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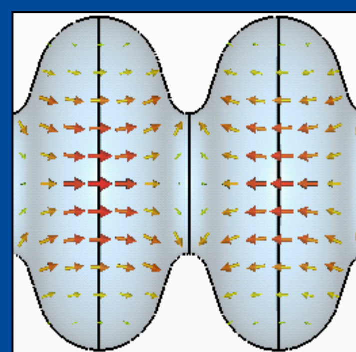

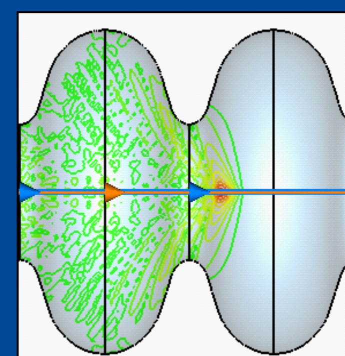

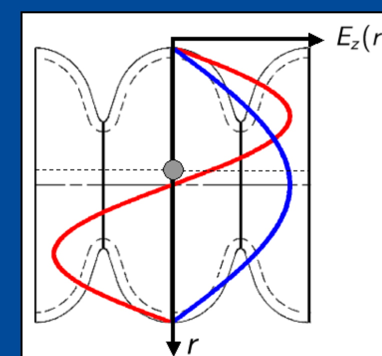

Results of RF Simulations for Chains of Superconducting Cavities

Thomas Flisgen, Johann Heller, and Ursula van Rienen

Eucard^2 WP 12 Annual Review Meeting 2015
DESY, Hamburg, Germany, 8th – 9th of April 2015

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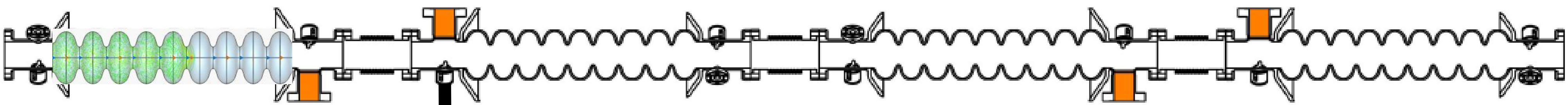
EuCARD²

Outline

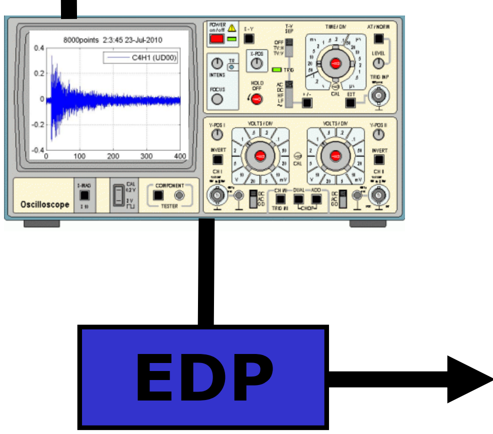
- Introduction motivation for computations of RF properties in long cavity chains
- Used Approach: State Space Concatenations
- Analysis of RF properties in rotationally symmetric chains of superconducting structures
- Analysis of RF properties in chains of superconducting structures with HOM and input couplers
- Conclusions and Outlook

Introduction and Motivation

Overall Goal: „Parasitical“ use of HOM couplers: Diagnostic System based on HOM port signals* of ACC39 mounted in FLASH



String of cavities in ACC39**



Information about:

- Transversal momentum and offset of bunch
- Perturbances of cavity
- Total charge of bunch

*Principle according to S. Molloy et al.: “High precision superconducting cavity diagnostics with higher order mode measurements", Phys. Rev. Spec. Top. Accel. Beams 9 (2006) 112802, 2006.

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

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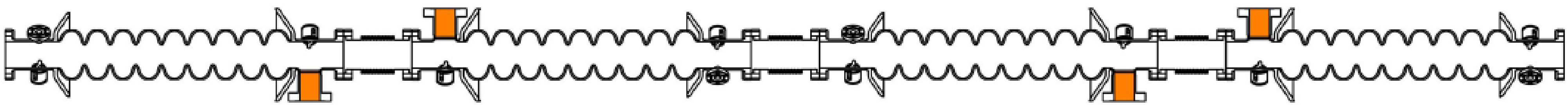
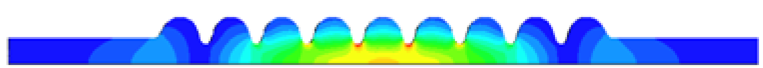
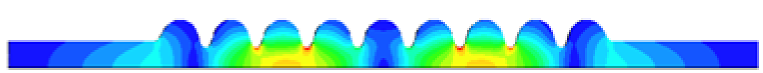
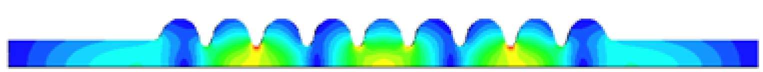
Recap

Numerical Characterizations of RF Properties for 3rd Harmonic Cavities accomodated in FLASH and XFEL



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

Cutoff 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.

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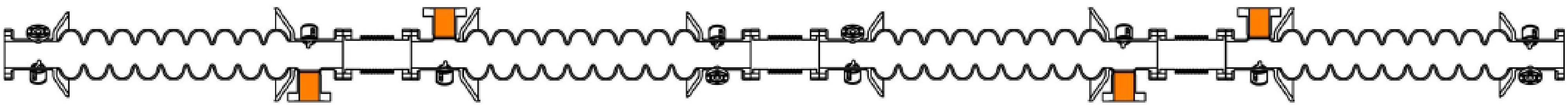
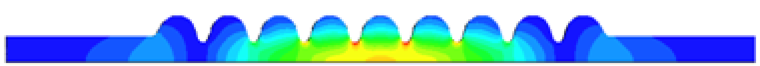
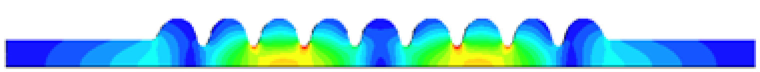
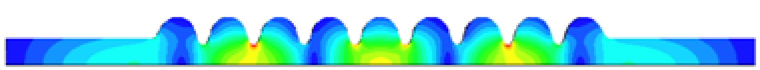
Recap

String of Cavities in ACC39 @ FLASH Beamline



String of cavities in ACC39 mounted in FLASH*

Electric field pattern of dipole modes (individual cavity)**	$\omega/2\pi$ (GHz)
	4.2953
	4.3580
	4.4460

Cutoff frequencies of beam pipes:

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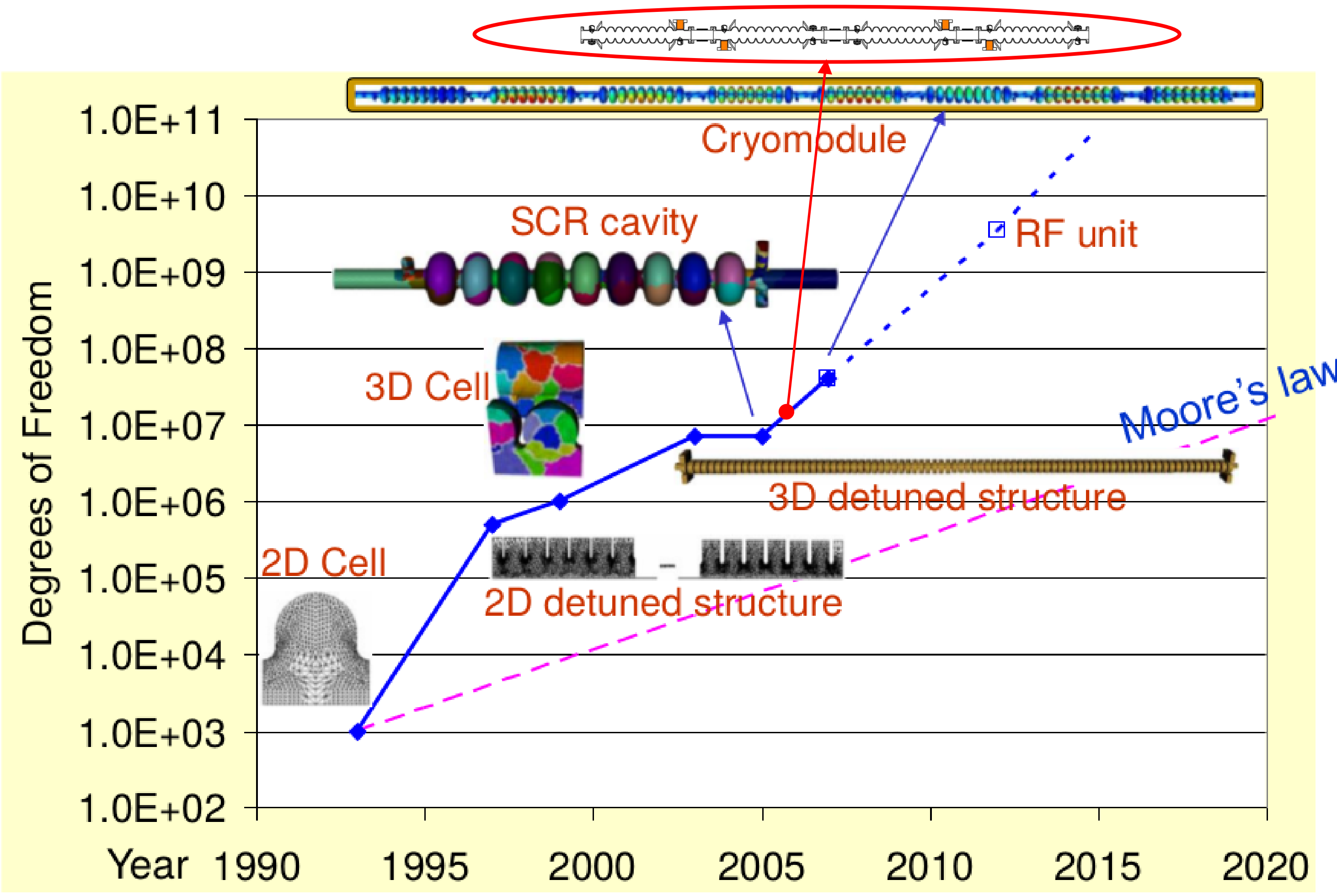
7. TM11 Pol. 1 fco = 9.1412 GHz
8. TM11 Pol. 2 fco = 9.1412 GHz
9. TE31 Pol. 1 fco = 10.022 GHz
10. TE31 Pol. 2 fco = 10.022 GHz

- RF properties are determined by entire string.
- Computation of RF properties is expensive.

*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.

Problem Complexity of Direct Computations



*Pictures courtesy Liling Xiao, Lixin Ge, Kwok Ko, Kihwan Lee, Zenghai Li, Cho-Kuen Ng: "Superconducting Cavity Imperfection Study for Projekt X Linac Using ACE3P", ComPASS All-Hands Meeting LBNL, Sept. 27 -28, 2012 and Kwok Ko et. al: "Advances in Parallel Electromagnetic Code for Accelerator Science and Development", Proceedings of the Linear Accelerator Conference 2010, pp. 1028 – 1032, Tsukuba Japan 2010

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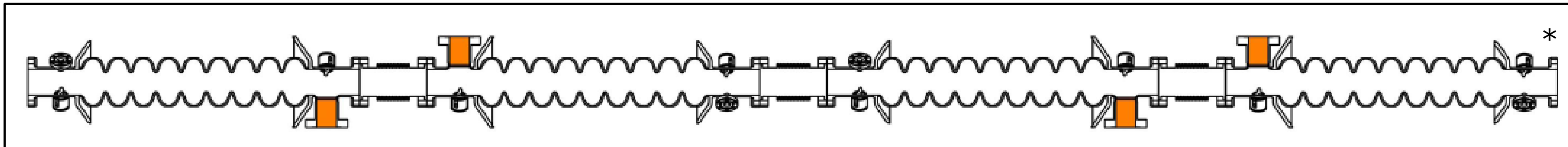
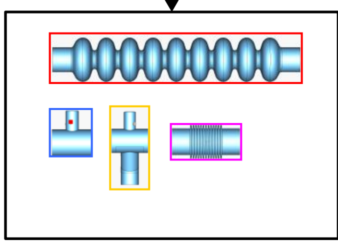
Concatenation Approach with Field Distributions: State Space Concatenations*

*T. Flisgen, H.-W. Glock, and U. van Rienen: "Compact Time-Domain Models of Complex RF Structures Based on the Real Eigenmodes of Segments", IEEE Transactions on Microwave Theory and Techniques, 61(6), June 2013.

Workflow State Space Concatenations





Eigenmode based
Model Order Reduction

Compact models
of individual segments

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

Topology Information

SSC

Compact model
of full structure

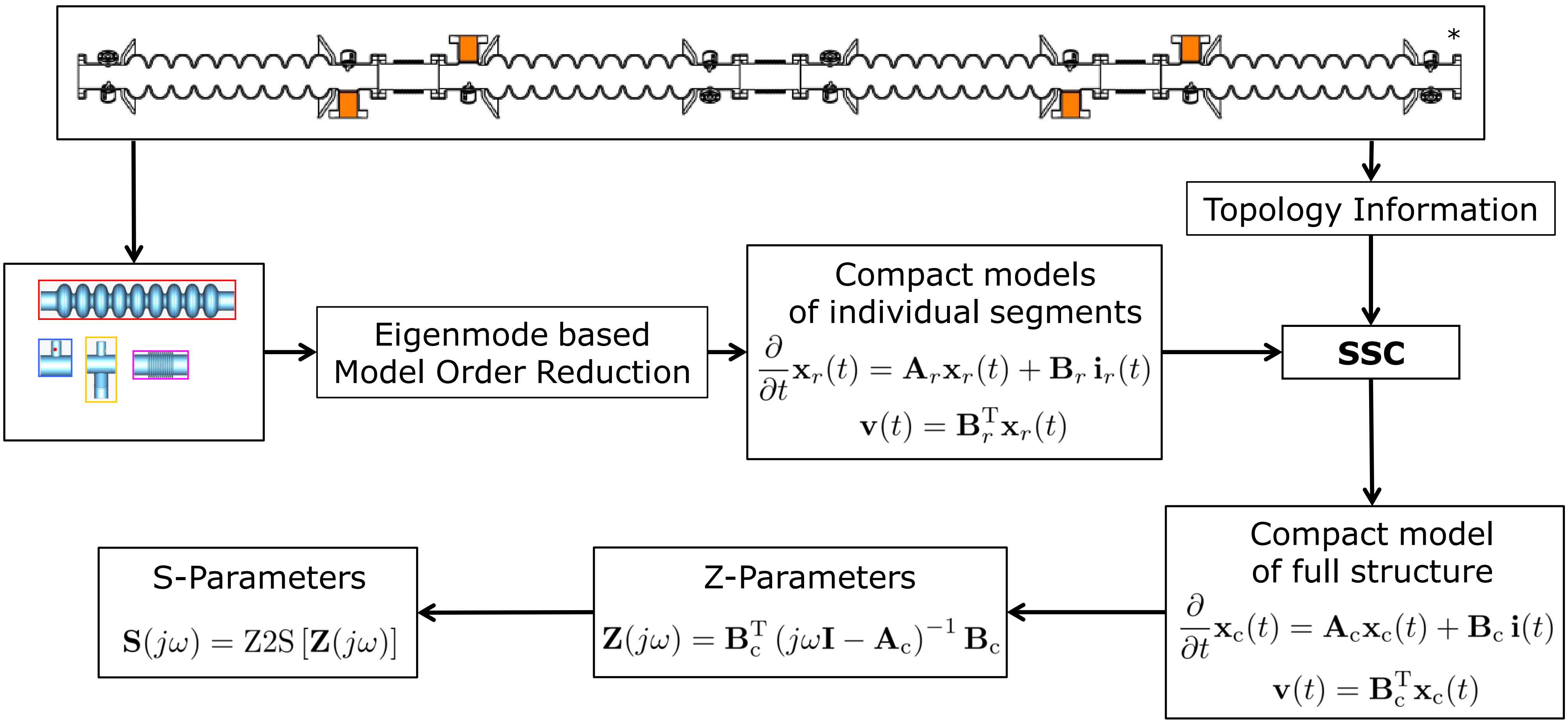
$$\frac{\partial}{\partial t}\mathbf{x}_{\mathrm{c}}(t) = \mathbf{A}_{\mathrm{c}}\mathbf{x}_{\mathrm{c}}(t) + \mathbf{B}_{\mathrm{c}}\,\mathbf{i}(t)$$
$$\mathbf{v}(t) = \mathbf{B}_{\mathrm{c}}^{\mathrm{T}}\mathbf{x}_{\mathrm{c}}(t)$$

Some advantages compared to CSC:

- Field distributions are directly available
- Approach is also highly suitable for time domain

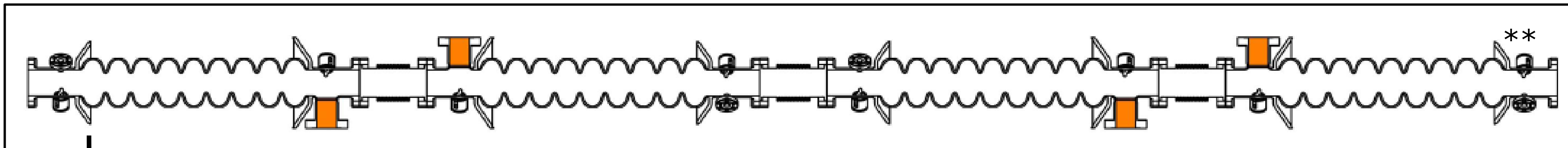
*Picture courtesy E. Vogel et al.: "Status of the 3rd harmonic systems for FLASH and XFEL in summer 2008", Proc. LINAC 2008.

Impedance or Scattering Parameters with SSC

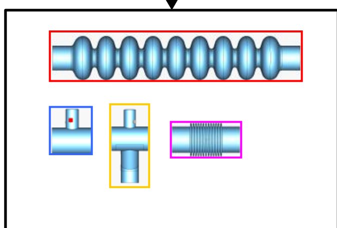


*Picture courtesy E. Vogel et al.: "Status of the 3rd harmonic systems for FLASH and XFEL in summer 2008", Proc. LINAC 2008.

External Quality Factor Computation with SSC



Topology Information



Eigenmode based Model Order Reduction

Compact models of individual segments

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

$$\mathbf{v}(t) = \mathbf{B}_r^{\mathrm{T}}\mathbf{x}_r(t)$$

SSC

Compact model of full structure

$$\frac{\partial}{\partial t}\mathbf{x}_{\mathrm{c}}(t) = \mathbf{A}_{\mathrm{c}}\mathbf{x}_{\mathrm{c}}(t) + \mathbf{B}_{\mathrm{c}}\,\mathbf{i}(t)$$

$$\mathbf{v}(t) = \mathbf{B}_{\mathrm{c}}^{\mathrm{T}}\mathbf{x}_{\mathrm{c}}(t)$$

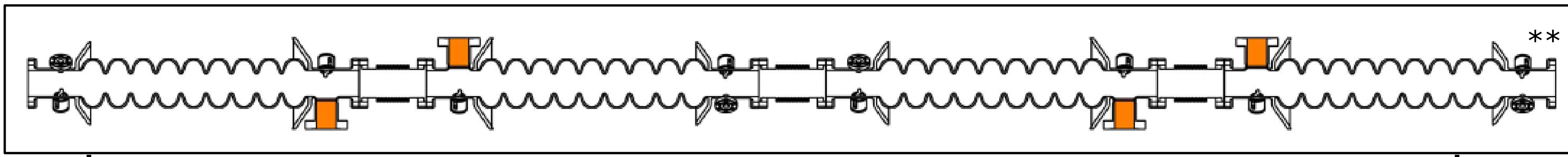
Perturbation Approach

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

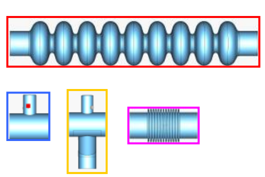
$$Q_{ext,\nu} = \frac{\omega_\nu W_{stored,\nu}}{P_{ports,\nu}} = \frac{\mathrm{Im}(\lambda_\nu)}{2\mathrm{Re}(\lambda_\nu)}$$

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

R/Q Factor Computation with SSC



Topology Information



Eigenmode based Model Order Reduction

Compact models of individual segments

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

$$\mathbf{v}(t) = \mathbf{B}_r^{\mathrm{T}}\mathbf{x}_r(t)$$

SSC

Compact model of full structure

$$\frac{\partial}{\partial t}\mathbf{x}_{\mathrm{c}}(t) = \mathbf{A}_{\mathrm{c}}\mathbf{x}_{\mathrm{c}}(t) + \mathbf{B}_{\mathrm{c}}\,\mathbf{i}(t)$$

$$\mathbf{v}(t) = \mathbf{B}_{\mathrm{c}}^{\mathrm{T}}\mathbf{x}_{\mathrm{c}}(t)$$

Constructing field distributions based on segment's eigenmodes and weighting factors

$$\mathrm{eig}(\mathbf{A}_c) = \{\mathbf{v}_1, \ldots\}$$

Eigenmodes of full structure:

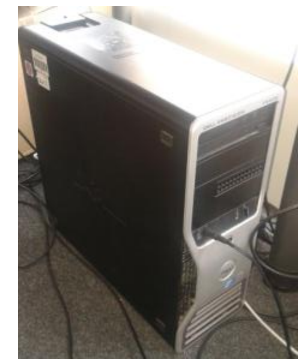
$$\tilde{\omega}_\nu, \tilde{\mathbf{E}}_\nu(\mathbf{r})$$

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

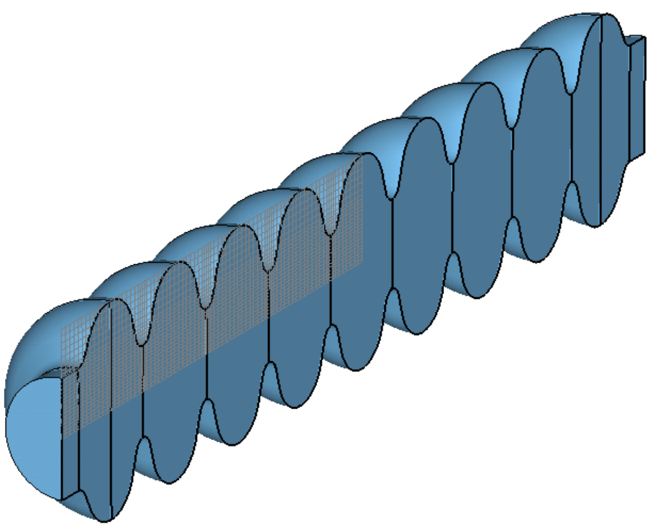
Analysis of Multi-Cavity TM01 and TE21 Modes in a Concatenated Arrangement of Third Harmonic Cavities with Bellows

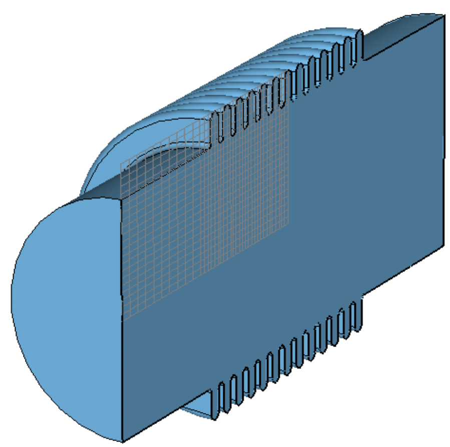
Models for 3rd Harmonic Cavity and Bellows

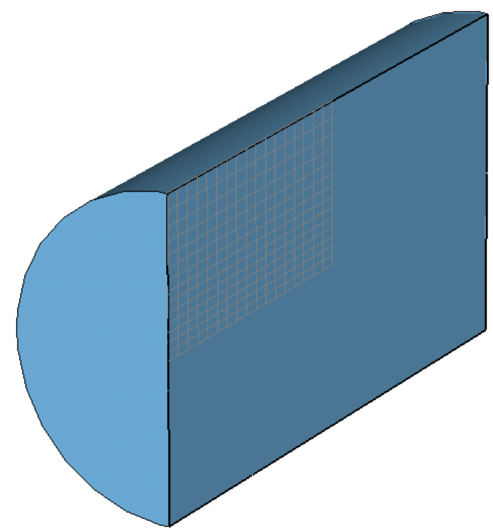
	Nine-Cell Cavity	Bellow	Beam Pipe
N_{s}	$(2\cdot)\,172{,}380$	$(2\cdot)\,61{,}893$	$(2\cdot)\,12{,}150$
N_{sr}	73	35	24
T_{rd}	2 min 49 sec	46 sec	10 sec



N_{s}: number of states of unreduced system
N_{sr}: number of states of reduced system
T_{rd}: computing time for reduction

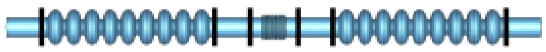






Computations performed on an Intel Core i5-2400 CPU @ 3.10 GHz machine equipped with 8 GB RAM

Validation of Scattering Parameters



$$\frac{\partial}{\partial t}\mathbf{x}_{\mathrm{c}}(t) = \mathbf{A}_{\mathrm{c}}\mathbf{x}_{\mathrm{c}}(t) + \mathbf{B}_{\mathrm{c}}\,\mathbf{i}(t)$$

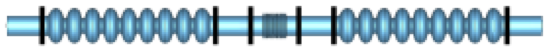
$$\mathbf{v}(t) = \mathbf{B}_{\mathrm{c}}^{\mathrm{T}}\mathbf{x}_{\mathrm{c}}(t)$$

(T = 4 min)

$$\mathbf{v}(j\omega) = \mathbf{B}_{\mathrm{c}}^{\mathrm{T}}\left(j\omega\mathbf{I} - \mathbf{A}_{\mathrm{c}}\right)^{-1}\mathbf{B}_{\mathrm{c}}\,\mathbf{i}(j\omega)$$

(T << 1 s)

Z2S



S-Parameter computation of Full structure using CST MWS® FR Solver with two symmetry planes (T = 22 min)

Comparison of S-Parameters

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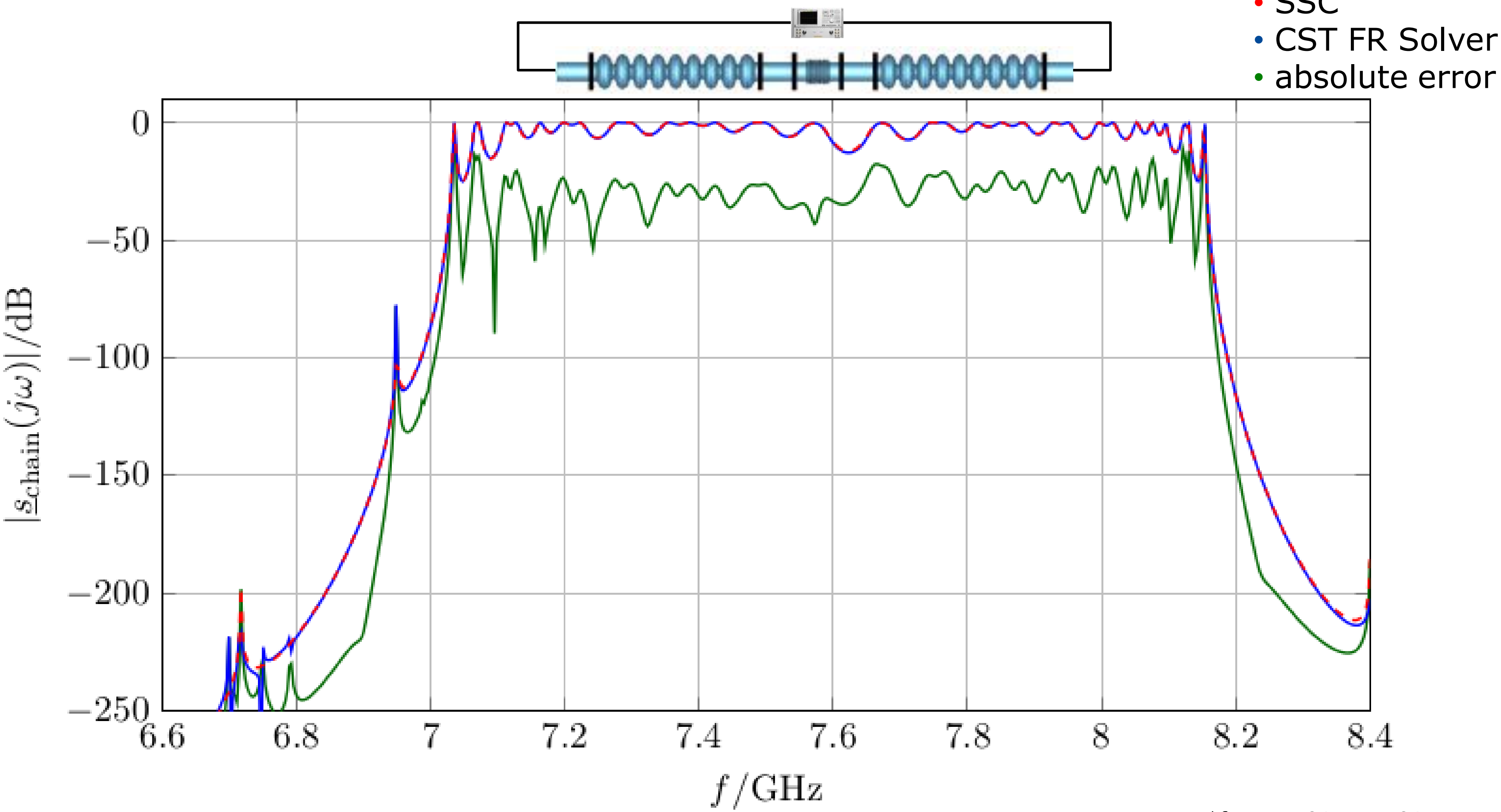
Scattering Parameter* Validation of SSC



*from TM01 to TM01 port modes

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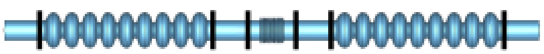
Validation of R/Q Parameter



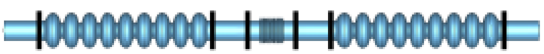
$$\frac{\partial}{\partial t}\mathbf{x}_\mathrm{c}(t) = \mathbf{A}_\mathrm{c}\mathbf{x}_\mathrm{c}(t) + \mathbf{B}_\mathrm{c}\,\mathbf{i}(t)$$

$$\mathbf{v}(t) = \mathbf{B}_\mathrm{c}^\mathrm{T}\mathbf{x}_\mathrm{c}(t)$$

(T = 4 min)

$$\mathrm{eig}(\mathbf{A}_c) = \{\mathbf{v}_1, \ldots\}$$

Constructing field distributions based on segment‵s eigenmodes and weighting factors (T << 1s)

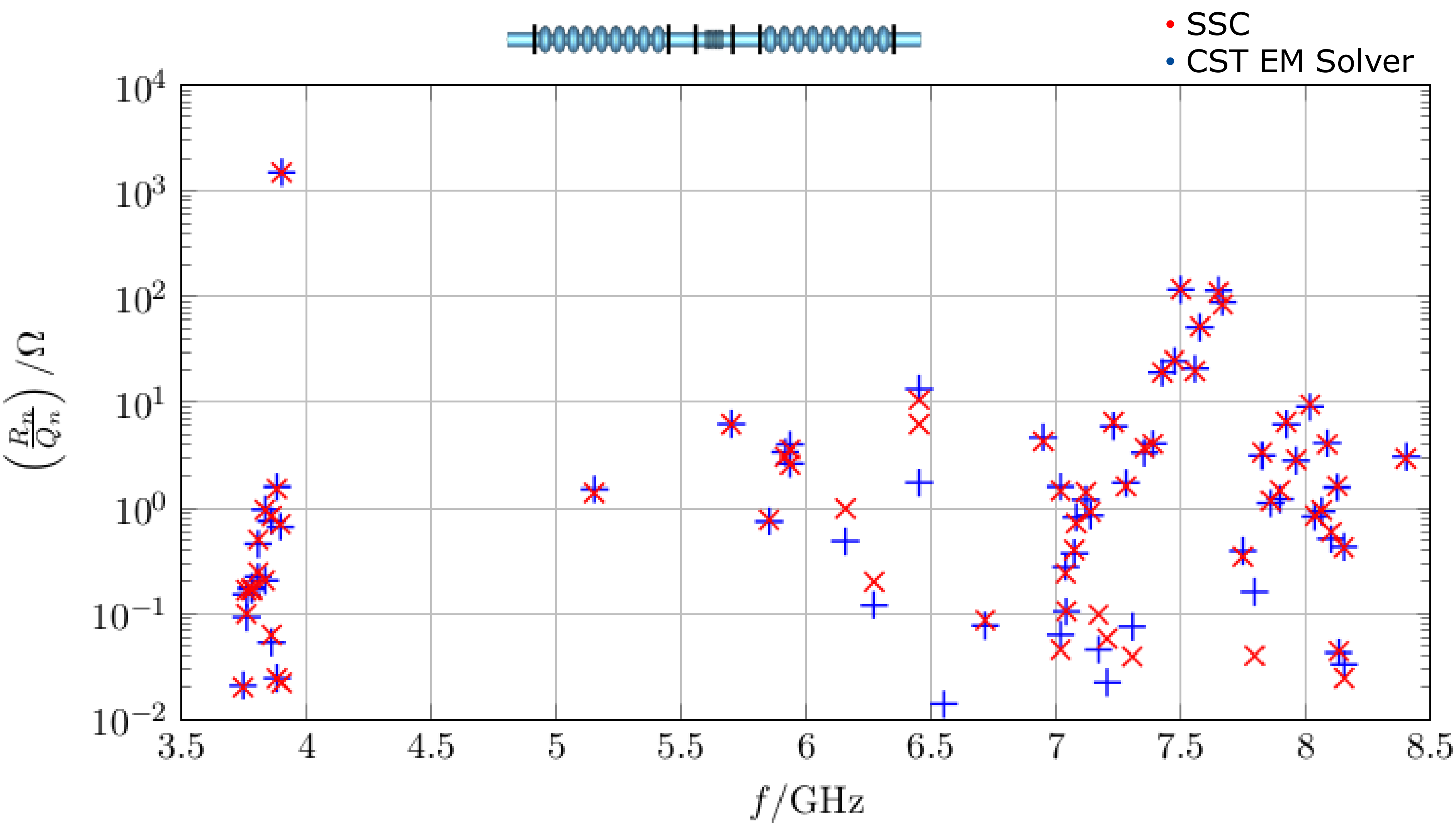


Computation of eigenmodes of full structure with CST MWS® EM JDM Solver employing all three symmetry planes (T = 11 h 16 min)

CST Template Based Post Processing

Comparison of R/Q

R/Q Parameter Validation of SSC



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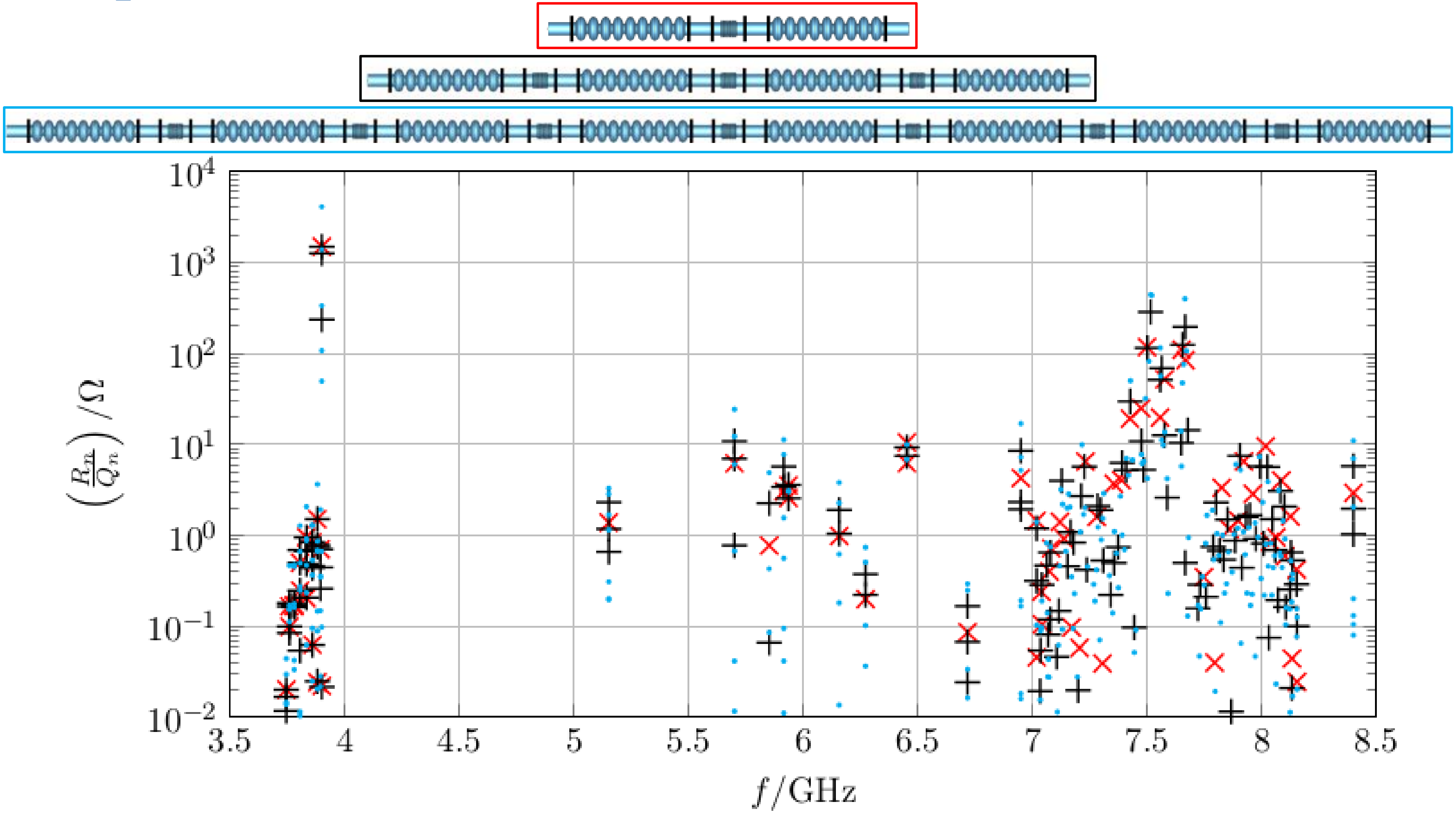
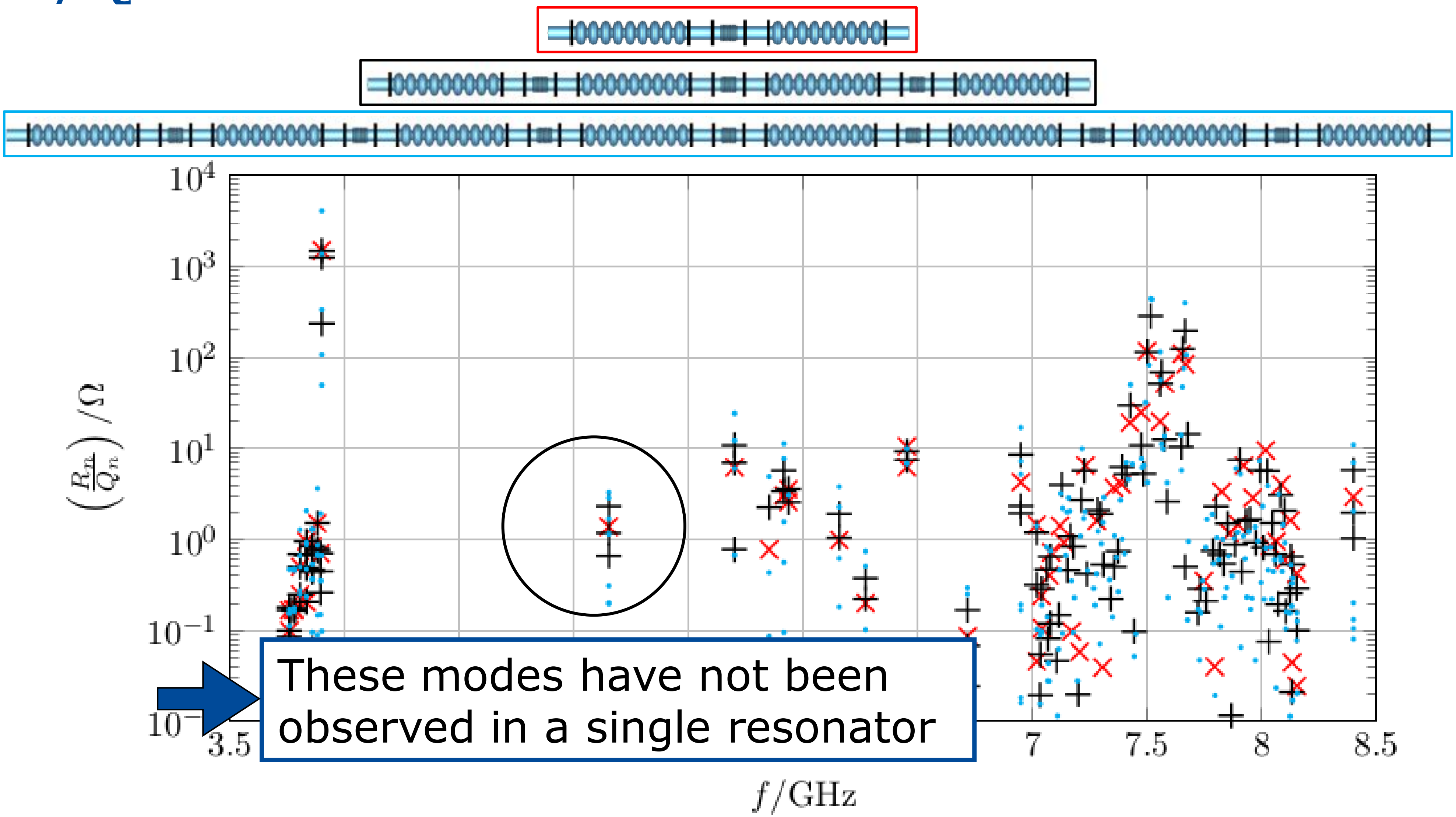
R/Q Parameters of Modes in Different Chains

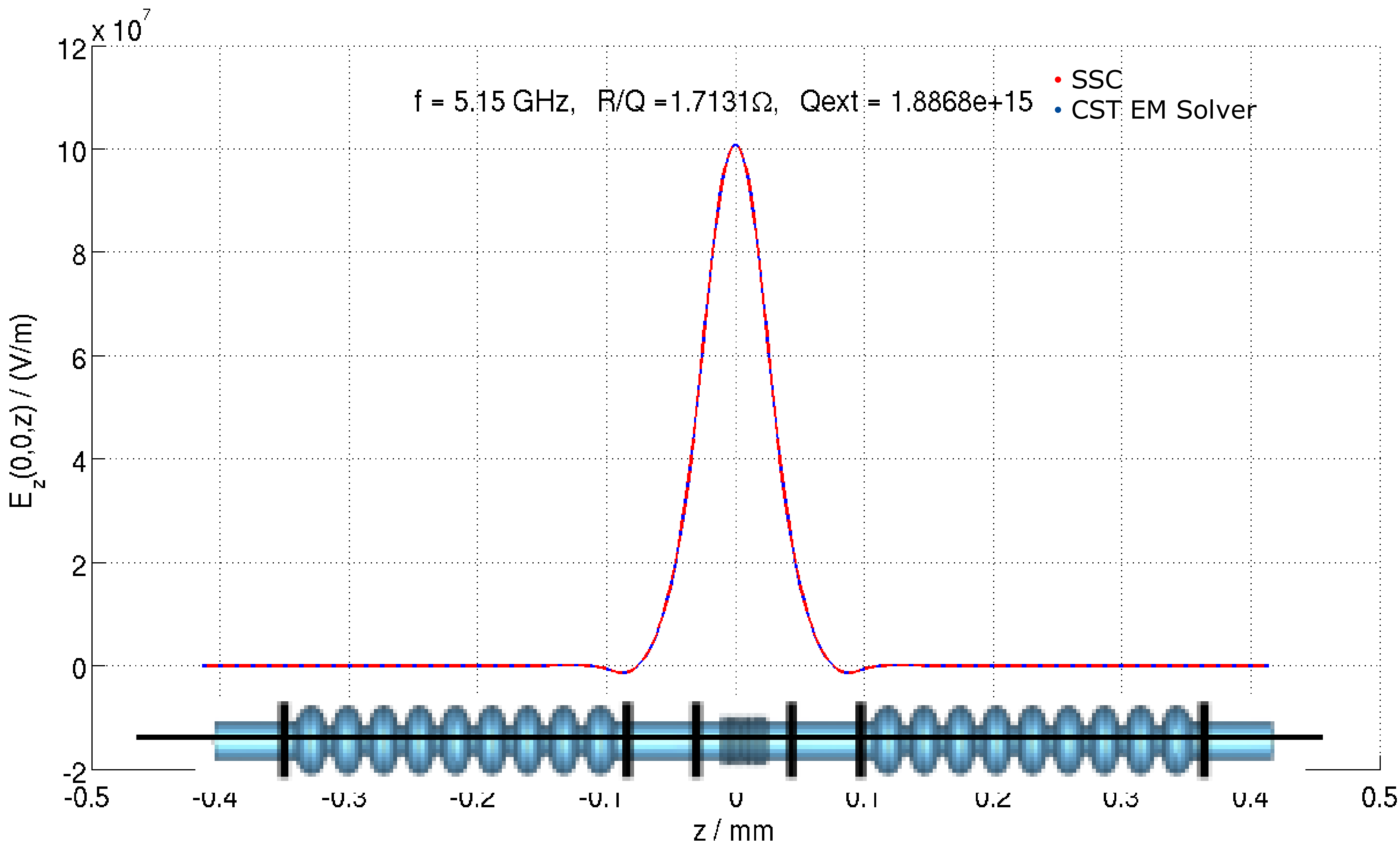


R/Q Parameters of Modes in Different Chains



These modes have not been observed in a single resonator

Electric Field Profile of Trapped Bellow Mode



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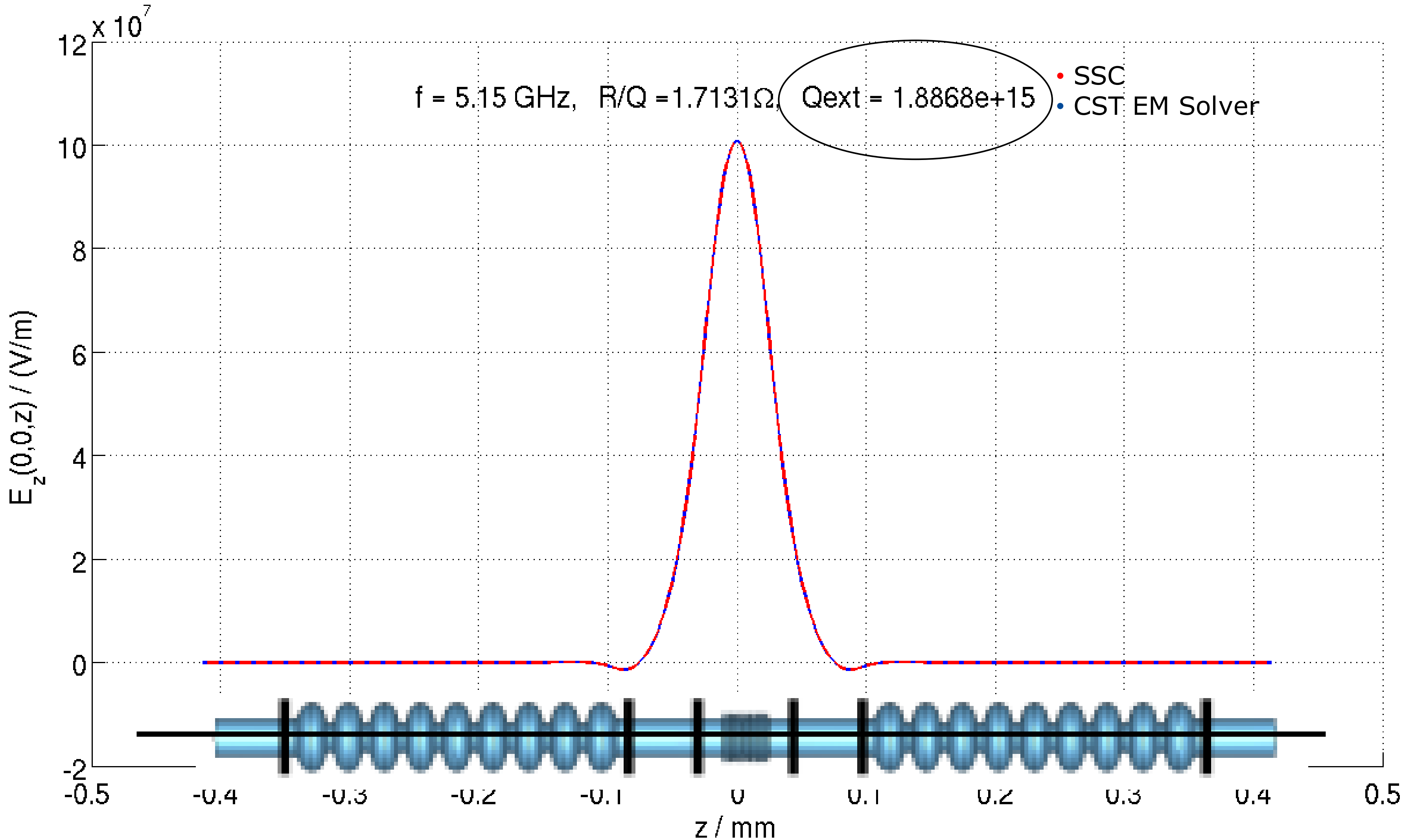
Electric Field Profile of Trapped Bellow Mode



Remark: Order of Magnitude of Quality Factor (1/2)*

- Quality factors in the order of 10^{15} are not observed at measurements
- Laboratory measurements deliver the total quality factor

$$\frac{1}{Q_{\text{tot}}} = \frac{1}{Q_0} + \frac{1}{Q_{\text{ext}}} \rightarrow Q_{\text{tot}} = \frac{Q_0 Q_{\text{ext}}}{Q_0 + Q_{\text{ext}}}$$

- Intrinsic quality factors Q_0 are in the order of 10^9 … 10^{11}, thus

$$Q_{\text{tot}} = \frac{Q_0 Q_{\text{ext}}}{Q_0 + Q_{\text{ext}}} = \frac{Q_0}{\frac{Q_0}{Q_{\text{ext}}} + 1} \approx Q_0 \quad \text{for} \quad \frac{Q_0}{Q_{\text{ext}}} \ll 1$$

- In other words, for this mode the intrinsic quality factor governs the observed quality factor, because the intrinsic quality factor is orders of magnitude smaller than the external quality factor.
- Model is broken for this mode because intrinsic losses are not covered.

*Q-factor issue has been brought up by Juliette Plouin during EuCARD 2 Meeting 2014 in Saclay

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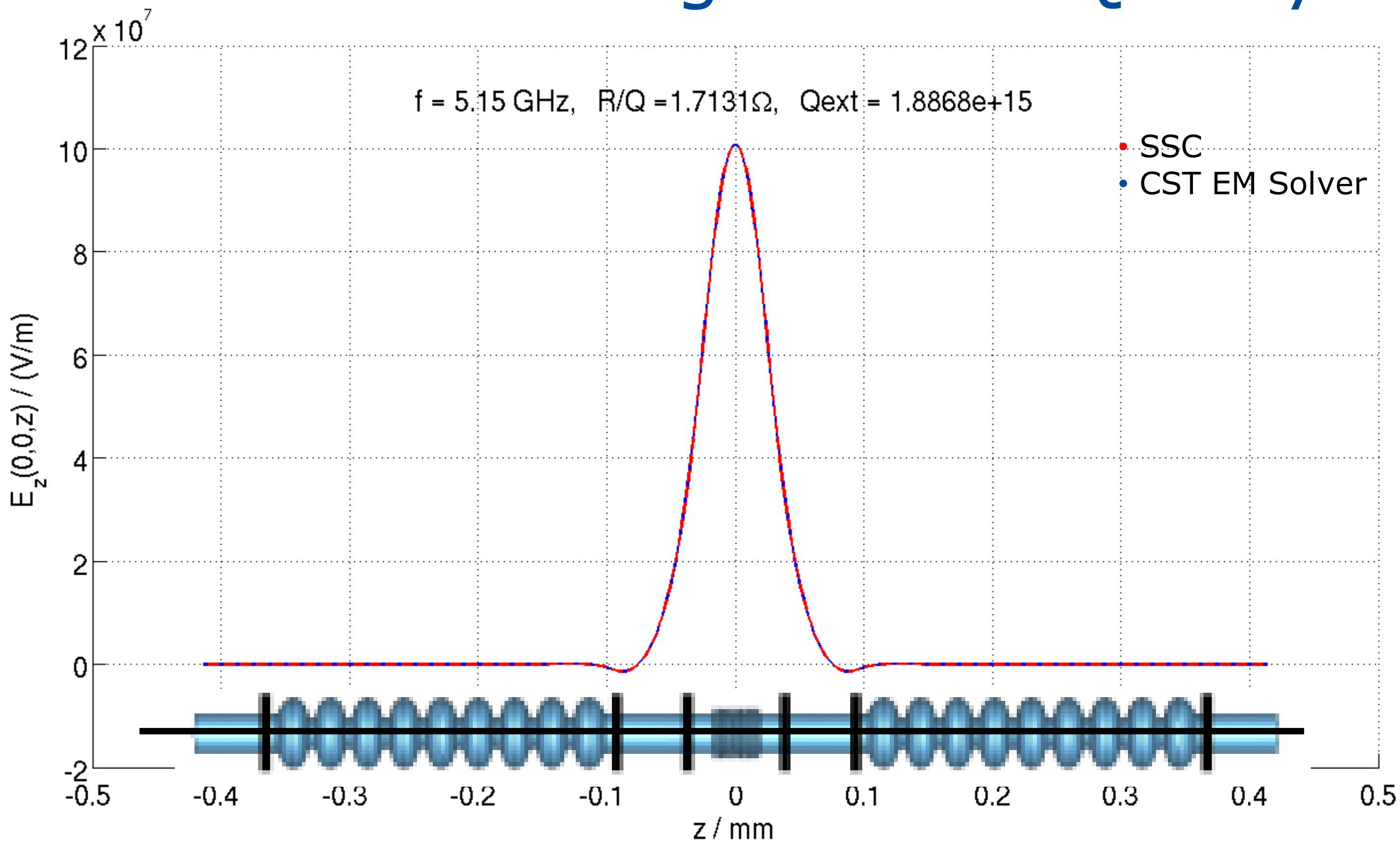
Remark: Order of Magnitude of Quality Factor (2/2)

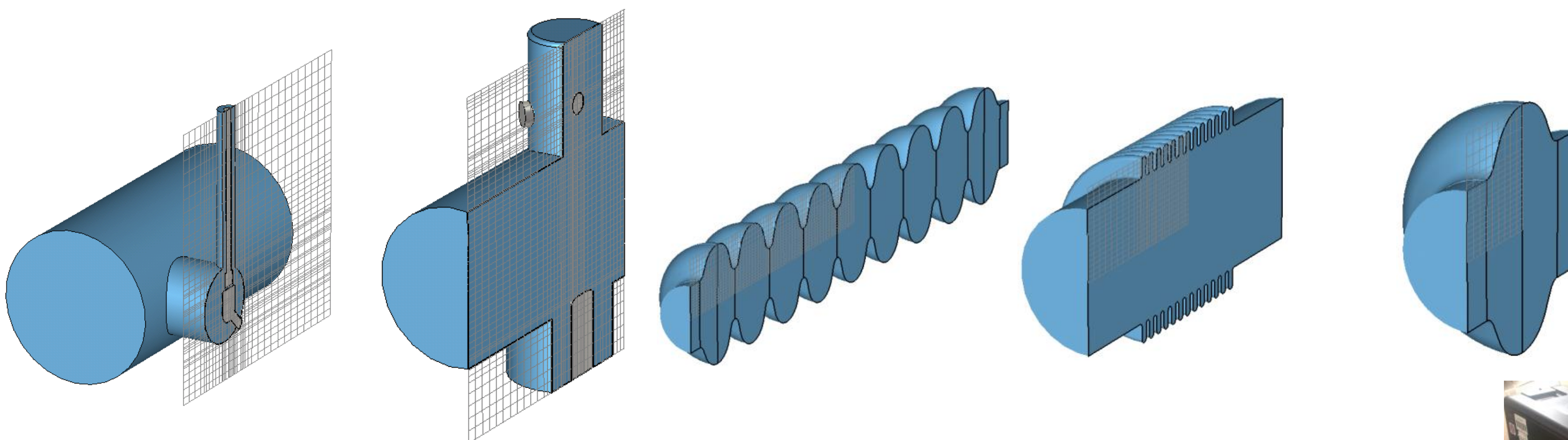


- Model is used beyond its validity range
- HOM und power couplers are located in the vicinity of the bellow
- They are expected to lower the Q_{ext} of the mode significantly

Analysis of Concatenated Arrangement of Third Harmonic Cavities with Bellows and Input and HOM Couplers

Models for 3rd Harmonic Cavity and Bellows

	HOMC	HOMPC	Nine-Cell Cav.	Bellow	Single-Cell Cav.
N_s	242,880	323,532	$(4\cdot)$ 71,478	$(4\cdot)$ 44,400	$(4\cdot)$ 2,916
N_sr	61	53	105	54	37
T_rd	9 min 1 sec	11 min 4 sec	1 min 3 sec	31 sec	6 sec



N_s: number of states of unreduced system
N_sr: number of states of reduced system
T_rd: computing time for reduction

Computations performed on an Intel Core i5-2400 CPU @ 3.10 GHz machine equipped with 8 GB RAM

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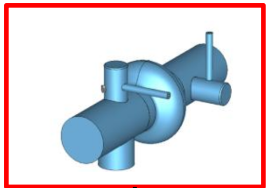
Validation of Scattering Parameters



$$\frac{\partial}{\partial t}\mathbf{x}_{\mathrm{c}}(t) = \mathbf{A}_{\mathrm{c}}\mathbf{x}_{\mathrm{c}}(t) + \mathbf{B}_{\mathrm{c}}\,\mathbf{i}(t)$$

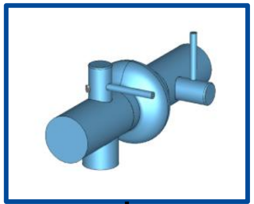
$$\mathbf{v}(t) = \mathbf{B}_{\mathrm{c}}^{\mathrm{T}}\mathbf{x}_{\mathrm{c}}(t)$$

(T = 22 min)

$$\mathbf{v}(j\omega) = \mathbf{B}_{\mathrm{c}}^{\mathrm{T}}\left(j\omega\mathbf{I} - \mathbf{A}_{\mathrm{c}}\right)^{-1}\mathbf{B}_{\mathrm{c}}\,\mathbf{i}(j\omega)$$

(T << 1 s)

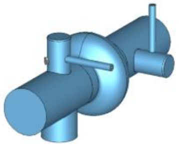
Z2S



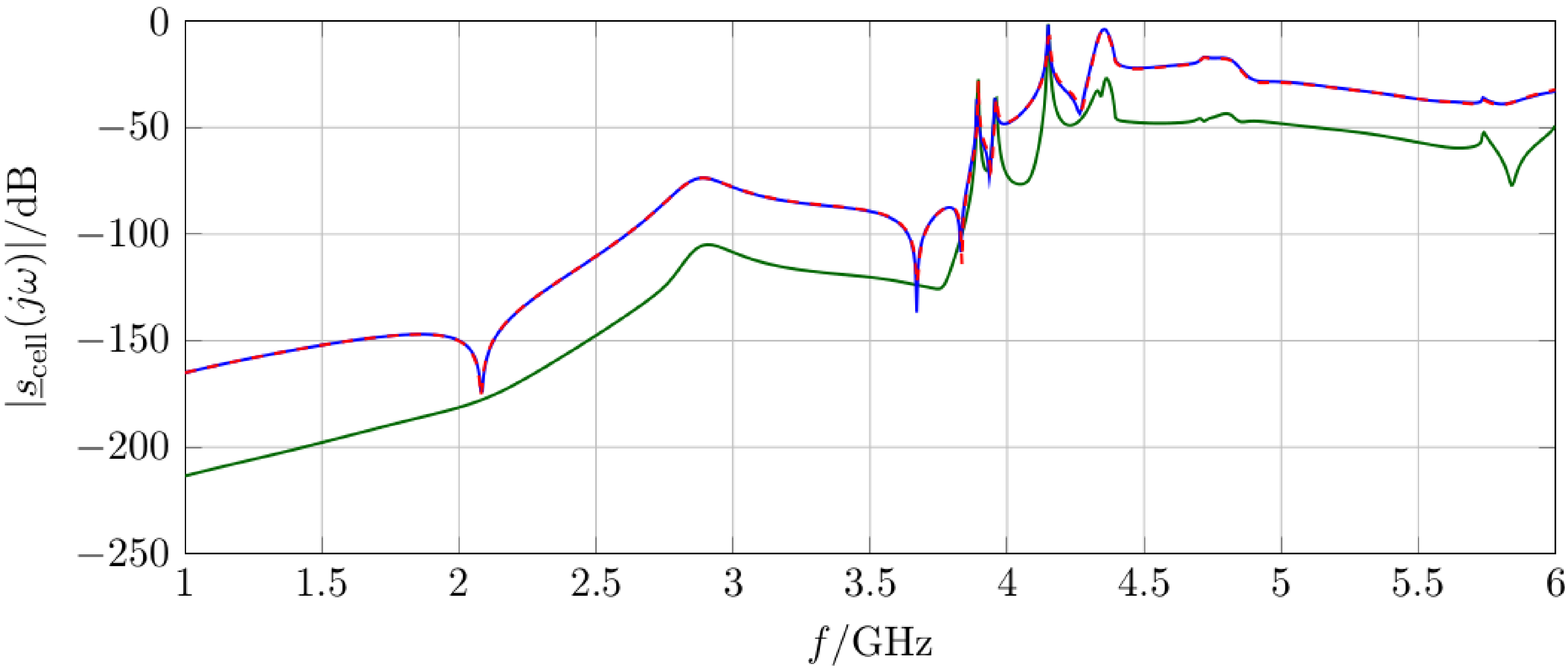
S-Parameter computation of Full structure using CST MWS® FR Solver (T = 20 min)

Comparison of S-Parameters

Scattering Parameter* Validation of SSC

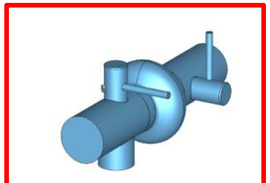


- SSC
- CST FR Solver
- absolute error



*from HOM coupler to HOM coupler

Validation of External Q Factor



$$\frac{\partial}{\partial t}\mathbf{x}_{\mathrm{c}}(t) = \mathbf{A}_{\mathrm{c}}\mathbf{x}_{\mathrm{c}}(t) + \mathbf{B}_{\mathrm{c}}\,\mathbf{i}(t)$$

$$\mathbf{v}(t) = \mathbf{B}_{\mathrm{c}}^{\mathrm{T}}\mathbf{x}_{\mathrm{c}}(t)$$

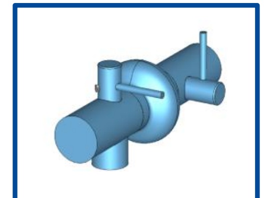
(T = 22 min)

Perturbation Approach

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

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

(T < 1 s)



Computation of eigenmodes of full structure with CST MWS® EM JDM Solver (T = 16 h 27 min)

CST Template Based Post Processing

Comparison of External Q's

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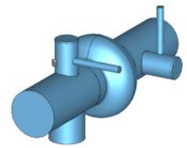
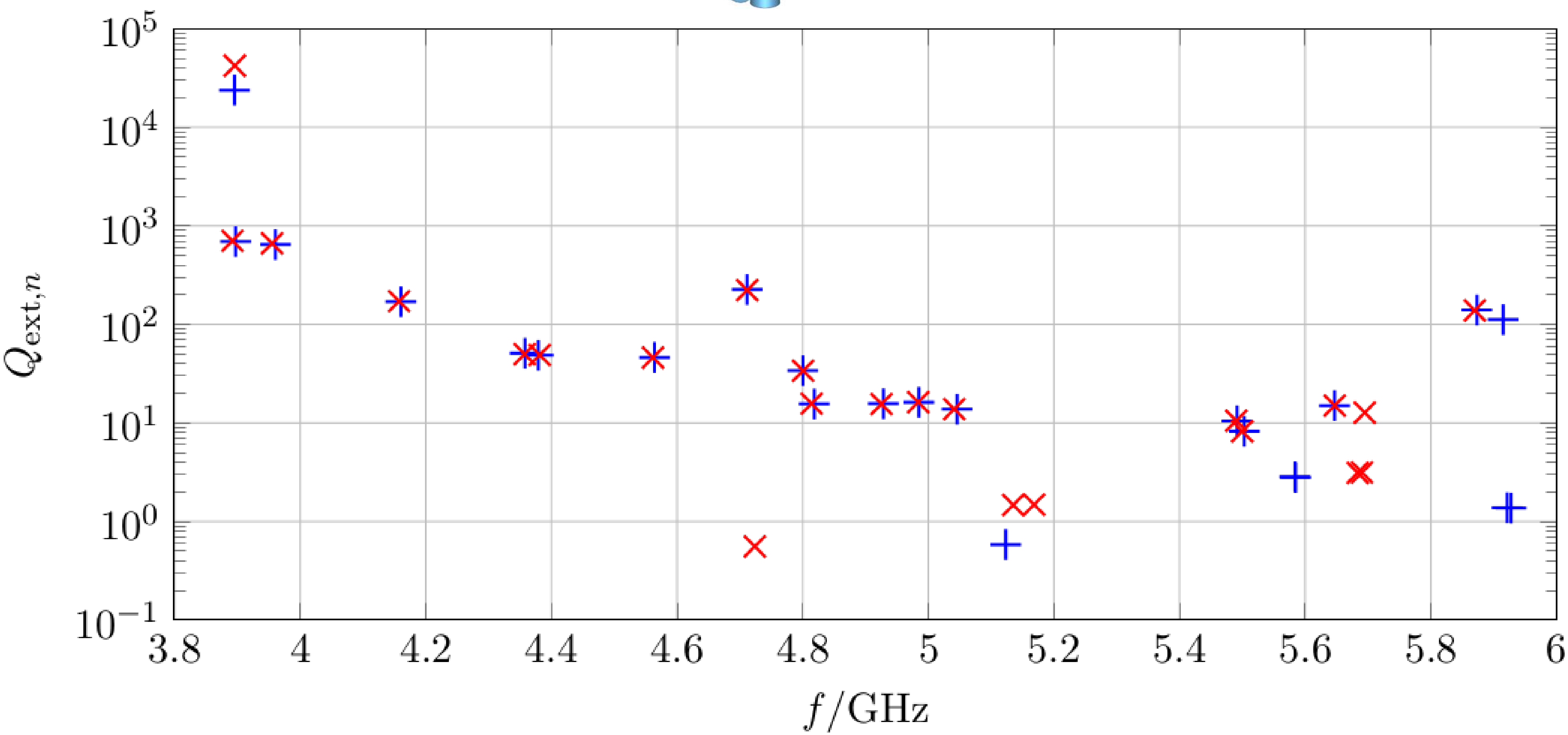
External Q Factor Validation of SSC



- SSC
- CST EM Solver



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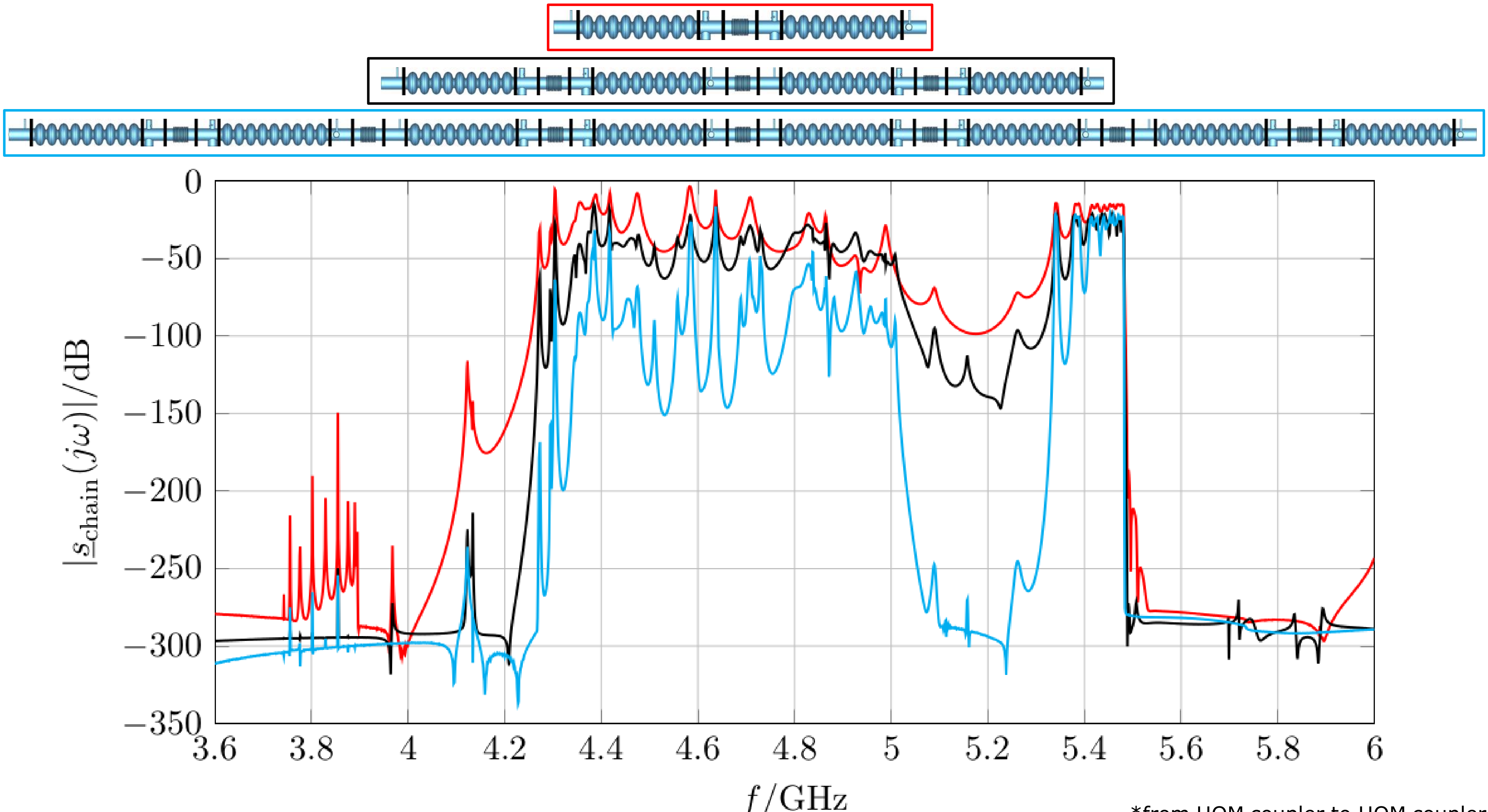
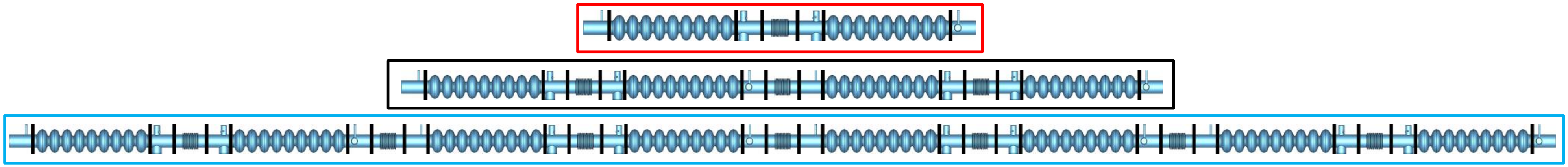
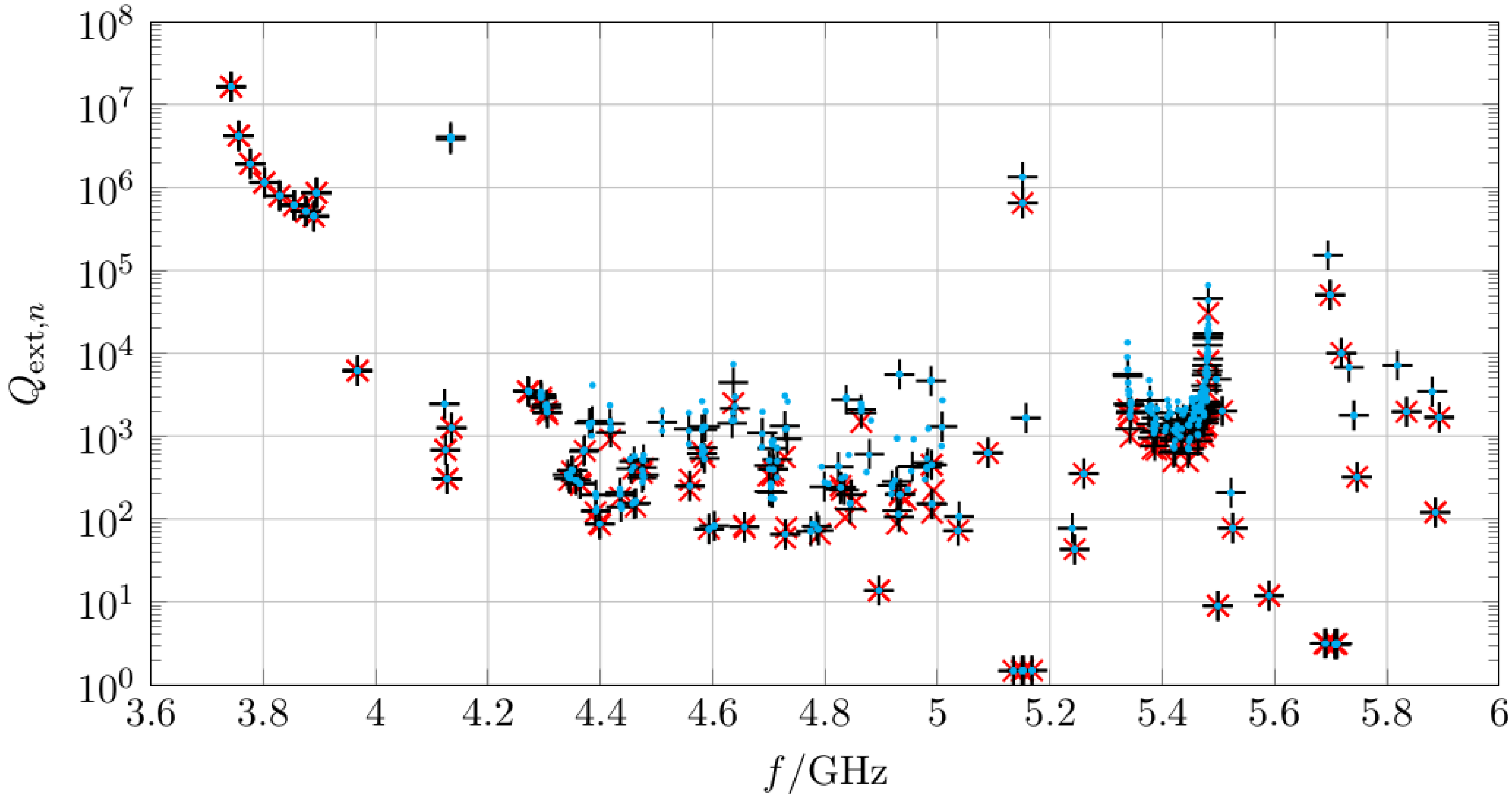
Scattering Transmission via entire Chains*



*from HOM coupler to HOM coupler

External Quality Factors in Chains





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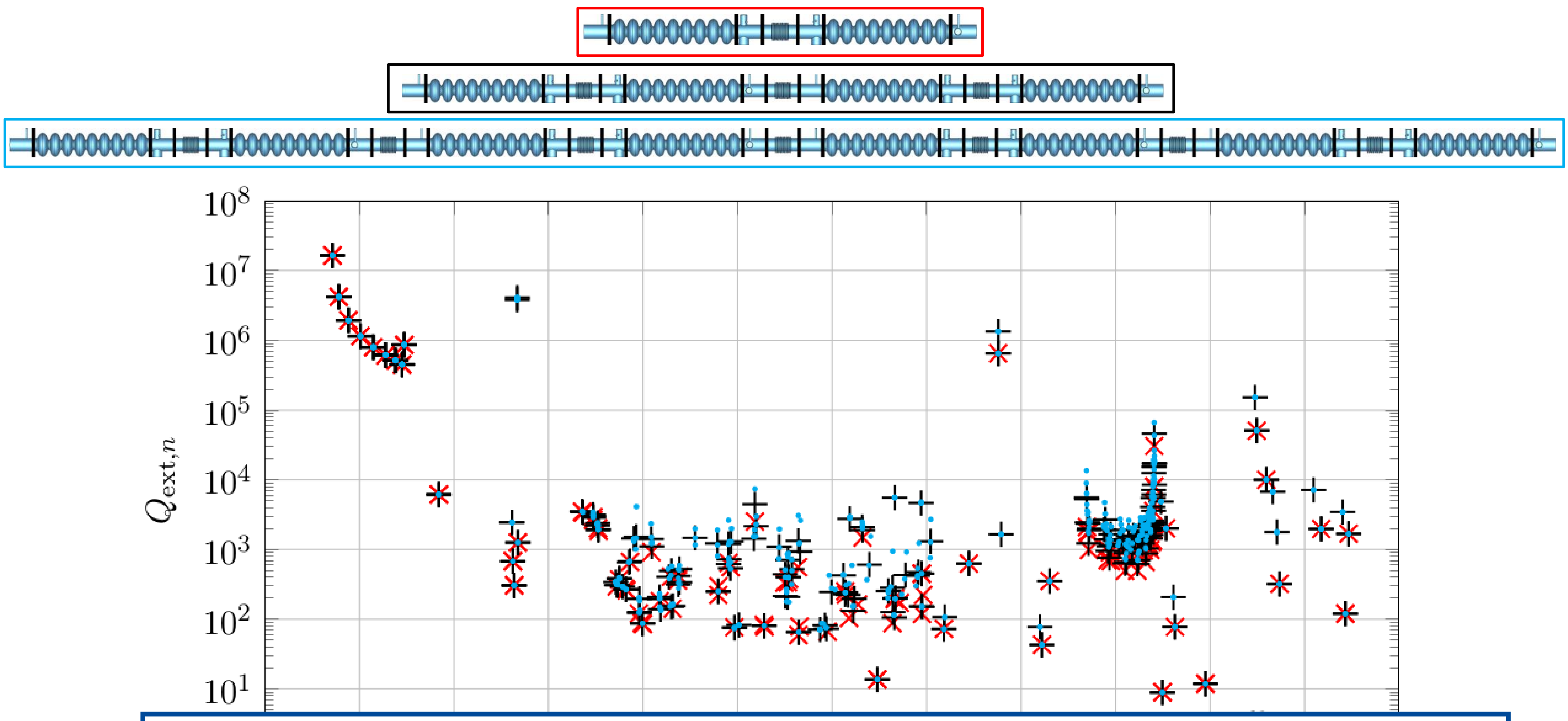
External Quality Factors in Chains



Q_{ext} of localized modes is almost constant but Q_{ext} of multi-cavity modes depends on number of cavities

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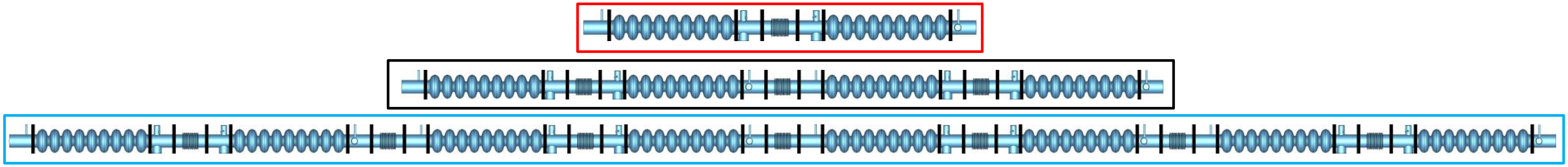
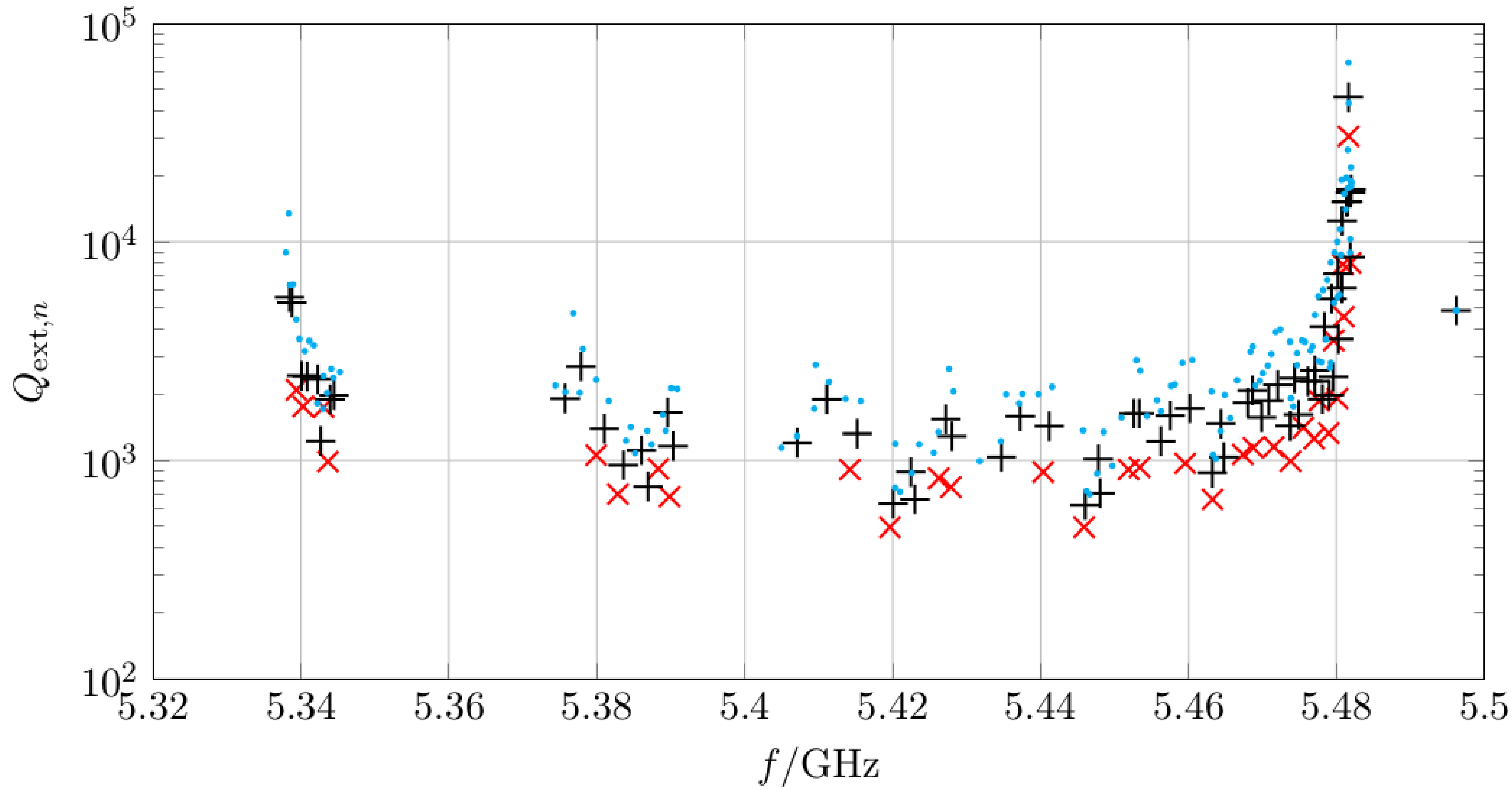
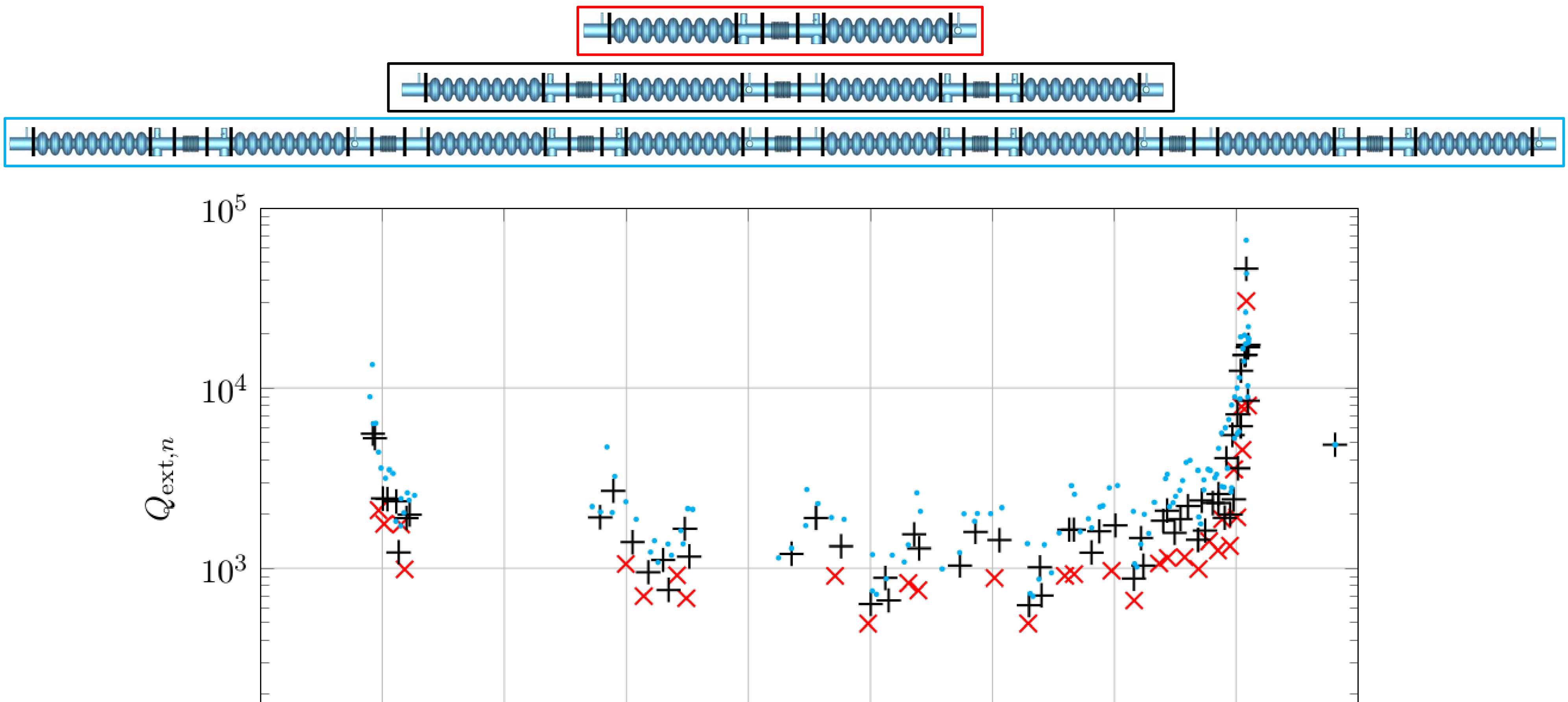
External Quality Factors in Chains





External Quality Factors in Chains

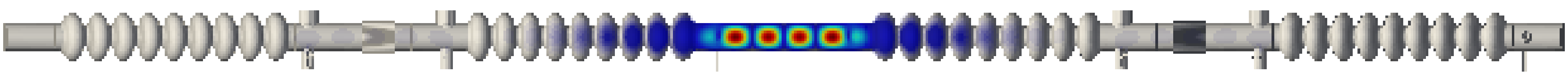


- The longer the chain, the more the bands are populated
- Tendency: longer chain, larger external Q factors

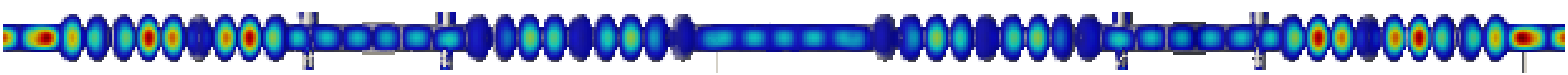
Latest Results: Field Plots* with ParaView

f = 3.9016 GHz

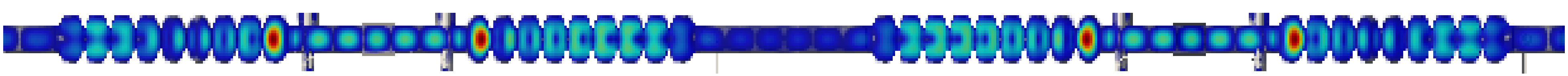
f = 3.9721 GHz



f = 5.2794 GHz



f = 5.4073 GHz



f = 5.4873 GHz

*absolute value of electric field

Conclusions and Outlook

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Summary

- The State Space Concatenation approach is used for real life structures, i.e. chains with HOM and input couplers
- Validation shows that SSC delivers reasonable results
- The field distributions of multi-cavity modes are more complex than modes in single cavities (see ParaView plots)
- Bands of long cavity chains are denser populated with modes and resonances in between the bands of single cavities occur
- The investigated structures show the tendency that the external Q and the R/Q are larger for longer chains

Future Plans

- Creation of modal compendium for eigenmodes in chains of four and eight cavities (FLASH and X-FEL chains)
- Direct comparison of the SSC scheme with other approaches such as ACE3P
- Using a tetrahedral mesh to discretize the segments of the cavity chain
- Publication of PhD thesis in terms of a monographie?

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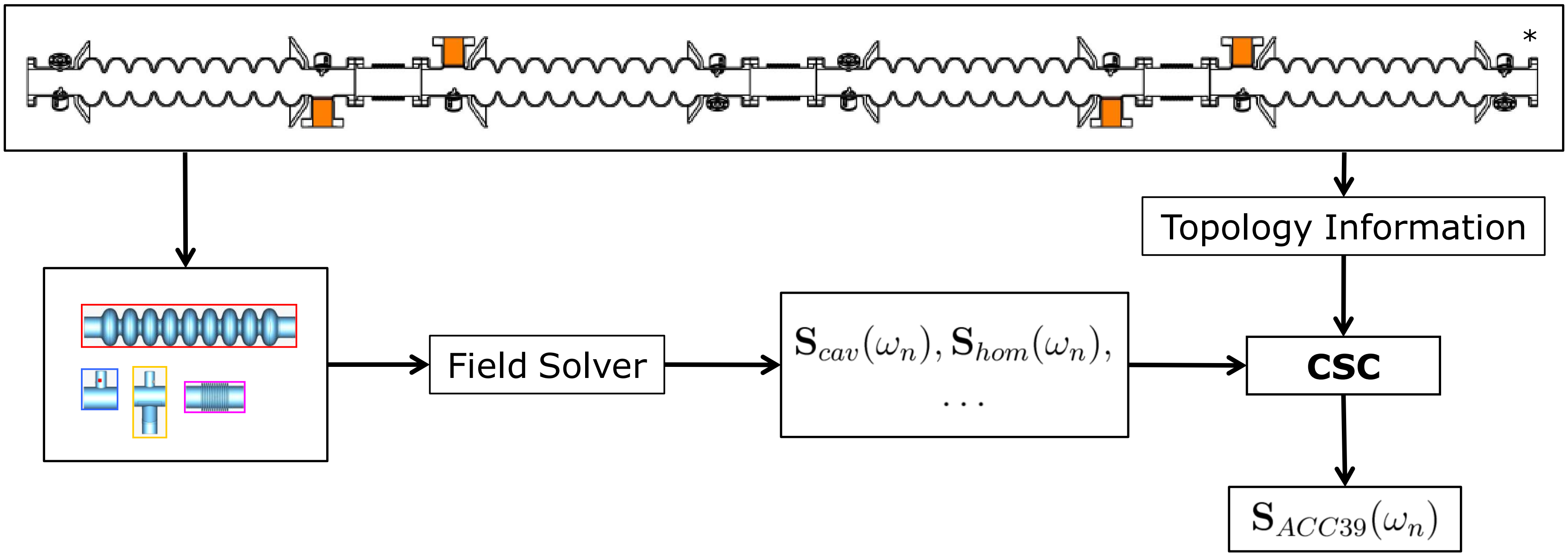
Further Slides

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

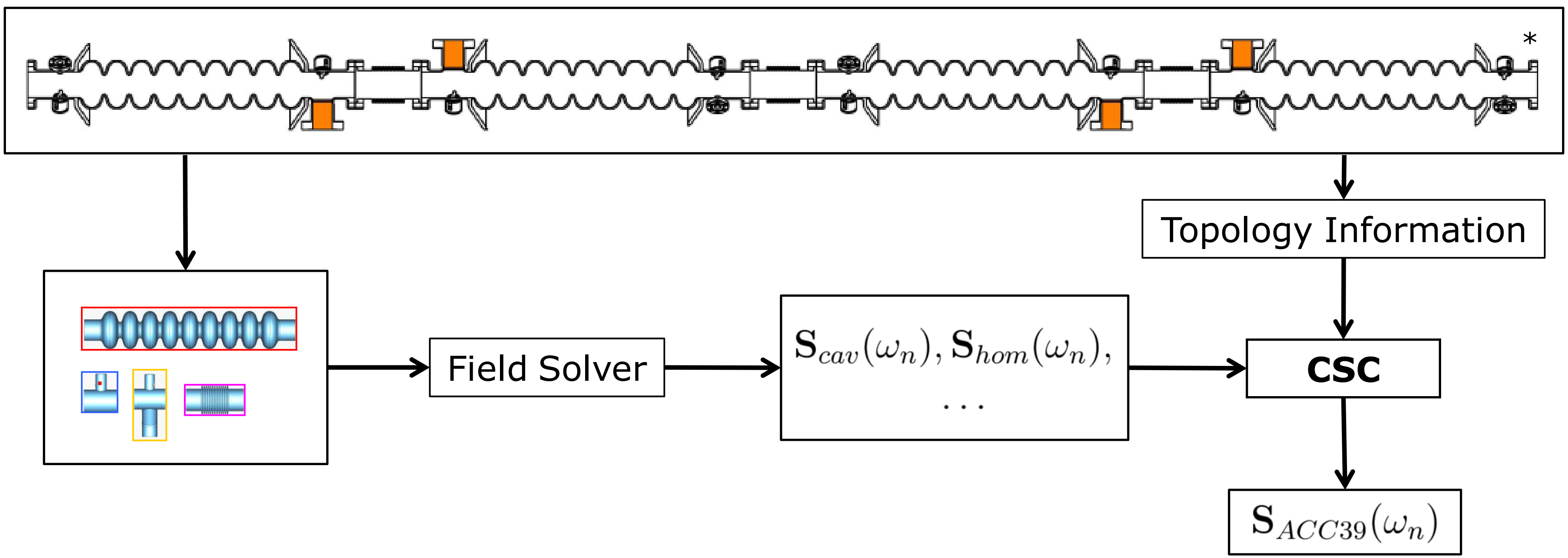
*H.-W. Glock, K. Rothemund, U. van Rienen: "CSC - A System for Coupled S-Parameter Calculations", TESLA-Report 2001-25
H.-W. Glock, K. Rothemund, U. van Rienen: "CSC - A Procedure for Coupled S-Parameter Calculations ", IEEE TransMag, Vol. 38, 2002

CSC Workflow



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

CSC Workflow

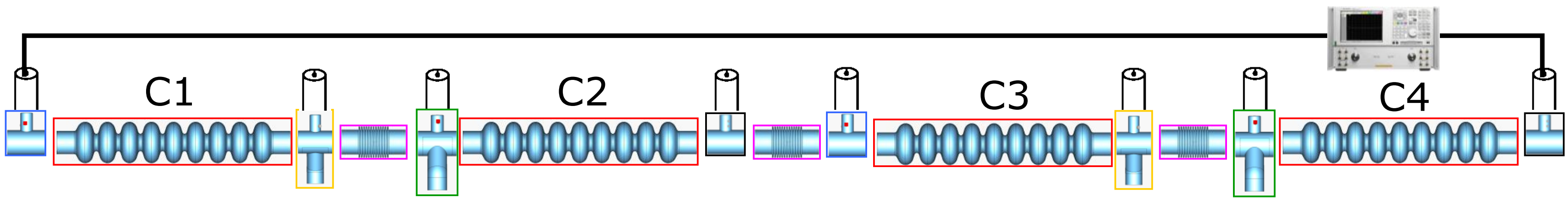


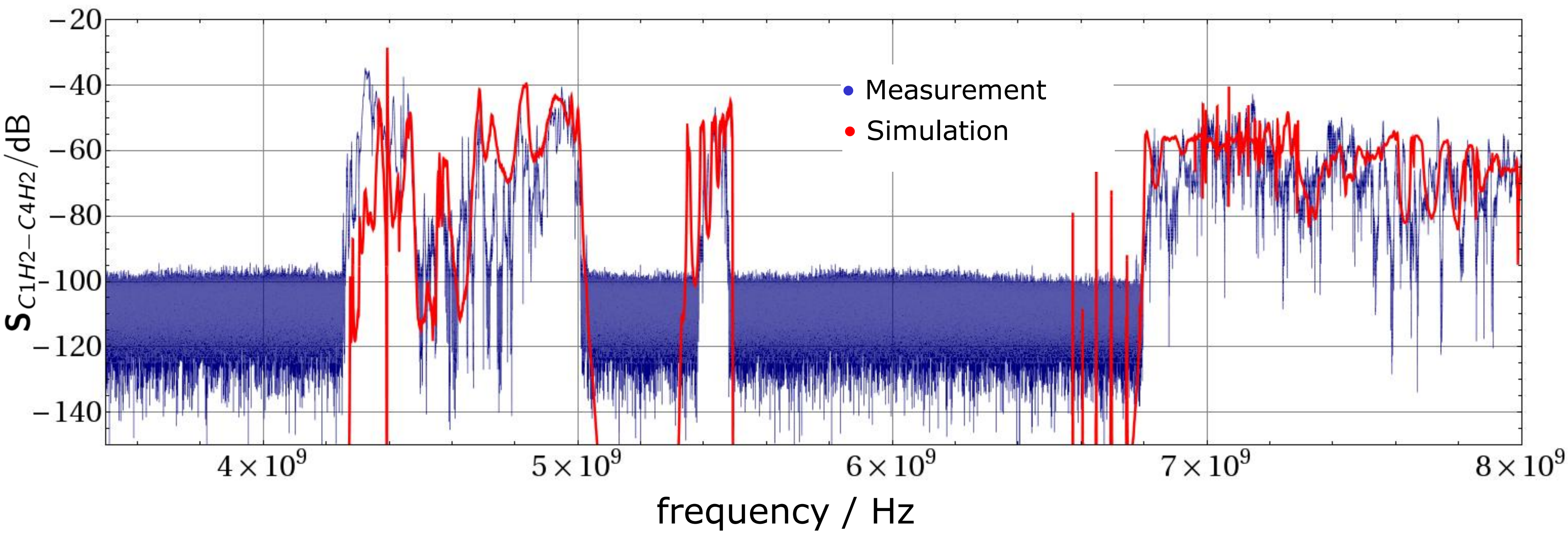
Some advantages of CSC:

- properties of equal segments need to be computed only once
- symmetry of segments can be employed to reduce computation costs
- highly 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.

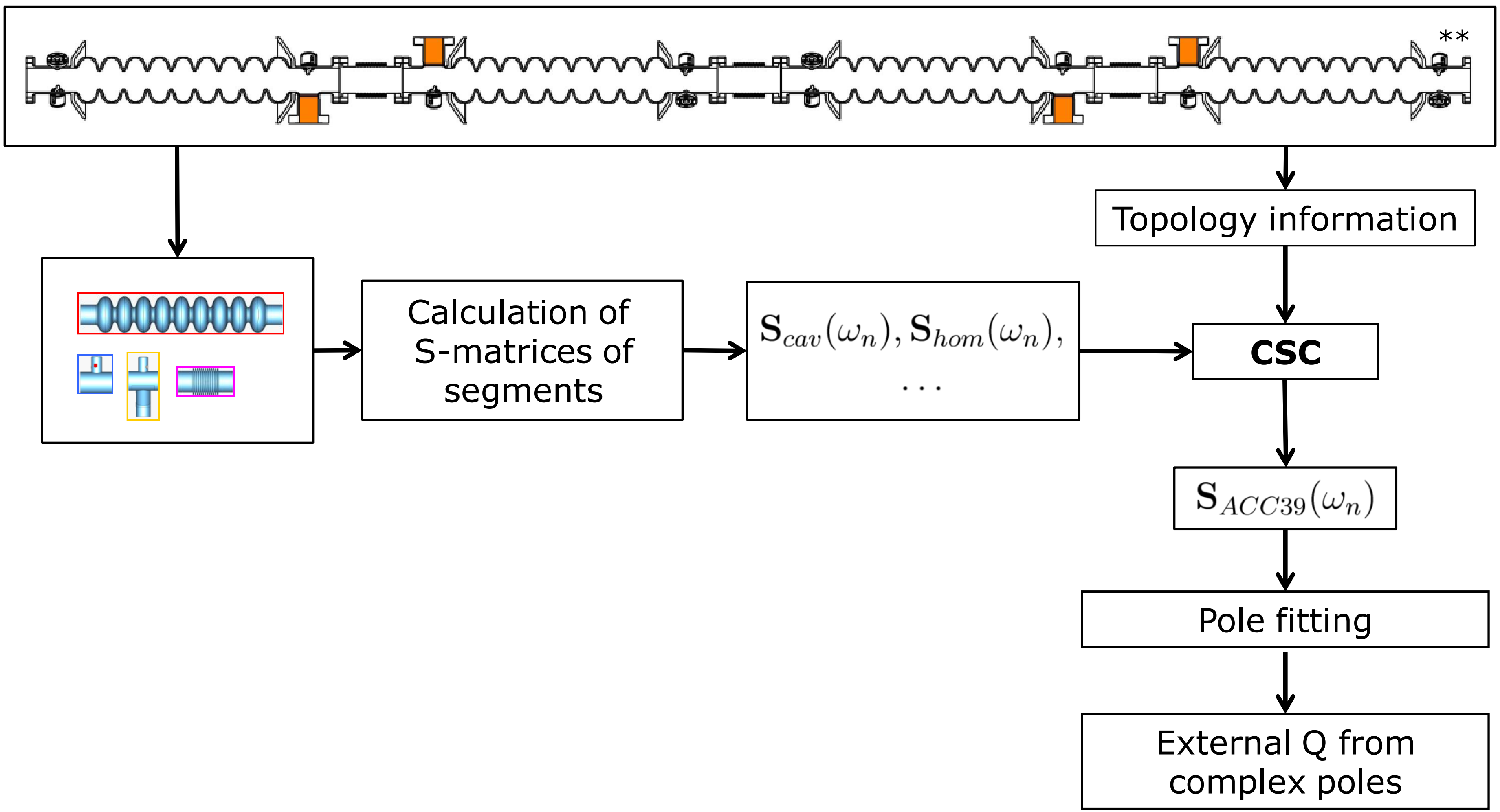
Transmission via ACC39 String





T. Flisgen, H.-W. Glock, P. Zhang, I. R. R. Shinton, N. Baboi, R. M. Jones, and U. van Rienen: "Scattering parameters of the 3.9 GHz accelerating module in a free-electron laser linac: A rigorous comparison between simulations and measurements", Phys. Rev. ST Accel. Beams, 17:022003, February 2014

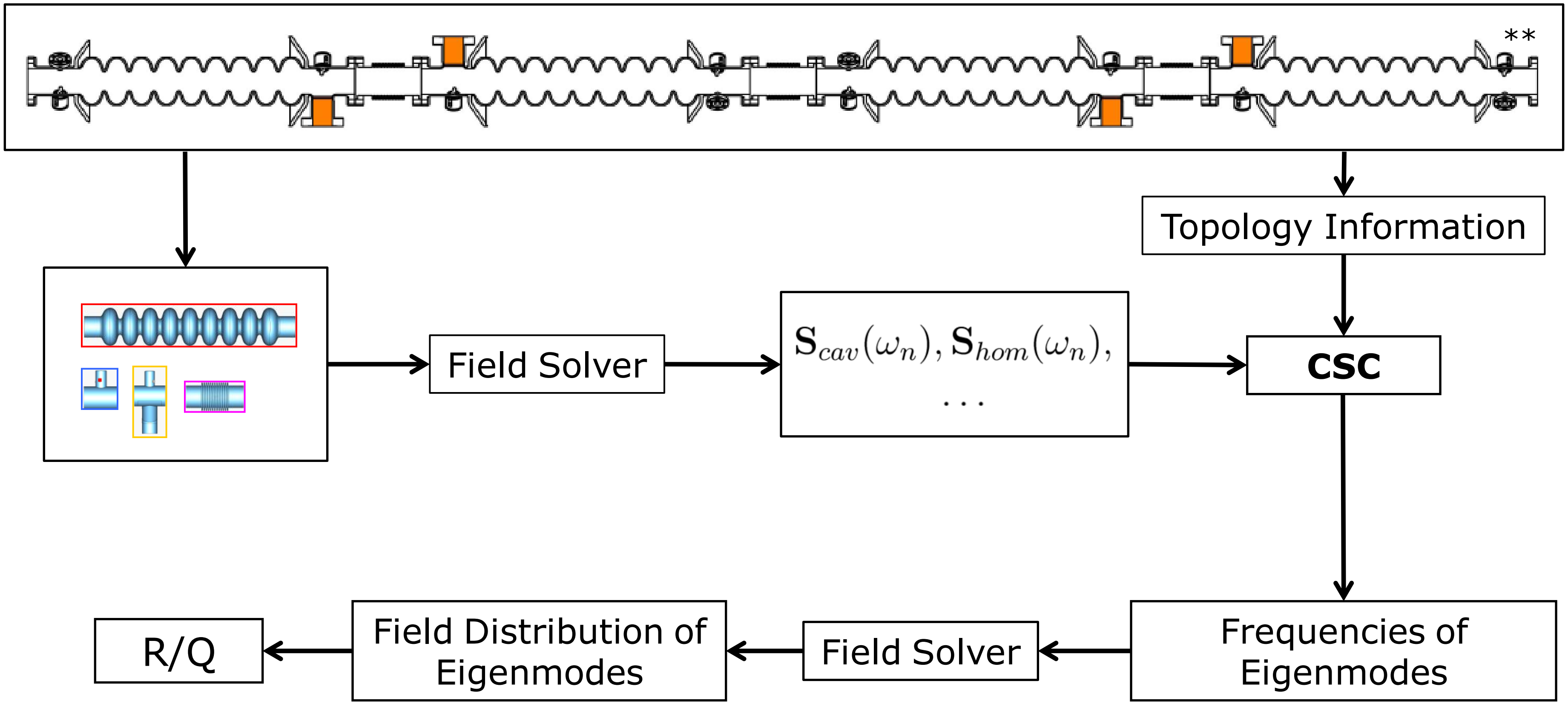
External Q Factor Computation with CSC*



*D. Hecht, K. Rothemund, H.-W. Glock, and U. van Rienen: "Computation of RF properties of long and complex structures", Proc. EPAC2002, pp. 1685

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

Eigenmode (and R/Q) Computation with CSC*



*K. Rothemund, H.-W. Glock, M. Borecky, and U. van Rienen: "Eigenmode Calculation in Long and Complex RF Structure Using the Coupled S-Parameter Calculation Technique", ´Proc. of the 6th Int. Computational Accelerator Physics Conference ICAP 2000, September 11-14, Darmstadt, Germany, (2000)

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

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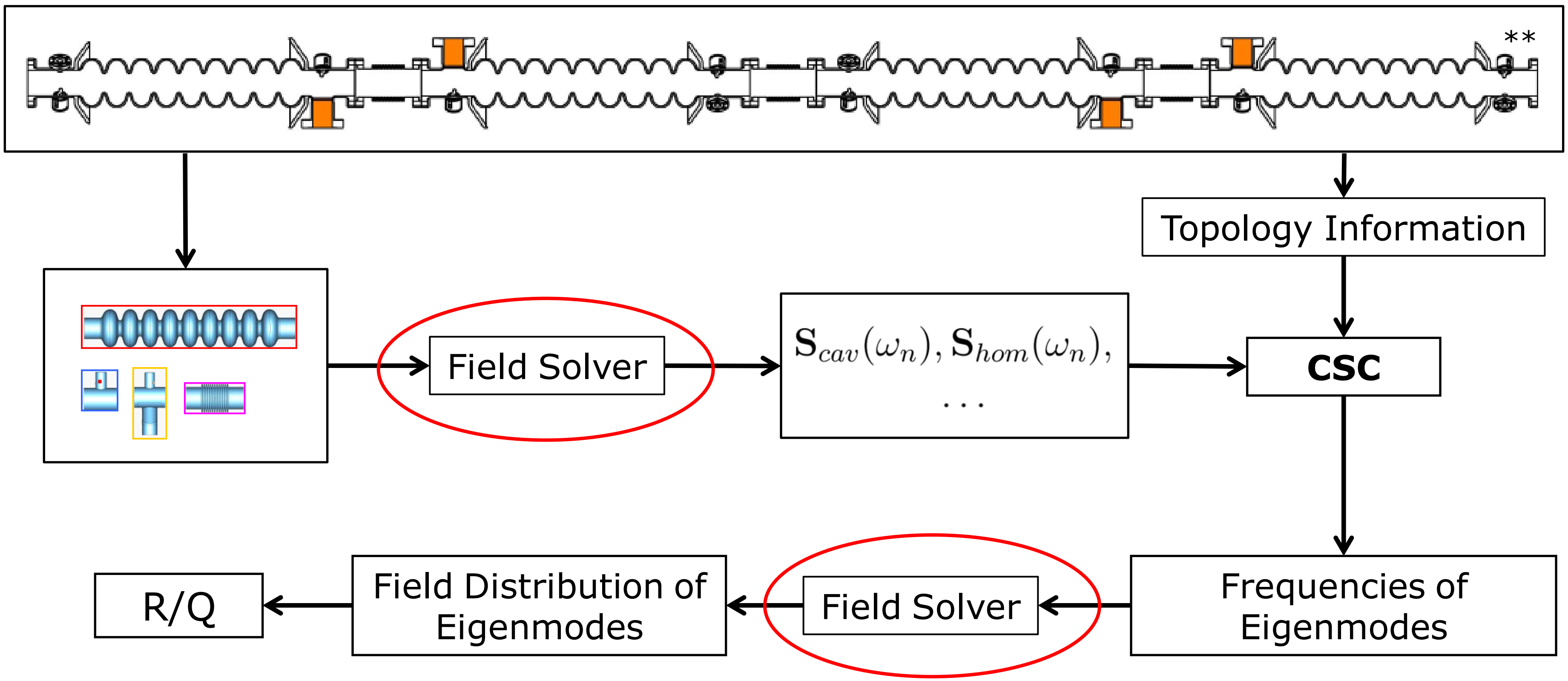
EuCARD²

Eigenmode (and R/Q) Computation with CSC*



Duplicative usage of field solver is inconvinient

*K. Rothemund, H.-W. Glock, M. Borecky, and U. van Rienen: "Eigenmode Calculation in Long and Complex RF Structure Using the Coupled S-Parameter Calculation Technique", ´Proc. of the 6th Int. Computational Accelerator Physics Conference ICAP 2000, September 11-14, Darmstadt, Germany, (2000)

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