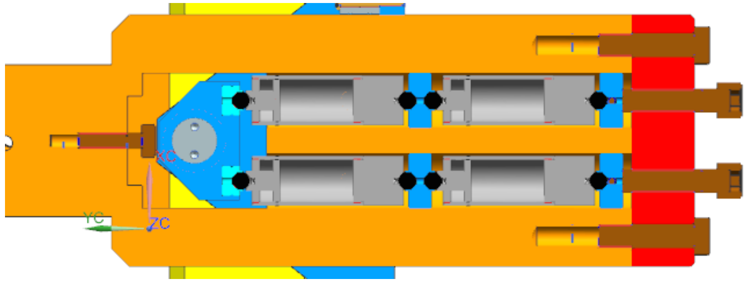
Piezo (1 top & 1 bottom) moved on the main lever arms to transfer stroke directly to cavity transition ring

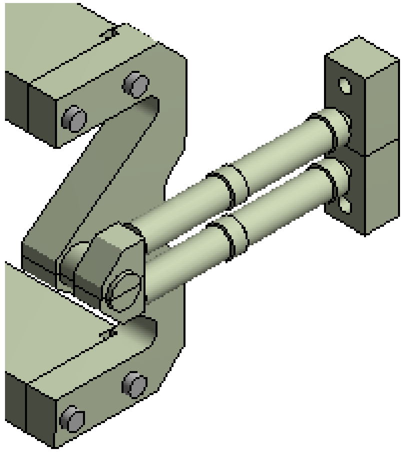


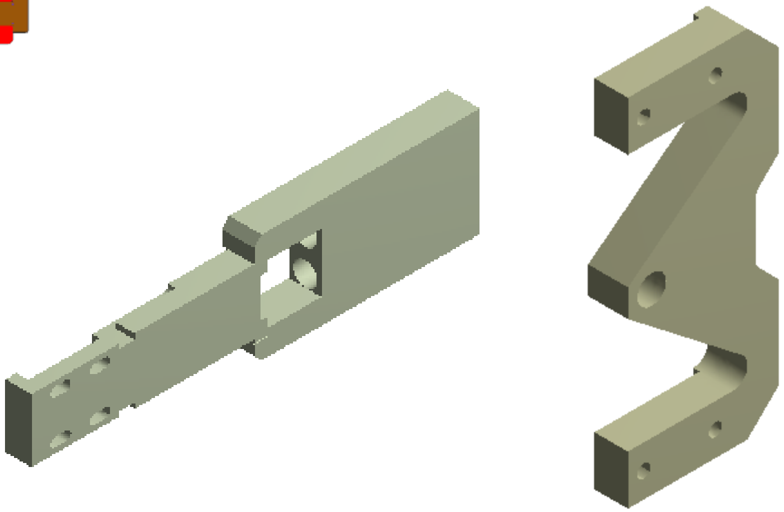
New (simplified) design

Prototype Tuner design

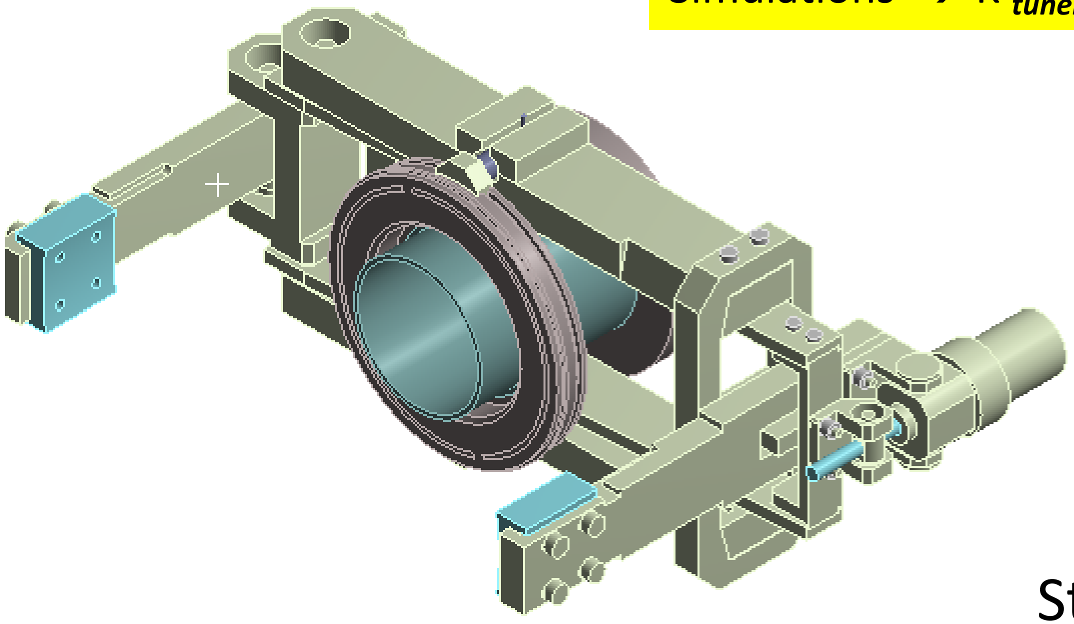


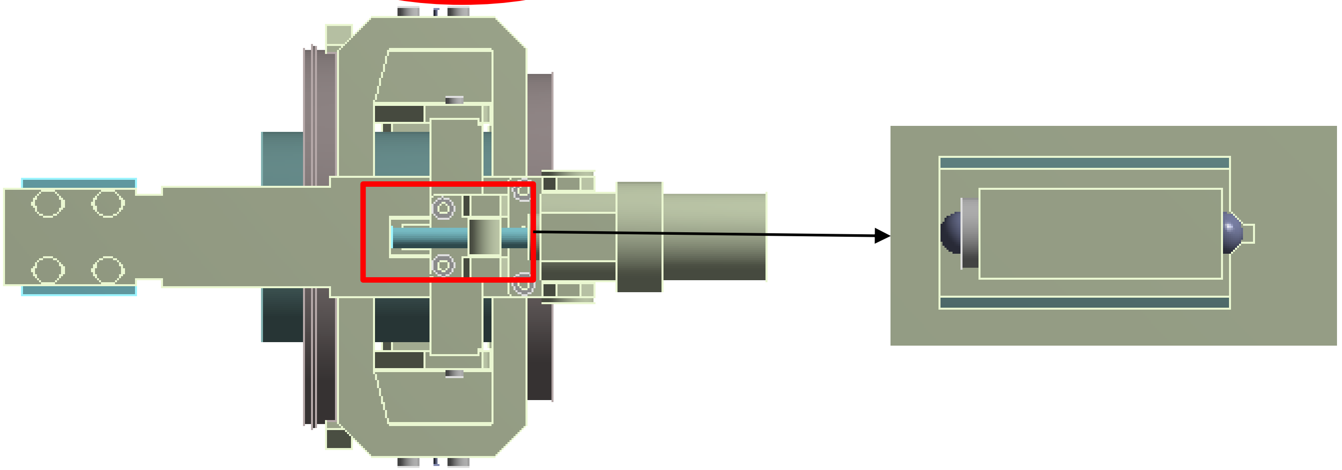






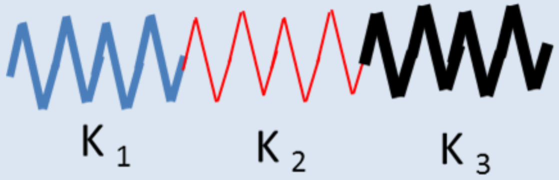
Simulations → $K_{\textit{tuner-dressed cavity system}}$ **=42kN/mm**





Stiffness of the **Tuner frame** **K_{tuner} ~140kN/mm**

without "piezo" and transition ring

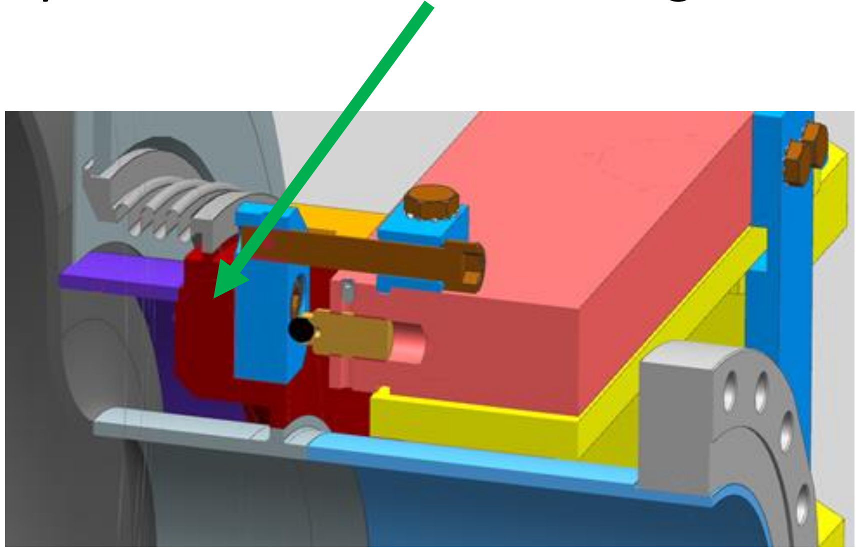


$k_1 := 100 \quad k_2 := 200 \quad k_3 := 300$

$$\left(\frac{1}{k_1}+\frac{1}{k_2}+\frac{1}{k_3}\right)^{-1} = 54.545$$

$k_1 := 150 \quad k_2 := 200 \quad k_3 := 300$

$$\left(\frac{1}{k_1}+\frac{1}{k_2}+\frac{1}{k_3}\right)^{-1} = 66.667$$

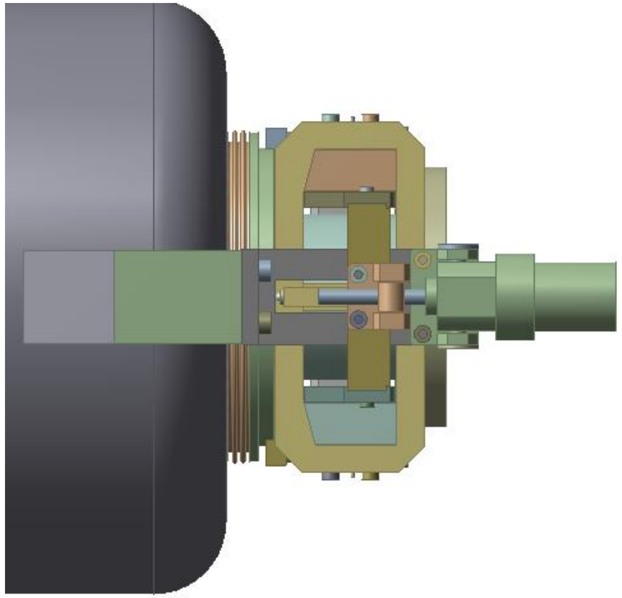


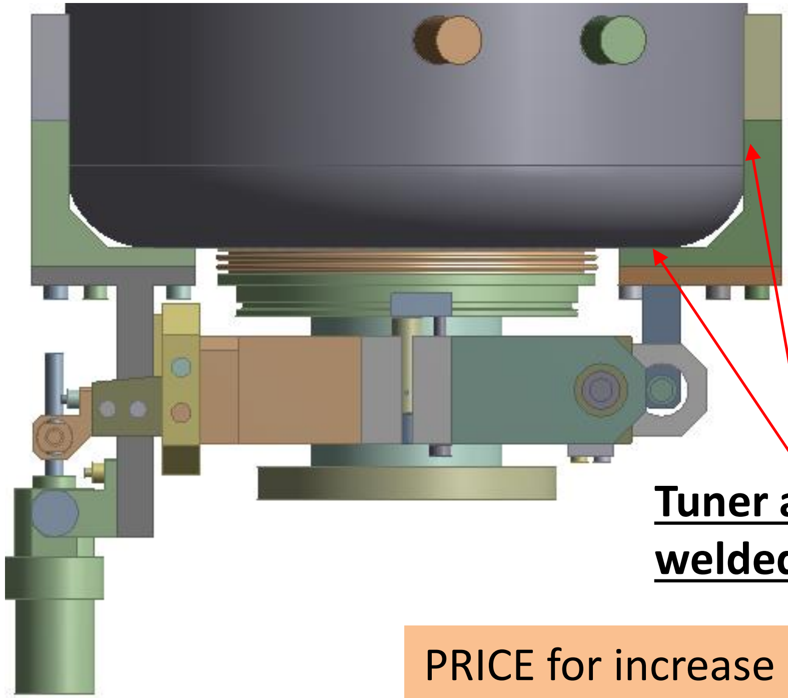
Latest upgraded version of the tuner with highest stiffness so far…

Simulations → $K_{\text{tuner-dressed cavity system}}$ **=55 kN/mm**

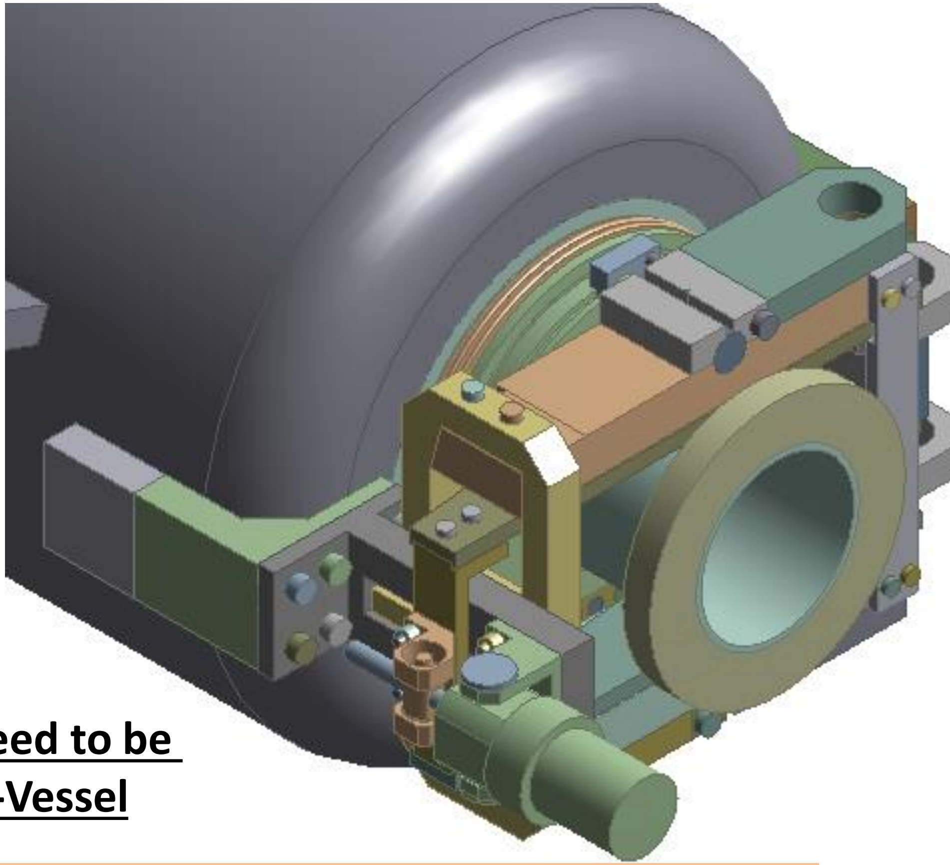
Stiffness of the Tuner frame K_{tuner} **~600kN/mm**

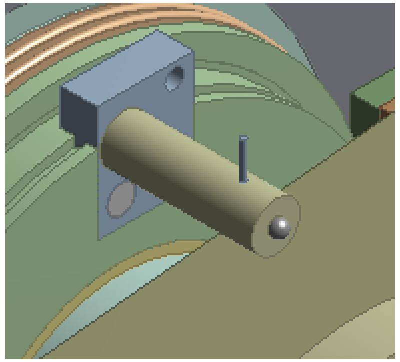
without piezo and transition ring

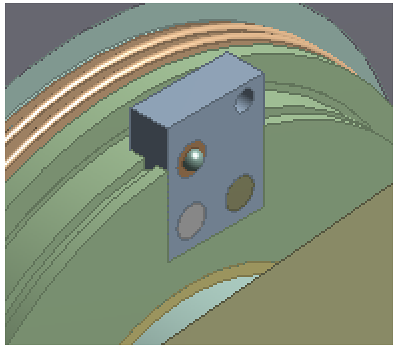




Tuner arms need to be welded to He-Vessel







PRICE for increase of Tuner frame stiffness in **3-4 times**:

(but increase of $K_{\text{tuner-cavity}}$ stiffness from 42 to 55kN/mm)

Significant modifications/ of the He Vessel /Tuner interface…

(a) arms must be welded to He vessel at several places..

(b) more complex adjustment of the tuner to cavities with different length

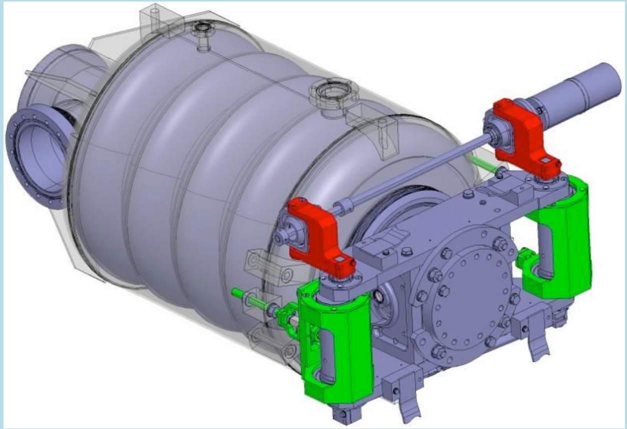
(c) endcap magnetic shielding (?)

(d) etc…

Summary
of Tuner/Dressed cavity system stiffness studies

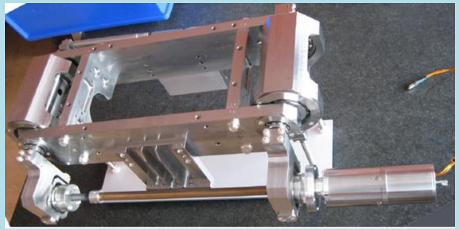
- Possible to design Tuner frame with stiffness several 100’s of kN/mm
- But it is close to impossible (without significant re-design of whole concept of dressed cavity & new piezo-capsule) to have stiffness of the tuner/dressed cavity system above 50kN/mm
- **We need to review parameters of the cavities (particularly LFD) with assumption that stiffness will be ~ 40kN/mm**

Examples of the large size cavities with tuner



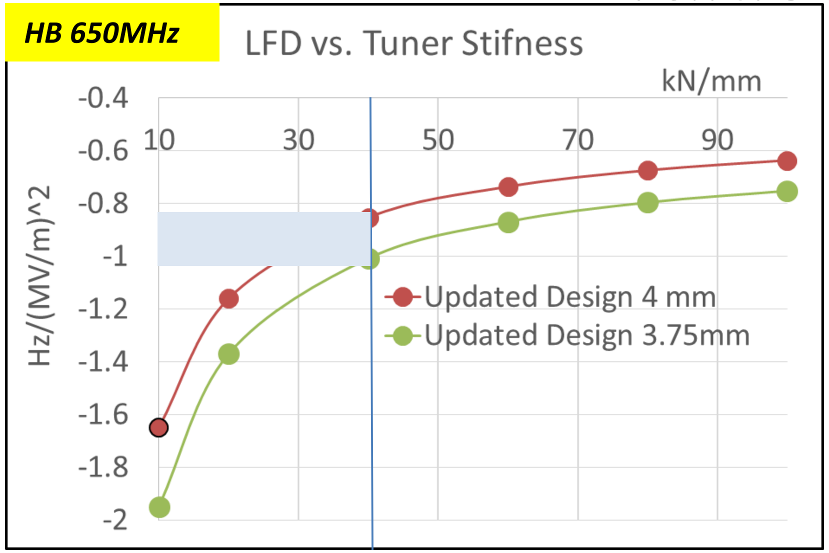
CERN (SPL) 704MHz 5-cell SRF cavity

$K_{tuner/vessel}$=23kN/mm



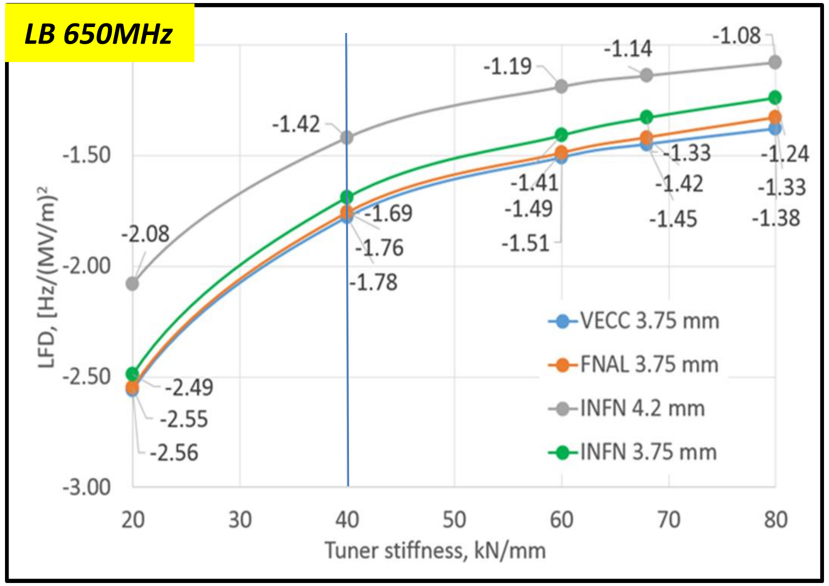
Lorentz Force Detuning (static)

values of expected (with 40kN/m)



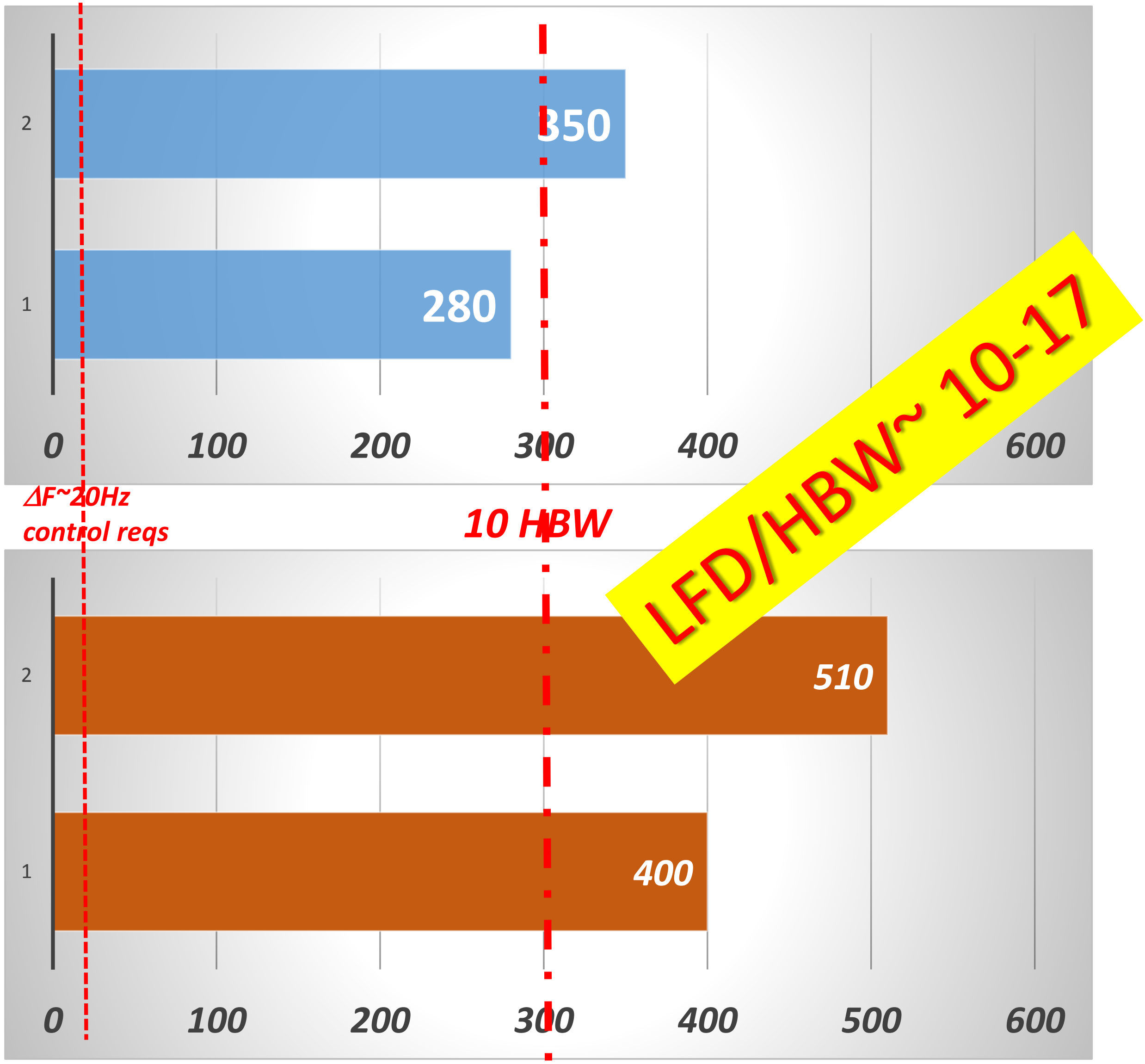
E_{ac}=18.8 MV/m

$K_{LFD\text{-}Static}$=0.8-1.0

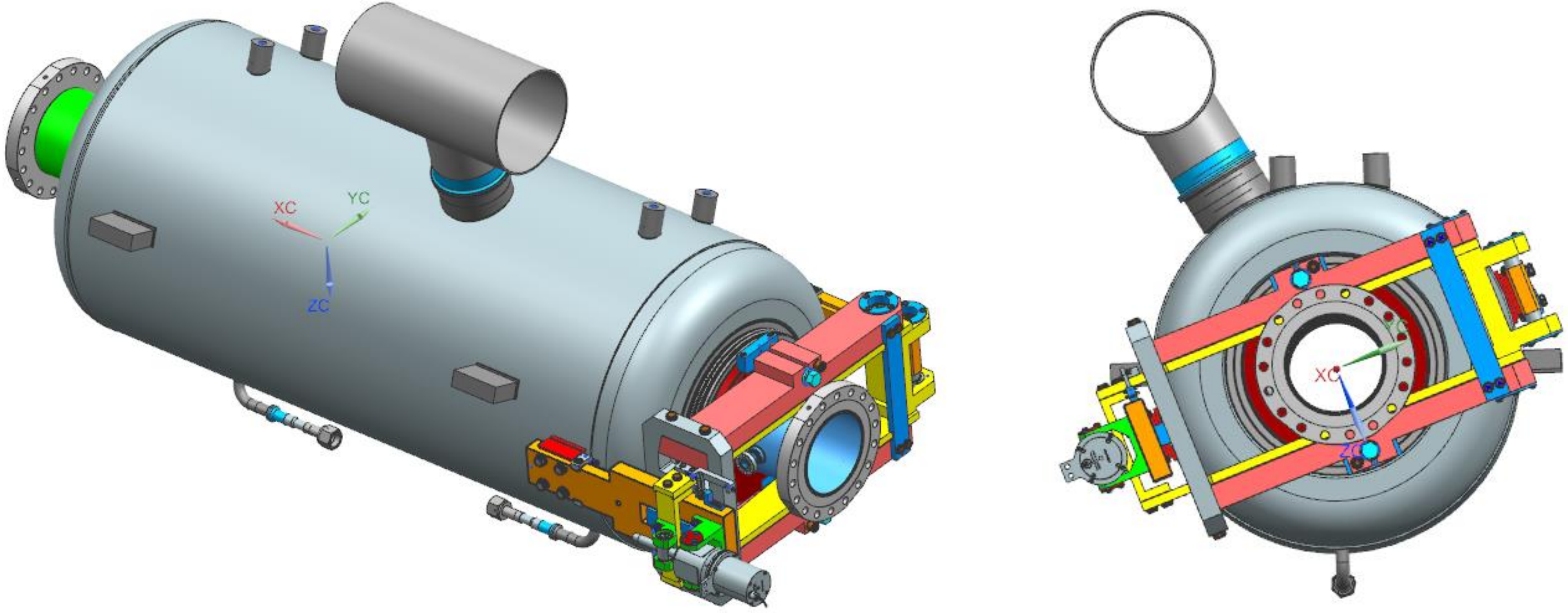


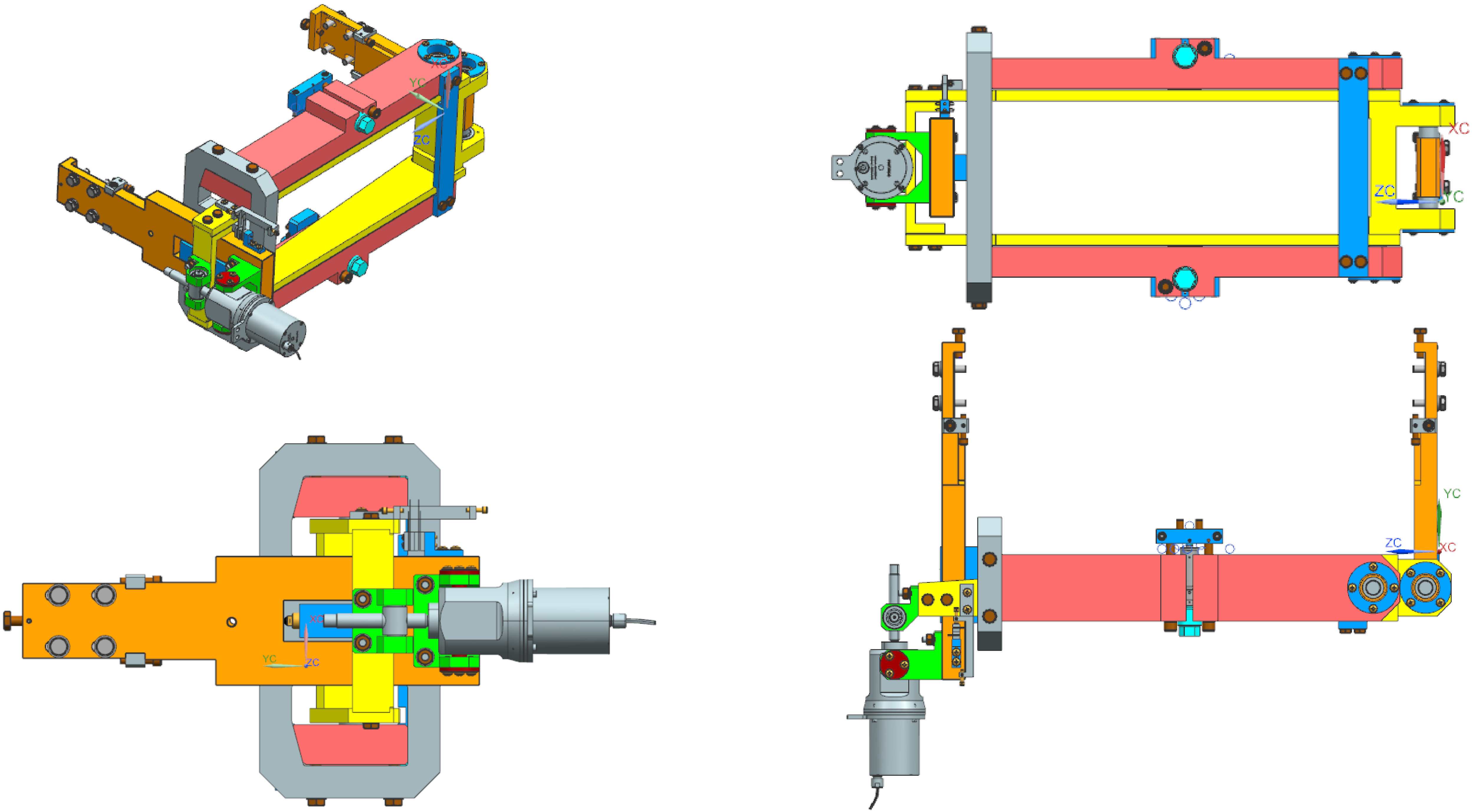
E_{ac}=16.9 MV/m

$K_{LFD\text{-}Static}$=1.4-1.8



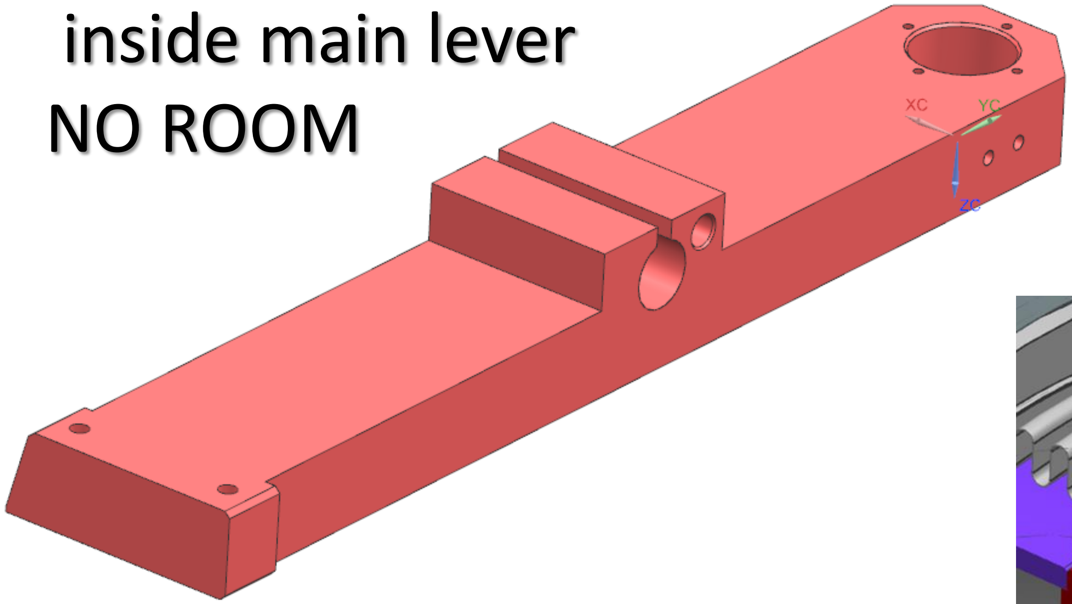
New Tuner for LB/HB650MHz

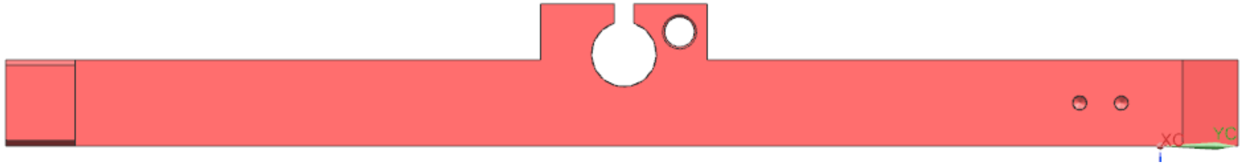


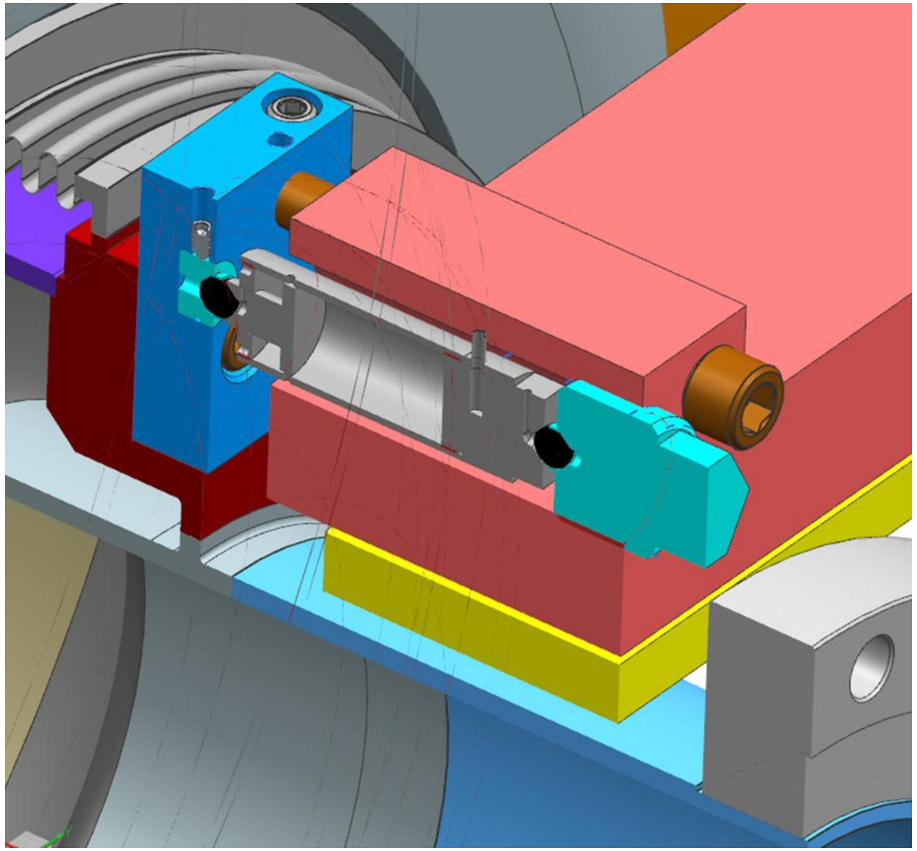


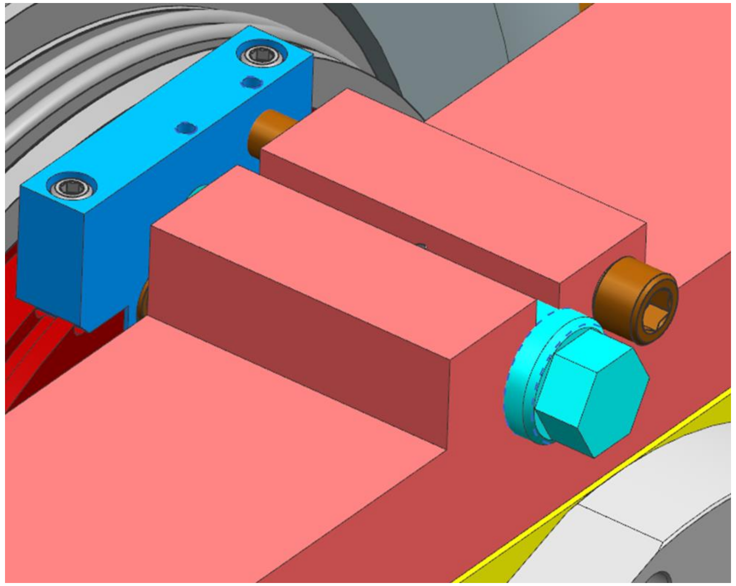
XC
YC
ZC
XC
ZC
YC
XC
YC
ZC
YC
ZC
XC

Housing of the piezo-capsule
inside main lever
NO ROOM

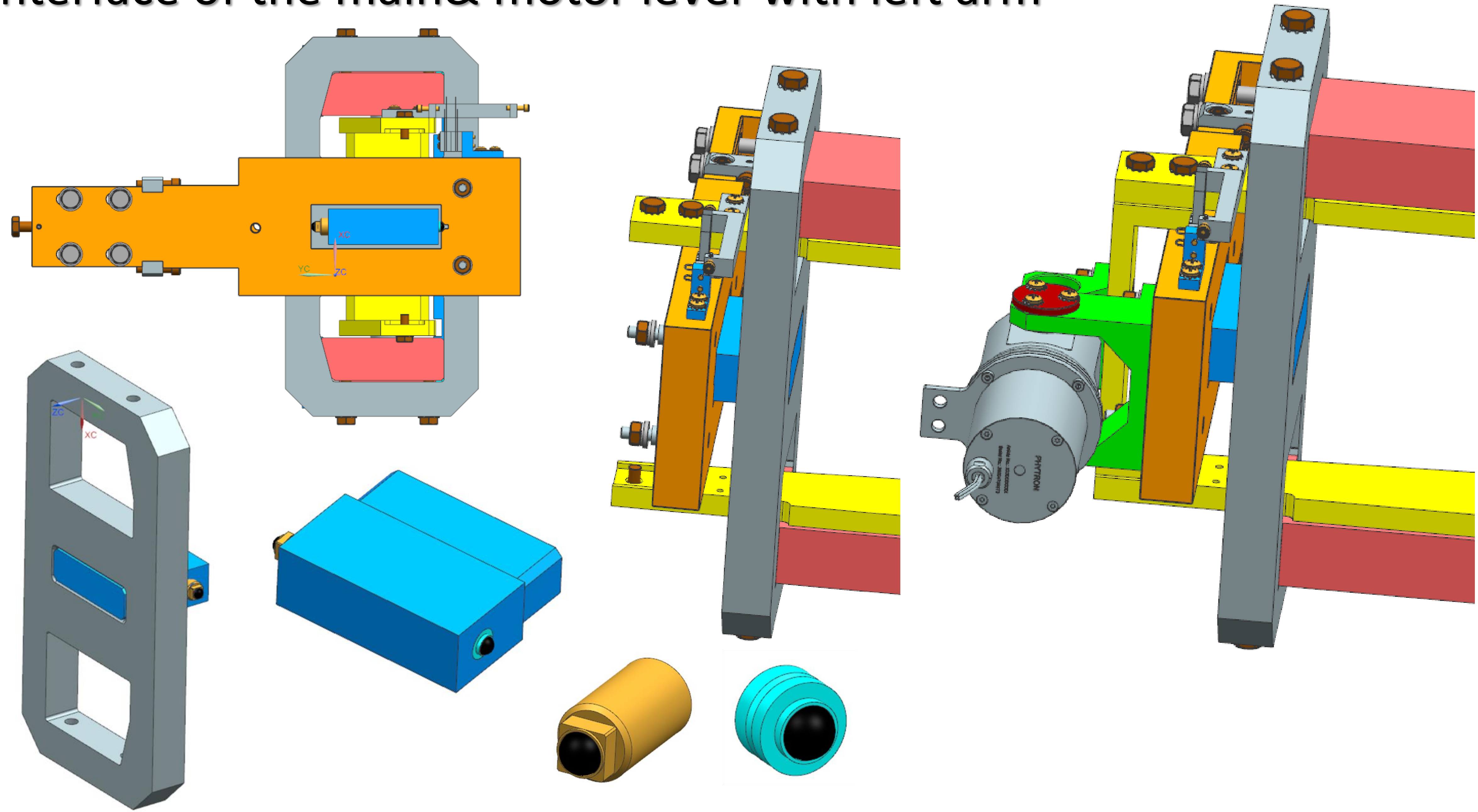


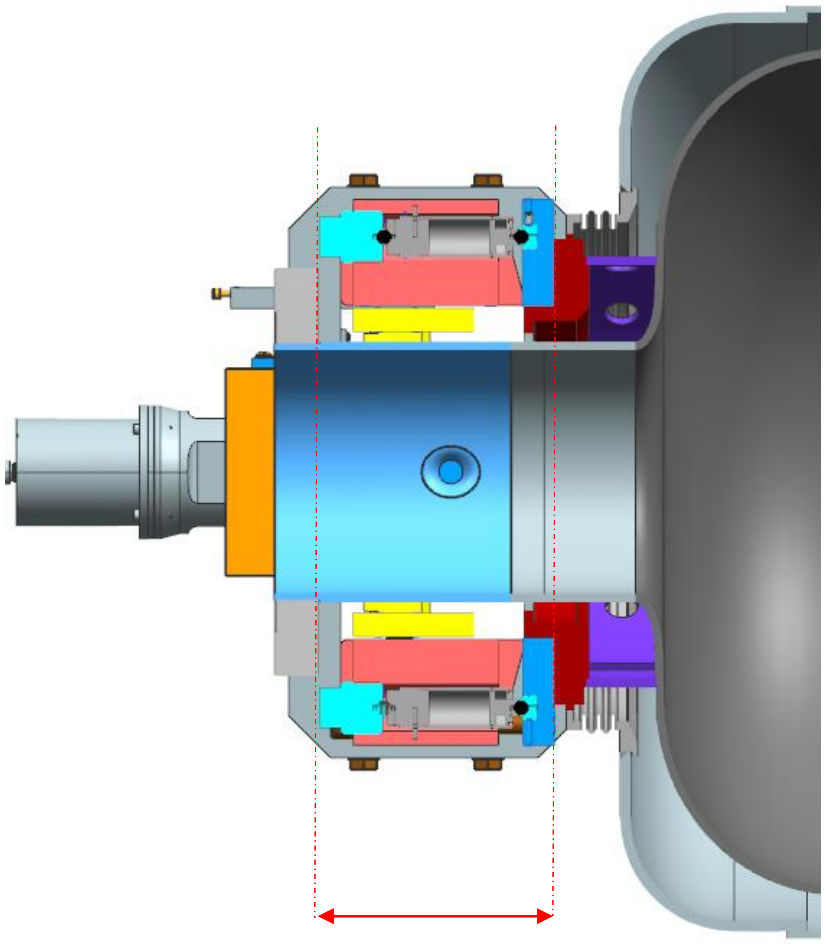


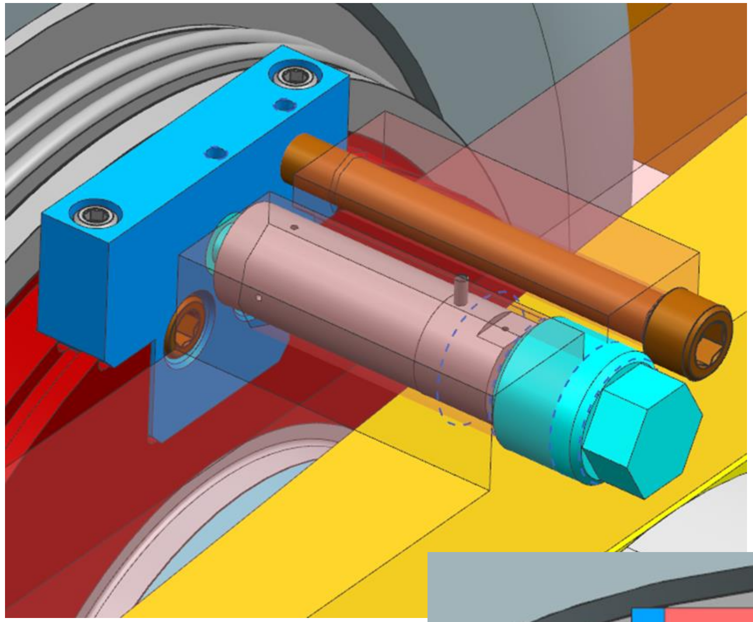




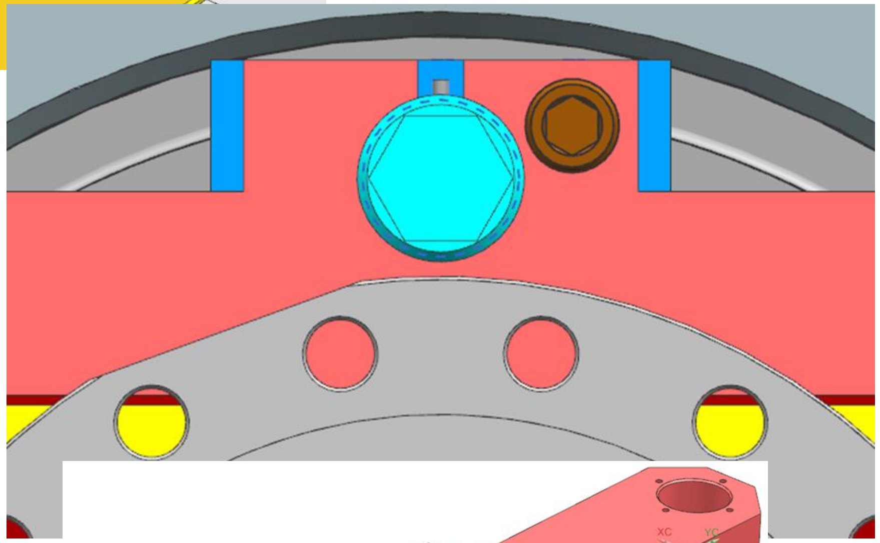
Interface of the main& motor lever with left arm

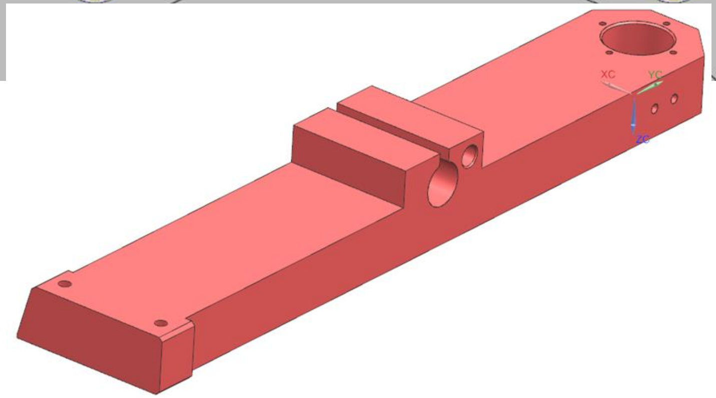






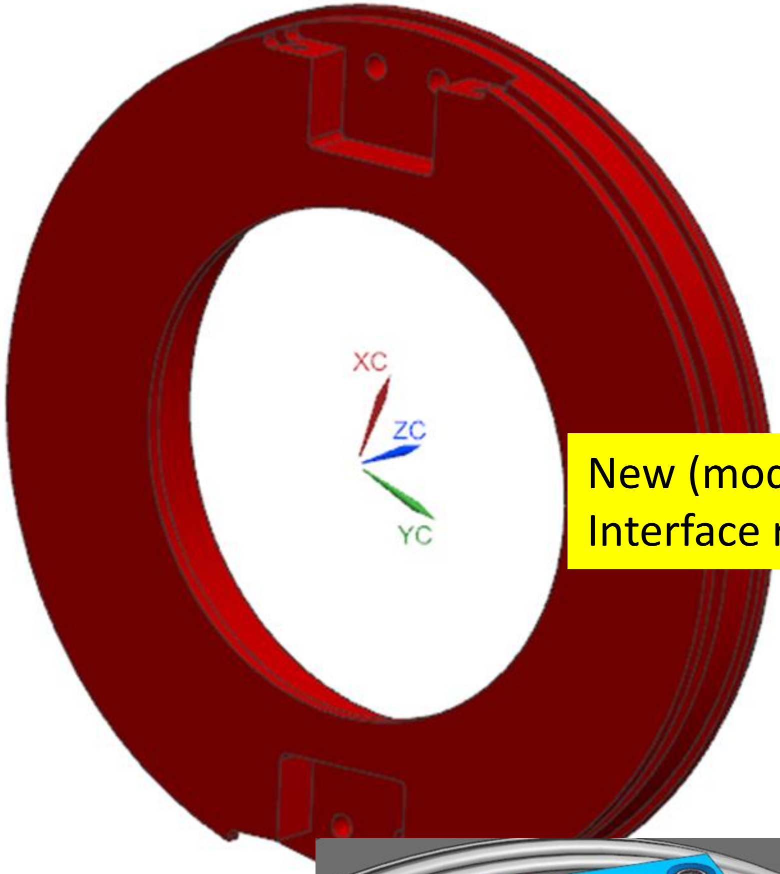
Cavity/tuner interface
piezo –to – NbTi ring

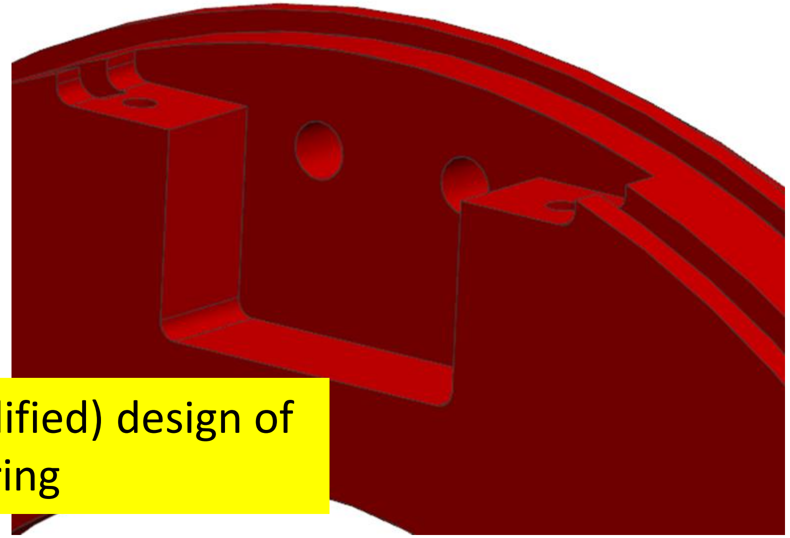




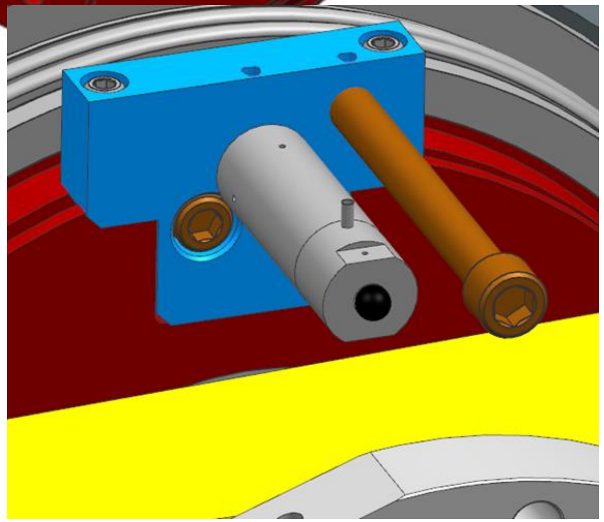
Why we "put ourselves into difficult position"
By making short beam-pipe ➔
limiting available space for tuner ???

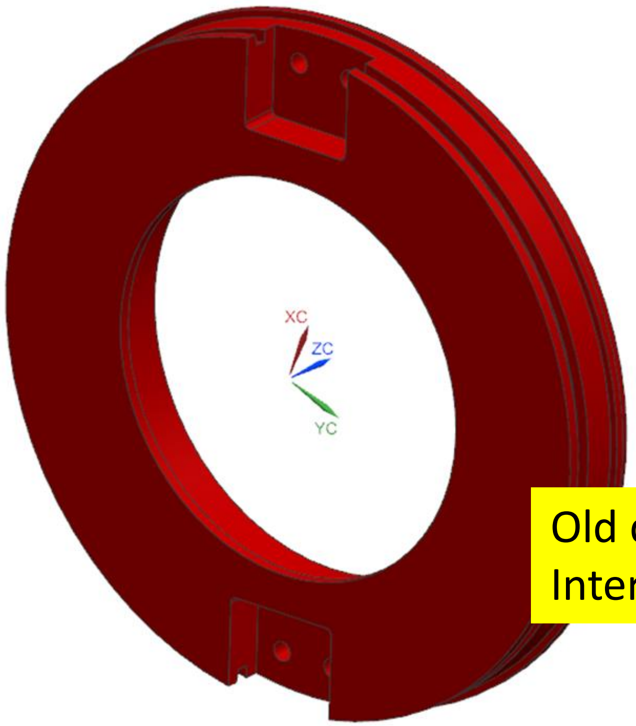
Cavity/tuner interface piezo –to – NbTi ring

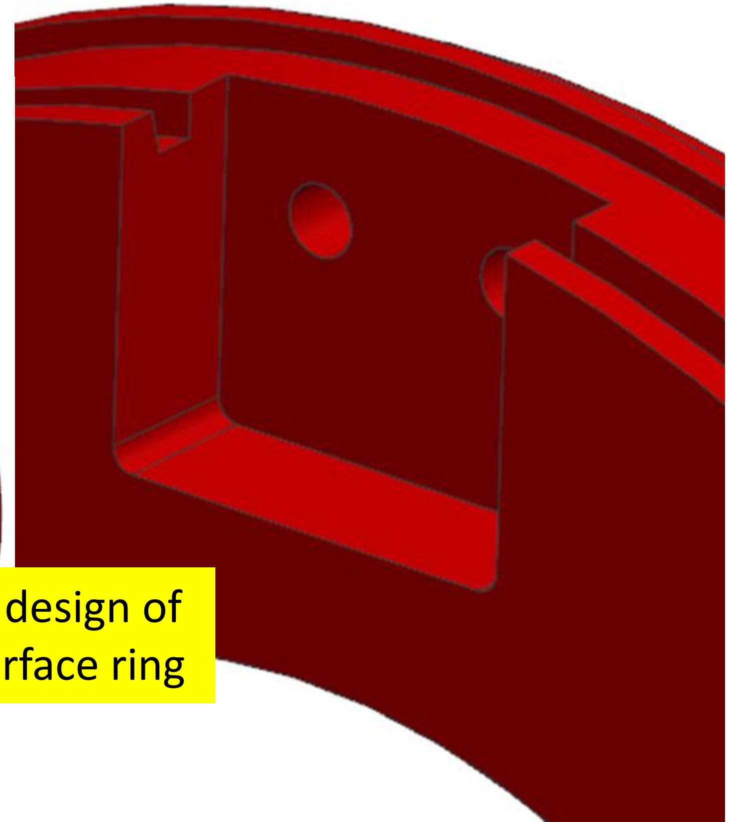




New (modified) design of Interface ring







Old design of Interface ring

Fast Tuner Piezo Stroke….

- Based on
  - the similarity of the LCLS II & 650MHz tuner design
  - On the stiffness of the 650MHz cavity ~4kN/mm
  - On the $\Delta F/\Delta L$ of the 650MHz ~200kHz/mm
  - On the LCLS II tests of piezo tuner

We are expecting that fast tuner tuning range

at T=2K for V_{piezo}=100V   will be **ΔF~2kHz**

Questions for Discussion

- What reasons are preventing us from make cavity's Nb beam pipe longer?
  - It will simplify tuner installation/replacement piezo-capsules
  - It will be not close options to make piezo-ceramics actuator longer… increase lifetime of piezo
- We need slightly change design (dimensions of the notch to mount bracket for piezo push point & safety rod)
  - It will increase stiffness of the overall system
  - It is important for translation from piezo to cavity stroke in the range of 10's of nanometers

Overall status of LB/HB650 Tuner

- ~~Model is ready~~
- ~~Will be reviewed by TD/SRF engineers~~ **DONE**
- Drawings will be ready in 2-3weeks **(STARTED)**
- Procurement & machining can be done in the scale of couple month
- Previous tuner production cost ~$17k
- New tuner tests (stiffness & piezo stroke) assembled on the "cavity mock-up" stand can be done during 2-3 weeks
- Warm Tuner design verification program will significantly benefit if tuner can be assembled and tested on the dressed cavity

What Lorenz force detune could we tolerate (compensate…)?

1. In all previous slides references were to simulated average STATIC detuning
2. Even if we assume that STATIS=Dynamic we also need to take into account that distribution of detuning from cavity-to-cavity is quite WIDE (σ ~30%)… and tuner/algorithms must be able to deal with highest possible detuning (not just average)…

3. Dynamic (RF-pulse mode) LFD detuning is function of
   1. RF-pulse length (fill-time; flat-top & decay)
   2. RF-pulse repetition rate….
   3. And of course, mechanical resonances (frequency & Q) of the cavity/He vessel/tuner/piping structure

Strategy and Status of the R&D – Resonance Control

PIP II LB/HB 650MHz cavities will experience LARGE LFD.
Operation with rep. rate 20Hz will add significant microphonics (residual vibration from previous pulse).
Cavities Resonance Control for narrow bandwidth cavities with ratio
LFD/HBW ~20 is extremely challenging:

- Large Lorentz Force Detuning
- Significant residual vibration/ excessive microphonics

Pulsed SRF accelerators, existing and projects	Cavities Half-bandwidth, Hz	LFD, Hz	LFD/HBW
SNS (LB/HB)	550/500	300/100	0.55/02
ESS(HB)	500	400	0.8
FLASH/XFEL	185/141	550	3/4
PIP II (LB/HB)	29/29	*300/500*	*10/17*
MaRIE	50	1000	20

Lorentz Force Detune is an issue!

FNAL's Resonance Control experience

Developed at FNAL Feed-Forward
Adaptive LS Lorentz Force Detuning Algorithm

(RF-pulse mode)

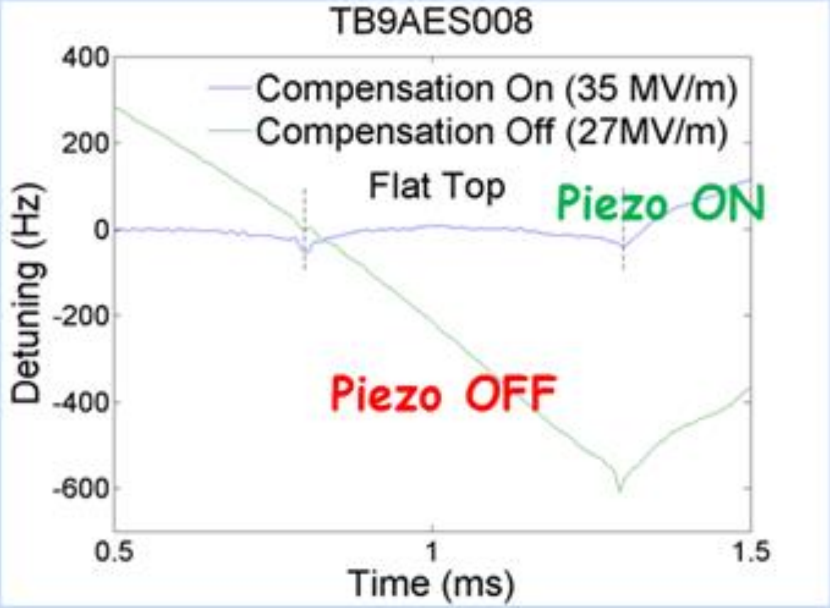
(1) 1.3 GHz (ILC & Project X)

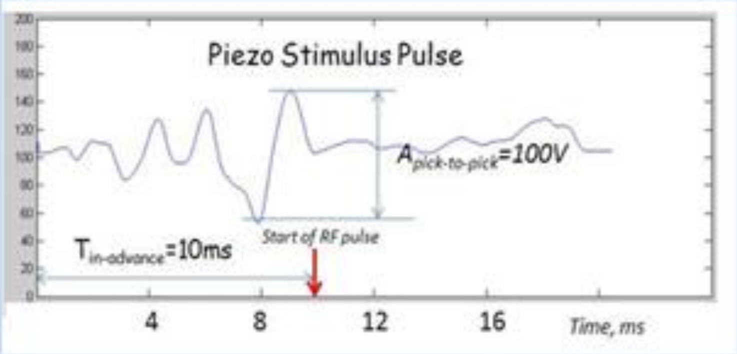
(2) SSR1(HINS and PIP II)

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

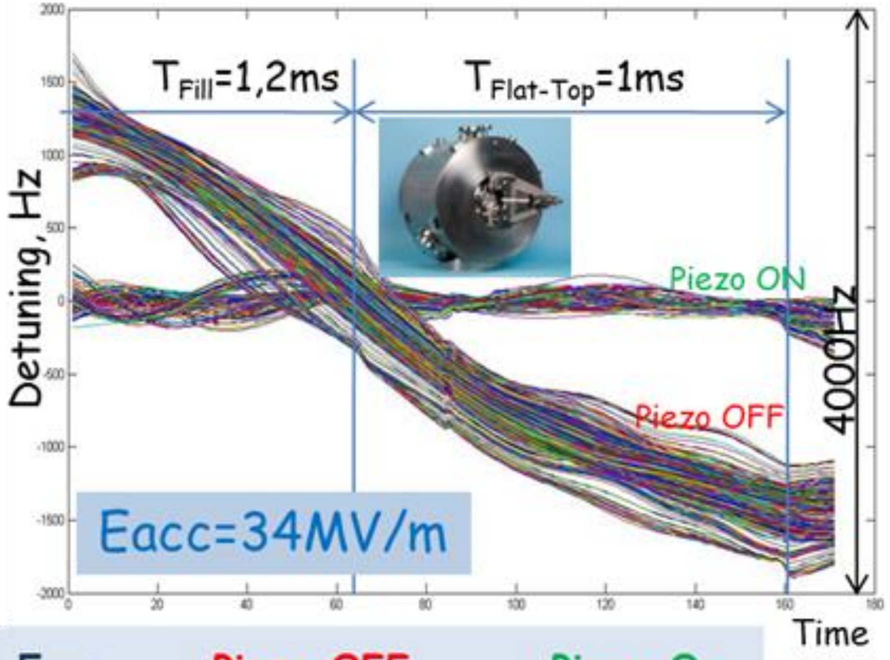
1.3GHz for ILC/XFEL pulse operation

LFD during 1,3ms RF-pulse (Fill+FlatTop) ~2300Hz
After LS LFD compensation -- to less than 20Hz during 1,3ms pulse





325MHz SSR1 cavity



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

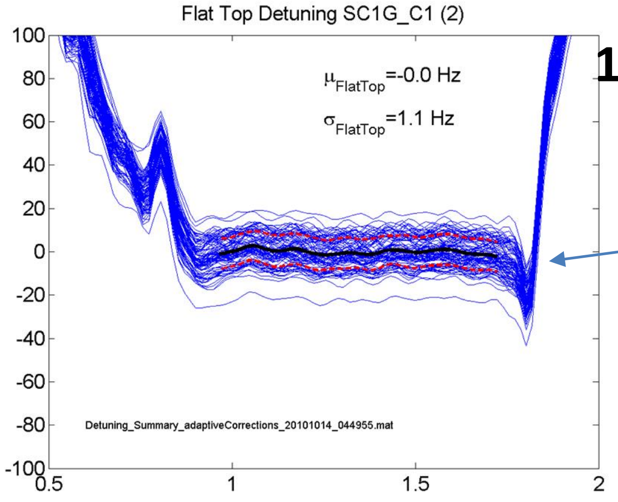
$\Delta F=-kE_{acc}^2$ K~1,2Hz/(MV/m)^2

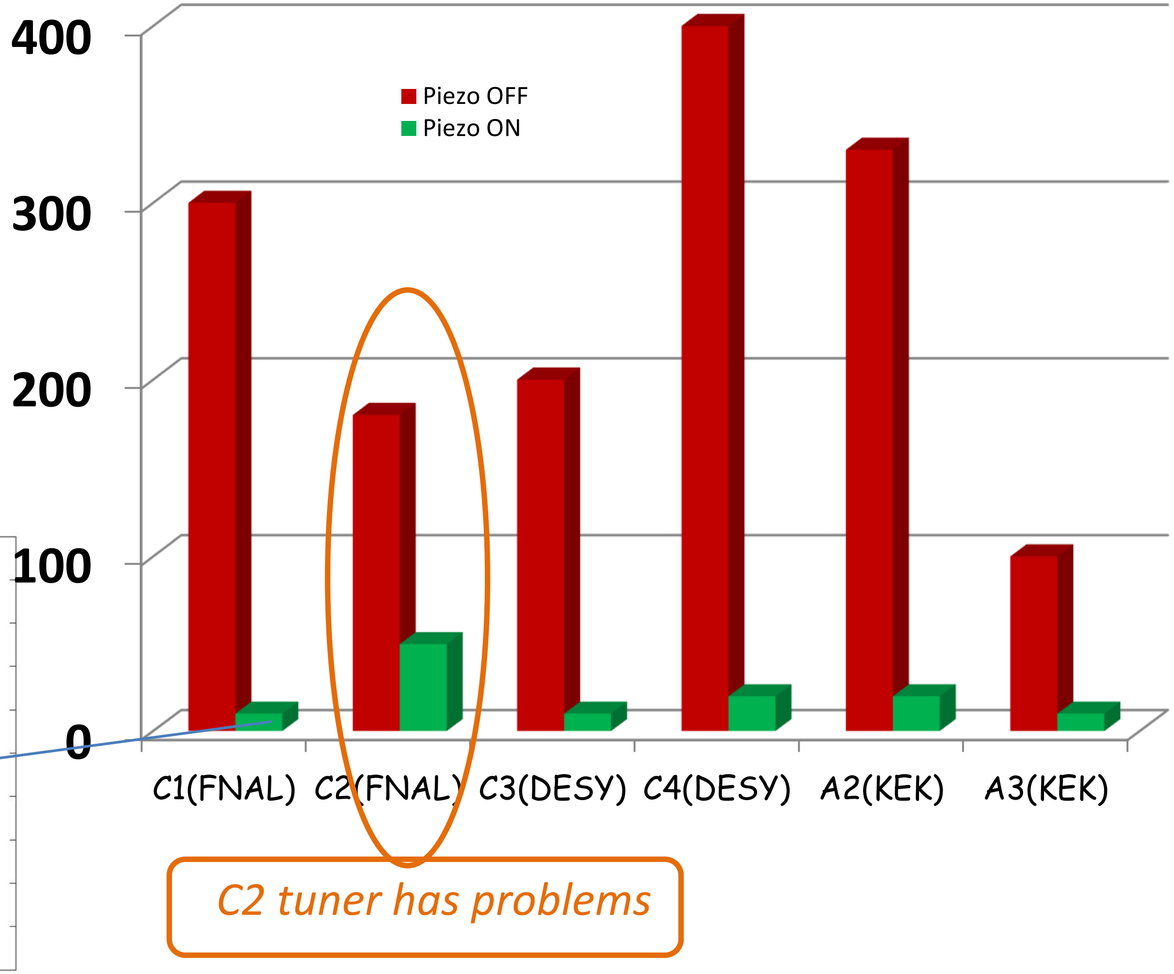
S1Global

Lorentz Force Detuning (Hz)

(during 1ms Flat-Top)

before and after Compensation





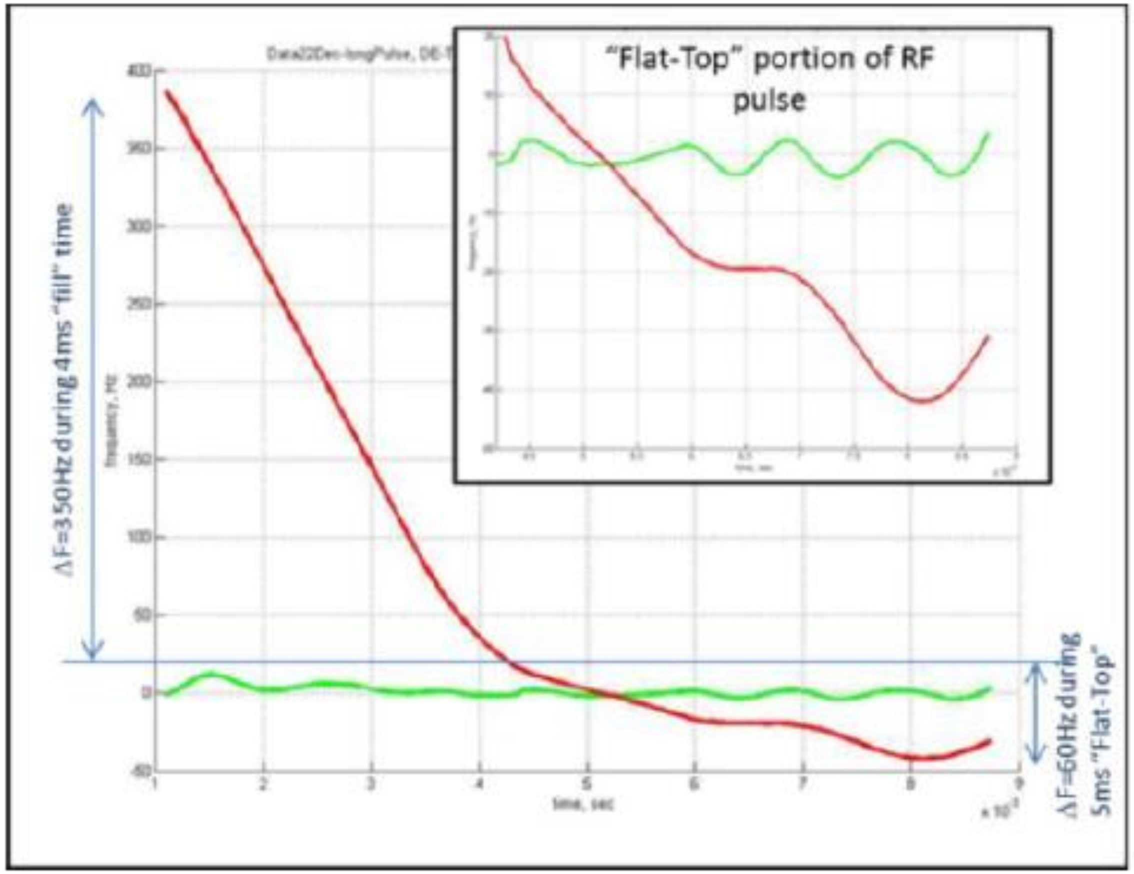
	Eacc	Piezo OFF	Piezo ON
C1(FNAL)	27	300	10
C2(FNAL)	22	180	50
C3(DESY)	18	200	10
C4(DESY)	25	400	20
A2(KEK)	39	330	20
A3(KEK)	31	100	10

Level of detuning is close to what we are excepting with 650MHz PIP II cavities

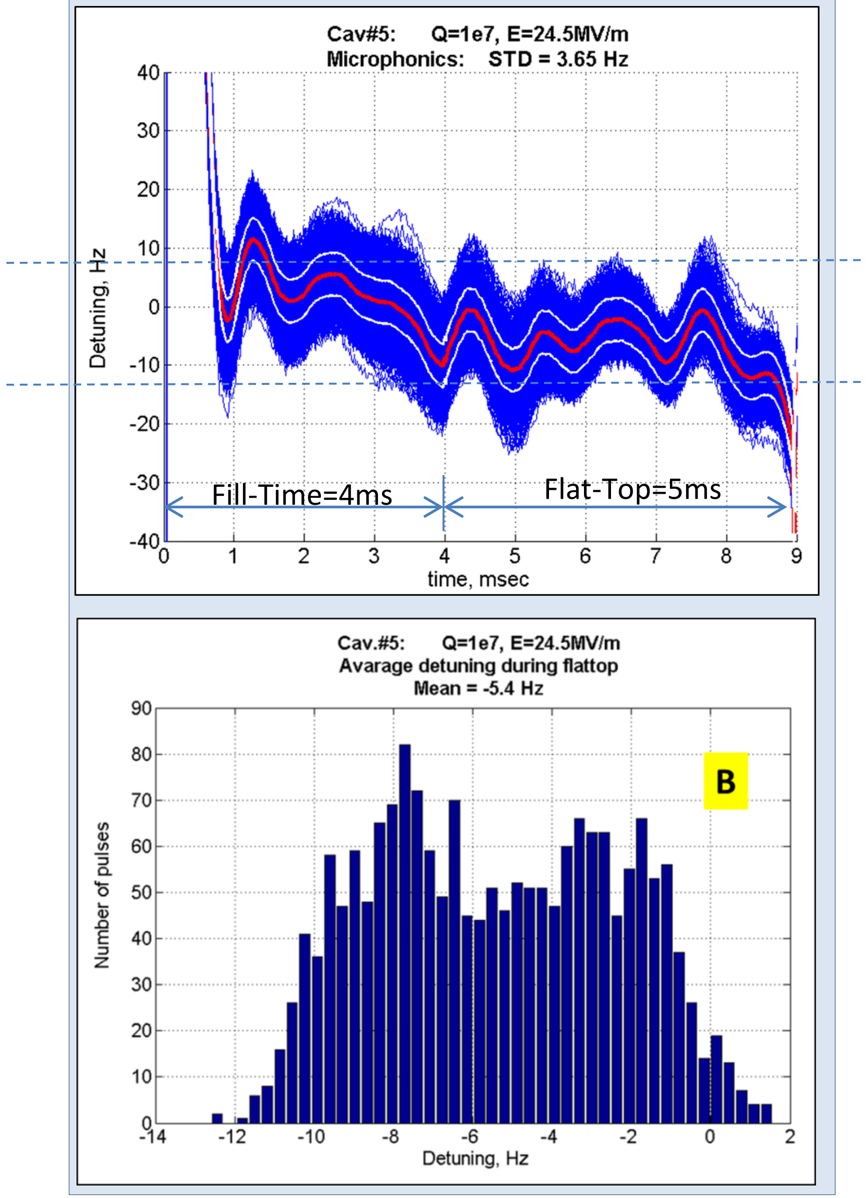
BUT

HBW for ILC is 200Hz or 7 times large than 650MHz…

1.3GHz Long Pulse (4ms-fill&5ms flat-top)



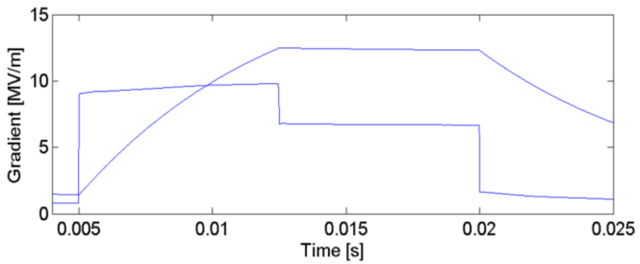
Residual Detuning over 30 minutes (1800pulses) during operation at $Q_L=10^7$ and E_{acc} =24.5 MV/m.

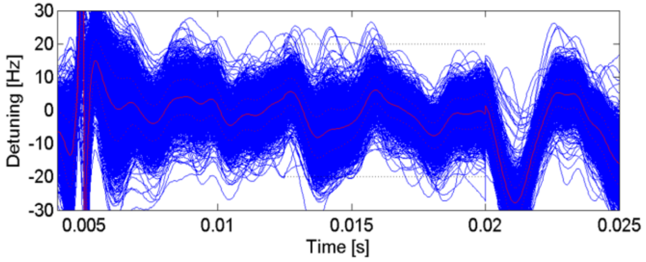


"Slow "-4ms- fill time of the cavity do not exited
"strong" 200Hz (5ms-period) main cavity resonance vibrations
Cavity "push" by LF on dF~350Hz

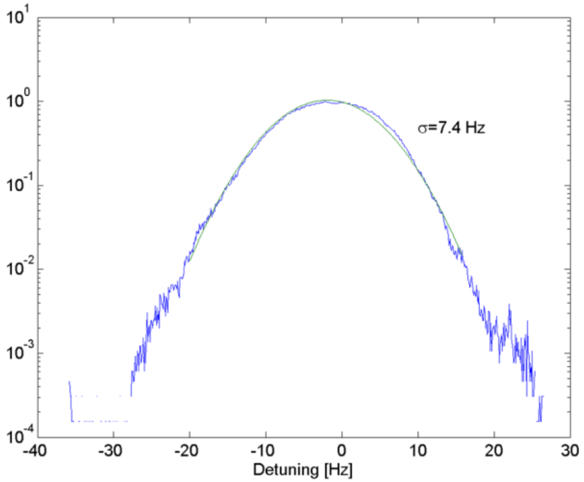
SSR1 at STC
PIP II operating conditions test

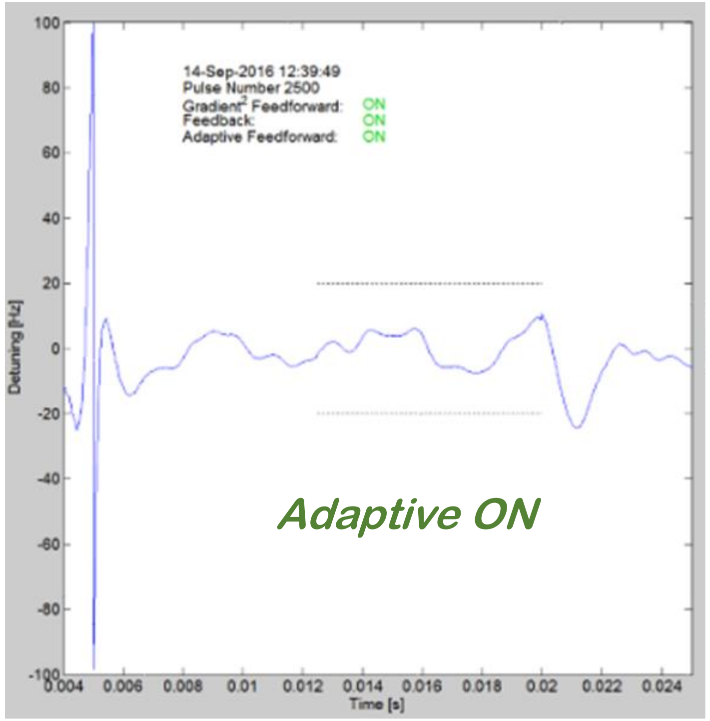
- PIP-II nominal operating conditions
  - 12.5 MV/m
  - 20 Hz repetition rate
  - 15% duty cycle
  - 0.5ms flattop
- STC operating condition
  - >12.5 MV/m
  - 25 Hz repetition rate
  - 7.5 ms fill
  - 7.5 ms flattop

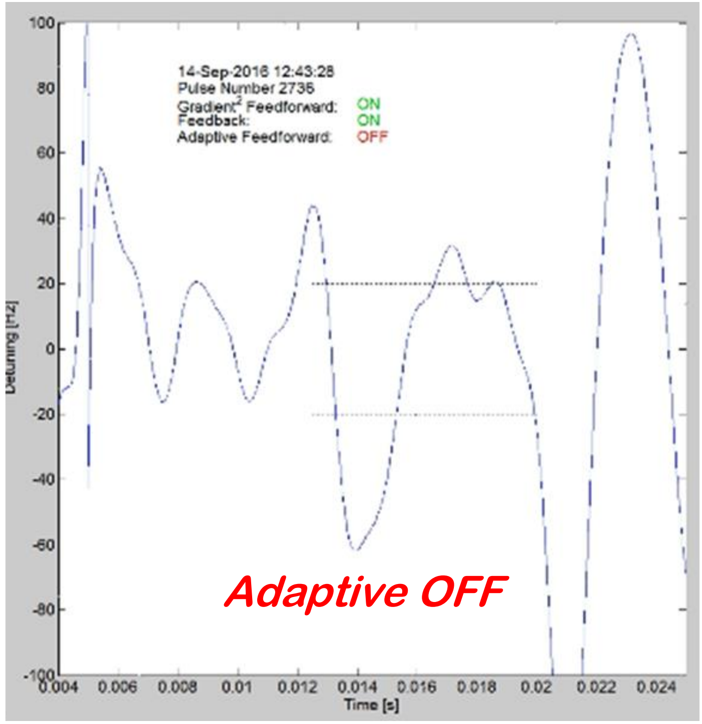




~7.4 Hz RMS detuning on the flattop. Specification is a peak detuning of 20 Hz, so a further improvement in RMS of ~2 is needed.







Without the adaptive compensation on , the detuning was almost an order worse. Without the other two compensation methods, the cavity rapidly fell off resonance.

Significant progress has been made toward PIP-II specification of detuning.
Plan for incoming test at STC:
- Improvements in feed back (automation of filter bank coefficients) should improve performance.
- May be possible to automatically extract optimal coefficients from delay scan data
- Further firmware improvements should allow more detailed studies of pulse structure.

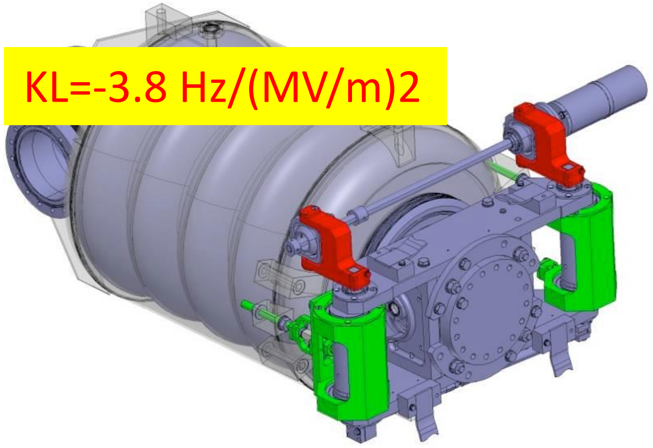
Summary of Pulsed Cavities Resonance Control

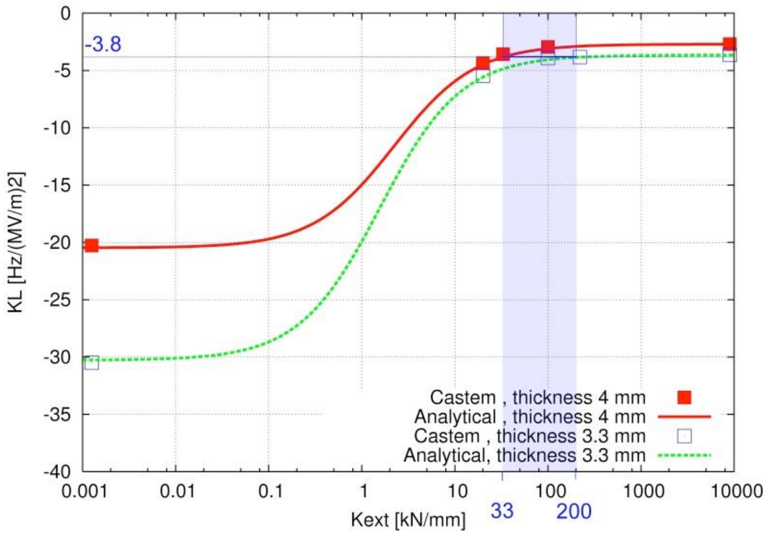
- FNAL accumulated significant experience of the Pulsed operations of the SRF cavities
  - (Developed at FNAL Feed-Forward Adaptive LS LFD Algorithm applied in all studies)
- So far we successfully worked in the range LFD/HBW ~3-5 … for LB/HB650MHz we need to move in the range of 10-12…

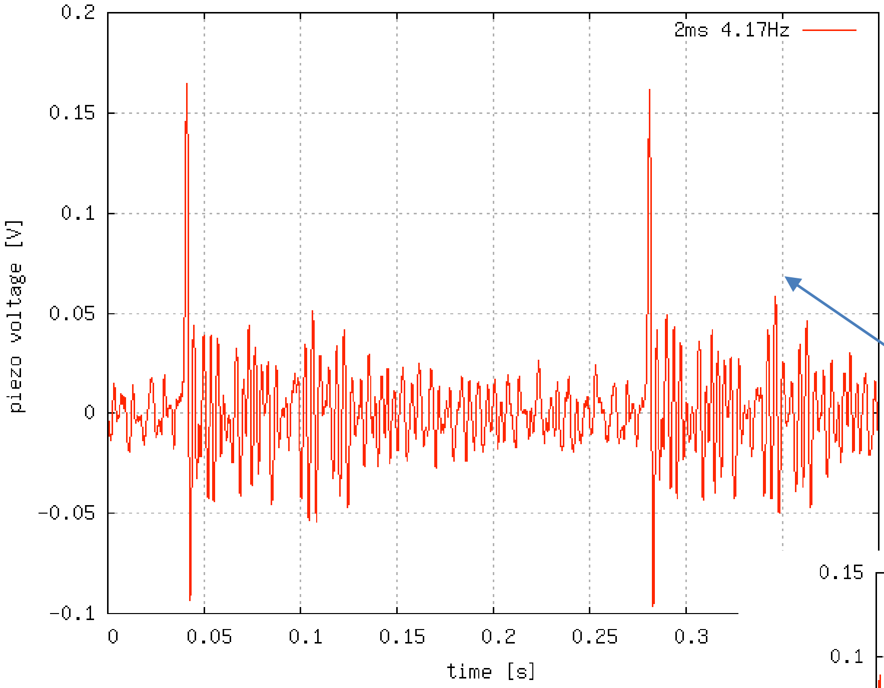
- **WE (AS A PIP II TEAM) MUST DEVOTE SIGNIFICANT AMOUNT OF "COLD CAVITY R&D TIME" FOR RESONANCE CONTROL. OTHERWISE …. (I am sure you could answer yourself what will be otherwise…)**
  - **We need cold LB/HB650 cavities installed at HTS(2?) and available for reasonable amount of the time for RCG study… not cavity = no progress**

Brief summary of CERN/SACLAY test of 5 cell 704MHz cavity in pulsed operation (SLHC-PP)

KL=-3.8 Hz/(MV/m)2

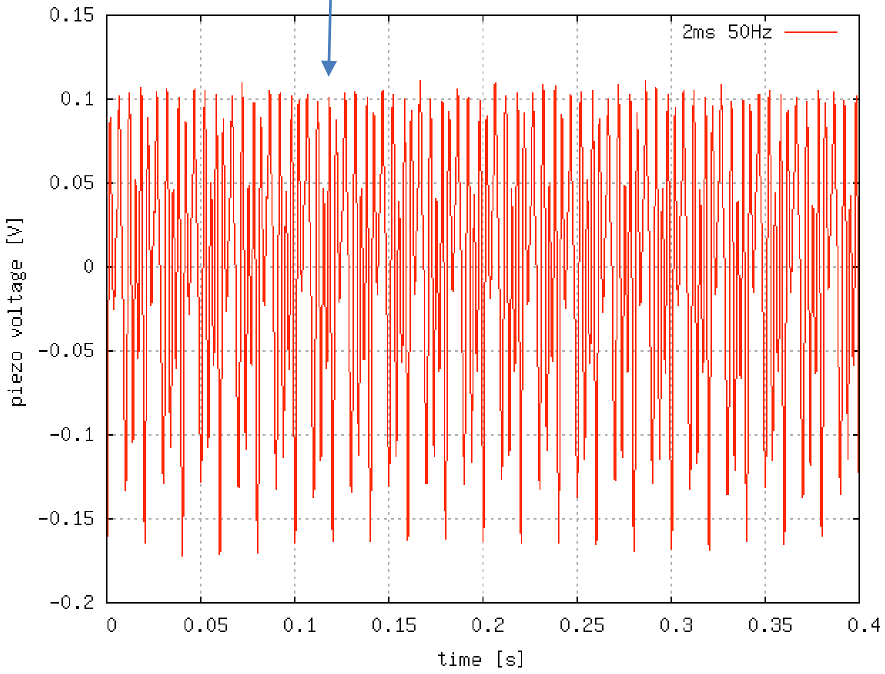


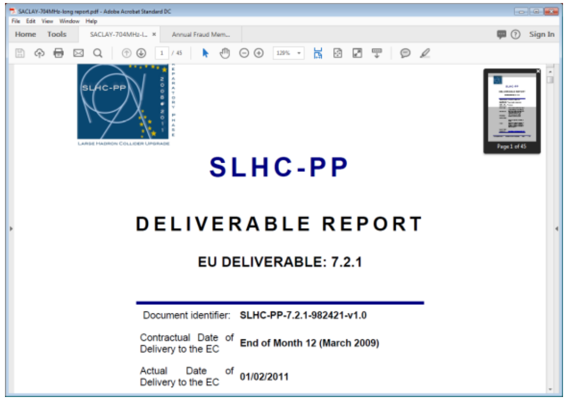




Piezo-as a sensor

2ms RF pulse with repetition rate 4Hz & 50Hz





FAST/Piezo TUNER

- So far there are NO any working machine that relay on the piezo control
- Many group around world building tuner's system that included fast/piezo tuner… but they doing this just fashionable … if you talk with them in private discussion they will tell you that piezo is not reliable…
- LCLS II will be first machine that MUST have working 24/7 piezo tuner - FNAL worked with PI engineers to develop custom piezo-capsule for LCLS II tuner…
- So far we do not have any other options at this moment as to adopt LCLS II piezo-capsule to PIP II tuners (SSR1 & LB/HB650)
- This technical decision is far from optimal (see next Table)…
- **If we want reliable PIEZO-TUNER we need to develop Piezo-ceramic actuator that will satisfy PIP II project requirements**

Requirements to the piezo for operation in XFEL/ ***PIP II*** *and LCLS II*
Impact on the longevity of the piezo

	XFEL/PIP II	LCLS II	FNAL-test-stand *(2month)*
Operation	10/20 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]	60/120	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
Heat dissipation, [mW]	90/200	0.05	6
Piezo ΔT raised	20K/ ~40K	0.1K	2K

*$P_{av}=\pi CU^2 f$ *D, where D is dissipation Factor (~5-20%)*

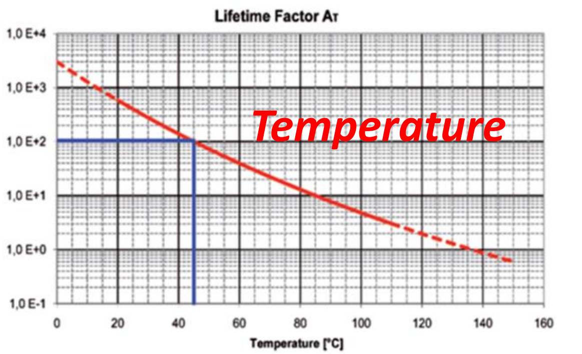
estimated

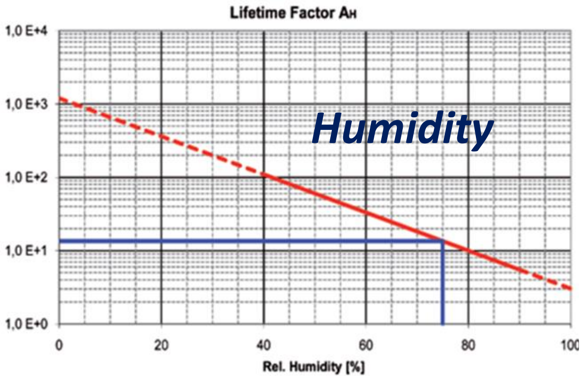
measured

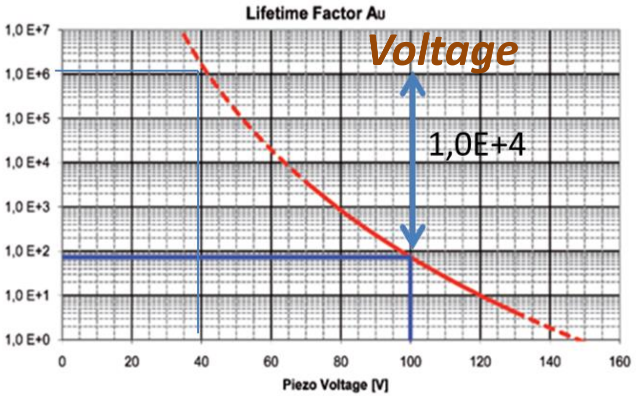
Operational voltage for PIP II piezo will be 60 times higher that for LCLS II.
Power dissipation inside piezo-ceramic actuator for PIP II is 4000 large than for LCLS II
Overheating of PIEZO is major problem.

Piezo Tuner Lifetime (1)

In contrast with electromechanical devices , cold vacuum is an almost ideal environment for piezo actuators.







…..cold vacuum is an almost ideal environment for piezo actuators… **except the problems to heat transfer from piezo inside insulated vacuum…**

Piezomechaniks ΔT~70Degree

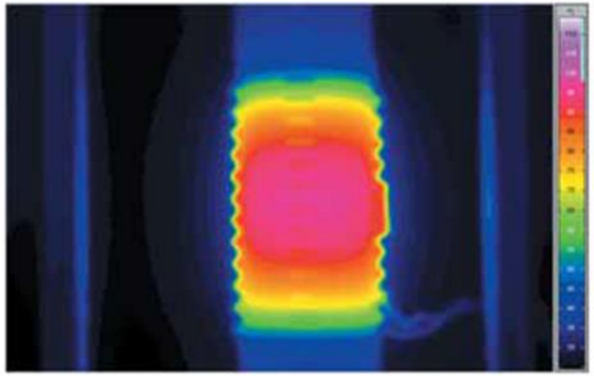
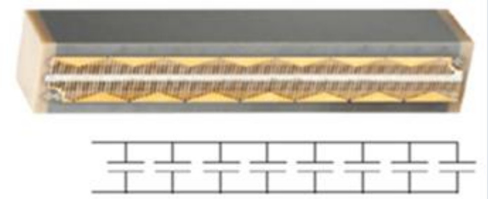


Fig. 5.1: Thermal image of a dynamically cycled high voltage actuator, clamped at its end faces. Environment: ambient air convection. Notice the cooling effect at the end-faces due to the clamping mechanics



In case of nonuniform current distribution at piezo structure the positive thermal feedback may happen! I↑ T↑ Z↓(C↑,R↓) I↑...

LLRF13 Lake Ta

M.Grecki, DESY

With decrease voltage lifetime increase exponentially

Decreasing operational voltage from 100V to 40V will increase lifetime in ***10,000 time.***

Do not design piezo-tuner with assumption to run NEAR Vmax.

Selected longer piezo/ to operate at lower possible Voltage

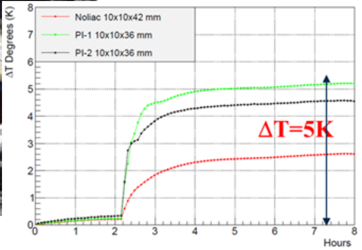
High reliability of tuner components (piezo-actuator)
Accelerated Piezo Lifetime test at FNAL

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)**



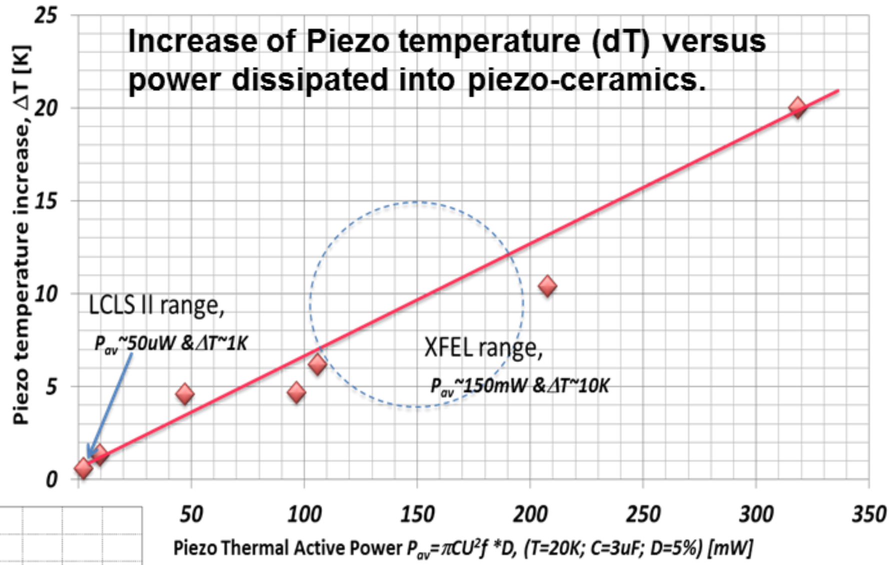
Accelerated piezo-stack lifetime test

$2*10^{10}$ *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

Summary

1. We must expect that tuner/dressed cavity/He vessel system will have stiffness **~40kN/mm.**
   - Expected value of LFD/HBW will be in he range of **12-15…**

2. FNAL Active Resonance Control Experience *(for range of LFD/HBW~5)* provide cautious optimism for compensation LFD/microphonics for LB/HB650MHz cavities.

3. Significant R&D time with "cold dressed LB/HB650MHz cavities" required.

4. To have RELABLE fast/piezo tuner we need to collaborate with piezo-ceramic company (PI ?) to develop PIP II specific piezo-actuator