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Prof. Dr.-Ing. Thomas Weiland
Institut für Theorie Elektromagnetischer Felder

# Future Directions in Computational Electromagnetics for Digital Applications

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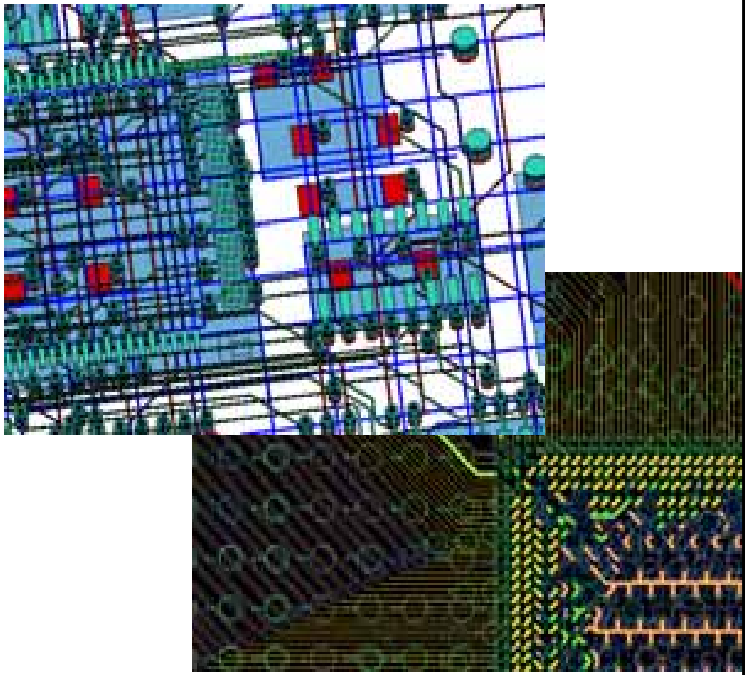
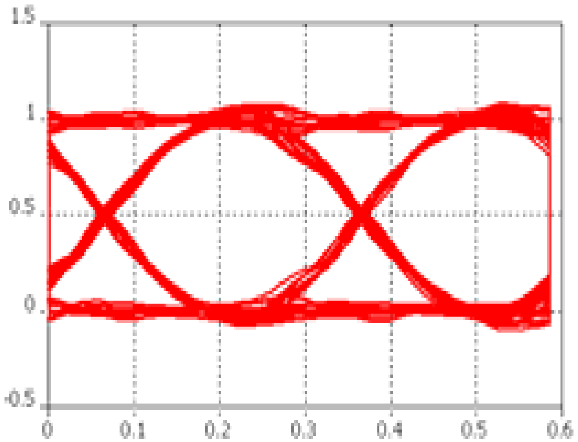
# Contents

# Motivation: Why 3D EM simulation?

- Growing frequencies / clock rates
- High density of components
- Increasing parasitics relevance
- Sophisticated packaging technologies
- 3D packaging



- No simple models available
- Increase in crosstalk problems
- EMI / EMC concerns
- Signal / power integrity issues
- 2 ½D solvers cannot cope with all 3D effects



# Contents

- Introduction
- State of the art
  - Three steps in solving an EM Problem
  - Finite Integration Technique as universal method
  - Wide choice of solution methods
- Future trends
  - Geometrically complex problems
  - EMC, Signal and Power integrity
  - Network Extraction, Passivity
  - Coupled problems
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- Conclusions

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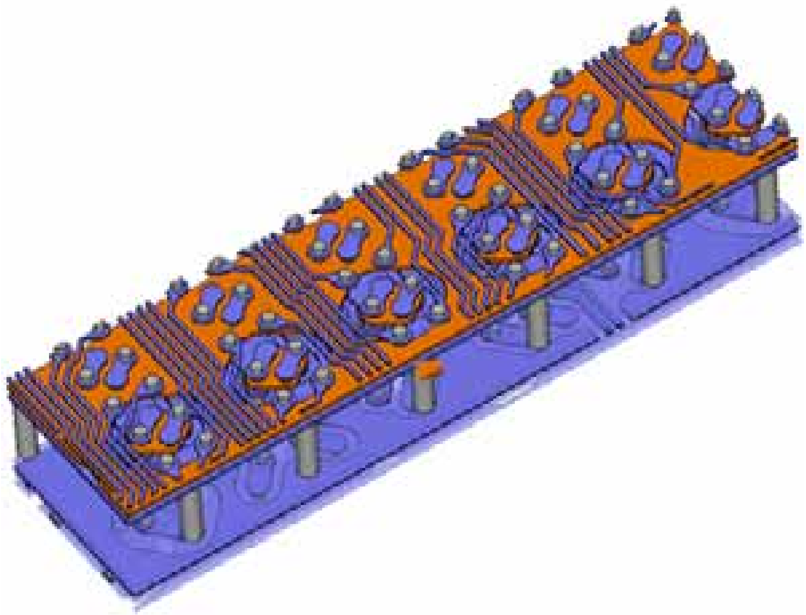
# EM Solution = 3 Steps

## 1 Spatial Discretization of geometry

- Staircase grid
- Tetrahedral grid
- Surface mesh
- Boundary fitted meshes
- ….



## 2 Local approximation of Maxwell‘s Equations

- Finite Difference
- Finite Integration Technique
- Finite Element
- Finite Volume
- ….

## 3 Solving the algebraic system

- Direct solver
- Iterative solver
- Eigenvalue solver
- Time stepping solver
- ….

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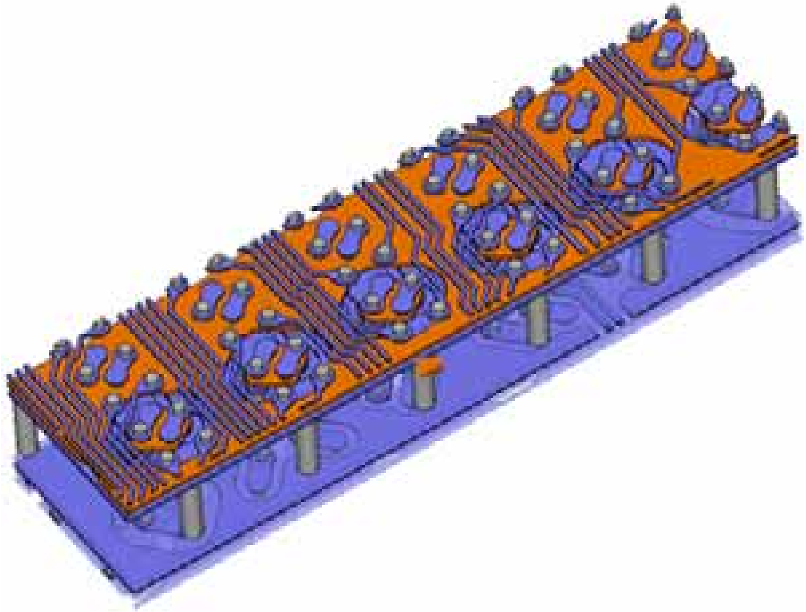

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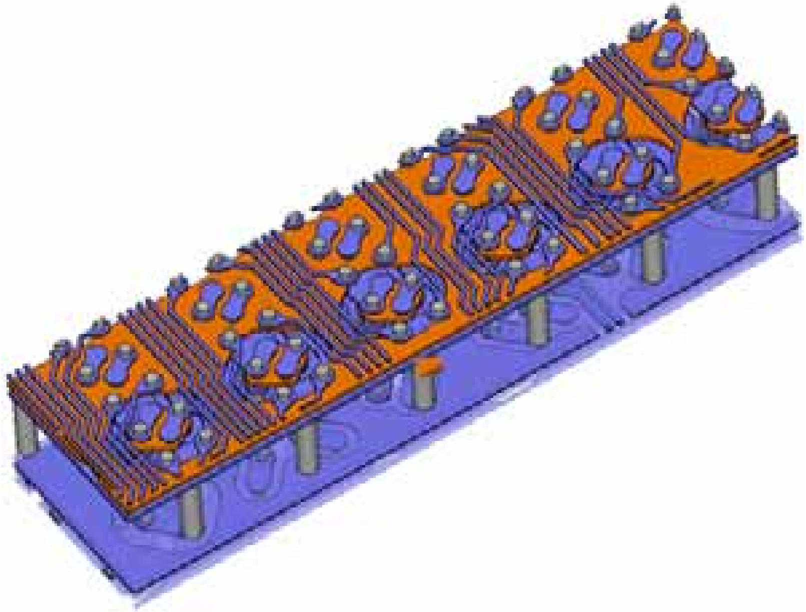

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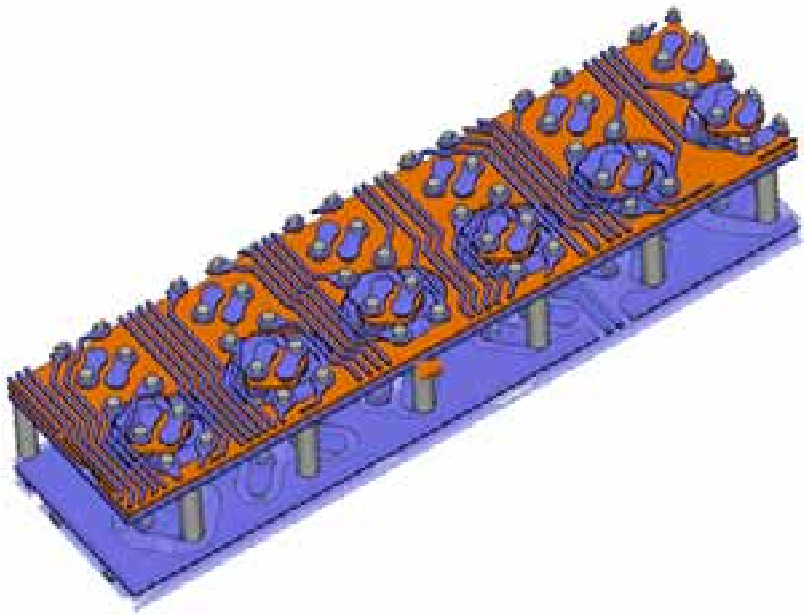

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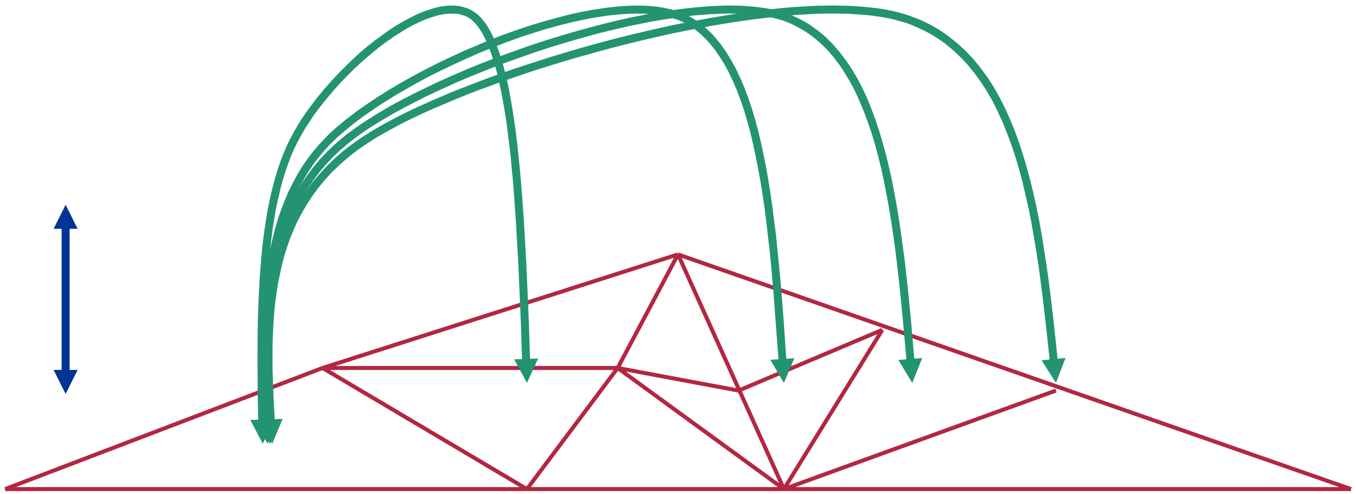
# Surface Meshing

Each patch talks to each patch



With **D** as linear dimension

„Method of Moments“

$N_{cell} \propto D^2$ ; Matrix rank $\propto D^2$

Matrix completely filled

Number of matrix elements $\propto D^4$

Solvers mostly $\propto (D^2)^3 = D^6$ ....$D^2 \log D^2$

Good for linear materials

Good for Volume/Surface=Large

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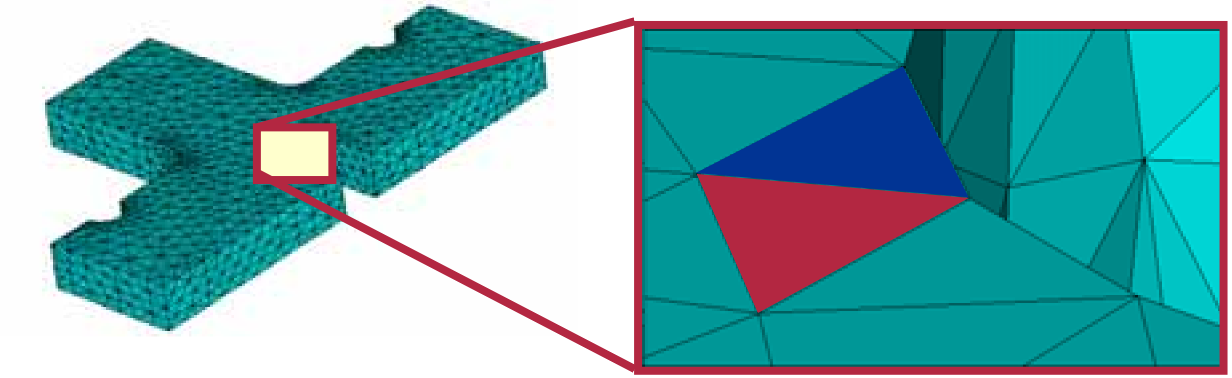
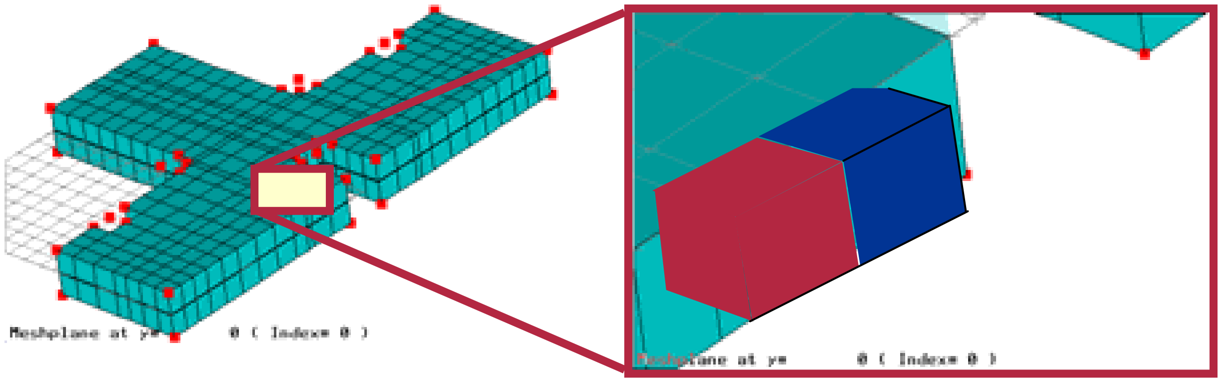


$\varepsilon_1, \mu_1, \kappa_1$

$\varepsilon_2, \mu_2, \kappa_2$

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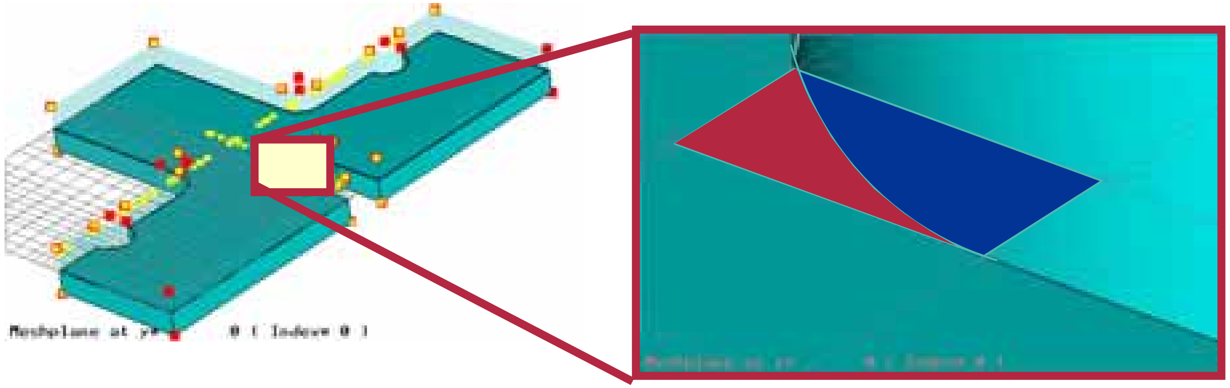


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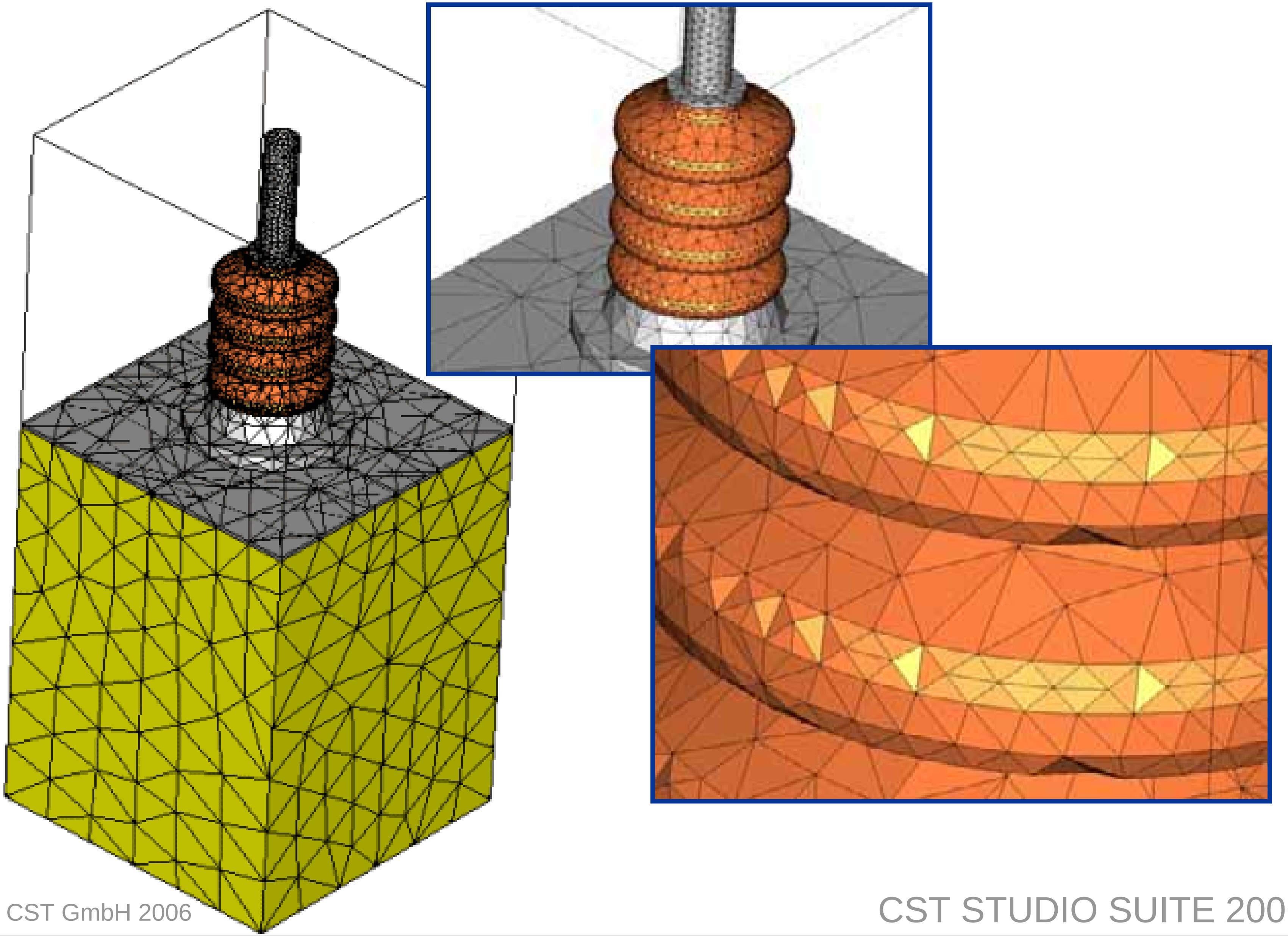
# High Voltage - Bushing



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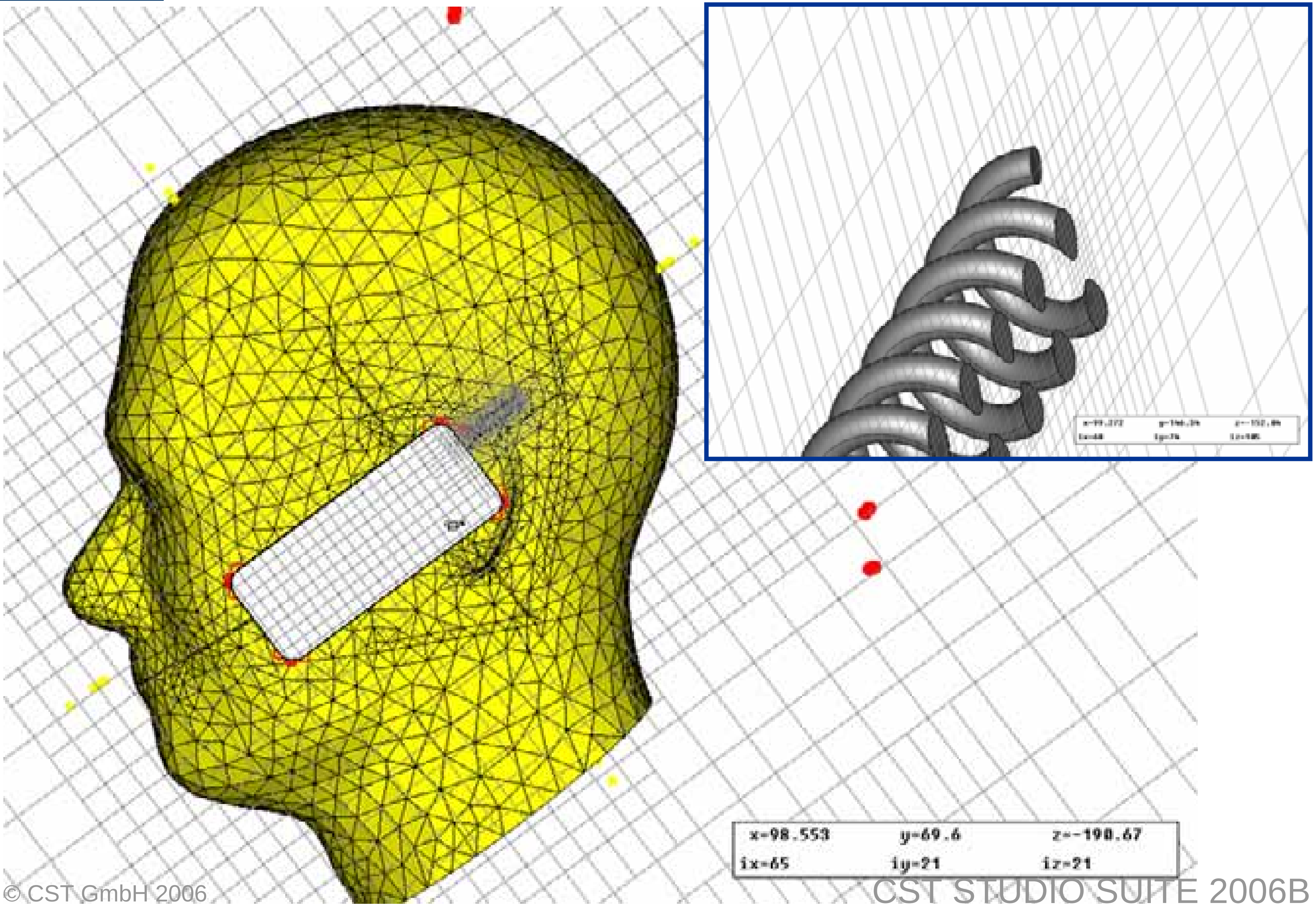
# Hexahedral - Subgrids



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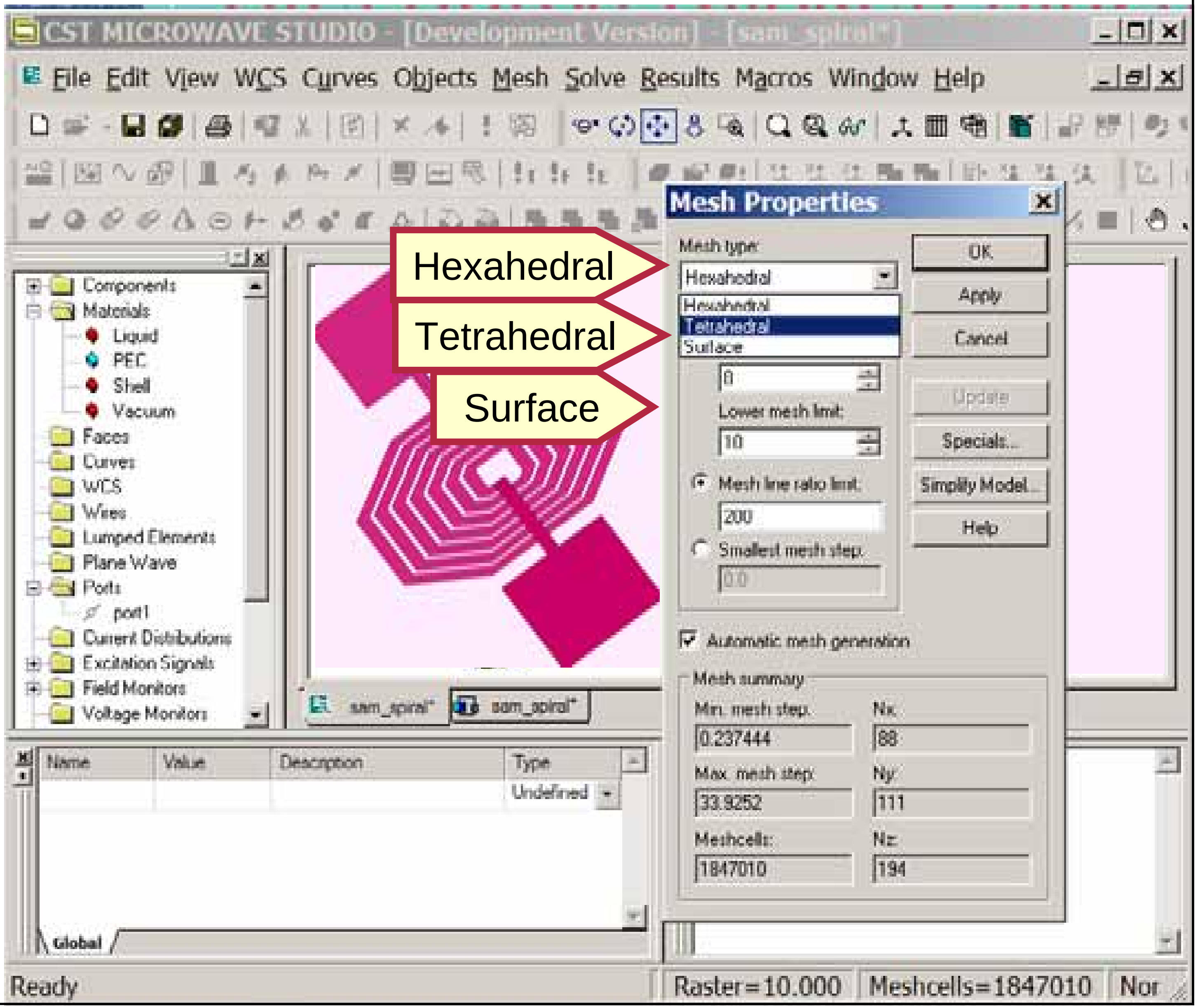
# Wide choice of mesh type

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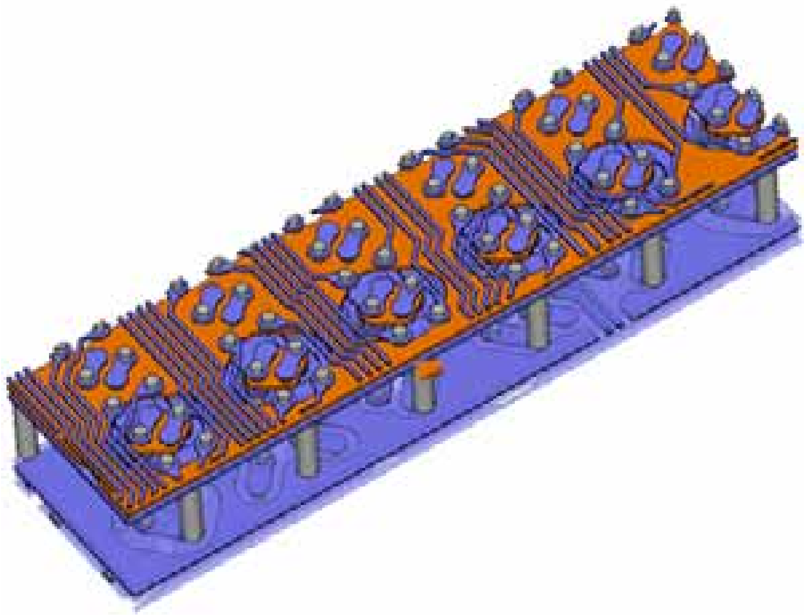

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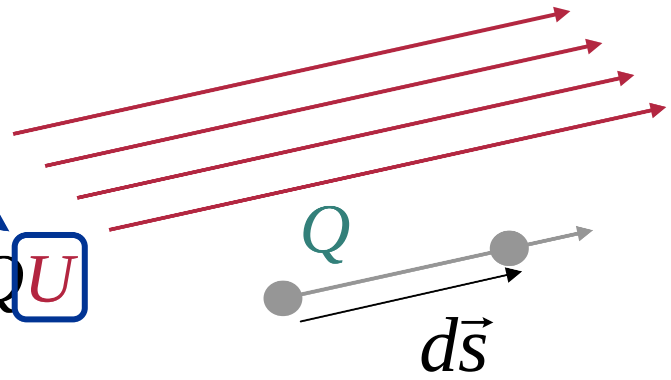
# Measurable=Integral Quantities

$$\vec{F} = Q\vec{E}$$

$$\vec{E} = \vec{F}/Q$$

$$\vec{F}\bullet d\vec{s} = \left(Q\vec{E}\right)\bullet d\vec{s} = Q(\vec{E}\bullet d\vec{s}) = QU$$




$$\vec{F} = Q\vec{v}\times\vec{B}$$

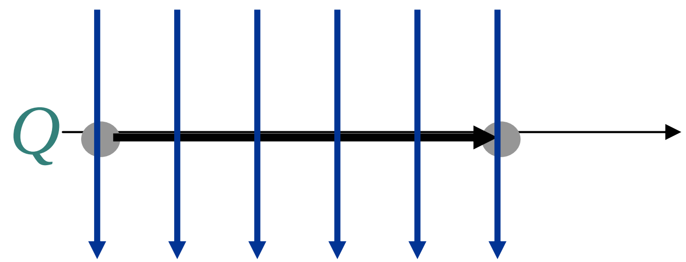
$$\Delta\vec{p} = \int \vec{F}dt$$

$$= Q\int\left(\vec{v}\times\vec{B}\right)dt = Q\vec{n}\int Bvdt$$

$$= Q\vec{n}\int\left(Bds\right) = Q\vec{n}\left(\Psi\right)$$

$\vec{n}\otimes$

$$d\vec{s} = \vec{v}dt$$




Tonti 75, Weiland 77

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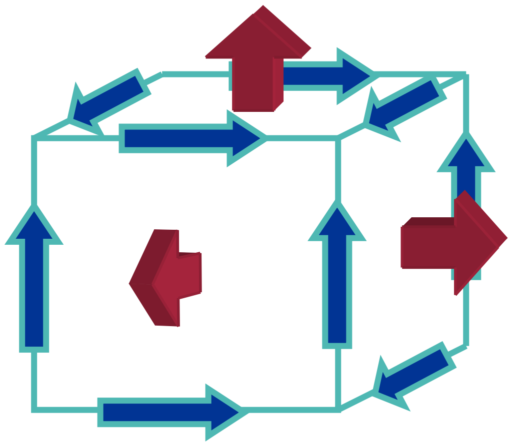
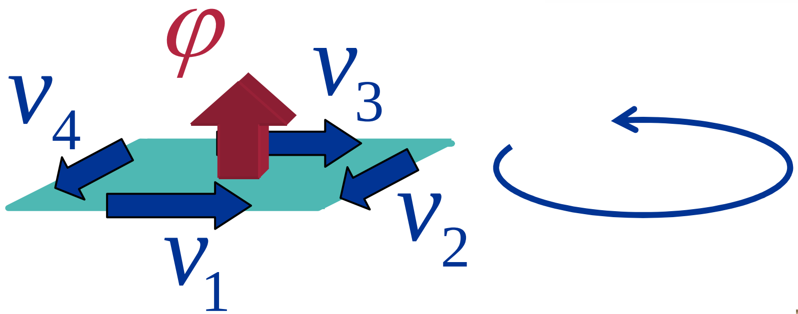
# FIT - Voltage and Flux

- Grid $G$



$$\oint_L \vec{E}\bullet d\vec{s} = -\int_A \frac{\partial}{\partial t}\vec{B}\bullet d\vec{A}$$

$$v_{\circ} = -\frac{d\varphi_{S_\Gamma}}{dt}$$




$$v_1 - v_2 - v_3 + v_4 = -\frac{d}{dt}\varphi$$

$$\varphi = \int_A \vec{B}\bullet d\vec{A}$$

$$v = \int_L \vec{E}\bullet d\vec{s}$$

$$\sum_{i=1,4} c_i v_i = -\frac{d}{dt}\varphi$$

$$c_i = +/-1$$

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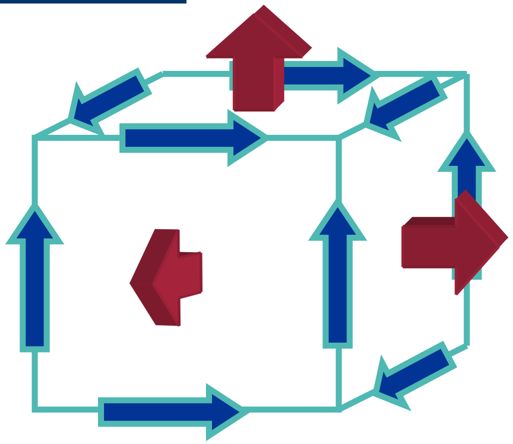
# FIT - Voltage and Flux



$$\sum_{i=1,4} c_i v_i = -\frac{d}{dt}\varphi_j$$

$$\mathbf{C}\mathbf{v} = -\frac{d}{dt}\boldsymbol{\varphi}$$

$$\mathbf{C}\widehat{\mathbf{e}} = -\frac{d}{dt}\widehat{\widehat{\mathbf{b}}}$$

$$\mathbf{C} = \begin{pmatrix} \cdots & & & & & & \\ & \cdots & & & & & \\ & -1 & +1 & & +1 & -1 & \\ & & & & & & \\ & & & & & & \cdots \end{pmatrix} \quad \mathbf{v} = \begin{pmatrix} v_1 \\ v_2 \\ \\ \cdots \\ v_N \end{pmatrix} \quad \boldsymbol{\varphi} = \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ \\ \cdots \\ \varphi_N \end{pmatrix}$$

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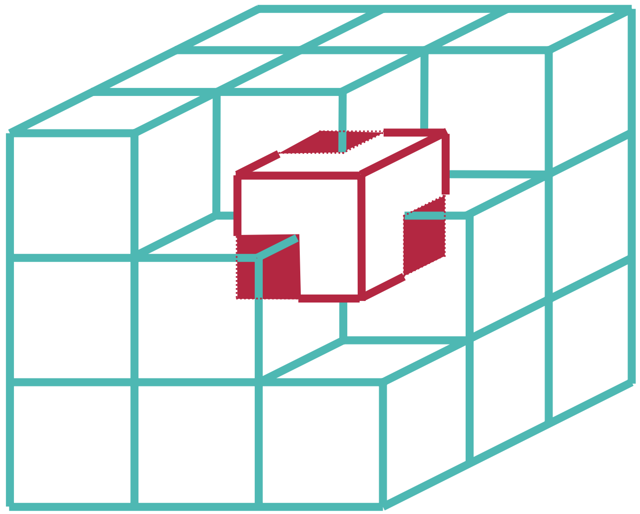
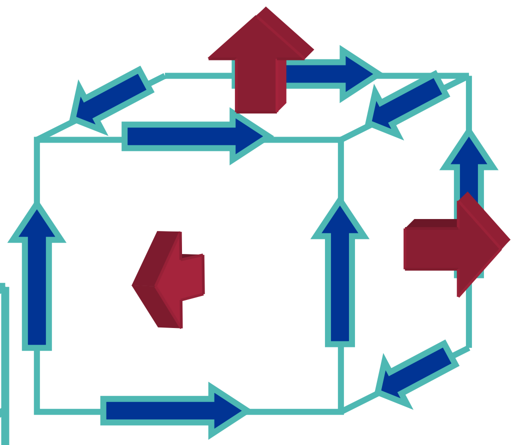
# FIT – Degrees of Freedom

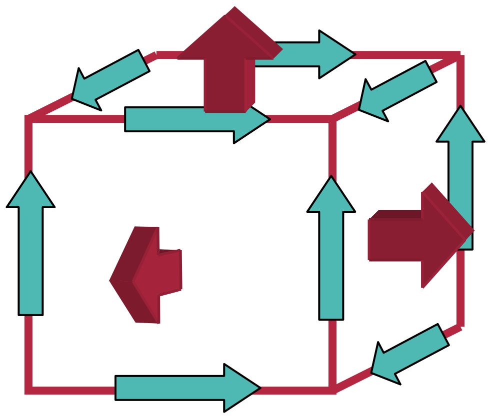
**Grid $G$ and $\tilde{G}$:**

$$C\widehat{e} = -\frac{d}{dt}\widehat{\widehat{b}}$$



$$\tilde{C}\widehat{h} = \frac{d}{dt}\widehat{\widehat{d}} + \widehat{\widehat{j}}$$





$$\widehat{\widehat{b}} = \int_A \vec{B}\bullet d\vec{A}$$

$$\widehat{e} = \int_L \vec{E}\bullet d\vec{s}$$

$$\widehat{\widehat{d}} = \int_A \vec{D}\bullet d\vec{A}$$

„Surface charge"

$$\widehat{h} = \int_L \vec{H}\bullet d\vec{s}$$

„Magnetic voltage"

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# Maxwell‘s Grid Equations

## Almost Complete Discrete Form of Maxwell’s Equations

$$\int_{\partial A} \vec{E}\cdot d\vec{s} = -\frac{\partial}{\partial t}\iint_{A} \vec{B}\cdot d\vec{A}$$

$$\int_{\partial A} \vec{H}\cdot d\vec{s} = \iint_{A}\left(\frac{\partial \vec{D}}{\partial t} + \vec{J}\right)\cdot d\vec{A}$$

$$\oiint_{\partial V} \vec{B}\cdot d\vec{A} = 0$$

$$\oiint_{\partial V} \vec{D}\cdot d\vec{A} = \iiint_{V} \rho \; dV$$

**Developed since 1975**

$$\mathbf{C}\widehat{\mathbf{e}} = -\dot{\widehat{\widehat{\mathbf{b}}}}$$

$$\tilde{\mathbf{C}}\widehat{\mathbf{h}} = \dot{\widehat{\widehat{\mathbf{d}}}} + \widehat{\widehat{\mathbf{j}}}$$

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

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

EXACT!!

continuous ⟷ discrete

$$\vec{D} = \varepsilon\cdot\vec{E} + \vec{P}$$

$$\vec{B} = \mu\cdot\vec{H} + \vec{M}$$

$$\vec{J} = \kappa\cdot\vec{E}$$

⟷ ?

# Material Equations

$$\mathbf{C}\widehat{\mathbf{e}} = -\dot{\widehat{\widehat{\mathbf{b}}}}$$

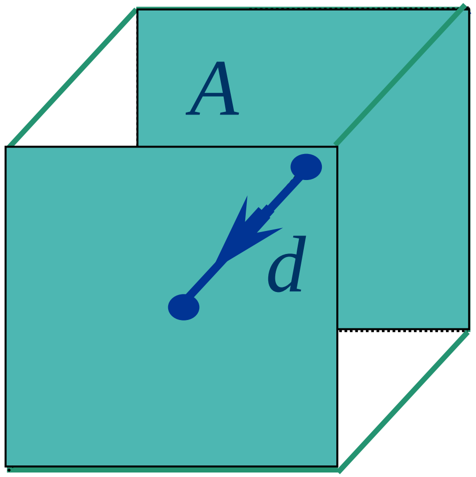
$$\tilde{\mathbf{C}}\widehat{\mathbf{h}} = \dot{\widehat{\widehat{\mathbf{d}}}} + \widehat{\widehat{\mathbf{j}}}$$

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

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

+ **Material relations** $\widehat{\widehat{\mathbf{d}}} - \widehat{\mathbf{e}},\ \widehat{\widehat{\mathbf{b}}} - \widehat{\mathbf{h}}$

***Equivalent of branch constitutive equations***




$$\widehat{e} \approx \vec{E} \bullet d\vec{s}$$

$$\widehat{\widehat{\mathbf{d}}} = \mathbf{M}_{\varepsilon}\widehat{\mathbf{e}} \qquad \mathbf{M}_{\varepsilon} : \frac{\varepsilon A}{d} \qquad \text{Capacitance}$$

**Similarly:**

$$\widehat{\widehat{\mathbf{b}}} = \mathbf{M}_{\upsilon}^{-1}\widehat{\mathbf{h}} \qquad \mathbf{M}_{\upsilon}^{-1} : \qquad \text{Inductance}$$

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$$\oiint_{\partial V} \vec{D}\cdot d\vec{A} = \iiint_V \rho \quad dV$$

Developed

1975

$$\mathbf{C}\widehat{\mathbf{e}} = -\dot{\widehat{\widehat{\mathbf{b}}}}$$

$$\tilde{\mathbf{C}}\widehat{\mathbf{h}} = \dot{\widehat{\widehat{\mathbf{d}}}} + \widehat{\widehat{\mathbf{j}}}$$

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

EXACT!!

Choice of FD/FE/FI/FV….

$$\vec{D} = \varepsilon\cdot\vec{E} + \vec{P}$$

$$\vec{B} = \mu\cdot\vec{H} + \vec{M}$$

$$\vec{J} = \kappa\cdot\vec{E}$$

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

$$\widehat{\widehat{\mathbf{b}}} = \mathbf{M}_\nu^{-1}\widehat{\mathbf{h}} + \widehat{\widehat{\mathbf{m}}}$$

$$\widehat{\widehat{\mathbf{j}}} = \mathbf{M}_\sigma\widehat{\mathbf{e}}$$

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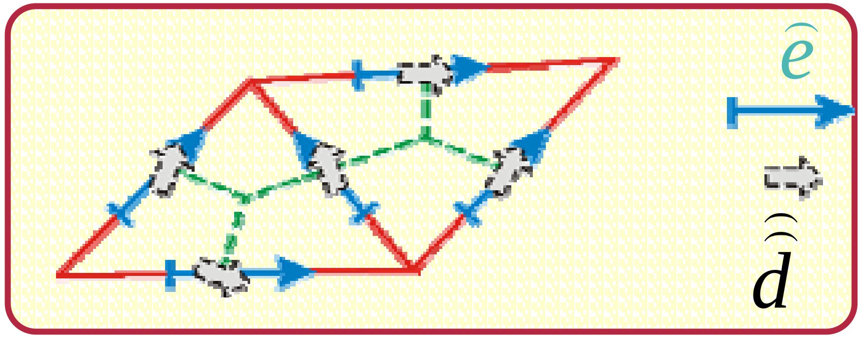
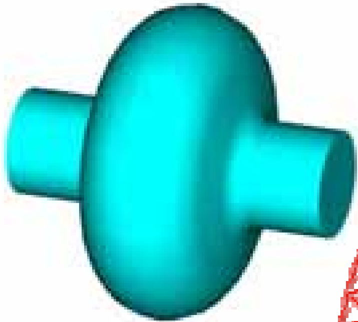
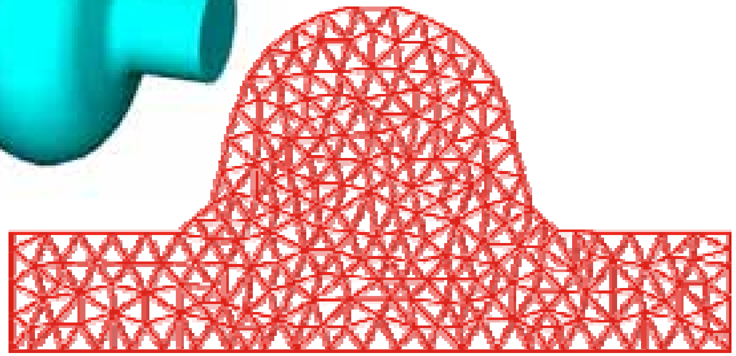
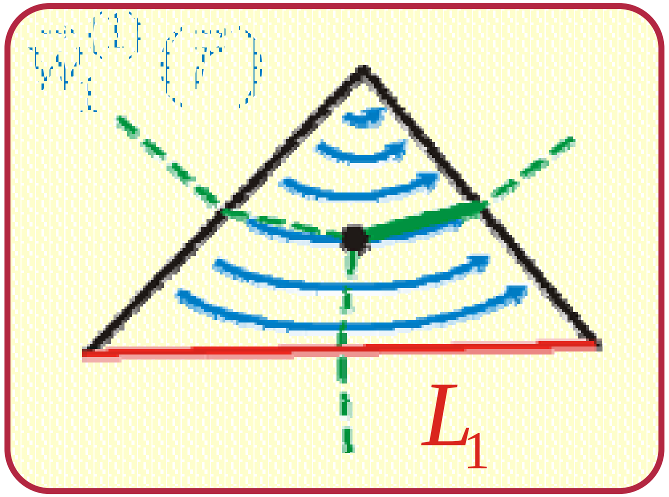
# FIT on Triangular Grids

Allocation of integral components
van Rienen **1983**



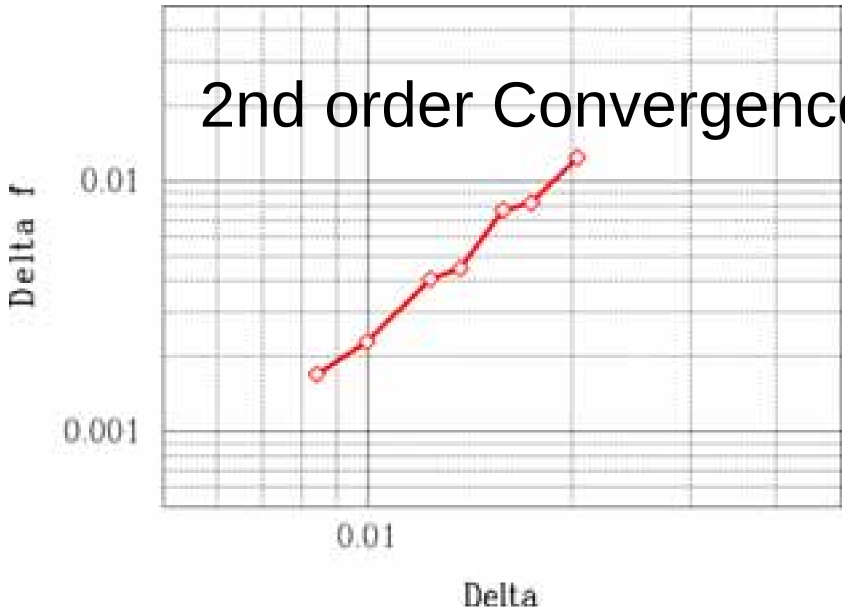







Discrete Material Relation
based on Whitney elements
R. Schuhmann **2001**

2nd order Convergence



# Circuits vs. FIT

**Circuit mesh analysis**

$$\frac{\partial}{\partial t} = 0$$

**Field analysis**

| Circuit equations | Field equations |
|---|---|
| $\mathbf{C}\mathbf{v} = 0$ | $\mathbf{C}\widehat{\mathbf{e}} = 0$ |
| $\mathbf{C}^T\mathbf{i}_m = \mathbf{i}$ | $\mathbf{C}^T\widehat{\mathbf{h}} = \widehat{\widehat{\mathbf{j}}}$ |
| $\mathbf{v} = \mathbf{R}\mathbf{i} + \mathbf{v}_S$ | $\widehat{\mathbf{e}} = \mathbf{M}_\rho \widehat{\widehat{\mathbf{j}}} + \widehat{\mathbf{e}}_S$ |
| $\mathbf{C}\mathbf{R}\mathbf{C}^T\mathbf{i}_m = -\mathbf{C}\mathbf{v}_S$ | $\mathbf{C}\mathbf{M}_\rho\mathbf{C}^T\widehat{\mathbf{h}} = -\mathbf{C}\widehat{\mathbf{e}}_S$ |

$\mathrm{C}$ :
incidence matrix of edges to the independent meshes of the network

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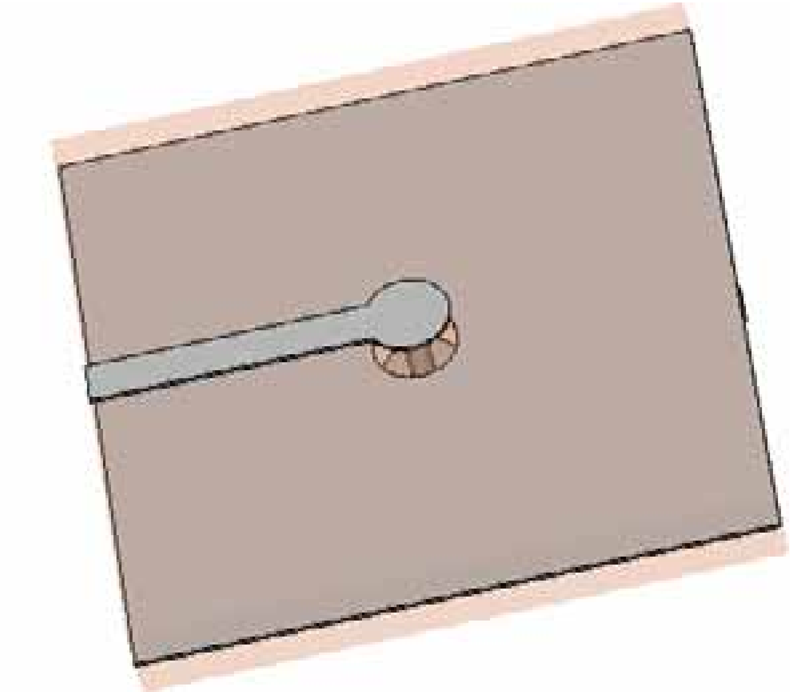
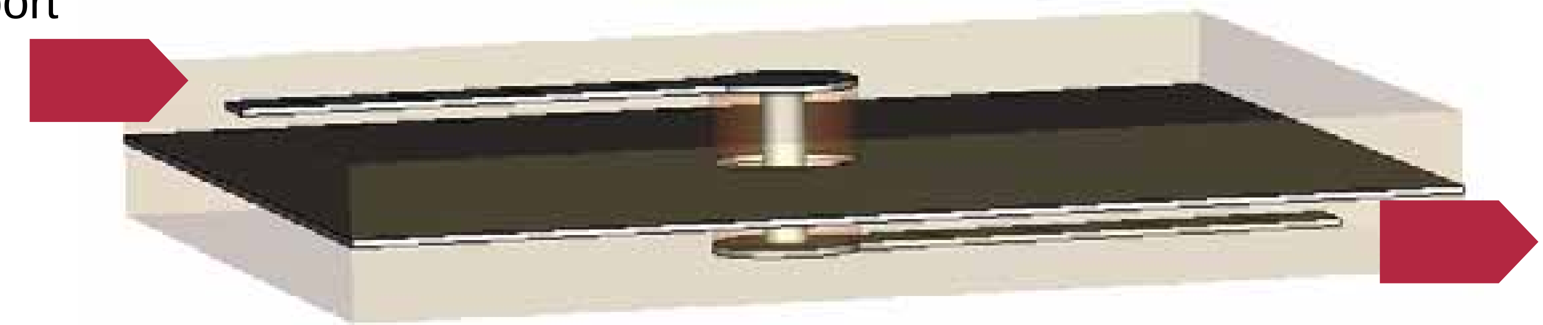
# Simple Via Structure



Input port



Output port

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- HEX Transient Solution
- HEX Frequency Domain
- TET  Frequency Domain
- Model Order Reduction

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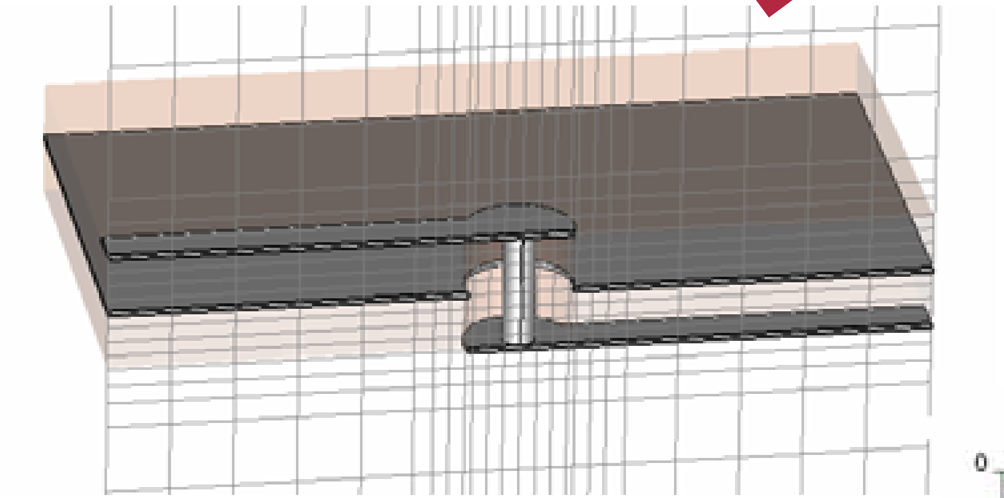
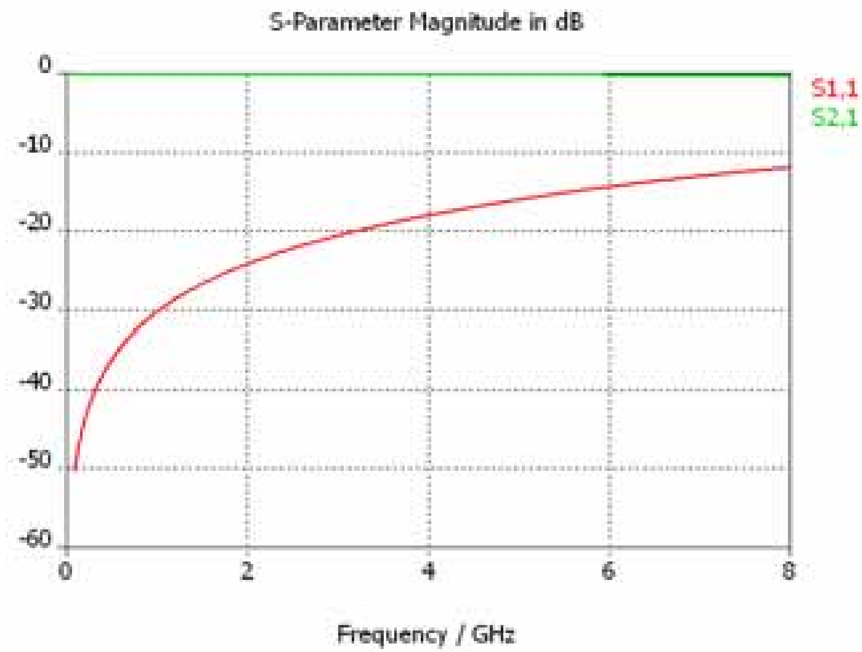
- HEX Transient Solution

$$\tilde{\mathbf{C}}\mathbf{M}_{\nu}\mathbf{C}\hat{\mathbf{e}} + \mathbf{M}_{\kappa}\frac{\mathrm{d}}{\mathrm{dt}}\hat{\mathbf{e}} + \mathbf{M}_{\varepsilon}\frac{\mathrm{d}^2}{\mathrm{dt}^2}\hat{\mathbf{e}} = -\frac{\mathrm{d}}{\mathrm{dt}}\hat{\hat{\mathbf{j}}}_s$$



FFT(Output) / FFT(Input)




- HEX Frequency Domain
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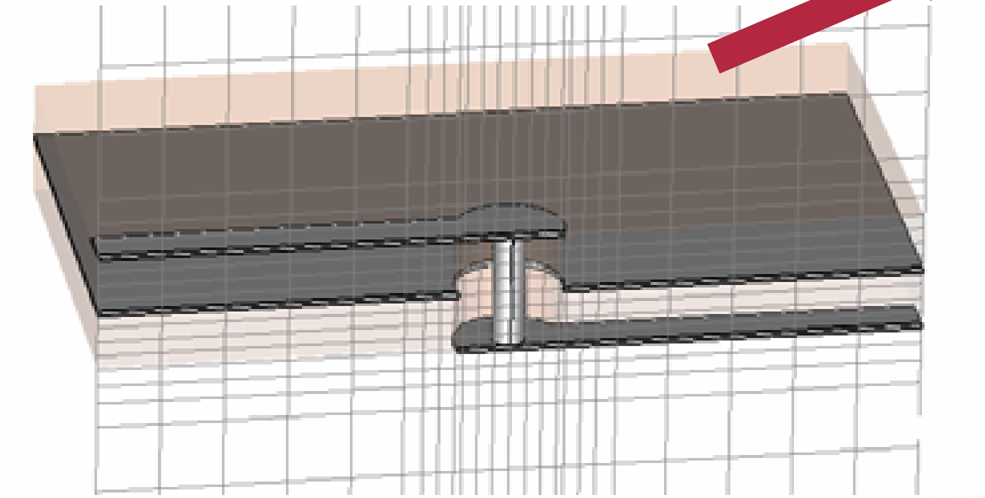
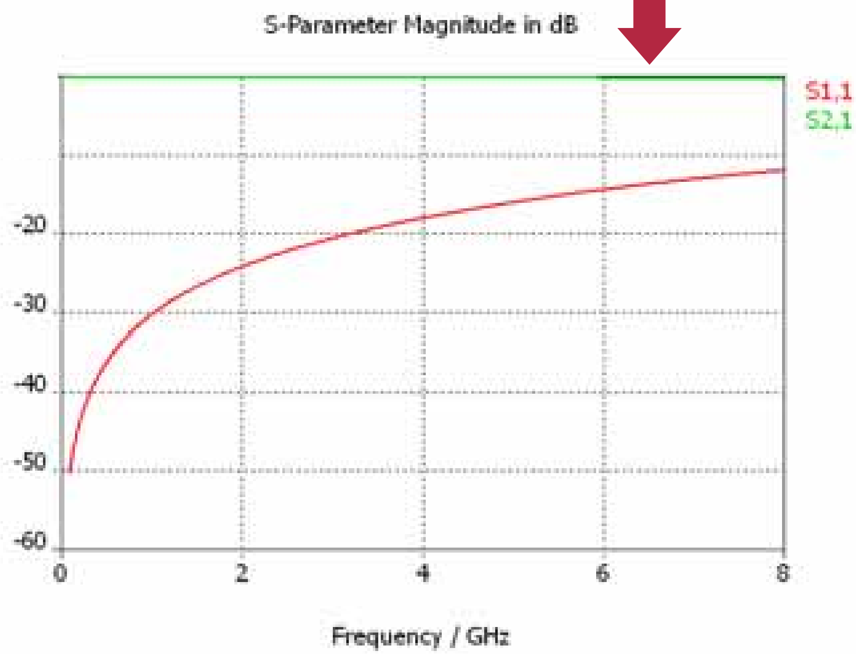
- HEX Transient Solution
- HEX Frequency Domain



$$(\tilde{\mathbf{C}}\mathbf{M}_{\nu}\mathbf{C} + i\omega\mathbf{M}_{\kappa} - \omega^2\mathbf{M}_{\varepsilon})\hat{\mathbf{e}} = -i\omega\,\hat{\mathbf{j}}_s$$

$$\mathrm{A}\,\hat{\mathrm{e}} = \mathrm{r}$$




- 
- TET  Frequency Domain
- Model Order Reduction

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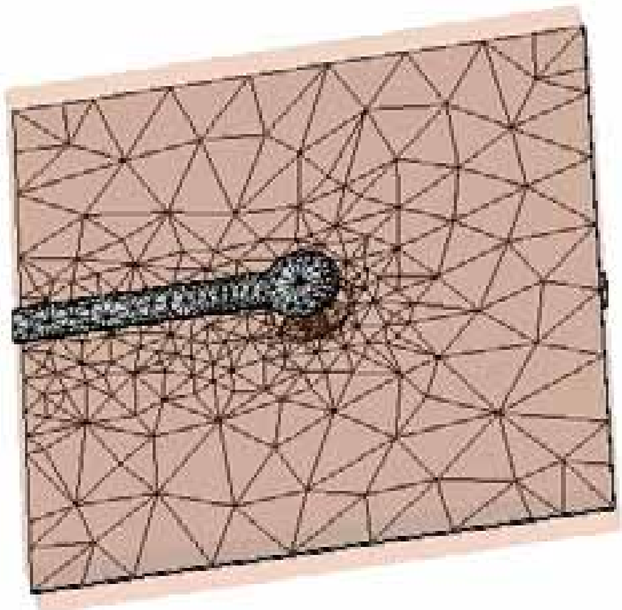
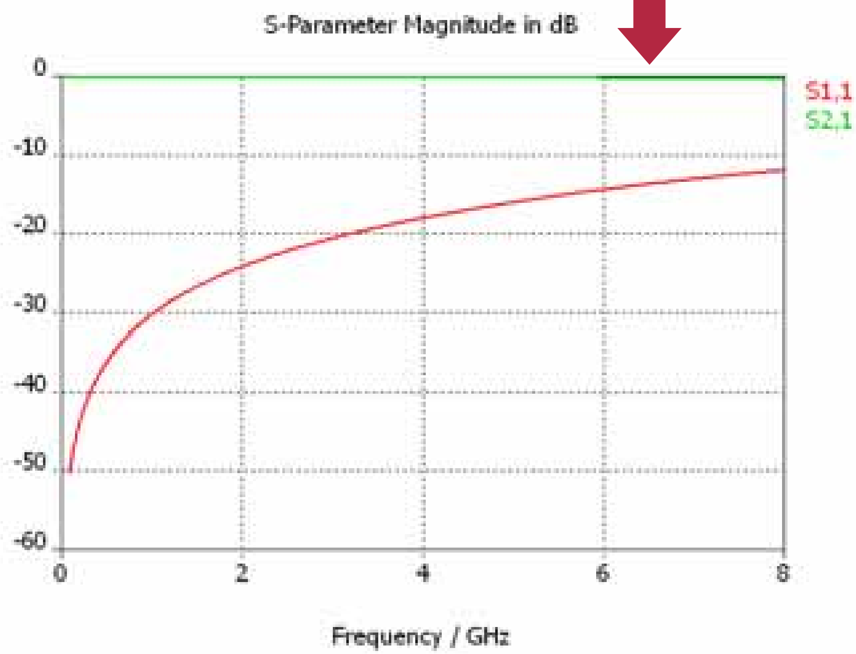
- HEX Transient Solution
- HEX Frequency Domain
- TET Frequency Domain



$$(\tilde{\mathbf{C}}\mathbf{M}_{\nu}\mathbf{C} + i\omega\mathbf{M}_{\kappa} - \omega^2\mathbf{M}_{\varepsilon})\hat{\mathbf{e}} = -i\omega\,\hat{\hat{\mathbf{j}}}_s$$

$$A\,\hat{e} = r$$




- Model Order Reduction

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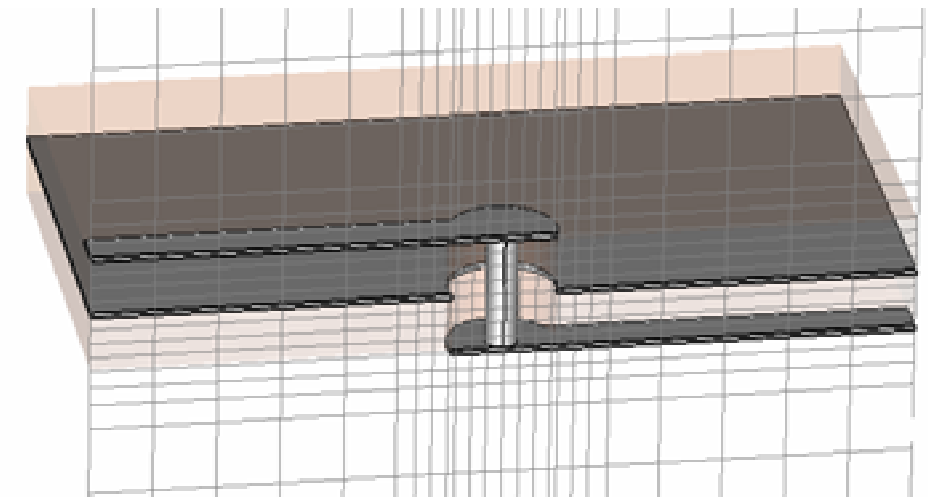
- HEX Transient Solution
- HEX Frequency Domain
- TET Frequency Domain
- Model Order Reduction

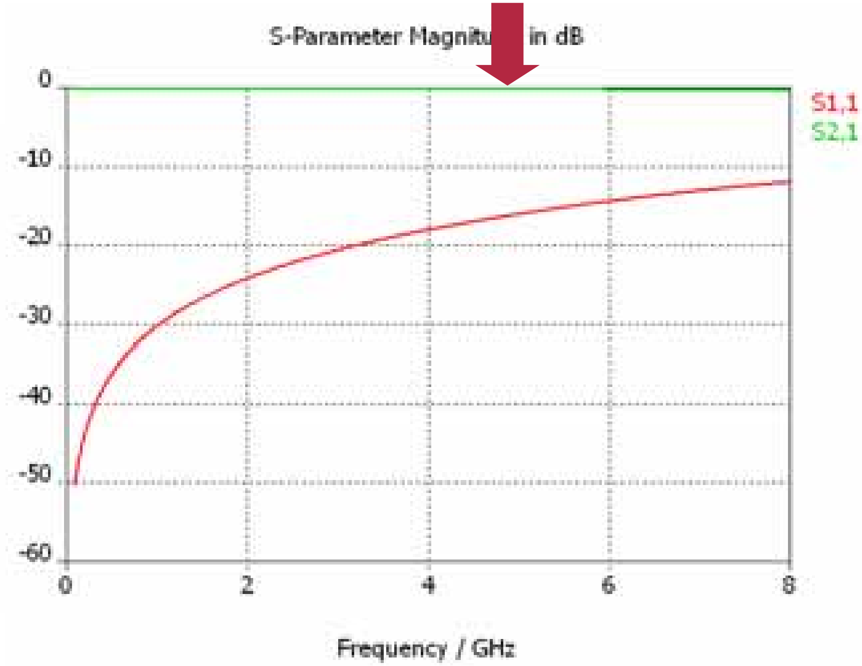
$$(\tilde{\mathbf{C}}\mathbf{M}_{\nu}\mathbf{C} + i\omega\mathbf{M}_{\kappa} - \omega^2\mathbf{M}_{\varepsilon})\hat{\mathbf{e}} = -i\omega\,\hat{\hat{\mathbf{j}}}_s$$

$$A_{NXN}\hat{e} = r$$

MOR

$$A_{nXn}\hat{e} = r$$



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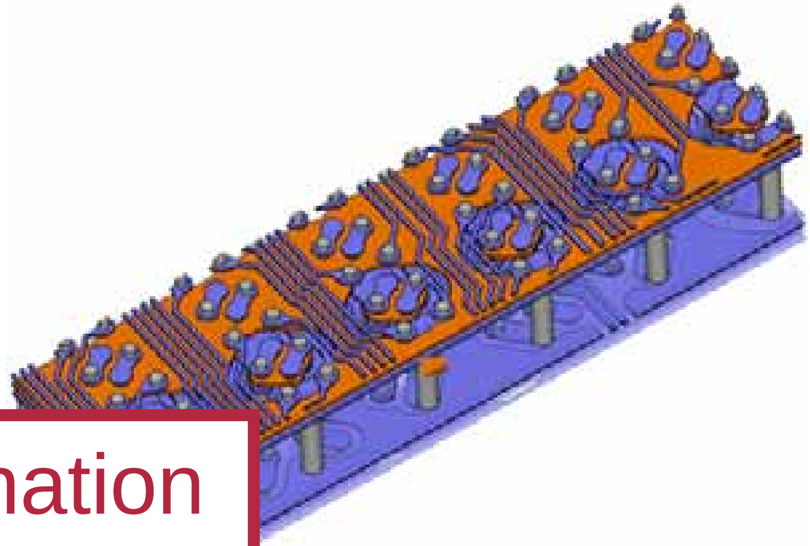
# EM Solution = 3 Steps

## 1 Spatial Discretization of geometry

- Staircase grid
- Tetrahedral grid
- Surface mesh
- Boundary fitte
- ....



Which combination

is the best ?

## 2 Local appr... Maxwell's Equations

- Finite Difference
- Finite Integration Technique
- Finite Element
- Finite Volume
- ....

## ...ng the algebraic system

- Direct solver
- Iterative solver
- Eigenvalue solver
- Time stepping solver
- ....

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# Selection of the “best” Algorithm

$$G = \frac{Q}{\$}$$

Required accuracy

Reliability

Robustness

Absolute Calc. Time

….

CPU

Memory

Manpower

….

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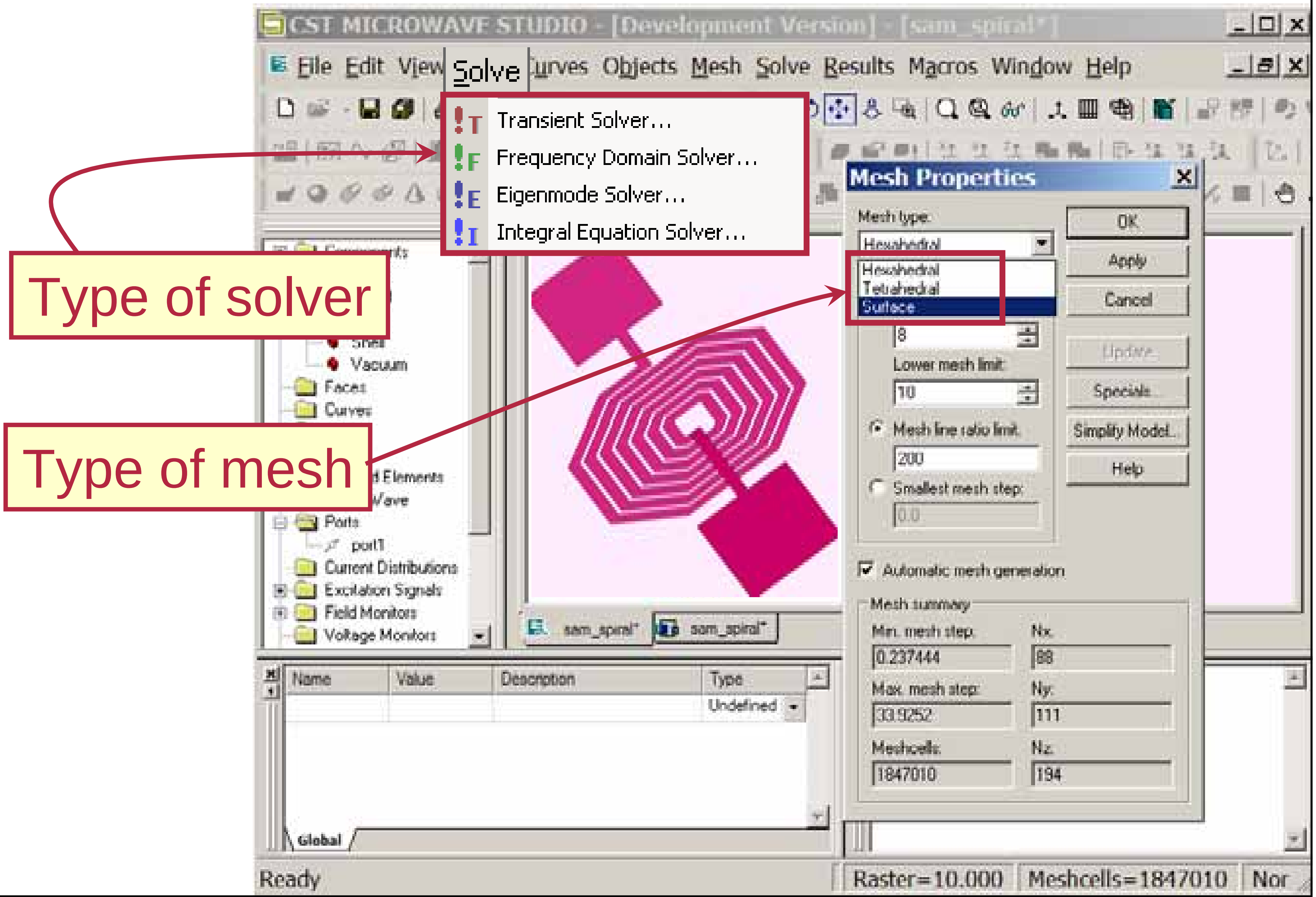
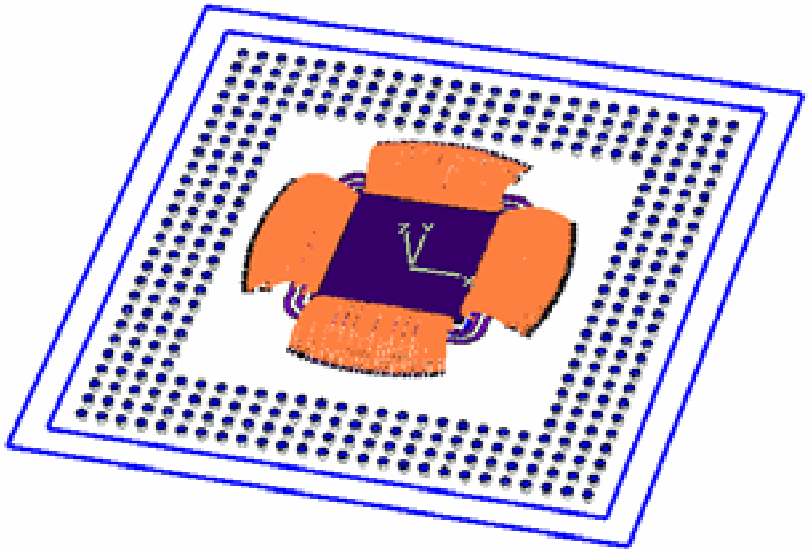
# Example of User Choice

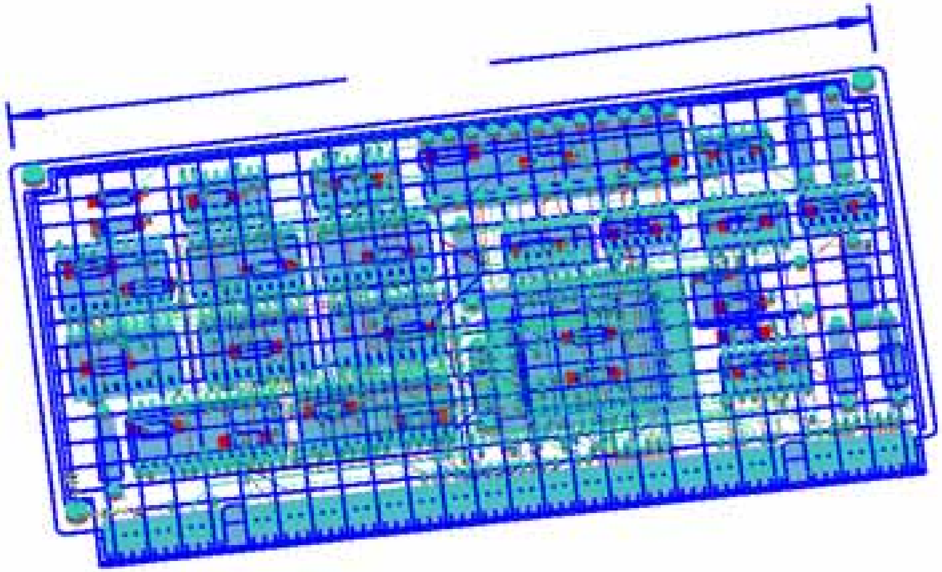


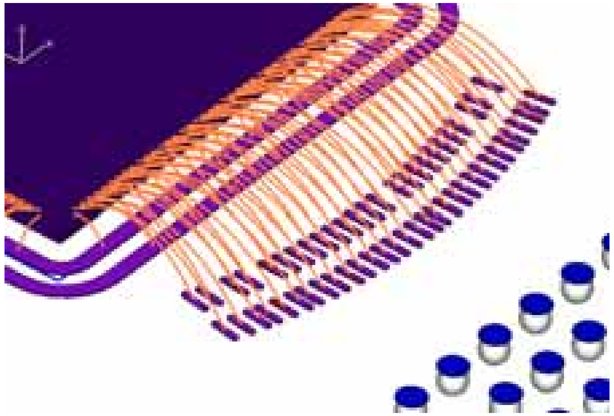
# Contents

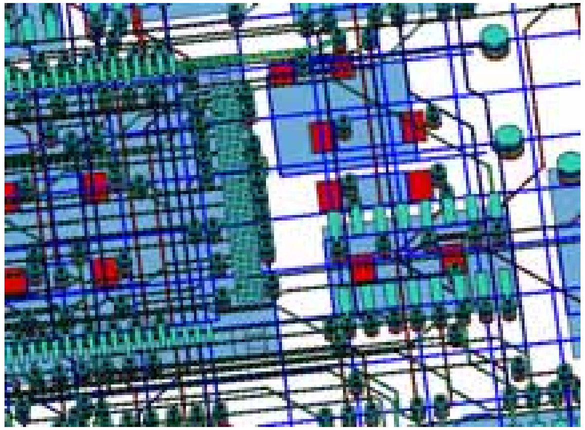
- Introduction
- State of the art
  - Three steps in solving an EM Problem
  - Finite Integration Technique as universal method
  - Wide choice of solution methods
- Future trends
  - Geometrically complex problems
  - EMC, Signal and Power integrity
  - Network Extraction, Passivity
  - Coupled problems
  - Integrated flows
- Conclusions

# Stuctures get more complex









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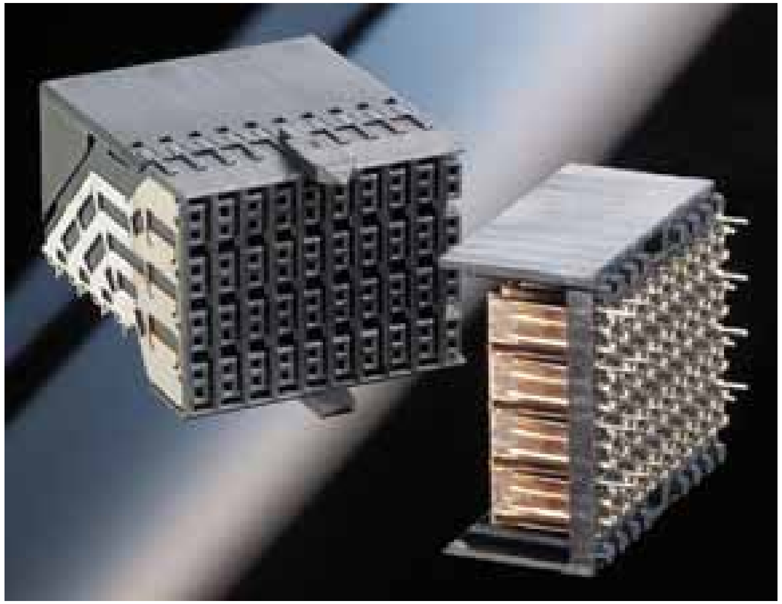
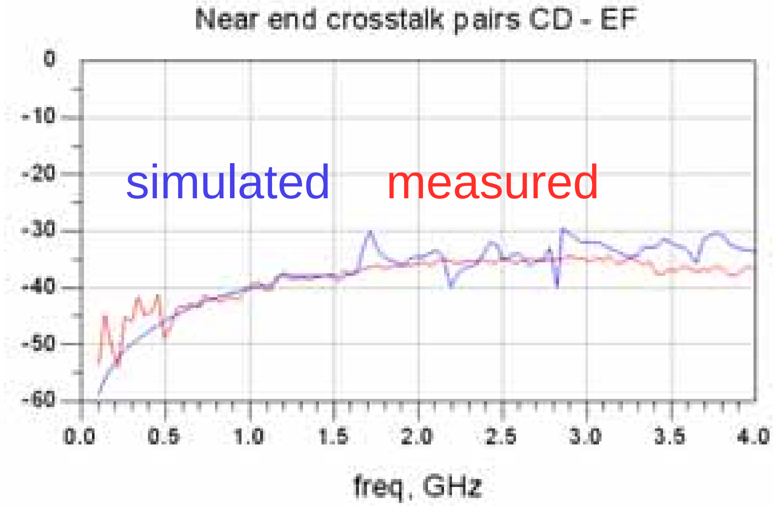
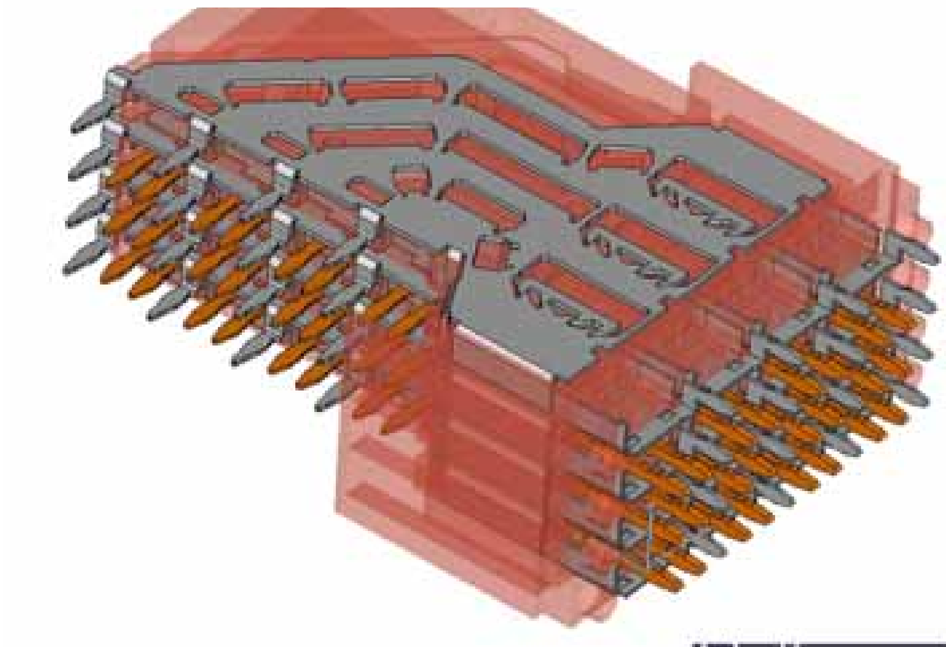
# ERNI ERmet zeroXT
# High Speed SMT Connector

Can handle differential signals up to 10 GBit/s





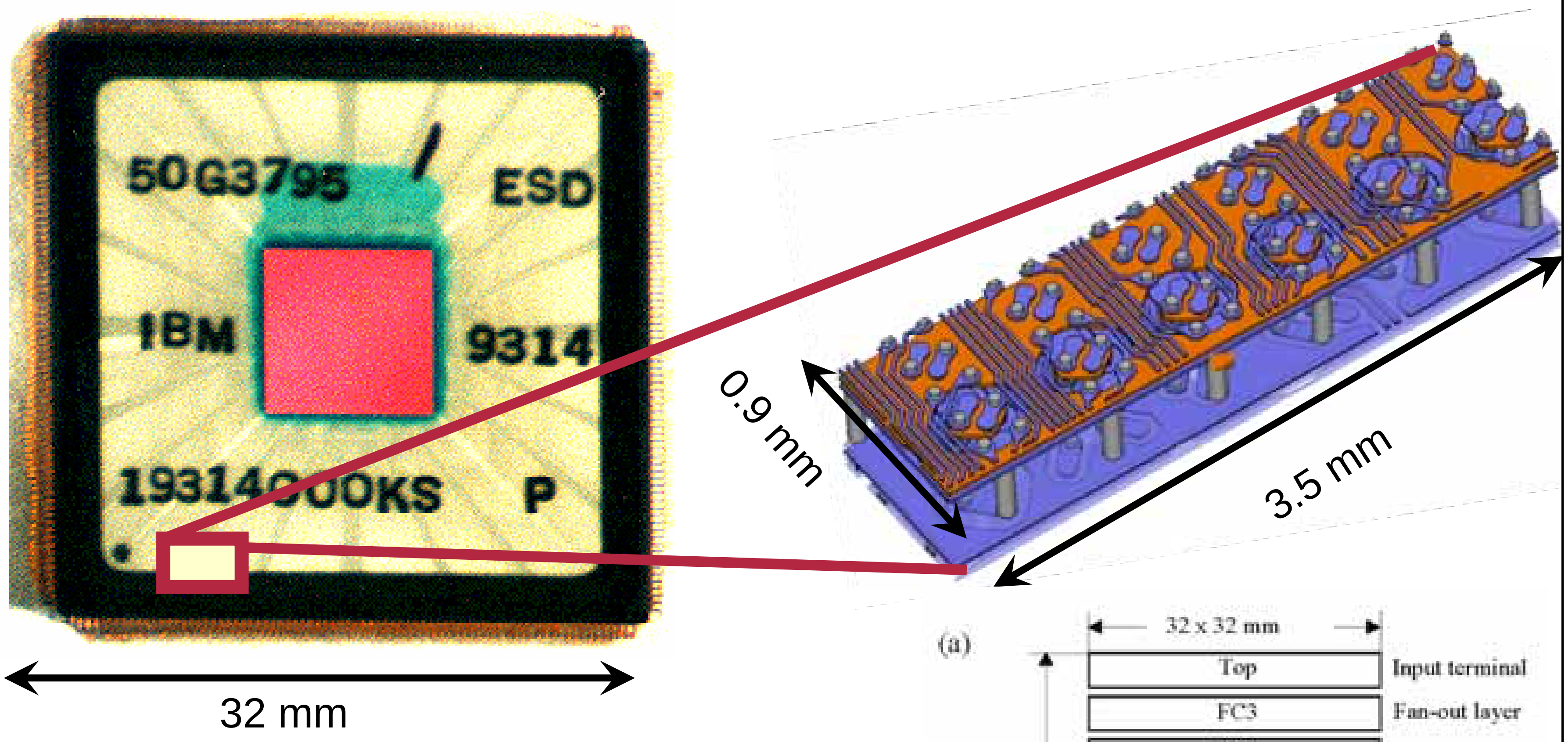



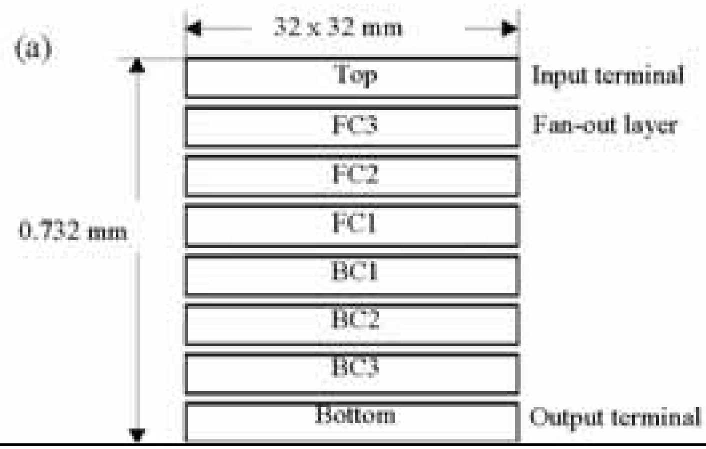
***ERNI:***
***… the connector could be manufactured without a major re-design in one pass....”***

AdMOS

# Very Large Problems

- IBM Example

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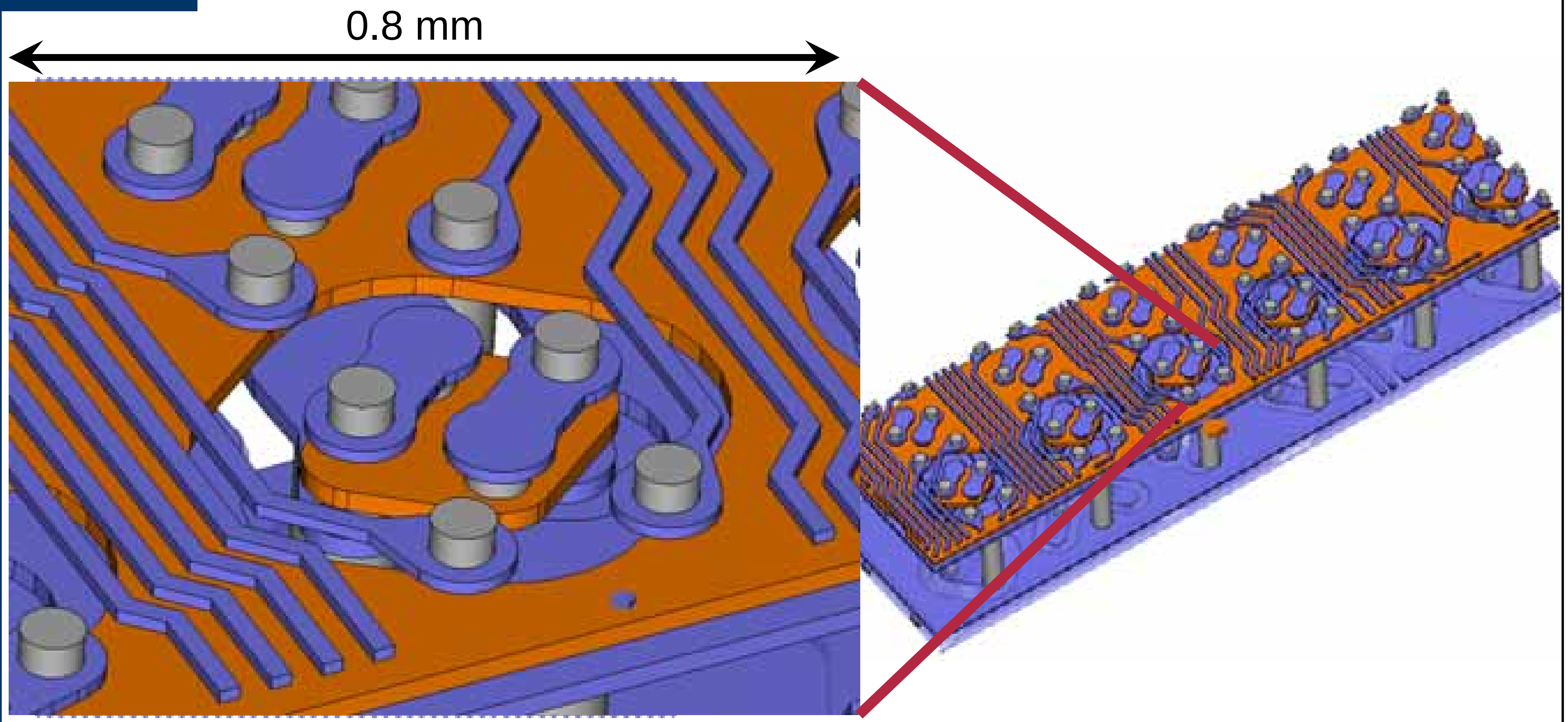
# E-Small Very Large Problems

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# Three Solutions

- Use commerical software „as is“

  *Limited by memory size of my computer (5GB)*

  *Size of domain only 25% of entire structure*

  - **Time domain hexahedral mesh (30 million cells)**
  - **Frequency domain tetrahedral mesh (5.3 million tet’s)**

  *Could be easily extended by a bigger computer*

- New parallel software
  - **Time domain  hexahedral mesh (650 million cells)**

  *Not yet with all features*

# Three Solutions

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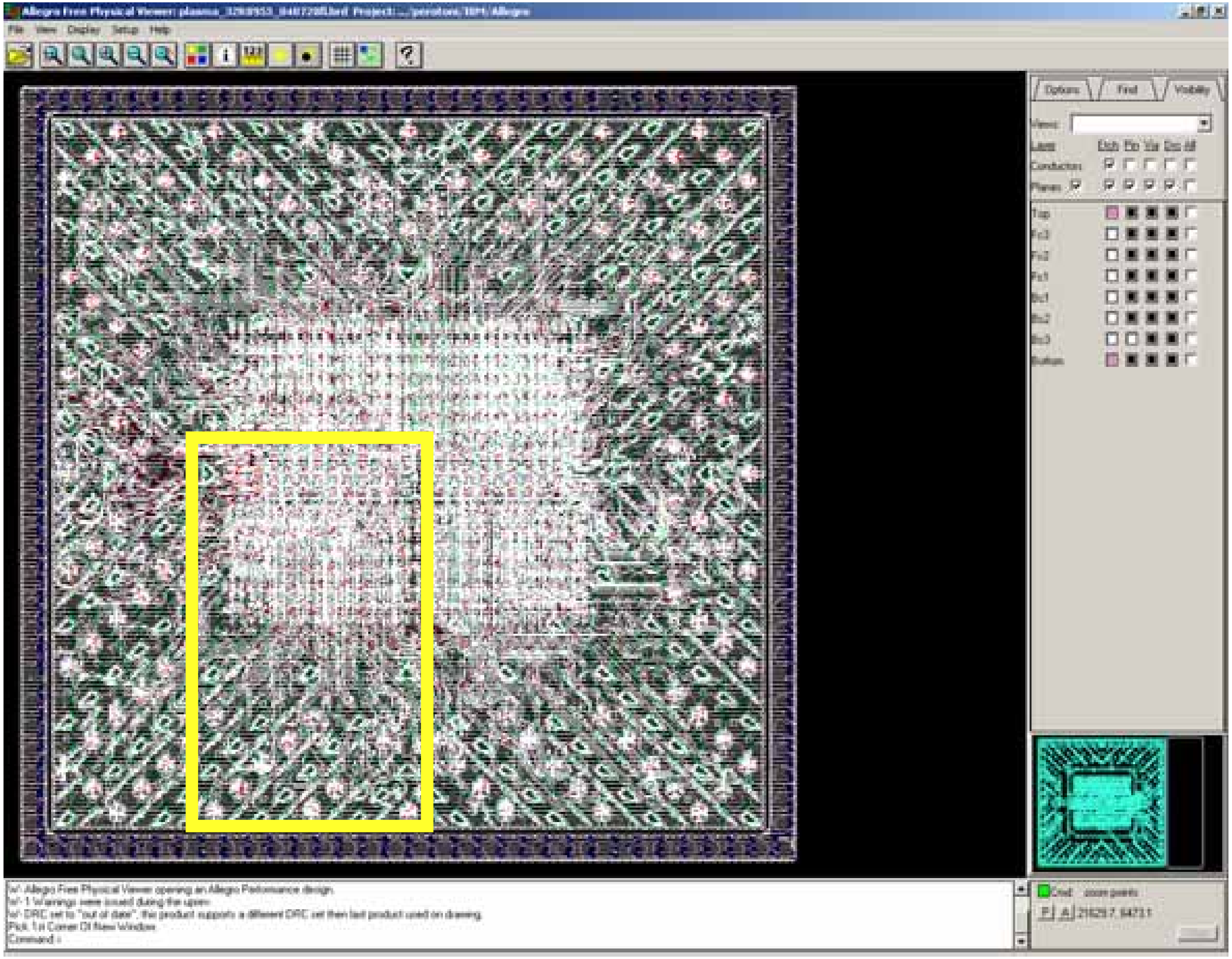

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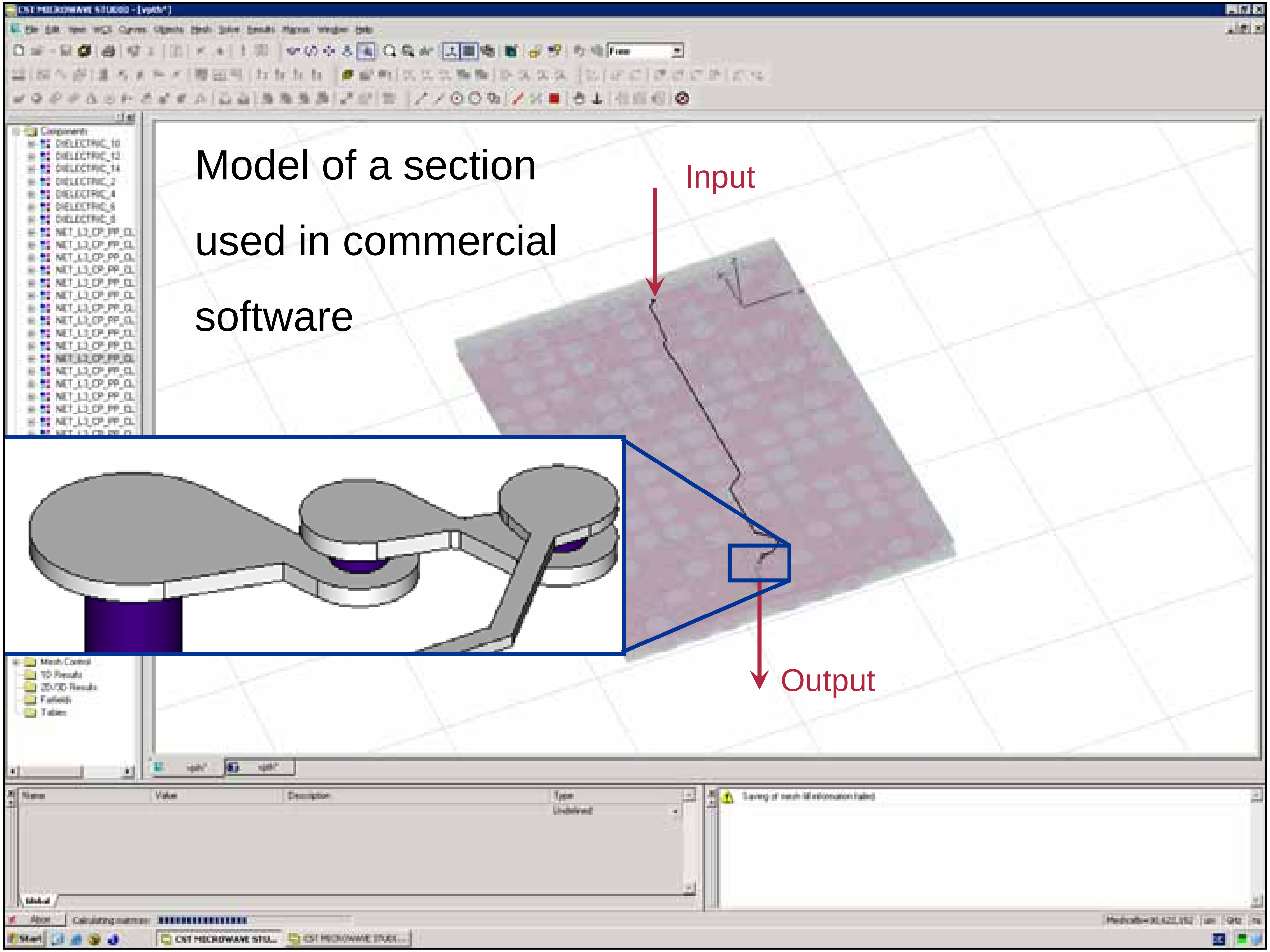
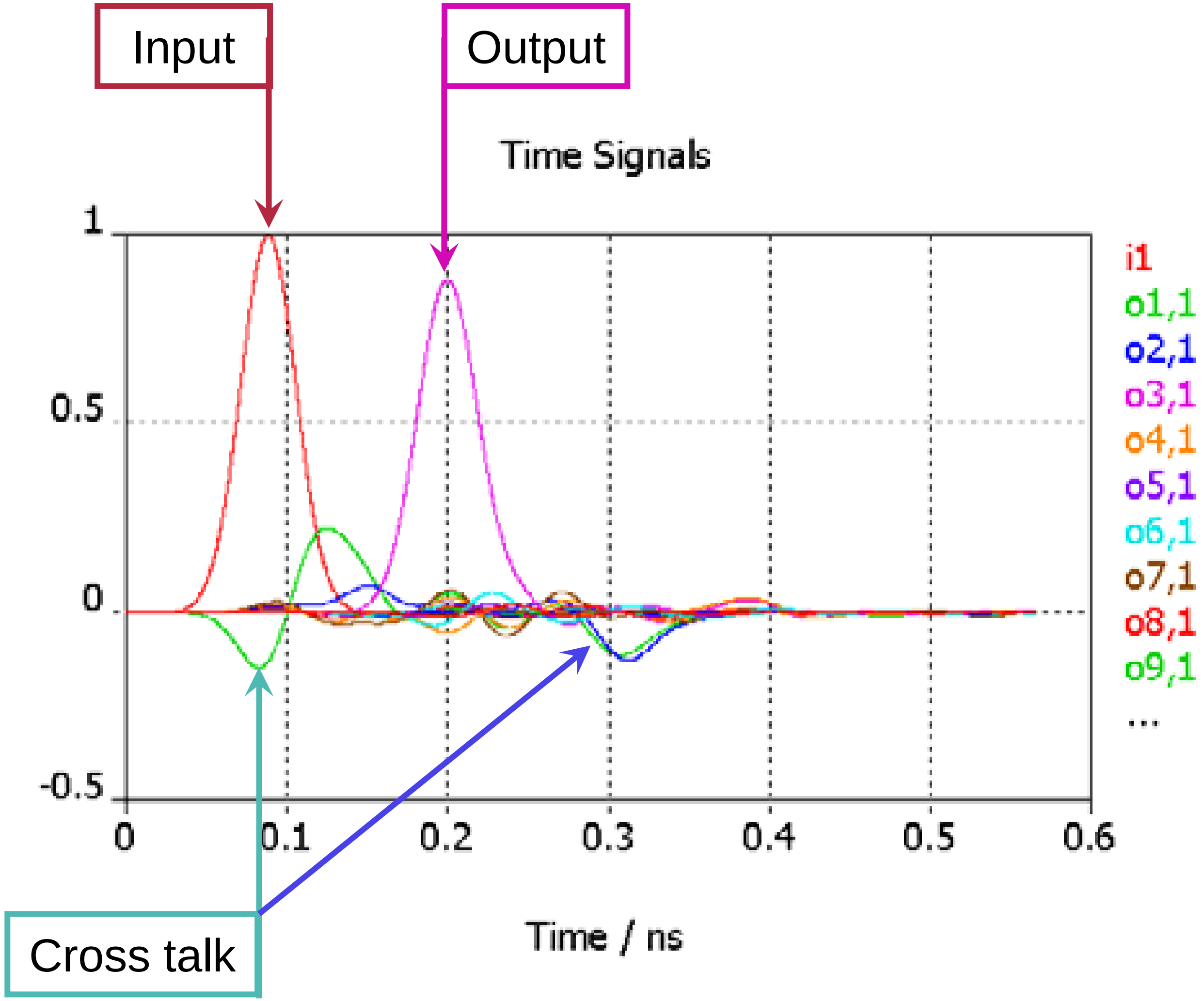


Model of a section used in commercial software
Input
Output

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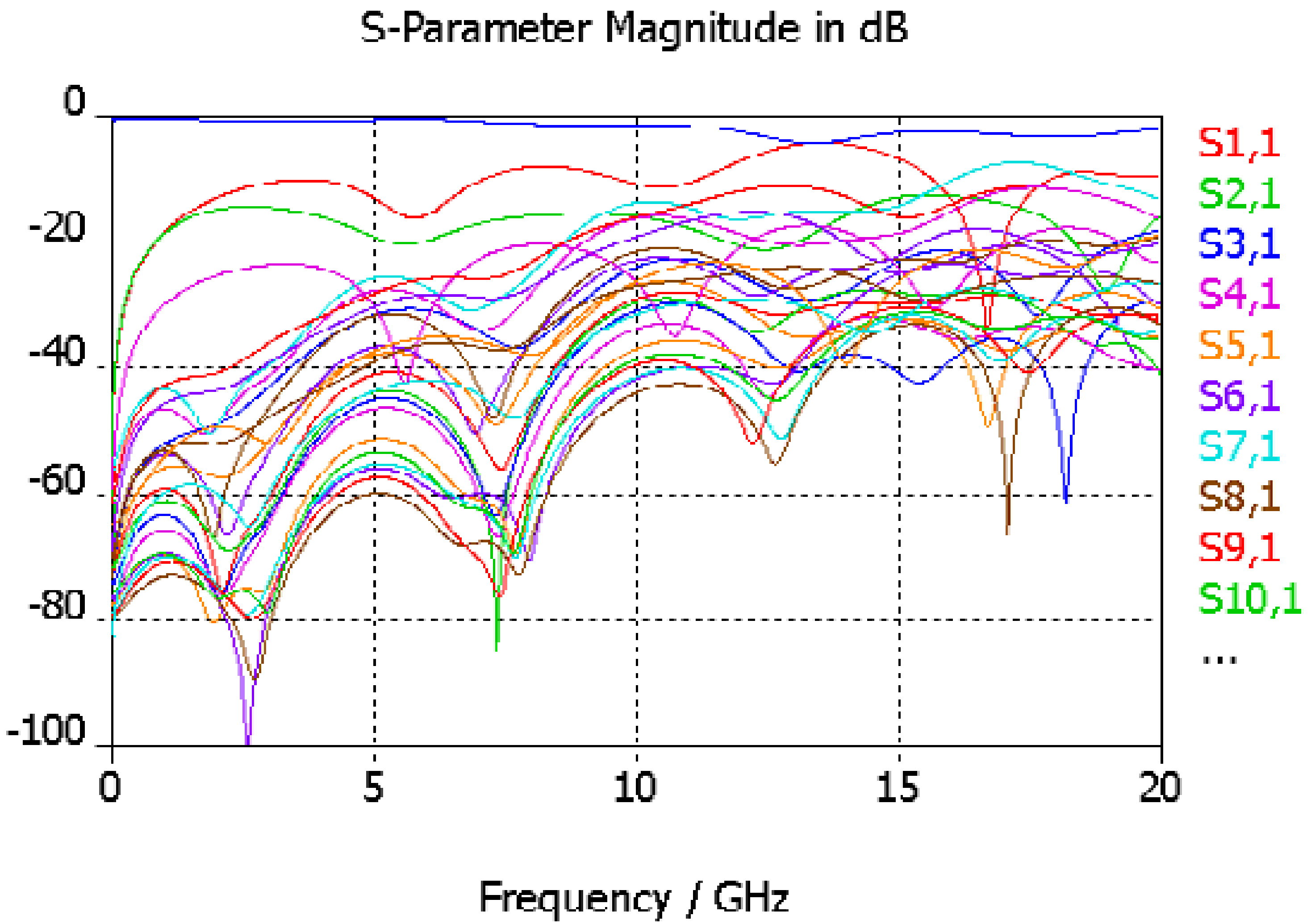
FFT(Output) / FFT(Input)
⇒ S-Parameter for 0 to 20 GHZ in One Go!

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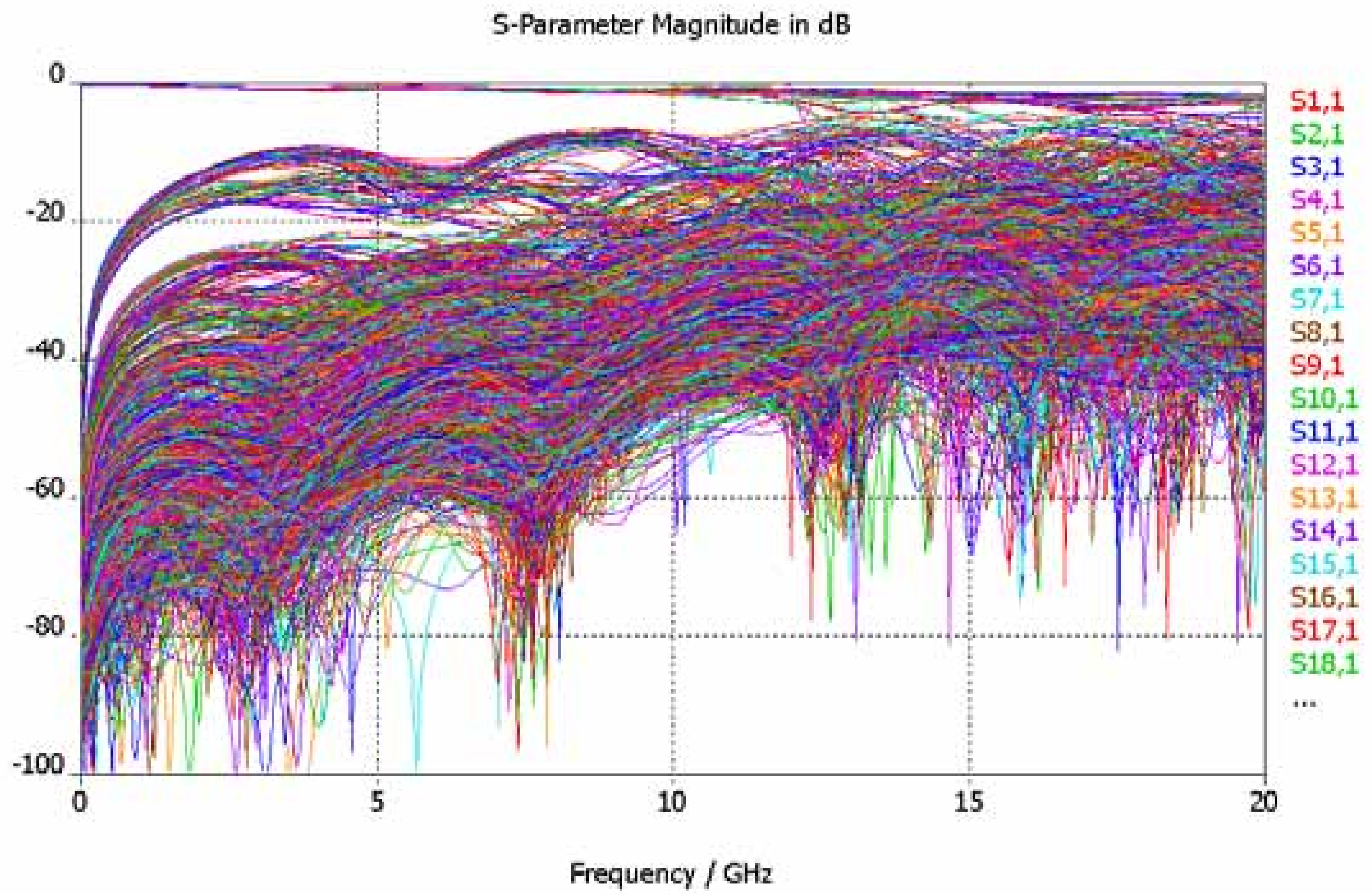
# All S-parameter in one Plot

FFT(Output) / FFT(Input)
$\Rightarrow$ S-Parameter for 0 to 20 GHZ in One Go! **1600 curves!**

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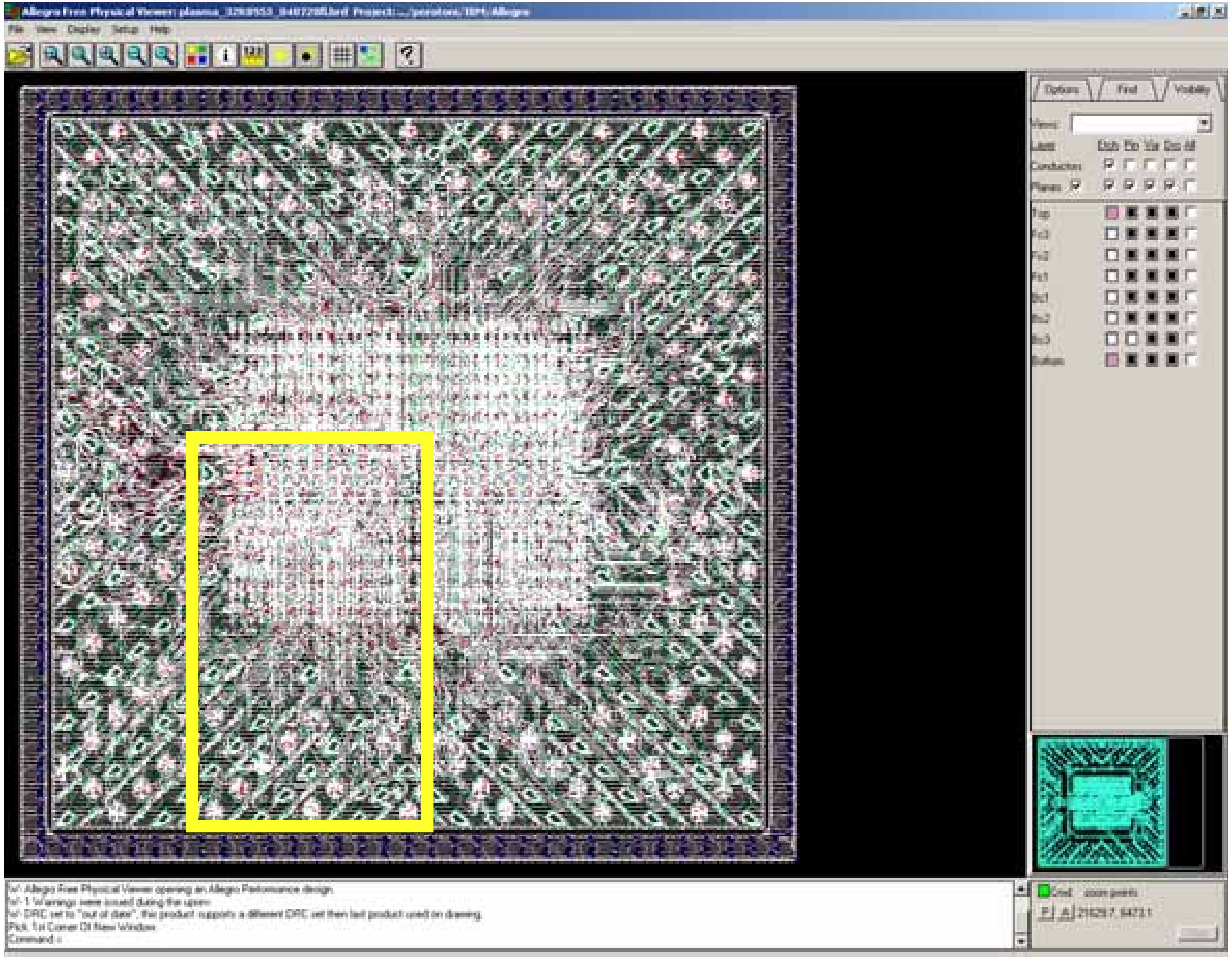


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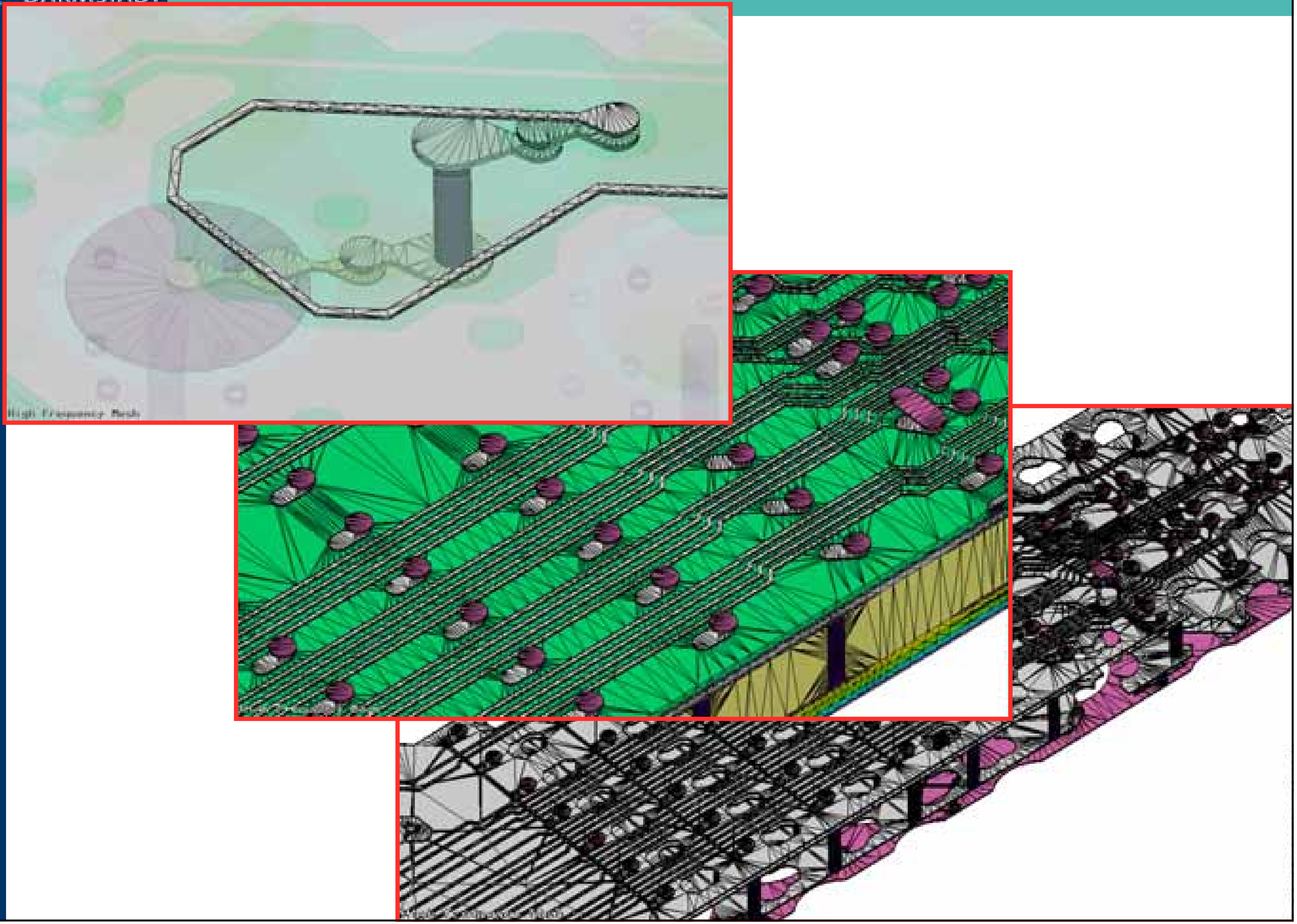


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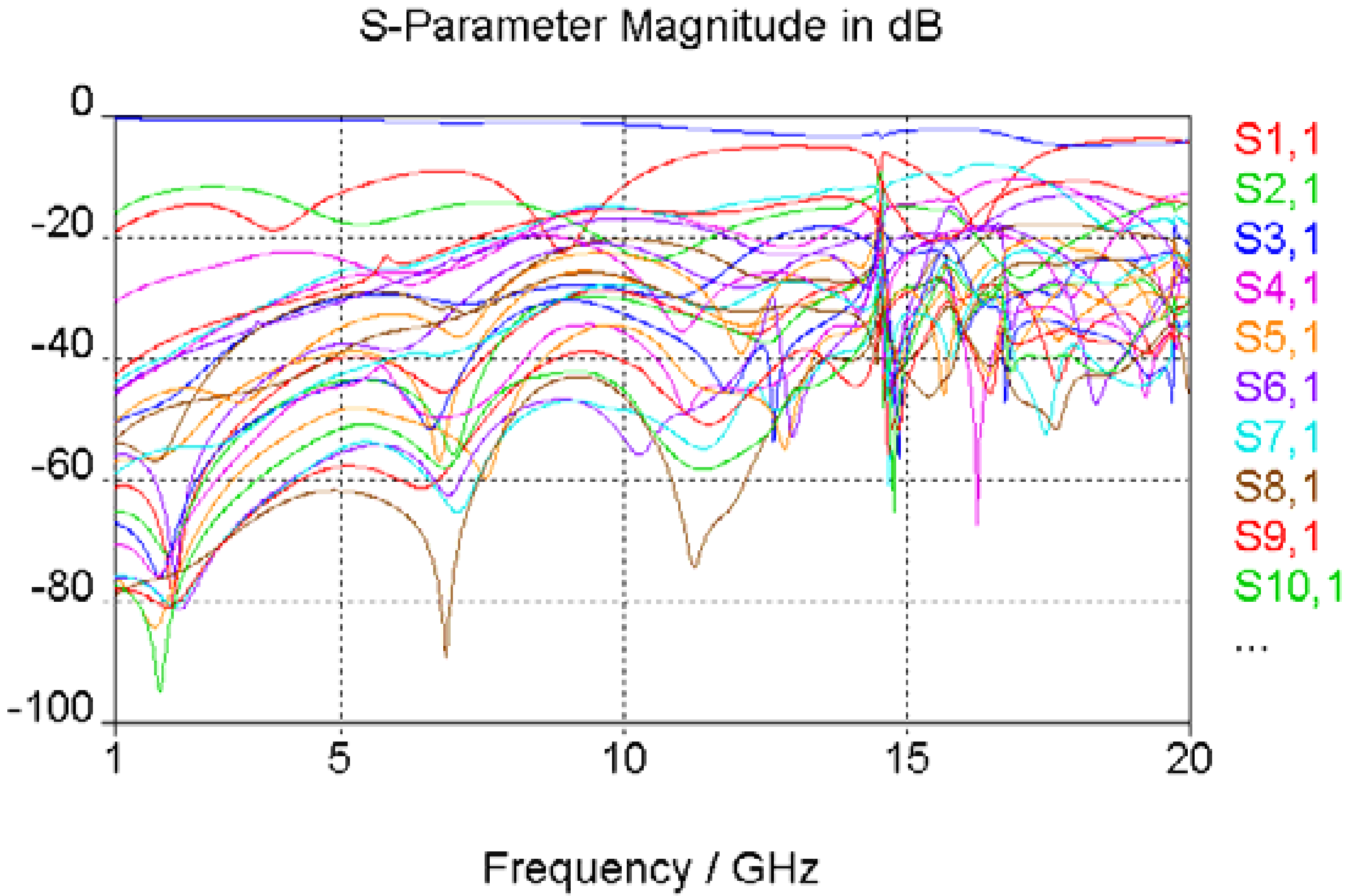
# S-Parameter Frequency Domain

## 5.3 million tet's, broad band frequency domain

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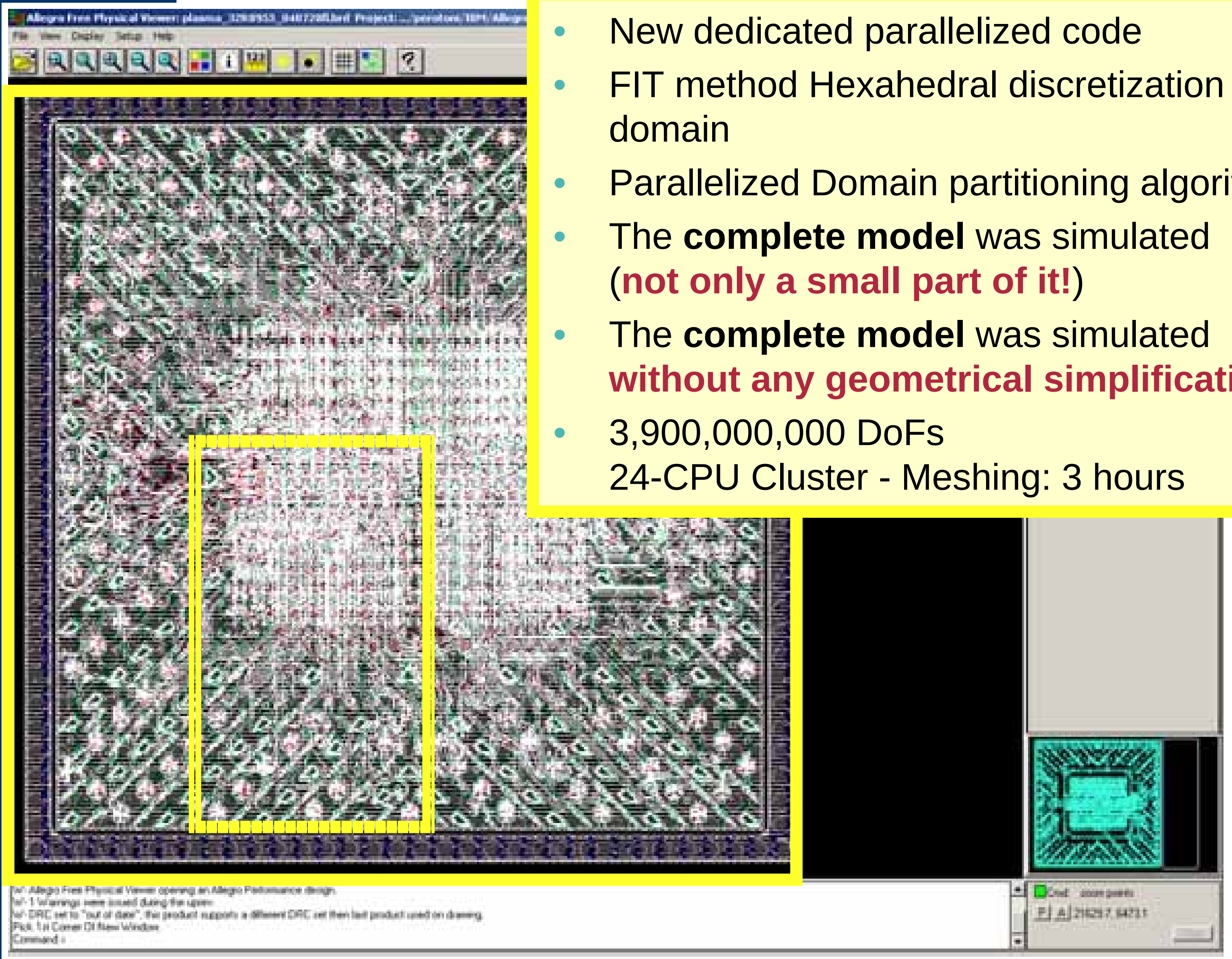
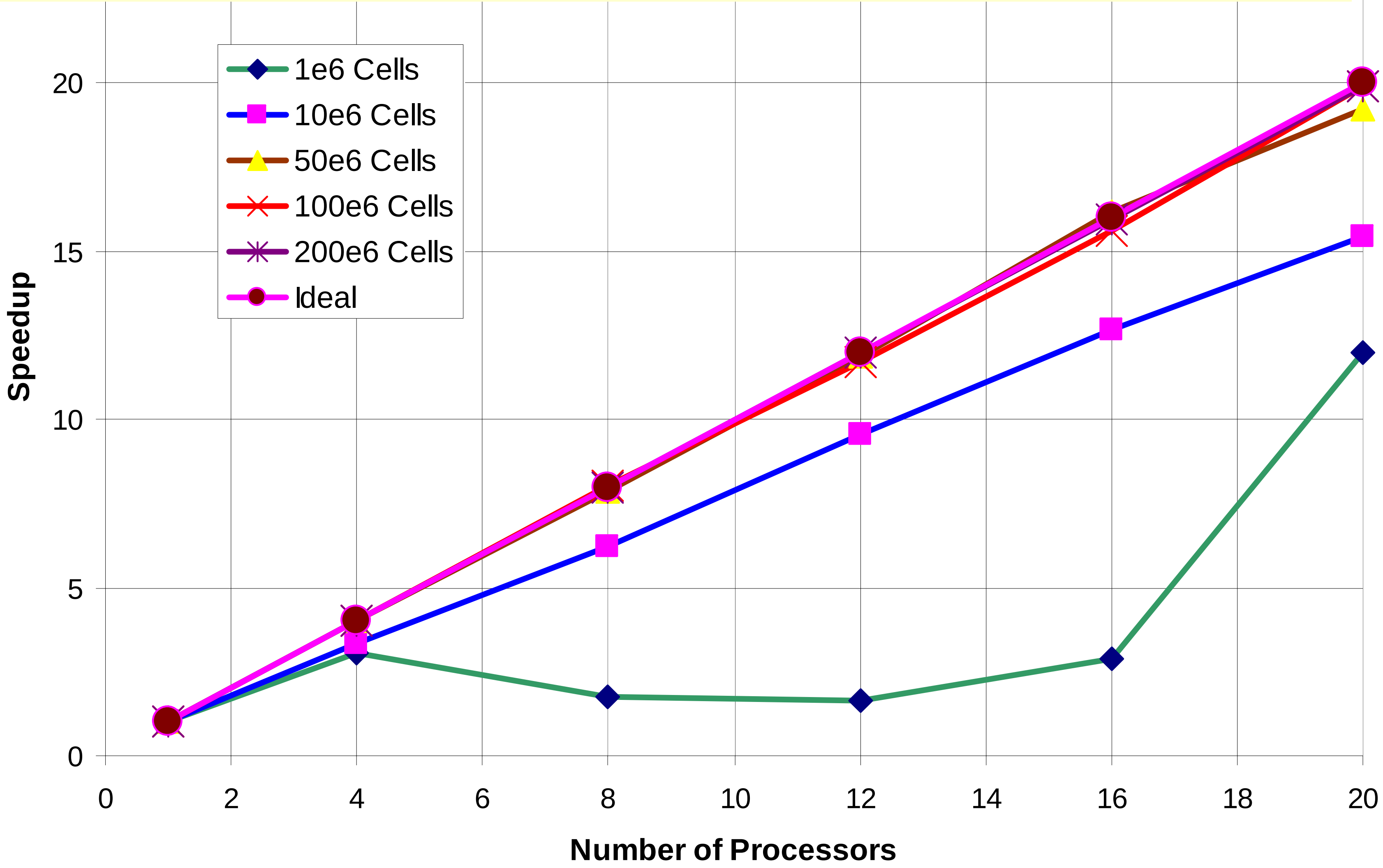


- New dedicated parallelized code
- FIT method Hexahedral discretization time domain
- Parallelized Domain partitioning algorithm
- The **complete model** was simulated (**not only a small part of it!**)
- The **complete model** was simulated **without any geometrical simplification**
- 3,900,000,000 DoFs
  24-CPU Cluster - Meshing: 3 hours

## Speedup for a simple test model (no ports)

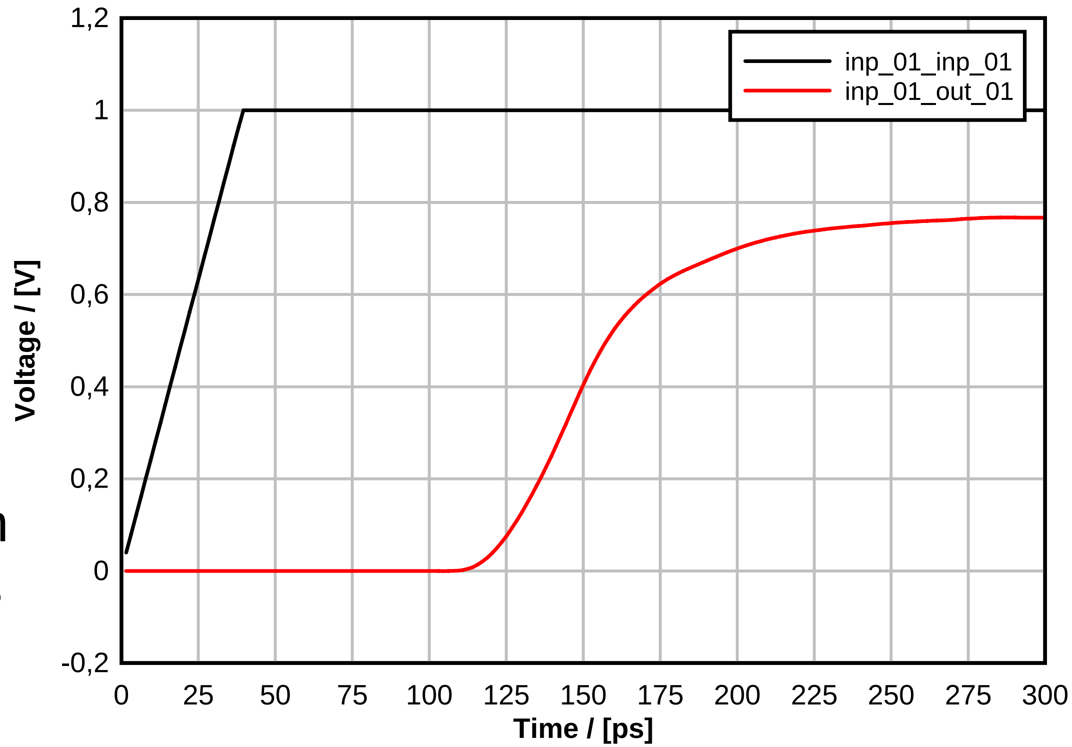


# Results

Input

Output

Good agreement with the measured results provided by IBM:




Dedicated talk/paper on Wednesday

**EPEP** - Session XIII

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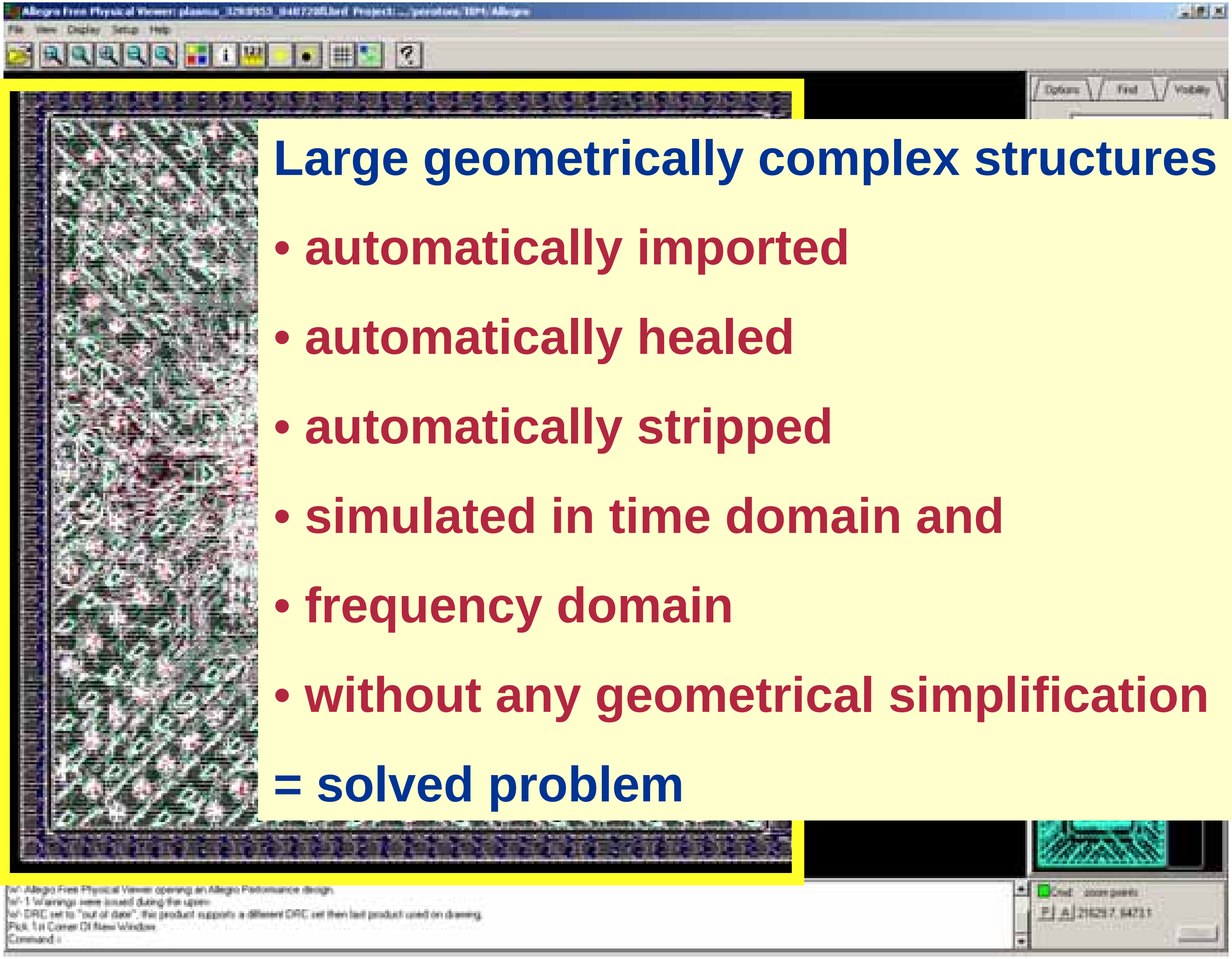

## Large geometrically complex structures can be

- automatically imported
- automatically healed
- automatically stripped
- simulated in time domain and
- frequency domain
- without any geometrical simplification

= solved problem

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# Hardware acceleration

**80-100 Mcells / 1 sec** for a realistic application (ideal up to **400 Mcells/sec**)

~ Factor 10 with respect to 32 bit processor

~ Factor 5 with respect to 64 bit processor

~ Factor 2 with respect to Woodcrest

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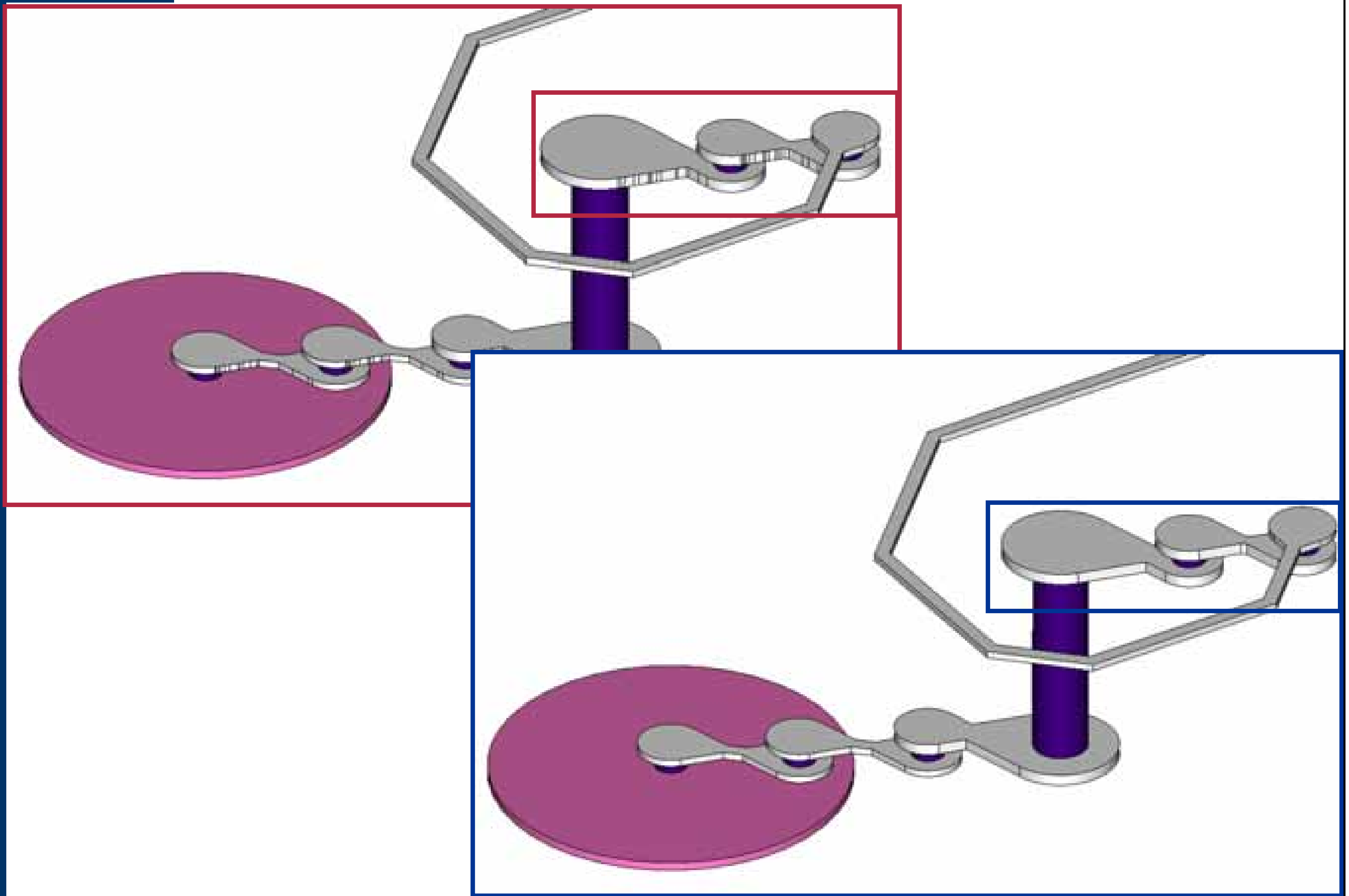
# The Real Challenge of Very Large Structures



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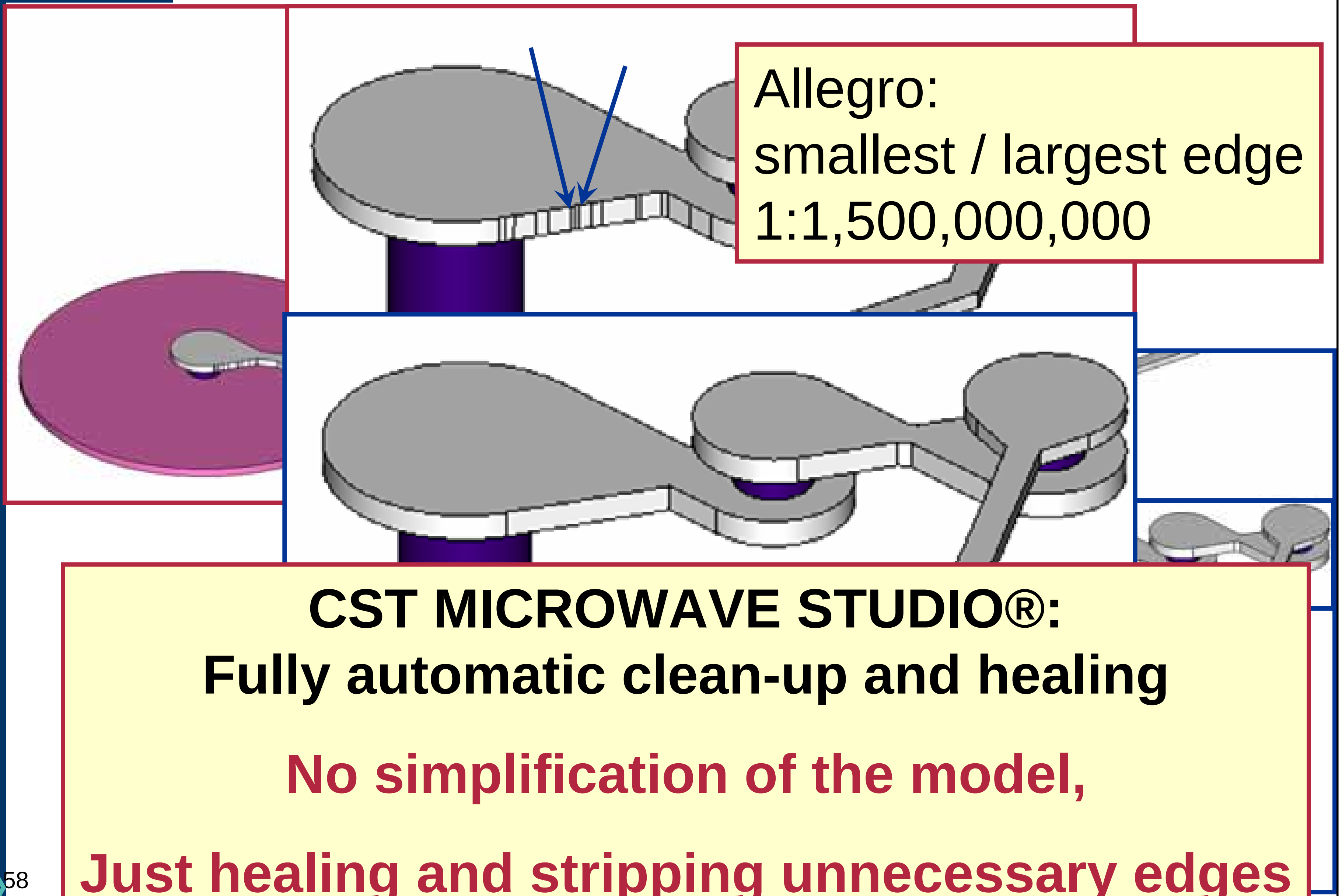

Allegro:
smallest / largest edge
1:1,500,000,000

**CST MICROWAVE STUDIO®:**
**Fully automatic clean-up and healing**

**No simplification of the model,**

**Just healing and stripping unnecessary edges**

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# Contents



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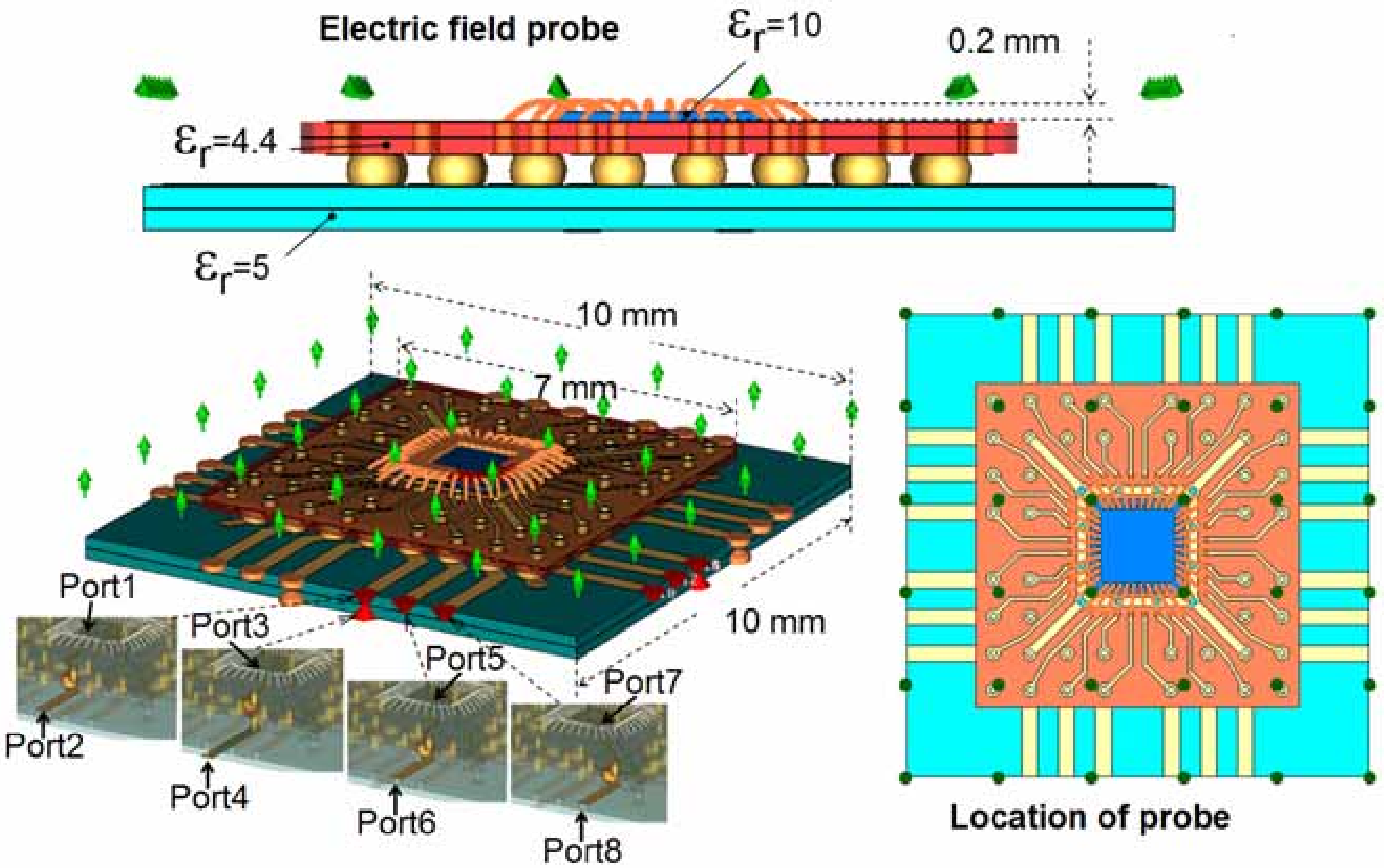
# Wire Bonding and Package Simulation Model




AET Japan

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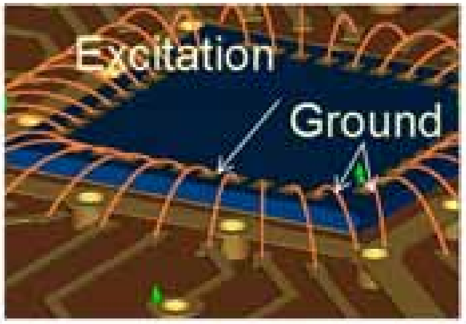


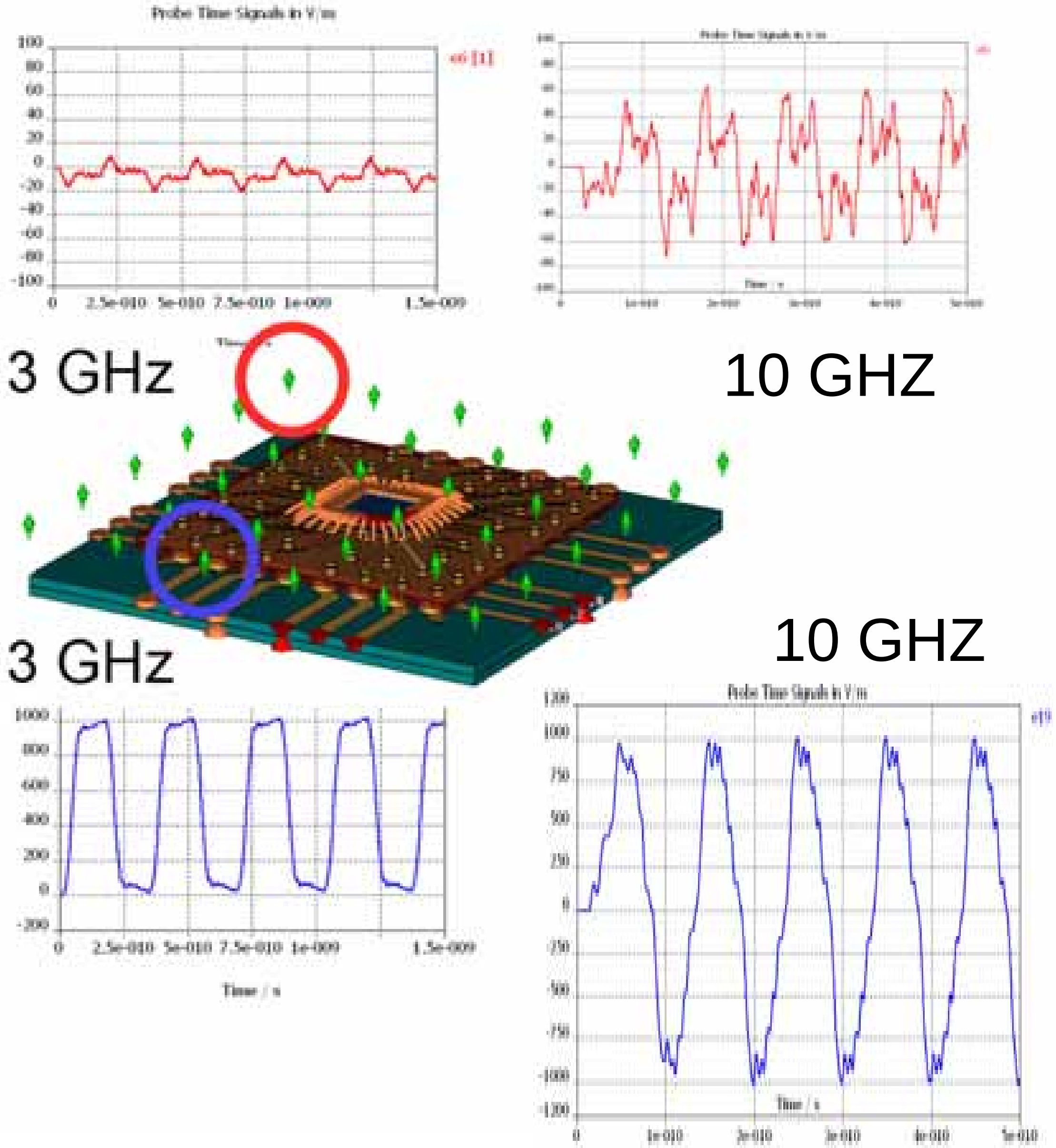


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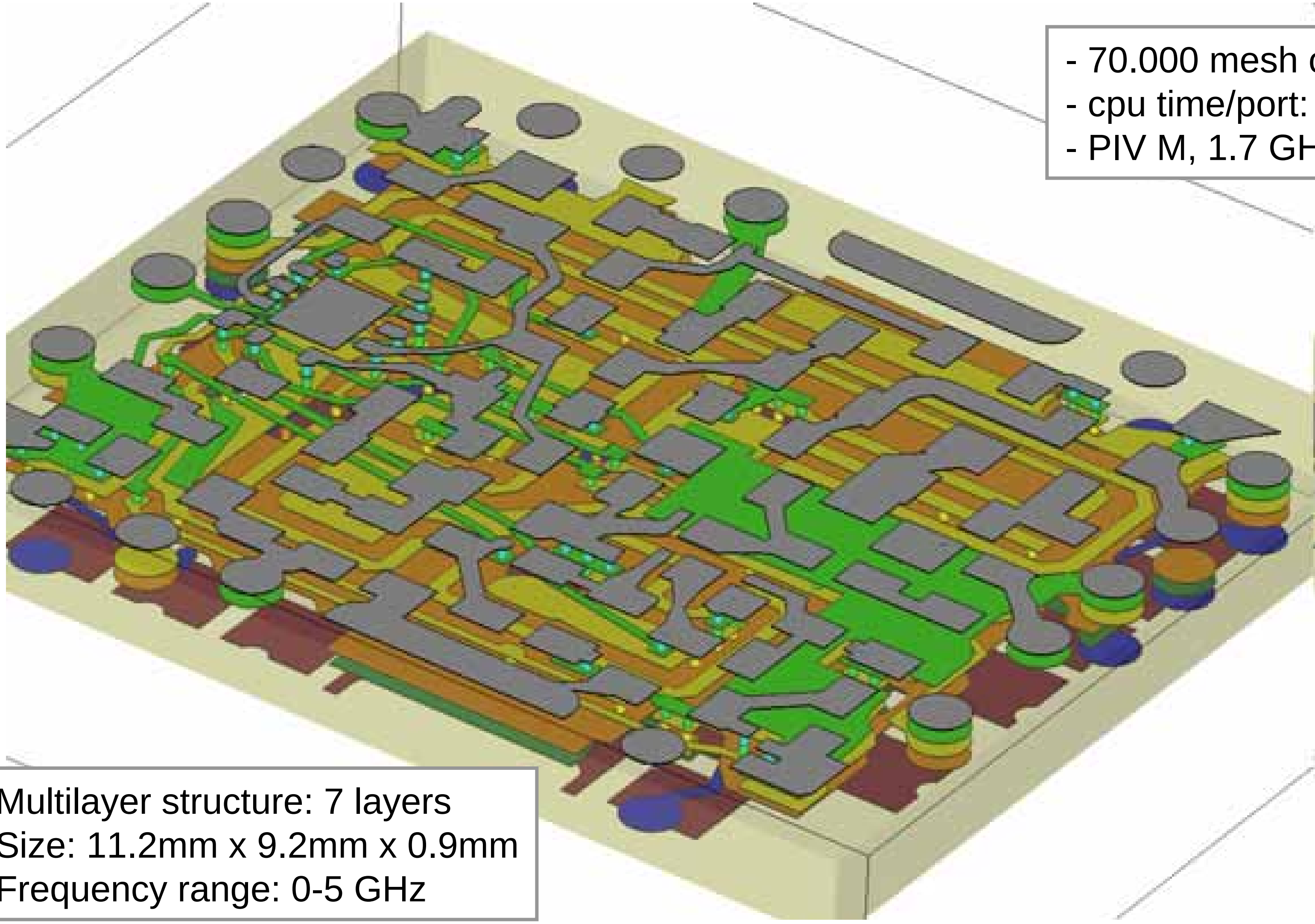
# Multilayer structure



- 70.000 mesh cells
- cpu time/port: 560 s
- PIV M, 1.7 GHz

Multilayer structure: 7 layers
Size: 11.2mm x 9.2mm x 0.9mm
Frequency range: 0-5 GHz

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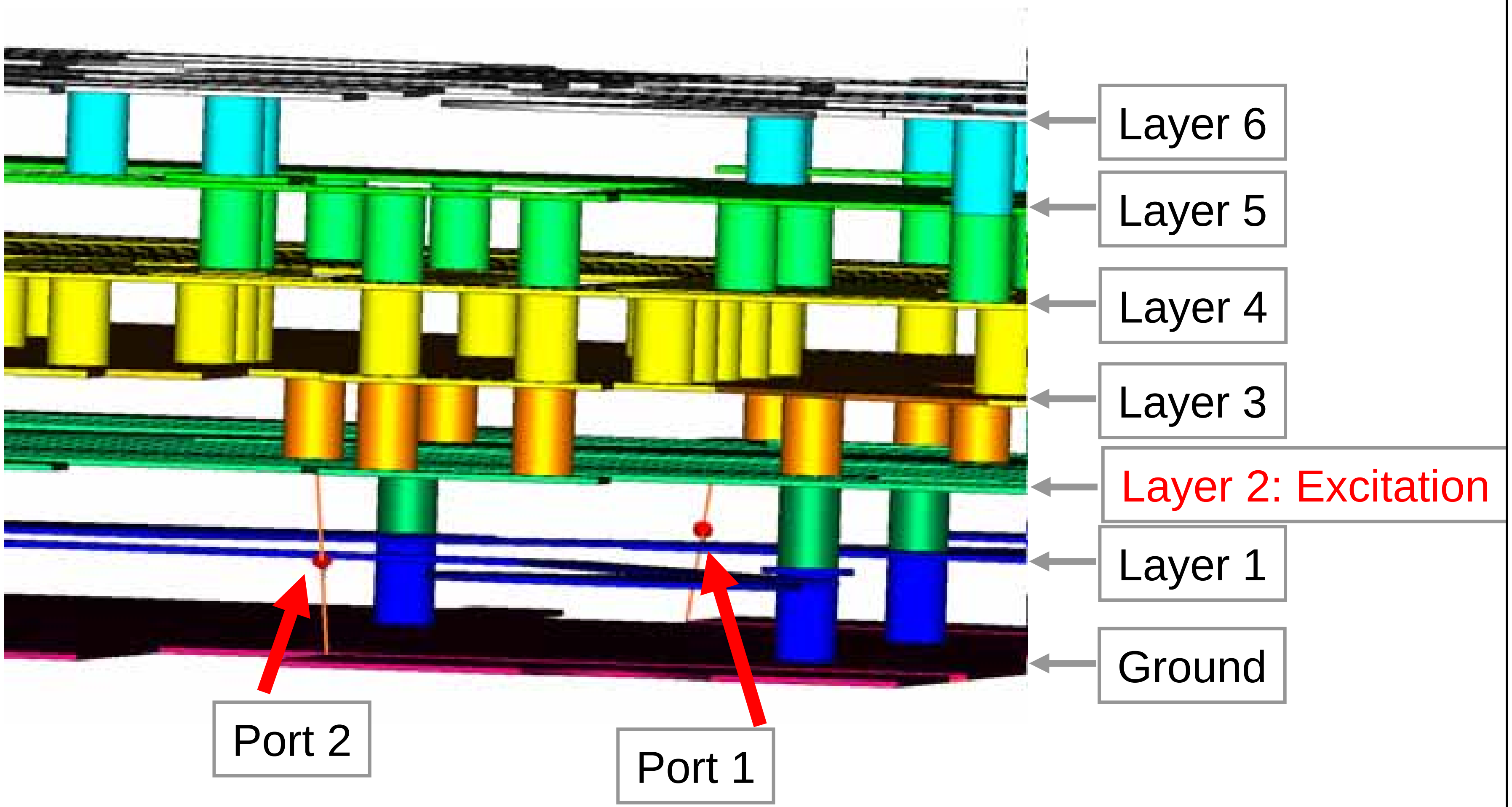
# 2-Port Study

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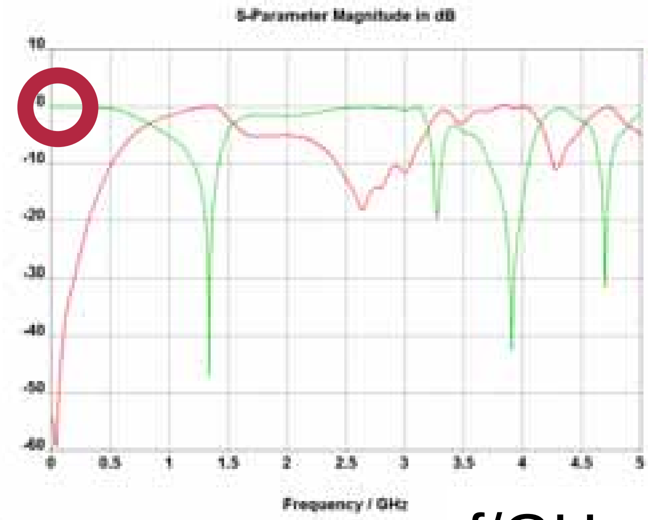
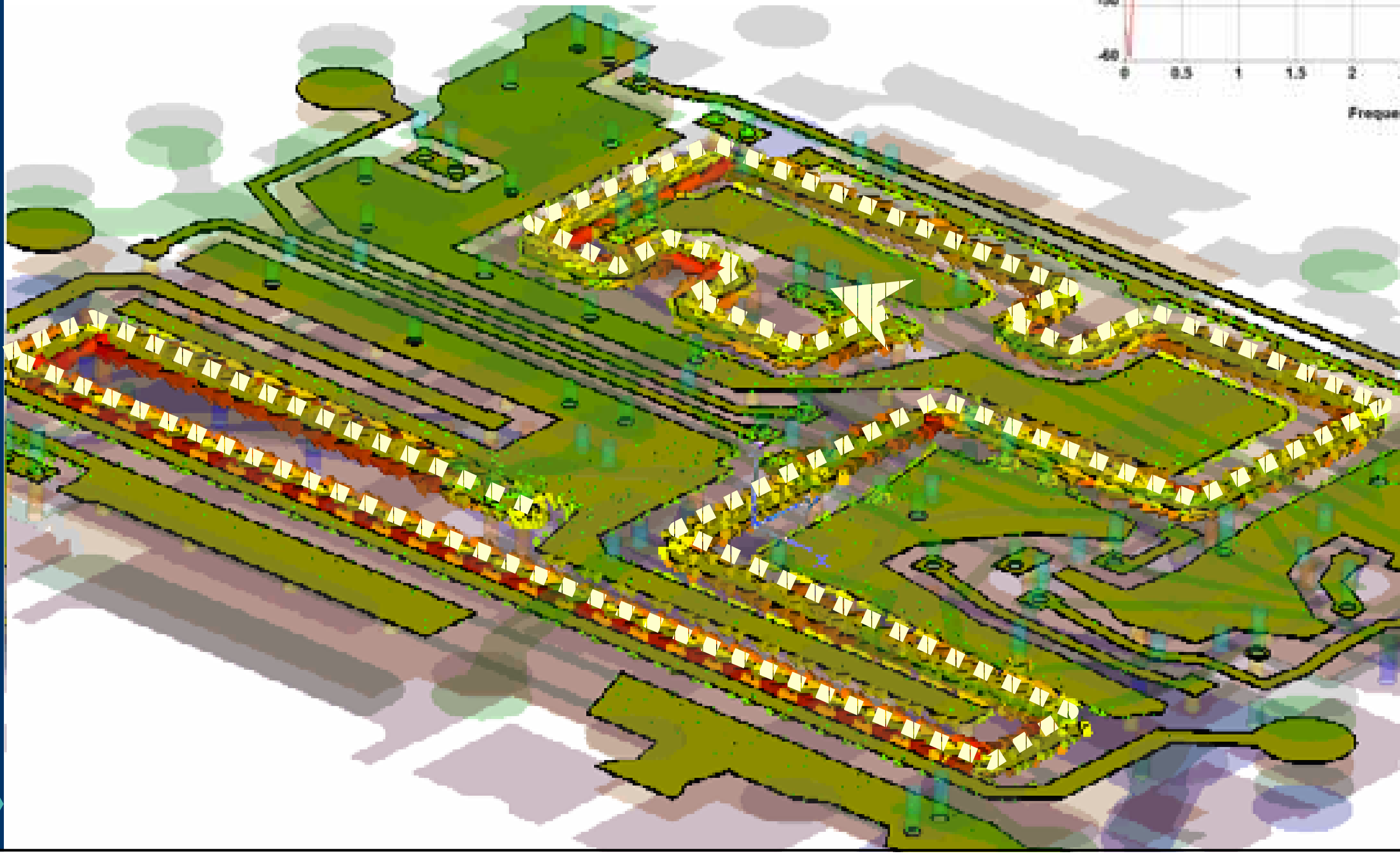
# 0.10 GHz

$S_{11}$, $S_{21}$




f/GHz



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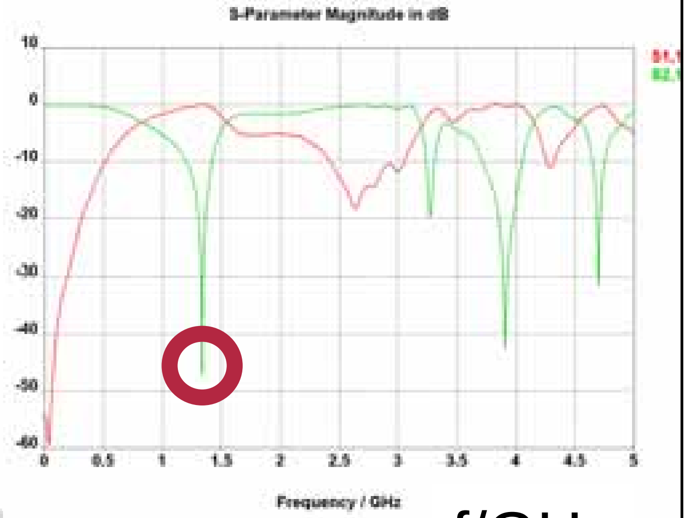
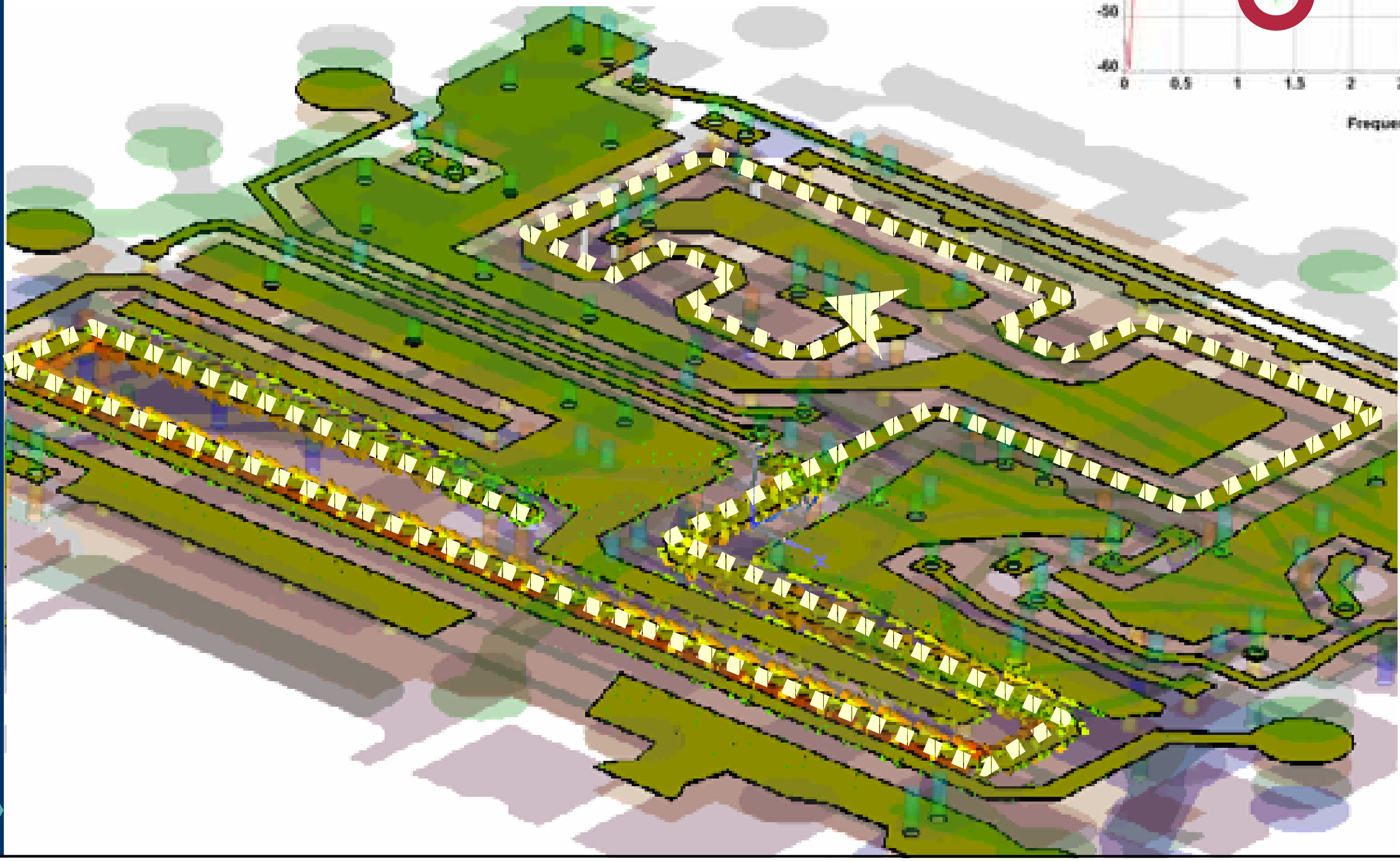
# 1.34 GHz

$S_{11}$, $S_{21}$




f/GHz



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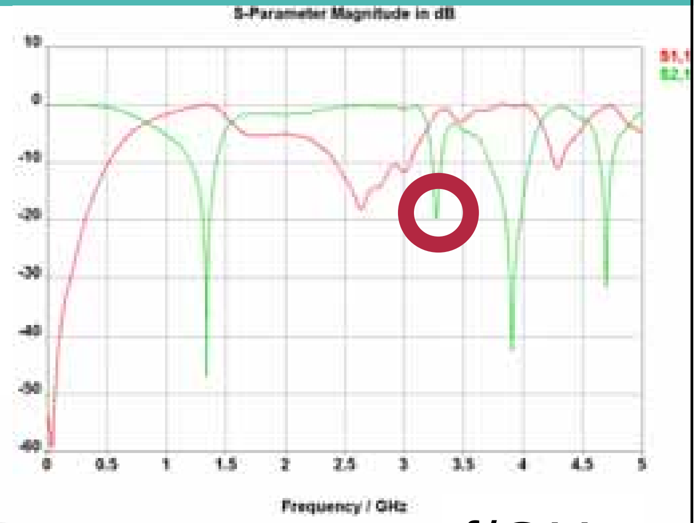
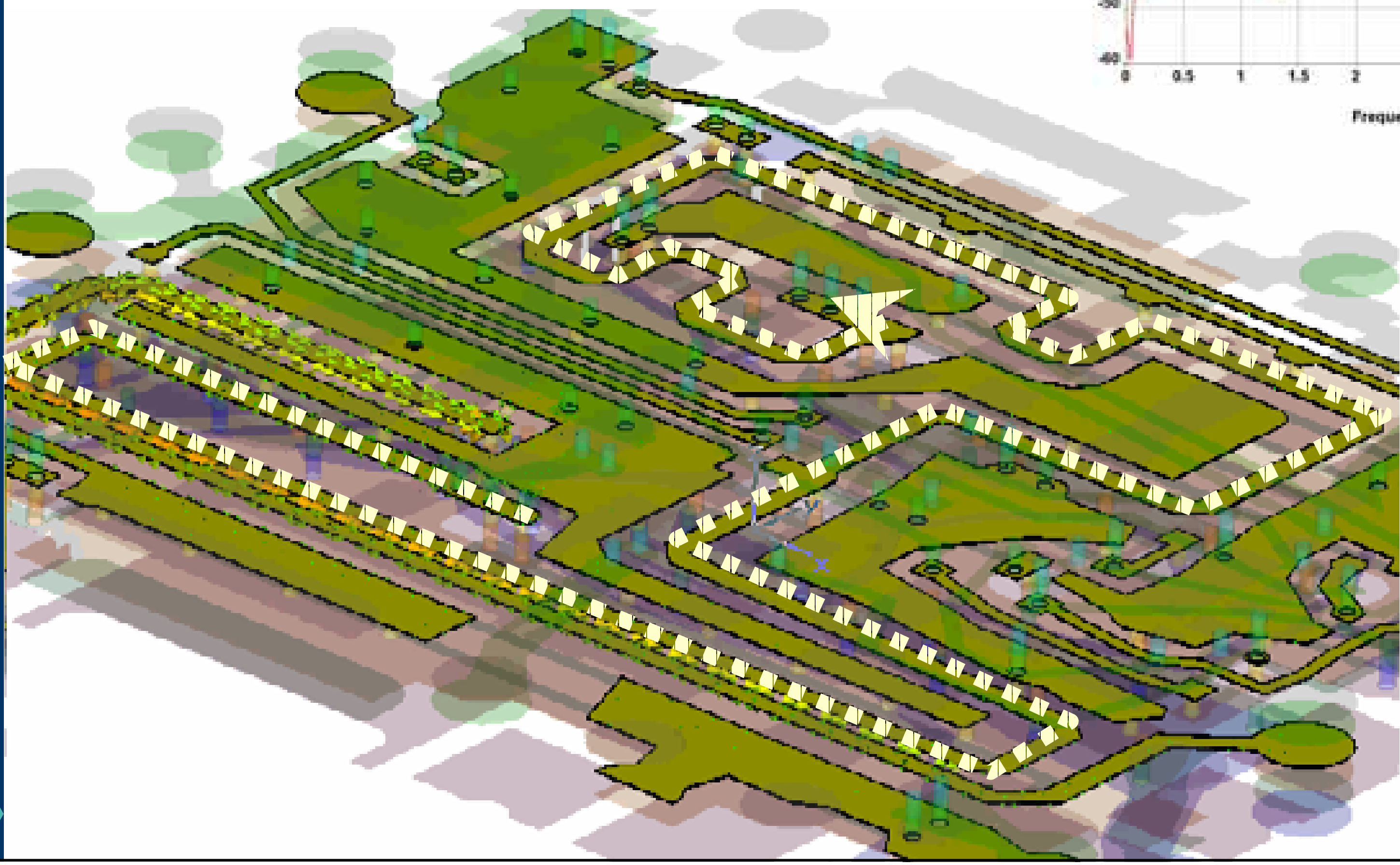
# 3.26 GHz

$S_{11}$, $S_{21}$




f/GHz

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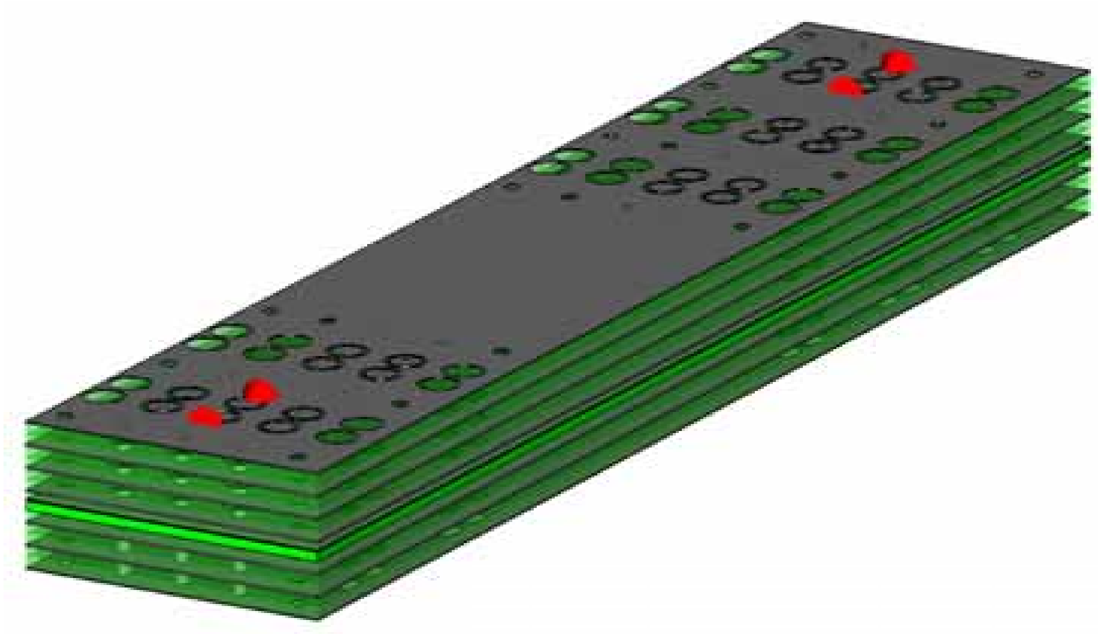
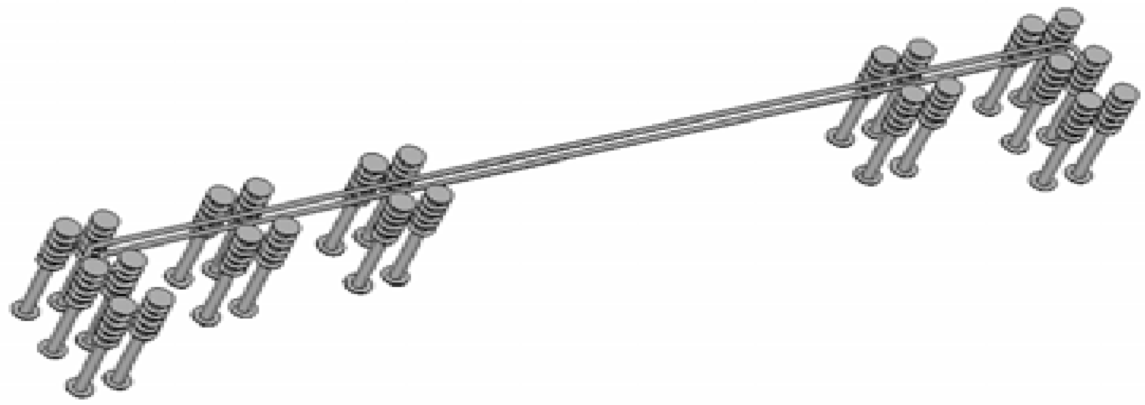
# Allegro import of backplane pair





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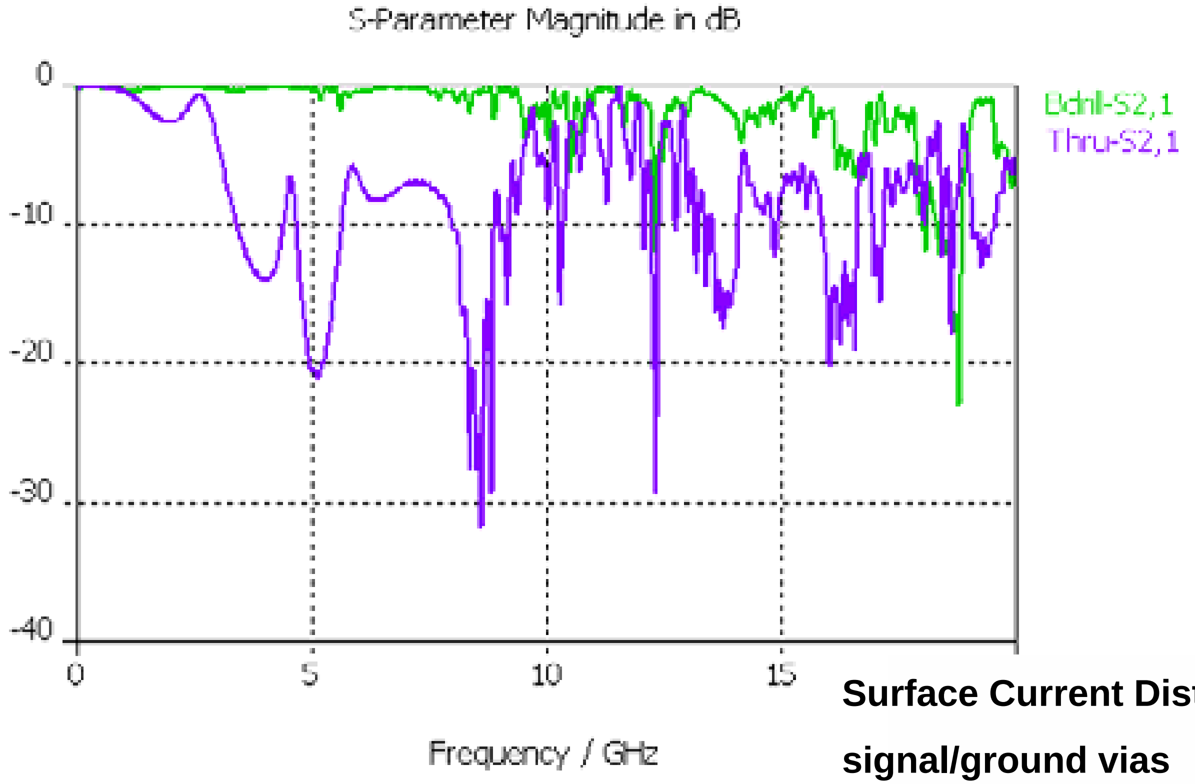
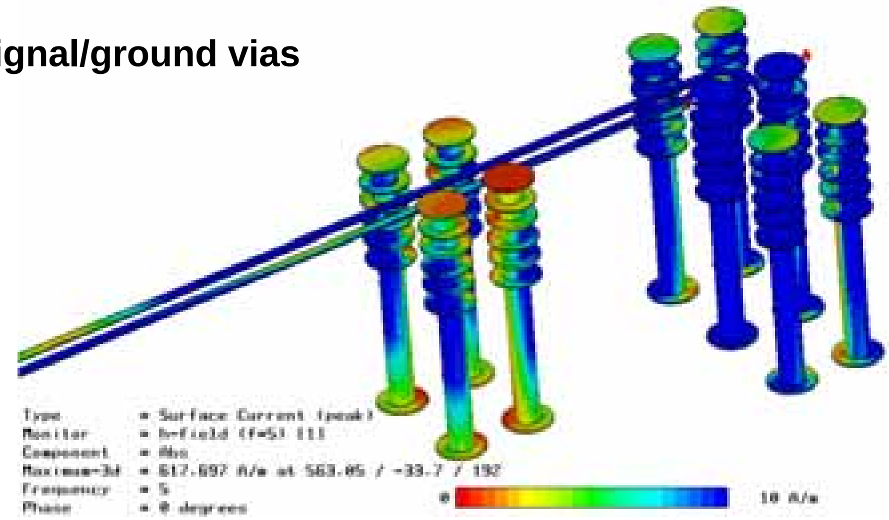
# S21 Thru via vs. back drilled via




**Surface Current Distribution on signal/ground vias**

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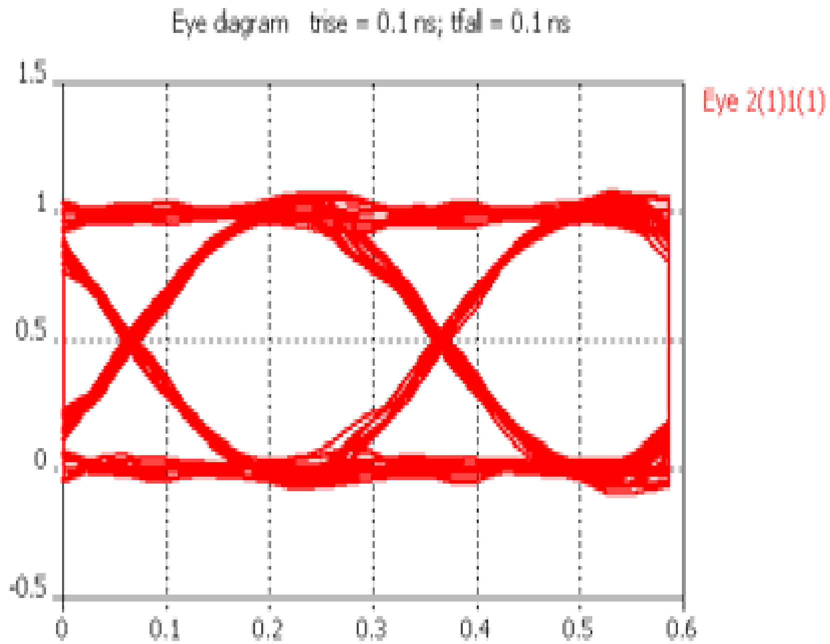
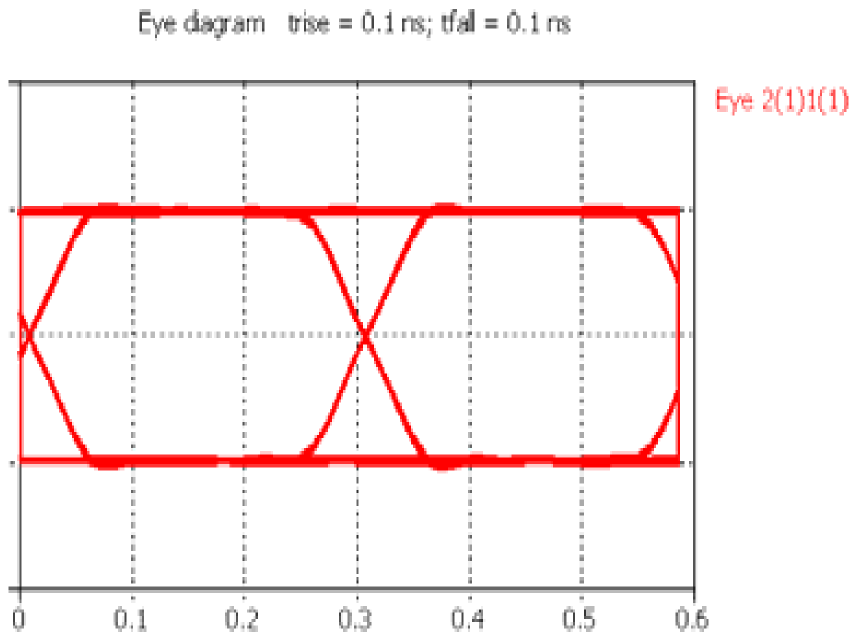
# Backplane pair Eye Pattern Through vs. Back Drill Via




**Through Hole Via**




**Back Drill Via**

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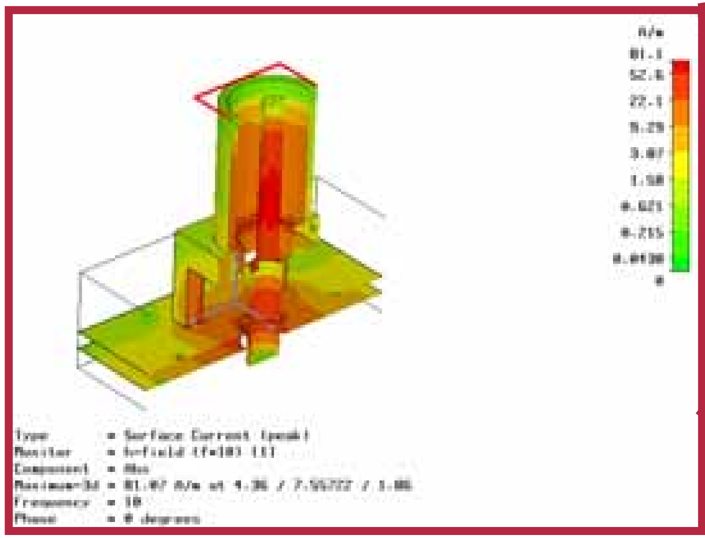
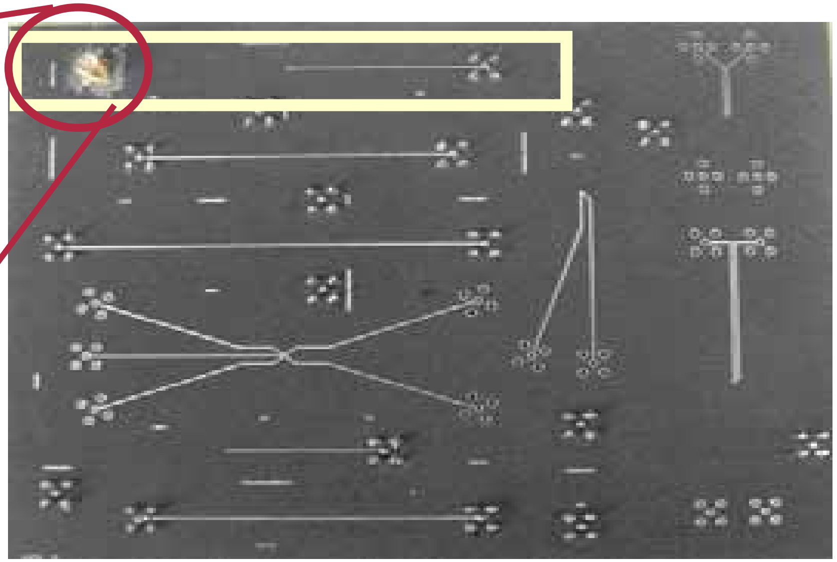
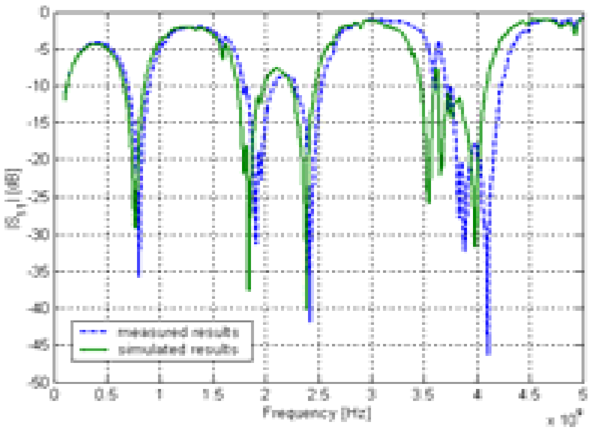
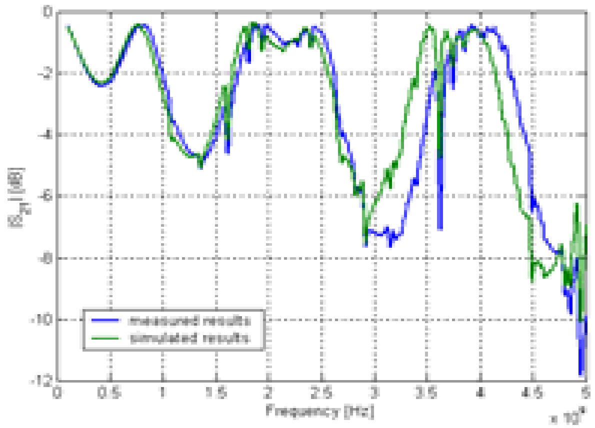
# Stripline and via hole on PCB board





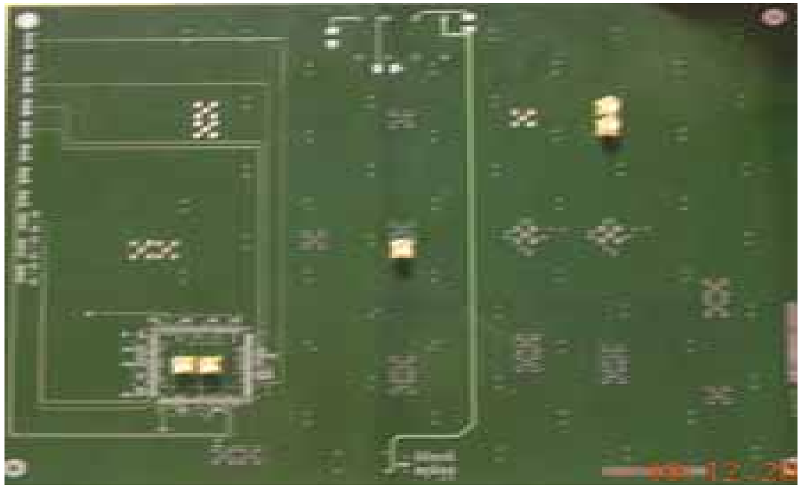
measured simulated

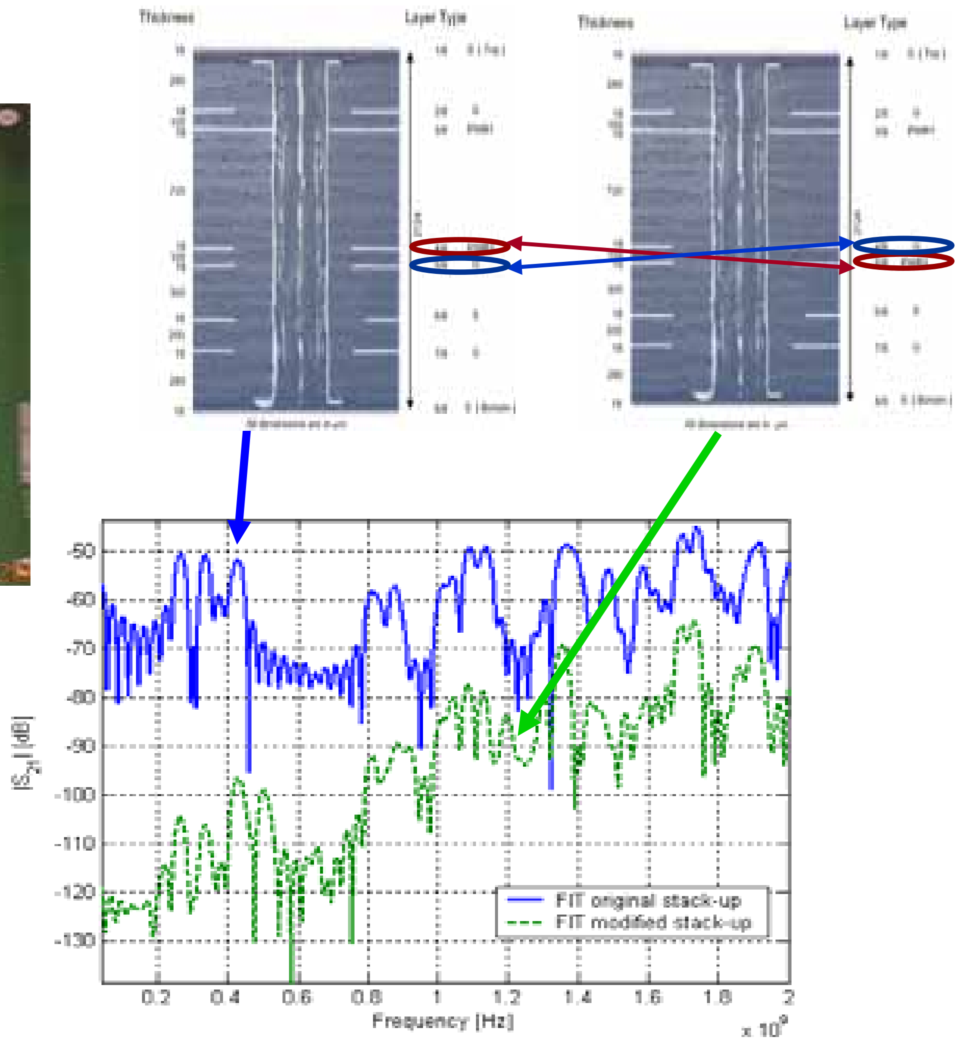



Model and simulation: UAq EMC Lab (L'Aquila, Italy)
Test board: UMR EMC Lab (Rolla, MO, USA) Courtesy Prof. A. Orlandi

# Cross SSN Analysis – Different Board Stack-ups

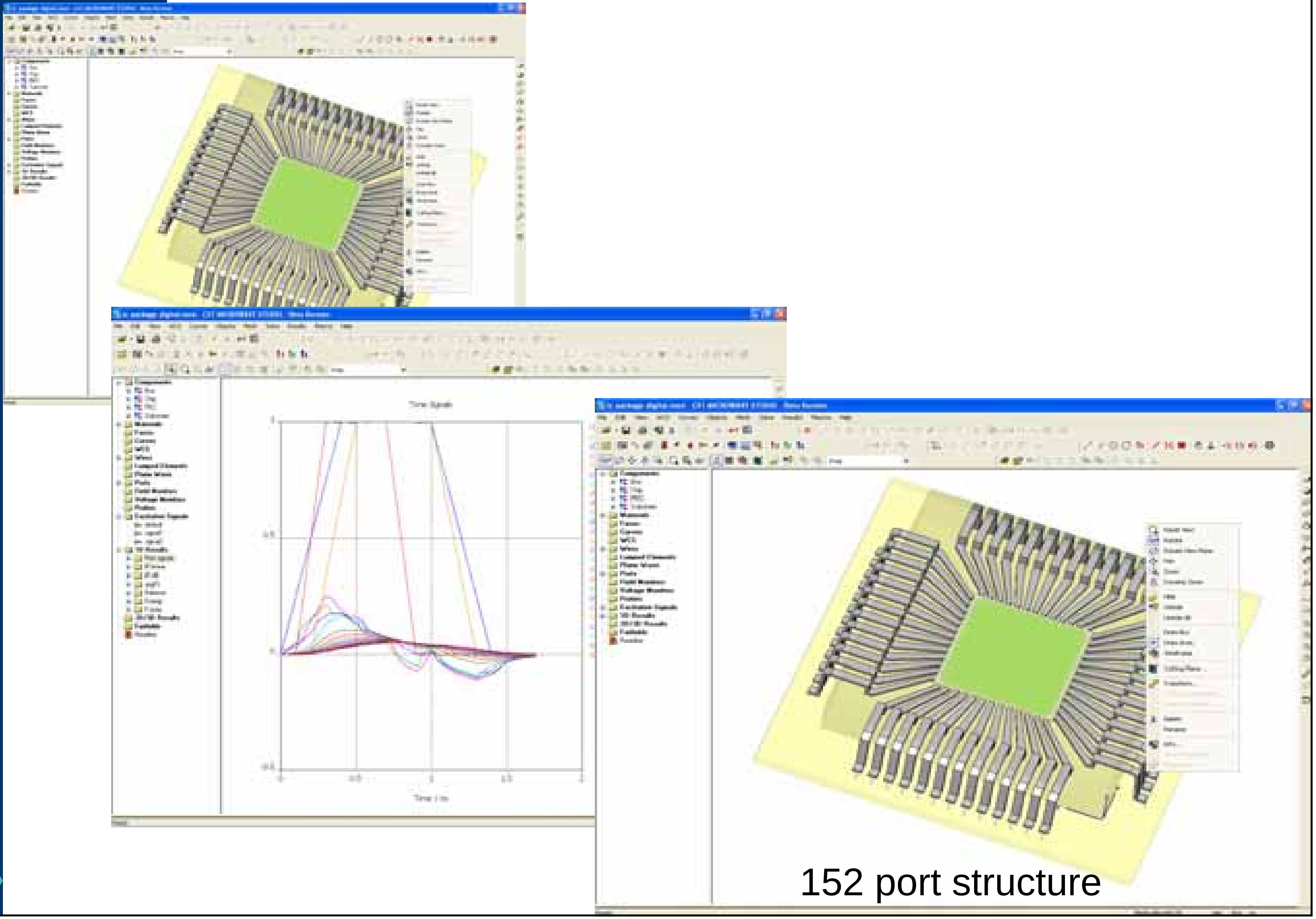





Swapping **PWR1** and **PWR2** drastically reduces the coupling between the power planes

Test board: Siemens C.N.X.- UAq EMC Lab
Model and simulation: UAq EMC Lab (L'Aquila, Italy)
Courtesy Prof. A. Orlandi

# IC Package – Digital signal simulation



152 port structure

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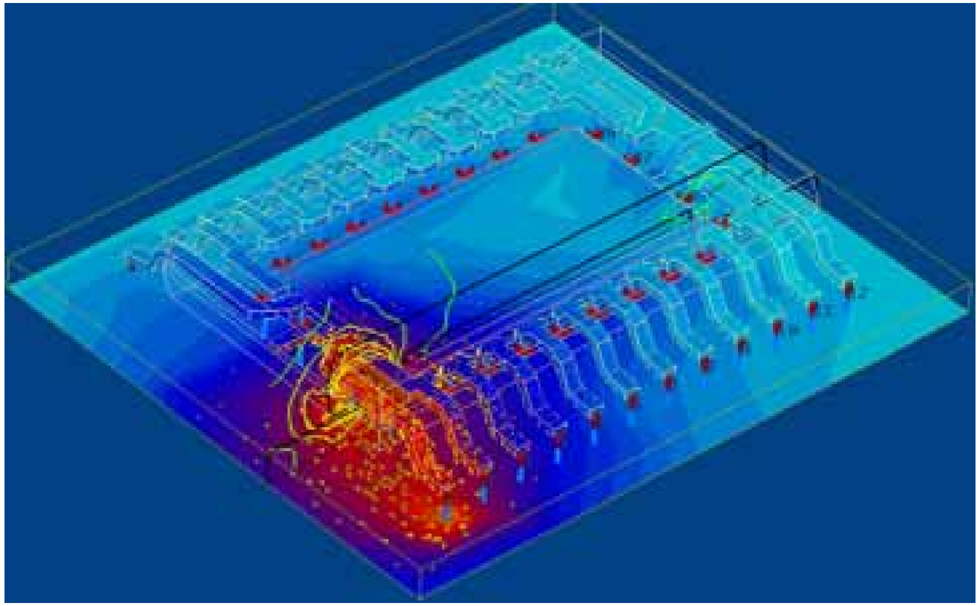
# SPICE Model Extraction

**Static extraction**

- Based on quasistatic fields
- Computes SPICE network from L,C
- Does not contain dynamic effects



**Dynamic extraction**

- Based on dynamic EM fields
- Computes SPICE network from S-parameters
- Allows cascaded networks

Full EM-SPICE

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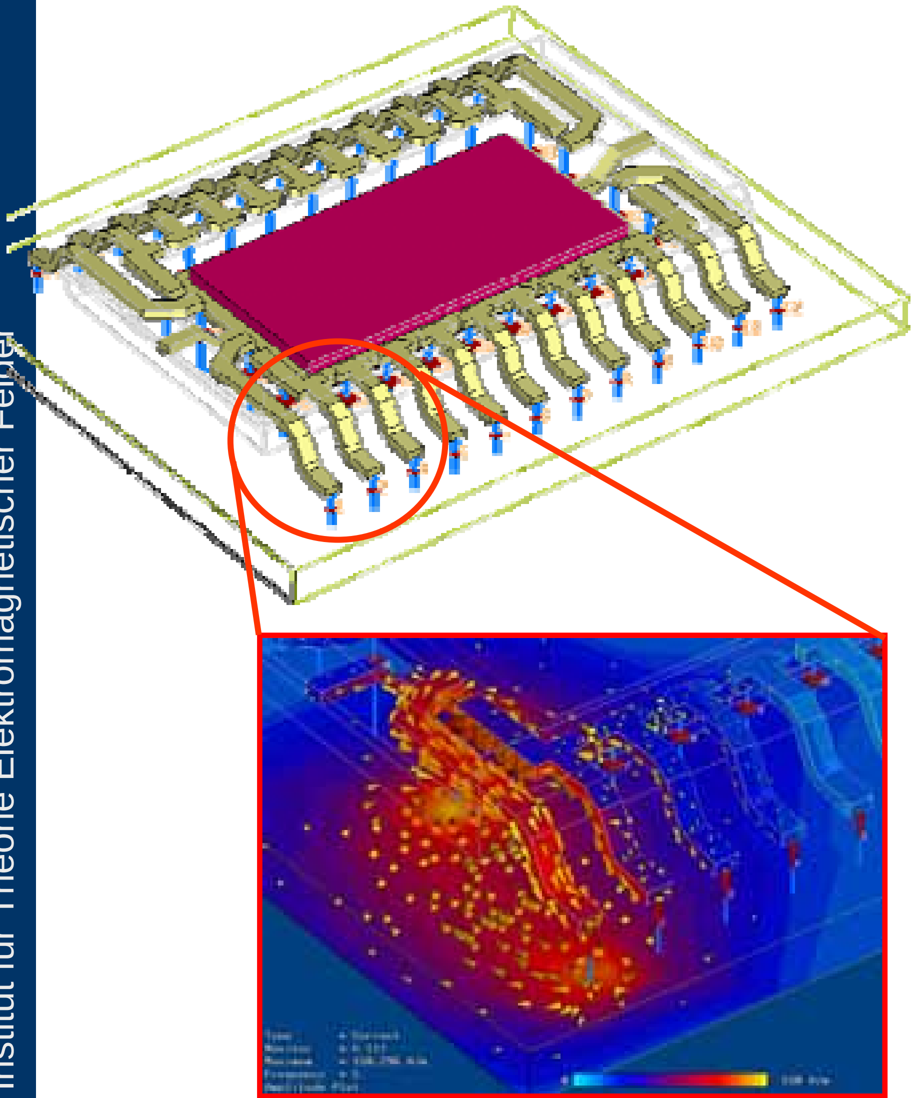
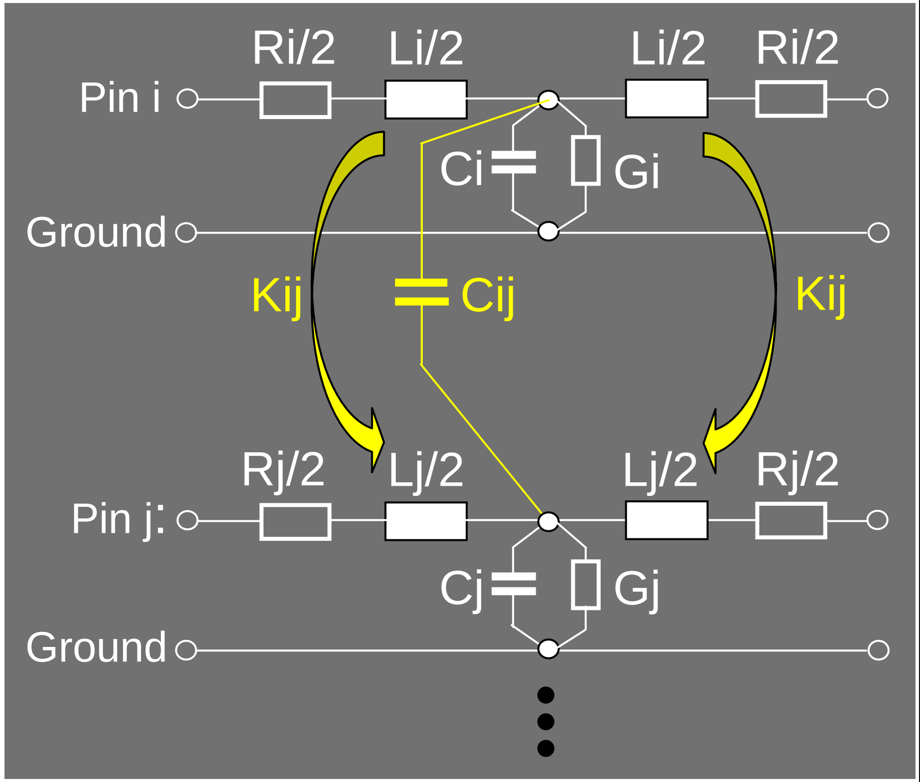
# SPICE Model 1



Fixed topology, R,L,C,G elements




Cascaded SPICE models needed to fit for larger frequency bands !

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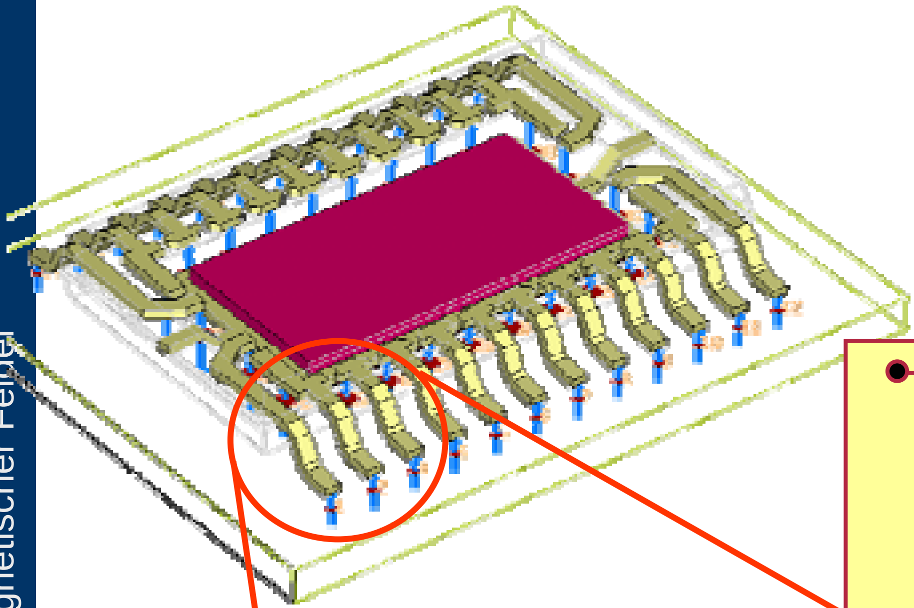
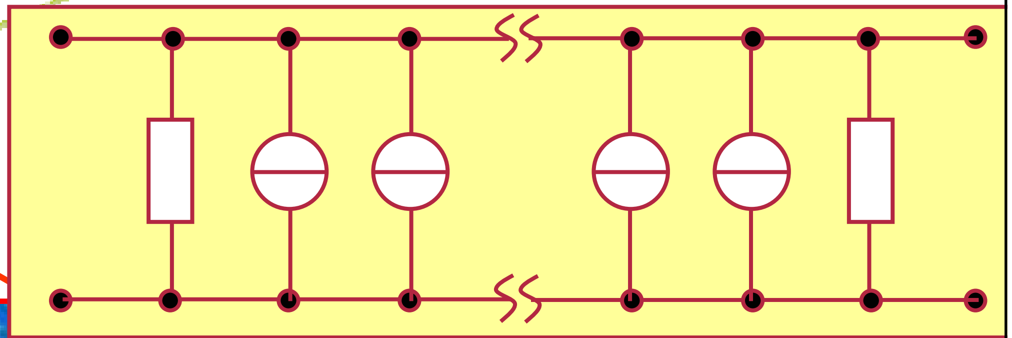
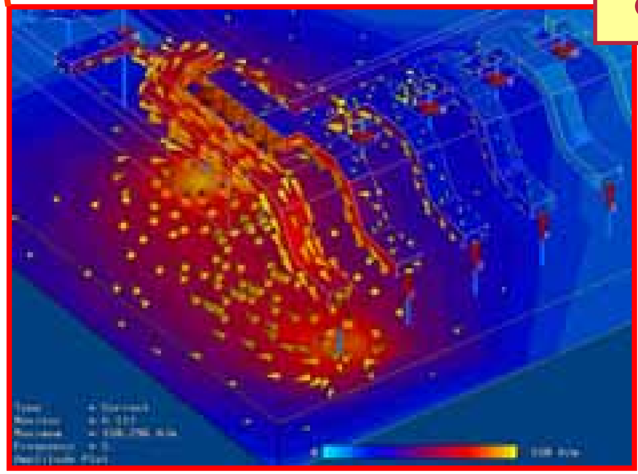
TECHNISCHE UNIVERSITÄT DARMSTADT

# SPICE Model 2: Extraction



Flexible topology, R,L,C,G elements
+ controlled sources





Fits naturally large frequency bands

Model should be stable and **passive** !

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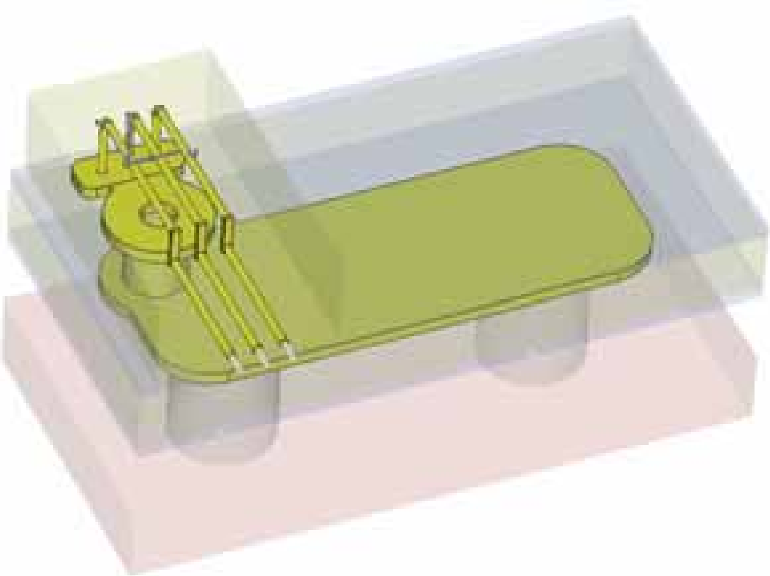
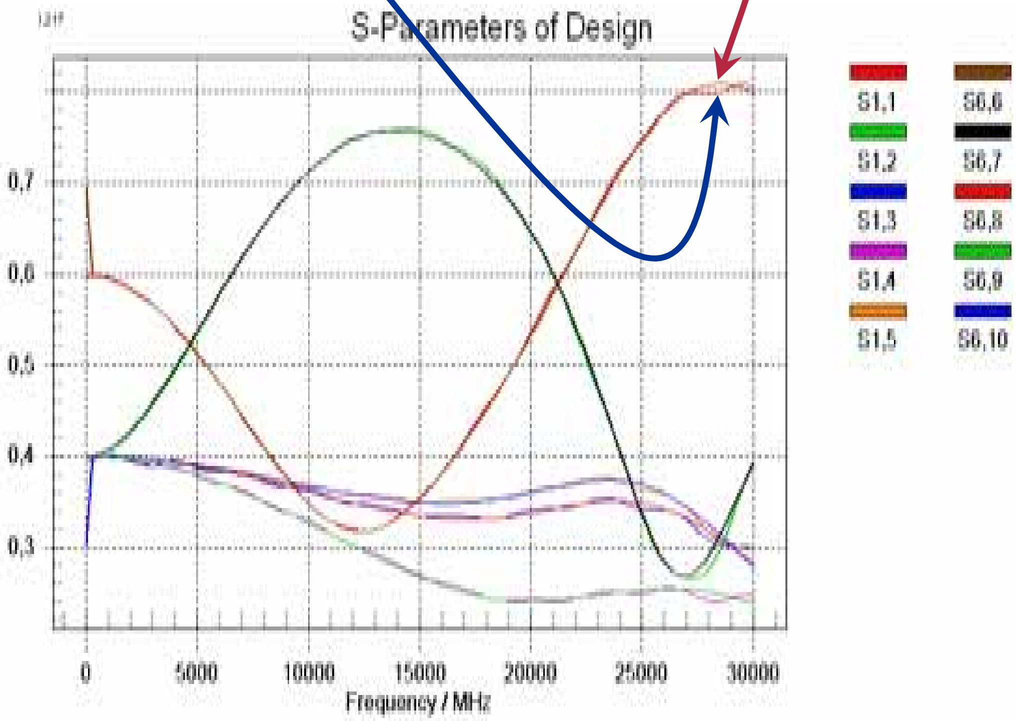
# Automatically Generated Netlist



Section of BGA integrated circuit package

Full-wave

Extracted network model




- 5 Port structure (discrete)
- Port impedance: 50 Ohm

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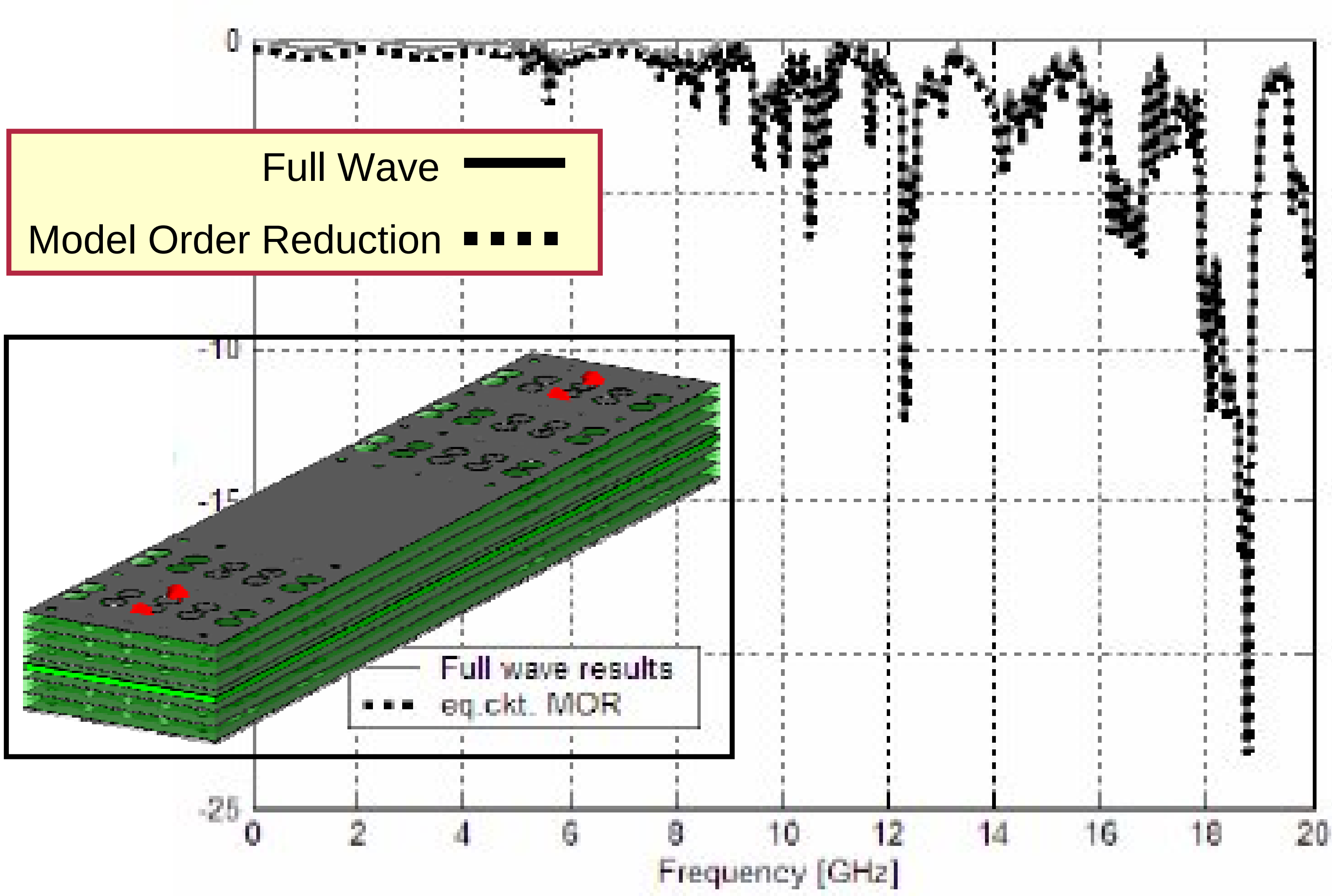
# SPICE Model Accuracy

**S21 of MWS simulation and extracted model**

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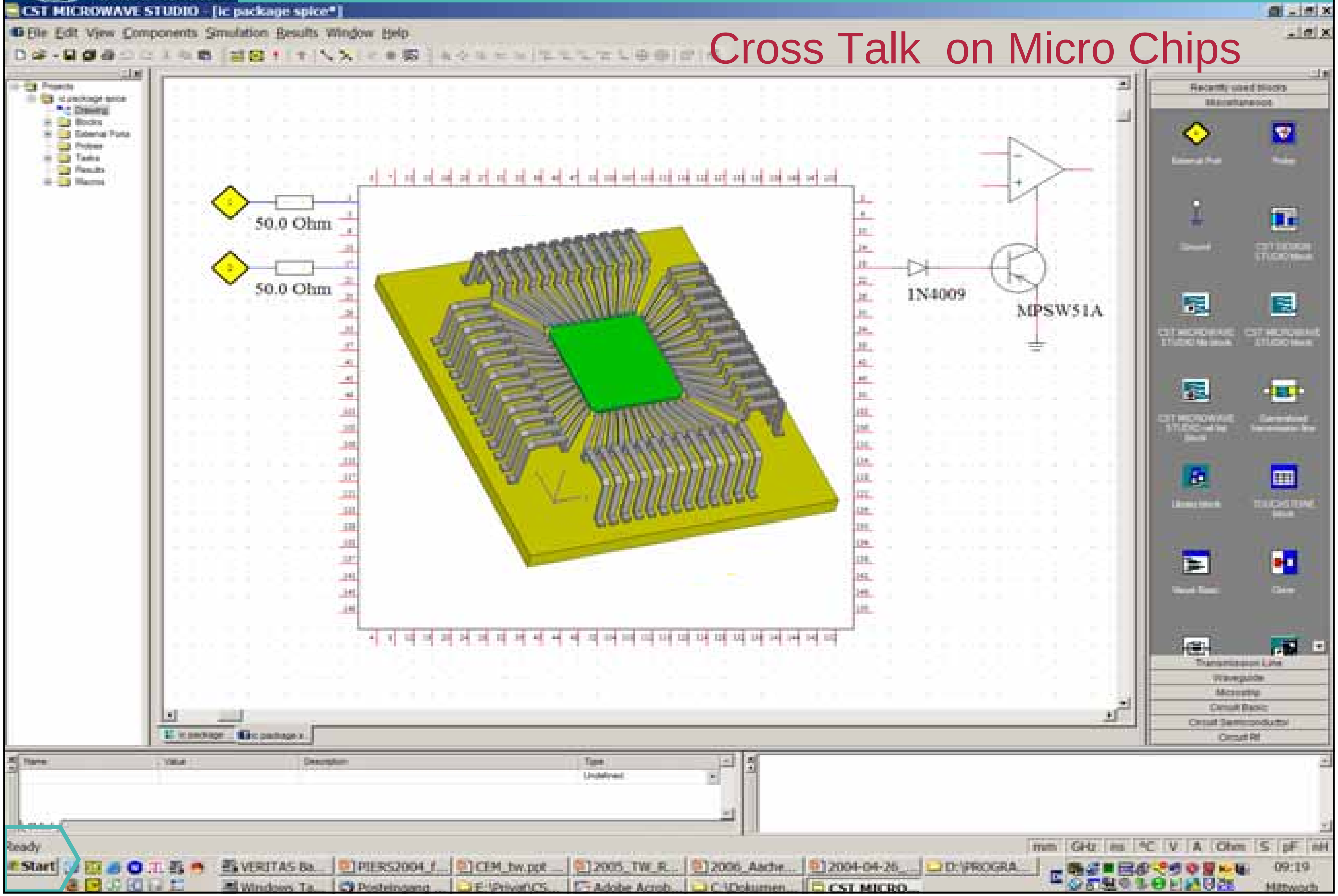
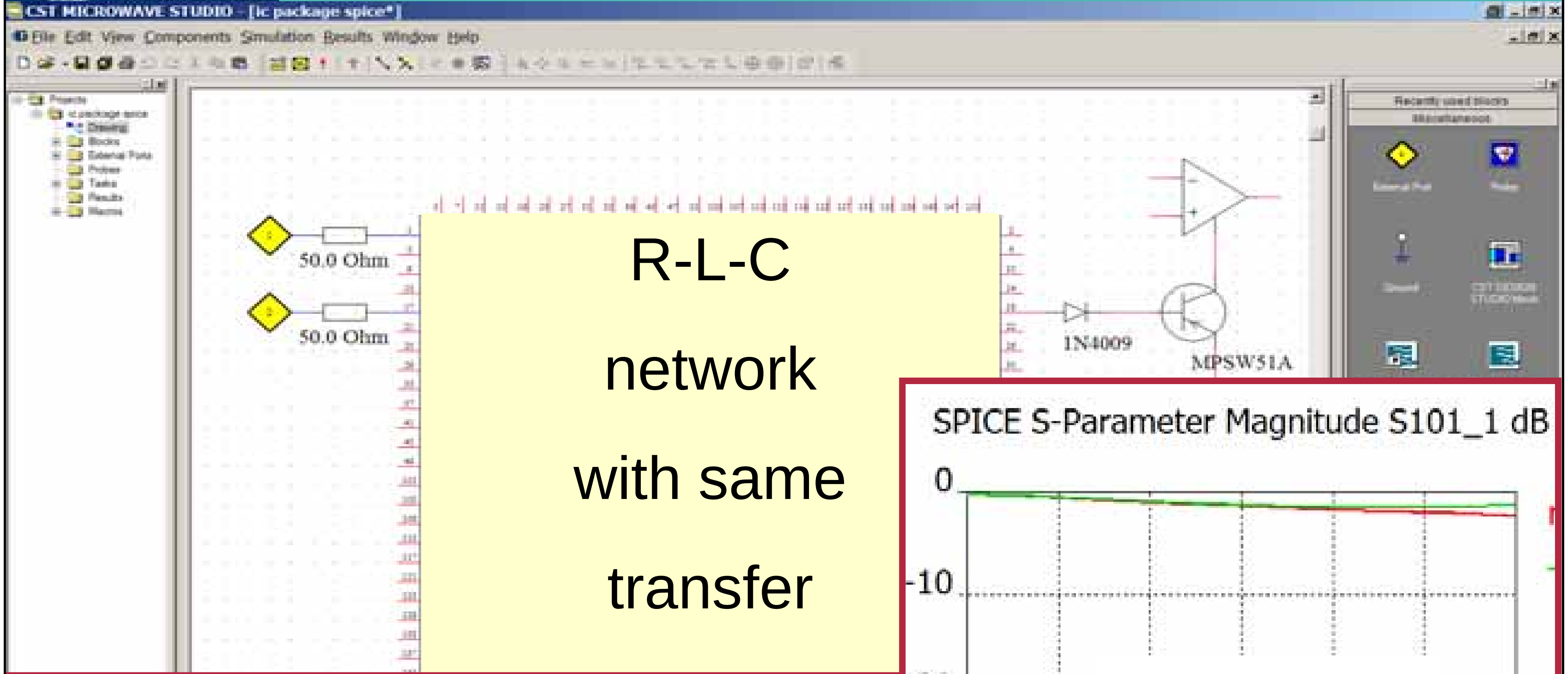
# Challenges

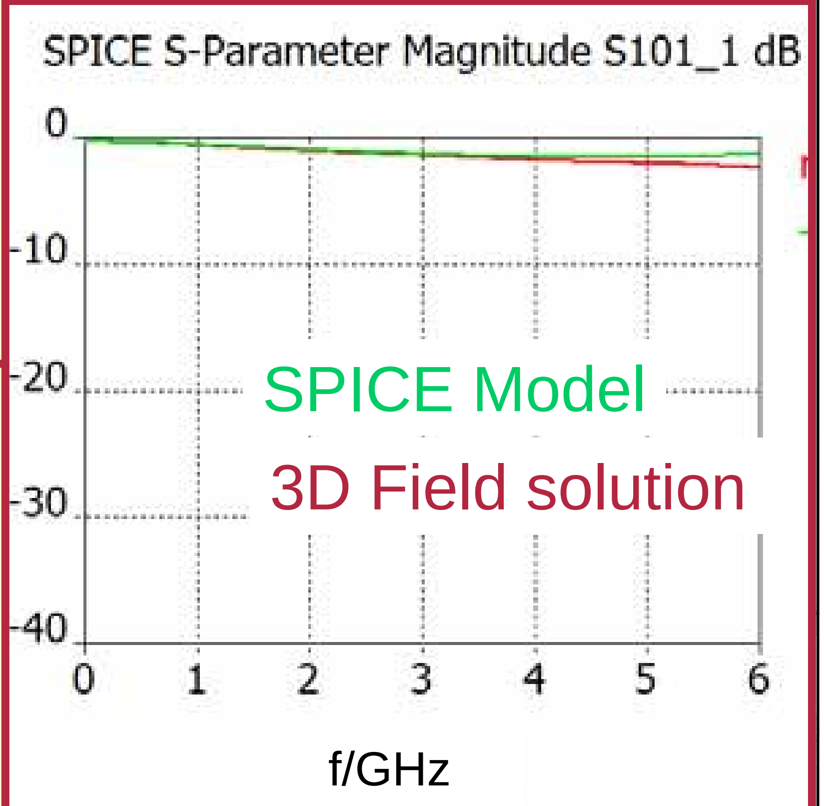
## Cross Talk on Micro Chips



# Challenges




R-L-C network with same transfer




Network parameter extraction for a 152x152 S-parameter matrix is still a challenge for many extractors !

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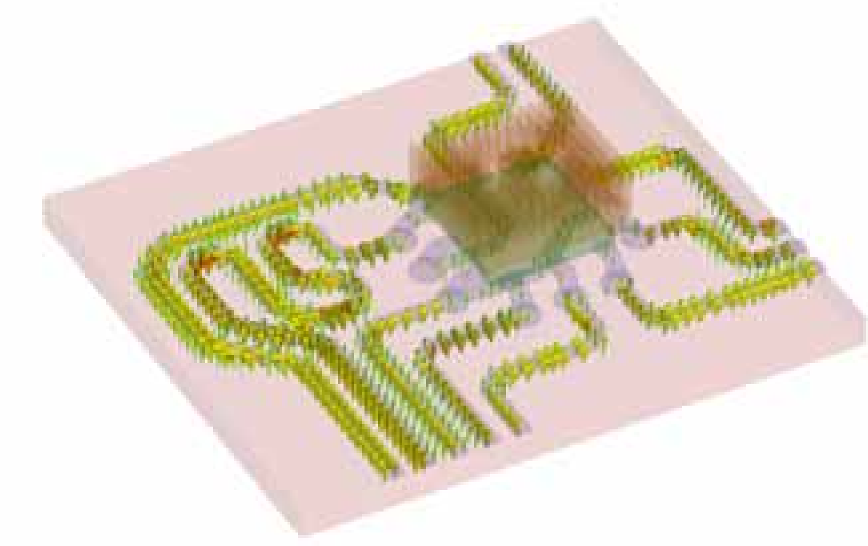
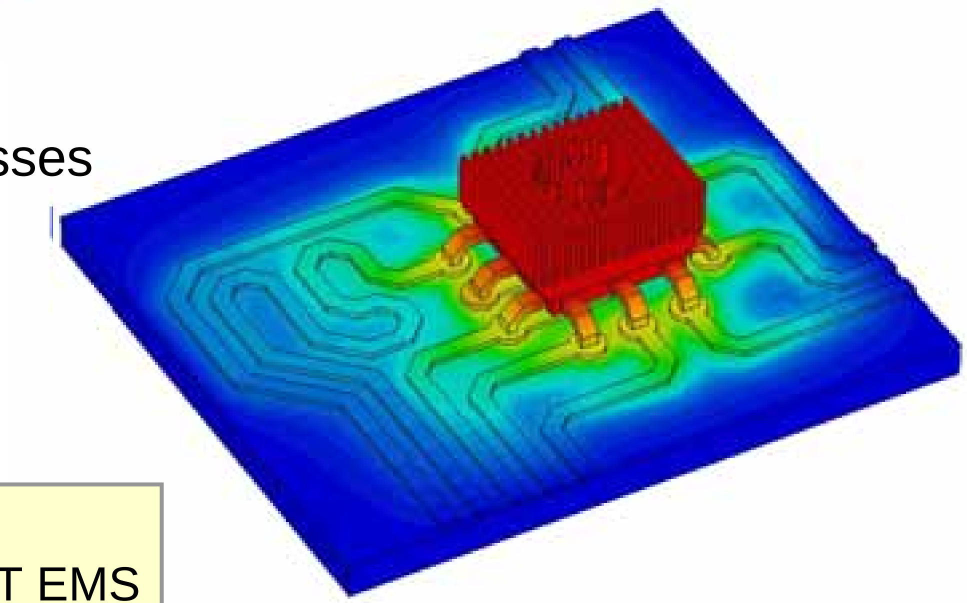
# HF- Thermal Solver Coupling



Thermal Analysis of electric losses



1. Currents: CST MWS
2. Temperature Analysis: CST EMS

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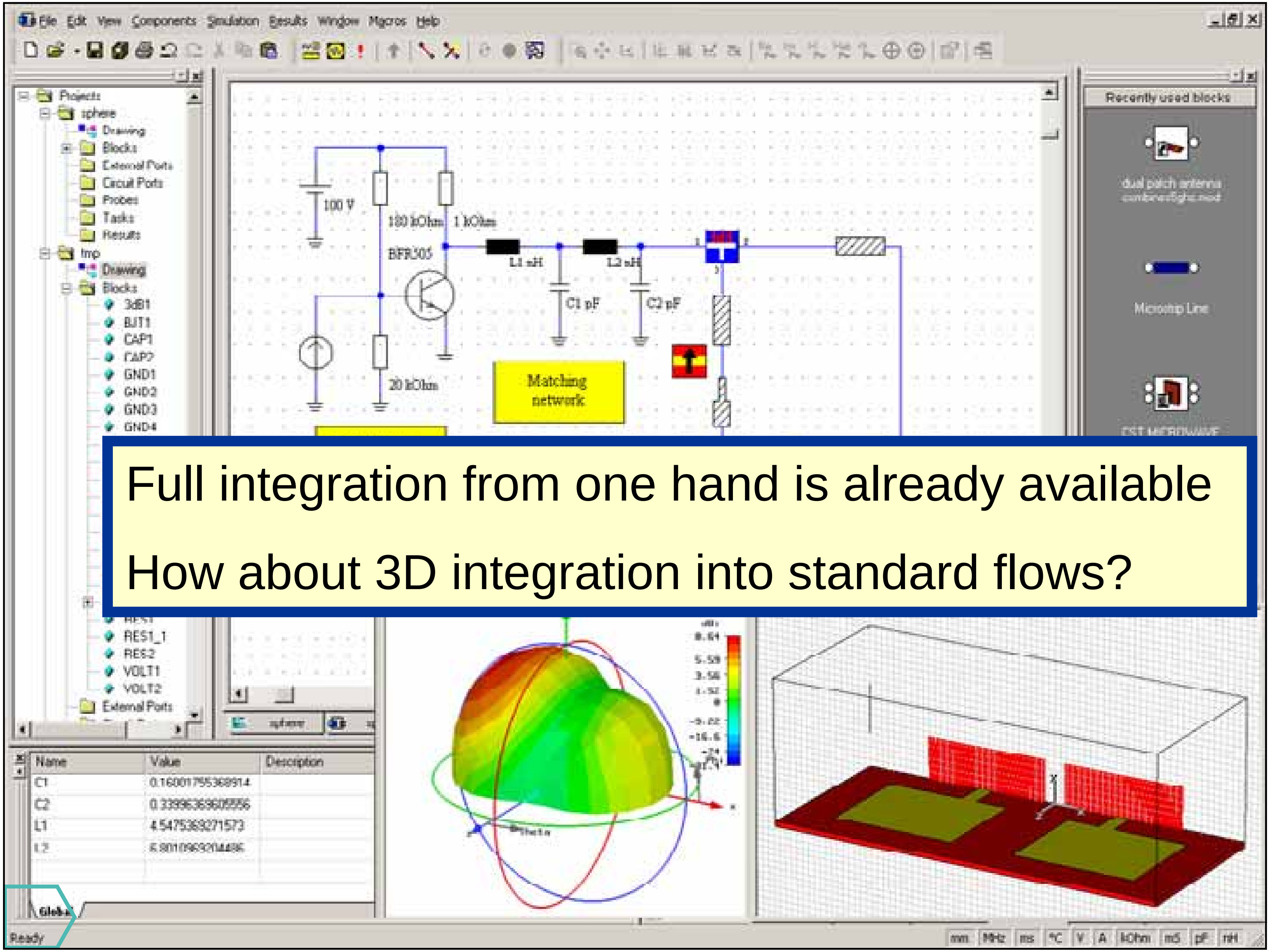
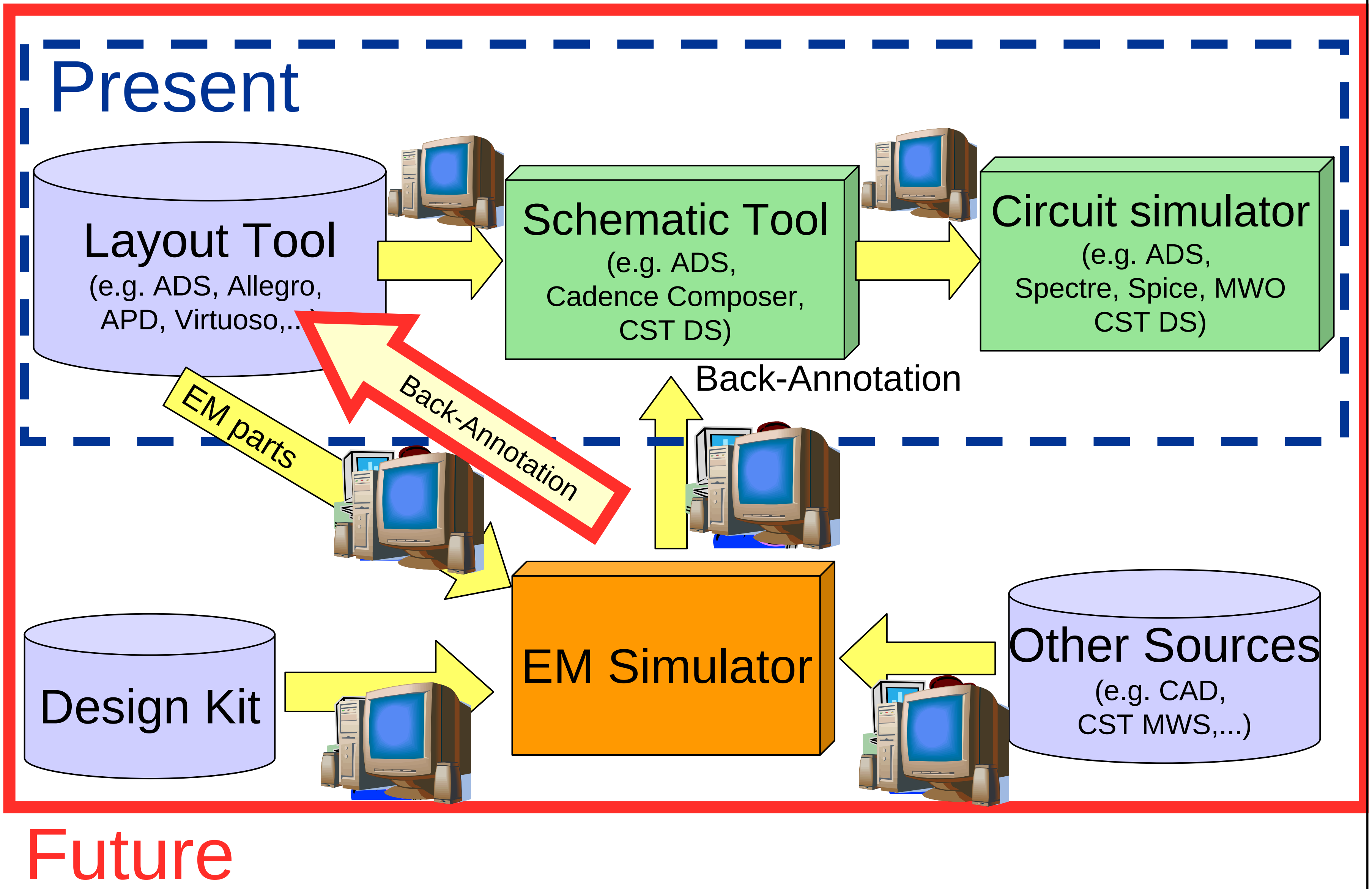


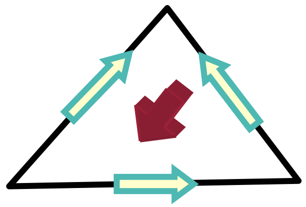
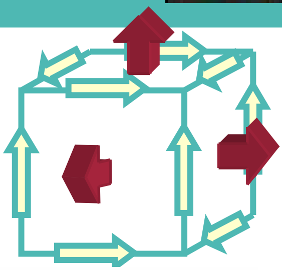

Full integration from one hand is already available

How about 3D integration into standard flows?

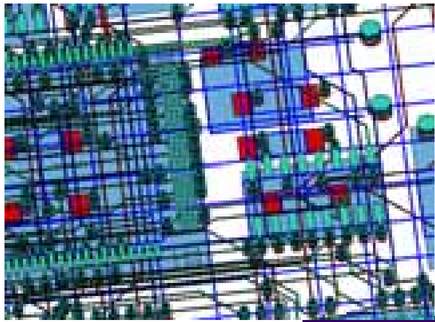
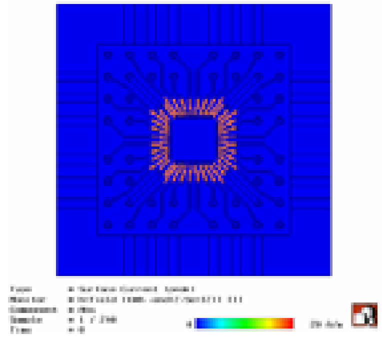
# Design Flow Integration



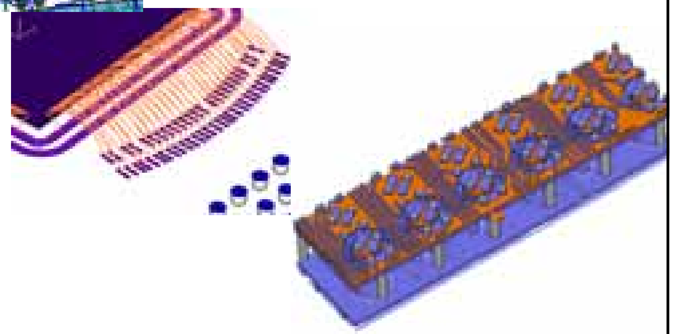
# Conclusions

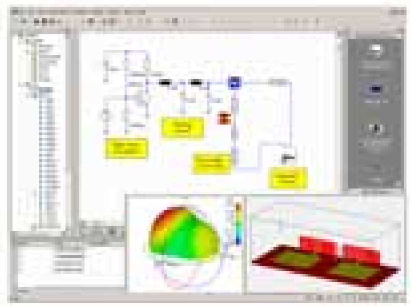
- EM field computation **tools**
  - Flexibility in Mesh Generation
  - Flexibility in local approximation (FI,FE,FV,..)
  - Wide choice of tools for one problem
  - for comparison + validation
  - Choose the best tool for your current problem

- Future trends
  - Larger problems: Parallel computing, hardware acceleration
  - Power and signal integrity, EMC issues



  - EM Simulation will need to be fully integrated in automated design flows



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