Resonance Control of LB650MHz and HB650MHz SRF Cavities

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in behalf of the Tuner Team

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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) \( K_{cav.stiffness} \sim 20 \text{ kN/mm} \) (several (4?) cavities built for Project X) \( \rightarrow F_{max} \sim 11 \text{ kN} \)
   b) \( K_{cav.stiffness} \sim 4 \text{ kN/mm} \) \( \rightarrow F_{max} \sim 4-5 \text{ kN} \) (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 \( K_{tuner.stiffness} \sim 70 \text{ kN/mm} \)
   ➢ To minimize \( K_{LFD} \)
### Tuner specs for 650MHz cavities (0.9; 0.92; 0.61)

<table>
<thead>
<tr>
<th>Requirement</th>
<th>0.9</th>
<th>0.92</th>
<th>0.61</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta</td>
<td>0.9</td>
<td>0.92</td>
<td>0.61</td>
</tr>
<tr>
<td>Stiffness, (N/um)</td>
<td>20</td>
<td>3-4</td>
<td>3-4</td>
</tr>
<tr>
<td>Cavity tuning sensitivity, [Hz/um]</td>
<td>180</td>
<td>160</td>
<td>240</td>
</tr>
<tr>
<td>Bandwidth ($F_{1/2}$), [Hz]</td>
<td>29</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>Lorentz Force Detuning coefficient, [Hz/MV/m]$^2$</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Cavity sensitivity to pressure, $dF/dp$ [Hz/mbar]</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Tuner stiffness [N/um]</td>
<td>&gt;40</td>
<td>&gt;40</td>
<td>&gt;40</td>
</tr>
<tr>
<td>Required coarse tuning range, [kHz]</td>
<td>100(60)</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Coarse tuner resolution, [Hz/step]</td>
<td>1-2</td>
<td>1-2</td>
<td>1-2</td>
</tr>
<tr>
<td>Fine tuner range, [Hz]</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Fine tuner range, [um] at T=20K (20% from RT)</td>
<td>6.7</td>
<td>7.5</td>
<td>5</td>
</tr>
<tr>
<td>Fine tuner range, [um] at T=300K</td>
<td>33.5</td>
<td>37.5</td>
<td>25</td>
</tr>
<tr>
<td>Cavity resonance control reqs (peak), [Hz]</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Fine(piezo) tuner resolution, [Hz]</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>max. forces on the tuner system, kN</strong></td>
<td>11(7)</td>
<td>5</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>max. forces on the each piezo-capsule, kN</strong></td>
<td>6(3.5)</td>
<td>2.5</td>
<td>1.7</td>
</tr>
</tbody>
</table>

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.
Tuner stiffness (Ivan’s simulations) ~34kN/mm
Initial ANSYS simulations (before prototype built) stated that 
$K_{\text{tuner}} \approx 65-70 \text{ kN/mm}$. 
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 $30\text{kN/mm}$ (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 $T=300K \ \Delta X \sim 17\text{um}$ instead of $\sim \Delta X \sim 36\text{um}$). It will translate to $\Delta F \sim 700-800\text{Hz}$ (at $T=20K$)

Both deficiencies (stiffness & piezo stroke) contributed to “complex” fast tuner design.
LFD_{static\textunderscore vs. Tuner Stiffness}

Estimated cavity detuning by LF (static)

- **HB 650MHz**
  - LFD vs. Tuner Stiffness
    - Updated Design 4 mm
    - Updated Design 3.75mm
  - kN/mm
  - 30kN/mm
  - 70kN/mm
  - 18.8 MV/m

- **LB 650MHz**
  - LFD vs. Tuner Stiffness
    - VECC 3.75 mm
    - INFN 4.2 mm
    - INFN 3.75 mm
  - kN/mm
  - 30kN/mm
  - 16.9 MV/m
  - 70kN/mm

- **Detuning**
  - 4mm
  - 3.75mm
  - 4mm
  - 10 HBW
  - 20 HBW
  - 330
  - 410
  - 500
  - 610
Measurements of Stiffness of the Tuner, mounted on the test stand

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

Prototype Tuner Stiffness

$\sim 30\text{kN/mm}$
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.
What part of the **prototype** Tuner contributed more into system stiffness?

**Fast/Piezo Tuner interface**
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 $K\approx20\text{kN/mm}$ with some limitations (shorter slow tuner range $\Delta F\approx50\text{kHz}$) - 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…

\[
\frac{1}{X_1} + \frac{1}{X_2} + \frac{1}{X_3} = \frac{1}{X}
\]

\[X_1=100\text{kN/mm}; \ X_2=200\text{kN/mm}; \ X_3=300\text{kN/mm} \rightarrow X=55\text{kN/mm}\]

\[X_1=150\text{kN/mm}; \ X_2=200\text{kN/mm}; \ X_3=300\text{kN/mm} \rightarrow X=66\text{kN/mm}\]
Sergey Cheban design

New (simplified) design

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

Prototype Tuner design
Simulations $\rightarrow K_{tuner-dressed\ cavity\ system} = 42\text{kN/mm}$

Stiffness of the Tuner frame $K_{tuner} \approx 140\text{kN/mm}$ without “piezo” and transition ring

\[
\begin{align*}
K_1 & \approx 100 \\
K_2 & \approx 200 \\
K_3 & \approx 300 \\
\left(\frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3}\right)^{-1} & = 34.545 \\
k_1 = 150 \\
k_2 = 200 \\
k_3 = 300 \\
\left(\frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3}\right)^{-1} & = 66.657
\end{align*}
\]
Latest upgraded version of the tuner with highest stiffness so far...

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

Stiffness of the Tuner frame $K_{\text{tuner}} \sim 600 \text{kN/mm}$

_without piezo and transition ring_

**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...

Tuner arms need to be welded to He-Vessel
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

$K_{\text{tuner/vessel}}=23\text{kN/mm}$
Lorentz Force Detuning (static)

values of expected (with 40 kN/m)

**HB 650MHz**

- $E_{ac} = 18.8 \text{ MV/m}$
- $K_{LFD-Static} = 0.8 \text{ to } 1.0$

**LB 650MHz**

- $E_{ac} = 16.9 \text{ MV/m}$
- $K_{LFD-Static} = 1.4 \text{ to } 1.8$

$LFD/\text{HBW} \approx 10 \text{ to } 17$
Housing of the piezo-capsule inside main lever
NO ROOM
Interface of the main and motor lever with left arm
Why we “put ourselves into difficult position”
By making short beam-pipe ➔
limiting available space for tuner  ???
New (modified) design of Interface ring

Old design of Interface ring

Cavity/tuner interface piezo –to – NbTi 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 $V_{\text{piezo}}=100V$ will be $\Delta F\sim 2\text{kHz}$
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
- Drawings will be ready in 2-3 weeks (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 ($\sigma \sim 30\%$)... 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

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

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)

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 L5 LFD compensation -- to less than 20Hz during 1.3ms pulse

TB9AES008

325MHz SSR1 cavity

\[ \Delta F = -kE_{acc}^2 \quad K \approx 1.2 \text{Hz/(MV/m)}^2 \]

\[ E_{acc} = 34 \text{MV/m} \]

Piezo Stimulus Pulse

\[ T_{in-advance} = 10 \text{ms} \quad \text{Start of RF pulse} \]

Piezo ON

Piezo OFF

Compensation On (35 MV/m)
Compensation Off (27 MV/m)

Flat Top

Time (ms)

Detuning (Hz)

Eacc = 34 MV/m

Piezo OFF

Piezo On

\[ T_{Fill} = 1.2 \text{ms} \]

\[ T_{Flat-Top} = 1 \text{ms} \]
Lorentz Force Detuning (Hz)
(during 1ms Flat-Top)
before and after Compensation

C2 tuner has problems

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

BUT
HBW for ILC is 200Hz or 7 times larger than 650MHz...
1.3GHz Long Pulse (4ms-fill & 5ms flat-top)

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

Residual Detuning over 30 minutes (1800 pulses)
during operation at Qc=10^7 and E_acc=24.5 MV/m.
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 feedback (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
• 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

<table>
<thead>
<tr>
<th>Requirement</th>
<th>XFEL/PIP II</th>
<th>LCLS II</th>
<th>FNAL-test-stand (2month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation</td>
<td>10/20 pulses/sec</td>
<td>CW</td>
<td>CW</td>
</tr>
<tr>
<td>stimulus pulse, Hz</td>
<td>200</td>
<td>40</td>
<td>5000</td>
</tr>
<tr>
<td>Vpp, V</td>
<td>120</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>piezo stroke, [um]</td>
<td>5</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>number pulses for 20 years</td>
<td>1E+10</td>
<td>2E+10</td>
<td>2E+10</td>
</tr>
<tr>
<td>total stroke of piezo for 20 years, [km]</td>
<td>60/120</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Piezo-stack motion speed (rms) (mm/s)</td>
<td>4.5</td>
<td>0.02</td>
<td>2.2</td>
</tr>
<tr>
<td>Piezo-stack motion acceleration (rms)(g)</td>
<td>0.6</td>
<td>0.0004</td>
<td>7</td>
</tr>
<tr>
<td>Heat dissipation, [mW]</td>
<td>90/200</td>
<td>0.05</td>
<td>6</td>
</tr>
<tr>
<td>Piezo ΔT raised</td>
<td>20K/ ~40K</td>
<td>0.1K</td>
<td>2K</td>
</tr>
</tbody>
</table>

\[ P_{av} = \pi C U^2 f \cdot D, \text{ where } D \text{ is dissipation Factor (~5-20%) } \]

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.

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**

Accelerated piezo-stack lifetime test

- **2*10^{10} pulses** \( V_{pp} = 2V \ & F = 40Hz \)
  - 20years → 2 month \( (40Hz \rightarrow 5kHz) \)
  - **LCLS II ---** \( P_{av} \sim 50\mu W \) \( (40Hz, 2V) \)
  - **During ALT at 5kHz** \( P_{av} \sim 6mW \) \( (\Delta T\sim 2K) \)

LCLS II Tuner piezo-stacks run for \( 2.5\times10^{10} \) pulses (or 125% of LCLS II expected lifetime) without any degradation or overheating
1. We must expect that tuner/dressed cavity/He vessel system will have stiffness $\sim 40 \text{kN/mm}$.  
   - Expected value of LFD/HBW will be in the range of 12-15...

2. FNAL Active Resonance Control Experience \textit{(for range of LFD/HBW$\sim 5$)} provide cautious optimism for compensation LFD/microphonics for LB/HB$650\text{MHz}$ cavities.

3. Significant R&D time with “cold dressed LB/HB$650\text{MHz}$ 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