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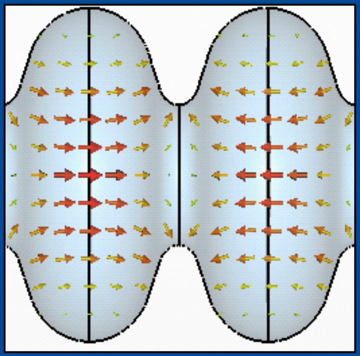

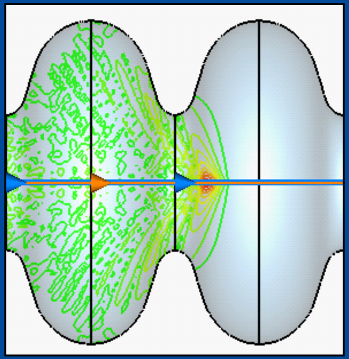

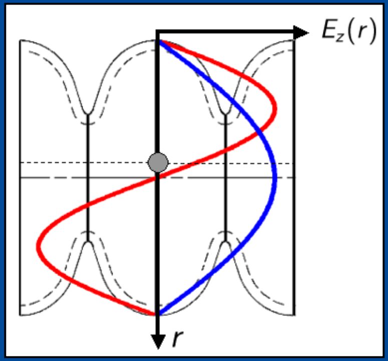

Progress on SSC Simulations in FLASH and XFEL Cavities

Thomas Flisgen, Johann Heller, and Ursula van Rienen

Eucard² 3rd Annual WP 12 Review Meeting 2016

STFC Daresbury Laboratory, Daresbury, UK, 4th – 5th of April 2016

Introduction and Motivation

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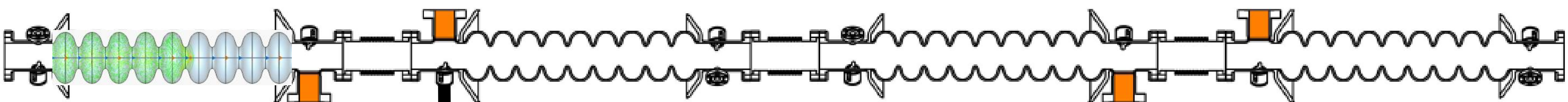
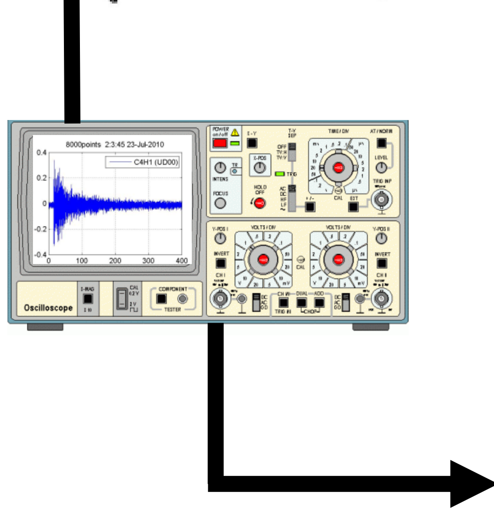
EuCARD²

Recap

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



String of 3rd harmonic cavities in FLASH**



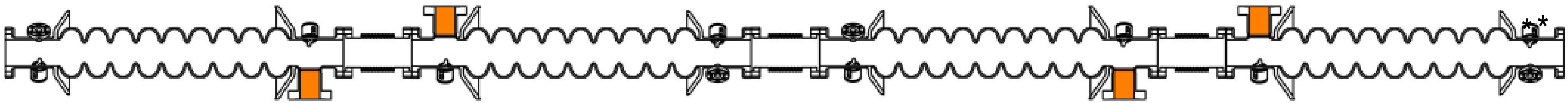
Information about:

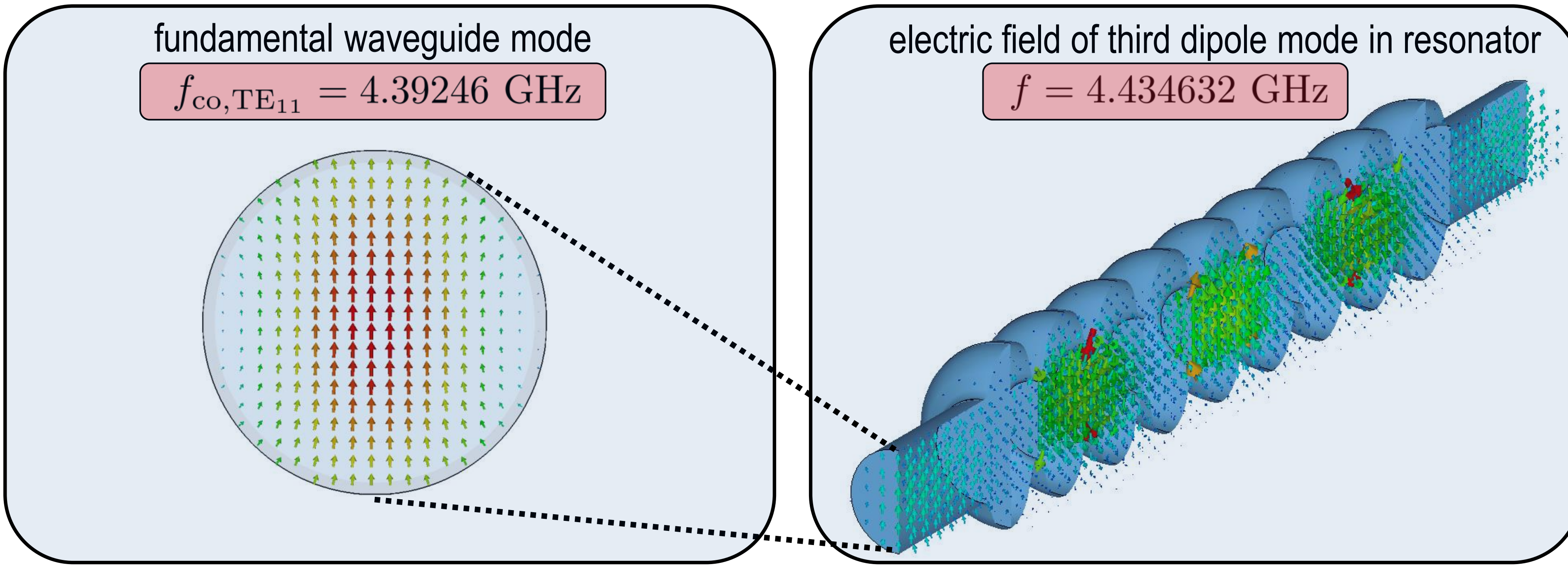
- Transversal momentum and offset of bunch
- Perturbances of cavity
- Total charge of bunch

*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

RF Properties of Chain of 3.9 GHz Resonators in FLASH and the European XFEL





- higher order modes are not required to be necessarily confined in the individual resonators
- consideration of entire cavity chain for a reasonable RF analysis is needed

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

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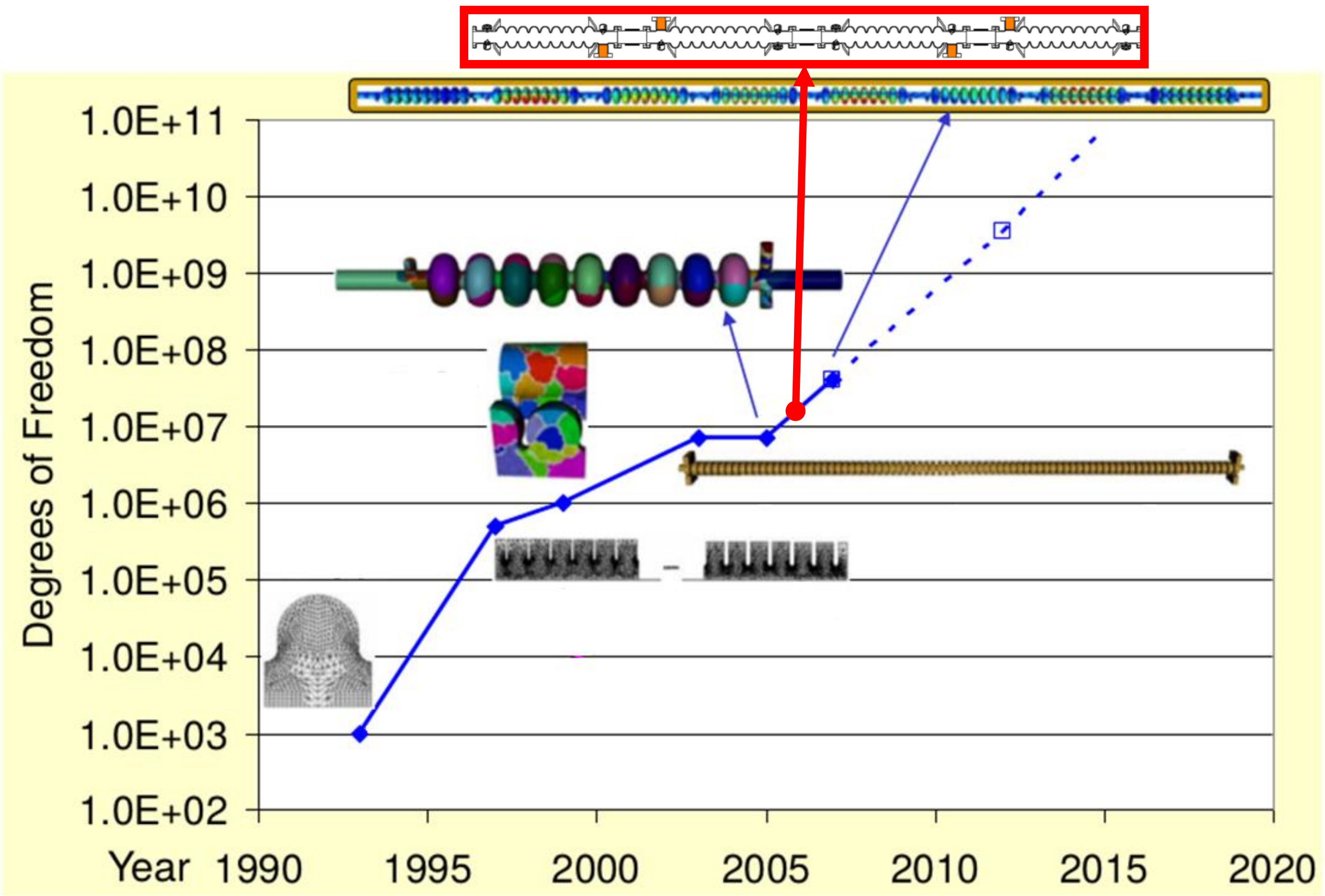
Recap

Problem Complexity of Direct Computations



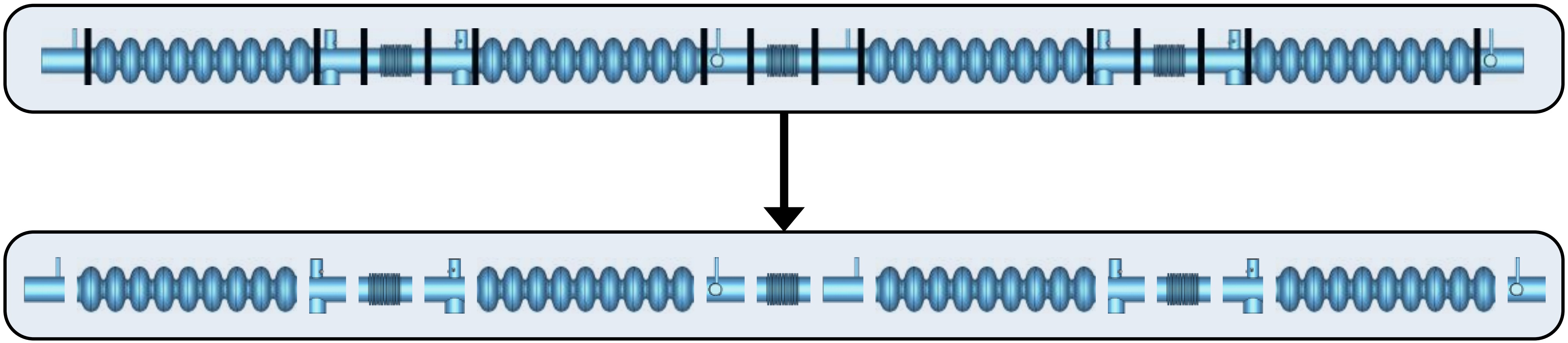
Liling Xiao, Lixin Ge, Kwok Ko, Kihwan Lee, Zenghai Li, Cho-Kuen Ng: “Superconducting Cavity Imperfection Study for Projekt X Linac Using ACE3P”, ComPASS All-Hands Meeting LBNL, Sept. 27 -28, 2012 und Kwok Ko et. al: “Advances in Parallel Electromagnetic Code for Accelerator Science and Development”,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

Are we able to avoid the need of supercomputers?

Alternative approach:
State-Space Concatenations

State-Space Concatenations (SSC)

1. Decomposition of the Structure at Regions of Constant Cross Section

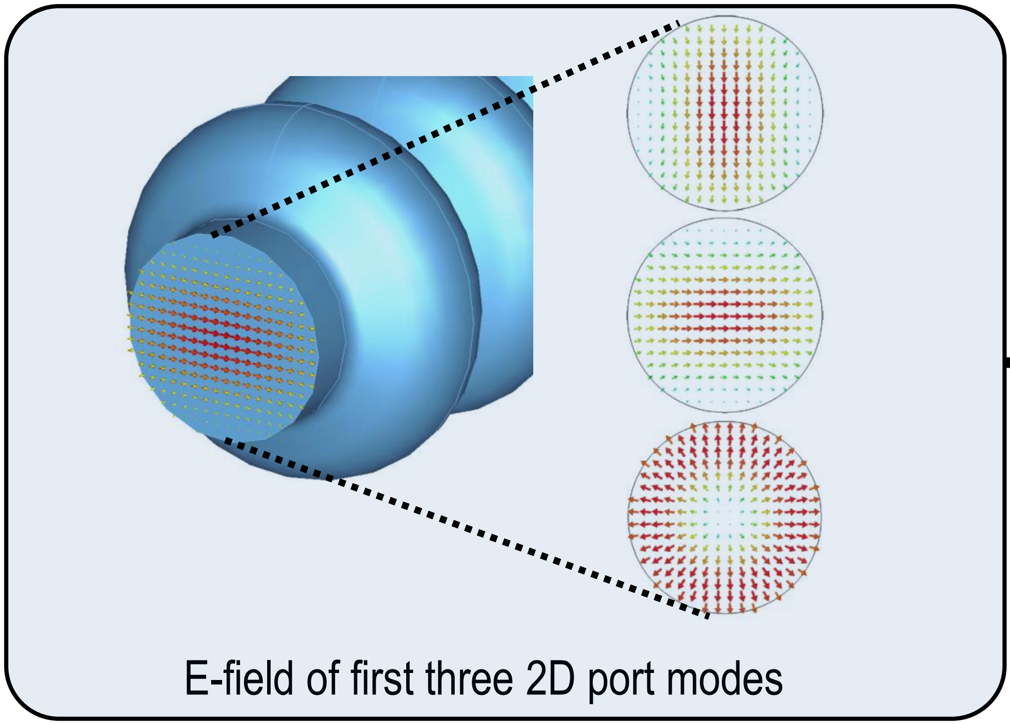


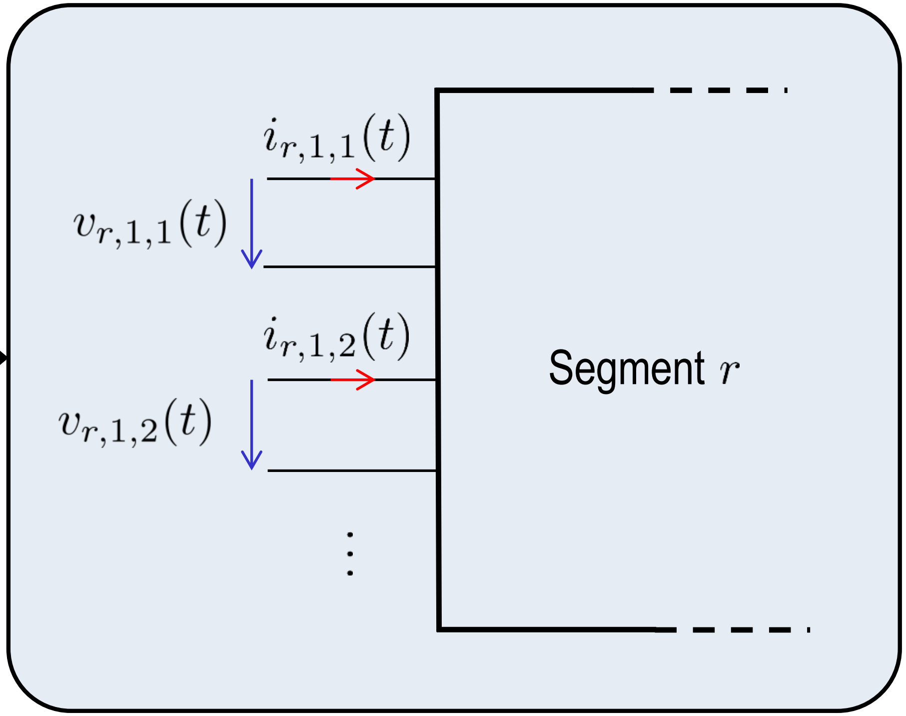
Important properties:

- (numerical) treatment of segments is computationally less demanding
- single treatment of identical segments
- segments with simple geometry can be treated semi-analytically, which is very fast
- employment of symmetry of segments is feasible

State-Space Concatenations (SSC)

2. Consideration of Segments as Blocks with Terminals

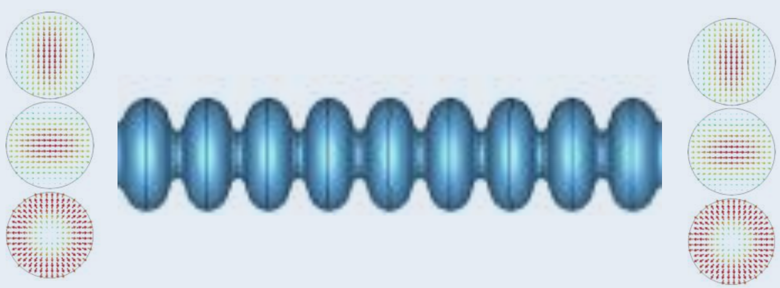




- Modal voltages $v_{r,p,m}(t)$ correspond to tangential electric fields of 2D port modes
- Modal currents $i_{r,p,m}(t)$ correspond to tangential magnetic fields of 2D port modes

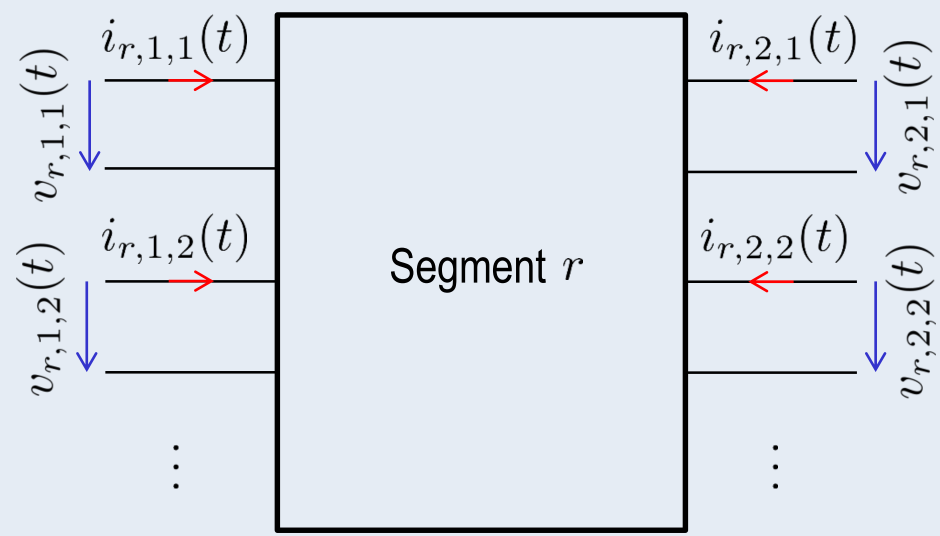
State-Space Concatenations (SSC)

3. Generation of Second-Order State-Space Equations for Segments



wave equation (PDE):

$$\Delta \mathbf{E}(\mathbf{r},t) = \varepsilon\mu \frac{\partial^2}{\partial t^2}\mathbf{E}(\mathbf{r},t) + \mu \frac{\partial}{\partial t}\mathbf{J}(\mathbf{r},t)$$



state-space system (ODE):

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}\mathbf{x}_r(t) = \mathbf{A}_r\mathbf{x}_r(t) + \mathbf{B}_r\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{i}_r(t)$$

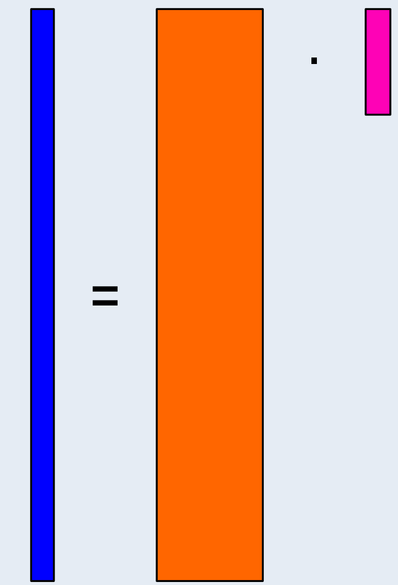
$$\mathbf{v}_r(t) = \mathbf{B}_r^{\mathrm{T}}\mathbf{x}_r(t)$$

State-Space Concatenations (SSC)

4. Model-Order Reduction for State-Space Systems

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}\mathbf{x}_r(t) = \mathbf{A}_r\mathbf{x}_r(t) + \mathbf{B}_r\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{i}_r(t)$$

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



$$\mathbf{x}_r(t) = \mathbf{W}_r \cdot \mathbf{x}_{\mathrm{rd},r}(t)$$

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}\mathbf{x}_{\mathrm{rd},r}(t) = \underbrace{\mathbf{W}_r^{\mathrm{T}}\mathbf{A}_r\mathbf{W}_r}_{\mathbf{A}_{\mathrm{rd},r}}\mathbf{x}_{\mathrm{rd},r}(t) + \underbrace{\mathbf{W}_r^{\mathrm{T}}\mathbf{B}_r}_{\mathbf{B}_{\mathrm{rd},r}}\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{i}_r(t)$$

$$\mathbf{v}_r(t) = \underbrace{\mathbf{B}_r^{\mathrm{T}}\mathbf{W}_r}_{\mathbf{B}_{\mathrm{rd},r}^{\mathrm{T}}}\mathbf{x}_{\mathrm{rd},r}(t)$$

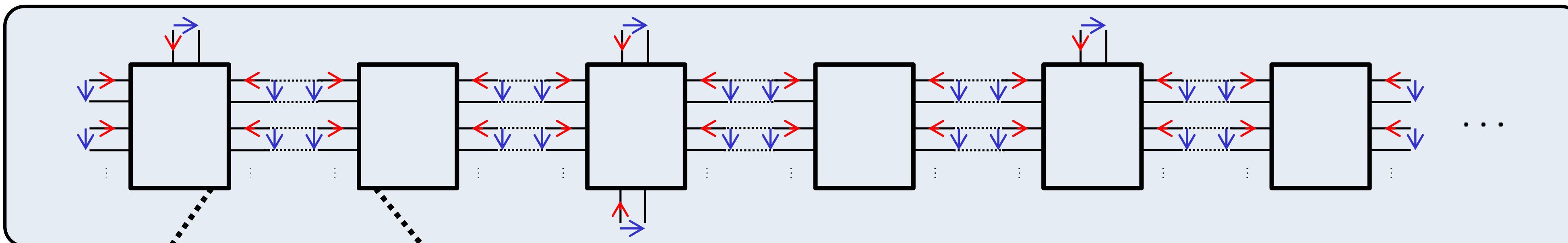
state vector: $\mathbf{x}_r(t) \in \mathbb{R}^{N_\mathrm{s}}, N_\mathrm{s} \approx 10^5$

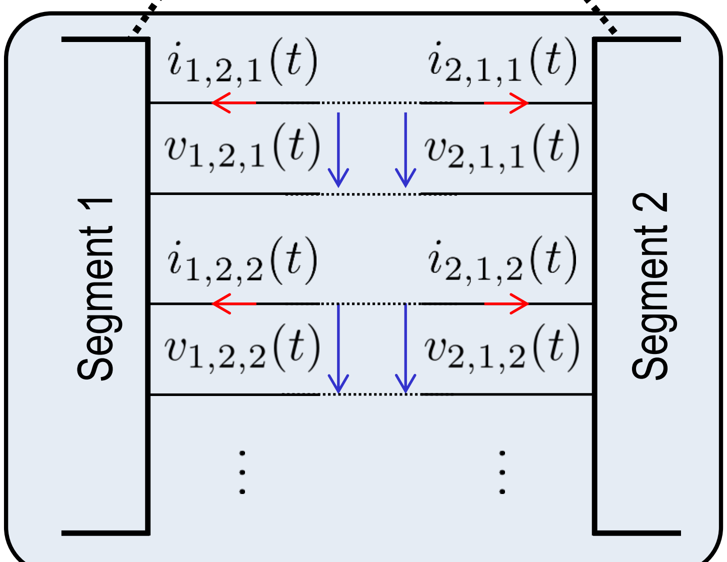
orthogonal projection matrix: $\mathbf{W}_r \in \mathbb{R}^{N_\mathrm{s} \times N_\mathrm{srd}}, \mathbf{W}_r^{\mathrm{T}}\mathbf{W}_r = \mathbf{I}$

reduced state vector: $\mathbf{x}_{\mathrm{rd},r}(t) \in \mathbb{R}^{N_\mathrm{srd}}, N_\mathrm{srd} < 10^2$

State-Space Concatenations (SSC)

5. Concatenation of Reduced-Order State-Space System





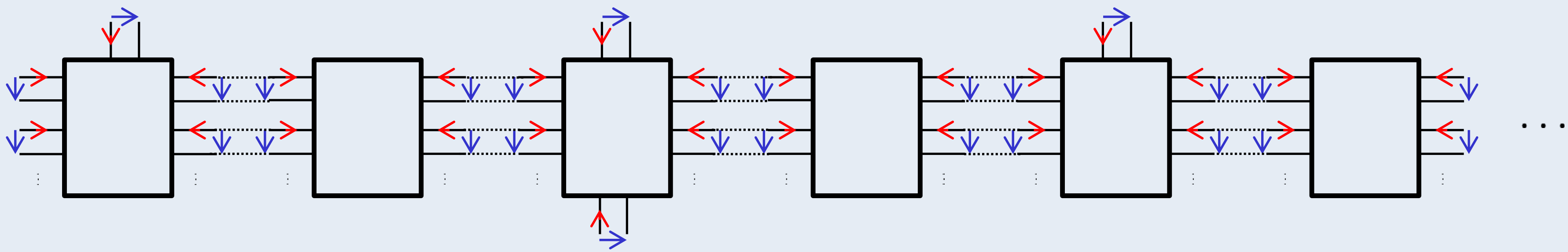
$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}\mathbf{x}_{\mathrm{rdc}}(t) = \mathbf{A}_{\mathrm{rdc}}\mathbf{x}_{\mathrm{rdc}}(t) + \mathbf{B}_{\mathrm{rdc}}\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{i}(t)$$

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

- Coupling constraints according to Kirchhoff's laws
- Arbitrary topologies and number of 2D port modes supported

State-Space Concatenations (SSC)

6. Computation of RF Properties by Means of the Reduced-Order Model



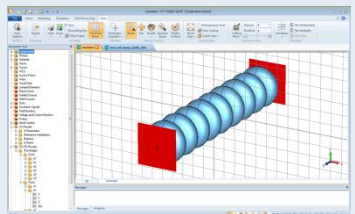
$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}\mathbf{x}_{\mathrm{rdc}}(t) = \mathbf{A}_{\mathrm{rdc}}\mathbf{x}_{\mathrm{rdc}}(t) + \mathbf{B}_{\mathrm{rdc}}\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{i}(t)$$

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

- impedance- and scattering parameters
- 3D field distribution due to port excitations
- frequencies and field distributions of eigenmodes
- external quality factors

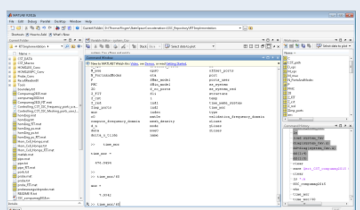
Implementation of SSC

CST Microwave Studio®



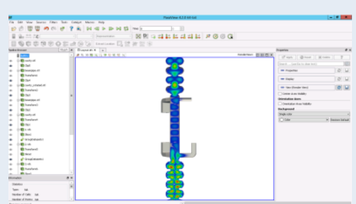
- geometrical modelling
- discretization

Matlab®



- model-order reduction
- concatenation
- computation of derived quantities

ParaView



- visualization of field distributions

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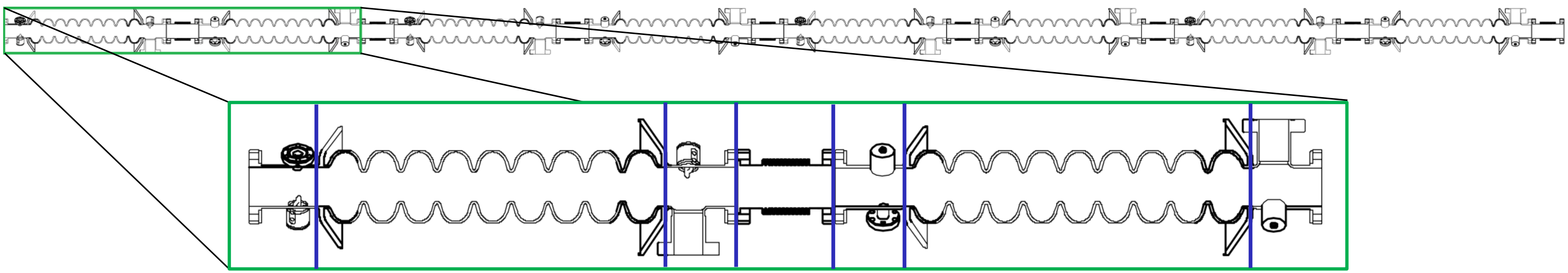
Full Analysis of Eigenmodes up to 8 GHz in Chain of Eight 3rd Harmonic Cavities for the European XFEL

Chain of Eight Superconducting 3rd Harmonic Cavities in XFEL

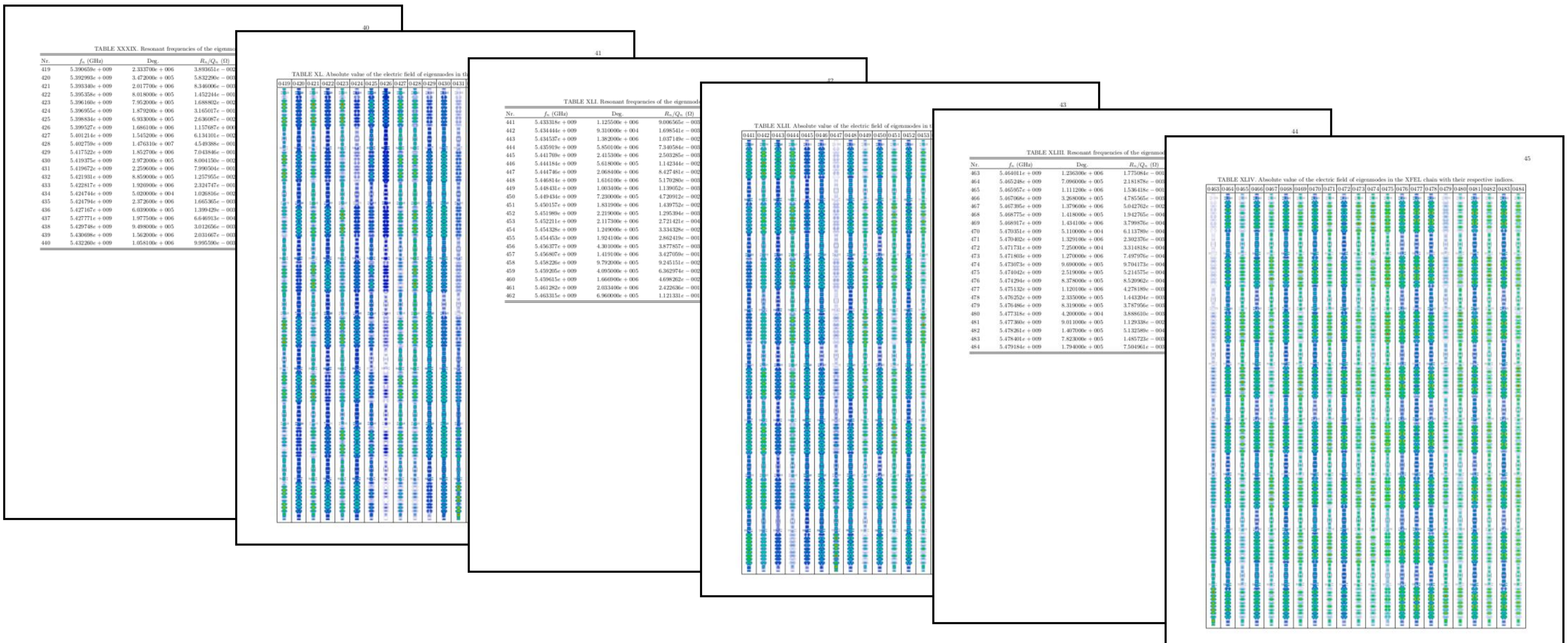


	HOM Coupler	Cavity	HOM Coupler with Power Coupler	Bellow	HOM Coupler (rotated)	HOM Coupler with Power Coupler (rotated)
N_{dof}	411,015	1,119,963	585,915	427,119	411,015	585,915
$N_{dof,red}$	138	258	164	145	138	164

- Full model of eight cavity chain is estimated to have N_{dof} = 20,239,977 degrees of freedom
- Reduced-order models of segments concatenated to reduced-order model of full chain with $N_{dof,red}$ = 2,931 degrees of freedom

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

Computation of Eigenmodes based on Reduced-Order Model



- Computed 1,479 eigenmodes in the interval 1 GHz to 8 GHz of the chain by means of a standard workstation computer
- Assembled a modal compendium for the chain with resonant frequency, external quality factor, R/Q, and electric field distribution of each mode
- In total, the compendium consists of 137 pages

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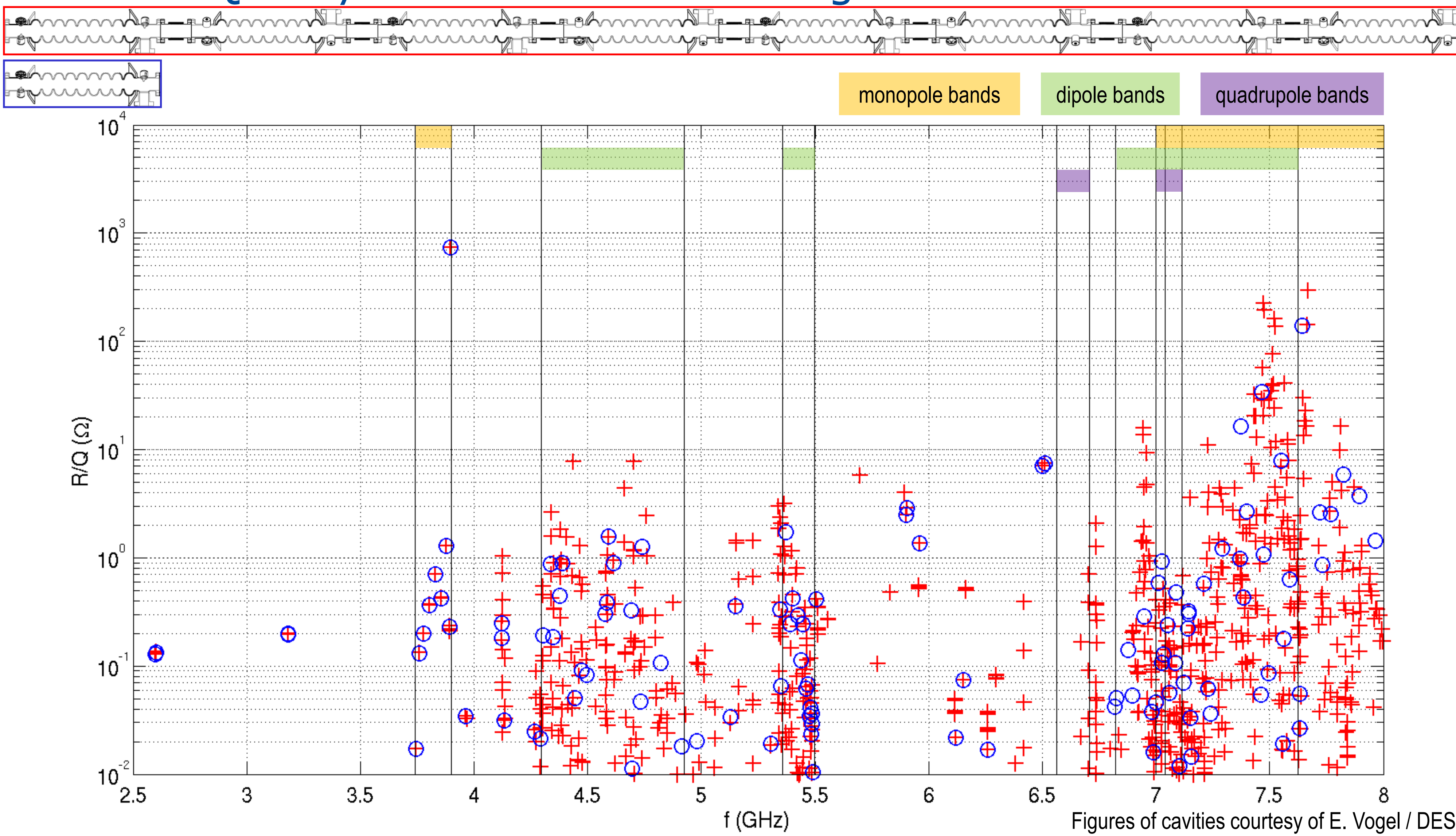
External Quality Factors in Chain of Eight 3rd Harmonic Cavities



Figures of cavities courtesy of E. Vogel / DESY

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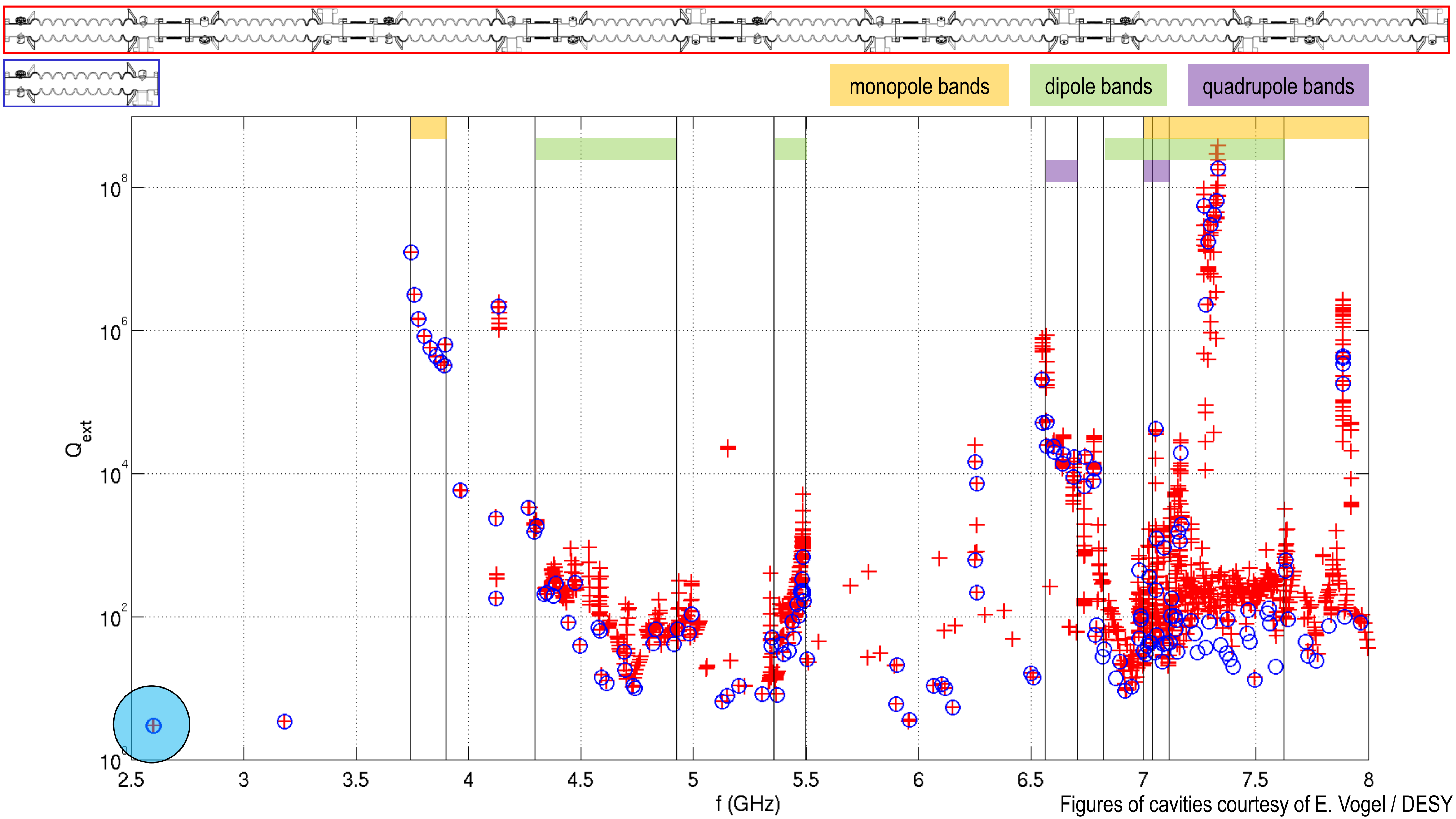
EuCARD²

External Quality Factors in Chain of Eight 3rd Harmonic Cavities



Figures of cavities courtesy of E. Vogel / DESY

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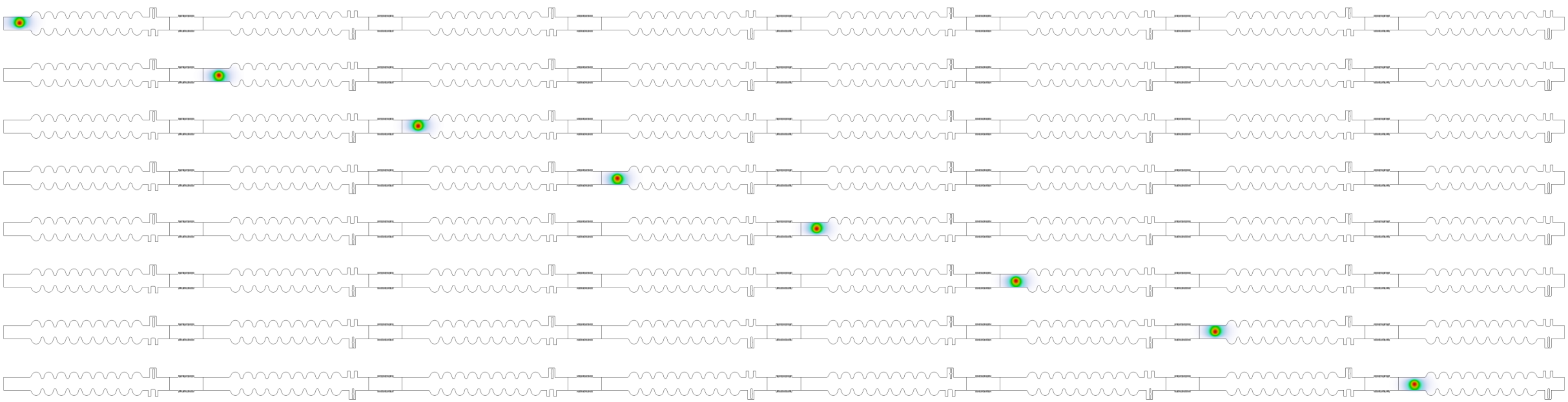
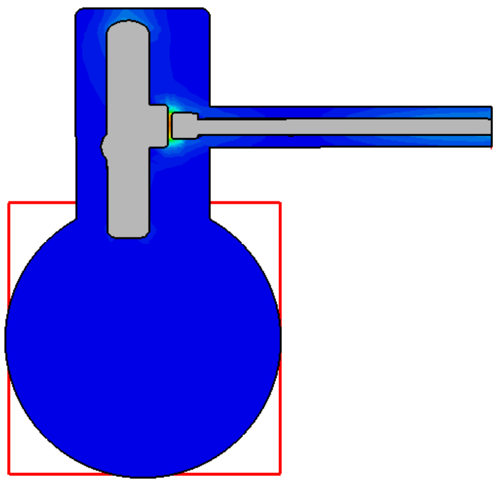
Modes Localized in HOM Couplers (I/II)



Index	f (GHz)	R/Q (Ω)	Q_{ext}
1 – 8	2.5987	$1.2829 \cdot 10^{-1}$	2.9707



The plots show the absolute value of the electric field.

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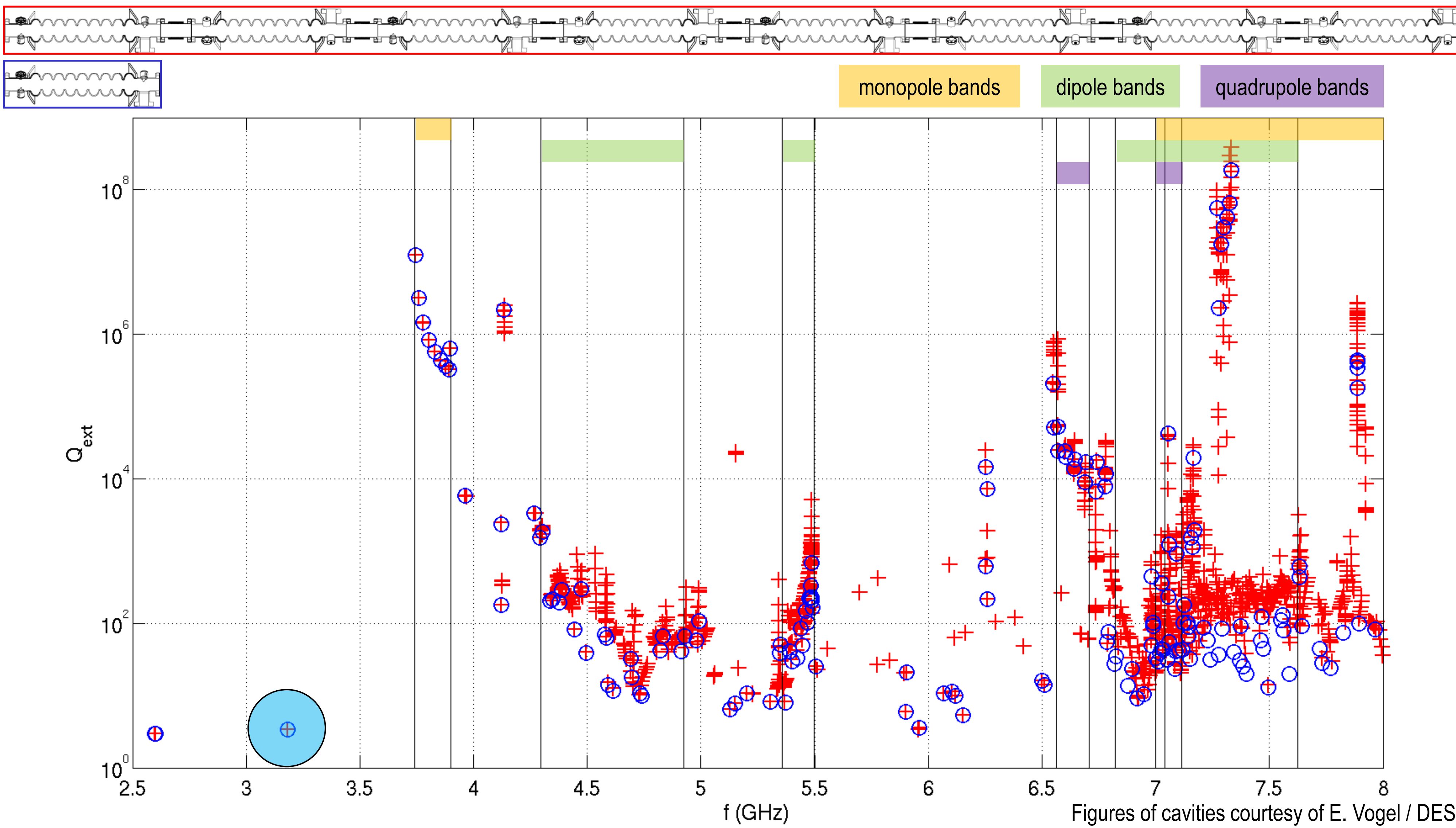
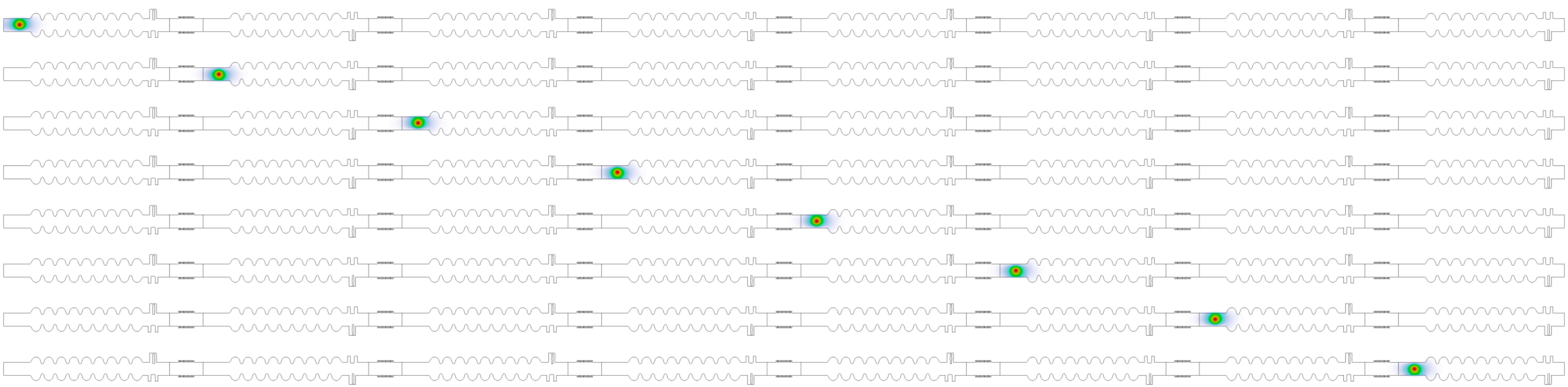
External Quality Factors in Chain of Eight 3rd Harmonic Cavities

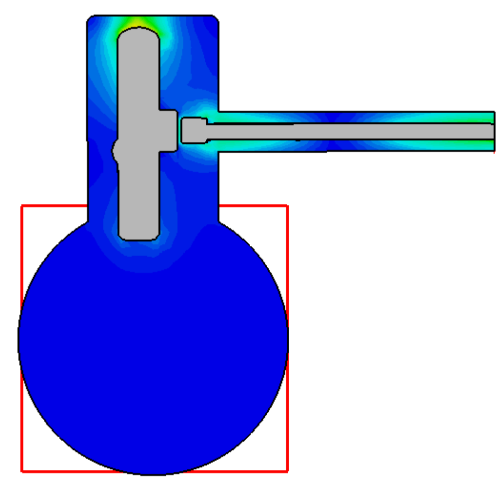


Figures of cavities courtesy of E. Vogel / DESY

Modes Localized in HOM Couplers (II/II)



Index	f (GHz)	R/Q (Ω)	Q_{ext}
17 – 24	3.1828	$1.9402 \cdot 10^{-1}$	3.395



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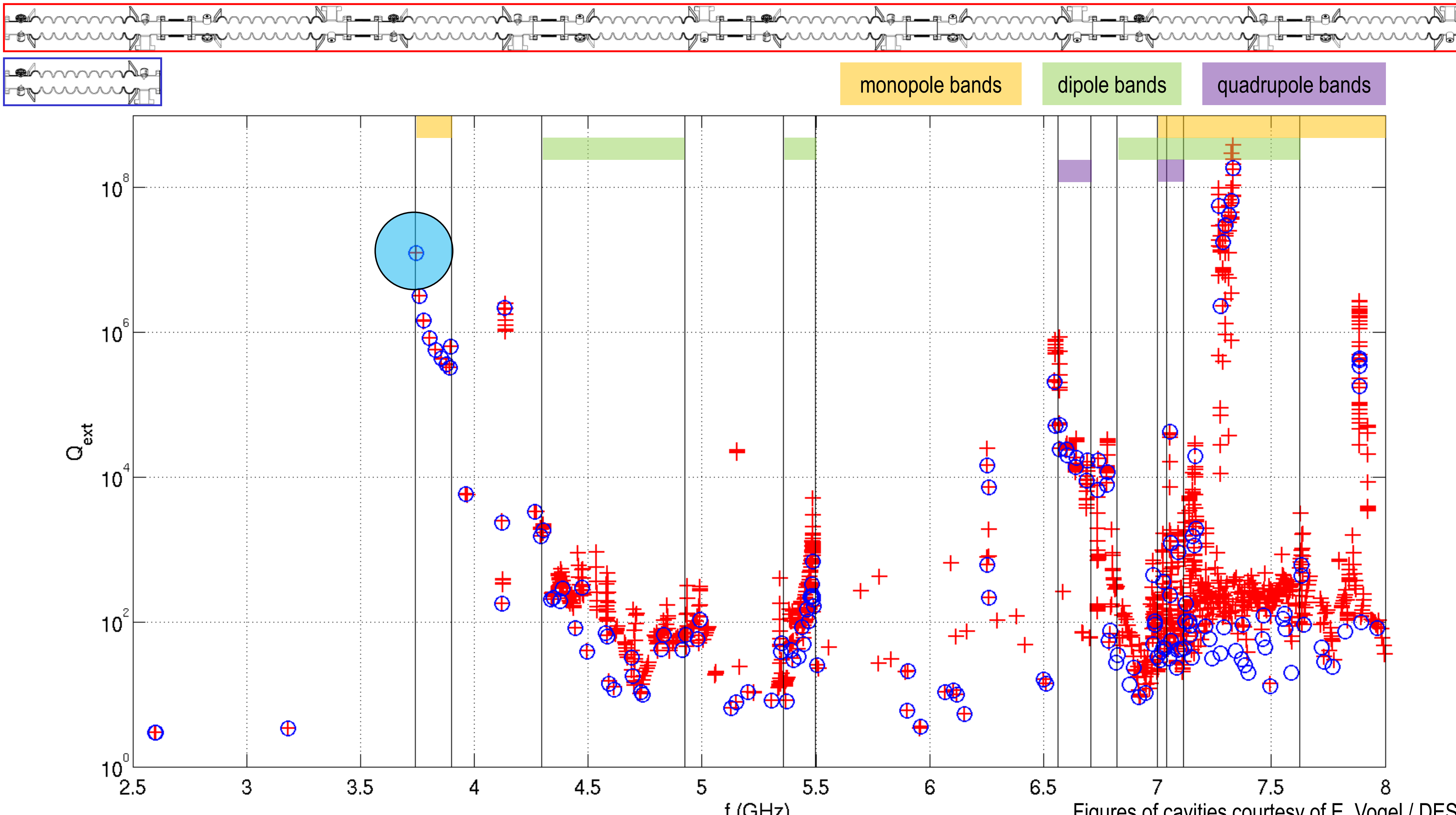
External Quality Factors in Chain of Eight 3rd Harmonic Cavities



Figures of cavities courtesy of E. Vogel / DESY

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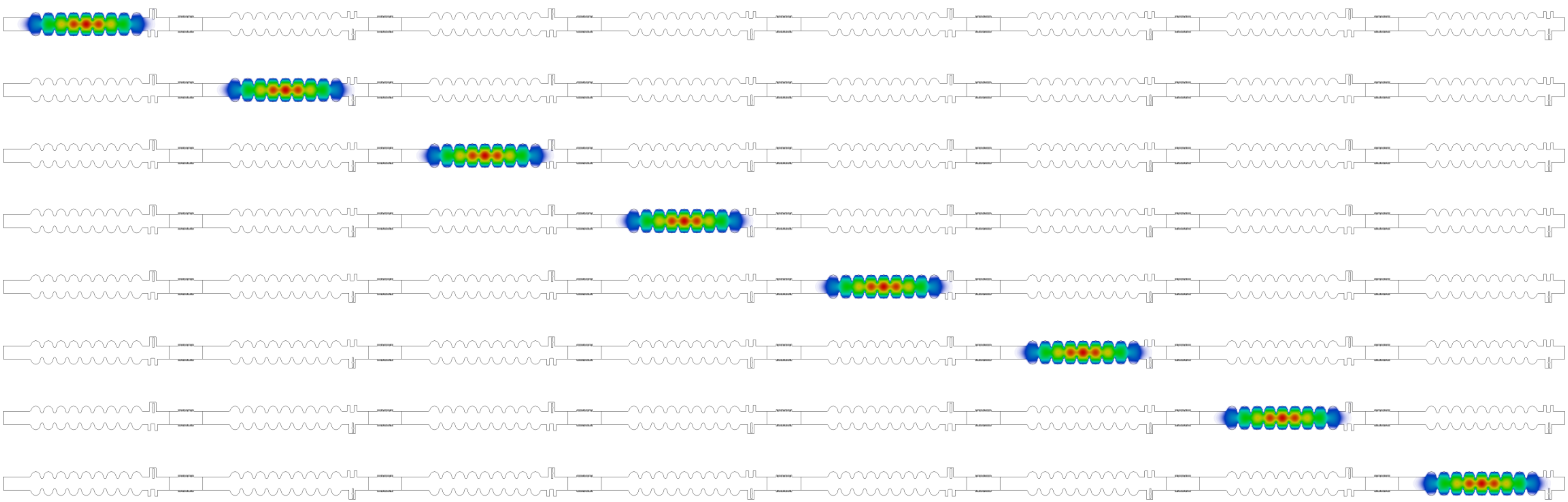
TM_{01}-π/9-Modes Localized in Cavities (I/II)



Index	f (GHz)	R/Q (Ω)	Q_{ext}
33 – 40	3.7442	$1.7069 \cdot 10^{-2}$	$1.2539 \cdot 10^{7}$

The plots show the absolute value of the electric field.

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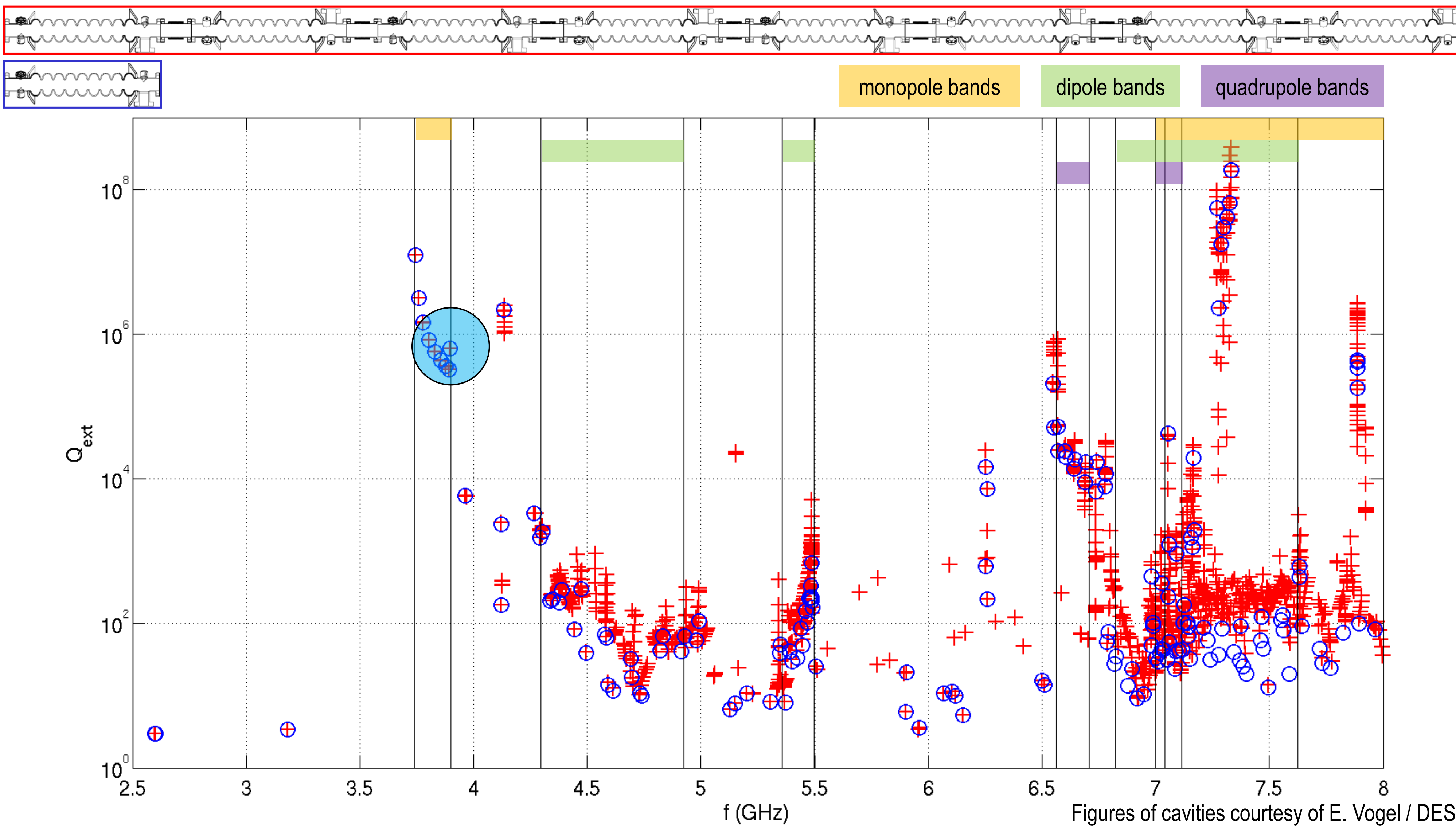
External Quality Factors in Chain of Eight 3rd Harmonic Cavities



Figures of cavities courtesy of E. Vogel / DESY

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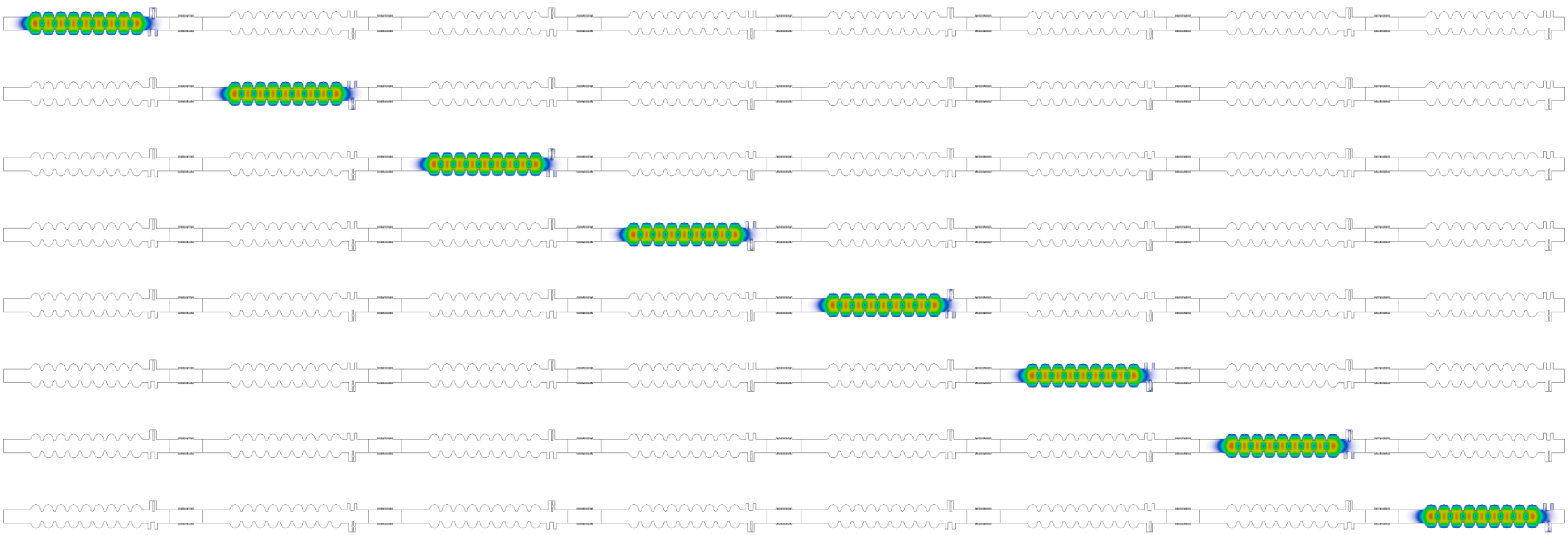
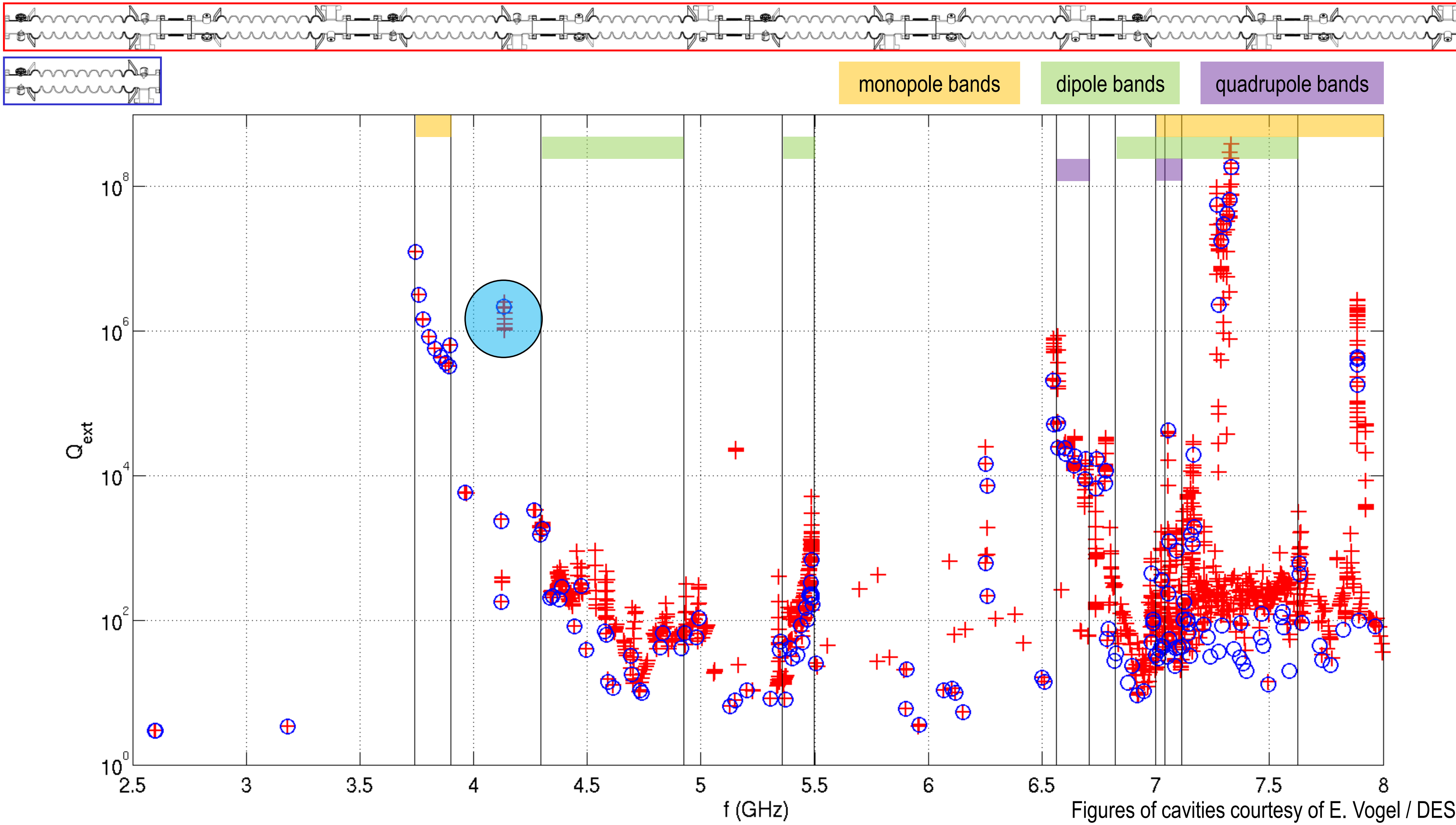
TM_{01}-π-Modes Localized in Cavities (II/II)



Index	f (GHz)	R/Q (Ω)	Q_{ext}
97 – 104	3.8976	$7.4322 \cdot 10^2$	$6.3826 \cdot 10^5$

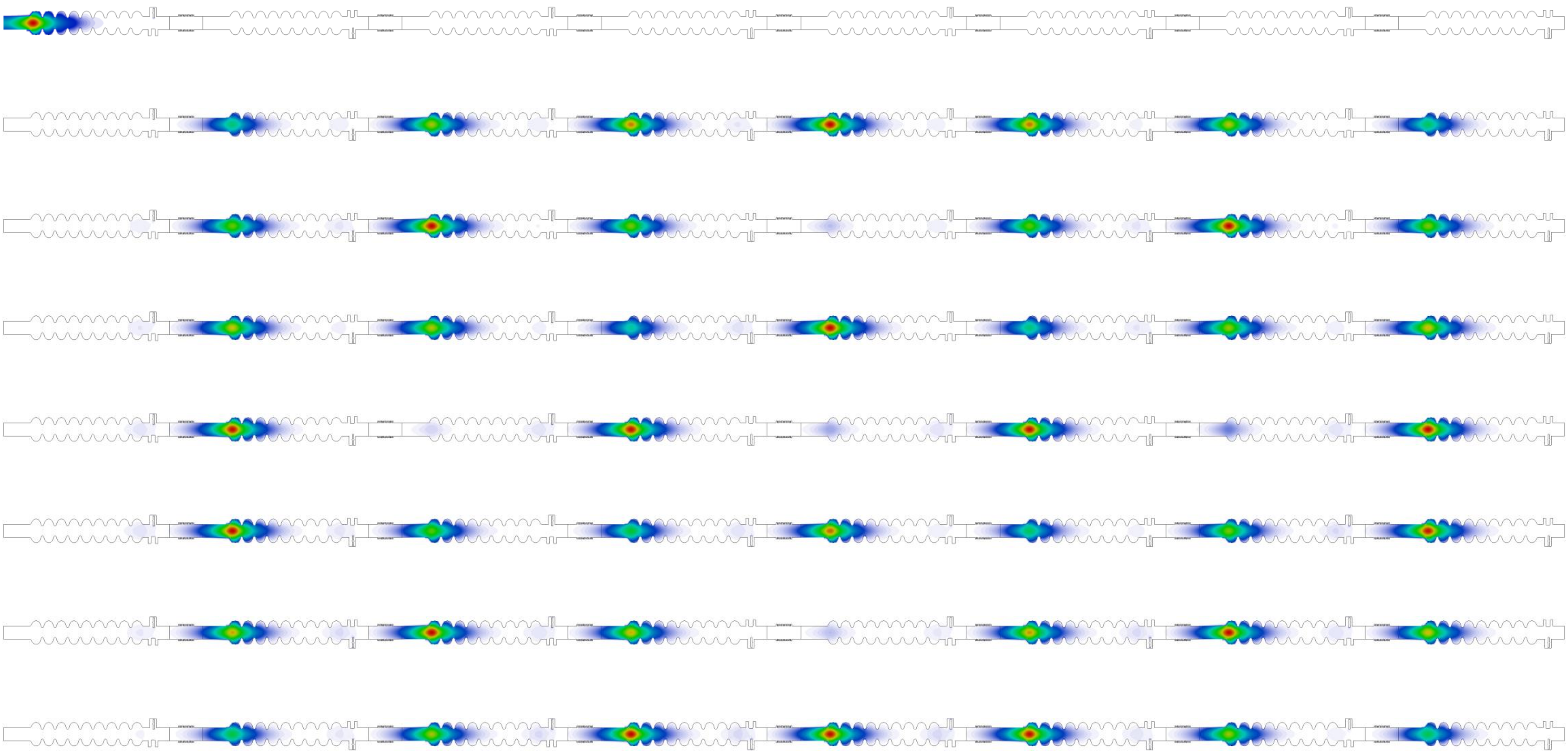
The plots show the absolute value of the electric field.

External Quality Factors in Chain of Eight 3rd Harmonic Cavities



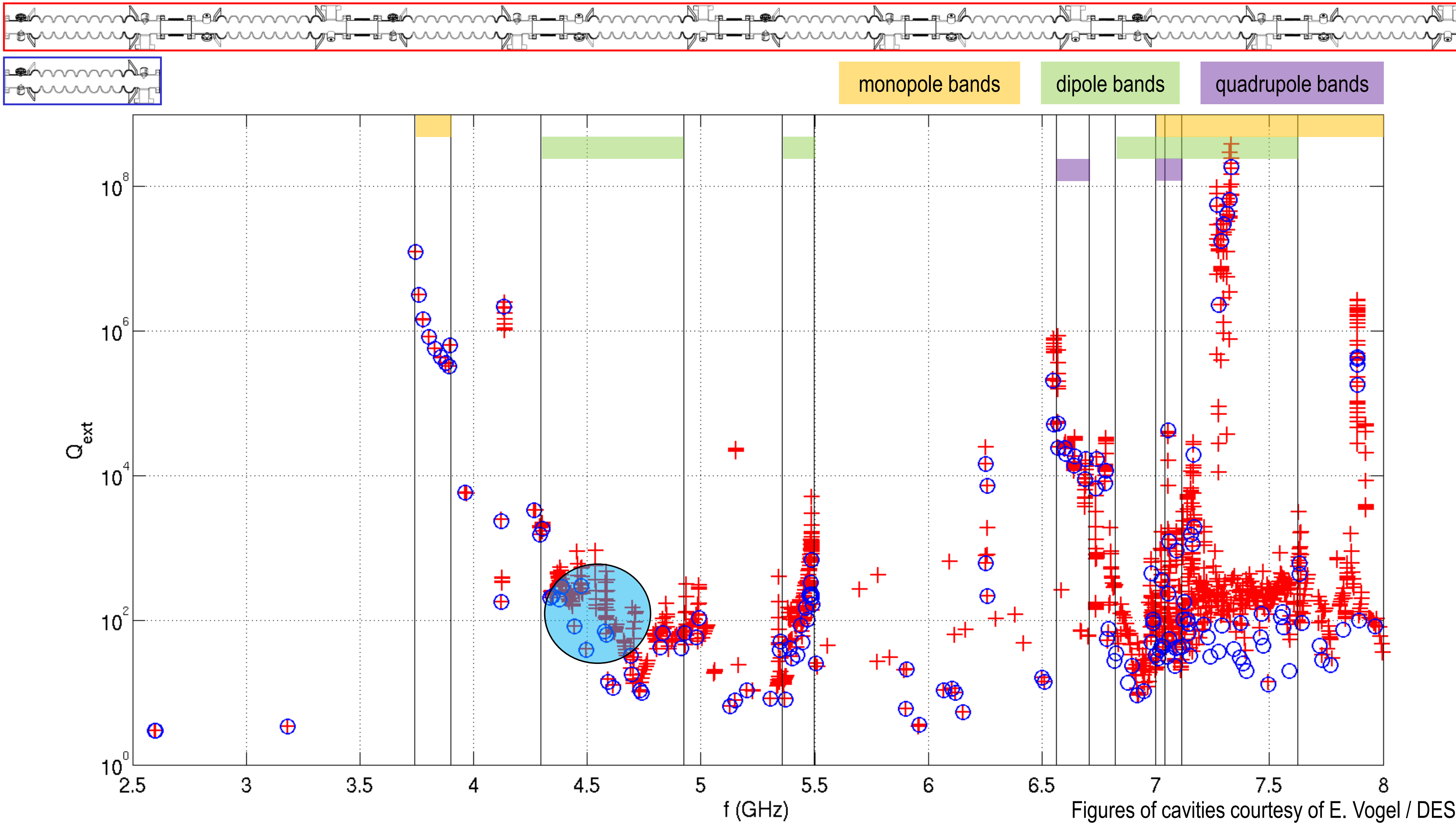
Figures of cavities courtesy of E. Vogel / DESY

Beam-Pipe Modes from 4.1329 GHz to 4.1354 GHz



The plots show the absolute value of the electric field.

External Quality Factors in Chain of Eight 3rd Harmonic Cavities



Figures of cavities courtesy of E. Vogel / DESY

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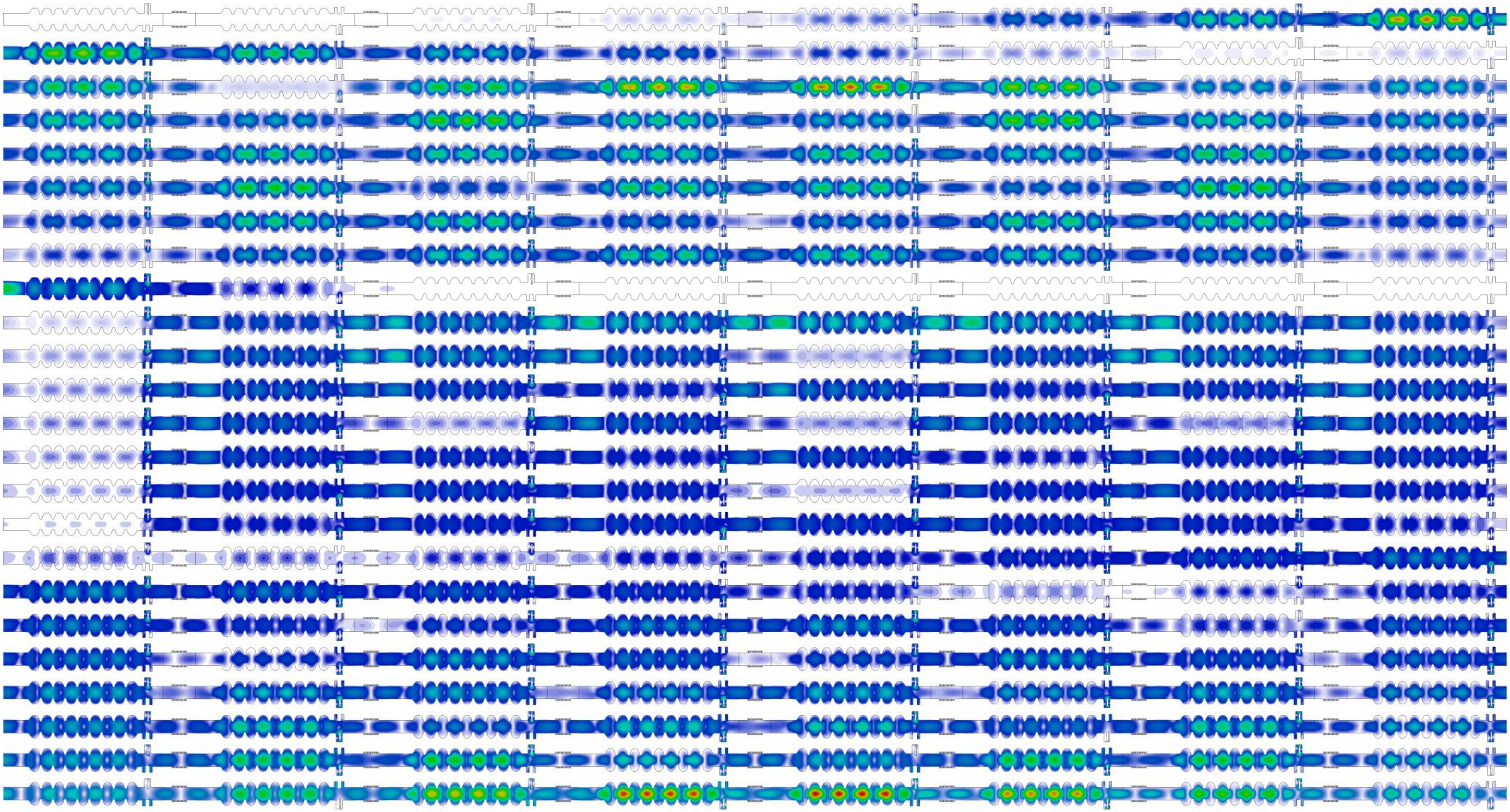
Multi-Cavity Modes from 4.4746 GHz to 4.5829 GHz



The plots show the absolute value of the electric field.

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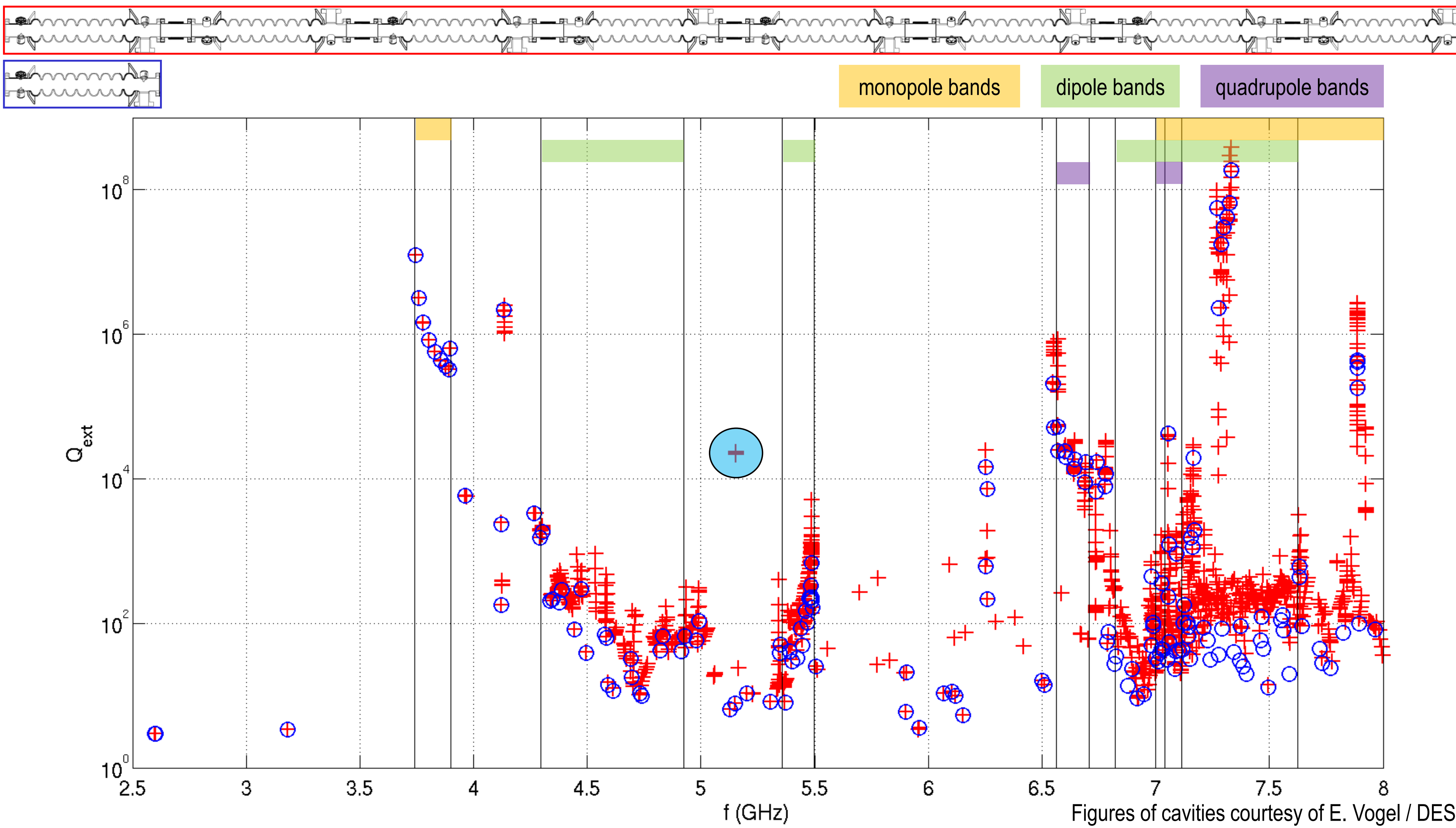
External Quality Factors in Chain of Eight 3rd Harmonic Cavities



Figures of cavities courtesy of E. Vogel / DESY

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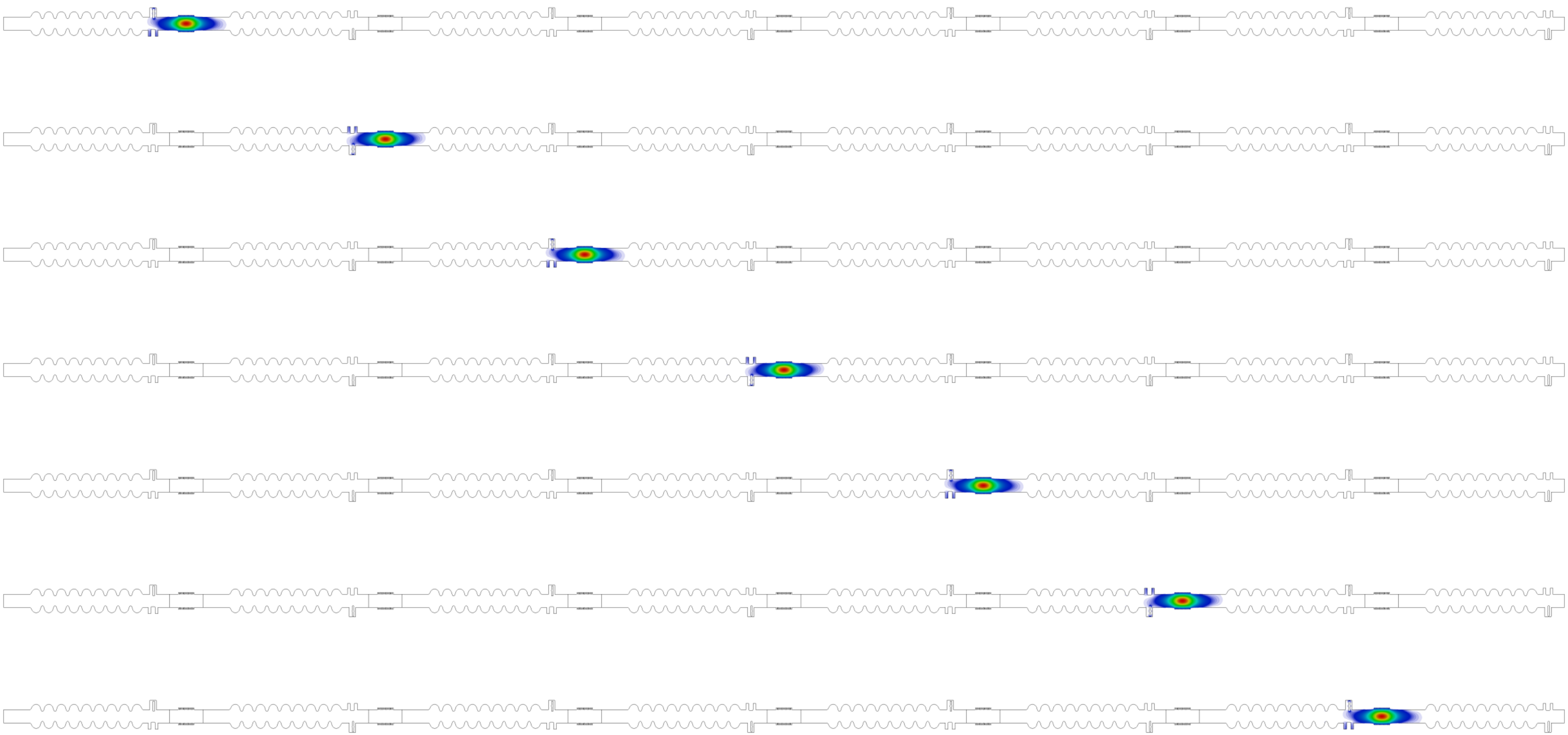
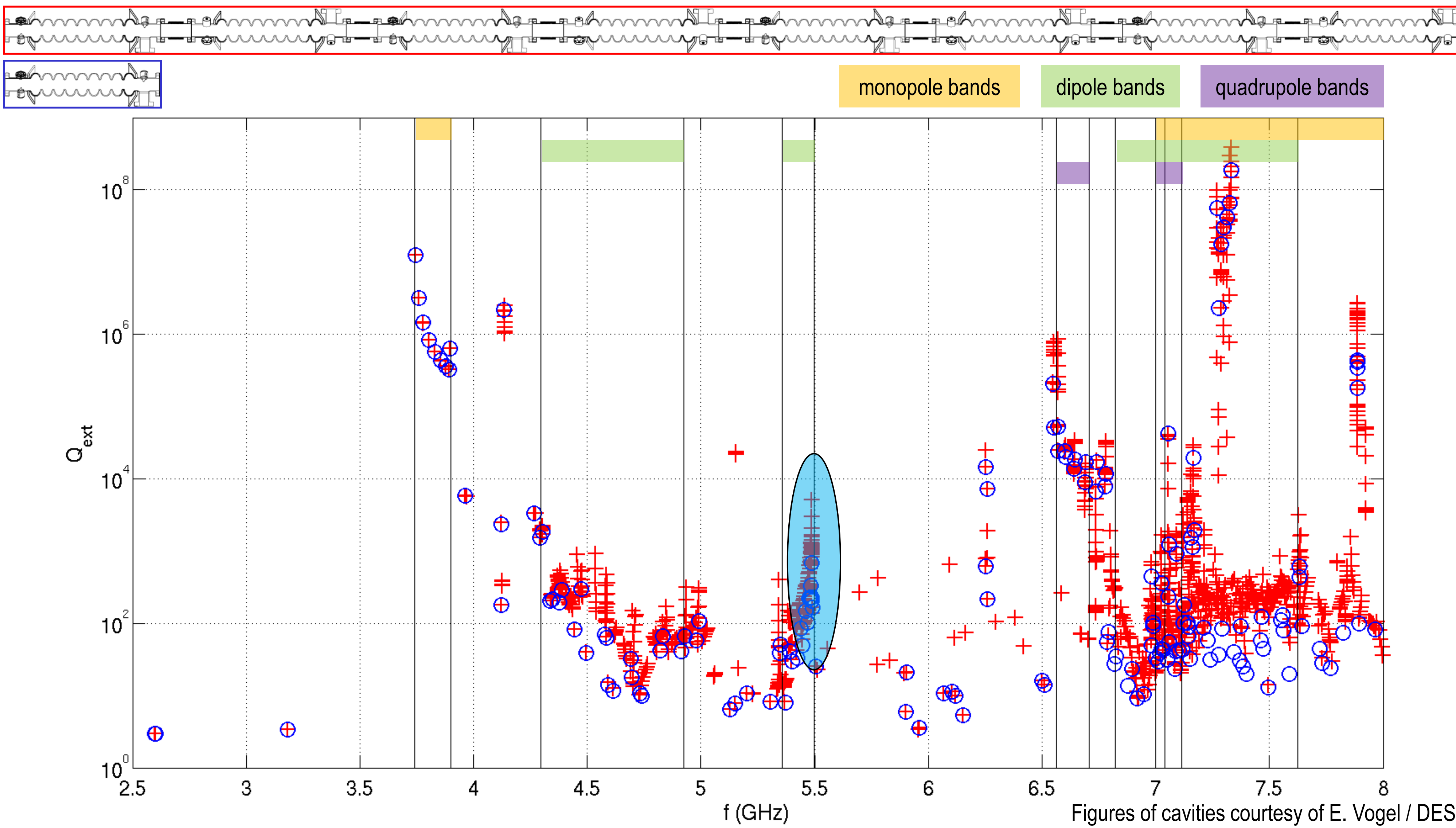
Pure Bellow Modes at 5.1524 GHz



The plots show the absolute value of the electric field.

External Quality Factors in Chain of Eight 3rd Harmonic Cavities



Figures of cavities courtesy of E. Vogel / DESY

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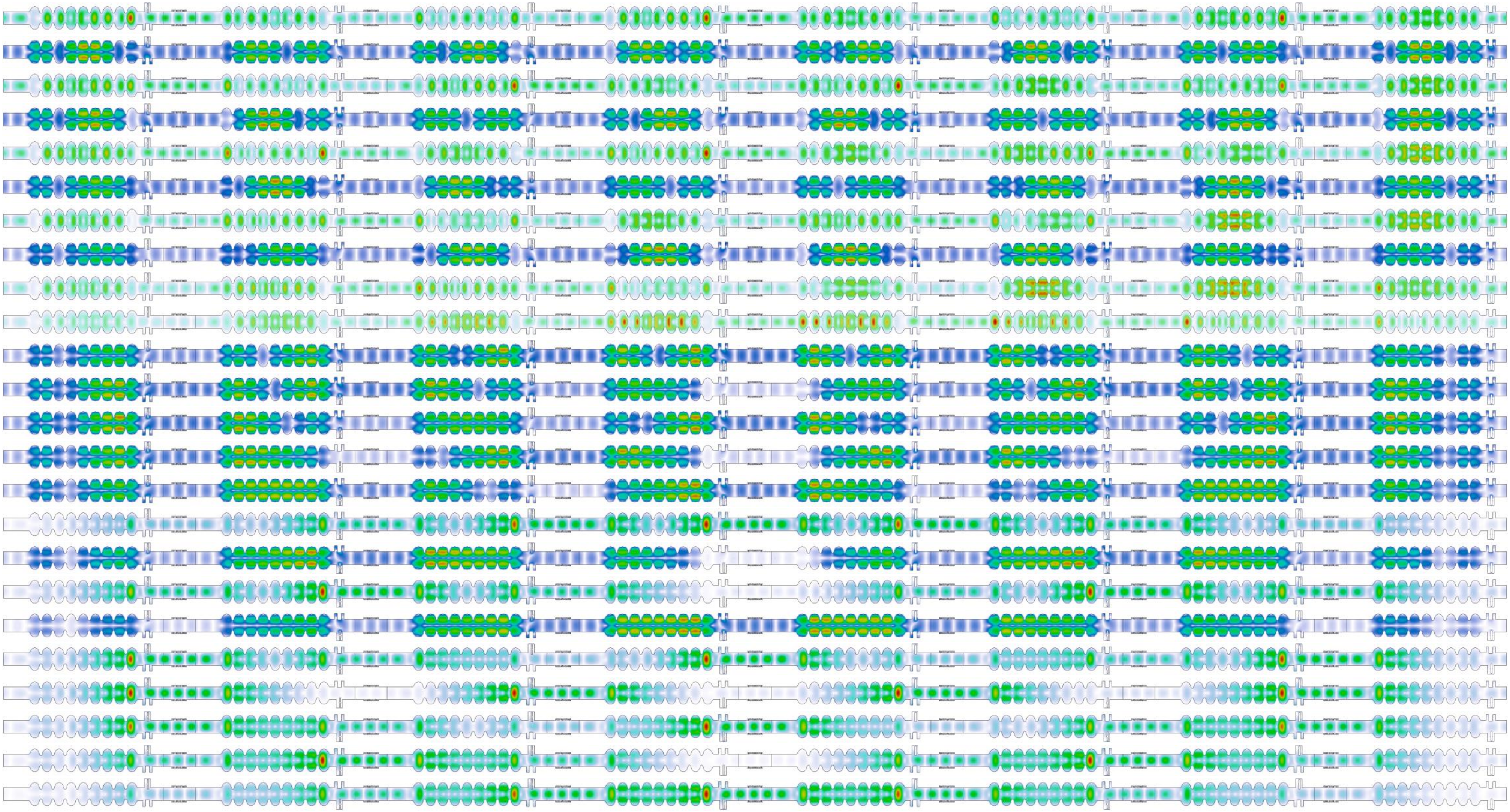
Multi-cavity Modes in the Vicinity of 5.5 GHz



The plots show the absolute value of the electric field.

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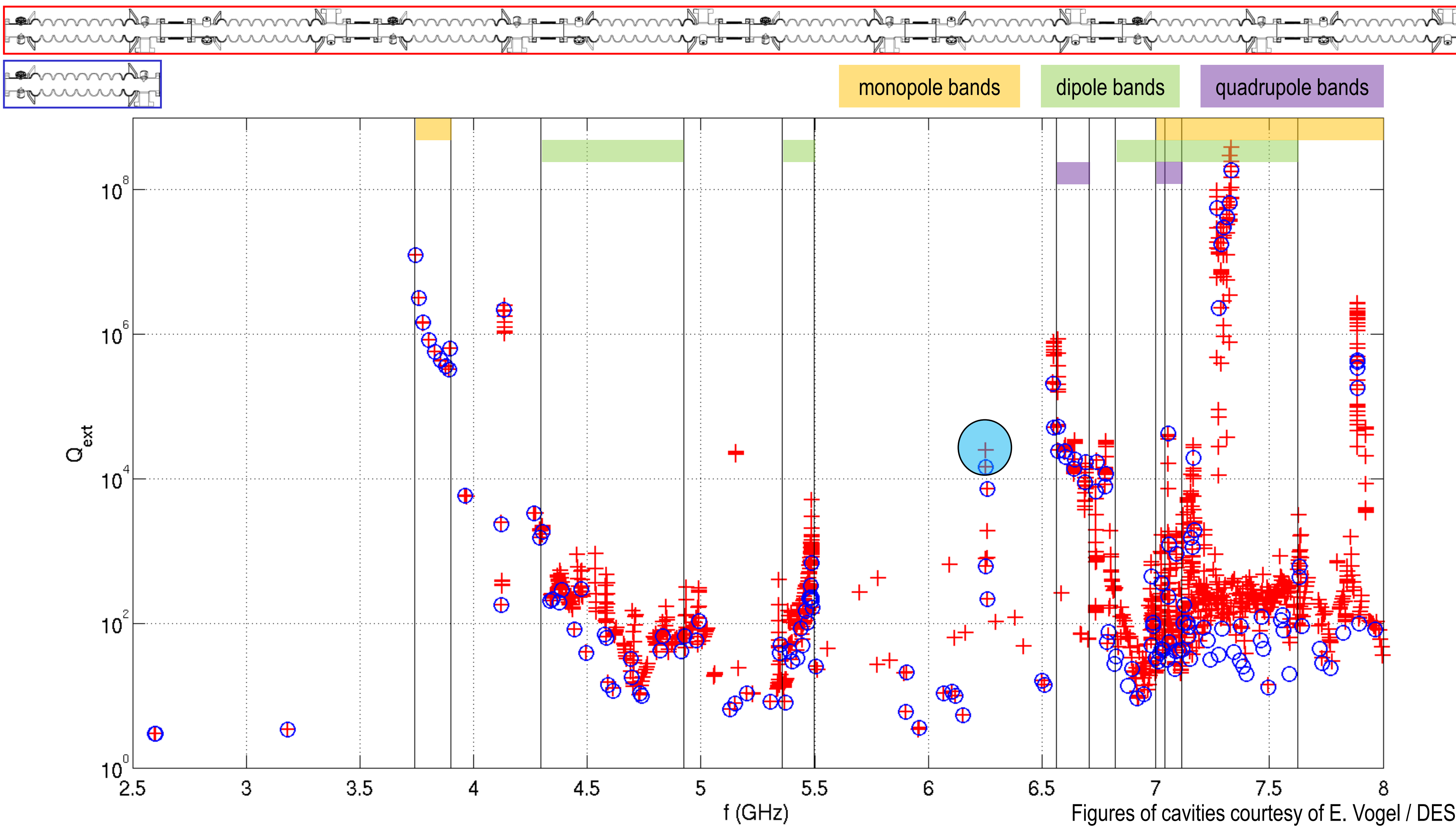
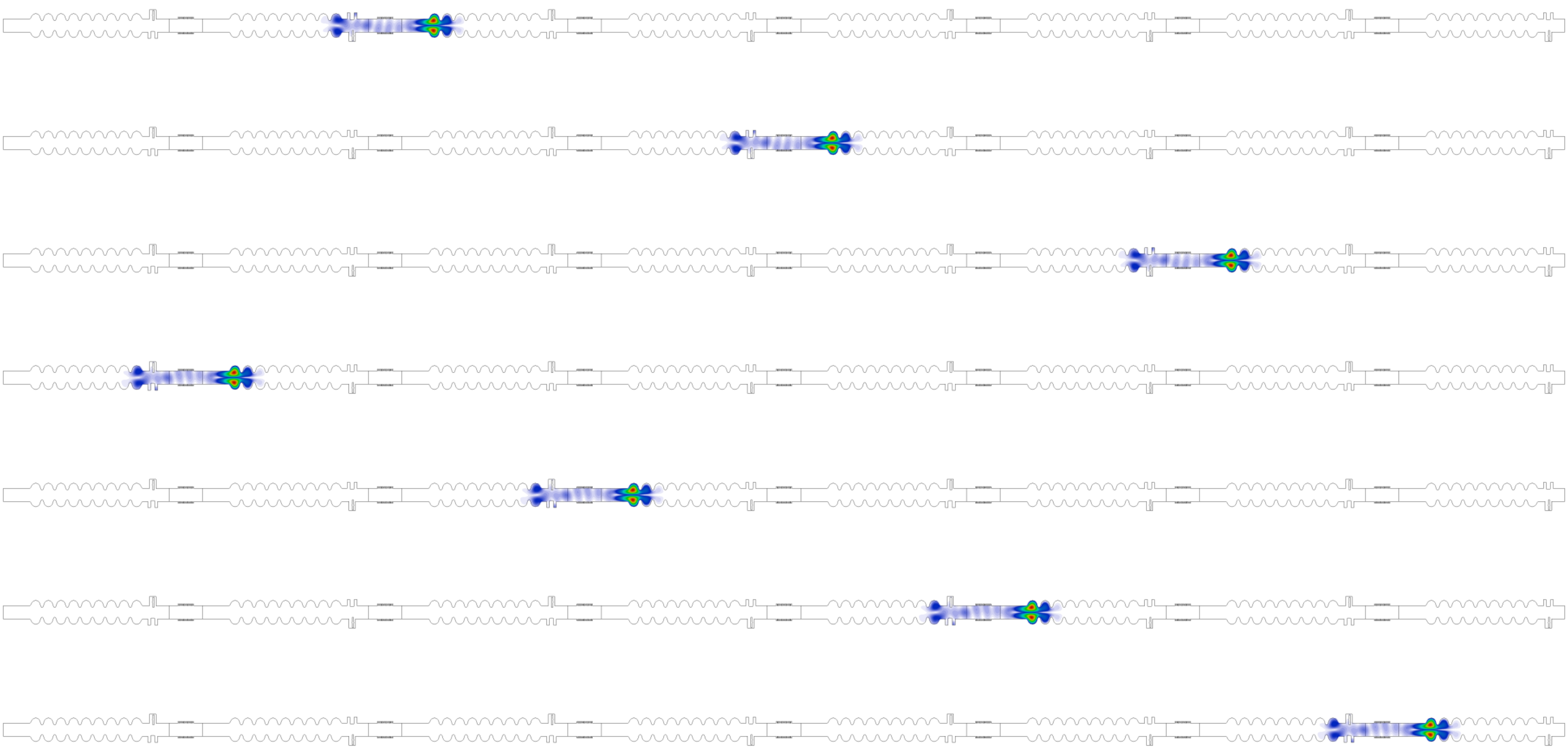
External Quality Factors in Chain of Eight 3rd Harmonic Cavities



Figures of cavities courtesy of E. Vogel / DESY

Bellow-Coupler-Endcell Modes at 6.2514 GHz



The plots show the absolute value of the electric field.

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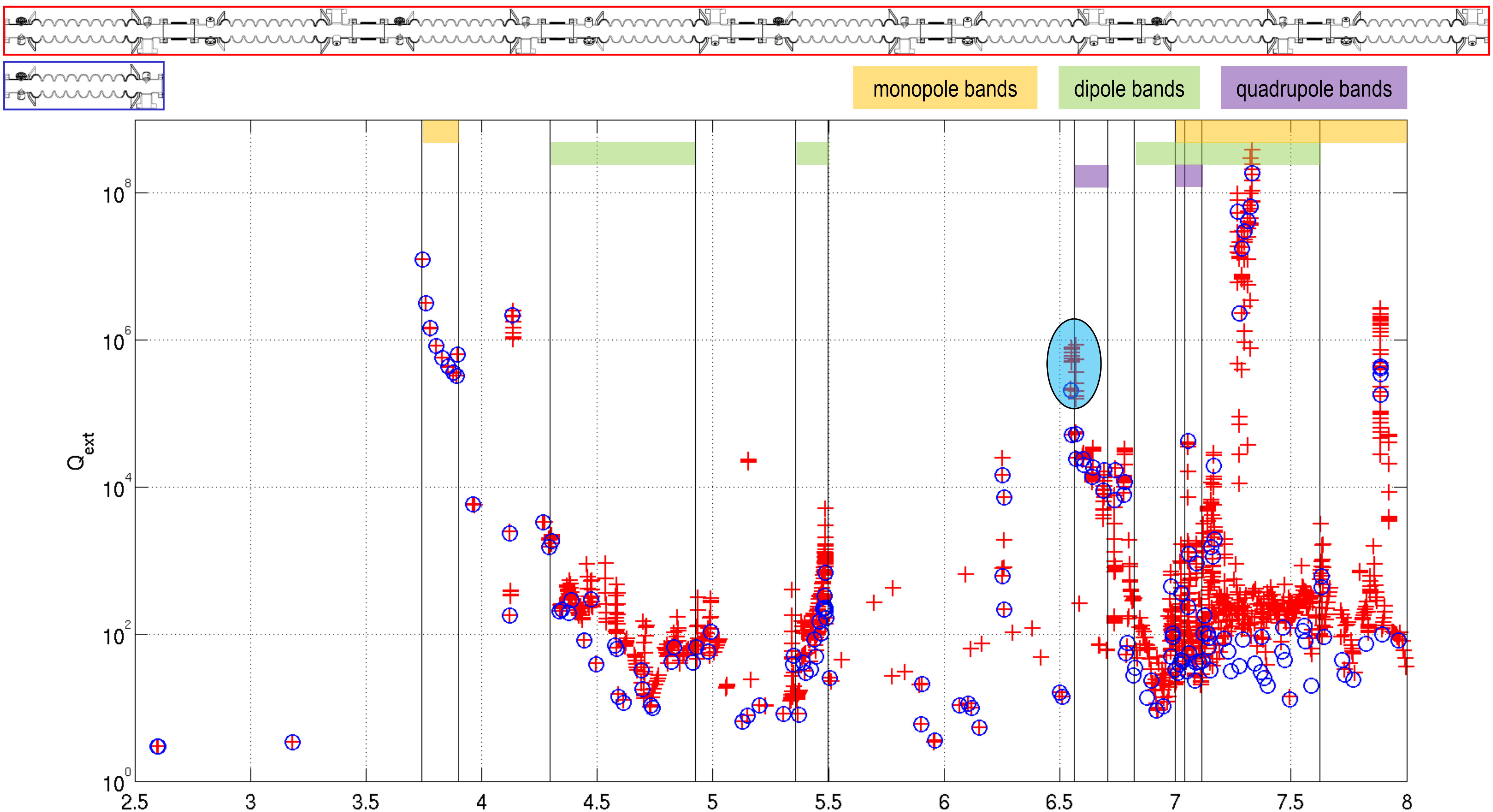
External Quality Factors in Chain of Eight 3rd Harmonic Cavities



Figures of cavities courtesy of E. Vogel / DESY

Quadrupole Modes at 6.5487 GHz

The plots show the absolute value of the electric field.

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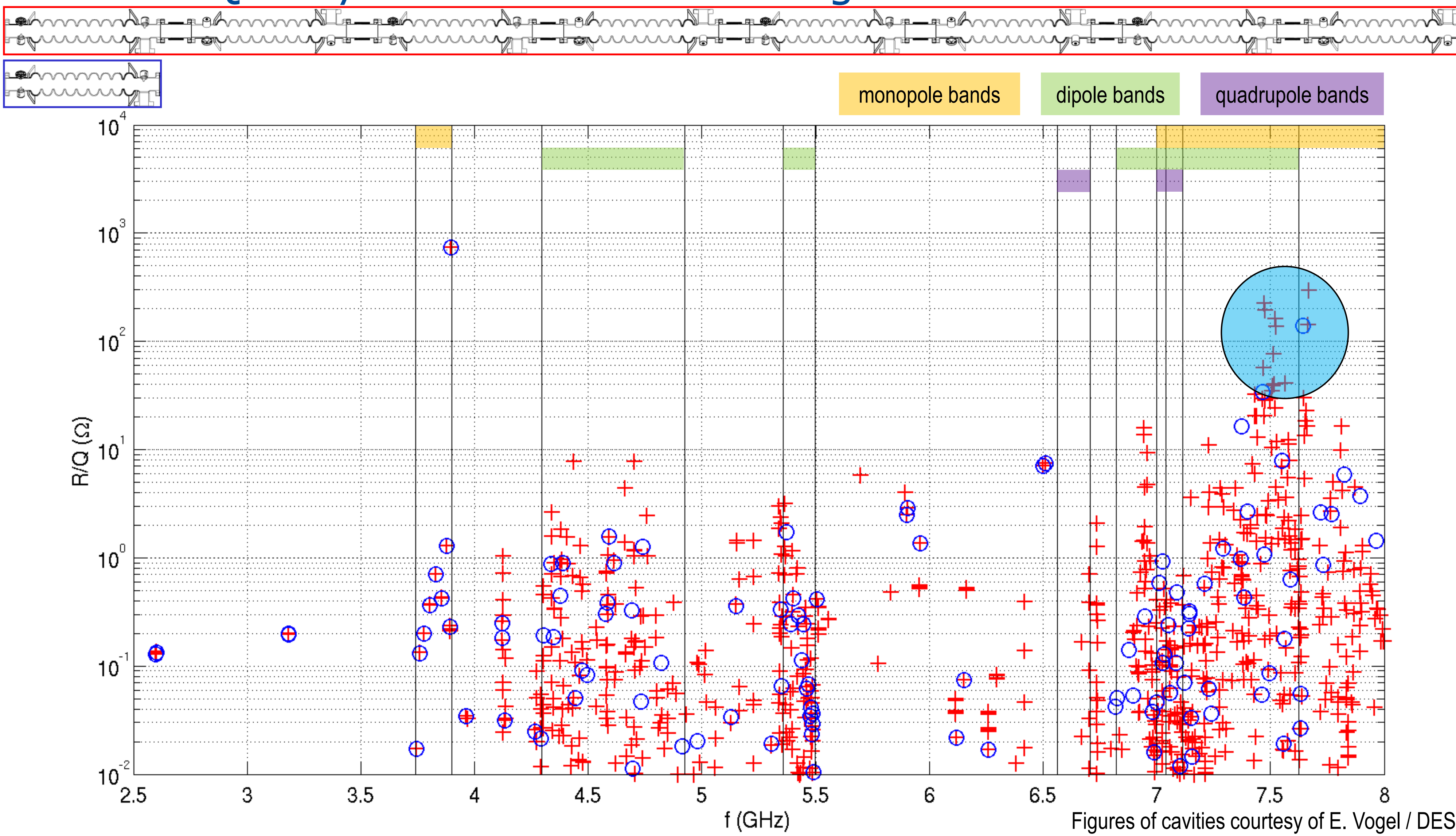
External Quality Factors in Chain of Eight 3rd Harmonic Cavities



Figures of cavities courtesy of E. Vogel / DESY

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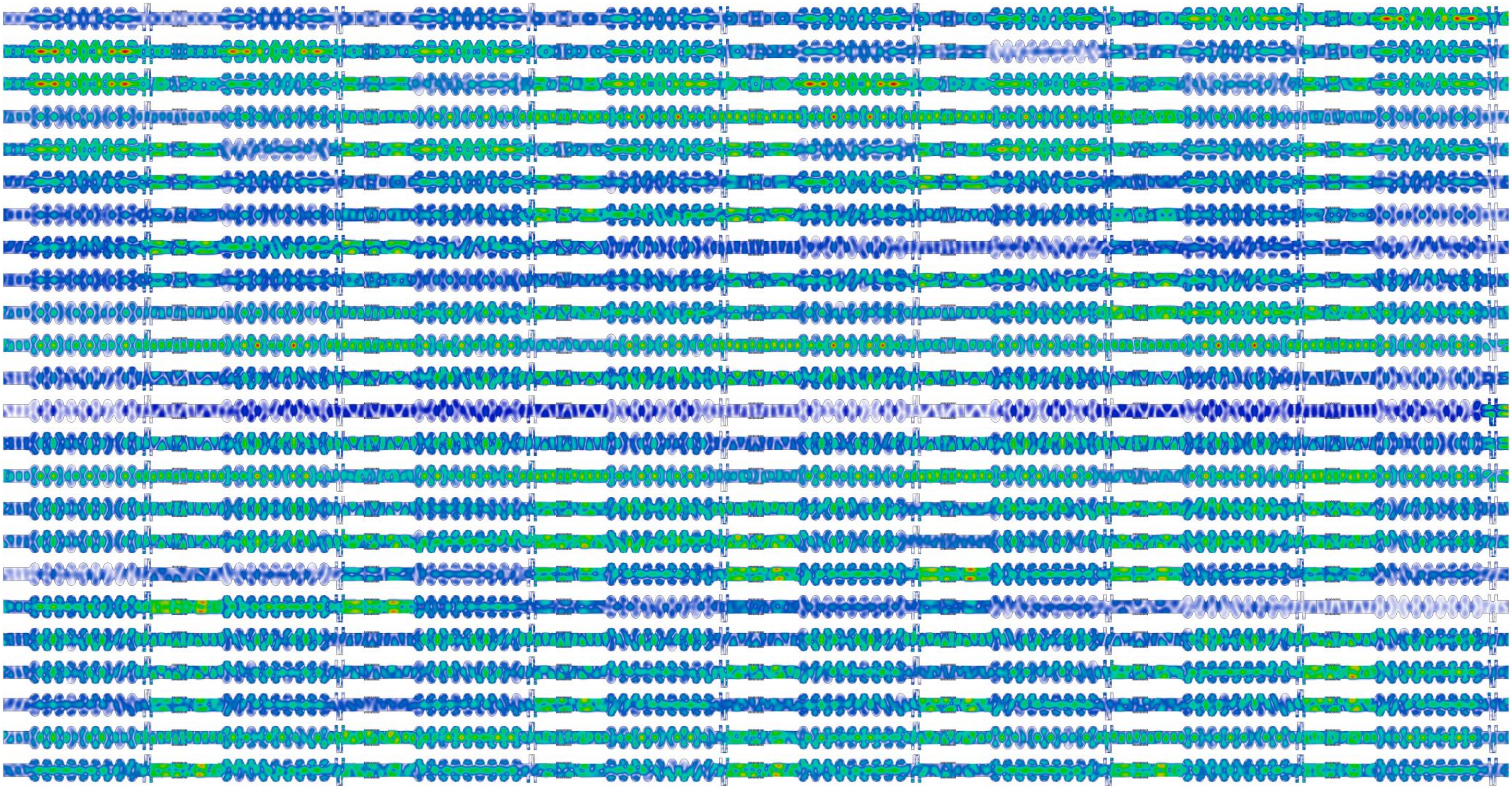
Modes with a Large R/Q in the Vicinity of 7.5 GHz



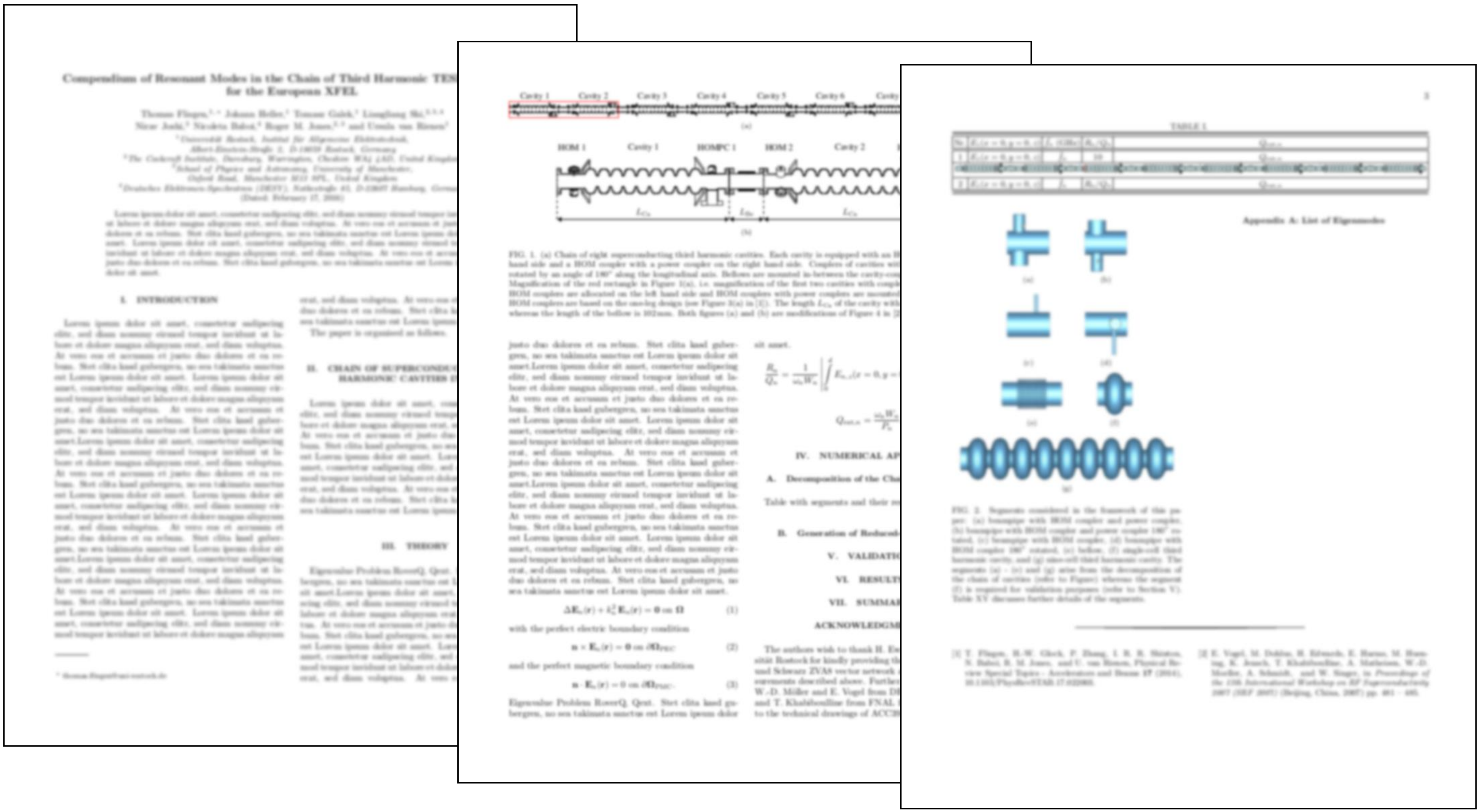
The plots show the absolute value of the electric field.

Conclusions and Future Plans

Conlusions

- Example for solution of large scale problems without using high performance computers by a priori reducing the complexity of the field problem
- As far as the authors can determine, a complete eigenmode computation of such a complex structure on such a wide band has never been done before (?)
- Results show that not restricting on single cavities but considering the entire cavity chain gives a more complete description of the spectrum of the structure (multi-cavity modes, bellow modes etc.)
- Bands are more densely populated with eigenmodes in the chain of cavities
- R/Q and Q_{ext} have the tendency to be larger in the chain of cavities

Future Plans – Assembly of PRSTAB Paper



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ICFA

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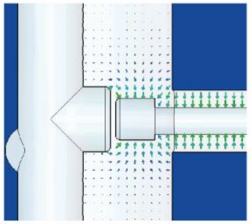
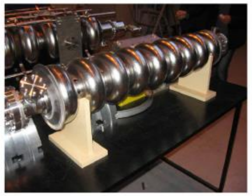
International ICFA Mini-Workshop on

High Order Modes in SC Cavities

Rostock-Warnemünde (Germany) at the Baltic Sea coast | August 22 - 24, 2016





General Information and Objectives

The workshop High Order Modes in Superconducting Cavities 2016 (HOMSC16) will be held on August 22 - 24, 2016 in Rostock-Warnemünde at the Baltic Sea. The conference venue will be "Technologiezentrum Warnemünde". The object of the workshop is to bring together researchers studying high order mode supression in superconducting cavities. The workshop will discuss the current status of both experimental and theoretical work. HOMSC16 follows HOMSC12 at the Cockcroft Institute and ASTeC, Daresbury, UK, and HOMSC14 at Fermilab, Batavia, USA.

Scientific Programme Committee (SPC)

Carsten Welsch / Cockcroft Institute
Erk Jensen / CERN
Georg Hoffstaetter / Cornell University
Jacek Sekutowicz / SLAC
Jean Delayen / Old Dominion University
Jens Knobloch / Helmholtz Zentrum Berlin
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Olivier Napoly / CEA Saclay
Roger Jones / University of Manchester
Ursula van Rienen (Chair) / Universität of Rostock
Vyacheslav Yakovlev / Fermilab

Local Organising Committee (LOC)

Ursula van Rienen (Chair) / Universität of Rostock
Thomas Flisgen / Universität of Rostock
Dirk Hecht / Universität of Rostock

Further Information and Registration

Early Bird Deadline: 25/06/2016

http://indico.cern.ch/event/465683

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