HIGHER ORDER MODES DAMPING IN 9-CELL SUPERCONDUCTING 
CAVITY WITH GROOVED BEAM PIPE* 

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Abstract
This paper is focused on higher order modes (HOM) 
damping efficiency analysis in 9-cell superconducting 
cavities with HOM couplers and with grooved beam pipe. 
Comparison of two methods of HOM damping is 
presented. In order to increase efficiency of damping of 
trapped modes the end cells of the structure were 
modified.

HIGHER ORDER MODES
A large number of modes in a broad frequency range 
are induced by the beam passing through the structure [1]. 
The on-axis movement of the bunch leads to the 
appearance of monopole modes, off-axis bunch also 
excites multipole HOM (dipole, quadrupole, etc).

HOM leads to a number of negative factors: energy 
losses, beam deflection from axis, additional heat load on 
cryogenics, beam break up etc.

Electrodynamic characteristics (EDC), such as external 
Q-factor (Q_{ext}) and shunt impedance $R_{sh}$ are used to 
evaluate the HOMs impact on bunch. Transverse shunt 
impedance to the Q-factor ratio can be calculated either 
through Panofsky-Wenzel theorem:

$$
\frac{R_{sh\perp}}{Q} = \left| \int_0^l \frac{1}{k_z} \frac{\partial E_z}{\partial r} e^{i k_z z} dz \right|^2
$$

where $W$-stored energy, $k_z$-wave number; or using direct 
integration of transverse magnetic H and electric fields:

$$
\frac{R_{sh\perp}}{Q} = \left| \int_0^l \left( \cdot c \cdot \mu_0 \cdot H_z(z) + E_z(z) \right) e^{i k_z z} dz \right|^2
$$

For axially symmetric structures longitudinal field 
derivative in (1) can be replaced by the difference, and 
given that the longitudinal field dipole waves on the 
structure axis are zero, the resulting expression will look 
like this:

$$
\frac{R_{sh\perp}}{Q} = \left| \int_0^l \frac{1}{k_z} \frac{E_z}{\Delta r} e^{i k_z z} dz \right|^2
$$

In order to decrease their influence on the travelling 
bunch it is necessary to decrease the HOM Q-factor 
values. The most common method for HOM damping in 
accelerating structure involves the coaxial couplers which 
extracts HOM power to the external load. Despite the fact 
that couplers provide a reasonable HOM damping they 
are often of complicated design and could be subject to 
multipacting discharge. Their presence also leads to break 
of accelerating structure axial symmetry. Kick momentum 
to the beam could be crucial for electron linear colliders, 
energy recovery linacs and particle accelerators with high 
beam current.

The resent progress allows applying complex 
geometries of superconducting cavities to minimize the 
effect of the HOMs [1-3]. Despite the very low achieved 
Q-values of HOM their complex geometry can increase 
the cost of cavity production. Several modifications of 
simple structure with grooved beam pipe were 
investigated in order to achieve the lowest values of HOM 
Q-factor.

9-CELL CAVITIES WITH 
CYLINDRICAL BEAM PIPES
In order to increase the HOM damping efficiency of 
trapped modes in [4] the different radiuses of end cells 
were used (Fig. 1(a)). This allowed increasing beam's 
energy to 80-100 MeV. For the 9-cell cavity with 
cylindrical beam pipes the field distribution for 
operational mode at 1300 MHz was flattened by the 
modification of the end-cells (Fig. 1(b)).

Figure 1: (a) Model of 9-cell cavity with cylindrical 
beam pipes and (b) electric field distribution for 
operational mode.

HOM EDCs were calculated for the 9-cell cavity with 
cylindrical beam pipes in frequency range up to 3 GHz. 
Dispersion curves (Fig. 2) helped to determine the most 
dangerous HOMs.

The monopole mode TM_{011}, dipole modes TE_{111}, TM_{110} 
and quadrupole modes TE_{211} and TM_{210} (Fig. 3) are of the 
most concern for this structure. The EH_{111} mode is the 
most “dangerous”, because its frequency (2576 MHz) is 
nearly the double accelerating frequency (1300 MHz). It 
means that EH_{111} can greatly impact on beam.

* This project is supported in part by the MEPhI 5/100 Program of the 
Russian Academic Excellence Project

TUPB052

SRF Technology R&D

Cavity
9-CELL CAVITY WITH HOM COUPLERS

The variation of Tesla-type coupler [5] was used in order to estimate the values that could be achieved with this damping methodic (Fig. 3 (a)). Couplers are located at cylindrical beam pipes of 9-cell 1300 MHz superconducting accelerating cavity (Fig. 3(b)) at 115° degree between each other.

Comparison of the results for 9-cell cavity with HOM couplers (Fig. 3 (b)) with 9-cell cavity with cylindrical beam pipes (Fig. 1(a)), showed that $Q_{ext}$ values for TE$_{111}$ and TM$_{101}$ and TM$_{011}$ modes are 100 times higher, 3 orders higher for quadrupole modes, and for EH$_{111}$ is nearly the same (Fig. 4 (a)). $R_{sh}$ values for 9-cell cavity with cylindrical beam pipes 10 times higher for dipole modes and $E_{020}$ wave, 2-3 orders higher for quadrupole waves and $E_{011}$ wave. All the monopole dipole and quadrupole modes of 9-cell cavity with HOMs have $R_{sh}$ values lower than 10$^6$ Ohm, except $H_{211}$ wave (Fig. 4 (b), (c)).

9-CELL CAVITY WITH CORRUGATED BEAM PIPES

We are considering corrugated beam pipes for three different beam pipe radius $d_{r1}$: 39, 48 and 56.5mm (Fig. 5) from each side.

Figure 5: Nine-cell cavity with corrugated beam pipe (a), corrugated beam pipe geometry (b)

We consider 6 types of cavities with different drift tube radius. Three types are demonstrated the best results in HOM damping (Fig. 6).
Figure 6: $Q_{\text{ext}}$ (a), shunt impedance $R_{\text{sh}}$ (b) for HOM’s in 3 types of 9-cell cavity with corrugated beam pipe and different external radius $d_{r1}$ (39, 48 and 56.5 mm). Results of EDC of three types of cavities with different radius $d_{r1}$ comparison are summarized in Table 1.

### Table 1: Comparison of 9 Cell Structure with Different Radius of Beam Pipe of End Cells

<table>
<thead>
<tr>
<th>$d_{r1}$-$d_{r2}$</th>
<th>39-39</th>
<th>56.5-56.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td>Best results for damping of TE$<em>{111}$, TM$</em>{011}$, EH$_{111}$ waves.</td>
<td>Best results for damping of TM$<em>{110}$, TE$</em>{211}$, TM$_{020}$ waves.</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>Worst results for damping of TM$<em>{110}$, TE$</em>{211}$ waves.</td>
<td>Worst results for damping of EH$_{111}$ wave.</td>
</tr>
</tbody>
</table>

Asymmetrical 9-cell cavity with corrugated beam pipes and radius $d_{r1} = 39$ mm on one side and $d_{r2} = 56.5$ mm on another provides a good damping of HOM for all waves. The $R_{\text{sh}}$ of 39-56.5 structure is lowest for EH$_{111}$ (56.5-56.5 has the highest $R_{\text{sh}}$) and TM$_{210}$ wave (39-39 has the highest $R_{\text{sh}}$).

Comparison of the results 9-cell cavity with cylindrical beam pipes (Fig. 7), showed that $Q_{\text{ext}}$ values for TE$_{111}$ and TM$_{110}$ and 2nd monopole waves are four orders higher, and 6 orders higher for quadrupole modes. $R_{\text{sh}}$ values for 9-cell cavity with cylindrical beam pipes 100 times higher for dipole modes, 2-3 orders higher for monopole waves, 6 orders higher for first quadrupole wave.

Comparison of the results with 9-cell cavity with HOM couplers (Fig. 8) showed that $Q_{\text{ext}}$ values for waves TE$_{111}$ and TM$_{110}$ and 2nd monopole is two orders higher, 3 orders higher for quadrupole modes, 1 orders higher for 3rd dipole mode. $R_{\text{sh}}$ values for 9-cell cavity with cylindrical beam pipes in 2 orders higher for dipole modes, 2-3 orders higher for monopole waves, 4 orders higher for first quadrupole wave, 1 order higher for 3rd dipole mode.

Figure 7: $Q_{\text{ext}}$ (a), transverse shunt impedance $R_{\perp}$ (b), long shunt impedance $R_{||}$ (c), for HOM’s in 9-cell cavity with cylindrical beam pipes and 9-cell cavity with corrugated beam pipe.
CONCLUSIONS

Asymmetrical 9-cell cavity with corrugated beam pipes and radius dr1 = 39 mm on one side and dr2 = 56.5 mm on another provides a good damping of HOMs for all modes. The $R_{sh}$ of 39-56.5 structure is lowest for EH_{111} (56.5-56.5 has the highest $R_{sh}$) and TM_{210} wave (39-39 has the highest $R_{sh}$).

REFERENCES