C-band two-cell high-gradient RF cavity for high power HOM absorber testing

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Higher-order modes damping

• Accelerator cell profile provided by SLAC and UCLA.

• Goal: reduction of quality factor and transverse kick-factor of monopole and dipole modes from 5 to 40 GHz.

$\text{TM}_{010}$ fundamental mode at 5.712 GHz

$\text{TM}_{110}$ first dipole mode at 9.245 GHz
Higher-order modes damping

- Approach: HOM damping waveguides.
- Damping load: NiCr or SiC coating layer.
- 20-cell studies in CST and Omega3P.
Higher-order modes damping study workflow

**Single cell** with periodic boundary

Find all monopole and dipole modes over 5 - 40 GHz.

Compute ohmic Q-factor, shunt impedance, kick-factor.

**20-cell** structure

Add waveguide slots with lossy material coating layers.

Compute ohmic Q-factor, shunt impedance, kick-factor, for modes identified in STEP 1.

Setup waveguide slot with impedance boundary.

Compute ohmic Q-factor with damping, for modes identified in STEP 1.

Compute Q-factor × kick-factor.
Example: TM$_{110}$ mode damping

- Undamped TM$_{110}$ mode (9.2 GHz).
  - Q factor: 18150
  - Q $\times$ transverse kick factor: $5.72 \times 10^4$ V/pC/m/mm

- Damped TM$_{110}$ mode in the individual cells of a 20-cell cavity.
  - With Design 1: straight waveguide slot.
  - SiC coating ($1.0 \times 10^2$ S/m).
Current best-performing design

- Design 3 – two-section taper waveguide slot
  - NiCr coating (1.0×10⁶ S/m).

- Optimization setup.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Length of first w/g slot (L_wg1)</td>
<td>2 to 8 mm</td>
</tr>
<tr>
<td>Length of second w/g slot (L_wg2)</td>
<td>4 to 10 mm</td>
</tr>
<tr>
<td>Thickness of initial w/g (t₁)</td>
<td>0.25 mm (constant)</td>
</tr>
<tr>
<td>Thickness of 1ˢᵗ tapered (t₂)</td>
<td>20, 40, 60, 80 and 100 μm</td>
</tr>
<tr>
<td>Thickness of 2ⁿᵈ tapered (t₃)</td>
<td>0.5 μm</td>
</tr>
</tbody>
</table>
**HOM absorber high power test**

- NiCr \((1.0 \times 10^6 \text{ S/m})\) coating layers.
- RF design verification at high accelerating gradient \((\sim 100 \text{ MV/m})\)
  - Breakdown test
  - Multipactor detection
- Absorber performance vs. breakdowns.
  - Damage examination
Two-cell cavity design

- $\pi$-mode operation, critical coupling.
- HOM damping: straight waveguide slot.
- HOM damping optimization.
  - Waveguide longitudinal extension length
  - Waveguide transverse sizes
    - Eigenmode optimization result: 34 mm & 50 mm
    - Finalized dimension: 45 mm
HOM damping waveguide transverse dimension
• Providing maximal damping of HOM.
• Rejecting additional parasitic modes introduced by the HOM damping waveguides.

\[ Q_{0, \text{NiCr-coated}} = 10721 \]
\[ Q_{0, \text{uncoated}} = 13152 \]
Two-cell cavity RF analysis

- 100-MV/m accelerating gradient.

### Design parameters

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<tr>
<td>Operating frequency $f_0$</td>
<td>5.712 GHz</td>
</tr>
<tr>
<td>unit cell shunt impedance $r_{sh}$</td>
<td>118 MΩ/m</td>
</tr>
<tr>
<td>unloaded quality factor $Q_0$</td>
<td>13500</td>
</tr>
<tr>
<td>unloaded quality factor, no absorber $Q_{0,\text{uncoated}}$</td>
<td>13525</td>
</tr>
<tr>
<td>Cavity coupling factor $\beta$</td>
<td>1.00</td>
</tr>
<tr>
<td>RF power for 100-MV/m gradient</td>
<td>4.4 MW</td>
</tr>
<tr>
<td>NiCr loss for 100-MV/m gradient</td>
<td>2.5 kW</td>
</tr>
<tr>
<td>NiCr average loss for 100-MV/m gradient, 1-μs pulse length, 100 Hz repetition rate</td>
<td>0.25 W</td>
</tr>
<tr>
<td>NiCr electrical conductivity</td>
<td>$1.0 \times 10^6$ S/m</td>
</tr>
</tbody>
</table>
Two-cell cavity RF analysis

• Local peak E-field normalized to $E_m$.
• Local peak H-field normalized to $(E_m/Z_0)$.
  - $Z_0 = 377 \, \Omega$.

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<th>Electric field local peak values</th>
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<td>Coupling slot</td>
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Two-cell cavity HOM damping

- NiCr ($1.0 \times 10^6$ S/m) coating layers
- HOM E-field magnitude distributions –

![NiCr-coated](image)

- TM110 (9.27 GHz)
- TM211 (12.28 GHz)
- TM120 (15.67 GHz)
- TM121 (17.65 GHz)
Fabrication and challenges

• OFHC copper cavity fabricated in quadrants, coated with NiCr layers, and then brazed together.
• Tuner design for quadrants.
• Machining error sensitivity.
  - 0.001-inch increase of the elliptical cell profile minor radius results in 5-MHz reduction in the cell resonant frequency.
Acknowledgments

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