Higher order mode damping considerations for the SPL cavities at CERN

W. Weingarten
Outline

- The SPL study at CERN
- HOM damping requirements for SPL study
- Optimisation of cavity geometry related to HOM damping
- Conclusion on geometry
  - damping HOMs
- Outlook

Spare slides
On longitudinal HOM excitation for pulsed beams
The SPL study at CERN

- International cross relations of interest with ESS, Project X, SNS, Myrrha, JPARC

- An international collaboration was established for the SPL study
  [http://indico.cern.ch/categoryDisplay.py?categId=1893](http://indico.cern.ch/categoryDisplay.py?categId=1893)

- Goal: develop multi-megawatt superconducting (sc) proton linac cryomodule as a driver for non-LHC physics programs such as neutrino and Radioactive Ion Beam (RIB) physics.

- Deliverable: developing, in collaboration with external labs, bulk niobium 5-cell 704 MHz elliptical cavities, to be tested at 2 K, around the beginning of 2013, in a 1/2 length cryo-module with 4 cavities.

- The Superconducting Proton Linac (SPL) study is now part of CERN’s Mid Term Plan.
# HOM damping requirements for SPL study

<table>
<thead>
<tr>
<th>Beam</th>
<th>bunch length</th>
<th>1.2</th>
<th>mm</th>
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<tr>
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<td>bunch charge $Q_b$</td>
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<td></td>
<td>average pulse current</td>
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<td>mA (0.4 ms pulse length with 50 Hz repetition rate)</td>
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<tr>
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<td>energy</td>
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<td>GeV</td>
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<tr>
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<td>beam power</td>
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</tr>
<tr>
<td></td>
<td>no. of cavities</td>
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<td></td>
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<tr>
<td>Cavity</td>
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<td>MHz</td>
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<tr>
<td></td>
<td>number of cells</td>
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<td></td>
<td>long. loss factor @ design bunch length</td>
<td>4.8 @ $\sigma = 2$ mm</td>
<td>V/pC</td>
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</table>
### HOM damping requirements for SPL study

<table>
<thead>
<tr>
<th>HOM</th>
<th>single bunch HOM power spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>av. HOM power per cavity ((k·Q_b·I))</td>
<td>22 W</td>
</tr>
<tr>
<td>worst case HOM power per cavity (resonant excitation of mode for (Q_{ext} = 10^4))</td>
<td>(~ 100) W</td>
</tr>
<tr>
<td>required damping (Q_{ext}), monopole modes</td>
<td>(10^5)</td>
</tr>
<tr>
<td>ditto, dipole modes</td>
<td>(10^7)</td>
</tr>
</tbody>
</table>

Below is a graph showing the peak power \(P_{max}\) as a function of frequency \(f\) in Hz.
HOM damping requirements for SPL study

Required $Q$ wrt beam break up for whole linac

$Q_{ex}$ limits based on beam dynamic simulations
Simulated cases: nominal, RF errors, chopped beams, fundamental pass-band modes

**Example: nominal**

![Graph showing Long Emittance growth rate vs $Q_{ex}$]

- $Q_{ex}$ values for different currents: $I_b$ = [0.40, 0.20, 0.10, 0.08, 0.04]

**Overall conclusion:**
To be on the save side and keep all operation options open a $Q_{ex} = 10^5$ is recommended!

**Courtesy:**
Marcel Schuh / CERN-BE-RF
HOM damping requirements for SPL study

**Required Q wrt power deposition per cavity**

\[ I = 40 \text{ mA}; \text{ pulse length } 1 \text{ ms}, \frac{R}{Q} = 100 \Omega; \]

\[ \text{Rep. rate } 50 \text{ Hz}; f_{\text{HOM}} = 2.1 \text{ GHz}; Q_0 = 10^{10} \]

Power built-up/decay during pulse of 1 ms

Maximum power vs. frequency showing principal Fourier components of beam
HOM damping requirements for SPL study

Required $Q$ wrt power deposition per cavity

$I = 40$ mA; pulse length 1 ms, $R/Q = 100 \, \Omega$ ;
Rep. rate 50 Hz; $f_{\text{HOM}} = 2.1$ GHz; $Q_0 = 10^{10}$

$f (\text{HOM})$ precisely on beam spectral line

\begin{align*}
\text{P}_{\text{rad}} \quad [\text{W}] \\
\text{P}_c \quad [\text{W}] \\
\text{Q}_{\text{ext}}
\end{align*}
HOM damping requirements for SPL study

Required Q wrt power deposition per cavity

\[ P_{\text{rad}} \quad \Delta f = 0.01 \text{ MHz} \]

\[ P_{\text{c}} \quad \Delta f = 0.01 \text{ MHz} \]

\[ P_{\text{rad}} \quad \Delta f = 0.1 \text{ MHz} \]

\[ P_{\text{c}} \quad \Delta f = 0.1 \text{ MHz} \]

\[ Q_{\text{ext}} \quad \Delta f = 0.01 \text{ MHz} \]

\[ Q_{\text{ext}} \quad \Delta f = 0.1 \text{ MHz} \]

I = 40 mA; pulse length 1 ms, R/Q = 100 \( \Omega \);

Rep. rate 50 Hz; \( f_{\text{HOM}} \) = 2.1 GHz; \( Q_0 = 10^{10} \)
HOM damping requirements for SPL study

Required Q wrt power deposition per cavity

Validation of recursive analytical calculations

Average power dissipation in a cavity close to ML without beam noise

Average power dissipation in a cavity close to ML with beam noise

Courtesy:
Marcel Schuh / CERN-BE-RF
HOM damping requirements for SPL study

Conclusion

- The main beam Fourier components (n·352 MHz) contribute significantly to the HOM power, the 50 Hz Fourier component, however, only marginally; to reduce the HOM power below 100 W, the Q-value of the HOM must be $< 10^4$

- Avoiding the main beam Fourier components by the HOM frequencies within 10 kHz reduces the HOM power significantly, with a tendency to become even smaller for larger Q-values ($P < 1 \text{ W} @ Q > 10^7$)

→ The HOM power could possibly be reduced by inelastic detuning or an appropriate design of the cavity (though without changing the fundamental mode frequency) with the aim to keep sufficiently off ALL HOM frequencies from the main Fourier components

I = 40 mA; pulse length 1 ms, $R/Q = 100 \Omega$;
Rep. rate 50 Hz; $f_{\text{HOM}} = 2.1 \text{ GHz}; Q_0 = 10^{10}$
Optimisation of cavity geometry related to HOM damping

Different beam tube diameters investigated

Reference design (Saclay): Ø 8 cm

Beam tube Ø 12 cm

Beam tube Ø 14 cm

Beam tube Ø 16 cm
Optimisation of cavity geometry related to HOM damping

Longitudinal Loss Factors

Source: R. Calaga
http://indico.cern.ch/conferenceDisplay.py?confId=80052
Optimisation of cavity geometry related to HOM damping

$Q_L$ vs. $f$ damping via normal conducting beam tube (plus normal conducting taper)

Most significant longitudinal monopole HOM for 5-cell 704 MHz cavity

with 8 cm (reference geometry), 12 cm, 14 cm & 16 cm beam tube diameter and
taper either sc or nc

$Q_0$ vs. frequency [MHz]

- Stainless steel and superconducting taper for reference geometry
- Taper sc
- Taper nc

High Al iron
Optimisation of cavity geometry related to HOM damping

$\frac{Q_{\text{HOM}}}{Q_{\text{fundamental mode}}}$ vs. $f$ damping via beam tube made of stainless steel

by Karol Krizka/University of Toronto and summer student at CERN: Technical Note, SPL cavity: Power dissipated at bellows, 9 July 2010
Optimisation of cavity geometry related to HOM damping

$Q_L$ vs. $f$ damping via two 50 $\Omega$ antennas in beam tube $\phi = 3.6$ cm

5-cell 704 MHz cavity (reference geometry)

with 8 cm beam tube diameter with 2 HOM antennas

$Q_L = Q_0 \cdot \frac{1}{1 + \frac{P_{ant}}{P_c}}$

$P_{ant} = \frac{1}{2} \cdot Z_0 \cdot I^2$

$I = j \cdot \pi r_i^2$

$j = \omega \varepsilon_0 E$

$P_{ant}[W] = 2862 \cdot (f/\text{GHz})^2 \cdot (E/\text{MV/m})^2$ for 3.6 cm dia port
Optimisation of cavity geometry related to HOM damping \( Q_L \) vs. \( f \) damping via coaxial antenna

Q-value spectrum for 0 mm antenna depth:

\[ Q \]

Target value

by far to heavy loading of fundamental mode => ...

shown at 4th SPL Collaboration Meeting - jointly with ESS at LUND (Sweden)

Courtesy Hans-Walter Glock/Uni Rostock

... the main message remains:

Pick-ups without fundamental mode filters will not be able both to preserve fundamental mode \( Q \) and damp all HOMs sufficiently.

Confirmed by Wolfgang Weingarten's 2D computations using beam pipe dampers.
Optimisation of cavity geometry related to HOM damping

$Q_L$ vs. $f$ damping with fundamental power coupler

for 50 Ω power coupler in beam tube $\varnothing = 10$ cm

$$Q_L = Q_0 \cdot \frac{1}{1 + \frac{P_{ant}}{P_c}}$$

$$P_{ant} = \frac{1}{2} \cdot Z_0 \cdot I^2$$

$I = j \cdot \pi r_i^2$

$$j = \omega \varepsilon_0 E$$

These numbers are only estimations!
Optimisation of cavity geometry related to HOM damping

$Q_L$ vs. $f$ damping with fundamental power coupler (FPC)

- HFSS: 180° model with lump circuit element at FPC window
- MicroWave Studio: full cavity (360°) with port at FPC window
- Calculate loaded $Q$ value of system (damping)

![Graph of $Q_L$ vs. $f_{HOM}$](chart.png)

Courtesy: Marcel Schuh / CERN-BE-RF

Int. Workshop on HOM Damping in SRF Cavities Cornell University

11 - 13 October 2010
Optimisation of cavity geometry related to HOM damping

Heat is dissipated in ss bellows

\[
P_{rad}(t) = \frac{P_{\text{HOM}}(t)}{1 + \frac{Q_{\text{ext}}}{Q_0}} \quad P_c(t) = \frac{P_{\text{HOM}}(t)}{1 + \frac{Q_0}{Q_{\text{ext}}}}
\]

- **Fundamental mode:** Heat dissipation in cavity @ 704 MHz, 25 MV/m, \(Q_0 = 10^{10}\): \(P_c = 123\) W CW => 5 ... 16 W pulsed

- Heat dissipation in SS bellows @ 704 MHz, 25 MV/m, equivalent \(Q_0 = 3\cdot10^{11}\):
  \(P_c = 4\) W CW => 0.04 ... 0.13 W pulsed

- **HOM:** Heat dissipation in SS bellows @ 2112 MHz, \(Q_0 = 2.5\cdot10^7\); construct HOM damper with \(Q_{\text{ext}} < 10^5\) or/and count on damping by power coupler: \(Q_{\text{ext}} < 10^4\) (to be checked!)

Under these assumptions the heat dissipated in the SS bellows for the HOM at 2.112 GHz is less than 3 W (worst case).
Conclusion on geometry

Present cavity/tuner/coupler/He tank/beam tube layout

- 704 MHz
- 5 cell cavity
- bulk Nb 2K
- 1 fundamental power coupler 1 MW pulsed
- 1 antenna probe
- 2 HOM coupler ports
- Inter-cavity bellows stainless steel, no active cooling
- 1.06 m active length (without beam tubes) 1.395 m overall
Conclusion on geometry
Present cavity/tuner/coupler/He tank/beam tube layout

Includes specific features for cryo-module integration (inter-cavity supports, cryogenic feeds, magnetic shielding …)

Courtesy: Th. Renaglia, V. Parma; CERN
Conclusion on damping HOMs

- In the frequency range $f = 1300 – 1500$ MHz, damping of HOMs is not sufficient, neither by
  - dissipation in beam tube (largely irrespective of absorber material) or
  - 50 $\Omega$ antenna placed in beam tube
- For $f > 1800$ MHz, damping of HOMs is stronger, in particular for larger beam tube diameter than our reference design, but still insufficient for our needs ($Q < 10^4$)
- Antenna HOM absorbers are needed that are trimmed for 1300 and 1500 MHz and reject the fundamental mode
- [Corollary: There may be a chance to damp the HOMs via the fundamental power coupler (to be confirmed by simulations and measurements of the impedance of the power coupler as “seen” by the cavity)]
Outlook

- There is a first design developed at Rostock University, based on the HOM couplers for LEP and LHC.

- The next steps are the:
  - Electrical validation and the
  - Mechanical/cryogenic validation of model
  - Prototype manufacture of HOM coupler and warm RF tests on Cu cavity model

Tuning to 704 MHz OK but cooling and construction to be checked.
Thank you for your attention!

Acknowledgements to my colleagues in CERN/BE-RF as well as the members of the SPL-cavity working group

http://indico.cern.ch/categoryDisplay.py?categId=2722
Spare slides
Insertion (on recursive analytical calculations)
On longitudinal HOM excitation for pulsed beams

CW beam:

\[ V = V_q \sum_{n'=0}^{\infty} e^{-n' p T_b} = \frac{V_q}{1 - e^{-p T_b}} \]
Insertion (on recursive analytical calculations)

On longitudinal HOM excitation for pulsed beams

\[ m(t) = \frac{t}{T_i} + 1 \text{ (truncated)} \]

\[ t^* = t - [m(t) - 1] \cdot T_i \]

\[ p = 2 \cdot \pi \cdot f \cdot i + \frac{1}{T_d} \]

\[ n(t) = \frac{t}{T_b} + 1 \text{ (truncated)} \text{ if } t^* \leq (N-1) \cdot T_b \text{ or } = N \text{ otherwise} \]

\[ T_d = \frac{Q_L}{\pi \cdot f} \]

\[ T_g = T_i - T_{ib} = T_i - (N - 1) \cdot T_b \]

\[ Q_L = \frac{1}{\frac{1}{Q_0} + \frac{1}{Q_{ex}}} \]

\[ V_q = \pi \cdot f \cdot \frac{R}{Q} \cdot q \]
Insertion (on recursive analytical calculations)

On longitudinal HOM excitation for pulsed beams

\[ V_{mn} = V_{m-1,N} \cdot e^{-pT_g} \cdot e^{-(n-1)pT_b} + V_q \cdot e^{-(n-1)pT_b} + V_q \cdot e^{-(n-2)pT_b} + \ldots + V_q = \]

\[ = V_{m-1,N} \cdot e^{-pT_i} \cdot e^{(N-n)pT_b} + V_q \cdot e^{-(n-1)pT_b} + V_q \cdot e^{-(n-2)pT_b} + \ldots + V_q \Rightarrow \]

\[ V_{mn} = V_q \cdot \left[ \frac{1-e^{-(m-1)pT_i}}{1-e^{-pT_i}} \cdot \frac{1-e^{-NpT_b}}{1-e^{-pT_b}} \cdot e^{-p[T_i-(N-n)T_b]} + \frac{1-e^{-npT_b}}{1-e^{-pT_b}} \right] \]

\[ V_{mn}(t) = V_{mn} \cdot e^{-p(t-t_{mn})}; \quad t_{mn} = [m(t)-1] \cdot T_i + [n(t)-1] \cdot T_b \]

\[ P_{HOM}(t) = \frac{V_{mn}(t) \cdot V_{mn}^*(t)}{R \cdot Q_L} \quad P_{rad}(t) = \frac{P_{HOM}(t)}{1 + \frac{Q_{ext}}{Q_0}} \quad P_c(t) = \frac{P_{HOM}(t)}{1 + \frac{Q_0}{Q_{ext}}} \]
List of monopole HOM calculated with Superfish between 0 and 3000 kHz

**Operating frequency mode**

(π) : \( f_0 \) = 704.4 MHz

**No monopole HOM at 2\( f_0 \)**

**Mode at 2111.64 MHz**

very near 3\( f_0 \)

**Cut-off frequencies for the mode TM010**

Ø 80 mm : 2865 MHz
Ø 130 mm : 1763 MHz
Ø 140 mm : 1637 MHz

Source: J. Plouin et al., 3rd SPL Collaboration Meeting
11-13 November, CERN

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<th>#freq</th>
<th>freq</th>
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**Axisymetric calculations**

**2111.640680**

10.636820 1.00 2.9464e+10 21.82

**2119.767790**

8.476595 1.00 2.6521e+10 21.97

**2138.944200**

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