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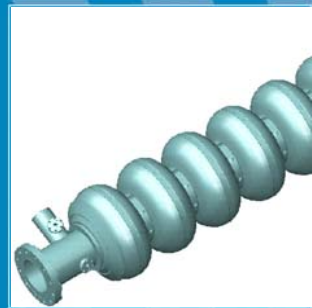

Methods and Simulation Tools for Cavity Design

Prof. Dr. Ursula van Rienen, Dr. Hans-Walter Glock

SRF09 Berlin - Dresden

Dresden 18.9.09

Overview

- **Introduction**
- **Methods in Computational Electromagnetics (CEM)**
- **Examples of CEM Methods:**
  - Finite Integration Technique (FIT)
  - Coupled S-Parameter Simulation (CSC)
- **Simulation Tools**
- **Practical Examples**
  - Some generalities
  - Some selected examples

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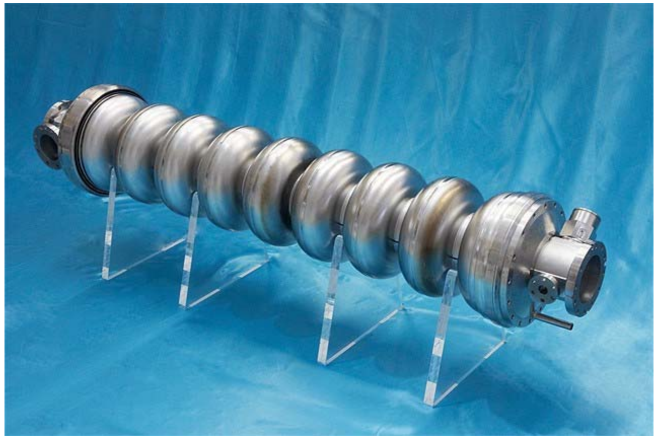
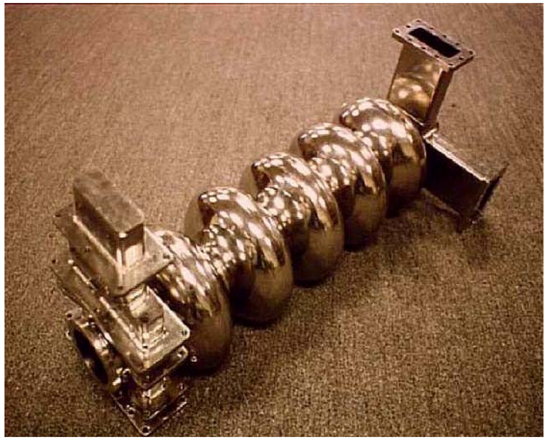
Superconducting accelerator cavities

www.kek.jp/intra-e/press/2005/image/ilc1.jpg

[Podl], IAP Frankfurt/M.



http://www.linearcollider.org/newsline/images/2008/
20080501_dc_1.jpg



Jefferson Lab /
http://www.physics.umd.edu/courses/Phys263/Kelly/cavity.jpg

http://irfu.cea.fr/Images/astImg/2407_2.jpg

... and some other types

=> Often chains of repeated structures, combined with flanges / coupling devices.

What do you need to know?

I) Accelerating Mode:

- **Do** $v_{part}/(2f_{res})$ and L_{cell} **match?**

- **How much energy does the particle gain?**

$$\Delta E_{kin} = q_{part} \int_{z=0}^{z=L_{cav}} E_z(z) \cdot \cos(2\pi f_{res} z / v_{part} + \varphi_0)\, dz$$

Jefferson Lab

- **How much energy is stored in the cavity?**

$$W_{stored} = \frac{\varepsilon_0}{2} \iiint_{V_{cav}} \left| \vec{E}_{amplitude} \right|^2 dV = \frac{\mu_0}{2} \iiint_{V_{cav}} \left| \vec{H}_{amplitude} \right|^2 dV$$

- **How big is the power loss in the wall? And how big is the unloaded quality factor?**

$$P_{loss} = \frac{R_{surface}}{2} \oiint_{cavity} \left| \vec{H}_{\tan} \right|^2 dA = \frac{1}{2} \cdot \sqrt{\frac{\omega_{res}\mu}{2\sigma}} \oiint_{cavity} \left| \vec{H}_{\tan} \right|^2 dA; \quad Q_0 = \frac{\omega_{res} W_{stored}}{P_{loss}}$$

- **Where are the maxima of electric (field emission) and magnetic (quench) field strength at the surface? Which values do they reach?**

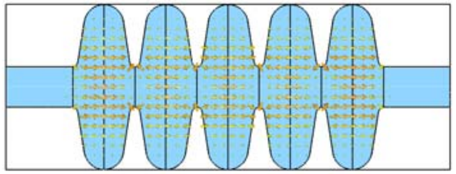
What do you need to know?

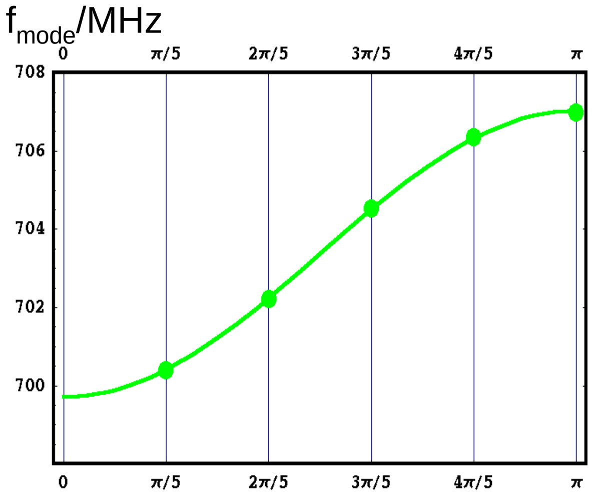
II) Fundamental passband:

• All resonant frequencies! Which frequency spread does the fundamental passband have? How close is the next neighbouring mode to the accelerating mode? → Cell-to-Cell coupling → filling time

• How strong is the beam interaction of all modes?
→ Look at "R over Q":

$$\frac{R}{Q} = \left(\frac{\Delta E_{kin}}{q_{part}} \right)^2 \Big/ \left(\omega_{res} W_{stored} \right)$$





cell-to-cell phase advance φ

III) Higher Order Modes (HOM):

• same questions as for fundamental passband

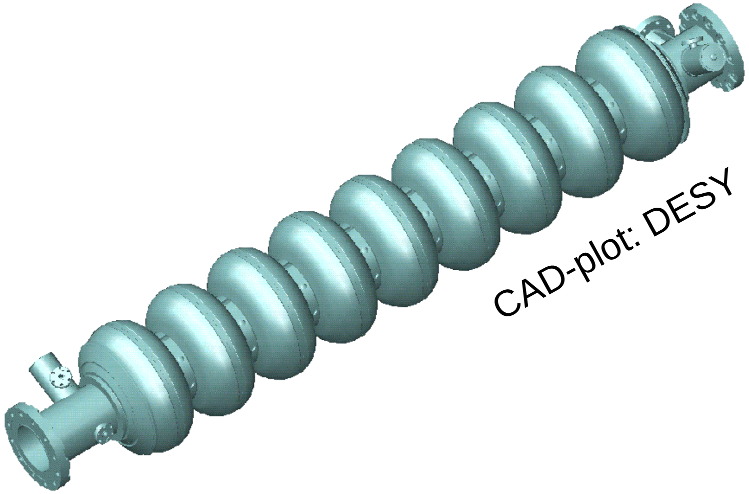
• wake potential → kick factor

• special field profiles strongly confined far away from couplers: "trapped modes"

What do you need to know?

IV) Input and HOM-coupler/absorber:

- Q_{loaded} of all beam-relevant modes
- Field distortions due to coupler?
- Field distribution within the coupler



V) Multipacting

VI) Mechanical stability wrt. Lorentz Forces

What do you need to know?

I) Accelerating mode

II) Fundamental passband

III) HOMs

IV) Input and HOM-coupler/absorber

V) Multipacting

VI) Mechanical stability wrt. Lorentz Forces

Jefferson Lab

<u>Eigenmodes</u> provide most of the information needed:

100% of I)
100% of II)
80% of III)
25% of IV)
25% of V)
50% of VI)

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Need for Numerical Methods

Most practical electrodynamics problems cannot be solved purely by means of analytical methods, see e.g.:

- **radiation caused by a mobile phone near a human head**
- **shielding of an electronic circuit by a slotted metallic box**
- **mode computation in accelerator cavities, especially in chains of cavities**

In many of such cases, numerical methods can be applied in an efficient way to come to a satisfactory solution.

Numerical Methods

Semi-analytical Methods

- Methods based on Integral Equations
- Method of Moments (MoM)

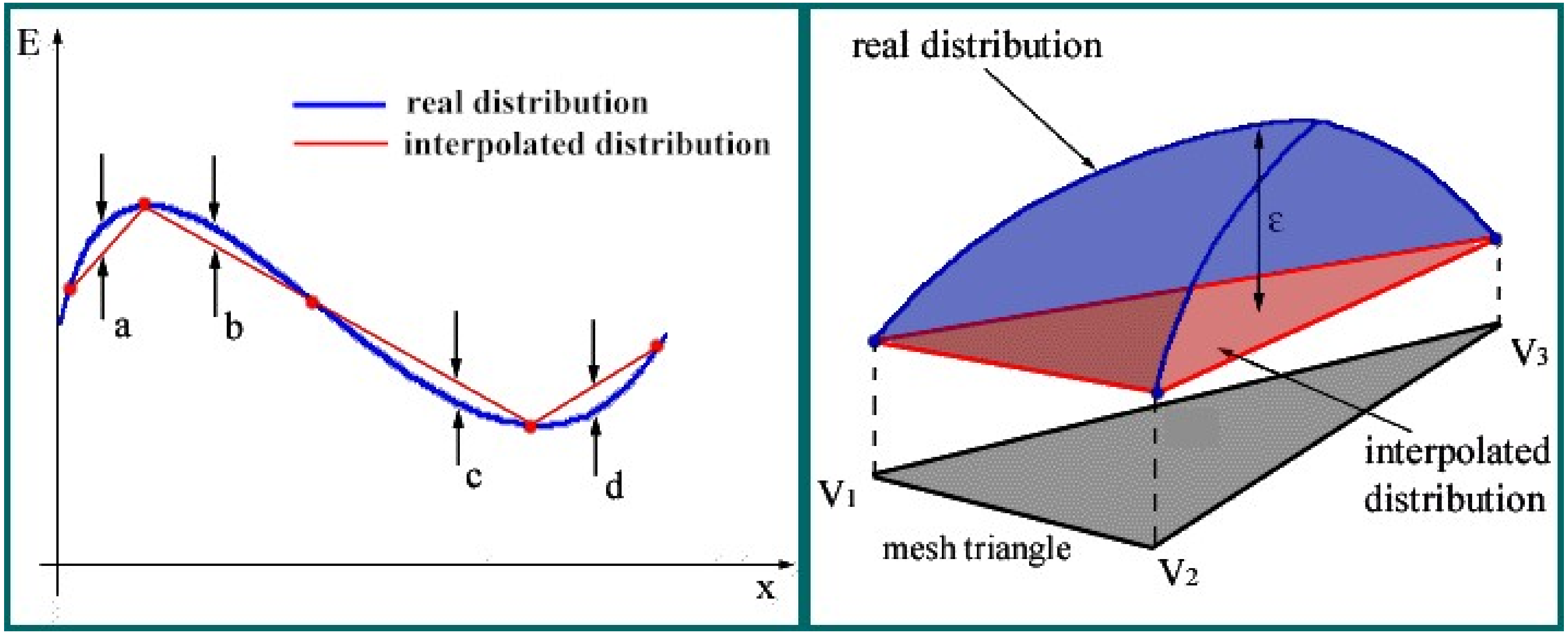
Discretization Methods

- Finite Difference Method (FD)
- Boundary Element Method (BEM)
- Finite Element Method (FEM)
- Finite Volume Method (FVM)
- **Finite Integration Technique (FIT)**

Possible Problems

- Need for geometrical simplifications → MoM
- Violation of continuity conditions → FD
- Unfavorable matrix structures → BEM
- Unphysical solutions → FEM if not mixed FEM
- Etc.

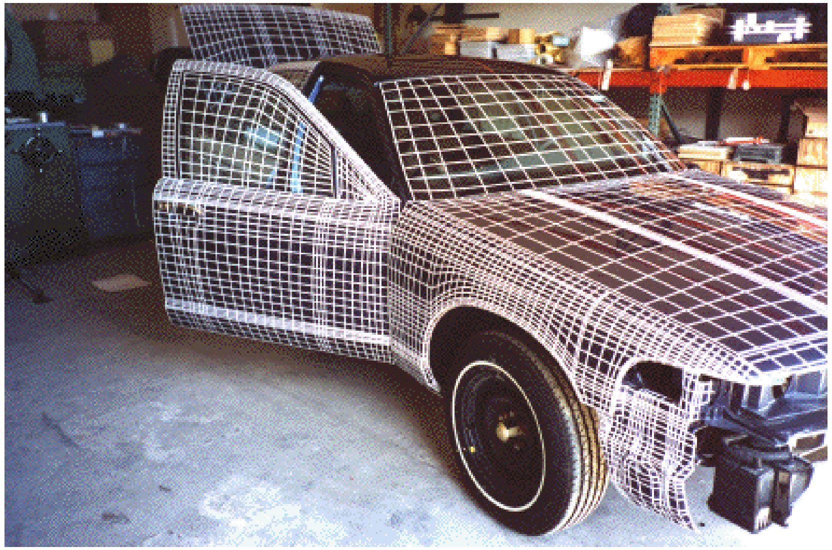
Discretization error; 1D and 2D

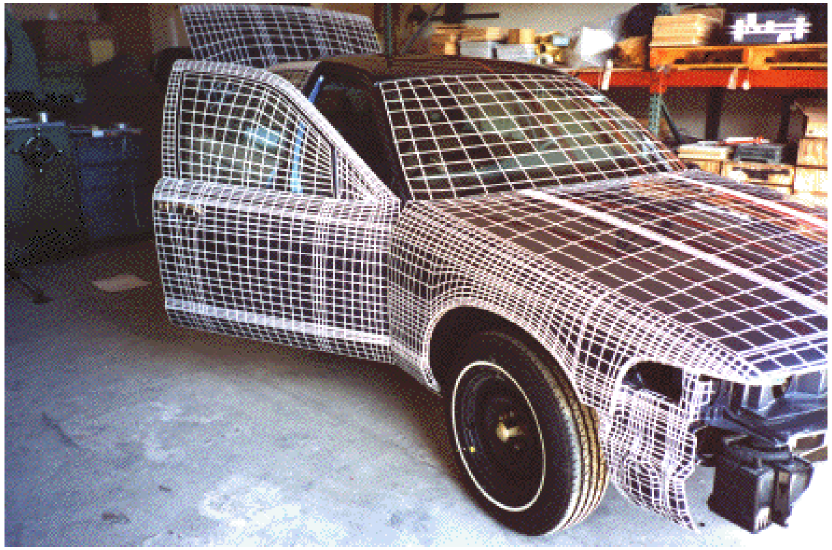


Picture source:
http://www.integra.co.jp/eng/whitepapers/inspirer/inspirer.htm

Discretization (II) of Boundary of Solution Domain

In general: geometrical error

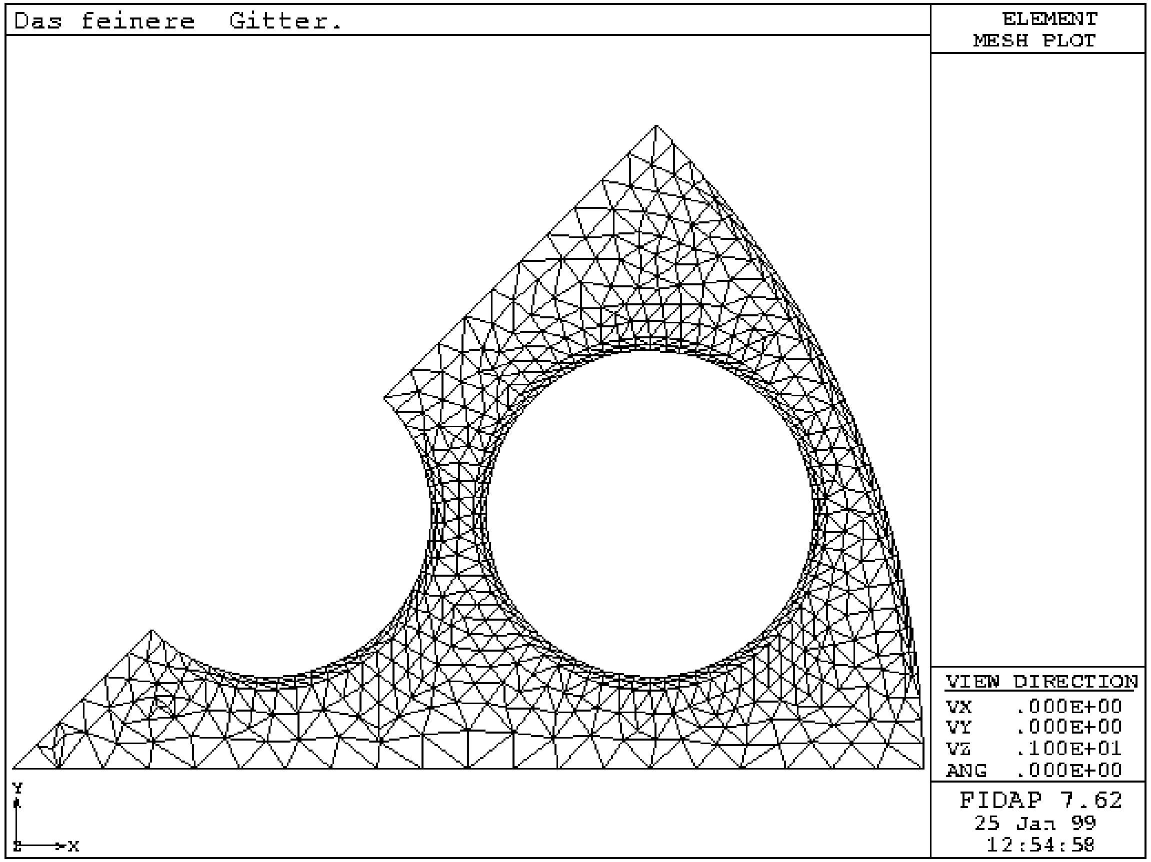




Structured „boundary-fitted“ grid

Picture source:
http://www.sri.com/poulter/crash/crown_victoria/crvic_figures/fig_cvic2.html

Unstructured 2D grid:

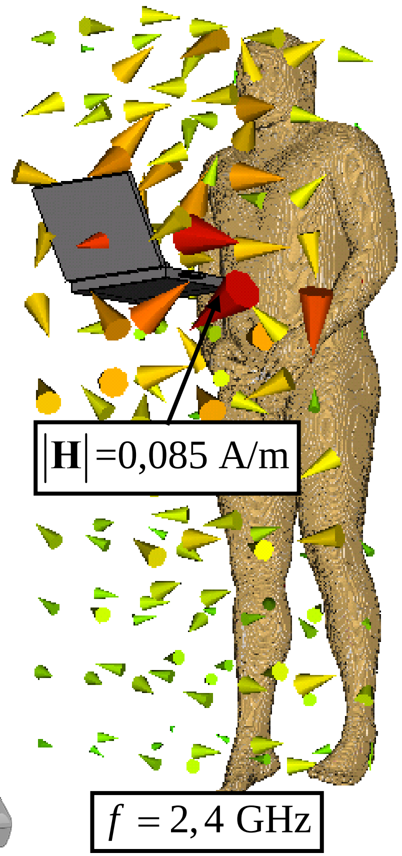


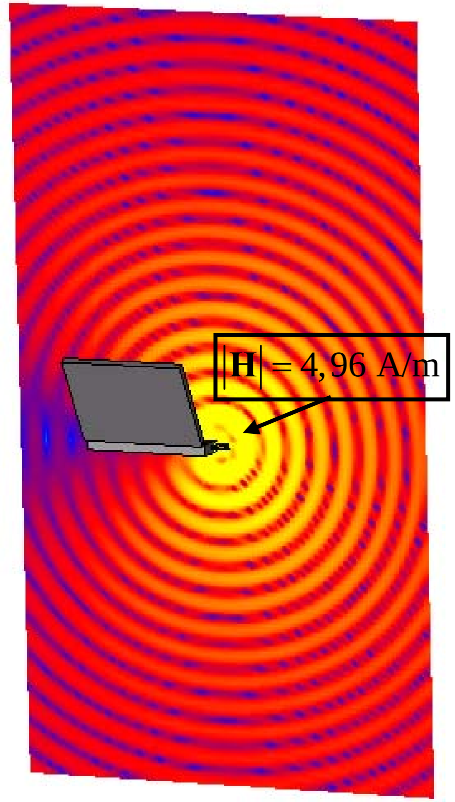
Picture source:
http://www.uni-karlsruhe.de/RZ/Dienste/GVM/DIENSTE/CAE-ANWENDUNGEN/FIDAP/erfahrung/node46.html

Discretization (V) – Space and Time

space	$\otimes$	time	$\rightarrow$	grid space	$\times$	grid time
$\mathbb{R}^3$	$\otimes$	$\mathbb{R}^+$	$\rightarrow$	G	$\times$	T

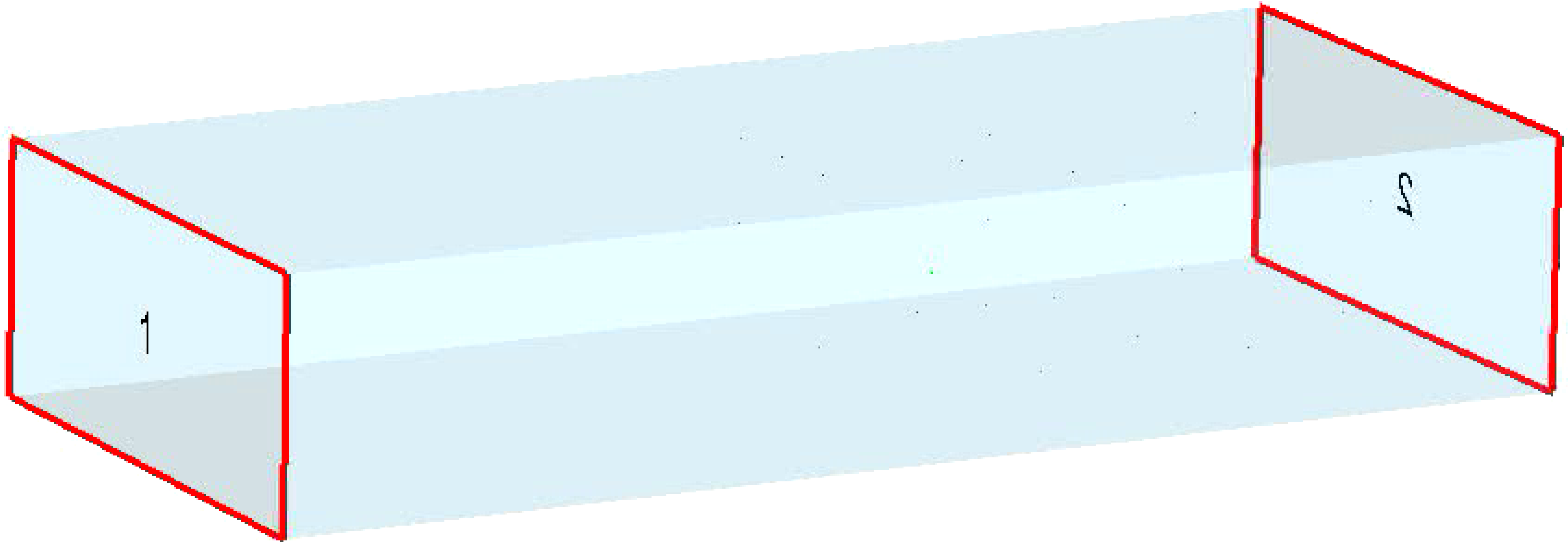
Laptop with WLAN card



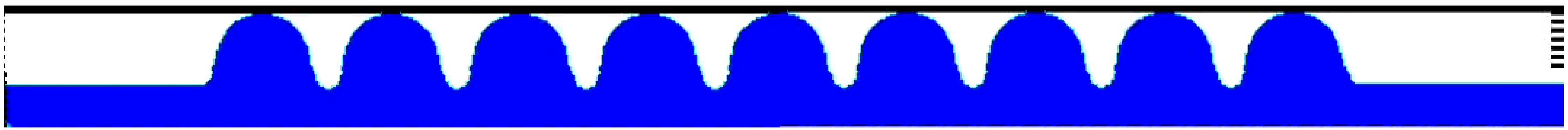


Computed with CST MWS

Wave propagation in rectangular waveguide



Energy density of „wake fields“ in the TESLA cavity



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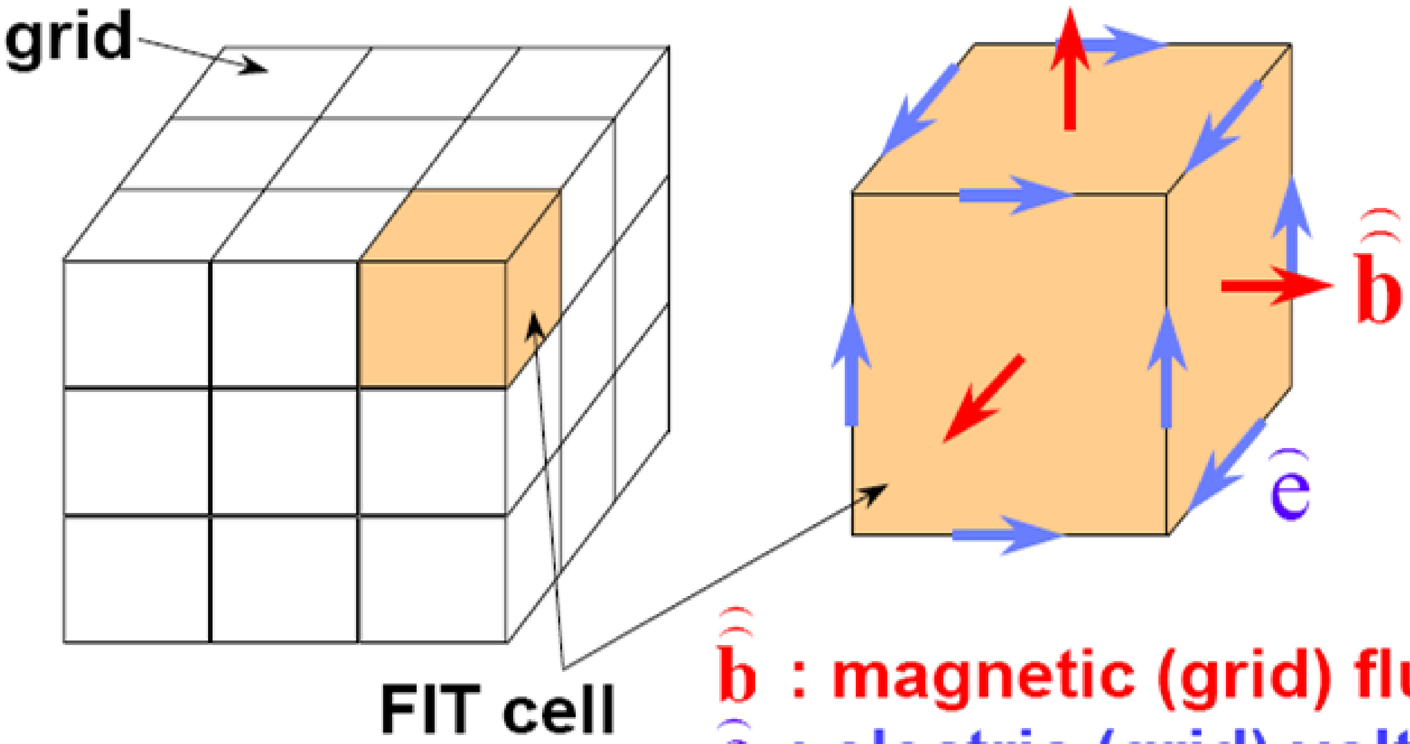
decomposition of solution space into grid cells

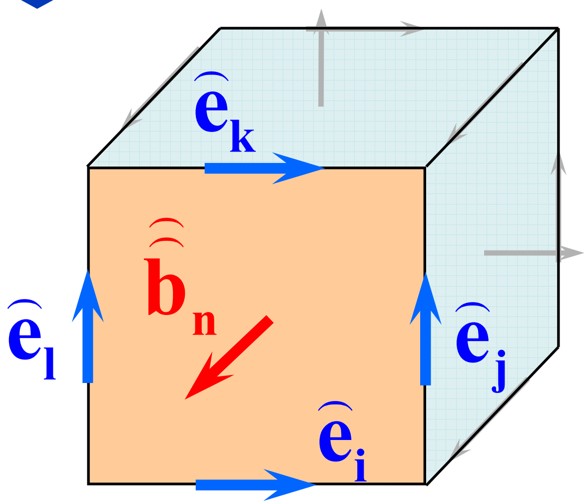


$\widehat{\widehat{b}}$: magnetic (grid) flux

$\widehat{e}$: electric (grid) voltage

FIT Discretization of Induction Law

$$\int_{\partial A} \vec{E}\cdot d\vec{s} = -\frac{\partial}{\partial t}\iint_{A} \vec{B}\cdot d\vec{A} \quad \hat{=} \quad \mathbf{C}\widehat{\mathbf{e}} = -\frac{\partial}{\partial t}\widehat{\widehat{\mathbf{b}}}$$

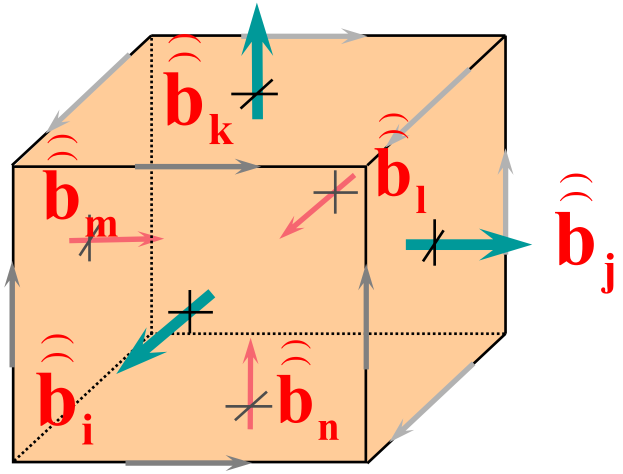


$$\widehat{e}_i + \widehat{e}_j - \widehat{e}_k - \widehat{e}_l = -\frac{\partial}{\partial t}\widehat{\widehat{b}}_n$$

$$\underbrace{\begin{pmatrix} & & & \cdot & \cdot & \cdot & & \\ 1 & \cdot & 1 & \cdot & -1 & \cdot & -1 \\ & & & \cdot & \cdot & \cdot & & \end{pmatrix}}_{\mathbf{C}} \underbrace{\begin{pmatrix} \widehat{e}_i \\ \cdot \\ \widehat{e}_j \\ \cdot \\ \widehat{e}_k \\ \cdot \\ \widehat{e}_l \end{pmatrix}}_{\widehat{\mathbf{e}}} = -\frac{\partial}{\partial t} \underbrace{\begin{pmatrix} \cdot \\ \widehat{\widehat{b}}_n \\ \cdot \end{pmatrix}}_{\widehat{\widehat{\mathbf{b}}}}$$

FIT Discretization of Gauss Law

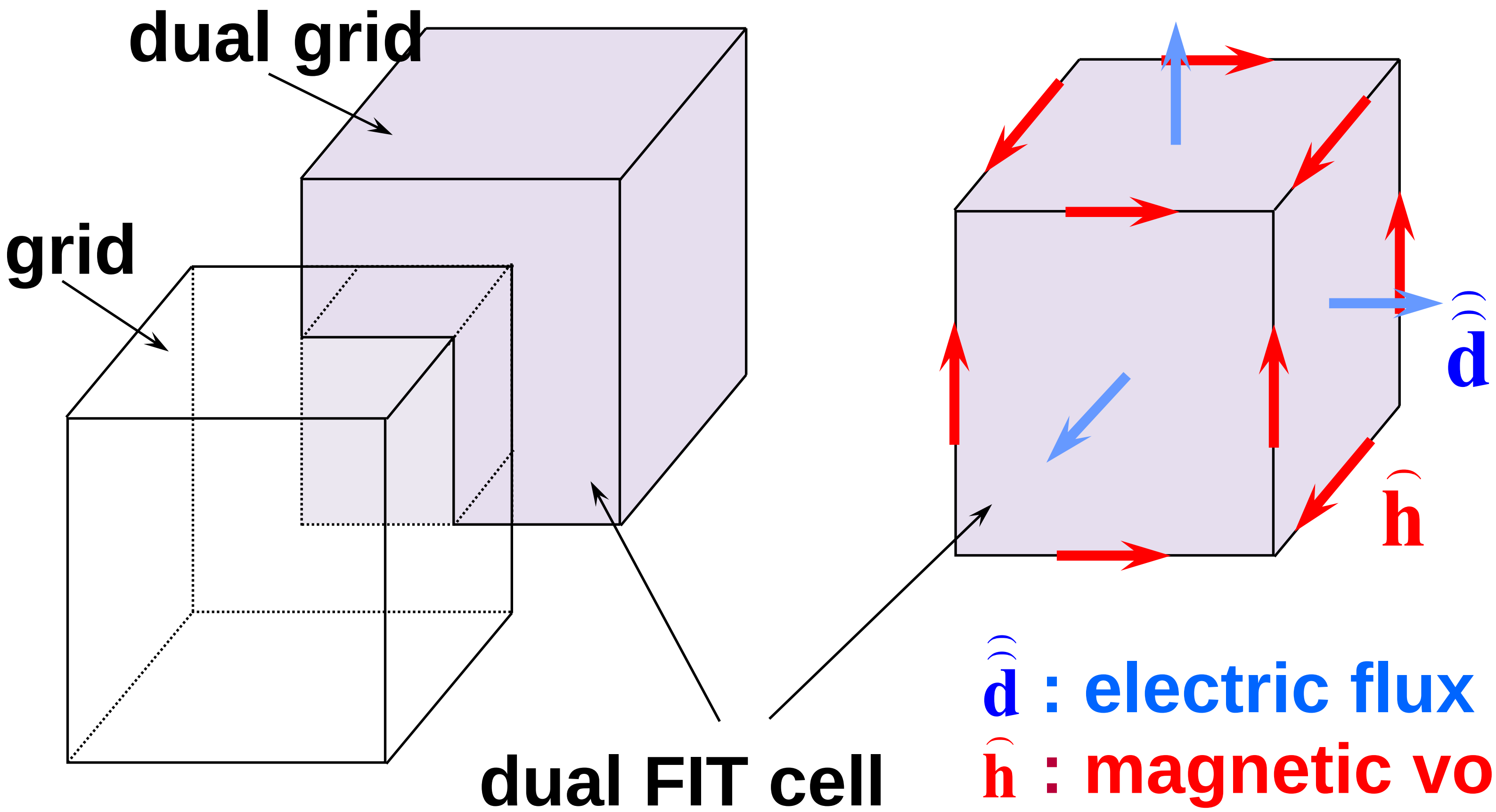
$$\oiint_{\partial V} \mathbf{B} \cdot d\mathbf{A} = 0 \quad \hat{=} \quad \mathbf{S}\widehat{\widehat{\mathbf{b}}} = \mathbf{0}$$



$$\widehat{\widehat{b}}_i + \widehat{\widehat{b}}_j + \widehat{\widehat{b}}_k - \widehat{\widehat{b}}_l - \widehat{\widehat{b}}_m - \widehat{\widehat{b}}_n = 0$$

$$\underbrace{\begin{pmatrix} & & & \cdot & \cdot & & & \\ \cdot & 1 & 1 & 1 & -1 & -1 & -1 & \cdot \\ & & & \cdot & \cdot & & & \end{pmatrix}}_{\mathbf{S}} \underbrace{\begin{pmatrix} \cdot \\ \widehat{\widehat{b}}_i \\ \widehat{\widehat{b}}_j \\ \widehat{\widehat{b}}_k \\ \widehat{\widehat{b}}_l \\ \widehat{\widehat{b}}_m \\ \widehat{\widehat{b}}_n \\ \cdot \end{pmatrix}}_{\widehat{\widehat{\mathbf{b}}}} = \mathbf{0}$$

introduction of *dual grid*



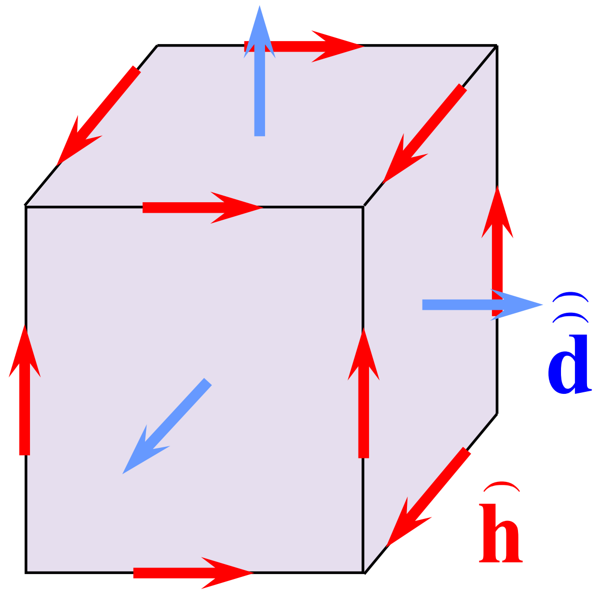
$\widehat{\widehat{d}}$: electric flux

$\widehat{h}$: magnetic voltage

FIT equations on the dual grid

$$\oint_{\partial A} \mathbf{H} \cdot d\mathbf{s} = \iint_A \left(\frac{\partial \mathbf{D}}{\partial t} + \mathbf{J} \right) \cdot d\mathbf{A} \quad \Rightarrow \quad \tilde{\mathbf{C}}\widehat{\mathbf{h}} = \frac{\partial}{\partial t}\widehat{\widehat{\mathbf{d}}} + \widehat{\widehat{\mathbf{j}}}$$

$$\oint\!\!\!\oint_{\partial V} \mathbf{D} \cdot d\mathbf{A} = \iiint_V \rho \cdot dV \quad \Rightarrow \quad \tilde{\mathbf{S}}\widehat{\widehat{\mathbf{d}}} = \mathbf{q}$$



Maxwell‘s „Grid Equations“ (MGE)

$$\operatorname{curl}\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\operatorname{curl}\mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

$$\operatorname{div}\mathbf{D} = \rho$$

$$\operatorname{div}\mathbf{B} = 0$$

$$\mathbf{D} = \varepsilon\,\mathbf{E}$$

$$\mathbf{B} = \mu\,\mathbf{H}$$

$$\mathbf{J} = \kappa\,\mathbf{E} + \mathbf{J}_e$$

FIT

$$\mathbf{C}\,\widehat{\mathbf{e}} = -\frac{\partial}{\partial t}\,\widehat{\widehat{\mathbf{b}}}$$

$$\tilde{\mathbf{C}}\,\widehat{\mathbf{h}} = \frac{\partial}{\partial t}\,\widehat{\widehat{\mathbf{d}}} + \widehat{\widehat{\mathbf{j}}}$$

$$\tilde{\mathbf{S}}\,\widehat{\widehat{\mathbf{d}}} = \mathbf{q}$$

$$\mathbf{S}\,\widehat{\widehat{\mathbf{b}}} = \mathbf{0}$$

$$\widehat{\widehat{\mathbf{d}}} = \mathbf{M}_\varepsilon\,\widehat{\mathbf{e}}$$

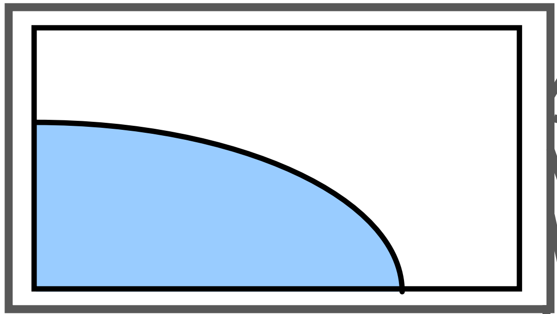
$$\widehat{\widehat{\mathbf{b}}} = \mathbf{M}_\mu\,\widehat{\mathbf{h}}$$

$$\widehat{\widehat{\mathbf{j}}} = \mathbf{M}_\kappa\widehat{\mathbf{e}} + \widehat{\widehat{\mathbf{j}}}_e$$

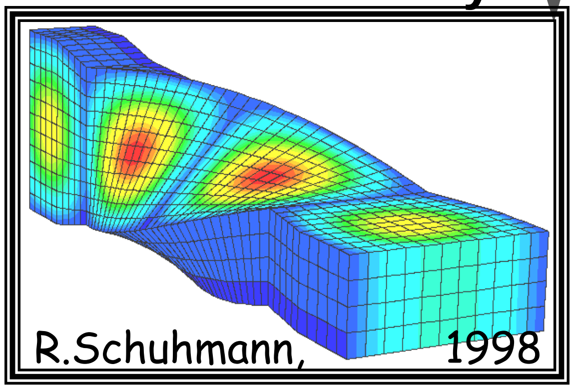
T. Weiland, 1977, 1985

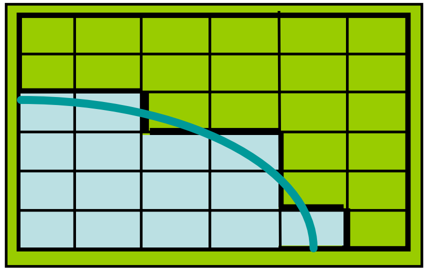
Shape Approximation on Cartesian Grids

Modelling Curved Boundaries

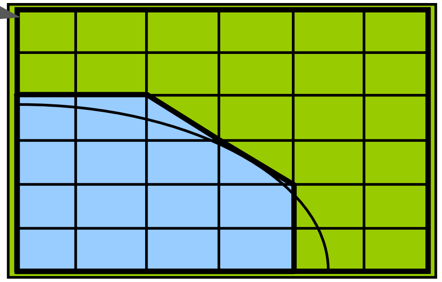


FIT on non-orthogonal grids
2^{nd} order accuracy

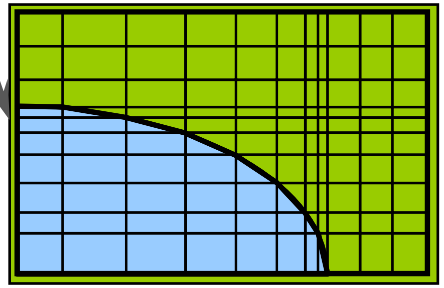




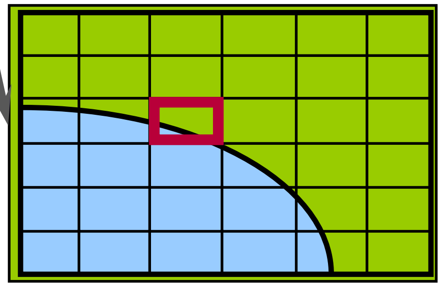
Staircase FDTD/FDFD (standard) : poor convergence



FIT with diagonal filling: better convergence
Weiland 1977



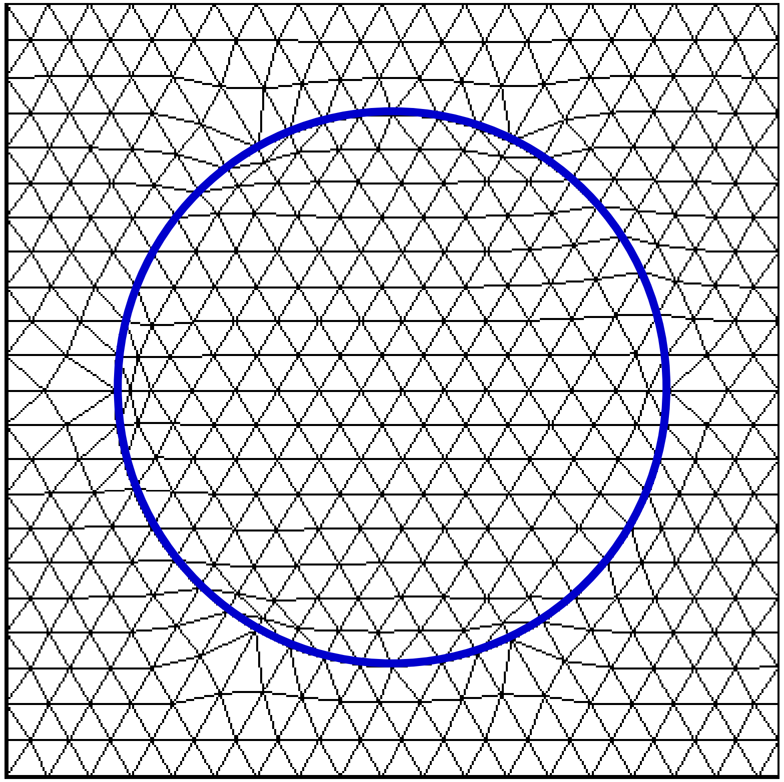
FIT with non-equidistant step size: 2^{nd} order convergence not always applicable
Weiland 1977



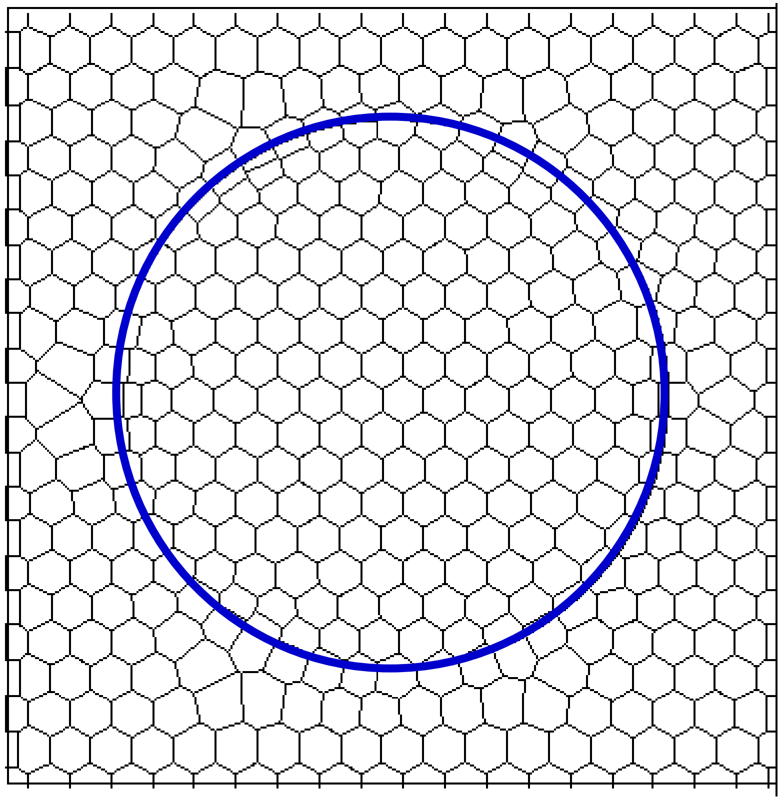
Conformal FIT / PBA: 2^{nd} order convergence always applicable
Krietenstein, Schuhmann, Thoma, Weiland 1998

FIT on Triangular Grids

Grid



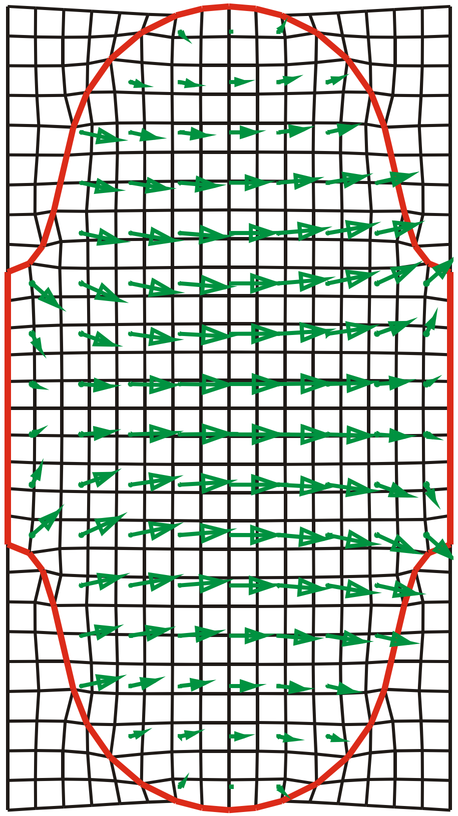
Dual grid



→ **URMEL-T**

U. van Rienen 1983

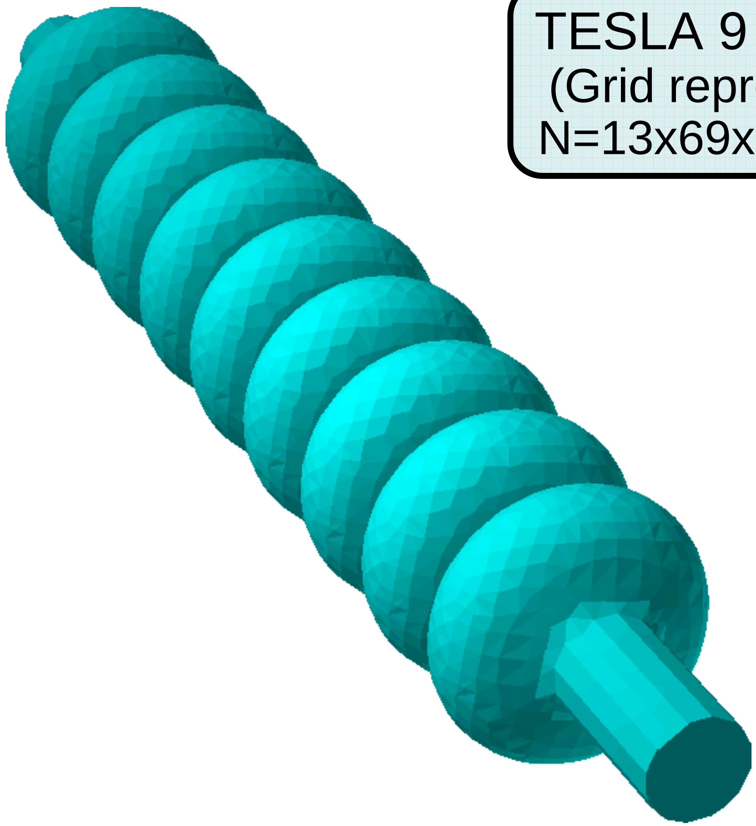
FIT on Non-Orthogonal Grids



Field in model of 1 cell

Hilgner, Schuhmann, Weiland

TU Darmstadt 1998



TESLA 9 cell struct.
(Grid representation,
N=13x69x13=11.661)

Maxwell's „Grid Equations" (MGE) → Curl Curl Equation

$$\operatorname{curl}\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\operatorname{curl}\mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

$$\operatorname{div}\mathbf{D} = \rho$$

$$\operatorname{div}\mathbf{B} = 0$$

$$\mathbf{D} = \varepsilon\,\mathbf{E}$$

$$\mathbf{B} = \mu\,\mathbf{H}$$

$$\mathbf{J} = \kappa\,\mathbf{E} + \mathbf{J}_e$$

FIT

T. Weiland, 1977, 1985

$$\mathbf{C}\,\widehat{\mathbf{e}} = -\frac{\partial}{\partial t}\,\widehat{\widehat{\mathbf{b}}}$$

$$\tilde{\mathbf{C}}\,\widehat{\mathbf{h}} = \frac{\partial}{\partial t}\,\widehat{\widehat{\mathbf{d}}} + \widehat{\widehat{\mathbf{j}}}$$

$$\tilde{\mathbf{S}}\,\widehat{\widehat{\mathbf{d}}} = \mathbf{q}$$

$$\mathbf{S}\,\widehat{\widehat{\mathbf{b}}} = \mathbf{0}$$

$$\widehat{\widehat{\mathbf{d}}} = \mathbf{M}_\varepsilon\,\widehat{\mathbf{e}}$$

$$\widehat{\widehat{\mathbf{b}}} = \mathbf{M}_\mu\,\widehat{\mathbf{h}}$$

$$\widehat{\widehat{\mathbf{j}}} = \mathbf{M}_\kappa\,\widehat{\mathbf{e}} + \widehat{\widehat{\mathbf{j}}}_e$$

In full analogy to analytical derivation of wave equation

Curl-Curl-Eigenvalue Equation

$\underline{\widehat{\widehat{\mathbf{j}}}}_S \equiv \mathbf{0}$ (no current excitation)

$\sigma = 0, \quad \varepsilon, \mu$ real (loss-free)

$$\mathbf{M}_{\varepsilon}^{-1}\,\tilde{\mathbf{C}}\mathbf{M}_{\mu^{-1}}\mathbf{C}\,\widehat{\mathbf{e}} = \omega^2\widehat{\mathbf{e}}$$

eigenvalue problem

$$\mathbf{A}\mathbf{x} = \lambda\mathbf{x}$$

$$\mathbf{A}_{CC} = \mathbf{M}_{\varepsilon}^{-1}\,\tilde{\mathbf{C}}\mathbf{M}_{\mu-1}\mathbf{C}$$

$$\varepsilon^{-1}\,\mathrm{curl}\,\mu^{-1}\,\mathrm{curl}\,\mathbf{E} = \omega^2\mathbf{E}$$

Curl-Curl-Eigenvalue Equation

Use transformation $\hat{\mathbf{e}}' = \mathbf{M}_{\varepsilon}^{1/2}\,\hat{\mathbf{e}}$ to derive an equation with symmetric system matrix

$$\boxed{\mathbf{M}_{\varepsilon}^{1/2}\tilde{\mathbf{C}}\mathbf{M}_{\mu^{-1}}\,\tilde{\mathbf{C}}\mathbf{M}_{\varepsilon}^{-1/2}\,\hat{\mathbf{e}}' = \omega^{2}\,\hat{\mathbf{e}}'}$$

system matrix

$$\begin{aligned}\mathbf{A}' &= \mathbf{M}_{\varepsilon}^{1/2}\,\mathbf{A}_{CC}\,\mathbf{M}_{\varepsilon}^{-1/2}\\ &= \mathbf{M}_{\varepsilon}^{-1/2}\tilde{\mathbf{C}}\mathbf{M}_{\mu-1}\mathbf{C}\mathbf{M}_{\varepsilon}^{-1/2}\\ &= \left(\mathbf{M}_{\varepsilon}^{-1/2}\tilde{\mathbf{C}}\mathbf{M}_{\mu}^{-1/2}\right)\left(\mathbf{M}_{\varepsilon}^{-1/2}\tilde{\mathbf{C}}\mathbf{M}_{\mu}^{-1/2}\right)^{T}\end{aligned}$$

is symmetric

Solution Space of Eigenvalue Problem

system matrix
$$\mathbf{A}' = \mathbf{M}_\varepsilon^{1/2}\ \mathbf{A}_{CC}\ \mathbf{M}_\varepsilon^{-1/2}$$
$$= \mathbf{M}_\varepsilon^{-1/2}\tilde{\mathbf{C}}\mathbf{M}_{\mu^{-1}}\mathbf{C}\mathbf{M}_\varepsilon^{-1/2}$$
$$= \left(\mathbf{M}_\varepsilon^{-1/2}\tilde{\mathbf{C}}\mathbf{M}_\mu^{-1/2}\right)\left(\mathbf{M}_\varepsilon^{-1/2}\tilde{\mathbf{C}}\mathbf{M}_\mu^{-1/2}\right)^T$$
is symmetric

Eigenvalues of **A**‘
(and thus of $\mathbf{A}_{CC}$ as well) are

1. real
2. non-negative

because

1. **A**‘ is symmetric
2. **A**‘ = matrix · (matrix)^T

⇒

Eigenfrequencies ω_i are real and non-negative as it should be for a loss-less resonator

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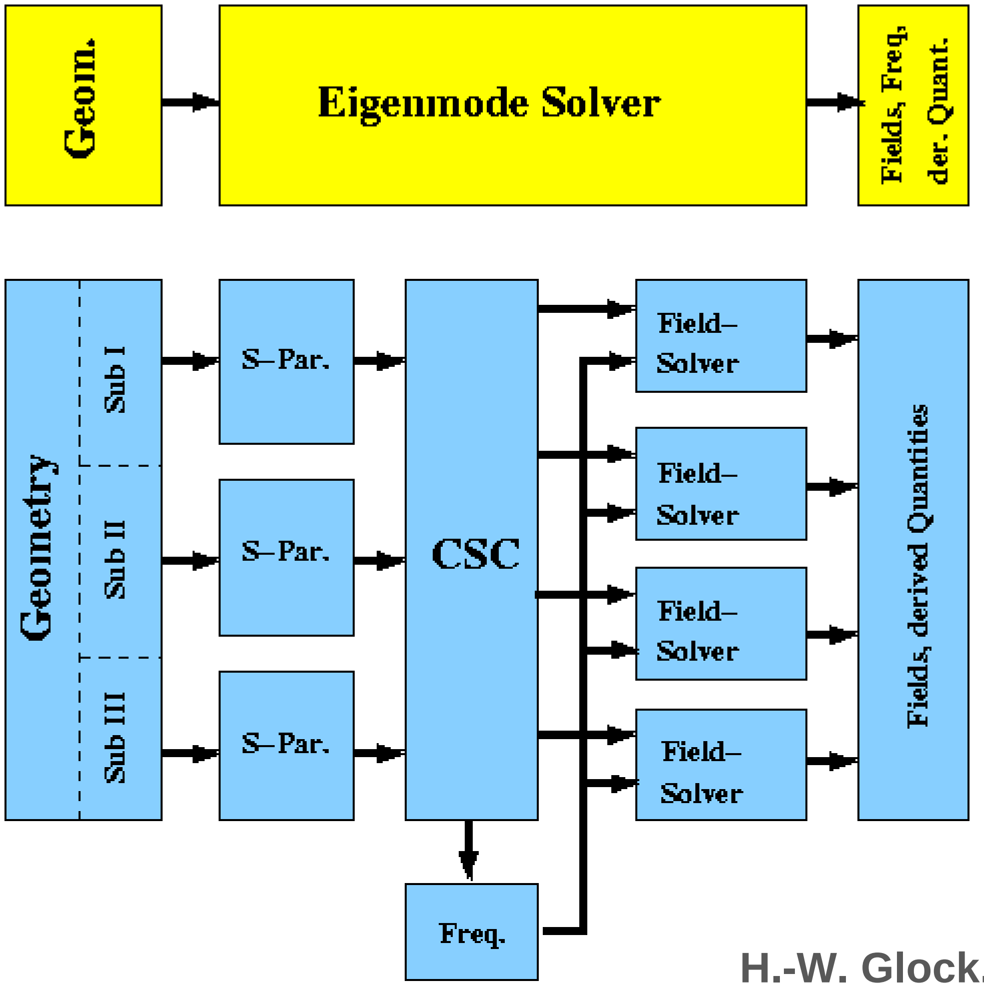
Coupled S-Parameter Calculation



H.-W. Glock, K.Rothemund, UvR 98

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CST MICROWAVE STUDIO®

-**Transient Solver**

- **Eigenmode Solver**

- **Frequency Domain Solver**

- **Resonant: S-Parameters and Fields**

- **Integral Equations Solver**

- **Predecessors for eigenmode calculation: MAFIA, URMEL, URMEL-T**

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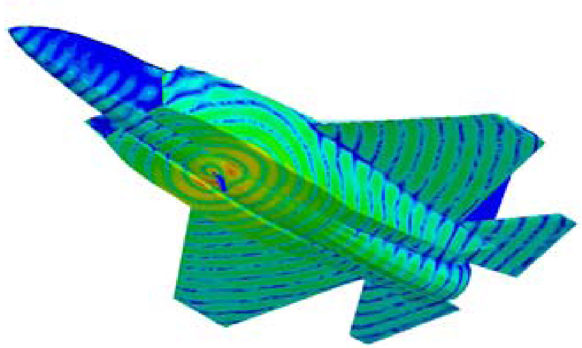
3D Full-wave Electromagnetic Field Simulation



HFSS™ is the industry-standard simulation tool for 3D full-wave electromagnetic field simulation. HFSS provides E- and H-fields, currents, S-parameters and near and far radiated field results. Intrinsic to the success of HFSS as an engineering design tool is its automated solution process where users are only required to specify geometry, material properties and the desired output. From here HFSS will automatically generate an appropriate, efficient and accurate mesh for solving the problem using the proven finite element method. With HFSS the physics defines the mesh, not the mesh defining the physics. Engineers rely on the accuracy, capacity, and performance of HFSS to design high-speed components including on-chip embedded passives, IC packages, PCB interconnects, and high-frequency components such as antennas, RF/microwave components, and biomedical devices.

The power of HFSS comes from many Ansoft pioneered research and development innovations. These breakthroughs have made HFSS the most widely used software for solving 3D full-wave electromagnetic field simulations.

- Tangential vector basis functions enabled the highly accurate finite element method for electromagnetic field solution
- Transfinite element method for fast and accurate multi-mode S-parameter extractions
- Automatic mesh generation and adaptive refinement for reliable, repeatable and efficient results

http://www.ansoft.com/products/hf/hfss/

ACE3P Suite

ACE3P - Advanced Computational Electromagnetic Simulation Suite
developed at SLAC by the group around Kwok Ko, Cho NG et al.

Module Name	Short Description	Home Institution
Omega3P	Frequency domain solver for computing resonant modes (with damping)	SLAC
[S3P]	Frequency domain solver for evaluating scattering parameters	SLAC
[T3P]	Time-domain solver for calculating transient effects and wakefields	SLAC
[Pic3P]	Particle-in-cell code for simulating space charge dominated devices	SLAC
[Track3P]	Particle tracking code for simulating multipacting and dark current	SLAC
[TEM3P]	Multi-physics module that includes electromagnetic, thermal and mechanical effects	SLAC
Paraview	Advanced visualization and analysis software	paraview.org

→ See examples in next part of the talk

https://confluence.slac.stanford.edu/display/AdvComp/Omega3P

Overview

- **Introduction**
- **Methods in Computational Electromagnetics (CEM)**
- **Examples of CEM Methods:**
  - Mode Matching Technique
  - Finite Integration Technique (FIT)
  - Coupled S-Parameter Simulation (CSC)
- **Simulation Tools**
- **Practical Examples**
  - Some generalities
  - Some selected examples

Workflow of eigenmode computation

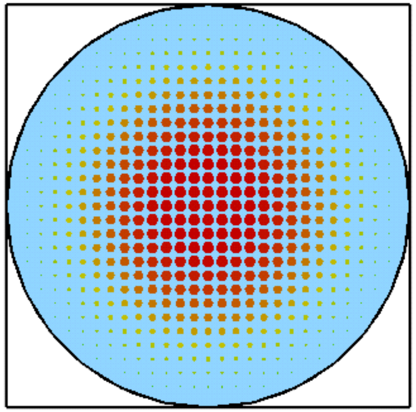
- define geometry / import CAD-data
- take care of your grid
- define material properties
- define symmetries and boundaries
- check solver parameters
- run solver (and maybe: wait)
- frequency range ok ???
- precision ok ???
- (quasi) mode degeneration ???
- post process: visualization
- post process: derived quantities

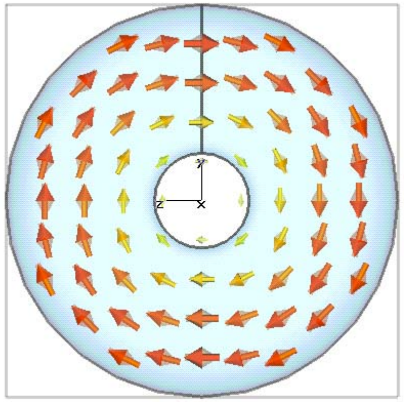
Workflow of eigenmode computation

define symmetries and boundaries

Passband Fields with E_{tan} = 0 in middle of the cavity

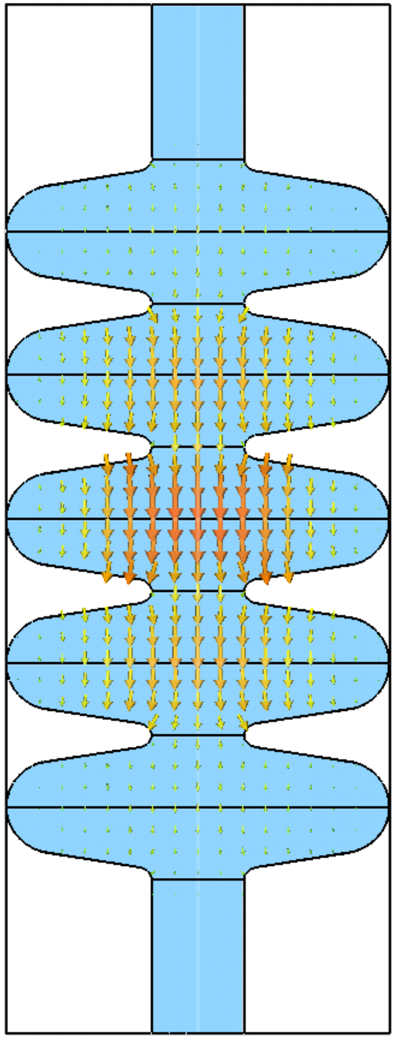
Make use of symmetry → compute only ½ of the cavity



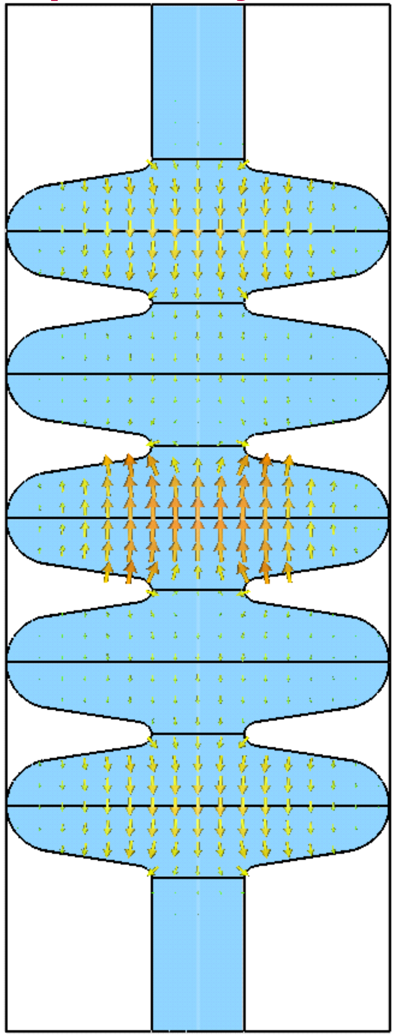


Monopole-type E- and H-field, common to all modes and cells

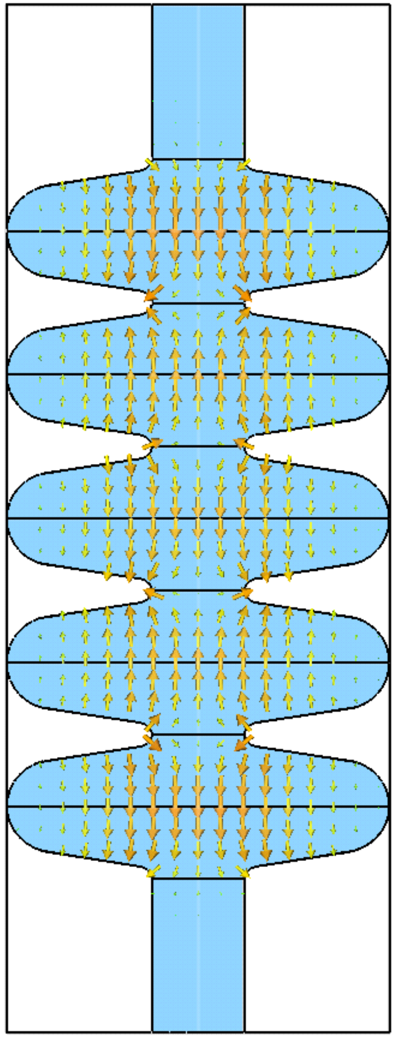
Computed with CST MWS



TM_{010}- $\pi/5$ (pseudo 0)



TM_{010}-$3\pi/5$



TM_{010}-π (accelerating)

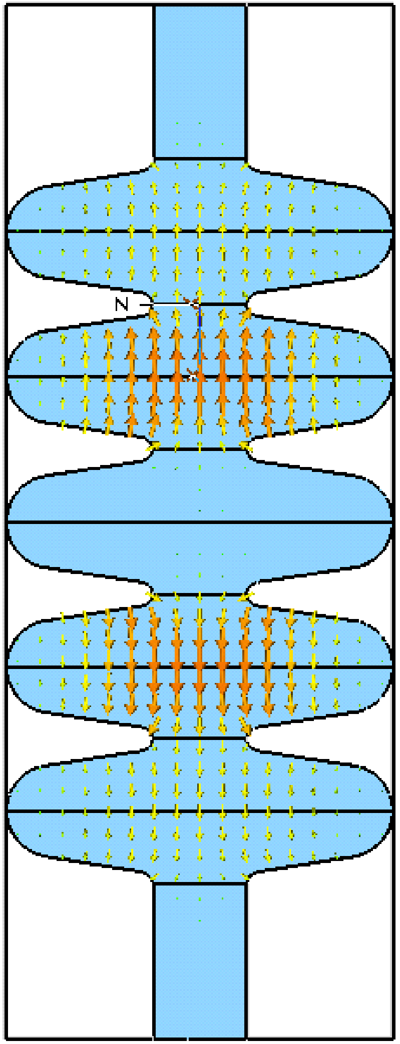
Passband Fields with $H_{tan} = 0$ in middle of the cavity

Use of symmetry → compute only ½ of the cavity

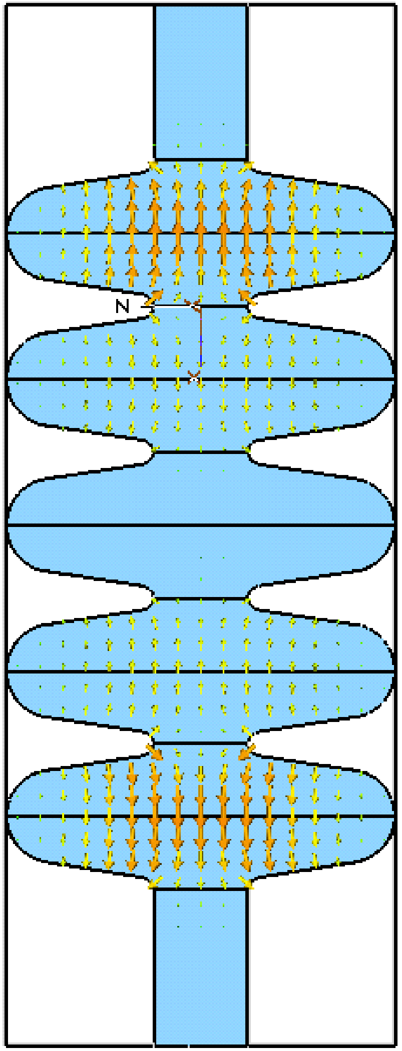
Needs of course 2 (shorter) runs!

Visualization of full cavity provided by CST MWS

Even 1/8 part might be enough for computation



TM_{010}-2π/5



TM_{010}-4π/5

Computed with CST MWS

Passband Fields altogether

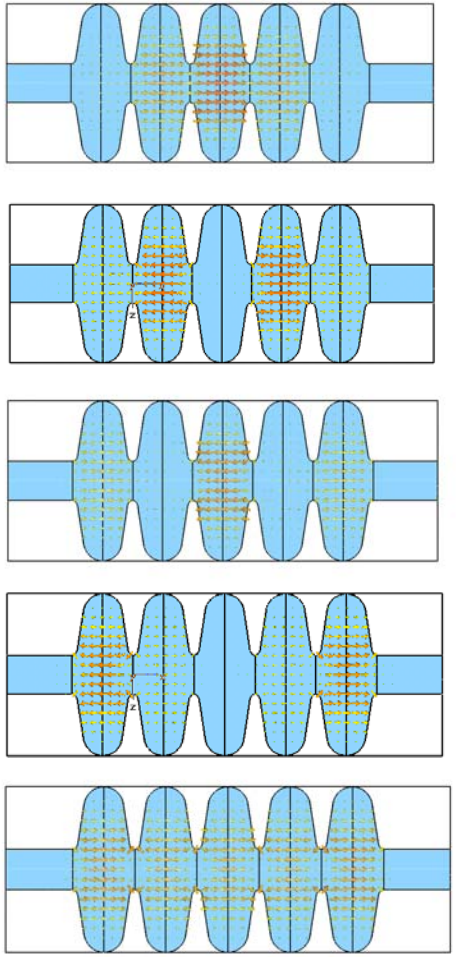
TM_{010}-$\pi/5$
700.40098 MHz

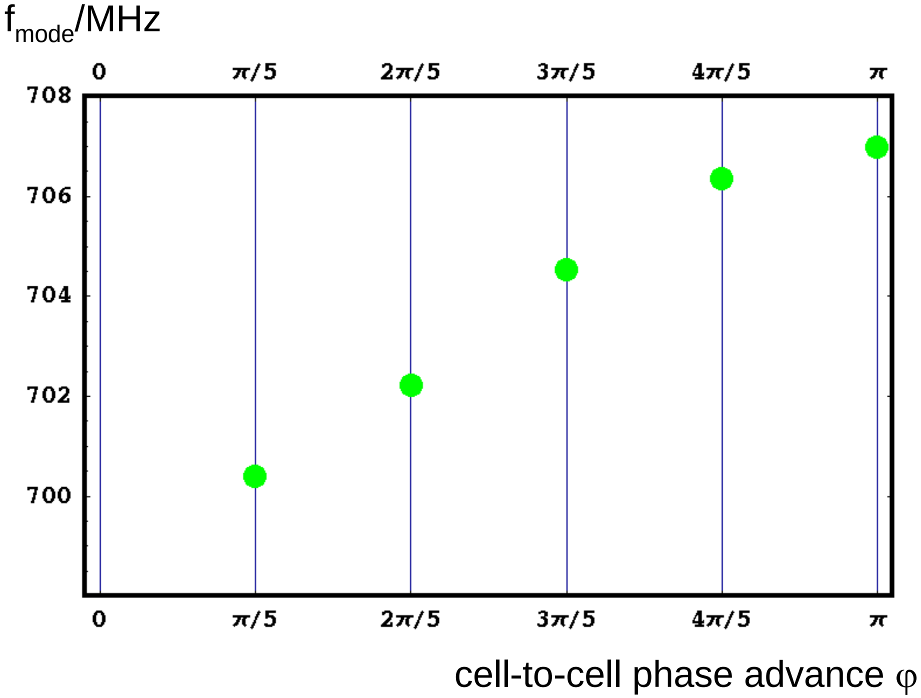
TM_{010}-$2\pi/5$
702.21446 MHz

TM_{010}-$3\pi/5$
704.52333 MHz

TM_{010}-$4\pi/5$
706.34471 MHz

TM_{010}-π
706.97466 MHz



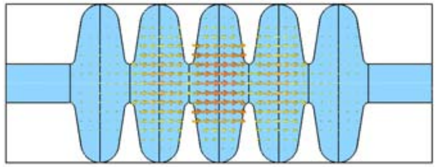


... which seems to obey some rule ?!

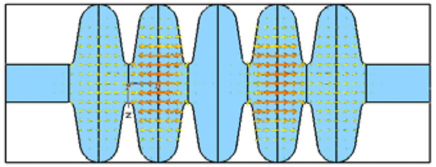
Computed with CST MWS

Passband fields altogether

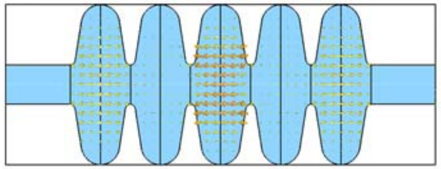
TM_{010}-$\pi/5$
700.40098 MHz



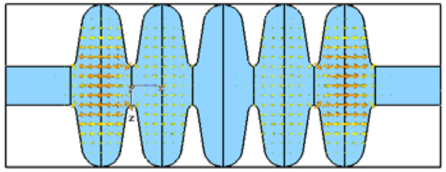
TM_{010}-$2\pi/5$
702.21446 MHz



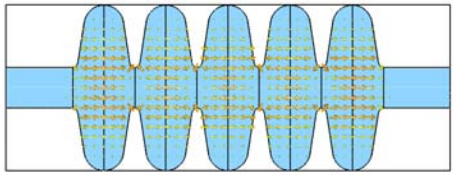
TM_{010}-$3\pi/5$
704.52333 MHz

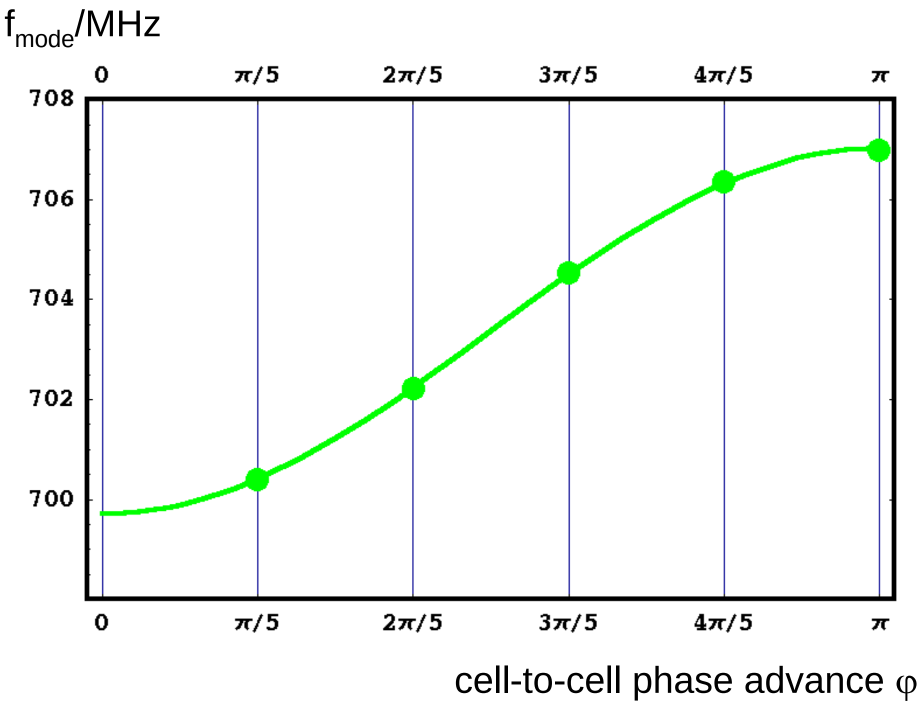


TM_{010}-$4\pi/5$
706.34471 MHz



TM_{010}-π
706.97466 MHz





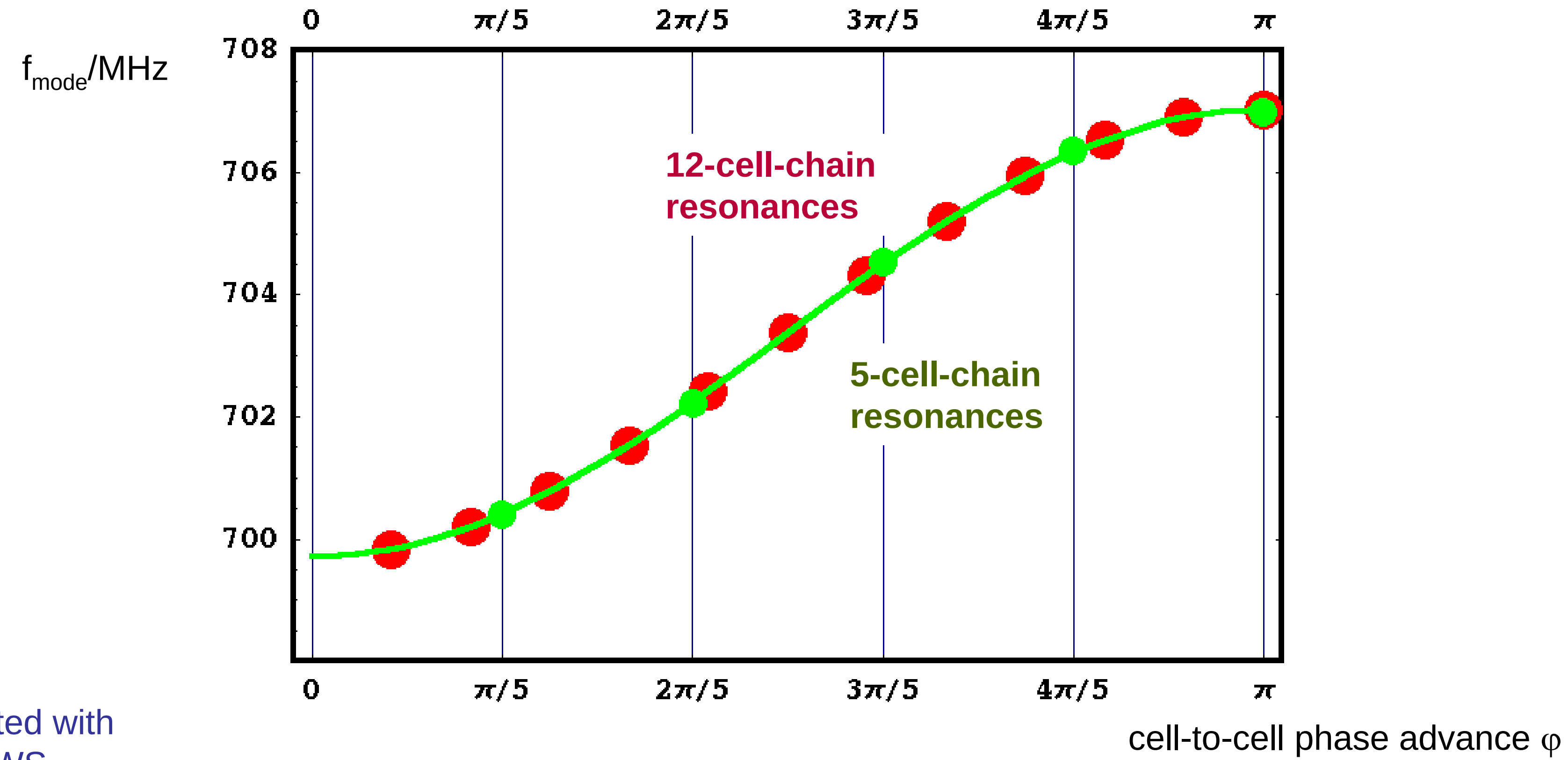
In fact: $$f_{mode} \approx \frac{f_0 + f_\pi}{2}\left[1 - \frac{\kappa_{cc}}{2}\cos(\varphi)\right]$$

κ_{cc} **: cell-to-cell coupling;**
compare K. Saito´s talk

Computed with
CST MWS

So, what are passbands?

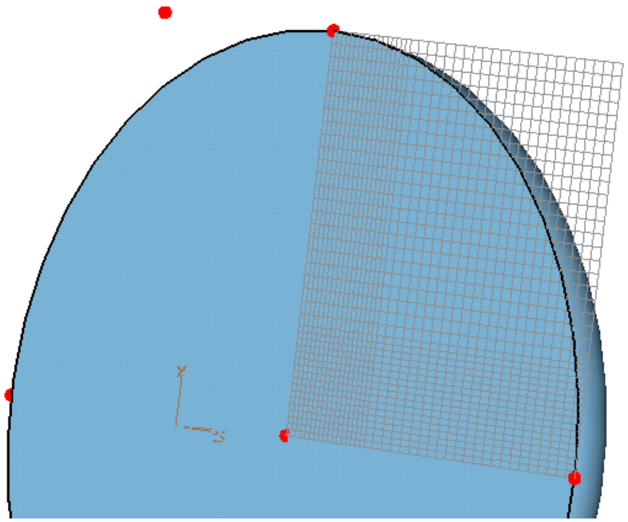
Cavities built by chains of *identical cells* show resonances in certain frequency intervalls, called passbands, *determined only by the shape of the elementary cell*.
The distribution of resonances in the band depends on the number of cells in the chain:

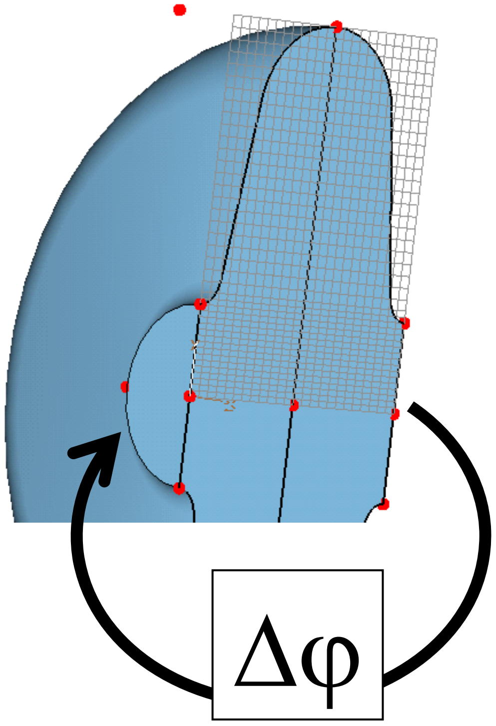


Computed with CST MWS

Periodic Boundary Conditions

In fact, it is possible, to calculate the spectrum of an infinite chain by discretizing a single cell (exploiting other symmetries as well) ...:



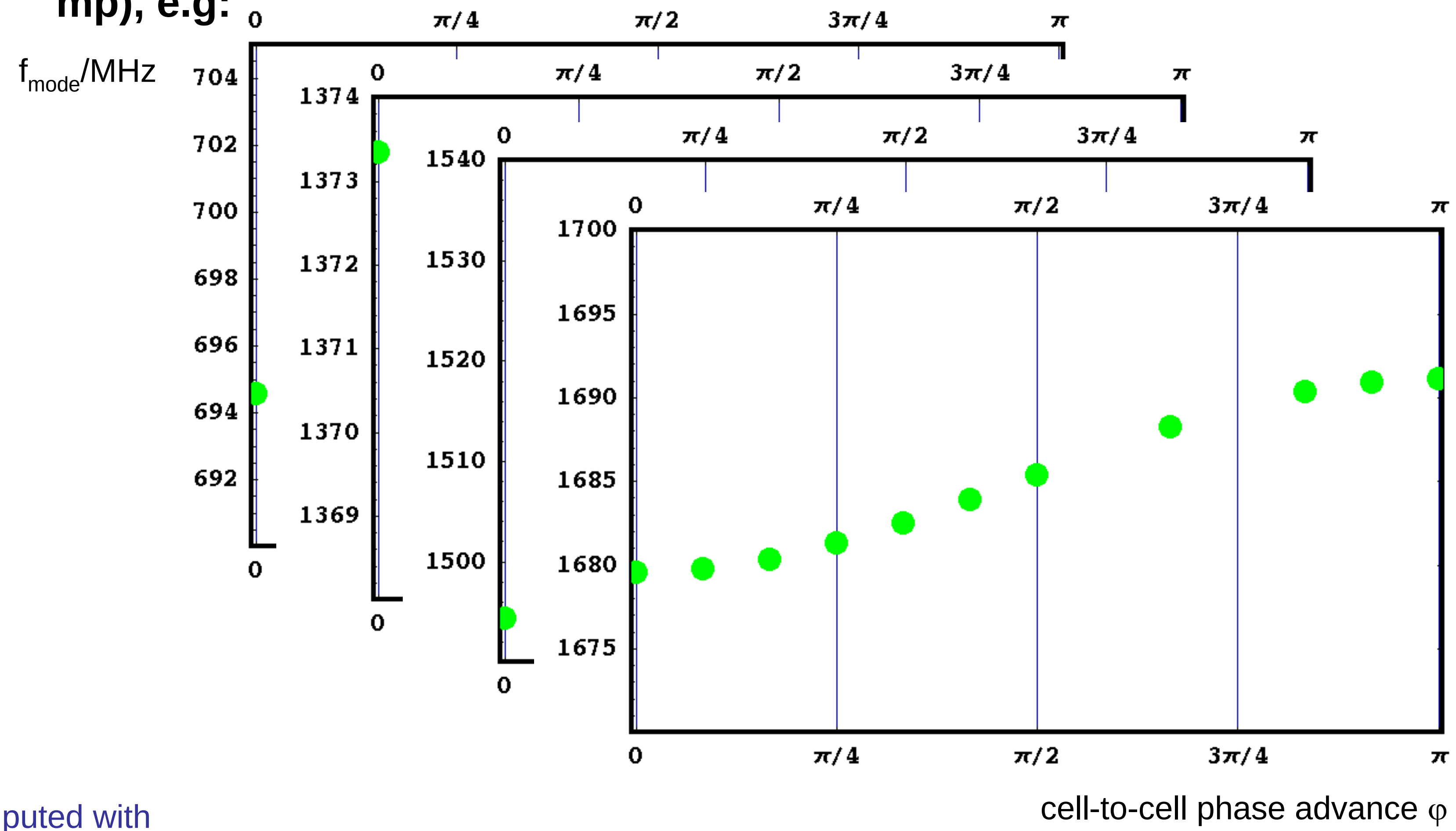


... and to preset the cell-to-cell phase advance by application of an appropriate longitudinal boundary condition.

Computed with
CST MWS

Periodic Boundary Conditions

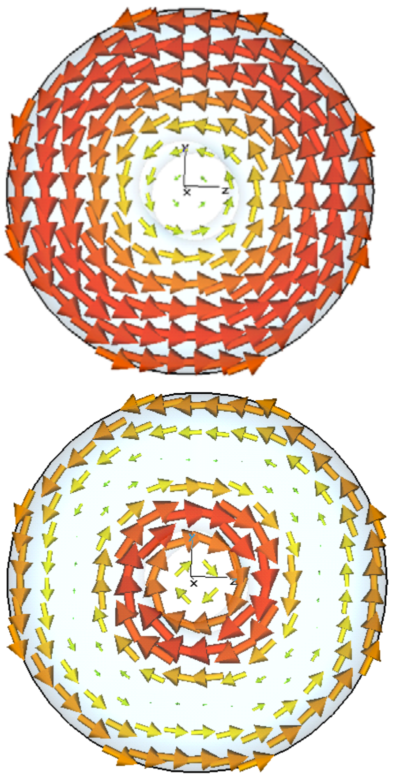
This needs only one single run for each Δφ, but gives eigenmode frequencies of several passbands with a very small grid (here 19,000 mp), e.g:



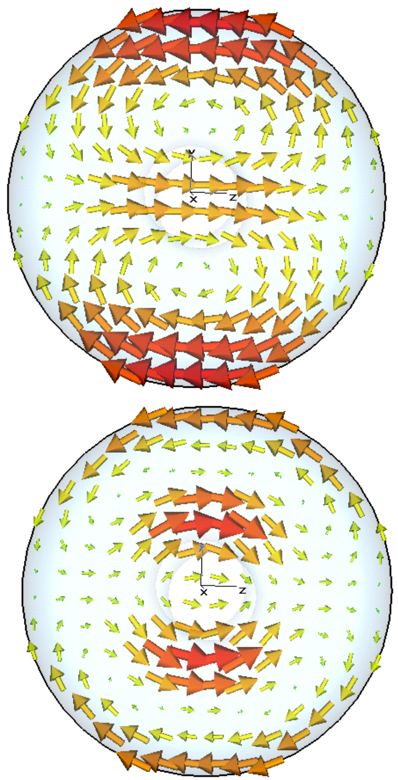
Computed with CST MWS

What are Monopole-, Dipole-, Quadrupole-Modes?

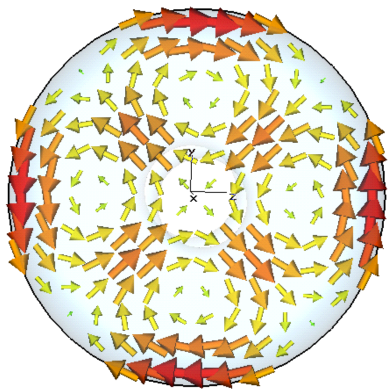
Consider structures of axial circular symmetry. Then all fields belong to classes with invariance to certain azimuthal rotations:



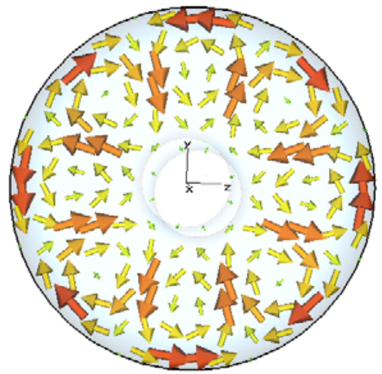
Monopole, any φ



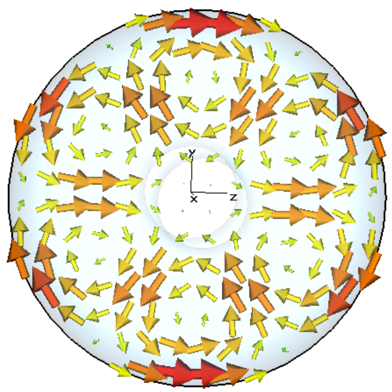
Dipole, φ =180°



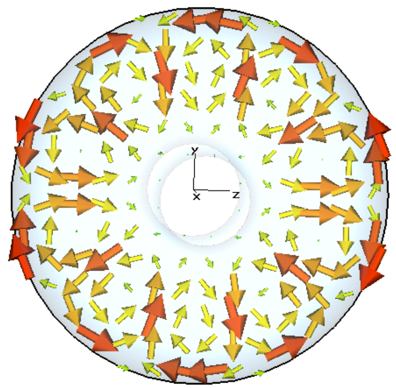
Quadrupole, φ =90°



Oktupole, φ =45°



Sextupole, φ =60°

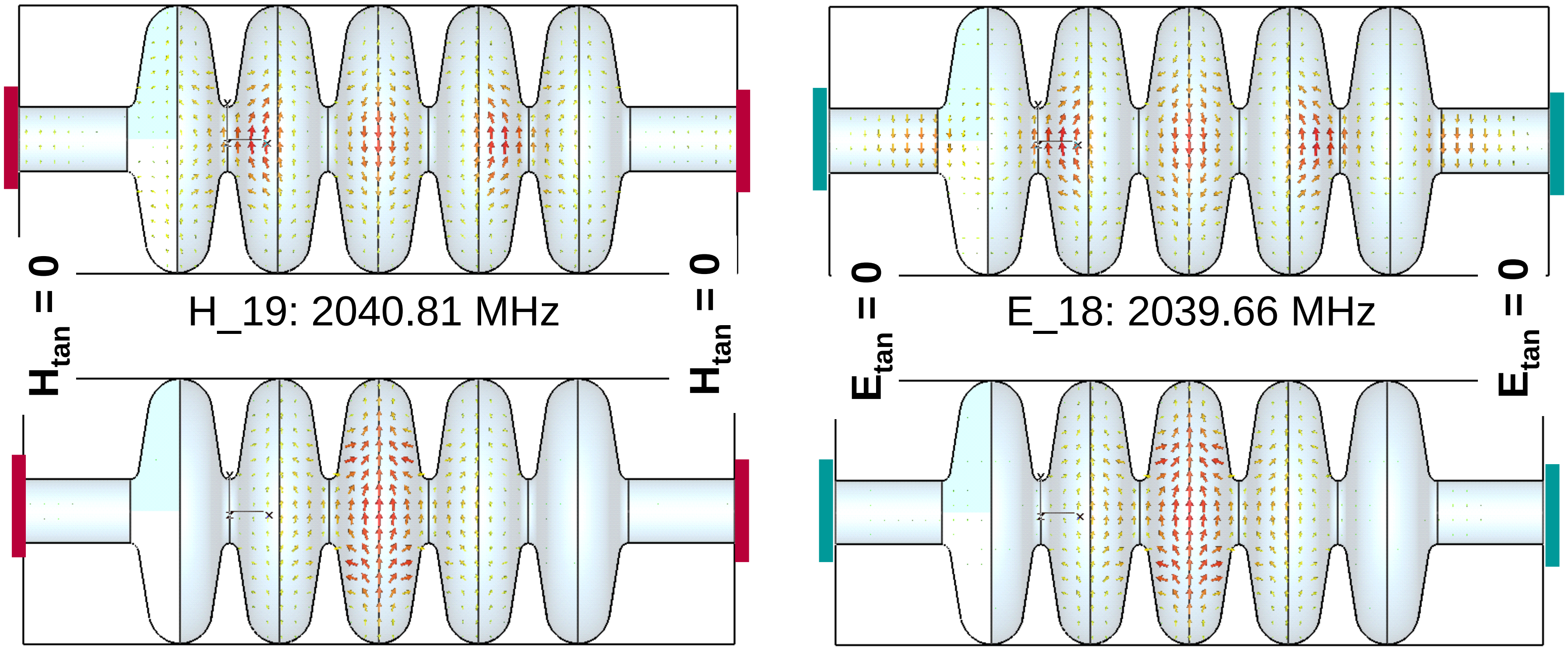


Dekapole, φ =36°

Computed with
CST MWS

Trapped Mode Analysis

Search for strongly confined field distributions by simulating same structure with different waveguide terminations at beam pipe ends. Compare spectra! Small frequency shifts indicate weak coupling.



H_18: 2037.1746 MHz

E_17: 2037.1373 MHz

Remark: TE_{11}-cut off of beam pipe at 1953 MHz

Computed with CST MWS

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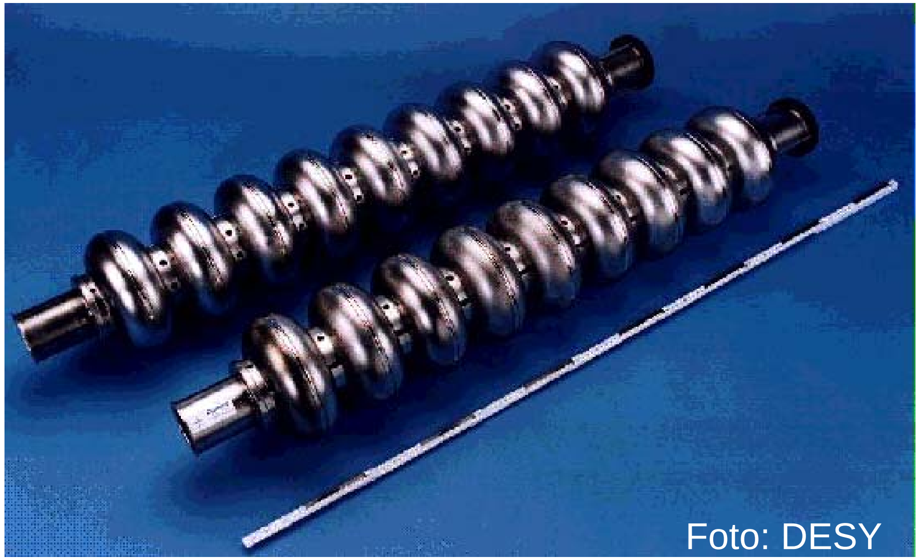
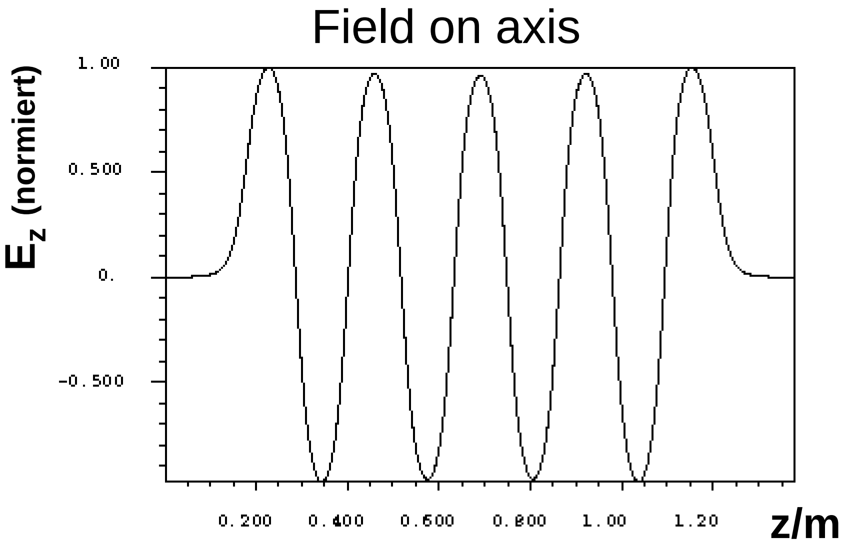
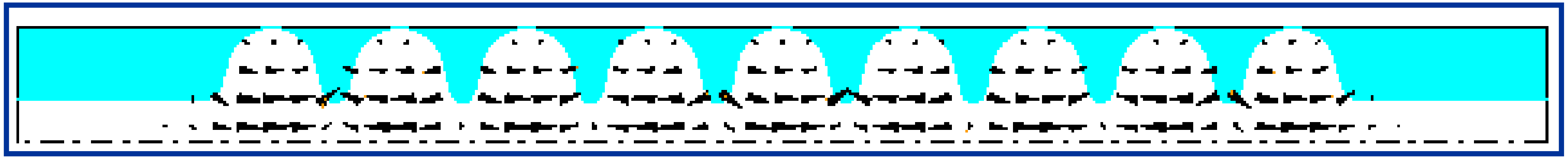
Niobium; acceleration at 1.3 GHz



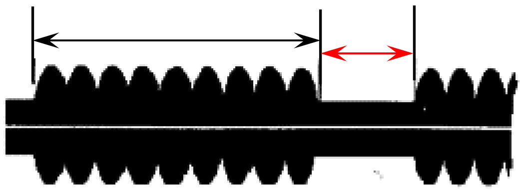




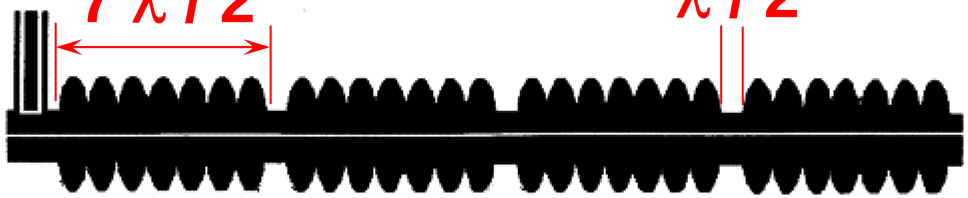
Computed with MAFIA

2D-simulation of upper half; only azimuthal symmetry exploited

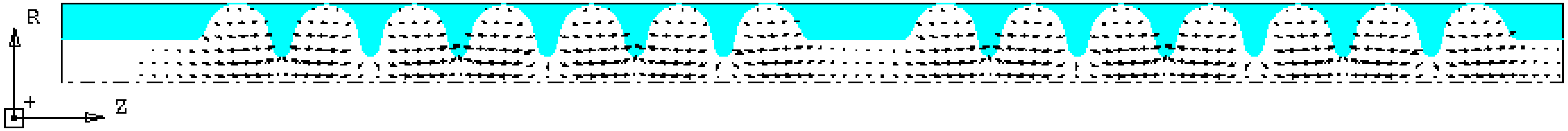
"Superstructure"- Semi-analytical calculation

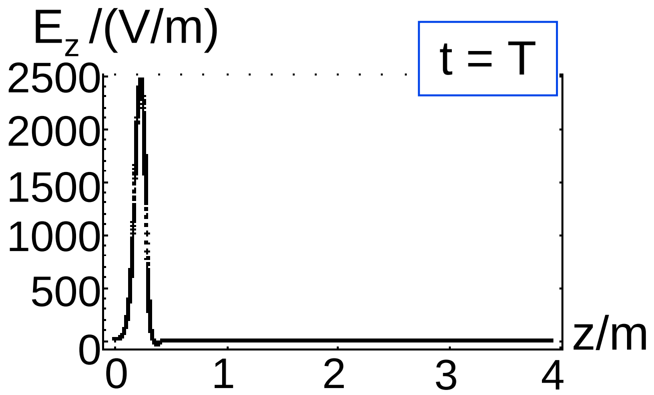


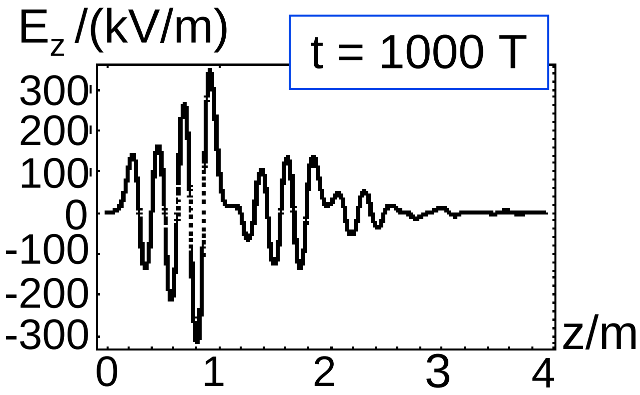
Structure of CDR

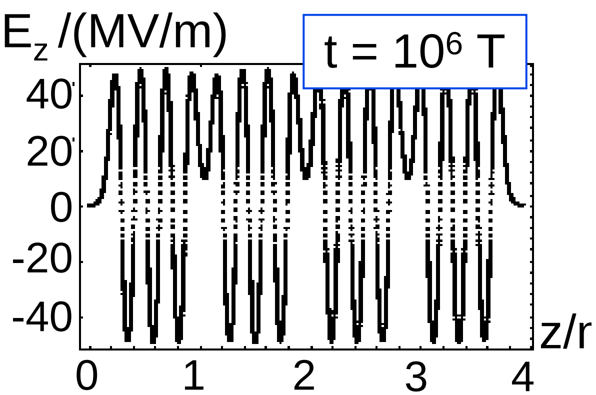


„Superstructure", J. Sekutowicz 1997







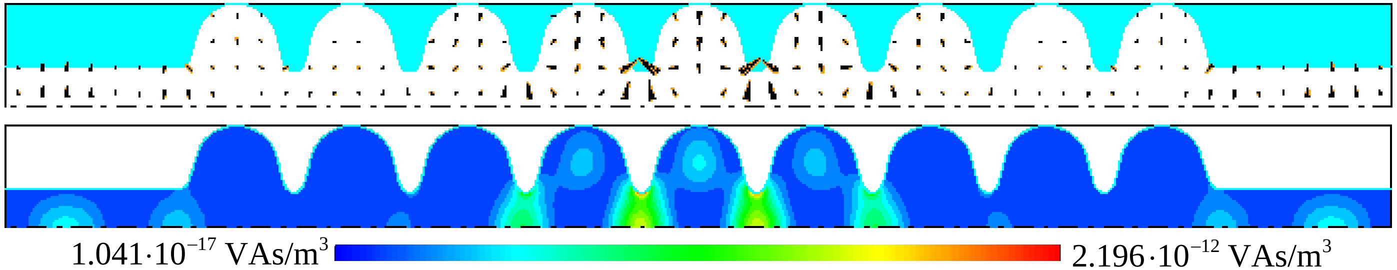


rf period T = 0.7688517112 ns

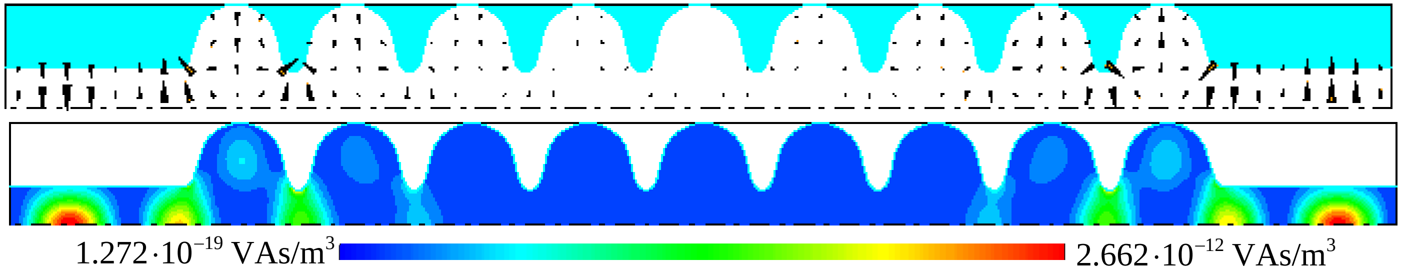
H.-W. Glock; D. Hecht; U. van Rienen; M. Dohlus. Filling and Beam Loading in TESLA Superstructures. Proc. of the 6th European Particle Accelerator Conference EPAC98, (1998): 1248-1250. Computed with MAFIA

Higher Order Modes in TESLA Structure

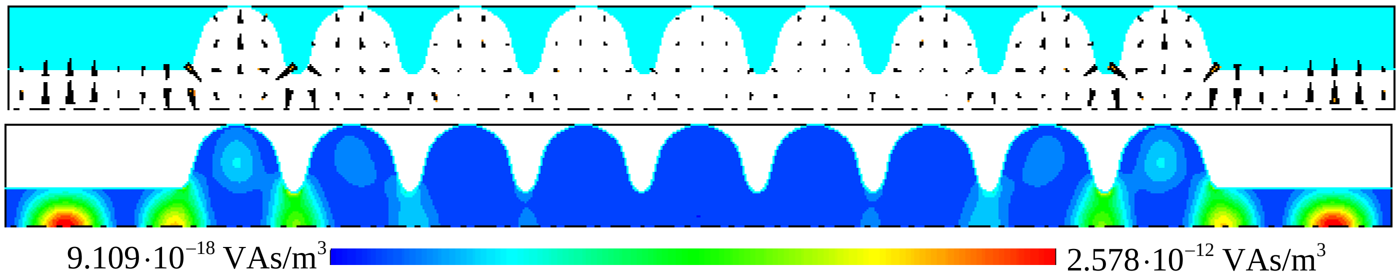
Dipole mode 28, f = 2. 574621 GHz



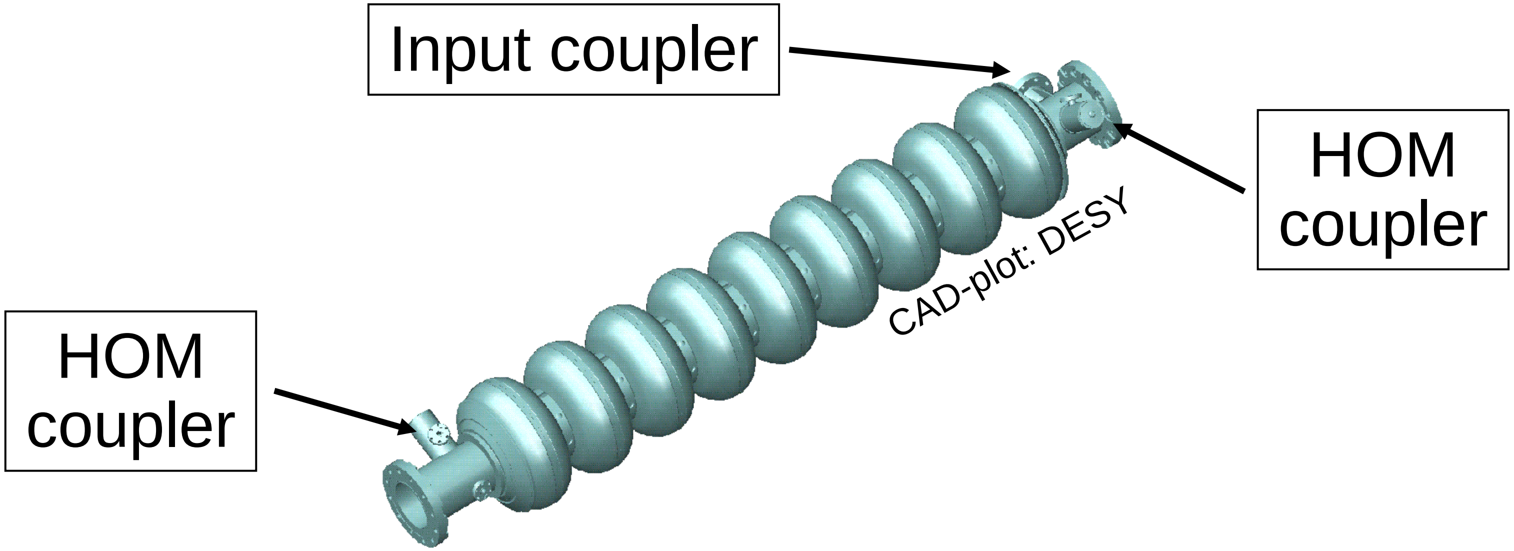
Dipole mode 29, f = 2. 584735 GHz



Dipole mode 30, f = 2. 585019 GHz



Computed with MAFIA

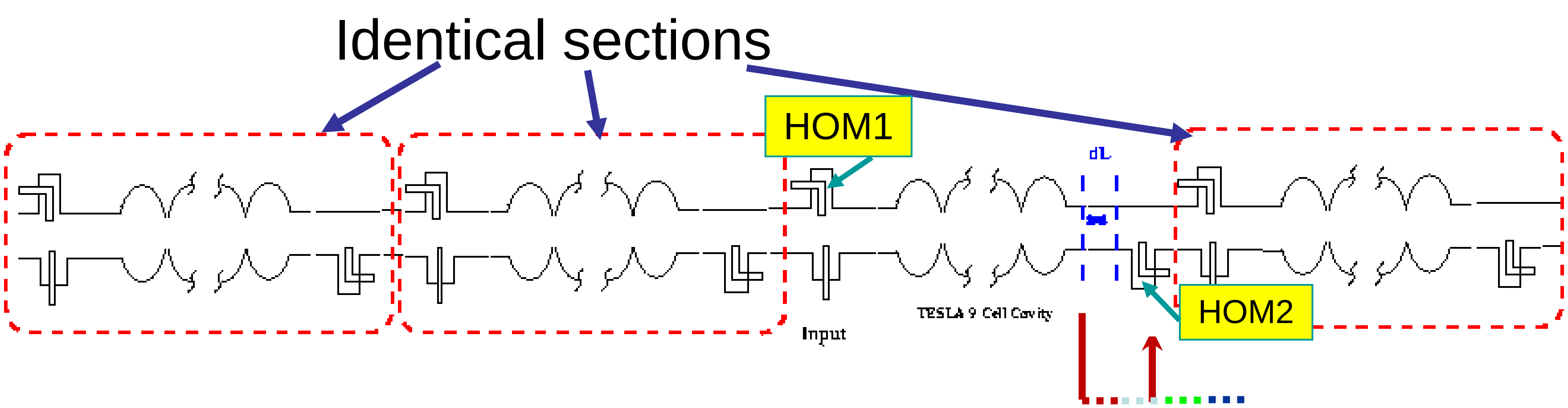


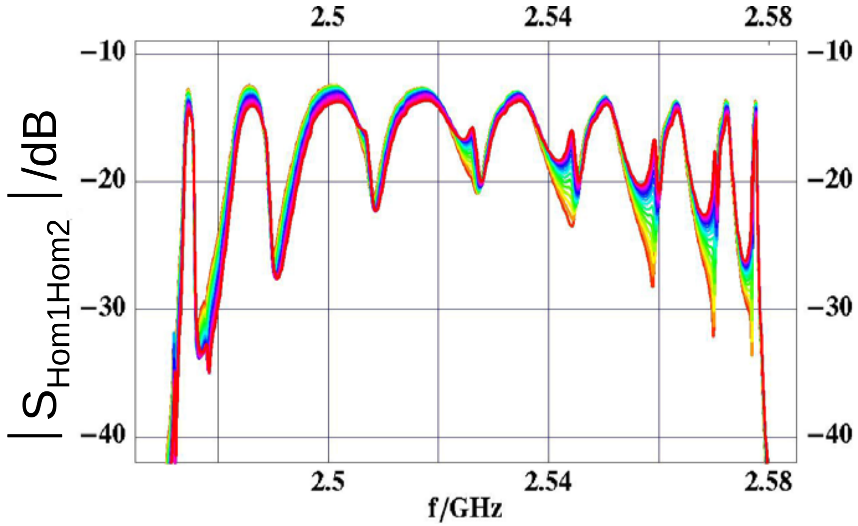
- Resonator *without* couplers: N ~ 29,000 (2D)

  N ~ $12 \cdot 10^6$ (3D)
- Resonator *with* couplers: N ~ $15 \cdot 10^6$ (3D)

  ⇒ N increases by ~ 500
- CSC: „Coupled S-Parameter Calculation“ allows for combination of 2D- and 3D-simulations

K. Rothemund; H.-W. Glock; U. van Rienen. Eigenmode Calculation of Complex RF-Structures using S-Parameters. IEEE Transactions on Magnetics, Vol. 36, (2000): 1501-1503.





Weak dependence on position

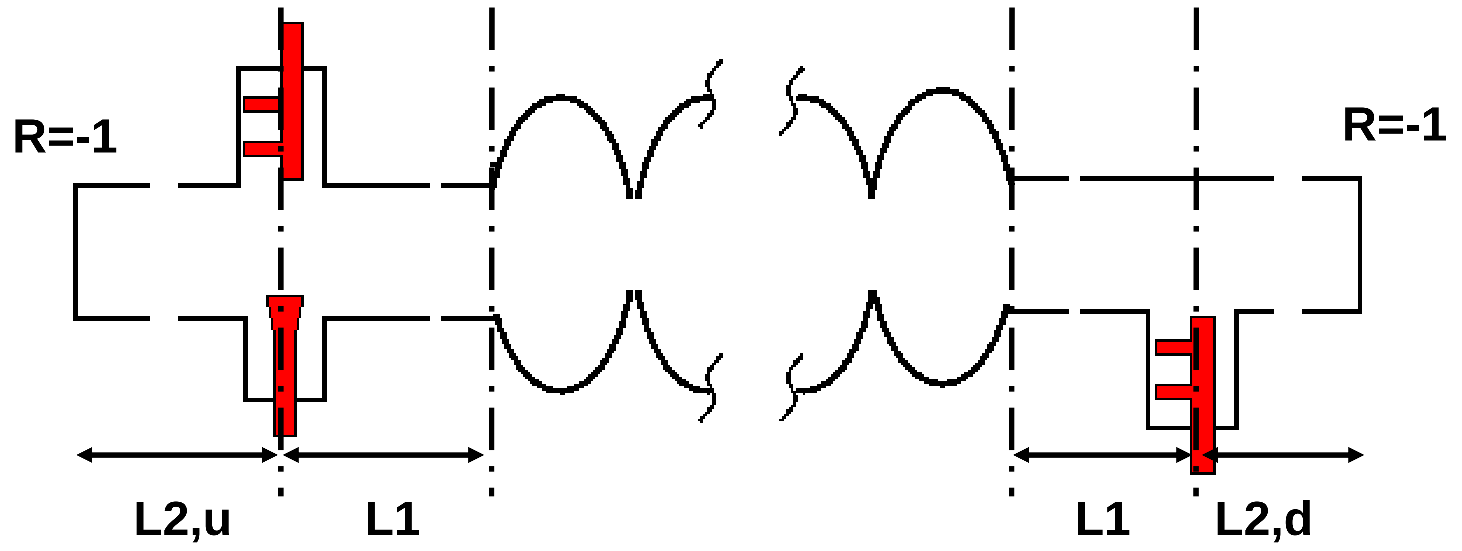
Variation of coupler position

1,000 frequency points
31 lengths
resulting S-matrix: 16 x 16

1h 12min, Pentium III, 1 GHz

Computed with MAFIA, CST MWS and our own Mathematica Code for CSC

Effect of Changed Coupler Design*



L1 = 45.0 mm
L2,u = 101.4 mm
L2,d = 65.4 mm

S-parameters of TESLA cavity:
Modal analysis**

S-parameters of HOM- & HOM-input-coupler:
CST MicrowaveStudio®

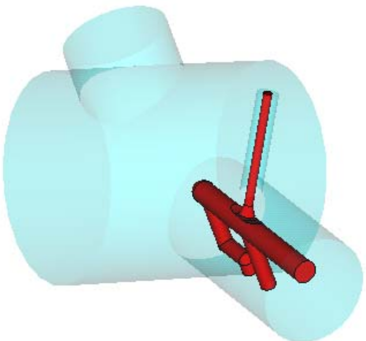
CSC to determine S-parameters of various object combinations

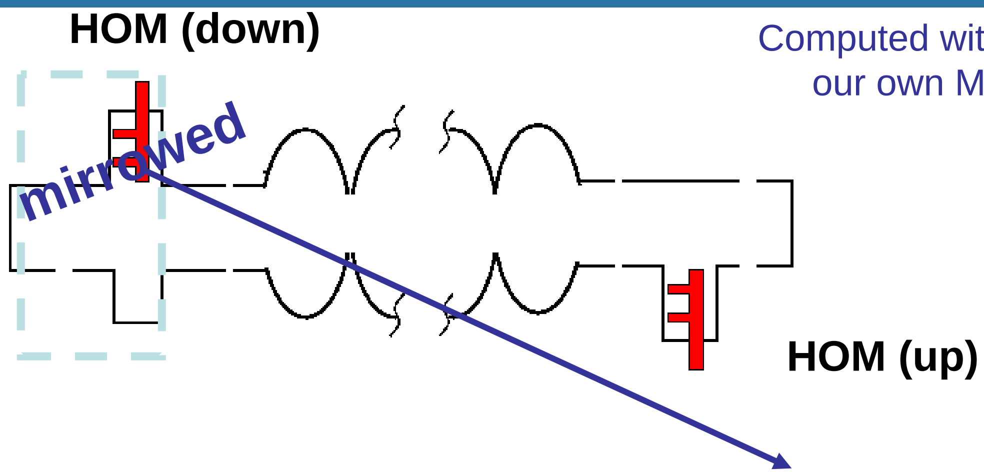
*New concept: M. Dohlus, DESY;
** Modal coeff. computed by M. Dohlus

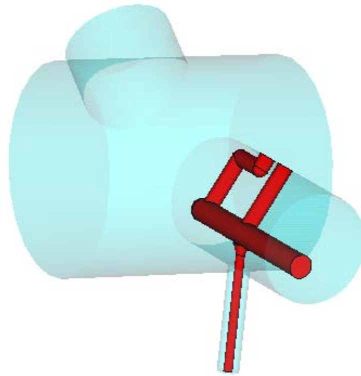
H.-W. Glock, K. Rothemund

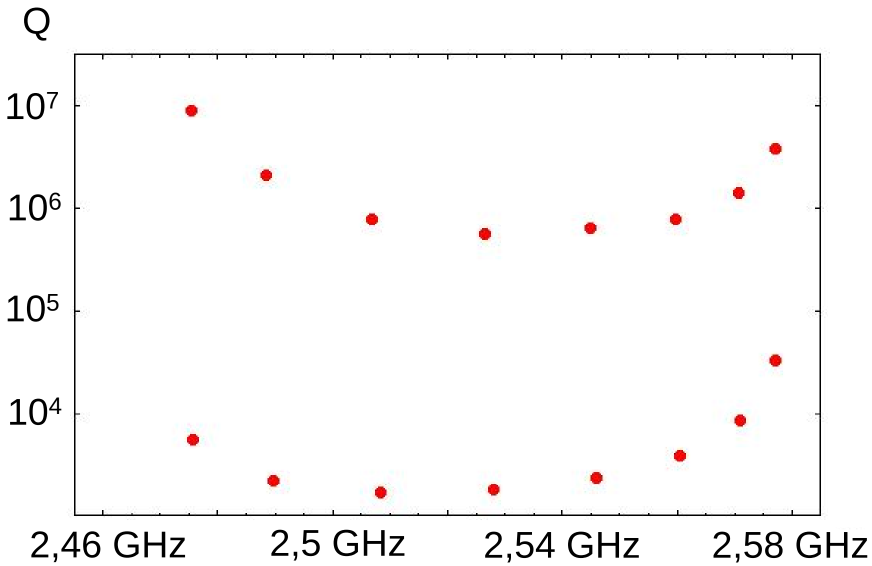
Comparison: HOM(original) – HOM(mirrowed)

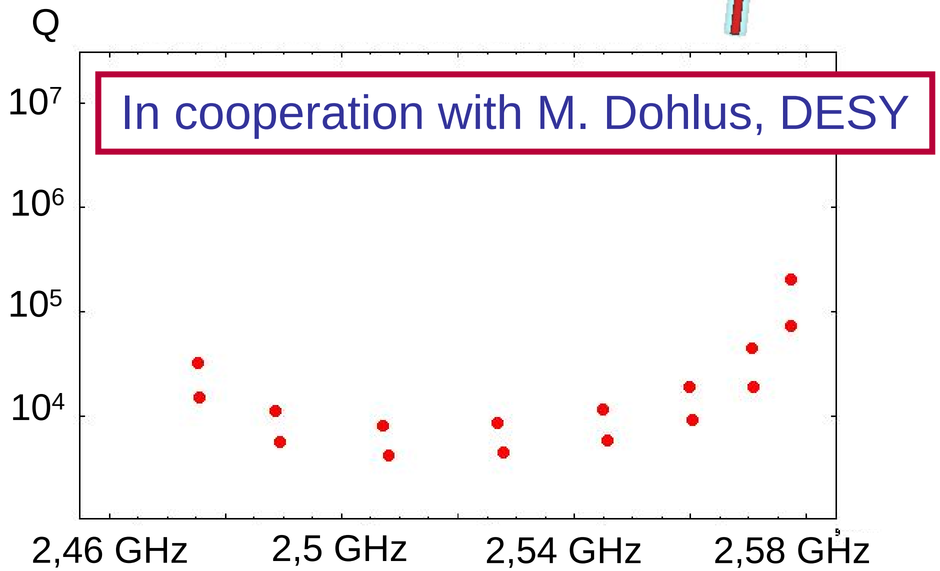
Computed with MAFIA, CST MWS and our own Mathematica Code for CSC











In cooperation with M. Dohlus, DESY

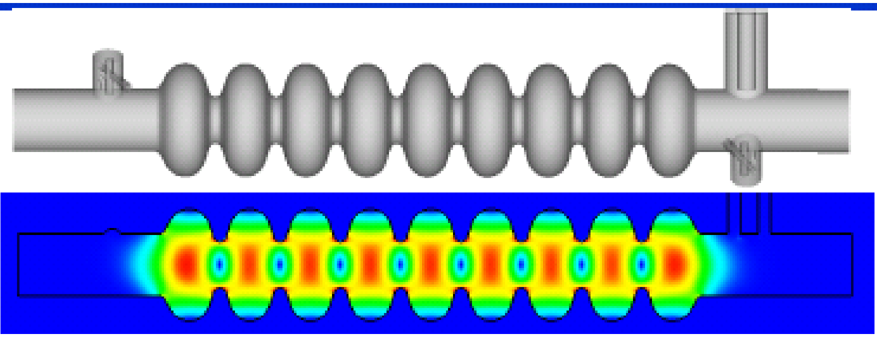
H.W. Glock; K. Rothemund; D. Hecht; U. van Rienen. S-Parameter-Based Computation in Complex Accelerator Structures: Q-Values and Field Orientation of Dipole Modes. Proc. ICAP 2002

Some of his slides …
Courtesy to Martin Dohlus

Fundamental Mode (rf coupler kick)

from Erion Gjonaj
TEMF, TU Darmstadt

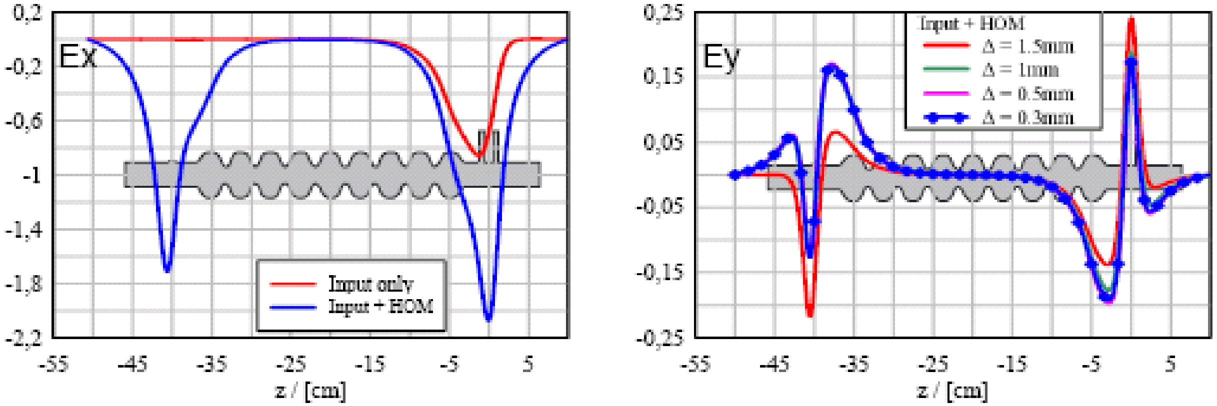
3.9 GHz cavity



electric
energy
density

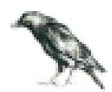
complete 3D model needed: f.i. Q_{ext} = 1.2E6 (input only)   0.9E6 (input+HOM)

Ex, Ey-field on axis:



integrated transverse fields are orders of magnitude smaller than longitudinal field; max(Ez)~200

see W. Ackermann, Thursday afternoon

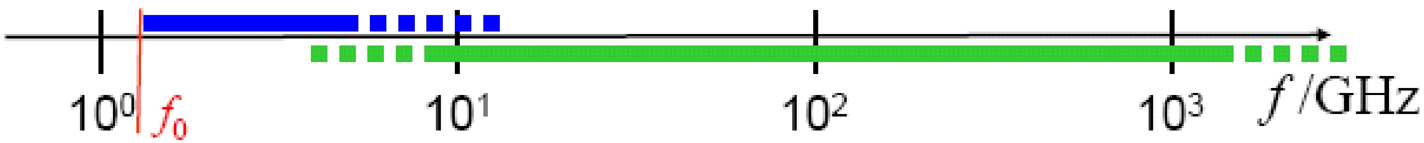


Courtesy of M. Dohlus, DESY – ICAP 2009

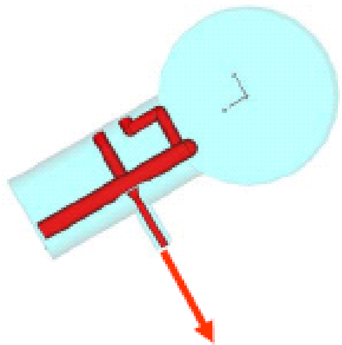
Higher Modes (HOM couplers and absorbers)

trapped &
quasi trapped modes:
~ resonant effects

propagating modes
~ single bunch effects

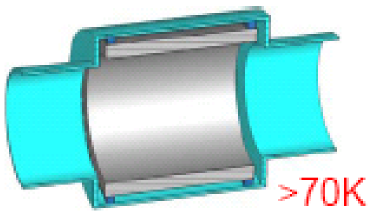


HOM couplers



coax to warm load

HOM absorbers



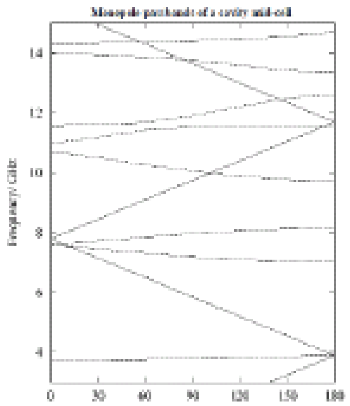
no transmission lines or waveguides
⇒ absorber at temperature level with
good cryo efficiency

absorbers in interconnections between modules
T > 70K

Courtesy of M. Dohlus, DESY – ICAP 2009

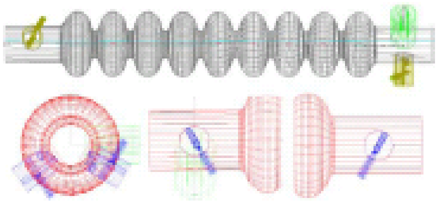
Higher Modes - HOM couplers

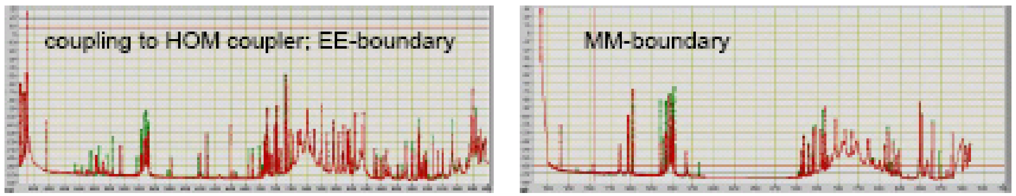
periodic rz simulation for one cell:
dispersion diagrams (monopole, dipole, …)
are usefull to localize bands of modes (multi-cell structures)
→ rough estimate of f and k values



broad band xyz simulation of one cavity (closed beam pipes):
estimate of f, k and Q values → investigation of multi bunch effects

T. Khabibouline, FERMILAB, see FERMILAB-TM2210, TESLA-FEL 2003-01





T. Khabibouline, FERMILAB, see FERMILAB-TM2210, TESLA-FEL 2003-01

models for cavity strings with geometric imperfections
still difficult: f.i. coupled S-matrix approach (TESLA module 3rd dipole band)
or rz-caluclations (→ trapped modes, PEC environment)

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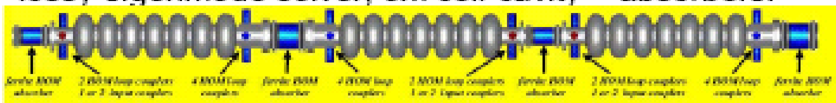
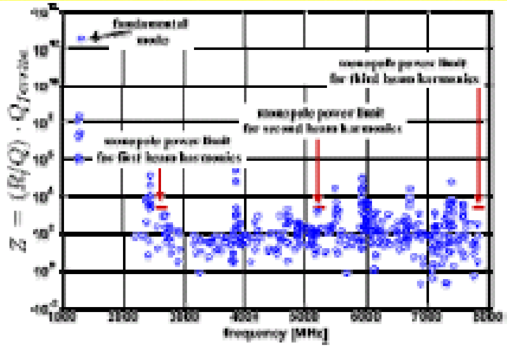
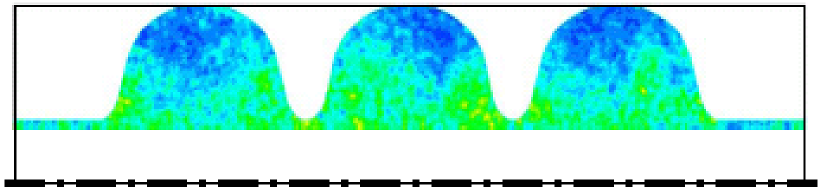
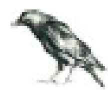
Models for Mode Absorption (based on field calculation)

model with symmetry of revolution sufficient ?
doable (if at all) only for rz-geometry

eigenmode analysis (monopoles)	time domain (monopoles)
M.Liepe: Conceptual Layout of Cavity String ... ERL ...; 11[th] workshop of RF SC, Travemuende, 2003 lossy eigenmode solver; 3x7cell-cavity + absorbers:   f_{max} = 8GHz ~ 400 modes	M.Dohlus: 3 cells between PEC boundaries (no losses) t_{max} ~ 1000/1.3GHz ~ 1μs time averaged energy distribution (few snapshots)  $\langle w(r,z,t)\rangle_t \propto r^{-1}$ for $r/\lambda >> 1$
idealized TESLA cavity between PEC boundaries: f_{max} = 20 GHz; ~ 1400 modes	
scaled to TESLA cryo-module (8 cavities) between PEC boundaries: f_{max}=100 GHz; ~ 280000 modes ???	TESLA cryo-module, f_{max}=100 GHz, 10μs ~ 10^7 … 10^8 meshcells ~ 10^7 … 10^8 timesteps possible !!! 

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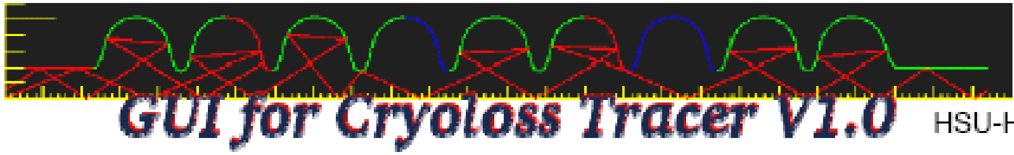
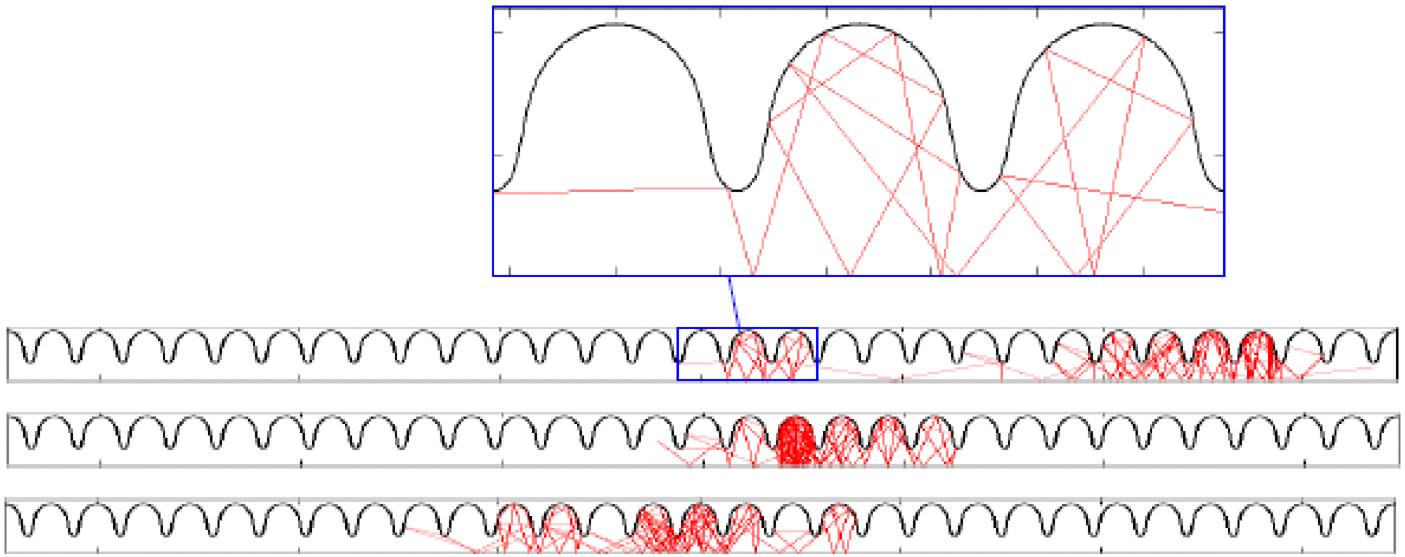
Models for Mode Absorption (geometrical optics)

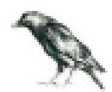


HSU-Hamburg

cryoloss:
(Voss, Clemens, Dohlus)

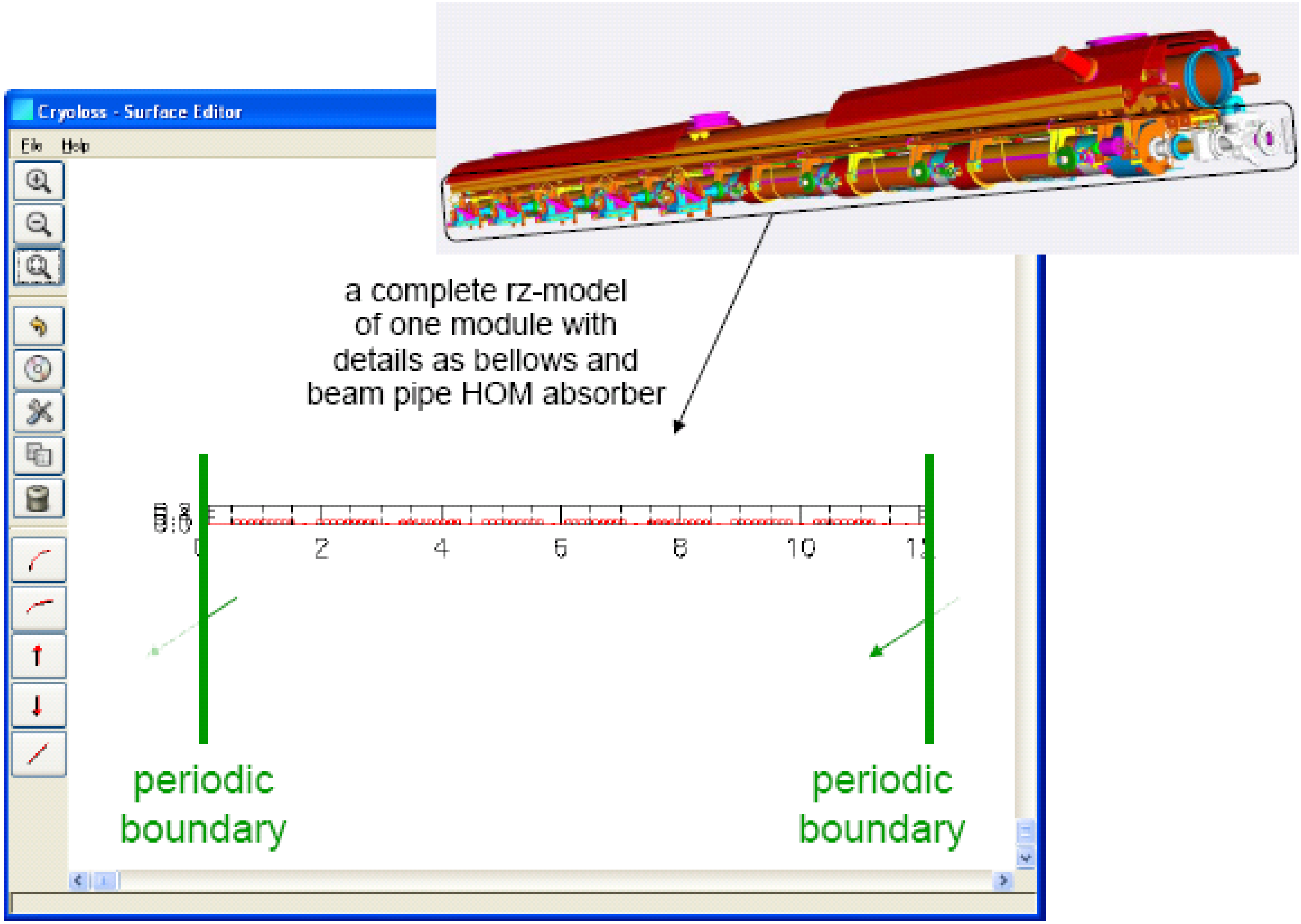
real rz-surface geometry of module; ray tracing; plane wave loss model for surface reflections; intensity reduction of plane wave; summation of surface losses → distribution of losses





Courtesy of M. Dohlus, DESY – ICAP 2009

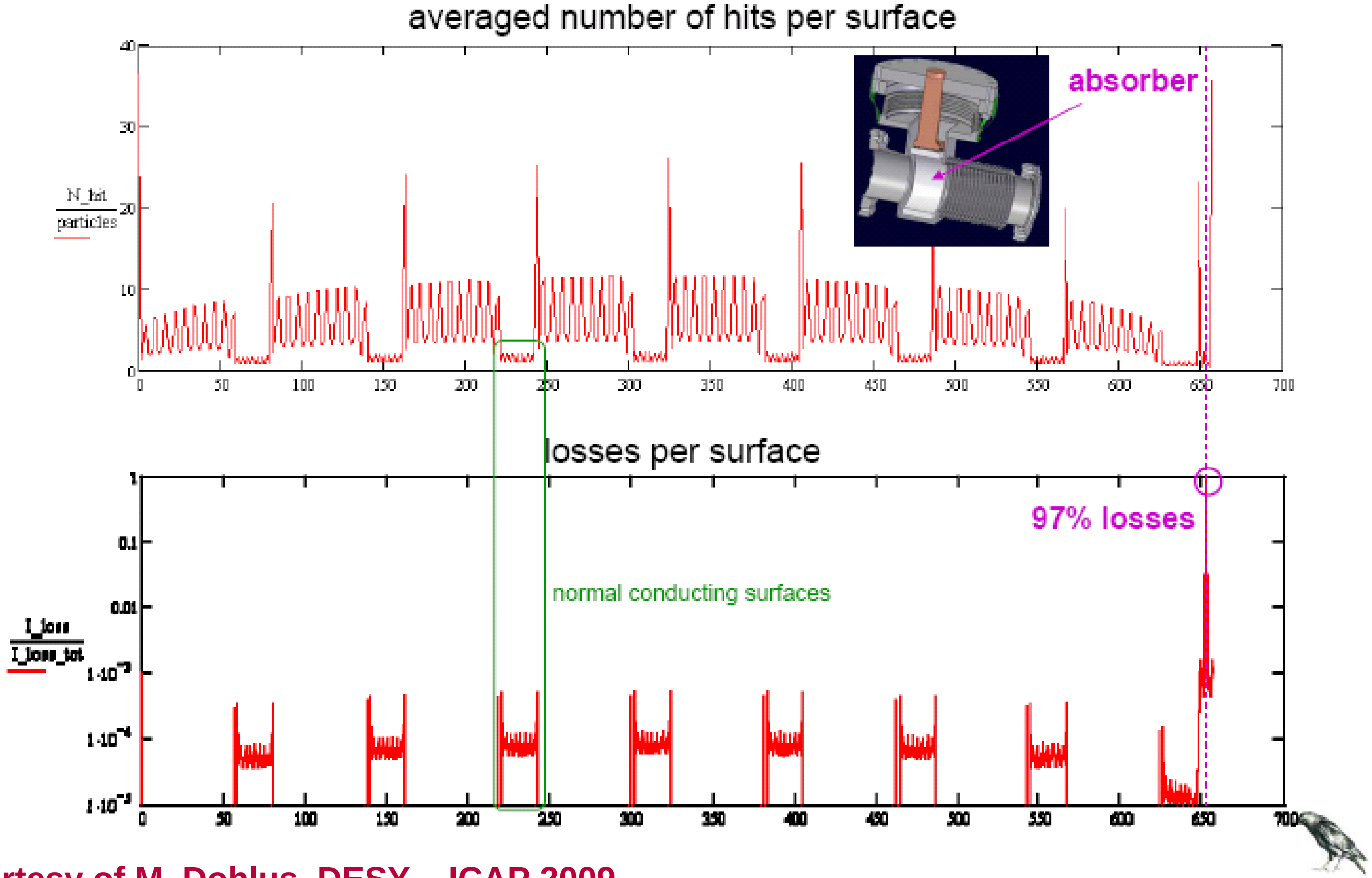
Models for Mode Absorption (geometrical optics)



= infinite string of cold modules !

Courtesy of M. Dohlus, DESY – ICAP 2009

Models for Mode Absorption (geometrical optics)



Courtesy of M. Dohlus, DESY – ICAP 2009

Simulation Multipacting and Dark Current in the CLIC Structure and Muon Cooling Cavity using Track3P

Lixin Ge

ACD

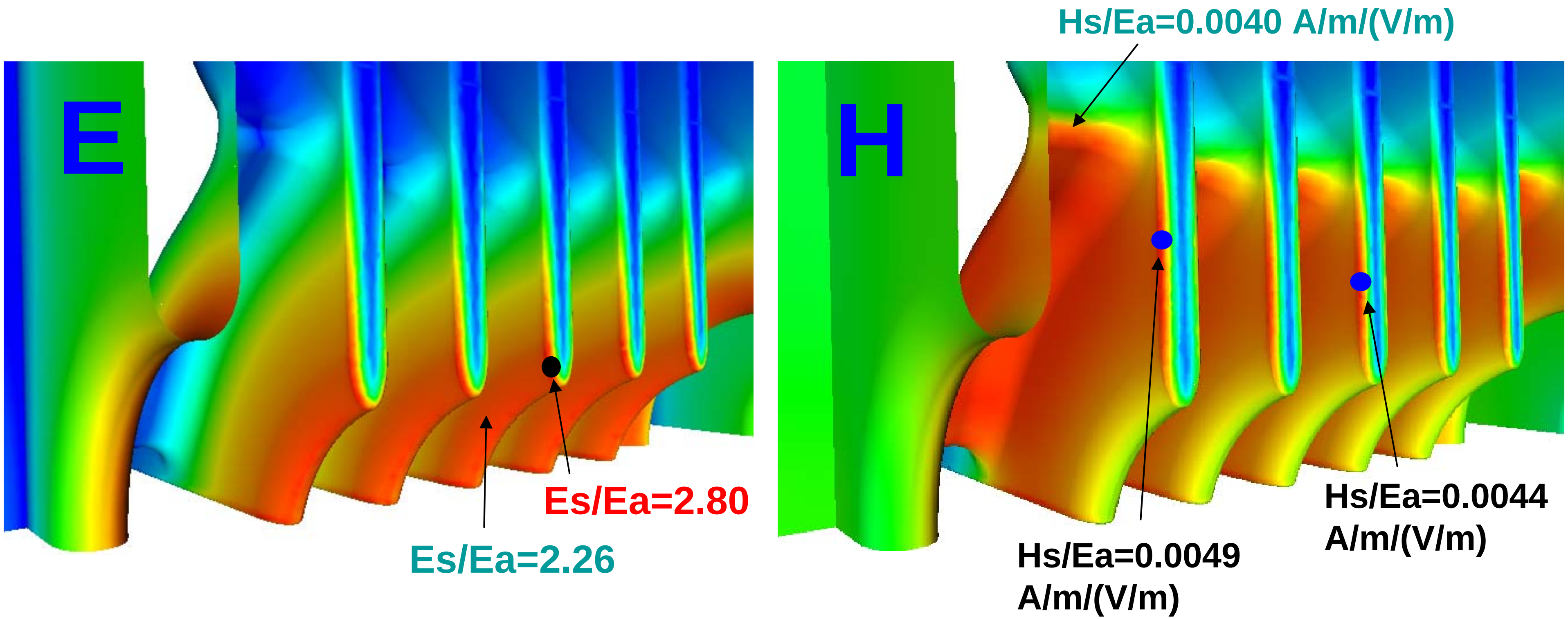
Liling Xiao, Zenghai Li

Accelerator Directorate, SLAC

Presented at ICAP09, Sept.03, 2009

Courtesy of Cho Ng, Lixin Ge

HDX Surface E & B Fields

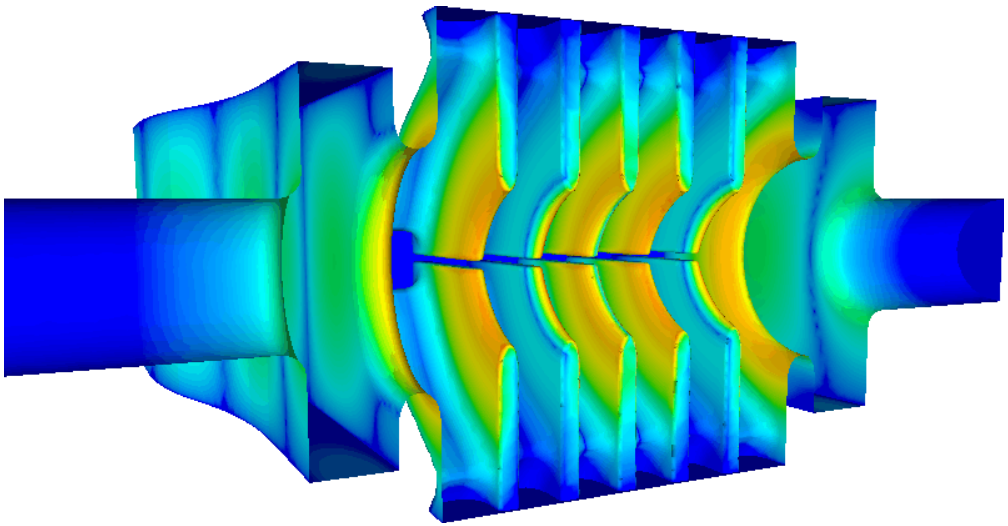


Courtesy of Cho Ng, Lixin Ge

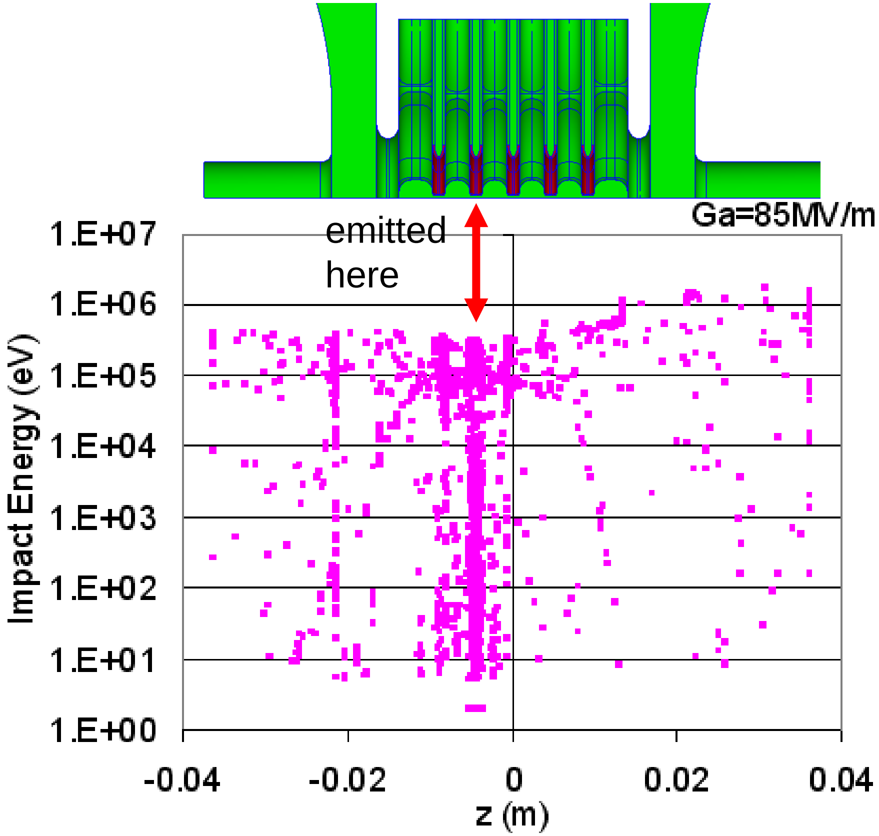
Fields enhanced around slot rounding

Electron Trajectory & Impact Energy

Courtesy of Cho Ng, Lixin Ge



Particles emitted from one of the irises

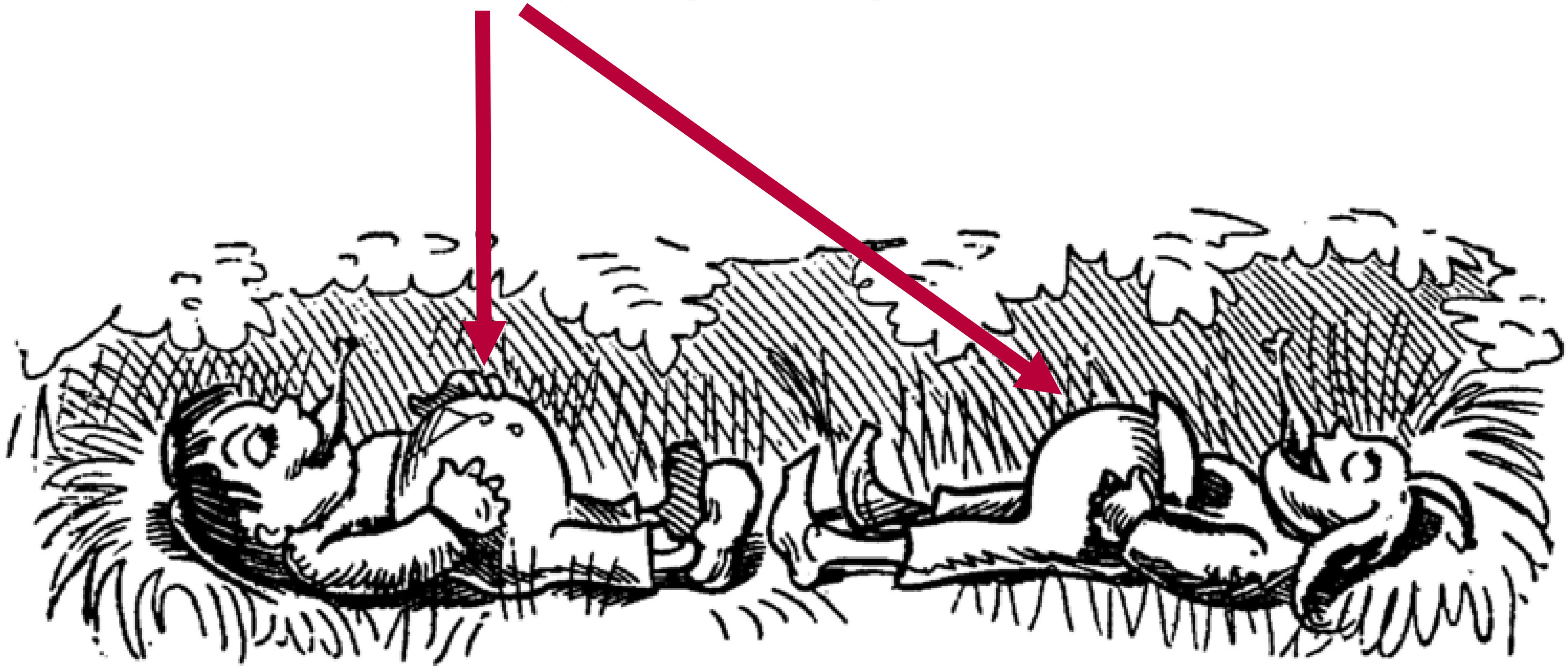


At 85 MV/m gradient, energy of dark current electrons can reach ~0.4 MeV on impact

SLAC NATIONAL ACCELERATOR LABORATORY

At the end ....

... some other "cavity" type. Hope, you feel better.



Wilhelm Busch: Max und Moritz, sometimes in the 19th century. Widely published
http://upload.wikimedia.org/wikipedia/commons/thumb/c/c2/Max_und_Moritz_(Busch)_026.png/800px-Max_und_Moritz_(Busch)_026.png

These are greetings of my co-author Hans-Walter Glock ….