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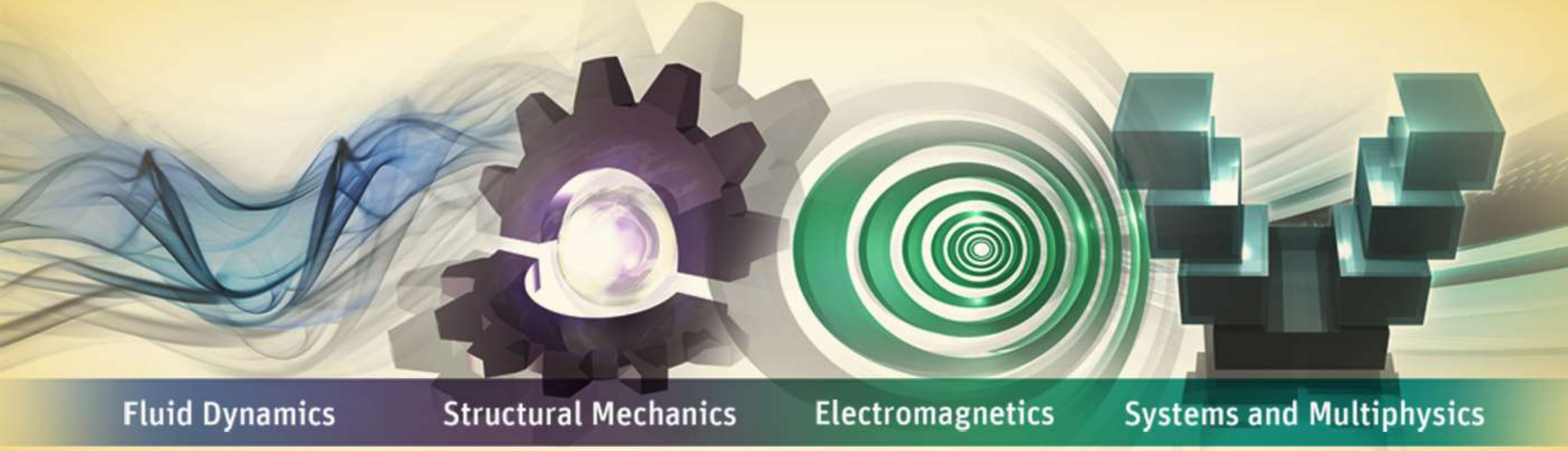
# Coupled Electromagnetic and Thermal Analysis of Ferrite Core Electronic Planar Transformer

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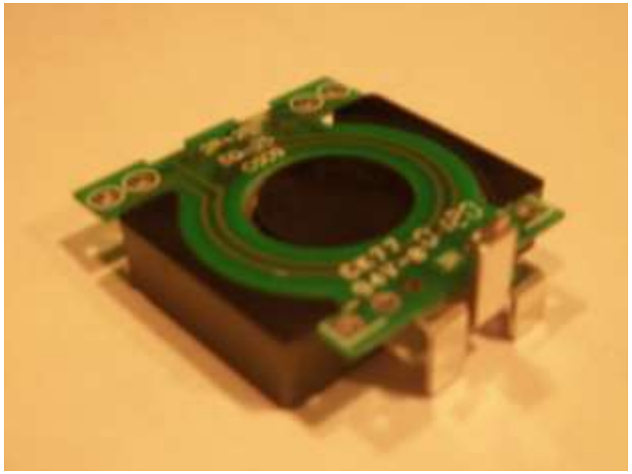
*Technical Manager*
*ANSYS, Inc*

# Outline

- Introduction
- Maxwell 3D Eddy Current and Electrostatic Simulation
- ANSYS Mechanical Thermal Simulation
- 2-way Thermal Coupling back to Maxwell
- Simplorer System Simulation using Maxwell State Space Dynamic model
- Summary

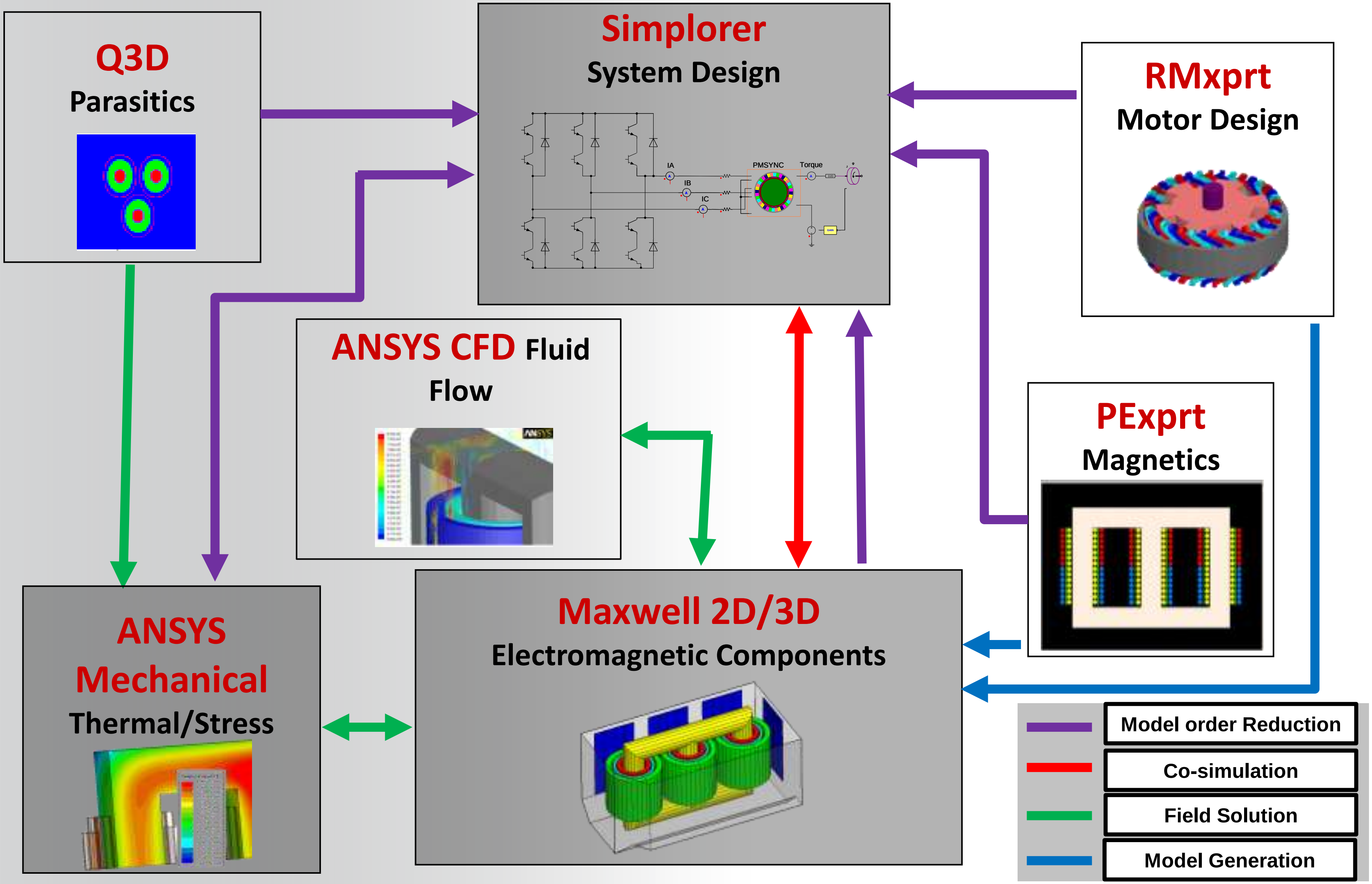


# Introduction

- Coupled electromagnetic-thermal analysis of a ferrite core electronic planar transformer
- Magnetic simulation done at fundamental frequency = 100kHz with harmonics up to 5MHz
- All sources of losses considered including: eddy current, skin, and proximity losses in the windings as well as eddy current and hysteresis losses in the ferrite core
- Losses are directly coupled into an ANSYS Mechanical Thermal simulation in order to determine temperature rise using element by element coupling
- Temperatures fed back to Maxwell for material changes
- System simulation done inside of Simplorer using dynamic state space frequency dependent model

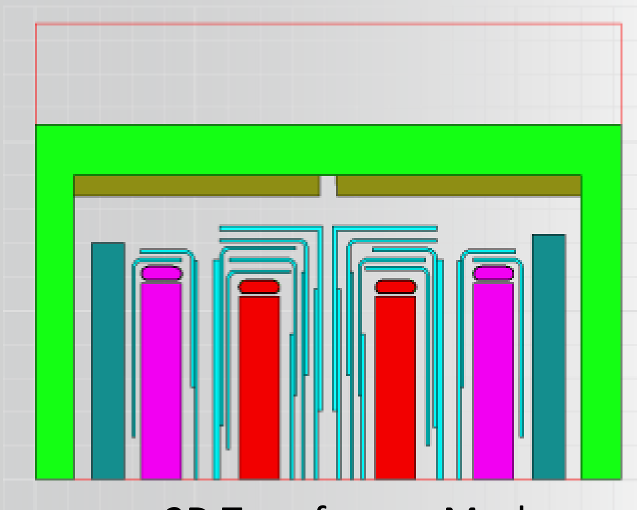
# Coupled Electromechanical Design Flow



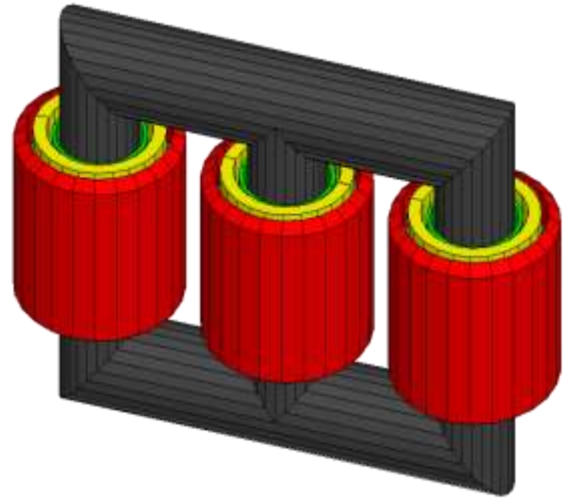

  

# FEA Adaptive Meshing

2D Transformer Model

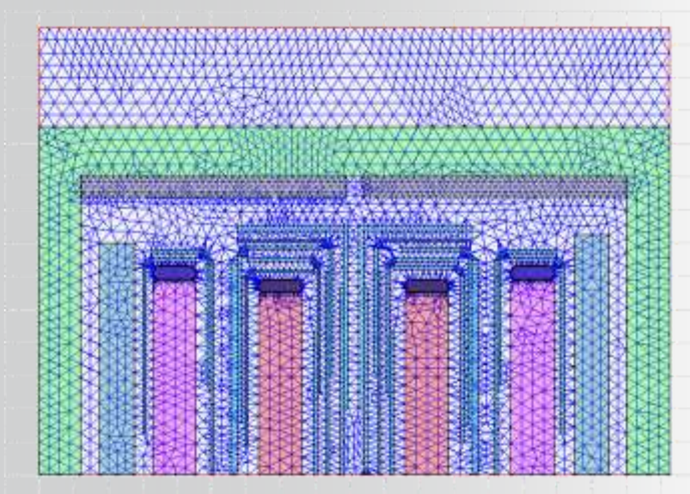


3D Transformer Model

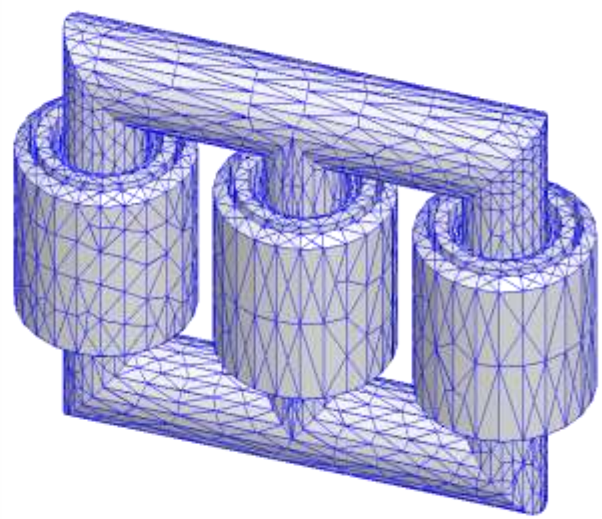


2D Transformer Mesh

In 2D, finite elements are triangles



3D Transformer Mesh

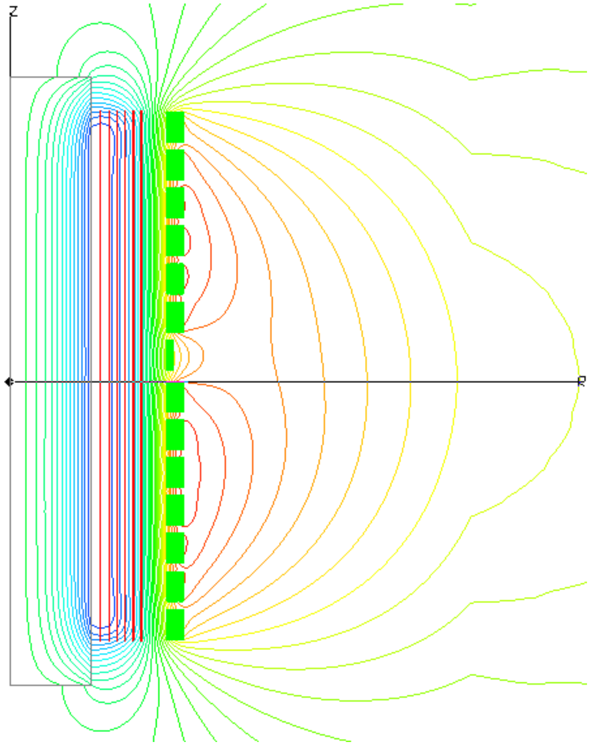


In 3D, finite elements are tetrahedra

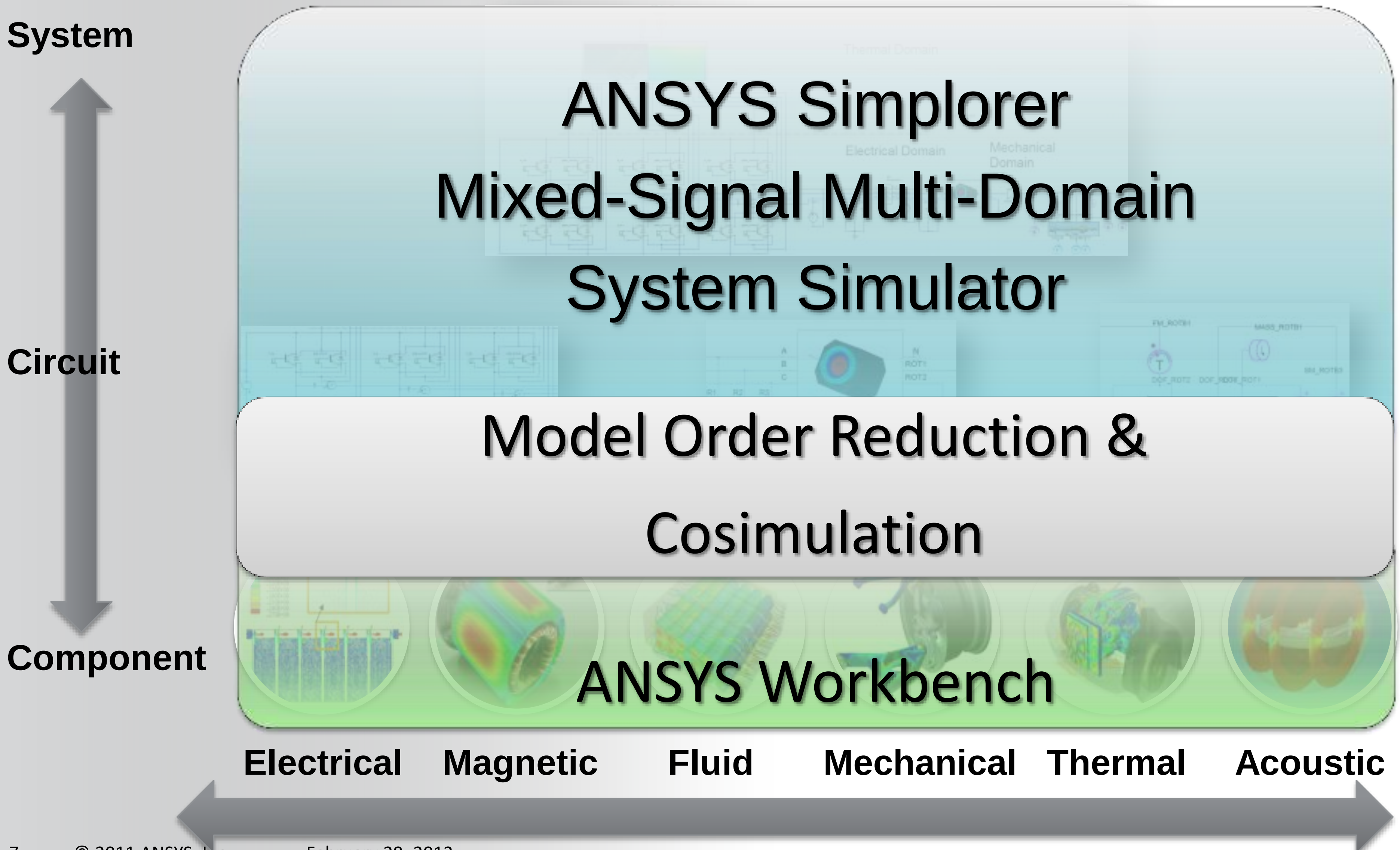
# Transformer Design Challenges

- Magnetic effects:
  - nonlinear materials
  - frequency dependent materials
  - temp dependent materials
  - eddy currents
  - proximity effects
  - eddy and hysteresis losses
  - time diffusion of magnetic fields
  - transient excitations



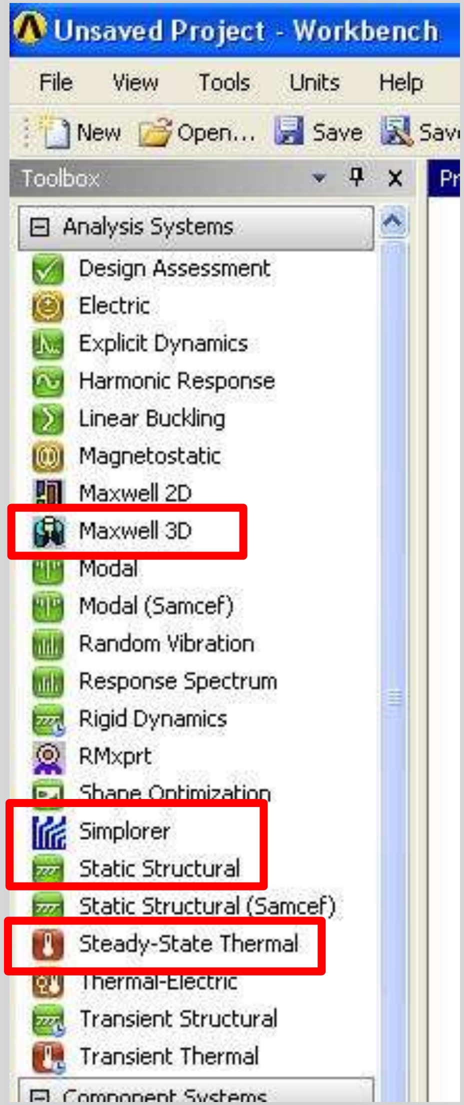
- Electric Field effects:
  - varying dielectric permitivities
  - varying dimensions and shape
  - 3D field effects

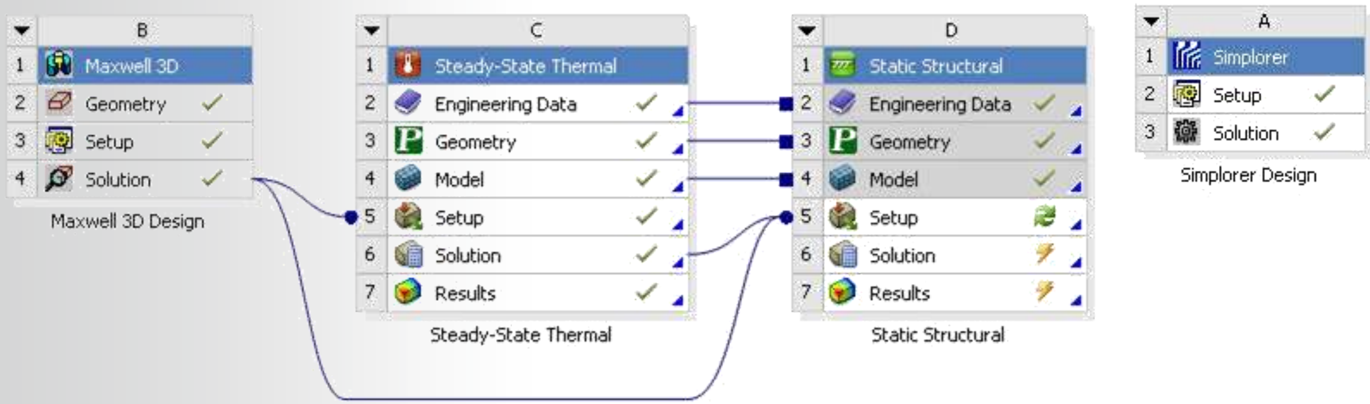
# ANSYS Comprehensive Solution



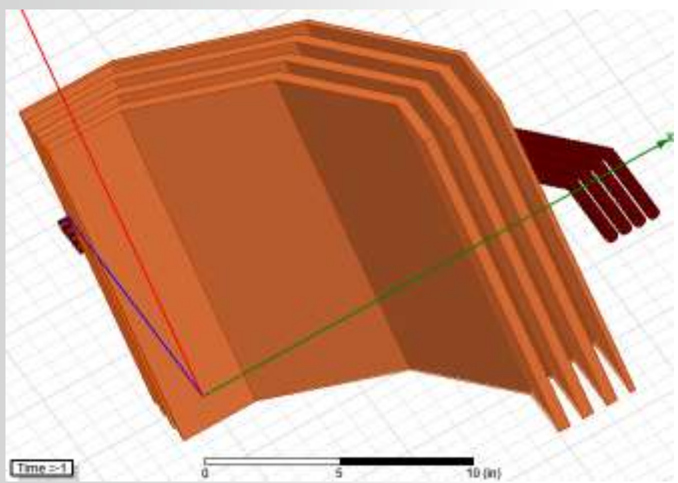

  

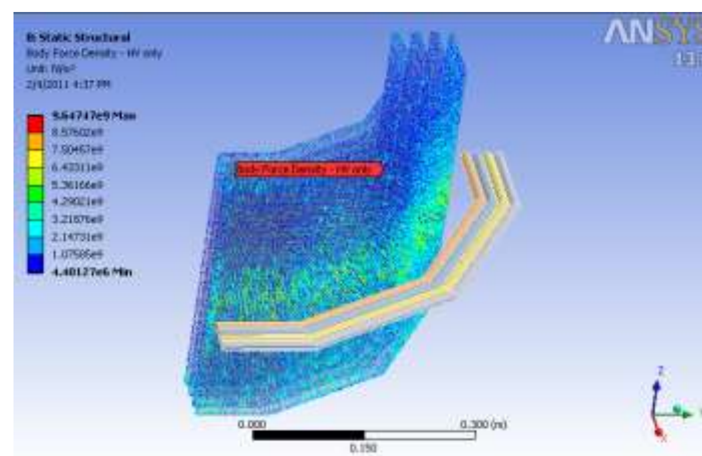
# Workbench Coupling Technology



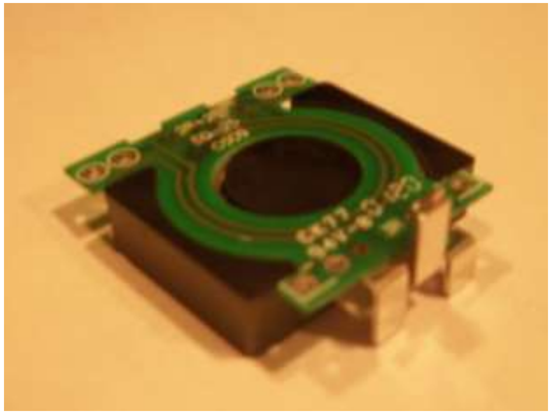

**Electromagnetic → Thermal → Stress → System**

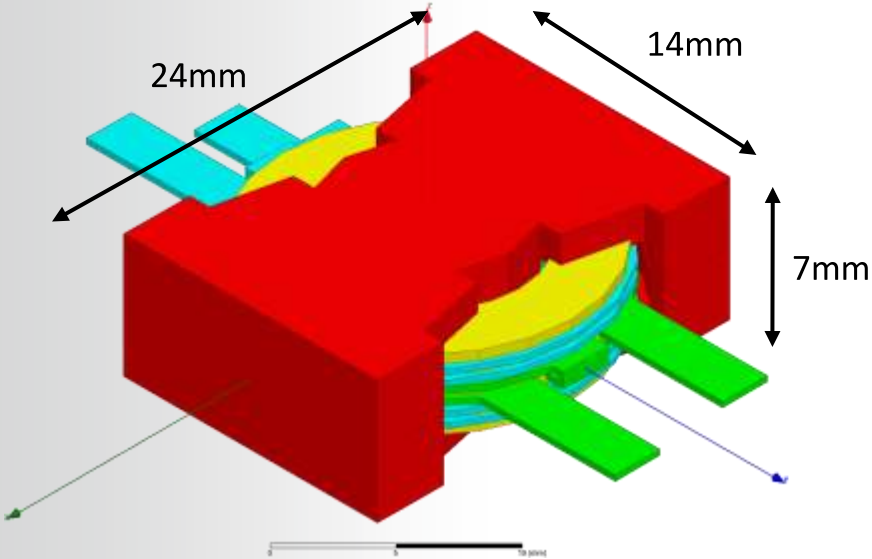




# Electronic Planar Transformer

- Ferrite PQ Core
- Primary turns = 4
- Secondary turns = 2
- Insulation layers between conductors
- Fundamental Frequency = 100kHz

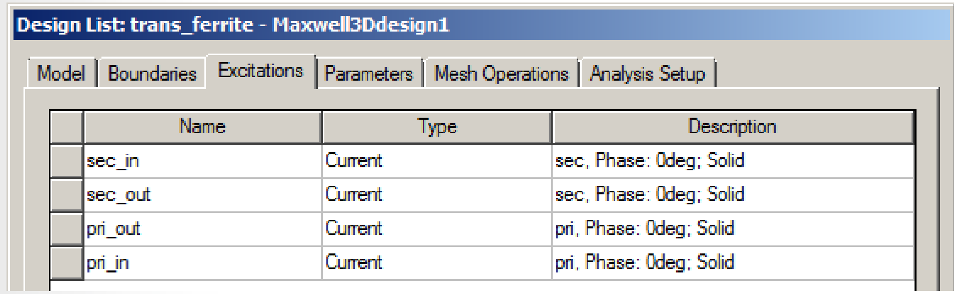




# Maxwell 3D Source Setup

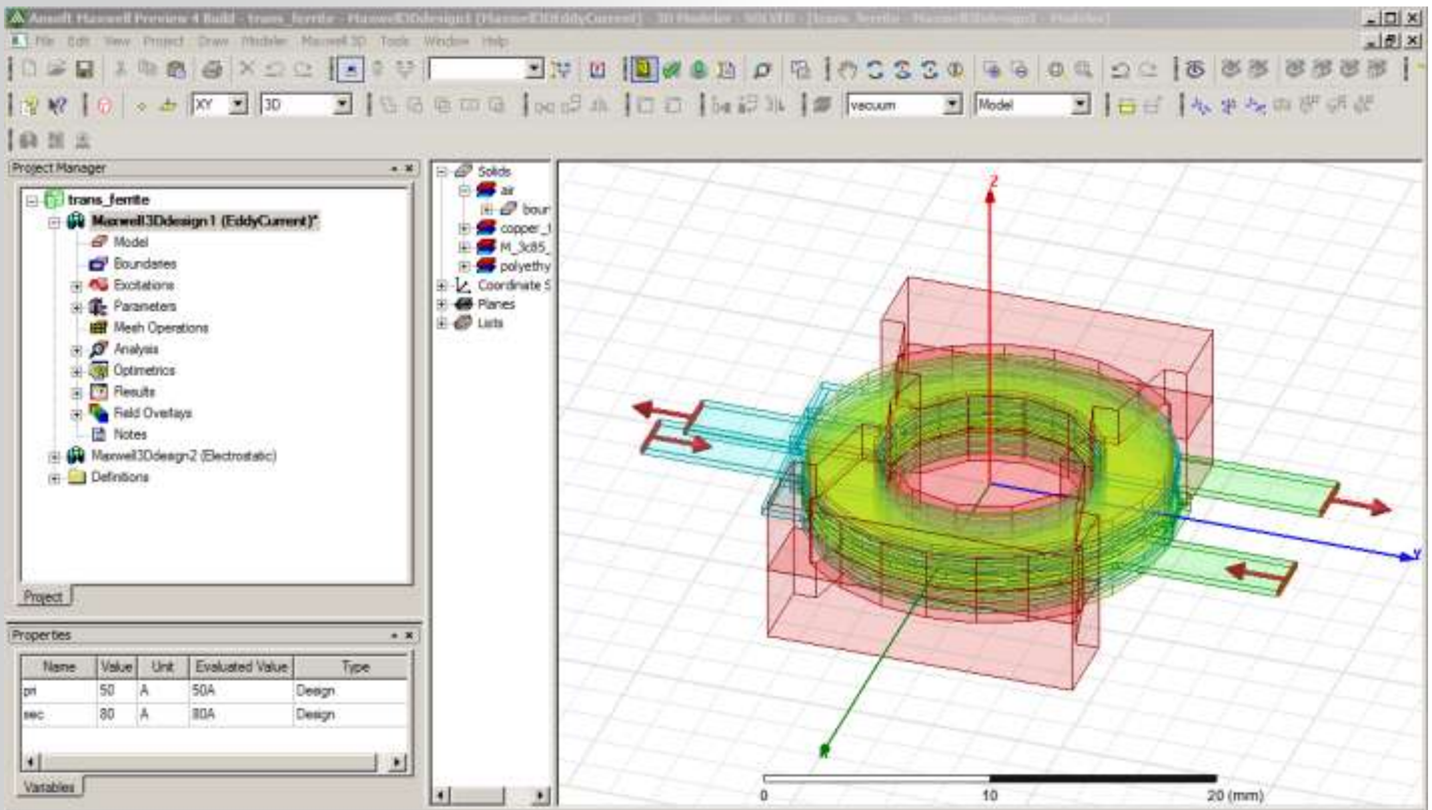
- Load case with Ipri = 50A and Isec = 80A
- Unbalanced A-turns for core excitation



Design List: trans_ferrite - Maxwell3Ddesign1

Model | Boundaries | Excitations | Parameters | Mesh Operations | Analysis Setup

| Name | Type | Description |
|---|---|---|
| sec_in | Current | sec, Phase: 0deg; Solid |
| sec_out | Current | sec, Phase: 0deg; Solid |
| pri_out | Current | pri, Phase: 0deg; Solid |
| pri_in | Current | pri, Phase: 0deg; Solid |




| Name | Value | Unit | Evaluated Value | Type |
|---|---|---|---|---|
| pri | 50 | A | 50A | Design |
| sec | 80 | A | 80A | Design |

# Ferrite Core Properties

**Frequency dependent permeability and imaginary permeability**

**Use Simplorer Sheetscan utility to grab permeability data points**

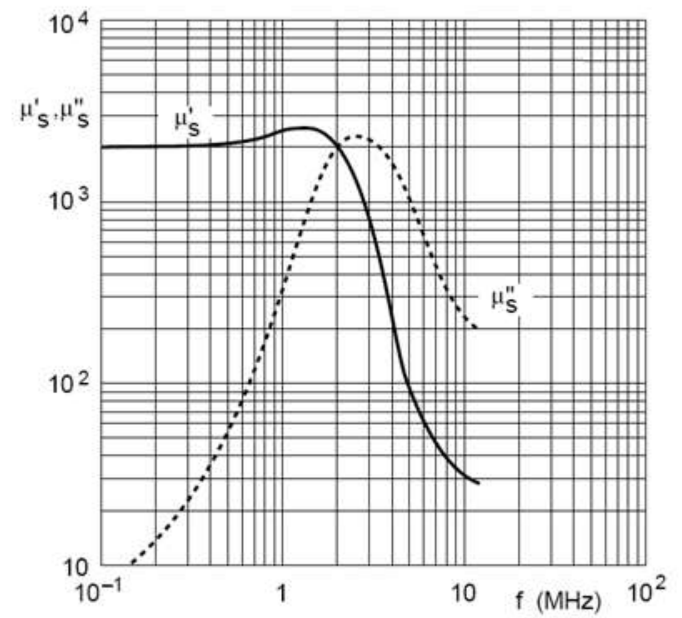
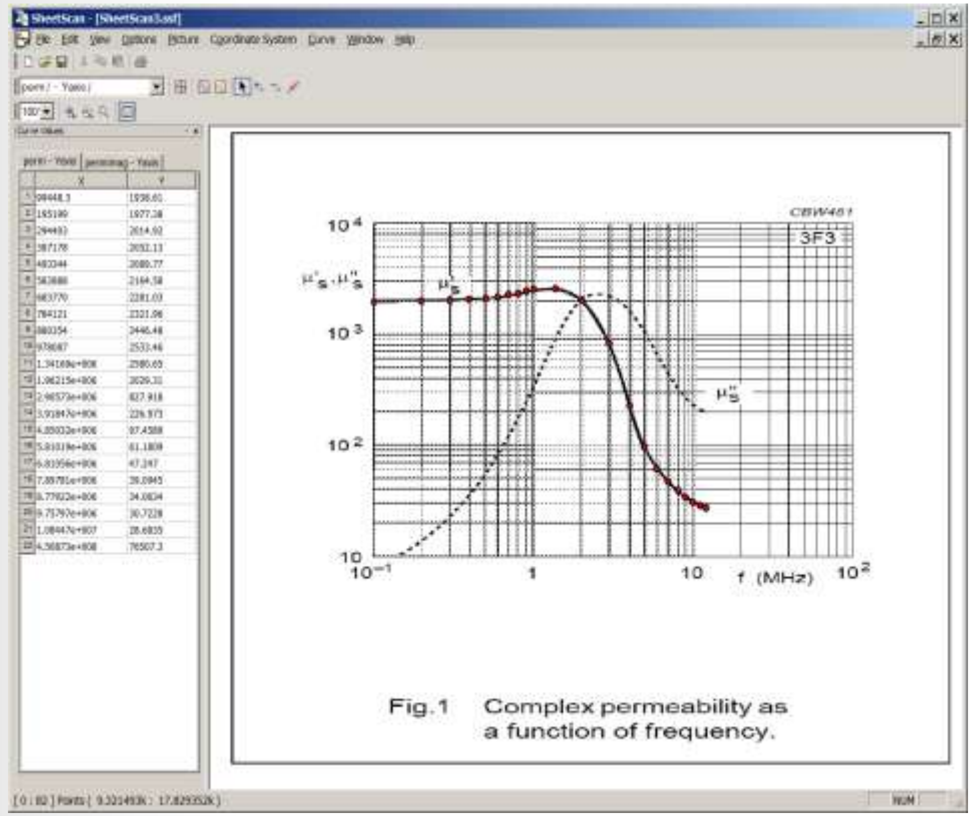



Fig.1 Complex permeability as a function of frequency.

Datasheet



Sheetscan

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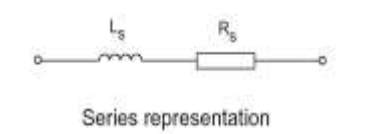
# Frequency Dependent Core Properties in Maxwell

**Required inputs for Maxwell are real permeability and loss tangent**

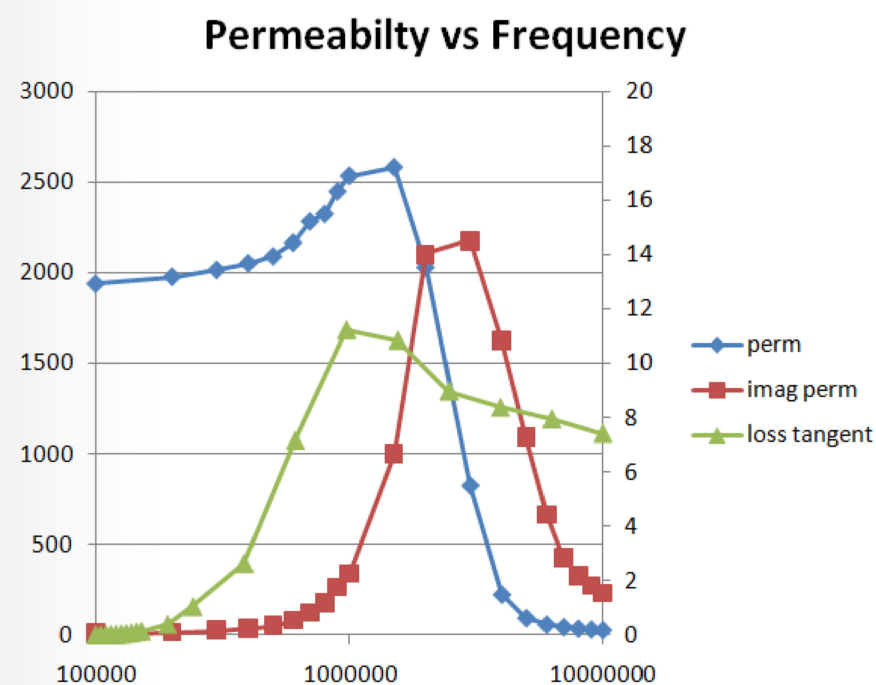
**Loss tangent based on series equivalent model**

$$\delta_s = \frac{\mu_s''}{\mu_s'} = \frac{R_s}{\omega L_s}$$




**Temp = 0 C**

| frequency | perm | perm_imag | loss tangent |
|---|---|---|---|
| 100000 | 1939 | 6 | 0.0032 |
| 200000 | 1977 | 13 | 0.0068 |
| 300000 | 2015 | 22 | 0.0110 |
| 400000 | 2052 | 35 | 0.0173 |
| 500000 | 2090 | 51 | 0.0244 |
| 600000 | 2165 | 79 | 0.0363 |
| 700000 | 2281 | 119 | 0.0522 |
| 800000 | 2322 | 174 | 0.0750 |
| 900000 | 2446 | 264 | 0.1078 |
| 1000000 | 2533 | 336 | 0.1326 |
| 1500000 | 2581 | 998 | 0.3869 |
| 2000000 | 2029 | 2101 | 1.0351 |
| 3000000 | 828 | 2178 | 2.6306 |
| 4000000 | 227 | 1626 | 7.1618 |
| 5000000 | 97 | 1093 | 11.2199 |
| 6000000 | 61 | 663 | 10.8398 |
| 7000000 | 47 | 424 | 8.9644 |
| 8000000 | 39 | 327 | 8.3658 |
| 9000000 | 34 | 271 | 7.9437 |
| 10000000 | 31 | 228 | 7.4132 |



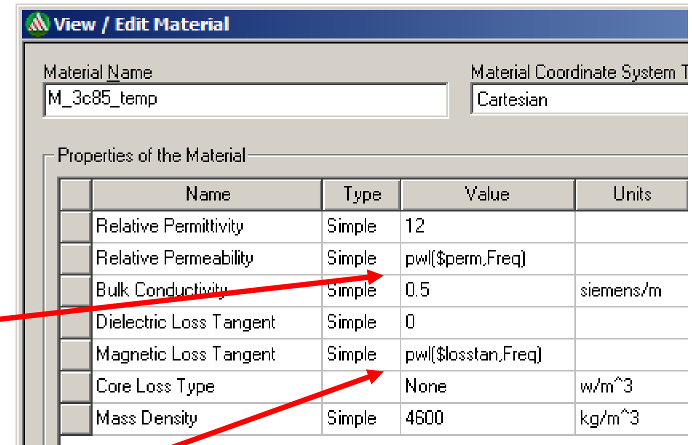
# Core Material Properties - Inputs

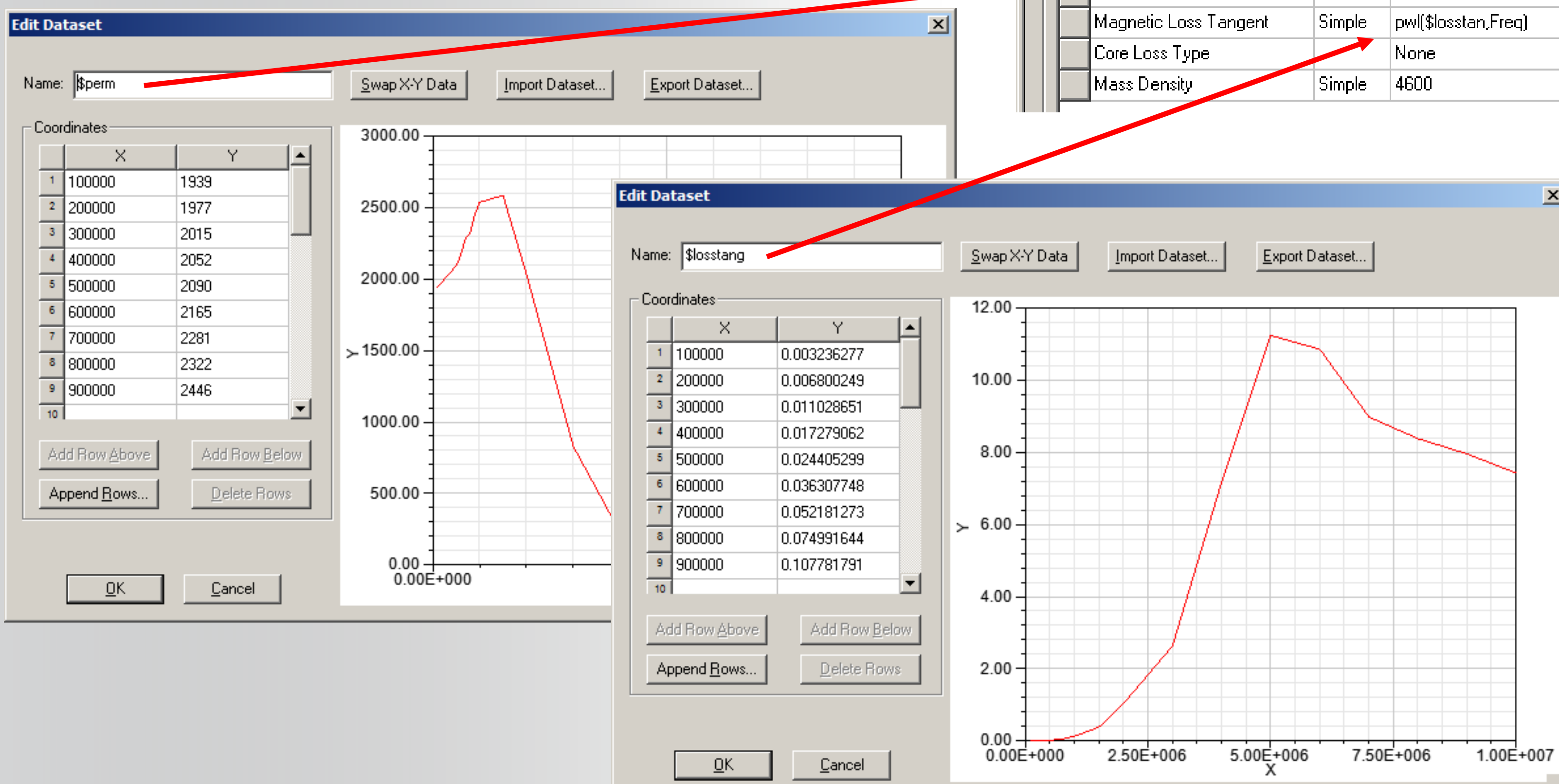
## Datasets used to define properties vs. frequency:

- Relative Permeability = pwl($perm,Freq)
- Magnetic Loss tangent = pwl($losstan,Freq)

## Relative permitivity = 12

## Conductivity = 0.5 (S/m)

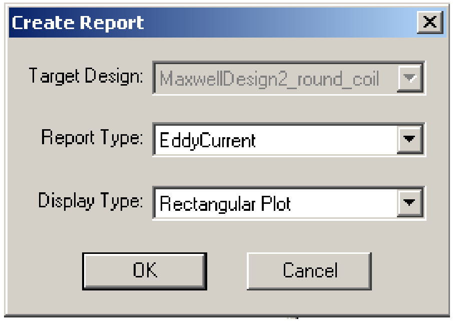


# Core Material Properties - Outputs

**Use "named expression" in calculator to verify the real and imaginary permeability**

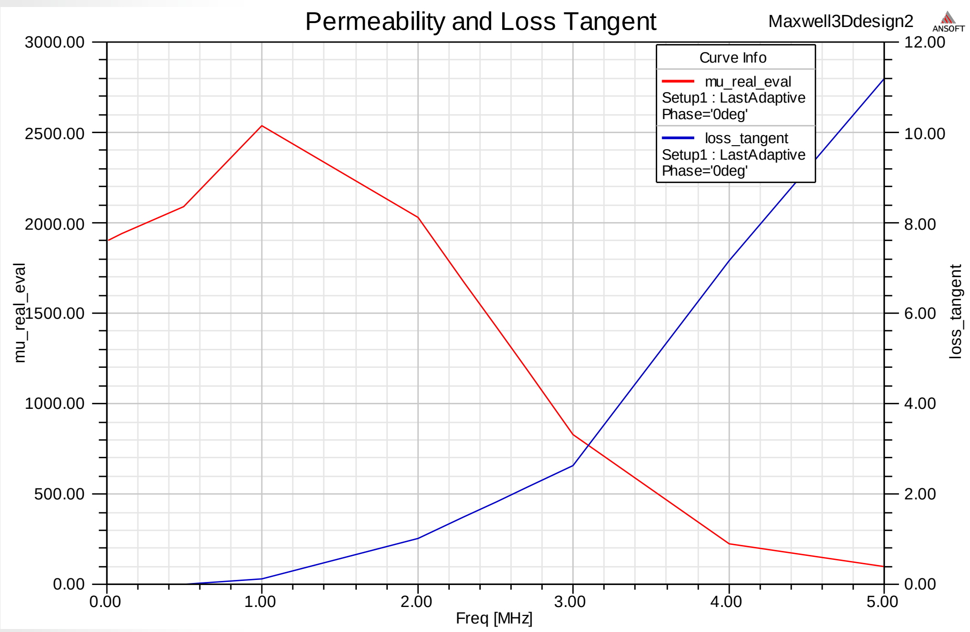
**Use report to plot μ' and loss tangent vs. frequency**




| Real permeability - μ' |
|---|
| Num > Vector > 1,0,0 |
| Material > perm > multiply |
| complex > real > mag |
| constant > mu0 > divide |

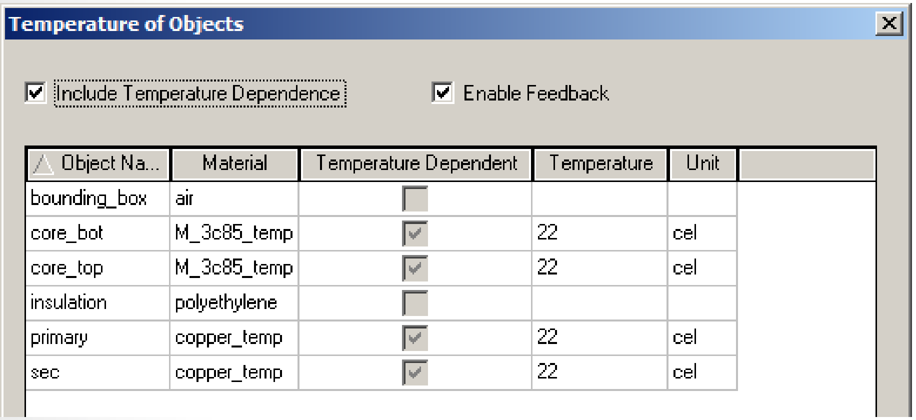
| Real permeability - μ" |
|---|
| Num > Vector > 1,0,0 |
| Material > perm > multiply |
| complex > imag > mag |
| constant > mu0 > divide |

| Loss tangent |
|---|
| δ = μ" / μ' |



# Temperature Settings in Maxwell

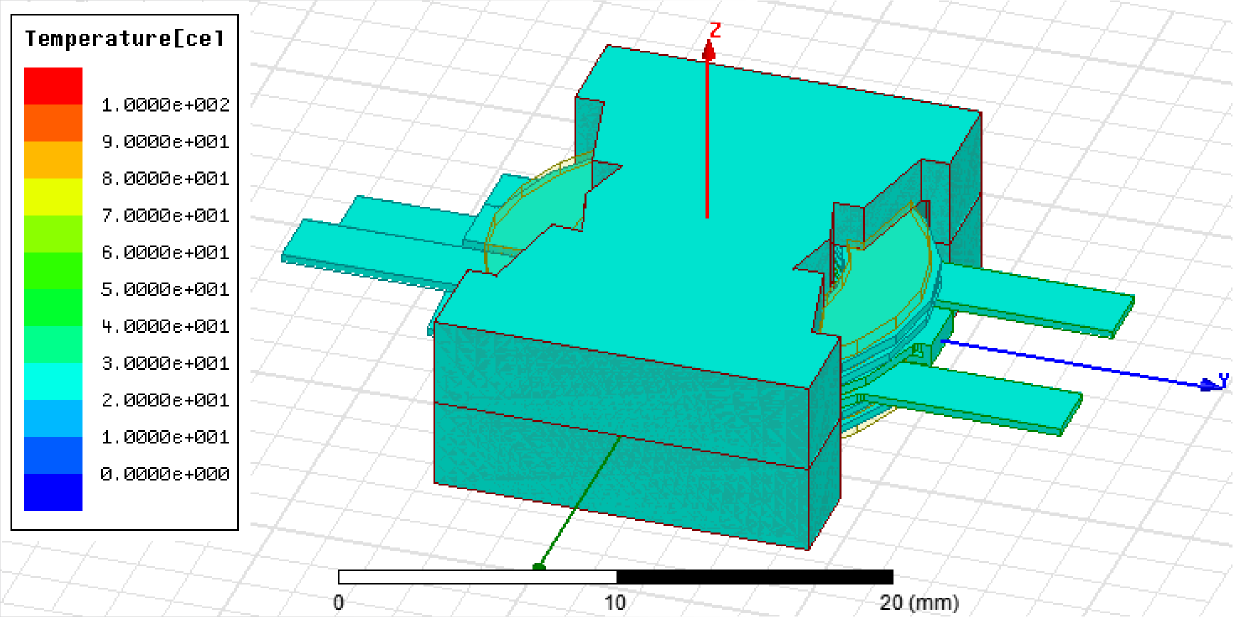
- Initial temperature = 22 C
- Core and windings have temp dependent materials



Temperature of Objects

☑ Include Temperature Dependence ☑ Enable Feedback

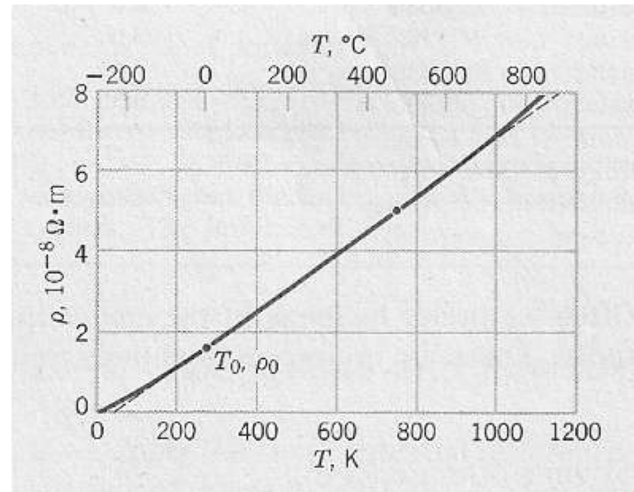
| Object Na... | Material | Temperature Dependent | Temperature | Unit |
|---|---|---|---|---|
| bounding_box | air | ☐ | | |
| core_bot | M_3c85_temp | ☑ | 22 | cel |
| core_top | M_3c85_temp | ☑ | 22 | cel |
| insulation | polyethylene | ☐ | | |
| primary | copper_temp | ☑ | 22 | cel |
| sec | copper_temp | ☑ | 22 | cel |

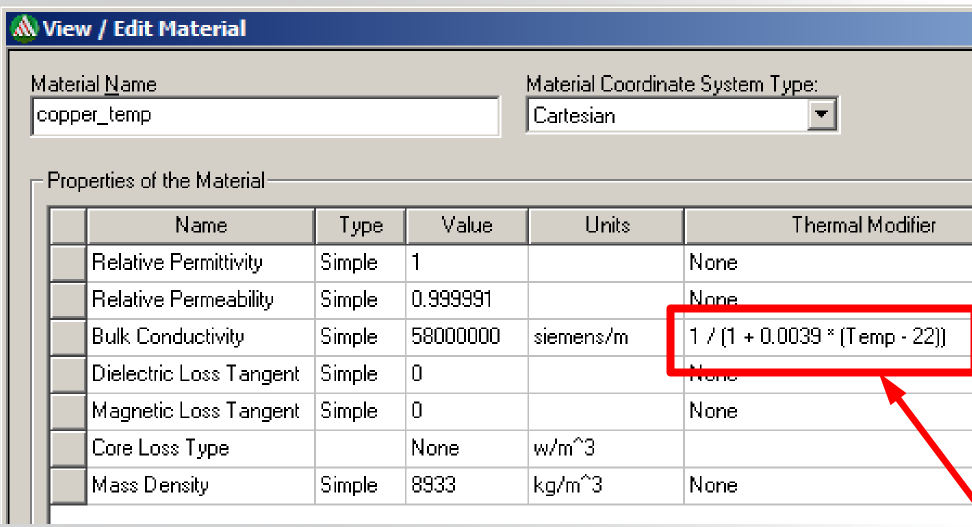


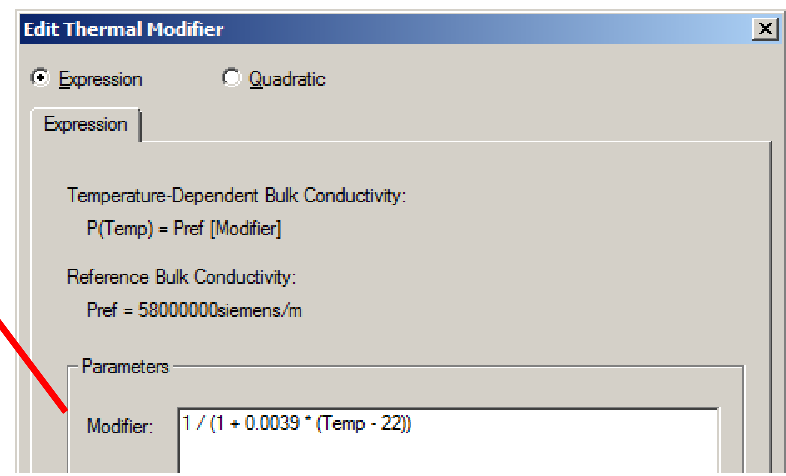
# Temperature dependent copper conductivity for 2-way coupling to Maxwell

$$\sigma = \frac{1}{(1+0.0039*(Temp-22))}$$



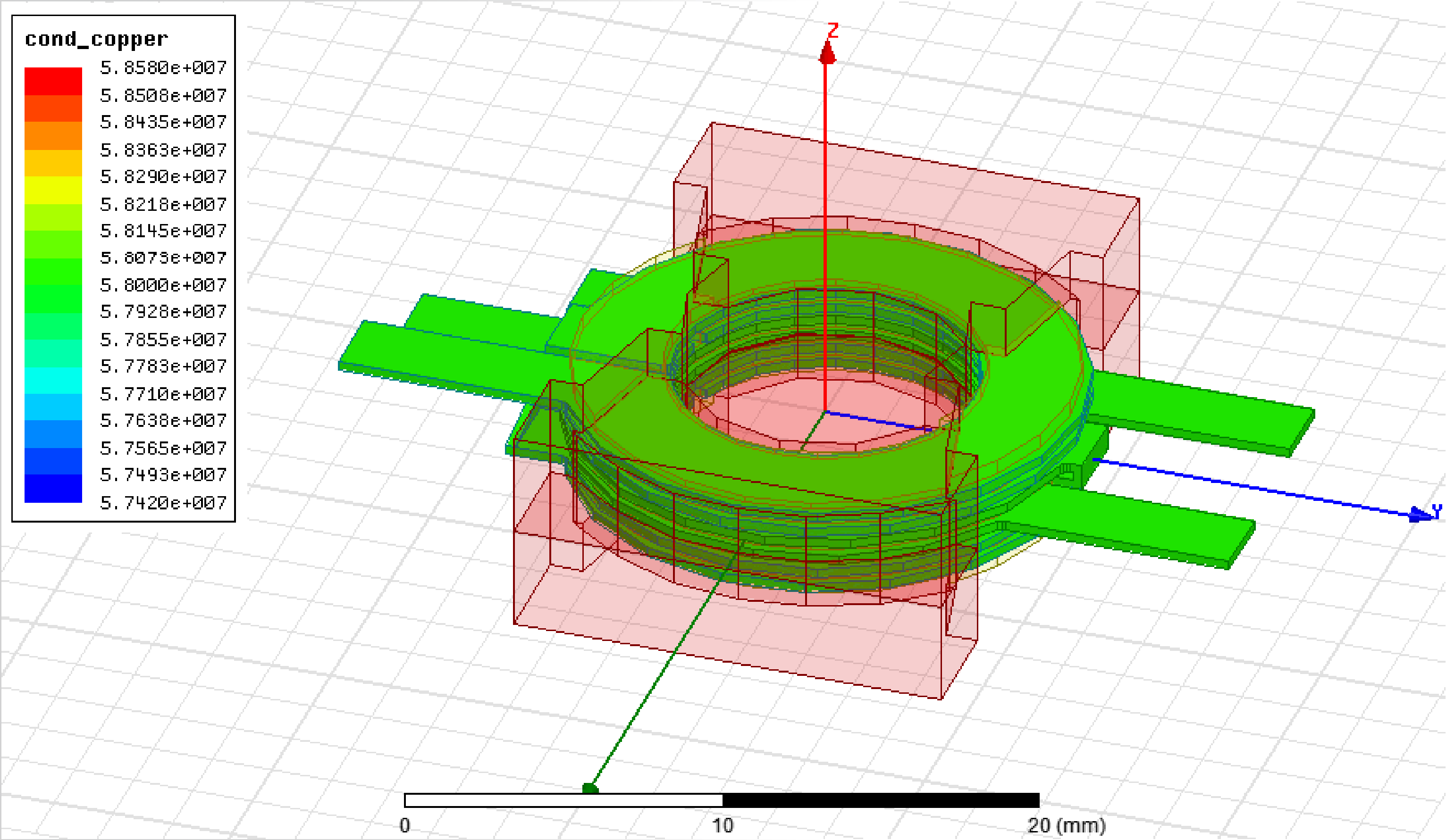




| Name | Type | Value | Units | Thermal Modifier |
|---|---|---|---|---|
| Relative Permittivity | Simple | 1 | | None |
| Relative Permeability | Simple | 0.999991 | | None |
| Bulk Conductivity | Simple | 58000000 | siemens/m | 1 / (1 + 0.0039 * (Temp - 22)) |
| Dielectric Loss Tangent | Simple | 0 | | None |
| Magnetic Loss Tangent | Simple | 0 | | None |
| Core Loss Type | | None | w/m^3 | |
| Mass Density | Simple | 8933 | kg/m^3 | None |



# Initial Conductivity at 100kHz, 22 deg C

- Conductivity = 5.8e$^7$ (S/m)
- Conductivity is constant throughout winding



# Temperature dependent ferrite permeability for 2-way coupling to Maxwell

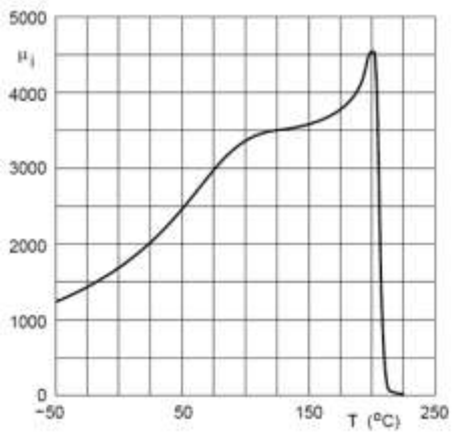
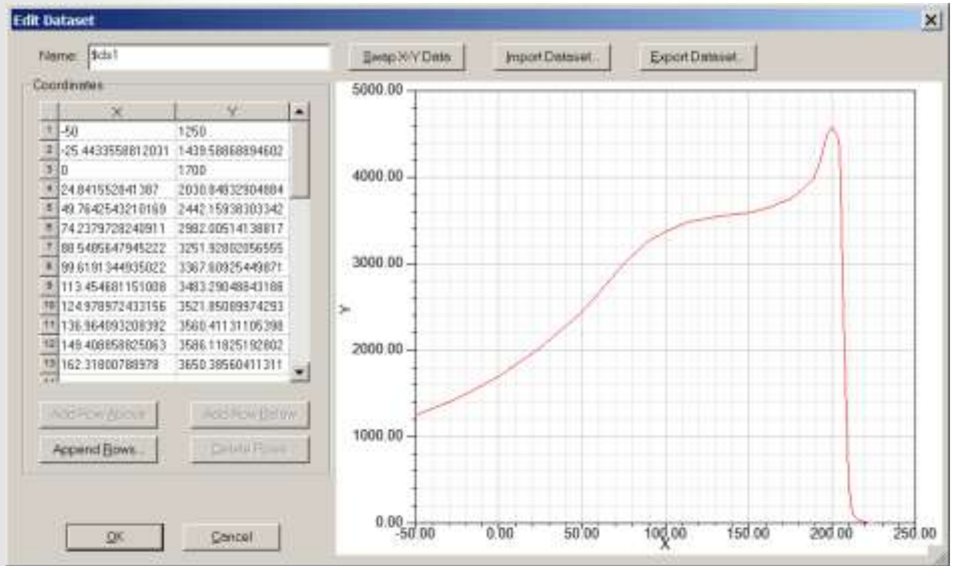
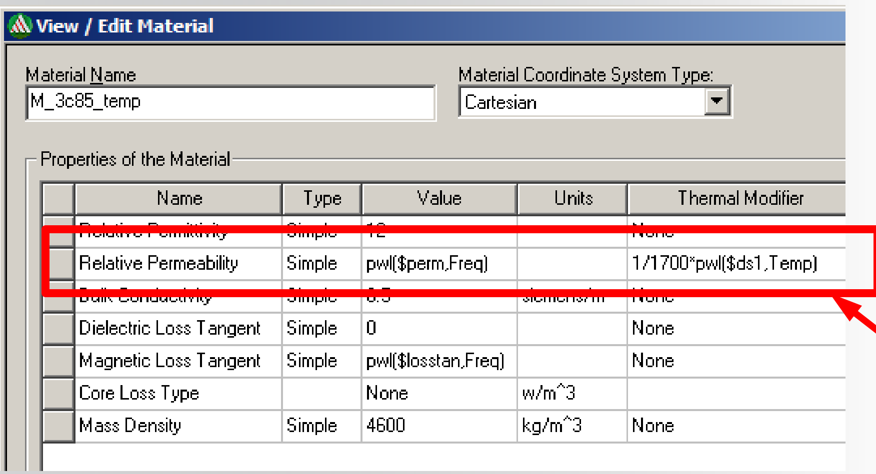
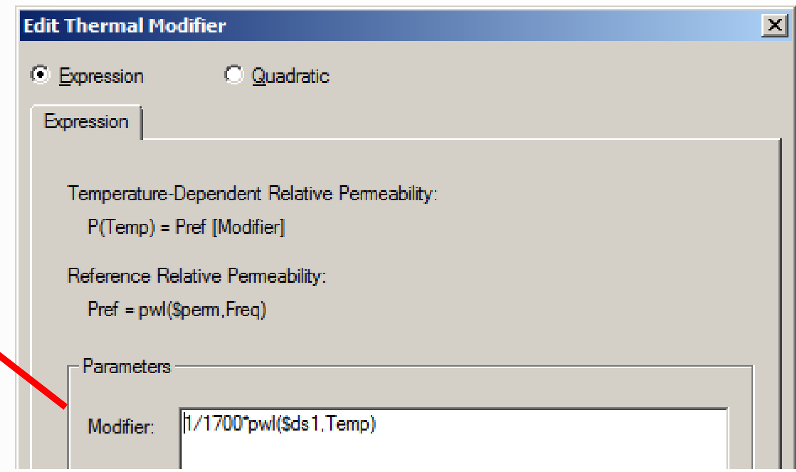



Fig.2 Initial permeability as a function of temperature.



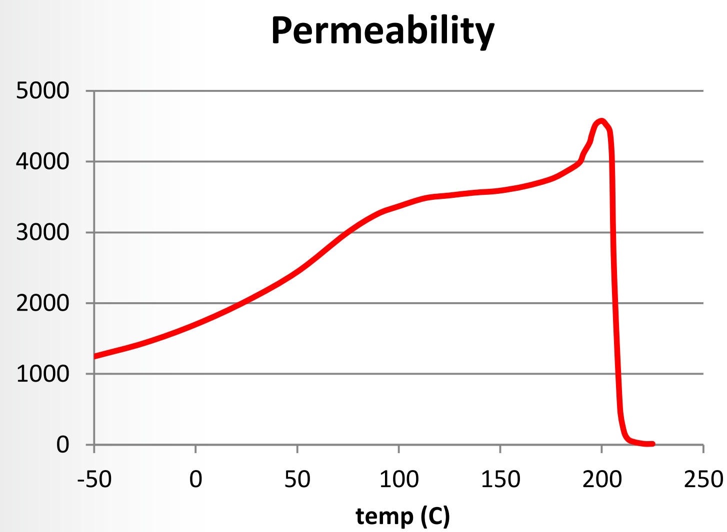

| | Name | Type | Value | Units | Thermal Modifier |
|---|---|---|---|---|---|
| | Relative Permittivity | Simple | 12 | | None |
| | Relative Permeability | Simple | pwl($perm,Freq) | | 1/1700*pwl($ds1,Temp) |
| | Bulk Conductivity | Simple | 0.5 | siemens/m | None |
| | Dielectric Loss Tangent | Simple | 0 | | None |
| | Magnetic Loss Tangent | Simple | pwl($losstan,Freq) | | None |
| | Core Loss Type | | None | w/m^3 | |
| | Mass Density | Simple | 4600 | kg/m^3 | None |

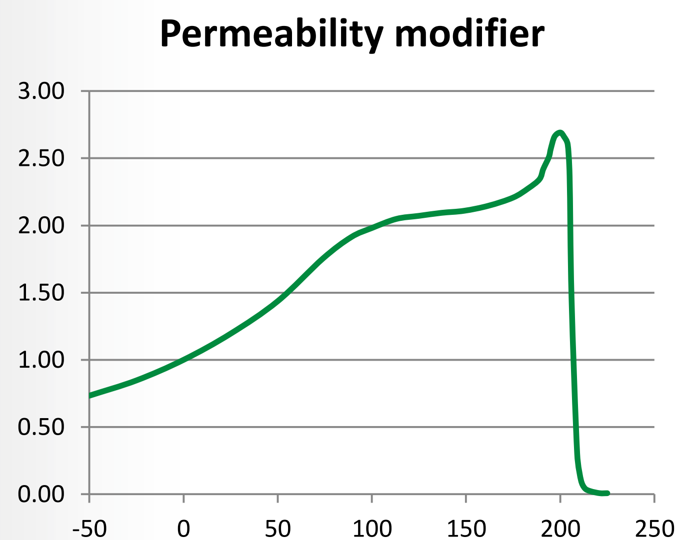


# 2-way coupling for temperature dependent permeability

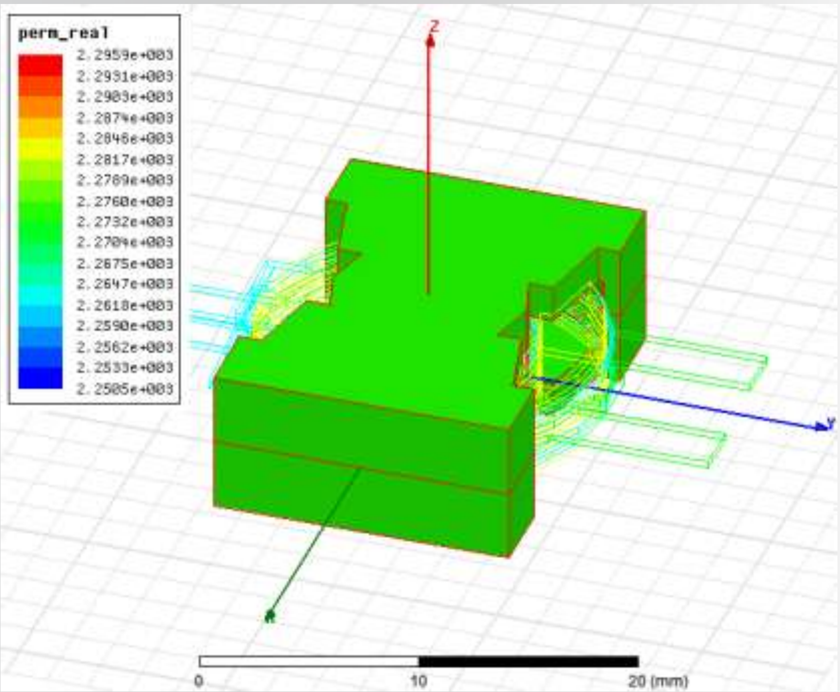
| deg C | perm | perm modifier |
|---|---|---|
| -50 | 1247 | 0.73 |
| -25 | 1440 | 0.85 |
| 0 | 1700 | 1.00 |
| 25 | 2031 | 1.19 |
| 50 | 2442 | 1.44 |
| 74 | 2982 | 1.75 |
| 89 | 3252 | 1.91 |
| 100 | 3368 | 1.98 |
| 113 | 3483 | 2.05 |
| 125 | 3522 | 2.07 |
| 137 | 3560 | 2.09 |
| 149 | 3586 | 2.11 |
| 162 | 3650 | 2.15 |
| 175 | 3753 | 2.21 |
| 183 | 3869 | 2.28 |
| 189 | 3985 | 2.34 |
| 191 | 4113 | 2.42 |
| 194 | 4267 | 2.51 |
| 195 | 4370 | 2.57 |
| 197 | 4524 | 2.66 |
| 200 | 4576 | 2.69 |
| 202 | 4524 | 2.66 |
| 204 | 4422 | 2.60 |
| 205 | 4023 | 2.37 |
| 206 | 2494 | 1.47 |
| 209 | 514 | 0.30 |
| 211 | 180 | 0.11 |
| 213 | 77 | 0.05 |
| 216 | 39 | 0.02 |
| 221 | 13 | 0.01 |
| 225 | 13 | 0.01 |



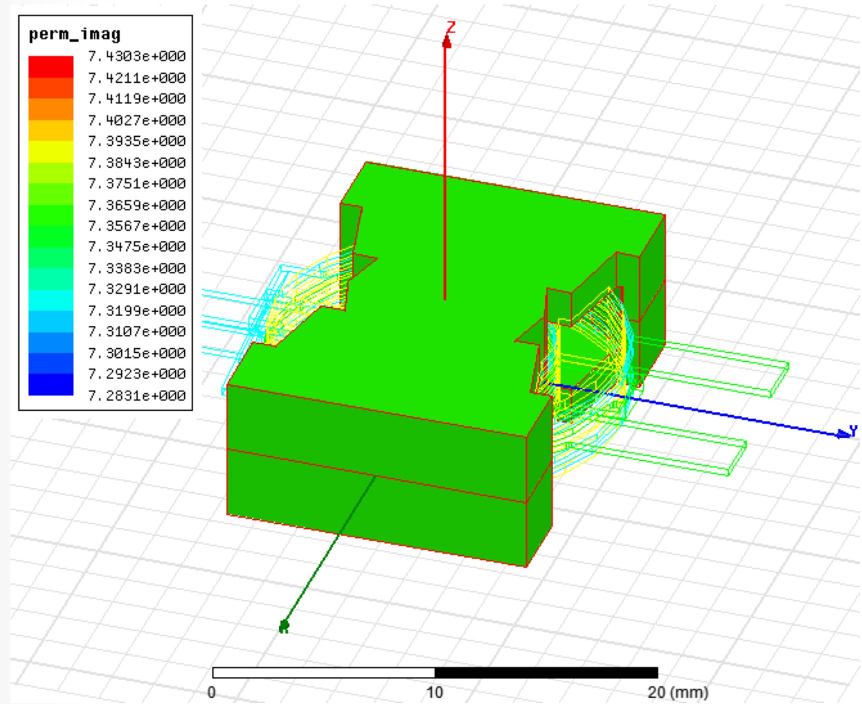



# Initial Permeability at 100kHz, 22 deg C




Real Permeability

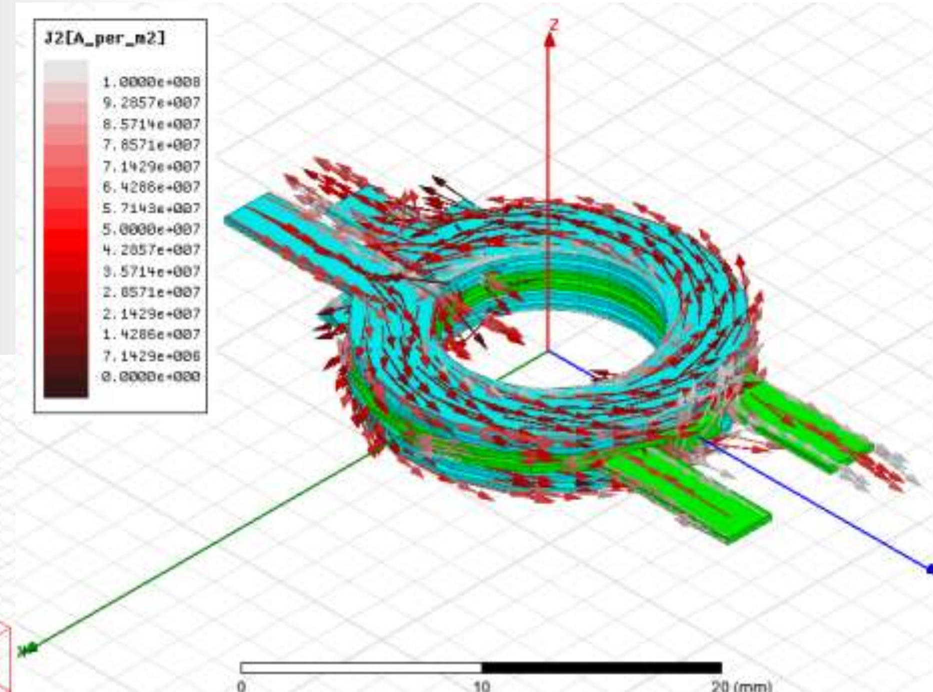


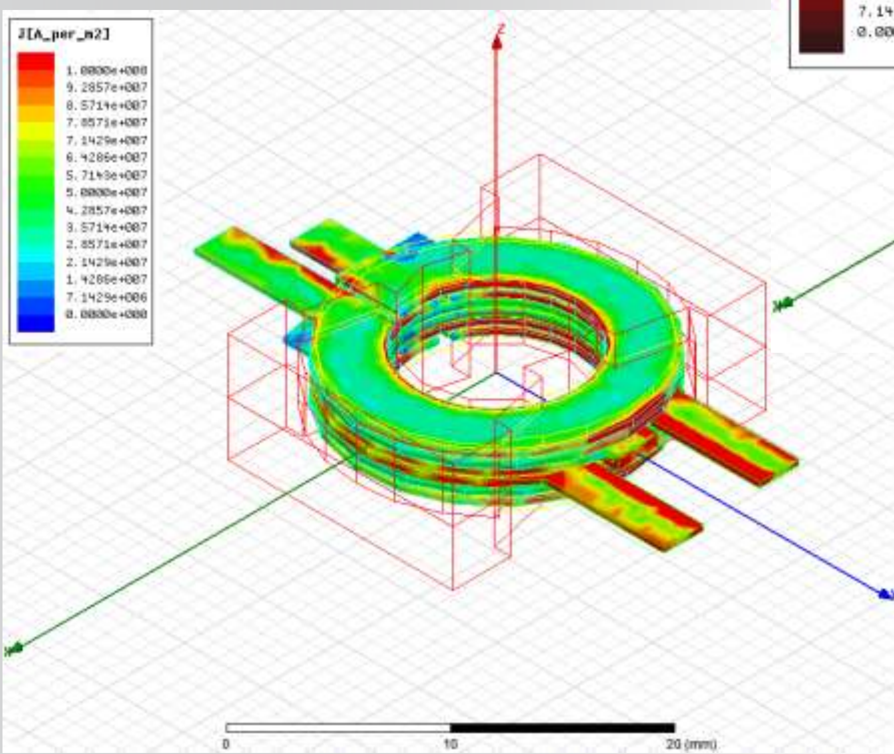

Imaginary Permeability

# Current Density at 100kHz, 22 deg C

- **Load case with Ipri = 50A and Isec = 80A**

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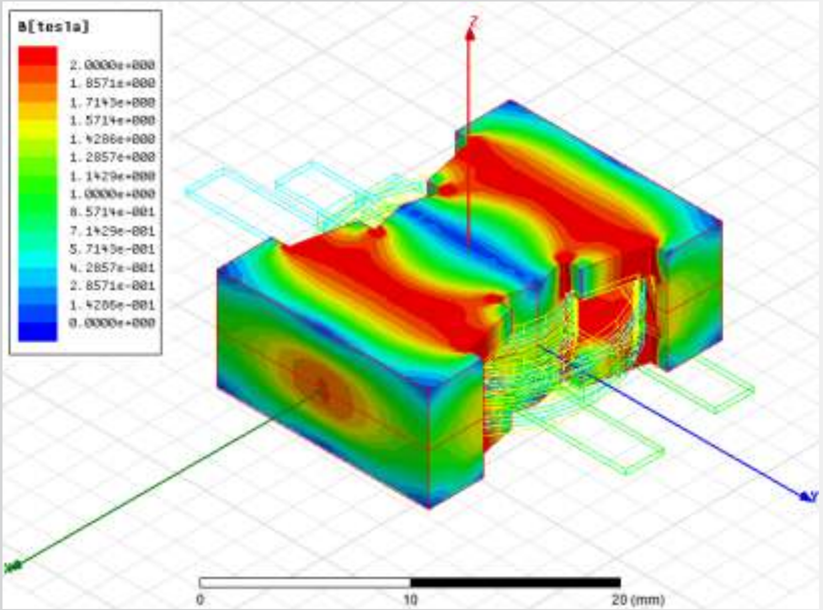
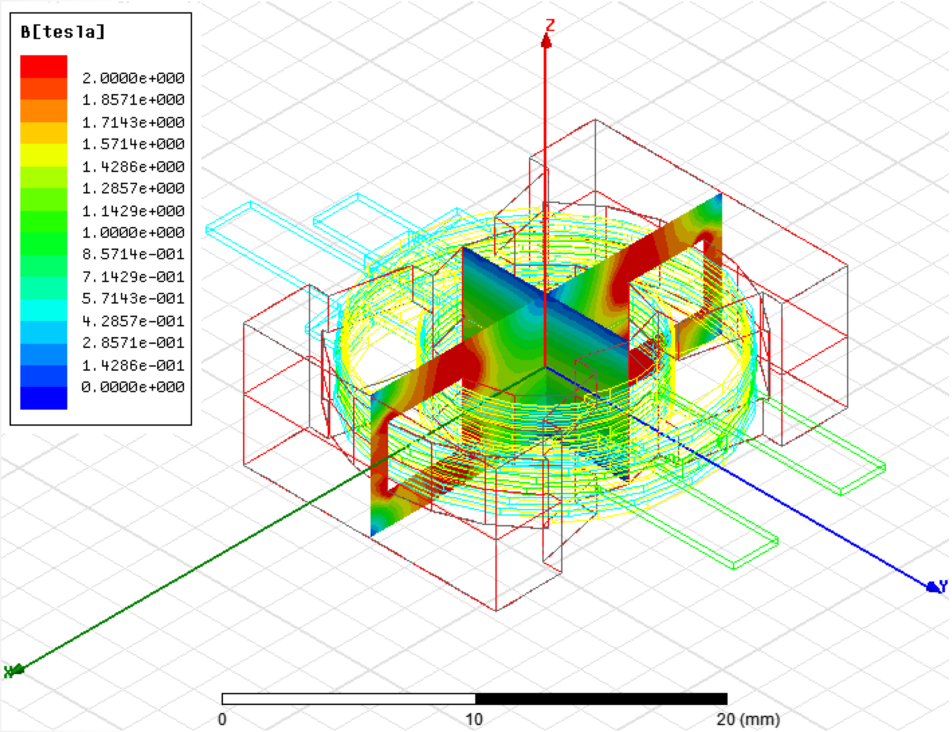
# Magnetic Flux Density at 100kHz, 22 deg C

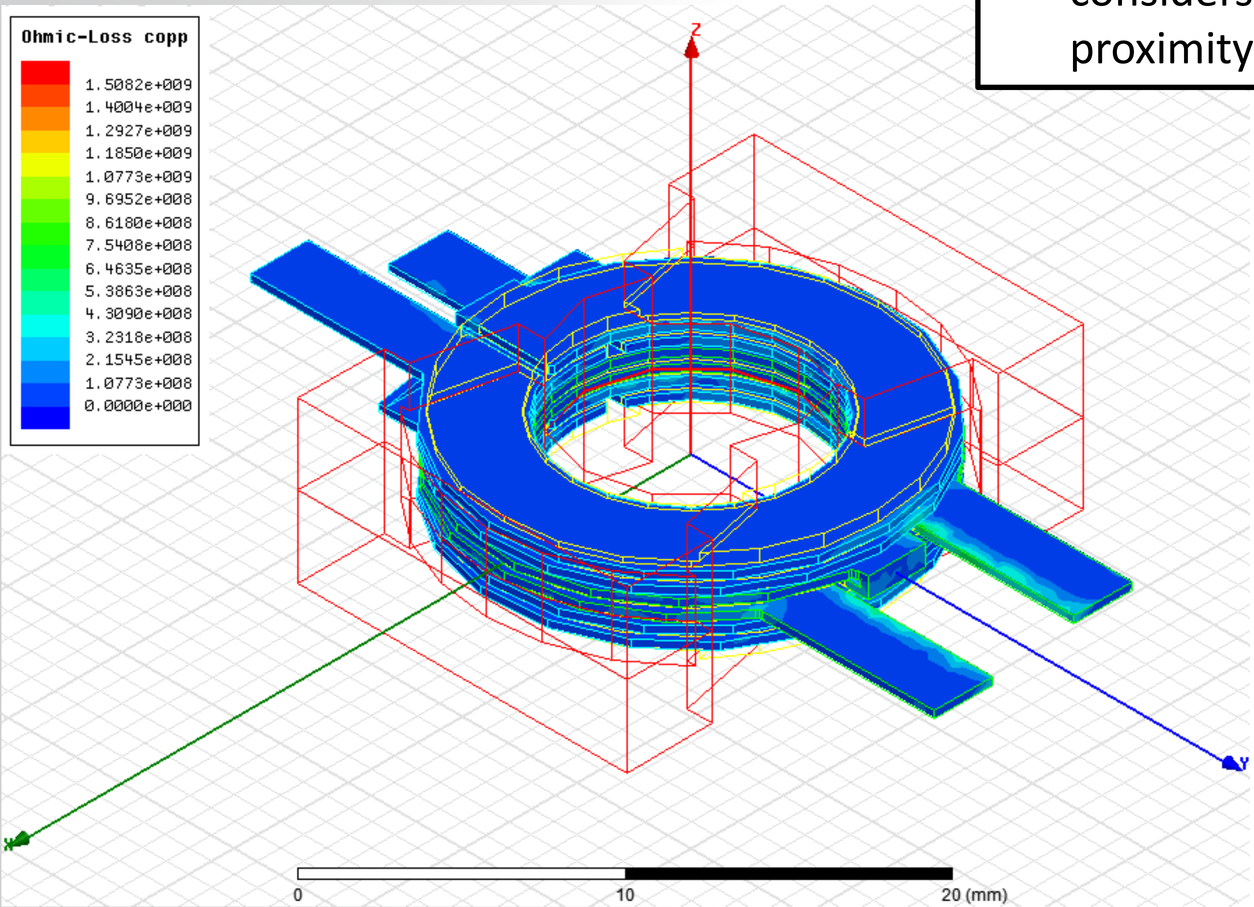


# Winding Eddy Current Loss Density at 100kHz, 22 deg C

Winding losses considers skin and proximity effects

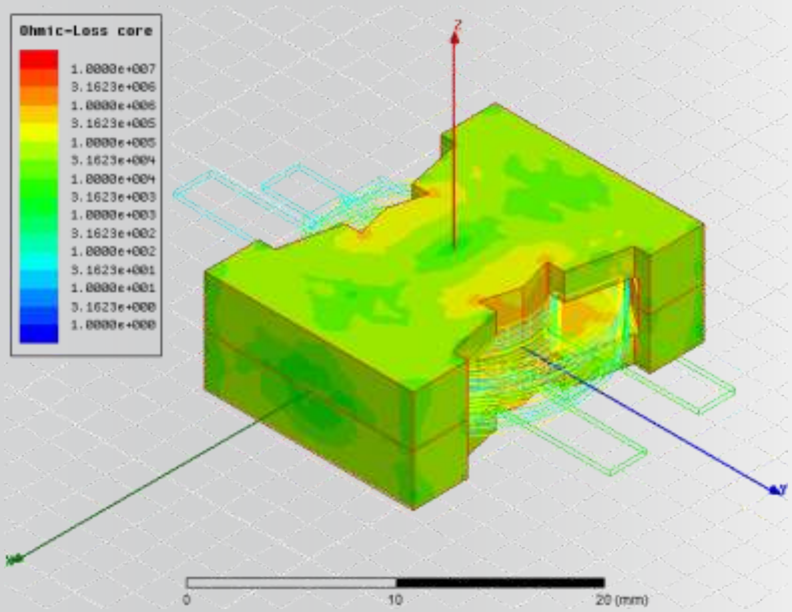


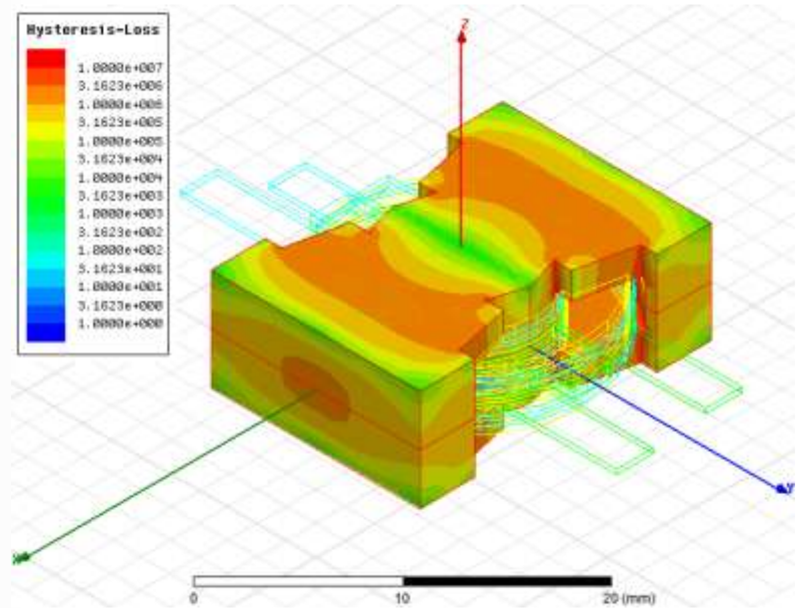
# Core Loss Density at 100kHz, 22 deg C

$$P_{eddy} = \frac{1}{2\sigma} \iiint_{vol} \mathrm{Re}\left(\vec{J} \bullet \vec{J}^*\right) dV$$

$$P_{hysteresis} = -\frac{1}{2}\omega \iiint_{vol} \mathrm{Im}\left(\vec{B} \bullet \vec{H}^*\right) dV$$




Ohmic Loss



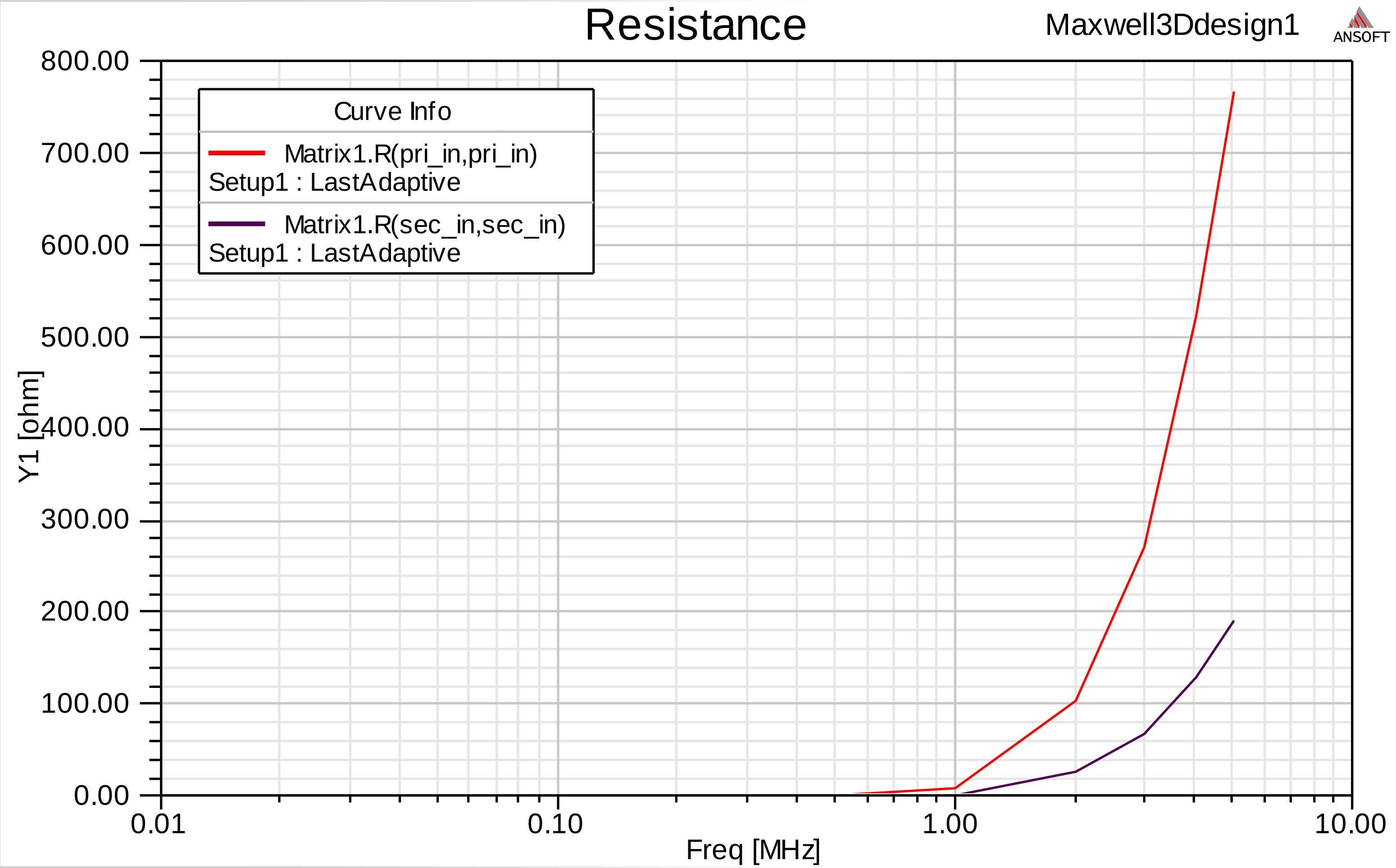

Hysteresis Loss

core hyster eddy losses

| | Freq [kHz] | core_hyster_loss Setup1 : LastAdaptive Phase='0deg' | core_eddy_loss Setup1 : LastAdaptive Phase='0deg' |
|---|---|---|---|
| 1 | 10.000000 | 0.001082 | 0.001897 |
| 2 | 100.000000 | 1.211527 | 0.191875 |
| 3 | 500.000000 | 44.428733 | 5.032800 |

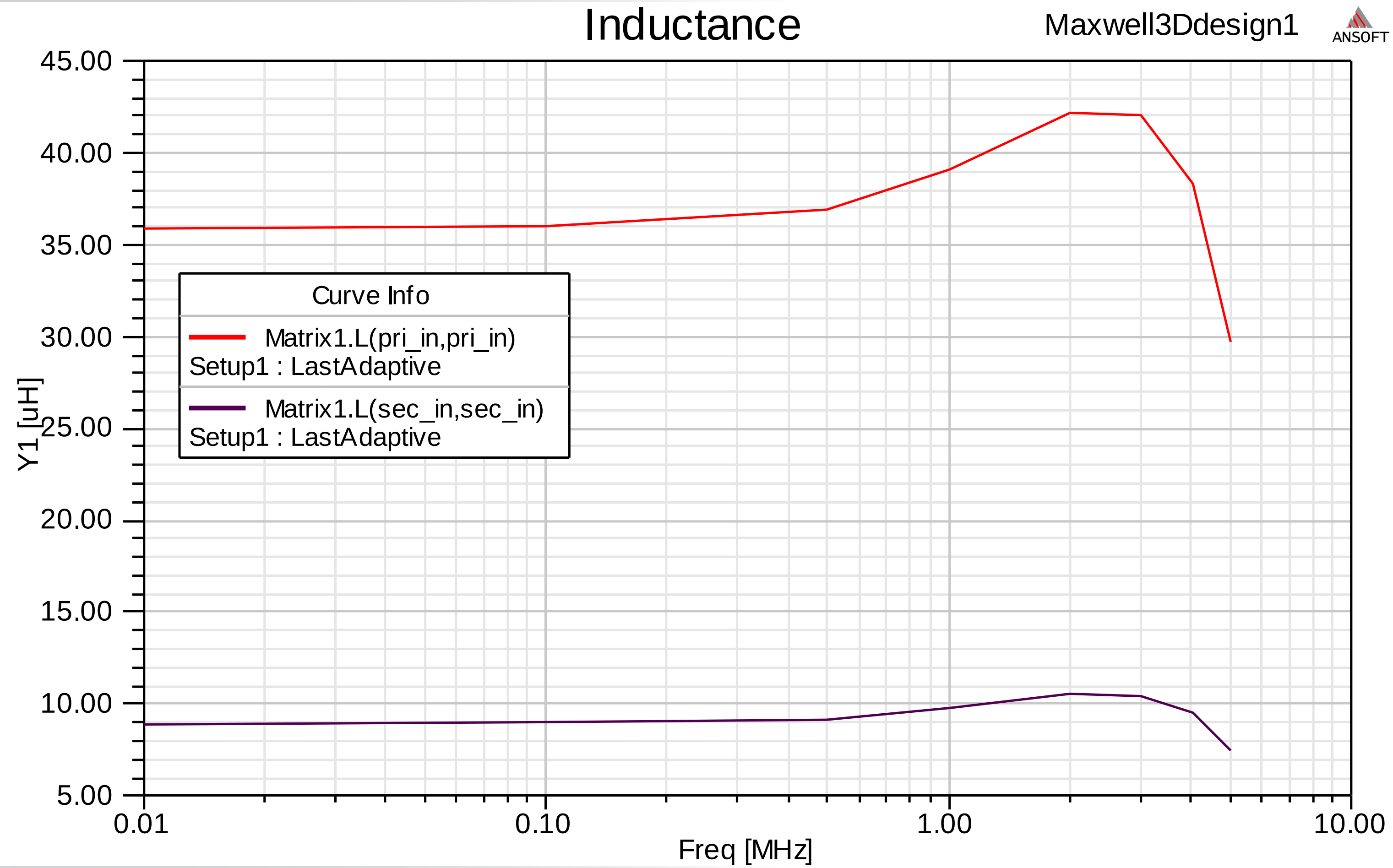
  

# Simulated Resistance, 22 deg C



# Simulated Inductance, 22 deg C

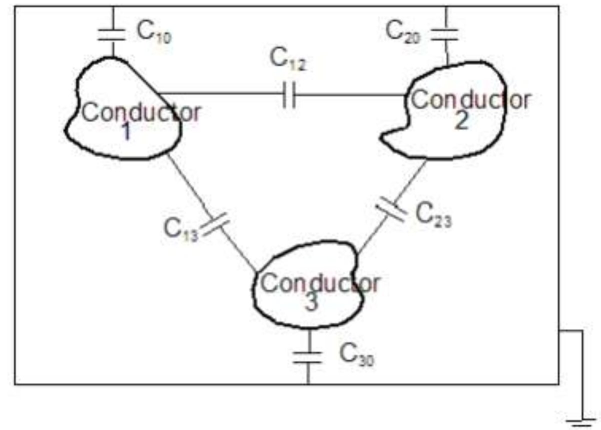


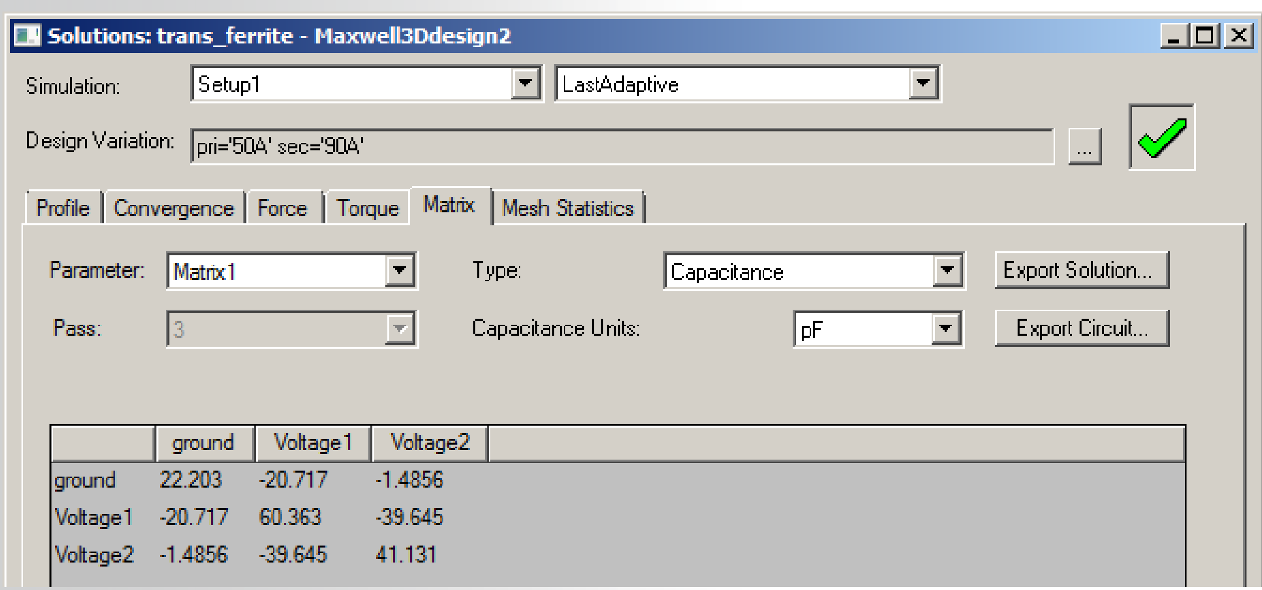

  

# Simulated Capacitance

**Use DC conduction solver to assign +1V and -1V to coils and on core**

$$\begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \end{bmatrix} = \begin{bmatrix} C_{10}+C_{12}+C_{13} & -C_{12} & -C_{13} \\ -C_{12} & C_{20}+C_{12}+C_{23} & -C_{23} \\ -C_{13} & -C_{23} & C_{30}+C_{13}+C_{23} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$



Solutions: trans_ferrite - Maxwell3Ddesign2

Simulation: Setup1 LastAdaptive

Design Variation: pri='50A' sec='90A'

Profile | Convergence | Force | Torque | Matrix | Mesh Statistics

Parameter: Matrix1 Type: Capacitance Export Solution...

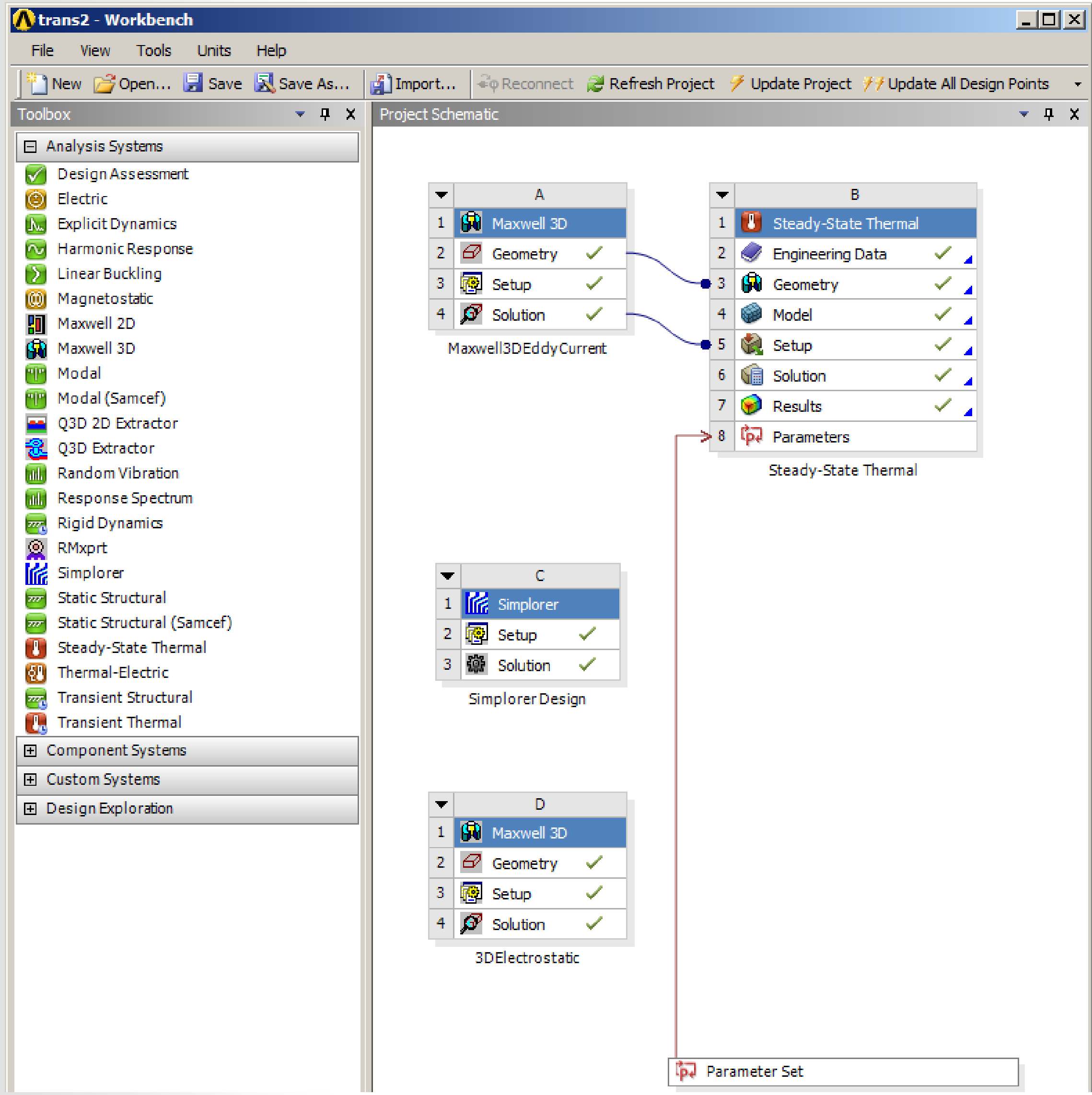
Pass: 3 Capacitance Units: pF Export Circuit...

| | ground | Voltage1 | Voltage2 |
|---|---|---|---|
| ground | 22.203 | -20.717 | -1.4856 |
| Voltage1 | -20.717 | 60.363 | -39.645 |
| Voltage2 | -1.4856 | -39.645 | 41.131 |

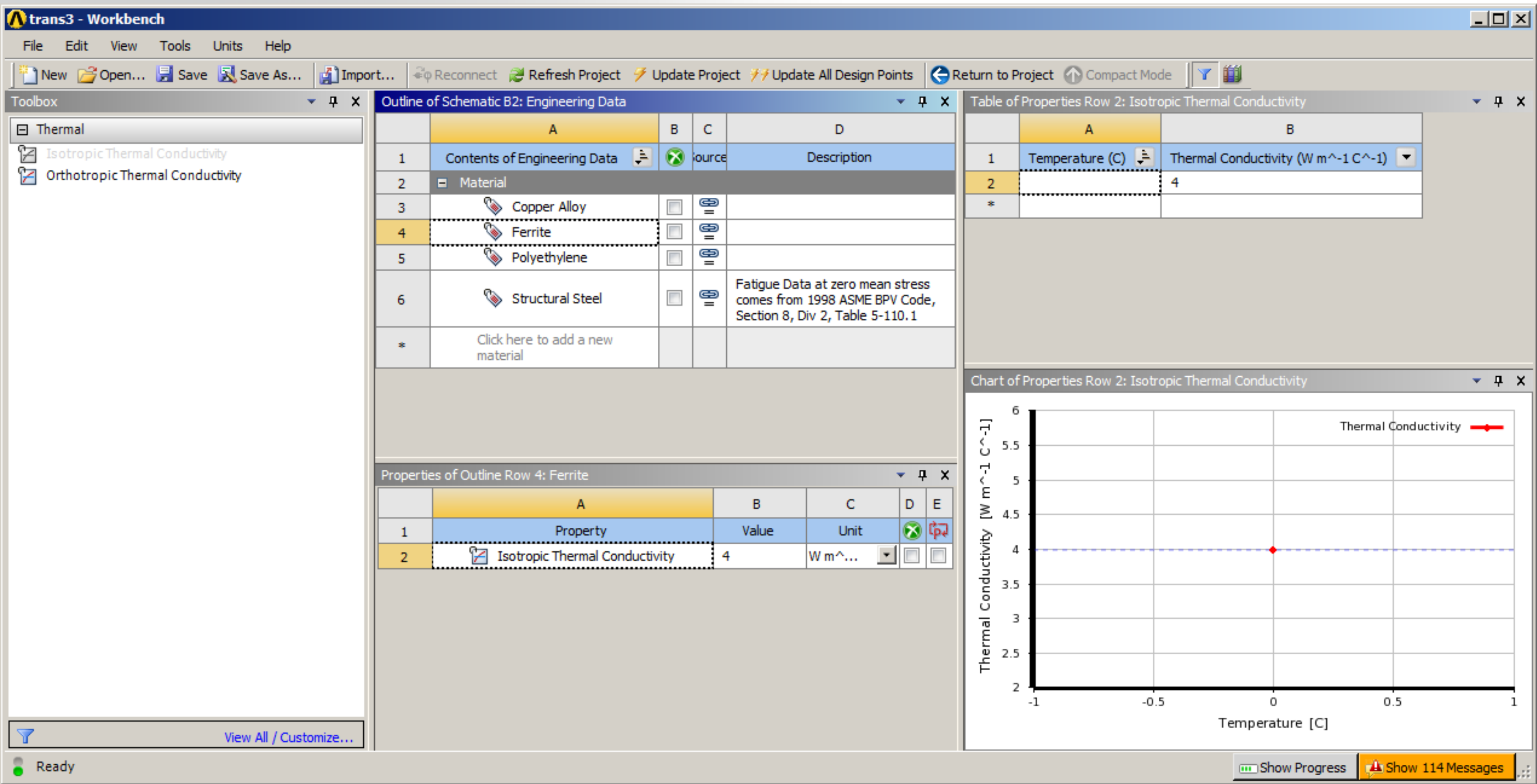
# Workbench Coupling

- Maxwell 3D Eddy Current calculates losses and couples directly to ANSYS thermal
- Maxwell 3D Electrostatic calculates capacitances between winding and core
- Maxwell 3D Eddy Current calculates R,L vs. frequency and inports directly into Simplorer via the State-space dynamic link



# Workbench Coupling

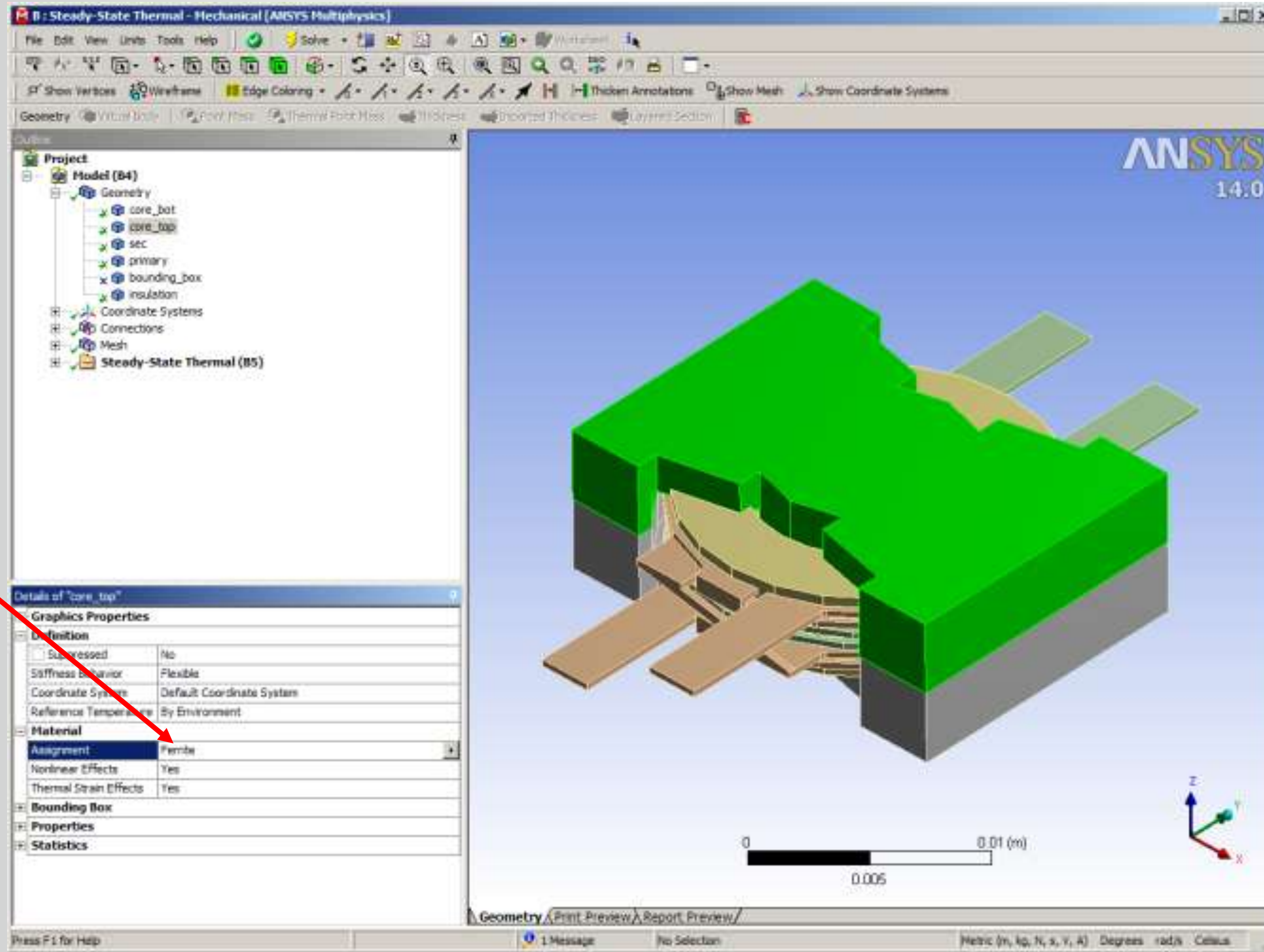
**Engineering Data allows materials to be chosen including thermal conductivity**



# Workbench Coupling

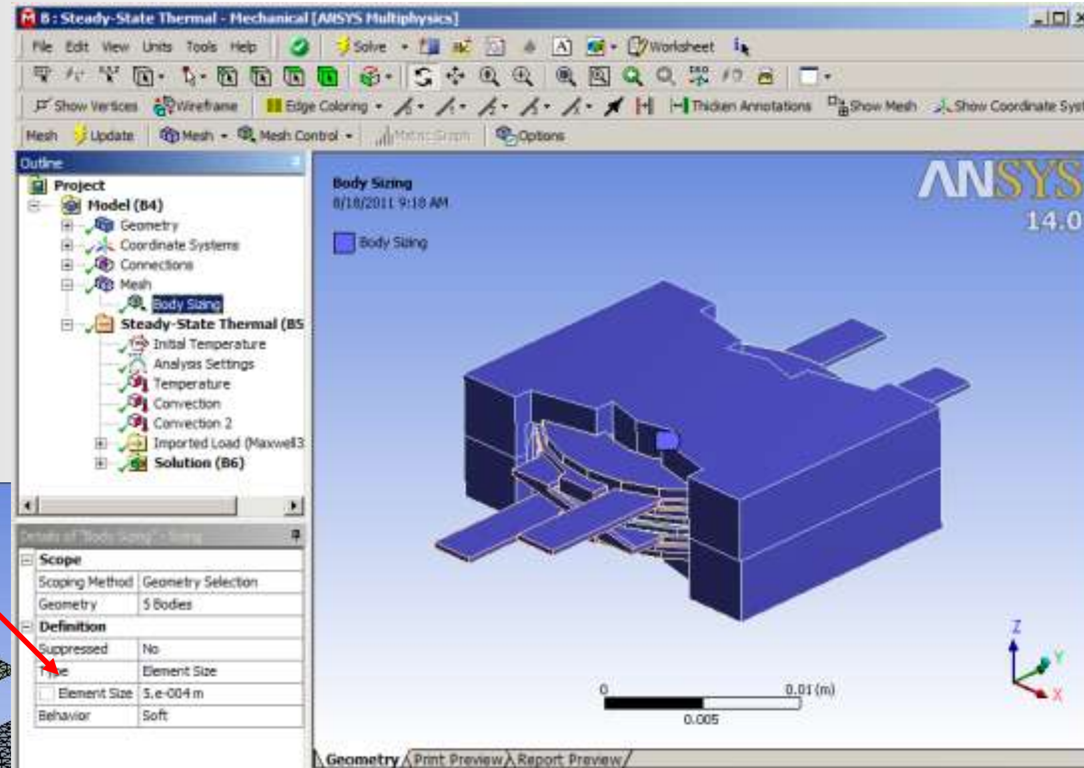
- Workbench geometry imported directly into Workbench
- Appropriate materials can then be assigned

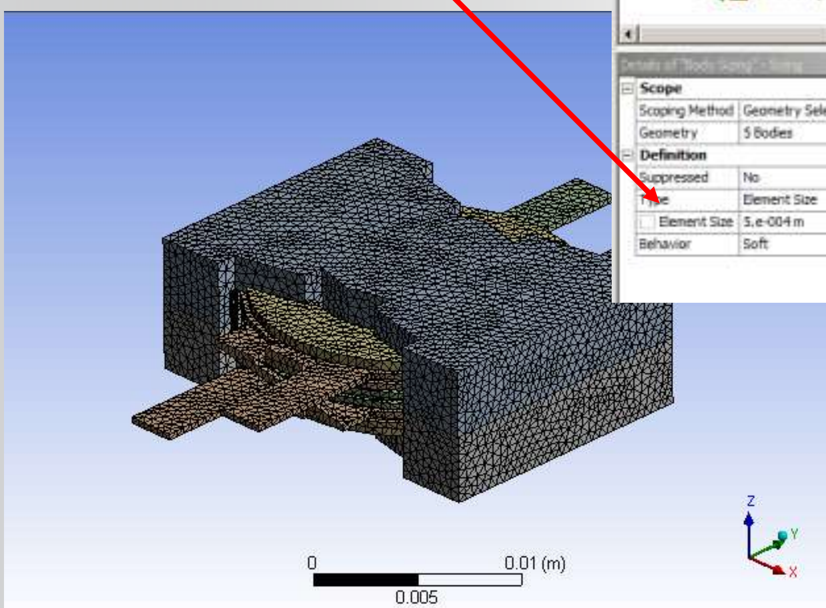


# Workbench Coupling

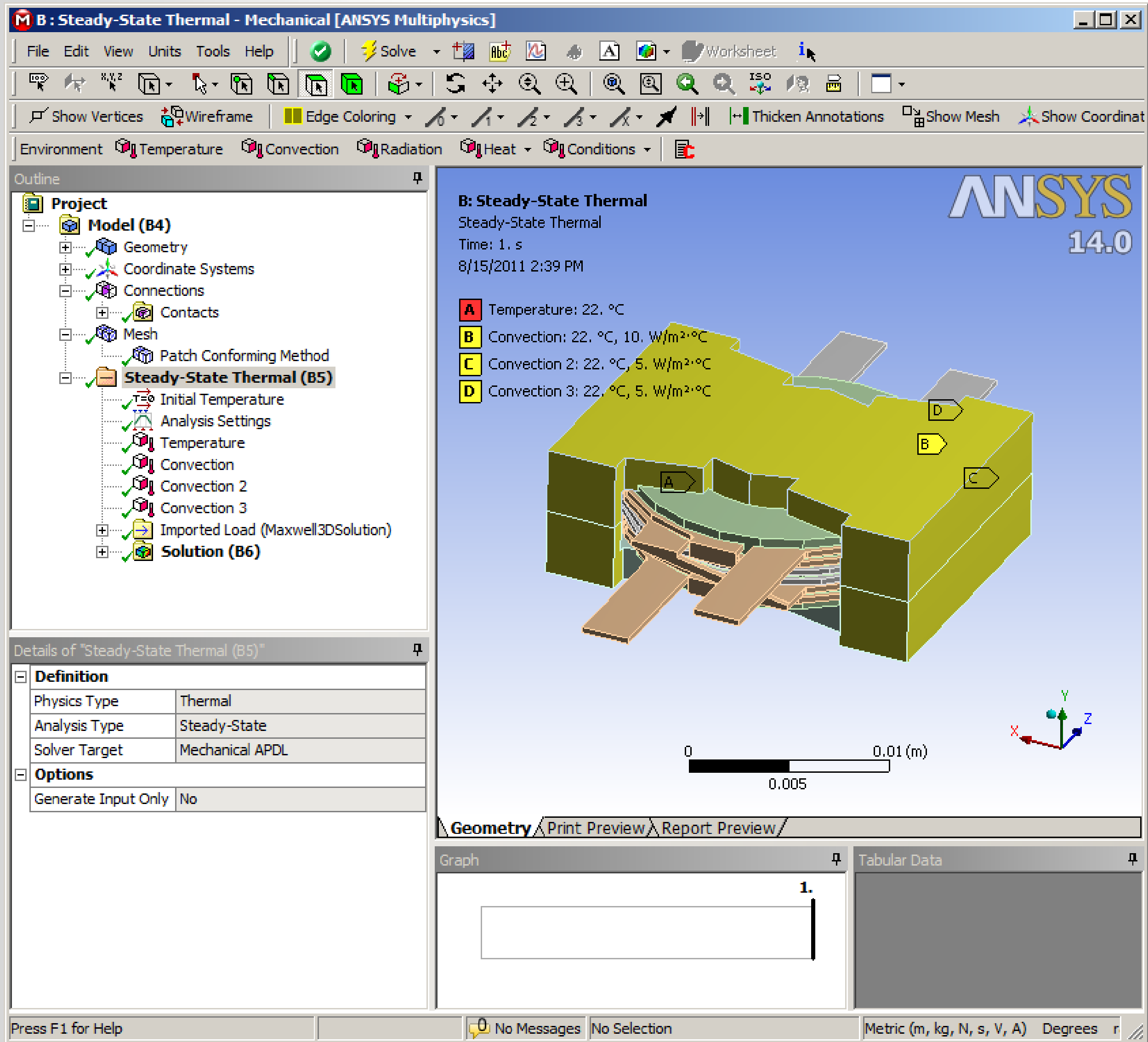
- Workbench mesh is different than Maxwell 3D mesh
- Set maximum element size = 0.5mm



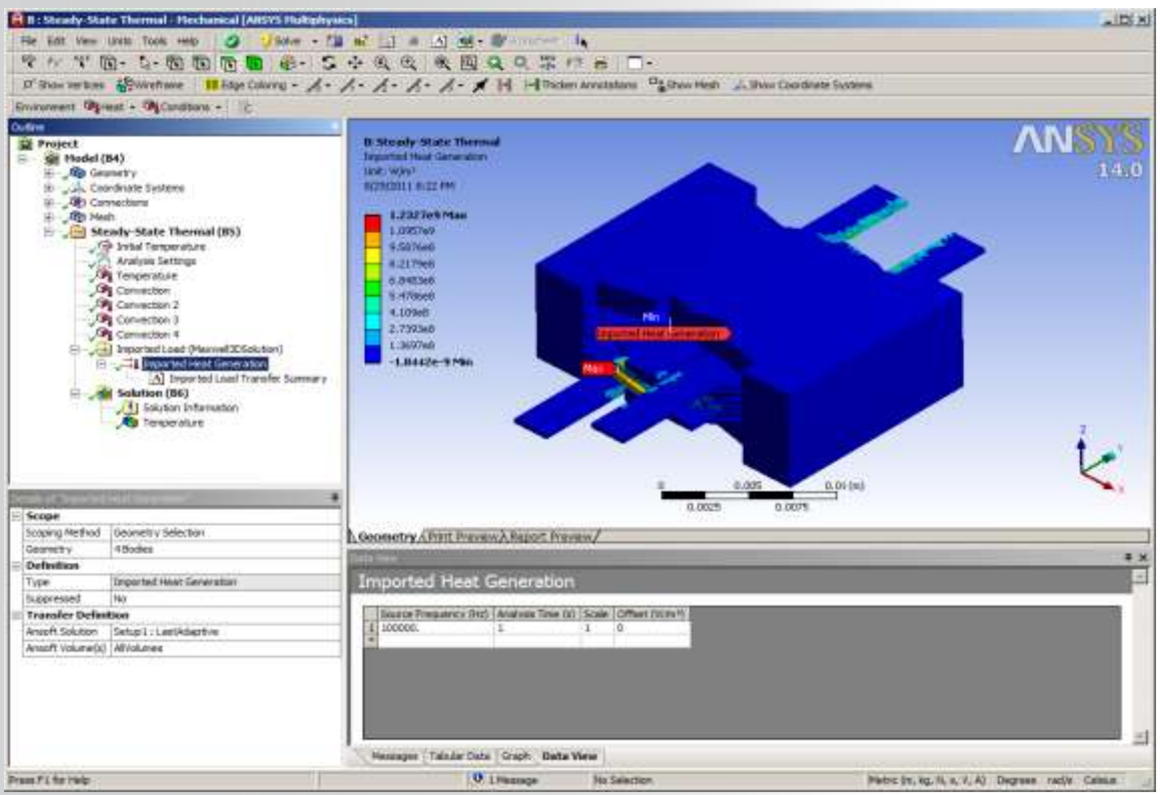
# ANSYS Workbench Coupling

- Fixed temperature cold plate assigned to base = 22 C
- Convection boundaries assigned to outer surfaces of core and coils = 5 $W/m^2$- C



# Workbench Coupling

- Imported Loss Density on core and windings at 100kHz
- Scaling Factor approximately ~ 1 indicates sufficient mesh and excellent loss mapping from Maxwell into Workbench




Exported loss density from Maxwell 3D

| | 1 |
|---|---|
| Freq [kHz] | 100.000000 |
| core_loss_bot<br>Setup1 : LastAdaptive<br>Phase='0deg' | 0.702112 |
| core_loss_top<br>Setup1 : LastAdaptive<br>Phase='0deg' | 0.701290 |
| sec_loss<br>Setup1 : LastAdaptive<br>Phase='0deg' | 6.712708 |
| pri_loss<br>Setup1 : LastAdaptive<br>Phase='0deg' | 6.657984 |

Exporting Volume Loss Density...

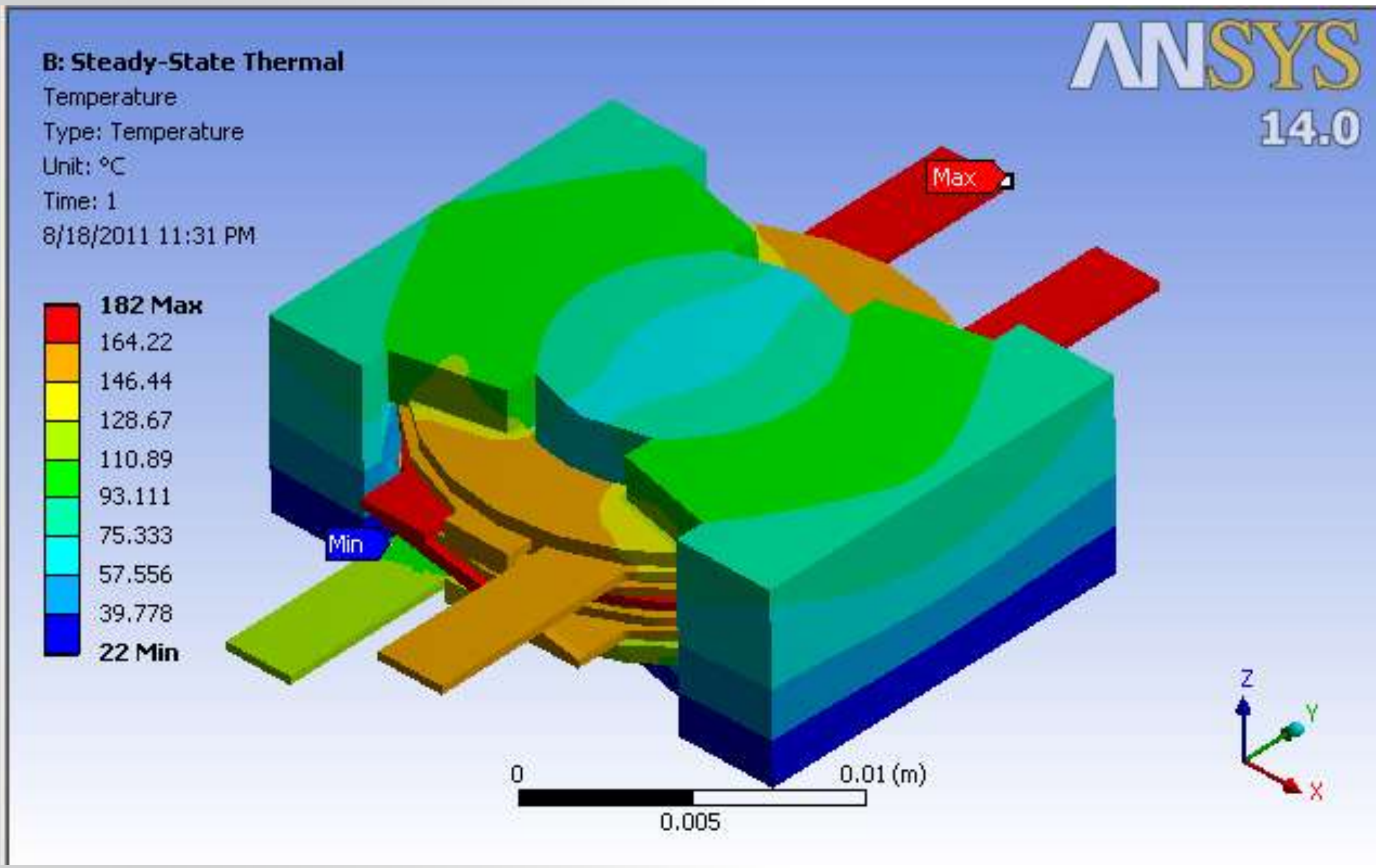
| Object | Total Loss | Scaling Factor |
|---|---|---|
| core_bot | 0.702112W | 1.00679 |
| core_top | 0.70129W | 1.00652 |
| sec | 6.71271W | 1.01602 |
| primary | 6.65798W | 1.03279 |

Imported loss density into Workbench

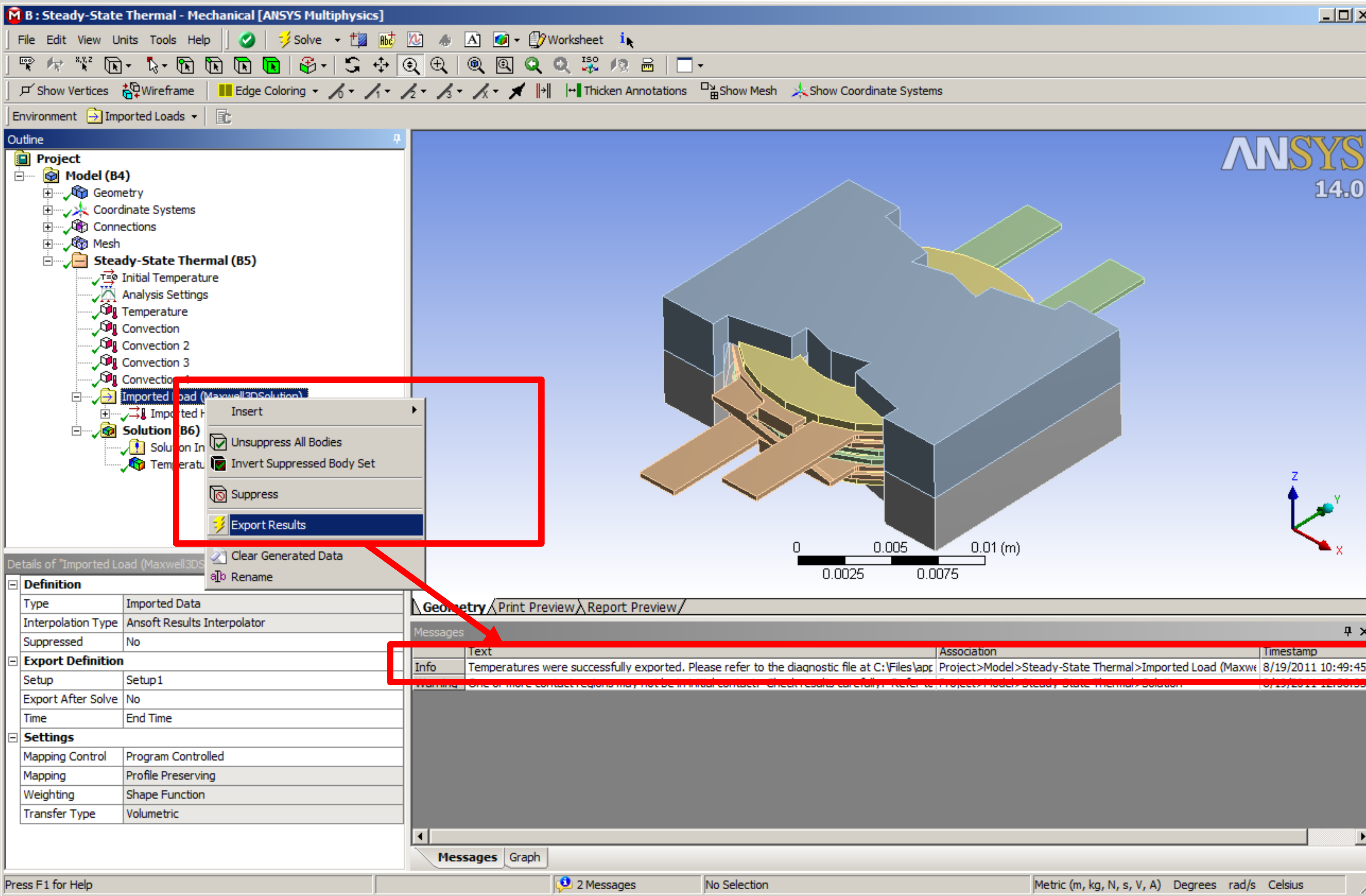
# Ferrite Core Transformer Temperature at 100kHz

- Temperature range from 22–182 deg C



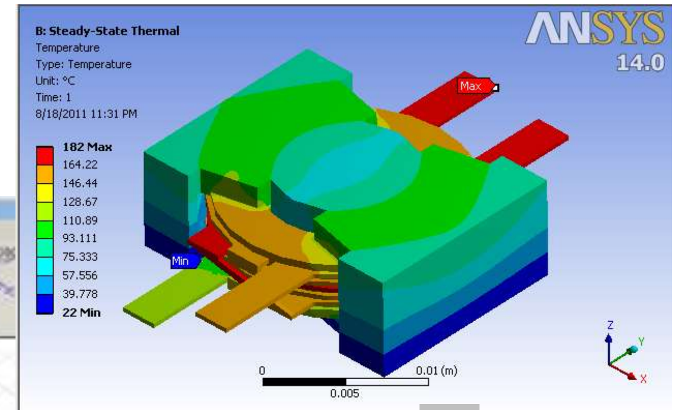

  

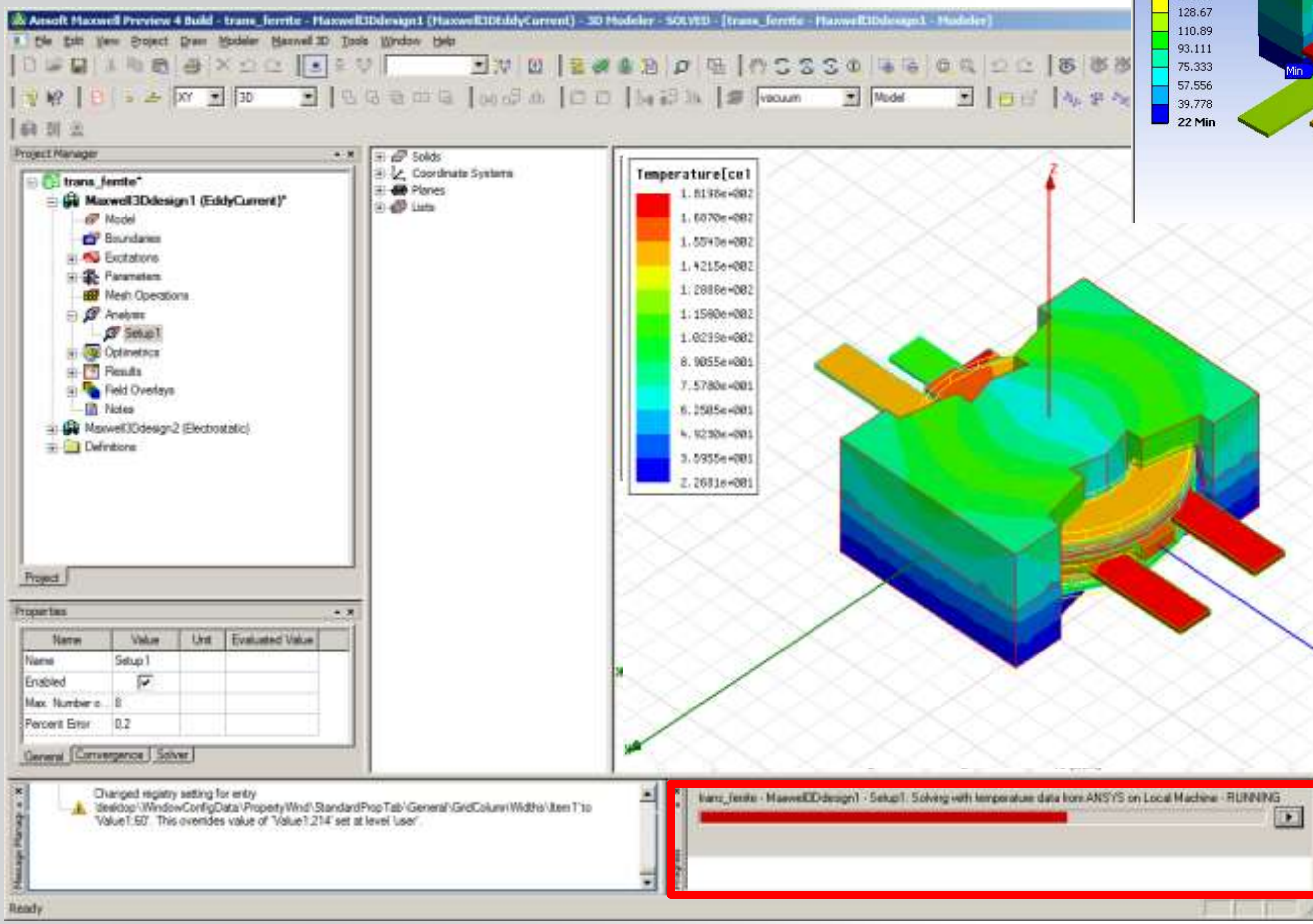
# Export temperature back to Maxwell



# Re-solve in Maxwell with actual temp from Workbench



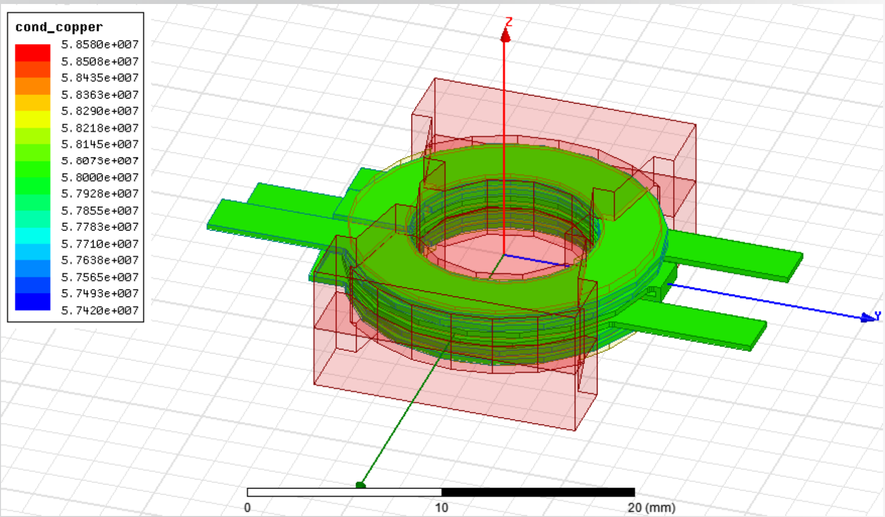




**Message: Solving with temperature data from ANSYS**

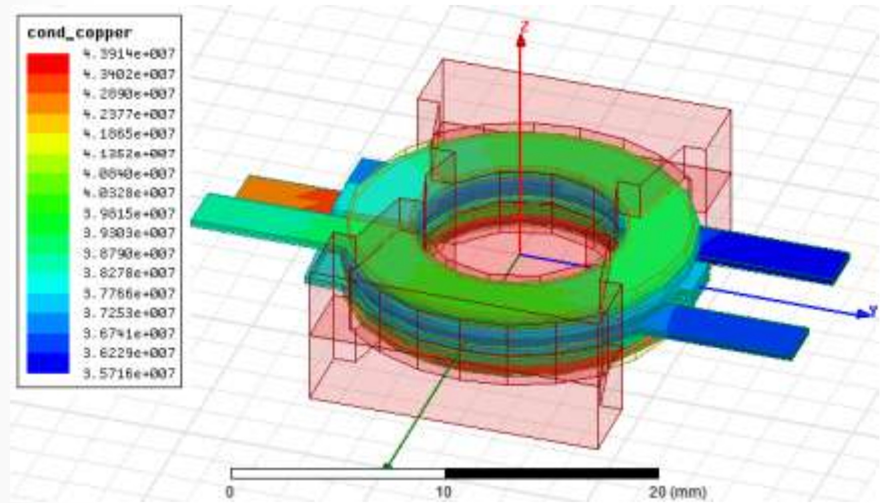
# Updated Copper Conductivity with 2-way coupling

## Initial Conductivity




- Initial conductivity at 22°C is uniform = $5.8e^7$ (S/m)

## Final Conductivity



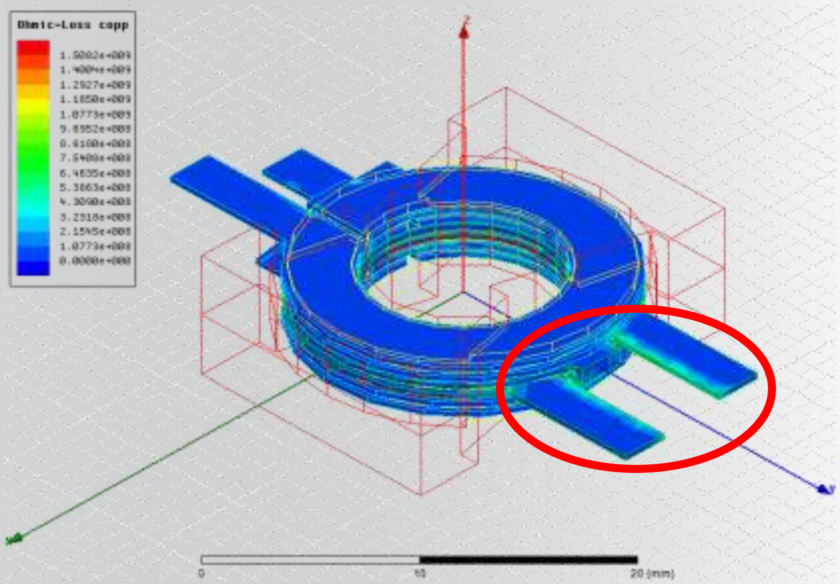

- As temp increases, conductivity decreases
- Final conductivity at operating temperature = $3.5e^7$ to $4.7e^7$ (S/m)

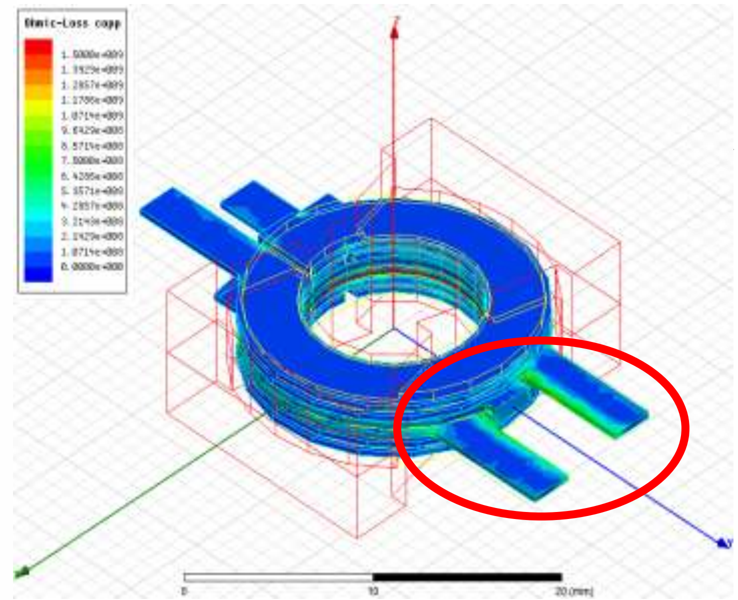
  

# Updated Loss density with 2-way coupling

**Initial Loss Density at 22 C**

**Increased Loss Density at operating temp**





total losses

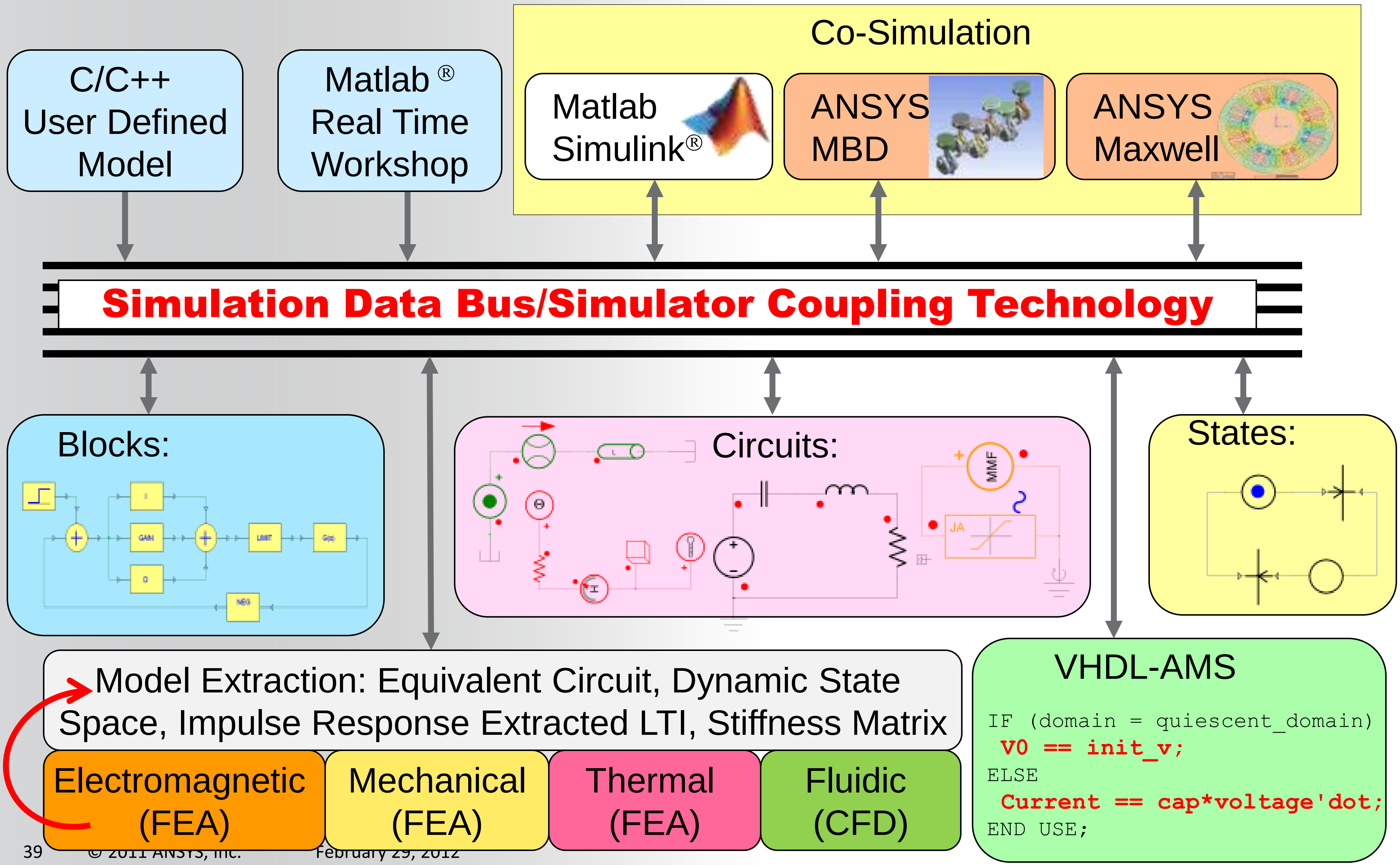
| | 1 |
|---|---|
| Freq [kHz] | 100.000000 |
| pri_loss<br>Setup1 : LastAdaptive<br>Phase='0deg' | 6.657984 |
| sec_loss<br>Setup1 : LastAdaptive<br>Phase='0deg' | 6.712708 |

total losses

| | 1 |
|---|---|
| Freq [kHz] | 100.000000 |
| pri_loss<br>Setup1 : LastAdaptive<br>Phase='0deg' | 9.867150 |
| sec_loss<br>Setup1 : LastAdaptive<br>Phase='0deg' | 10.490194 |

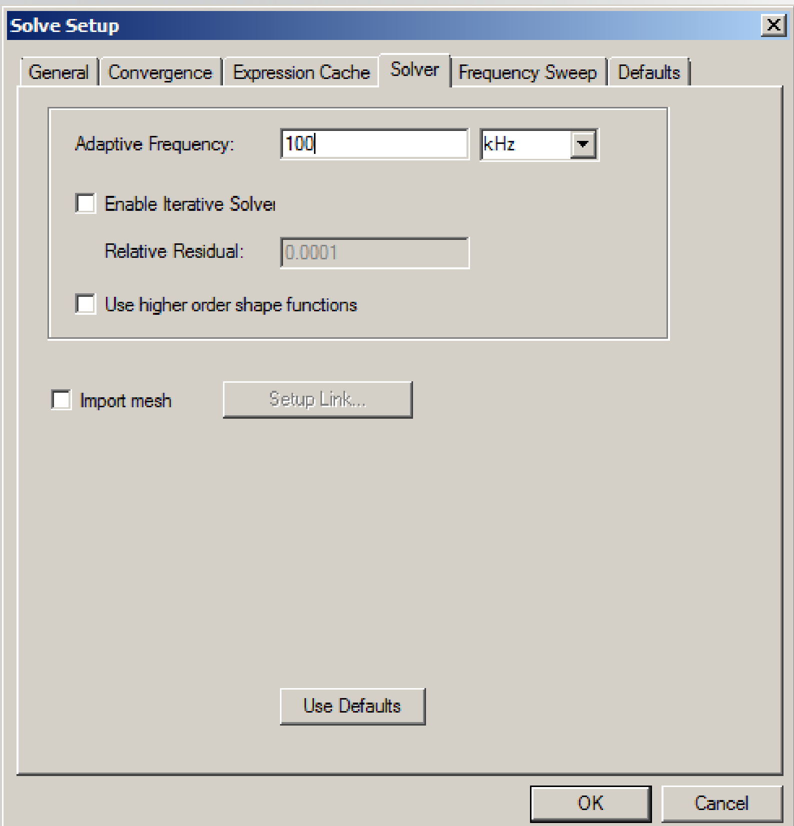
  

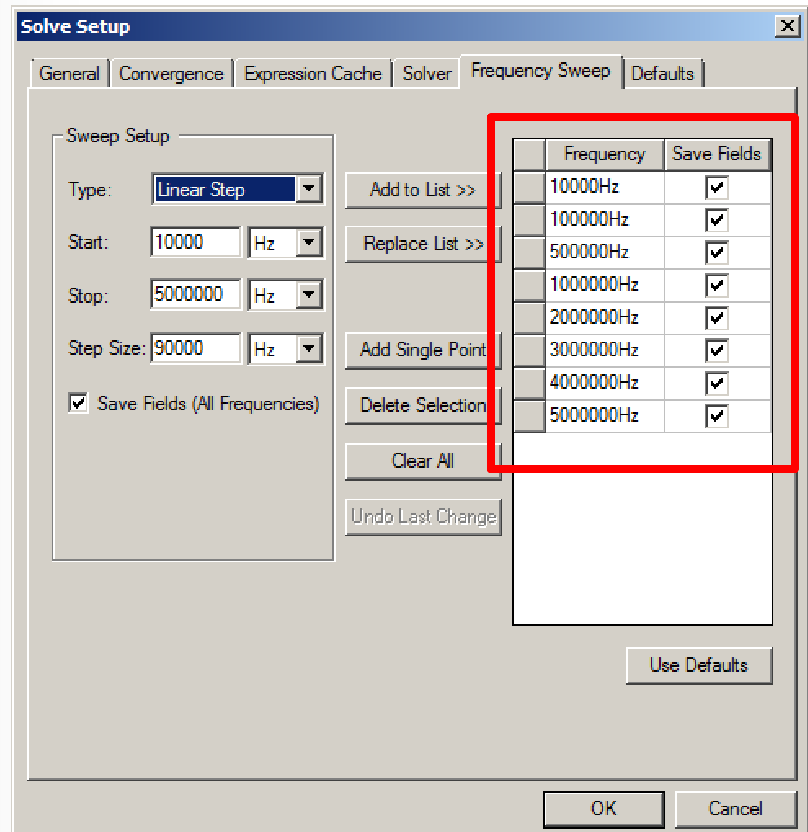
# Simplorer Architecture



# Simplorer System Simulation

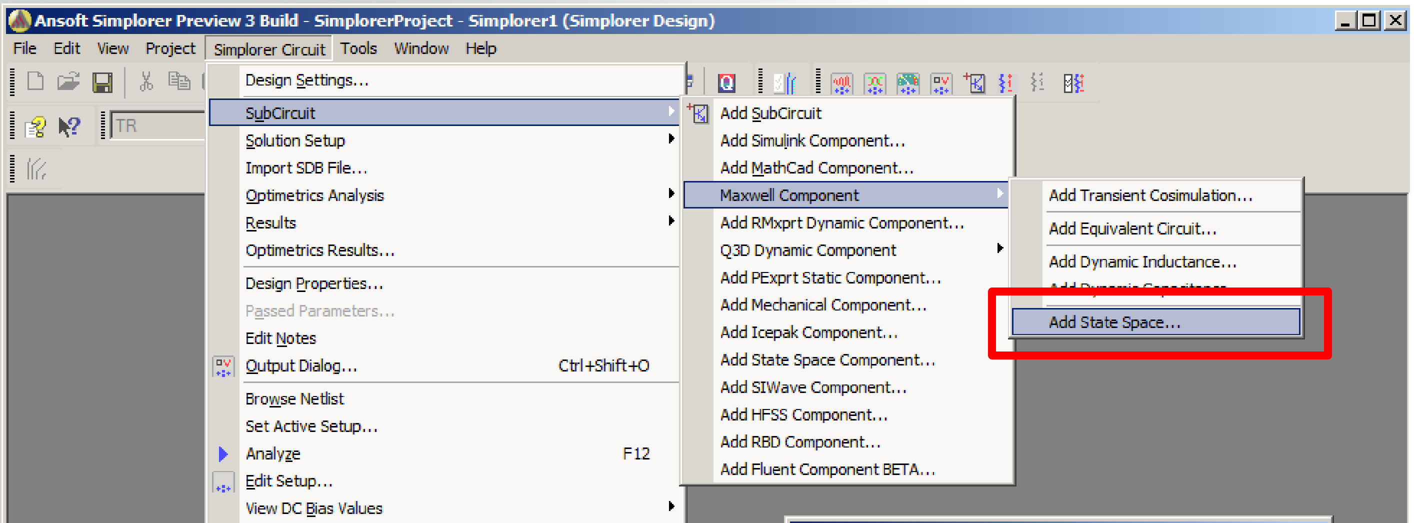
## Maxwell 3D Frequency Sweep

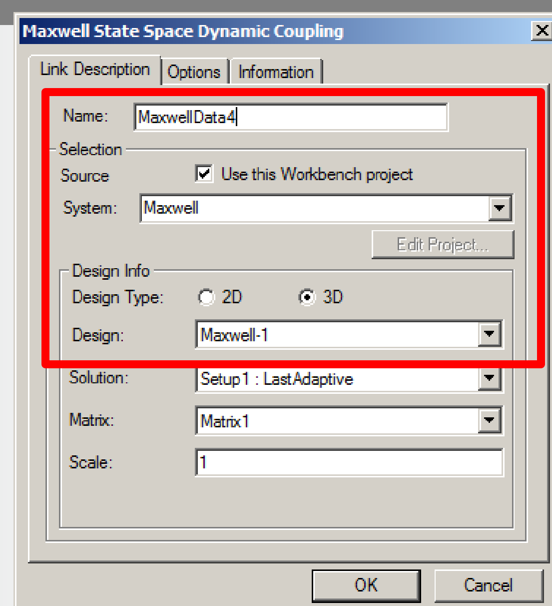


# Simplorer System Simulation



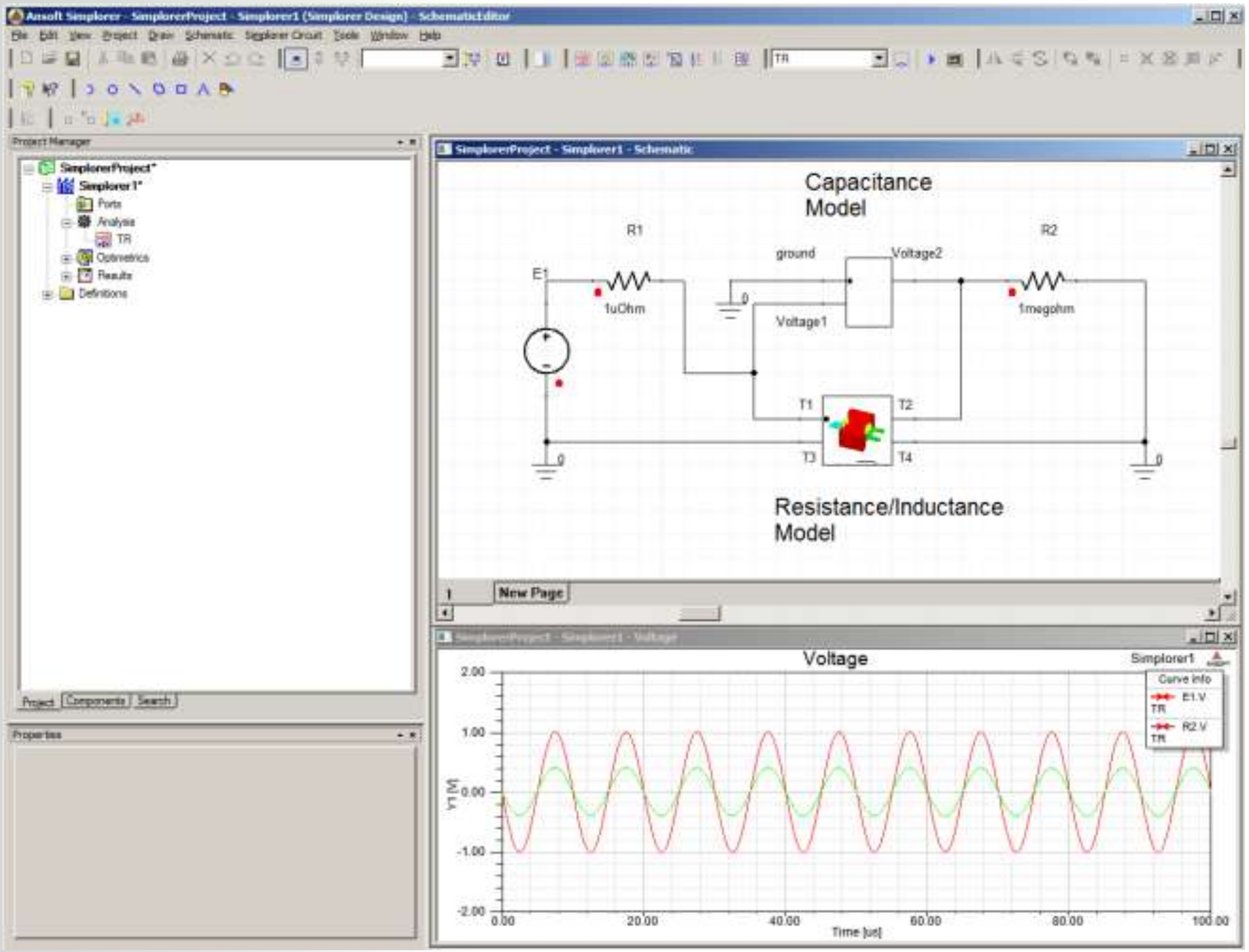




**Select appropriate Maxwell 3D design with frequency sweep**

# Simplorer System Simulation

- Imported frequency dependent R,L model (state-space)
- Imported capacitance model
- Apply appropriate sources and loads




  February 29, 2012

# Conclusions

- Maxwell 3D determines R, L and loss components (eddy current, hysteresis, proximity, skin) at multiple frequencies as well Capacitance
- Using Workbench, Maxwell loss densities are coupled to ANSYS Mechanical for temperature rise calculation
- Resulting temperature rise can be coupled back into Maxwell to change material properties such as permeability and conductivity and determine thermal operating point and calculate higher losses
- Maxwell 3D can export a frequency dependent transfer function using Dynamic State Space coupling inside of Simplorer to allow for a complete system simulation