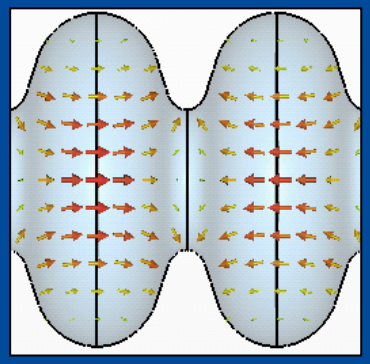
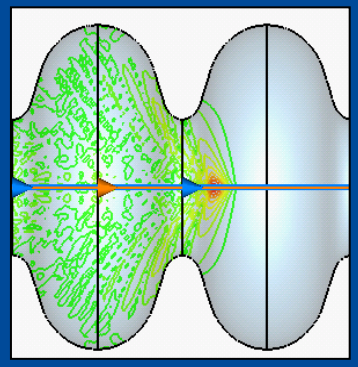
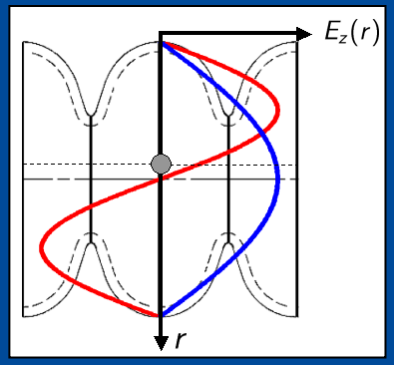
Universität Rostock

Traditio et Innovatio







Measurements of Complex Structures' RF Properties and their Simulation by means of Concatenation Techniques

Thomas Flisgen

Joint DESY and University of Hamburg Accelerator Physics Seminar
DESY, Hamburg, Germany, 29th of January 2013

Outline

- Short introduction and motivation
- Simulation of S-parameters using coupling methods
- Measurements of S-parameters
- Comparison of simulation and measurement

Part I

- Improvement of coupling method
- Validation results
- Conclusions

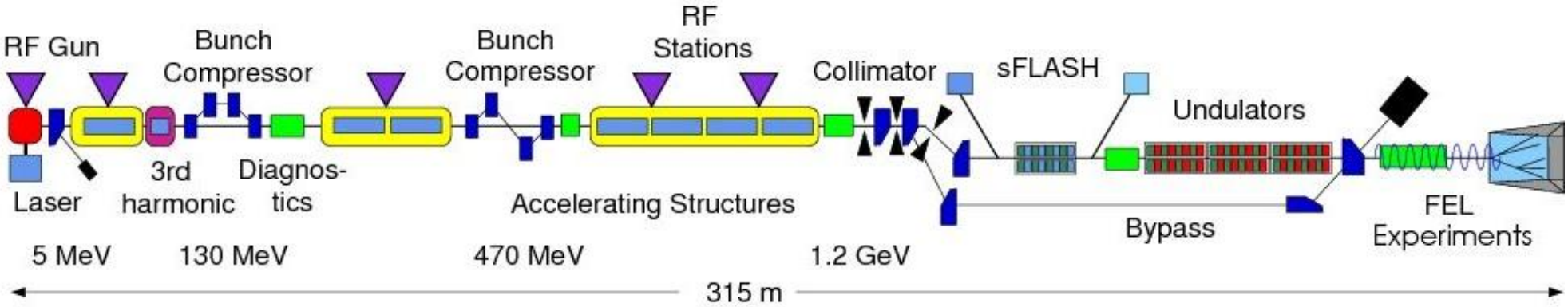
Part II

Part I

Introduction: FLASH and the 3rd Harmonic Module ACC39

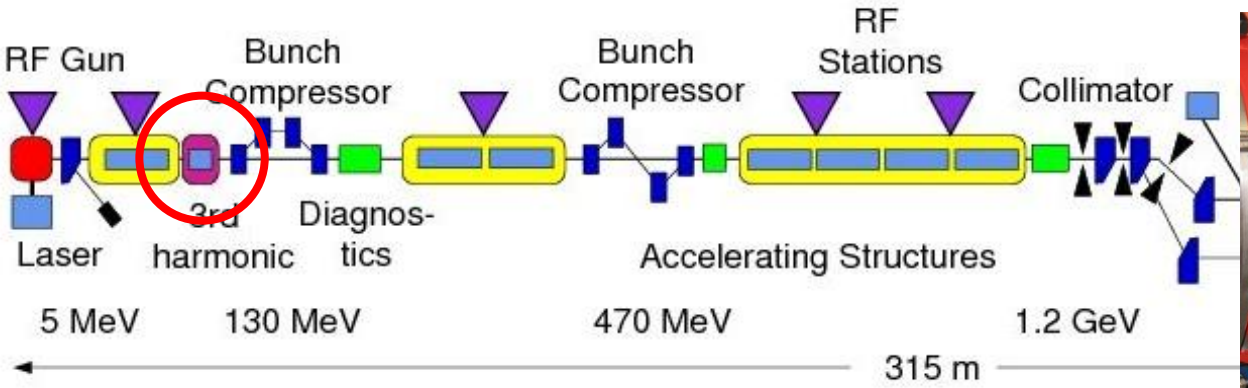
Free electron LASer Hamburg

- Superconducting linear accelerator with free electron laser based on SASE principle
- FLASH generates ultra-short X-ray laser pulses with variable wavelength to observe fast reactions of tiny structures
- Test device for future light sources like X-FEL as well as user machine available for experiments with the generated light



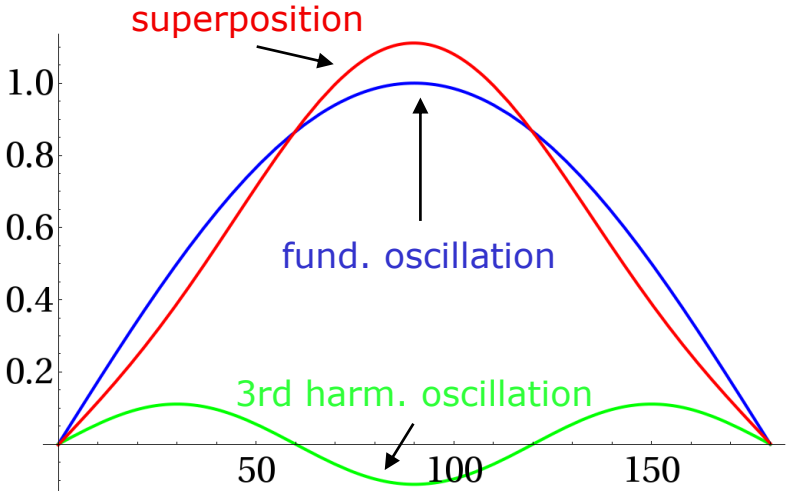
Source: http://flash.desy.de/

3rd Harmonic Module ACC39



Source: http://flash.desy.de/

- ACC39 compensates the non-linear interaction of bunch and accelerating RF fields in 1.3 GHz module (ACC1)
- ACC39 consists of four superconducting cavities operating at 3.9 GHz which is in fact three times the frequency of ACC1
- In combination with the magnetic chicanes ACC39 enables higher beam currents needed for the SASE process



Motivation for Investigation of S-Parameters

Motivation for Investigation of S-Parameters

- After modeling ACC39 with RF CAD tools based on technical drawings we have to ensure that the generated computer model reflects the physical properties of ACC39
- S-parameters allow for model validation because we can measure them at FLASH and we are able to compute them using FIT or FEM codes

$$\mathbf{S}_{Meas}(\omega) \overset{?}{=} \mathbf{S}_{Simul}(\omega)$$

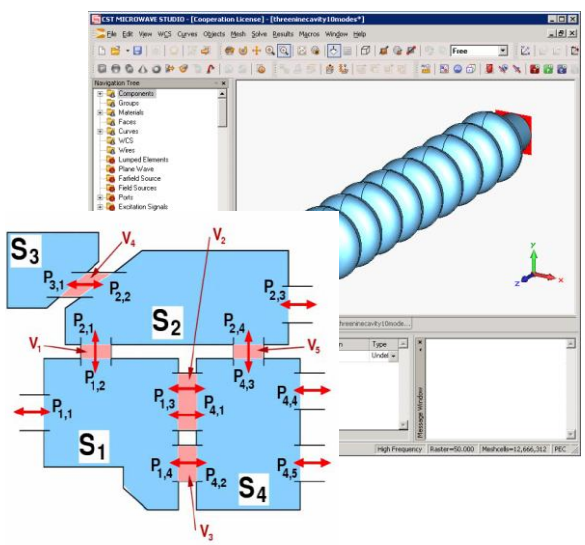
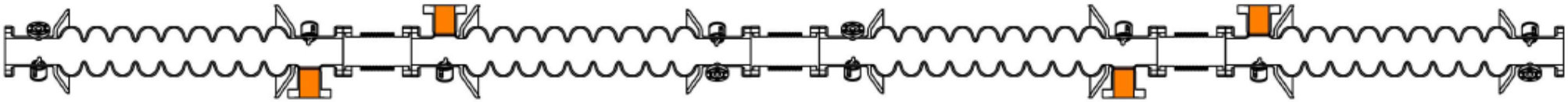


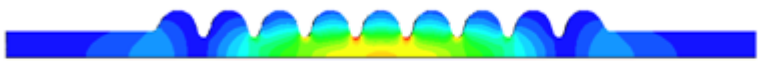
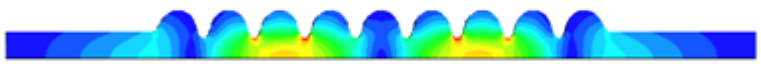
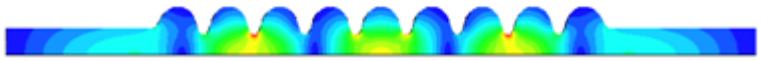
Figure courtesy of K. Rothemund

Simulation of S-Parameters

String of Cavities in ACC39 @ FLASH Beamline



String of cavities in ACC39 mounted in FLASH*

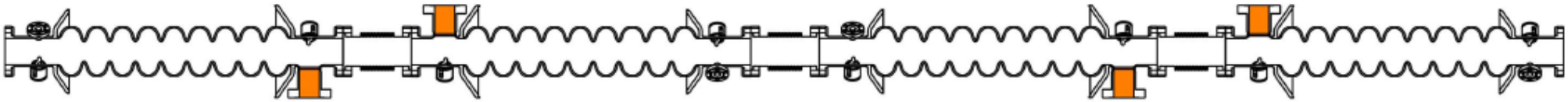
Electric field pattern of dipole modes (individual cavity)**	ω/2π (GHz)
	4.2953
	4.3580
	4.4460

Cut off Frequencies of beam pipes:

1. TE11 Pol. 1 fco = 4.3920 GHz
2. TE11 Pol. 2 fco = 4.3920 GHz
3. TM01 fco = 5.7371 GHz
4. TE21 Pol. 1 fco = 7.2858 GHz
5. TE21 Pol. 2 fco = 7.2858 GHz
6. TE01 fco = 9.1412 GHz
7. TM11 Pol. 1 fco = 9.1412 GHz
8. TM11 Pol. 2 fco = 9.1412 GHz
9. TE31 Pol. 1 fco = 10.022 GHz
10. TE31 Pol. 2 fco = 10.022 GHz

* Picture courtesy E. Vogel et al.: "Status of the 3rd harmonic systems for FLASH and XFEL in summer 2008", Proc. LINAC 2008.
** I. R. R. Shinton, N. Juntong, R. M. Jones "Modal Dictionary of Cavity Modes for the Third Harmonic XFEL/FLASH Cavities", DESY note: DESY 12-053.

String of Cavities in ACC39 @ FLASH Beamline



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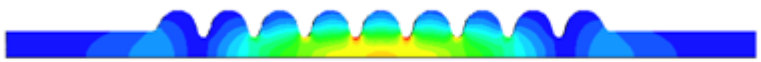
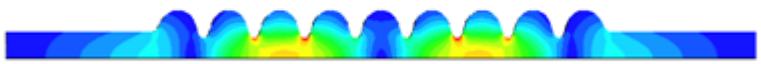
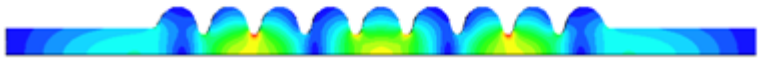
	4.2953
	4.3580
	4.4460

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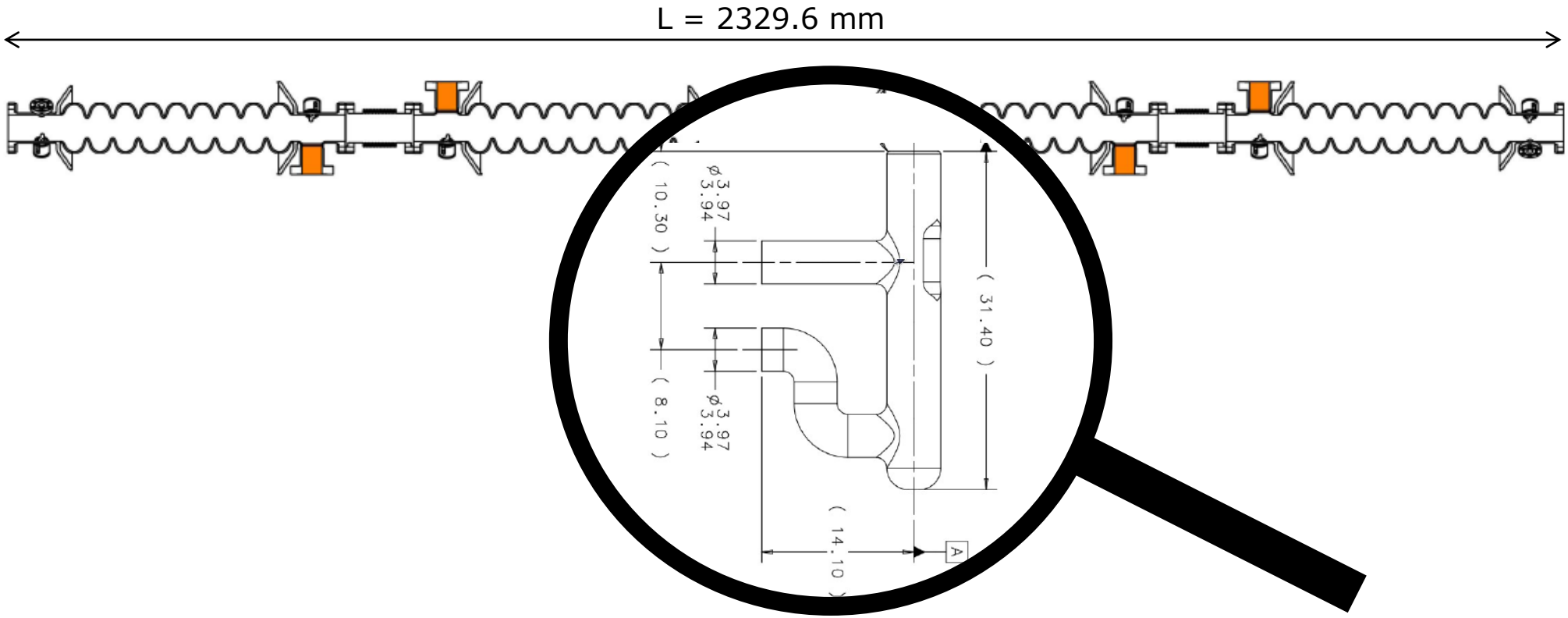
9. TE31 Pol. 1 fco = 10.022 GHz
10. TE31 Pol. 2 fco = 10.022 GHz

RF properties are determined by entire string

* Picture courtesy E. Vogel et al.: "Status of the 3rd harmonic systems for FLASH and XFEL in summer 2008", Proc. LINAC 2008.
** I. R. R. Shinton, N. Juntong, R. M. Jones "Modal Dictionary of Cavity Modes for the Third Harmonic XFEL/FLASH Cavities", DESY note: DESY 12-053.

String of Cavities in ACC39 @ FLASH Beamline



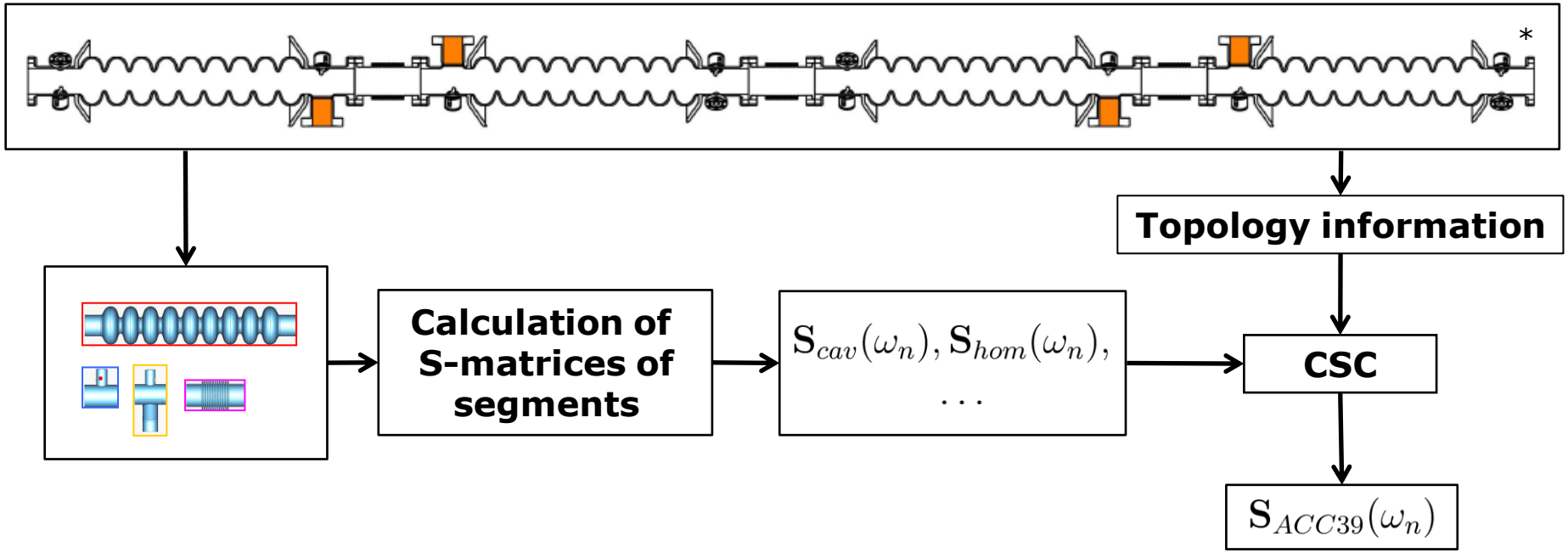
Treatment of string is numerically expensive, because mesh needs to resolve tiny structures e.g. of the formteil.

* Picture courtesy E. Vogel et al.: "Status of the 3rd harmonic systems for FLASH and XFEL in summer 2008", Proc. LINAC 2008.

Approach to determine S-Parameters of large/long Structures: Coupled S-Parameter Calculations*

* H.-W. Glock, K. Rothemund, U. van Rienen: "CSC - A System for Coupled S-Parameter Calculations", TESLA-Report 2001-25

CSC Workflow

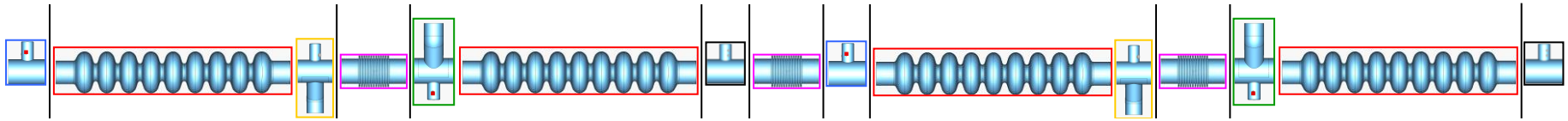


Some further advantages:

- properties of equal segments need to be computed only once
- symmetry of segments can be employed to reduce computation costs
- suitable to perform parameter studies

* Picture courtesy E. Vogel et al.: "Status of the 3rd harmonic systems for FLASH and XFEL in summer 2008", Proc. LINAC 2008.

Details of ACC39 S-Parameter Simulation



CSC Device	Number of Meshcells	Duration of Computation*
Cavity	12,666,312	56 h 21 min
HOM2Leg	5,873,684	11 h 34 min
HOM2LegIC	12,999,168	15 h 53 min
HOM1Leg	5,482,620	17 h 13 min
HOM1LegIC	12,751,200	22 h 58 min
Bellow	3,413,800	6 h 22 min

*S-Parameter computed in the frequency interval from 3.5 GHz to 8 GHz sampled with Δf=0.45 MHz (10001 frequency samples) using CST's Resonant Fast S-Parameter Module

Considered pipe modes for expansion:

1. TE11 Pol. 1 fco = 4.3920 GHz
2. TE11 Pol. 2 fco = 4.3920 GHz
3. TM01 fco = 5.7371 GHz
4. TE21 Pol. 1 fco = 7.2858 GHz
5. TE21 Pol. 2 fco = 7.2858 GHz
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8. TM11 Pol. 2 fco = 9.1412 GHz
9. TE31 Pol. 1 fco = 10.022 GHz
10. TE31 Pol. 2 fco = 10.022 GHz

CSC coupling (T ≈ 10 min) results in $\mathbf{S}_{ACC39,Simul} \in \mathbb{C}^{32\times 32}$

Measurement of S-Parameters*

*performed by N. Baboi (DESY), T. Flisgen and H.-W. Glock (Universität Rostock), I. Shinton (formerly University of Manchester/Cockcroft Institute now Elekta), Pei Zhang (formerly University of Manchester/DESY now CERN)

Measurement Setup

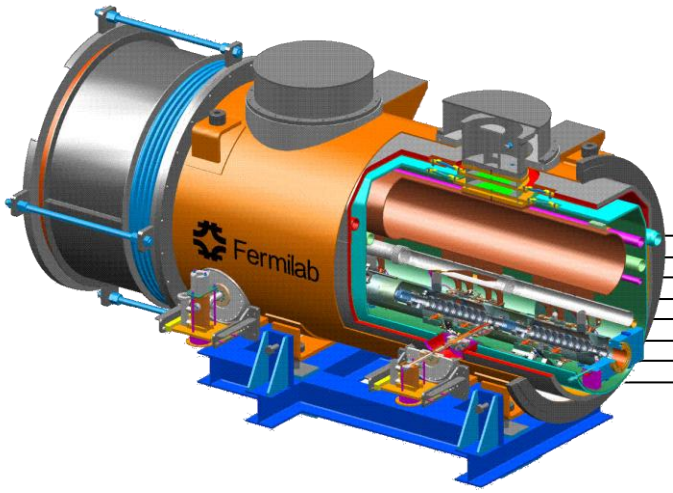
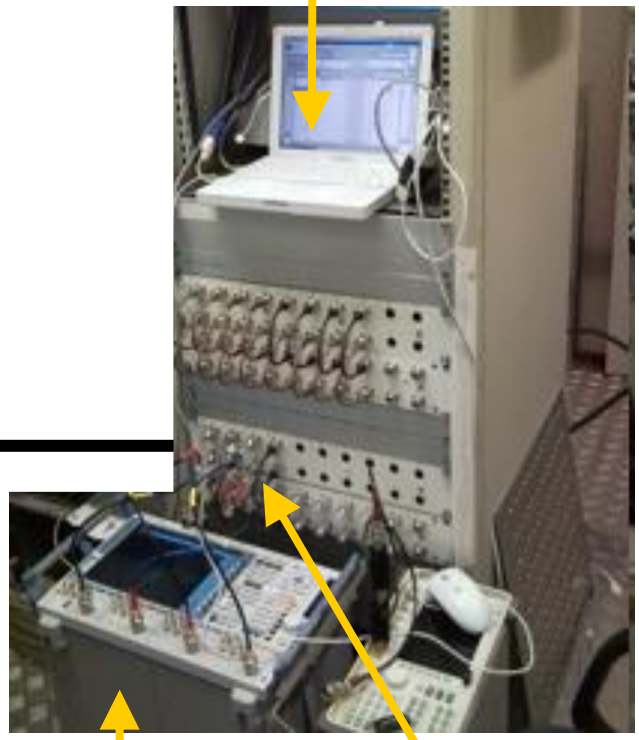


Figure courtesy of E. Vogel

8 cables to HOM ports

Laptop with LabView to control NWA

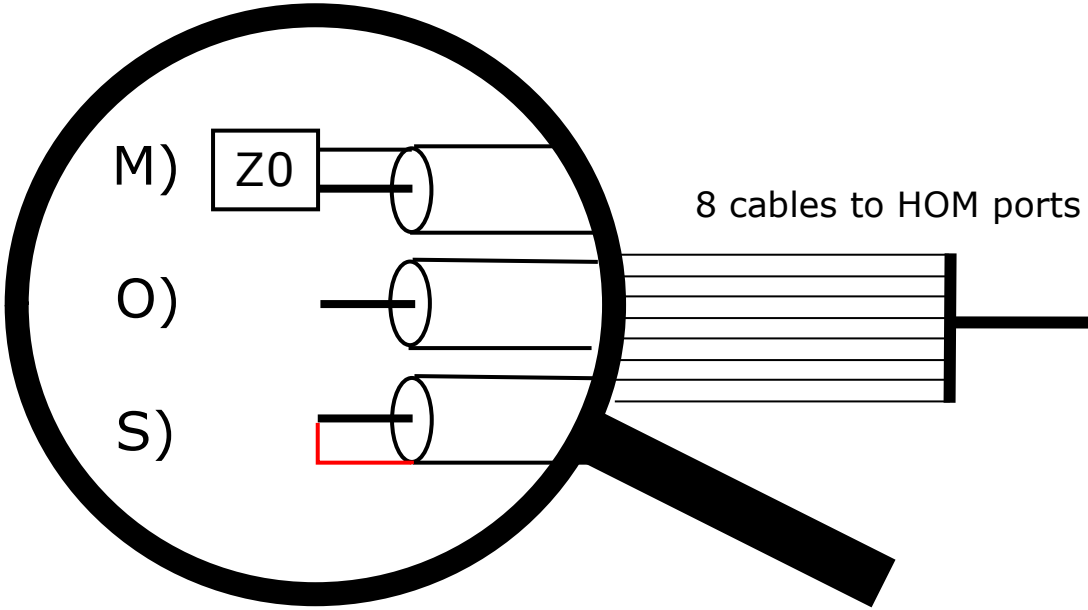


ACC39 HOM Rack

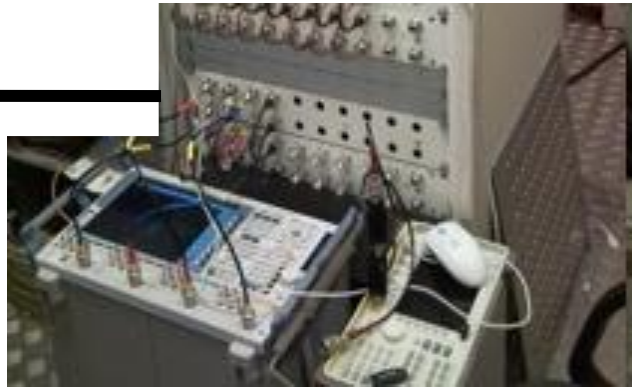
R&S ZVA8 NWA

- 28 transmission and 8 reflection spectra measured
- interval from 3.5 GHz to 8 GHz sampled with Δf=10kHz (450001 frequency samples) to capture high Q peaks

One port M-O-S Calibration of Cables*



Measurements of reflections with three different terminations

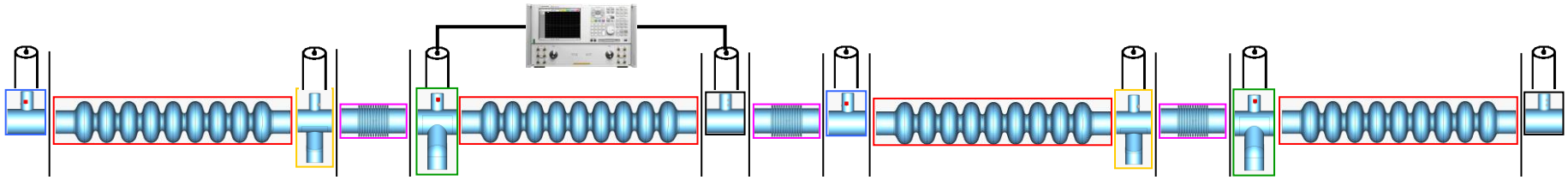


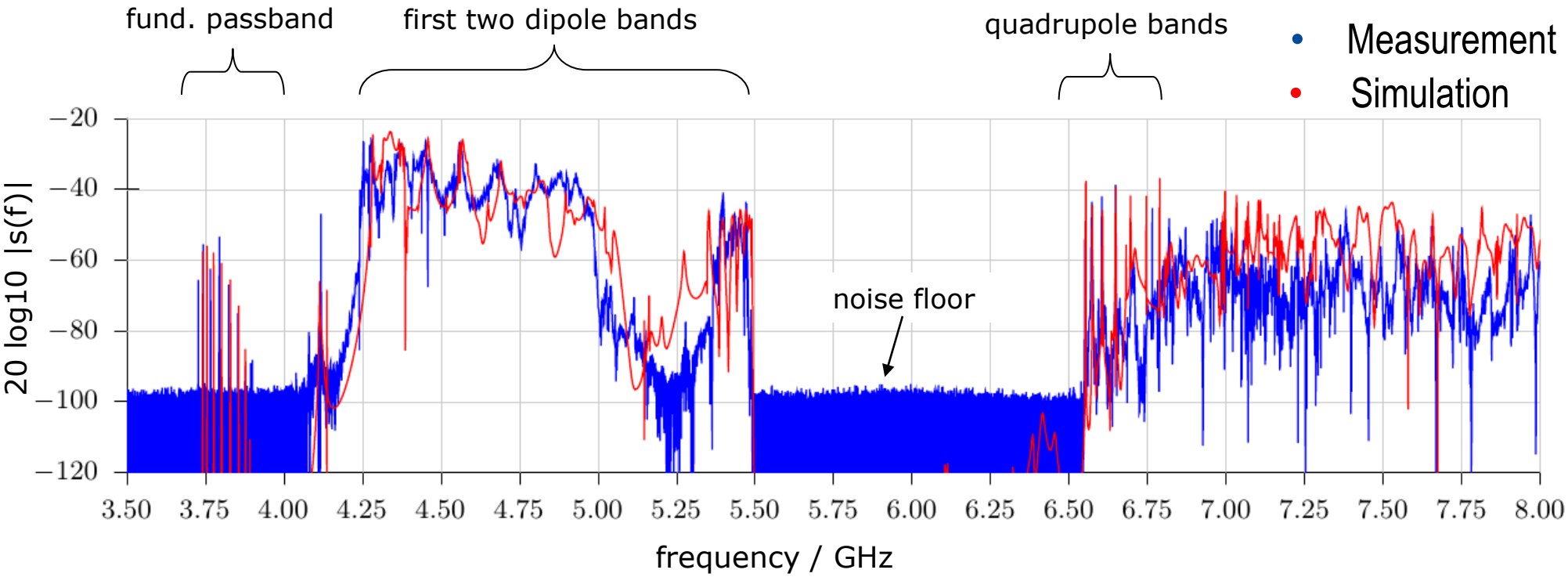
*Direct measurement of cable transmission was not possible due to fixed installation of cables

Measurements (total sweep time T ≈ 4 d) result $\mathbf{S}_{ACC39,Meas} \in \mathbb{C}^{8\times 8}$ and eight matrices $\mathbf{S}_{Cable,Meas} \in \mathbb{C}^{2\times 2}$

Comparison between Measurement and Simulation

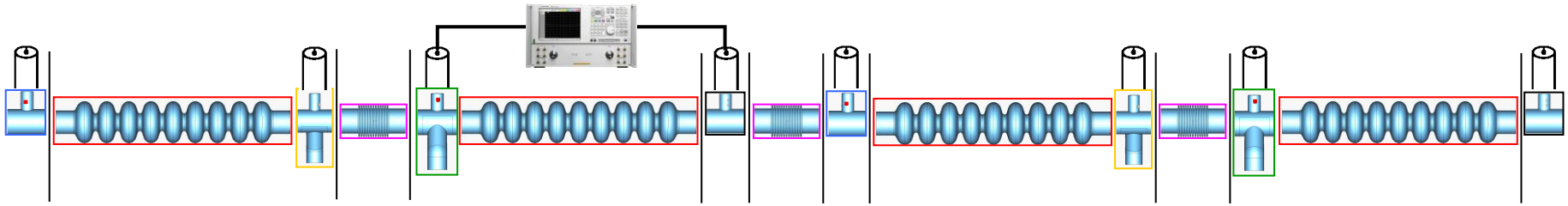
Example I: Transmission via Cavity 2

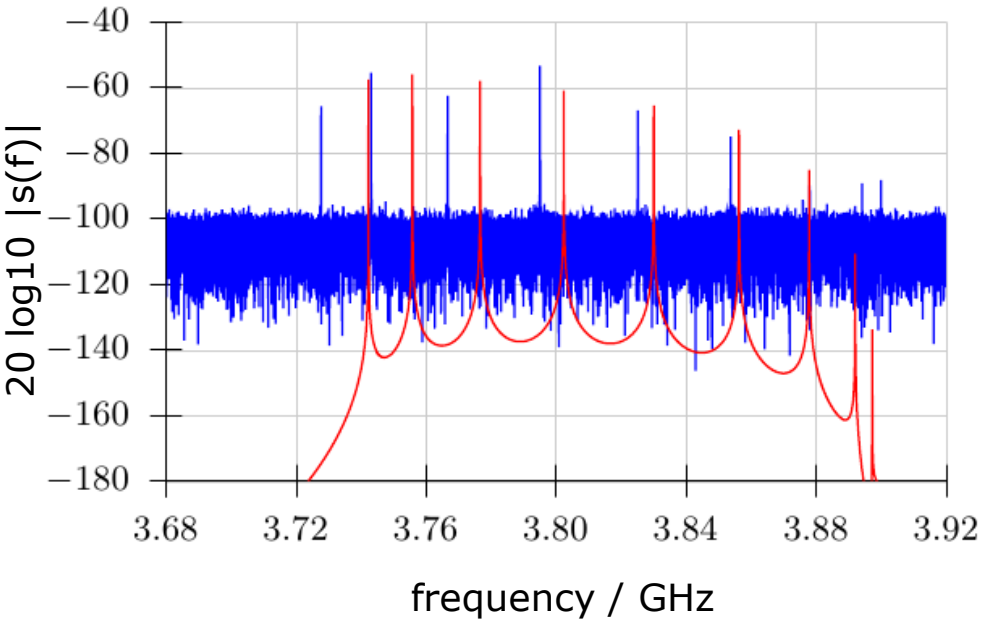


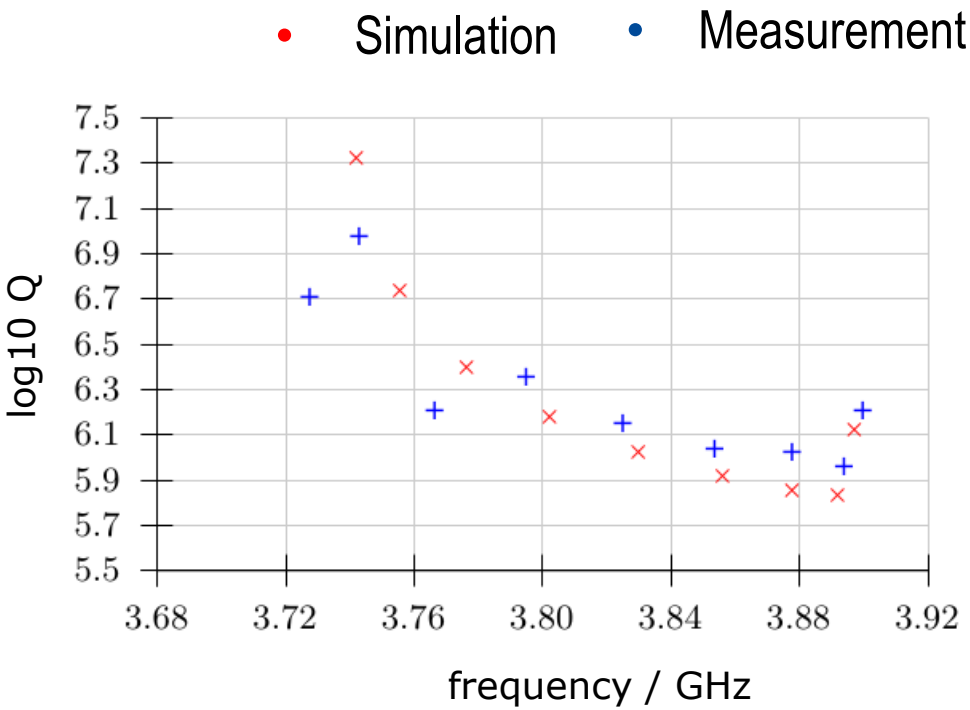


Locations of pass- and stopbands nicely agree between measured and simulated spectra.

Example I: Transmission via Cavity 2 (Fund. Monopole PB)

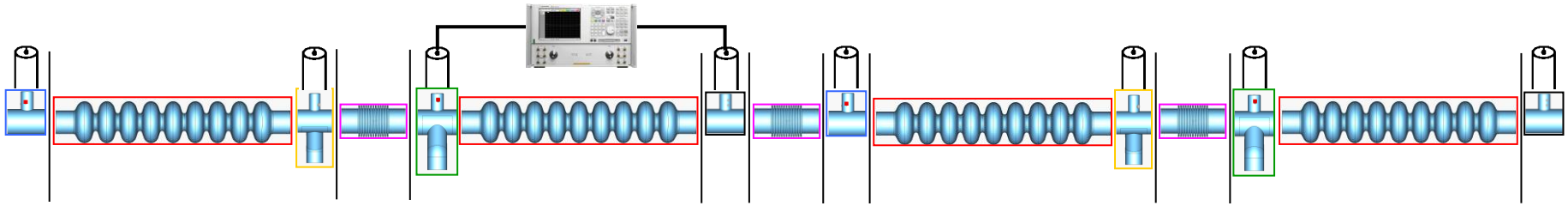


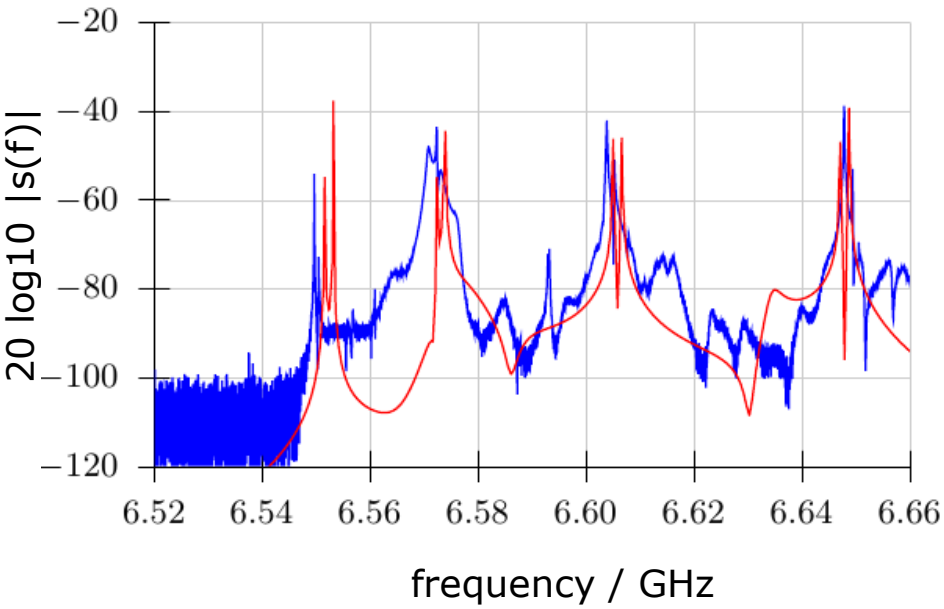


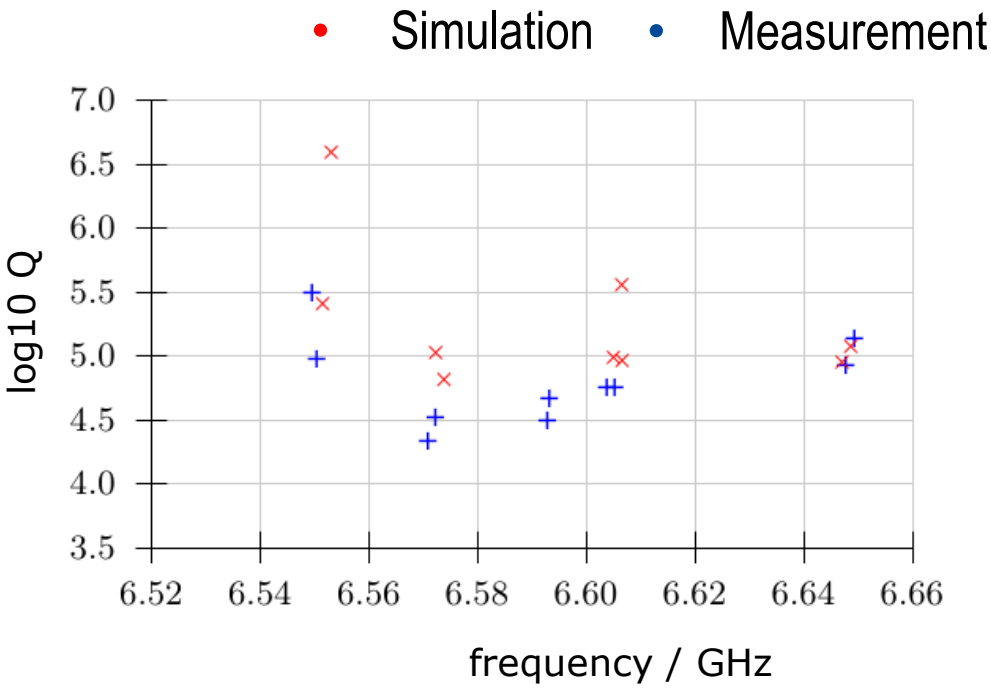


All nine modes of fundamental passband are observable in both spectra with comparable Q factors. Frequency shifts can be effects of imperfections of the cavity (tuning, fabrication tolerances etc.)

Example I: Transmission via Cavity 2 (Quadrupole PB)

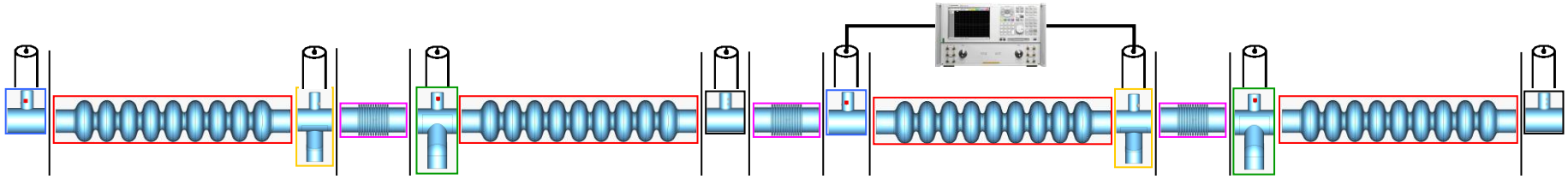


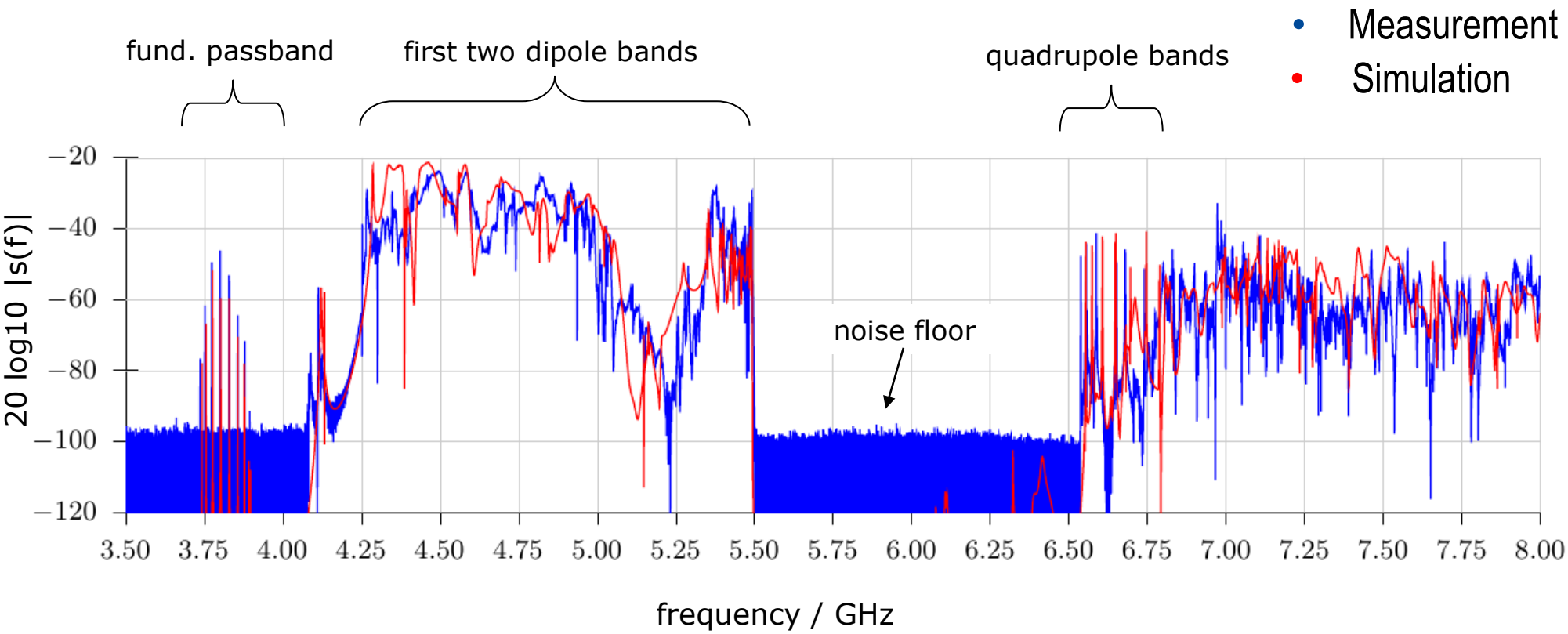




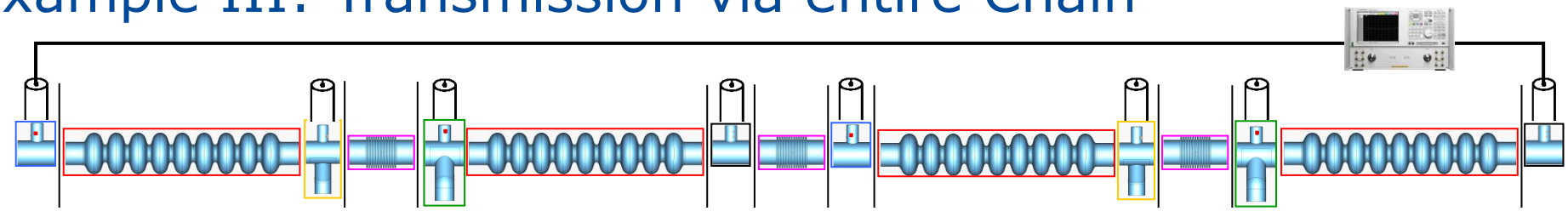
Closely spaced peaks could belong to degenerated modes, whose resonant frequency slightly differs due to the roational symmetry breaking couplers.

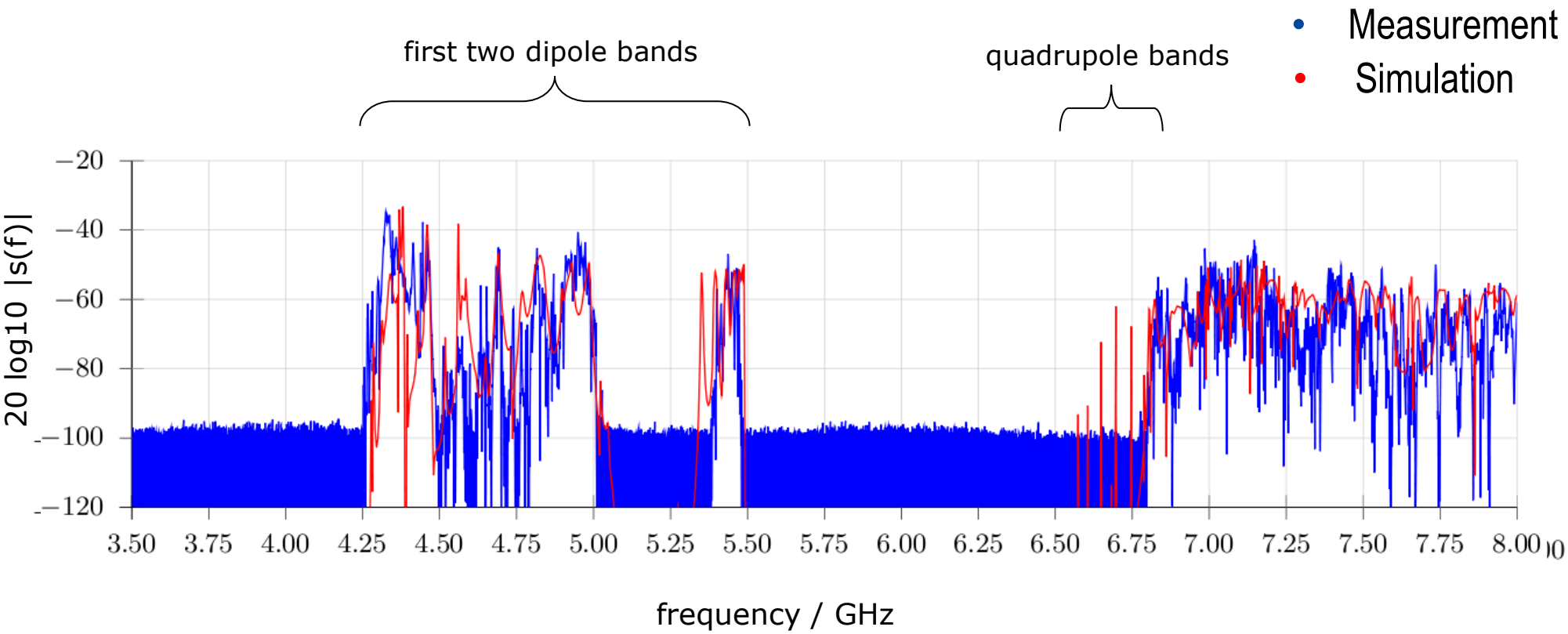
Example II: Transmission via Cavity 3





Example III: Transmission via entire Chain





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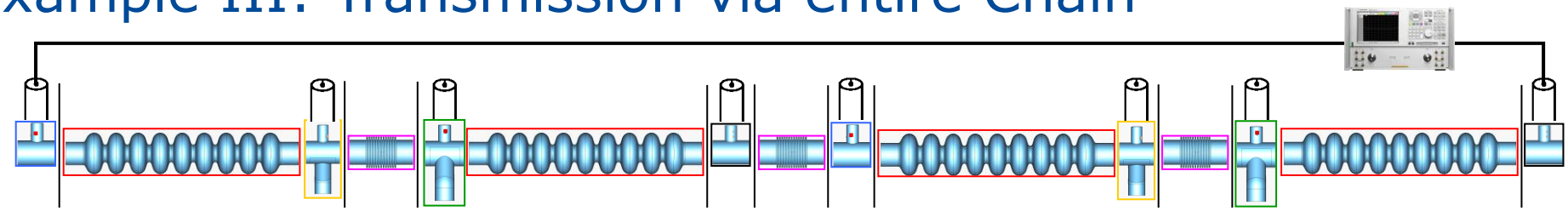
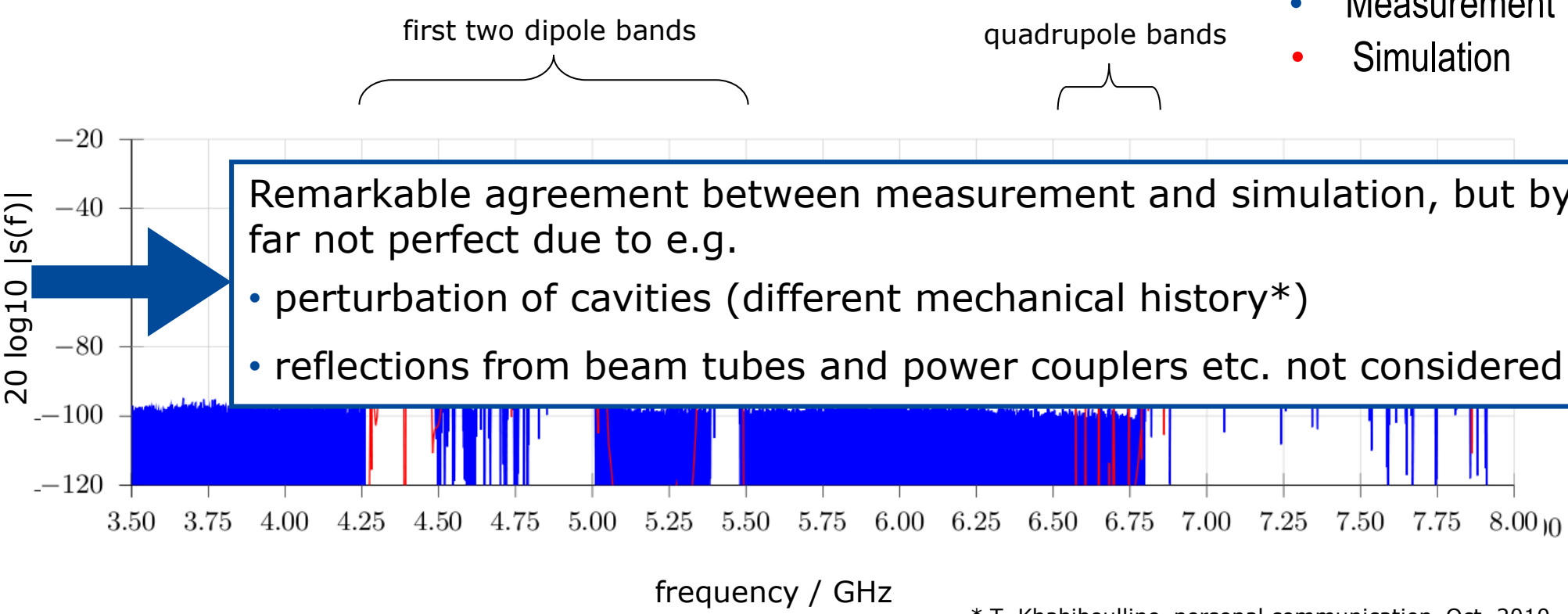




Remarkable agreement between measurement and simulation, but by far not perfect due to e.g.

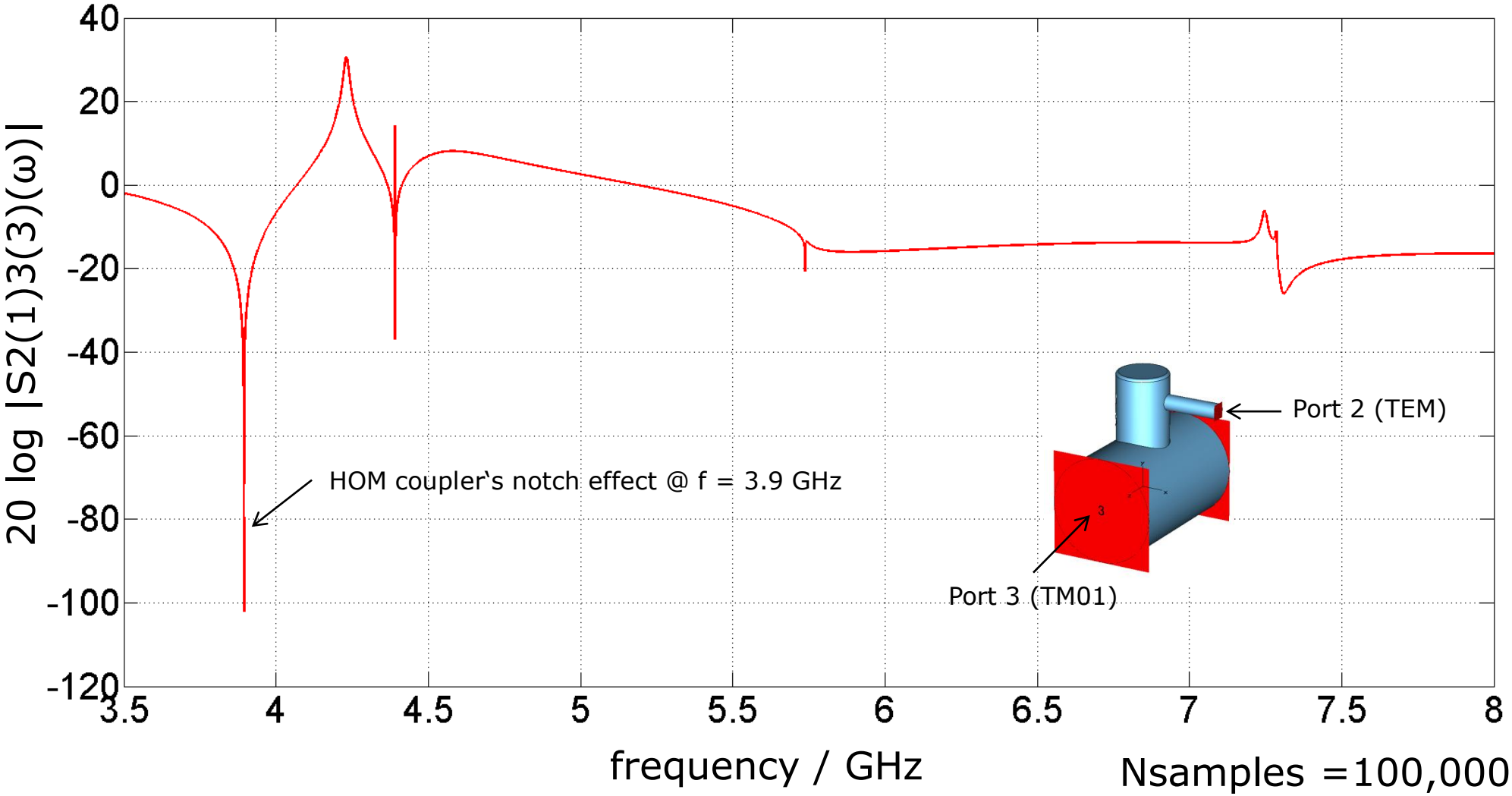
- perturbation of cavities (different mechanical history*)
- reflections from beam tubes and power couplers etc. not considered

* T. Khabiboulline, personal communication, Oct. 2010

Part II

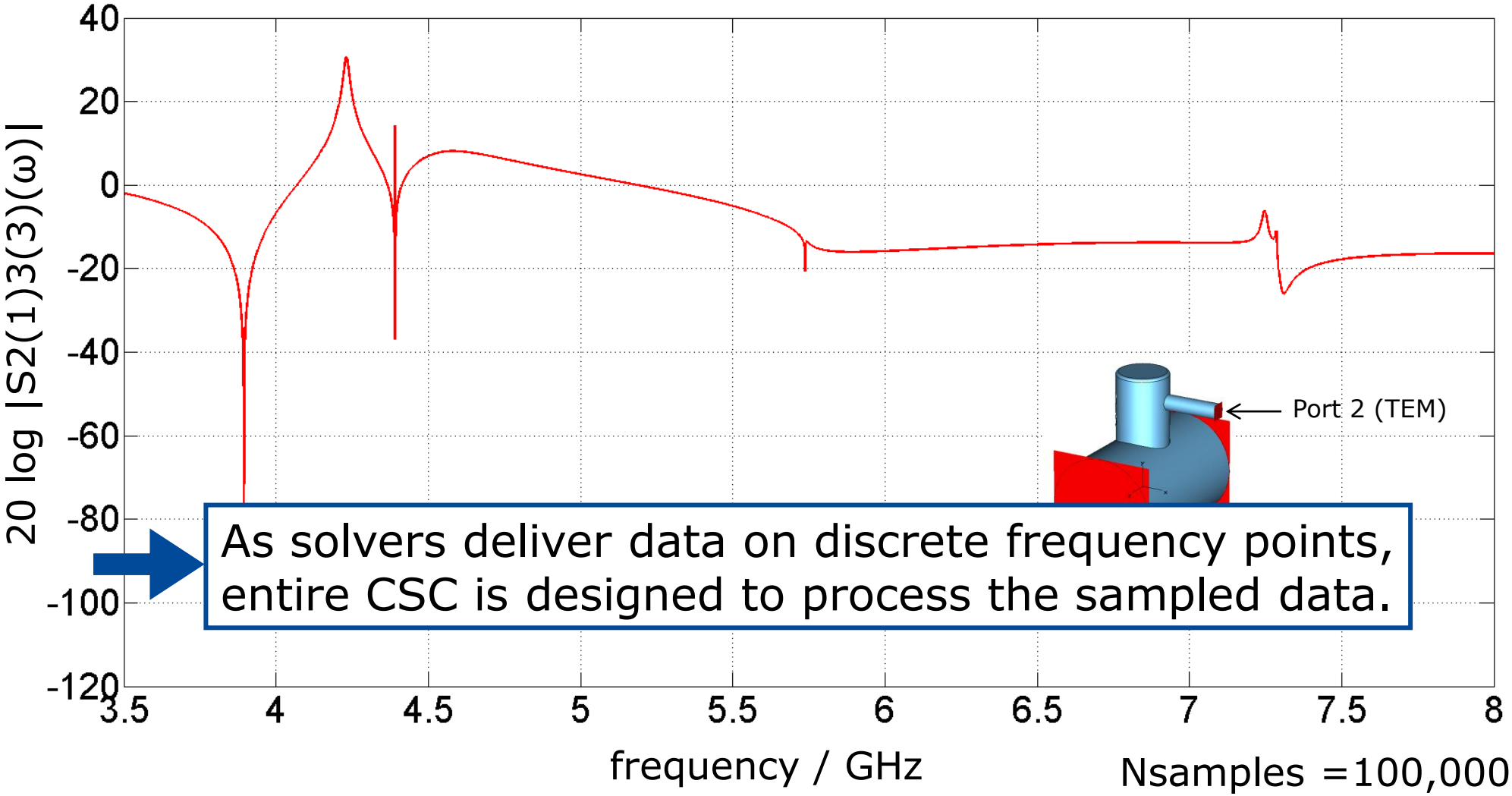
Back to Theory and Simulations: A Closer Inspection on Input Data Needed for the CSC scheme

Example: Simulated Transmission HOM Coupler



Nsamples =100,000

Example: Simulated Transmission HOM Coupler



As solvers deliver data on discrete frequency points, entire CSC is designed to process the sampled data.

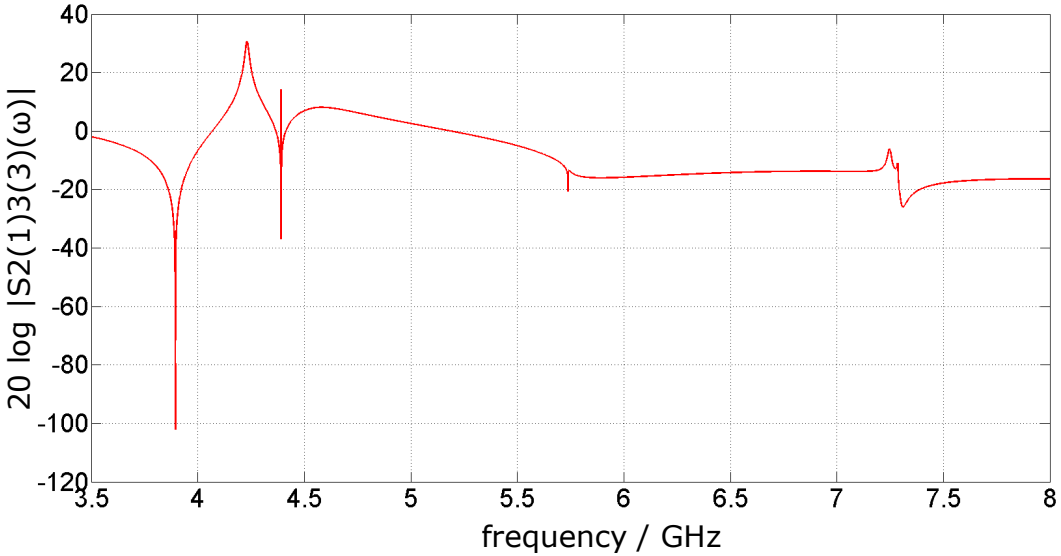
Nsamples =100,000

Pole-Zero based Description

- From theory it is known that

$$s(\omega) = \sum_{k=1}^{\infty} \frac{a_k}{j\omega - p_k}$$

as parameters are integral quantities derived from a field problem governed by set of PDEs.

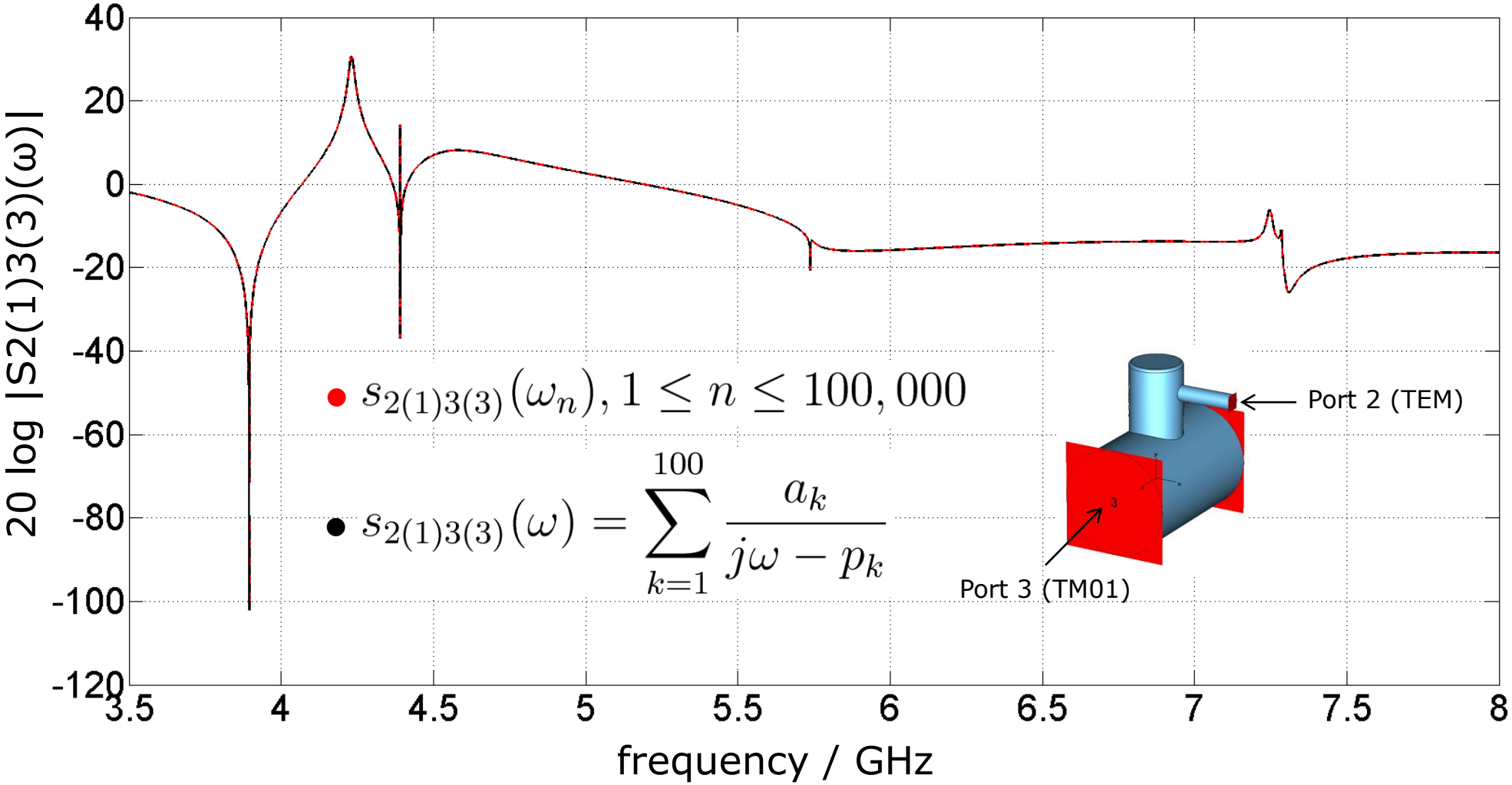


- Restriction on finite frequency interval:

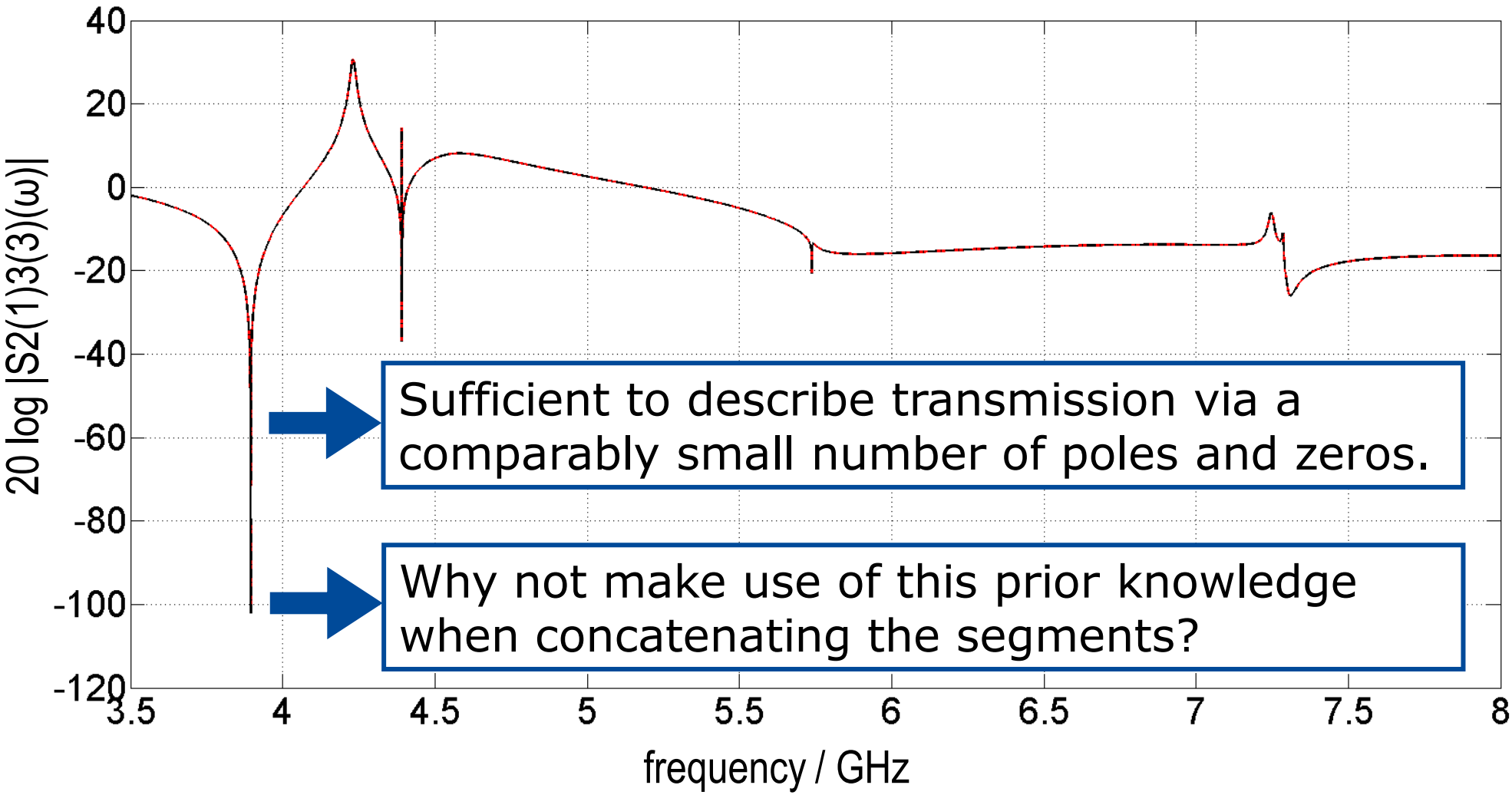
$$s(\omega) = \sum_{k=1}^{N_{poles}} \frac{a_k}{j\omega - p_k} = c_0 \frac{\prod_{k=1}^{N_{poles}-1} (j\omega - \tilde{z}_k)}{\prod_{k=1}^{N_{poles}} (j\omega - z_k)}$$

→ Sampling leads to redundant information!

Redundancy in Description of HOM Coupler



Redundancy in Description of HOM Coupler



Sufficient to describe transmission via a comparably small number of poles and zeros.

Why not make use of this prior knowledge when concatenating the segments?

State Space Coupling* for Creation of Lumped Model of Complete Structure

*Inspired by M. Dohlus, R. Schuhmann, T. Weiland: "Calculation of frequency domain parameters using 3D eigensolutions", Int. J. Numer. Model. 12, 41-68 (1999) and H.-W. Glock, K. Rothemund, U. van Rienen: "CSC - A System for Coupled S-Parameter Calculations", TESLA-Report 2001-25

Description of Segments via Lumped Models

- Redundant-free description of segment´s in an impedance formulation by:

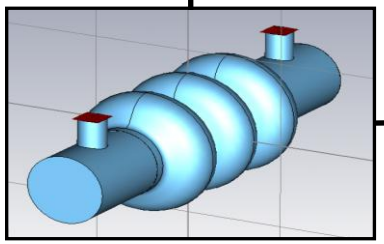
$$\frac{\partial}{\partial t}\underbrace{\mathbf{x}_r(t)}_{\text{state}} = \underbrace{\mathbf{A}_r}_{\text{state matrix}}\,\mathbf{x}_r(t) + \overbrace{\mathbf{B}_r}^{\text{input matrix}}\,\underbrace{\mathbf{i}_r(t)}_{\text{port currents}} \qquad \overbrace{\mathbf{v}_r(t)}^{\text{port voltages}} = \underbrace{\mathbf{C}_r}_{\text{output matrix}}\,\mathbf{x}_r(t)$$

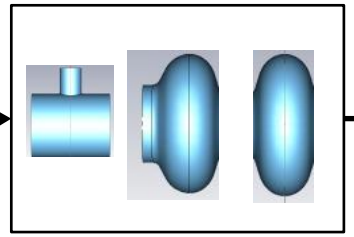
- Respective matrices computed solving real eigenproblems for each segment*
- Upper equations are referred to as lumped equivalent model as they do not have spatial expanses or spatial derivatives.
- Segment‘s transfer function in freq. domain:

$$\mathbf{Z}_r(j\omega) = \mathbf{C}_r\Big(j\omega\,\mathbf{I} - \mathbf{A}_r\Big)^{-1}\mathbf{B}_r = \sum_{k=1}^{N_{poles}} \frac{\mathbf{M}_k}{j\omega - p_k}$$

*M. Dohlus, R. Schuhmann, T. Weiland: “Calculation of frequency domain parameters using 3D eigensolutions“, Int. J. Numer. Model. 12, 41-68 (1999)

Demonstration Example for State Space Coupling





Solve real (!) eigenproblem for each segment + correction term

$$\frac{\partial}{\partial t}\mathbf{x}_r(t) = \mathbf{A}_r\,\mathbf{x}_r(t) + \mathbf{B}_r\,\mathbf{i}_r(t)$$
$$\mathbf{v}_r(t) = \mathbf{C}_r\,\mathbf{x}_r(t)$$

State Space Coupling

Topology information

$$\frac{\partial}{\partial t}\mathbf{x}(t) = \mathbf{A}\,\mathbf{x}(t) + \mathbf{B}\,\mathbf{i}(t)$$
$$\mathbf{v}(t) = \mathbf{C}\,\mathbf{x}(t)$$

Impedance formulation of full structure in time domain

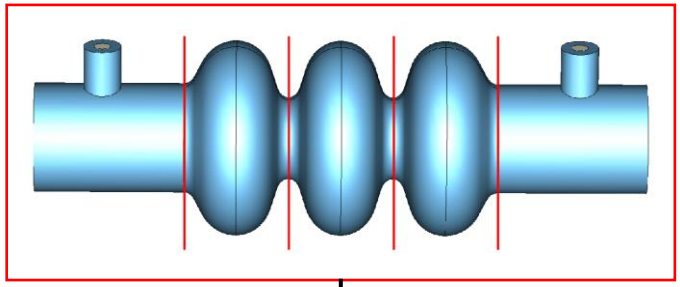
$$\frac{\partial}{\partial t}\mathbf{x}_{sc}(t) = \mathbf{A}_{sc}\,\mathbf{x}_{sc}(t) + \mathbf{B}_{sc}\,\mathbf{a}(t)$$
$$\mathbf{b}(t) = \mathbf{C}_{sc}\,\mathbf{x}_{sc}(t) - \mathbf{I}\,\mathbf{a}(t)$$

Scattering formulation of full structure in time domain*

*transient system response available using Ordinary Differential Equations (ODE) Solver

Validation Results

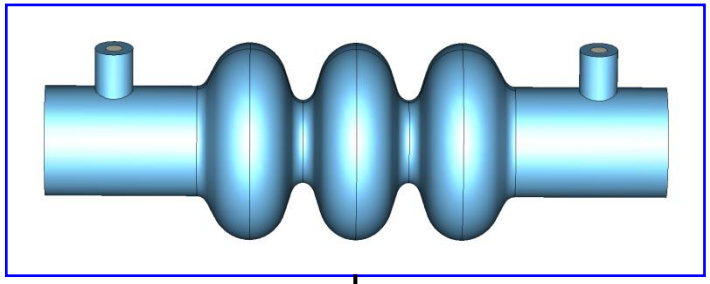
Validation using S-Parameters



$$\frac{\partial}{\partial t}\mathbf{x}_{sc}(t) = \mathbf{A}_{sc}\,\mathbf{x}_{sc}(t) + \mathbf{B}_{sc}\,\mathbf{a}(t)$$

$$\mathbf{b}(t) = \mathbf{C}_{sc}\,\mathbf{x}_{sc}(t) - \mathbf{I}\,\mathbf{a}(t)$$

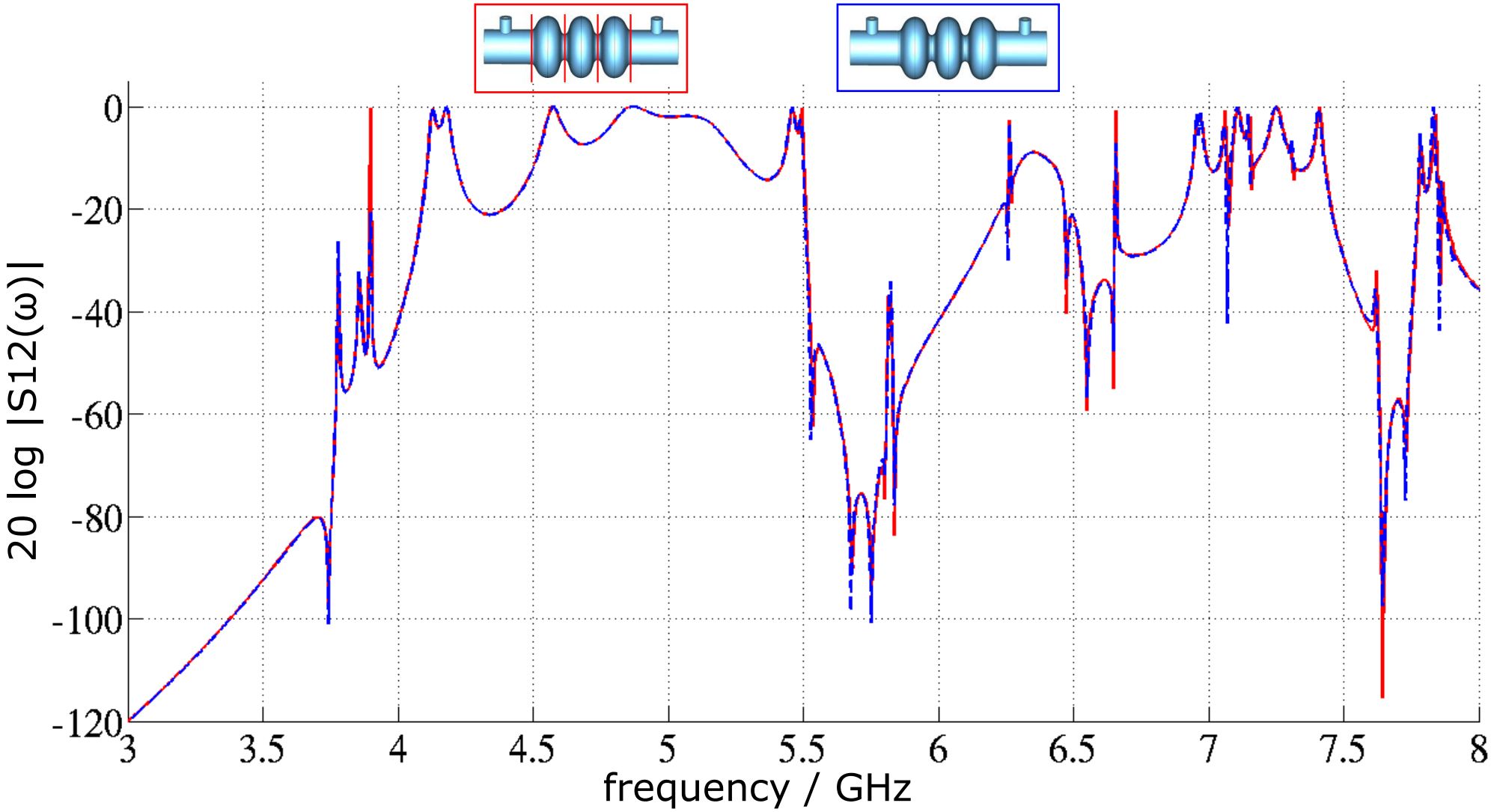
$$\mathbf{S}(j\omega) = \mathbf{C}_{sc}\Big(j\omega\,\mathbf{I} - \mathbf{A}_{sc}\Big)^{-1}\mathbf{B}_{sc} - \mathbf{I}$$



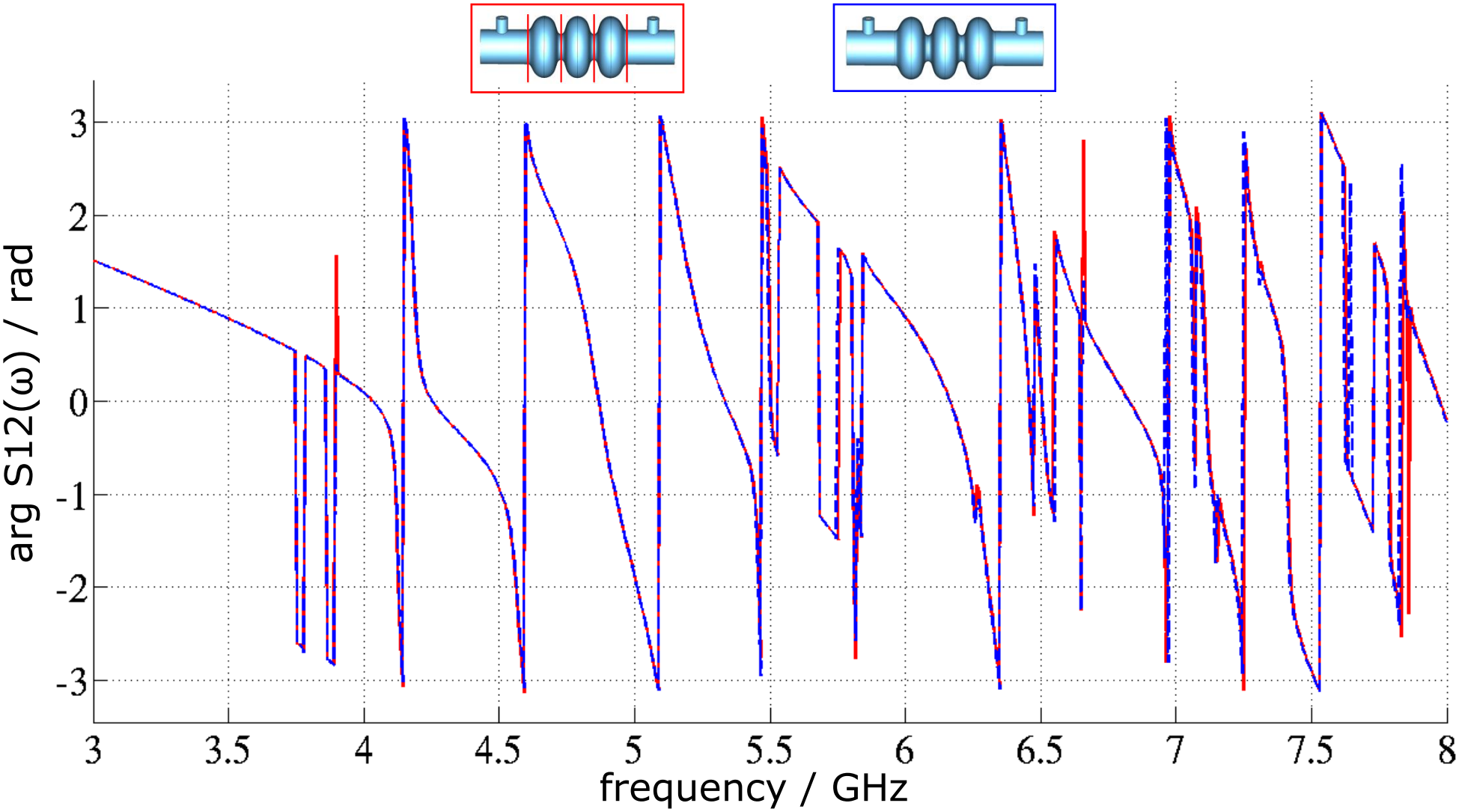
Full structure's S-Parameter Calculation using CST MWS® FR Solver

Comparison of S-Parameters

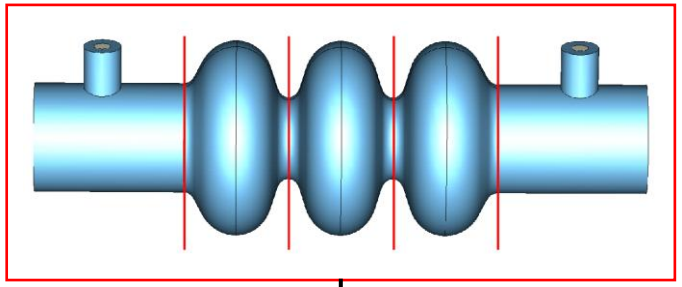
Comparison State Space Coupling vs. Direct



Comparison State Space Coupling vs. Direct



Validation using External Q Factors

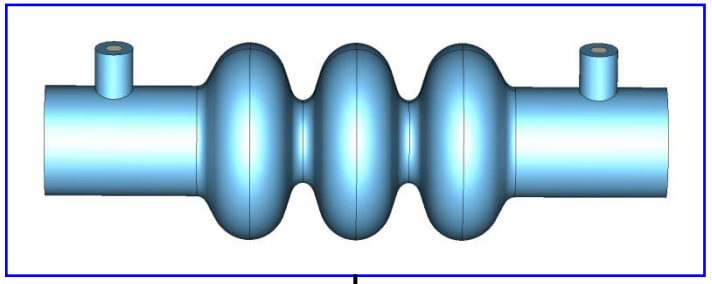


$$\frac{\partial}{\partial t}\mathbf{x}_{sc}(t) = \mathbf{A}_{sc}\,\mathbf{x}_{sc}(t) + \mathbf{B}_{sc}\,\mathbf{a}(t)$$

$$\mathbf{b}(t) = \mathbf{C}_{sc}\,\mathbf{x}_{sc}(t) - \mathbf{I}\,\mathbf{a}(t)$$

$$Q_{ext,\nu} = \frac{\omega_\nu W_{stored,\nu}}{P_{ports,\nu}} = \frac{\mathrm{Im}(\lambda_\nu)}{2\mathrm{Re}(\lambda_\nu)}$$

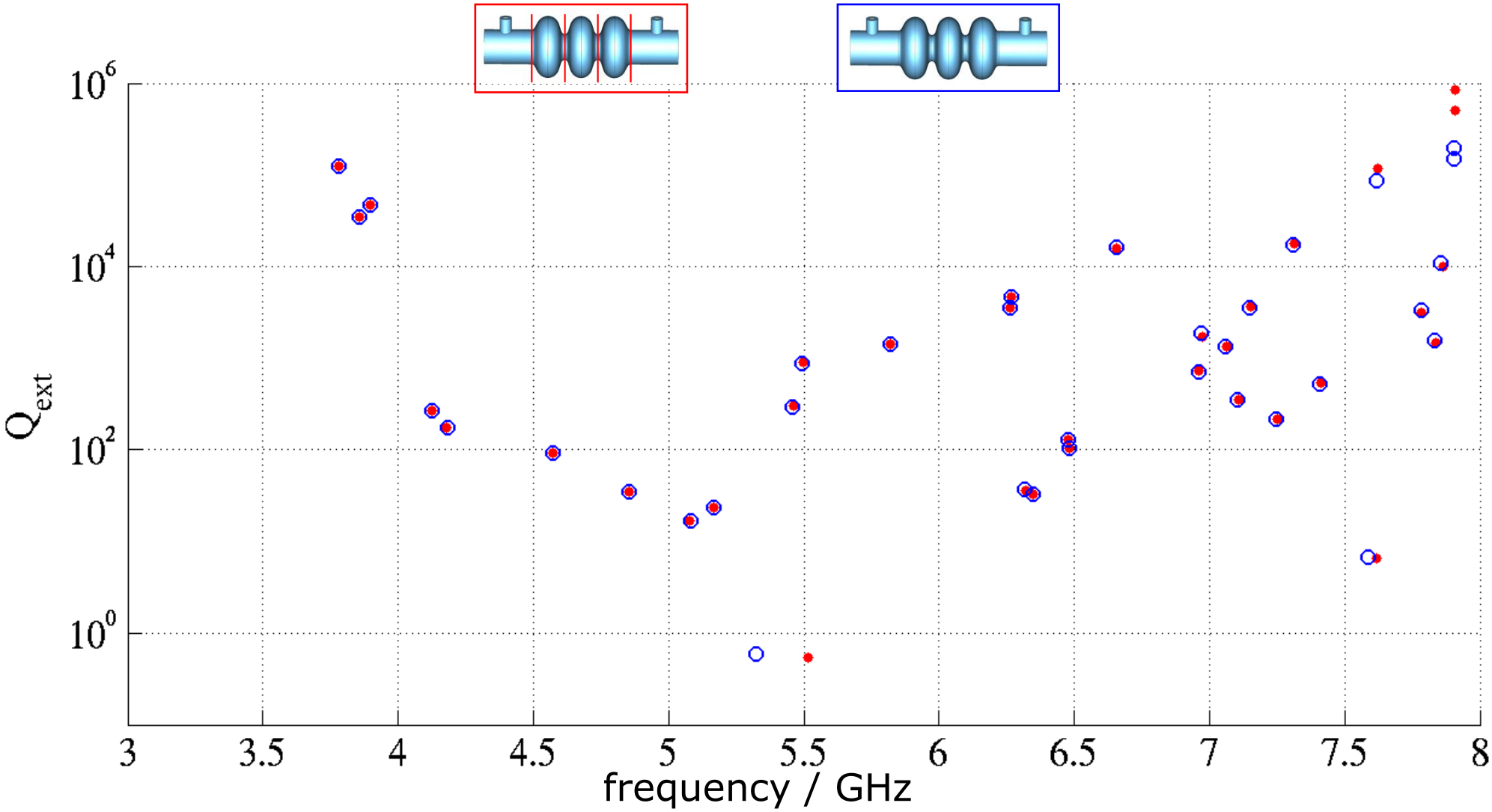
$$\mathrm{eig}(\mathbf{A}_{sc}) = \{\lambda_1, \ldots, \lambda_\nu, \ldots\}$$



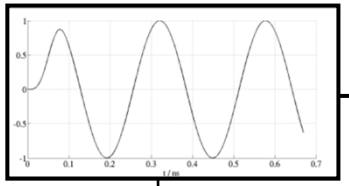
Full structure's eigenmode calculation using CST MWS® EM Solver

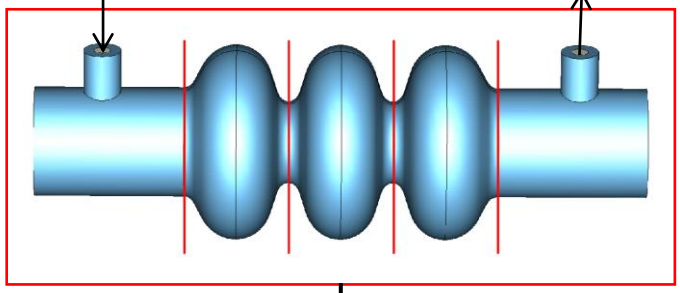
Comparison of External Q's

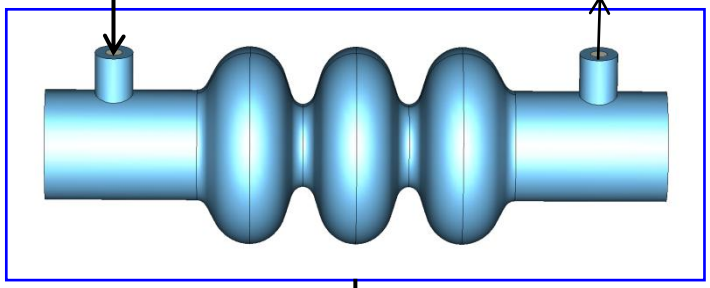
Comparison State Space Coupling vs. Direct



Validation using Transient System Responses







$$\frac{\partial}{\partial t}\mathbf{x}_{sc}(t) = \mathbf{A}_{sc}\,\mathbf{x}_{sc}(t) + \mathbf{B}_{sc}\,\mathbf{a}(t)$$

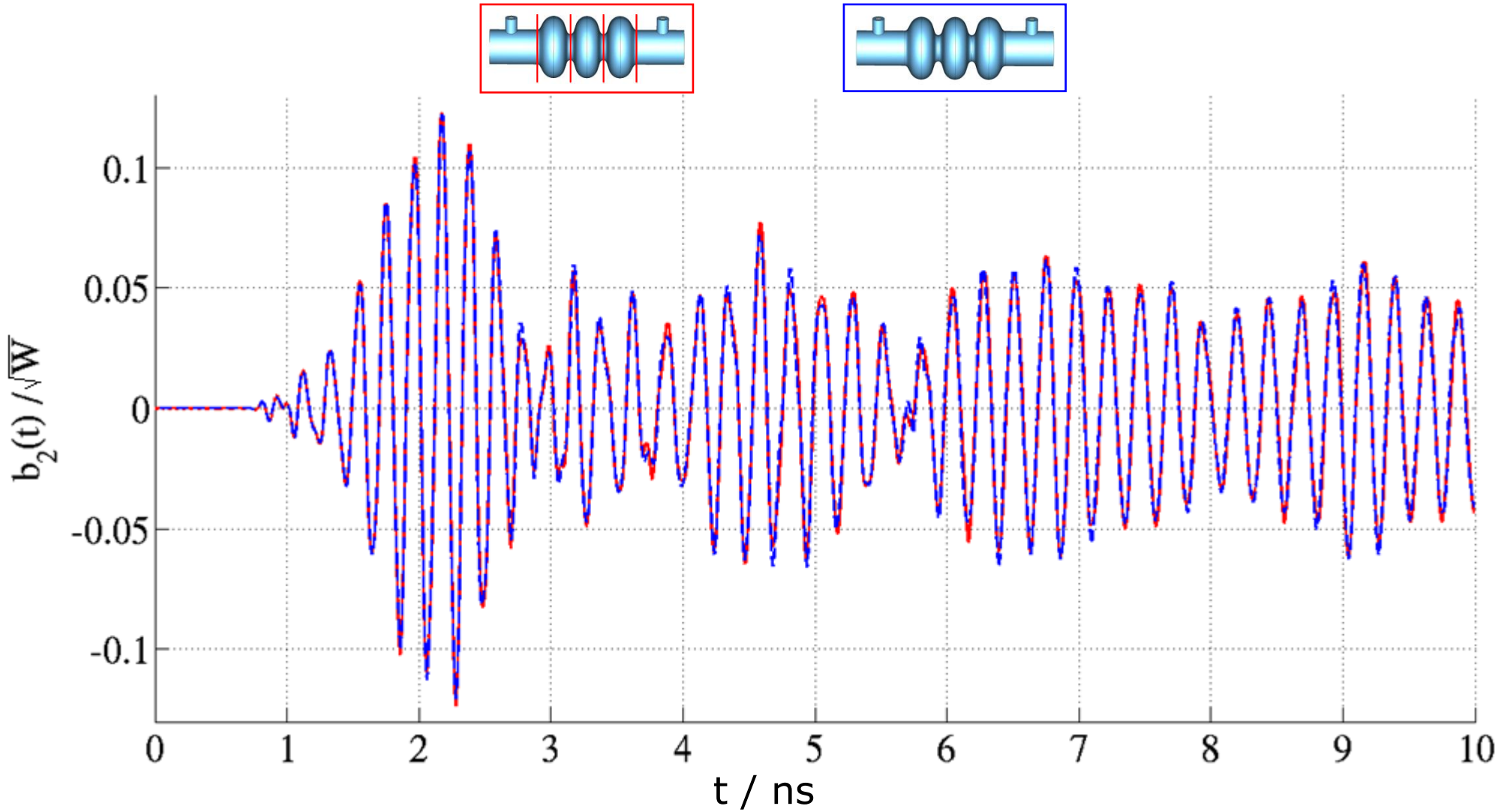
$$\mathbf{b}(t) = \mathbf{C}_{sc}\,\mathbf{x}_{sc}(t) - \mathbf{I}\,\mathbf{a}(t)$$

Computation of system response by means of ODE solver

Full structure's transient simulation using CST MWS® Transient Solver

Comparison of Responses

Comparison Direct vs. State Space Coupling



Conclusions

Conclusions

- Remarkable agreement between measurement and simulation, but by far not perfect due to a large variety of not considered effects

Part I

- State space coupling enables the creation of lumped equivalent models of complex structures.
- In comparision to CSC no redundant sampling of S-matrices.
- The lumped model directly allows for computation of S-Parameters, transient system responses, external quality factors and other secondary quantities.
- The validation example shows a good agreement between results obtained by direct and piecewise computations over a wide frequency range.

Part II