SSR1-G3 Tuner
State of the art and future work

Donato Passarelli
Leonardo Ristori
Mechanical engineers
SRF Dept. - Fermilab

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Our contribute to the SSR1 Cryomodule:
- 8 dressed SSR1-G3 cavities:
  - 4 type A + 4 type B
- 8 Tuner mechanisms
• 10 bare cavities generation-2 completed and delivered at Fermilab

• 9 bare cavities have been qualified in VTS: $Q_0 > 0.5 \cdot 10^{10}$ at $E_{acc} = 12 \text{ MV/m}$

• 7 cavities updated to generation-3 (S1H-NR-107, S1H-NR-108)

• 1 dressed cavity generation-3 (S1H-NR-107)
Jacketed SSR1-G3

The first prototype of dressed SSR1-G3 cavity was received at Fermilab in August 2013.
Manufacturer: Meyer Tool
~3 months for the bid
~4 weeks for parts procurement
~4 weeks for welding and final machining

More pictures are available online
**SSR1 Tuner**

- Design of Tuner mechanism
  - Technical Specifications
  - Conceptual design
  - Detailed design and prototyping
  - Mitigation of known risks
- Dummy Tuner
- Future work
## Requirements and data

### Fundamental Tuner Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Frequency Range</td>
<td>&gt; 135 kHz</td>
<td>From FRS</td>
</tr>
<tr>
<td>Frequency Resolution of stepper motor</td>
<td>&lt; 20 Hz</td>
<td>From FRS</td>
</tr>
<tr>
<td>Piezo Frequency Range</td>
<td>&gt; 1 kHz</td>
<td>From FRS</td>
</tr>
<tr>
<td>Tuner Passive spring constant</td>
<td>30 kN/mm</td>
<td>Derives from df/dP requirement</td>
</tr>
<tr>
<td>Sensitivity of end-wall</td>
<td>540 kHz/mm</td>
<td>Simulation/Experimental</td>
</tr>
<tr>
<td>Cavity wall spring constant (Kcav)</td>
<td>30 kN/mm</td>
<td>Simulation/Experimental</td>
</tr>
</tbody>
</table>

### Piezo and motor datasheet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stepper motor max force</td>
<td>± 1300 N</td>
<td>Symmetrical</td>
</tr>
<tr>
<td>Stepper motor resolution*</td>
<td>0.1 μm (100 nm)</td>
<td>At interface with 2\textsuperscript{nd} lever</td>
</tr>
<tr>
<td>Piezo stroke @ RT</td>
<td>64 μm ± 2%</td>
<td>Measured</td>
</tr>
<tr>
<td>Piezo stroke @ operating T</td>
<td>15μm (25% of RT)</td>
<td></td>
</tr>
<tr>
<td>Piezo max rated force</td>
<td>3360-5040 N</td>
<td>4200 N ± 20% (blocking force)</td>
</tr>
<tr>
<td>Piezo max operating force</td>
<td>2688 N</td>
<td>3360 · 80%</td>
</tr>
</tbody>
</table>

### Mechanical Requirements*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Travel at beam pipe</td>
<td>&gt; 0.25 mm</td>
<td>135/540 kHz</td>
</tr>
<tr>
<td>Piezo Travel at beam pipe</td>
<td>&gt; 1.85 μm</td>
<td>1/540 kHz</td>
</tr>
<tr>
<td>Maximum Force at beam pipe</td>
<td>7500 N</td>
<td>0.25 mm · 30000 N/mm</td>
</tr>
<tr>
<td>Motor Resolution at beam pipe</td>
<td>&lt; 37 nm</td>
<td>20/540000 mm</td>
</tr>
<tr>
<td>Motor Tuning Efficiency (Te)</td>
<td>&lt; 37 %</td>
<td>37/100 nm</td>
</tr>
<tr>
<td>Motor Mechanical Advantage (M)</td>
<td>&gt; 5.8</td>
<td>7500/1300 N, picked 6</td>
</tr>
<tr>
<td>Piezo Tuning Efficiency (Te)</td>
<td>&gt; 12 %</td>
<td>1.85/15 μm</td>
</tr>
<tr>
<td>Piezo Mechanical Advantage (M)</td>
<td>&gt; 1.4</td>
<td>0.5 · 7500/2688 N, picked 2</td>
</tr>
<tr>
<td>Piezo Elastic Efficiency (E)</td>
<td>&gt; 24 %</td>
<td>2 · 12 % (Te · M)</td>
</tr>
</tbody>
</table>

Specification document for SSR1 tuner available on Teamcenter: **ED0000165**

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D. Passarelli – PIP II meeting – April 1, 2014
SSR1 Tuner concept

- Double Lever Tuner
- Fine tuning
- Coarse tuning
- Made of SS316L

It was object of FNAL review in March 2013
Acting forces

Introduction
• Tuner design
• Dummy tuner

Angles:
\[ \alpha = 0.05^\circ \]
\[ \beta = 1.2^\circ \]

\[ L_1 = 335 \, mm \]
\[ L_2 = 308 \, mm \]
\[ L = L_1 + L_2 = 643 \, mm \quad \text{Length of Main arm} \]
\[ S_1 = 60 \, mm \]
\[ S_2 = 28 \, mm \]
\[ S = S_1 + S_2 = 88 \, mm \quad \text{Length of 2nd arm} \]

\[ F_c = 7500N \]
\[ F_p = \frac{F_c}{L/L_2} = \frac{7500}{643/308} = 3600N \]
\[ F_m = \frac{F_p}{S/S_2} = \frac{3590}{88/28} = 1150 \, N \]

Piezo mech advantage \[ \frac{L}{L_2} = \frac{643}{308} = 2.09 \quad (\text{spec} > 1.4) \]

Motor mech advantage \[ \frac{L}{L_2} \cdot \frac{S}{S_2} = 6.6 \quad (\text{spec} > 5.7) \]

Maximum motor force 1150 N \quad (\text{spec} < 1300N)

Maximum piezo force 1800N \quad (\text{spec} < 2700N)
Lumped parameters model to balance the stiffness of each component in order to achieve required values of stiffness and efficiency in all operating configurations.
• The kinematics of the mechanism was studied. It works in all operating scenarios...

Now working on:
• Tribology: type of contact and materials are under study...
• Easy installation...
• FE analysis...
The tuner mechanism will be the same for all type of cavities!
A list of known risks is guiding the design of the system. These items of risk are considered and mitigated in the ways deemed more appropriate.

**Reliability**  
The reliability of a frequency-tuning system is always of great concern. The actuators are prone to failures if not integrated and operated carefully. Failure of the tuning system has an immediate impact on the accelerator complex.

**Hysteresis**  
The resolution requested from the tuning system is extremely fine. The details of each joint in the mechanism shall be carefully evaluated and measures taken to mitigate phenomena such as stick-slip, play, backlash that would increase the hysteresis.

**Maintainability**  
Due to the concerns on reliability, the system shall be designed to allow the replacement of the actuating devices in case of failure or deterioration. Maintenance operations shall be simplified where possible considering the system will be serviced manually through access ports in the cryomodule's vacuum vessel.

**Magnetism**  
Magnetic permeability of components may affect cavity performance. “Low” magnetic permeability materials shall be utilized such as Stainless Steel of the 300 series (e.g. 316).

**Precision fitting**  
Cavities have manufacturing variances; also they may be shortened or lengthened (inelastic tuning) at different stages of development. The changes in dimensions (especially flange-to-flange length) may cause interface and assembly issues. A fine-adjustment system, fixed or free, should be integrated to compensate for these variances.

**Cleanliness**  
Cavities are often handled in clean-room environment. Tuner parts must be easy to clean and keep clean.

**Installation**  
The system and its components will be installed and uninstalled frequently, especially on the first prototype. Design must be robust in this aspect. Weak links such as wires, small fasteners and all other delicate parts shall be resistant to normal handling at a minimum.

**Bench tests**  
The system will be tested prior to installation on the cavity. Aspects to be considered are: self-consistent sub-assemblies, ease of transport, locking features, protection features.

**Transmission**  
The actual displacement the cavity will see may result being smaller than anticipated due to excessive flexibility of components, excessive stiffness of cavity, erroneous mechanical advantage. A safety margin shall be considered.
Removable cartridge

Actuators and critical components grouped on removable cartridge for reliability and maintainability reasons.
Encapsulated piezos

Floating encapsulated piezo
- Protect the ceramic piezo from shear forces
- Electrical and “thermal” insulation
- Preload the piezo for standalone tests and measurements

“Subject to cryogenic temperatures and thousands of kilos, it needs to be well protected against the harsh working conditions to ensure decades of service. [L.R.]”
Encapsulated piezos

- Introduction
- Tuner design
- Dummy tuner
In case of failure of one of the two piezos, the mechanism continue two work without overloading components. Of course, motor adjustments are needed and the cavity sees ~0.5 times the initial stroke of the piezo...

Tests will be performed to simulate that condition and to study the behavior of the mechanism.
Flexible Joints

- Behavior of two types of flexible joints (leaf and notch) have been studies. Notch type were chosen.
- A design has been proposed
- Theory, Finite Element Analyses and Measurements are compared
- Bending test on the prototype gives a result with approximately 10% error from the predictions. Good result

Angles:
\[ \alpha = 0.05^\circ \]
\[ \beta = 1.2^\circ \]

Theoretical bending stiffness \( 7.09 \times 10^5 \text{ Nmm/\text{rad}} \)
Measured bending stiffness \( 6.7 \times 10^5 \text{ Nmm/\text{rad}} \)
Error \( \approx 10\% \)
Dummy Tuner
“A simplified Tuner”

- What it is...
- Why we made it...
- What will we do with it...
• Introduction
• Tuner design
• Dummy tuner
Inelastic tuning was made on the dressed cavity in order to achieve a frequency of 324.808 MHz.

Starting from this value and adding the contributes due to the BCP and the cooldown, it is expected a resonant frequency of 325.232 MHz when the cavity is in HTS at 2K (if not tuned).

The operation was made using the Dummy Tuner, load cells and network analyzer.

<table>
<thead>
<tr>
<th>Frequency goal of dressed cavity @2K and tuner engaged</th>
<th>f [MHz]</th>
<th>Positive shift [MHz]</th>
<th>Negative shift [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Piezos preload of 6085N (=360N + 2725N) at BP (Piezo min operating force + 67.5kHz = 135/2))</td>
<td>325.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency goal of dressed cavity @2K and tuner not engaged</td>
<td>325.068</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sources of frequency shift (estimation):
- Shrinkage due to cooldown (by FE simulation)
  - 293K -> 2K: 0.285
- Cavity filling: Air -> Vacuum: 0.100
- Light BCP treatment (10um): 0.040
- 30mbar He pressure at 2K: -0.001
- Welding process: -0.156

| Frequency goal of SSR1-107 bare cavity @ root temp - tuner not engaged | 324.800 |
| Frequency SSR1-107 after welding Trans Ring | 324.134 |
| Inelastic Tuning (pre-welding) | 0.666 |
| Frequency SSR1-107 (pre-welding) | 324.800 |
| Welding process | 0.240 |
| Frequency SSR1-107 (post-welding) | 325.040 |
| Inelastic Tuning (post welding) | -0.232 |
| Frequency SSR1-107 (pre-BCP) | 324.808 |
| Expected frequency in HTS at 2K | 325.232 |
| Simulated stiffness [N/mm] | 21800 |
| df/dL [kHz/mm] | 0.540 |
Measurements of pressure sensitivity have been done at room temperature on the dressed S1H-NR-107.

- Pressure range in the helium space: 0 bar (vacuum) up to 1.38 bar.
- Atmospheric pressure in the RF volume and around the helium vessel.
- Pressure variations: “quasi static” and defined by accurate pressure gauge.

**Measurements**

- Stiffness of the dressed cavity at the actuation flange: $k_{cav} = 22$ kN/mm
- Tuning sensitivity at the actuation flange: $df/dL = 550$ Hz/mm
- Stiffness of the “dummy tuner” (both arms): $k_{dtun} = 60$ kN/mm
- Pressure sensitivity without the dummy tuner: $(df/dp)_{free} = +8$ Hz/Torr
- Pressure sensitivity with the dummy tuner engaged: $(df/dp)_{eng} = +5$ Hz/Torr

**FE Simulations**

- Stiffness of the dressed cavity: $k_{cav} = 21.8$ kN/mm
- Tuning sensitivity: $df/dL = 540$ Hz/mm
- Pressure sensitivity no tuner engaged: $(df/dp)_{free} = -25$ Hz/Torr
- Pressure sensitivity with 30kN/mm engaged at the BP: $(df/dp)_{eng} = 0$ Hz/Torr

The specification of $\leq 25$ Hz/Torr was exceeded with a measured value of $+5$ Hz/Torr.
Dummy Tuner with piezos

Configuration of the S1H-NR-107 for tests in Spoke Test Cryostat (STC)
Future work

- **Conceptual Design**: completed and reviewed
- **Detailed Design**: in progress
- **Manufacturing**: piezo encapsulation. Next complete the actuation group (removable cartridge)
- **Testing**: several tests have to be performed on single components before to assemble everything together...
  i.e. The piezo encapsulation will be object of test at room and cryogenic temperature...
- **First prototype made by end of the year (2014)**

*if there will be financial and technical support
Thanks...