Recent Progress in HOM Damping from Around The World

- News from the 2010 HOM Workshop at CORNELL -

Matthias Liepe
Cornell University
Outline

• HOM10: Introduction  
  – Why this workshop and what was covered?
• Antenna / loop HOM couplers
• Waveguide couplers
• Beamline dampers
• RF absorbing materials
• HOM measurement and simulation tools
• Summary
HOM10: Introduction
HOM Damping Workshop

- October 11 – 13, 2010 (2.5 days)
- At Cornell University
- Topic: Methods of damping Higher-Order-Modes in superconducting RF cavities

 Cornell University
 International Workshop on
 Higher-Order-Mode Damping in
 Superconducting RF Cavities

October 11–13, 2010
701 Clark Hall, Cornell University

The workshop will be held on the beautiful upstate New York Cornell University campus. It will address different methods of damping Higher-Order-Modes in superconducting RF cavities.

Specific subjects of interest are:
- RF absorbing materials
- Antenna HOM absorbers
- Beampipe HOM absorbers
- Waveguide HOM absorbers
- HOM simulation tools
- HOM measurement methods

For information or to register, visit: www.lepp.cornell.edu/Events/HOM10
• ~40 participants
• From 15 different labs/ universities from Asia, Europe and U.S.
• Nearly all experts on HOM damping
• 35 presentations
• http://www.lepp.cornell.edu/Events/HOM10/Agenda.html
The success of SRF is pushing the beam parameter envelope constantly

- Higher currents
  - >1 A in rings
  - > 100 mA in linacs
- Higher bunch charges
  - Up to 10’s of nC
- Shorter bunches
  - Down to 25 μm
HOM Damping for (Future) SRF Projects

- CEBAF Upgrade @ TJNAF
- Project X @ FNAL
- XFEL @ DESY
- SPL @ CERN
- APS Upgrade SPX @ ANL
- BERLinPro @ HZB
- KEK-cERL @ KEK
- Cornell ERL @ Cornell
- eRHIC @ BNL
- KEKB @ KEK

- Different projects -> different beam parameter -> different HOM damping schemes
### Beam Current and HOM Damping Requirements

<table>
<thead>
<tr>
<th>Project</th>
<th>Beam current [mA]</th>
<th>Average HOM power per cavity [W]</th>
<th>Required monopole Q &lt;</th>
<th>Required dipole Q &lt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEBAF 12GeV</td>
<td>0.10</td>
<td>0.05</td>
<td>1.40E+09</td>
<td>1.50E+09</td>
</tr>
<tr>
<td>Project X</td>
<td>1</td>
<td>0.06</td>
<td>2.00E+07</td>
<td>1.00E+09</td>
</tr>
<tr>
<td>XFEL</td>
<td>5</td>
<td>1</td>
<td>1.00E+05</td>
<td>1.00E+05</td>
</tr>
<tr>
<td>SPL</td>
<td>40</td>
<td>22</td>
<td>1.00E+04</td>
<td>1.00E+07</td>
</tr>
<tr>
<td>APS SPX</td>
<td>100</td>
<td>2,000</td>
<td>5.00E+02</td>
<td>2.00E+02</td>
</tr>
<tr>
<td>BERLinPro</td>
<td>100</td>
<td>150</td>
<td>1.00E+04</td>
<td>1.00E+04</td>
</tr>
<tr>
<td>KEK-CERL</td>
<td>100</td>
<td>185</td>
<td>1.00E+06</td>
<td>1.00E+04</td>
</tr>
<tr>
<td>Cornell ERL</td>
<td>100</td>
<td>200</td>
<td>5.00E+03</td>
<td>1.00E+04</td>
</tr>
<tr>
<td>eRHIC</td>
<td>300</td>
<td>7,500</td>
<td>1.00E+04</td>
<td>4.00E+04</td>
</tr>
<tr>
<td>KEKB</td>
<td>1,400</td>
<td>15,000</td>
<td>1.00E+02</td>
<td>1.00E+02</td>
</tr>
</tbody>
</table>

- High beam current requires high power handling capabilities of HOM damping scheme

\[ P_{avg} = k || Q I \]

- Risk of resonant mode excitation and beam stability require strong HOM damping by HOM damping scheme
### Bunch Length and HOM Damping Requirements

- Short bunch length requires broadband HOM damping scheme: few GHz to tens of GHz

<table>
<thead>
<tr>
<th>Project</th>
<th>Bunch length [ps]</th>
<th>90% HOM power below [GHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>APS SPX</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td>KEKB</td>
<td>25</td>
<td>9</td>
</tr>
<tr>
<td>eRHIC</td>
<td>7</td>
<td>25</td>
</tr>
<tr>
<td>SPL</td>
<td>4</td>
<td>17</td>
</tr>
<tr>
<td>Project X</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>BERLinPro</td>
<td>2</td>
<td>45</td>
</tr>
<tr>
<td>KEK-CERL</td>
<td>2</td>
<td>52</td>
</tr>
<tr>
<td>Cornell ERL</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>CEBAF 12 GeV</td>
<td>0.30</td>
<td>100</td>
</tr>
<tr>
<td>XFEL</td>
<td>0.08</td>
<td>100</td>
</tr>
</tbody>
</table>
Depending on project, the HOM damping scheme must:
- Efficiently handle high power up to several kW per cavity
- Provide very strong HOM suppression of monopole, dipole, quadrupole modes with Q=100 - 10,000
- Be broadband (up to ~100 GHz)
- Be inexpensive / require little beam line length

Fortunately, usually not all of these are required at the same time.

Different requirements -> different solutions.
Damping Schemes

Antenna / loop HOM couplers

Waveguide HOM dampers

RF absorbing materials

Beamline HOM loads
Antenna / loop HOM couplers
Why consider Antenna HOM Couplers?

- Require no extra beamline length
  - But filter is needed to suppress coupling to fundamental mode
- Relatively easy to clean
- HOM power can be absorbed at room temperature
Antenna HOM Damping Efficiency

HOM loop coupler:
- Imbalance between horizontal and vertical dipole mode damping (not good)
- Performance depends strongly on HOM frequency
- RF feedthrough also impacts broadband performance
- Poor coupling at high frequencies
BNL QWR HOM and FPC Coupler

- HOM coupler for 56 MHz QWR
- Chebyshev high-pass filter reduces coupling to fundamental mode

BNL Gun HOM Coupler

HOM damping by BNL fundamental power coupler

- HOMs couple significantly to fundamental power coupler
- HOM power must be intercepted in FPC waveguide with little reflection

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Capacitive and 2-Stage HOM Couplers

BNL Capacitive HOM Couplers

- HOM couplers provide good damping of lower frequencies HOMs (Q of 1e2 to 1e5)
- Filter needs to be added to suppress coupling to fundamental mode

BNL 2-stage HOM Coupler Filter

- Filter to suppress coupling to fundamental mode

50 Ω transmission line to room temperature

D=72 mm
3.9 GHz FNAL/FLASH cavities

- Initial problems with the HOM coupler in 3.9 GHz cavity (MP → overheating → fracture)
- Solution: New designs (one or two legs) reduce MP, field level in coupler and improved thermal properties
- Also observed MP in SNS couplers

$F_2 = 4400 \text{ MHz}$

T. Khabiboulline
Matthias Liepe, SRF Conference 2011, 29 July 2011
Thermal Issues in CW operation

- Pick-up „sees“ a small part of the accelerating field
  - Heating (<< 1 W)
  - HOM feedthroughs with Saphire window are essential for sufficient cooling of inner conductor in CW mode
- Pick-up cables are a significant source of heat! These need a thermal anchor and/or low conductivity cables must be employed
- Modified coupler geometries (JLAB, DESY) reduce temperature increase further
## Antenna / Loop Couplers: Status

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current status</th>
<th>Improvement needed</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>3 x fundamental</td>
<td>Feedthrough, Geometry</td>
<td>6 x fundamental</td>
</tr>
<tr>
<td>Power</td>
<td>100 W</td>
<td>Transmission line needs improvement</td>
<td>1 kW</td>
</tr>
<tr>
<td>Q-factors</td>
<td>Monopole: 1e3 (100 for single-cell); Dipole: 1e5 (100 for single-cell); Quadrupole: 1e9 (quads – limited by field in end-cells)</td>
<td>For Quads: improve cell to cell coupling, cell geometry, reduce number of cells, fluted tube (KEK)</td>
<td>Quads: 1e8 – 1e5</td>
</tr>
<tr>
<td>Eacc (CW)</td>
<td>15 MV/m (KEK); 20 MV/m (mod. TTF); &gt; 38 MV/m (CEBAF)</td>
<td>Coupler design, Feedthrough thermal conductivity</td>
<td></td>
</tr>
<tr>
<td>Filling Factor</td>
<td>good</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cleaning</td>
<td>No problem (demonstrated by TTF)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical issue</td>
<td>Sensitive to tuning; Sensitive to MP &amp; FE bombardment; Feedthrough issues</td>
<td>Use high-pass filter for tuning</td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>Low cryogenic load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long term reliability</td>
<td>good (TTF, HERA); poor (SNS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>25 kEUR (5 loop couplers including LHe cooling)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coupler kicks</td>
<td>Must symmetrize</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other issues</td>
<td>losses in transmission cable at higher HOM powers -&gt; heating of antenna and feed through?</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Waveguide couplers
Why consider waveguides?

- Waveguide is a natural high-pass filter
- High power-handling capability
- Small beamline length required
- Loads can be at higher temperature
- Good experience at PEP-II and CEBAF
- Easy to fabricate
Waveguide HOM Damping Efficiency

- Waveguides give effective, smooth and broadband performance
- But: performance depends on waveguide length

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JLab Waveguide HOM Damping Studies

Copper 5-cell model

748.5 MHz High Current Cavity

ANL SPX baseline cavity

1497 MHz High Current
Most parasitic HOMs measured on warm model
Simulation also performed with Eigenmode solver of CST Microwave Studio (MWS)
Conclusion: HOM damping requirements can be met to support Ampere-level of current
Simulation and measurement in good agreement

Slide 24

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HOM Waveguide Load

High-power HOM load concept

**RF heat summary**

<table>
<thead>
<tr>
<th>Freq. GHz</th>
<th>Input Power, W</th>
<th>Dielectric Loss, W</th>
<th>Surface loss, W</th>
<th>Total power loss, W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.497</td>
<td>1775.200</td>
<td>1764.876</td>
<td>7.7799</td>
<td>1772.6557</td>
</tr>
<tr>
<td>2.994</td>
<td>1923.921</td>
<td>1909.972</td>
<td>8.6038</td>
<td>1918.5754</td>
</tr>
<tr>
<td>4.5</td>
<td>150.700</td>
<td>149.195</td>
<td>0.8314</td>
<td>150.0267</td>
</tr>
<tr>
<td>6</td>
<td>150.179</td>
<td>148.113</td>
<td>1.0018</td>
<td>149.1147</td>
</tr>
<tr>
<td>Sum</td>
<td>4000</td>
<td>3972.156</td>
<td>18.217</td>
<td><strong>3990.372</strong></td>
</tr>
</tbody>
</table>

99.5% of the RF heat is absorbed in tiles. Only ~0.5% surface heat loss.

**Joule heat densities**

Joule heat densities at the interested four frequencies are calculated and superimposed for thermal analysis.
## Waveguide HOM Dampers: Status

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current status</th>
<th>Improvement needed</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>Potentially &gt; 40 GHz</td>
<td>Gentle curves of WG, no (thin) window</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q-factors</td>
<td>1e3 (mono); 1e5 (dipole); 1e9 (quads)</td>
<td>For Quads: improve cell to cell coupling, cell geometry</td>
<td></td>
</tr>
<tr>
<td>Eacc (CW)</td>
<td>No limit?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filling Factor</td>
<td>Good</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cleaning</td>
<td>Easy but more connections</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical issue</td>
<td>Low frequency resonances due to long</td>
<td>Study in test facilities</td>
<td></td>
</tr>
<tr>
<td>Thermal issues</td>
<td>High static heat leak (Order 1 W per WG); High cryogenic load</td>
<td>Reduce this, e.g., thin wall, improved thermal intercepts</td>
<td></td>
</tr>
<tr>
<td>Long term reliability</td>
<td>Good</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>18 kEUR (to WG flange) for 2 BT with 6 WG stubs; need to add cost for waveguides, thermal intercepts and loads to this</td>
<td>Reduce number of WG (can couple to both polarizations of dipoles!) -&gt; still sufficient damping</td>
<td></td>
</tr>
<tr>
<td>Coupler kicks</td>
<td>Must symmetrize</td>
<td>Stubs opposite to symmetrize if only one WG</td>
<td></td>
</tr>
<tr>
<td>Other issues</td>
<td>need to verify efficient coupling at higher frequencies</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Beamline dampers
Why consider Beamline HOM Dampers?

- Beampipe is a natural high-pass filter
- High power-handling capability
- Very broadband
- Radial symmetry helps avoid beam kicks
- Radial symmetry ensures all HOM polarizations are damped
- Can incorporate bellow sections between cavities
- Good experience with CESR, KEKB
- Relatively simple design
HOM Damping Efficiency

- Beampipe absorber give very effective, smooth and broadband performance

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BNL and Cornell Beamline Loads

- Ferrite tiles surrounding a ceramic break
- Ceramic break ferrite from beam vacuum
- Good HOM damping verified

- Based on simplified and improved version of ERL injector HOM load
- Full-circumference heat sink to allow >500W dissipation @ 80K
- Includes bellow sections
- New beamline flanges, variations of the KEK “Zero Impedance Flange”
KEK ERL and Resonant Beamline Loads

- Conceptual design
- Resonant grooves in absorbing material can be tuned to provide strongest damping of most dangerous modes

KEK ERL HOM Load

- HIP ferrite of new-type IB004
- Comb-type RF bridge
- Frist cryo tests revealed some issues

Resonant HOM Load (V. Shemelin)

- Bellows
- 4K Anchor
- 80K Anchor

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FLASH/XFEL and Muon Inc. Beamline Loads

FLASH/XFEL HOM Load
- Absorbing ceramic ring brazed to Cu stub
- At “80” K
- Low cost
- Capacity ~ 100 W
- Tested with beam at FLASH

Muon Inc. HOM Load
- Modified version of Cornell ERL injector HOM load
- Solid rings inside, tiles outside
- Studied hot compression ring assembly of inner absorber ring (no braze)

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KEKB and PEP II Beamline Loads

KEKB HOM Load

- HIP ferrite ring absorber
- Water cooled
- 14 kW HOM power intercepted per cavity

PEP II HOM Load

- 25 absorbers installed in ring
- Absorb several kW each
- Use Ceralloy 137 type ceramic
- HOM trapping slots

Absorbing Tile
2.75” long by .24” wide HOM Trapping Slots
## Beamline HOM Dampers: Status

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Beam-tube absorber</th>
<th>Improvement needed</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>&gt; 40 GHz</td>
<td>Don’t worry about it (EPC)</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>200 W at 80 K, &gt;5 kW at room temp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q-factors</td>
<td>1e2 (mono) 1e4 (dipole), 100 for single cell 1e9 (quads)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eacc (CW)</td>
<td>No limit provided the absorber is far enough from the cavity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filling Factor</td>
<td>Poor</td>
<td>Simplified design (e.g. DESY design)</td>
<td>Easy</td>
</tr>
<tr>
<td>Cleaning</td>
<td>Difficult</td>
<td>Simplified design (e.g. DESY design)</td>
<td></td>
</tr>
<tr>
<td>Mechanical issue</td>
<td>Good thermal contact, Stresses</td>
<td>Consider DESY design to extract HOMs to higher temp, check IR radiation load</td>
<td>Moderate cryogenic load.</td>
</tr>
<tr>
<td>Thermal issues</td>
<td>High dynamic cryogenic load</td>
<td>New materials, Brazing, compression rings, Quality control ... connect process parameters with performance</td>
<td></td>
</tr>
<tr>
<td>Long term reliability</td>
<td>Good for RT, Bad for Cryotemps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>10 to 45 kEUR</td>
<td>10 kEUR</td>
<td></td>
</tr>
<tr>
<td>Coupler kicks</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other issues</td>
<td>Direct interaction with beam</td>
<td>check this for short bunches</td>
<td>&lt; 20%</td>
</tr>
</tbody>
</table>
RF absorbing materials
RF Absorbing Materials: Ferrites

- Very lossy at certain frequency bands
- Temperature dependent
- Not broadband
- Relative brittle
- Low CD conductivity (risk of charging up)
RF Absorbing Materials: Graphite loaded SiC

- Broadband
- Temperature independent
- Sufficient DC conductivity @ 300K and 80K
- Not as lossy as ferrite
- Used for Cornell ERL
RF Absorbing Materials: Ceralloy CA137

- Broadband
- Temperature independent
- Sufficient DC conductivity @ 300K and 80K (most of the time)
- Not as lossy as ferrite
- Poor reproducibility of properties
RF Absorbing Materials: Carbon-Nanotube loaded Alumina Ceramics

- Quite lossy and broadband
- Temperature independent
- Sufficient DC conductivity at 300K and 80K
- Currently only available in small samples
- Still in R&D phase
HOM measurement and simulation tools

Expanded views of input and HOM couplers

Fields in beam frame moving at speed of light
Accelerator Modeling with EM Code Suite ACE3P

Meshing - CUBIT for building CAD models and generating finite-element meshes.

 Modeling and Simulation – SLAC’s suite of conformal, higher-order, C++/MPI based parallel finite-element electromagnetic codes

ACE3P (Advanced Computational Electromagnetics 3P)

Frequency Domain:  
Omega3P – Eigensolver (damping)  
S3P – S-Parameter

Time Domain:  
T3P – Wakefields and Transients

Particle Tracking:  
Track3P – Multipacting and Dark Current

EM Particle-in-cell:  
Pic3P – RF gun (self-consistent)

Multiphysics:  
TEM3P – Thermal, RF and Structural

Postprocessing - ParaView to visualize unstructured meshes & particle/field data.
http://www.paraview.org/.

Goal is the Virtual Prototyping of accelerator structures
T3P – Beam Transit in ILC Cryomodule

ILC cryomodule of 8 Superconducting RF cavities

Expanded views of Input and HOM couplers

Fields in beam frame moving at speed of light

Visualization by Greg Schussman
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## Capability Comparison

<table>
<thead>
<tr>
<th>Capability</th>
<th>ANSYS</th>
<th>MWS</th>
<th>ACE3P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenmode Solver</td>
<td>⭐️</td>
<td>⭐️</td>
<td>⭐️</td>
</tr>
<tr>
<td>Time Domain (wakefields)</td>
<td></td>
<td>⭐️</td>
<td>⭐️</td>
</tr>
<tr>
<td>S-Parameters</td>
<td>⭐️</td>
<td>⭐️</td>
<td>⭐️</td>
</tr>
<tr>
<td>Multipacting</td>
<td></td>
<td></td>
<td>⭐️</td>
</tr>
<tr>
<td>Coupled EM-Thermal-Structural</td>
<td>⭐️</td>
<td>⭐️</td>
<td>Not Yet</td>
</tr>
<tr>
<td>Complex μ and ε</td>
<td>⭐️</td>
<td>⭐️</td>
<td>⭐️</td>
</tr>
<tr>
<td>Parallel Computing</td>
<td>⭐️</td>
<td>⭐️</td>
<td>⭐️</td>
</tr>
</tbody>
</table>

**ANSYS:** Excellent for thermal, structural analyses! Not capable of introducing particles. Not intended for accelerator applications!
HOM Experiments

V. Shemelin: RF absorber studies with waveguides

Roger Jones: 3rd harmonic cavity HOM studies

T. Khabiboulline: HOM spectra manipulation by tuning
Summary
Summary

• New SRF accelerators put high demands on the HOM damping schemes (high power, broadband...)
• Lots of activity worldwide
  – Antenna HOM couplers
  – Waveguide HOM couplers
  – Beamline loads
• Several good RF absorbing materials are available for operation at room temperature and cryogenic temperatures
• This summary is by no means complete (my apologies if I did not include your favorite slide from your talk...)

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Thank you for your attention!