Overview of Existing Tuner Systems

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Outline

- Acknowledgements
- Introduction
- Requirements & Specifications
- Mechanical Design Descriptions
- Test Results / Operations
- Design Features and Impacts
- Summary
Acknowledgements

• Original CEBAF Tuner (JLAB nee CEBAF)

• Upgrade Tuners for SL21, FEL03 and Renascence (JLAB 12 GeV Prototypes)

• SNS Tuner - Original Design from Saclay via the TESLA collaboration

• RIA Tuner (MSU)
  – MSU: T. Grimm, M. Johnson

• TESLA Blade Tuner (INFN, DESY)
  – INFN: Danilo Barni, A. Bisotti, C. Pagani, DESY: R. Lange, H-B. Peters

• Energen Magnetostrictive Actuator
  – A. Mavanur, C. Joshi
Introduction – “Big Picture” for Tuners

- SRF/RF system should consume RF power efficiently
  - Minimizes klystron size and capital cost
  - Higher $Q_{\text{external}} (> 10^7)$ $\leftrightarrow$ more efficient ER
  - Reduced Microphonics – actively controlled?
- RF Stability
  - Attained by controlling cavity RF phase (0.05°, RMS) and RF amplitude (2 x $10^{-4}$, RMS)
- Availability / Reliability / Maintainability
  - Use machine as scheduled
  - Operate machine as desired
  - Repair machine (if required) for use and operation

→ Examine what has been achieved on some existing systems to stimulate discussion
## Introduction: Pertinent Cavity Info

### (ERL-compatible Parameters)

<table>
<thead>
<tr>
<th></th>
<th>CEBAF</th>
<th>CEBAF Upgrade (SL21,FEL03)</th>
<th>CEBAF Upgrade (Renascence)</th>
<th>RIA, $\beta=0.47$</th>
<th>SNS, $\beta=0.61$</th>
<th>SNS, $\beta=0.81$</th>
<th>TESLA 500</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency (MHz)</strong></td>
<td>1497</td>
<td>1497</td>
<td>1497</td>
<td>805</td>
<td>805</td>
<td>805</td>
<td>1300</td>
</tr>
<tr>
<td><strong>Gradient (MV/m)</strong></td>
<td>5</td>
<td>12.5</td>
<td>18</td>
<td>10</td>
<td>10.3</td>
<td>12.1</td>
<td>23.4</td>
</tr>
<tr>
<td><strong>Operating Mode</strong></td>
<td>CW</td>
<td>CW</td>
<td>CW</td>
<td>CW</td>
<td>Pulsed, 60 Hz, 7%</td>
<td>Pulsed, 60 Hz, 7%</td>
<td>Pulsed, 60 Hz, 1%</td>
</tr>
<tr>
<td><strong>Bandwidth (Hz)</strong></td>
<td>220</td>
<td>75</td>
<td>75</td>
<td>40</td>
<td>1100</td>
<td>1100</td>
<td>520</td>
</tr>
<tr>
<td>$Q_{\text{external}}$</td>
<td>6.6 x 10^6</td>
<td>2.0 x 10^7</td>
<td>2.0 x 10^7</td>
<td>2.0 x 10^7</td>
<td>7.0 x 10^5</td>
<td>7.0 x 10^5</td>
<td>3.0 x 10^6</td>
</tr>
<tr>
<td><strong>Lorentz Detuning (Hz)</strong></td>
<td>75</td>
<td>312</td>
<td>324</td>
<td>1600</td>
<td>470</td>
<td>1200</td>
<td>434</td>
</tr>
<tr>
<td><strong>Microphonics (Hz, 6\sigma)</strong></td>
<td>-</td>
<td>±10</td>
<td>±10</td>
<td>±10</td>
<td>±100</td>
<td>±100</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Stiffness (lb/in)</strong></td>
<td>26,000 (calc'd)</td>
<td>37,000 (calc'd)</td>
<td>20,000-40,000 (calc'd)</td>
<td>&lt; 10,000</td>
<td>8,000 (meas'd)</td>
<td>17,000 (meas'd)</td>
<td>31,000 (est'd)</td>
</tr>
<tr>
<td><strong>Sensitivity (Hz/µm)</strong></td>
<td>373</td>
<td>267</td>
<td>~300 (calc)</td>
<td>&gt; 100</td>
<td>290</td>
<td>230</td>
<td>315</td>
</tr>
</tbody>
</table>
# Tuner Requirements & Specifications (ERL-compatible Parameters)

<table>
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<tr>
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<th>CEBAF Upgrade (SL21,FEL03)</th>
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<th>SNS, $\beta=0.81$</th>
<th>TESLA 500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Range (kHz)</td>
<td>$\pm200$</td>
<td>$\pm400$</td>
<td>950</td>
<td>$\pm245$</td>
<td>$\pm220$</td>
<td>$\pm220$</td>
</tr>
<tr>
<td>Coarse Resolution (Hz)</td>
<td>NA</td>
<td>$2 - 3$</td>
<td>$&lt; 1$</td>
<td>$2 - 3$</td>
<td>$2 - 3$</td>
<td>$&lt; 1$</td>
</tr>
<tr>
<td>Backlash (Hz)</td>
<td>$&gt;&gt; 100$</td>
<td>$&lt; 3$</td>
<td>NR</td>
<td>$&lt; 10$</td>
<td>$&lt; 10$</td>
<td>NR</td>
</tr>
<tr>
<td>Fine Range</td>
<td>No Fine Tuner</td>
<td>$&gt; 550$ Hz / 150 V</td>
<td>$1.2$ kHz / $1000$ V</td>
<td>$11$ kHz / $100$ V</td>
<td>$&gt; 2.5$ kHz / $1000$ V</td>
<td>No Fine Tuner</td>
</tr>
<tr>
<td>Fine Resolution (Hz)</td>
<td>NA</td>
<td>$&lt; 1$</td>
<td>$&lt; 1$</td>
<td>$&lt; 1$</td>
<td>$&lt; 1$</td>
<td>$&lt; 1$</td>
</tr>
<tr>
<td>Demo of Active Microphonics Damped?</td>
<td>No</td>
<td>?</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Tuning Method</td>
<td>Tens. &amp; Comp.</td>
<td>Tension</td>
<td>Tension</td>
<td>NA</td>
<td>Comp.</td>
<td>Comp.</td>
</tr>
<tr>
<td>Mechanism, Drive Comp.</td>
<td>Immersed, Vacuum, Vac/Warm</td>
<td>Vacuum, Vac/Cold</td>
<td>Vacuum, Vac/Ext</td>
<td>Vacuum, Vac/Cold</td>
<td>Vacuum, Vac/Cold</td>
<td>Vacuum, Vac/Cold</td>
</tr>
</tbody>
</table>
Upgrade Tuner for SL21 and FEL03 Cryomodules - Description

- **Scissor jack mechanism**
  - Ti-6Al-4V Cold flexures & fulcrum bars
  - Cavity tuned in tension only
  - Attaches on hubs on cavity
- **Warm transmission**
  - Stepper motor, harmonic drive, piezo and ball screw mounted on top of CM
  - Openings required in shielding and vacuum tank
- **No bellows between cavities**
  - Need to accommodate thermal contraction of cavity string
  - Pre-load and offset each tuner while warm
Warm Drive Components and Cross Section of Upgrade CM

- Stepper Motor
  - 200 step/rev
  - 300 RPM
- Low voltage piezo
  - 150 V
  - 50 µm stroke
- Harmonic Drive
  - Gear Reduction = 80:1
- Ball screw
  - Lead = 4 mm
  - Pitch = 25.75 mm
- Bellows/slides
  - axial thermal contraction
Renascence Tuner Assembly with Two Cold Piezo Actuators

Motor: Phytron VSS-52, 52 in*oz.,
Harmonic Drive: HDC-14-100-2ASP
With 100:1 Reduction

Piezo Actuator in SST Cartridge – 40mm Stack
(Model # PSt 1000/16/40 VS25)

316L Stainless Steel Frame

Primary lever that transmits tuning force

Secondary lever – divides load symmetrically

Dicronite-coated Beryllium Copper Drive Screw, M12 x 1.5
Renascence Tuner Description

- Mechanism – “Rock Crusher” – All cold, in vacuum components
  - Stainless steel frame
  - Attaches to chocks on cavity
  - Attaches via shoulder bolts to helium vessel head
  - Dicronite coating on bearings and drive screw
  - Cavity tuned in tension only

Shown hanging in VTA Test Stand, attached to EP3 cavity, ready for cold testing
RIA Tuner - Description

• Mechanism
  – Stainless steel rocker arm and drive rod
    ▪ Attaches to chocks on cavity
    ▪ Attaches via flexures and threaded studs to helium vessel head
  – Cavity tuned in compression only(?)
• Cold transmission – compressive force on drive rod
• Stepper motor and piezo external to vacuum tank
• Bellows on vacuum tank
  – Need to accommodate relative thermal contraction of cavities
  – Allow tuner transmission to float (unlocked) during cooldown
  – Pre-load each tuner while warm, account for vacuum loading on bellows
RIA Tuner – Rocker Arm / Schematic
SNS Tuner - Description

• Mechanism scaled from original DESY/Saclay design
  – Stainless steel frame
    ▪ Attaches to chocks on cavity
    ▪ Attaches via flexures and threaded studs to helium vessel head
  – Dicronite coating on bearings and drive screw
  – Cavity tuned in compression only

• Cold transmission
  – Components in insulating vacuum space
  – Stepper motor and harmonic drive rated for UHV, cryogenic and radiation environment

• Bellows between cavities
  – Need to accommodate relative thermal contraction of cavities
  – Pre-load each tuner while warm
SNS Tuner Assembly w/ Piezo Actuator

Motor: Phytron VSS-52, 52 in*oz.
Harmonic Drive: HDC-14-100-2ASP
With 100:1 Reduction

316L Stainless Steel Frame and Lever – 20:1 Mechanical Advantage

Dicronite-coated Beryllium Copper Drive Screw, M12 x 1.5

Flexure Connection to Cavity (2X)

Flexure Connection to Helium Vessel (2X)

Piezo Actuator in SST Cartridge (Model # PSt 1000/16/200 VS25)
SNS Tuner with Piezo Actuator
Installed on Helium Vessel & Cavity
TESLA - Blade Tuner

- Mechanism – All cold, in vacuum components
  - Titanium frame
  - Attaches to helium vessel shell
  - Pre-tune using bolts pushing on shell rings
  - Dicronite coating on bearings and drive screw
  - Cavity tuned in tension or compression – blades provide axial deflection
Upgrade Tuner – SL21 / FEL03:
Range and Resolution (Piezo Hysteresis)

Cavity Position #5 (SL21) Tuner Performance

\[ y = 4 \times 10^{-6}x + 1497.4 \]
\[ R^2 = 0.9993 \]

Piezo tuner voltage vs frequency Difference From Maximum for FEL03-6 at 10 MV/m

First cycle
Second cycle
Renascence Tuner – VTA Testing:
Range (Helium vessel compliance reduces actual stroke)

Renascence Cavity Frequency Response:
VTA Test Data & Ideal Curve - High Gradient and Low Loss Cavities

![Graph showing frequency change in kHz against stepper motor driver steps]
- Calculation (300kHz/mm, No flex)
- HGPT Measurement
- LL004 Measurement
RIA Tuner – Test Results:
Coarse and Fine Tuner Range; Active Feedback Control

![Graphs showing test results](image_url)
SNS Tuner – CMTF Test Results:
Fine Tuner Range and Hysteresis; Piezo Compensation

Piezo Tuner Range H05 - 4

Cavity # 2 @ 10 MV/m, with and without piezo compensation
Renascence Cavity – VTA Test Results:
Magnetostrictive Actuator on Tuner

Range of the Magnetostrictive Tuner at Different Loads

<table>
<thead>
<tr>
<th>Compressive Load (N)</th>
<th>Max. Tuning Range (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Load</td>
<td>2,600</td>
</tr>
<tr>
<td>7,100</td>
<td>5,892</td>
</tr>
<tr>
<td>10,200</td>
<td>3,423</td>
</tr>
<tr>
<td>14,000</td>
<td>3,088</td>
</tr>
</tbody>
</table>

Tuning Range at 14000 N compressive load

Frequency shift (Hz)

Input current (A)

Cavity and He vessel

Slow Tuning motor and drive

Tuning Linkage mechanism
SNS Cryomodule:
Current Openings for Access to Tuner Components – CM CutAway

- Vacuum Tank Port
- Motor & Harmonic Drive
- Piezo Linkage
Upgrade Cryomodule – Access to Tuner Drive Components

Motor, Limit Switches, Harmonic Drive and Piezo Actuator are all situated on the stack
Comparing SNS Tuner Motor Rotor/Shafts: Prototype (left) and Production (right)

- Series of wavy washers provides pre-load on the shaft while allowing compliance during cooldown and operation at 4K.
- Accelerated Life Testing $\rightarrow > 20$ yrs

- Single wavy washer to the right of the bearing provides pre-load and compliance – cost reduction by vendor
- Pass vendor acceptance testing
- Compliance drastically reduced
- Motors bound up and didn’t work!!
Closing / Summary: Comparison of Tuner Features

- **Coarse Tuning Mechanism**
  - Typically cold, must be reliable and maintainable → access ports
  - Direct cavity drive reduces stiffness requirements on helium vessel
  - Tuner/HV stiffness > 10x cavity
  - Flexures exhibit reduced backlash

- **Fine Tuning Actuators**
  - Piezo – operate in compression, warm range 5-10x > cold range, capacitive device, minimize voltage, consider hysteresis
  - MST – must operate cold, consider lead thermal design, inductive element, minimize current, consider hysteresis

- **Transmission Location (maintainability)**
  - Cold placement requires proper materials, cyclic life testing and access for repair or replacement, electrical feedthroughs
  - Warm placement requires cooldown/tuning compliance, access ports, bellows

- **Testing (minimizes risk associated with reliability and availability)**
  - Perform accelerated life tests on critical components
  - Feedback results into design prior to production
  - Develop thorough acceptance tests to verify operation