Engineering for Particle Accelerators

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U.S. Particle Accelerator School (USPAS)
SRF cavity design, RF measurements and tuning
20 June 2017
Engineering for Particle Accelerators

Instructors: Vyacheslav Yakovlev, Timergali Khabiboulline, Thomas Nicol and Vladimir Kashikhin, Fermilab, Batavia

One-week course at USPAS 2017, Lisle, Il
June 19-23, 2017

Daily Schedule

Monday 6/19
9:00-12:00    Yakovlev, Lectures: The fundamentals of large scale accelerator engineering.
14:00 -17:00  Yakovlev, Continuation

19:00-24:00   Study and tutoring

Tuesday 6/20
9:00-12:00    Khabiboulline, lectures: SRF cavity EM and mechanical design, RF measurements and tuning
14:00-17:00   Khabiboulline, Continuation

19:00-24:00   Study and tutoring
# Engineering for Particle Accelerators

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albright, Robert</td>
<td>Lawrence Berkeley National Lab</td>
</tr>
<tr>
<td>Alonso, Inigo</td>
<td>European Spallation Source</td>
</tr>
<tr>
<td>Alvarez, Henry</td>
<td>SLAC</td>
</tr>
<tr>
<td>Antonini, Piergiorgio</td>
<td>INFN</td>
</tr>
<tr>
<td>Baketz, Sherry</td>
<td>Fermilab</td>
</tr>
<tr>
<td>Berry, Robert</td>
<td>RadiaBeam Technologies</td>
</tr>
<tr>
<td>Contreras, Crispin</td>
<td>Michigan State University</td>
</tr>
<tr>
<td>Di Ciocchis, Franco</td>
<td>Fermilab and University of Pisa</td>
</tr>
<tr>
<td>Gao, Jiani</td>
<td>EPFL and Paul Scherrer Institut</td>
</tr>
<tr>
<td>Gurung, Ujir</td>
<td>Cosmos International College</td>
</tr>
<tr>
<td>Kiemschies, Oliver</td>
<td>Fermilab</td>
</tr>
<tr>
<td>Kutsaev, Sergey</td>
<td>RadiaBeam Technologies</td>
</tr>
<tr>
<td>Liu, Zunping</td>
<td>Argonne National Lab</td>
</tr>
<tr>
<td>Martin, Brian</td>
<td>Brookhaven National Lab</td>
</tr>
<tr>
<td>Patel, Niral</td>
<td>Fermilab and Indiana University</td>
</tr>
<tr>
<td>Zhang, Bo</td>
<td>Dexter Magnetic Technologies</td>
</tr>
</tbody>
</table>
SRF Cavities Applications

Modern SRF cavities cover wide diapasons of particles beta (0.05..1), operating frequencies (0.072..4 GHz) and beam currents (1mA..100mA, CW & Pulsed)
SRF cavity design

SRF cavity is a complicated electro-mechanical assembly and consist of:
- bare cavity shell with power and HOM couplers
- stiffening elements (ring, bars)
- welded LHe vessel
- Slow and fast frequency tuners
- vacuum ports

The design of SRF cavity requires a complex, self consistent electro-mechanical analysis in order to minimize microphonics and/or Lorentz force detuning phenomena and preserving a good cavity tenability simultaneously!
Problems of Superconducting Particle Accelerators

- Acceleration efficiency
  - max R/Q & min surface field enhancement factors (electric & magnetic)

- High Order Modes (HOMs) dumping
  - incoherent effect (loss factors, cryogenic losses)
  - coherent effects (emittance dilution, cryo-losses)
  - collective effects (transverse & longitudinal beam instabilities)

- Operation with small beam current
  - narrow cavity bandwidth & microphonics

- Field Emission
  - multipactor & dark current

- High Gradient pulsed operation
  - Lorentz force detuning

- Input Power Coupler
  - CW operation (min RF loss & static heat load)

- Beam Instrumentation
  - Cold Beam Position Monitor (low & high relativistic beam)
Main characteristics of SC acceleration structure

- \(\frac{r}{Q}\) determines the relation ship between the acceleration gradient and energy stored in the acceleration structure \(W\) per unit length:
  \[
  \left( \frac{r}{Q} \right) = \frac{E^2}{\omega W}
  \]

- Coupling to the feeding line:
  \[
  \beta = \frac{P_{\text{rad}}}{P_{\text{Ohm}}}
  \]

- Loaded \(Q\):
  \[
  Q = \frac{\omega W}{P} = \frac{Q_0}{1 + \beta}
  \]

- Field enhancement factors:
  a) Electric: \(k_e = \frac{E_{\text{surf pk}}}{E}\);
  b) Magnetic: \(k_m = \frac{B_{\text{surf pk}}}{E}\);

Geometry of an inner half-cell of a multicell cavity and field distribution along the profile line.
Main characteristics of SC acceleration structure

- Coupling coefficient:
  \[ k_c = 2 \frac{f_\pi - f_0}{f_\pi + f_0}; \]

- High Order Modes (HOM):
  a) Monopole HOM spectrum – losses, bunch-to-bunch energy spread;
  b) Dipole HOM spectrum – transverse kick, beam emittance dilution.

HOM frequencies, \((r/Q)s\) and loaded Q-factors are critical, and are the subject of the structure optimization.

- The structure cell geometry:

  Constrains:
  - low field enhancement factors;
  - no multipactoring.
  Elliptical shape for the cell and the iris.

Examples:
- TESLA structure;
- Low Loss structure;
- Re-Entrant structure.
Main characteristics of SC acceleration structure

- Resonance frequency of the operating mode $f_0$;

- Acceleration gradient $E$;

- Shunt impedance $r$ per unit length; Shunt impedance is relationship between the acceleration gradient and dissipated power $P$ per unit length of the structure. $P$ is the sum of Ohmic losses in the structure $P_{Ohm}$ and the power radiated through the coupling ports $P_{rad}$.

$$ r = \frac{E^2}{P} $$

- Unloaded quality factor $Q_0$ and geometry factor $G$:

$$ Q_0 = \frac{\omega W}{P_{Ohm}} = \frac{\omega \mu_0 \int_{V} |H|^2 dV}{\frac{1}{R_s} \int_{S} |H|^2 dS} \equiv \frac{G}{R_s}, $$

$$ \frac{\omega \mu_0 \int_{V} |H|^2 dV}{\int_{S} |H|^2 dS} \quad \text{geometry factor} \ G \ (R_s \text{ is the surface impedance, } W \text{ is the energy stored in the structure per unit length} \).$$
High Order modes

- HOM extraction/damping.

Criteria:
- Transverse modes: beam emittance dilution;
- Longitudinal modes: power losses, field enhancement, bunch-to-bunch energy spread.

- Trapped modes.

The end cells are to be optimized in order to prevent the field distribution for HOMs having small field in the end cavities, so-called trapped modes. For the trapped modes it is a problem to reduce the loaded Q-factor to acceptable level.

Coaxial loop coupler for superconducting TESLA cavities
Lorentz Force Detuning

- Amplitude (Norm.) vs. Detuning (Norm.)
- Energy Content (Normalized) vs. Detuning (Hz)

- CEBAF 6 GeV
- CEBAF Upgrade
Development of SC accelerating structures

Machine requirements
- Pulsed operation
- CW operation
- High beam current
- High beam power transfer
- Beam quality (emittance) preservation
- Low beam power

Effects/cavity parameters
- Lorentz force detuning
- RF power dissipation in cavity walls
- Beam stability (HOMs)
- Heavy beam loading
- Low Qext
- Availability of high-power RF sources
- Parasitic interactions (input coupler kick, alignment)
- High Qext, microphonics

Cryomodule design
- Cryostat design
- Input coupler design
- HOM damper design
- Tuner design
- RF controls

RF design:
- Mechanical design: stiffness, vibration modes, tunability, thermal analysis
- RF frequency & operating temperature choice, optimal gradient, cavity shape optimization, number of cells, cell-to-cell coupling, HOM extraction, RF power coupling

Availability of high-power RF sources
- Parasitic interactions (input coupler kick, alignment)
- High Qext, microphonics

Beam quality (emittance) preservation
- Low beam power
Tools for SC structure simulations

I. Field calculations:
- Spectrum, (r/Q), G, β
- Field enhancement factors
  - HFSS (3D);
  - CST(3D);
  - Omega-3P (3D);
  - Analyst (3D)
  - COMSOL (3D)

II. Multipactoring (2D, 3D)
  - Analyst;
  - CST (3D);
  - Omega-3P

III. Wakefield simulations (2D, 3D):
  - GdfidL;
  - PBCI;
  - ECHO.

IV. Mechanical simulations:
  Lorenz force and Lorenz factor,
  Vibrations,
  Thermal deformations.
  a. ANSYS
  b. COMSOL
### Software packages for SRF cavity design

#### Software for eigenmode EM simulation.

<table>
<thead>
<tr>
<th>Feature</th>
<th>OMEGA3P</th>
<th>COMSOL*</th>
<th>CST*</th>
<th>SLANS</th>
<th>HFSS*</th>
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<tbody>
<tr>
<td>Domain</td>
<td>3D</td>
<td>2D, 3D</td>
<td>3D</td>
<td>2D</td>
<td>3D</td>
</tr>
<tr>
<td>Curved elements</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Mesh type</td>
<td>Tetra</td>
<td>Tetra</td>
<td>Hex</td>
<td>Tetra</td>
<td>Quad</td>
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<tr>
<td>Complex solver</td>
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<td>✓</td>
<td>✓</td>
<td>-</td>
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<tr>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>H-field enhancement**</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>-</td>
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</table>

* commercial software  
** weighted residual method is applied in order to improve field calculations.
# CST Studio Suit Solvers

<table>
<thead>
<tr>
<th>Mesh Type</th>
<th>CST PARTICLE STUDIO®</th>
<th>CST MPHYSICS® STUDIO</th>
<th>CST MICROWAVE STUDIO®</th>
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</thead>
<tbody>
<tr>
<td>HEX</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>TET</td>
<td>X</td>
<td>X</td>
<td>X</td>
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</tbody>
</table>

## Sub-solvers

- \( \beta = 1 \)
- \( \beta < 1 \)

- Lossless: AKS, TET Complex: JDM

## Solver Type

<table>
<thead>
<tr>
<th>Solver Type</th>
<th>CST PARTICLE STUDIO®</th>
<th>CST MPHYSICS® STUDIO</th>
<th>CST MICROWAVE STUDIO®</th>
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</thead>
<tbody>
<tr>
<td>Direct</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Iterative</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Fermilab
1. What we are doing?

2. What tool do we need?

3. How to use the tool?
# CST Simulation Workflow

1. **Creation of the project 3D model**  
   - Drawing in the CST GUI (takes time, full-parametrization, easy modification)  
   - Geometry import from 3rd parties CADs (quick, need special license, limited parametrization, potential mesh problem)

2. **Choosing a proper solver**  
   - Depends on the problem, available hardware, simulation time ...

3. **Setting boundary conditions**  
   - Frequency, symmetries, ports, materials, beam excitation, temperature, ...

4. **Checking the mesh quality**  
   - Generate and visualize the mesh, set initial mesh size, create sub-volumes and modify models if needed, mesh fine-tuning (curvature order, surface approximation)

5. **Solver fine-tuning**  
   - Direct or iterative, parallelization, special settings, ...

6. **Running first simulation**  
   - Check the results, set postprocessing steps, tune & modify the mesh, ...

7. **Setting optimization**  
   - Set parameters sweep, define the goal function, simplify the model
Secondary electron emission RF discharge or multipactor (MP) might be a serious obstacle for normal operation of SC cavities and couplers (simulation of SSR1 cavity for PIP-II).
Loss factor depends strongly on the $\sigma_{\text{field}}$!

- $f_{\text{max}} \sim \frac{c}{\sigma_{\text{bunch}}}$
- for $\sigma_{\text{bunch}} = 50\mu$, $f_{\text{max}} < 6$ THz

Solve in TD
- computing wakefield and wake potentials

Incoherent losses introduced by radiated wakefield might be an essential part of the total cryolosses in the SC accelerating structure.
Effect of dark current

- heat and RF loading of the cavity
- production of avalanches of secondary electrons
- accelerating to hundreds of MeV before being kicked out by downstream quadrupoles
- originating electromagnetic cascade showers in the surrounding materials

Challenges of dark current simulations:
- initial broad angular, space and phase distribution
- realistic model of emitters (Uniform, Gaussian, Fouler-Nord.)
- influence of SE emission
- detailed statistics on lost and accelerated particles
### CST PS Loss Factor Simulation

<table>
<thead>
<tr>
<th>Time Domain</th>
<th>Time Domain</th>
<th>Frequency Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-relativistic beam ($\beta=1$)</td>
<td>Highly-relativistic beam ($\beta&gt;0.9$)</td>
<td>Weakly-relativistic beam ($\beta&lt;0.9$)</td>
</tr>
</tbody>
</table>

#### Short bunches ($\sigma_z < 1$mm)
- required memory $\sim (a/\sigma_z)^3$
- computation time $\sim (a/\sigma_z)^4$
- long catch up distance $\sim a^2/2\sigma_z$

Solution: Indirect methods

#### Static Coulomb forces
- $E_{\text{static}} \gg W_z$
- Wrong convolution: $\int (E_z + W_z)\sigma_z dz$

Solution: Two simulations to exclude $E_{\text{static}}^*$

#### HOM modes
- HOM spectrum above beam pipe cut-off freq.

Solution: Take modes with max $R/Q$, Multi-cavity simulation

CST Design Studio Scattering Matrix Analysis

ILC 9-cell Structure Decomposition

S-matrix (Upstream End Group) + 9 x S-matrix (Middle Cell) + S-matrix (Downstream End Group)

End Cell (17 modes)

Port2 HOM1 Coupler

Beam Pipe (8 modes)

Port1 (Main coupler)

9 Mid Cells (17 modes)

TE_{11} Mode (Vert)

TE_{11} Mode (Gor)

TM_{01} Mode (Operating)

Port4 (pick-up)

Port3 (HOM2 Coupler)
CST Design Studio Scattering Matrix Analysis

**Full Structure S-matrix**

**Key features**

- Fast analysis
- Precise frequency resolution
- Easy phase manipulation
- Multi-structure chain simulation

**Tips:**

- The components have to be non-resonant!
- Leave the regular waveguide section!
- Use proper mode alignment!
Frequency shifts due helium pressure fluctuations (~few mbar) $\frac{df}{dp}$ is a major issue in superconducting RF cavities. Narrow BW cavities with high microphonics levels require more RF power. Beam can be lost if sufficient reserve RF power to compensate for detuning is not available.

Helium Vessel pressure surface

Piezos are used for fast tuning.
COMSOL. Frequency Sensitivity to Pressure in SSR

**Electromagnetic Waves**
- Solving only for the RF domain
- Applying the proper boundary conditions

**Solid Mechanics**
- Solving only for the Cavity Vessel
- Applying the proper fixed constraints, symmetries, displacements, and boundary load

**Moving Mesh**
- Solving for all domains
- Applying the proper prescribed and free mesh deformation/displacement

---

**Three Multiphysic Modules**

**Two Simulation Studies**

**Study 1**
- Eigen-frequency (to find $f_0$)

**Study 2**
- Stationary (solving only for solid mechanics and moving mesh)
- Eigen-frequency (to find $f_p$)

---

**Solid Mechanics**
- Find the deformation under given pressure load ($P_L$)

**Moving Mesh**
- Update the mesh after deformation

**EM**
- Eigen frequency simulation to find the resonant frequency ($f_0$)
- Eigen frequency simulation to find the resonant frequency after deformation ($f_p$)

$$\frac{df}{dp} = \frac{f_p - f_0}{P_L}$$
Moving Mesh

- Solving for all domains
- Applying the proper prescribed and free mesh deformation/displacement

Solid Mechanics

- Solving only for the Cavity Vessel
- Applying the proper fixed constraints, symmetries, displacements, and boundary load

Electromagnetic Waves

- Solving only for the RF domain
- Applying the proper boundary conditions

Stainless Steel Vessel

- Nb cavity

Symmetry Boundaries

- $x = 0$
- $y = 0$

Pressure Boundary Load

Free Deformation

Fixed Constraint

PMC
**Elliptical cavity design**

df/dP optimizations of new design for end lever tuner

**HB650 MHz cavity**

<table>
<thead>
<tr>
<th>df/dP, Hz/mbar vs. Tuner Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness</td>
</tr>
<tr>
<td>- Bellow 115mm</td>
</tr>
<tr>
<td>- Bellow 135mm</td>
</tr>
<tr>
<td>- Bellow 165mm</td>
</tr>
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</table>

Stiffness of $\beta=0.92$ cavity

kN/mm vs. Radius of the Regular stiffening ring
- Stiffness of $\beta=0.9$ cavity

**df/dP, Hz/mbar vs Tuner Stiffness**

- 0.9 $R_{\text{end}}=R_{\text{reg}}=110$
- 0.92 $R_{\text{end}}=R_{\text{reg}}=110$
- 0.92 $R_{\text{end}}=110$ $R_{\text{reg}}=120$

**kN/mm vs. $R_{\text{reg}}$, mm**

- 5
- 6
- 7
- 8
Electromagnetic fields inside the cavity develop pressure on the cavity inside walls that is defined as

\[ P_{rad} = \frac{1}{4} \left( \mu |H|^2 - \varepsilon |E|^2 \right) \]

Pressure exerted by the magnetic field is positive (push) pressure, while it is negative (pull) for the electric field.

Overall frequency shift will always be negative since the repulsive magnetic field forces and the attractive electric field forces both work together to decrease the resonance frequency of the deformed cavity, called LFD.

Lorentz forces exerted on the 650 MHz \( \beta = 0.9 \) single cell cavity ahead with the radiation pressure values in mbar at the 3.5 MV cavity voltage. Deformation is exaggerated by 20000 times.
COMSOL. LFD simulations

Radiation pressure

\[ P = \frac{1}{4} \left( \mu_0 |H|^2 - \varepsilon_0 |E|^2 \right) \]

\[ \Delta f = Kl |E_{acc}|^2 \]

Blue: Niobium
Red: Ni-Ti
Green: Ti

<table>
<thead>
<tr>
<th>Spring Const [KN/mm]</th>
<th>LFD [Hz/(MV/m)^2]</th>
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</thead>
<tbody>
<tr>
<td>Fixed</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>-1.26</td>
</tr>
<tr>
<td>100</td>
<td>-1.36</td>
</tr>
<tr>
<td>40</td>
<td>-1.46</td>
</tr>
<tr>
<td>20</td>
<td>-1.65</td>
</tr>
<tr>
<td>10</td>
<td>-1.85</td>
</tr>
<tr>
<td>5</td>
<td>-2.14</td>
</tr>
<tr>
<td>Free</td>
<td>-3.69</td>
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</table>

Graph showing the relationship between Spring Constant [KN/mm] and LFD [Hz/(MV/m)^2].
COMSOL. Modal Analysis

- Modal eigen-frequencies of each cavity structure can be numerically calculated using a solid mechanics solver.
- Any modification on the cavity structure would necessarily change the modal frequencies.
- The frequency shift in the electromagnetic resonance frequency due to the excitation of a certain modal eigen-frequency could be computed knowing the energy of that eigen-frequency.
- Moreover, we believe that the modal frequency will be affected by the liquid Helium filling the cavity during operation.

Modal frequencies of the 650 MHz β=0.9 cavity:
- 33 Hz
- 88 Hz
- 108 Hz
COMSOL. Modal Analysis

10 Lowest Mechanical Resonance
Total Energy normalized on 1mm max-displacement
Stiffness of the Tuner = 0

HB650 MHz cavity
COMSOL. Modal Analysis

Mechanical resonances HB650 MHz dressed cavity with tuner

Mechanical 1st Transverse Mode

Mechanical 1st Longitudinal Mode

Mechanical 2nd Longitudinal Mode

Mechanical 3nd Longitudinal Mode

R = 90 mm

R = 100 mm
COMSOL. Frequency tuning simulations

- 649.0937 MHz, 96.9%
- 649.2468 MHz

\[ \Delta L = 0.783 \text{ mm}, \ \eta = 58\% \]
\[ \Delta F \approx 153.100 \text{ KHz} \]

-0.305 mm, Fixed -1.35 mm

-1.088 mm
Given the several models of Kapitza Resistance, we tried to use our experience with the third harmonic cavity to check which one is closer to measurements. Mittag model looks the closest with quench field 126mT vs 120mT observed in measurements, thus it will be adopted.

Kapitza Layer thickness is 0.5 mm.
SRF cavity production technology

Parts: sheets, tubes
Parts QC  Half cell forming  Iris welding  Dumbbell, end ass. RF QC  Equator welding  QC

Fabrication  Quality Control  Chemical Processing  Heat Treatment  Frequency Tuning  Light Chemistry  Baking  VTS Testing

Vessel Welding  Light Chemistry  Quality Control  HTS Testing

String Assembly  Quality Control  Cryomodule Assembly  Cryomodule Testing
Material quality control

Technical Specification to Niobium Sheets for XFEL Cavities

<table>
<thead>
<tr>
<th>Concentration of impurities in ppm</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ta</strong></td>
<td>≤ 500</td>
</tr>
<tr>
<td><strong>W</strong></td>
<td>≤ 70</td>
</tr>
<tr>
<td><strong>Ti</strong></td>
<td>≤ 50</td>
</tr>
<tr>
<td><strong>Fe</strong></td>
<td>≤ 30</td>
</tr>
<tr>
<td><strong>Mo</strong></td>
<td>≤ 50</td>
</tr>
<tr>
<td><strong>Ni</strong></td>
<td>≤ 30</td>
</tr>
</tbody>
</table>

No texture: The difference in mechanical properties (Rm, Rp₀₂, AL₃₀) orthogonal and parallel to main rolling direction < 20% (cross rolling).
Material quality control

Disks are cut from high purity niobium sheet and eddy current scanned for pits, scratches or inclusions of foreign materials.

Discs with inclusions of foreign materials or damage are rejected.
Material quality control

Example of the Nb sheet eddy current scanning test. Arrow indicates the suspicious spot.

The spot was identified as an inclusion of foreign material. Cu and Fe signal has been observed in the SURFA spectrum in the spot area.

SURFA (Synchrotron Radiation Fluorescence Analysis). Spectrum of K-lines at the spot area (dashed line) in comparison with spot free area (full line).
Material quality control

Development of SQUID based scanning system for testing of niobium sheets

An excitation coil produces eddy currents in the sample, whose magnetic field is detected by the SQUID.

Prototype of SQUID based scanning system for niobium sheets (in work)
Elliptical cavity production

**Fabrication:** Conventional fabrication (deep drawing and EB welding of fine grain Nb). Experiences of ca. 20 years of industrial cavity fabrication are available.

- **Half cells are produced by deep drawing.**
- **Dumb bells are formed by electron beam welding.**

After proper cleaning eight dumb bells and two end group sections welded by electron beam together.

Important: clean conditions on all steps shape accuracy, preparation and EB welding.
Elliptical cavity production

Cavity welding: the general way
There are differences of welding processes in industry

1. Degreasing and rinsing of parts
2. Drying under clean condition
3. Chemical etching at the welding area (Equator)
4. Careful and intensive rinsing with ultra pure water
5. Dry under clean conditions
6. Install parts to fixture under clean conditions
7. Install parts into electron beam (eb) welding chamber
   (no contamination on the weld area allowed)
8. Install vacuum in the eb welding chamber <= 1E-5 mbar
9. Welding and cool down of Nb to T < 60 C before venting
10. Leak check of weld
Elliptical cavity production

Cavity (9 cell TESLA/TTF design)

Dumb-bell

End group 1

End group 2

A. Matheisen, DESY
Elliptical cavity production

3.9 GHz half cells and dumbbell measurement fixture
Elliptical cavity production

3.9 GHz, 1.3 GHz and 650 MHz dumbbell measurement fixtures
Elliptical cavity production

Frequency vs. L2 length
Magnetic BC on iris side

<table>
<thead>
<tr>
<th>L2</th>
<th>0</th>
<th>2</th>
<th>4</th>
</tr>
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<tbody>
<tr>
<td>F, MHz</td>
<td>649.493</td>
<td>647.273</td>
<td>645.169</td>
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</table>

\[
\frac{dF}{dL} = -1.125
\]

Electrical BC on both sides

<table>
<thead>
<tr>
<th>L2</th>
<th>0</th>
<th>2</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>F, MHz</td>
<td>644.194</td>
<td>642.14</td>
<td>640.193</td>
</tr>
</tbody>
</table>

\[
\frac{dF}{dL} = 0.223 \quad \frac{dF}{dL} = -1.04
\]

650 MHz beta 0.90 copper dumbbell

<table>
<thead>
<tr>
<th>L, mm</th>
<th>F0, MHz</th>
<th>F1, MHz</th>
<th>dF, MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>213.05</td>
<td>639.37</td>
<td>644.47</td>
</tr>
<tr>
<td>Expected</td>
<td>213.8</td>
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<td>646.206</td>
</tr>
<tr>
<td>dF, MHz</td>
<td>-1.797</td>
<td>-1.736</td>
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</tr>
</tbody>
</table>
Elliptical cavity production

Cavity production steps:
- Eddy current scanning of Nb shits.
- Cut disk blanks with hole in the center
- Flow forming of half cell and trimming iris and equator area with extra length for tuning and welding shrinkage compensation. No extra length for a tuning in mid-cells. If pass visual inspection:
  - Frequency and length measurements. Sensitivity of the frequency to extra length is 14 MHz/mm at iris and -55 MHz/mm at equator.
- EB welding of two half cell at iris to form dumbbell. Partial penetration welding from both sides. If pass visual inspection:
  - Frequency and length measurements of the dumbbells. Both mode frequencies $F_0$ and $F_{\pi}$ measured 3 times: 1) without perturbation $F_0$ and $F_1$, 2) with perturbation in 1st half cell $F_{01}$ and $F_{11}$ 3) with perturbation in 2nd half cell $F_{02}$ and $F_{12}$.
  - Difference of the frequencies of two half cell can be calculated from these data:
    
    \[ dF = F_2 - F_1 = (F_{01} - F_{11} + F_{12} - F_{02})/(F_{01} + F_{11} - F_{02} - F_{12}) \times k \times F_0 \]
    
    Where $k \sim 4(F_{\pi} - F_0)/(F_{\pi} + F_0)$, for a 3rd harmonic cavity $k \sim 0.08$ MHz.
- Trimming calculations:
  - Equator trimming
  - Equator welding
  - Mechanical and RF QC of the new cavity.
- Bulk BCP and 800C baking,
- RF tuning of the cavity
Multi-cell cavity field flatness tuning

“Iris”, axial tuning fixture

“Equator”, radial tuning fixture
Multi-cell cavity field flatness tuning

FNAL elliptical 9 cell cavity tuning procedure. This technique based on bead-pull measurements of field distribution on operating (pi-mode). Amplitudes of E-field in the center of each cell used for frequency of individual cells.

Normalized field distribution is uniform, $A_i=1$ for $i=1,2, \ldots 8,9$, if frequency of each cell are same. When frequency of the cell $#n$ is shifted by $dF_n=1$ kHz field distribution will change by $dA_i$.

$$dA_i = K_{in} * dF_n$$

Perturbation of frequency of each will change field distribution:

Let us solve this equation to find frequency perturbation from field distribution:

$$dA = K * dF \Rightarrow K^{-1} * dA = K^{-1} K * dF = dF$$

Where sensitivity coefficients matrix $K$ calculated from HFSS simulations.

During RF tuning of the cavity we need to tune its operating mode frequency $F_9$. Also we can not measure individual cell frequency but can measure $F_9$. Tuning of cell $#n$ by $dF_n$ shifts also cavity frequency by $dF_9\sim dF_n/9$. If design frequency is $F_90$ tuning of the cell should be done by shifting operating mode frequency by:

$$dF_9 = (F_90 - F_9 - dF_n) / 9$$

This technique works best when field flatness of the cavity is close to ideal. Because it linear and based on small perturbations. Tuning is better to start with most perturbed cell. If field flatness still not acceptable the additional tuning cycle should be done.

Before tuning. FF 65%, slope +28 %

After tuning. FF 98%, slope +0.64 %
Cavity cell centers measurements technique based on bead-pull

We need to measure cavity alignment. Usually people measure it mechanically on the outside surface of the cavity. This measurements time consuming, needs additional equipment and not possible for a cavity welded to He vessel.

Calculations of the electrical center of the each cell of the cavity based on bead pull measurements. It includes next steps:
- Bead pull measurements setup allows positioning of the fishing line in the plane perpendicular to cavity axes Z. Initial position of the line is go through centers of beam flanges
- Field distribution measurements in several positions shifted in XZ plane on line parallel to cavity axes. Usually 5 measurements with displacements -2d, -d, 0, d, 2d.
- Calculations of field Anm maximum in each cell #n center and measurement #m.
- Calculations of electric cell center Xn for each cell #n as a position of 2nd order best fit line maximum. An(x)=A0-k(X-Xn)^2.
- Similar calculations for YZ plane.
- At the end we have coordinates (Xn,Yn) of electric centers for each cell of the cavity.
- Cavity rotates by 180 degree around beam pipe flanges and measurements and calculations repeated. Combination of these two measurements allow us exclude error of initial positioning of fishing line.

\[ \Delta \varphi = k_H \mu_0 H^2 - k_E \varepsilon_0 E^2 \]

CMM and bead-pull cell center measurements.

Amplitude

Coordinate at axis X, mm

X before

X after

Y before

Y after
ICL Cavity Tuning Machine
ICL Cavity Tuning Machine

\[ \frac{\Delta \omega}{\omega_0} = \frac{\Delta U}{U} = -\frac{\pi r^3}{U} \left[ \varepsilon_0 \left( \frac{\varepsilon_r - 1}{\varepsilon_r + 2} \right) E_r^2 + \mu_0 \left( \frac{\mu_r - 1}{\mu_r + 2} \right) H_o^2 \right] \]

\[ \frac{\Delta \omega}{\omega_0} = \frac{1}{2Q_L} \tan \Phi \]
Electrical Tuning Model

\[ C_b = C_k / 2 \]

\[ \frac{\omega_m^2}{\omega_0^2} = 1 + 2k \left( 1 - \cos \frac{\pi m}{n} \right) \]

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Example Bead-Pull Frequency Data from a 9-Cell Tesla Style Cavity
ICL Cavity Tuning Machine

Cavity Alignment

[Image of a cavity alignment setup with labeled components: Camera, Laser, and Mirror, along with an associated software interface showing a laser and camera view.]
ICL Cavity Tuning Machine

Laser based alignment correction

Frequency tuning of the cavity cell in the Cavity Tuning Machine based on deformation of the cell in axial direction. Deformation provided by three motorized Arms located around the cell in the plane perpendicular to cavity axes uniformly every 120 degrees. Arm #1 is located on the top of the cell. Arm #2 is in the right side of the cavity, when we look from power coupler end of the cavity. Arm #3 is in the left side of the cavity in same view.

Each Arm ends with Jaw each side located in plane of one (of two) Irises of the cell. Jaw distance can be changed by stepper motor with gear box independently for each Jaw.

During the tuning Jaw distances change causing axial deformation of the cell. Frequency of the cell and cavity drops when distances decrease and the frequency goes up when distances increases. Note: for safe operation Jaws can not move in opposite direction.

We need to redistribute Jaws motions to improve cavity alignment. Laser based Cavity Alignment Control System is used for this purpose. Beam emitted from Laser installed on Cavity Coupler end Beam Pipe Flange reflects from mirror installed on another end Beam Pipe Flange. Retuned laser beam image detected by camera installed on same flange as Laser. Any angular change between two Beam pipe flanges cause change of laser beam image spot position. Alignment conservation technique is based on keeping laser beam image spot position as close as possible to the initial position during cell tuning.

Another advantage of laser based Cavity Alignment Control System is possibility to perform control during aligning of the cavity. It is necessary for a cavity with bad alignment originally, before tuning.

So we need a technique to control cavity alignment during frequency tuning. It will allow us to keep cavity alignment and even improve it.
HOM notch frequency tuning

S21 power coupler to PU
S21 power coupler to HOMpu
S21 HOMc to PU

S21 power coupler to PU
Red curve $|S21/S21|$
Black curve $|S21/S21|$
HOM notch frequency tuning

- Green: S21 main coupler to peek-up PU.
- Red: S21 main coupler to HOMpu.
- Black: S21 HOMc to PU

Table:

<table>
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<tr>
<th>F_r, MHz</th>
<th>Q</th>
<th>PU</th>
<th>HOMpu</th>
<th>HOMc</th>
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<td>1.01E-01</td>
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Graphs:

- $y = -0.1449x + 187.96$
- $y = -0.1474x + 191.29$
HOM notch frequency tuning

Notch frequency tuning tool
HB650 $\beta=0.9/0.92$ cavity for PIP-II design

### PIP-II Layout

<table>
<thead>
<tr>
<th>Section</th>
<th>Freq</th>
<th>Energy (MeV)</th>
<th>Cav/mag/CM</th>
<th>Type</th>
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<tr>
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<td>162.5</td>
<td>2.1-10.3</td>
<td>8/8/1</td>
<td>HWR, solenoid</td>
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<td>SSR1 ($\beta_{opt}=0.22$)</td>
<td>325</td>
<td>10.3-35</td>
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<td>SSR, solenoid</td>
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<td>SSR2 ($\beta_{opt}=0.47$)</td>
<td>325</td>
<td>35-185</td>
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<td>LB 650 ($\beta_g=0.61$)</td>
<td>650</td>
<td>185-500</td>
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<td>HB 650 ($\beta_g=0.92$)</td>
<td>650</td>
<td>500-800</td>
<td>24/8/4</td>
<td>5-cell elliptical, doublet</td>
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HB 650 MHz  Cavity Helium Vessel

components:

1. Long Cylinder
2. Transition ring MC end
3. Transition ring FP end
4. Bellow assembly
5. Support lugs
6. Lifting lugs
7. Helium inlet
8. 2-phase pipe assembly
9. Tuner mounting lugs
10. Bellow restraints
11. Magnetic shielding (external)
The Scope of EM-Mechanical Design

- Minimize a sensitivity to microphonics due to He pressure fluctuations (df/dP) and mechanical vibrations
- Minimize a Lorentz Force Detuning (LFD) coefficient
- To keep the stiffness and tuning sensitivity at suitable level to allow for tuning.
- Keep provision for slow and fast tuner integration.
- Enough strength to withstand atmospheric pressure
- Dressed cavity has to be qualified in 5 different load conditions by stress analysis
  1. Warm Pressurization
  2. Cold operation at maximum pressure
  3. Cool down and tuner extension
  4. Cold operation at maximum pressure and LHe weight
  5. Upset condition – Insulating and beam vacuum failure
Cavity stiffness simulations

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<td>115</td>
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<td>125</td>
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<td>130</td>
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<td>140</td>
<td>14.7</td>
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<table>
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<tr>
<td>x2, mm</td>
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<td>σ bellow, MPa</td>
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<td>σ cavity, MPa</td>
<td>10</td>
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<table>
<thead>
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<th>Young’s modulus 293K/2K</th>
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<td>105/118</td>
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<td>Titanium</td>
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<tr>
<td>Niobium-Titanium</td>
<td>62/68</td>
<td>0.33</td>
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</table>

F, N = 1000, x1 = 0.295 mm, x2 = 0.016 mm, σ bellow = 52 MPa, σ cavity = 10 MPa
## Stress analysis

### Load Case 1
- **Loads:** 1. Gravity<br> 2. \( P_1 = 0.2 \) MPa<br> 3. \( P_2 = P_3 = 0 \)
- **Condition Simulated:** Warm pressurization
- **Applicable Temperature:** 293 K
- **Applicable Stress Categories:** \( P_m, P_L, Q, P_m + P_b, P_L + Q \)

### Load Case 2
- **Loads:** 1. Gravity<br> 2. Liquid Helium head<br> 3. \( P_1 = 0.4 \) MPa<br> 4. \( P_2 = P_3 = 0 \)
- **Condition Simulated:** Cold operation, full LHe, maximum pressure – no thermal contraction
- **Applicable Temperature:** 2 K
- **Applicable Stress Categories:** \( P_m, P_L, Q, P_m + P_b, P_L + Q \)

### Load Case 3
- **Loads:** 1. Cool down to 1.88 K<br> 2. Tuner extension of 2 mm
- **Condition Simulated:** Cool down and tuner extension, no primary loads
- **Applicable Temperature:** 2 K
- **Applicable Stress Categories:** Q

### Load Case 4
- **Loads:** 1. Gravity<br> 2. Liquid Helium head<br> 3. Cool down to 1.88 K<br> 4. Tuner extension of 2 mm<br> 5. \( P_1 = 0.4 \) MPa<br> 6. \( P_2 = P_3 = 0 \)
- **Condition Simulated:** Cold operation, full LHe inventory, maximum pressure – primary and secondary loads
- **Applicable Temperature:** 2 K
- **Applicable Stress Categories:** Q

### Load Case 5
- **Loads:** 1. Gravity<br> 2. \( P_1 = 0 \)<br> 3. \( P_2 = P_3 = 0.1 \) MPa
- **Condition Simulated:** Insulating and beam vacuum upset, helium volume evacuated
- **Applicable Temperature:** 293 K
- **Applicable Stress Categories:** \( P_m, P_L, Q, P_m + P_b, P_L + Q \)
### Stress analysis. Allowable Stresses (MPa)

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<table>
<thead>
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**Note:** The allowable stresses have not been reduced by 0.8 (recommended by point 3.4.1.10 of TD-09-005, confirmed by Tom Peterson). For welds it has been reduced by factor of 0.6.

Pm = primary membrane stress; P_L = primary local membrane stress P_b = primary bending stress
Q = secondary stress
### Stress analysis. Linearized Stress Table (MPa)

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<td>4.46</td>
<td>15</td>
<td>5.53</td>
<td>30</td>
</tr>
<tr>
<td>F (Nb weld at Iris)</td>
<td>4.28</td>
<td>15</td>
<td>7</td>
<td>22.5</td>
</tr>
<tr>
<td>G (Nb material near stiffening ring)</td>
<td>5.66</td>
<td>25</td>
<td>12.4</td>
<td>37.5</td>
</tr>
<tr>
<td>H (Nb weld at equator)</td>
<td>6.33</td>
<td>15</td>
<td>11.62</td>
<td>22.5</td>
</tr>
<tr>
<td>I (Nb-Ti weld coupler end)</td>
<td>4.92</td>
<td>93.6</td>
<td>7.1</td>
<td>140.4</td>
</tr>
</tbody>
</table>
### Simulation of stresses during production

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Protection</th>
<th>The steps during cavity assembly or operations</th>
<th>Insulated Vacuum, bar</th>
<th>Cavity Beamline, bar</th>
<th>He Vessel, bar</th>
<th>Forces on the cavity flange for fully constrained cavity, kN</th>
<th>Cavity length changes, for non-constrained cavity, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>300K</td>
<td>Safety Brackets</td>
<td>Cavity after dressing</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cavity leak check at the clean room</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>-3.83</td>
<td>-1.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>He Vessel leak check during CM assembly</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0.014</td>
<td>-0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>He Vessel pressure test during CM assembly</td>
<td>1</td>
<td>1</td>
<td>3.3</td>
<td>-0.03</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Tuner Installed</td>
<td>He Vessel leak check during CM testing</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-4.4</td>
<td>-1.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>He Vessel pressure test during CM assembly</td>
<td>1</td>
<td>0</td>
<td>3.3</td>
<td>-3.87</td>
<td>-1.01</td>
</tr>
<tr>
<td>5K</td>
<td>Tuner Installed</td>
<td>Start of cooling down CM or HTS</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
<td>-0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>2K</td>
<td>Tuner Installed</td>
<td>Operating condition</td>
<td>0</td>
<td>0</td>
<td>0.03</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>5K</td>
<td>Tuner Installed</td>
<td>Cold loss of vacuum accident</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>-0.05</td>
<td>0.10</td>
</tr>
</tbody>
</table>

*The steps during cavity assembly or operations*

- Cavity after dressing
- Cavity leak check at the clean room
- He Vessel leak check during CM assembly
- He Vessel pressure test during CM assembly
- He Vessel leak check during CM testing
- He Vessel pressure test during CM assembly
- Start of cooling down CM or HTS
- Operating condition
- Cold loss of vacuum accident

*Fermilab*
LCLS-II Tuner Electro-Mechanical Design

- Tuner must tune cavity (slow and fast) and protect cavity/He Vessel system during CM production cycle and operation of the accelerator
- Tuner needs to fit the existing inventory of cavities at FNAL. ..”short-short” (cavity built for slim blade tuner for CM3/4/5…).
- Active tuner components (electromechanical actuator & piezo-stack) need to be replaceable through special ports;
- High reliability of tuner components (electromechanical actuator and piezo-actuator);
- Tight requirements for slow/coarse & fast/fine tuning resolution \( \rightarrow \) cavity has narrow bandwidth \( (F_{1/2} \sim 15\text{Hz}) \) and resonance control requirements \( \Delta F_{peak} = 10\text{Hz} \) (or \( \sigma = 1.5\text{Hz} \))
# LCLS-II Tuner Electro-Mechanical Design

<table>
<thead>
<tr>
<th></th>
<th>nominal</th>
<th>maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow Tuner frequency range</td>
<td>250kHz</td>
<td>450kHz</td>
</tr>
<tr>
<td>Slow Tuner dimensional range</td>
<td>0.75mm</td>
<td>1.3mm</td>
</tr>
<tr>
<td>Slow Tuner sensitivity</td>
<td>1-2Hz/step</td>
<td></td>
</tr>
<tr>
<td>Fast Tuner frequency range</td>
<td>1kHz</td>
<td></td>
</tr>
<tr>
<td>Fast Tuner dimensional range</td>
<td>3um</td>
<td></td>
</tr>
<tr>
<td>Fast Tuner tuning resolution</td>
<td>1Hz</td>
<td></td>
</tr>
<tr>
<td>Fast Tuner stroke resolution</td>
<td>3nm</td>
<td></td>
</tr>
<tr>
<td>Fast Tuner response bandwidth</td>
<td>5kHz</td>
<td></td>
</tr>
<tr>
<td>Min. tuner stiffness</td>
<td>30kN/mm</td>
<td></td>
</tr>
<tr>
<td>Min. tuner mechanical resonance</td>
<td>5kHz</td>
<td></td>
</tr>
<tr>
<td>Tuner operating condition</td>
<td>insulated vacuum T=20-60K</td>
<td></td>
</tr>
<tr>
<td>Slow Tuner/ electromechanical actuator lifetime (20 years)</td>
<td>1000 spindle rotation</td>
<td></td>
</tr>
<tr>
<td>Fast Tuner/ electromechanical actuator lifetime (20 years)</td>
<td>$4 \times 10^9$ pulses</td>
<td></td>
</tr>
</tbody>
</table>
LCLS II Tuner Schematics

- Slow/Coarse Tuner is double lever tuner (close to design of the SACLAY 1)
- Coarse Tuner ration 1/20 (Saclay 1 ~ 1/17)
- Fast Tuner - two piezo installed close to flange of cavity /translation of the stroke from piezo directly to the cavity
Design of the LCLS II Tuner

design included several features specific to requirements that electromechanical actuator and piezo-elements replaceable through special designated port
Details of FAST (piezo) Tuner design

Encapsulated piezo designed and manufactured by Physik Instrumente (PI) per FNAL specifications.

Each capsule has inside two 18*10*10mm PICMA piezos. Piezo preloaded with 800N.
# Forces/stroke on the cavity/He vessel system

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Insulated Vacuum (bar abs)</th>
<th>Cavity Beamline (bar abs)</th>
<th>Helium Vessel (bar abs)</th>
<th>Forces on cavity flange with absolutely restrained cavity, kN</th>
<th>Cavity length will changes if flange non-restrained, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Cavity is relaxed after HV welding</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>Cavity/He Vessel Leak Checkt at MP9</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Cavity/He Vessel Pressure test at MP9</td>
<td>1</td>
<td>1</td>
<td>3.3</td>
<td></td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>Cavity/He Vessel Leak Check in CM</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
<td>-0.8</td>
</tr>
<tr>
<td>4</td>
<td>Cavity/He Vessel leak check in Clean Room</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>He Vessel pressure test in CM</td>
<td>1</td>
<td>0</td>
<td>3.3</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Start of cooling down CM</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>7</td>
<td>Linac maintenance (e.g., tuner or interconnect access)</td>
<td>1</td>
<td>0</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8a</td>
<td>Tuner access and disconnect (e.g., replace piezo), what is max cryo system pressure</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
<td>-0.8</td>
</tr>
<tr>
<td>8b</td>
<td>End of cooling down</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Operating condition</td>
<td>0</td>
<td>0.03</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Worst case cold loss of vacuum accident. Will piezo and tuner survive?</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>10.4</td>
<td></td>
</tr>
</tbody>
</table>

---

**Requirements:** \(|X_{T=300K}| < 0.6\text{mm}\)

To preserve cavity in elastic region

Final design of the Tuner and restrained brackets included requirements to protect cavity during all steps. **Cavity will be always in elastic region**

Piezo-stack will handle these forces

---

*Director’s Review, February 17-19, 2015*
Tuner Test results at HTS
Tuner Test results at HTS

Cavity Frequency vs Motor Steps (cavity at 2K)

- **450kHz**
- **K=1.4Hz/step**

<table>
<thead>
<tr>
<th>Slow Tuner frequency range</th>
<th>nominal</th>
<th>250kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum</td>
<td>450kHz</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Slow Tuner dimensional range</th>
<th>nominal</th>
<th>0.75mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum</td>
<td>1.3mm</td>
<td></td>
</tr>
</tbody>
</table>

| Slow Tuner sensitivity      | 1-2Hz/step |
Piezo Tuner Range

<table>
<thead>
<tr>
<th>Fast Tuner frequency range</th>
<th>1kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Tuner dimensional range</td>
<td>3\mu m</td>
</tr>
</tbody>
</table>

![Graph](image)

- Cavity Frequency Detuning, Hz
- Piezo Voltage (DC), V

- \( \Delta F = 2.7\text{kHz} \) (100V)
- \( T_{\text{piezo}} \approx 20-60\text{K} \)

Fermilab
High reliability of tuner components

1. Phytron electromechanical Actuator (stepper motor/planetary gear/Ti spindle) *(designed per FNAL specs in the frame of the Project X.)*
   Joint test (JLAB/FNAL) of production unit is underway at JLAB

<table>
<thead>
<tr>
<th>Picture</th>
<th>Name</th>
<th>Motor</th>
<th>Gear Box</th>
<th>Spindle/Nut</th>
<th>Forces</th>
<th>Longevity tested</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td>LCLS II</td>
<td>Phytron 1.2A</td>
<td>planetary gear (ration 1:50)</td>
<td>Titanium &amp; SS M12^21</td>
<td>+/-1300N</td>
<td>tested in ins. vacuum at HTS for 5000 turns <em>(5 XFEL lifetimes)</em>. In the force range +/-1500N. Motor run with current 0.7A</td>
</tr>
</tbody>
</table>

2. Piezo actuator – encapsulated piezo made at PI Ceramics per FNAL specification for LCLS II project
   *(Designated piezo lifetime program is underway at FNAL)*
LCLS-II Tuner Summary

- Design of the LCLS II prototype cryomodule Tuner is mature. Several small issues found during prototype assembly and testing were corrected. Questions/comments from previous reviews were addressed.

- Tuner parameters, measured during tuner test at HTS, meet/exceed technical requirements specifications.

- Reliability of the tuner is addressed by two measures: tuner is accessible through designated ports and the active components (electromechanical actuator & piezo-actuator) illustrated reasonable longevity.

- Preservation of the cavity Q0 with tuner (remnant magnetic field) will be tested in mid-March.

- Procurement of long (~3 months) lead components (stepper motor and piezo-actuators) can be started.
Power coupler design

\[
P_g = \frac{V_{cav}^2}{4(\frac{R}{Q}) \cdot Q_L} \left\{ (1 + \frac{R}{Q} \cdot Q_L I_{b0}}{V_{cav}} \cos \phi_b)^2 + (\tan \psi + \frac{R}{Q} \cdot Q_L I_{b0}}{V_{cav}} \sin \phi_b)^2 \right\}
\]

\[
\tan \psi = -2Q_L \frac{\omega - \omega_0}{\omega_0} = -2Q_L \frac{\Delta f}{f_0}
\]

TTF-3 Coupler
Power coupler design

waveguide to coax transition

room temperature window

light detector (PM)

warm vacuum pumping port

warm coax
Ø 62 mm
Z= 50 Ohm

cold coax
Ø 40 mm
Z= 70 Ohm

cold window

4.2 K point

bias voltage feedthrough

e⁻ 3 pickup

Qext tuning knob

Qext tuning rod

isolating Kapton foil

room temperature isolation vacuum flange

70 K point

e⁻ 1 pickup

1.8 K flange to cavity
Power coupler design

TRISTAN Type Coaxial Disk Ceramic

Warm window

Cold window

Qext = 2.0 x 10^6
Prf = 350 kW

80 K     5 K     2 K
Static Loss  5 W    1.1 W   0.05 W
Dynamic Loss 3 W    0.2 W   0.03 W
Power coupler design

Cold measurement.

TOSHIBA did mechanical job perfectly! These rather complicated devices was built without any single preliminary RF cold measurements. But we got good SWR instantly just after assembling! It was a big relief.
Power coupler design

Components for High Power Test Stand

Input Couplers

Coupling Waveguides

Doorknobs
Power coupler design

Capacitive-coupling Coupler

Coupler can be modified to have changeable coupling. Two bellows allow to move middle part of coupler with antenna.
Power coupler high power tests

![Diagram of power coupler setup]

- Water load
- Movable short
- Vac pump
- Arc detector
- Couplers
- Waveguide
- IR sensor
- DC
- RF power

[Image: Power coupler high power tests setup at Fermilab]
Power coupler high power tests

- PIN
- POWER SUPPLY
- POWER METER
- INTERLOCK MODULE
- RF TRIGGER STATUS
- SET TRIP LEVEL
- INTERLOCK MODULE
- to INTERLOCK MODULE
- CCG
- BA
- IP
- to RF LOAD
- POWER METER
- 1 MW
- 0.1 μsec
- 1 MW
- 0.5 μsec
- 1.3 msec, 1 MW, 5 pps

NOTE: Cross section [cm²]
ILC45MVM: 22.6
S-band: 24.5
C-band: 10.5
325 MHz coupler

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>325 MHz</td>
</tr>
<tr>
<td>Pass band ((S_{11}&lt;0.1))</td>
<td>&gt; 1 MHz</td>
</tr>
<tr>
<td>Operating power ((\text{CW}))</td>
<td>25 kW</td>
</tr>
<tr>
<td>HV bias</td>
<td>\sim 2 kV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(P_i), kW</th>
<th>(2K / P_i), W</th>
<th>(15K / P_i), W</th>
<th>(125K / P_i), W</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.06 / 52</td>
<td>0.58 / 151</td>
<td>2.02 / 40</td>
</tr>
<tr>
<td>3</td>
<td>0.10 / 86</td>
<td>0.81 / 211</td>
<td>2.35 / 47</td>
</tr>
<tr>
<td>6</td>
<td>0.15 / 129</td>
<td>1.03 / 268</td>
<td>2.68 / 54</td>
</tr>
<tr>
<td>20</td>
<td>0.35 / 301</td>
<td>2.07 / 538</td>
<td>4.25 / 85</td>
</tr>
<tr>
<td>30</td>
<td>0.50 / 430</td>
<td>2.82 / 733</td>
<td>5.36 / 107</td>
</tr>
</tbody>
</table>

- **Cryomodule flange**
- **Spring to compensate thermal expansion**
- **“80K” intercept**
- **“5K” intercept**
- **Ceramic window**
- **Antenna**
- **Cold flange**
- **Bellows**
- **3”x 0.0158” stainless steel tube**
- **e-pickup port**
- **Heater (~ 10W)**
- **3-1/8” coaxial input**
- **Air inlet**
- **Capacitor**
- **Matching bump**
- **Arc detector**
Coaxial power coupler

1. Given:
   1. External conductor with outer diameter D1, SS wall thickness d1, Cu coating thickness d2
   2. Length L, internal conductor diameter D2
   3. RF power P in TW regime.
   4. One end temperature 300K other end 4K, 70K heat sink in the middle
   5. Thermal conductivity p1 for SS and p2 for copper not depend on temperature.
   6. Electrical surface resistance SS Rs1 and Cu Rs2
   7. Thermal radiation is negligible. Attenuation of RF power is negligible
   8. Efficiency of 70 K cooler is 5%, efficiency of 4K cooler is 0.5%

2. Assumptions:
   1. Thermal radiation is negligible. Vacuum.
   2. Attenuation of RF power is negligible.

1. Questions:
   1. What heat power flow at 70K and 4K intercepts at P=0 W?
   2. What is power consumption at cryoplant at P=0 W?

\[ P_t = \frac{\partial Q}{\partial t} = p \iiint_S \nabla T \cdot dS = p \cdot \frac{\Delta T}{L} \cdot S \]