Computation of Coupler Damping Properties in Concatenated Arrangements

H.-W. Glock

Universität Rostock - Institut für Allgemeine Elektrotechnik

HOM10 - Workshop

Cornell University, 11.10.2010
- A module ...
- ... consists of several cavities, ...
- ... which consists of several components,...
- ... that we should try to treat separately (as far as possible).
Overview:

- Who we are and what we are doing (30 sec)
- Use of scattering properties = S-parameters. Why and how?
- Experimental comparison: FNAL's 3rd Harmonic Module @ DESY
- How to extract loaded Qs
- Coupler design in terms of S-parameters
- Some ideas
DoHRo*, EUCARD**, CERN-SPL***-Study @ Rostock

*DoHRo: Dortmund-HZB-Rostock – "Innovative Technologien und Komponenten zukünftiger Teilchenbeschleuniger in Strahlungsquellen, funded by German Federal Ministry of Research+Education, Project 05K10HRC

**EUCARD: EU FP7 Research Infrastructure Grant No. 227579

***CERN-SPL: "Design of HOM-Damping for CERN-SPL"; funded by German Federal Ministry of Research+Education, Project: 05H09HR5

DoHRo* – HOM:

- AP 1: HOM damping design for BERLINPRO
- AP 2: HOM damping design for ESS – high energy part of p-linac
- AP 3: Simplified electronics for HOM coupler signal based beam analysis

EUCARD** – WP 10.5.3:

HOM distribution and geometrical dependencies (FLASH-1.3, FLASH-3.9, XFEL(?)) needed for HOM coupler signal based beam analysis

CERN-SPL***:

HOM damping design for CERN-SPL-Study
DoHRo, EUCARD, CERN-SPL-Study @ Rostock

### Staff (% of FTE):

<table>
<thead>
<tr>
<th>Name</th>
<th>Percentage Details</th>
<th>Funding</th>
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<tbody>
<tr>
<td>Prof. Ursula van Rienen</td>
<td>~ 5%</td>
<td>Universitä Rostock</td>
</tr>
<tr>
<td>Dr. Dirk Hecht</td>
<td>administrative; now ~ 5%</td>
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</tr>
<tr>
<td>Dipl.-Ing. Thomas Flisgen</td>
<td>80% EUCARD, 20% teaching</td>
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<td>Dipl.-Ing. Korinna Brackebusch:</td>
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<td>Dr. Carsten Potratz</td>
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</table>

### Funding:

- 25% DoHRo
- 25% EUCARD
- 50% CERN-SPL

Thanks to all of them for contributions + discussions
*Source: Google Maps
Concatenation procedure based on scattering properties: Coupled S-Parameter Computation = CSC

- Split structure in sections
- Compute scattering (S-) parameters of all sections individually with appropriate solvers
- Compute overall S-parameters as function of f with special algorithm*, applicable to any structure topology and mode number

Why description in terms of (multimodal) S-parameters?

- Waveguide mode amplitudes (complex-valued) of interfacing cross sections are a "canonical" set of variables, i.e. least number of variables for given precision
- Delivered by most codes (rotational 2D / 3D) (our workhorse: CST Suite)
- Measurable in single-mode, normalized impedance (usually 50 Ohms) regimes
- Simple analytical description of beam pipe = waveguide; rotations wrt. beam axis = rotation matrix according to non-monopole waveguide modes
- Appropriate both above and below cut-off
## Methods in CST for S-parameter computation

<table>
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<tr>
<th>Method</th>
<th>Pro</th>
<th>Contra</th>
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</thead>
<tbody>
<tr>
<td>Transient Solver Hexahedral Grid</td>
<td>Straight forward time stepping; broadband computation of S-Parameters via FFT.</td>
<td>(Too) many time steps are needed to reach steady state in structures of large time constants.</td>
</tr>
<tr>
<td>Frequency Solver Hexahedral Grid</td>
<td>Appropriate for structures with high quality factors. Weak coupling between orthogonal modes in rotational symmetric structures. Nice for field distributions</td>
<td>Long computational time, since single run needed for every frequency sample.</td>
</tr>
<tr>
<td>Frequency Solver Tetrahedral Grid</td>
<td>Appropriate for structures with high quality factors. Less number of unknowns compared to hexahedral mesh. Fast solver available for tetrahedral grids.</td>
<td>Strong artificial coupling between orthogonal modes in rotational symmetric structures (e.g. cavity), due to non symmetric grid.</td>
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</tbody>
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Workflow

Structure

Set of Sub-Structures

S-matrix computation
(CST, HFSS, GPU-Discontinuous Galerkin, analytical, recycling, ...)
Effort: minutes ... hours ... days

Concatenation
(own Mathematica package: import, interpolation, concatenation, derived quantities, export, visualization)
Effort: seconds ... minutes
As an example:
Fermilab-build 3.9 GHz-3rd Harmonic Module @ FLASH

picture taken from: D. Mitchell, N. Solyak, T. Khabiboulline et.al., "Mechanical Design and Engineering of the 3.9 GHz, 3rd Harmonic, SRF System at Fermilab", Poster presented at SRF03

Module of 4 x

9-cell-cavity, each: 1 power coupler, 2 HOM-coupler, 1 pickup
Single cavity eigenmode spectrum: CST Studio (3D) / MAFIA (2D)

- **TM0 Modes**
- **Dipole Modes**
- **TE0 Modes**
- **Transmission (amplified)**
  Cavity 1
  HOM1 to HOM2
  (T. Khabiboulline, 23 Oct 2009)
Specific: Large beam pipe diameter
=> almost everything propagating
=> computations on entire module

- $\text{TE}_{11}: 4.40 \text{ GHz}$
- $\text{TM}_{01}: 5.74 \text{ GHz}$
- $\text{TE}_{21}: 7.29 \text{ GHz}$

Transmission (amplified)
Cavity 1
HOM1 to HOM2
(T. Khabiboulline, 23 Oct 2009)
CSC-simulation @ 3rdHarm: 
HOM-HOM transmission in module vs. single cavity

Pipe length L=102mm

Modelling of entire module is needed!
CSC-simulation @ 3rdHarm:
HOM to HOM transmission via beam pipe in module

Pipe length L=102mm

Modelling of entire module is needed!
CSC+Measurement @ 3rdHarm (IPAC`10, WEPEC052):
HOM-HOM transmission single cavity C3 and module start-end

Nice, but not perfect – problems: cable calibration, main coupler, next modules …
CSC-simulation@3rdHarm: Cavity composed of single cells

- 3,090,528 hexahedral cells
- 8 modes excited in beam pipe
- 20 modes excited in cavity waist
- computing time*: 3h 5 min

- 3,130,608 hexahedral cells
- 20 modes excited on both ports
- computing time*: 6h 18 min

*using FR solver
Transmission of TE11 dipole mode

Direct computation with $N=8.12$ Mio hexahedral meshcells, computing time FR solver: $T=11h$

CSC coupling of mid- and endcell elements (only TE11 mode is considered), computing time CSC: couple of seconds

Parasitarical TM010 passband of direct computation
Transmission of TM01 monopole mode

Direct computation with N=8.12 Mio hexahedral meshcells, computing time FR solver: T=11h

CSC coupling of mid- and endcell elements (only TM01 mode is considered)

CSC coupling of mid- and endcell elements (TM01 and TM02 modes are considered)

Surprisingly low number of port modes needed, even with extremely short beam pipe connections.
Geometry perturbations - example:

Effect of perturbed resonator in the middle of the cavity

Length of mid cup h is 18.2167 mm instead of 19.2167 mm!
Effect of perturbed resonator on TE11 transmission

Unperturbed structure

Perturbed structure

S21(TE11) / dB

frequency / Hz

-150 x 10^9 to 6.0 x 10^9 Hz
Concatenation procedure based on scattering properties: Coupled S-Parameter Computation = CSC

- Split structure in sections
- Compute scattering (S-) parameters of all sections individually with appropriate solvers
- Compute overall S-parameters as function of f with special algorithm*, applicable to any structure topology and mode number
- Derive loaded Q-values from S-parameter spectra

Example: SPL-$\beta=1$-cavity: HOM-$Q_{\text{load}}$ from full setup computation of coax-coax-transmission

following Nov'09 SPL Meeting proposal: 30 mm diameter coaxial couplers

Do they provide sufficient HOM damping without fundamental mode filter?
Coax with antenna tip depth = 0:

- to avoid extreme Q-values
- scaling in a second step using coupler section's S-parameters in order to reach design fundamental mode Q
Entire transmission spectrum 0.65 – 2.80 GHz:
- more than 400 resonances with wide Q-range
Using Pole-fitting algorithm* to determine loaded Q's

\[ S_{21}(f) = \sum_{k} \frac{a_k}{2\pi i f - p_k} \]

\[ Q_k = -\frac{\text{Im}\{p_k\}}{2\text{Re}\{p_k\}} \]

fundamental mode passband - dots: cstStudio© computation - line: fit result

Pole-fitting algorithm: "Old" version

"Old" algorithm  (see reference)
**Improved pole-fitting algorithm**

**Improved algorithm**\* - corrects for higher order contributions (but still not working in any case)

\* Glock, Galek, Pöplau, van Rienen: "HOM spectrum and Q-factor estimations of the high-beta CERN-SPL-cavities", Proc. IPAC2010, WEPEC008
Several HOM modes with Q values as high or above fundamental mode (holds also for reduced coupling) –

**Couplers without filters are not an acceptable solution!**
Coupler optimization in terms of scattering properties

- Try to improve beam-pipe-coax coupling everywhere ...
- ... except for TM01 @ fundamental mode frequency: notch filter
- Example CERN-SPL: 704.4 MHz, 36 mm coupler diameter, demountable, classical hook preferred
"Classical" LEP hook design as starting point (priv.com. WW)

- coaxial 50-Ohm-port (connector not modelled)
- adjustable capacitive coupling
- support carries liquid helium
- combined E-/H-field coupling, capacity couples to outer conductor
E-field geometry @ 704 MHz

strong capacitive coupling between "hook" and outer conductor
Waveguide-Coax-Transmission used to assess coupling – e.g. example geometry - dependence on hook rotation

60° good compromise for both polarizations

coax - TE11: E par. coupler

c coax - TE11: E ortho. coupler
Pure hook (36 mm diam.) not tunable for 704 MHz =>
Modification of hook end to adjust fundamental mode filter

enlarge capacitive coupling
at hook with additional surface element
Waveguide(TM\textsubscript{0})–Coax–Transmission blocked @ fundamental mode frequency => Tuning ok

\textbf{but:} cooling + construction to be checked
Very recent idea: Coupler loop with LHe flow

Coupler loop as sequence of circular bends

**but:** no computation/tuning yet; construction to be checked – please comment
Thank you.
Reserve

- CSC validation example
- Effect of shortened beam pipes on spectrum
Validation procedure of CSC using a benchmark structure

Computation of S-Parameters of complete benchmark structure

Element-wise computation of S-Parameters

Coupling of elements via CSC procedure

Comparison of S-Parameters
Validation of CSC using a simplified benchmark structure

Simplifications:
- no rotation of two leg formteil.
- 90° rotation angle between HOM couplers (instead of 115°).
- no input coupler is modelled.
- PEC boundaries at the ends of the beam pipes.
Components for Coupled-S-Parameter-Calculation benchmark

Considered modes:
1. TE11 Pol. 1
2. TE11 Pol. 2
3. TM01
4. TE21 Pol. 1
5. TE21 Pol. 2
6. TE01
7. TM11 Pol. 1
8. TM11 Pol. 2
Transmission of benchmark structure from HOM1 to HOM2

Direct computation of S-Parameters using CST's Fast Resonant Solver on hex. grid

Elementwise computation of S-Parameters using CST's Fast Resonant Solver on hex. grid

![Graph of S21 vs Frequency]

S21 / dB

frequency / Hz

0 50 100 150

3.5 x 10^9 4.0 x 10^9 4.5 x 10^9 5.0 x 10^9 5.5 x 10^9 6.0 x 10^9
Transmission of benchmark structure from HOM1 to HOM2

Direct computation of S-Parameters using CST’s Fast Resonant Solver on hex. grid

Elementwise computation of S-Parameters using CST’s Fast Resonant Solver on hex. grid

Arg(S21) / rad

frequency / Hz

3.5 × 10^9
4.0 × 10^9
4.5 × 10^9
5.0 × 10^9
5.5 × 10^9
6.0 × 10^9

Arg(S21) / rad

3
2
1
0
-1
-2
-3

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H.-W. Glock - Thomas Flisgen
Effect of electrical shortcuts at ends of pipe on transmission from HOM1 to HOM2

- Electrically closed beam pipes
- Open beam pipes

- High Q peaks vanish
- Overall slope is introduce

<table>
<thead>
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<th>frequency / Hz</th>
<th>S21 / dB</th>
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<tbody>
<tr>
<td>$3.5 \times 10^9$</td>
<td>-150</td>
</tr>
<tr>
<td>$4.0 \times 10^9$</td>
<td>-100</td>
</tr>
<tr>
<td>$4.5 \times 10^9$</td>
<td>-50</td>
</tr>
<tr>
<td>$5.0 \times 10^9$</td>
<td>0</td>
</tr>
<tr>
<td>$5.5 \times 10^9$</td>
<td>-50</td>
</tr>
<tr>
<td>$6.0 \times 10^9$</td>
<td>-100</td>
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