



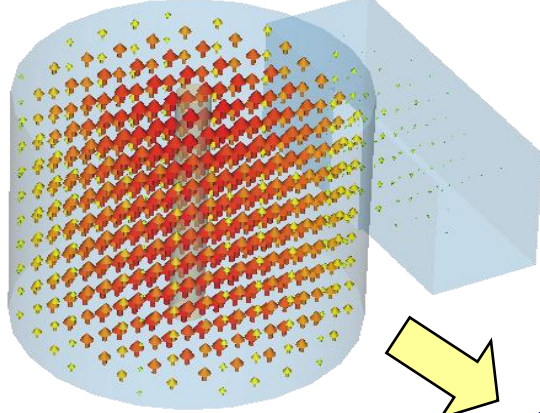
# A Glimpse into Multiphysic-Analyses using **CST STUDIO SUITE™**

Accounting for thermal heating effects and mechanical  
deformation in the electrical design

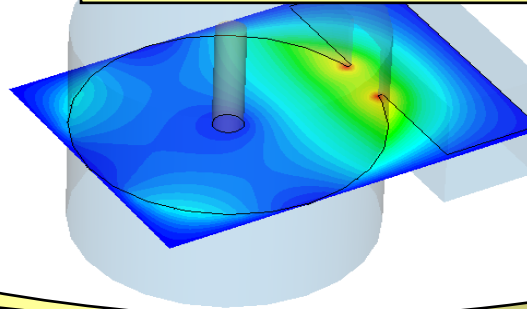


# The Motivation ...

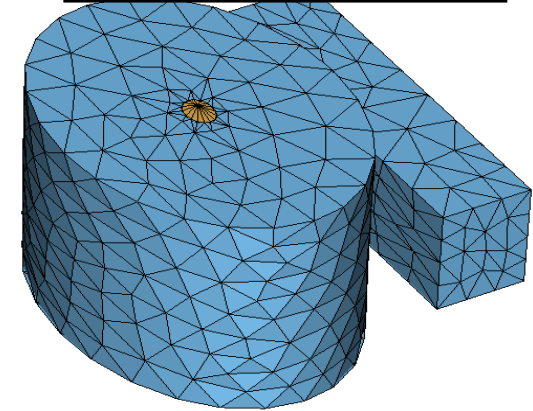
**EM-field computation**



**Thermal  
analysis**



**Stress analysis /  
deformation**

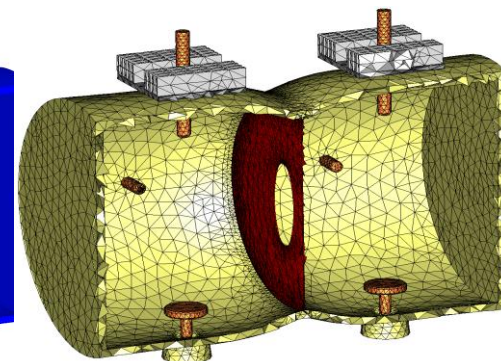
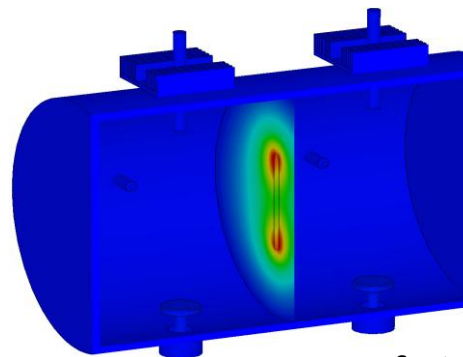
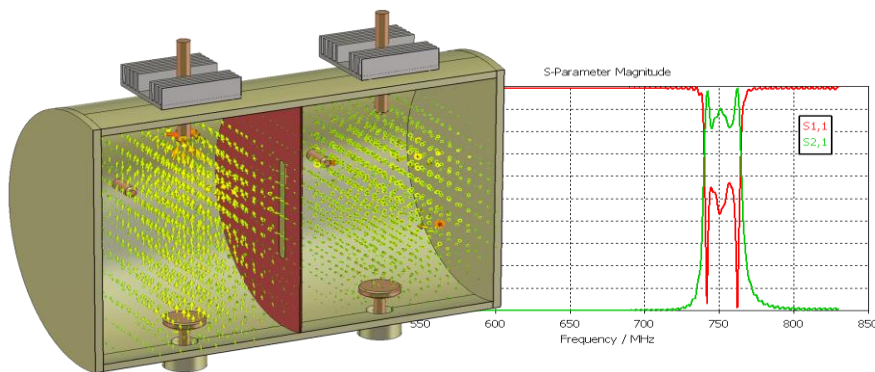


**EM-properties of deformed geometry  
can be fed into sensitivity analysis**

# CST MPHYSICS STUDIO™



- Thermal Simulation
- Mechanical Stress Simulation



Courtesy of Spinner GmbH, Germany

# Online Demo

# Example : 2-Post Bandpass Filter



## Filter Tutorial

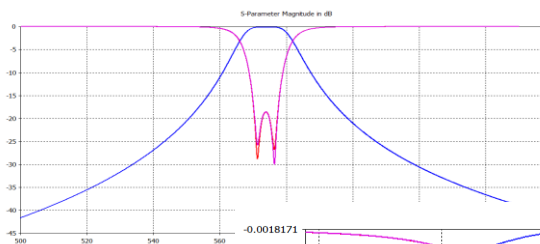
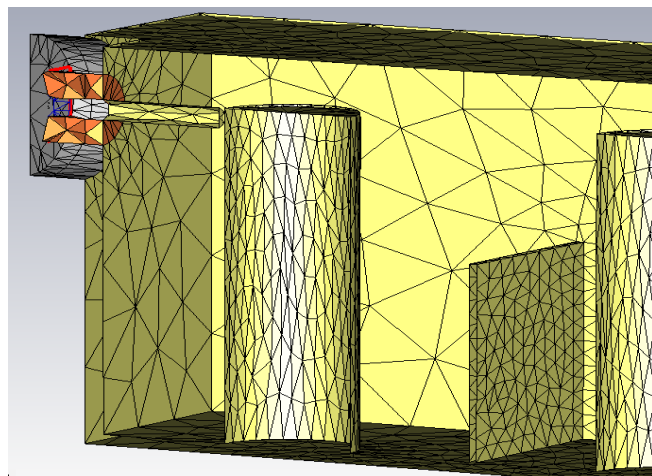
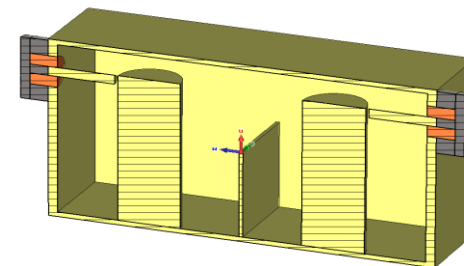
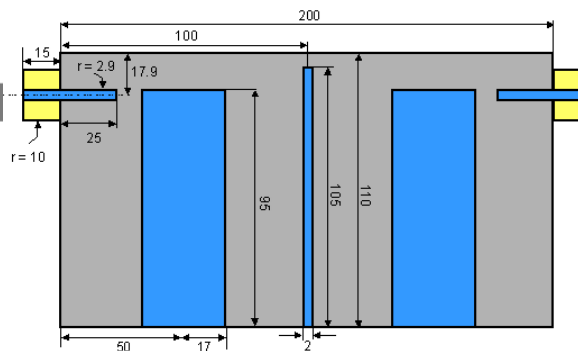
### Tutorials

Frequency Domain Tetrahedral:

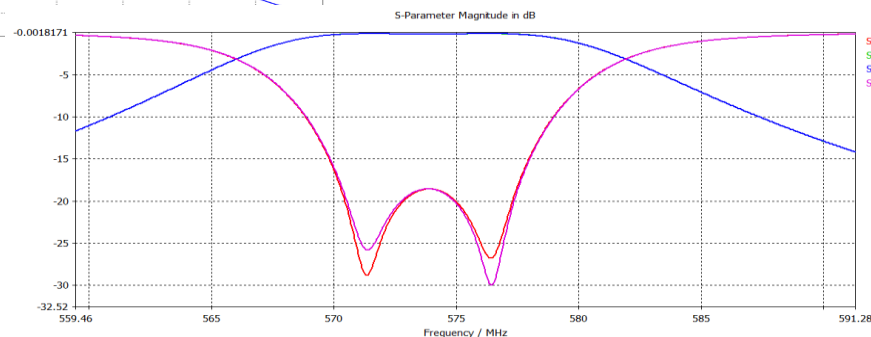
Run Example

Frequency Domain Resonant:

Run Example

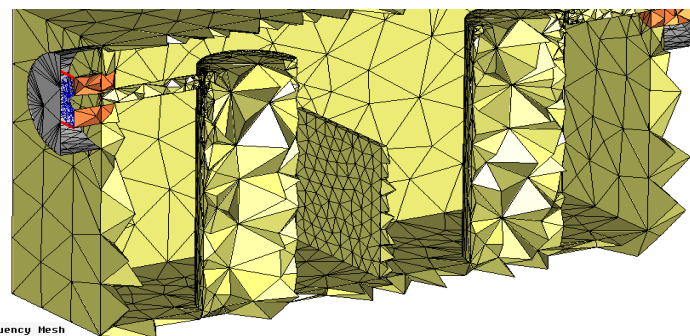
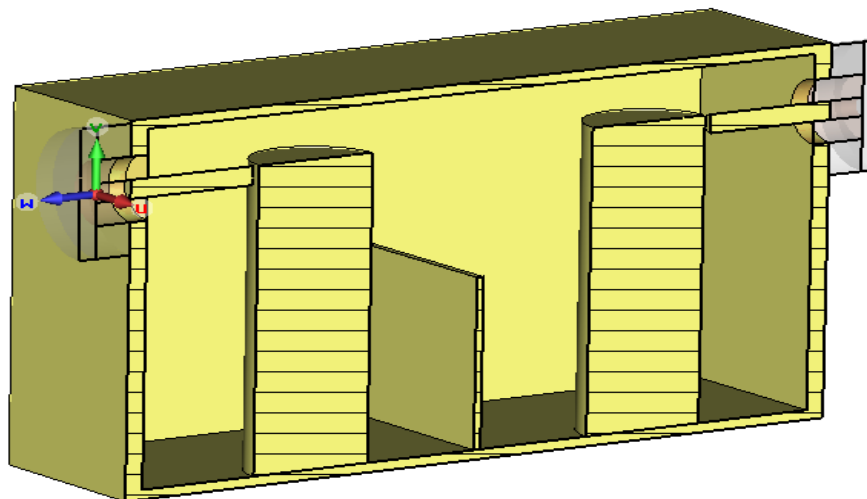


Rel Bandwidth: 0.9 %



# 1) EM (FD tet)

Material	brass
Type	Normal
Epsilon	1
Mue	1
El. cond.	1e+007 [S/m]
Therm.cond.	30 [W/K/m]
Young's Mod.	100 [kN/mm <sup>2</sup> ]
Poiss.Ratio	0.34
Thermal Exp.	15 [1e-6/K]



Type: High Frequency Mesh

# 1D Results > |S| dB



## Tchebychev Filter

=====

Order = 2  
Bandwidth = 5 MHz  
Center Frequency = 570 MHz  
Passband ripple = 0,01 dB (1,100747 VSWR)  
Return loss = -26,3828 dB

## Normed g values:

-----

g1 = 0,4489  
g2 = 0,4078  
g3 = 1,1008

## Corresponding coupling coefficients in MHz / (rel):

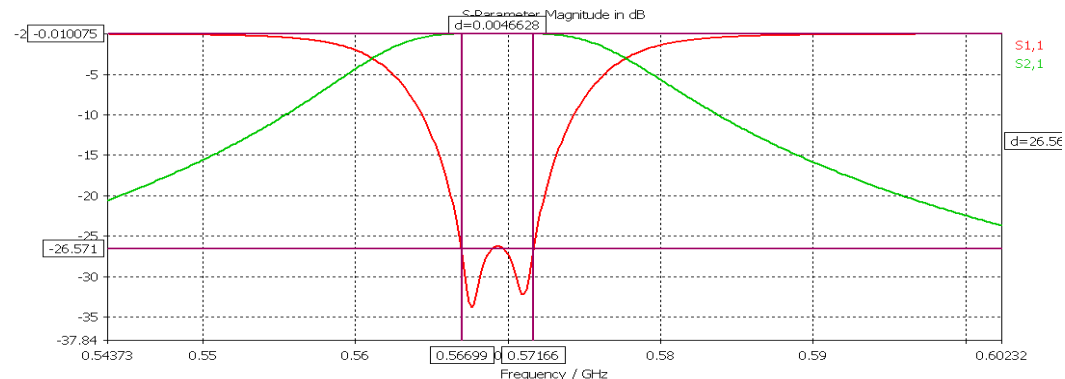
-----

k\_E = 11,14 (0,0195413)  
k1\_2 = 11,69 (0,0205021)  
k\_out = 11,14 (0,0195413)

## Group Delay Time

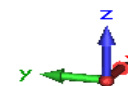
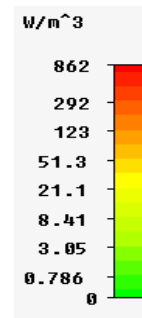
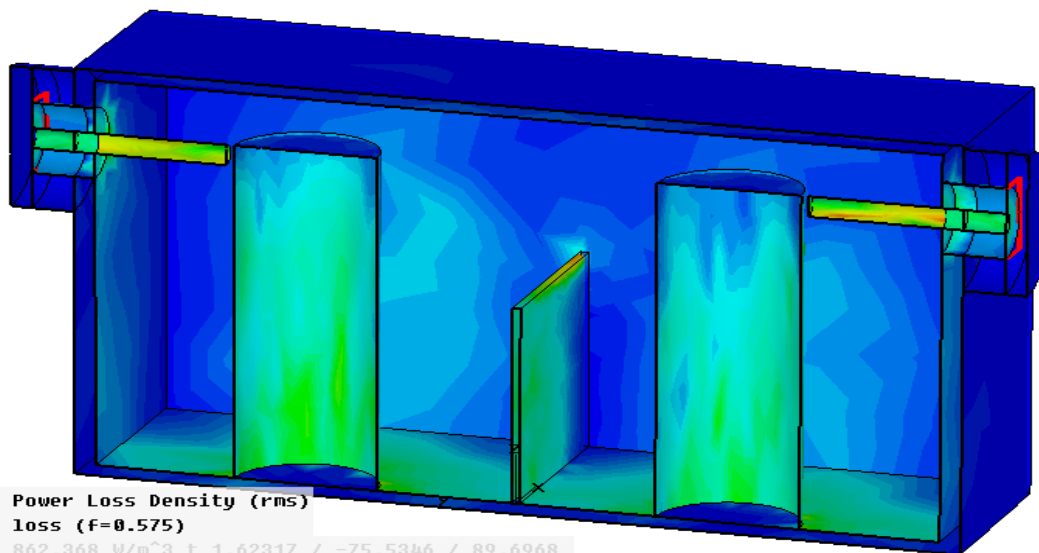
-----

t\_d1 = 57,153 ns  
t\_d2 = 51,922 ns  
t\_d3 = 0, ns



# Power Loss Dens. > loss (f=0.575)

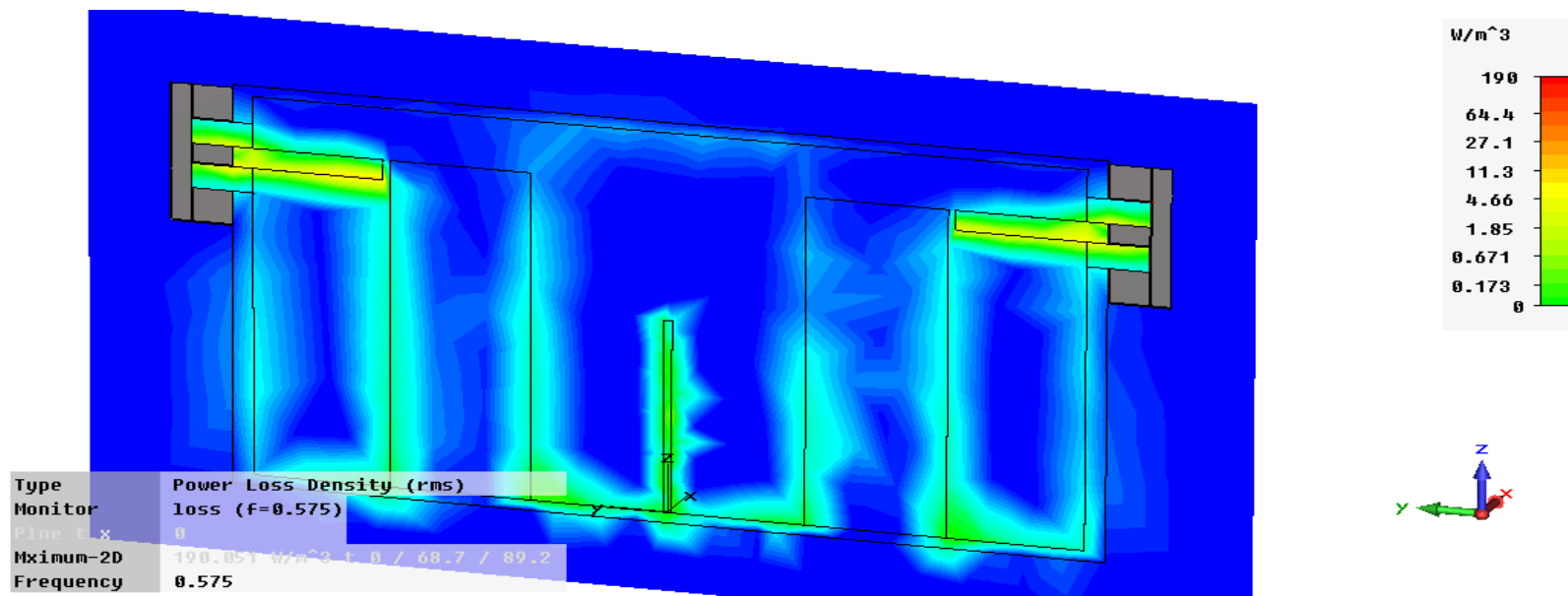
Inside plot



Type	Power Loss Density (rms)
Monitor	loss (f=0.575)
Maximum-3D	862.368 W/m <sup>3</sup> t 1.62317 / -75.5346 / 89.6968
Frequency	0.575

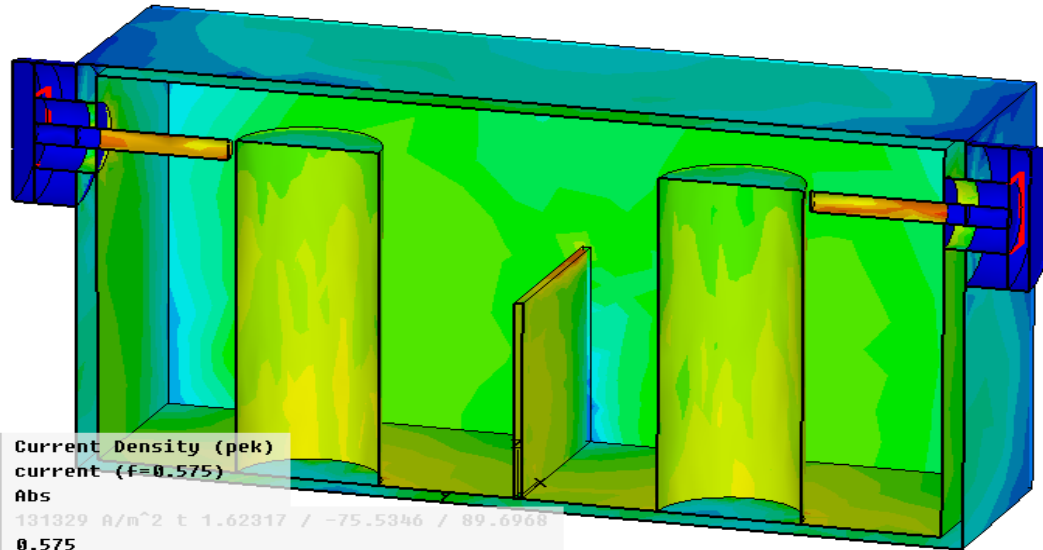


# Power Loss Dens. > loss (f=0.575)



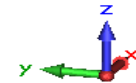
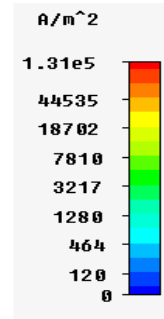
# Current Density ( $f=0.575$ )

Inside plot



Type  
Monitor  
Component  
Maximum-3D  
Frequency  
Amplitude Plot

Current Density (pek)  
current ( $f=0.575$ )  
Abs  
131329 A/m<sup>2</sup> t 1.62317 / -75.5346 / 89.6968  
0.575



# Export the Thermal losses

**Thermal Loss Calculation Settings**

Consider surface losses on boundaries:

☐ Xmin ☐ Xmax ☐ Ymin ☐ Ymax ☐ Zmin ☐ Zmax

Default conductivity for PEC:

☒ Export selected losses only:

Active	Source Name	Frq. [GHz]
<input checked="" type="checkbox"/>	Frequency Domain: S-Parameter [f=5.75e+008 1(1)]	0.575
<input type="checkbox"/>	Frequency Domain: S-Parameter [f=5.6e+008 1(1)]	0.56

**Calculate** **Cancel** **Help**

**Navigation Tree:**

- Excitation Signals
- Field Monitors
- Voltage Monitors
- Probes
- Mesh Control
- 1D Results
  - ISI linear
  - ISI dB
  - arg(S)
  - S polar
  - Smith Chart
  - All S-Parameters
  - Balance
  - Port Information
  - Convergence
  - Adaptive Meshing
- 2D/3D Results
  - Port Modes
  - E-Field
  - H-Field
  - Surface Current
    - h-field (f=0.56) [1]
    - h-field (f=0.575) [1]
  - Current Density
    - current (f=0.56) [1]
    - current (f=0.575) [1]
  - Power Loss Dens.
  - Surface Power Loss Dens.
  - Farfields
  - Tables
  - Thermal Losses

**Monitor**

Component: **current (f=0.575)**

Maximum-3D: **1.71096e+006 A/m^2 at 2.43279**

Frequency: **0.575**

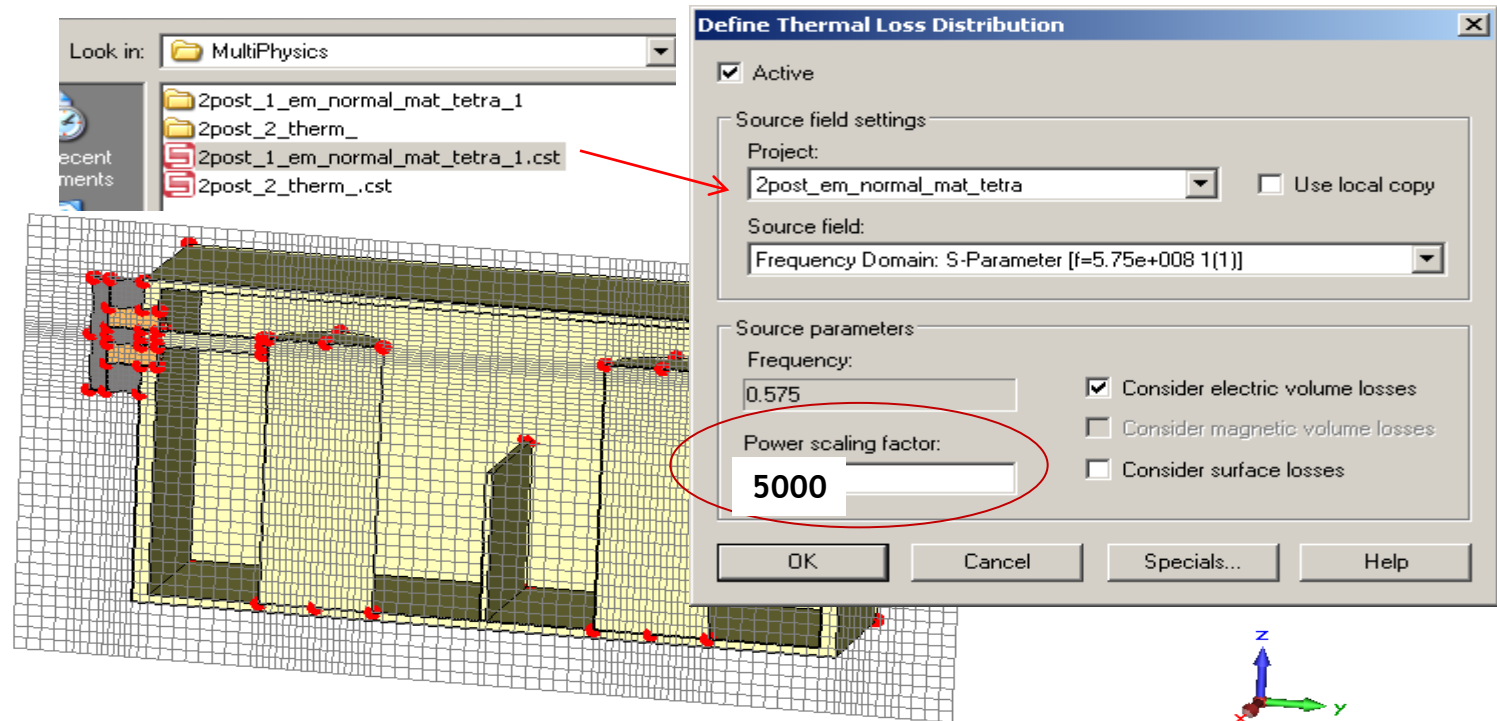
Amplitude Plot

**Parameters**

Name	Value	Description
Input_coupling_1	6.3	6.3
Input_coupling_2	6.3	6.3
Global		

## 2) Thermal Solver

### Import the losses from EM FD

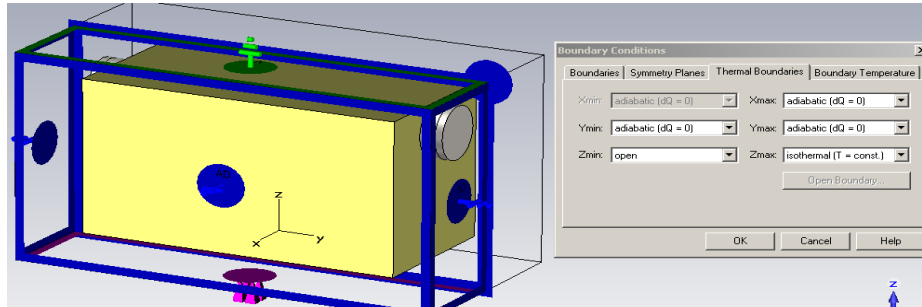


Type Low Frequency Mesh  
Meshplane at x 0 ( Index= 0 )

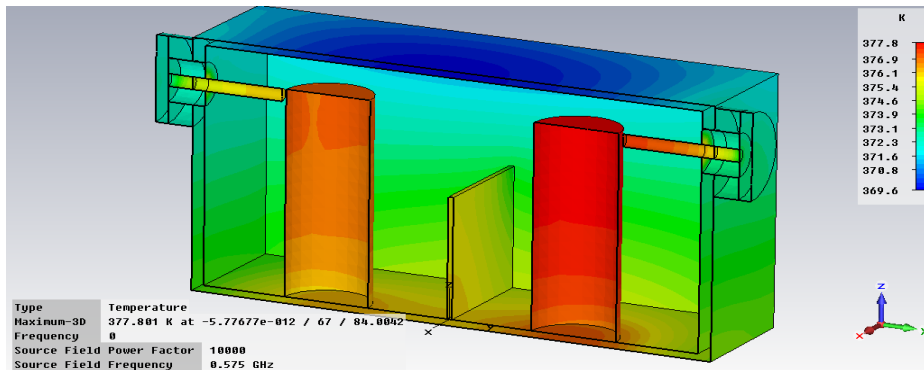
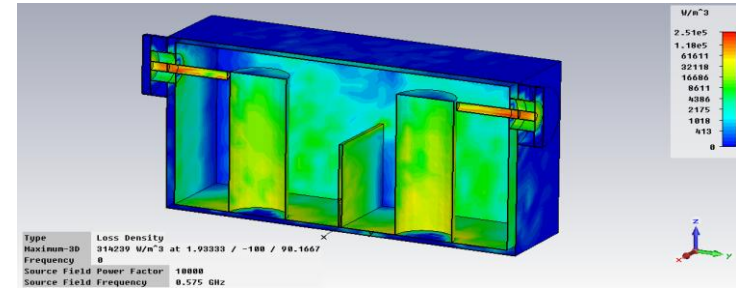
x=0 y=-52.281 z=124.78  
ix=0 iy=32 iz=53

# Thermal boundaries

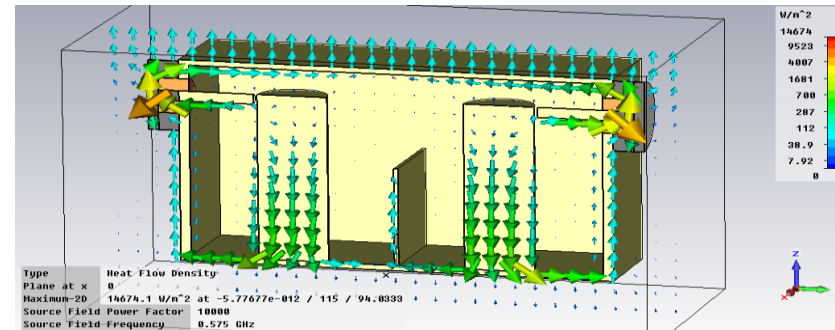
## Thermal boundaries



## Thermal volume losses as source

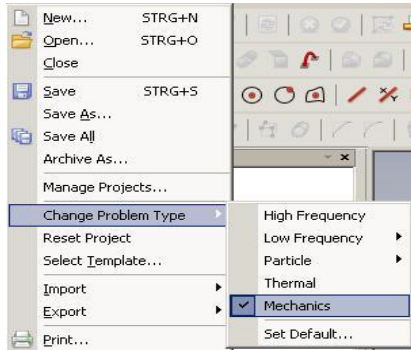


## Temperature

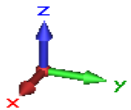
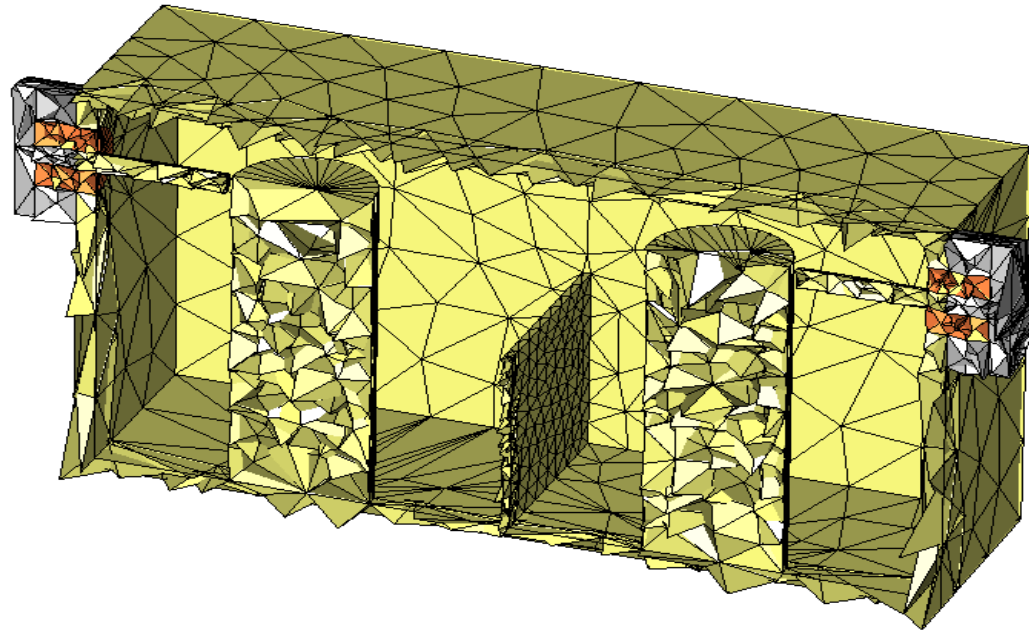


## Heat flow

# 3) Mechanical Solver



$$\cancel{[M][\ddot{x}]} + \cancel{[B][\dot{x}]} + [K][x] = [F]$$



Type Mechanics Mesh



## Strain

Strain can be expressed as

$$\text{strain} = dL / L \quad (1)$$

where

$$\text{strain} = (m/m) \text{ (in/in)}$$

$$dL = \text{elongation or compression (offset) of the object (m) (in)}$$

$$L = \text{length of the object (m) (in)}$$

## Stress

Stress can be expressed as

$$\text{stress} = F / A \quad (2)$$

where

$$\text{stress} = (N/m^2) \text{ (lb/in}^2, \text{ psi)}$$

$$F = \text{force (N) (lb)}$$

$$A = \text{area of object (m}^2\text{) (in}^2\text{)}$$

## Young's Modulus (Tensile Modulus)

Young's modulus or Tensile modulus can be expressed as

$$E = \text{stress} / \text{strain} = (F / A) / (dL / L) \quad (3)$$

where

$$E = \text{Young's modulus (N/m}^2\text{) (lb/in}^2, \text{ psi)}$$

$$\sigma = \epsilon \cdot E$$

To describe elastic properties of linear objects like wires, rods, or columns which are stretched or compressed, a convenient parameter is the ratio of the stress to the strain, a parameter called the "Young's modulus" or "Modulus of Elasticity" of the material. Young's modulus can be used to predict the elongation or compression of an object as long as the stress is less than the yield strength of the material.

Material	Young's Modulus (Modulus of Elasticity) - E -		Ultimate Tensile Strength - S <sub>u</sub> -	Yield Strength - S <sub>y</sub> -
	(10 <sup>6</sup> psi)	(10 <sup>9</sup> N/m <sup>2</sup> , GPa)	(10 <sup>6</sup> N/m <sup>2</sup> , MPa)	(10 <sup>6</sup> N/m <sup>2</sup> , MPa)
ABS plastics		2.3	40	
Acrylic		3.2	70	
Aluminum	10.0	69	110	95
Antimony	11.3			
Beryllium	42			
Bismuth	4.6			
Bone		9	170 (compression)	
Boron				3100
Brasses		100 - 125	250	
Bronzes		100 - 125		
Cadmium	4.6			
Carbon Fiber Reinforced Plastic		150		
Cast Iron 4.5% C, ASTM A-48			170	
Chromium	36			
Cobalt	30			
Concrete, High Strength (compression)		30	40 (compression)	
Copper	17		220	70
Diamond		1,050 - 1,200		
Douglas fir Wood		13	50 (compression)	
Steel, Structural ASTM-A36		200		

$$1 \text{ GPa} = 1 \text{ kN/mm}^2$$

- $1 \text{ N/m}^2 = 1 \times 10^{-6} \text{ N/mm}^2 = 1 \text{ Pa} = 1.4504 \times 10^{-4} \text{ psi}$
- $1 \text{ psi (lb/in}^2\text{)} = 144 \text{ psf (lb/ft}^2\text{)} = 6,894.8 \text{ Pa (N/m}^2\text{)} = 6.895 \times 10^{-3} \text{ N/mm}^2$

## Poisson's ratio

From Wikipedia, the free encyclopedia

**Poisson's ratio** ( $\nu$ ), named after [Siméon Poisson](#), is the ratio, when a sample object is stretched, of the contraction or transverse [strain](#) (perpendicular to the applied load), to the extension or axial strain (in the direction of the applied load).

When a sample cube of a [material](#) is stretched in one direction, it tends to contract (or occasionally, expand) in the other two directions perpendicular to the direction of stretch. Conversely, when a sample of [material](#) is compressed in one direction, it tends to expand (or rarely, contract) in the other two directions. This phenomenon is called the **Poisson effect**. Poisson's ratio  $\nu$  (*nu*) is a measure of the Poisson effect.

The Poisson's ratio of a stable, [isotropic](#), linear [elastic](#) material cannot be less than  $-1.0$  nor greater than  $0.5$  due to the requirement that the [elastic modulus](#), the [shear modulus](#) and [bulk modulus](#) have positive values <sup>[1]</sup>. Most materials have Poisson's ratio values ranging between  $0.0$  and  $0.5$ . A perfectly incompressible material deformed elastically at small strains would have a Poisson's ratio of exactly  $0.5$ . Most steels and rigid polymers when used within their design limits (before [yield](#)) exhibit values of about  $0.3$ , increasing to  $0.5$  for post-yield deformation (which occurs largely at constant volume.) Rubber has a Poisson ratio of nearly  $0.5$ . Cork's Poisson ratio is close to  $0$ : showing very little lateral expansion when compressed. Some materials, mostly polymer foams, have a negative Poisson's ratio; if these [auxetic materials](#) are stretched in one direction, they become thicker in perpendicular directions. While anisotropic materials can as well have Poisson ratios in some directions above  $0.5$ .

Assuming that the material is compressed along the axial direction:

$$\nu = -\frac{\epsilon_{\text{trans}}}{\epsilon_{\text{axial}}} = -\frac{\epsilon_x}{\epsilon_y}$$

where

$\nu$  is the resulting Poisson's ratio,

$\epsilon_{\text{trans}}$  is transverse strain (negative for axial tension, positive for axial compression)

$\epsilon_{\text{axial}}$  is axial strain (positive for axial tension, negative for axial compression).

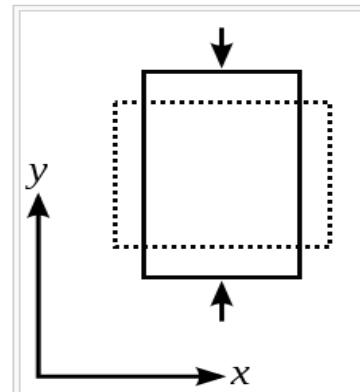


Figure 1: Rectangular specimen subject to compression, with Poisson's ratio circa 0.5

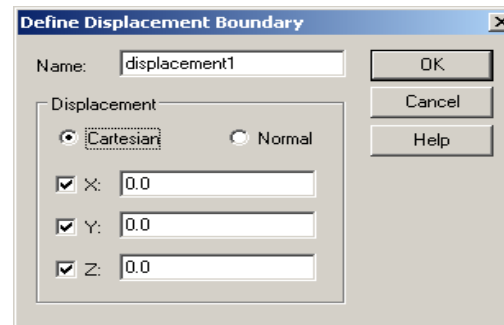
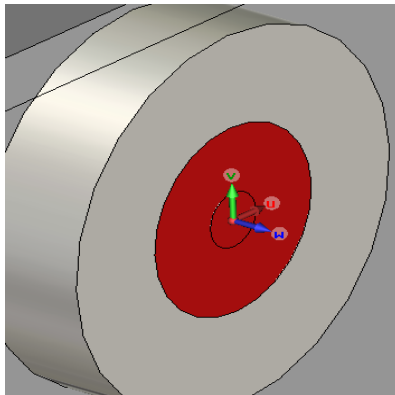
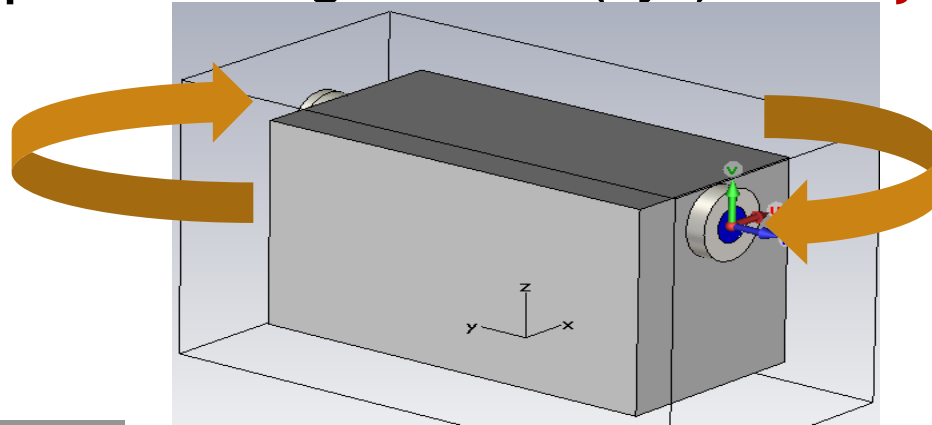
material	poisson's ratio
rubber	~ 0.50
gold	0.42
saturated clay	0.40-0.50
magnesium	0.35
titanium	0.34
copper	0.33
aluminium-alloy	0.33
clay	0.30-0.45
stainless steel	0.30-0.31

steel	0.27-0.30
cast iron	0.21-0.26
sand	0.20-0.45
concrete	0.20
glass	0.18-0.3
foam	0.10 to 0.40
cork	~ 0.00

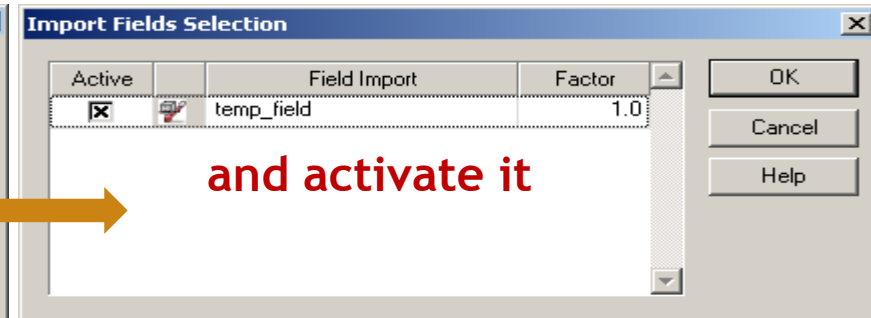
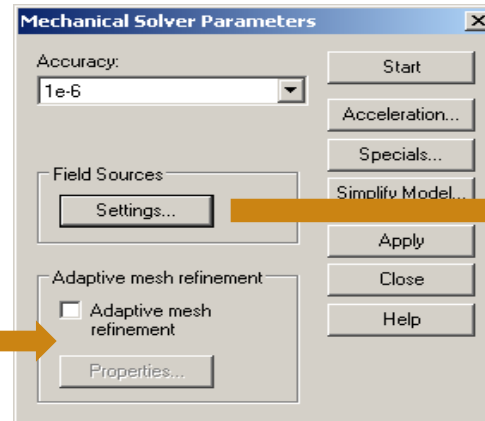
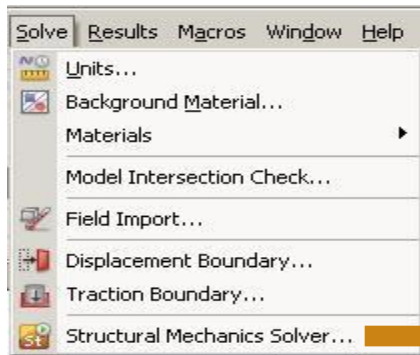
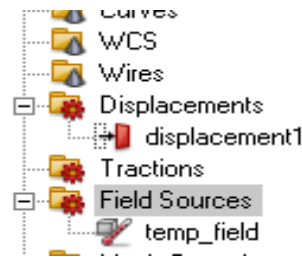
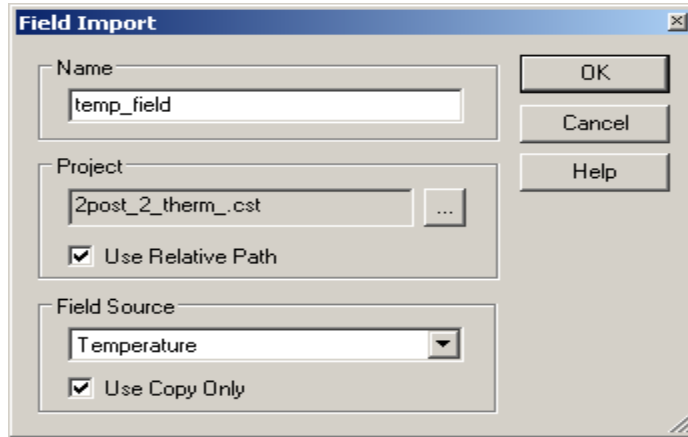


# Displacements > displacement

Define a displacement eg at a face (xyz) **directly** at the WG-Port

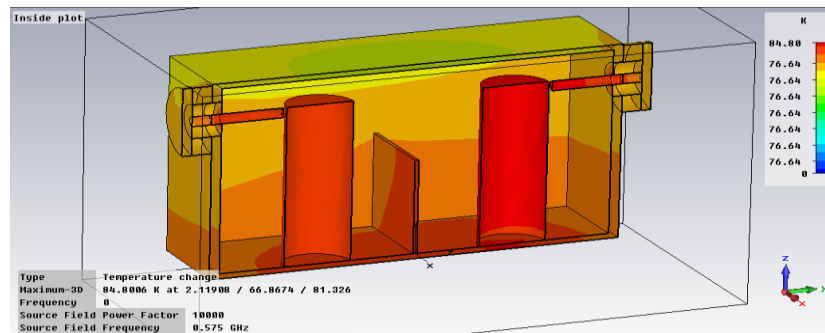


# Import a field source (from therm)

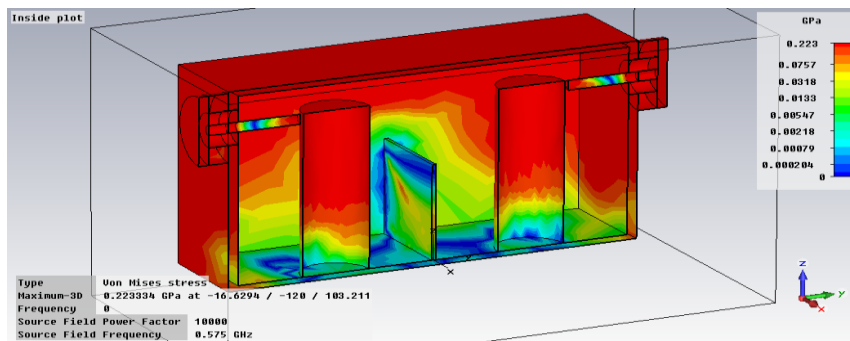
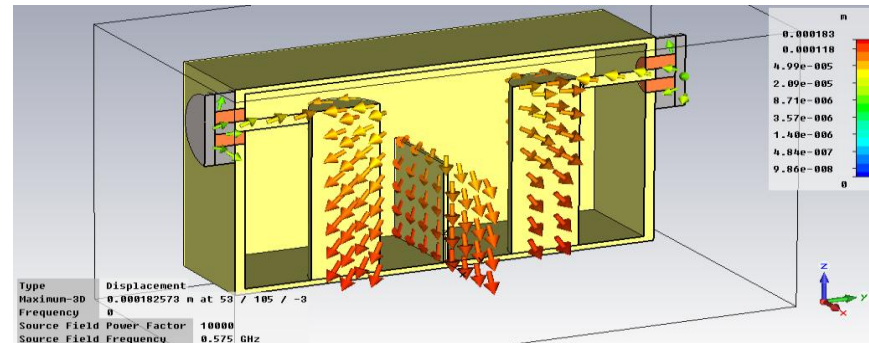


# 2D/3D Results > Displacement

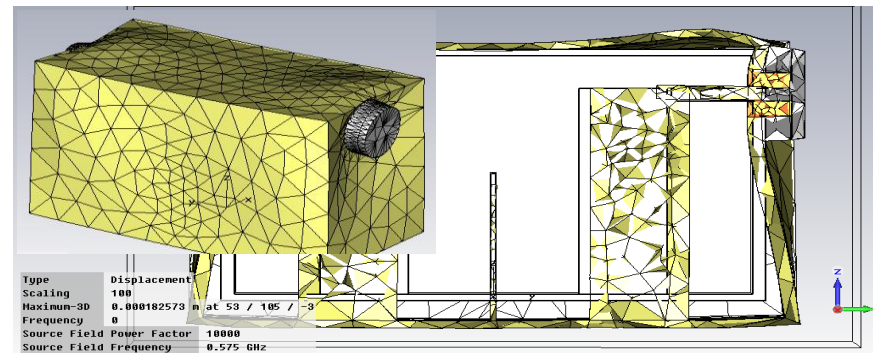
## Temperature change as source



## Mech. Displacements



## Von Mises Stress



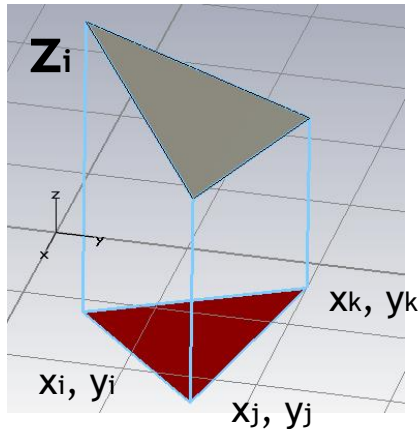
## Deformed Mesh

# 4) Sensitivity ( Introduction)

Matrix to solve:  $[K]\{E\} = \{Q\}$



$[K]$ : symmetric, complex, contains geometry, material, frequency



Example: Linear Shape functions for a 2D element in xy

$$[N] = -\frac{1}{2\Delta} [1, x, y] \begin{bmatrix} a_i & a_j & a_k \\ b_i & b_j & b_k \\ c_i & c_j & c_k \end{bmatrix}; a_{ijk} = x_j y_k - y_j x_k; b_{ijk} = y_j - y_k; c_{ijk} = x_k - x_j$$

$$z = [N_i, N_j, N_k] \begin{Bmatrix} z_i \\ z_j \\ z_k \end{Bmatrix}$$

Example: electrostatic

$$k_{m,n} = \iint_{xy} (\epsilon_x \frac{\partial N_m}{\partial x} \frac{\partial N_n}{\partial x} + \epsilon_y \frac{\partial N_m}{\partial y} \frac{\partial N_n}{\partial y}) dx dy; m, n = i, j, k$$

$[E]$ : unknowns  $z$

$[Q]$ : Sources

# Introduction to Sensitivity

## S-Parameters:

3D Fieldsolution



$$S(\omega, p) = \frac{1}{-j\omega\mu_0} E^T(\omega, p) K^T(\omega, p) E(\omega, p)$$

[K] ...left hand side, E (Fields at ports, p... any parameter

## Sensitivity of S-parameter vs. parameter change:

$$-j\omega\mu_0 \frac{\partial S}{\partial p} = E^T \left( \frac{\partial K}{\partial p} \right) E$$

Direct analytical derivation of K-matrix elements via e.g. [N]

Same 3D Fieldsolution

# Introduction to Sensitivity

Numerical calculation of gradients is expensive and unstable

Here: Sensitivity of S-parameter vs. parameter change

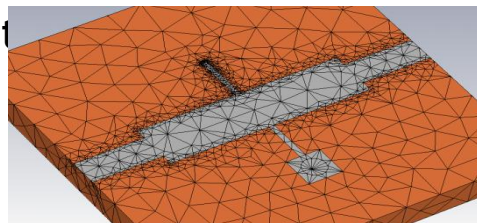
$$-j\omega\mu_0 \frac{\partial S}{\partial p} = E^T \frac{\partial K}{\partial p} E$$

no additional 3D solution required (only another S-Parameter computation)

Very efficient computation of sensitivities

Result: S-parameter ranges for tolerant parameter

Currently available for FD-Tet solver



# Introduction to Sensitivity




What is it good for?

- The sensitivity helps estimate „new“ S-parameters due to the (small) change of the parameter, at no extra cost

Suppose the parameter  $p$  changes by a quantity  $\Delta p$  :

$$S(x + \Delta p) \approx S(x) + \sum_p \frac{\partial S}{\partial p} \Delta p$$

 exact computation of the Sensitivity  
(Approximated by 1st order Taylor expansion)

- The various sensitivities are used in an optimizer to solve for  $\Delta p$  as variables to best fit the S-parameter goals.

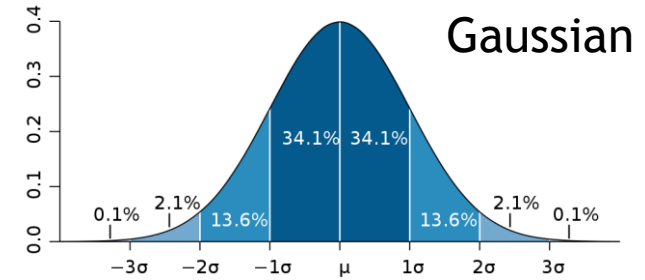
$$S_{nm} \Leftarrow S_{nm(3D-MWS)} + \sum_p \frac{\partial S}{\partial p} \Delta p$$



$\Delta p$  ... face constraints

# What is the Yield Analysis

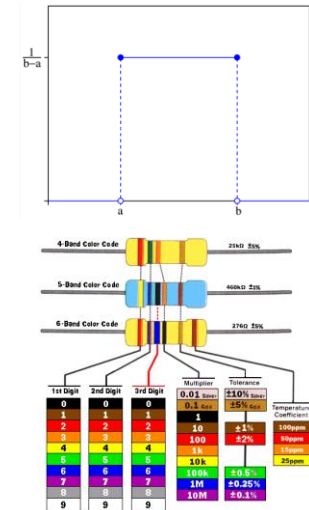
For every product, there are:  
Technical specifications  
Fabrication tolerances



The fabrication tolerances will lead to some products not fulfilling the specifications

Yield:  $yield = \frac{\#Passed}{\#Total}$

Uniform





# Typical Approach vs. CST Approach



How is yield calculated typically?

Parameters vary according to a known probability curve

Repeat

Change the value of all parameters

Simulate

Check if specification (in our case for S-params.) is met

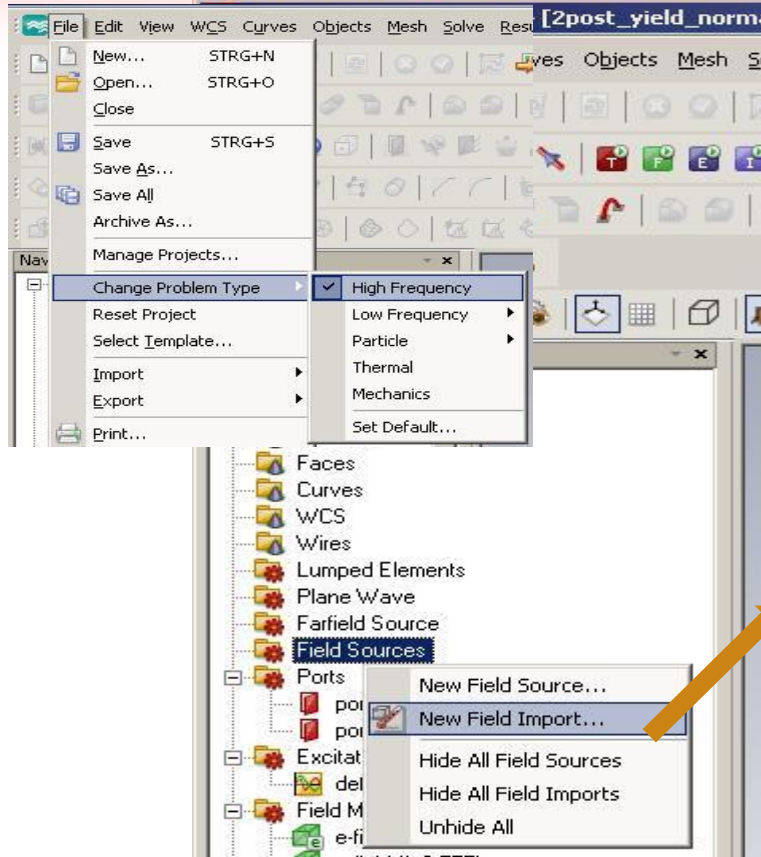
Until the number of simulations is statistically relevant

This is a large number of EM simulations - typically hundreds or thousands!!!

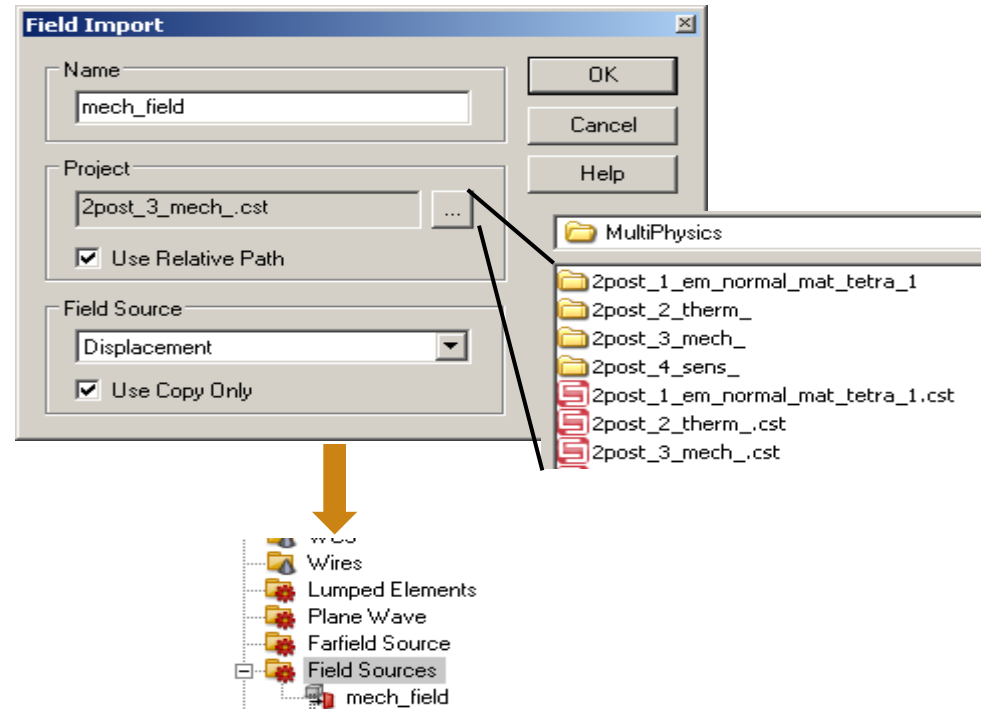
Knowing the sensitivity, there is **no need to perform 3D simulations**, at least if the **parameters vary in a small range**.

The efficiency of this new sensitivity analysis approach makes Monte-Carlo based yield analysis feasible even for complex multi-parametrical three-dimensional structures

# 4) Sensitivity (based on mech. Displacements)



## Import the displacements



# 4) Sensitivity

## Setup Sensitivity Analysis

**Frequency Domain Solver Parameters**

**Method**

- ☒ General Purpose
- ☐ Resonant: Fast S-Parameter
- ☐ Resonant: S-Parameter, fields

Mesh type:  
Tetrahedral Mesh

**Solver settings**

- ☐ Save all field results
- ☐ Store result data in cache
- ☐ Calculate modes only

Accuracy (tetrahedral mesh):  
1e-4

**Excitation settings**

Source type: Port 1 Mode: 1

**S-parameter settings**

- ☐ Normalize to fixed impedance

50 Ohms

**Frequency samples**

	Auto	Samples	From	To	Unit
Max.Range	<input type="checkbox"/>		0.4	0.8	GHz
Adapt.Freq.	<input checked="" type="checkbox"/>	1	.575		GHz
Frequency	<input checked="" type="checkbox"/>				GHz
Frequency	<input type="checkbox"/>				GHz
Frequency	<input type="checkbox"/>				GHz

☐ Do not calculate field monitors  
☒ Use broadband frequency sweep

**Adaptive mesh refinement**

- ☐ Adaptive tetrahedral mesh refinement

**Sensitivity analysis**

- ☒ Use sensitivity analysis

Buttons: Start, Optimize..., Par. Sweep..., Acceleration..., Specials..., Simplify Model..., Apply, Close, Help

**Sensitivity Analysis**

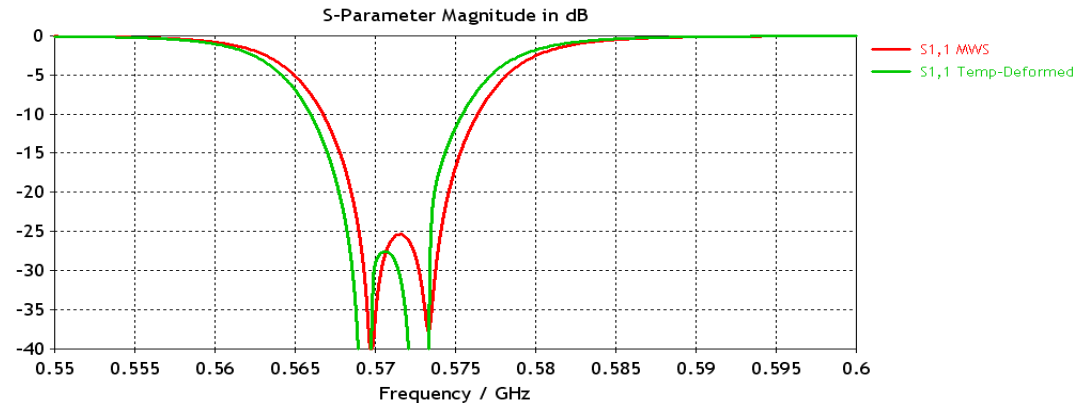
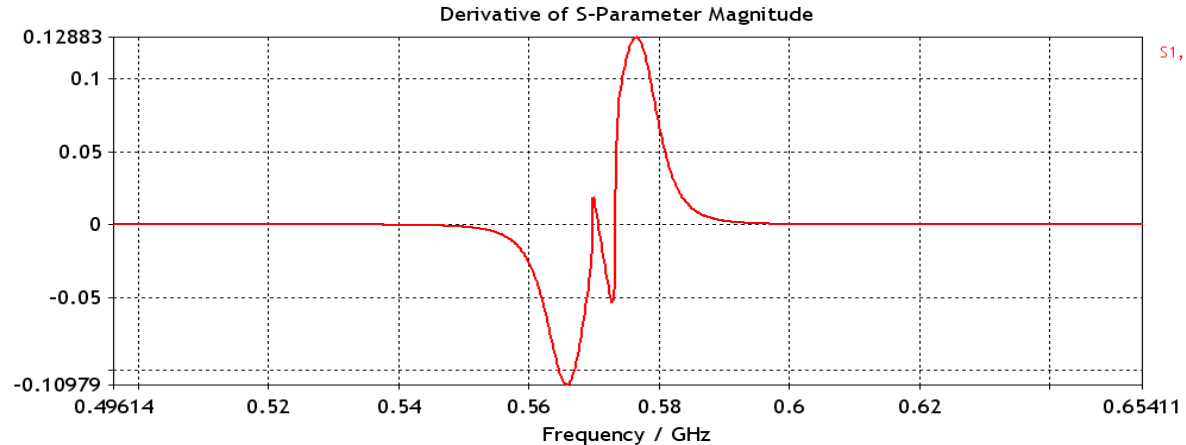
<input type="checkbox"/>	Parameter	Value	Description
<input checked="" type="checkbox"/>	mech_field	1	Imported displacement field

Buttons: OK, Cancel, Help


# 4) Sensitivity

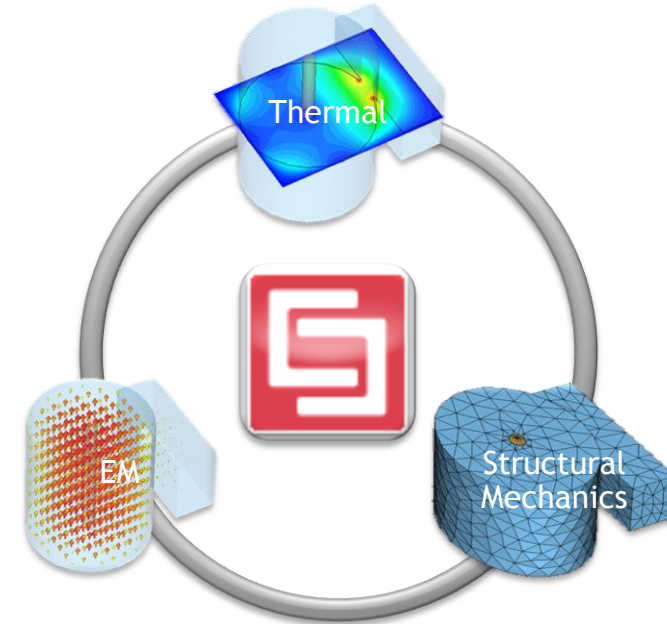


## Display S-parameter Sensitivity



# Summary

- Integrated workflow with CST M<sup>PHYSICS</sup> STUDIO™ 
- Ease-of-use: New solvers within well known frontend
- Accuracy of integrated solution and solver technology
- Wide application range due to tight integration within CST STUDIO SUITE™



Thank you for your attention!